Grant Agreement No: 312453

EuCARD-2

Enhanced European Coordination for Accelerator Research & Development

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures,
Combination of Collaborative Project and Coordination and Support Action

PROJECT FINAL REPORT

FINAL EUCARD-2 PROJECT REPORT

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Name of the scientific representative of the project's coordinator, Title and Organisation:	Maurizio Vretenar, Project Coordinator
Tel:	+41 22 76 72925
Fax:	+41 22 76 78666
Email:	Maurizio.Vretenar@cern.ch
Project website address:	http://cern.ch/eucard2

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I. PUBLISHABLE SUMMARY

EXECUTIVE SUMMARY

Particle accelerators are contributing to the advancement of physics and, through accelerator-based X-ray and neutron sources, to the progress of medicine, biology and material science. With more than 30,000 accelerators worldwide in the industrial and health sectors their use is rapidly spreading outside of the scientific environment, to address societal challenges and to generate economic growth. To deal with the increasing demands from basic science and to enhance the diffusion of accelerator technologies towards applied science and societal applications, future particle accelerators need to be more powerful but at the same time have smaller footprint, better energy efficiency, and higher reliability. A common development strategy to face these challenges was the subject of the EuCARD-2 (Enhanced European Coordination for Accelerator Research and Development) Integrating Activity Project. It brought together a consortium of 40 European universities, accelerator laboratories and technological institutes on a programme that, over 4 years, has mobilised a community of more than 350 researchers, organising more than 100 workshops and events and producing 62 high-level deliverable reports, 282 publications and dissemination activities and 4 applications for patents.

The EuCARD-2 Networks have generated a large amount of studies, initiatives and new ideas in a wide range of fields related to accelerator technologies. Activities were centred on future circular particle colliders, storage rings for intense beams, superconducting hadron linacs, and polarization challenges. Novel ideas included sequences of large circular colliders, new schemes for the production of cold muon beams, future acceleration concepts based on crystals or nanotubes, and new concepts and techniques for lattice optimisation in synchrotron light sources. The activities on Novel Acceleration techniques generated a new successful series of bi-annual international Workshops and a new Design Study supported under Horizon 2020. Other Networks covered subjects closely related to innovation, societal challenges and applications, organising three “EuCARD-2 meets industry” events on selected subjects from the project technology portfolio: medical isotope production with accelerators, new materials for extreme thermal management, and environmental applications of low-energy electron accelerators. Other activities covered the evaluation of conceptual aspects of the energy efficiency of particle accelerators, as well as the efficiency of typical component technology used in particle accelerators. The Network on Accelerator Applications has identified existing and new applications that could benefit from accelerator technology, documenting these in a comprehensive document, the “Applications of Particle Accelerators in Europe”.

Three accelerator test facilities provided Transnational Access for a total of 10,557 access units.

A Joint Research Activity (JRA) made remarkable progress in the application of High Temperature Superconductivity (HTS) to particle accelerators, selecting suitable superconductor, tape and cable design, and achieving the world record of 1.3 kA/mm^2 current and realising a coil tested in a magnet at 3.3 T field. Another JRA developed and improved novel composite materials for collimators exposed to high luminosity beams. A third JRA on innovative Radio-Frequency technologies has demonstrated new thin film deposition techniques to realise superconducting accelerating cavities at lower cost, and has contributed to the design manufacturing and testing of high gradient accelerating and deflecting structures to very high performance. The last JRA progressed in the field of plasma wakefield accelerator. Higher brightness beams, external injection, and feasibility of femtosecond-level synchronisation between lasers and beams have been demonstrated, together with the particular operating regime of a plasma excited by an intense proton beam.

PROJECT CONTEXT AND OBJECTIVES

2.1. CONTEXT

Accelerator-based activities are rapidly growing today, with more than 30,000 accelerators currently in operation world-wide. While a few large accelerator research infrastructures are particularly visible, and the Higgs search at the Large Hadron Collider (LHC) at CERN has fascinated the public as well as particle physicists, most particle accelerators are dedicated to applied research, medicine and industry. A marked interest has arisen in the fields of energy and environment, where the potential of particle accelerators could become revolutionary. With such a multitude of applications, accelerator technology is reaching the frontiers of performance, energy efficiency, cost, and size to name a few. Advances in technology are needed to face the challenges of both research and society.

In this context, the main drive for particle accelerator development still comes from fundamental research in particle physics, which is now at a turning point. The start of operation in 2009 of the LHC has allowed Europe to regain the world leadership in particle physics, a key sector of knowledge and technology. A challenging upgrade of the extremely complex LHC collider has been recently approved, requiring new sophisticated technologies and putting new strain on the operational parameters of the entire CERN accelerator complex. This major step will deliver sufficient information on rare processes to shed light on the existence of new particles.

In parallel, three major accelerator projects which represent important milestones in the ESFRI (European Strategy Forum on Research Infrastructures) roadmap are starting operation or are in an advanced construction phase. The European XFEL at DESY (Hamburg) is beginning its operation; providing ultra-short intense X-ray pulses at short wave-length to a variety of users it will open new perspectives for a wide range of applied sciences. The European Spallation Source (ESS) laboratory in Lund, Sweden, is in an advanced stage of construction and will provide its first neutron beam to users in 2019. This third generation neutron source will give a new insight on all types of materials, from molecules to medicines, from plastics to proteins. Finally, a new large international accelerator complex, FAIR, is in construction at GSI (Darmstadt). Its goal is to gain new insight into nuclear matter by providing ion beams at the intensity frontier, with increased energy, brilliance and beam power. Besides these large international research infrastructures, a significant number of small but unique research accelerators share the objectives of enhancing performance, while reducing cost and environmental impact.

In a similar way, applications of accelerators are rapidly growing. One of the most visible fields is cancer therapy, where particle therapy, directly based on the technology of research accelerators, is increasingly successful. With 19 centres for particle therapy in operation and 10 more under construction, Europe is the leader in this advanced health treatment, whose diffusion is only limited by the cost and complexity of the accelerator and beam delivery system. While the use of small scale electron and ion accelerators keeps growing in industry, accelerators have high potential in new domains related to the energy and environmental challenges that our society is facing.

In this stimulating environment, two fundamental requirements have to be fulfilled to face the demands of the present and future generations of particle accelerators. The first is the need for international collaboration: all present and future large projects go beyond the capabilities of individual European countries and need to be implemented as large European or world-wide collaborations. Setting up a European collaborative environment today is instrumental to achieving the goals of tomorrow. The second requirement is the availability of new technologies which may be brought to maturity in a collaborative environment and made available to the wider community, across projects and national borders.

2.2. PROJECT OBJECTIVES

In this particular and challenging context, the main objectives of the EuCARD-2 project were:

- To connect transversally the different large accelerator laboratories and reinforce a collaborative approach to outstanding upgrades of major accelerator infrastructures, by establishing links between laboratories, universities, research institutes and industry.
- To concentrate the common resources on focused Research and Development activities of excellence, where Europe can keep or gain leadership in outstanding research infrastructures and develop favourable conditions for innovation beyond the primary research goals.
- To share the challenges of high-gain high-risk R&D studies.

These wider objectives translate into more focused objectives for the individual Networks, Transnational Access (TNA) and Joint Research Activities (JRA) that are given below.

WP2 (Innovation): Its main objective was to maximize the likelihood that the knowledge and technology produced across the EuCARD-2 work packages (WP) is transferred to society and industry, thus enhancing the resulting impact. The strategy to achieve this objective was based on examining the technology developments made within the project in detail, and then ensuring that these were known to industry, via joint workshops with members of industry and/or via the Technology Transfer offices of each partner. The collaboration between research laboratories, universities, specialized institutes and applied research institutes was intended to facilitate the identification of potential innovations and route to exploitation. The organization of "EuCARD-2 meets industry" events on selected topics aimed to create direct person-to-person contacts and collaborations, thus filling the observed gap between academia and industry.

WP3 (Energy Efficiency): New particle accelerator based research facilities aim for increased performance, but this often corresponds to higher energy consumption. The goal of this WP was to analyse conceptual aspects of modern accelerators as well as specific accelerator subsystems defining strategies and technologies aimed at reducing the electric power from the grid during operation while keeping the required performance. The key technologies for maximising energy efficiency of accelerator facilities analysed by this Network were heat recovery from cooling circuits, efficient Radio Frequency (RF) generation, energy management in a virtual power plant, energy storage, and energy efficient beam transport.

WP4 (Applications): Particle accelerators are already extensively used for a range of applications, in particular in the health and industrial areas, with more than 30,000 in regular use. However, the accelerator technology used is rather old. The aim of this Network was to study both applications and the accelerators required for their use, to assess areas which could benefit from newer accelerator technology developed for Research Infrastructures (RI), as well as identifying possible new applications. This was achieved by the organization of workshops on a wide range of topics and documenting the knowledge gained via a high-level document. An additional objective was to identify further work to be done and to form collaborations to carry it out.

WP5 (Extreme Beams): The WP5 Network explored the collider and accelerator frontiers with the objective of pushing the limits of present accelerator beams, in terms of energy, luminosity, intensity and polarization, and, specifically, at maximizing the performance of major European projects now under construction or being proposed, in particular the High-Luminosity LHC (HL-LHC), FAIR, ESS, and future accelerators presently in the design stage. The primary goal was to provide a forum for exchanges between researchers, to discuss innovative ideas and to define common strategies or solutions for the upgrade and/or construction of large accelerator facilities. This Network also aimed at enlarging the boundaries of the community, interconnecting with similar initiatives outside Europe and with other scientific communities whose competences relate to the challenges of future accelerators. The final goal was defining European strategies for the development of future extreme beam facilities.

WP6 (Low Emittance Rings): The Network's objectives focused on ultra-low emittance rings, i.e. pushing the beam density in lepton storage rings by reducing its size, well beyond present limitations. Its primary goal was to bring together a large community of accelerator physicists and engineers working on three different types of accelerators, damping rings, colliders and synchrotron light sources that have been traditionally separate, despite the many common scientific and technological challenges. The overarching goal was to communicate, identify and promote common work on topics affecting the design of low emittance electron and positron rings, with a particular focus on increasing the performance of the large and strategic European infrastructure of synchrotron light facilities. The main topics considered were lattice design, beam dynamics and technical challenges.

WP7 (European Network for Novel Accelerators): The goal of this Network was to promote novel accelerator technologies that can provide orders of magnitude higher accelerating fields and thus have the potential for significantly reducing the size and cost for new accelerators. The first goal, bringing together 54 institutes worldwide, was to structure and coordinate a strong but dispersed European community, with solid connections outside of Europe and with other scientific communities, such as the teams working on lasers. The Network's objective was fostering research on alternative acceleration techniques (mainly plasma acceleration), collecting the experience of small laboratories and fusing the community on the exigencies of large-scale facilities. A specific objective was to focus the diverse plasma wake field community to define a common roadmap.

WP8 (Ionisation Cooling Test Facility): This work package intended to provide Transnational Access to the Ionisation Cooling Test Facility, which comprises specifically developed target and beam-line at the proton synchrotron of the STFC's Rutherford Appleton Laboratory. The objective foreseen for ICTF was to deliver at least 2,280 access units (hours) to an estimated number of 40 users from 20 projects.

WP9 (HiRadMat and MagNet): This work package was intended to provide Transnational Access to two facilities based at CERN: the High Radiation Materials test stand (HiRadMat) using a high-intensity high-energy proton beam from the SPS accelerator, and a test stand for superconducting magnets and equipment (MagNet) operating at cryogenic temperatures based in the SM18 Hall. The objectives foreseen for HighRadMat were to deliver at least 2,400 access units (hours) to an estimated number of 40 users from 8 projects. The objectives foreseen for MagNet were to deliver at least 1,920 access units (hours) to an estimated number of 64 users from 8 projects.

WP10 (Future Magnets): The goal of this Joint Research Activity was to advance the development of accelerator magnet in HTS (High Temperature Superconductor), to reach magnetic fields beyond 16 T, which is the limit of the present (second) generation of magnets based on Nb_3Sn technology. A substantial step in reaching fields of about 20 T will open new perspectives for high-energy hadron colliders and will pave the way to new accelerator designs and possibly a large wealth of applications outside particle physics. The precise objective of the JRA was the design, characterization, construction and test of the first full-bore demonstrator collider magnet using HTS technology reaching a magnetic field compatible with operation at 20 T as an insert in a Nb_3Sn accelerator magnet.

WP11 (Collimator Materials): This JRA aimed to increase the capability of beam collimators to handle very high brightness beams that are required by major European projects like HL-LHC at CERN and FAIR at GSI. Peak energy densities up to 15 GJ/mm^2 that are now imaginable in the LHC beam constitute a completely unknown territory for collimators in terms of materials and design. The JRA's objective was to focus efforts on new extreme brightness and on some successful materials already identified, to come to the final choice of material and design for extreme brightness collimators, selecting between new types of Molybdenum carbide-graphite and metal-diamond composites. To this aim, extensive material studies, modelling and characterization in the partner laboratories, production by industrial partners of several material grades, and a number of irradiation campaigns under ion and proton beams to study material response were foreseen.

WP12 (Radio-Frequency): Reducing size, energy consumption and overall cost are of primary importance for all accelerators being developed today. The Innovative Radio-Frequency (RF) Technologies JRA contributed to this overall goal by focusing on the development of a range of technical solutions, with the potential to achieve a significant performance increase in gradient, efficiency and beam quality of RF-based accelerator systems. Several novel techniques in the field of normal and Superconducting RF technology have been selected, presenting the highest impact potential for the accelerator community. The main objectives being: a) the development of multi-layer SRF thin films in order to break new ground in achieving gradients well beyond present Nb technology; b) the development and test of efficient normal-conducting structures capable of high gradient operation (Eacc > 100 MV/m) but free from dangerous wakefield contributions; c) demonstration using Higher Order Mode (HOM) signals from accelerating cavities as beam position diagnostics in high-energy electron linear accelerators, with the goal of reducing accelerator cost and length; d) the development of a new generation of advanced photocathodes for use in RF injectors, thereby enhancing the ability to reach fs-scale response time, more effective electron beam generation, capture and transport with high brightness and low intrinsic emittance.

WP13 (Novel Acceleration Techniques): The objective of this JRA was to create opportunities for collaborative studies on topics exploring novel frontiers of particle accelerators having in common the extreme high-gradient acceleration of particles within plasmas. Three subjects were selected as requiring further studies. Two were related to plasma wake field acceleration, while the third was related to production and control of ultra-short electron pulses; all these activities were concerned by femtosecond time scales. The objective of the first activity was to compare methods for the production of high brightness electron beams by external or optical electron injection into a laser-driven wake field plasma accelerator. The second investigated the feasibility of coherent waves in very long plasma cell, a critical component of a proton-driven plasma wake field accelerator. The objectives of the third activity were to control at bunch level ultra-short beams at the femtosecond scale.

THE MAIN S&T RESULTS / FOREGROUNDS

WP2: CATALYSING INNOVATION (INNOVATION)

The Innovation WP of EuCARD-2 has:

1. Enhanced collaboration between academia and industry in the field of particle accelerators, enlarging the particle accelerator R&D community to include industry as a strategic partner;
2. Identified three accelerator-related technologies that are close to market; for each of them organised a workshop to establish connections with industrial partners and defined strategies for common development. 62 European companies participated in the three events.
3. Prepared the ground for larger industry involvement in future accelerator projects in the Horizon 2020 programme and beyond.

A preliminary initiative was to carry out technology scouting of all work packages in the form of interviews with all WP coordinators, to identify developments and technologies that are closer to market and are ready to engage with industry. These interviews have highlighted three topics that became the focus for three **'EuCARD-2 meets industry'** events, which brought researchers and members of industry together with a view to forming new partnerships and exploring the potential for knowledge and technology transfer. The following workshops were organised:

WP4 (Accelerator Applications)	WP2 (Collimator Materials)	WP4 (Accelerator Applications)
Topic: Compact Accelerators for Isotope Production	**Topic: Applications of Thermal Management Materials**	**Topic: Low energy electron beams for industrial and environmental applications**
26-27 March 2015, STFC (UK)	*6 November 2015, CERN*	*8-9 December 2016, WUT (Poland)*
Attendance: 70 (24 from industry)	Attendance: 85 (20 from industry)	Attendance: 70 (18 from industry)
Main outcomes: The workshop brought together industry, clinicians and academia to explore how accelerator technologies can be applied to future medical isotope production needs for both diagnostics and therapy. The aim of the workshop was not only to review the state of the art of novel accelerator technologies for production of radioisotopes, but also to initiate future joint clinical/industrial/academic collaborative projects addressing the demand in future radioisotopes. Understanding industry requirements was critical to propose strategies for continued research.	**Main outcomes:** Materials for collimators and other beam-intercepting devices share many requirements with advanced thermal management applications. The aim of the workshop was to understand the needs and requirements of industrial companies and institutions, essential for adequate knowledge and technology transfer. The workshop clarified the requirements and overlapping interest of the participants, through discussions and a questionnaire. Such new materials have applications in power electronics, aerospace, advanced braking systems and hot components for gas turbines.	**Main outcomes:** The workshop aimed to provide an overview of the state of the art and highlight new uses/developments of electron accelerators in sterilization of healthcare products, curing of materials, new materials synthesis (composites, nanostructures, grafted surfaces and gels) and the treatment of industrial flue-gases, waste water and sludge. Leading industry experts with unique experience were brought together with researchers for presentations and a panel debate from which it became clear that low-energy electron beams hold a much higher industrial and societal potential than the present usage suggests. Understanding the barriers of market entry when conducting R&D is vital for future progress.

The first workshop sought to address the expected increase in future demand of medical isotopes for diagnostics and for targeted cancer therapies. Radioactive isotopes are commonly used in nuclear medicine for imaging of active physiological functions within the body like cancers. They are presently produced either by nuclear reactors (Technetium 99 for SPECT analysis) or by dedicated cyclotron accelerators based in large production facilities (Fluoride 18 and other isotopes for the more accurate PET – Positron Emission Tomography). The use of therapeutic isotopes for localised cancer treatment is only starting and could become an essential tool for future personalised cancer treatment. The workshop identified areas of action for the accelerator community, such as addressing concerns related to the global supply chain for Te99, which comes exclusively from a small number of aging research nuclear reactors, and developing compact low cost accelerators for production of F18 and short-life isotopes directly in the hospitals. The international meeting with industry addressed the technological and economic challenges, as well as significant regulatory aspects to consider.

The second workshop sought to investigate how novel thermal management materials used to handle the large amount of energy deposited in accelerator collimators and other beam-intercepting devices (BIDs) can be applied to industrial domains such as automotive, aerospace, electronic packaging, fusion and solar energy. Although accelerators represent a very narrow application, the materials developed for accelerator BIDs share many requirements with advanced thermal management applications in industry and aerospace. Both a dedicated survey and discussions during the workshop proved that several companies have a strong interest in the new accelerator thermal management materials, in particular molybdenum graphite (MoGr). However, production capacity was identified as a potential bottleneck: because some of the advanced materials such as MoGr are at an early development and manufacturing stage, very few actors have the capacity for manufacture of such material in volumes that are still limited. This, however, may well change in the near future.

For the third and final workshop, the selected topic was "Low energy electron beams for industrial and environmental applications". A large fraction of more than 30,000 accelerators in operation worldwide are low-energy electron accelerators used in industry, and reviewing their status and perspectives was considered very important from the industrial and societal point of view. Although such accelerators are common or even standard in certain applications, e.g. for polymer modification, the workshop identified fields where there appears to be a very large untapped industrial potential.

Most notably, electron accelerators hold huge potential for treatment of wastewater, sludge, and flue gases. Studies show that electron accelerators can provide more efficient treatment than conventional methods while being also more cost-effective, as confirmed by several pilot plants and a few full-scale operational plants. By bringing in some of the leading experts with operational experiences, it was possible to shed more light on the barriers preventing widespread adoption and how these can be overcome. Limits to the diffusion of accelerators are related to permissive regulations, to high capital costs for a technology that becomes cost effective on the medium-long term, and to the hesitance of well-established industry to follow new approaches. If a certain number of new accelerator-based centres for treatment of wastewater, sludge, and flue gases are built in the near future, it could lead to a rapid acceleration in industrial adoption of this technology. One important message is that the focus for subsequent research and development of low-energy electron accelerators should lie in scaling down: the technology is already good enough, but must be made cheaper, simpler, and more practical in order to better appeal to industry. Therefore, the workshop resulted in the definition of a common programme bringing together accelerator manufacturers with operational experience and researchers that will be part of the next particle accelerator Integrating Activity.

WP3: ENERGY EFFICIENCY (ENEFFICIENT)

The new Energy Efficient Network of EuCARD-2 has:

1. Performed eight dedicated studies on critical topics for an efficient energy management of present and future accelerator infrastructures.
2. Compiled an important amount of information on energy management that will be available to the planners of future infrastructures.
3. Contributed to the development of specific accelerator components aimed at reducing energy consumption, as tunable quadrupole magnets and high-efficiency klystrons.
4. Increased the awareness on energy and energy management in the community of particle accelerator designers, providing them with specific knowledge and tools to increase the efficiency of new and existing designs.

The overall energy efficiency of particle accelerator infrastructures is usually quite low. Transforming the energy from the electricity grid into the energy of a particle beam is a long and complex process with inherent energy loss at different stages; beam quality requirements usually drive the design resulting in poor energy efficiencies. This Network has been the first attempt in Europe to federate a large community using sharing experience, tools and ideas towards an improved energy management.

Heat recovery from conventional or accelerator structures is a promising avenue to increase energy efficiency of research facilities. Some accelerator sub-systems, like cryogenics or Radio Frequency, are inherently inefficient and waste significant portions of the electrical energy as heat. The activities of the Network have identified potential solutions, such as:

a. Implement heat recovery systems from RF power units, as already done in some laboratories and under study for the ESS project.
b. Use waste heat for heating buildings, to reduce energy consumption and possibly generate income (Figure 1). Heat recovery systems need to be combined with heat pumping systems in order to increase the output temperature up to the minimum required by the district heating system.

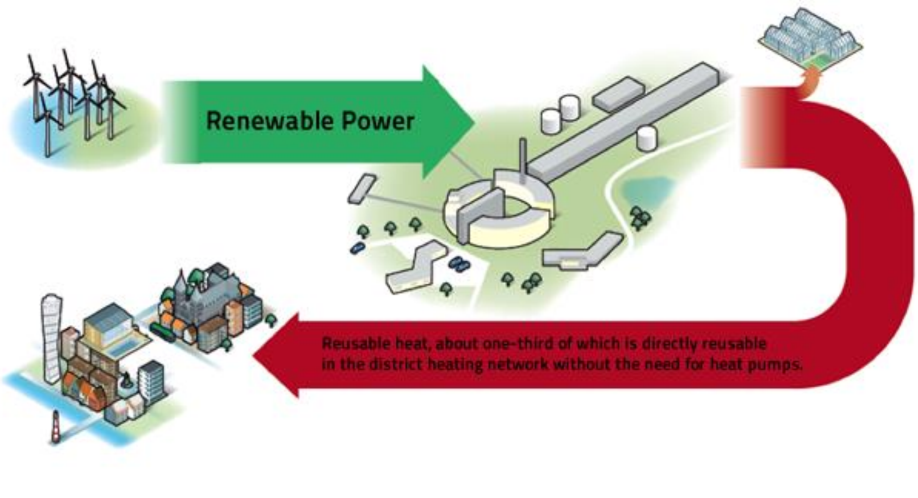


Figure 1: Conceptual view of heat recovery from an accelerator based facility to district heating system, from the ESS project. The district heating system includes a low temperature system, i.e. a green house facility. One part of the district heating system can be the local facilities heating system.

Improving the **efficiency of RF power systems** above values that are often below 50% in operation can have a strong impact on the overall efficiency of accelerator facilities. The Network analysed in detail three technical options:

a. a new bunching mechanism called the Core Oscillation Method, which could boost klystron (electronic) efficiencies from presently 65% to up to 90%;
b. the possibility to increase the output power of the (already quite efficient) Inductive Output Tubes power sources into the MW-class by developing a multi-beam version of this device;
c. design cavity power combiners that could allow to make solid state power amplifiers attractive for large accelerators by combining the power of hundreds or even thousands of transistors to reach the MW-class.

Particle accelerators utilize **energy storage systems** in many areas. Storage technologies include mechanical systems and energy storage in electric or magnetic fields covering a wide range of timescales, capacities and power rates; besides the technical parameters also reliability, lifetime, and possible failure scenarios are important. Capacitive and inductive storage provide high efficiency and high power rates, but have limited energy capacity and relatively high costs. The Network explored the following options:

a. Capacitor Banks, for which research aims to develop capacitors with lower fault rate and avoiding fault mechanisms that result in a shortcut of the capacitor challenge.
b. Superconducting Magnet Storage: the development of new superconductor cables can make these systems very attractive for future facilities.
c. Large capacity systems, whose importance will increase with the fraction of renewable energy sources in the overall energy mix. The Network supported the LIQHYSMES system proposal[1], which is an interesting option to combine the fast reaction time of inductive storage with the huge capacity of chemical storage. Moderately sized, this system is a valid option for an uninterruptable power supply for an entire accelerator facility.

Besides energy storage, another mean of facing fluctuating energy production and demand can be a **virtual power plant**, formed by a pool of distributed power producers and consumers to increase the overall availability and stability of the combined energy sources towards the public energy market. Large consumers in the pool can be switched off to lower consumption on demand; accelerator facilities are major energy consumers and so offer potential switchable loads. Lowering their consumption in times of high energy demand can help stabilize the network and reduce operation costs for the facility. The WP has surveyed the overall energy consumption of eight large European facilities which operate accelerators and investigated possible scenarios for reducing consumption on demand, such as introducing energy saving cycles with lower physics output and less overall energy demand. One limitation to these approaches is that complex processes tend to work best in a steady-state operation and switched operations carry intrinsically more complexity and risk of failure.

Beam transfer lines can contribute at a fraction of the total energy consumption of any high-energy accelerator facility. A comparative study of a number of beam transfer line design options was performed (Figure 2) for a specific case, comparing normal conduction magnets (NC), cosine-theta (SC) and super-ferric (SF) super-conducting magnets, high current pulsed magnets (HCP), and

[1] Sander, M., Gehring, R., LIQHYSMES—A Novel Energy Storage Concept for Variable Renewable Energy Sources Using Hydrogen and SMES, IEEE Transactions on Applied Superconductivity, Vol. 21, Issue 3, June 2011.

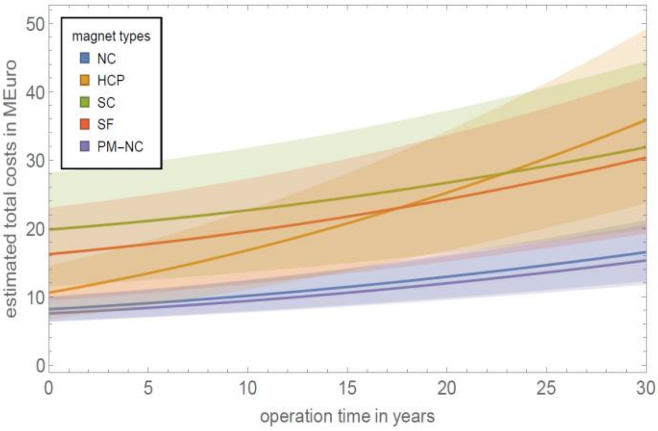


Figure 2: Estimated sum of total investment and operation/energy consumption cost of NC, HCP, SC, SF and PM-NC magnet systems for a heavy ion beamline from the SIS100 at FAIR to a target or an experiment.

permanent magnets (PM). The final cost depends on the operation time (trade-off between investment cost and operation cost) but shows a clear advantage for permanent magnet systems. For the transport of bunched beams, the magnetic guiding fields are required only for the duration of the pulse length and so **high current, pulsed magnetic lenses** with low inductance are a valid solution. A novel pulsed quadrupole design developed at GSI was tested up to a current level of 30 kA; field quality and reproducibility were adequate for energy efficient pulsed beam transfer lines for bunched beams.

WP4: ACCELERATOR APPLICATIONS (ACCAPPLIC)

The new Accelerator Applications Network of EuCARD-2 has:

1. Highlighted the potential of particle accelerators for new and advanced societal applications in medicine and industry.
2. Structured the European accelerator community active on accelerator applications, fostering its connections with industry that has actively participated to its initiatives, and connecting with national programmes in Europe and outside.
3. Identified two promising directions to exploit the potential of particle accelerators: compact accelerators for radioisotope production and low-energy electron accelerators for industrial and environmental applications.
4. Produced a seminal report on "Applications of Particle Accelerators in Europe" that will be the reference for all future European developments in the field.

The Network assessed the application potential of four types of accelerators and of one sub-system.

Low energy (<20 MeV) accelerators for ions are mainly used for ion implantation, to modify the electrical, mechanical and chemical properties of materials. In particular, the doping of silicon with ions such as boron, arsenic and phosphorus to make semi-conductors is a huge multi-national industry. At higher energies, protons and ions are used for ion beam analysis, to determine the surface composition and structure of materials, and radioisotope production, for imaging and cancer therapy. The latter was identified as one of the main application for which accelerator technology has a strong potential to bring improvements. A number of new and developing applications have been identified, as new engines for satellite propulsion using the Hall effect to accelerate Xe ions to as low an energy as to 300 eV, that is an exhaust speed of 20 km/s, optimal for some satellite orbit tasks. At higher energy, proton accelerators are being studied for the production of specialized neutron spectra for applications such as boron neutron capture therapy (BNCT) and for material analysis. Critical for most low-energy applications is the target where beam energy is converted into other particles, particularly neutrons. New target cooling prescriptions and a collaboration to optimize BNCT targets are among the outcomes of the WP.

Electron accelerators up to 10 MeV have a huge potential for new environmental applications in the areas of flue gas treatment, eliminating Nitrogen and Sulphur from the smokes thus reducing acid rain, and water and biological sludge treatment, killing bacteria to reduce contamination. This has resulted in the formation of a new collaboration that is endeavouring to obtain funding to study the water and sludge applications in both the developed and developing world. This was the second topic identified as bearing a large potential for future developments.

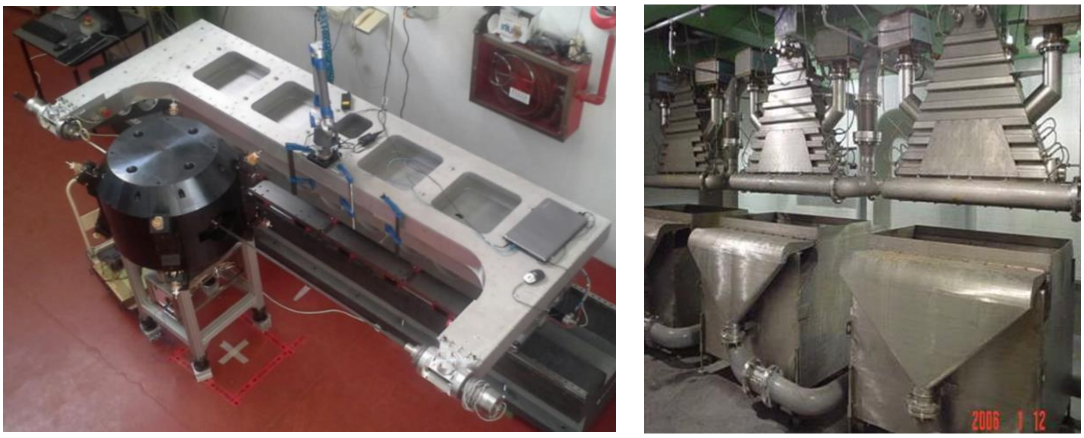


Figure 3: Two applications of accelerator technology: the new AMIT cyclotron for medical isotope production at CIEMAT (Spain) undergoing magnetic field measurements (left) and an industrial water treatment plant using an electron beam in South Korea (right).

Intermediate energy proton and ion accelerators have mainly applications in medicine, for the production of radioisotope for nuclear medicine and ion beam therapy for cancer treatment. Medical applications of ion beams and, in particular, proton cancer therapy, have rapidly grown over the last ten years. While accelerators for proton therapy are already commercial items, there is a wide space for new developments in the field of gantries, the complex rotatable beam transport systems that are installed after the accelerator to irradiate the tumour from any direction. Three workshops have been organized on the design of gantries and related technology. Economical solutions based on the application of superconducting (SC) magnets for the accelerators and for beam transport in the gantry have been investigated; a first workshop has allowed establishing relevant contacts with industry, while a second workshop was essential to establish the contacts between the various groups working on different aspects of superconductivity. SC technology can also help reduce the size of the particle accelerator: after SC cyclotrons, the development of SC synchro-cyclotrons may result in even smaller accelerators with more stringent beam delivery requirements. These issues were addressed in a third workshop, which resulted in the remarkable success that commercial providers of synchro-cyclotrons are now offering pencil beam scanning for their system. Another workshop to analyse and promote the use of Helium beams for ion cancer therapy, rather than the usual Carbon, was successful. Using Helium results in significantly smaller and cheaper ion treatment facilities, with benefits about half-way between protons and carbon ions.

High beam power proton and ion accelerators have applications in the domain of Accelerator Driven Systems (ADS) for driving thorium nuclear reactors and for nuclear waste transmutation. Their potential impact is related to the use of thorium as nuclear fuel, more available than uranium and without risks of nuclear proliferation, and to reducing the environmental impact of conventional nuclear power by reducing the waste lifetime. ADS development faces several technical challenges requiring strong R&D investment. This WP contributed by way organizing three workshops on this subject, promoting interdisciplinary networking and fostering links between different universities, laboratories and industries. A direct outcome of a workshop organised on the subject of accelerator reliability was the setting up of a new collaboration to: a) collecting and sharing information related to the availability and fault tracking in accelerators via databases and web resources, and b) developing from these studies some guidelines to inform the design of accelerator projects. A final workshop on the status of ADS systems attracted participation of worldwide scientific experts from as far as India, China, and United States. It united the two different communities of accelerator and target/nuclear physicists and created useful connections between the European initiatives and their counterparts in China and India. An indirect result was to help build up momentum in Europe on R&D advancement on ADS technologies by fostering contact and networking between scientific experts and political parties from official atomic and EC institutions.

The **high beam power targets** used for particle production are a critical sub-component common to many of the applications considered in the WP, as the production of radioisotopes and neutrons. New technologies were explored, as the use of targets with particle beams accelerated using lasers.

Notwithstanding its many technological advances, the main scientific result of the Network was the production of a document for European science and technology policy makers, entitled **Applications of Particle Accelerators in Europe (APAE)**. This effort describes the current applications of accelerators, improvements in cost and performance that can be achieved by exploiting technology from RIs, possible new applications and what work needs to be done to achieve these. It comes in two parts: a 6-page summary brochure and a 113 page main document with all the details. Printed copies of the brochure will be distributed and the main document will be made available online.

WP5: EXTREME BEAMS (XBEAM)

The Network on Extreme Beams has:

1. Organized a large number of Workshops (35) covering all aspects of frontier accelerator performance, which have structured and enlarged the European accelerator community and connected European accelerator research with ongoing developments in the US and Asia.
2. Defined a European strategy in four critical fields for future accelerator development: colliders, hadron beams, superconducting linacs, and polarised beams.
3. Started in EuCARD and continued in EuCARD-2 the study of a new very large circular electron and hadron collider in Europe, which resulted in the Future Circular Collider (FCC) study at CERN and in the EuroCirCol Design Study in Horizon 2020.
4. Originated and promoted new ideas and developments in many accelerator fields, as extreme energy frontiers, muon collider designs, advanced photonics applications, etc.

Addressing open questions in particle physics calls for collisions at higher luminosities and/or higher energies. The next important step for **e^+e^- colliders** is the commissioning of the high luminosity SuperKEKB B-factory in Japan, along with the design work being carried out for the “Higgs, Z, top, W” factories FCC-ee, hosted by CERN, and CEPC, its Chinese twin project. The Network has demonstrated that the design of these accelerators can exploit the lessons learnt at past and present colliders. These include: a) the possibility of high beam currents thanks to the control of Higher Order Modes and electron cloud; b) the feasibility of the crab-waist collision scheme, as demonstrated at the DAFNE collider in Frascati/Italy; and c) the need for, and possibility of top-up injection, used at many synchrotron-light sources. Novel effects must be considered in the coming projects; for example, beamstrahlung, i.e. the radiation emitted during the collision by particles of one beam experiencing the field of the other beam, will increase the energy spread and bunch length and at highest energy and may even affect the beam lifetime.

Recently, there is a renewed interest in **muon colliders** thanks to the first results from the MICE cooling experiment in the UK, to further improve cooling schemes, and, mostly, to novel proposals to produce the muons already with a low emittance. WP5 workshops have revealed that low-emittance muons can be generated if produced close to threshold either by the annihilation of positrons e+e- → μ+μ-, or by colliding laser photons with a high-energy proton beam circulating in the LHC or in FCC-hh. The main challenge is the low production cross section. One proposal to meet this challenge is using an e+ ring, with a thin internal target. The simplification of the muon collider thanks to using positrons for muon production is evident in Figure 4. In the long term, once low-emittance muon beams are available, the 26.7 km LHC tunnel could be filled with ~5 km of 16 T SC magnets and ~20 km of ±3.5 T pulsed magnets plus an additional 7 GeV from a pulsed superconducting radiofrequency (SRF) system in the straight sections, to construct a 14 TeV muon collider. The ultimate lepton collider might be an X-ray driven muon crystal linear collider, with an accelerating gradient of up to 10 TeV/m and a final crystal funnel. A variant would replace the crystals with carbon-nanotube accelerators and carbon nanotube funnels, respectively.

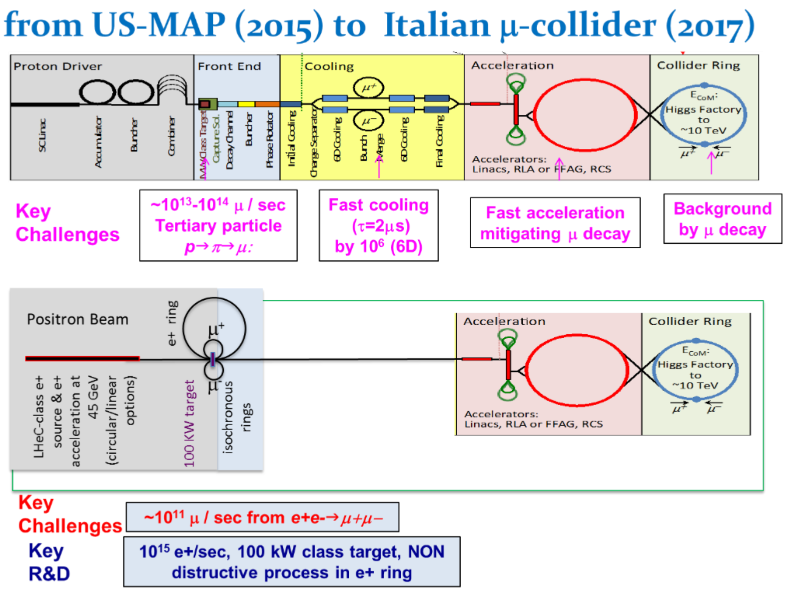


Figure 4: From the US MAP based on a proton driver to the slimmer Italian muon collider based on an e+ storage ring with internal target (M. Boscolo, EuCARD-2 WP5 Strategy Workshop, Valencia, 2017).

Circular hadron colliders are discovery machines, their reach determined by beam energy, which depends on only two parameters: the magnetic field in the dipole magnets and the size of the collider. Historically, new colliders were always larger and used stronger magnets than their predecessors. The 100 TeV hadron version of the Future Circular Collider (FCC-hh), addressed in several WP5 workshops, requires 16 Tesla dipole magnets in a 100 km ring. No other proposed concept, not even a muon collider, appears technically ready to provide collision energies in the 10s of TeV energy range within the next 50 years.

WP5 workshops revealed two attractive routes forward, which combine the aforementioned approaches: one such route starts from a circular e^+e^- collider (FCC-ee/CEPC), proceeds to a 100 TeV hadron collider (FCC-hh/SPPC), and culminates in a 100 TeV muon collider ("FCC-μμ"), which could be constructed towards the end of the century. The other route begins with 25 TeV hadron collisions (HE-LHC) followed by a 25 TeV muon collider in the existing LHC tunnel. Supporting such strategy are two possible figures of merit for future colliders: (1) The effective beam power at the collision point(s) divided by the total electrical power of the facility, and (2) the total luminosity per electrical input power. Both figures of merit clearly reveal the advantages of circular design approaches, where the same particles are made to collide over many turns.

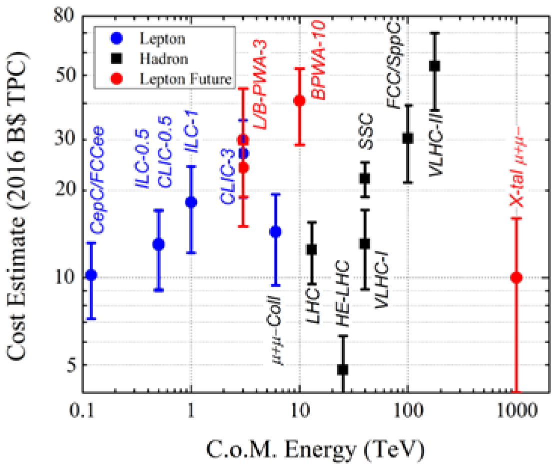


Figure 5: Estimated prices of various proposed collider projects at present technology prices as extrapolated from the "αβγ model with historical coefficients (V. Shiltsev, EuCARD-2 WP5 Strategy Workshop, Valencia) 2017).

For future large projects, efficiency and cost minimization become ever more important. Figure 5 indicates that with present technologies and technology prices only the LHC energy upgrade (HE-LHC) and the FCC-ee/CEPC may be considered affordable (with an estimated cost of about or below 10 B$ using US accounting). The cost of a 100 TeV hadron collider, FCC-hh, can, however, be reduced by three steps: a) building this collider on a site with an existing injector complex, such as CERN, b) staging (e^+e^- 1st, pp 2nd), and c) reducing the superconductor/magnet cost. The FCC-hh would become affordable via a staged approach (i.e. following the FCC-ee in the same tunnel), or if the cost coefficients, in particular that of high-field magnets, can be reduced by targeted R&D efforts. Other novel technologies and concepts (e.g. ionization-cooling-free muon colliders and crystal acceleration) and tools (e.g. electron lenses) may also help reduce the price of future facilities.

A number of large **hadron facilities** are under construction or being upgraded around the world (see Figure 6), including several in Europe. WP5 has coordinated and integrated the activities of the accelerator, nuclear and particle physics communities towards reaching the optimum performance of FAIR, ISIS and PSI-HIPA, and helping guide the upgrade strategy for the LHC injector complex. Identifying and overcoming ultimate performance limitations for the aforementioned facilities have been a primary subject. WP5 has also supported studies on critical beam diagnostics (e.g. continuous emittance control, beam-loss and halo measurements) and supported Fixed-Field Alternating Gradients (FFAGs) development in the UK.

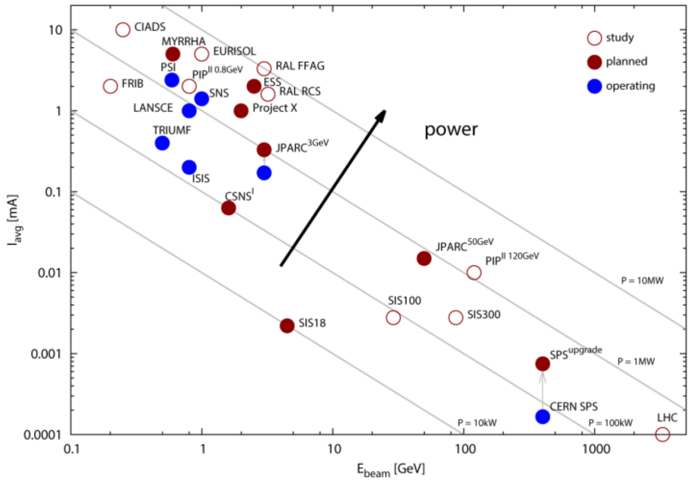


Figure 6: Operating points of various extreme-ring and extreme-linac facilities in the plane spanned by average beam current and power.

WP5 has catalyzed community discussions on the various performance limitations of high-intensity high-brightness hadron rings. Preliminary roadmaps for the upgrade of several European facilities have been developed and validated. In particular, WP5 has brought together beam dynamicists, magnet specialists, and beam instrumentation experts in order to identify optimum upgrade solutions, including risk mitigation. Integration of the efforts has been advanced through the joint fora involving universities, small institutes and large laboratories.

The ever-increasing beam power of rings and linacs calls for better beam control and diagnostics. Concerning **extreme hadron linacs**, WP5 workshops revealed some key points for optimum performance. These are: a) enhanced collaboration and sharing of expertise between similar projects for fast progress at minimum cost; b) beam-loss minimization for achieving the desired levels of availability and hands-on maintenance; c) properly specified and well-functioning low-level radiofrequency system, along with good temperature control of the timing reference lines; and d) thorough preparation for beam commissioning with special attention to (redundant) key diagnostics.

Polarization offers additional handles for discovery and precision studies at lower energy. WP5 discussions revealed that: a) a state-of-the-art laser system at the FCC-ee and Compton polarimeter can measure the beam polarization with a precision of 0.1-0.2% turn-by-turn and bunch-by-bunch; b) the installation of a large number of "partial Siberian snakes" could allow for polarized proton beams in a 100- TeV hadron collider; and c) the effect of thermal stress and long-term availability of the ILC positron conversion target could be tested with a CW electron beam. In several polarization areas, further networking and R&D activities are needed. For future large-scale machines (FCC, etc.) modelling tools need to be optimized and technologies to be updated in order to make reliable predictions of what can (and what cannot) be achieved with respect to polarization performance. Significant breakthroughs can be obtained by techniques which are outside the scope of established methods, like using a cryogenic photocathode vacuum vessel together with RF operation to solve the ion back-bombardment problem for high intensity spin polarized sources.

WP5 results underline that strengthening pan-European and global collaboration is a recipe for continued success. European accelerator networks continue to play a key role in all the aforementioned areas, and they provide key ingredients for the future of accelerator development. During the next couple of years, several new projects are upcoming, such as SuperKEKB, IOTA, ESS, NICA, HEPS, HL-LHC and MESA, which are certain to provide new lessons. Many other machines, such as ESSnuSB, JEDI, FCC, CEPC, LHC-based Gamma-Factory, $\gamma\gamma$ colliders, etc. are also being proposed. Next-generation facilities offer an exciting perspective for the future, enhanced by possible novel uses of storage rings (e.g. for the detection or generation of gravitational waves), new methodologies for modelling accelerator performance and pushing their availability to unprecedented levels.

WP6: LOW EMITTANCE RINGS (LOW-E-RING)

The new Network on Low-Emittance Rings has:

1. Federated for the first time three accelerator communities sharing common problems and technologies: damping rings for electron colliders, advanced factories (e+/e- colliders), and synchrotron light sources.
2. Transferred to the European Synchrotron Light facilities the expertise and competence of the accelerators for fundamental physics research, which resulted in the implementation of the 4th generation of light sources based on the Hybrid-Multi-Bend Achromat.
3. Fostered synergies within the low emittance ring community, disseminating new techniques for lattice optimisation and supporting common R&D activities, via the organization of 4 general and 6 topical Workshops.

The emittance is the main component of the brilliance of a synchrotron light source, which is its main figure of merit. The four years of activity of the Low-e-Ring Network have seen a jump in the emittance achieved or targeted in the light source facilities with respect to the third generation ones, at the point that we can now speak of a **4th generation of light sources**, entirely originated in Europe. In *Figure 7* the emittance divided by γ^2 as a function of the circumference is plotted: the new facilities (in construction, approved or proposed) lie on a line about one order of magnitude lower than the third generation rings.

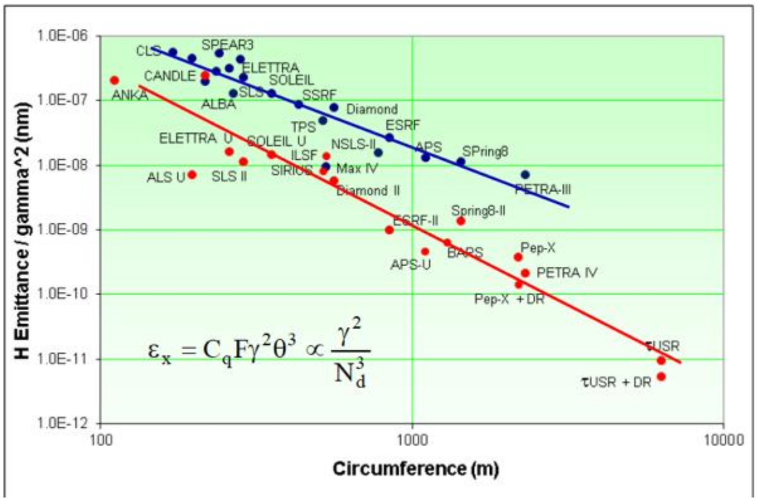


Figure 7: Emittance normalized to beam energy vs. circumference for storage rings in operation and under construction or being planned. The ongoing generational change is indicated by the transition from the blue line to the red line. (Bartolini LER 2013, updated 2016)

The activities on **Low Emittance Ring Design** have fostered the emergence of ever more aggressive lattice design, targeting emittance in the order of tens of pm, in medium size machines. These lattices are based on ambitious extensions of the Multi-Bend Achromat (MBA) concept to build cells with M in excess of ten (M = 18 in the proposal for the upgrade of MAX IV). The original MBA is based on a rather relaxed optics, resulting in low chromaticity and relatively large dispersion, and thus moderate sextupole strength. Low emittance is obtained from the large number of cells. Miniaturization is the base for the new generation of MBA lattices. Vacuum chamber dimensions are reduced by approximately a factor of 3 compared to 3rd generation light sources and smaller vacuum chambers are the base for miniaturization of magnets, resulting in higher focusing gradients. A Hybrid-MBA cell was developed for ESRF-EBS and adopted by many other projects like APS-U, Spring-8-II, HEPS and PETRA IV. The DTBA lattice is proposed at Diamond, based on SuperB cell combined with MAX IV MBA cell and it includes transverse and longitudinal gradient dipoles to further reduce the emittance. This option is consequently exploited at SLS-2, where anti-bends are also added for optimum matching to the longitudinal gradient bendings. Dynamic aperture optimization is one of the most challenging tasks in low emittance lattice design. Different methods have been presented and discussed, such as: minimization of nonlinear drive terms, multi-objective genetic algorithms, or Beam-Based Optimization of Nonlinear Dynamics by means of robust minimizers like robust conjugate direction search.

Very aggressive designs cope with reduced dynamic aperture and explore on-axis injection schemes, because off-axis injection is no longer possible. The emergence of novel concepts for injection was another hot topic intensely discussed in the collaboration. Swap out on-axis injection seemed to take a major role in this new project and it is strongly underpinned by the progress in faster kicker technology, yet another example of successful cross fertilization between different accelerator communities of light sources and damping rings, as supported by the network.

Several methods were presented and discussed for reducing **instabilities, impedances and collective effects** in low emittance rings. These include numerical wake field calculations and optimization of vacuum component designs, theoretical approaches to short-range wakes, beam-based and bench measurement of impedance, impact of harmonic cavities on collective effects, development of simulation codes, comparison of beam-based measurement of instability and impedance with simulations, simulation of electron cloud build-up and use of the former in electron cloud instabilities, mitigations for the suppression of secondary electron yield, measurements of electron cloud, lattice design reducing intra-beam scattering, advanced single shot measurement using ultra-fast detectors.

The large number of studies presented at the workshops, along with their high quality, confirms the recognition by the community of the high degree of importance in understanding and mastering the beam collective effects in present and future low emittance rings, which aim to reach their designed performance via high beam intensity and low emittance.

Activities on **Low Emittance Rings technology** concentrated on creating a communication platform to exchange information and build collaborations on common issues affecting the design of the technical systems in present and future ultra-low-emittance rings. This extended to industry that actively participated in the Network activities. The major topics presented and discussed during the workshops, for which significant progress has been reported, are insertion devices, magnet design and alignment, instrumentation, fast kicker systems.

Either for producing high-brilliance X-rays or for damping the beam to ultra-low emittances, the magnet design and optimization with respect to field errors and alignment is fundamental for the performance of modern storage rings. The technical challenges and R&D needed include pushing the limits of high gradient and small bore apertures, the review of tolerance requirements, the development of complex dipoles (combined function, longitudinal gradient), the use of permanent magnets for achieving very large gradients, cost-effective series production of permanent magnets, precision machining (poles, mating surfaces, etc.), magnetic measurements (stretched wire with small bores) and in situ alignment. The collaboration between colliders and light sources was primarily important in the development of wigglers for fast damping of the injected beam in the case of damping rings or to be used as a photon source for light sources, in design of stripline kickers with fast rise-time and very good stability, and in the development of correction methods and beam instrumentation for achieving and measuring ultra-low emittances.

WP7: NOVEL ACCELERATORS (EURONNAC2)

The Network on Novel Accelerators has:

1. Federated and coordinated a large collaboration of 54 member institutes, mainly European, to develop novel “ultra-high gradient” particle accelerator technologies and to direct their development towards pilot applications.
2. Enlarged the scope from originally plasma acceleration (particle and laser driven) to additionally dielectric vacuum accelerators driven by optical lasers or THz sources.
3. Coordinated and set up the successful EuPRAXIA Design Study proposal for Horizon 2020 and participated to advanced R&D projects (AWAKE at CERN and AXSIS at DESY).
4. Established the European Advanced Accelerator Concepts Workshop (EAAC) and organized EAAC2013 (145 participants) and EAAC2015 (258 participants).
5. Fostered a high number of peer-reviewed publications, supporting and promoting PhD students and young researchers.
6. Co-organized the first CERN Accelerator School (CAS) on plasma acceleration with more than 100 students.

Accelerators of charged particles have been a high impact success story since the invention of radio-frequency (RF) acceleration in 1927. In their 90 years of history, particle accelerators based on (conventional) RF technology are at the core of some of the largest or most powerful research facilities ever built. Accelerators serve a huge variety of applications, including those for use in the industrial and medical fields, often limited only by the size and cost for the required RF technology. However, the potential for particle acceleration in the fundamental equations is far from being exploited. Today new ideas and technologies allow for accelerating fields that are 2-3 orders of magnitude above those used in conventional RF accelerators: for example, multi-GeV electron beams have been already successfully produced within a few cm's of laser-driven plasma channels.

The European Network for Novel Accelerators (EuroNNAc) is promoting the research on novel "ultra-high gradient" particle accelerator technologies and development towards first applications. This goal is achieved primarily through the EuroNNAc workshops that provide a forum to form a community, to discuss results, to exchange ideas, to define common standards, to self-organize work in various experimental facilities, to explore common strategies and to bring together specialists from the accelerator, laser, plasma and application domains. The activities of the Network over the last four years resulted in a complete document on the present state of the European strategy for novel accelerators and on the roadmap to future pilot applications, published as a EuCARD-2 Deliverable (D7.2). A coordinated strategy for novel accelerators in Europe is very important given the distributed character of the research and the large variety of experimental facilities in Europe (see Figure 8). While the network is centred in Europe it is open to associated partners in Asia and the US.

A major outcome of the Network is the founding of the **European Advanced Accelerator Concepts Workshop** (EAAC) and its successful organization in 2013 and 2015. It is interleaved with the long-standing Advanced Accelerator Concepts Workshop (AAC) in the US that takes place in even years. The EAAC provides for the first time a European forum for advanced accelerators. The 2nd EAAC in 2015 attracted 258 registered participants, illustrating the interest and wide support for such a European event. About 16% of all participants were female scientists and about 20% were doctoral students. While there is still an imbalance in gender distribution, the innovative research on novel accelerators proves to attract more female scientists and more young researchers than usual in the accelerator field. The scientific outcome of the EAAC 2015 was impressive, with a total of 176 talks and 76 posters presented. From the first two EAAC workshops, 131 peer-reviewed papers were published, documenting the results and progress achieved. The EAAC2015 proceedings include 81 papers published in 2016. Within one year these papers were cited 83 times, illustrating the relevance and impact of this work.

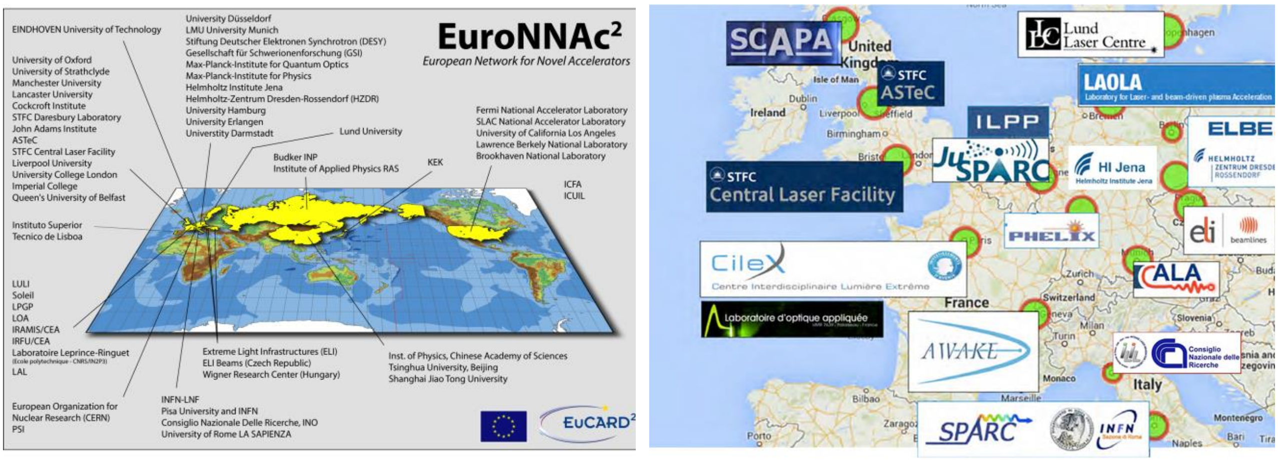


Figure 8: European Network for Novel Accelerators: Membership and geographic distribution of the network (left). Major experimental facilities for novel accelerator R&D in Europe (right).

The activity of the Network clearly underlined that plasma accelerators have reached the energy regime of ongoing construction projects and highly interesting applications have been identified. For example, laser-plasma based radiation sources or a plasma-based free-electron laser seem within reach for energy, while important design work on beam quality remains to be performed. There was a great interest to work together on these ideas that could have a huge impact on European science, but it clearly appeared that all resources of the participating laboratories are dedicated to achieving their internal goals, with no further resources for common work on a European facility available. This was the main motivation for a Design Study proposal that was submitted in 2014 in the Horizon 2020 Research Infrastructure programme: European Plasma Research Accelerator with eXcellence In Applications (EuPRAXIA).

This common strategic project includes 16 partners and 18 associated partners from the EuroNNAc environment was approved and funded with 3 M€ by the EU. It started in November 2015 and will provide a conceptual design report for a European plasma accelerator facility with applications by October 2019. While EuPRAXIA pursues and coordinates a common technical design, the EuroNNAc network is continuing to support the networking aspects and the strategic discussions. Common workshops ensure that the two efforts progress in full synergy and stay well aligned.

Following community demands and interests, the EuroNNAc network has expanded its scope to include all ultra-high gradient acceleration methods, not to be restricted to plasma acceleration.

WP8: ICTF@STFC

The Ion Cooling Test Facility Transnational Access at STFC provided access to 45 users from 5 institutes grouped in 5 projects, for a total of 1,186 user days and 4,957 access units, largely exceeding its initial requirement of 2,280 units.

The access opportunities to ICTF@STFC were advertised widely on websites, newsletters and specifically directed communications to laboratory directors eligible for support. All applications submitted for access were approved to receive funding under the EuCARD-2 TNA scheme. The applications came from 5 institutes, all members of the Muon Ionisation Cooling Experiment (MICE) collaboration, which is the main user of the ICTF facility. A summary of the TNA activity of the groups supported at ICTF is given below.

University of Geneva: contributed to the detector operation and support for the MICE experiment. Activities included: coordinating the work in the MICE online group; maintenance of the Data Acquisition (DAQ) system; development of a FPGA-based trigger system for MICE; tests and integration of the new trigger system into the MICE DAQ; development of a software framework for real-time data reconstruction during the data taking process (Online Reconstruction).

University of Sofia: participation in commissioning and data taking phase of the MICE experiment; maintenance of the KL detector; development, maintenance and improvement of the computer code for Monte-Carlo simulation and data reconstruction of the KL detector; data analysis.

INFN: the activity mainly concerns the PID detectors (TOF & KL systems), maintenance & running during STEP IV of the MICE project.

University of Belgrade: attendance during required shifts of data taking for the MICE experiment; training on data taking and visits to RAL on shifts trainings.

University of Radboud / NIKEF: participation in the data taking and particular focus on the analysis and characterising the effects of different absorbers in the multiple scattering distributions.

Access was provided to 45 users, for a total of 1,186 user days and 4,957 access units, largely exceeding its initial requirement of 2,280 units. With the input gained from the scientists and engineers from the supported institutes, the MICE collaboration has been able to gather valuable data to show the measurement of the multiple coulomb scattering through a LiH absorber placed in the beam line within the Focusing coil section of the cooling channel.

WP9:HIRADMAT@SPS AND MAGNET@CERN

The High Irradiation to Materials (HiRadMat) Transnational Access at CERN provided access to 32 users from 13 different institutes grouped in 7 projects, for a total of 2,940 access units, exceeding the initial requirement of 2,400 units.

The MagNet TNA at CERN provided access to 34 users from 15 different institutes, for a total of 2,660 access units, exceeding the initial requirement of 1,920 units.

HiRadMat (High Irradiation to Materials) is a facility designed to provide high-intensity pulsed beams to an irradiation area where material samples as well as accelerator component assemblies can be tested. The facility was initial contemplated as a test bed for collimator related issues. Within the years since commissioning, the research topics were gradually extended to other elements of accelerator technologies, supported by granting beam time to external users.

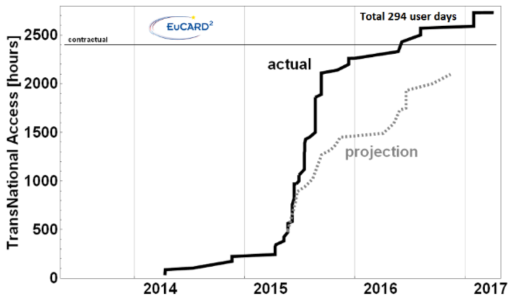


Figure 9: Transnational Access units to the HiRadMat facility during EuCARD-2.

Within the EuCARD-2 framework, seven user teams using Transnational Access could take advantage of the facility, out of the 19 proposals that were submitted. Researchers primarily from all over Europe, but also from the US, gained access to the facility amounting to 2,940 Transnational Access units (Figure 9). The programme was dependent on the CERN accelerator programme, meaning operational conditions and experiments could not take place during the 2014 CERN accelerator shut-down. In addition a failure of the SPS beam dump in 2016 limited intensity and forced rescheduling some experiments to 2017.

One of the main aims of the facility was the validation test of collimator systems suitable for CERN accelerator operation within the High Luminosity LHC project. An important outcome of this international effort was that Molybdenum Carbide – Graphite (MoGr) and Copper-Diamond (CuCD) composites were validated as robust materials for the upgrade of the LHC accelerator.

In 2016, the HRMT34-ESScoat experiment performed an in-beam test successfully validating the proposed concept of an on-target coating allowing a screen-based beam monitoring system for the AWAKE experiment. One experiment in 2015 focused on the structural strength of vacuum windows for high power proton beams; in a wide international collaboration Beryllium was tested as window material. The primary purpose is the proton beam line for the neutrino production at FNAL, but test results will extend to other high-intensity applications. The experiment HRMT17-dBM with team leadership from the Czech Republic investigated the performance of beam monitoring based on diamond detectors. The aim of the HRMT38-FlexMat experiment was to test the dynamic response to intense proton beam induced shock for low density, high damping carbon materials and for composite carbon targets including high stiffness and high damping materials. This will include pre-irradiated materials such as flexible graphite and graphitic foams, in order to confirm that the properties' degradation of these materials due to radiation damage proceeds slower than in isotropic graphite grades.

MagNet supported 9 projects, selected among 10 projects submitted, and provided access to interesting "high tech" projects mostly linked to superconducting and cryogenic technologies.

The very first project (FOSxCRYO), proposed by an international team with Italian leadership, is so far the most documented in international conferences, proceedings and reviews of all the projects supported by MagNet. This project is a bridge between optical fibre technologies and cryogenic applications for superconductors. The successful fibre technology is well known at room temperature, while due to material properties its use is very limited at low temperature. Developments are limited by the testing capacity in liquid Helium installation and for this reason the MagNet support was crucial for the team. A dedicated cryogen free cryostat and numerous real applications (magnets and superconducting link) were the test bed for this new technology with great success worldwide. Today, the results of this team are the references in Europe and in the US in the subject.

Another interesting test has been performed on a superconducting NbTi solenoid at low temperature (Figure 10, left). The project, from CIEMAT (Spain), was intended to "train" the superconducting magnet being the major component of a cyclotron for radioisotope production for medical diagnostics. Once the full system is finished (Figure 10, right), it will operate in a stand-alone mode in a closed cycle, but prior to this phase, the magnet must be checked to verify if it is working correctly, and as all superconducting magnets trained for the operational conditions. The goal of these measurements was to carry on the training test of the solenoids, recording as much information as possible to determine quench origins and overall performance.

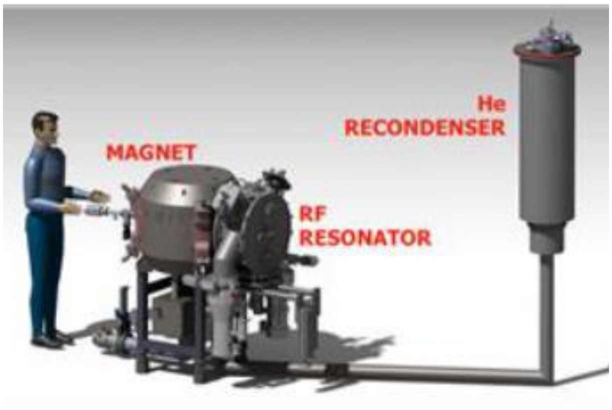



Figure 10: The solenoids on the test bench (left). General arrangement of the cyclotron (right).

In the last period of EuCARD-2, MagNet supported a team designing a Superconducting Shield septum. The project, proposed by the Wigner Research Centre for Physics (Budapest, Hungary), aimed to evaluate the feasibility of using a superconducting shield to create a high field extraction septum magnet for high-energy accelerators. This very exciting project had performed the first run of tests with not only the MagNet installation, but also using a LHC spare magnet as part of the service. After having the first excellent and promising results using MgB_2, the team is planning a second run with different superconductors. This technology is very promising in other applications where high field has to be shielded as in medical installations or in space.

In addition to these projects a number of measurements have been performed on short model coils (SMC), a test bed developed at CERN for different studies and for different teams. Nb_3Sn superconductors are planned to be used in the next decades for HL-LHC, ITER and FCC. It is therefore important to develop models that are correctly simulating the behavior of such conductors for the design of the future magnets. Measurements performed in the test facility contributed to the development of such tools by comparing measurements results with simulations.

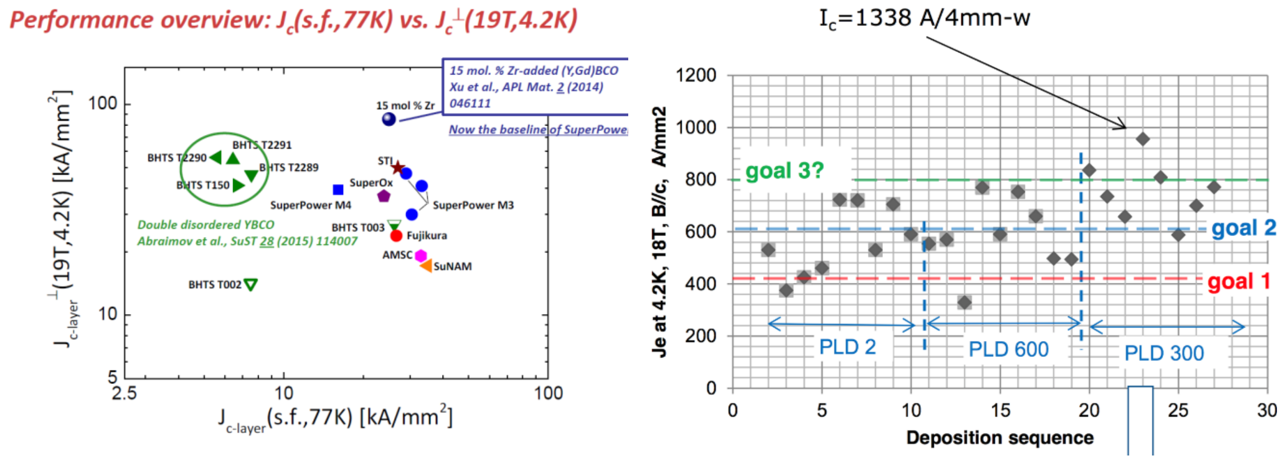
WP10: FUTURE MAGNETS (MAG)

The Joint Research Activity on Future Magnets has:

1. Organised and coordinated a community, mainly European but open to contributions from other areas, determined to develop a new generation of high-gradient accelerator magnets based on High Temperature Superconductivity (HTS).
2. Compared different options and selected the most promising technologies in terms of superconductor (YBCO), tape structure, cable type (Roebel geometry) and magnet design (aligned block coil).
3. Developed and characterised the world record current density tape in YBCO.
4. Designed, constructed and tested a coil and a magnet to qualify the cable for accelerator magnets.
5. Positioned European industry at the forefront of HTS development and brought to Europe the leadership in HTS technology.

Today no single laboratory can provide significant results on HTS, given the complexity of a system that needs a multi-physics approach: from material science to thin film deposition in ultra-high vacuum, from metal shaping and delicate cabling process to cryogenics technology, and from magnetic and electrical characterization in high field-high current to sophisticated diagnostics for quench protection. To establish and consolidate a network in this field, a series of workshops on Accelerator Magnets in HTS were organised by the EuCARD-2 Consortium, to form a stable network, going beyond the institutes participating in EuCARD-2 WP10 (CERN, CEA, UniGE, UniTwente, KIT, SOTON, INFN-Milano, INP Grenoble, DTI, BHTS), to include laboratories and universities from European countries (EFL-CRRP in CH, LNCMI Grenoble and ENEA), Japan (University of Kyoto and KEK), USA (LBNL, BNL, NHMFL, University of North Carolina, University of Houston) and Russia (Bochvar Institute). About 10 companies working in the field also attended the workshops with various presentations.

The consortium has developed and characterized the world record current density **YBCO tape**. This has been the fruit of a specific optimization for high field-low temperature range. Before EuCARD-2, all optimization and comparison were carried out at 77 K self-field, because of the easiness of measurements and perspective use for energy application. However, the goals dictated by EuCARD-2 have now become a new standard. Figure 11 (a) shows the value of critical current density at 19T, 4.2 K vs. the value in self field, 77 K. The EuCARD-2 tapes made by Bruker, a partner in the project, despite their lower value at 77K self-field, are much better than any other tape at 19T, 4.2k (apart one single measurement on a US non-industrial tape). The success of the EuCARD-2 development has been possible thanks to the very advanced process of Bruker HTS: substrate in stainless steel, buffer layers deposited in alternate beam assisted deposition and YBCO layer deposited via plasma laser deposition and to a new dedicated line at Bruker, called PLD300. After various optimization steps, the results have been quite positive, even beyond the most optimistic target of EuCARD-2, see Figure 11 (b). In this figure, where the engineering current density Je is reported for various production run, the red line goal 1 is the initial goal of EuCARD-2, so the reference goal in terms of reaching the objectives of the program. The blue line goal 2 indicates the enhanced goal set after the first success, to push performance beyond initial targets. The values of Je obtained with the last production carried out with the line PLD300 are steadily above goal 2. Thanks to the developments in EuCARD-2 WP10, Europe has gained a prominent position in this technology.



(a) (b)

Figure 11: (a) Comparison between various tapes; (b) Je measurements on EuCARD-2 tape.

Figure 12: The first Roebel cable produced for EuCARD-2.

The **Roebel cable** has been deeply investigated and characterized. Basic work on topology has allowed identifying the criteria to optimize the cable vs. the number of strands (tapes in this case). A noticeable difference between even and odd numbers of strands was observed and subtle optimization in terms of angle of punching and filling factor in various direction established. KIT, with the support of CERN has set up a better line for punching and cable formation, which has resulted in a faster and more uniform cabling. In Figure 12 the first Roebel cable produced for EuCARD2 is shown. This cable has been used for winding the magnets Feather_M0, the first HTS coil for accelerator and successfully tested until 12 kA. The cable has been extensively tested under pressure and found that, if impregnated, it does not degrade until a pressure of more 400 MPa. This value has to be compared with the 150 MPa normally considered the maximum pressure admissible for Nb_3Sn conductor.

The three **configurations of magnet**, which have been studied, are described below.

1) The classical race-track, based on rectangular conductor blocks with flare ends that are bent in the non-easy direction. However, the race track was special in the sense that a new design aligning the cable along the magnetic field lines was developed. This has increased the usable critical density (YBCO is highly anisotropic, Jc being maximum when the wide face of the tape is parallel to field lines), making the best use of the material and minimizing the superconductor quantity, which is a great advantage given the prohibitively high cost. This layout is called **Aligned Block Coil**. The Magnet is called Feather_M2 and the first one is specifically the Feather_M2.1-2.2. Before this complete dipole, a shorted and smaller version with only one coil and few turn, called Feather_M0, was produced. The first with HTS, after a few with dummy cable, was Feather_M0.4. Both F-M0.4 and F-M2.1-2.2 were designed, manufactured and tested. The latter is the magnet of reference and the main deliverable of the program, together with the first piece length of Roebel cable.

2) The second type of magnet was a classical **Cosϑ dipole** layout but adapted to Roebel cable. Various studies demonstrated that the end needed to be optimized. Despite the fact that the field is intrinsically lower than in the Aligned Block Coil (because here the anisotropic behaviour plays against with field line perpendicular to the conductor wide face) the study is very interesting because cosϑ is a well-

known technology and there is easy benchmark with Nb-Ti and Nb_3Sn dipole. The cosϑ magnet designed within EuCARD-2 is now under construction with the direct support of the participating laboratories.

3) The third layout that has been studied is the **stacked tape cable**. It is based on smaller, 4 mm tapes that are simply stacked without transposition. The coil is basically a race track of rectangular block coil, with flare ends. To avoid huge unbalance due to lack of transposition, the cable is twisted once per turn, near the ends. The conceptual design has been carried out.

The results of the test of F-M0.4 and F_M2.2-2.2, the latter being the main deliverable of the whole program, and the test that validate the use of 5-10 kA Roebel cable in an accelerator magnet are shown in the figures below.

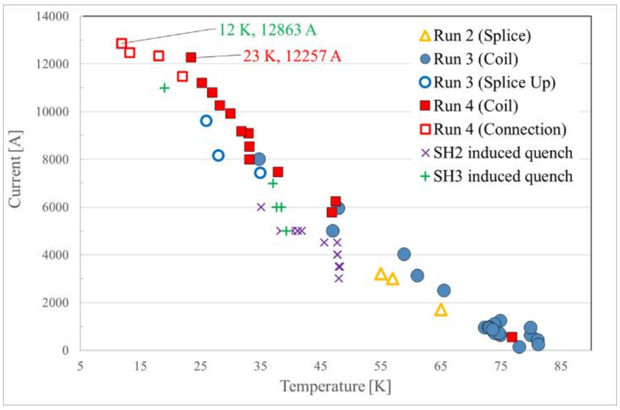


Figure 13: Test of F_M0.4: 12 kA reached at 20 K.

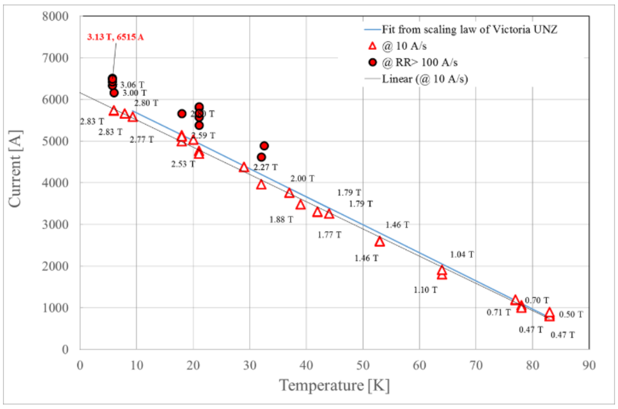


Figure 14: Test of FM_2: 6 kA reached at B>3 T.

WP11: COLLIMATOR MATERIALS (COMA-HDED)

The Joint Research Activity on Collimator Materials has:

1. Selected two families of advanced materials as best candidates for the new generation of beam collimators at HL-LHC (CERN) and at the FAIR project (GSI, Germany): copper-diamond and molybdenum carbide-graphite composites.
2. For each family, analysed and tested different composition and grades narrowing the choice to few materials presenting the required characteristics.
3. Introduced in the landscape of new materials and thoroughly analysed, boosting their production capability in industry, two new families of materials with potential applications in industry, e.g. aerospace, thermal management and automotive.

Beam collimators are an essential component of modern high-energy, high-intensity accelerators, which have to absorb on small surfaces the large amounts of power carried by particles that are outside of the main beam volume. This JRA focused towards gaining a deeper understanding of collimators and of their materials under high-energy particle impact and irradiation. The composite materials studied within this project were designed and processed in collaboration with industrial partners exploring a broad set of sintering, heat treatment and machining processes. Their potentialities and the optimal parameters combinations were extensively studied. New collimation schemes relying on these materials were implemented and simulated with different tracking codes and in the different laboratories participating in the JRA.

WP11 selected two families of materials for the new generation of collimators, and for both it has furthered the analysis and selected specific grades. The first family is that of Copper – Diamond composites (CuCD). Maximization of properties such as thermal conductivity, mechanical resistance and stability after repeated thermal cycles was pursued, acting on the initial binder type and content, as well as on the heating ramps and dwell time at the sintering temperature. The second family is that of Molybdenum Carbide-Graphite composite (MoGr). Their electrical resistivity, thermal stability and radiation hardness were optimized working on the processing temperatures and composition, with the addition of other carbide formers such as Titanium, leading to additional improvements of the mechanical strength. Five different generations of MoGr, each one including several material grades, were conceived and produced in the course of the project, varying their composition (molybdenum, graphite, carbon fibres and dopants) and several processing parameters, such as temperature, pressure, time and post-sintering heat treatments.

The experimental work included extensive thermo-physical and mechanical characterizations of the novel materials, including a large number of tests under beam or under irradiation, at CERN, GSI, Kurchatov Institute, BNL and POLITO. Results were used to upgrade composition and production parameters for further grades and, in parallel, to update constitutive models implemented in advanced simulations to predict the response of the materials in nominal and accidental operating conditions. Measured data were also exploited to redefine a set of figures of merit to rank relevant materials in the preliminary design phase of collimators and other beam intercepting devices.

Two components (jaws) of the new collimator design, embarking respectively CuCD and MoGr from last generations, were tested at CERN for qualifying the new collimator design and materials against the nominal and accidental scenarios defined for HL-LHC and for benchmarking the numerical models against experimental measurements for beam impact. A good response of both materials to beam impacts was ascertained. Several complex finite elements models simulations were run to mimic the behaviour of the jaws: a particularly interesting behaviour was observed with CuCD, which exhibited a higher than expected damping ratio against beam-induced pressure waves, possibly because of the strongly non-linear constitutive model.

Radiation resistance of different grades of MoGr was tested using swift ions at GSI and high-energy protons and fast neutrons at BNL. GSI irradiations were used for optimization of the MoGr processing and composition, to improve radiation stability (Figure 15, left). High temperature sintering, annealing and Ti addition are shown to reduce the deformation of the material at high doses. To reduce the radiation-induced hardening and the degradation of electrical and thermal conductivity, addition of short pitch-derived carbon fibres seems to be a good compromise solution (Figure 15, right).

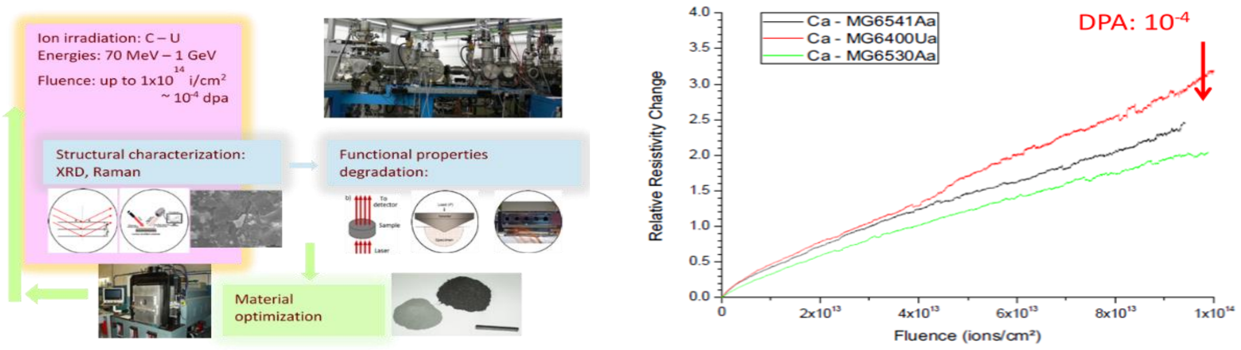


Figure 15: Feed-back loop for optimization activities of MoGr, with respect to radiation resistance (left); dependence of the relative resistivity change of irradiated MoGR, as respect to the corresponding pristine, of accumulated displacement damage for 4.8 MeV/u Ca irradiation, for different grades (right).

The grade MG6451 from the 7th (latest) generation of optimized MoGr batches is one of the favourites; irradiation experiments confirmed the improved radiation resistance of these composites.

CuCD composites were exposed to 30 MeV protons at Kurchatov Institute. A good stability of material density, 10% increase of electrical resistivity, 30 – 40% increase of the coefficient of thermal expansion and a 20-30% reduction of thermal conductivity for doses up to 10^{18} p/cm^2 indicate that the composite has a good stability in radiation fields.

WP12: INNOVATIVE RADIO FREQUENCY (RF) TECHNOLOGIES

The Joint Research Activity on Innovative Radio Frequency Technologies has:

1. Developed a novel deposition scheme for Niobium on Copper with performance similar to Niobium at lower cost, and has advanced the studies on other types of coating techniques and high temperature materials.
2. Developed the principle of a new type of high-efficiency klystron and attracted industrial interest in furthering the development.
3. Advanced knowledge on High Order Modes, for their suppression and their use for diagnostics, on wakefield monitors, on crab cavities, and on RF photocathodes.
4. Established a platform for exchange of information and identification of synergies between the superconducting and normal conducting RF communities.

Radio Frequency accelerating technology is at the core of accelerators. Dimensions, power efficiency and performance critically depend on the accelerating gradient, on the energy transformation efficiency and on the field quality of their RF accelerating system. EuCARD-2 has addressed a number of advanced RF technologies meant to improve performance of a large variety of accelerators.

Superconducting coatings (**SRF thin films**) on copper could dramatically reduce the cost of superconducting RF systems possibly achieving higher gradients or increasing power efficiency. Deposition conditions for Niobium films on copper have been explored, and favourable parameters identified. Twelve prototype cavities have been tested at CERN. The best cavities exhibit a behaviour close to bulk niobium, with much better performance than what can be obtained with the classical DC magnetron sputtering. For higher Tc materials, two processes which are able to produce crack-free dense grainy Nb_3Sn layers have been developed also at CERN. Atomic Layer Deposition (ALD) has been used to study three different organometallic precursors on NbN at INP Grenoble. Thin layers with the correct crystalline structure have been produced and Chemical Vapor Deposition has also been used to produce very high Tc NbN layers (see Figure 16).

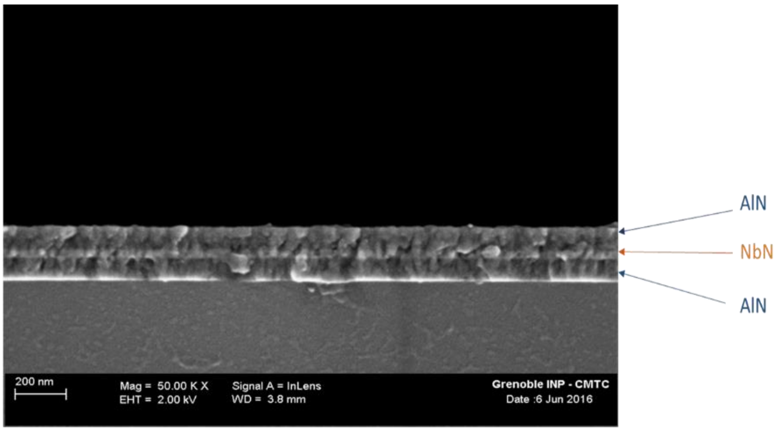


Figure 16: AlN/NbN/AlN multilayer structure deposited by ALD showing high homogeneity of the films and high quality of interfaces. The NbN layer, albeit non superconductive, presents the expected crystalline structure.

Characterization tools, such as a Quadrupole Resonator with removable samples has been successfully commissioned at HZB, and systematically used to characterize superconducting properties of newly developed materials or processes. A local magnetometer has also been developed at CEA Saclay, allowing measurement of a series of Nb/MgO/NbN with different thicknesses of NbN in order to determine if there was an optimum thickness as determined by recent theoretical optimization calculations.

High-gradient normal conducting accelerating structures at high frequency are often plagued by unwanted higher-order modes that spoil beam quality. An RF design, based on long-range wakefield suppression using the Damped Detuned Structure (DDS) has been developed at Manchester University, as an alternative for the CLIC linear collider under study at CERN. The structure design and optimization process take into account the fundamental mode performance and high gradient limits along with transverse wakefields.

A new **high efficiency klystron** principle has been developed at CEA Saclay, the ‘kladistron’ and a collaboration formed with Thales (France) as an industrial partner. A prototype has been designed and first proof-of-concept RF cavities have been fabricated and successfully tested. These tests include a check of the tuning mechanism and a titanium coating for multi-pactor suppression. The fabrication of the full prototype is nearing completion. Modification to existing commercial solid-state modulators have also been studied at Uppsala University with Scandinova (Sweden) as an industrial partner, in order to adapt them to high-efficiency klystrons and critical issues were identified and preliminary solutions proposed.

Wake field monitors have been developed at PSI to directly measure the alignment between the beam and RF accelerating structure via the transverse higher order mode spectrum. A front end electronic system for the monitors of the multipurpose X-band structure installed at the SwissFEL at PSI has been developed. A final prototype has been fabricated and beam test evaluations completed with the PSI test linac. The first-generation prototype has been upgraded and significant improvements in sensitivity, insertion loss and noise has been verified in laboratory tests and upgraded systems now installed and awaiting tests on the SwissFEL accelerator.

A new optimised CLIC **crab cavity structure** has been designed at Lancaster University and STFC, fabricated and high power tested, with operating performance exceeding considerably the required deflecting gradient. The feasibility of a new CLIC crab cavity stabilization has been demonstrated by Lancaster University with an active waveguide phase stabilization system. Operation of the system showed that phase could be stabilized to the 20 milli-degree level with the feedback engaged, compensating for the phase shift induced by a heat source, thereby validating the concept.

Higher Order Modes (HOM) could be used for **HOM-based beam diagnostics** of SRF cavities. A procedure has been developed to use HOM signals from 1.3 GHz superconducting accelerating cavities for beam position monitoring stably over several months at the European XFEL (DESY). A setup for beam phase measurement with respect to accelerating RF field has been built and tested on the FLASH facility: a resolution below 0.12 deg rms at a charge of 0.4 nC was demonstrated, and the expected performance of the specially designed electronics defined.

For the 3.9 GHz cavities, simulations of the chain of 8 coupled cavities installed at the Eu-XFEL has been conducted. The feasibility of concatenation techniques, State-Space Concatenation (SSC) and Generalised Scattering Matrix (GSM) has been studied for such large linac structures and which have now been validated by Rostock and Manchester Universities respectively. A compendium of modes has been generated, which serves as a basis for the ongoing monitor developments. Electronics has been designed for both 1.3 and 3.9 GHz cavities. The results are of great interest to other facilities worldwide based on SC RF technologies.

Investigations for superconducting and normal conducting **RF photocathodes** have been undertaken, with 63.5 MV/m cathode field being reached during tests of a 1.5 cell superconducting gun at DESY with an un-coated Nb Photocathode (PC) plug, the highest ever demonstrated for a superconducting injector cavity. Various techniques have been developed at NCBJ for Pb cathodes to obtain smooth, droplet-free Pb surfaces: surface flattening with plasma pulses, post-deposition surface treatment. The influence of the roughness on electron emission has also been investigated, resulting in a stable photocurrent of ~1 µA at 100 kHz being obtained over several hours of operation at the HZDR gun.

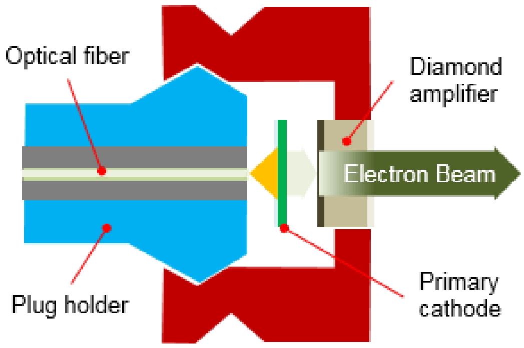


Figure 17: Implementation of back-illuminated DAC plug.

A Diamond Amplifier Cathode (DAC) with back illuminated primary photocathodes has been developed by HZB for the TESLA-like electron gun capable of providing high peak and high average current beams (see Figure 17). A new Field Emission facility has been also commissioned at HZB. In addition, at HZDR the SRF Electron Gun II has been run in CW with a Mg photocathode on the ELBE facility without QE decrease over an extended period of time. The obtained results fundamentally demonstrate the viability of normal-conducting PC operating in SRF E-guns.

A Multiprobe System for Metal Photocathode Research has been developed and commissioned at STFC for research into metal photocathodes for NC RF photoinjectors. It uses various analytical techniques, such as X-ray photoelectron spectroscopy (XPS), Atomic Force Microscopy (AFM), Kelvin probe and Quantum Efficiency (QE) measurements. The system was used for investigation of cleaning procedures for bulk PC samples of various materials. The highest QE equal to 1×10^{-3} has been measured for the ion sputtered Mg photocathode. A new metal Photocathode Preparation Facility and a load lock system and transport vessel for dedicated PC plug transfer has also been commissioned and implemented at the VELA accelerator at STFC Daresbury laboratory.

WP13: NOVEL ACCELERATION TECHNIQUES (ANAC2)

The Joint Research Activity on Novel Acceleration Techniques has:

1. Fostered collaboration within the wide community performing experimental activities on plasma wakefield acceleration.
2. Supported experimental work that has produced high-brightness electron beams from laser plasma accelerators.
3. Developed the beam instrumentation for the successful 1st phase of the AWAKE experiment.
4. Demonstrated femtosecond level synchronization between electron beams and lasers.

The first challenge of this WP was the achievements of **high brightness electron beams with laser plasma accelerators**. High quality and stable beams have been successfully produced at LOA resulting from the interaction of a single laser pulse with a sharp density gradient produced by placing a solid obstacle, a blade, in the path of a supersonic gas jet. Another approach performed at Lund Laser Centre was to inject a small jet at 90 degrees of a longer gas jet. Since the position of the first gas jet, the gas density and/or gas composition of each gas jet can be changed independently, this approach offered more flexibility. Electrons were first injected and accelerated in a target where gas was supplied only from a 2 mm gas nozzle. The observed beams of electrons had the typical characteristics of self-injection in gas jets, with limited reproducibility and a bunch charge of the

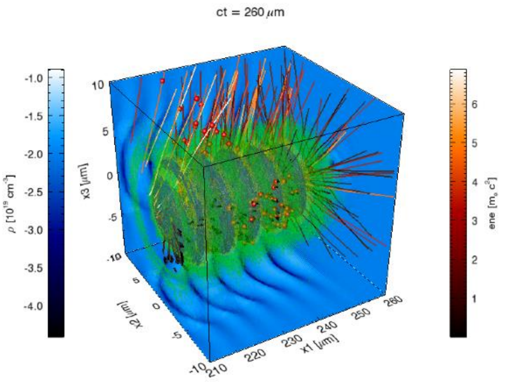


Figure 18: Properties of sample electrons ejected at wide angles obtained from 3D PIC simulation. Trajectories of 200 electrons are superimposed on a snapshot of the electron density after 260 μm propagation.

order of 30 pC with a standard deviation higher than 50%. When adding gas also from the narrow tube, beams of accelerated electrons were observed for 100% of the laser pulses sent onto the target. In addition to improving the stability, this scheme also allows precise control of the electron beam charge and peak energy. At STRATH, experimental and theoretical investigations into the properties of wide-angle electron beams, in the forward and backward directions, were performed. Beams with 1–2 MeV energy and nC level charge are emitted in a forward cone with aperture angle of about 30°–50° from the laser propagation axis. This cone is hollow when plasma electrons are not injected into the bubble and fills in with more energetic electrons when injection occurs and high-energy forward beams are produced. Oblique electrons therefore appear as a high-charge background halo around the high-energy short bunches accelerated inside the bubble. Because of the high charge, wide-angle beams can generate a significant amount of bremsstrahlung radiation and cause damage to equipment, which is a particular concern for laser-plasma accelerators based on capillaries. Wide-angle electron beams can also carry a significant fraction of laser energy out of the plasma, limiting the efficiency of the accelerator, which could have an impact on the use of the LWFA as stages for a linear collider.

As a first achievement of the LWFA with external injection, at INFN electron beams of charge as low as 20 pC and rms lengths down to 20 fs have been produced and measured. The procedure started with the photo-generation of a sub-ps electron beam, obtained by illuminating the cathode with a 200 fs laser pulse at 266 nm. A value of 20 pC of charge was measured with a beam current monitor. The extracted electrons were then propagated along a linac and compressed by velocity bunching, injecting the electrons into the first accelerating structure close to the zero crossing phase. At maximum compression, corresponding to about 20 fs, the electron bunch mean energy was 114 MeV and the projected energy spread was evaluated at less than 0.36 MeV. At HZDR, in order to control the timing of injection, the ELBE accelerator and the DRACO laser system were synchronized by phase locking the laser oscillator repetition rate to the 6^{th} harmonic of the ELBE RF master oscillator. A time jitter of better than 100 fs was electronically realized. However, shot-to-shot variations of the electron beam energy as well as pointing jitter of laser beams can lead to variations of the bunch arrival time, which limits the absolute time resolution. A single-shot beam arrival time monitor has been successfully installed and a balanced detection scheme was implemented. The time resolution of better than 200 fs was successfully demonstrated.

The second wakefield accelerator explored by the WP was **proton beam driven,** in the context of the AWAKE project at CERN. This is a proof-of-principle experiment to demonstrate proton-driven plasma wakefield acceleration, which relies on the use of protons of energy 400 GeV and high charge, about 3×10^{11} protons. As the proton bunches are long, in order to attain high electric fields, the experiment relies on an effect known as the self-modulation instability (SMI), leading to the microbunching of the long proton bunch in the plasma that is seeded by a high-power laser. The much shorter and denser microbunches are then expected to constructively interfere and so produce fields of the order of 1 GeV/m. Theoretical works have been performed to study the transverse stability of a pre-modulated bunch train in the plasma. The result shows that to excite focusing fields of the same intensity for increasing propagation distances, it is required a longer section of the bunch, due to the decreasing density of the front. On the experimental side, a plasma with challenging requirements (length ~10 m, plasma electron density n_e = 1-10 $\times 10^{14}$ cm^{-3}, radius r ≥ 1 mm and with a density uniformity $\delta n_e/n_e$ ~ 0.2%) has been developed in a plasma cell of Rubidium (Rb) vapour ionised by a laser pulse. During the EuCARD-2 project, the AWAKE experiment has gone through development, preparation, installation and commissioning phases. A suite of diagnostics to measure the modulation of the proton beam was installed and commissioned. An indirect measurement of the SMI relies on observing the transverse blow-up of the proton beam by using two screens downstream of the proton beam and comparing the distributions when there is no plasma and when there is a plasma. The measurement results are shown in Figure 19. Where there is no plasma (left), the proton beam has a faint halo, whereas where the plasma is on (right) the proton beam has a distinct halo and demonstrates that there is transverse blow-up of the proton beam. This result indicates a strong transverse electric fields, as would be expected if the proton beam has undergone SMI.

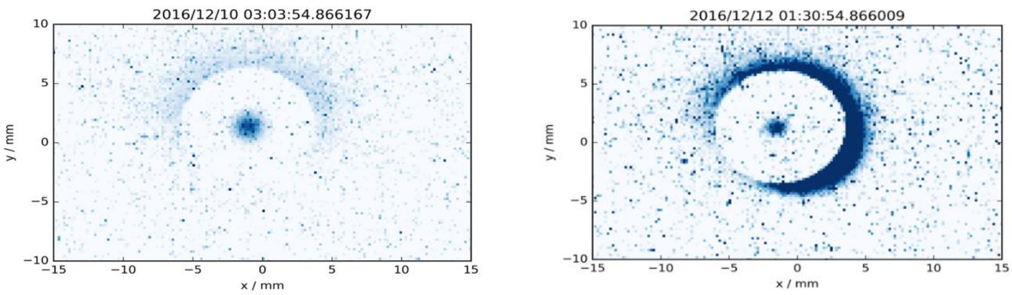


Figure 19: Spatial images of the proton beam on a screen downstream of the plasma cell. Left shows the case where there is no plasma and right where there is a plasma.

A direct method to measure modulation of the proton bunch relies on optical and coherent transition radiation. Figure 20 shows images of the proton beam measured with a streak camera for where there is no plasma (left) and when there is plasma (right). When there is plasma, the image shows a clear modulation of the proton beam, with microbunching on the scales expected.

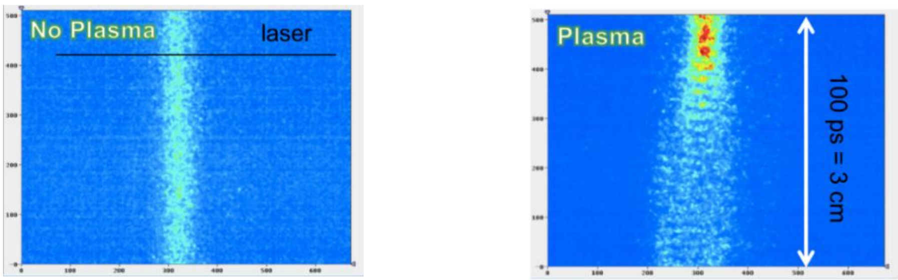


Figure 20: Streak camera images of the proton beam when there is no plasma (left) and when there is plasma (right).

Present-day and future accelerator facilities require femtosecond precision synchronization between the electron beam and external laser systems. This challenging task is crucial for the studies of ultra-fast phenomena in domains such as chemistry, biology or physics. A fast beam-based feedback was planned at FLASH, the Free Electron Laser (FEL) in Hamburg. Arrival time fluctuations of the electron beam were correctable by introducing small energy modulations prior to the magnetic bunch compressor. Design, characterization and the later tunnel integration of an ultra-fast actuator (NRF cavity) with large bandwidth, mandatory to correct fast arrival time fluctuations were achieved. The design and measurements on the ultra-fast normal conducting corrector cavity were achieved. Additional high frequency components needed for cavity operation and its digital low-level radio frequency regulation system were successfully characterized to reach arrival time stabilization towards one femtosecond range.

POTENTIAL IMPACT, DISSEMINATION, EXPLOITAITON OF RESULTS

4.1. IMPACT

4.1.1. Improving performance of existing and future accelerators

EuCARD-2 primarily focused on improving the present and future European accelerator-based Research Infrastructures. This has been achieved by acting at three levels. The first level consisted in improvements applicable at short-term and consisting in the development of specific technologies or instrumentations for accelerator infrastructures currently in operation or in construction, which present an added value from cooperative multi-laboratory developments. The second level was focused on the medium-term and consisted in the definition of new designs and in the contribution to existing design studies aimed at future accelerator infrastructures. The third level is long-term, where collaborative generic R&D that cannot be carried out by individual institutions may have the potential to open new horizons for the accelerator field.

4.1.1.1. Short term

The EuCARD-2 activities have contributed to almost all ongoing particle accelerator projects in the ESFRI roadmap and beyond.

The **HL-LHC** (High-Luminosity upgrade of the LHC) at CERN is the largest ongoing particle physics project in Europe. EuCARD-2 has contributed through WP11 to the development of new material composites based on copper-diamond and on molybdenum carbide-graphite that will equip the HL-LHC collimation system, a critical item to cope with the huge beam densities that will be achieved in this high-luminosity collider. These new materials were tested at the HiRadMat TNA facility (WP9).

The same materials are being considered for the different collimation systems of the **FAIR** project at GSI (Germany), which will accelerate unprecedented ion intensities.

In Europe, there are currently 12 **synchrotron radiation facilities** in operation, generating an enormous and growing research output across different scientific disciplines; many more are now under study. The EuCARD-2 low emittance ring network (WP6) has addressed one the most important challenges in the upgrade of the existing and in the design of the next generation light sources, the generation and control of extremely bright and small particle beams, with emittances down a factor 100 compared to the accelerators currently in operation. This reduction will drastically increase the brilliance of the beam available to users. The exchange of information between accelerators for fundamental research and synchrotron light facilities has paved the way for the ongoing transition from the 3rd generation to a new 4th generation of light sources.

In recent decades, there have been major advances in the development and construction of light sources based on electrons accelerated in linacs. Free-Electron Laser (FEL) light sources can provide a highly coherent X-ray beam with considerably increased scientific range. EuCARD-2 has contributed to two FEL projects commissioned during its lifetime, the **European XFEL** at DESY (Hamburg) and the **SwissFEL** project at PSI (Switzerland), via its innovative Radio-Frequency WP12. Higher-Order-Mode and wakefield monitor diagnostics systems were established and tested with beam and they will provide a new cost-effective and high-performance diagnostic capability for advanced FEL accelerators.

The design of the European Spallation Source (**ESS**) at Lund (Sweden) has profited from the interaction with the Accelerator Driven Systems community via workshops organised by WP5. Smaller linac-based facilities like **CLARA and VELA** (STFC, UK) and **ELBE** (HZDR, Germany) have profited from the developments of cathode materials and deposition processes for RF photocathodes carried out in WP12.

4.1.1.2. Medium term

The concept of the Future Circular Collider (**FCC**) study at CERN for a 100 TeV circular collider in the Geneva area, is the result of a series of workshops and discussions that took place in EuCARD, the project which preceded EuCARD-2. In EuCARD-2 WP5, the FCC basic parameters were discussed and compared to other ongoing studies.

The design of the Compact Linear Collider (**CLIC)** at CERN aiming at a 3 TeV electron linear collider is at an advanced stage of maturity. WP12 contributed to the design and optimization of key CLIC RF components as the high field accelerating and deflecting RF structures, including significant suppression of higher-order modes and wakefields. One of the main challenges for CLIC consists in reducing its power consumption; EuCARD-2 has contributed with ideas and technologies originating from WP3 Energy Efficiency. In particular, WP3 and WP12 have participated in the development of new high-efficiency klystrons that are crucial in reducing the power consumption of a normal-conducting collider.

A promising option to extend the energy reach of present accelerators without large investments in tunnels or infrastructure is the upgrade in energy of the Large Hadron Collider, consisting in the replacement of all its magnets with higher magnetic field units. A very promising long-term alternative for this High-Energy LHC (**HE-LHC**) relies on the development of a third generation of superconducting accelerator magnets based on High-Temperature Superconductors (HTS) reaching a magnetic field of 20 T, 2.5 times the limit of the present LHC magnets. The HTS development was the subject of EuCARD-2 WP10. Thanks to this WP, a new cable in HTS respecting the requirements for HE-LHC together with a compatible magnet design, were developed. Only this technology can today allow a goal of >30 TeV in the HE-LHC (20 T dipole with 33 TeV in the centre of mass).

EuCARD-2 WP7 has been at the origin of **EuPRAXIA**, a seminal Design Study recently approved under the Horizon 2020 program. This concerns an ultra-compact, multi-GeV accelerator and photon source as a user facility based on plasma wakefield acceleration.

Muon colliders represent another alternative to, or possible future extension of, high-energy proton and electron colliders. EuCARD-2 contributed in two directions to improving their design. The Transnational Access to ICTF (WP8) supported several experiments related to the Muon Ion Cooling Experiment (MICE) in the UK, contributing to its recent success in demonstrating ion cooling. Two WP5 workshops revealed the possibility of new, more compact muon-collider designs relying on novel sources of cold muons, either based on the annihilation of positrons from a storage ring with internal target, or through the production of pions in collisions of a high-energy proton beam with repetitive laser pulses.

Reaching higher beam power from the ESS linac was the subject of a WP5 workshop that contributed to the design of a neutrino production facility using the ESS linac. This activity supported the **ESS-nu-SB** Design Study proposal submitted to the Horizon 2020 programme in 2017.

4.1.1.3. Long term

EuCARD-2 WP5 helped shaping the **future generation of accelerator facilities**, by defining a global accelerator roadmap for colliders, hadron storage rings, hadron linacs and beam polarization, and by guiding pertinent R&D efforts. More specifically, WP5 developed several attractive roadmaps for the medium and long-term future, identified promising novel approaches, and singled out specific key areas requiring further effort to optimize the performance of accelerator facilities presently under construction or to improve the design of proposed future machines.

In an effort to determine how to make a **100 TeV hadron collider** more affordable, WP5 identified three key factors for consideration: site selection, staging possibilities, and targeted superconductor/magnet development. For the long-term future, WP5 supported studies on novel production concepts for low-emittance muon beams, the exploration of advanced acceleration schemes based on crystals or nanotubes, and the use of large hadron storage rings for new types of physics, e.g. the generation of X-ray bursts and the excitation or detection of gravitational waves.

Other results from WP5 include the validation of the ILC positron target with a beam test and the demonstration that polarized hadron beams at energies of tens of TeV may be more possible than previously thought. A commissioning strategy for ESS was also worked out, as were polarization requirements needs for the MESA facility at Mainz.

Reducing the size and cost of particle accelerators is one of the main drivers of present day particle accelerator research. One road to be followed consists in improving the present accelerator schemes, whilst another important approach consists of finding disruptive technologies that require R&D investment but have a strong potential for the long-term future. In EuCARD-2, WP7 has promoted **novel acceleration methods** that have the potential to overcome many practical limitations. Novel accelerators may provide accelerating fields of several orders of magnitudes higher than is currently possible. Once the required beam quality can be guaranteed, a new and revolutionary generation of particle accelerators will provide unique beam parameters (ultra-short pulses) with significantly reduced cost and size. WP7 contributed with the development of new concepts for a plasma-based high energy physics collider that will be presented at the European Strategy on Particle Physics that will take place in 2019-2020.

On the experimental side, WP13 contributed to overcoming the technical challenges of **novel laser plasma accelerators**, demonstrating that they can now deliver high quality electron beam in the 100 MeV to a few GeV energy range in a compact distance. The advances in two-stage plasma accelerators are very promising and they will pave the way for multi-stage plasma accelerators based on external injection and/or on all optical injection for delivering higher energy electron beams. Thanks to the progress in reducing the jitter between the laser and the electron beams, the multi-stage approach made significant progress. The plasma wakefield driven by a proton beam, with the results obtained during the course of the EuCARD-2 project, open new horizons for high energy physics.

The impact of the WP3 Network on Energy Efficiency, ranges across short, medium and long terms. New potential facilities will be more powerful, yet this often comes hand in hand with higher energy consumption. The efforts of this Network were aimed at **improving sustainability** and the energy efficiency of concepts and subsystems for particle accelerators. This is an important and necessary activity for the development of future research infrastructures.

4.1.2. Innovation potential of accelerators and accelerator technologies

4.1.2.1. Potential for accelerator applications

More than 30,000 particle accelerators are nowadays in operation worldwide, the large majority being used in industry or medicine. The EuCARD-2 ambition was to have an impact on this large inventory of accelerators responding to societal needs, by transferring the competences and experience from research accelerators to this field.

In this respect, a fundamental step was the publication of the **Applications of Particle Accelerators in Europe** (APAE) document, prepared by WP4. This 113-page reference document includes the direct contributions of 20 experts in the field, with many more contributing to the preparatory meetings. The report describes the current applications of accelerators, achievable improvements in cost and performance via the exploitation of technology from RIs, possible new applications and actions necessary to achieve these applications. It is expected that this document will break the ground towards many further developments in accelerator applications. To complement the extended version, a 6-page summary brochure for the general public and policy-makers has been produced and will be circulated and translated into multiple European languages.

More in detail, WP4 identified many **existing and new accelerator applications** which could benefit from technology developed for RIs. Examples include:

- new environmental applications of low energy electron beams
- industrial applications of low energy electron beams
- implantation of ions with a range of energies (1 keV to 10 MeV) at different depths (detailed circuit printing or etching, or gross material modifications, curing, hardening)
- low energy neutron production (for BNCT, material inspection, material tests)
- use of ion beams for fusion and for satellite propulsion
- radioisotope production
- new accelerator technologies for cancer therapy with ion beams
- cancer therapy with high electron beams
- new accelerator technologies for ADS

In the medical field, EuCARD-2 has contributed to a coordinated effort to develop **accelerators for medical isotope production**, based on linacs or on compact cyclotrons. The AMIT superconducting cyclotron of CIEMAT (Spain) has been presented within WP4, selected for further support under ARIES, and supported by an experiment in the WP9 Transnational Access. Further progress could be brought into the field of compact medical cyclotrons by the use of high-temperature superconductivity technology developed in WP10. With HTS, the magnet can be more compact and /or work comfortably at 30 K, which makes cryogenics much easier, by using a simple cryo-cooler. The HTS could also be applied to **high field magnets for NMR.** HTS using YBCO superconductor is the only way to go beyond the 23 T at 1.9 K given by Nb_3Sn technology. The developments of high current density coils for high field in WP10 has a big impact in this area.

The studies of applications for low-energy electron accelerators have indicated that these accelerators have large potential in the **treatment of wastewater, sludge, and flue gases**. Here accelerators would not only have a major economic impact, but would also carry extensive environmental and health-related socio-economic impact. A prospective collaboration was formed, which will continue this activity as part of the new ARIES project.

Finally, the longer-term development of plasma-based acceleration techniques (WP7 and 13) could potentially lead to **table-top accelerators** capable of moving accelerator technologies into unexplored territories.

4.1.2.2. Potential for other technologies

The material studies on Molybdenum carbide– Graphite composites and other **thermal-management materials** in WP11 is of strong relevance to high-performance industries. This type of novel material with low density and high thermal conductivity may potentially be appealing to a range of domains, as high-end thermal management applications in power electronics, avionics and aerospace, advanced braking systems for automotive and aerospace and hot components in gas turbines.

The development of laser-based plasma wakefield acceleration (via WP7 Network and WP13 Joint Research Activity) has a strong impact on the European **laser industry**. High power lasers are the drivers for one of the most promising classes of novel accelerators, which requires high performance and is already a new test bench for future laser developments. EuCARD-2 WP7 has worked in close connection with the European laser industry, the leading global manufacturer for lasers with high peak power.

As large energy consumers, accelerators actively participate in the global effort to optimise **electric power generation, distribution and consumption**. The dynamic regulation strategies including virtual power plant technologies and the large energy storage system analysed in WP3 are meant at managing the fluctuations of power generation on the grid coming from a larger contribution of sustainable energy sources as wind and solar power. In the energy production field, there may be a significant impact of the WP10 HTS technology for **eolic systems** for renewable energy production. Windmills of large power (>10 MW) require a superconducting generator, to avoid excessive size and weight; here the possibilities opened by the HTS conductor are certainly significant.

4.1.3. Structuring the European Research Area

4.1.3.1. Structuring and integrating the European accelerator community

The EuCARD-2 consortium has mobilised more than 350 participants, representing major European laboratories, research institutes, universities and industries. The members operate very large or large-scale world renowned accelerator infrastructures or contribute to their construction and upgrades or to the R&D for future infrastructures.

With its four Annual Meetings, its 54 thematic Workshops, its more than 40 other events, and the common daily effort on R&D activities that took place in Networks, Transnational Access and Joint Research Activities, EuCARD-2 has created a culture of **open collaboration** and exchange of ideas and information, across borders and technical cultures, and between academia and industry.

While in the past, accelerator R&D and project design were predominantly carried out in individual laboratories, the partnerships at the European level created by FP6 CARE, FP7 EuCARD and now EuCARD-2, continue to enhance a culture of collaboration that is recognized at world level. This includes scientific communities outside of Europe, as testified by the appreciating remarks expressed in the reports of the EuCARD-2 Scientific Advisory Committee, where two out of the three members come from outside of Europe. The deliberate choice to favour a large number of partners, in spite of the limited budget, has been instrumental in enhancing cross-fertilization between European accelerator laboratories, including CERN, Universities, Technology Institutes and SMEs.

The impact of the EuCARD-2 strategy can be measured by the number of **new collaborations** formed within EuCARD-2 that will now continue inside the next project ARIES or independently.

WP4 on **accelerator applications** has been particularly active in creating new collaborations and supporting existing collaborations, in initiating new studies, and promoting the exchange of ideas on common specific subjects and fostering dialogue between political/official representatives from EC institutions, scientific experts and industry. Examples include collaborations to study water and biological sludge treatment, including institutes from Ghana and Uganda, and European water companies; a collaboration to study aspects of accelerator-driven BNCT; a collaboration between the scientific institutes PSI, LBNL (USA) and the company Varian to build a prototype of a SC magnet based on a canted-cosine-theta design.

WP5 greatly contributed to strengthening the synergies between previously separated communities, such as magnet developers, diagnostics experts, vacuum and surface physicists, etc. The WP5 networking effort established new discussion fora, which are enthusiastically maintained by the communities concerned.

WP6 has federated for the first time three accelerator communities sharing common problems and technologies: damping rings for electron colliders, synchrotron light sources, and advanced factories. For the developers and operators of synchrotron light facilities, a strategic setup of European Research Infrastructures, this was a unique occasion of sharing a forum for open discussion and exchange and for identifying synergies and common strategies. The emergence of this new community has already contributed to improving the performance of high-ranking synchrotron light facilities.

WP7 had a crucial role in federating all European efforts in the study of novel accelerators based on lasers and plasmas. This rather dispersed community, characterised by a large share of small universities and only few large laboratories has been boosted by the appearance of the EuroNNAc Network, first in EuCARD and then in EuCARD-2. WP7 has directed the effort towards common goals and has created a permanent coordination structure at the European level that is already moving to Europe the focus of a new technology that was basically started in the US.

The EuCARD-2 WP9 Transnational Access has operated towards not only providing service to users, but also towards creating a user community that could share ideas and resources, with the organization of dedicated user workshops as the HiRadMat Users' day (>50 participants) and the MagNet International Workshop of the Superconducting Magnets Test Stands (>60 participants).

Particular effort within the project went into providing opportunities for employment, education and career advancement for young people, by opening positions and offering supervision of bachelor, master and PhD students. Training of the new generation of scientists was one of the project priorities, via a large number of PhD theses (18), and via special prizes and focus groups for students that were organised by the Networks WP5, 6 and 7.

Gender balance was another project priority. A large number of the students supported by the project were young women, which were constantly encouraged to pursue an education and career path related to innovative technologies. The presence in the EuCARD-2 management of a number of female colleagues as well as of a female member in the Scientific Advisory Committee has provided adequate role models of females with a successful career in science.

4.1.3.2. Development of world-class infrastructures

The activity of EuCARD-2 has contributed to keeping the European particle accelerator infrastructure at world-class level. This concerns the High-Luminosity upgrade of the LHC, the recently commissioned European XFEL and SwissFEL, the ongoing FAIR and ESS projects, and the upgrades of the many European synchrotron light facilities including the ESRF upgrade.

For the design of future infrastructure, EuCARD-2 has contributed to FCC and CLIC at CERN, to the ESS-nu-SB and EuPRAXIA Design Studies, to the high-energy upgrade of the LHC and to the design of a future muon collider.

4.1.3.3. Synergies with other European and International projects and programmes

The activities of EuCARD-2 took place in close coordination with ongoing programmes in Europe and outside. Participation to the TIARA Committee ensured the coordination with EC supported projects, as the Design Study EuPRAXIA that was structured to be complementary with WP7 and 13, and a coordination of initiatives in the field of communication, education and technology transfer. EuCARD-2 is also complementary with the EuroCirCol Design Study; the HTS magnet technology developed in WP10 is intended to constitute a valid alternative to the Nb_3Sn technology adopted for FCC and EuroCirCol.

The presence in the EuCARD-2 Scientific Advisory Committee of members from Japan and from the US provided a welcome connection with similar initiatives in Japan and US.

4.1.4. Impact on European science and society

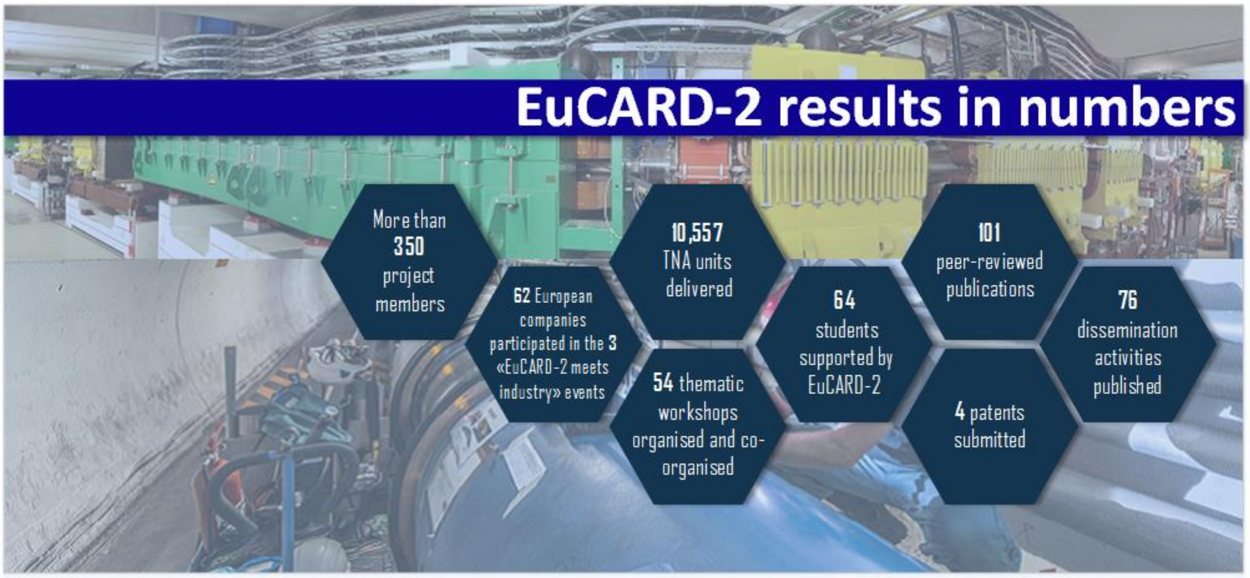


Figure 21: Some EuCARD-2 results in numbers, showing the impact on European science and society.

The exciting developments in particle physics and in fundamental science have been driving the remarkable progress of modern particle accelerators since their invention 90 years ago. While scientific discoveries related to particle accelerators, as the acclaimed Higgs boson, with their wide media coverage convey to the public opinion a positive and progressive image of European scientific research, the impact of particle accelerator technology on European science and society goes much beyond fundamental science. Accelerator technology is now rapidly moving from basic science towards applied science, represented by the multitude of accelerator-based X-ray and neutron sources, and finally to medicine and industry where accelerators have a huge and only partially exploited potential.

The priority of the EuCARD-2 project has been to accompany and favour this transition of accelerator technology, creating bridges and connexions between different accelerator communities and between academia and industry. The project has supported with similar vigour both large projects for fundamental science and smaller initiatives for applied science. At the same time, it has identified promising avenues to exploit the potential of particle accelerators to address European societal challenges, such as providing better medicine for an aging population, reducing the environmental impact related to high living standards, and increasing technological content and competitiveness of industry.

By attracting a large number of students to enter the field of accelerator research and development under the Ph.D. programmes of the participating universities and research centres, EuCARD-2 has contributed to the development of the human resource potential in accelerator science and technology in Europe. Accelerator research is largely multidisciplinary and requires, at the same time, theoretical and technical skills. Training in accelerators in a collaborative environment, has provided students with competences that will be extremely valuable in their future careers, both in science or in industry. By giving relevance to successful cases of young female researchers as role models, EuCARD-2 has contributed to the promotion of women in science and of gender diversity in working environments.

Promotion of accelerator science and outreach were other EuCARD-2 priorities. Particle accelerators represent a success story for European science, and the resonance of the project outreach events was an indication of the impact on the people of the challenges and fascination of research with and on particle accelerators. Presenting accelerator science as a way to find answers not only to fundamental scientific questions, but as well to societal challenges, addressing in particular the young public, was a way to underline the positive role of science in society.

Although the impact of the project is largely demonstrated by its scientific results including 282 publications, its four applications for patents, the support to 64 students, the more than 100 workshops and events organised, and by the large involvement of European industry, it also goes beyond these result and will be in the medium and longer terms, through its contribution to the advancement of a knowledge-based, science and technology driven European society.

4.2. DISSEMINATION ACTIVITIES AND EXPLOITATION OF RESULTS

The communication and dissemination activities of EuCARD-2, under WP1, Task 1.2, included both internal and external communication, ensuring information about the project reached a range of audiences: project members, the wider scientific community, members of industry and the public.

4.2.1. Communication inside the project

The main communication tools and activities for the project members were the internal collaborative workspace (**Intranet**), where the project documentation was stored and shared, the **Steering Committee meetings**, where the WP Coordinators provided activity reports, and the **Annual Meetings**, where EuCARD-2 partners met to discuss the project scientific and technical achievements (Figure 22).

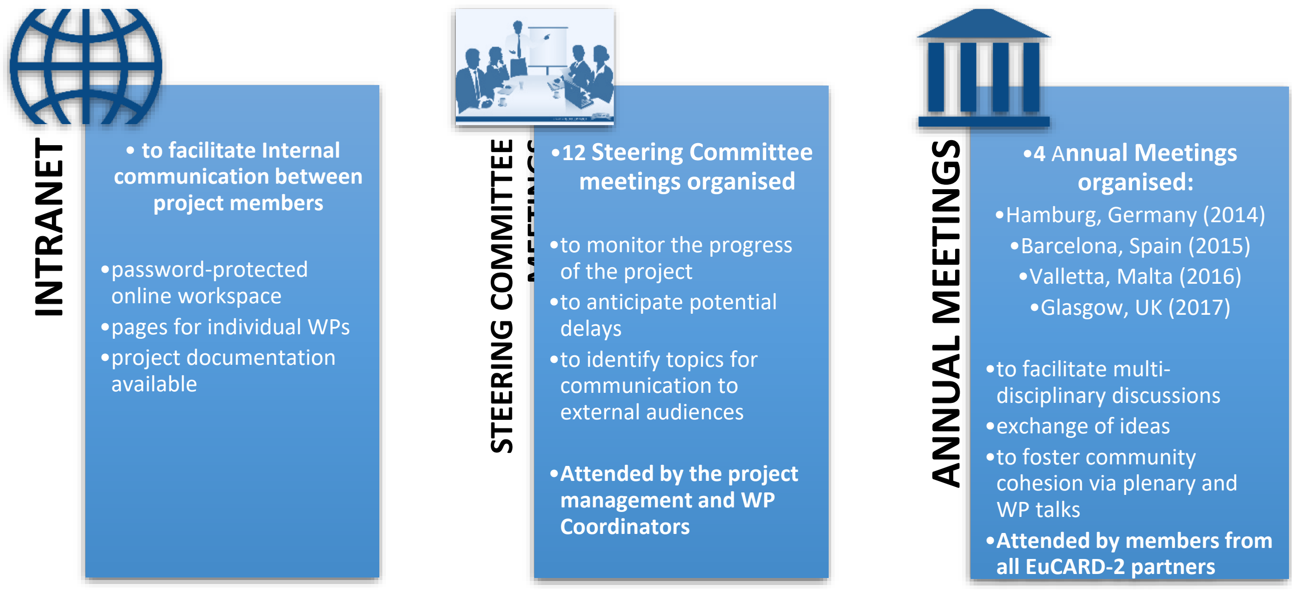


Figure 22: Internal communication between project members via the intranet, Steering Committee meetings and Annual Meetings.

Publications

EuCARD-2 publications are stored in an open access database and amount to a total of 282.

Peer-reviewed journal publications	*Conference/ workshop papers*	*Theses*	*Scientific monographs**	*Articles & Newsletter*	*Presentations*	*Other***	***Total***
101	75	18	5	38	27	18	**282**

*The total number of scientific monographs published during EuCARD-2 amounts to 19 and it includes 14 theses, counted in the Theses category in this table.

***Other* includes: non peer-reviewed journal publications, scientific & technical reports, flyers, posters

Scientific and technical results were published in **peer-reviewed journals** such as: *IEEE Transactions on Applied Superconductivity*, *Physical Review Accelerators and Beams*, *Applied Physics Letters*, *Superconductor Science and Technology* to name a few.

In addition, results were also presented at **major international conferences** including: International Particle Accelerator Conference (IPAC) or International Beam Instrumentation Conference (IBIC).

4.2.2. Dissemination to the scientific accelerator community

Website

The EuCARD-2 project website (http://cern.ch/eucard2) was the primary tool for communication to project members and stakeholders. The site hosted information about the EuCARD-2 work programme, participants, goals, schedule and results. Events, vacancies, outreach, and Transnational Access information were also provided. The site served as a point of access for the publication database, intranet, and project meetings.

Newsletter

The "Accelerating News" (http://acceleratingnews.eu) newsletter grew from the EuCARD quarterly newsletter to include additional accelerator projects and EuCARD-2 became a key contributor. The first issue EuCARD-2 contributed to was published in June 2013 and 15 issues have been published since, which included 30 EuCARD-2 articles. The newsletter has a core subscription base of 1,300+ and is also disseminated to FCC members, an additional ~1,500 recipients.

Network events

The project network events aimed to gather members of the particle accelerator community, including audiences far beyond EuCARD-2, to foster multidisciplinary links and investigate novel concepts and solutions in accelerator science. Across the duration of the project, 82 network events took place.

4.2.3. Dissemination to scientific policy-making bodies

The EuCARD-2 community was well positioned to disseminate its knowledge and results to policy-making bodies, as it represented a wide intersection of European organizations involved in particle accelerator research. EuCARD-2 progress and results were reported to key policy-making bodies through a range of media: newsletter articles, oral reports, meetings and workshops.

EuCARD-2 activity was reported to the CERN Council periodically, as well as to meetings of the European Steering Group for Accelerator R&D (ESGARD). The project also strengthened links with the European Strategy Forum on Research Infrastructures (ESFRI) as the WP7 European Network for Novel Accelerators (EuroNNAC) investigated the ability of the EuPRAXIA project to contribute to the ESFRI roadmap.

A strong and constructive relationship with the European Commission was maintained through regular meetings with the Project Officers, and via participation in consultations and workshops. As a result, EuCARD-2 was able to offer its experience in the management of Research Infrastructures, to contribute to discussions regarding strategies for the future.

In addition, WP4 Task 4.1 led the preparation of the "Applications of Particle Accelerators in Europe (APAE)" document, aimed at policy and decision makers, as well as having scope for members of the public and industry.

4.2.4. Dissemination to industry

A dedicated Work Package (WP2) was set up to foster links between project members, academia and industry, enhancing collaboration and establishing new partnerships.

4.2.5. Outreach towards the general public and media

To raise awareness and provide the most up to date information about EuCARD-2 to the public and the media, the project website was regularly updated with news and results from its work programme. In addition, dedicated articles detailing specific developments were published in Accelerating News, and via additional channels, such as the CERN Bulletin. Both the EuCARD-2 and Accelerating News websites regularly received a higher number of visitors to the site than the number of project members, and included visitors from non-member countries. As such, publicising project information via these channels allowed an audience beyond project members.

The EuCARD-2 website also included an outreach and engagement page, which collected outreach materials for school and university students, teachers, and the public. In addition, the site hosted the project video, which aimed to engage a wide range of audiences to inform them about the project, the applications of accelerators, and to inspire them to pursue accelerator science as a career.

Additional outreach activities included: providing support for accelerator schools aimed at university students, public talks, seminars, publication of articles in several outlets, and the provision of outreach and education materials.

EuCARD-2 supported the Joint University Accelerator School (JUAS) in 2015 and 2016. The project contributed funds and participants presented talks to the attendees.

The project was also featured on the Television of Malta during the 3rd Annual Meeting in 2016, where the Project Coordinator and three EuCARD-2 members were interviewed during the morning show.

Project members also presented public talks and seminars, took part in science festivals and contributed to the Interactions Collaboration (http://www.interactions.org/) comprised of particle physics communicators.

II. USE AND DISSEMINATION OF FOREGROUND

SECTION A: DISSEMINATION MEASURES (PUBLIC)

LIST OF PUBLICATIONS

Table A1: List of scientific (peer reviewed) publications

No	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2]	Is/Will open access[3] provided to this publication?
1	Synchrotron micro-tomography investigation of the filament microstructure in differently processed Bi-2212 wires	Scheuerlein, C. et al	IEEE Transactions on Applied Superconductivity	vol. 27, no.4	IEEE	USA	2017	-	Link	No
2	Partially Insulated Twisted Stacked Cable for HTS Insert of a Particle Accelerator	Himbele, J. et al	IEEE Transactions on Applied Superconductivity	vol. 27, no.4	IEEE	USA	2017	-	Link	No
3	Predicting Heat Propagation in Roebel-cable Based Accelerator Magnet Prototype: One-Dimensional Approach with Coupled Turns	Ruuskanen, J. et al	IEEE Transactions on Applied Superconductivity	vol. 27, no.4	IEEE	USA	2017	-	Link	No

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

4	In-Field Electrical Resistance at 4.2 K of REBCO Splices	Fleiter, J., Ballarino, A.	IEEE Transactions on Applied Superconductivity	vol. 27, no.4	IEEE	USA	2017	-	Link	No
5	First Cold Powering Test of REBCO Roebel Wound Coil for the EuCARD2 Future Magnet Development Project	Kirby, G. et al	IEEE Transactions on Applied Superconductivity	vol. 27, no.4	IEEE	USA	2017	-	Link	No
6	Eigenmode Compendium of the Third Harmonic Module of the European XFEL Computed by SSC	Flisgen, T. et al	Phys. Rev. Accel. Beams	20, 042002	APS	Online	2017	-	Link	Yes
7	Three electron beams from a laser-plasma wakefield accelerator and the energy apportioning question	Yang, X. et al	Scientific Reports	7, 43910	Nature Publishing	Online	2017	-	Link	Yes
8	Experimental characterization of active plasma lensing for electron beams	Pompili, R. et al	Appl. Phys. Lett.	110, 104101	AIP Publishing	USA	2017	-	Link	No
9	Design of beam optics for the future circular collider e+ e− collider rings	Oide, K. et al	Physical Review Accelerators and Beams	19 (11), 111005	APS	Online	2016	-	Link	Yes
10	High Luminosity LHC: challenges and plans	Arduini, G. et al	Journal of Instrumentation	11, C12081	IOP Publishing	Online	2016	-	Link	Yes
11	Comparison of microstructure, second phases and texture formation during melt processing of Bi-2212 mono- and multifilament wires	Scheuerlein, C. et al	Superconductor Science and Technology	vol.29, no.10	IOP Publishing	Online	2016	-	Link	No
12	Unbalanced Cylindrical Magnetron for Accelerating Cavities Coating	Rosaz, G. et al	International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering	vol.10, no.6	WASET	Online	2016	763-766	Link	Yes

13	Commissioning experience and beam physics measurements at the SwissFEL Injector Test Facility	Schietinger, T. et al	Phys. Rev. Accel. Beams	19, 100702	APS	Online	2016	-	Link	Yes
14	Injection of electrons by colliding laser pulses in a laser wakefield accelerator	Hansson, M. et al	Nucl. Instrum. Meth A	829	Elsevier	Netherlands	2016	99-103	Link	Yes
15	AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN	Bracco, C. et al	Nuclear and Particle Physics Proceedings	273-275	Elsevier	Online	2016	175-180	Link	Yes
16	3D printing of gas jet nozzles for laser-plasma accelerators	Dopp, A. et al	Review of Scientific Instruments	87, 073505	AIP Publishing	USA	2016	-	Link	No
17	Femtosecond timing-jitter between photo-cathode laser and ultra-short electron bunches by means of hybrid compression	Pompili, R. et al	New Journal of Physics	vol.18	IOP Publishing	Online	2016	-	Link	Yes
18	Path to AWAKE: Evolution of the concept	Caldwell, A. et al	Nucl. Instrum. Meth. A	829, 3	Elsevier	Netherlands	2016	-	Link	Yes
19	Towards Future Circular Colliders	Benedikt, M. and Zimmermann, F	Journal of the Korean Physical Society	Volume 69, Issue 6, pp 893–902	Springer Berlin Heidelberg	Germany	2016	-	Link	No
20	Influence of the oxygen partial pressure on the phase evolution during the melt processing of Bi-2212 superconducting wires	C. Scheuerlein	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
21	Comparison of electromechanical properties and lattice distortions of different cuprate high temperature superconductors	C. Scheuerlein et al.,	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
22	Development of a Roebel-cable-based cos-theta dipole: design and windability of magnet ends	C. Lorin,	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No

23	HTS dipole magnet for a particle accelerator using a twist stack cable	J. Himbele	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
24	Enhancement of the transverse stress tolerance of REBCO Roebel cables by epoxy impregnation	S. Otten	Superconductor Science and Technology	Volume 28, Number 6	IOP Publishing	Online	2016	-	Link	No
25	Advances in the Development of a 10-kA Class REBCO cable for the EuCARD-2 Demonstrator Magnet	L. Bottura	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
26	Measurement and Numerical Evaluation of AC-Losses in a ReBCO Roebel Cable at 4.5 K	L. Bottura	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
27	Electromechanical behaviour of REBCO tape lap splices under transverse compressive loading	A. Grether	Superconductor Science and Technology	Volume 29, Number 7	IOP Publishing	Online	2016	-	Link	No
28	Magnetization Losses of Roebel Cable Samples With 2G YBCO Coated Conductor Strands	Y. Yang	IEEE Transactions on Applied Superconductivity	Volume: 26 Issue: 3	IEEE	USA	2016	-	Link	No
29	Voronoi Particle Merging Algorithm for PIC Codes	P.T. Luu	Computer Physics Communications	Volume 202, May 2016, Pages 165-174	Elsevier	Netherlands	2016	-	Link	No
30	Electron Beam Final Focus System For Thomson Scattering At Elbe	J.M. Krämer et al	Nucl. Instrum. Meth. A	Volume 830, Pages 532-535	Elsevier	Netherlands	2016	-	Link	Yes
31	Energy boost in Laser-Wakefield Accelerator using sharp density transitions	A. Döpp et al	Physics of Plasmas	23, 056702 (2016)	AIP Publishing	USA	2016	-	Link	No

32	Localization of ionization-induced trapping in a laser wakefield accelerator using a density down-ramp	M. Hansson et al.	Plasma Physics and Controlled Fusion	58 055009	IOP Publishing	Online	2016	-	Link	Yes
33	Direct acceleration of electrons by a CO2 laser in a curved plasma waveguide	L. Yi et al	Scientific Reports	6, Article number: 28147	Nature.com	Online	2016	-	Link	Yes
34	Characterization of the equilibrium configuration for modulated beams in a plasma wakefield accelerator	R. Martorelli et al.	Physics of Plasmas	23, 053109 (2016)	AIP Publishing	Online	2016	-	Link	No
35	Quasi-stable injection channels in a wakefield accelerator	M. Wiltshire-Turkay et al	Physics of Plasmas	23, 053112 (2016)	AIP Publishing	Online	2016	-	Link	No
36	Bright X-Ray Source from a Laser-Driven Microplasma Waveguide	L. Yi et al.,	Phys. Rev. Lett.	116, 115001	APS	USA	2016	-	Link	No
37	A non-linear theory for the bubble regime of plasma wake fields in tailored plasma channels	J. Thomas et al	Physics of Plasmas	23, 053108 (2016)	AIP Publishing	Online	2016	-	Link	No
38	Investigation of ionization-induced electron injection in a wakefield driven by laser inside a gas cell	T. L. Audet et al.	Physics of Plasmas	23, 053110 (2016)	AIP Publishing	Online	2016	-	Link	No
39	Supersonic jets of hydrogen and helium for laser wakefield acceleration	K. Svensson et al.,	Physical Review Accelerators and Beams	19, 051301	APS	Online	2016	-	Link	No
40	AWAKE, The advanced proton driven plasma wakefield acceleration experiment at CERN	AWAKE Collaboration et al.,	Nucl. Instrum. Meth. A	Volume 829, Pages 76-82	Elsevier	Netherlands	2016	-	Link	Yes
41	Single Shot Betatron Source Size Measurement From a Laser Wakefield Accelerator	A. Köhler et al	Nucl. Instrum. Meth. A	Volume 829, Pages 265-269	Elsevier	Netherlands	2016	-	Link	No
42	Tomographic characterisation of gas-jet targets for laser wakefield acceleration	J.P. Couperus et al.	Nucl. Instrum. Meth. A	Volume 830, Pages 504-509	Elsevier	Netherlands	2016	-	Link	No

43	Non-linear theory of a cavitated plasma wake in a plasma channel for special applications and control	Johannes Thomas et al	Physics of Plasmas	23, 053108	AIP Publishing	USA	2016	-	Link	No
44	Raman amplification in the coherent wave-breaking regime	Farmer, J.P., Pukhov, A.	Physical Review E	92, 063109	APS	USA	2015	-	Link	No
45	Simulation of density measurements in plasma wakefields using photon acceleration	Kasim, M. F. et al	Physical Review Accelerators and Beams	18, 032801	APS	Online	2015	-	Link	Yes
46	Quantitative single shot and spatially resolved plasma wakefield diagnostics	Kasim, M. F. et al	Physical Review Accelerators and Beams	18, 081302	APS	Online	2015	-	Link	Yes
47	Electron Rephasing in a Laser-Wakefield Accelerator	Guillaume, E. et al	Phys. Rev. Lett.	115, 155002	APS	USA	2015	-	Link	No
48	The EuCARD-2 Future Magnets European Collaboration for Accelerator-Quality HTS Magnets	Rossi, L.	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2015	-	Link	No
49	High-Energy Physics Strategies and Future Large-Scale Projects	Zimmermann, F	Nucl. Instrum. Meth. B	355 , 4–10	Elsevier	Netherlands	2015	-	Link	Yes
50	Extending the Nonlinear-Beam-Dynamics Concept of 1D Fixed Points to 2D Fixed Lines	Franchetti, G., Schmidt, F	Phys. Rev. Lett	114, 234801	APS	USA	2015	-	Link	Yes
51	Optimizing integrated luminosity of future hadron colliders	Benedikt, M., Schulte, D., and Zimmermann, F.	Physical Review Accelerators and Beams	18, 101002	APS	Online	2015	-	Link	Yes
52	On-line control of the nonlinear dynamics for synchrotrons	J. Bengtsson et al.:	Physical Review Accelerators and Beams	18, 074002	APS	Online	2015	-	Link	Yes
53	On Roebel Cable Geometry for Accelerator Magnet	J. Fleiter	IEEE Transactions on Applied Superconductivity	Volume 26, Issue 3	IEEE	USA	2015	-	Link	No

54	Strain induced irreversible critical current degradation in highly dense Bi-2212 round wire	C. Scheuerlein	Superconductor Science and Technology	Volume 28, Number 6	IOP Publishing	Online	2015	-	Link	No
55	Hot Spot Temperature in an HTS Coil: Simulations With MIITs and Finite Element Method	E. Härö	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 2	IEEE	USA	2015	-	Link	No
56	Modeling of Minimum Energy Required to Quench an HTS Magnet With a Strip Heater	E. Härö	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 6	IEEE	USA	2015	-	Link	No
57	Variation of Quench Propagation Velocities in YBCO Cables	E. Härö	Journal of Superconductivity and Novel Magnetism	Volume 28, Issue 6, pp 1705–1710	Springer Berlin Heidelberg	Germany	2015	-	Link	No
58	Field and temperature scaling of the critical current density in commercial REBCO coated conductors	C. Senatore et al	Superconductor Science and Technology	Volume 29, Number 1	IOP Publishing	USA	2015	-	Link	No
59	Mechanical characterization and modeling of the heavy tungsten alloy IT180	M.Scapin	International Journal of Refractory Metals and Hard Materials	Volume 50, May 2015, Pages 258-268	Elsevier	Netherlands	2015	-	Link	Yes
60	Thermomechanical response of Large Hadron Collider collimators to proton and ion beam impacts	M. Cauchi et al.	Physical Review Accelerators and Beams	18, 041002	APS	Online	2015	-	Link	Yes
61	Thermomechanical assessment of the effects of a jaw-beam angle during beam impact on Large Hadron Collider collimators	M. Cauchi et al.	Physical Review Accelerators and Beams	18, 021001	APS	Online	2015	-	Link	Yes
62	Experimental investigation of the behavior of tungsten and molybdenum alloys at high strain-rate and temperature	M. Scapin et al	EPJ Web of Conferences	94, 01021 (2015)	EDP Sciences	France	2015	-	Link	Yes

63	Phase field modelling of dynamic thermal fracture in the context of irradiation damage	A. Schlüter et al	Continuum Mechanics and Thermodynamics	Volume 29, Issue 4, pp 977–988	Springer Berlin Heidelberg	Germany	2015	-	Link	No
64	Material-related issues at high-power and high-energy ion beam facilities	M. Bender et al	Journal of Physics: Conference Series	Volume 599, conference 1	IOP Publishing	USA	2015	-	Link	No
65	Computational benefits using an advanced concatenation scheme based on reduced order models for RF structures	J. Heller et al	Physics Procedia	Volume 79, 2015, Pages 38-45	Elsevier	Netherlands	2015	-	Link	Yes
66	Stability and resolution studies of HOMBPMs for the 1.3 GHz superconducting accelerating cavities at FLASH	L. Shi	Physics Procedia	Volume 77, 2015, Pages 42-49	Elsevier	Netherlands	2015	-	Link	Yes
67	Down-ramp injection and independently controlled acceleration of electrons in a tailored laser wakefield accelerator	M. Hansson, et al	Physical Review Accelerators and Beams	18, 071303	APS	USA	2015	-	Link	Yes
68	Laser fields in dynamically ionized plasma structures for coherent acceleration	P. Luu-Thanh	The European Physical Journal Special Topics	Volume 224, Issue 13, pp 2625–2629	Springer Berlin Heidelberg	Germany	2015	-	Link	No
69	Field-reversed bubble in deep plasma channels for high quality electron acceleration	Pukhov, A. et al	Phys. Rev. Lett.	113, 245003	APS	USA	2014	-	Link	Yes
70	Dynamics of ionization-induced electron injection in the high density regime of laser wakefield acceleration	Desforges, F.G. et al	Physics of Plasmas	21, 120703	AIP Publishing	USA	2014	-	Link	No
71	Accelerator-driven boron neutron capture therapy	Edgecock, R	International Journal of Modern Physics A	Vol. 29, No. 14 (2014) 1441004	World Scientific Publishing Company	Singapore	2014	-	Link	No

72	Transverse Thermal Conductivity of REBCO Coated Conductors	M. Bonura	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	No
73	Modeling Quench Protection Heater Delays in an HTS Coil	Salmi, T, Stenvall, A	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	No
74	Cos-θ design of dipole inserts made of ReBCO-Roebel or BSCCO-Rutherford cables	Lorin, C, et al	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	No
75	High-field thermal transports properties of REBCO coated conductors	Bonura, M, Senatore, C	Superconductor Science and Technology	28 (2015) 025001 (9pp)	IOP Publishing	USA	2014	-	Link	No
76	Study of a 5T Research Dipole Insert-Magnet using an Anisotropic ReBCO Roebel Cable	Van Nugteren, J, et al	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	Yes
77	Accelerator Quality HTS Dipole Magnet Demonstrator designs for the EuCARD-2, 5 Tesla 40 mm Clear Aperture Magnet	Kirby, G, et al	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	Yes
78	Performance tests of prototype high field HTS coils in Grenoble	Miyoshi, Y, et al	IEEE Transactions on Applied Superconductivity	Volume 25, Issue 3	IEEE	USA	2014	-	Link	Yes
79	Scattering Parameters of the 3.9 GHz Accelerating Module in a Free-Electron Laser Linac: A Rigorous Comparison Between Simulations and Measurements	T Flisgen et al	Physical Review Accelerators and Beams	Volume 17, 022003	APS	USA	2014	-	Link	Yes
80	Time-Domain Absorbing Boundary Terminations for Waveguide Ports Based on State-Space Models	T. Flisgen et al	IEEE Transactions on Magnetics	Volume 50, N°2	IEEE	USA	2014	-	Link	Yes

81	Deposition and optimization of thin lead layers for superconducting accelerator photocathodes	J. Lorkiewicz et al	Physica Scripta	Volume 2014, number T161	IOP Publishing	USA	2014	-	Link	No
82	Niobium nitride thin films deposited by high temperature chemical vapor deposition	Mercier, F et al	Surface & Coatings Technology	Volume 260, 126-132	Elsevier	Netherlands	2014	-	Link	No
83	Design of a plasma discharge circuit for particle wakefield acceleration	M. P. Anania et al	Nucl. Instrum. Meth. A	740 (2014) 193–196	Elsevier	Netherlands	2014	-	Link	No
84	Ultra-short electron bunches by Velocity Bunch in gas required for plasma wave accelerations	A. Bacci, A. R. Rossi	Nucl. Instrum. Meth. A	740 (2014) 42–47	Elsevier	Netherlands	2014	-	Link	No
85	Reproducibility of electron beams from laser wakefield acceleration in capillary tubes	F. G. Desforges et al	Nucl. Instrum. Meth. A	740 (2014) 54–59	Elsevier	Netherlands	2014	-	Link	No
86	Enhanced stability of laser wakefield acceleration using dielectric capillary tubes	M. Hansson et al	Phys. Rev. ST Accel. Beams	17, 031303	APS	USA	2014	-	Link	Yes
87	Numerical investigation of beam-driven PWFA in quasi-nonlinear regime	P. Londrillo, C. Gatti, M.Ferrario	Nucl. Instrum. Meth. A	740 (2014) 236–241	Elsevier	Netherlands	2014	-	Link	No
88	Transformer ratio studies for single bunch plasma wakefield acceleration	F. Massimo et al	Nucl. Instrum. Meth. A	740 (2014) 242–245	Elsevier	Netherlands	2014	-	Link	No
89	First single-shot and non-intercepting longitudinal bunch diagnostics for comb-like beam by means of Electro-Optic Sampling	R. Pompili, et al	Nucl. Instrum. Meth. A	740, (2014), 216-221	Elsevier	Netherlands	2014	-	Link	No
90	The External Injection experiment at the SPARC_LAB facility,	Andrea R. Rossi et al	Nucl. Instrum. Meth. A	740, (2014), 60-66	Elsevier	Netherlands	2014	-	Link	No
91	Scaling electron acceleration in the bubble regime for upcoming lasers	O. Jansen, T. TÅNuckmantel, and A. Pukhov	The European Physical Journal Special Topics	May 2014, Volume 223, Issue 6, pp 1017–1030	Springer Berlin Heidelberg	Germany	2014	-	Link	No

92	Near QED regime of laser interaction with overdense plasmas	L.L. Ji, A. Pukhov, E.N. Nerush, I.Yu. Kostyukov, K.U. Akli, and B.F. Shen	The European Physical Journal Special Topics	May 2014, Volume 223, Issue 6, pp 1069–1082	Springer Berlin Heidelberg	Germany	2014	-	Link	No
93	Coherent acceleration by laser pulse echelons in periodic plasma structures	A. Pukhov, I. Kostyukov, T. TÅNuckmantel, Ph. Luu-Thanh, and G. Mourou	The European Physical Journal Special Topics	May 2014, Volume 223, Issue 6, pp 1197–1206	Springer Berlin Heidelberg	Germany	2014	-	Link	No
94	Laser pulse shaping for multi-bunches photoinjectors	F. Villa, S. Cialdi, M. P. Anania, G. Gatti, F. Giorgianni, R. Pompili	Nucl. Instrum. Meth. A	740, (2014) 188-192	Elsevier	Netherlands	2014	-	Link	No
95	Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics	R. Assman et al	Plasma Physics and Controlled Fusion	56 (2014) 084013 (7pp)	IOP Publishing	USA	2014	-	Link	No
96	Collider Beam Physics	Zimmermann, F	Reviews of Accelerator Science and Technology	Vol. 7 (2014) 177–205	World Scientific Publishing Company	Singapore	2014	-	Link	No
97	Radiation-Reaction Trapping of Electrons in Extreme Laser Fields	L. L. Ji, A. Pukhov, I. Yu. Kostyukov, B. F. Shen, and K. Akli	Phys. Rev. ST	112, 145003 (2014)	APS	USA	2013	-	Link	Yes
98	Characterization of a Superconducting Pb Photocathode in a Superconducting RF Photoinjector Cavity	R. Barday et al	Physical Review Accelerators and Beams	Volume 16, 123402	APS	USA	2013	-	Link	Yes

99	The role of the gas/plasma plume and self-focusing in a gas-filled capillary discharge waveguide for high-power laser-plasma applications	C. Ciocarlan et al	Physics of Plasmas	20, 093108 (2013)	AIP Publishing	USA	2013	-	Link	No
100	Plasma density measurements using chirped pulse broad-band Raman amplification	G. Vieux et al	Applied Physics Letters	103, 121106 (2013)	AIP Publishing	USA	2013	-	Link	No
101	Angular-Momentum Evolution in Laser-Plasma Accelerators	Thaury, C et al.	Research in Optical Sciences	paper HTh1B.4	OSA Publishing	Online	2013	-	Link	No

Table A2: List of dissemination activities and other publications[4]

No Link	Type of publications[5]	Lead author	Title	Date	Place	Type of audience[6]	Size of audience	Countries addressed
1 Link	Article	Skarda, V.	Low Energy Electron Beams for Industrial and Environmental Applications, *PTJ (Postepy Techniki Jadrowej)*, vol. 60 Z. 1, 2017	2017	INCT, Poland	Scientific community	-	International
2 Link	Publication	Murtomaeki, Jaako et al.	Mechanical Effects of the Non-Uniform Current Distribution on HTS Coils for Accelerators Wound with REBCO Roebel Cable	2017	-	Scientific community	-	International
3 Link	Presentation	Zimmermann, F.	Progress Towards Next Generation Hadron Colliders: FCC-hh, HE-LHC and SPPC, *APS April Meeting*	2017	Washington DC, USA	Scientific community	-	International
4 Link	Presentation	Zimmermann, F.	CERN-CONACyT BEAM programme for doctoral and technical students	2017	CERN	Scientific community	-	International
5 Link	Scientific monograph	Vretenar, M. et al	EuCARD-2 Final Project Report (vol.45)	2017	WUT & CERN	Scientific community	-	International

[4] The dissemination activities are listed in chronological order and by type of publication.

[5]Type of publications: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[6] Type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

6 Link	Scientific monograph	D'Agnolo, R. et al	Strategy for Future Extreme Beam Facilities (vol.44)	2017	WUT, Poland	Scientific community	-	International
7 Link	Article	EuCARD-2 Collaboration	Daresbury workshop focuses on electron-positron factories, *CERN Courier*	2017	CERN	Scientific community, Medias	-	International
8 Link	Article	Bellachioma, M.C., Franchetti, G., Casalbuoni, S.	Vakuum, Strahldynamik, Kollimatoren und Oberflächen lachten in Karlsruhe, *GSI Kurier*	2017	GSI, Germany	Scientific community, Medias	-	International
9 Link	Newsletter	Toes, J.	Accelerators for testing energy efficiency, *Accelerating News Issue 20*	2017	CERN	Scientific community, Medias	-	International
10 Link	Newsletter	Toes, J.	ADS research workshop held at CERN, *Accelerating News Issue 20*	2017	CERN	Scientific community, Medias	-	International
11 Link	Publication	R. Martorelli et al	Optimized stability of a modulated driver in a plasma wakefield accelerator *Laser and Particle Beams ,Volume 34, Issue 3 September 2016, pp. 519-526*	2016	-	Scientific community	-	International
12 Link	Publication	A. Pukhov	Particle-in-Cell Codes for plasma-based particle acceleration *Proceedings of the CAS-CERN Accelerator School: Plasma Wake Acceleration*	2016	CERN	Scientific community	-	International
13 Link	Conference/ workshop	Stadlmann, J. et al	Analysis of Electrical Energy Consumption of Accelerator Research Facilities, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
14 Link	Conference/ workshop	Bruton, D. et al	A Compact and High Current FFAG for the Production of Radioisotopes for Medical Applications, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
15 Link	Conference/ workshop	Aull, S. et al	Electrical Power Budget for FCC-ee, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
16 Link	Conference/ workshop	Canton C.G. et al	Simulating Proton Synchrotron Radiation in the Arcs of the LHC, HL-LHC and FCC-hh, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
17 Link	Conference/ workshop	Valdivia Garcia, M.A. et al	Effect of Beamstrahlung on Bunch Length and Emittance in Future Circular e+e- Colliders, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International

18 Link	Conference/ workshop	Valdivia Garcia, M.A. et al	Towards a Monochromatization Scheme for Direct Higgs Production at FCC-ee, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
19 Link	Conference/ workshop	Zimmermann, F. et al	Luminosity Targets for FCC-hh, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
20 Link	Conference/ workshop	Ghasem, H. et al	Nonlinear Optimization of CLIC DRS New Design with Variable Bends and High Field Wigglers, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
21 Link	Conference/ workshop	Bartolini, R.	Design and Optimisation Strategies of Nonlinear Dynamics for Diffraction Limited Synchrotron Light Source, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
22 Link	Conference/ workshop	Bartolini, R. et al	Analysis of Multi-bunch Instabilities at the Diamond Storage Ring, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
23 Link	Conference/ workshop	Bartolini, R. et al	Concepts for a Low Emittance-High Capacity Storage Ring for the Diamond Light Source, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
24 Link	Conference/ workshop	Bartolini, R. et al	Study of a Double Triple Bend Achromat (DTBA) Lattice for a 3 GeV Light Source, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
25 Link	Conference/ workshop	Onishi, Y. et al.	Optics Measurements and Corrections at the Early Commissioning of SuperKEKB, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
26 Link	Conference/ workshop	Papaphilippou, Y. et al	Design Guidelines for the Injector Complex of the FCC-ee, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
27 Link	Conference/ workshop	Valloni, A. et al	MERLIN Cleaning Studies with Advanced Collimator Materials for HL-LHC, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
28 Link	Conference/ workshop	Quaranta, E. et al	Radiation-Induced Effects on LHC Collimator Materials under Extreme Beam Conditions, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
29 Link	Conference/ workshop	Joshi, N. et al	Simulation of Electromagnetic Scattering through the E-XFEL Third Harmonic Cavity Module, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
30 Link	Conference/ workshop	Shi, L. et al	Measurement of Beam Phase at FLASH using HOMs in Accelerating Cavities, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
31 Link	Conference/ workshop	Mistry, S. et al	A Comparison of Surface Properties of Metallic Thin Film Photocathodes, *IPAC2016*	2016	Busan, Korea	Scientific community	-	International
32 Link	Conference/ workshop	Bartmann, W. et al	Beam dynamics issues in the FCC, *HB2016*	2016	Malmo, Sweden	Scientific community	-	International

33 Link	Conference/ workshop	Franchetti, G. et al	First Analysis of the Space Charge Effects on a Third Order Coupled Resonance, *HB2016*	2016	Malmo, Sweden	Scientific community	-	International
34 Link	Conference/ workshop	Kesting, F., Franchetti, G.	Mitigation of Numerical Noise for Beam Loss Simulations, *HB2016*	2016	Malmo, Sweden	Scientific community	-	International
35 Link	Conference/ workshop	Zimmermann, F.	Higgs Factory Concepts, *eeFACT2016*	2016	Daresbury, UK	Scientific community	-	International
36 Link	Conference/ workshop	Zimmermann, F.	Summary of Impedance Issues and Beam Instabilities, *eeFACT2016*	2016	Daresbury, UK	Scientific community	-	International
37 Link	Conference/ workshop	Zimmermann, F., Blondel, A., Assmann, R.	Summary of Design Concepts, *eeFACT2016*	2016	Daresbury, UK	Scientific community	-	International
38 Link	Conference/ workshop	Mollard, A. et al	High-Efficiency Klystron Design for the CLIC Project, *IVEC*	2016	Monterey, USA	Scientific community	-	International
39 Link	Conference/ workshop	Flisgen, T. et al	Combined Domain Decomposition and Model Order Reduction to Solve Complex RF Problems Using FeniCS, *FEM2016*	2016	Florence, Italy	Scientific community	-	International
40 Link	Conference/ workshop	Baboi, N. et al	HOM Characterization for Beam Diagnostics at the European XFEL Injector, *IBIC2016*	2016	Barcelona, Spain	Scientific community	-	International
41 Link	Presentation	Zimmermann, F.	Future Circular Colliders: *Particle Physics Colloquium at Ruprecht-Karls-Universität Heidelberg*	2016	Ruprecht-Karls-Universität Heidelberg, Germany	Scientific community	-	International
42 Link	Presentation	Zimmermann, F.	Future Circular Collider Study, *XII Quark Confinement and the Hadron Spectrum Conference (Conf12) - Satellite Workshop: Accelerators Revealing the QCD Secrets*	2016	Thessaloniki, Greece	Scientific community	-	International
43 Link	Presentation	Goldacker, W. et al	Latest developments and challenges in developing Coated Conductor magnets for accelerators within EuCARD-2	2016	KIT, Germany	Scientific community	-	International
44 Link	Scientific monograph	Wronka, S.	Interlaced Energy Linac with Smooth Energy Regulation (vol.37)	2016	WUT, Poland	Scientific community	-	International
45 Link	Scientific monograph	Densham, C. et al	The Energy Efficiency of Proton Driver Accelerators (vol.43)	2016	WUT, Poland	Scientific community	-	International

46 Link	Scientific monograph/ Thesis	Franciello, O.	Wake Fields and Impedance Calculations of LHC Collimators' Real Structures (vol.38)	2016	Sapienza University of Rome, Italy	Scientific community	-	International
47 Link	Scientific monograph/ Thesis	Lipinski, M.	Methods to Increase Reliability and Ensure Determinism in a White Rabbit Network (vol.40)	2016	WUT, Poland	Scientific community	-	International
48 Link	Scientific monograph/ Thesis	Graczyk, R.	Dependable control and measurement systems modelling for unmanned spacecraft (vol.41)	2016	WUT, Poland	Scientific community	-	International
49 Link	Scientific monograph/ Thesis	Rychter, A.	Measurement Based Characterisation and Modelling of Micropixel Avalanche Photodiodes (vol.42)	2016	WUT, Poland	Scientific community	-	International
50 Link	Thesis	Gardlowski, P.	Energy Efficient Beam Transfer Channels for High Energy Particle Accelerators	2016	TUD, Germany	Scientific community	-	International
51 Link	Thesis	Von Nugteren, J.	High Temperature Superconductor Accelerator Magnets	2016	UT, Netherlands	Scientific community	-	International
52 Link	Scientific Report	Von Nugteren, J.	E3SPreSSO A Quench Protection System for High Field Superconducting Magnets	2016	CERN	Scientific community	-	International
53 Link	Newsletter	Assmann, R., Ratoff, P., Zimmermann, F.	eeFACT2016 held in Daresbury UK, *Accelerating News Issue 19*	2016	CERN	Scientific community, Medias	-	International
54 Link	Newsletter	Toes, J.	ARIES approved by European Commission, *Accelerating News Issue 18*	2016	CERN	Scientific community, Medias	-	International
55 Link	Newsletter	Toes, J.	EuCARD-2 3rd Annual Meeting highlights, *Accelerating News Issue 17*	2016	CERN	Scientific community, Medias	-	International
56 Link	Newsletter	Toes, J.	EuCARD2 WP3 Workshop on Proton Driver Accelerator Energy Efficiency, *Accelerating News Issue 16*	2016	CERN	Scientific community, Medias	-	International
57 Link	Publication	Franchetti, G. and Schmidt, F	Fix-lines and stability domain in the vicinity of the coupled third order resonance	2015	CERN	Scientific community	-	International

58 Link	Publication	Zimmermann, F. et al	Status and Challenges for FCC-ee	2015	CERN	Scientific community	-	International
59 Link	Publication	Benedikt, M., Zimmermann, F	Outline and Status of the FCC-ee Design Study	2015	CERN	Scientific community	-	International
60 Link	Publication	Zimmermann, F. et al	Beam Dynamics Challenges for FCC-ee	2015	CERN	Scientific community	-	International
61 Link	Conference/ workshop	Petzenhauser, I. et al	Efficient Pulsed Quadrupole, *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
62 Link	Conference/ workshop	Seidel, M. et al	Improving the Energy Efficiency of Accelerator Facilities, *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
63 Link	Conference/ workshop	Benedikt, M., Goddard, B., Schulte, D., Zimmermann, F. and Syphers	FCC-hh Hadron Collider—Parameter Scenarios and Staging Options *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
64 Link	Conference/ workshop	Benedikt, M et al	Combined Operation and Staging for the FCC-ee Collider *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
65 Link	Conference/ workshop	Aleksan, R., et al	Scenarios for Circular Gamma-Gamma Higgs Factories *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
66 Link	Conference/ workshop	Ohmi, K. and Zimmermann, F	Study of Beam-Beam Effects in FCC-he *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
67 Link	Conference/ workshop	Ohmi, K., Mether, L., Schulte, D., Zimmermann, F	Study of Electron Cloud Instabilities in FCC-hh *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
68 Link	Conference/ workshop	Aulenbacher, K., Biagini, M., Eshraqi, M., Franchetti, G, Struckmeier, J., Zimmermann, F.	The Extreme Beams Initiative in EuCARD-2 *IPAC2015*	2015	Richmond, USA	Scientific community	-	International

69 Link	Conference/ workshop	S. Papadopoulou et al	Alternative optics design of the clic damping rings with variable dipole bends and high-field wigglers *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
70 Link	Conference/ workshop	B. Wooley et al	High Gradient Testing of an X-Band Crab Cavity at XBOX2 *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
71 Link	Conference/ workshop	L. Deacon et al	Development of a spectrometer for proton driven plasma wakefield accelerated electrons at AWAKE *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
72 Link	Conference/ workshop	M. Fakhari et al	Design of a Normal Conducting Cavity for Arrival Time Stabilization at FLASH *IPAC2015*	2015	Richmond, USA	Scientific community	-	International
73 Link	Conference/ workshop	E. Quaranta et al.	Collimation cleaning at the LHC with advanced secondary collimator materials	2015	Richmond, USA	Scientific community	-	International
74 Link	Conference/ workshop	Benedikt, M. and Zimmermann, F	Future Circular Colliders *Future Research Infrastructures: Challenges and Opportunities*	2015	Varenna, Italy	Scientific community	-	International
75 Link	Conference/ workshop	Benedikt, M. and Zimmermann, F	Future Circular Colliders *27th International Symposium on Lepton Photon Interactions at High Energies*	2015	Ljubljana, Slovenia	Scientific community	-	International
76 Link	Conference/ workshop	Benedikt, M. and Zimmermann, F	Status and Challenges of the Future Circular Collider Study *12th International Topical Meeting on Nuclear Applications of Accelerators*	2015	Washington, DC, USA	Scientific community	-	International
77 Link	Conference/ workshop	N. Baboi et al	Commissioning of the Electronics for HOM-based Beam Diagnostics at the 3.9 GHz Accelerating Module at FLASH *International Beam Instrumentation Conference*	2015	Tsukuba, Japan	Scientific community	-	International
78 Link	Conference/ workshop	T. Galek et al	Analysis of Higher Order Modes in Large Superconducting Radio Frequency Accelerating Structures *2015 International Conference on Electromagnetics in Advanced Applications (ICEAA)*	2015	Turin, Italy	Scientific community	-	International

79 Link	Conference/ workshop	J. Heller et al	Uncertainty Quantification for Complex RF-structures Using the State-space Concatenation Approach *PIERS Proceedings*	2015	Prague, Czech Republic	Scientific community	-	International
80 Link	Conference/ workshop	G. Rosaz et al	Development of Nb3Sn coatings by magnetron sputtering for SRF cavities *17th International Conference on RF Superconductivity*	2015	Whistler, Canada	Scientific community	-	International
81 Link	Conference/ workshop	N. Katyan et al	Characterization of Thin Films Using Local Magnetometer *17th International Conference on RF Superconductivity*	2015	Whistler, Canada	Scientific community	-	International
82 Link	Conference/ workshop	Kleindienst, R. et al	Commissioning Results of the HZB Quadrupole Resonator *17th International Conference on RF Superconductivity*	2015	Whistler, Canada	Scientific community	-	International
83 Link	Conference/ workshop	Keckert, S. et al	Design and First Measurements of an Alternative Calorimetry Chamber for the HZB Quadrupole Resonator *17th International Conference on RF Superconductivity*	2015	Whistler, Canada	Scientific community	-	International
84 Link	Conference/ workshop	G. Rosaz et al	Biased HiPIMS technology for superconducting rf accelerating cavities coating *6th International Conference on Fundamentals and Industrial Applications of HIPIMS 2015*	2015	Braunschweig, Germany	Scientific community	-	International
85 Link	Conference/ workshop	Flisgen, T. et al	Computation of External Quality Factors for RF Structures by Means of Model Order Reduction and a Perturbation Approach	2015	Montréal, Canada	Scientific community	-	International
86 Link	Presentation	Zimmermann, F.	Future Highest Energy Circular Colliders	2015	CERN	Scientific community	-	International
87 Link	Presentation	Franchetti, G.	Space charge studies between theory, simulations and experiments *Forschungszentrum Juelich, IKP4*	2015	CERN	Scientific community	-	International
88 Link	Presentation	Zimmermann, F.	Future High-Energy Colliders – Charting the Unknown *OIST, Japan*	2015	CERN	Scientific community	-	International
89 Link	Presentation	Zimmermann, F.	Advanced Collimators for Future Colliders or Status of R&D on Collimators for e+e- LCs & HL-LHC *CAS/USPAS Joint Accelerator School, Newport beach, CA*	2015	CERN	Scientific community	-	International

90 Link	Scientific Report	Chmielewska-Smietanko, D.	The Industrial and Environmental Applications of Electron Beams	2015	INCT, Poland	Scientific community	-	International
91 Link	Scientific Report	C. Scheuerlein et al	Report on Bi-2212 precursor production and Bi-2212 bulk and wire studies in the frame of EuCARD-2 WP10	2015	CERN	Scientific community	-	International
92 Link	Scientific monograph/ Thesis	Chiuchiolo, A.	Cryogenic Fiber Optic Sensors for Superconducting Magnets and Power Transmission Lines in High Energy Physics Applications (vol.39)	2015	Universita' degli Studi del Sannio, Benevento, Italy	Scientific community	-	International
93 Link	Scientific monograph/ Thesis	Fiergolski, A.	Hardware implementation of the track identification algorithm in the Scalable Readout System for the TOTEM experiment (vol.28)	2015	WUT, Poland	Scientific community	-	International
94 Link	Scientific monograph/ Thesis	Spera, M.	Pinning Mechanisms in YBCO Tapes (vol.29)	2015	POLIMI, Italy	Scientific community	-	International
95 Link	Scientific monograph/ Thesis	Mirarchi, D.	Crystal Collimation for LHC (vol.31)	2015	Imperial College London & CERN	Scientific community	-	International
96 Link	Scientific monograph/ Thesis	Cauchi, M.	Thermo-Mechanical Studies of Large Hadron Collider Collimators in Accident Scenarios (vol.32)	2015	University of Malta	Scientific community	-	International
97 Link	Scientific monograph/ Thesis	Flisgen, T.	Compact State-Space Models for Complex Superconducting Radio-Frequency Structures Based on Model Order Reduction and Concatenation Methods (vol.33)	2015	Rostock University, Germany	Scientific community	-	International
98 Link	Scientific monograph/ Thesis	Salmi, T.	Optimization of quench protection heater performance in high-field accelerator magnets through computational and experimental analysis (vol.34)	2015	Tampere University, Finland	Scientific community	-	International
99 Link	Thesis	Keckert, S	Optimizing a Calorimetry Chamber for the RF Characterization of Superconductors	2015	Universität Siegen, Germany	Scientific community	-	International
100 Link	Newsletter	Plouin, J., Mollard, A., Peauger, F.	The "kladistron project" for high-efficiency klystrons, *Accelerating News Issue 15*	2015	CERN	Scientific community, Medias	-	International

101 Link	Newsletter	Syratchev, I.	Towards 90% power conversion efficiency for klystrons, *Accelerating News Issue 14*	2015	CERN	Scientific community, Medias	-	International
102 Link	Newsletter	Dehler, M., Baboi, N.	Wake field monitoring to improve FEL performance, *Accelerating News Issue 14*	2015	CERN	Scientific community, Medias	-	International
103 Link	Newsletter	Szeberenyi, A.,	Delivering impact of particle accelerators, *Accelerating News Issue 14*	2015	CERN	Scientific community, Medias	-	International
104 Link	Newsletter	Faus-Golfe, A., Edgecock, R.	Applications for Particle Accelerators in Europe, *Accelerating News Issue 13*	2015	CERN	Scientific community, Medias	-	International
105 Link	Conference/ workshop	Stadlmann, J. et al	Energy Effciency of Particle Accelerators - A Networking Effort within the EUCARD2 Program, *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
106 Link	Conference/ workshop	Edgecock, R.	A Study of the Production of Neutrons for Boron Neutron Capture Therapy using a Proton Accelerator, *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
107 Link	Conference/ workshop	Schippers, J.M.	Accelerators for Medical Application: What is so Special? *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
108 Link	Conference/ workshop	Ohmi, K, Zimmermann, F	FCC-ee/CepC Beam-Beam Simulations with Beamstrahlung *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
109 Link	Conference/ workshop	F. Carra, et al	Mechanical engineering and design of novel collimators for HL-LHC *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
110 Link	Conference/ workshop	Flisgen, T, Heller, J, Rienen, U	Computation of eigenmodes in long and complex accelerating structures by means of concatenation strategies *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International
111 Link	Conference/ workshop	Heller, J, Flisgen, T, Schmidt, C, van Rienen, U	Quantification of Geometric Uncertainties in Single Cell Cavities for BESSY VSR Using Polynomial Chaos *IPAC2014*	2014	Dresden, Germany	Scientific community	-	International

112 Link	Conference/ workshop	Schmidt, F	Summary of the Space Charge Collaboration Meeting May 2014 *SC collaboration meeting May 2014*	2014	Geneva, Switzerland	Scientific community	-	International
113 Link	Conference/ workshop	Zimmermann, F, et al	FCC-ee Overview *HF2014 Beijing*	2014	Beijing, China	Scientific community	-	International
114 Link	Conference/ workshop	A. Bertarelli et al	Development and testing of novel advanced materials with very high thermal shock resistance *Tungsten, Refractory and Hard materials IX, May 2014*	2014	Orlando, USA	Scientific community	-	International
115 Link	Conference/ workshop	C. Fichera, L. Peroni, M. Scapin	Dynamic high temperature behavior of heavy sintered materials *Workshop on dynamic behaviour of* *Materials and its applications in* *Industrial processes, June 2014*	2014	Warsaw, Poland	Scientific community	-	International
116 Link	Conference/ workshop	Wamsat, T, Baboi, N	First tests of a Micro-TCA-Based downconverter electronic for 5GHz higher order modes in third harmonic accelerating cavities at the XFEL *International Beam Instrumentation Conference*	2014	Tsukuba, Japan	Scientific community	-	International
117 Link	Conference/ workshop	Shi, L, Baboi, N, Jones, R M	Stability study of the higher order mode beam position monitors at the Accelerating cavities at FLASH *International Beam Instrumentation Conference*	2014	Tsukuba, Japan	Scientific community	-	International
118 Link	Conference/ workshop	Bertarelli et al	Novel materials for collimators at LHC and its upgrades	2014	East-Lansing, USA	Scientific community	-	International
119 Link	Publication	Aleksan, R.	Summary of the 1st EuCAN Workshop "Universities meet laboratories (ULA2014)"	2014	Goethe-University Frankfurt, Germany	Scientific community	-	International
120 Link	Publication	Torberntsson, J.	Heat Recovery at European Accelerator Based Facilities - Possibilities and Opportunities	2014	Lund Institute of Technology, Sweden	Scientific community	-	International

121 Link	Scientific note	Lombardi, A. et al	Report on Workshop: Accelerators for ADS	2014	CERN	Scientific community	-	International
122 Link	Scientific note	Owen, H. et al	Report on Workshop: Modern Hadron Therapy Gantry Developments	2014	Cockroft Institute, UK	Scientific community	-	International
123 Link	Presentation	Vretenar, M.	Accélérateurs de Particules et Projets de l'Union Européenne	2014	CERN	Scientific community	-	International
124 Link	Presentation	Zimmermann, F.	Challenges for Highest Energy Circular Colliders	2014	KEK, Japan	Scientific community	-	International
125 Link	Presentation	Zimmermann, F.	The Next-Generation Particle Accelerator : With emphasis on TLEP (FCC-ee) vs ILC	2014	CERN	Scientific community	-	International
126 Link	Presentation	Zimmermann, F.	Der Future Circular Collider am CERN - Beschleuniger und Physik	2014	KIT, Karlsruhe	Scientific community	-	International
127 Link	Presentation	Zimmermann, F.	Future Accelerators	2014	oPAC School, Royal Holloway	Scientific community	-	International
128 Link	Presentation	Zimmermann, F.	Future Highest-Energy Circular Colliders	2014	Corfu Summer School and Workshop	Scientific community	-	International
129 Link	Presentation	Papaphilippou, Y, Bartolini, R, Guiducci, S	LOW - ε - RING network: Update	2014	CERN	Scientific community	-	International
130 Link	Presentation	Assmann, R	Beam Propagation, effects and parameters of the accelerated beam	2014	CERN	Scientific community	-	International
131 Link	Presentation	Lucio, R	Superconducting Magnets R&D in the 10-20 T range for energy frontier machines	2014	CERN	Scientific community	-	International
132 Link	Presentation	Malka, V	Compact accelerators with plasmas and lasers	2014	Paris, France	Scientific community	-	International
133 Link	Presentation	Zimmermann, F.	Future Colliders – Overview & Status	2014	CERN	Scientific community	-	International
134 Link	Presentation	Zimmermann, F.	DAFNE Test Facility, LNF What Next?	2014	CERN	Scientific community	-	International

135 Link	Presentation	Zimmermann, F.	CERN program, HEP strategy & future large scale projects	2014	CERN	Scientific community	-	International
136 Link	Presentation	L. Rossi	Alla scoperta della realta: le nuove frontiere di Fisica e tecnologia al CERN	2014	CERN	Scientific community	-	International
137 Link	Scientific note	Jowett., J	What next LNF: Perspectives of fundamental physics at the Frascati Laboratory	2014	CERN	Scientific community	-	International
138 Link	Scientific note	M. Tomut et al	Heavy ion induced radiation effects in novel molybdenum-carbide graphite composite materials	2014	CERN	Scientific community	-	International
139 Link	Poster	Malka, V	Story of Plasma Wake Acceleration	2014	CERN	Scientific community	-	International
140 Link	Scientific monograph	Juszczyk, B., Kasprowicz, G.	MicroTCA based Platform for advanced particle accelerators diagnostics (vol. 27)	2014	Warsaw, Poland	Scientific community	-	International
141 Link	Scientific monograph/ Thesis	Domínguez Sánchez de la Blanca	Electron cloud studies for the LHC and future proton colliders (vol.23)	2014	EPFL, Switzerland	Scientific community	-	International
142 Link	Scientific monograph/ Thesis	Abelleira Fernandez, J.L.	Optics Designs of Final-Focus Systems for Future LHC Upgrades (vol.24)	2014	EPFL, Switzerland	Scientific community	-	International
143 Link	Scientific monograph/ Thesis	Shipman, N.	Experimental study of DC vacuum breakdown and application to high-gradient accelerating structures for CLIC (vol.35)	2014	Manchester University, UK	Scientific community	-	International
144 Link	Article	Koutchouk, J-P., Szeberenyi, A.	EuCARD comes to a successful end, *CERN Courier*	2014	CERN	Scientific community, Medias	-	International
145 Link	Article	Benedikt, M., Zimmermann, F.	The Future Circular Collider study, *CERN Courier*	2014	CERN	Scientific community, Medias	-	International
146 Link	Article	Malka, V	Laser plasma accelerators, *horizon 2020 projects: portal, issue four*	2014	CERN	Scientific community, Medias	-	International

147 Link	Article	Malka, V	An ambitious exploration, *horizon 2020 projects: portal, issue three*	2014	CERN	Scientific community, Medias	-	International
148 Link	Newsletter	Szeberenyi, A., Kirby, G.	Accelerator quality HTS dipole magnet demonstrator design, *Accelerating News Issue 12*	2014	CERN	Scientific community, Medias	-	International
149 Link	Newsletter	Jensen, E., Houghton, E.	First Energy Efficient RF Sources Workshop, *Accelerating News Issue 12*	2014	CERN	Scientific community, Medias	-	International
150 Link	Newsletter	Franchetti, G., Zimmermann, F.	Universities and Laboratories for a common goal, *Accelerating News Issue 12*	2014	CERN	Scientific community, Medias	-	International
151 Link	Newsletter	Synanidi, M. et al	New approach to characterize RF properties in complex structures, *Accelerating News Issue 12*	2014	CERN	Scientific community, Medias	-	International
152 Link	Newsletter	Franchetti, G.	Beam Dynamics meets Magnets supported by EuCARD-2, *Accelerating News Issue 11*	2014	CERN	Scientific community, Medias	-	International
153 Link	Newsletter	Hind, T.	EuCARD-2 Highlights from Hamburg, *Accelerating News Issue 10*	2014	CERN	Scientific community, Medias	-	International
154 Link	Newsletter	Bertarelli, A., Redaelli, S.	Novel Materials for Multi TeV Beam Collimation, *Accelerating News Issue 10*	2014	CERN	Scientific community, Medias	-	International
155 Link	Newsletter	Lombardi, A.	Workshop on Accelerators for ADS, *Accelerating News Issue 10*	2014	CERN	Scientific community, Medias	-	International
156 Link	Newsletter	Szeberenyi, A.,	New video introducing EuCARD-2, *Accelerating News Issue 9*	2014	CERN	Scientific community, Medias	-	International
157 Link	Newsletter	Edgecock, R.	Explore accelerator applications with EuCARD-2, *Accelerating News Issue 9*	2014	CERN	Scientific community, Medias	-	International

158 Link	Newsletter	Bottura, L.	A step towards Next Generation Magnets, *Accelerating News Issue 9*	2014	CERN	Scientific community, Medias	-	International
159 Link	Newsletter	Benedikt, M, Zimmermann, F	CERN prepares for Future Circular Collider Study *Accelerating News Issue 9*	2014	CERN	Scientific community, Medias	-	International
160 Link	Conference/ workshop	Barlow, R J. et al	PIP : A Low Energy Recycling Non-scaling FFAG for Security and Medicine, *IPAC2013*	2013	Shangha, China	Scientific community, Medias	-	International
161 Link	Conference/ workshop	C.B. Baumier et al	Multilayers Activities at Saclay/Orsay, *SRF2013 Proceedings*	2013	Paris, France	Scientific community, Medias	-	International
162 Link	Conference/ workshop	G. Terenziani et al	Nb coating developments with HIPIMS for SRF applications *SRF2013 Proceedings*	2013	Paris, France	Scientific community, Medias	-	International
163 Link	Conference/ workshop	R. Kleindienst et al	Development of an optimized quadrupole resonator at HZB *SRF2013 Proceedings*	2013	Paris, France	Scientific community, Medias	-	International
164 Link	Conference/ workshop	F. Weiss et al	Chemical vapour deposition techniques for the multilayer coating of superconducting RF cavities, *SRF2013 Proceedings*	2013	Paris, France	Scientific community, Medias	-	International
165 Link	Conference/ workshop	Baumier, C, et al	Multilayers activities at SACLAY / ORSAY *SRF2013 Proceedings*	2013	Paris, France	Scientific community, Medias	-	International
166 Link	Conference/ workshop	M Dehler et al	Wake field monitors in a multipurpose X Band accelerating structure *International Beam Instrumentation Conference, 2013*	2013	Oxford, UK	Scientific community, Medias	-	International
167 Link	Conference/ workshop	R. Nietubyć et al	Recent development in optimization of superconducting thin film lead photocathodes at NCBJ *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2013*	2013	Wilga, Poland	Scientific community, Medias	-	International

168 Link	Thesis	Ripp, C.	Analysis of the electrical energy requirements of the GSI facility	2013	TUD, Germany	Scientific community	-	International
169 Link	Article	Chaudron, M.	From EuCARD to EuCARD-2, *CERN Bulletin*	2013	CERN	Scientific community, Medias	-	International
170 Link	Newsletter	Szeberenyi, A., Lapadatescu, L.	EuCARD wrap-up and beyond, *Accelerating News Issue 8*	2013	CERN	Scientific community, Medias	-	International
171 Link	Newsletter	Seidel, M., Chaudron, M.	Towards energy efficient particle accelerators, *Accelerating News Issue 8*	2013	CERN	Scientific community, Medias	-	International
172 Link	Newsletter	Zimmermann, F., Chaudron, M.	Exploring the accelerator frontiers, *Accelerating News Issue 7*	2013	CERN	Scientific community, Medias	-	International
173 Link	Newsletter	Gschwendtner, E., Malka, V.	A novel technique for compact accelerators, *Accelerating News Issue 7*	2013	CERN	Scientific community, Medias	-	International
174 Link	Newsletter	Chaudron, M., Palladino, V.	Accelerator neutrinos are recovering their lead, *Accelerating News Issue 7*	2013	CERN	Scientific community, Medias	-	International
175 Link	Newsletter	Burt, G., Chaudron, M.	New developments in unconventional RF structures, *Accelerating News Issue 7*	2013	CERN	Scientific community, Medias	-	International
176 Link	Newsletter	Chaudron, M.	From EuCARD to EuCARD-2, *Accelerating News Issue 6*	2013	CERN	Scientific community, Medias	-	International
177 Link	Flyer/ Brochure	The EuCARD-2 collaboration	Catalogue of profiles for the Science-Business Workshop on Advanced Materials and Surfaces (WAMAS)	2013	CERN	Scientific community	-	International
178 Link	Presentation	Zimmermann, F.	LHC & Future High-Energy Frontier Circular Colliders	2013	CERN	Scientific community	-	International

179 Link	Presentation	Zimmermann, F.	Future High Energy Circular Colliders	2013	CERN	Scientific community	-	International
180 Link	Presentation	Zimmermann, F.	Zukünftige Beschleunigerprojekte am CERN	2013	CERN	Scientific community	-	International
181 Link	Presentation	Zimmermann, F.	CERN Future Circular Colliders Study	2013	CERN	Scientific community	-	International

SECTION B: EXPLOITABLE FOREGROUND (PUBLIC)

LIST OF APPLICATIONS FOR PATENTS

Table B1: List of applications for patents, trademarks, registered designs, etc.					
Type of IP Rights: Patents, Trademarks, Registered designs, Utility models, Others	Confidential (yes, no)	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)
Patent	Yes	31/07/2017	P.419131	A method for hygienization of sewage sludge	Institute of Nuclear Chemistry and Technology in Warsaw, BIOPOLINEX Ltd. in Lublin, University of Huddersfield
Patent	No	N/A	EP2701468	Method and system for stable dynamics and constant beam delivery for acceleration of charged particle beams in a non-scaling fixed field alternating gradient magnetic field accelerator	Particle Accelerator Corporation in US, University of Huddersfield in UK (to be added soon)
Patent	Yes	N/A	European Patent Application No. 16204679.1	Metallization process on YBCO tapes	Bruker HTS - CERN
Patent	No	N/A	EP3066063A1, US20160297714	A Molybdenum Carbide / Carbon Composite And Manufacturing Method	CERN, BREVETTI BIZZ S.R.L.

EXPLOITABLE FOREGROUND

Table B2: Exploitable foreground

WP	Foreground no.	Type of Exploitable Foreground[7]	Description of exploitable foreground	Confidential (yes, no)	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
WP3	1	GAK	Investigation of low temperature district heating systems, e.g. heating of green-houses	No	N/A	Report	Accelerators, general research facilities, and industry	Medium	N/A	Industry, accelerators, civil housing companies
WP3	2	GAK	Analysis and documentation of heat recovery from RF sources and cryogenic systems	No	N/A	Report	Accelerators	Medium	N/A	Accelerator community
WP4	3	EUP in part, mostly GAK	Improvement of BNCT (Boron Neutron Capture Therapy) targets and other targets	No	N/A	Collaborative research	Low energy accelerators	Medium or Long	N/A	INFN-LNL, HUD, Pavia
WP4	4	GAK	Improved use of superconductivity for ion beam gantries	No	N/A	Interdisciplinary networking	Medical applications	Medium	N/A	EuCARD-2 Consortium, PSI, UNIMAN
WP4	5	GAK, EUP	Applications of Particle Accelerators in Europe document and brochure	No	N/A	Exploitable knowledge	Health, Material science, Energy, Security	Short, Medium & Long	N/A	EuCARD-2 Consortium
WP4	6	ERI	Use of electron beams for environmental applications	Yes	31/07/2017	Exploitable knowledge	Water treatment	Short	Yes	HUD
WP4	7	CER	Improved technology for radioisotope production	Yes	31/05/2018	Exploitable accelerator design	Radioisotope production	Short & Medium	Yes	HUD

[7] Type of foreground: General advancement of knowledge (GAK), Commercial exploitation of R&D results (CER), Exploitation of R&D results via standards (ERS), exploitation of results through EU policies (EUP), exploitation of results through (social) innovation (ERI).

WP4	8	GAK	Use of helium ions for cancer therapy	No	N/A	Exploitable knowledge	Medical application	Medium	N/A	EuCARD-2 Consortium
WP4	9	GAK	Development of a super-conducting accelerator for helium ion therapy	No	N/A	Interdisciplinary networking	Medical applications	Medium	Yes	HUD
WP5	10	GAK, EUP	Roadmap for future extreme beam facilities, figures of merit for collider ranking	No	N/A	Roadmap report	Accelerators, particle physics, and nuclear physics	Medium & Long	N/A	EuCARD-2 Consortium, Accelerator and physics communities
WP5	11	GAK, EUP	Novel options for low-emittance muon beam generation and smaller muon colliders	No	N/A	Workshop presentations	Accelerators, particle physics	Medium & Long	N/A	INFN, CERN, international accelerator community
WP5	12	GAK	Proposing nuclear photonics as a new science field	No	N/A	Collaboration involving EU-XFEL and ELI-NP, workshop and conference presentations	Accelerators, material science	Medium & Long	N/A	INFN, DESY, photon science, materials and nuclear science communities
WP5	13	EUP	Enhancing performance and physics potential of existing or proposed new hadron facilities	No	N/A	EuCARD-2 workshops and presentations	Accelerators, particle physics and nuclear physics	Medium & Long	N/A	Particle physics and nuclear physics
WP6	14	GAK	Development of new lattice concepts	No	N/A	Collaborative research	Light sources accelerators, HEP accelerators	Medium	N/A	Accelerator community
WP6	15	GAK	Development of new optimization tools for nonlinear dynamics	No	N/A	Collaborative research	Light sources accelerators, HEP accelerators	Short & Medium	N/A	Accelerator community
WP7	16	GAK	Establishment of the Advanced Accelerator Concepts Workshop series	No	N/A	Collaborative research	Novel accelerators	Short to Long	N/A	Accelerator community

WP7	17	GAK, EUP	Definition of a roadmap for pilot novel accelerator applications	No	N/A	EuPRAXIA project	Novel accelerators	Medium/Long	N/A	Novel accelerator community
WP8	18	GAK	Demonstration of muon cooling	No	N/A	Experimental results, scientific publications	Muon colliders, neutrino factories	Medium/Long	N/A	MICE collaboration
WP8	19	GAK	Novel LiH Absorber	No	N/A	Absorber material for Muon Cooling	Muon storage and acceleration rings	Long	N/A	STFC, DOE
WP9	20	GAK	Thin-coating beam detectors placed directly on the front of beam production targets to allow measuring the beam position and size	No	N/A	Experimental results, scientific publications	High-power accelerators like ESS	Medium	N/A	CERN, ESS
WP9	21	GAK	Creation of a new multidisciplinary collaboration and development of optical fiber sensors for cryogenic application and in high filed	No	N/A	Experimental results, scientific publications	Cryogenic installations, superconducting devices, industry	Short & Medium	N/A	Partner institutions
WP9	22	GAK	Compact shielding of magnetic fields	No	N/A	Experimental results, scientific publications	Accelerators, medical and space applications	Medium	N/A	Industry, CERN, WIGNER
WP10	23	GAK	HTS multi-kA cable	No	N/A	Report, process	HEP	Medium & Long	N/A	Accelerator community
WP10	24	CER	HTS Tapes of very high performance at highest field	No	N/A	Material process	NMR and medical application	Medium & Long	N/A	NMR community and Medical accelerator
WP10	25	CER	HTS cable and coil technology	Yes	N/A	Design and Process	Renewable Energy	Medium	Yes	Power sector

WP11	26	GAK	Optimization of Molybdenum Carbide-graphite composites with respect to radiation hardness	No	N/A	Report	High-energy and high power accelerators for research and applications	Short	N/A	CERN, GSI, NRC KI, BNL
WP11	27	GAK	Optimization of Molybdenum Carbide-graphite composites with respect to robustness to beam impact	No	N/A	Report	High-energy and high power accelerators for research and applications	Short	N/A	CERN, POLITO, GSI, UM
WP12	28	CER	Composite superconductor fabrication for accelerator applications	Yes	N/A	Collaborative research	Accelerators	Medium to Long	N/A	CEA, Grenoble INP
WP13	29	GAK	Achievement of femtosecond jitter for ultra-fast phenomena	No	N/A	Report	Accelerators, ultra-fast sciences	Short	N/A	DESY, INFN, HZDR

WP	Foreground no.	Its purpose	How the foreground might be exploited, when and by whom	IPR exploitable measures taken or intended	Further research necessary, if any	Potential/expected impact (quantify where possible)
WP3	1	Low grade heat is available in many facilities; a promising application is greenhouse heating where a few degrees higher temperature leads to significantly faster biological growth rates	By new projects in the field of large accelerator driven research facilities; possibly also in industrial applications generating low grade waste heat	N/A	Quantitative model studies	Efficient use of electrical power; improve public acceptance for large research facilities; potential synergy with industry
WP3	2	A large fraction of power is typically lost in the form of heat in RF generation devices and in cryogenic cooling plants; for these types of systems heat recovery is most valuable	By new projects in the field of large accelerator driven research facilities	N/A	Study efficient implementation of heat recovery, for example through cooling circuits at elevated temperature	Efficient use of electrical power specifically in particle accelerators
WP4	3	Study feasibility of improved target for BNCT and/or general purposed low energy neutron production	By new projects in the field of BNCT	N/A	Experiment on diffusion of H into pure materials and transition layers (existing data may be too optimistic)	Cross-discipline fertilization

WP4	4	Investigate the potential and feasibility to apply superconducting technology in the design of particle gantries. Create a network to establish multidisciplinary contacts with required experts	By cancer therapy accelerator projects using gantries	N/A	Further collaborative work	Promote and accelerate multidisciplinary development
WP4	5	Identify existing or new applications that could benefit from RI technology and what developments are required to deliver these	By researchers, general public and policy makers	Yes	Specific technology development	New and improved accelerator applications
WP4	6	Treatment of water and biological sludge using electron beams	By local communities	Yes	Development of compact, very reliable, high current accelerators	Improved treatment without the use of chemicals, producing clean, zero-carbon power and clean organic fertiliser
WP4	7	Develop improved technology for radioisotope production for imaging and cancer therapy	By medicine	Yes	Further development of the accelerator technology	More cost effective production of PET, SPECT and therapy isotopes
WP4	8	Demonstration of the benefits of helium ion therapy over protons and the reduced cost compared to carbon	By producing smaller and less expensive accelerators for ion therapy	N/A	Radiobiological and by-stander effect studies	More cost effective ion beam therapy
WP4	9	Design of FFAGs using super-conducting magnets for the isochronous acceleration of helium ions for cancer therapy	By producing smaller and less expensive accelerators for ion therapy	Yes	Further development of the accelerator technology	More cost effective ion beam therapy facility
WP5	10	Guide the directions of future accelerator R&D, introduce concepts, highlight critical and promising topics	Exploited and pursued in ARIES, input to European Strategy update for particle physics 2019/20	N/A	R&D on high-field magnets, low-emittance muon production, crystal/carbon-nanotube acceleration, other uses of large hadron storage rings, high-energy hadron beam polarization, polarimetry, EDM rings, etc.	Will help formulating the optimum strategy for accelerator R&D and for future accelerator facilities
WP5	11	Overcome limitations of the US muon collider design	Input to European Strategy update for particle physics 2019/20, exploited in ARIES	N/A	Further pursue two alternative paths of low-emittance muon beam production, possibly the first in collaboration with the FCC-ee design, the second in collaboration with ELI-NP and ThomX	Will provide a long-term perspective for particle physics

WP5	12	Use newly available accelerator technologies to enable fundamentally new fields of science	Exploited in ARIES	N/A	Study of expected FEL and quantum FEL performance with 50 GeV e- beam and few-mm undulator, facility design, optimized photon spectral density and achievable bandwidth	Eventually a new 50 GeV electron beam facility for pioneering ground-breaking research
WP5	13	Option of polarized high-energy hadron beams, and/or other performance enhancement measures for hadron storage rings	Exploited in ARIES and by the FCC study	N/A	Further studies and improved modeling of polarization preservation in high-energy hadron storage rings, also study of polarized targets, electron-cloud mitigation, halo and beam-loss, advanced beam stabilization techniques	Option of polarized hadron beam as possible input to the FCC CDR and to the European Strategy Update; better performing hadron storage rings
WP6	14	New lattice concepts will enable the reduction of the beam emittance and improving the beam quality for the required application of the accelerators	Exploited in EuCARD-2	N/A	R&D will continue to support the next class of accelerators with diffraction limited beams	Will allow a decrease in the beam emittance by a factor 100 compared to existing
WP6	15	Tackle the beam dynamics problem that prevent a stable operation of such accelerators	Exploited in EuCARD-2	N/A	R&D continues to provide more effective and faster tools to optimize apertures and beam lifetimes	Will enable more aggressive design for low emittance ring
WP7	16	Creating a European community on Novel Acceleration techniques	By the accelerator community	N/A	The Workshop series will continue in ARIES	Will federate European effort creating synergies and collaborations
WP7	17	Define a strategy for a pilot European user facility based on new acceleration techniques	By the final users	N/A	Further design	Will boost applications of plasma wakefield technologies
WP8	18	Demonstrate ion cooling at the MICE experiment	By the designers of neutrino factories and muon colliders	N/A	Test of ion acceleration	Will demonstrate feasibility
WP8	19	LiH Absorbers to be used for the cooling of Muons in accelerator and storage. The LiH discs (current design) are inherently safer and improve ease of handling with respect to the use of liquid Hydrogen. Reduction of financial and technical issues.	The LiH absorber could be utilized within a large scale Muon collider. With the reduced financial and technical burden the technology becomes more attractive over the use of Liquid Hydrogen.	N/A	Current designs are for a disc, future investigations and usage may move towards wedge construction, an extremely difficult undertaking for Liquid Hydrogen	N/A

WP9	20	Thin-coating, e.g. placed directly on the front of beam production targets allow measuring the beam position and size	Can be exploited by spallation neutron sources like ESS and similar accelerator projects	N/A	ESS is analyzing and publishing the experimental data, further optimization might be required depending on the results	N/A
WP9	21	Build sensors using optical fibers having the great advantage of being electrically natural, of very small size with high capability of multiplexing. Sensing can be in the domain of temperature, strain, humidity, magnetic field, noise.	Sensors can be built by industry and used by industry, laboratory and in medical applications when superconductors and cryogenics are needed.	N/A	Further research is necessary to develop robust techniques to allow separate strain and temperature effect as well as to develop coating methods with different materials allowing sensitivity at lower temperature.	Impact not only in the sensing domain, but also in material science since the development for low temperature application to study material properties is typically unknown in this domain.
WP9	22	Build a shield for magnetic field for a septa magnet of accelerators	Building different shields based on different superconducting materials and developing its fabrication process. The integration of the shield into the septa with its cryostat is still a challenge. Industrial partners working in superconductivity and cryogenics are the candidates to exploit this result.	N/A	Further research is necessary as between the two materials tested one was observed to be working well, while other showed its potential only. Most of the applications known today in the domain of superconductivity are using cables and conductors, not easy to be adapted to the given application. Therefore, the whole process of fabrication is currently a challenge.	Impact in the domain of high temperature superconductors development, as well as in medical and space technology thanks to the potential in shielding magnetic fields.
WP10	23	Cables used in high field magnets for accelerators, rated for current > 10 kA and multi-strands structure. The high current is a must for magnet protection and the multi-strand allow current sharing and increase stability	EuCARD-2 beneficiaries and other companies or accelerators laboratory also outside EU	A part of the cable process will be covered by a patent made by two beneficiaries. The rest is open.	The Roebel cable topology and Je the performance of tapes need to be improved. ARIES will partly take care of this.	It will allow boosting the beam energy of a post-LHC hadron collider by 25%, making cryogenics easier. Open the way also to low-medium hadron synchrotron/cyclotron with HTS.
WP10	24	HTS may increase 30-50% the field in NMR spectroscopy magnets, opening the way toward 1.5 GHz (35 tesla!)	By using the HTS tape developed in EuCARD-2, as some of the magnet technology	N/A	A specific program addressing the NMR junctions and the protection of large stored magnets with high inductance	NMR is the largest market of SC after MRI. The success of a 1.5 GHz NMR spectroscopy may open new roads in material analysis and biophysics.

WP10	25	The cable design may be used, with some adaptation, for power transmission lines and the magnet design may be used for Windmill generators and FCL (Fault Current Limiter).	The basic tape is the most direct equipment that can be used for such application, but in general, many concepts we develop may be adapted for them.	Use of the tape in Roebel cable might use the patent mentioned above.	A specific R&D program studying how to adapt the EuCARD-2 technologies to the power and renewable energy application must be set up.	Larger power wind mill generator, which may make more economic Eolic energy; improvement of the electrical distribution network via superconducting transmission lines and FCL
WP11	26	Optimize Molybdenum carbide-graphite composition for increased radiation hardness	Knowledge will be exploited in designing new radiation hard composites for other accelerator applications such as high power targets, beam windows, beam diagnostic	Process may partly use EU/US patent mentioned above.	Continue R&D on new composite materials using carbide and carbon parts reinforcement with various matrix	Novel materials solutions to address complex challenges in applications in extreme conditions: novel accelerators, thermal management, fission and fusion, energy and space
WP11	27	Identify Molybdenum carbide-graphite materials that can resist high level energy deposition by beam impact while showing appropriate characteristics in ultra-high vacuum	ARIES will take over the R&D; New materials foreseen to be implemented	Process may partly use EU/US patent mentioned above.	R&D on optimization as respect to vacuum properties	Will allow an increase of beam power for the LHC upgrade, with a goal of a factor of 10 increase in LHC performance.
WP12	28	Achieve the fabrication of new composite superconductors tailored for SRF applications	Not ready for exploitation	N/A	Further optimization of the structure and the fabrication process; demonstration with test elliptical cavity	Break Nb monopoly for SRF accelerators (double accelerating field, decrease cryogenics power)
WP13	29	Tackle problems in the study of ultra-fast phenomena	In progress with EuCARD-2 and EuPRAXIA	N/A	To be used in real conditions To be applied in beam and laser plasma accelerator	Huge impact in fs time resolution for crystallography, biology and material science

ANNEX I: GLOSSARY

ADS	Accelerator Driven Systems
AFM	Atomic Force Microscopy
ALD	Atomic Layer Deposition
AWAKE	Proton Driven Plasma Wakefield Acceleration Experiment (CERN)
BID	Beam-intercepting devices
BNCT	Boron Neutron Capture Therapy
CEPC	Circular Electron Positron Collider
CLIC	Compact Linear Collider
CuCD	Copper-Diamond
CVD	Chemical Vapor Deposition
DAC	Diamond Amplifier Cathode
DAQ	Data Acquisition
DDS	Damped Detuned Structure
FAIR	Facility for Antiproton and Ion Research (GSI)
FCC	Future Circular Collider
FEL	Free-Electron Laser
FFAG	Fixed-Field Alternating Gradient
FLASH	Free-Electron LASer in Hamburg (DESY)
FPGA	Field Programmable Gate Array
GSM	Generalised Scattering Matrix
HE-LHC	High-Energy LHC
HL-LHC	High-Luminosity LHC
HOM	Higher Order Modes
HTS	High Temperature Superconductor
ICTF	Ion Cooling Test Facility
ILC	International Linear Collider
LHC	Large Hadron Collider (CERN)
LWFA	Laser-Plasma Wakefield Accelerator
MBA	Multi-Bend Achromat
MICE	Muon Ionization Cooling Experiment
MoGr	Molybdenum Graphite

NC	Normal conducting
NMR	Nuclear magnetic resonance
PET	Positron Emission Tomography
QE	Quantum Efficiency
QPR	Quadrupole Resonator
RI	Research Infrastructure
RF	Radio Frequency
SC	Superconducting
SMI	Self-modulation instability
SPECT	Single-photon emission computed tomography
SSC	State-Space Concatenation
SRF	Superconducting Radio Frequency
WFM	Wake field monitors
XPS	X-ray photoelectron spectroscopy