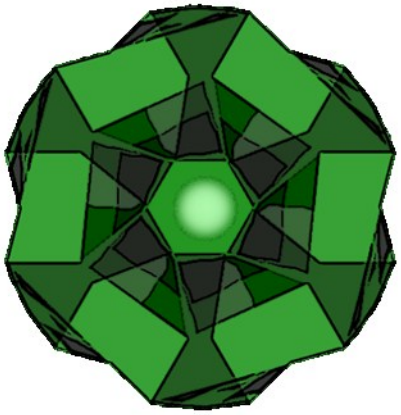
MAGDRIVE

Magnetic-superconductor cryogenic non-contact harmonic drive



SUMMARY ON TECHNOLOGICAL DEVELOPMENTS

This document describes the main technologies and capabilities developed during the FP7 Space Project MAGDRIVE funded by the European Commission under grant agreement n° 263014.

25th February 2014

www.magdrive.eu

SEVENTH FRAMEWORK PROGRAMME

European Commission

LIST OF CONTENTS

SEVENTH FRAMEWORK PROGRAMME

MAGDRIVE

European Commission

SCHEDULE

MAGDRIVE started on 1st February 2011 and ended on 31st January 2014.

OBJECTIVE

The objective of this project was to design and build a harmonic drive able to work under cryogenic conditions, with an extremely low friction, long life time and no wear. This harmonic drive should achieve a great reduction ratio, being able to function at cryogenic temperatures.
Based on the non-contact interaction between magnets, soft magnetic materials and superconductors, it uses no lubrication and is completely wear-free.

CONSORTIUM

MAGDRIVE project was coordinated by professor J.L. Pérez-Díaz in Universidad Carlos III de Madrid (Spain). The consortium included CNR-SPIN and University of Cassino (Italy), the University of Lisbone (Portugal), the companies BPE (Germany), CAN Superconductors (Czech Republic) and LIDAX (Spain).

SPIN-OFF COMPANY

A spin-off company has been incorporated for the exploitation of the results: MAG SOAR SL

MAG SOAR

www.magsoar.com

www.magdrive.eu

MAGDRIVE TECHNOLOGY

MAGDRIVE is a magnetic gear with an input axle and an output axle. The output axle is driven to turn by turning the input axle with a fixed ratio between input and output speeds. The MAGDRIVE technology replaces conventional "touching" teeth in gear by non-contact magnetic teeth.

The absence of contact removes most of the limiting problems of conventional gear: wear, fatigue, lubrication or transmission of vibrations. Therefore, the maintenance requirements is minimized providing a reliable and robust solutions for long lifetime applications. Additionally, as no debris is generated, MAGDRIVE is clean, vacuum compatible and environmentally friendly.

MAGDRIVE also provides overload protection: in case of jamming of the output axle the gear just "slides". The torque never overpasses the maximum transmission torque, stated by design, protecting the entire kinematic chain from permanent damage.

It has through wall capability as well. Besides that, it can act as a reduction or an amplification stage and motion direction is reversible. In addition, it exhibits vibration damping and very quiet operation properties. The elastic nature of the force transmission

Finally, MAGDRIVE prototypes have demonstrated to operate in very different environments with temperatures ranging from -240 ºC to 60, even in high vacuum conditions.

MAGDRIVE TECHNOLOGY

- *No friction, no wear,*
- *no lubrication required*
- *MINIMIZED MAINTENANCE*
- *OVERLOAD PROTECTION*
- *Very quiet operation*
- *Customizable damping*
- *Through- wall capability*
- *Reversible (CW or CCW)*
- *Invertible: (r=1:n or n:1)*
- *Service temperature: -240 to 250 ºC*

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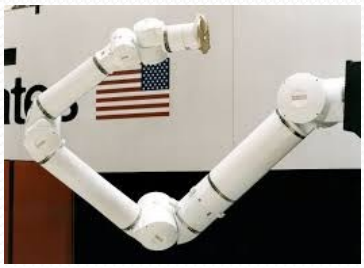
MAGDRIVE TECHNOLOGY

POTENTIAL APPLICATIONS

Magdrive can substitute any conventional gear or reducer. Some expected fields in which the characteristics of MAGDRIVE can be clearly advantageous are the following:

- **Space: long lifetime zero-maintenance harmonic drives**

- **Aircrafts: high reliable reducers**
- **Wind power: gearboxes with overload protection**
- **Robotics: accurate zero-backlash mechanisms**



- **Automotive: wheel electric motor design**
- **Biomechanical contactless pumps**
- **Cryogenic and vacuum pumps and valves systems**

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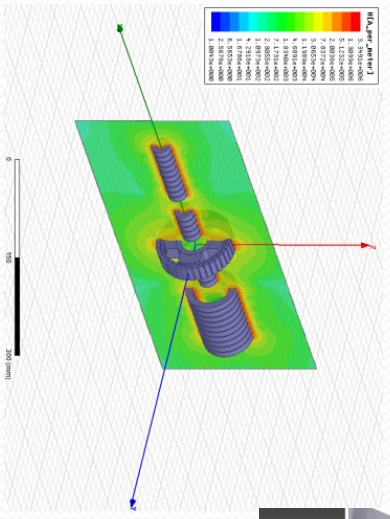
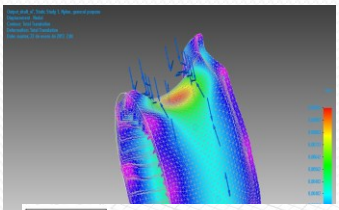
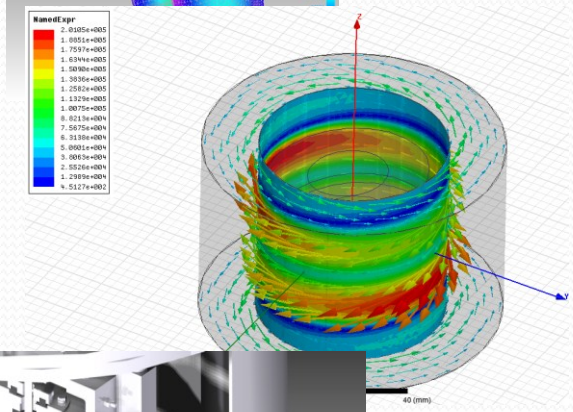
TECHNOLOGICAL DEVELOPMENTS

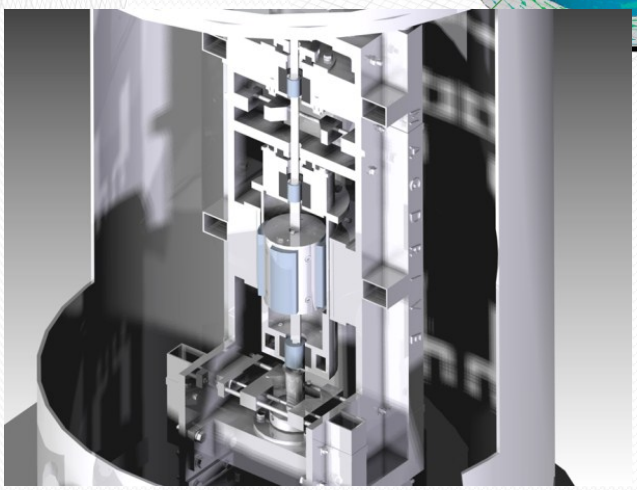
MULTIPHYSICS FEM ANALYSIS AND DESIGN

During the development of the project, analytical and simulation tools and programming codes were used and some of them specifically created to allow MAGDRIVE gearboxes analysis and design. These tools have been evaluated and experimentally demonstrated.







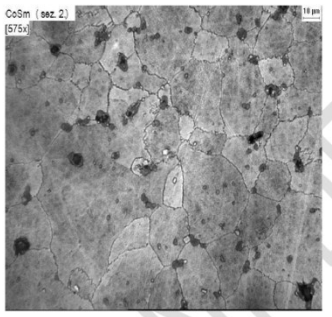


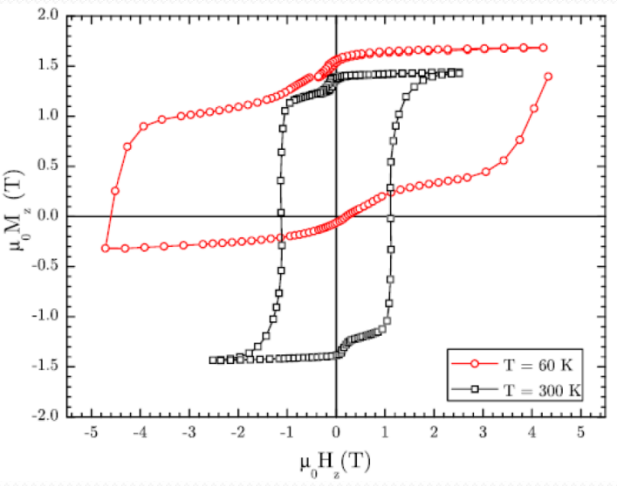
TECHNOLOGICAL DEVELOPMENTS

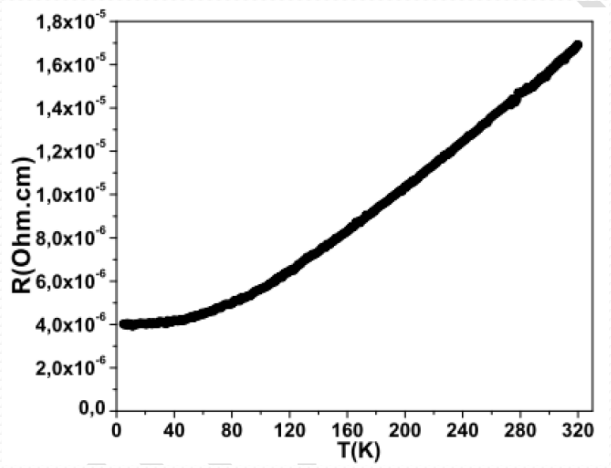
MAGNETIC MATERIAL CHARACTERIZATION

Soft and hard magnetic materials and non magnetic materials at cryogenic temperature were characterized. Invariance of magnetization axis under spin reorientation transitions in NdFeB magnets has been reported for the first time in MAGDRIVE project.

- **Morphological characterization**
- **Magnetic characterization of hard magnets**
- **Magnetic characterization of soft magnets**
- **Magnetic field profiles and quality**
- **Electrical resistivity**





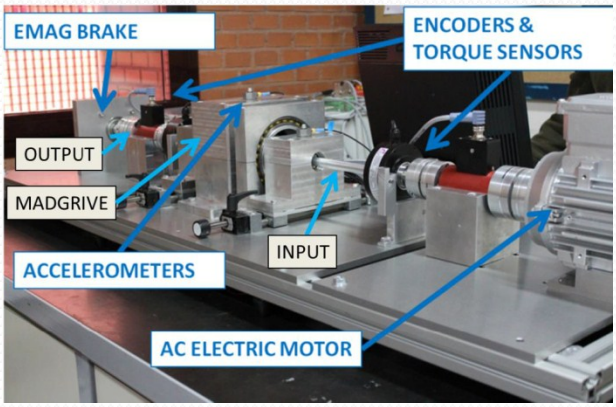


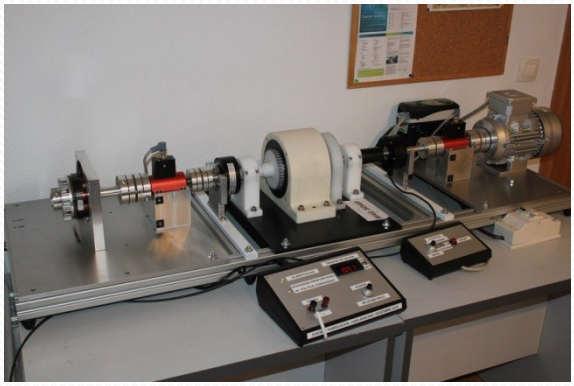
TECHNOLOGICAL DEVELOPMENTS

TEST BENCH DESIGN AND SET UP

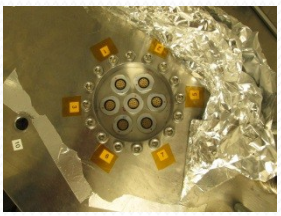
Room temperature test benches were designed and built. A cryostat and a cryogenic test bench were also designed, built and set up to run the experiments in the MAGDRIVE project.

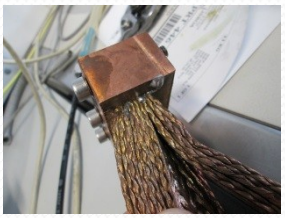
ROOM TEMPERATURE TEST BENCHES

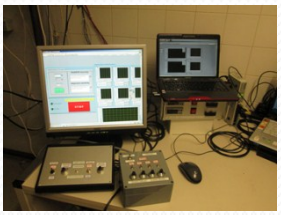




THERMAL VACUUM CHAMBERS AND CRYOGENIC SET UPS



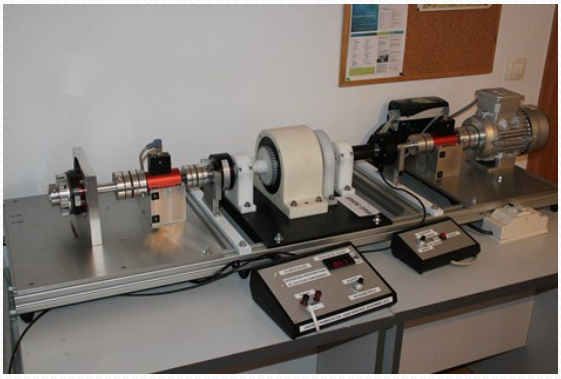




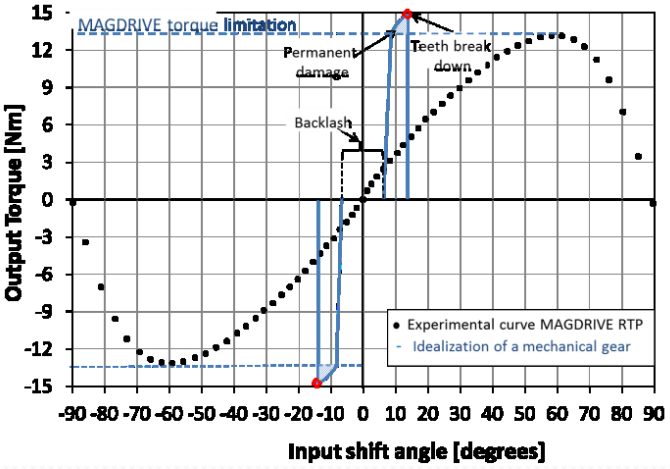
TECHNOLOGICAL DEVELOPMENTS

ROOM TEMPERATURE MAGDRIVEs

Two room temperature prototypes (Ø=120 mm, l= 110 mm) were built and tested with a reduction ratio of 1:21 to demonstrate the technology. Different combinations of magnetic materials were combined in these prototypes. Experimental results were in very good agreement with simulations and experiments. For these prototypes maximum torques of 15 Nm were demonstrated, providing torque densities about 11 kNm/m^3. Overload protection, damping and contactless reversible motion were demonstrated. Backlash was measured to be "zero" (that means below the resolution of the measurement system).



Zero-backlash & Overload protection



TECHNOLOGICAL DEVELOPMENTS

ROOM TEMPERATURE MAGDRIVEs

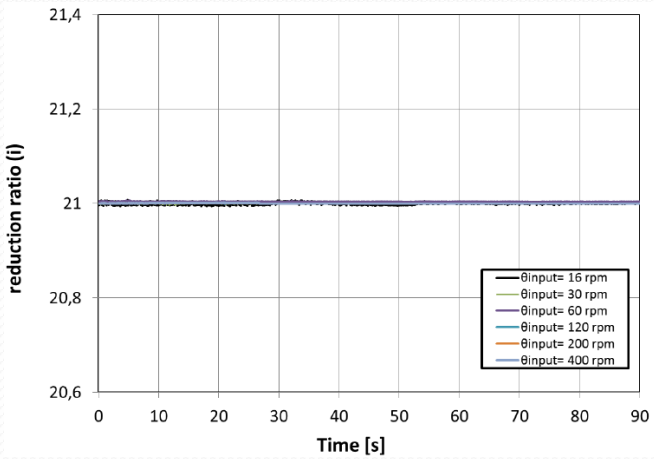
Damping can be customized. Particularly one of the prototypes was designed to be highly-damped. The tests confirmed that high damping ratio.

Al MAGDRIVE

- ***High damping***
- ***Robust and reliable device***
- ***Wide range of temperatures:***

  -50 to 250 ºC
- ***Vacuum suitable models***

Reduction ratio	21
Output torque [Nm]	13
Maximum input speed [rpm]	2000
Service temperature [˚C]	-50 to 250



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TECHNOLOGICAL DEVELOPMENTS

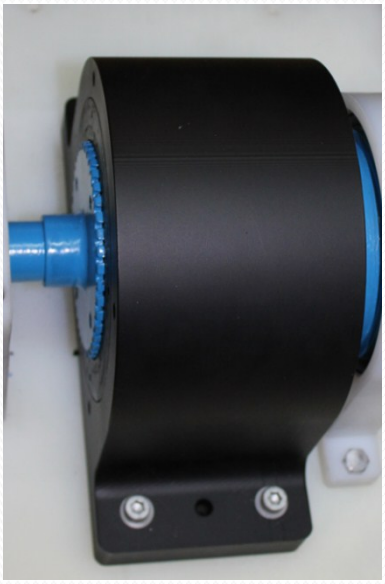
ROOM TEMPERATURE MAGDRIVEs

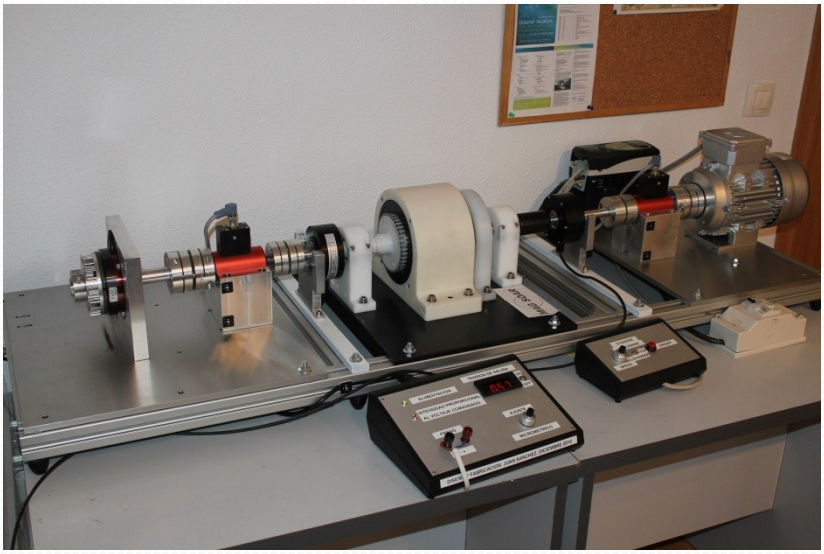
A second prototype was intended to be light and efficient. A housing made of polymeric materials was designed, built and tested.

Polymeric MAGDRIVE

- ***Light-weight solution***
- ***Minimized power losses***
- ***Vacuum suitable models***

Reduction ratio	21
Output torque [Nm]	13
Torque density [kNm/m³]	12
Maximum input speed [rpm]	4
Service temperature [°C]	-50 to 80





ROOM TEMPERATURE MAGDRIVE

Link to video of Room Temperature Magdrive demonstration

ROOM TEMPERATURE MAGDRIVE

Link to video showing Antijamming effect.

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TECHNOLOGICAL DEVELOPMENTS

CRYOGENIC MAGDRIVE

MAGDRIVE technology was demonstrated testing a cryogenic prototype at -240ºC. **Superconducting magnetic bearings** were used to eliminate any contact between the moving parts, improving reliability and lifetime of the magnetic harmonic drive.

- ***Contactless levitating system***
- ***Through-wall capability***
- ***No lubrication required***
- ***Extended operation lifetime***
- ***Overload protection***
- ***Vacuum suitable. Cryogenic temperatures up to -240ºC***

MAGDRIVE DEMONSTRATED PERFORMANCE

Reduction ratio	-20
Output torque [Nm]	3
Rotational accuracy [arcim]	+- 6
Maximum input speed [rpm]	3000
Tested temperature [˚C]	-240
Tested pressure [mbar]	$3 \cdot 10^{-5}$

TRL 5 DEMONSTRATOR

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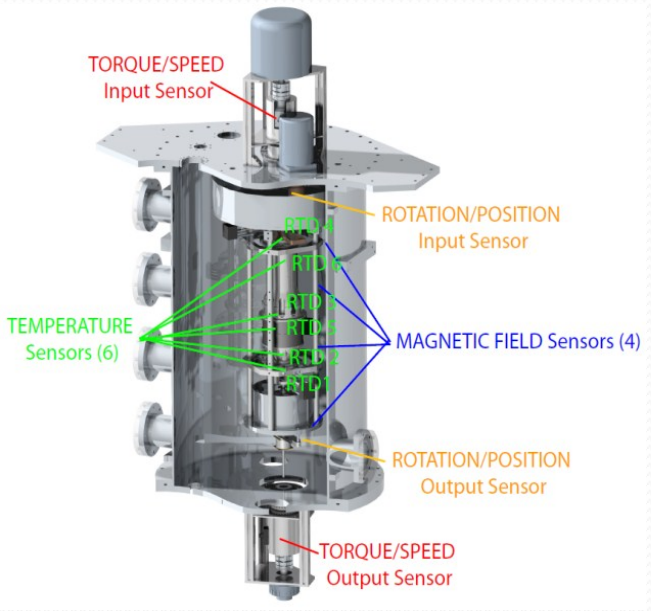
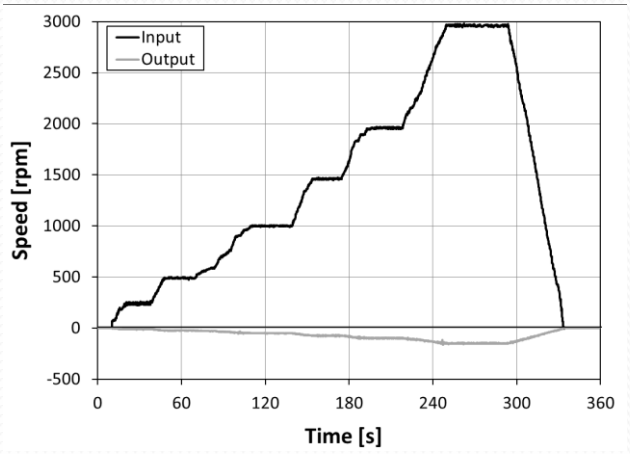
TECHNOLOGICAL DEVELOPMENTS

CRYOGENIC MAGDRIVE: TESTS

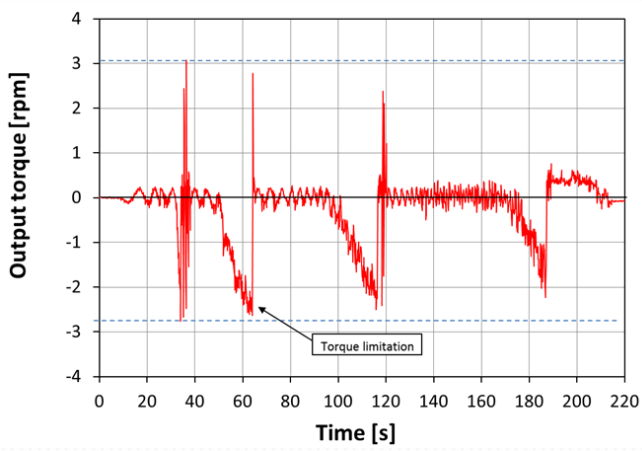
DEMONSTRATION IN A RELEVANT ENVIRONMENT (-240 °C, 3·10^{-5} mbar)



Reduction ratio -20,
Input speed up to 3000 rpm



Overload protection: > 3 Nm



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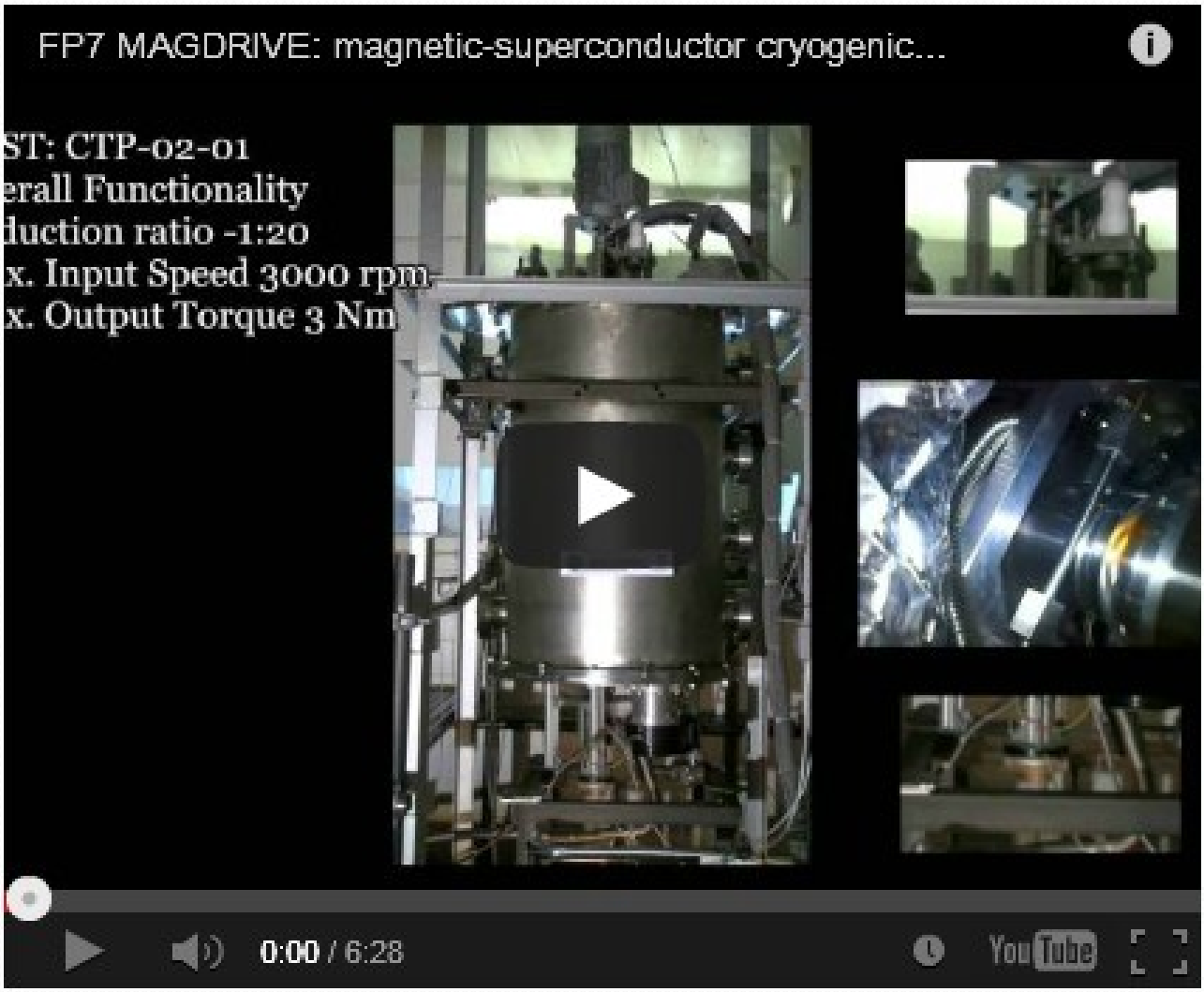
TECHNOLOGICAL DEVELOPMENTS

CRYOGENIC MAGDRIVE: TESTS



Link to video.

TECHNOLOGICAL DEVELOPMENTS

SUMMARY OF EXPECTED PERFORMANCE

MAGDRIVE project has proved the feasibility of the magnetic harmonic drive and related technologies up to TRL5 (in relevant environment). Using this know-how as a basis, we can derive the expected performance for optimized MAGDRIVE gear as follows:

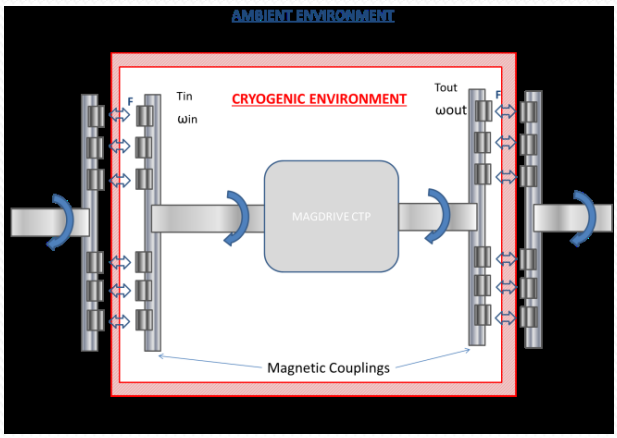
REQUIREMENTS		OPTIMIZED FEASIBLE PERFORMANCE	
REF	FUNCTIONAL	MAGNETIC HARMONIC DRIVE + CRYOGENIC MECHANICAL BEARINGS	MAGNETIC HARMONIC DRIVE + SUPERCONDUCTING MAGNETIC BEARINGS
F-1	Reduction Ratio	from 2 to 125 (single stage)	from 2 to 125 (single stage)
F-2	Rotation accuracy	±1 arcmin	±1 arcmin
F-3	Rotation resolution	±1 arcmin	±1 arcmin
F-4	Repeatibility	±1 arcmin	±1 arcmin
F-5	Backlash	Zero (elastic behavior)	Zero (elastic behavior)
F-6	Maximum Output Torque	from 0,1 to 100 Nm	from 0,1 to 100 Nm
F-7	Torque density	100-150 kN/m3	20-30 kN/m3
F-9	Torsional Stiffness	> 120 Nm/rad	> 120 Nm/rad
F-8	Maximum input speed	3000 rpm	from 3000 to 6000 rpm
F-10	Efficiency at maximum torque	89%	90%
REF	MECHANICAL		
M-1	Overall mass	maximum output torque dependent	maximum output torque dependent
M-2	Envelope (ODxL) [mmxmm]	maximum output torque dependent	maximum output torque dependent
REF	THERMAL		
T-1	Operative Temperature	-250 (limited by bearing) to +135˚C	-270 to -196˚C
T-2	Non-operative temperature range	-270 to 135˚C	-270 to 135˚C
T-3	Operational pressure	$3 \cdot 10^{-5}$ mbar	$3 \cdot 10^{-5}$ mbar
T-4	Stabilization temperature	-	-
T-5	Time of stabilization	-	-
REF	PRODUCT ASSURANCE		
Q-1	Outgassing for material selection	Acceptable	Acceptable
Q-2	Debris generation	Only debris from mechanical bearings	Zero wear and debris generation
Q-3	Through- wall capability	Yes	Yes
Q-2	Damping / Vibration isolation	Optional	Optional
REF	LIFETIME		
L-1	Probed lifetime (hours)	Limited by mechanical bearings life	SYSTEM REBOOTABLE
L-2	Input Cycles	Reduced loads on Mechanical bearings	Limited by Hold Down & Release mechanism life

TECHNOLOGICAL DEVELOPMENTS

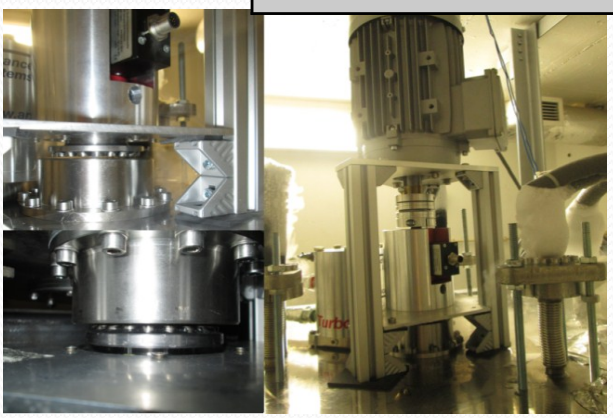
THROUGH WALL MAGNETIC COUPLING

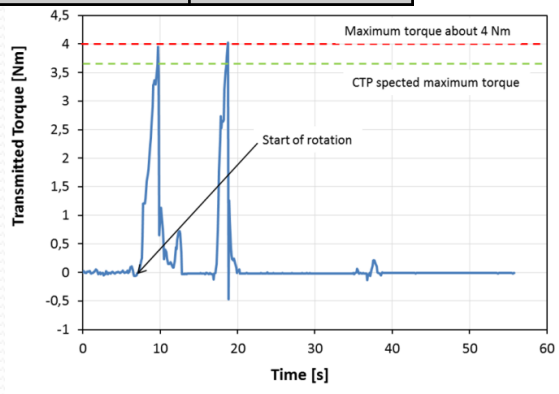
Non-contact through-wall transmission of forces and torques is possible using optimized magnetic couplings developed in MAGDRIVE project.

- ***No wear, no friction***
- ***No lubrication***
- ***No power consumption***
- ***Overload protection***
- ***Vibration absorption***
- ***Automatic synchronization***



Transmission ratio	1:1
Gap [mm]	0,5 to 100
Transmitted torque [Nm]	0,5 to 300
Service temperature [°C]	-200 to 250





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THROUGH WALL MAGNETIC COUPLING

Through-wall magnetic couplings developed in MAGDRIVE

Link to video

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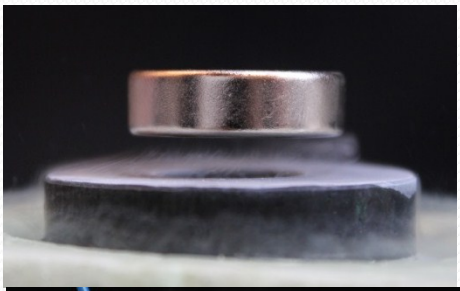
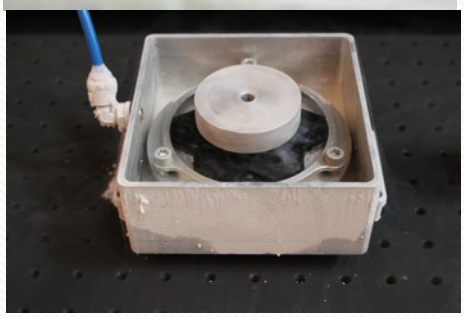
TECHNOLOGICAL DEVELOPMENTS

SUPERCONDUCTING MAGNETIC BEARINGS

High performance superconducting magnetic bearings were developed and used in the MAGDRIVE cryogenic temperature prototype to support MAGDRIVE and bear the dynamic forces and weight of the MAGDRIVE.





- ***Contactless***
- ***Self-stable***
- ***No wear, no friction***
- ***Lubrication free***
- ***Maintenance free***
- ***Extended service lifetime***
- ***Cryogenic and vacuum suitable***

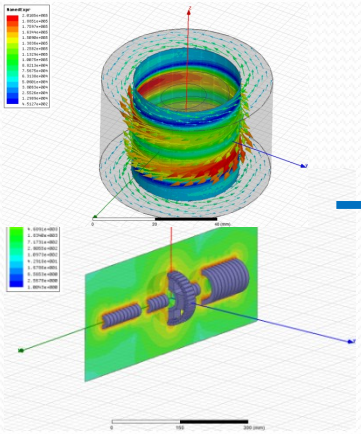
The Superconducting magnetic bearings developed in the MAGDRIVE project keep both input and output shafts floating and without contact with any other part. This makes the cryogenic prototype of MAGDRIVE to be an absolutely contact-free machine. A patent has been applied.

TECHNOLOGICAL DEVELOPMENTS

SUPERCONDUCTING MAGNETIC BEARINGS: DESIGN AND CHARACTERIZATION

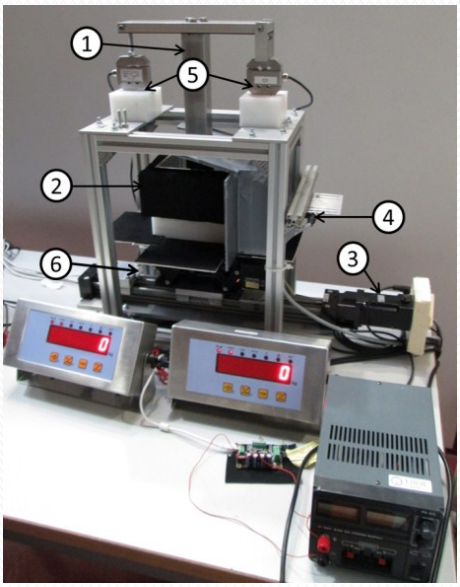
Unique analytical and FEM models were specifically generated for calculation of superconducting bearings. In addition, an automatized test bench and standardized test procedures were developed.

FEM SOFTWARE



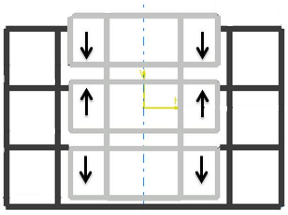
SC MANUFACTURING

EXPERIMENTAL CHARACTERIZATION

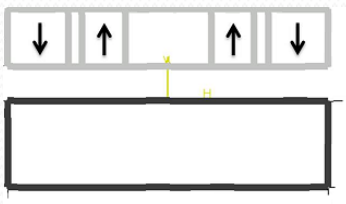


- AUTOMATIZED TESTBENCH
- OWN SOFTWARE CODES
- SUPERCONDUCTOR MANUFACTURING

RADIAL GAP BEARINGS



THRUST BEARINGS



RADIAL BEARINGS

- High loads
- Larger displacements

THRUST BEARINGS

- High stiffness
- Higher force densities

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SUPERCONDUCTING MAGNETIC BEARINGS: DESIGN AND CHARACTERIZATION

Thrust bearing. Magnet spinning&floating over a superconductor base.

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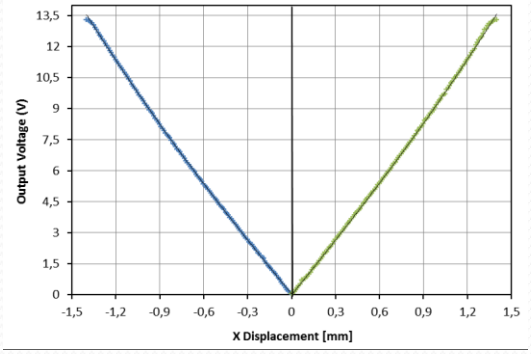
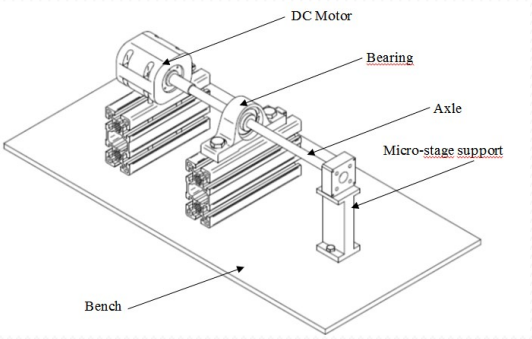
TECHNOLOGICAL DEVELOPMENTS

CONTACTLESS 6 DoF POSITION SENSOR

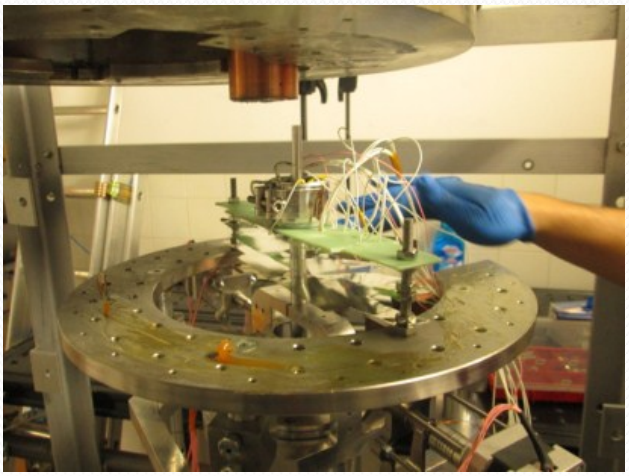
A contactless 6 coordinates position sensor has been developed and patented in MAGDRIVE. It is able to measure 3 coordinates of displacement in space but also 3 angles or rotations was developed. Vacuum and cryogenic suitable models are available. It has a good linearity.

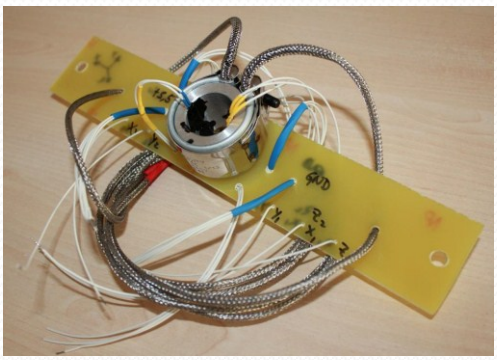
Bandwidth	30 kHz
Motion range [x,y,z]	3 mm
Position resolution [µm]	1
Angular resolution [rad]	0.01
Service temperature [°C]	-240 to 80 C





CRYOGENIC 6 DoF Sensor in MAGDRIVE demonstrator





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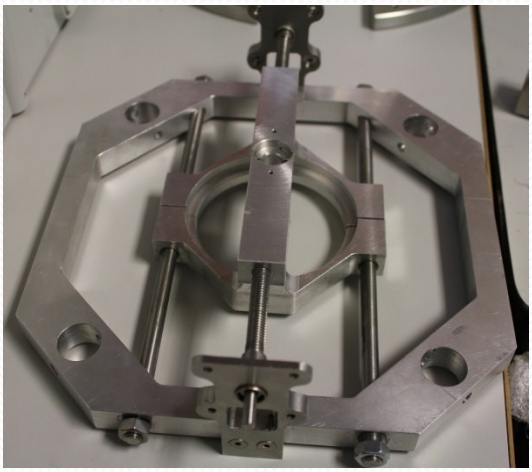
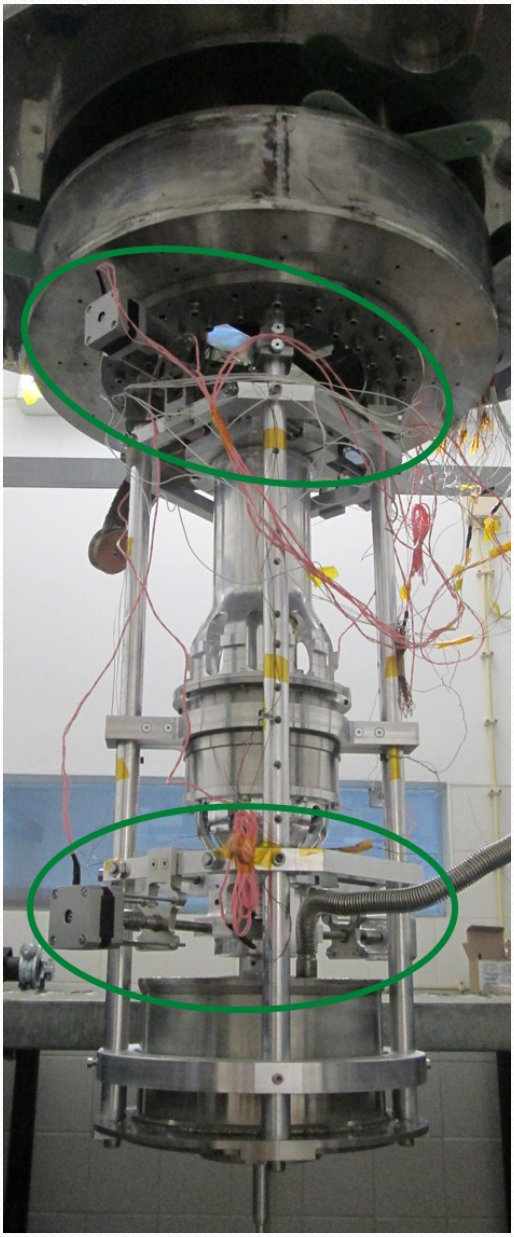
TECHNOLOGICAL DEVELOPMENTS

HOLD DOWN AND RELEASE MECHANISMS

Hold down and release mechanisms (cryogenic and vacuum suitable models are available) were designed, built and tested for the cryogenic tests. Two mechanisms were specifically designed to launch & lock the MAGDRIVE cryogenic prototype.





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