Alternative Superconducting Magnets
Energy Saving Solutions for Beam Line Magnets

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iFAST
UNIONE EUROPEA
Fondo Sociale Europeo
Ministero dell'Università e della Ricerca
PON
RICERCA E INNOVAZIONE
2014 - 2020

Problem: High Power Dissipation

Large Energy Consumption in Accelerator Facilities (hadron especially)

Revamping existing beamline magnets?

«Study of new cryogen-free superferric magnets in MgB_2 (and HTS) to substitude resistive magnet for heavy particles beam lines»

↓

Reduce from 10 to 50 times the peak power loss of resistive magnets

Energy saving factor 3 to 4, working @ T= 8-20 K with solid conduction cooling

NA62-CERN-PH SPS north area

MNP33-2016:
7560 MWh
378 kCHF/year

SM2-2016:
6953 MWh
348 kCHF /year

Courtesy: Philip Schwarz, CERN

4 Possible paths to be studied…

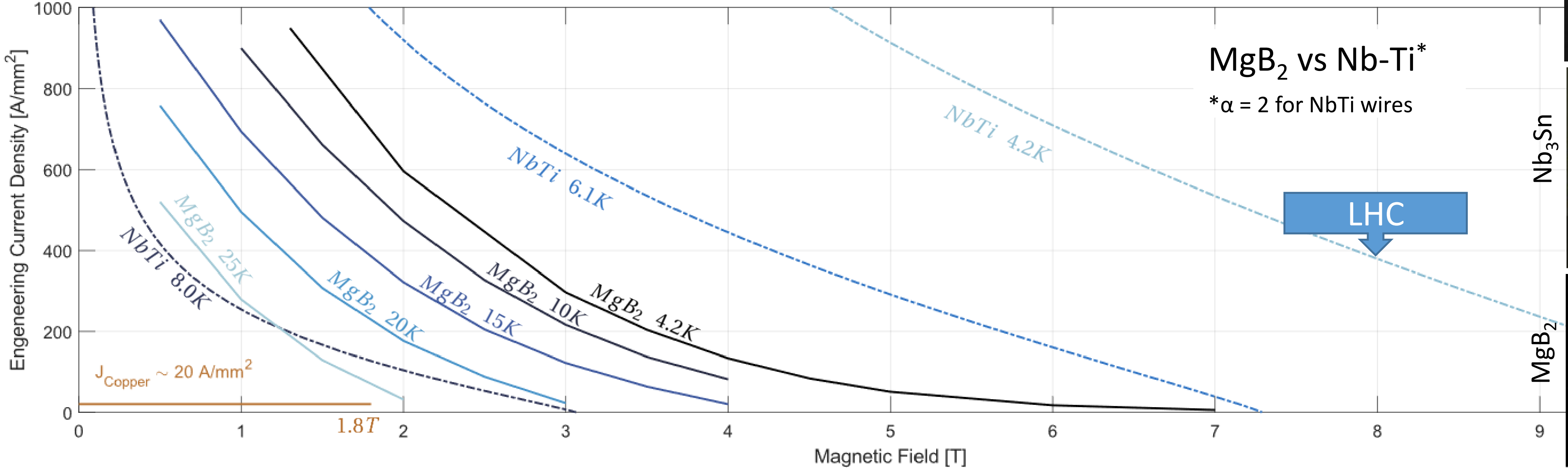
1. Revamping → reuse the same iron yoke and magnet interfaces
   - Substitute copper coil, only, with MgB_2 (or HTS conductors)

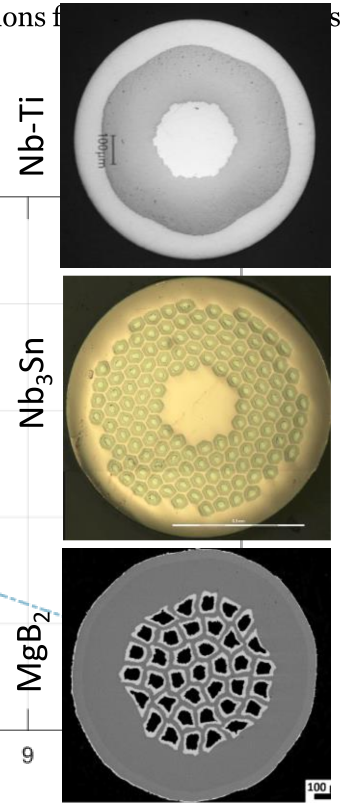
2. Develop superferric magnets for accelerators and beamlines suitable designed and optimized for low power consumption
   - Possibility to exploit coil dominated configurations

3. Design of optimized solutions for HTS/Hybrid magnets to achieve high fields with low power consumptions

4. New beamline magnet (RCSM)

Superconductors @ Cryogenic Temp

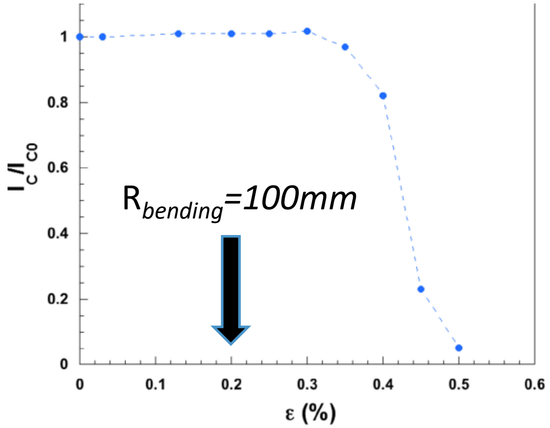




- Modern superconducting magnets are made with Nb-Ti/Nb_3Sn and work at cryogenic temperatures (LHe T≤ 4.2 K)
- Competitors (especially at T>10 K) are MgB_2 and HTS

Why MgB2 over HTS?

Round Wire, Easy winding and cabling, Low cost



Strain Sensitivity

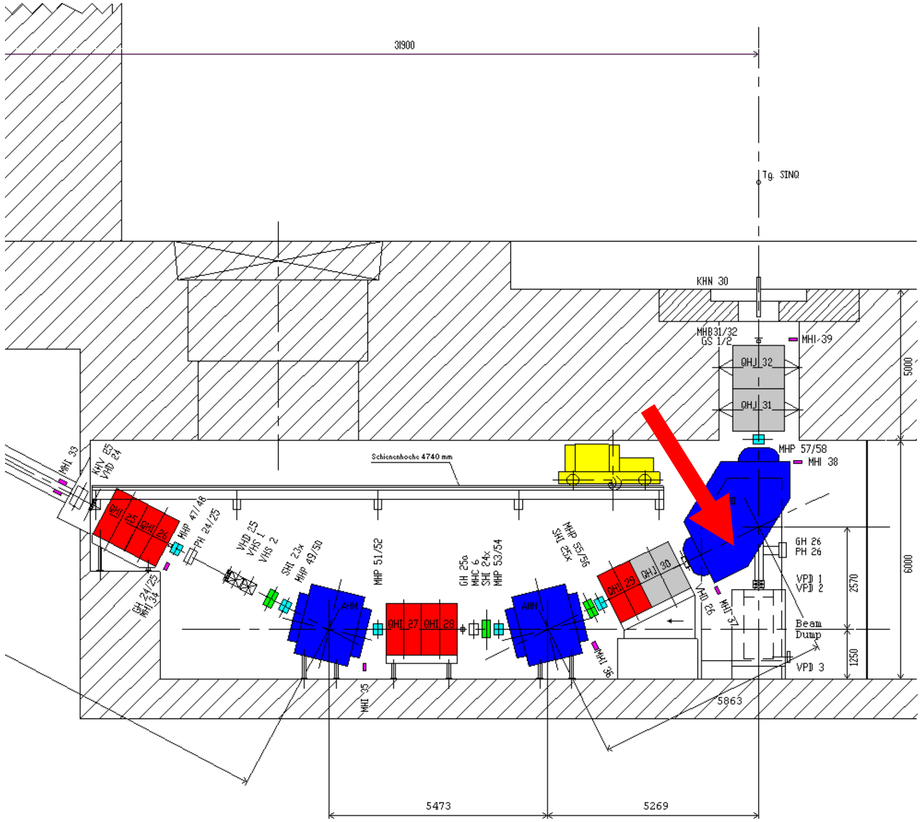
Beam Lines dipoles: AHO Magnet

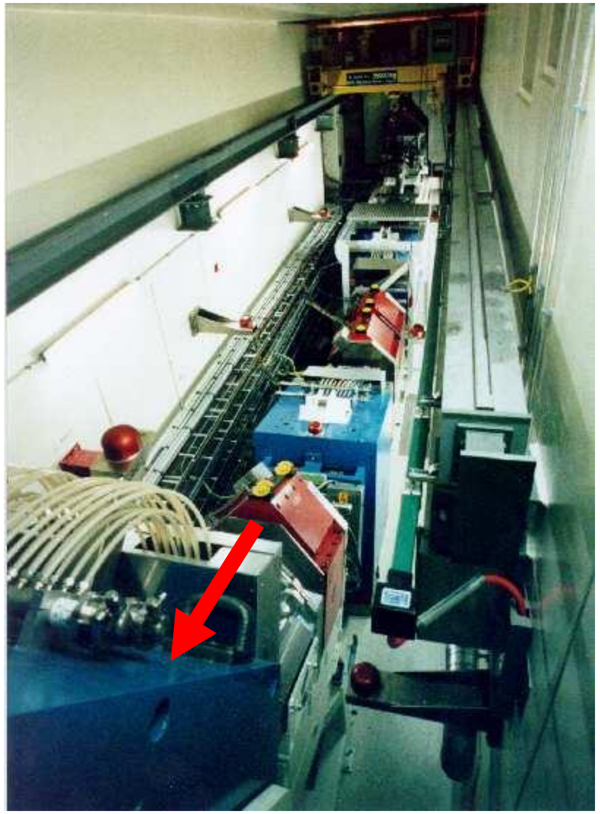
- Originally a switching magnet, actually a bending unit, just before SINQ (Spallation source);
- 50 tons magnet, giving 1.45 T on 2.780 m radius for 64 deg. Power required with cooling 190 kW;
- SINQ runs continuously mid-May to mid-Dec.

MAGNET PARAMETERS

	AHO
Air Gap	100 mm
Max. Current	1000 A
Max. Voltage	95 V
Max. Power	95 kW
R @ 20°C	83 mΩ
Cond. Dimensions	18.5×18.5 mm
Cooling Channel Diam.	11.5 mm
Water Flow	60 l/min
Pressure drop	8 bar
T Rise	23°C
Turns	144

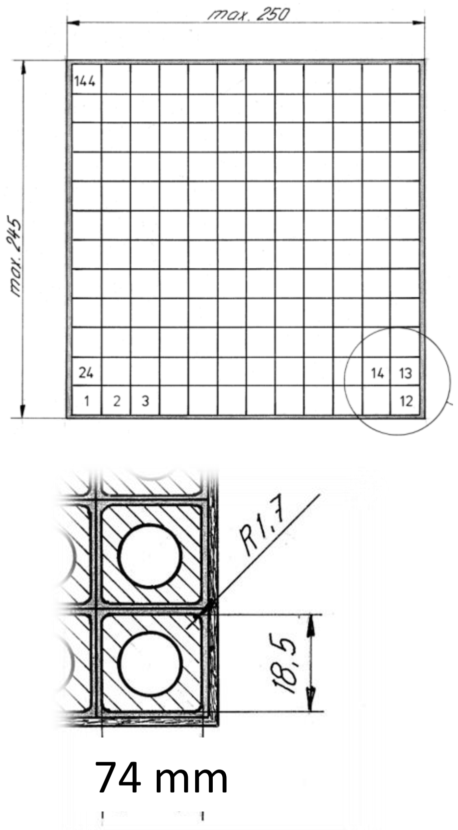
715 MWh per year

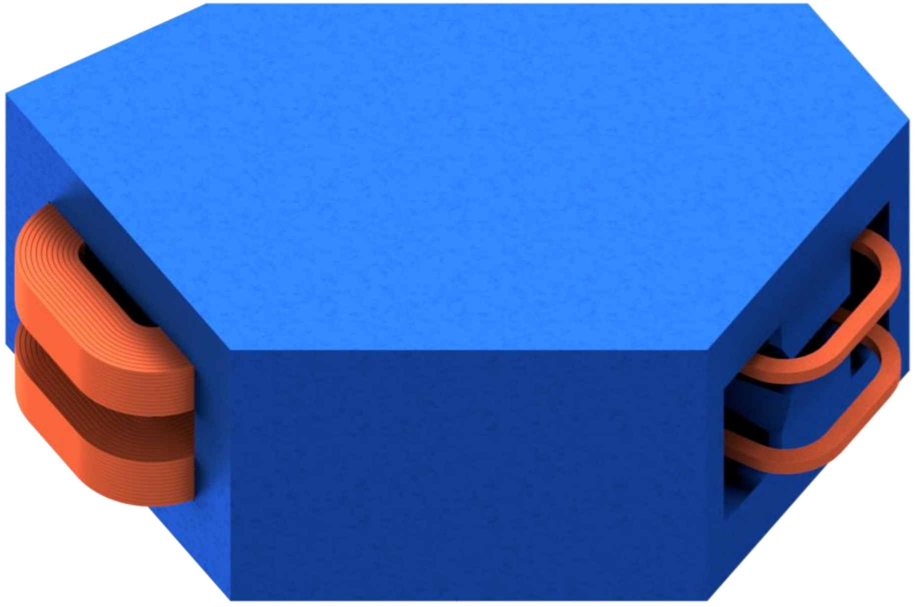




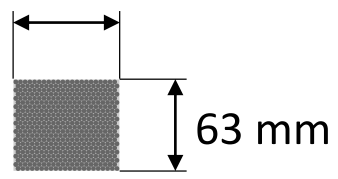
Electromagnetic Design

- Iron-dominated magnet with 1.45 T at magnet center. The field quality is given by the yoke poles, while the coil has the function of magnetizing it. Updated magnet maintains the same $N \times I$ (144×1000 A).
- The superconducting cable is made by a rope with 4 MgB_2 conductors and 3 high-purity copper wires. Each rope carries 300 A, so that 484 turns are needed.

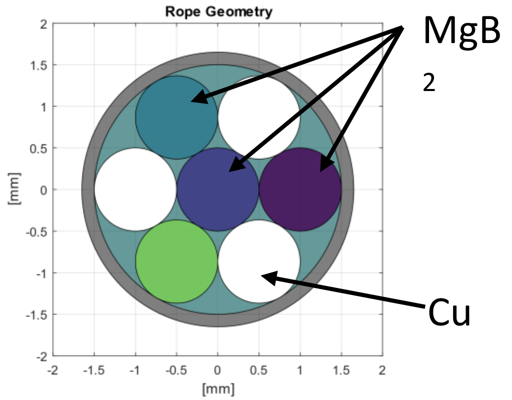




Courtesy: Stefano Sorti, UNIMI

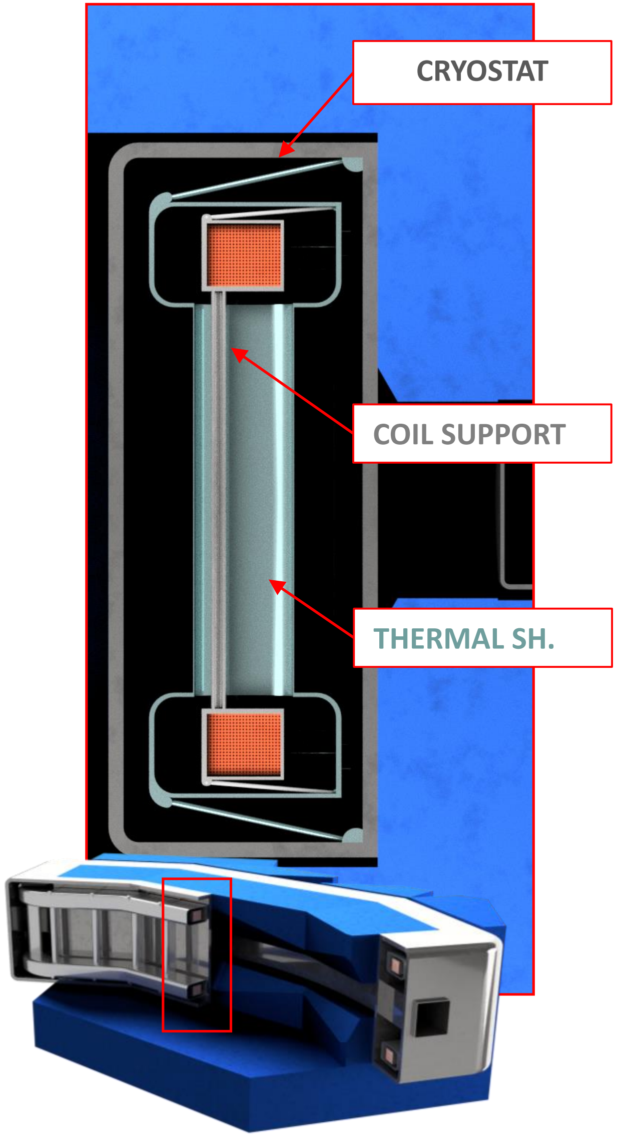


In scale with resistive coil drawing on the left

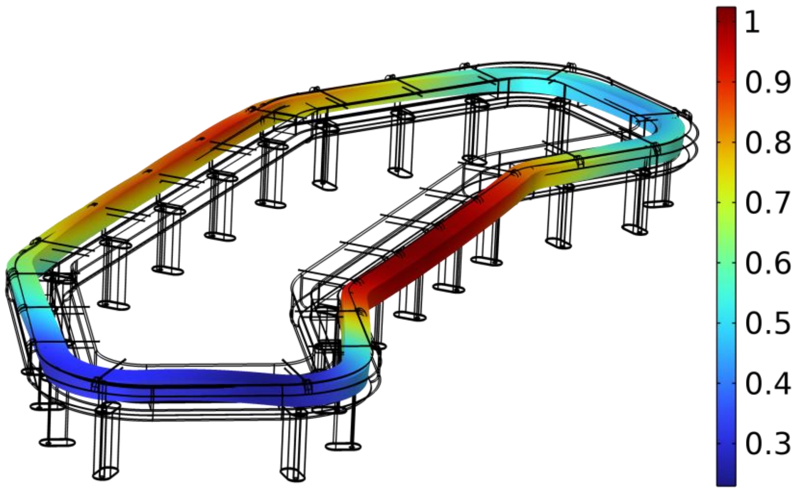


Mechanical Structure

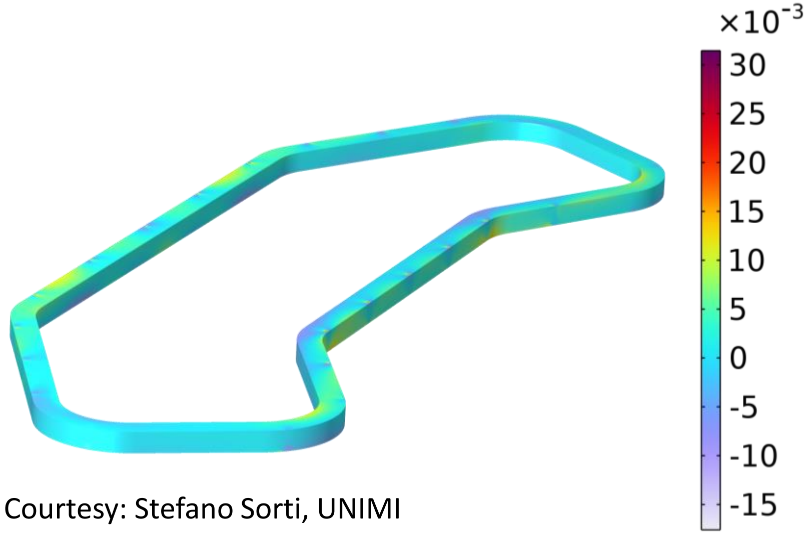
- The first layer of mechanics is a 3-mm-thick **collar** to contain coil deformations.
- To support the coil a distributed set of tie-rods is adopted.
- The same **tie-rods** concept is adopted to sustain an active thermal shield (70 K) within the cryostat covered with MLI to reduce the radiation power.
- Collar and rods are in stainless steel 316LN. Thermal shield is Aluminium 6063 working at 70 K.



Coil Displacement [mm]



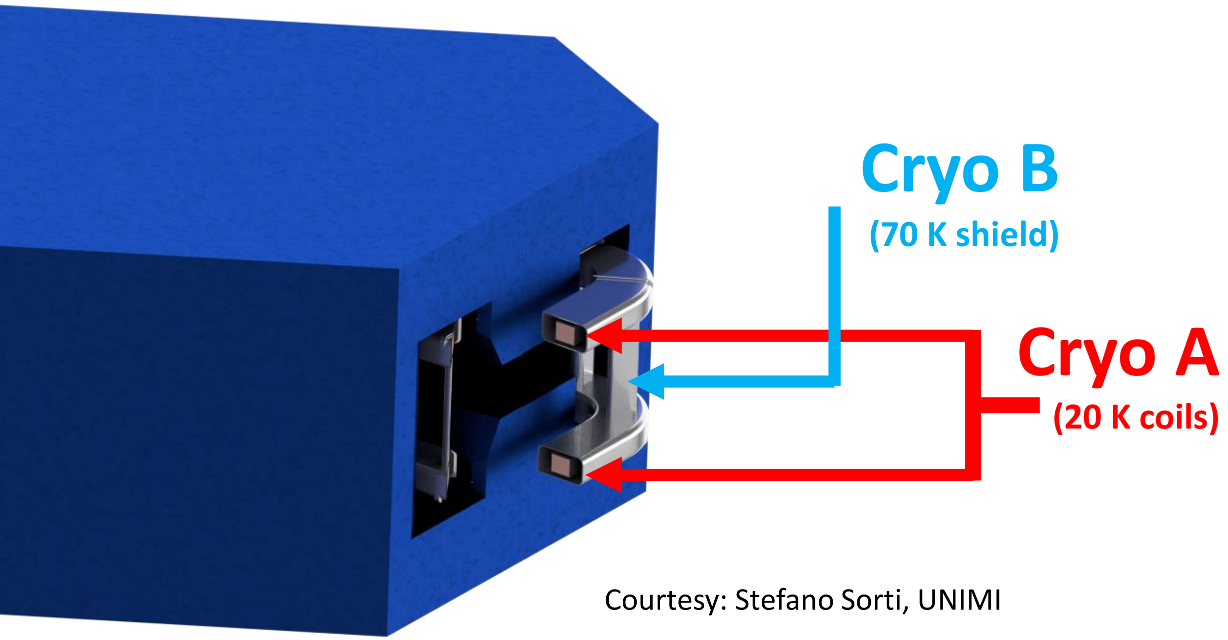
Principal strain 1 (%)



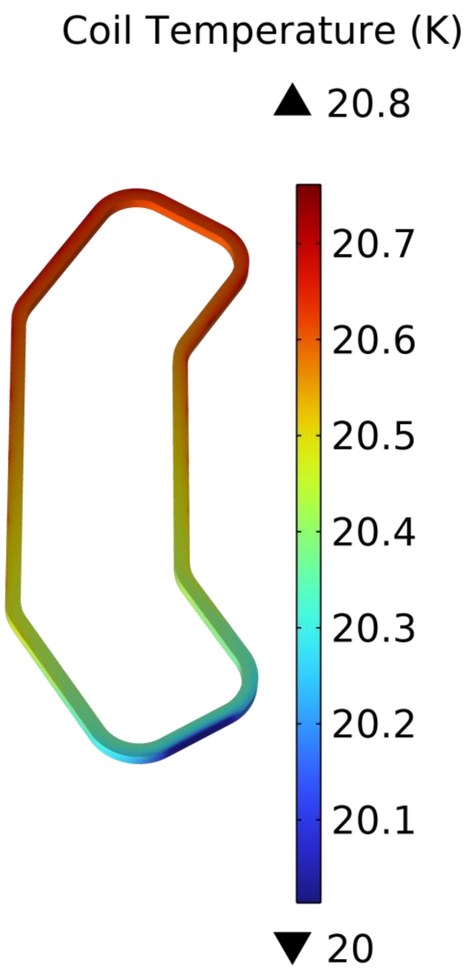
Courtesy: Stefano Sorti, UNIMI

Thermal Analysis

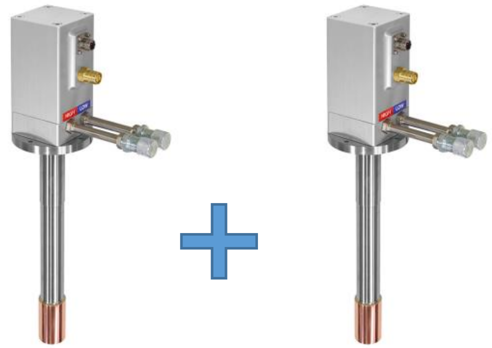
- We assume to cool both the coils and the shield from one side with **Thermal shield (8** mm thick) made by Aluminium 6063 and HTS link from the thermal shield to the coil
- A **zero-order plant** is proposed to estimate total the power consumption, resulting in a total of **5 kW for the entire magnet**.



Courtesy: Stefano Sorti, UNIMI



MAGNET	Coils At 20 K	Shield At 70 K
Q support [W]	1.35	12
Q Current Leads [W]	0.2	24
Q radiation [W]	0.45	11
Q tot [W]	2	47



A: Cryomech Al63
5W @ 20K
P = 3.2 kW

B: Cryomech Al60
47W @ 70K
P = 1.7 kW

Obtained Scaling Factor ≅ 40

Beam Lines dipoles: AHC Magnet

- Main 37.4° bending magnet for one of the 590 MeV lines;
- The magnet provide 1.64 T on 2.451 m radius
- Runs continuously mid-May to mid-Dec

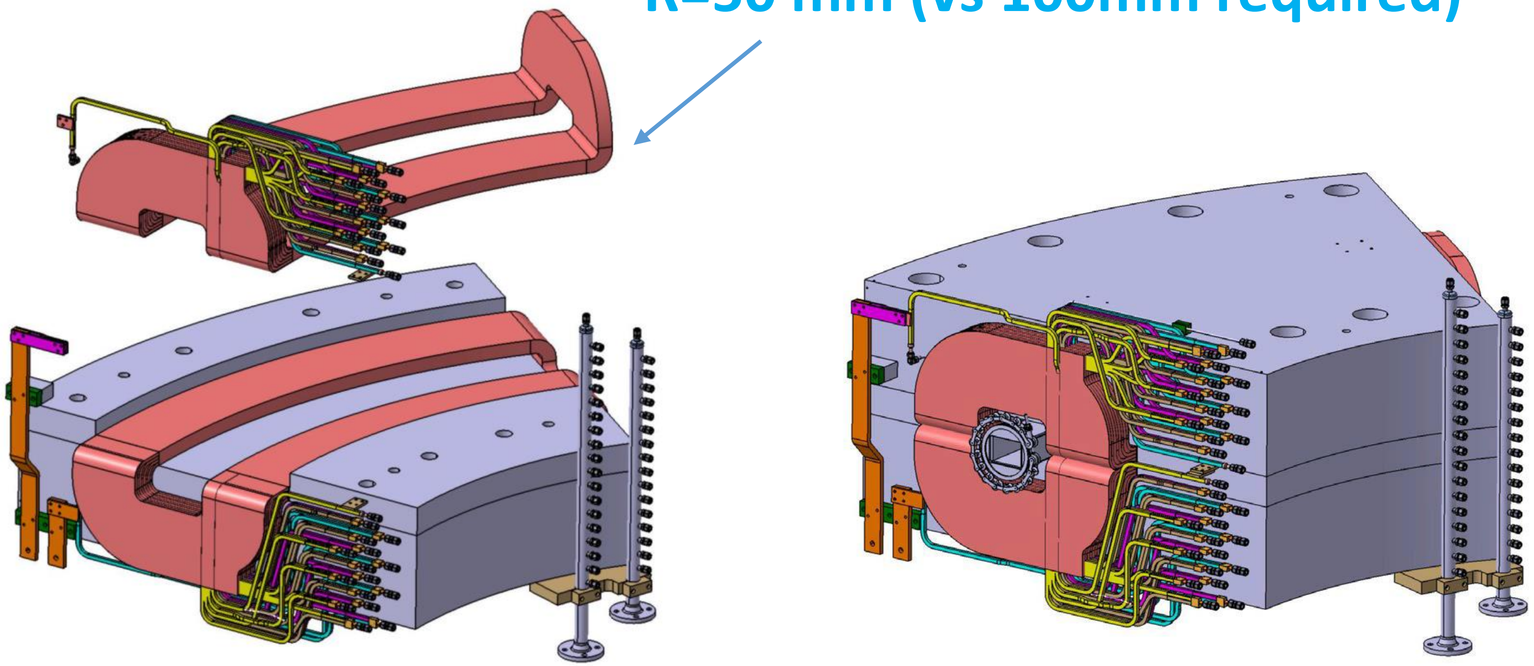
PARAMETERS
MAGNET PARAMETERS

	AHC
Air Gap	100 mm
Max. Current	970 A
Max. Voltage	63.5 V
Max. Power	61.6 kW
R @ 20°C	73 mΩ
Cond. Dimensions	12×11 mm
Cooling Channel Diam.	7 mm
Water Flow	35 l/min
Pressure drop	6 bar
T Rise	23°C
Turns	76

560 MWh per year

Working in Progress

Coil Geometry may not meet MgB_2 bending radius requirement R=50 mm (vs 100mm required)

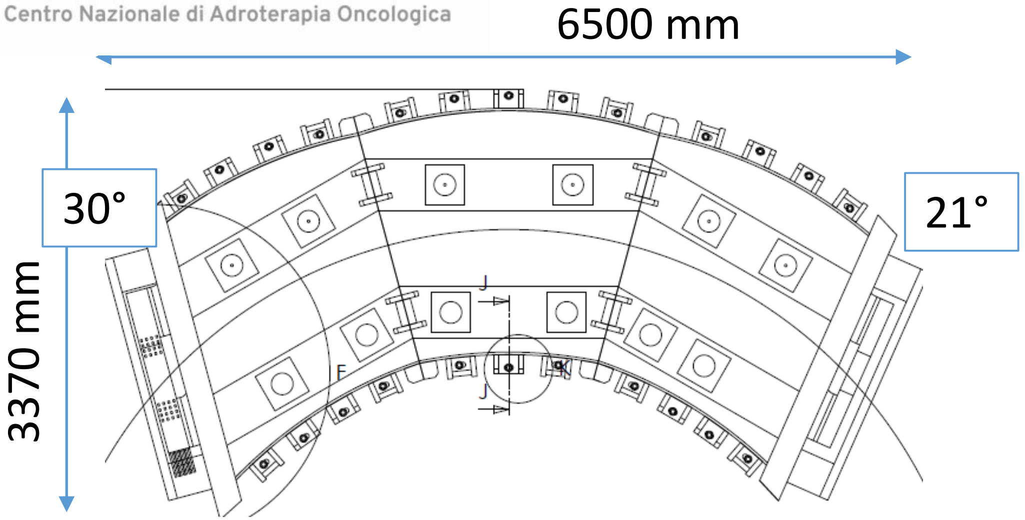


Hadron Therapy Applications
CNAO 90° Dipole

CNAO Centro Nazionale di Adroterapia Oncologica

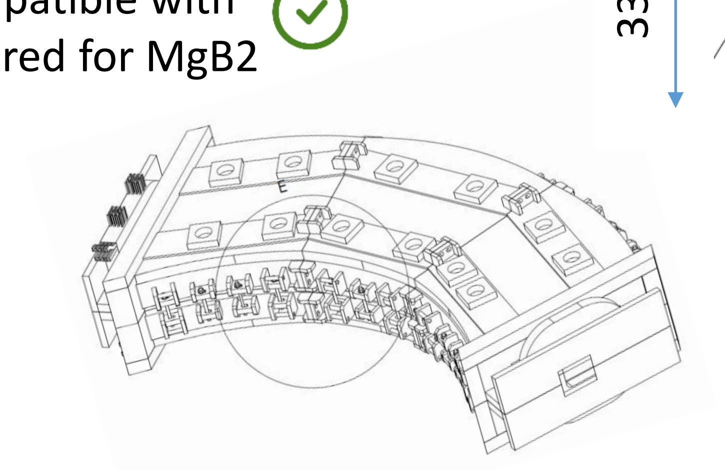
Dipolar «Window-Frame» Bending Magnets
Possible Candidate for the superconducting MgB_2 conversion currently installed at CNAO

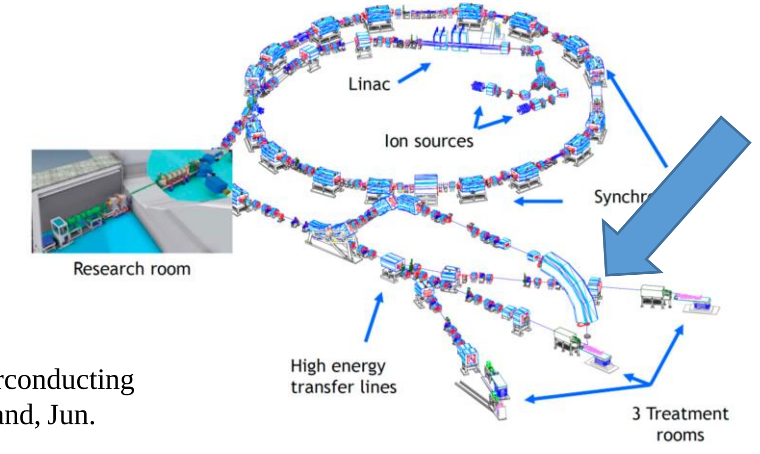
Dimensions of the coil are compatible with minimum bending radius required for MgB2



MAGNET PARAMETERS

Nominal Current	2280 A
Min Current	380 A
Nominal Field	1.74 T
Magnetic Lenght	5740 mm
Entrance Angle	30°C
Exit Angle	21°C
Field Homogenity	2 units
Maximum Power	700 kW





G. Bisoffi *et al.*, “Energy Comparisonof Room Temperature and Superconducting Synchrotrons for HadronTherapy”, in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 3080-3083.doi:10.18429/JACoW-IPAC2022-THPOMS049

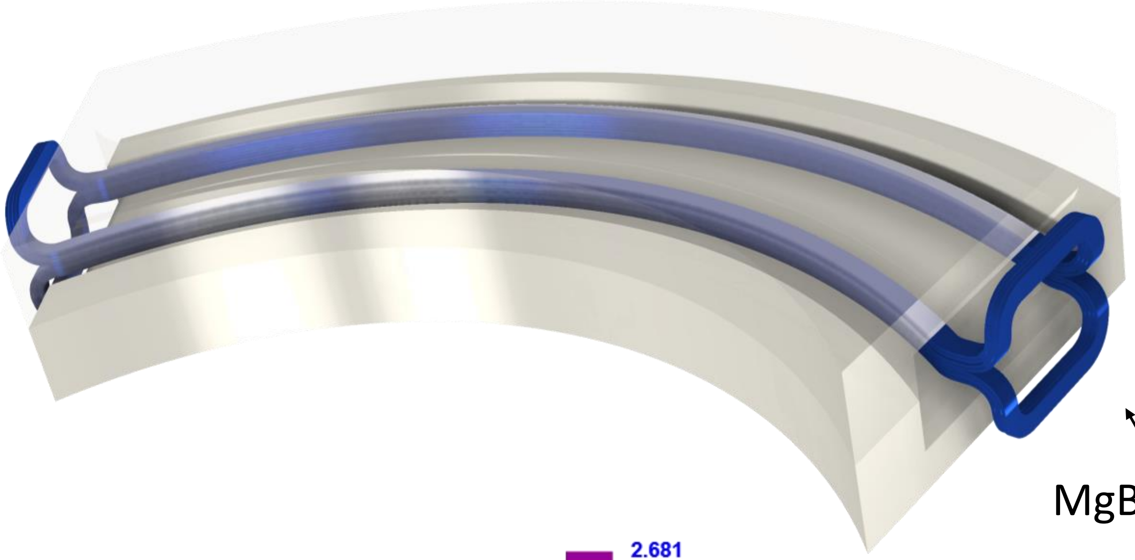
262 MWh per year

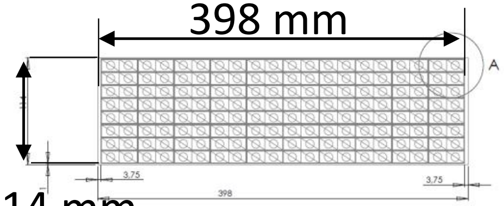
Goal: 3 kW DC (year av.) → Scaling Factor ≅ 10

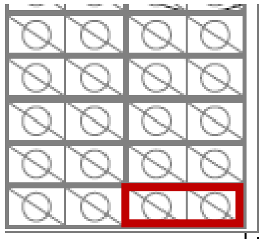
EM Design

Iron dominated magnet with field quality controlled by coil effects: very small pole on Iron laminations

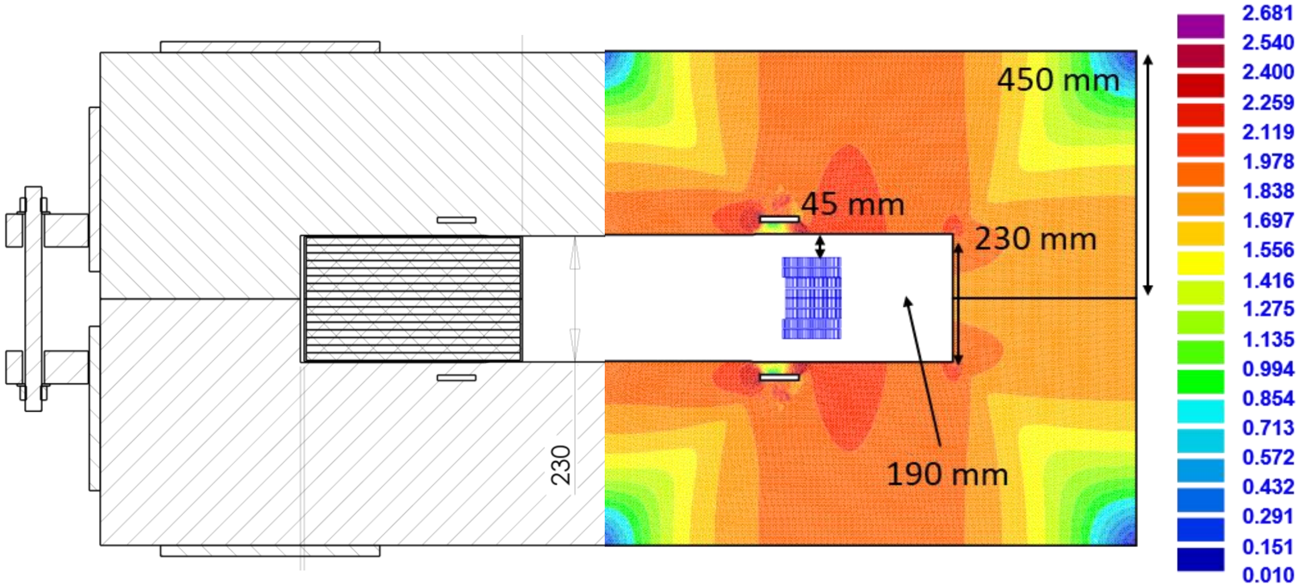
- Old Coil has 80 channels each carrying 2.28 kA
- The superconducting cable is made by a rope with 3 MgB_2 conductors and 4 high-purity copper wires. Each of the 630 ropes carries 276 A

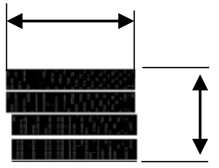


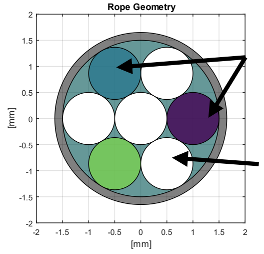




Copper Channels





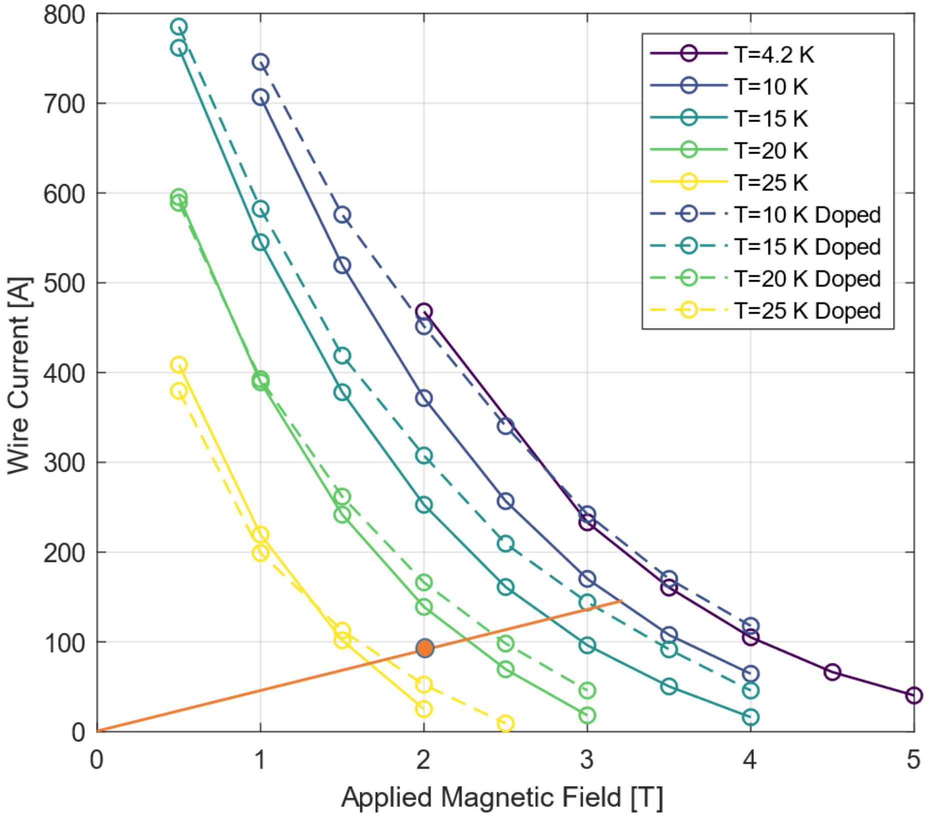


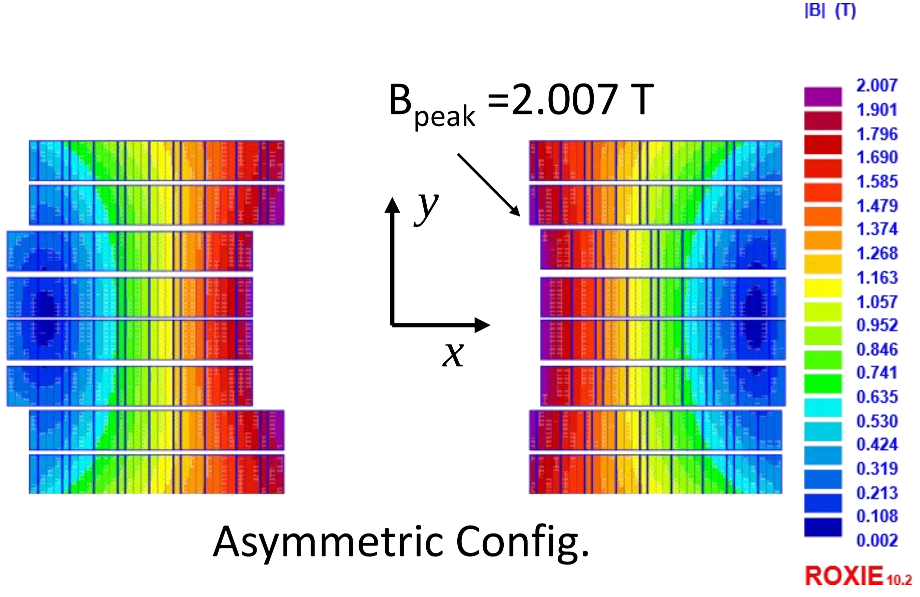
Magnetic Field Quality

Main Challenge on the entire beam aperture

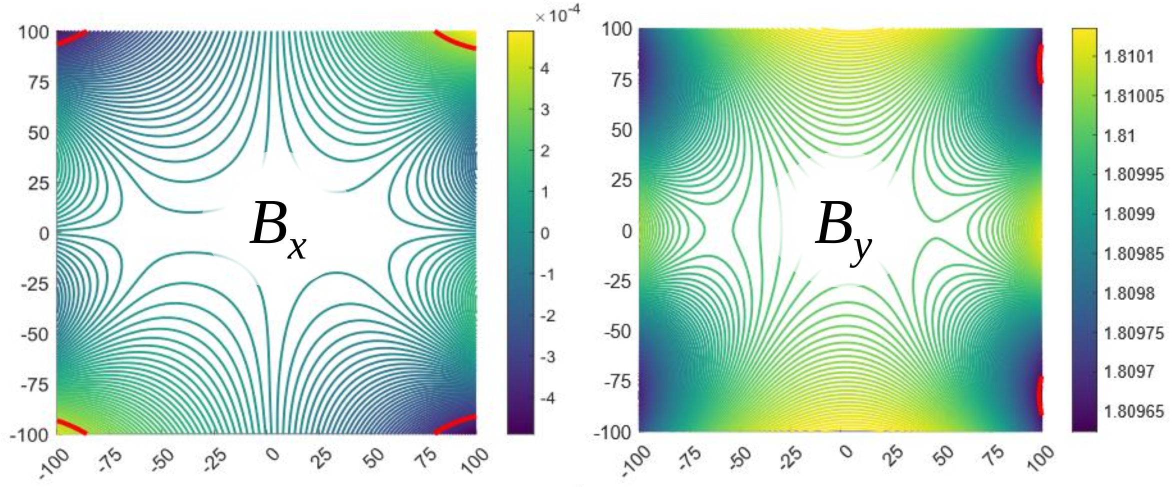
- Required Field Quality: $\Delta B/B \pm 2\ 10^{-4}$ (200x200 mm^2)

Goal of the design: Margin on LL > 40% with 2 T on the conductor



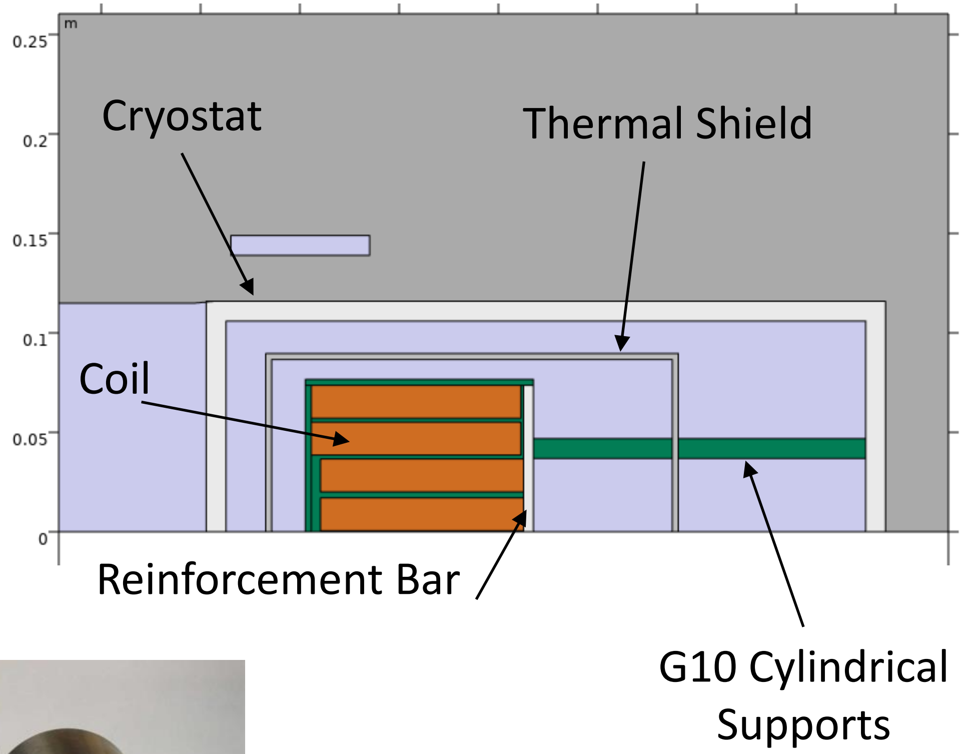


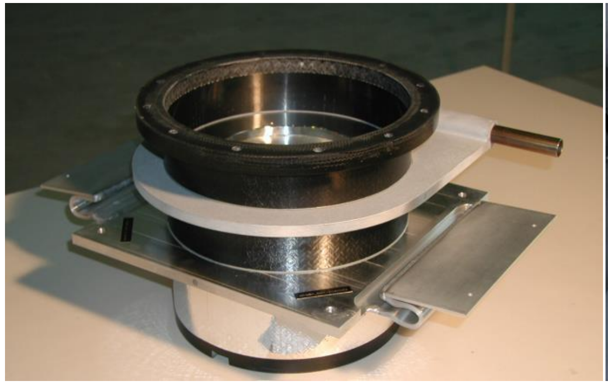
Asymmetric Config.



Mechanical & Thermal Design

- Rigid reinforcement bar used to reduce coil deformations.
- Lorentz Forces are distributed to a set of **cylindrical insulation supports** which act also as thermal barrier.
- The same **cylinders** are used to discharge the forces from the thermal shield (60 K) to the cryostat.
- The alimunum thermal shield is covered with MLI to reduce radiation heat while the reinforcement bar is made with stainless steel 316LN.



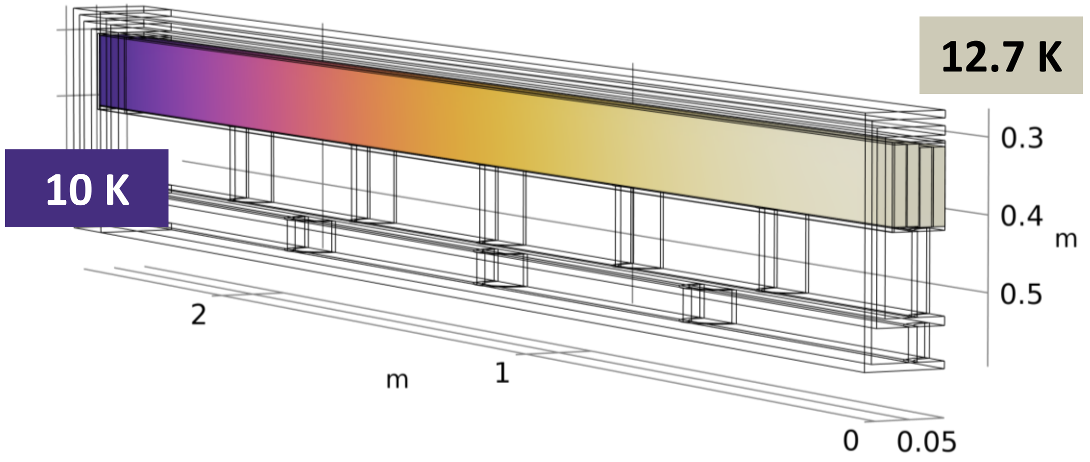


Power Consumption

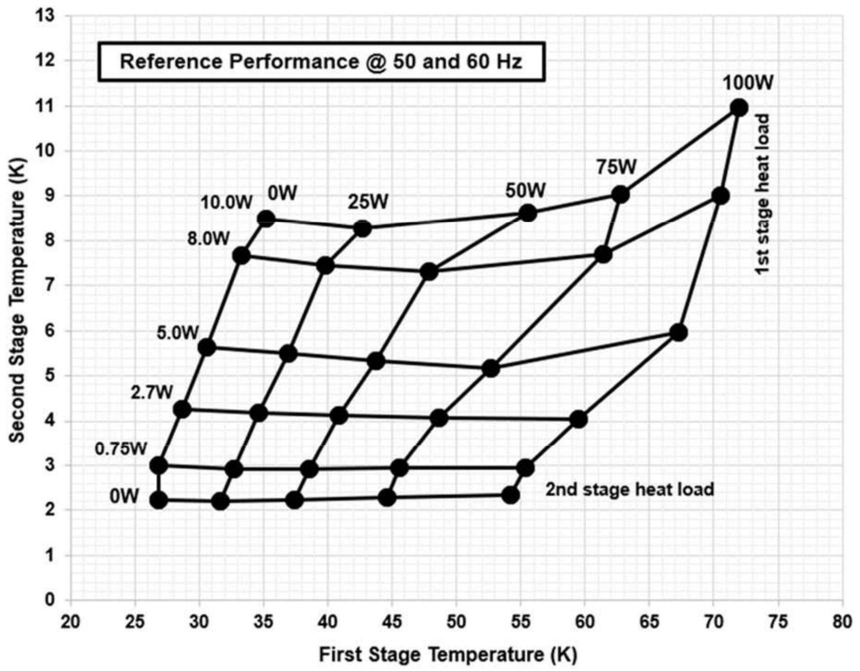
- We assume to cool the coils and the shield from **both sides** of the magnet. HTS link from the thermal shield to the coil is necessary for power consumption.
- Estimate total power consumption:

6 Cryocoolers

(4 for coils and thermal shield, 2 for the current leads)
10.5 kW DC/year for the entire magnet.



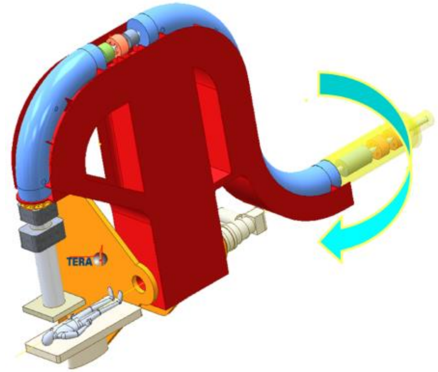
Cryomech PT425
10W @ 10K

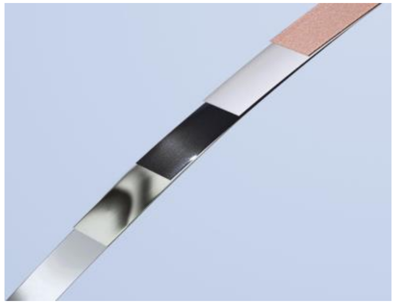


Obtained Scaling Factor ≅ 3
Expected Scaling Factor @ 20 K
At least 6/8

CCT HTS Development Program

- *Permanent **European Strategy Group**, opened to worldwide partners, to discuss the European strategy for HTS magnets for accelerators, and to improve Industry involvement in this technology;*
- *Exploring **Canted Cosine Theta with HTS superconductor (main goal),** proceeded by a **combined function CCT based on LTS** → involving the industries that want to learn about the CCT magnets;*
  - *Magnet parameters as HITRIplus program (Hadron Therapy magnet);*
  - *Straight geometry → HTS is already difficult enough!;*
- ***Construction of the two demonstrators**: winding and magnet assembly, magnet test and validation;*

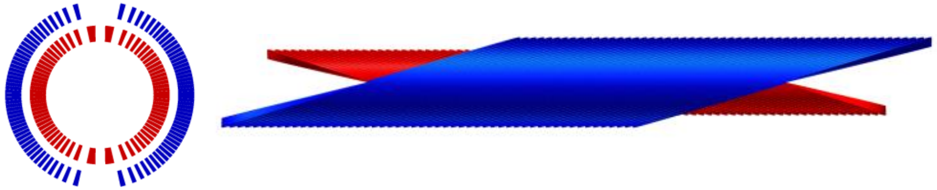




12 mm HTS REBCO tape

BERKELEY LAB

Courtesy of Xiaorong Wang



CCT dipole
4 T target
Ø =80 mm; L <= 1000 mm

Courtesy of Tengming Shen

Development Program

The main goal of the WP8

- Baseline (**4 T dipole @ 10 K**, > 15 K of margin);
- Superconductor **ReBCO** (Tapes);

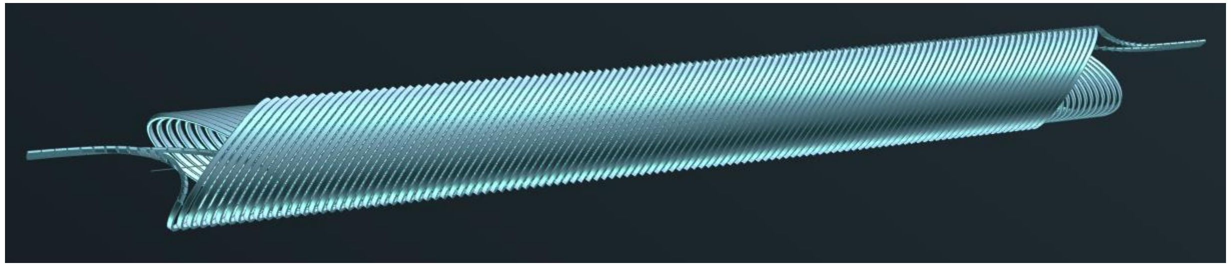
Technical Challenges to face: **Control the Insulation**

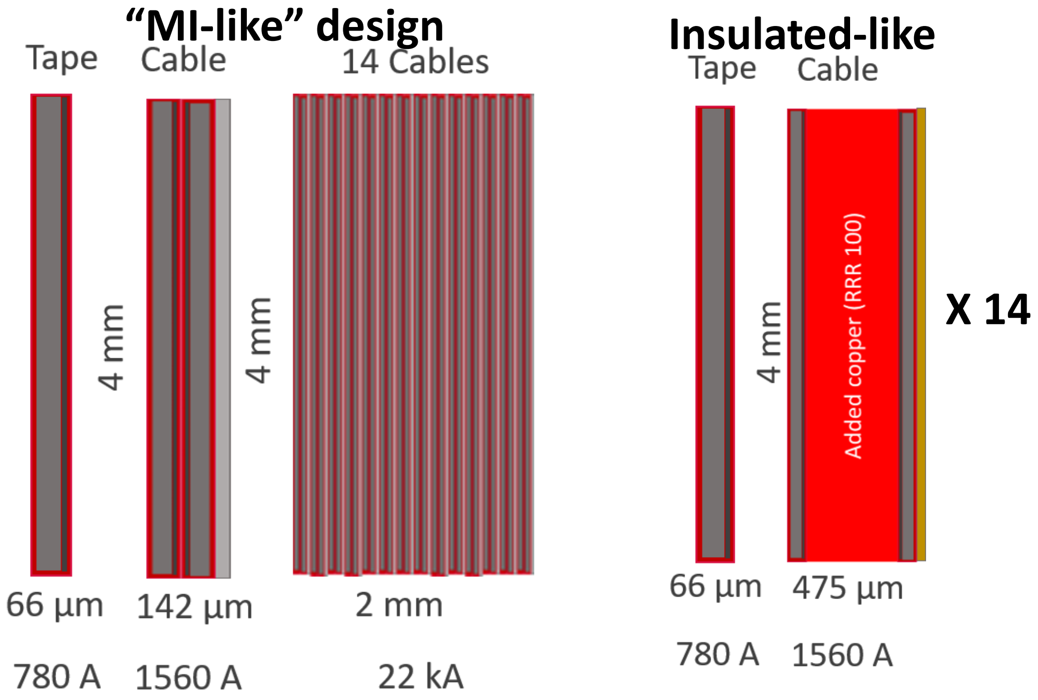
- "**Metal Insulation-like**" design with 2 layers cable
- "**Insulated-like**" design (added copper to conductor);

Protection aspect is the critical point for both:

- No classical protection for the MI-like;
- Use of cable like for EuCard2: too big current → high losses in the Current Leads
- 10-50 µV threshold and 10 ms delay (Insulated-like) adding more than 320 µm of copper;

[1]T. Lecrevisse, "**Conceptual Design of HTS Magnet**", IFAST WP8.3 Milestone 33, Zenodo, https://doi.org/10.5281/zenodo.6979877





Round Coil Superferric Magnet

I. F. Malyshev (1973)

A novel type of magnet for Magnetic Lens

I. F. Malyshev, Multipole Magnetic Lens USSR, Patent 1689890/26-25, published 12.10.1973, Bulletin 41

V. Kashikhin (2010)

Quadrupole magnets for Linear Accelerators

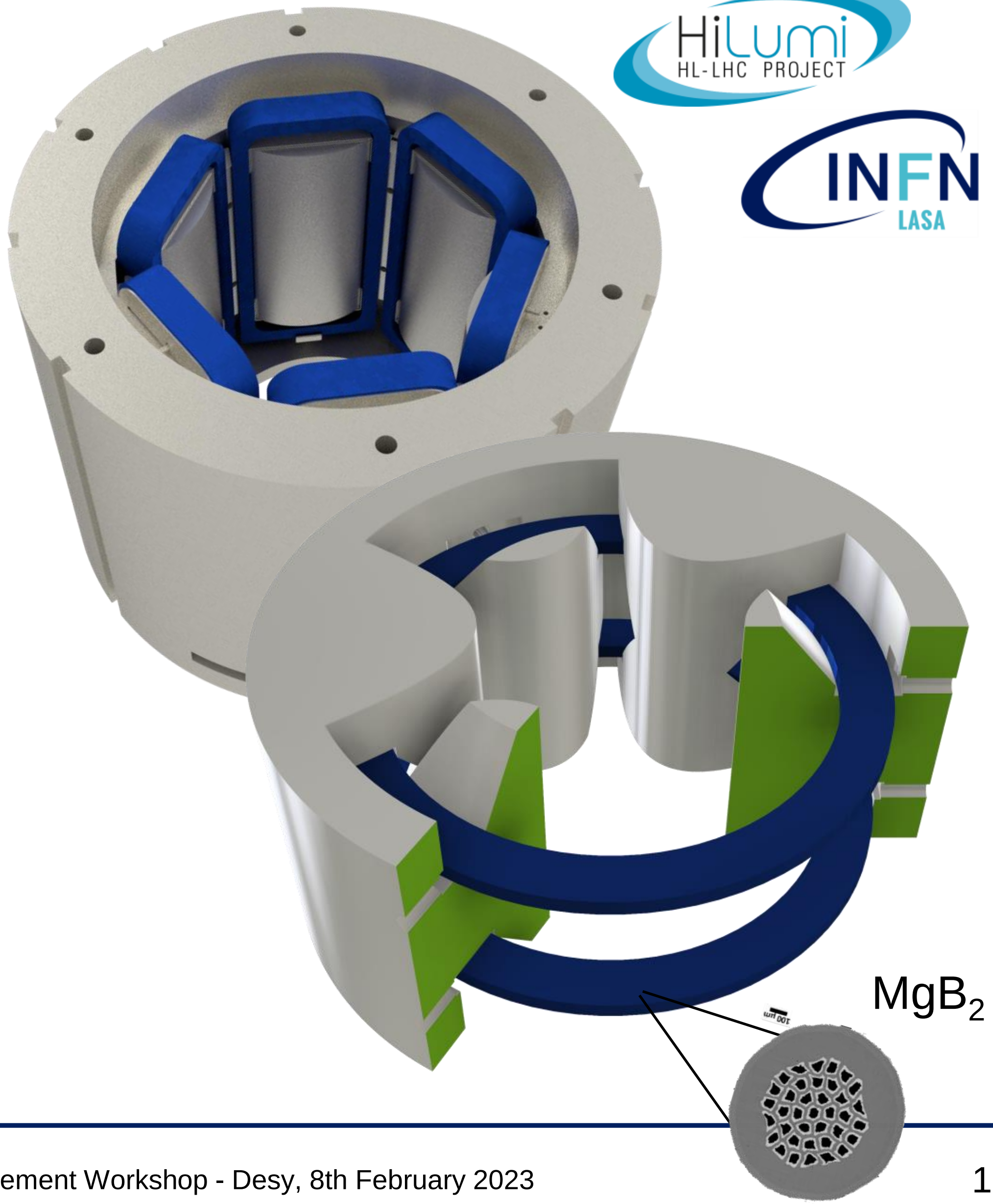
V. Kashikhin, “A novel design of iron dominated superconducting multipole magnets with circular coils,” IEEE Transactions on Applied Superconductivity, vol. 20, pp. 196–199, June 2010

G. Volpini (2015)

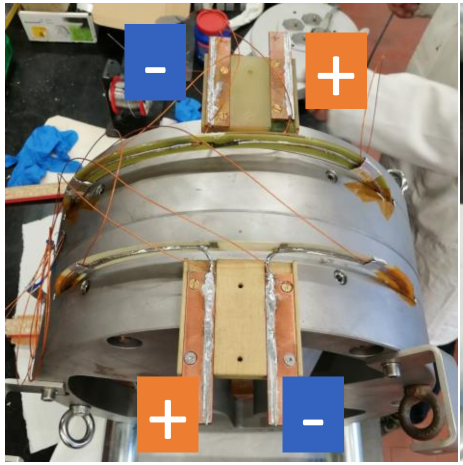
Application to strain-sensitive superconductors

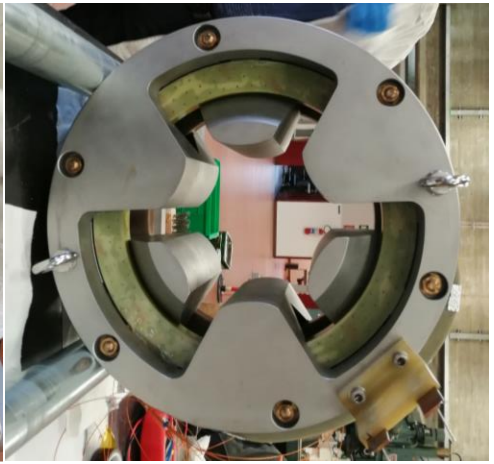
G. Volpini, J. Rysti and M. Statera, "Electromagnetic Study of a Round Coil Superferric Magnet," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1-5, June 2016.

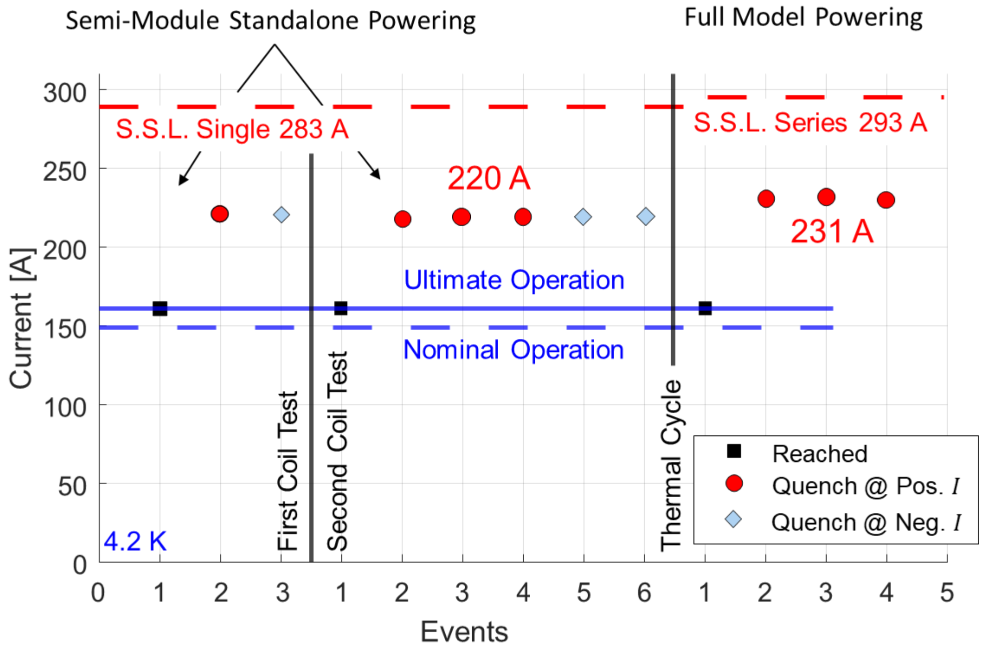
- Superferric Corrector Magnets
- Sextupole configuration
- MgB_2 conductor tapes and then realized with round wires



RCSM Complete Magnet







First MgB_2 Magnet for particle accelerators

- Exceed design performances (I=155% design)
- **Good** field quality as expected from simulations

Next Step:

- Testing of the magnet at **T > 10 K**
- Improvement of magnet topology

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FACOLTÀ DI SCIENZE E TECNOLOGIE

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Ministero dell'Università e della Ricerca

PON RICERCA E INNOVAZIONE 2014 - 2020