Final Report

EUROFEL

European FEL Design Study

Design Study

implemented as

Specific Support Action

Update 2008-03-13

Contract number: 011935

Project coordinator: Deutsches Elektronen-Synchrotron DESY

Project website: http://www.eurofel.org

Project Duration: 36 months from 01/01/2005 to 31/12/2007

Project funded by the European Community
under the "Structuring the European Research Area" specific programme
Research Infrastructures Action

A. ACTIVITY REPORT

1. Project logo

EURO FEL

2. List of contractors

Partici-pant No.	Organisation (name, city, country)	Short name
1	Stiftung Deutsches Elektronen Synchrotron DESY, Hamburg, Germany	DESY
2	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung mbH, Berlin, Germany	BESSY
3	Science & Technology Facilities Council , Swindon, United Kingdom	STFC
4	Commisariat a l' Energie Atomique, Paris, France	CEA
5	Centre National de la Recherche Scientifique, Paris, France	CNRS
6	Sincrotrone Trieste S.C.p.A., Trieste, Italy	ELETTRA
7	ENEA - Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Roma, Italy	ENEA
8	Forschungszentrum Rossendorf e.V., Dresden, Germany	FZR
9	Istituto Nazionale di Fisica Nucleare, Frascati, Italy	INFN
10	MAX-lab, Lund University, Lund, Sweden	MAX-lab
11	Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin, Germany	MBI
12	Synchrotron SOLEIL Societé, Saint Aubin, France	SOLEIL
13	Institut für Theorie Elektromagnetischer Felder, Technische Universität Darmstadt, Darmstadt, Germany	TEMF-TUD
14	Universität Hamburg, Hamburg, Germany	Uni-HH
15	University of Rome “La Sapienza”, Roma, Italy	URLS
16	University of Strathclyde, Glasgow, United Kingdom	USTRAT

3.1 Overview

The EUROFEL Design Study was a coordinated, joint effort of 16 European organisations to develop key technologies required for the design and construction of next generation free electron laser (FEL) sources that have been proposed as new European research infrastructures in France, Germany, Italy, Sweden and the United Kingdom. The EUROFEL project started 1st January 2005 and finished 31st December2007; it was coordinated by DESY. The project focused on six areas: electron injectors, beam dynamics, synchronisation, seeding and harmonic generation, high duty-cycle superconducting accelerators, and technology transfer to industry for the production of complete superconducting accelerator modules. 223 person-years were spent on this work, 139 of which were funded by the EC giving many young scientists the opportunity to participate in exciting fore-front research in an international collaboration. The project has produced 23 publications in refereed journals, about 230 presentations on conferences and workshops, and 103 deliverables; several further publications are in preparation. It is impossible to include all details in this final report; it rather reviews the work and highlights some prominent examples. This review has also been submitted to Synchrotron Radiation News for publication in the second issue of 2008. It is planned to publish a more comprehensive article in Physical Review Special Topics.

3.2 Project objectives and partners involved in the Tasks

The overall objective of the EUROFEL project was to combine the European efforts towards new research infrastructures based on free electron lasers into a coordinated, joint activity, and to develop the key technologies required for their design and construction. The most critical research and development areas were identified and grouped into six Tasks. The objectives of the project are described Task by Task:

Task DS 1: Photo-Guns & Injectors aimed at the optimisation of sources of high brightness electron beams for future free electron lasers in Europe. In order to meet the tight requirements of FEL operation, electron beams of extremely high quality have to be produced. The project focused therefore on the design, construction and testing of new components, subsystems, materials and techniques for the production, manipulation, diagnostics, and control of low emittance and high current beams, up to the early stage of acceleration. The new components, devices and techniques were to be tested at the test facilities PITZ and SPARC, and in the existing major European Laboratories.
Partners involved in DS 1: INFN (task leader), BESSY, CEA, CNRS, DESY, ELETTRA, ENEA, MBI, STFC, TEMF-TUD, URLS

Task DS 2: Beam Dynamics aimed to study the critical beam dynamics effects that impact on the transport of such high quality electron beams, specifically the case of small emittance (~1 µm) combined with short bunch length (<1 ps) and high charge (~1 nC). This included the development and use of codes and models to allow the reliable simulation of high quality beam transport. These tools were planned to be applied to optimise and characterise the design of proposed European FEL based facilities.
Partners involved in DS 2: STFC (task leader), CEA, DESY, ELETTRA, ENEA, INFN, SOLEIL (AR1, p. 7), TEMF-TUD, URLS

Task DS 3: Synchronisation focused on synchronisation issues of the FEL machine design. The goal of this work package was to characterise and to identify suitable components, subsystems and methods to provide femtosecond synchronisation which is required for

seeding and harmonic generation (see below) and for user experiments in order to exploit the ultra short FEL pulses for high-resolution time-resolved experiments. Other important objectives of this Task were to make use of specific know-how existing in the laser community, to test concepts in an accelerator environment and to gain own experience.
Partners involved in DS 3: ELETTRA (task leader), CEA, DESY, CNRS, ENEA, INFN, MAX-lab, STFC

Task DS 4: Seeding and Harmonic Generation is necessary to ensure stable and well-defined output characteristics of the new FEL sources in the VUV and soft X-ray region. Most scientific applications in this spectral region rely on well-defined, reproducible photon pulses with single-line intensity distribution both in frequency and time. Such pulses are not produced by FELs based on SASE (self-amplified spontaneous emission, i.e. amplified noise), but require the use of seeding and harmonic generation techniques. The aim of DS4 was to study the critical issues relevant for reaching short wavelengths (1 nm and below) and high photon beam quality (in terms of coherence, line width, pulse length, and stability) by the techniques of seeding and harmonic generation. The objective was to provide the fundamental know-how and the experience necessary for the designs of seeded harmonic generation sources which will form the basis of most of the new FEL infrastructures planned in Europe.
Partners involved in DS 4: MAX-lab (task leader), BESSY, CEA, ELETTRA, ENEA, SOLEIL, STFC, Uni-HH, USTRAT

Task DS 5: Superconducting CW and Near-CW Linacs addressed critical aspects of CW (continuous wave) operation of superconducting linacs (linac = linear accelerator) for FEL/ERL (combination of free electron laser and energy recovery linac) light sources, using a combination of numerical simulations/design studies and prototype testing. The HoBiCaT test facility served as a dedicated facility for cryogenic testing of CW superconducting cavity equipment.
Partners involved in DS 5: BESSY (task leader), CEA, DESY, FZR, INFN, STFC

The objective of *Task DS 6: Cryomodules Technology Transfer* was to establish design and assembly procedures for superconducting accelerator modules (cryomodules), which are adapted and qualified for industrial series production, including the verification of these procedures by testing complete cryomodules on a test bench.
Partners involved in DS 6: DESY (task leader), BESSY

3.4 Work performed and end results

3.4.1 Photo-guns and injectors

The photo-guns and injectors work package focused on the improvement of normal conducting high-brightness electron sources. The electron bunches in FELs need low normalized slice emittance of approximately 1µm. Various effects such as space charge and wake fields can spoil the beam quality. Simulations with tracking codes and validation with measurements are mandatory for understanding the complicated beam dynamics phenomena that occur in the low energy part of the injector and are therefore essential for an optimized design. In addition, high precision and possibly non-destructive diagnostic tools are needed to measure bunch length, projected and slice emittance with sufficient resolution. Finally, electron injectors must provide high beam stability and reliability. All these issues have been successfully addressed in this work package; a few selected results are described in more detail below.

Simulations predict that the lowest emittance is achieved for a flat top electron distribution with sub-ps rise time. This requires a uniform photocathode with high quantum efficiency, low dark current and long lifetime at high field gradients. Therefore, the degradation of cesium telluride photocathodes has been studied and new cathode materials such as magnesium and carbon nanotubes have been prepared and tested. Since the electron distribution from a uniform photocathode reproduces the laser pulse shape incident on the cathode, the production of a flat-top laser profile has been a major activity. Different concepts were tested to manipulate the transverse and longitudinal intensity profile. A refractive transverse beam shaper with two aspheric lenses demonstrated high throughput but also showed the increased sensitivity to the quality and stability of the incident laser beam. As to longitudinal pulse shaping, a complete Fourier-type shaping system in the UV using a deformable mirror turned out to be a powerful approach. The generation of 10 ps flat-top laser pulses with a rise time shorter than 1 ps is a remarkable result.

Many developments and experiments were done at the photo-injector test facility at DESY-Zeuthen (PITZ) [1]. A major achievement has been the outstanding performance of the DESY RF gun operating in the L-band (1.3 GHz). It delivers bunches of 1 nC charge and 20 ps duration with an emittance below 1.3 µm at a field gradient at the cathode of 60 MV/m, thus meeting the requirements for the European XFEL. Based on the DESY gun design a prototype gun with an optimized cooling layout has been developed at BESSY for high average power levels of ~100 kW as demanded by future high duty cycle FELs.

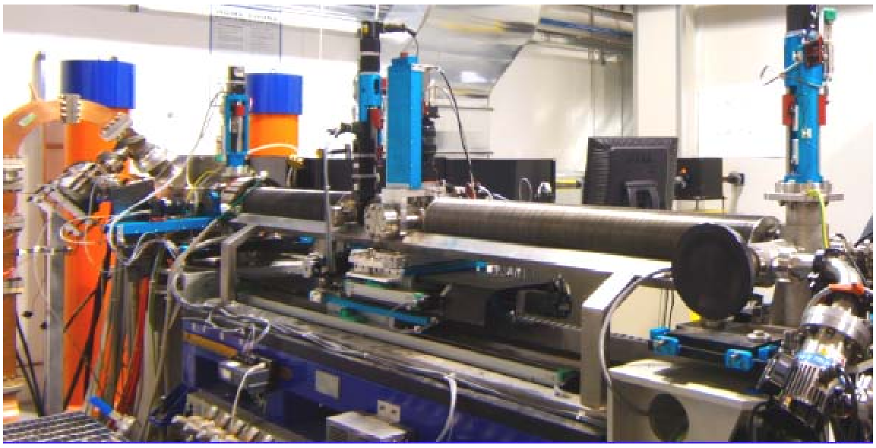

Figure 1: The emittance meter (centre) installed behind the RF gun (on the left) at SPARC.

In order to measure the electron beam quality during the emittance compensation process, a dedicated movable emittance measurement device (Fig. 1) has been developed by INFN [2]. This device allows to measure beam parameters in the range 1000 mm to 2100 mm from the cathode location. After a preliminary benchmark at PITZ in 2005, the emittance evolution along the drift downstream the RF gun at SPARC [3] has been studied systematically [4], comparing the beam dynamics for different bunch shapes. The best emittance has been achieved with a flat top laser pulse shape corresponding to 1.5 mm-mrad. An important result is the first experimental observation of the double emittance minimum in agreement with theoretical models and numerical simulations (Fig. 2) [5].

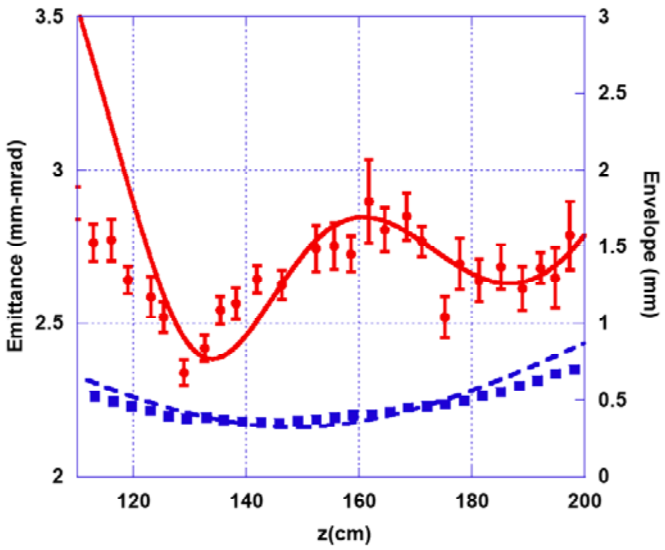

Figure 2: Evolution of envelope (blue) and emittance (red) of a “flat top” bunch downstream the RF gun. Simulations (lines) are compared with measurements (dots).

Despite some initial delays, the work foreseen by the implementation plan has been successfully completed by the partners. All the expected reports were delivered and the design, construction and installation of new equipment have been done in due time. Excellent results have been obtained concerning laser pulse shaping, new cathode materials research, and the development of RF guns and diagnostics tools. Experiments with the electron beam achieved very low emittance at PITZ and a deeper understanding of the emittance compensation process at SPARC. Only two experiments, tomography measurements at PITZ and velocity bunching measurements at SPARC, have been prepared but could not be completed during the runtime of the project due to unexpected delays caused by machine break down or late delivery of main components. This work will be completed at the beginning of 2008.

3.4.2 Beam dynamics

Free electron lasers require pulsed electron beams with extreme peak currents. These bunches with high charge density are formed in longitudinal bunch compression systems and transported through the driver linac. Self-interaction with the bunch’s own strong electric fields can occur as space charge effects and via reflection from the surrounding vacuum chamber (wake fields). On curved trajectories, the electric field of the bunch tail, traveling on a straight line, can reach the head and cause coherent synchrotron radiation (CSR). All of these effects can seriously deteriorate the beam quality, so reliable tools are needed to calculate their impact on beam parameters with precision.

As part of EUROFEL, the RETAR, HOMDYN, and TREDI codes [6] were developed to model strong space charge effects, like the impact of transverse cathode inhomogeneities upon emittance compensation. Comparison with experimental results from the SPARC photo injector [7] shows good agreement. The CSRtrack code [8] was augmented to produce three-dimensional CSR calculations and applied to the European XFEL design [9]. A CSR calculation for FLASH is compared with an experimental measurement in Fig. 3. The three dimensional ECHO-3D code for wake field calculation was developed at TEMF [10]. Most of the simulation codes have been made available in a code repository which allows all partners to use up-to-date, proven codes for their design work in the future.

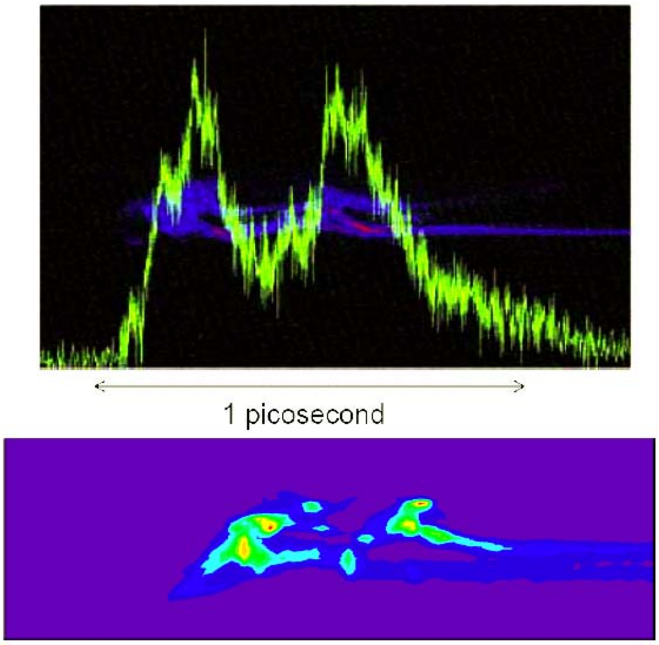

Figure 3: Charge distribution within an electron bunch at FLASH. The upper panel shows a screen image of the high-density part of a single bunch expanded by a strong transverse RF field. The green curve is the longitudinal current profile. The lower panel shows the numerical simulation using the CSRtrack code. Note that for normal FEL operation the machine is tuned such that only a single maximum is present.

CSR and space charge can drive micro-bunching instabilities in systems with strong bunch compression. Instability suppression using a “laser heater” has been simulated for the 4GLS [11] and FERMI@Elettra [12, 13] injectors, and included in their compression designs. The use of an ellipsoidal longitudinal laser distribution has been shown in calculations to improve transverse beam quality of the ARC-EN-CIEL [14] injector. FERMI@Elettra requires a flat output bunch distribution to drive a harmonic cascade FEL. Based on simulations it is proposed to achieve this by a ramped injector current to cancel the strong normal-conducting cavity wakes [13, 15].

Both the 4GLS and ARC-EN-CIEL projects propose a high-current energy recovery linac (ERL). For 4GLS an optimized higher-order-mode-damped 7-cell cavity was designed to increase the maximum beam current. A design for a 100 mA, 500 kV DC photocathode injector for 4GLS has been developed, utilizing a load-lock system for daily change of the limited-lifetime GaAs cathode.

Practically all the work foreseen was successfully finished and all the deliverables submitted. In a few cases some work had to be changed mainly because the ERL Prototype at Daresbury [11] was not yet available for experiments as originally expected. All deliverables were completed.

3.4.3 Synchronisation

Since most FEL projects plan to use seeding techniques (see below), it is mandatory to synchronise all sub-systems to the sub-100 fs level. Extremely good synchronisation is particularly demanded by user experiments in order to exploit the ultra short FEL pulses for high-resolution time-resolved experiments; for example, FEL pulses of ~10 fs duration are generated at FLASH [16,17]. A generic layout of the synchronisation system for a FEL facility is shown in Fig. 4. Due to advances in fibre laser technology there is a general consensus to base the synchronisation on optical signals distributed, by means of length-stabilized optical fibre links, to the various sub-systems along the facility, including the gun laser, the RF stations driving the photo-injector and the accelerator, seed lasers and lasers in the experimental area.

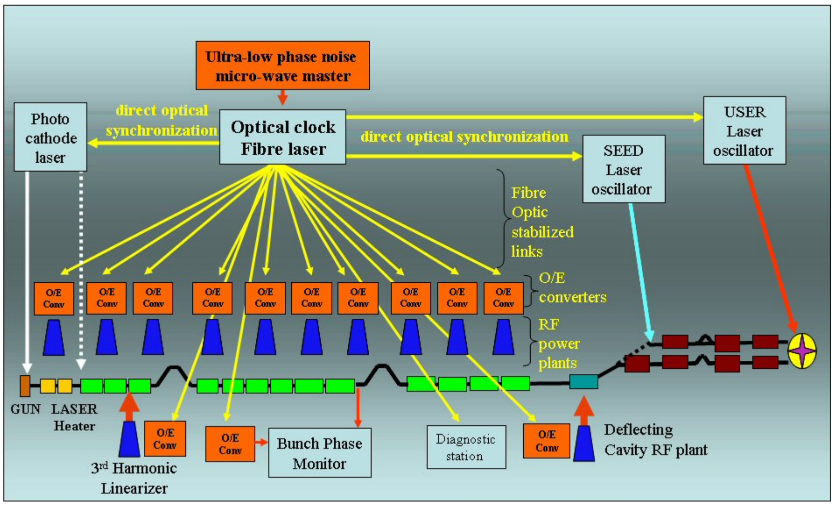

Figure 4: Generic layout of the synchronization system for a FEL facility.

A major activity of this task was the development and characterization of suitable fibre lasers for the optical master oscillator as well as the distribution of a reference signal to the remote clients of the timing system. Appropriate measurement capabilities have been installed at several partner laboratories to investigate the phase noise and drift of components at the femtosecond level. The main results of this activity have been the identification of the optimum type of fibre laser (passively mode locked), the demonstration of the reference signal distribution in an accelerator environment without spoiling the original ultra low phase noise of the optical oscillator, and the relationship between the optical oscillator and its microwave reference in terms of phase noise. In short, a deep understanding of all the critical components of an optical synchronisation system has been achieved.

As critical as the distribution of a stable optical reference signal is its locking to the remote optical lasers and the RF power feeding the accelerator cavities. While locking of lasers can now be done with a precision of ~1 fs [18], the synchronisation of the electron beam is more difficult. Due to the energy dependent path length of the electron beam in the bunch compressor chicanes, the amplitude and phase of the high-power RF pulses need to be stabilised at a level of 10^{-4} and 0.01°, respectively, for the accelerator section in front of the chicanes. Suitable multi-channel electronics have been developed and successfully tested at the superconducting accelerator FLASH in Hamburg and the normal-conducting structures at SPARC in Frascati, where an innovative intra RF pulse feedback system was used.

A bunch arrival time monitor with a resolution below 30 fs [19] has been developed and installed at FLASH to study the various different sources of timing jitter that may be found in a real accelerator environment. The improvement of this system has been a joint activity of DESY, ELETTRA and a group from the Ljubljana University.

Impressive progress has been made by this work package providing new concepts for highly stable timing and synchronisation systems based on optical techniques. The technology and the know-how for achieving sub-100 femtosecond resolution in an accelerator environment are now available. The objectives of this task have been fully achieved and all deliverables submitted.

3.4.4 Seeding and harmonic generation

In their simplest form, free electron lasers for short wavelengths are based on the concept of self-amplified spontaneous radiation (SASE). In general, the output radiation is only partially coherent in the longitudinal direction. Fully coherent radiation can be produced by seeding the FEL process with a coherent signal well above the noise level. However, tunable seed sources with sufficient power are not available at sub-nanometer wavelengths, and a combination of techniques and further development are necessary to cover even the 1-100 nm range. The physics of the seeding process in the FEL, the seed source and different concepts for seeding have been addressed by this work package.

The storage ring FEL at ELETTRA [20] has been complemented with a Ti:Sa laser with 780 nm wavelength, 100 fs pulse duration and 1 GW peak power and used for seeding the modulator of the optical klystron. The coherent radiation generated by the radiator tuned to the third harmonic (harmonic generation – HG) at 260 nm had a peak power of ~1 MW corresponding to approximately 10^9 photons per pulse. In the near future it is planned to generate coherent radiation down to or even below 100 nm by using the second and third harmonic of the Ti:Sa laser as a seed.

The main objective of this work package has been seeding at wavelengths below ~200nm. One possibility is to seed directly with High Harmonic Generation (HHG) sources where intense optical laser pulses are focused in a gas jet or capillary [21]. Promising computer simulations of the FEL process were made supporting this idea [22]. A suitable HHG source has been developed in a CEA-SOLEIL collaboration and installed at the SPARC facility for first seeding experiments in early 2008. The HHG system is already operational and has produced third harmonic radiation of the Ti-Sa laser with a nice transverse profile and a measured energy per pulse of 2.5 µJ. The concept of seeding a FEL with HHG, using a similar HHG source, has recently been demonstrated on the SCSS prototype [23, 24] in a RIKEN (Japan)-CEA-SOLEIL collaboration.

In order to develop these concepts, the SPARC facility at Frascati (Fig. 5) and the FEL test facility at MAX-Lab (Fig. 6) have been built with support from the EUROFEL project. Table 1 summarises the different parameters. The aim of these installations is to address a broad range of technical issues including RF gun operation and emittance control, bunch compression and beam transport, seed laser beams with synchronisation and spatial overlap, stability and jitter, diagnostics, characterisation of the FEL radiation and the test of new concepts. Ideas for such concepts have been elaborated and include harmonic lasing [25] and superradiance phenomena [26].

Figure 5: The SPARC facility including the linac with solenoids for velocity bunching (far right), the seed laser injection chicane (middle) and the undulator during installation (left).

Figure 6: The optical klystron (modulator undulator- chicane - radiator undulator) at MAX-lab. The electron beam enters from the right.

All the objectives of the simulation and theory part have been achieved and much of this work has been published. The design and construction work for the ELETTRA, SPARC, MAX-lab and FLASH facilities has been finished successfully. It included, among others, fundamental subsystems such as the HHG chamber for SPARC, the optical klystron for MAX-lab, a micro-chicane for SPARC, a feedback system for FLASH and the seed laser injection for ELETTRA. Several subsystems have been implemented and tested, although not always fully to the ambitious extent expected at the start of the project, and the objectives have been achieved. EUROFEL has significantly contributed to the construction of the test facilities for seeding at ELETTRA, SPARC and MAX-lab. Remarkable results were obtained at ELETTRA, while delays in the schedules at SPARC and MAX-lab prevented seeding experiments before the end of the project. However, also these installations have been completed and will produce experimental results within the next months.

Table 1: Parameters of the two facilities for research on Seeding and Harmonic Generation

	SPARC	Test FEL MAX-Lab
Type	HGHG	HG
Electron energy	200 MeV	400-500 MeV
Seed source	HHG @ 266 130 nm	Ti:Sa @ 266 nm
Wavelengths	114/88 nm	88/55 nm
Undulators	6 undulators	1+1 undulator
Pulse length (electrons)	10 ps	~500 fs

3.4.5 Superconducting CW and near-CW linacs

This work package focused on continuous wave (CW) superconducting RF (SRF) technology for future FELs and ERLs. CW operation bears advantages over pulsed systems: For one, the FEL can provide a high average flux and flexible bunch timing. Furthermore, the beam is more stable, thus improving the FEL output. And for high-current machines (>10 mA), energy recovery and hence CW SRF must be used. The work package targeted three areas: CW SRF guns, injectors for ERLs, and main-linac acceleration.

For the first time, an SRF gun [27], developed by an FZD-BESSY-DESY-MBI collaboration, generated electrons. This system is being used to verify simulations by STFC and FZD for several operating modes of FELs/ERLs, and serves as a baseline for the development of a 100-mA-class ERL injector by STFC. Studies also showed that the field of a focusing solenoid can be sufficiently shielded to not impact the cavity's performance. Hence, a "split" injector, similar to normal-conducting guns, is being developed by INFN-Frascati and others [28]. It promises to provide micrometer emittances at high current and nC bunch charge.

For the main linac, most CW FELs adopted TESLA technology [29], in part because its reliability was demonstrated in FLASH. However, it was designed for pulsed operation and hence one focus of this work package was to identify changes required for CW operation. The activities included the cryogenic installation (optimization of the cavities’ operating point, minimization of the cryogenic load, analysis of the stability limits of the cryogenics), RF power (development of suitable CW RF sources and input couplers), RF stability (precise RF control and compensation of microphonics) and CW operation (CW tests of TESLA cavities *with all ancillary components* to demonstrate their suitability for CW operation).

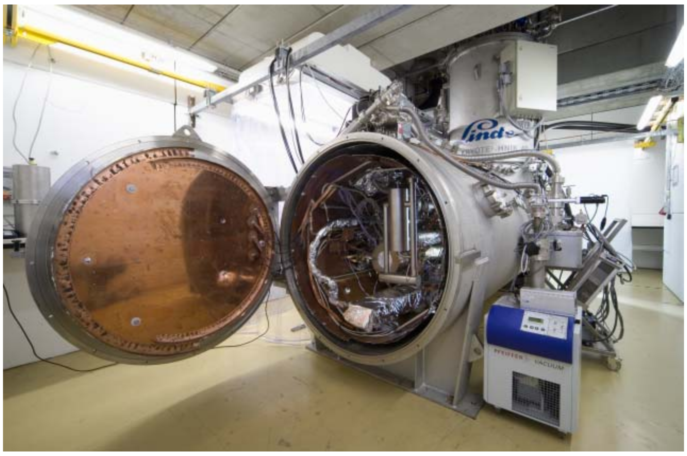

Figure 7: The HoBiCaT facility at BESSY has been used for many cavity tests.

Tests indeed demonstrated that TESLA technology is suitable for CW linacs. A modified unit exceeded the design goal for many FELs ($Q = 1.3 \times 10^{10}$ and $E_{\mathrm{acc}} = 16$ MV/m). A key to many measurements has been the HoBiCaT facility at BESSY, used by several EUROFEL partners [30]. This facility (Fig. 7) permits tests of cavity units under conditions similar to those in an accelerating module. The measured dynamic losses were only half that budgeted for by some FEL proposals. If the performance is extended to a whole linac, the cryoplant-related investment savings can be of order millions of Euros. Also studied was the extraction of the losses by the helium system. Measurements and numerical analyses of the helium distribution provided the needed insight to design modifications to handle kW linac loads.

Two options for CW RF sources were studied: Transmitters for individual cavities and larger units to power several cavities. For the single-cavity transmitter, an IOT (inductive output tube) based prototype system is now operating at HoBiCaT. For the multiple-cavity system, the design of a 120-kW IOT was completed by DESY and CPI/BMD company (USA) and a tube has been built for operation in 2008. Since TESLA RF couplers were not designed for high-average power, cooling modifications for 20-kW operation were incorporated and will be tested soon [31]. Also, a coupler test stand was constructed by FZD for tests under cryomodule-like conditions. Here, fixed-input ELBE couplers [32] were demonstrated to handle at least 20 kW average power, exceeding the requirements of most CW FELs.

Critical for future FELs/ERLs is the cavity field stability to provide a jitter-free beam. Tests in ELBE, Cryholab (Saclay) and HoBiCaT demonstrated that microphonics are a significant noise source. To combat this, piezo stacks were integrated in the cavity's tuner and used for the first time to actively compensate microphonics [33] (Fig. 8). The results point the way to achieving a phase stability around 0.02°.

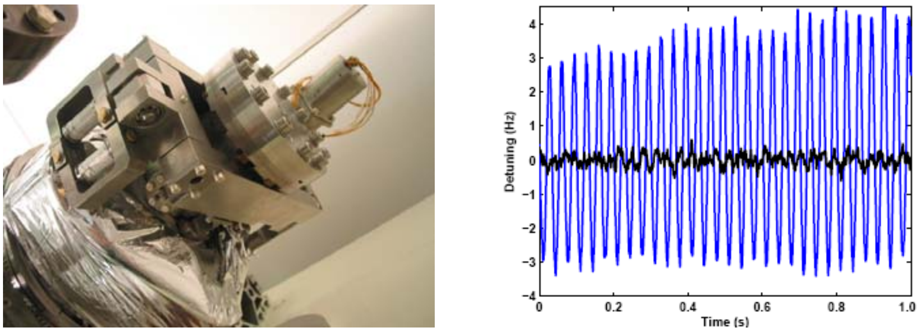

Figure 8: Left: Piezo stacks in the mechanical tuner of a cavity. Right: Compensation of microphonics (blue = off, black = on).

Nearly all tasks have been completed as originally planned. Some deviation from the original plan was necessary for measurements intended with upgraded ELBE modules. Generally speaking, though, the proof-of-principle of fully CW operating superconducting technology for future light sources has been performed successfully. This is especially true for the main linac units, where it was shown that TESLA technology can be adapted to operate CW. The necessary modifications have been identified and were validated by tests.

3.4.6 Cryomodule technology transfer

Several FEL projects, in particular the European XFEL, plan to use superconducting linear accelerators based on cryomodules which were developed by the TESLA Collaboration [29] in the 1990s and which are currently in use at FLASH. For the reliable and cost effective construction of these facilities it is necessary to move from prototyping to industrial production of complete crymodules. The objective of this work package has been to establish adequate design and assembly procedures, including their verification on a test bench. A cryomodule assembly study was sub-contracted to a potential industrial supplier; the key aspects were the definition of the assembly procedure and the final design of the cryomodules, the definition of measures for cost-reduction and performance improvement, and a cost estimate for the module production. Part of the study was also dedicated to issues associated with a modified, CW-capable module as needed for machines such as the FEL proposed by BESSY.

The industry study showed that, in general, the existing cryomodule design and the assembly procedures are already suited for an industrial serial production in the order of 100 cryomodules at a production rate of 1-2 modules per week. A number of procedures were identified that can be optimized or automated to decrease the assembly time considerably.

Figure 9: Installation of a 12 m long cryomodule in the CryoModule Test Bench (CMTB) at DESY.

To verify the design and the assembly procedures, the Cryomodule Test Bench (CMTB) was built at DESY. It operates down to temperatures of 1.5 K and can adapt different cryomodule designs. It is used to measure static and dynamic cryogenic heat losses, study fault conditions, measure dark currents, test helium relief system designs, and define the most effective operating temperature. Figure 9 shows a cryomodule during installation in the CMTB. Three cryomodule prototypes were extensively tested and subsequently installed in the FLASH accelerator. No leaks were observed and the alignment of critical components like couplers has been repeatable. The measured values for static and dynamic heat loads were in agreement with the design values. Moreover, the cavity performance was measured and the conditioning of couplers and the fast tuners were tested. All these tests have been completely satisfactorily.

The objectives of this task have been fully achieved and all deliverables submitted.

3.5 Summary and impact

EUROFEL has successfully integrated various local activities working towards the design and construction of the European XFEL [34] and several nationally funded FEL facilities, and has, for the first time, coordinated them on a European level. The project tackled key issues of single-pass free electron lasers and contributed to the development of fundamental technologies and know-how. Considerable work on normal-conducting photo-guns and injector components has resulted in proven designs and demonstration of state-of-the-art performance sufficient for driving a hard X-ray FEL. Much progress has been made in simulating and understanding the complicated electron beam dynamics including space charge, wake fields and CSR. Fundamental technology for sub-femtosecond synchronisation has been developed and tested in an accelerator environment. Seeding experiments have been set up and performed in different laboratories to test harmonic generation and seeding by optical laser and HHG sources. Extensive work has been done on CW superconducting RF technology for future FELs and ERLs. Finally, a cryomodule test bench has been constructed and used for optimising the design and assembly procedures for industrial production of complete cryomodules.

During the last few years Europe has made enormous progress towards free electron laser based research infrastructures and is in fact the main player in this field worldwide. The FLASH facility [16] at DESY in Hamburg, Germany, has been in user operation since summer 2005, FERMI@Elettra [12] in Trieste, Italy, is under construction, the European XFEL [34] in Hamburg will start construction in summer 2008, and several other FEL projects are being prepared in France, Germany, Italy, Poland, Sweden, Switzerland and the UK. In addition, a number of dedicated test facilities have become available including the photo-injector test facility (PITZ) [1] and the cryomodule test bench (CMTB) [35] at DESY, the HoBiCaT facility [30] at BESSY, Berlin, Germany, for testing superconducting cavities, the SPARC facility [3] at INFN-LNF in Frascati, Italy, for testing injector and seeding concepts, the test FEL at MAX-lab (see section 3.4.4) in Lund, Sweden, for testing seeding concepts, and the ERL Prototype (ERLP) [11] at Daresbury Laboratory, UK, for investigating specific issues of energy recovery and high current beams. They have been strongly supported by the national stakeholders with significant additional funding through the EUROFEL project in order to prepare the design of new FEL sources. Without the contributions of EUROFEL the FEL test facilities in Europe would be far from the state they are in the beginning of 2008.

In the future it is planned to facilitate and reinforce this successful, European-wide FEL collaboration by establishing a formal, trans-European network of national FEL facilities. A FP7 grant for the preparatory phase of new European research infrastructures included in the ESFRI 2006 roadmap [36] has just been awarded to construct this network in the years 2008 to 2011.

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