MgB_2 development for magnets in medical application

Matteo Tropeano, Giovanni Grasso

Columbus Superconductors

Superconductivity and other new Developments in Gantry Design for Particle Therapy
17-19 September 2015

Outline

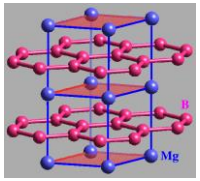
- Why MgB_2?
- Interesting properties since its discovery in 2001
- Companies dealing with the manufacturing MgB_2 wires or related applications

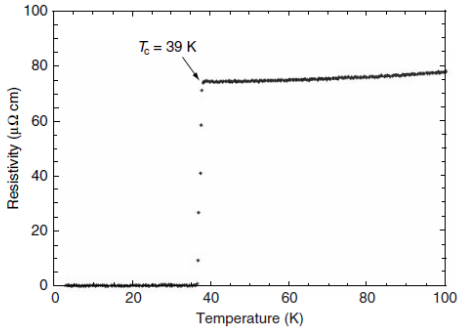
- PIT technique
- Main critical issues
- Columbus Superconductors
- Wire formats: round wires for cable applications
- Wire formats: copper stabilized tapes for magnets applications

- Achieved results and new projects
- Medical application
- Final remarks

Why MgB_2?

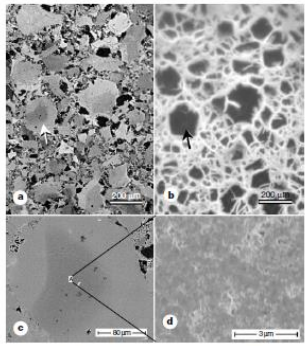
Relatively high Tc, simple structure and common materials





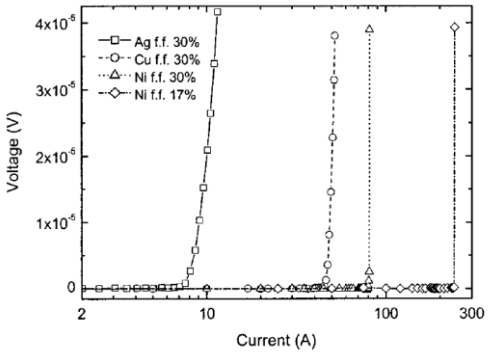
Nagamatsu et al. 2001
Superconductivity at 39K in magnesium diboride
Nature 410 63-4

No evidence of "weak link", no need of high degree of texturing



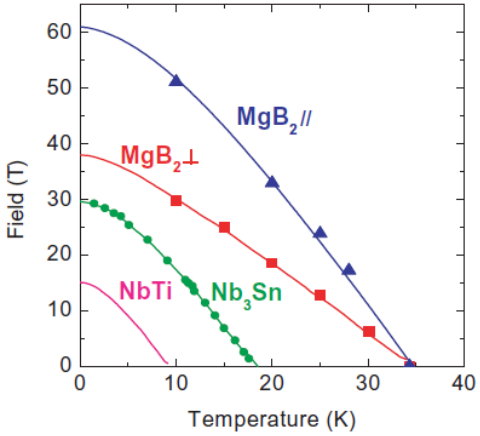
D.C Larbalestrier et al. 2001
Strongly linked current flow in polycrystaline form of the superconductor MgB_2
Nature 410

PIT process for the fabrication of wire



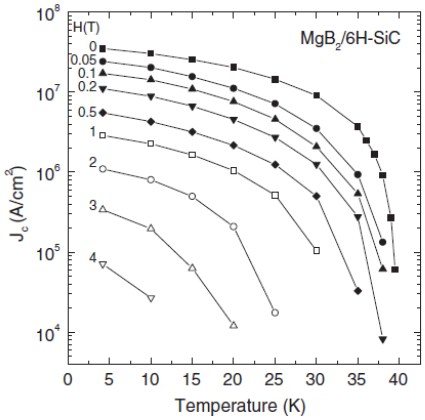
G.Grasso et .al. 2001
Large transport current in unsintered MgB_2 SC tapes
APL Volume 72, number 9

High critical field



Iwasa Y et al. 2006
A round table discussion on MgB_2: towards a wide market or a niche production?
IEEE Trans. Appl. Supercond 16 1457-64

Large critical current density



Zeng et al. 2003
Superconducting MgB_2 thin film on silicon carbide substrate by HPCVD
APL 82 2097-9

Low density

Compound	Mass density
Copper	8,96 g/cm^3
NbTi	6 g/cm^3
Nb3Sn	5,4 g/cm^3
YBCO	6,35 g/cm^3
BSCCO-2223	6,5 g/cm^3
MgB_2	2,6 g/cm^3

MgB_2 wire manufacturing companies

Hyper Tech Research, Inc.

Columbus Superconductors

Ready for industrial production
2 different manufacturing process
ex-situ and in-situ technique

EPOCH WIRES
infinite superconductivity

Early stage New York based company,
granted as SME partner by UK for R&D activities on MgB_2

Cutting Edge Superconductors Inc.

Interested in commercial production
of wires or wires+magnet

MgB_2 wires for Cryo-free MRI
Summer 2015 for MRI magnet 1.5T-3T magnet

Interested in the MgB_2 technology

BRUKER **Bruker BEST**

1000 m of MgB2 wire
already demonstrated
in collaboration with IFW Dresden

HITACHI

Patents on MgB2 wires
Several R&D activities

SUPERCON INC

Western Superconducting Technologies Co., Ltd.

2003

Columbus Superconductors srl

75% CNR+Researchers
25% ASG

2005

R&D target →

First 1.6 km MgB_2 long wire in a single unit length

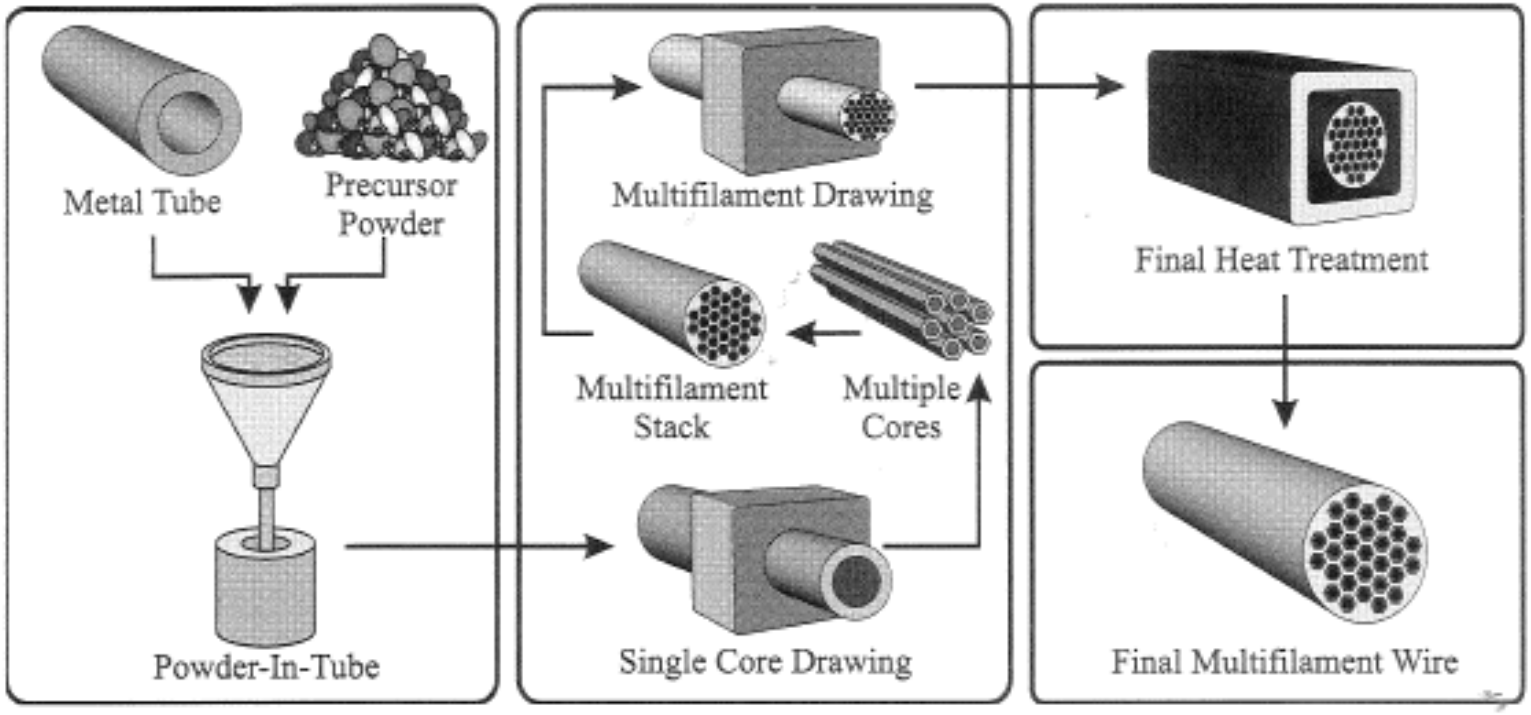
2006

Columbus Superconductors SpA

ASG became the main shareholder to sustain industrial investment and to start the business plan

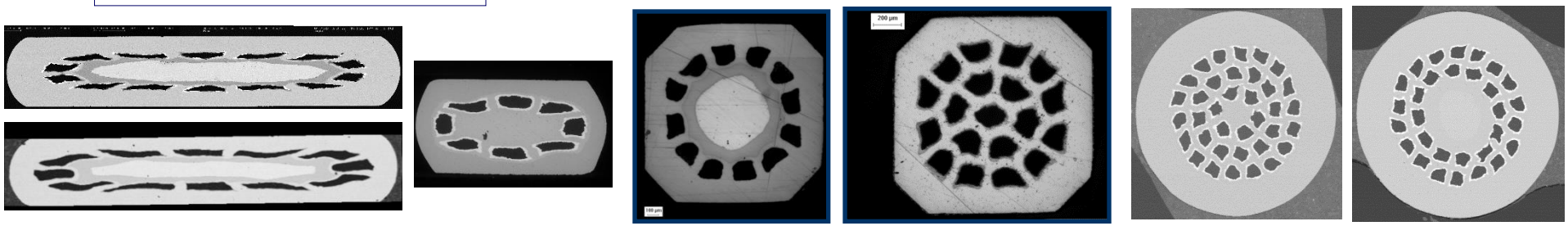
Superconducting wire → Superconducting magnet → MRI

Columbus PIT ex situ process



Conductors configuration:
different shape, aspect ratio, number of filaments, materials

Home made MgB_2 powders
Precursor quality, doping
synthesis temperature, granulometry



Critical issues

Powder optimization

- Purity and granulometry control
- Grain connectivity
- MgO at grain boundaries
- Pinning and/or doping control

Sheath materials

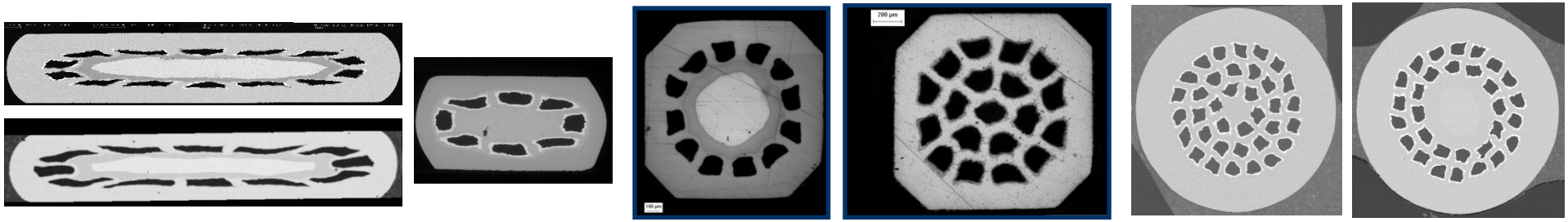
- Mechanical properties of the raw metals
- MgB_2 / sheath reaction

Optimization of intermediate (500-800°C) and final thermal treatment (900°C)

Application voted design

Layout of the conductor: shape, dimensions, number of filament

Magnetic, electrical, thermal and mechanical properties



Columbus plant

- The actual plant is fully operational for **MgB_2 wire production** and is under scaling up
- **MgB_2 chemical synthesis** is now also fully implemented
- Wire unit length today up to **2- 4 Km in a single piece –length**
- It will be possible up to **20 Km** with the full scale up of the process and of the plant with a nominal full capacity exceeding 5000Km/y
- Columbus **MgB_2 wires production for MRI** has exceeded **500 Km** of fully tested and qualified wires
- Total plant area **3'400 m^2** increased by further **1'000 m^2 by September 2012**

Columbus Superconductors Plant

Clean synthesis of powders

Multistep rolling machine

High power straigth drawing machine

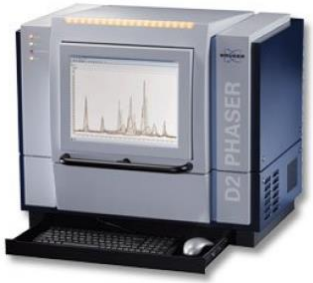
- 39 new machines
- 15 existing machines will be still used over 21,
- 10 main upgrades to the technical infrastructures
- 1 new 2 floors buildiing
- 2.280m^2 of covered workshop area
- 20 direct production units

20 meter long in-line furnace

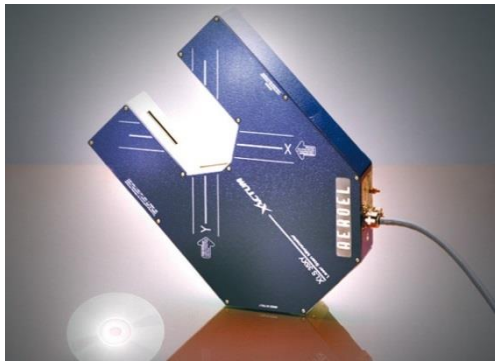
Multistep drawing machine

4 meter furnace for annealing HT

Quality control



- Quality Control is done through all the process area from **incoming raw material** to the **final product**
- Defined responsibility in the control process
- Dedicated operative instructions and procedure
- Real time data collections of production and quality records
- Materials traceability



- SEM with EDX
- Optical stereomicroscopes
- Fast XRD
- Particle size analyzer
- Laser wire size and shape online monitoring during the deformation process

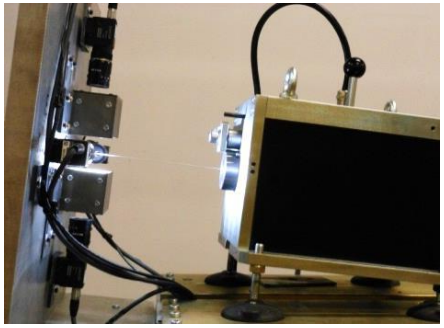
- Industrial video cameras for surface defect detection
- **Eddy currents defect detector**

100% of our products passes trough this detectors

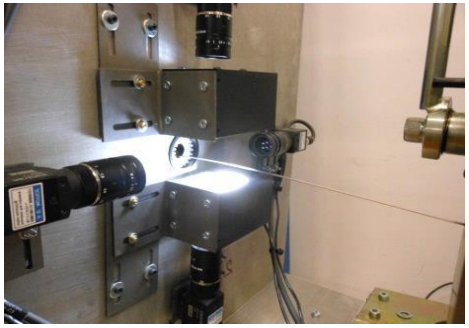
- Quality management system is in compliance with the standard ISO 9001:2008

In-line defect detector

Eddy current detector
to check the product integrity



4 camera visual inspection
to check the surface appereance

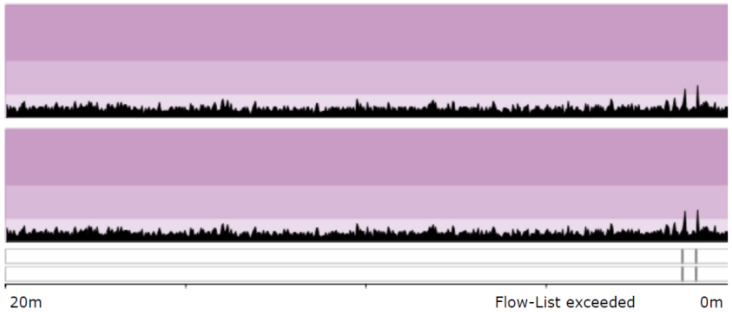


TEST REPORT- V66_4

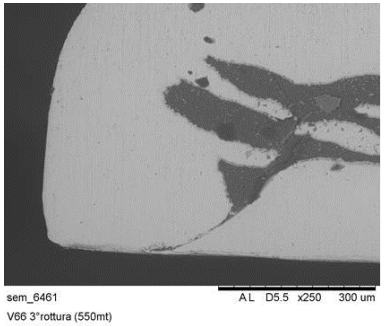
Test station: DEFECTOMAT CI

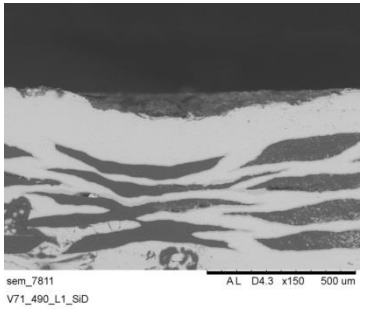
Request: V66

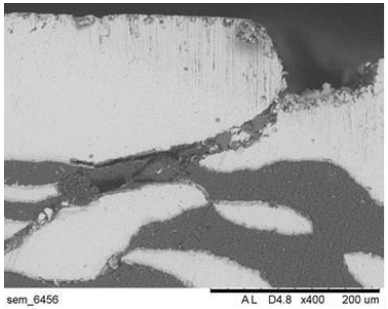
FOERSTER



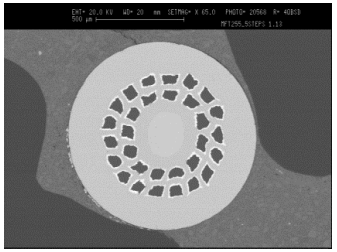
Outer
Inner defects



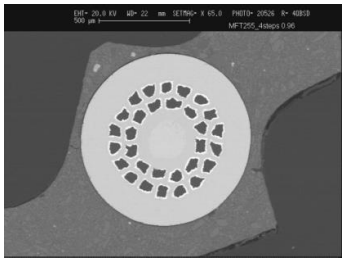




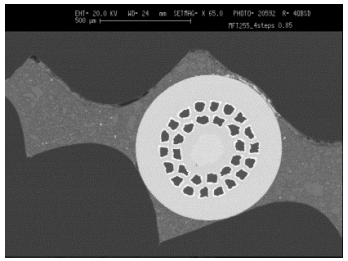
Round wires



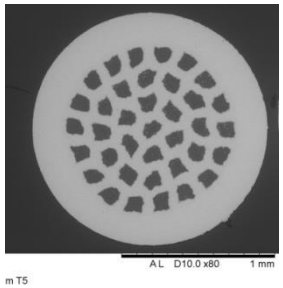
Diameter 1.13mm



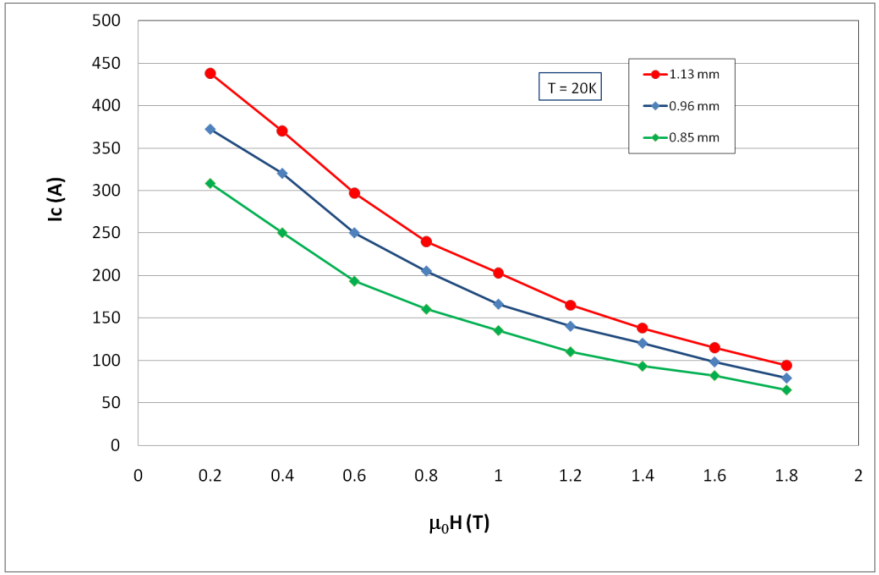
Diameter 0.96mm

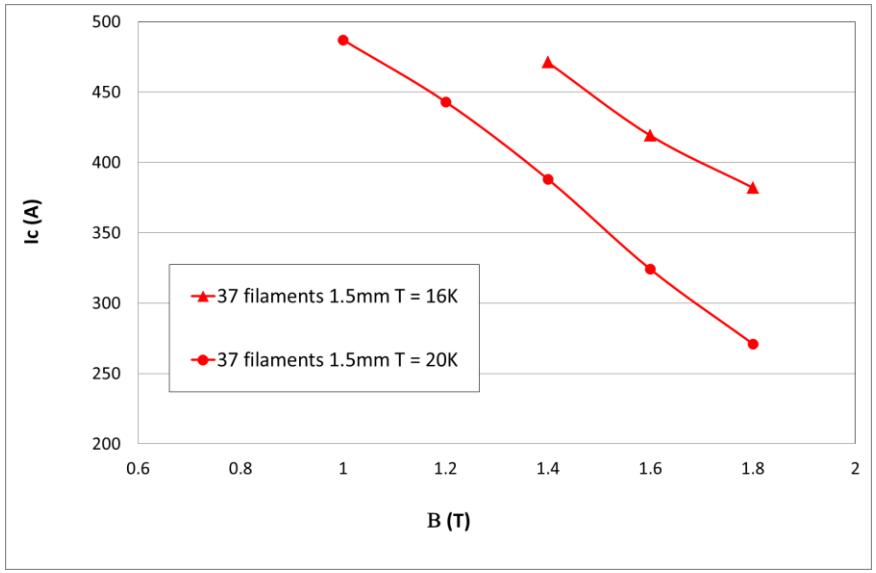


Diameter 0.85mm



Diameter 1.5mm





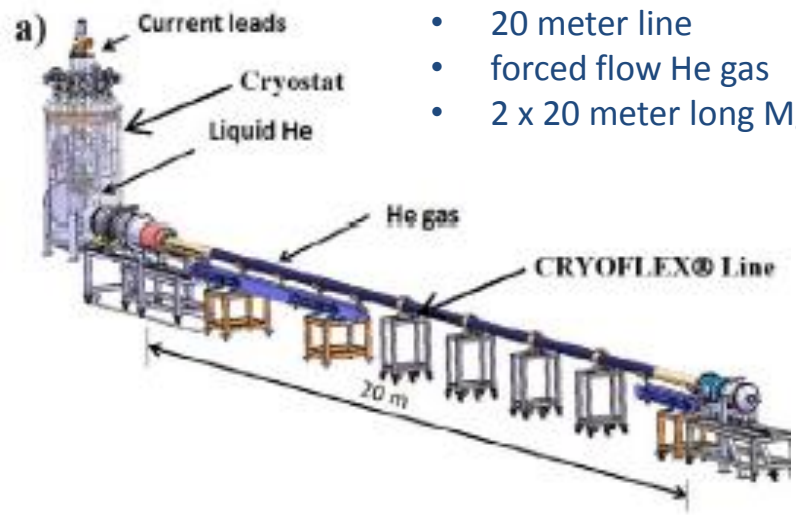
Round wires are produced in different configuration at diameter even smaller than 1mm

For application in power cable
An external copper layer (30-40 μm) could also be provided trought an electrodepostion process to improve the interstrand conductance and current distribution

CERN Bulletin
Issue No. 16-17/2014 - Monday 14 April 2014
More articles at: http://bulletin.cern.ch

WORLD-RECORD CURRENT IN A SUPERCONDUCTOR

In the framework of the High-Luminosity LHC project, experts from the CERN Superconductors team recently obtained a world-record current of 20 kA at 24 K in an electrical transmission line consisting of two 20-metre long cables made of Magnesium Diboride (MgB_2) superconductor. This result makes the use of such technology a viable solution for long-distance power transportation.



- 20 meter line
- forced flow He gas
- 2 x 20 meter long MgB_2 powered to 20KAmps

Long R&D effort started in 2008
between Columbus and CERN

Nexans cable – Russian program

Nexans POSE²IDON

Short cable prototype

16,5 MW MgB_2 bipolar power distribution system

Characteristic	
System	2 twisted strands
Operating voltage	3.3 kV
Operating current @ 20K	> 2500 A
Operating current @ 25 K	> 2100 A
Cooling medium	G He 20 bar
Outer diameter	60 mm
Iop/Ic	75%

Experimental Hybrid Power Transmission Line with Liquid Hydrogen and MgB_2-Based Superconducting Cable

V. V. Kostyuk, I. V. Antyukhov, E. V. Blagov*, V. S. Vysotsky, B. I. Katorgin, A. A. Nosov, S. S. Fetisov, and V. P. Firsov

Institute of Nanotechnology for Microelectronics, Russian Academy of Sciences, Moscow, 119991 Russia

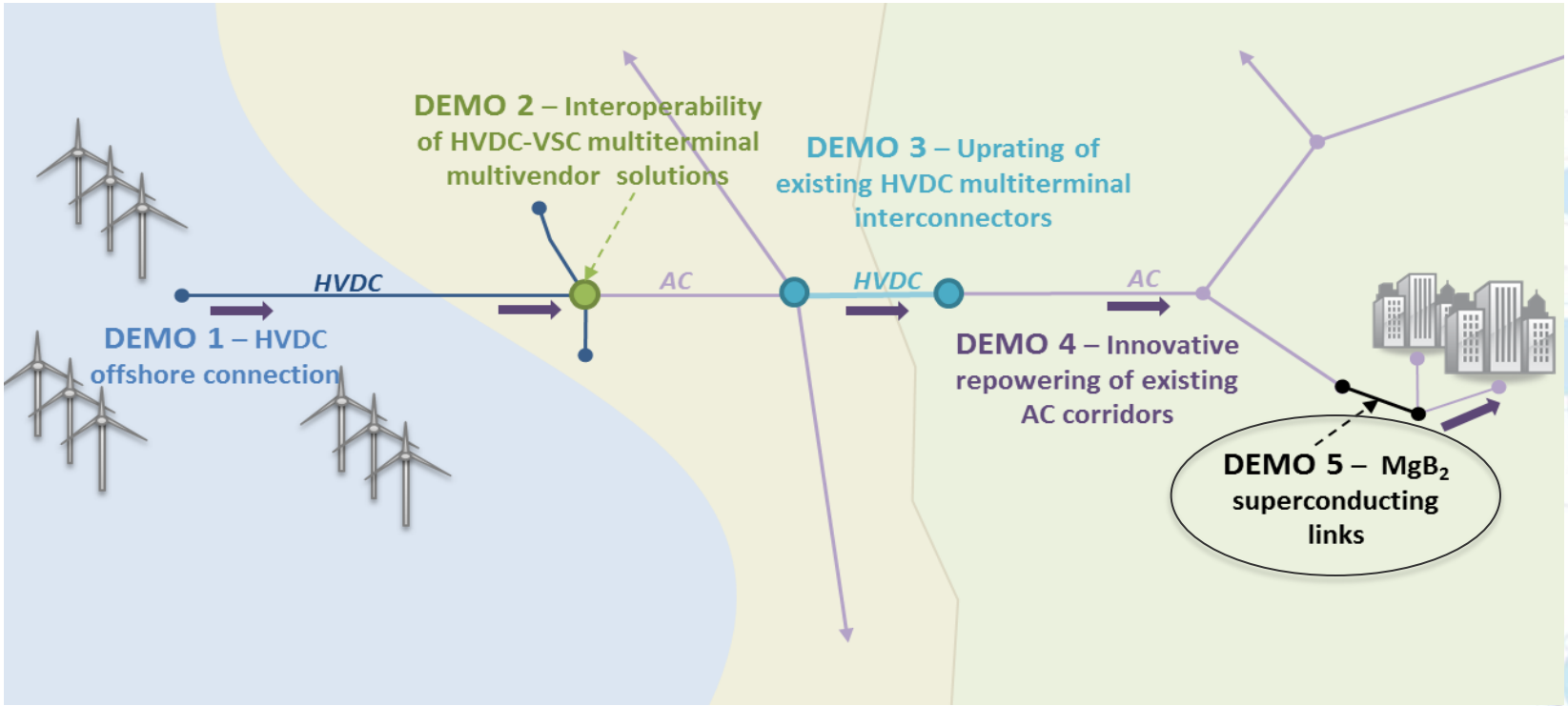
**e-mail: blagovev@mail.ru*

Received November 23, 2011

1. Best Paths project

Objectives

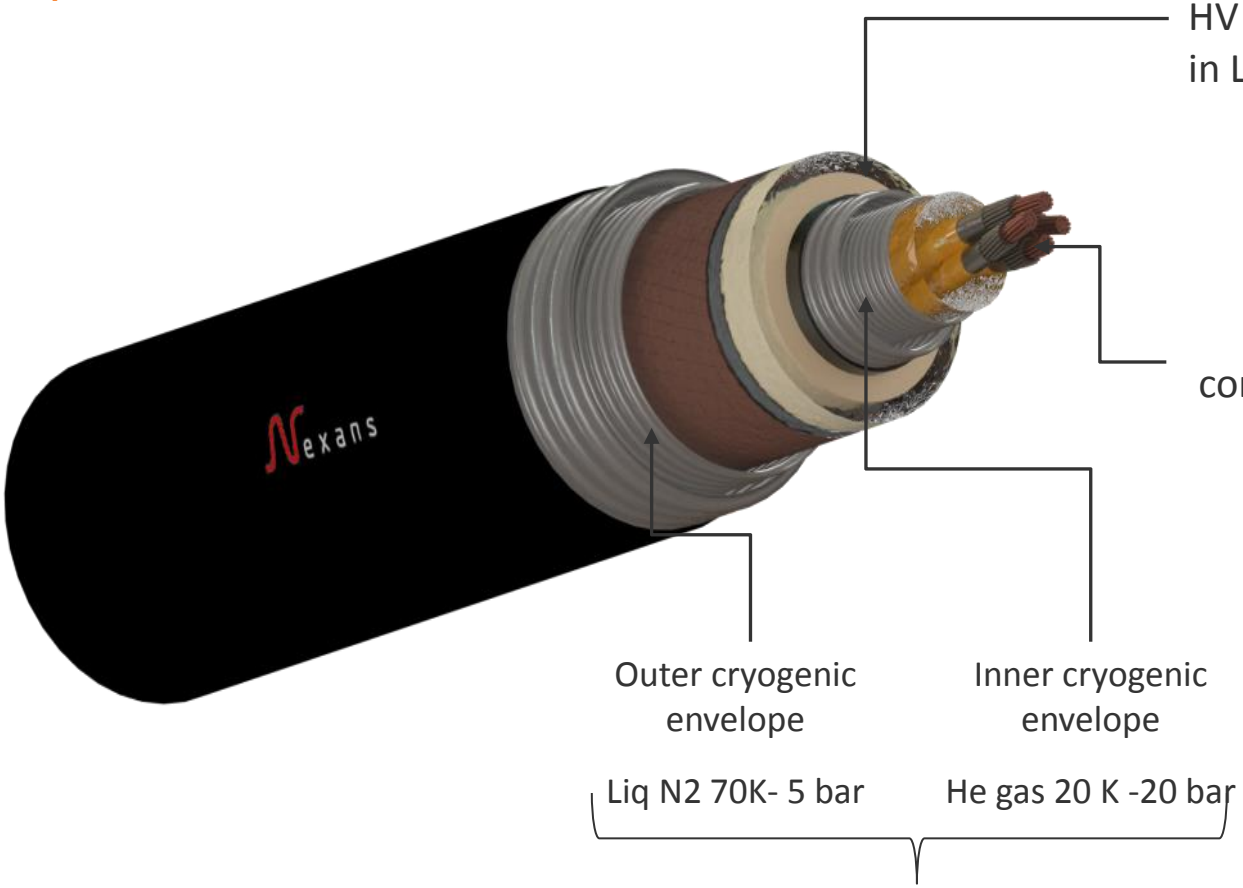
5 top technology demonstrations including a HVDC MgB2 superconducting link



BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

2.Technical specifications

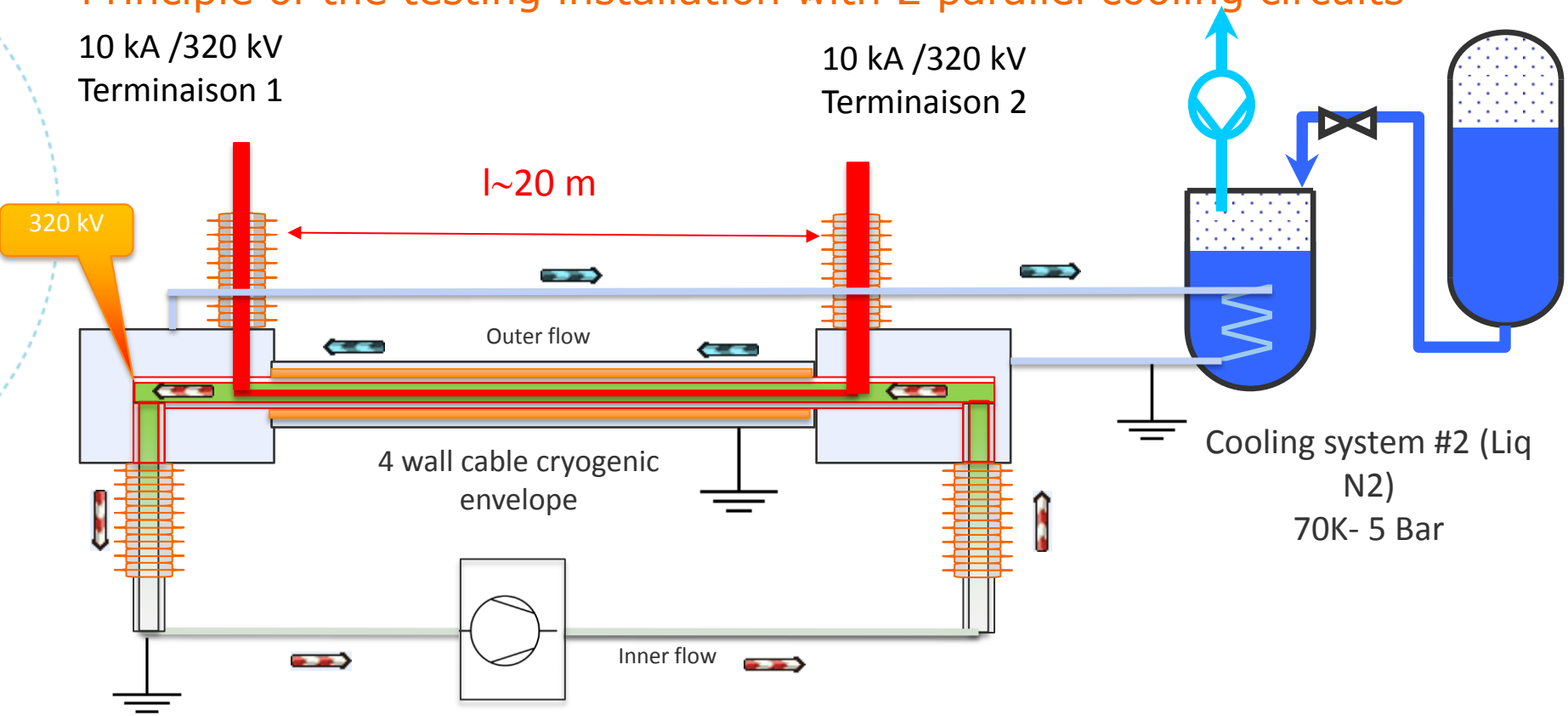
Conceptual design of the cable with to 2 fluids to guaranty the safety of the operation



BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

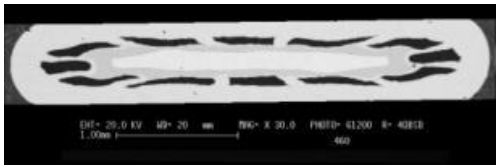
2.Technical specifications

Principle of the testing installation with 2 parallel cooling circuits



BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

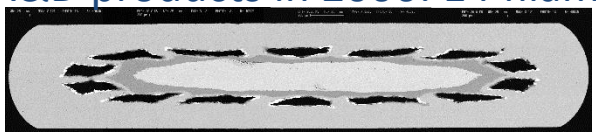
Copper Stabilized Tape: 3.50 x 0.65mm^2



Material	Area (mm^2)	%
MgB_2	0.23	10
Ni	1.55	65
Iron	0.23	10
Copper	0.36	15
Total	2.37	100
Dimension	3.5 x 0.65	

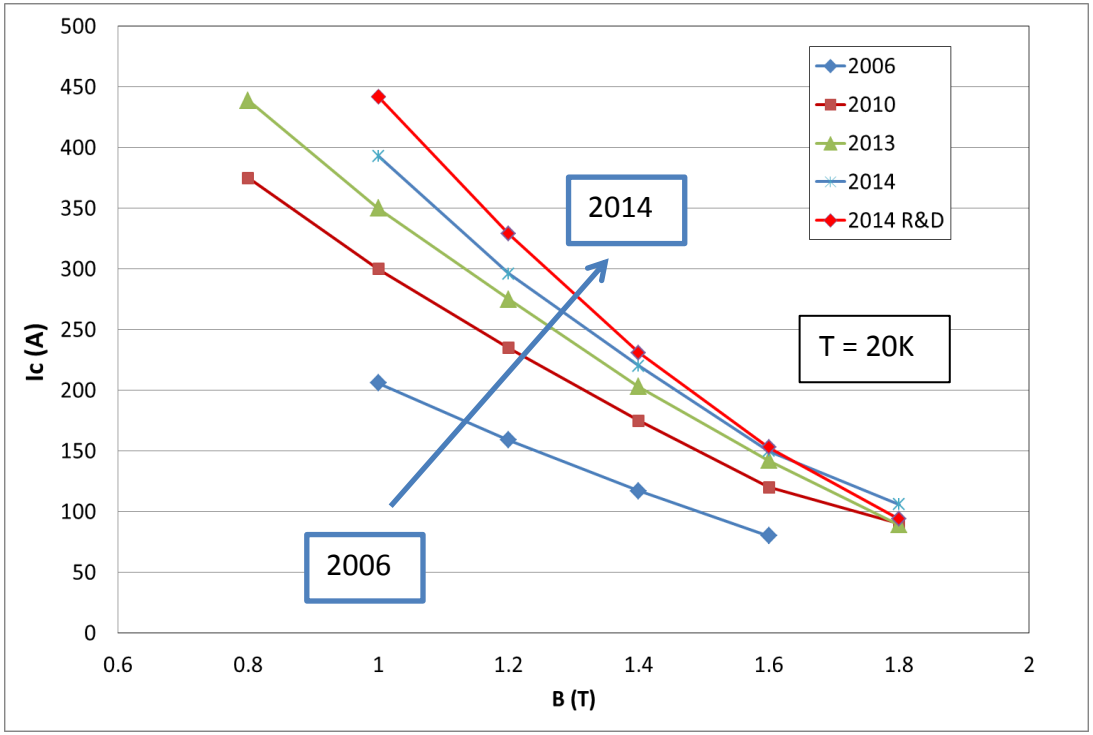
Unit length 3.2Km

R&D products in 2006: 14 filaments



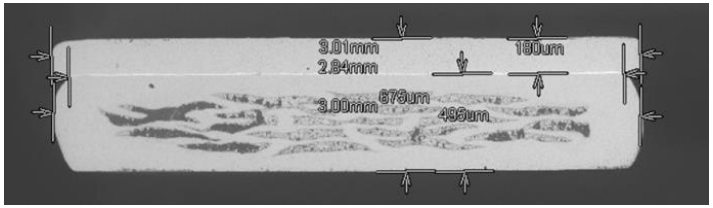
Starting from 2010:

- 12 filaments
- improved fabrication process
- synthesis in controlled atmospheres

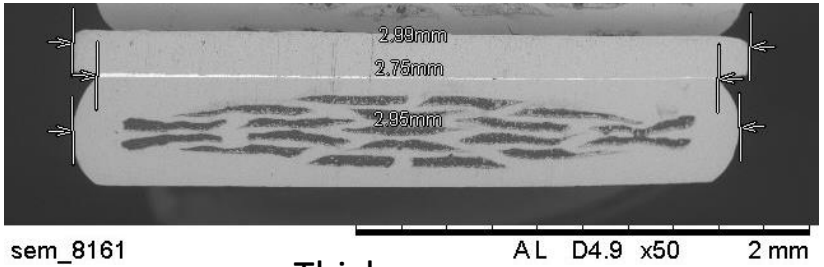


Sandwich wire: 3 x 0.5 mm^2

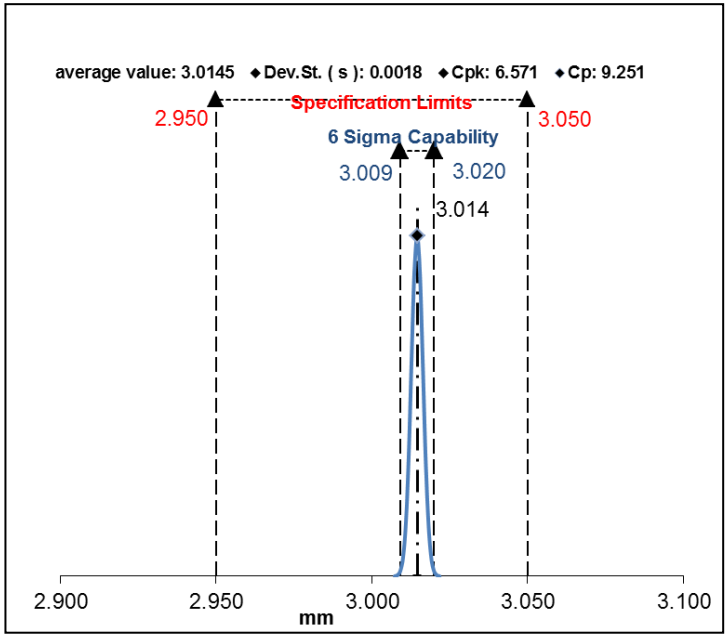
19 filaments nickel tape can be produced in unit length up to 3Km
Lamination process is now reliable and uniform over all the length

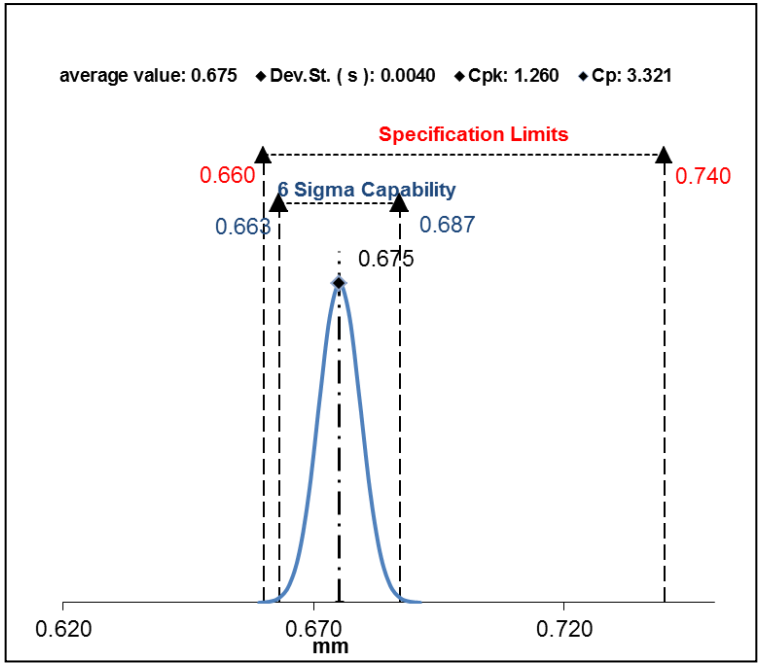


Width



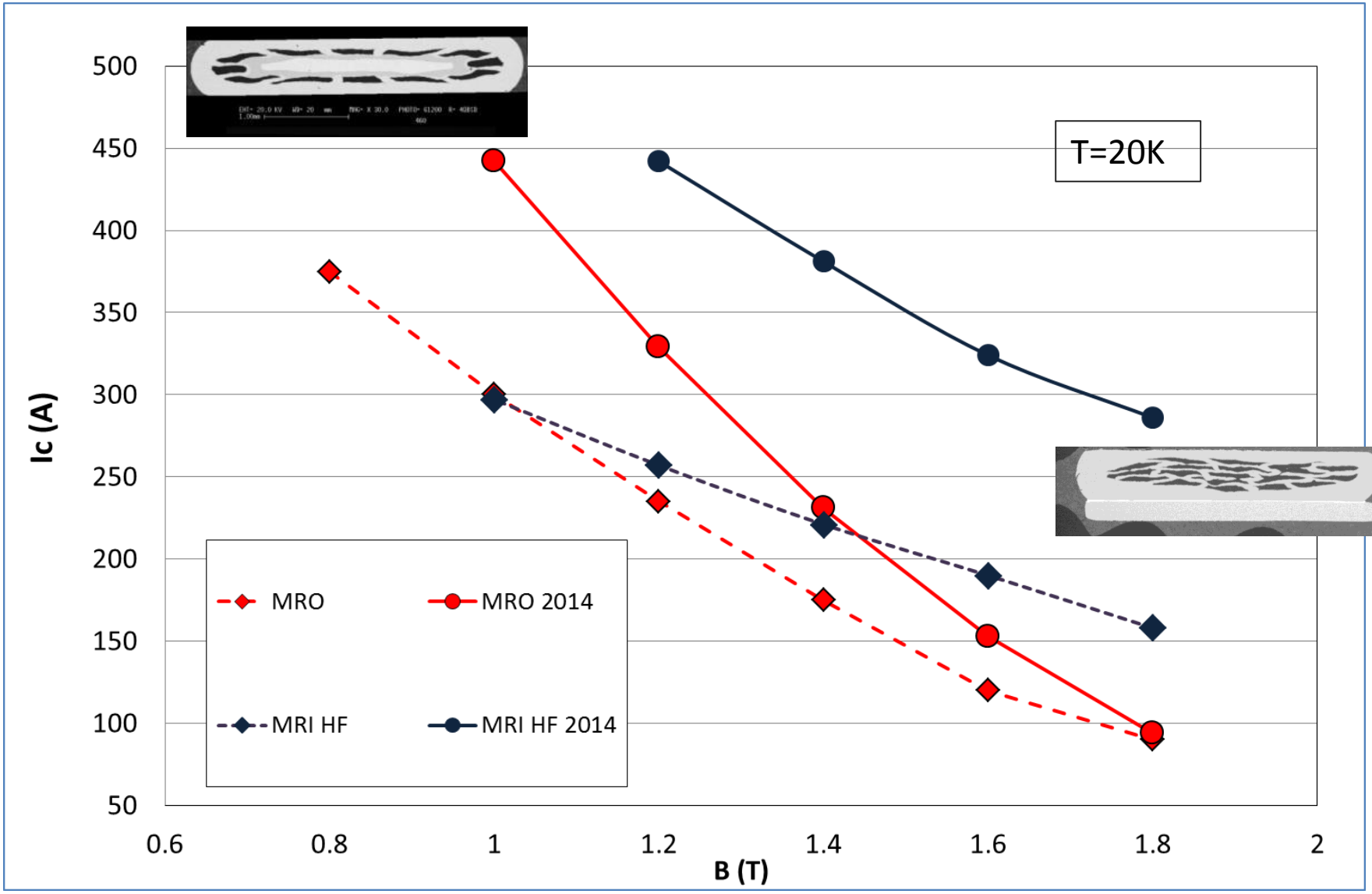
Thickness





Perfect copper to MgB_2 tape alignment is confirmed by the statistical analysis of the data from laser in-line micrometers

Performance improvements



Superconducting joint

Starting from ASG experience,
the feasibility has been already demonstrated in two different tapes,
stabilized and sandwich like
with high persistent current in several turns coil

(12) **United States Patent**
Nardelli

(10) **Patent No.: US 8,238,990 B2**
(45) **Date of Patent: *Aug. 7, 2012**

(54) **GRANULAR SUPERCONDUCTING JOINT**

(75) Inventor: **Davide Nardelli**, Genoa (IT)

(73) Assignee: **ASG Superconductors, S.p.A.**, Genova (IT)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 595 days.

This patent is subject to a terminal disclaimer.

5,581,220	A	12/1996	Rodenbush et al.
5,604,473	A	2/1997	Rodenbush
7,226,894	B2	6/2007	Raber et al.
7,337,527	B2	3/2008	Grasso et al.
2003/0051901	A1 *	3/2003	Morita et al. 174/125.1
2008/0020137	A1 *	1/2008	Venkataramani et al. 427/215

FOREIGN PATENT DOCUMENTS

DE	10 2006 020 829	A1	11/2007
EP	1 526 586	A2	4/2005
GB	2 448 051	A	1/2008
JP	2003-86265	A	3/2003
WO	WO-2007/128635	A1	4/2007

OTHER PUBLICATIONS

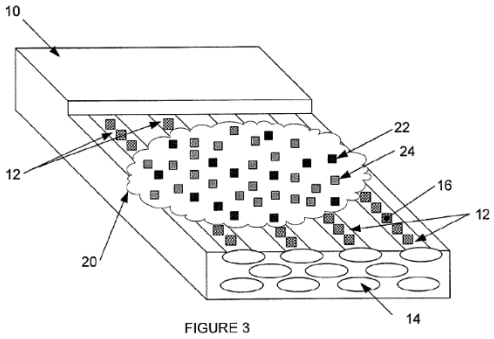


FIGURE 3

Granular precursor substance
on the exposed filaments
containing the granular SC

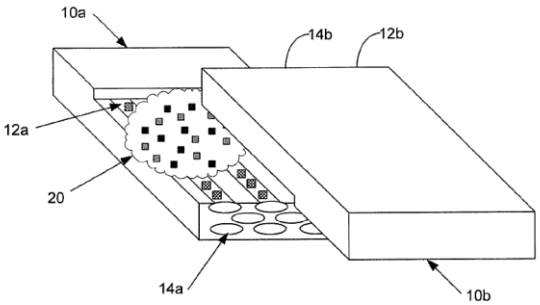


FIGURE 4

Granular precursor
substance
between opposing exposed area

Side by side SC joint

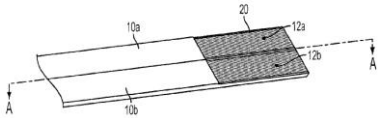


FIG. 5a

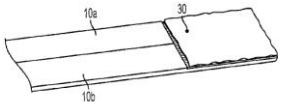


FIG. 5b

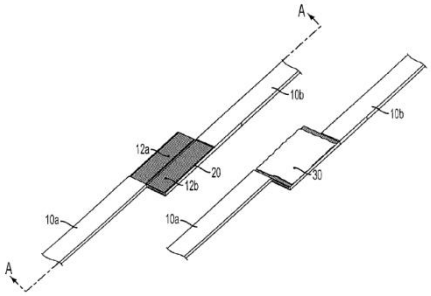
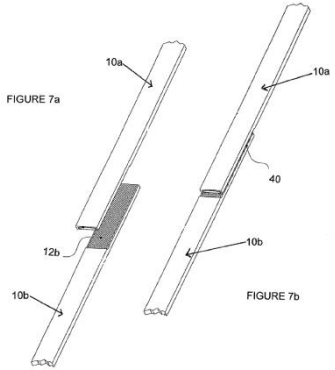
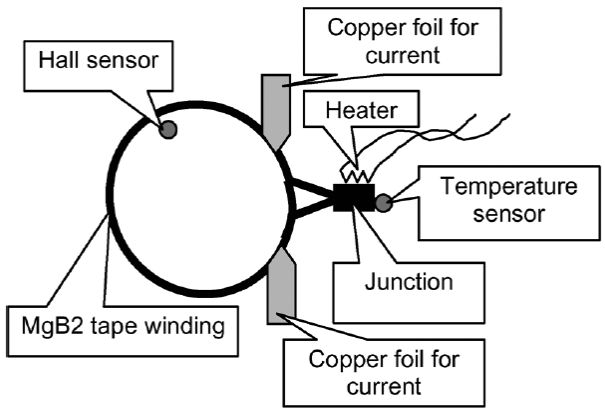


FIG. 6a FIG. 6b

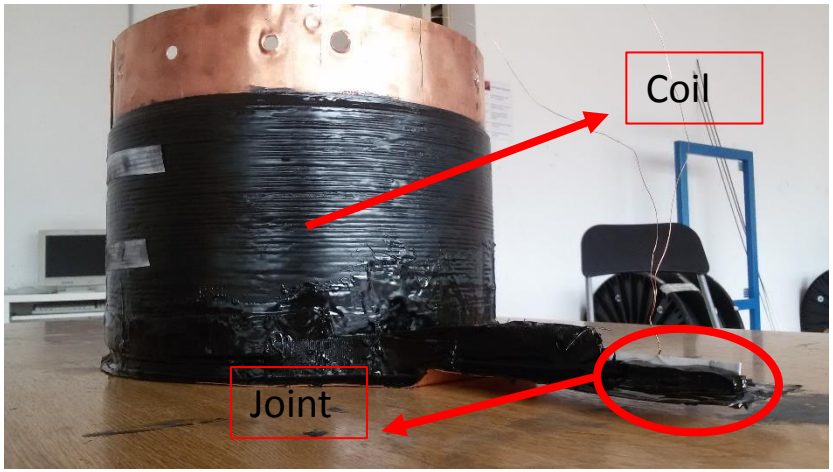
Overlapping SC joint



Superconducting joint



Development of superconducting joint on MRI wire.
More than 30 single-joint samples realized with Ip/Ic > 50%, with total resistance of < 10-14 Ohm.



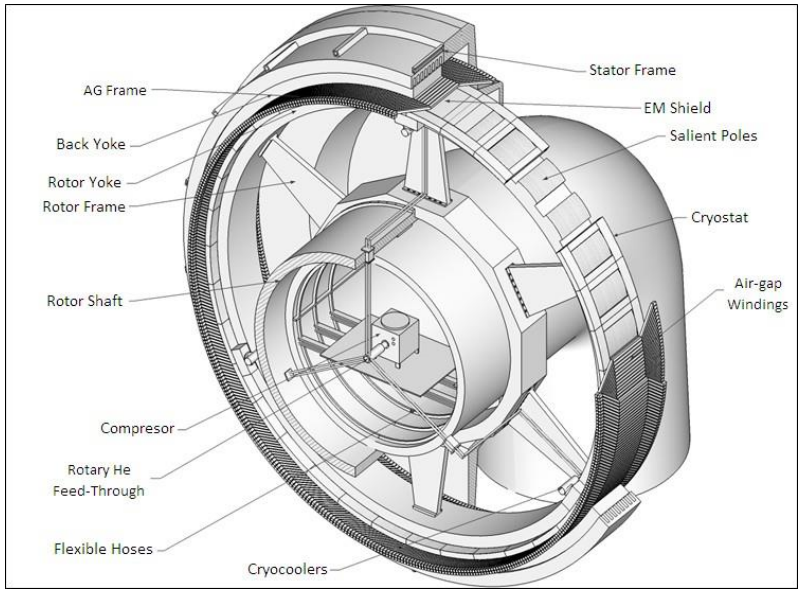
Recently built and measured a 200m long coil with single joint.
At **15 Kelvin** reached:
280 Ampere in Persistent Mode (I.E. < 10-14 Ohm)
0,3 Tesla on inner surface
0,2 Tesla in the center of coil.

NEXT STEP:
1Km long magnet with switch device
UNDER CONSTRUCTION with ASG Superconductors

suprapower

Superconducting light generator for large offshore wind turbines

This project has received funding from European Union's FP7 Programme, under grant agreement No 308793



SC wind generator according to TECNALIA's concept (EP2521252A1)

The aim is to develop a new concept of innovative, lightweight, robust and reliable superconducting

10MW offshore wind turbine generator

Validation of generator concept through a scale machine (coils and cryostat at real scale)

tecnalia Inspiring Business

2013	2014	2015	2016
MgB2 wire design, characterization and Manufacture	First MgB2 coil construction and test	Full scale generator design and integration	Scale machine Validation
Cryostat Concept Design	Scale machine Design	Cryostat first module test	Industrialization Studies
	Rotary joint	Scale machine construction	Business Plan

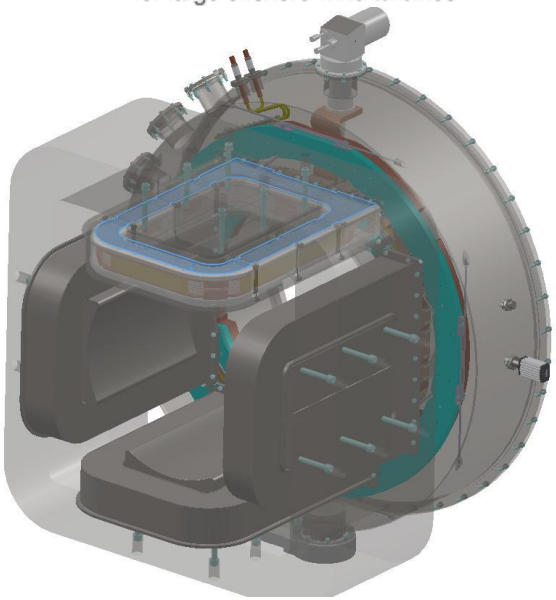
Suprapower: objectives and partners at the beginning

suprapower

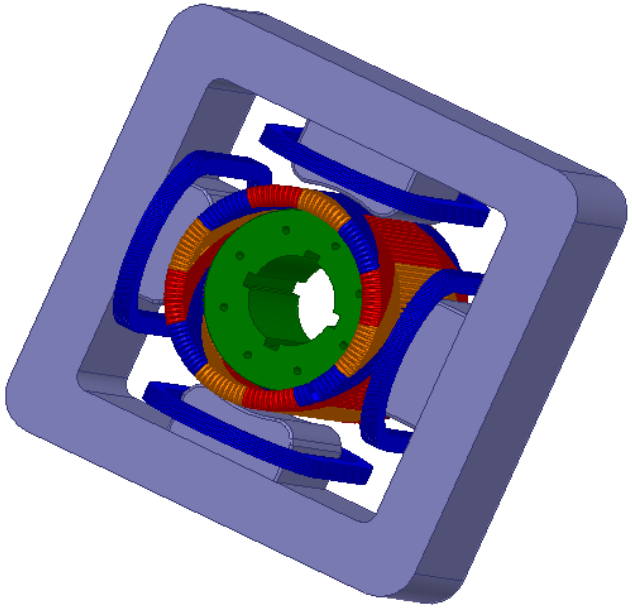
Superconducting light generator
for large offshore wind turbines

This project has received funding from
European Union's FP7 Programme,
under grant agreement No 308793

Double pancakes MgB2 coils of the scale machine
Source: Tecnalia



Scaled machine cryostat design
Source: TECNALIA



Scaled generator
Source: TECNALIA

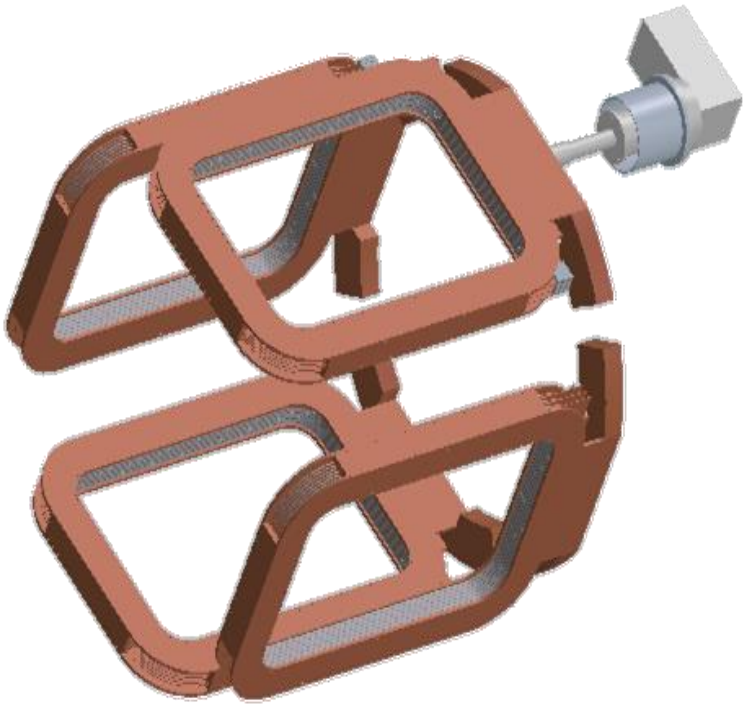
Suprapower: field coil

Columbus Superconductors

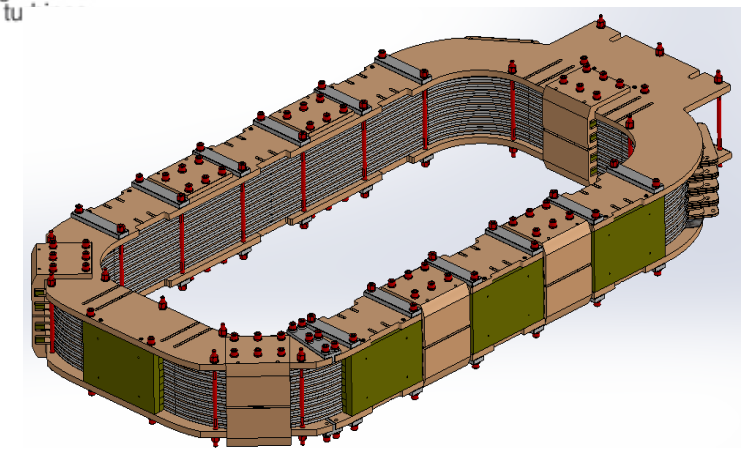
suprapower

Superconducting light generator for large offshore wind tu

This project has received funding from European Union's FP7 Programme, under grant agreement No 308793

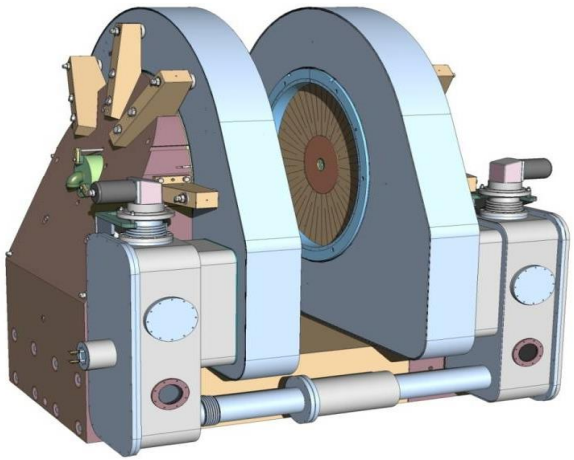


Double pancakes MgB2 coils of the scale machine
Source: Tecnalia



Coil	Stack of racetrack DPs
Number of DPs	9
Number of copper caps	2
Thickness of copper cap	8 mm
Insulation layers between DPs	G11
Insulation layer thickness	0.2 mm
Total thickness stack	~77.6 mm
Coil radius (curved parts coil ends) inner/outer	100 mm / 165 mm
Total thickness	~93.6 mm
Straight side length end parts	185
Straight side body	622
Total Wire length	~ 3200 m

Industrial production



Main Magnet Parameters	
Nominal Field	0.5 T
Peak Field on the Conductor	1.3 T
Nominal Current	90 A
Conductor critical current	400 A
Conductor price (€/kAm) at 20 K, 1 T	< 7
Number of Pancakes	12
Conductor Length (total)	18 Km
Inductance	60 H
Overall Dimensions	2x2x2.4 m
Patient Available Gap	0.6 m

MRopen

Columbus Superconductors
ASG Superconductors
PARAmed MEDICAL SYSTEMS

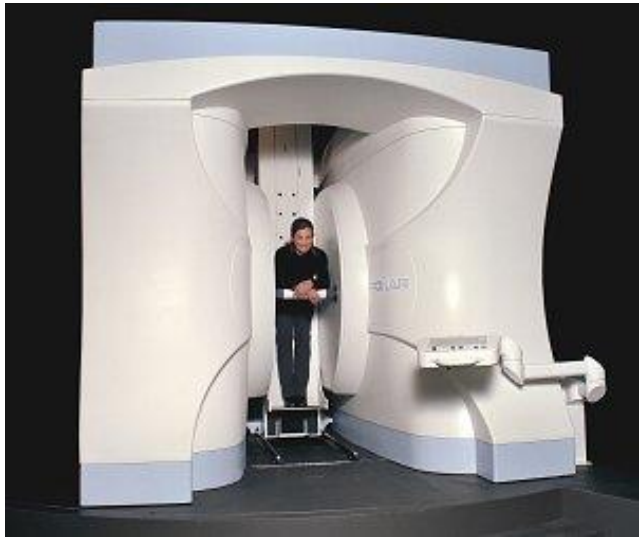
Unique **fully dry** superconducting MRI system
Unique superconducting open-sky MRI system currently on the market

No liquid helium required

Also highly suitable for r**emote installation** because electricity is the only requirement to setup/start/run the system

Copper wires Vs Superconducting wires

MR with conventional magnet (FONAR)



- 200 Tons
- 200 KW

MR with MgB2 coil (PARAMED)

- 25 Tons
- 16 KW

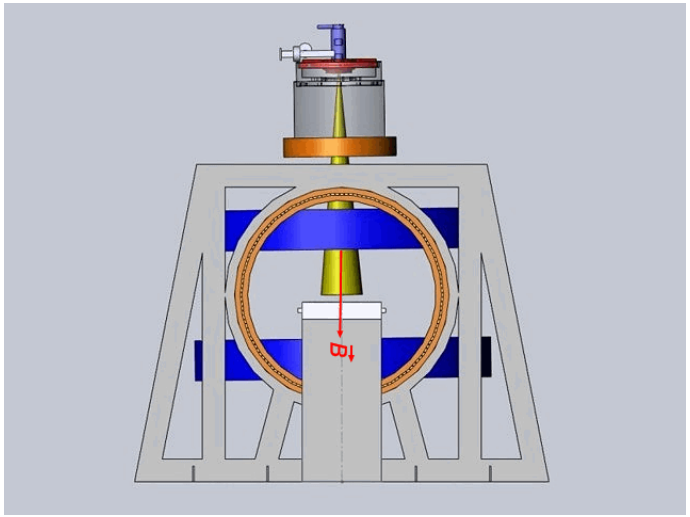
The next step will be to implement our new MgB_2 superconducting technology in the broad whole body market thanks to the following key factors:

- Easier operation than other superconductors
- Higher stability than other superconductors (due to the highrt temperature margin)
- Cost comparable to the actual solution

Liquid helium-free MgB_2 technology will be of particular attractiveness for installation in remote areas where the supply and handling of a cryogenics liquid is highly problematic

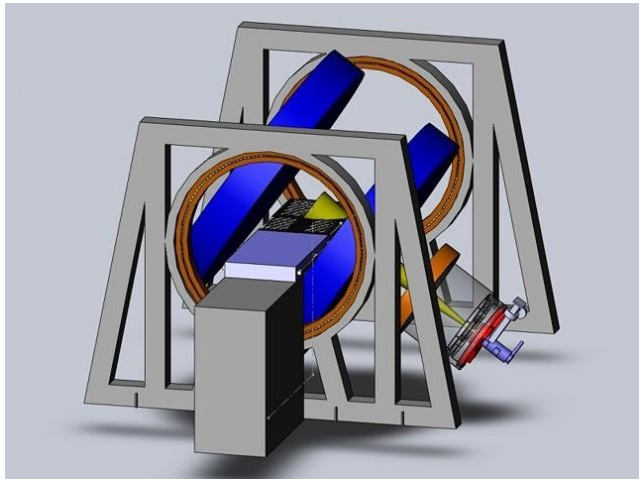
Hybrid Linac MRI System

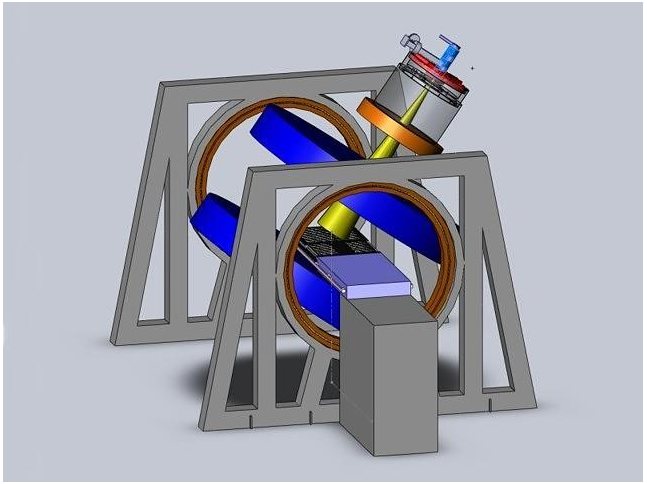
New prototype machine at the Cross Cancer Institute, Edmonton, Alberta-Canada



The linac-MR consists of a LINAC
that rotates in-unison with the biplanar 0.5 T MRI in transverse plane.
The MRI's Bo field and the central axis of the 6 MV beam are parallel to each other.
This parallel configuration avoids large increases in dose at tissue/air interfaces and at beam exit

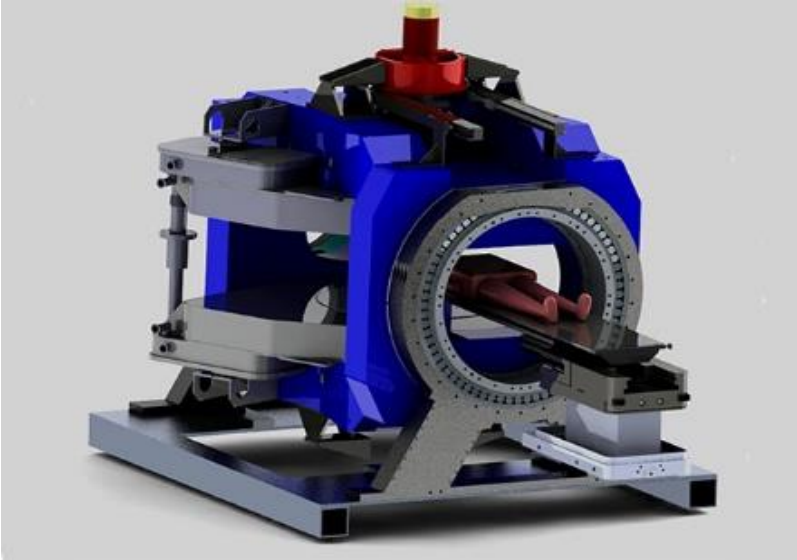
The open configuration of the systems allows real-time MRI guided radiotherapy of all tumors including peripheral tumours (eg, in breast, etc) with imaging and treatment performed concurrently.

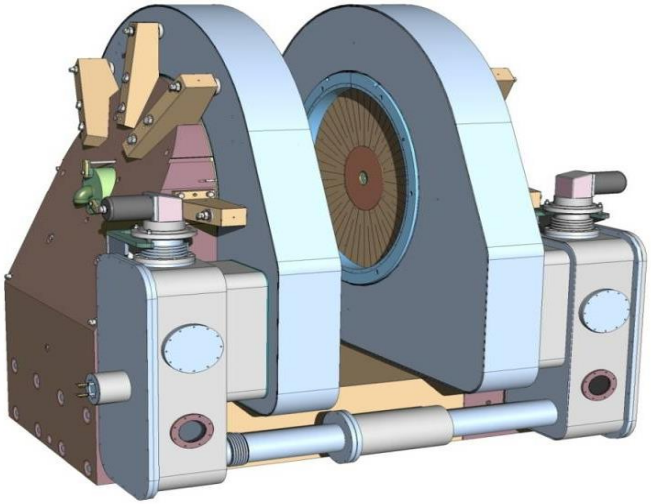


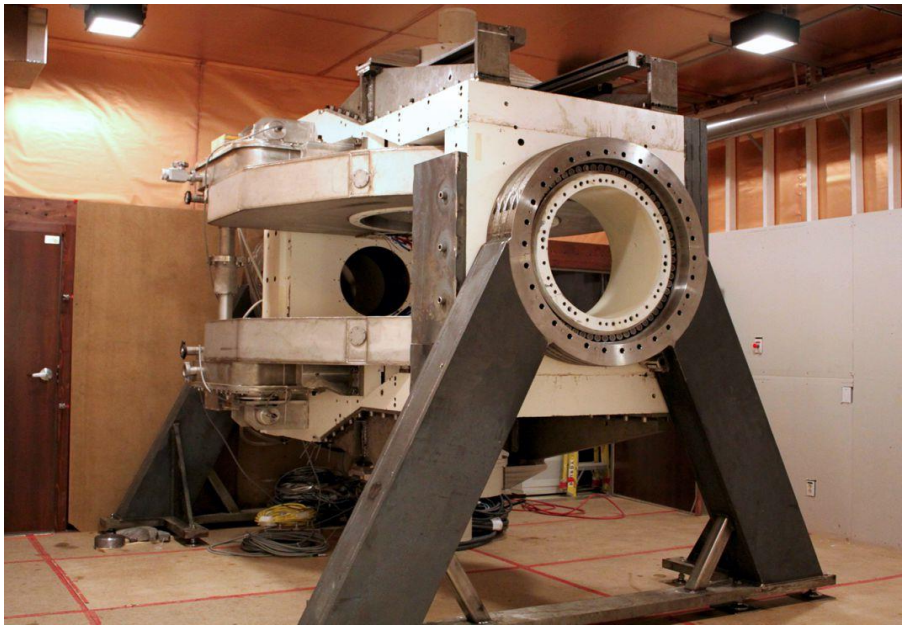


http://www.mp.med.ualberta.ca/linac-mr/

Hybrid Linac MRI System







- cryogen-free superconducting magnet not requiring a helium vent
- Possibility to turn to turn magnet off or on in a few minutes for servicing
- possibility to rotate the charged magnet

- provides high-quality MR images during irradiation
- 6 MV Linac
- can treat all tumours, including peripheral tumors (eg, in the breast)

Final remarks

MgB_2 is a new technology in comparison to the other technical SC but has been already implemented with excellent results in several prototype devices and in industrial products:

- long record of fully tested and qualified wires

- world record current in a SC at CERN
- challenging application in the framework of the High Luminosity LHC project for the development of SC link

- demonstrative activities in rotating machine (generator for a wind power application)

Medical devices:

- more than 20 magnet working in MRI MrOpen medical system
- new prototype hybrid LINAC-MRI system
- exploring the whole body MRI market

- ……. SC Gantry?

MRI machine

Paramed image

Siemens image

- The progress in MRIs is strongly linked to the creation of new devices with always-stronger fields

- Stronger the **magnetic field**
- Stronger the signal
- Better the images

- The main magnetic field is created by a large superconducting electromagnet in which a current flows

- The weak resistance of superconductors allows very strong currents to flow with **no heating in the material**, and hence enables to get very high field values of several teslas.

This project has received funding from European Union's FP7 Programme, under grant agreement No 313224

SR2S
Space Radiation Superconducting Shield

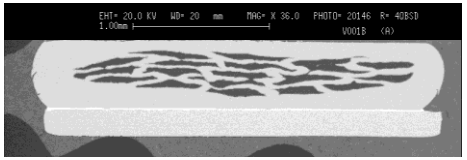
The aim of the project is to develop, validate and increase the Technology Readiness Level (TRL) of the most critical technologies related to a **magnetic shielding system** for protecting astronauts' lives during long duration space missions.

Active shielding

↓

Static magnetic field using a SC coil

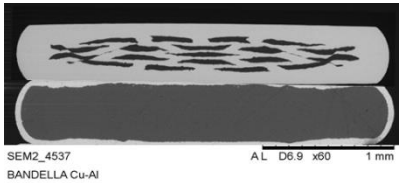
How can we reduce the averall weight for reducing the launching load?



FROM:

3x0,5 nickel clad wire

3x0,2 copper stabilization



TO:

3x0,5 titanium clad wire

3x0,5 alluminum stabilization

FROM 17grams TO 10.2 grams,

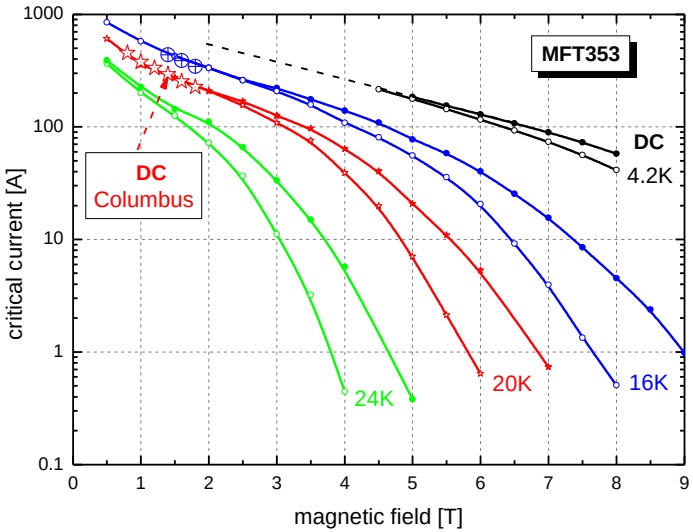
40% weight reduction

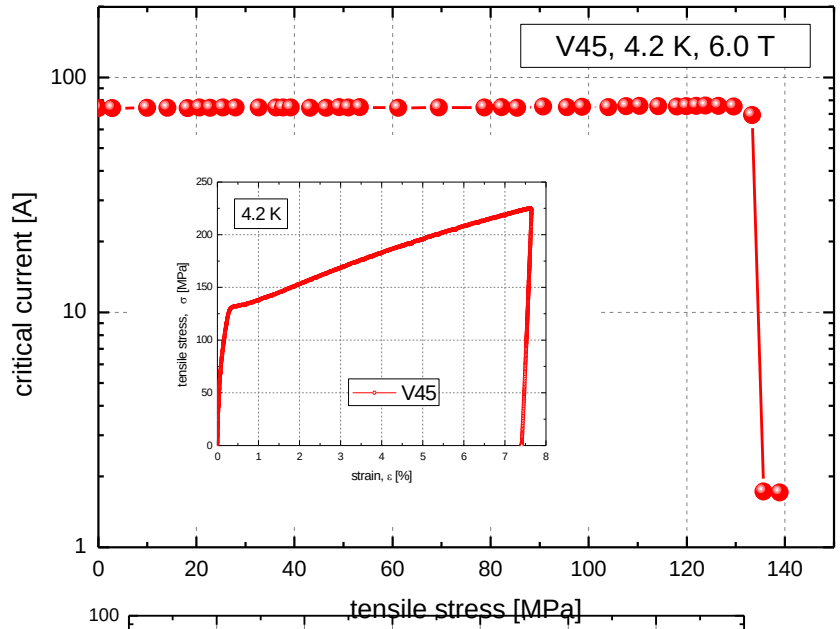
INFN CERN Columbus Superconductors cea ThalesAlenia Space OHB CGS Carr Communications

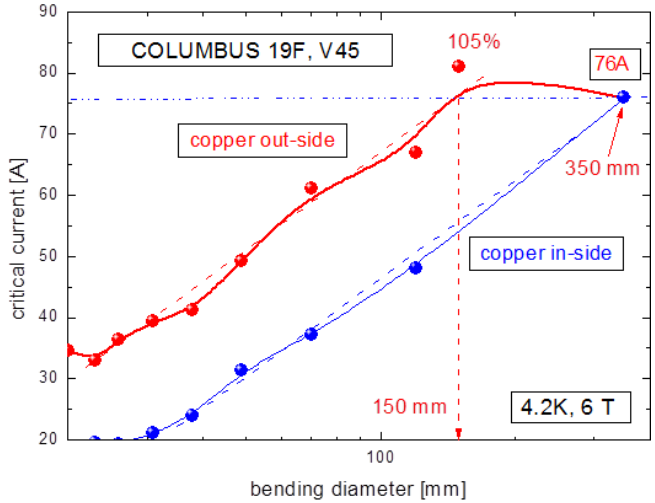
Electro-mechanical characterization

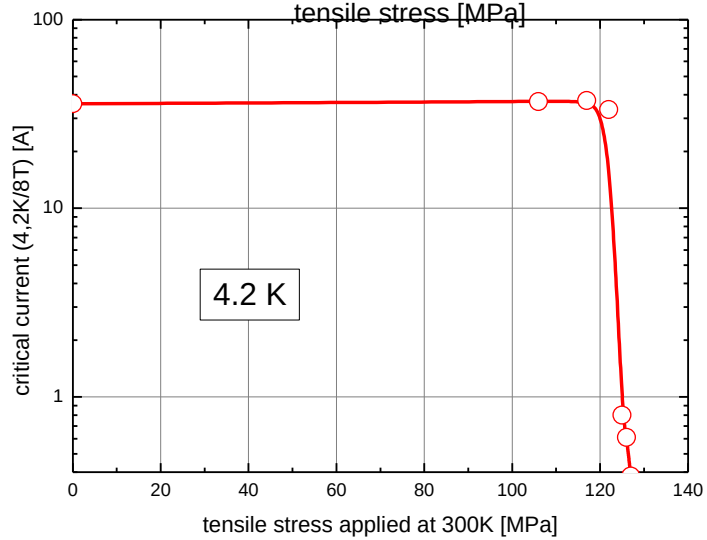
Electro-mechanical characterization performed at
Institute of Electrical Engineering,
Slovak Academy of Sciences Bratislava, Slovakia
Courtesy of P.Kovac

Properties related to the operations
and to the implementation are required by costumers

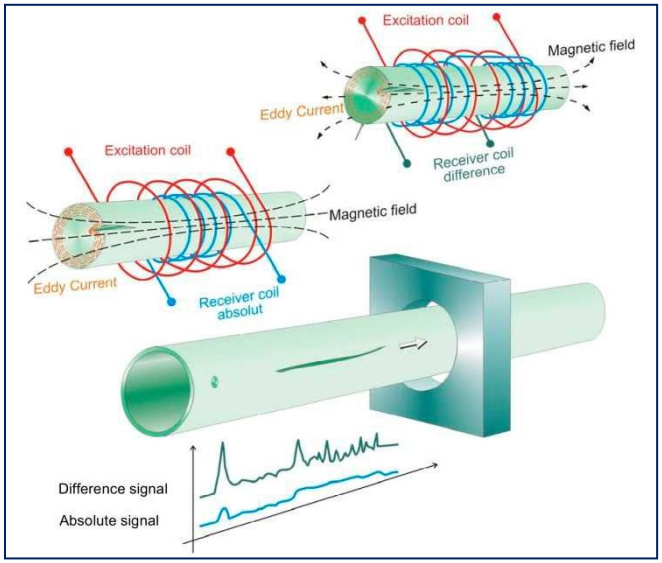


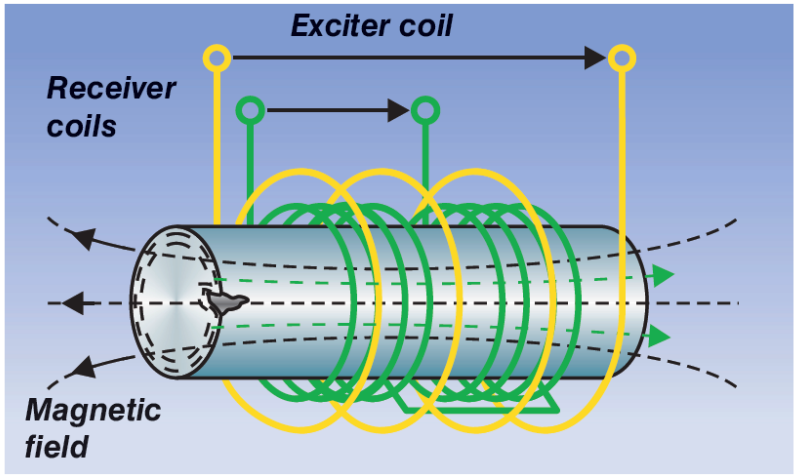




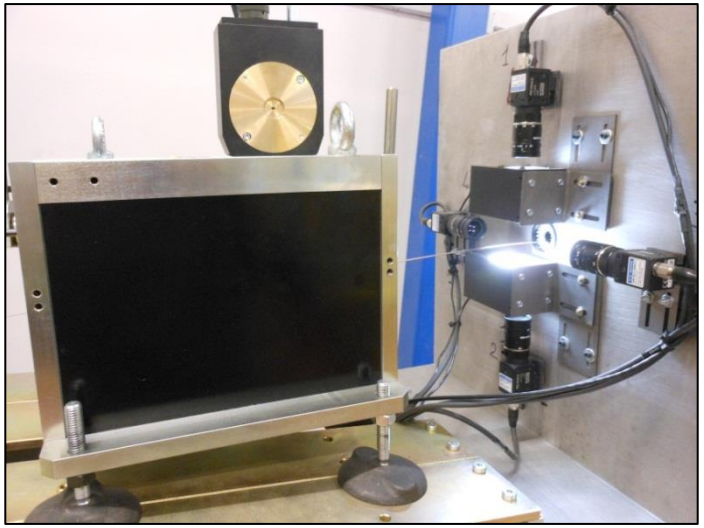


Eddy currents detector





The differential through-type coil detects hole flaws and transverse flaws in addition to longitudinal flaws on the basis of their depth gradient.



It's possible to operate with

- Frequency
- Gain
- Filter
- Threshold

Results are the absolute value and phase along the wire from detectors:

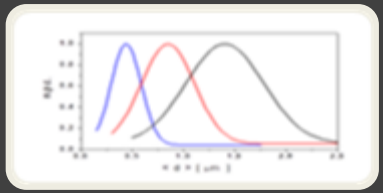
DF1: 10 KHz (inner defects)
DF2: 60 KHz (outer or superficial defects)

Columbus Superconductors

Essentials of wire improvement plan

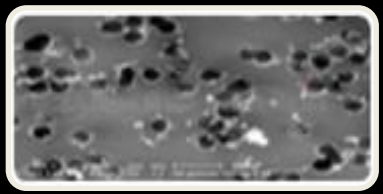
Boron

- Boron of higher quality than presently used (99% and + compared to 95% of today) is known to allow for 50-100% performance improvement
- A source of reasonably priced 99% pure Boron is under advanced evaluation, and shall be implemented in some wires during H2 2013



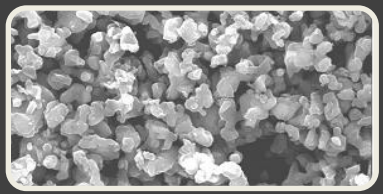
Particle size control

- Control of particle size is fundamental to achieve high MgB_2 density, and increase in-field performance
- Although R&D techniques have led to successful results, industrial methods need to be identified and introduced (expected in 2014 on mass production)



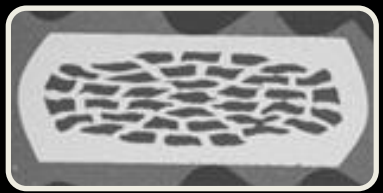
MgB_2 doping

- So far, MgB_2 doping in Columbus has been optimized for wire performance at 12-20 Kelvin, 2-4 Tesla
- Optimal Carbon doping concentration (2-5%) and vehicles for it will be introduced in production wires during H1 2014
- Complex Carbon sources with combined effects (boron AND substitution) will be implemented within H2 2014 to enhance in-field properties without depressing T_c



Connectivity

- Lack of MgB_2 density, lack of texture and impurities at grain boundaries as a consequence of Boron impurities and oxygen contamination are limiting the connectivity
- Higher MgB_2 density in final wire, and more clean MgB_2 powders thanks to the new system for their handling and treatment in controlled atmosphere will increase connectivity further during 2015



Superconductor filling factor

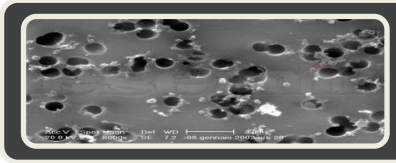
- The know-how learned from several years of industrial MgB_2 wire processing will help us pushing the superconductor to matrix ratio much higher than toay
- Increasing the active fraction of the superconducting wire is essential – trials to reach 40% at R&D level were already successful – stable results over long lengths are expected in production wires from 2015

Columbus Superconductors

Essentials of cost reduction plan

Boron

- Boron is currently the most important key-element to balance cost / performance ratio of MgB_2 wires
- Today Columbus is employing industrial grade 95% pure Boron in its production wires to minimize cost impact & have access to large suppliers



Doping Source

- Doping is achieved by nanoparticles additions of carbon-containing phases (graphite, SiC, diamond, etc)
- Although being special products, our doping approach limits their use to low-cost carbon sources and in concentration below 5 %, diluting the impact on wire cost at the moment

Nickel alloy tubes

- It is the most important raw material cost today – western suppliers are still privileged in order to guarantee the quality of supply – we currently pay this approach with an extra cost of 400% with respect to the nickel LME price – target is to bring it below 200%
- A different long term strategy is under development with increasing volumes,by selecting lower-cost suppliers of sufficient reliability

Mechanical Processing (cold working)

- The new production line for significant wire quantities (>3'000 Km/y) has been completed and put in operation successfully
- Further dedicated investments will be put in place in order to be able to exceed 5'000 Km/y beyond 2015 – single piece unit lengths exceeding 10 Km will be implemented for every wire format already within 2014

Heat Treatments

- Furnaces for MgB_2 synthesis, wire annealing during cold working, and final wire sintering have sufficient capacity and reliability
- Optimization of the thermal processes (large batches, cheaper gas atmospheres, shorter cycles) will minimize gas and power bills

Quality assurance tests

- Significant investment on QA technology already in place (SEM, XRD, lasers, eddy currents, particle size analyzers, cameras, etc)
- A strategy for systematic critical current measurements with faster data acquisition, less manpower, will be implemented

Team training

- Manpower in the production dept are currently going through intensive training on material processing and handling
- Manpower efficiency will dramatically improve in 2013-2015 once the new workforce skills will reach our standards