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Energy-saving superconducting magnets in accelerators and beamlines

3rd I.FAST Annual Meeting

Samuele Mariotto
on Behalf of LASA research Group

iFAST
Ministero dell'Università e della Ricerca
PON
RICERCA E INNOVAZIONE
2014 - 2020

Project Goal and Objectives

- Energy consumption of particle accelerator facilities is expected to increase in the future: **Upwards electricity price** trend is foreseen
- Need for «Improvement of energy efficiency»
  - ***European Strategy for Particle Physics 2020***

- «Cryogen-free superconducting magnets instead of common resistive magnet for heavy particles beam lines»

- Objectives:
  - Use of MgB2 or HTS conductors
  - Energy consumption 5-20 lower
  - Work @ T=8-20 K with solid conduction cooling to reduce cryogenic power consumption

Courtesy D. Tommasini, CERN

MNP33-Dipole
NA62-CERN
7560 MWh

SM2-Dipole
Compass-CERN
6953 MWh

4 Possible Ways

1. **Revamping**

   Reuse the same iron yoke and magnet interfaces substituting copper with superconductors.

   - Possible superconducting material for the coil: MgB2 or HTS conductors
   - **Cheapest** solution

2. **Superferric magnets**

   Modified iron geometries optimizing the shape to accommodate the superconducting coils and exploit its potential for low power consumption

3. **Coil dominated design**

   Use **HTS conductors** for high fields with coil geometries optimized according to beam requirements

   - Suitable for higher field values compared to resistive or iron-dominated magnets
   - Magnet dimensions reduced

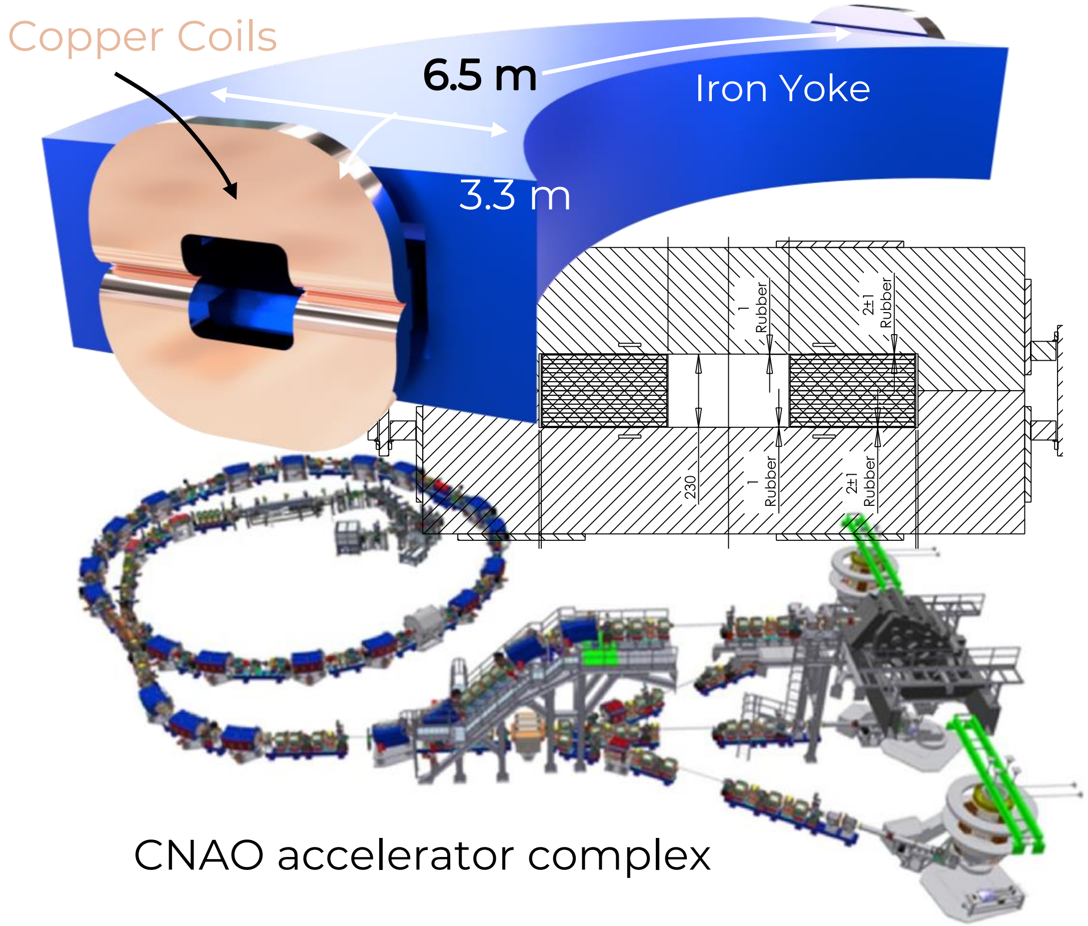
4. **Exotic designs**

   Compact and **combined-function magnets**

   - Specific design used to reduce space in the beamline and reduction of magnet numbers

Ramped Magnet Case Study

Centro Nazionale di Adroterapia Oncologica



CNAO accelerator complex

Dipolar «Window-Frame» Bending Magnets installed at CNAO. Dimensions of the coil are **compatible** with minimum bending radius (100 mm) required for **MgB_2**

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 Comparison of Room Temperature and Superconducting Synchrotrons for Hadron Therapy", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 3080-3083.doi:10.18429/JACoW-IPAC2022-THPOMS049

Main Challenges:

1. Field quality: ± 2E-4 $\Delta B/B0$ in 200x200 mm^2 aperture
2. Duty cycle depends from treatment

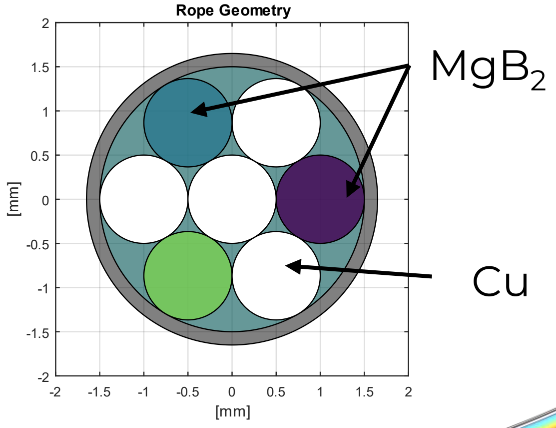
30 kW DC
262 MWh/year

MgB_2 Design @ 20 K

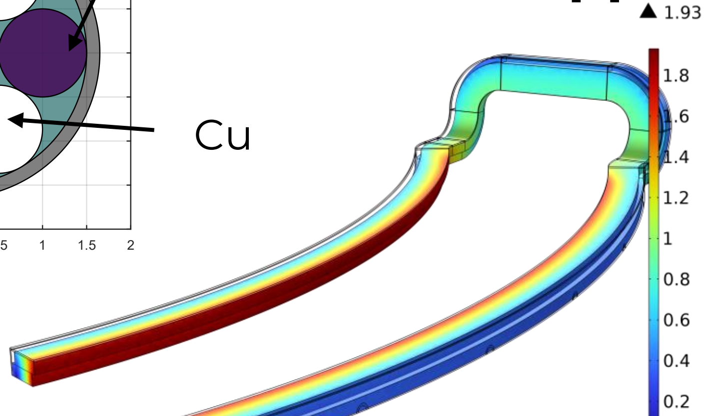
EM Design Target:
Bore Field of 1.74 T with FQ<± 2 units

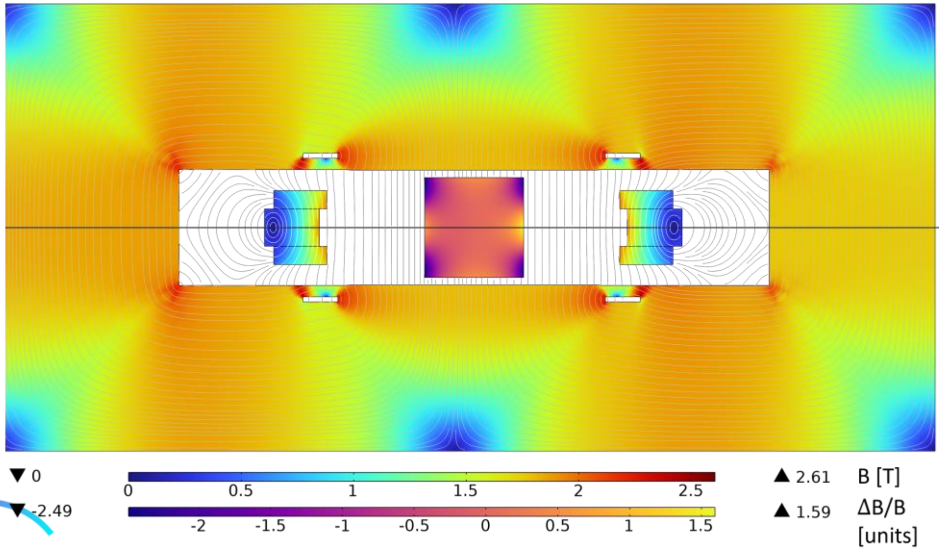
756 Ropes MgB_2 rope conductor
- 2D Optimization and 3D simulation analysis
- Nominal current 226 A (old design 276 A)

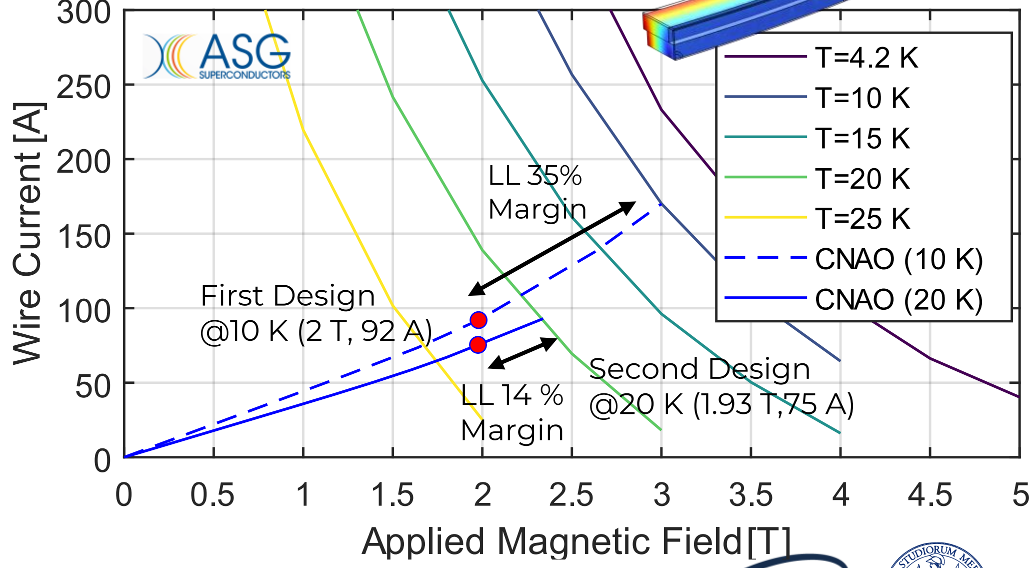
(14 % margin LL, 3.6 K temperature margin)
Warning: optimization @ nominal current: FQ: 2.6 units



Coils Peak Field 1.93 [T]







LL 35% Margin

First Design @10 K (2 T, 92 A)

LL 14 % Margin

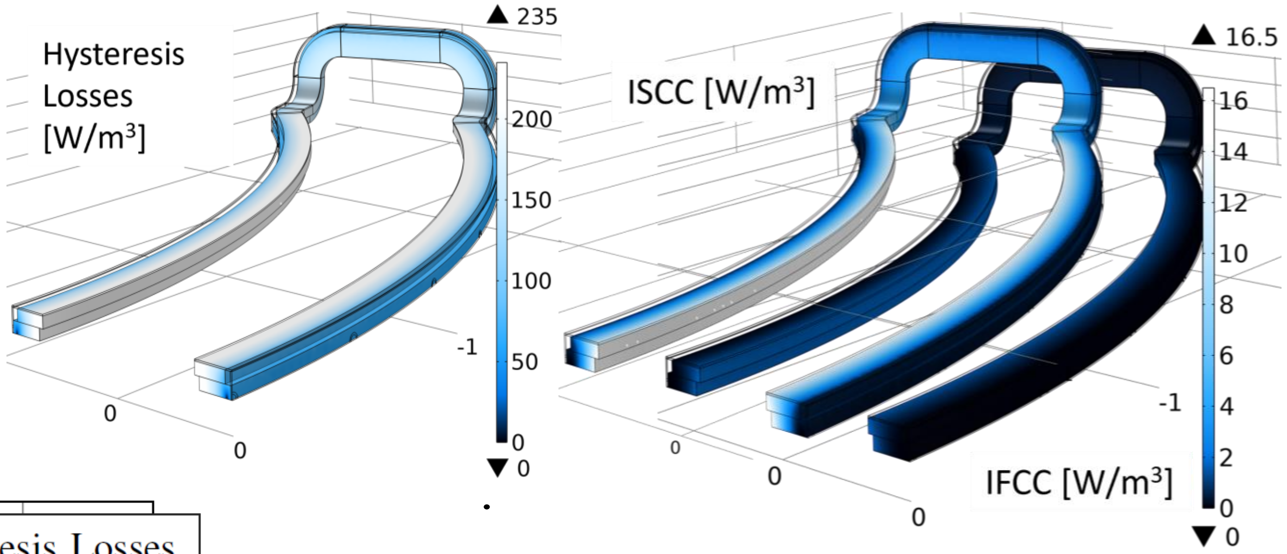
Second Design @20 K (1.93 T,75 A)

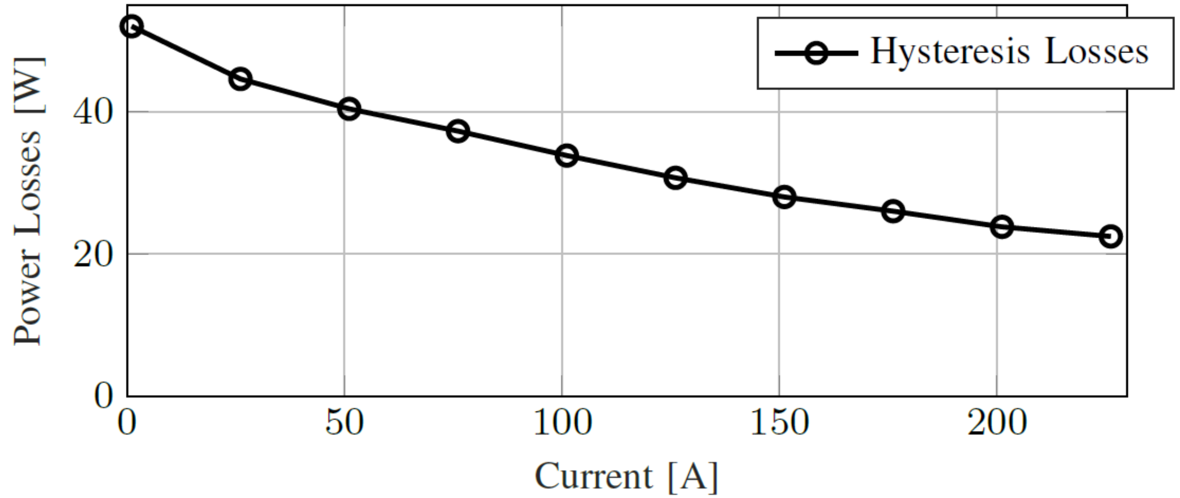
Losses Calculation

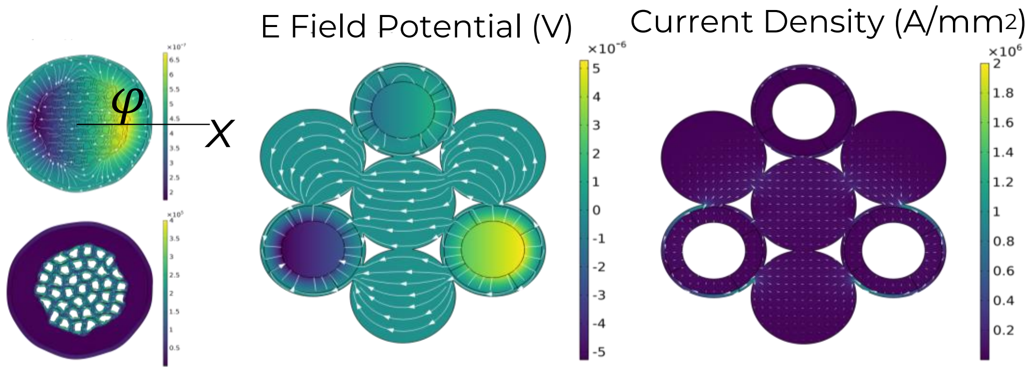
Equivalent magnetization model used to evaluate average hysteretic losses in the conductor.

- Filament diameter equals to 55 μm
- 3D static heat map source
- IFCC and ISCC: $f\,(\rho_{\text{eff}},L_{\text{Pitch}})$

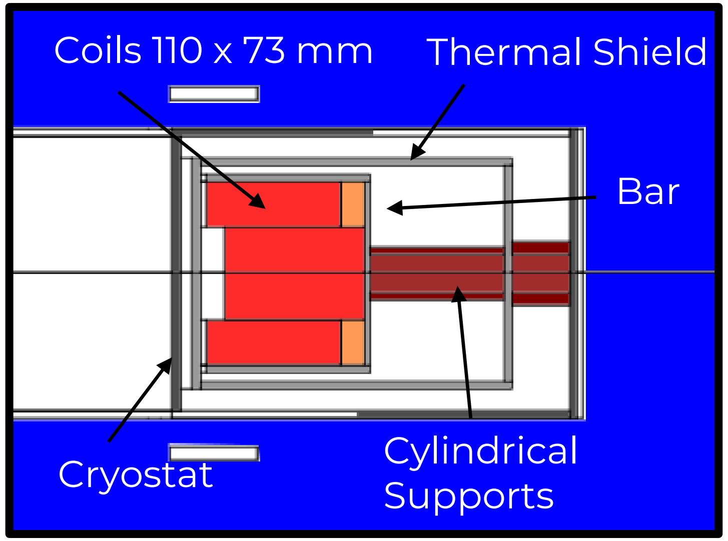
Volumetric Losses Density



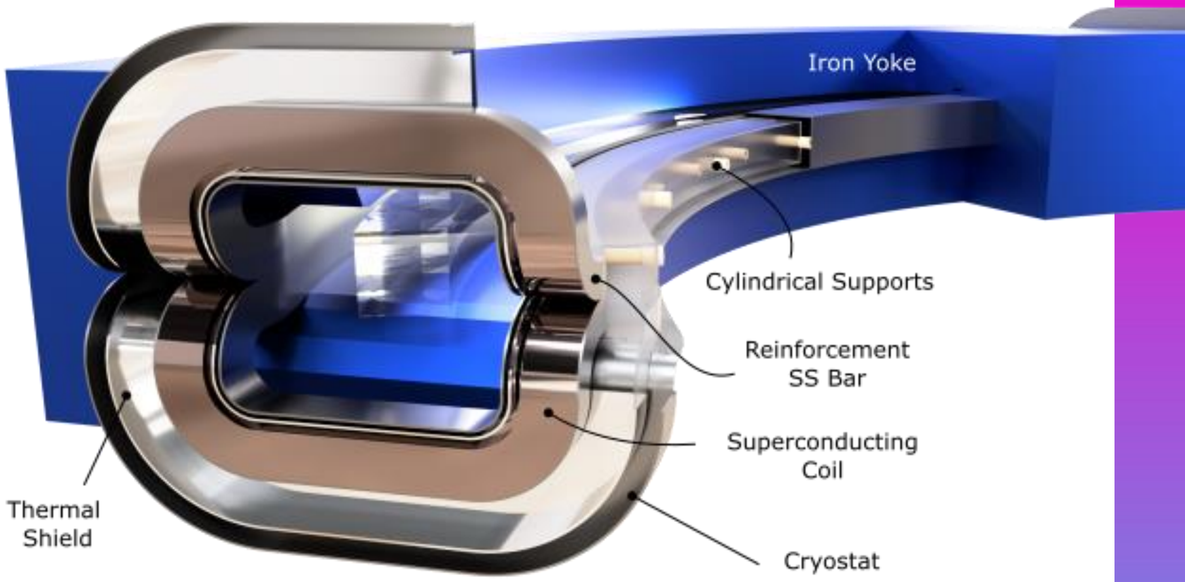




Mechanical Design



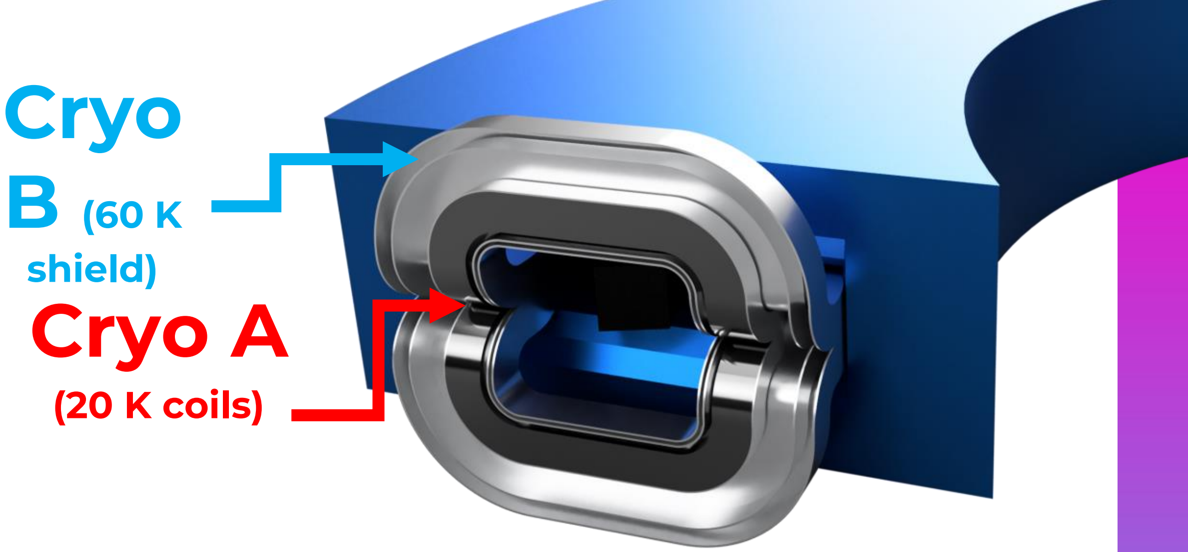
	External Supports	Internal Supports
Diameter	50 [mm]	42 [mm]
Thickness	9 [mm]	6 [mm]
Length	47 [mm]	107 [mm]



- 5-mm-thick SS 316LN **reinforcement bar** around coils to limit deformations.
- A distributed **set of 36 G10 cylindrical supports** is adopted to sustain an active aluminium **thermal shield** (@ 60 K) and coils (@ 20 K).

Optimization of cylindrical supports dimensions and positioning to **minimize conduction heat load** on coil and thermal shield but able to withstand **200 MPa** of compressive load

Thermal Design



Aluminum **thermal shield** (6 mm thickness) working **@ 60 K** covered with **30 MLI** layers (minimzation of radiation load).

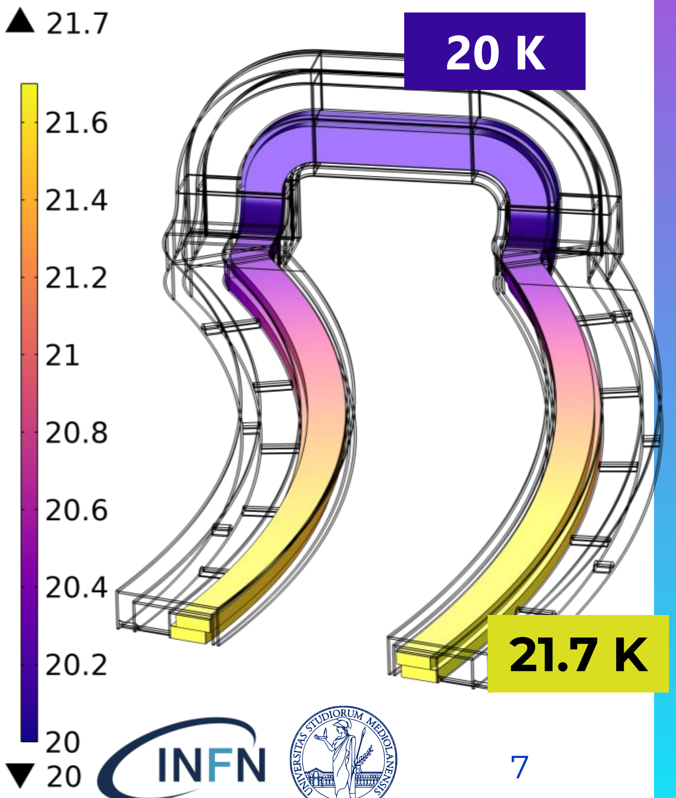
<table>
<tr><th>MAGNET</th><th colspan="2">Coils @ 20 K</th><th colspan="2">Shield @ 60 K</th></tr>
<tr><td>Q support</td><td colspan="2">1.1 [W]</td><td colspan="2">35 [W]</td></tr>
<tr><td>Q CL</td><td colspan="2">0.2 [W]</td><td colspan="2">24 [W]</td></tr>
<tr><td>Q radiation</td><td colspan="2">0.38 [W]</td><td colspan="2">19.52 [W]</td></tr>
<tr><td rowspan="2">LOSSES</td><td>Hyst</td><td colspan="2">ISCC</td><td>IFCC</td></tr>
<tr><td>34.2 [W]</td><td colspan="2">.1.55 [W]</td><td>0.17 [W]</td></tr>
</table>

Cryocoolers installed on **both side** of the magnet

- TS (3.4 kW) 2 AL230
- Coils (8.4 kW only for 1/10 of the year) 2 AL60

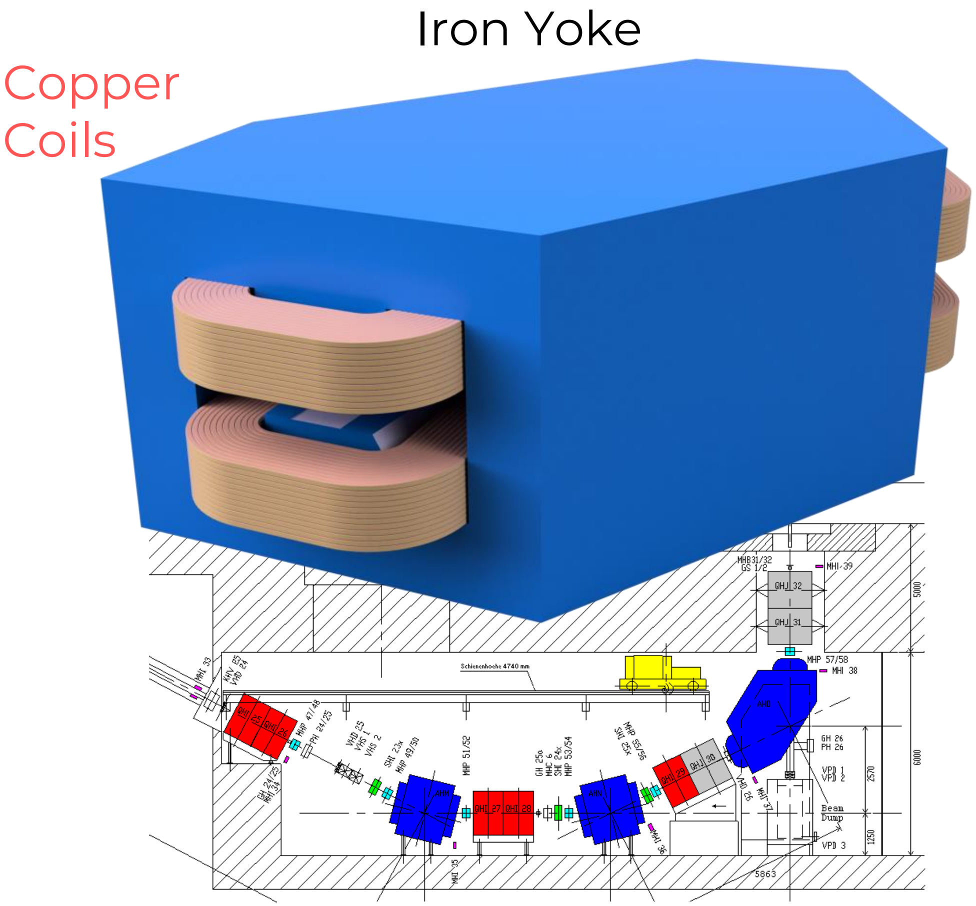
Total magnet energy consumption: **4.3 kW** (vs 30 kW DC resistive).

≈ 7 times lower



AL230 Cryomech and AL60 Cryomech

Steady State Case Study



SINQ beam line facility

Originally a switching magnet, actually a bending unit before SINQ (Spallation source) with **50 tons** of weight. Produced field of **1.45 T** on **2.780 m** radius for **64 deg**.

Cooling power **190 kW** 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

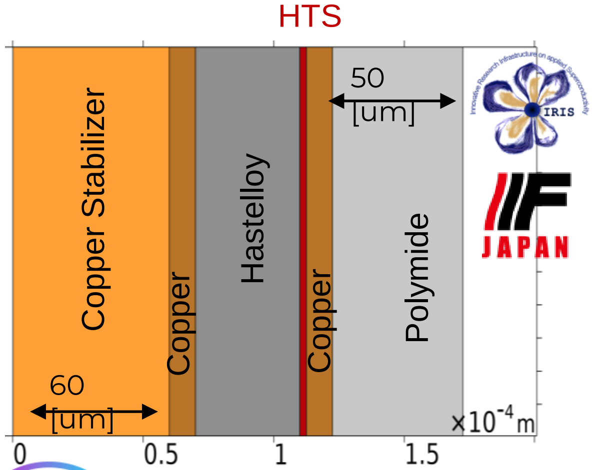
715 MWh/year

HTS @ 50 K EM Design

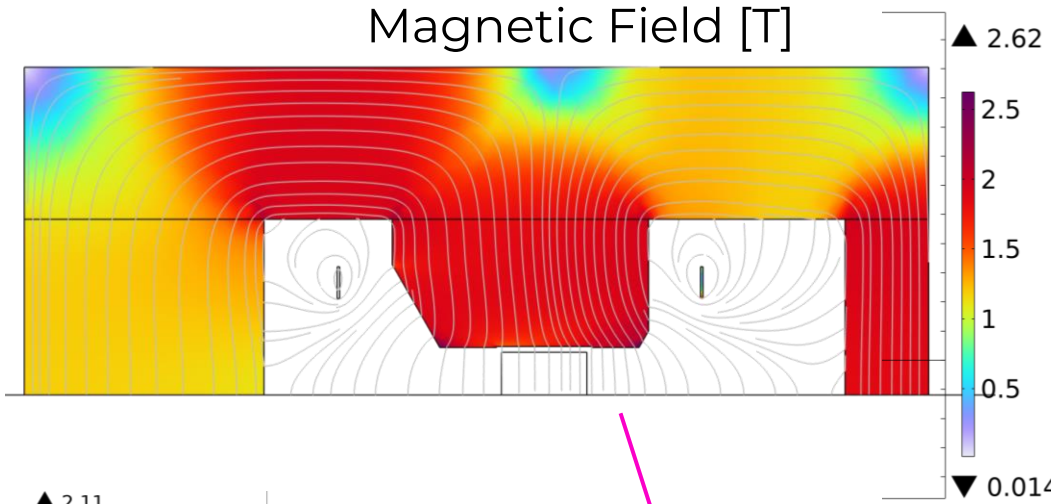
Target of the electromagnetic design optimization

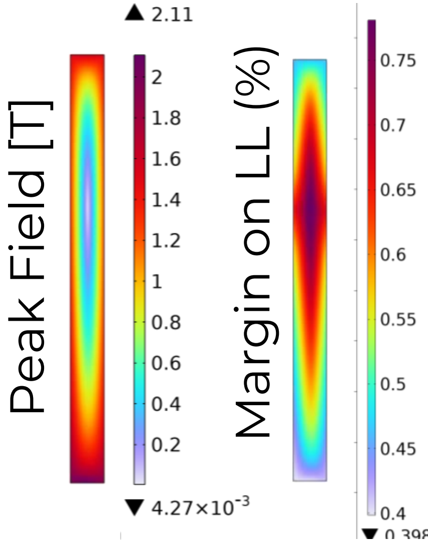
- Magnetic field of **1.45 T** at center.

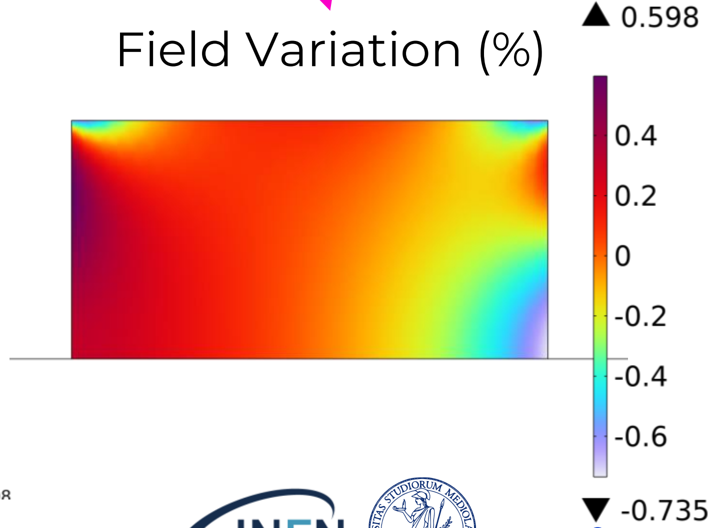
- **2D Field optimization** of coil cross-section
- Minimize Peak Field on conductor while obtain the maximum **margin on LL (> 40%)**
  - Scaling of the old ampere-turns (144 A x 1000 turns)



Dimensions	**4 mm × 67 µm**
Substrate Hastelloy	40 µm
Copper stabilizer	2 × 10 µm, RRR>20
Easy-way minimum bend	10 mm
Allower longitudinal strain	-0.4 % to 0.3 %
I_c, 50 K, 2 T	Min. 500 A with $B_\perp$ Max. 830 A with $B_\parallel$



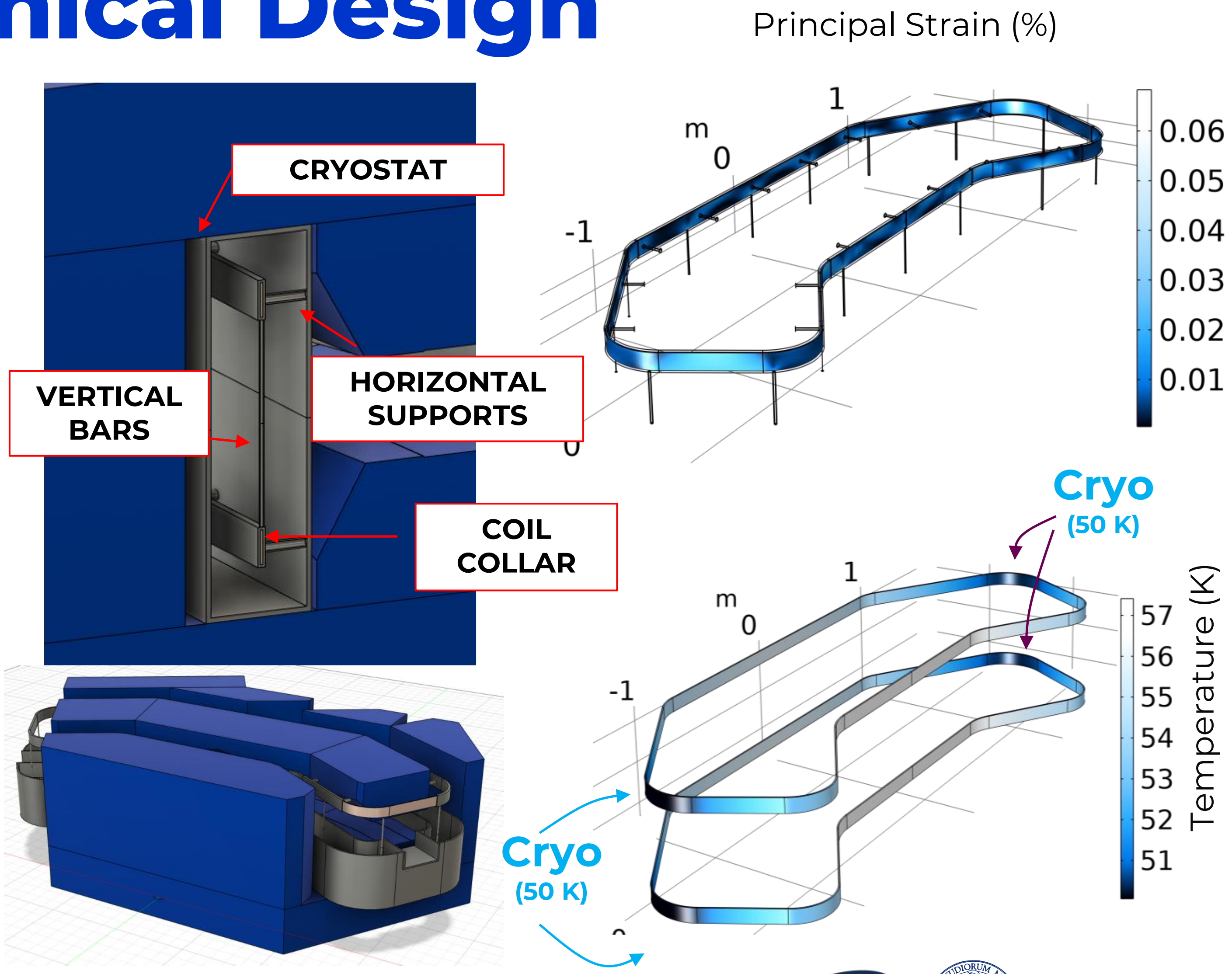




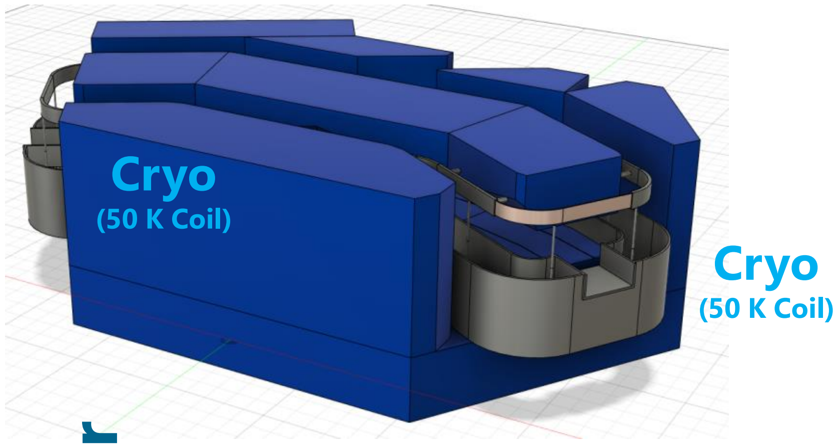
Thermo-Mechanical Design

- 5-mm-thick SS 316LN **collar** around the coil and **set of SS 316LN rods** to limit deformations during energization.
- Connection with Cryostat towards coil center performed with **set of 16 G10 cylindrical supports**
- MLI (30 Layers) used to reduce the radiation power on thermal shield
- Single stage **current lead** down to 50 K coil. Heat load = **28 W**.
- Total energy consumption: **3.4 kW**
  - (vs 190 kW resistive)

≈ **56 times lower**



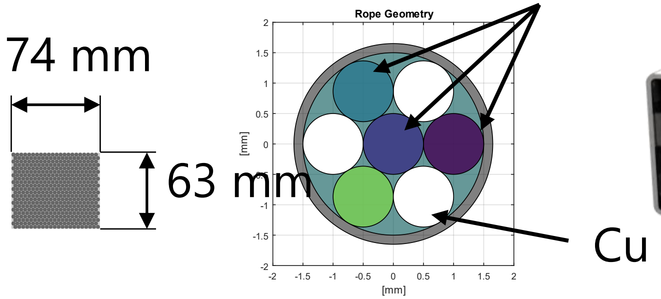
Other possible Solutions: MgB_2

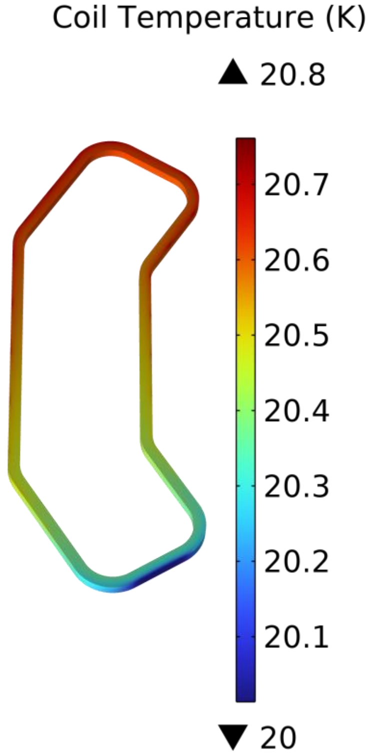


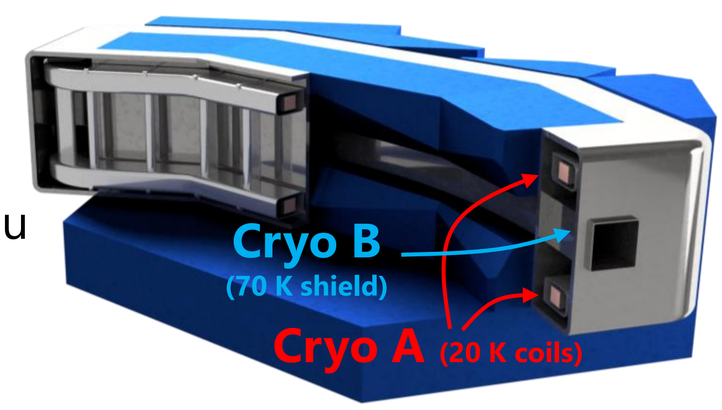
Cryomech Al60
30 W @ 50K, P = 1.7 kW

MAGNET	Coil @ 50 K
Q support	4.6 [W]
Q Current Leads	28 [W]
Q radiation	11.7 [W]
Q tot	44.3 [W]

≈ 56 times lower







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

B: Cryo Al60 48W @ 70K, P = 1.7 kW

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

≈ 40 times lower

Conclusions

Development project based on **cryogen-free superconducting magnets**

- **MgB_2** or **HTS** conductors @ **T=20 K**
- Conduction cooling solutions

Case studies: **CNAO** 90° Dipole (ramped magnet) and **PSI** bending dipole (steady-state)

- **Coil geometry** suitable for MgB2 and HTS **curvature requirements**

3D Models developed using MgB2 rope conductor or HTS tapes

- Field requirements fulfilled at nominal current
- **Ramped magnets** (consumed energy scaling =**1/7**)
  - (Heat load and T_{op} balance optimization)
- **Steady-state solutions**
  - Model developed to work **@ 50 K** with **HTS (consumed energy scaled by 1/56)**
  - **No need of thermal shield** - easier manufacturing process
  - **Comparison of HTS with MgB_2** (energy scaling **1/40 for the MgB2 config.**)
    - Comparable results (Conductor cost/m and number of needed cryocoolers)

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Thank you for the Attention

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