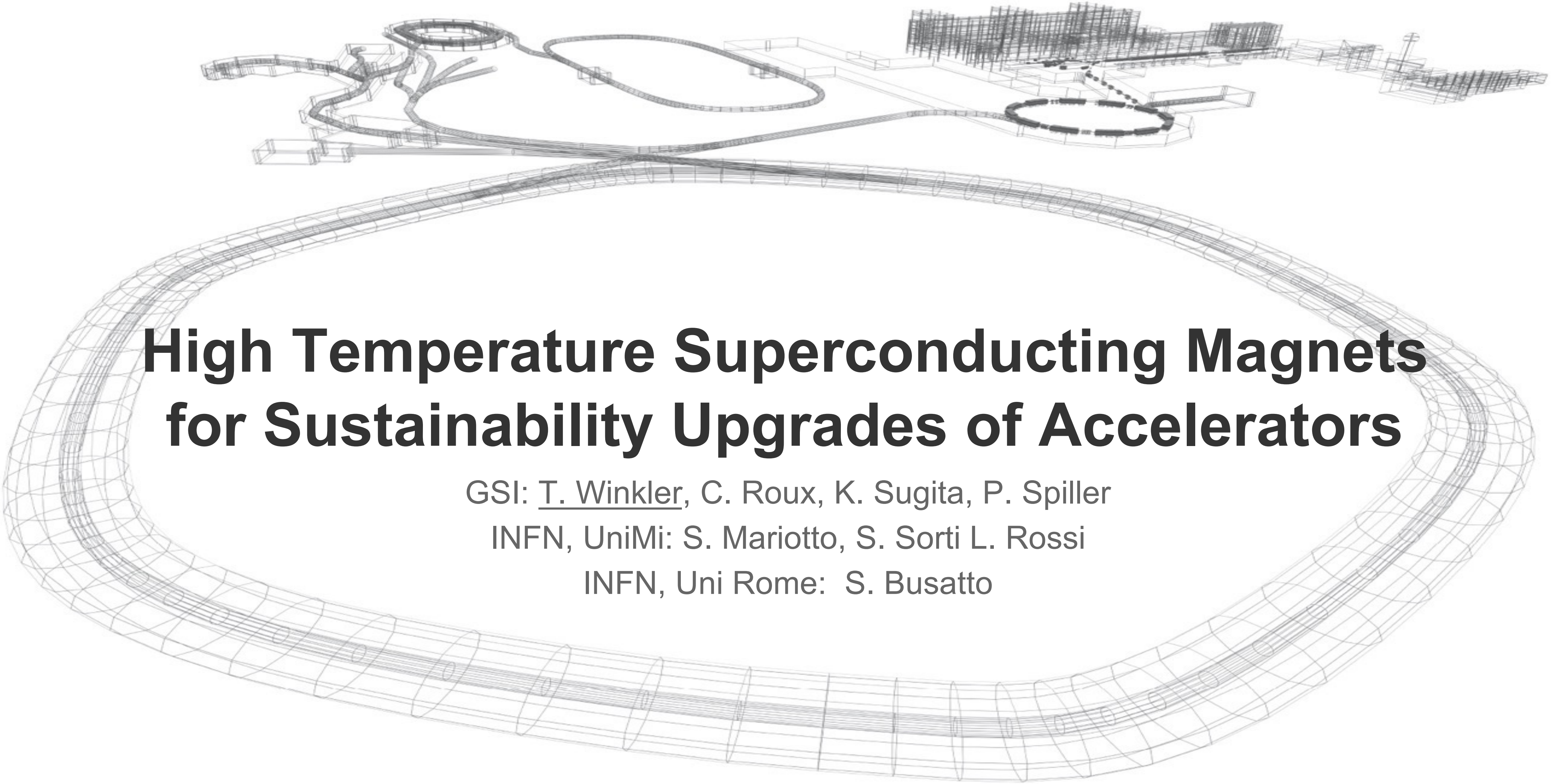


High Temperature Superconducting Magnets for Sustainability Upgrades of Accelerators

GSI: T. Winkler, C. Roux, K. Sugita, P. Spiller

INFN, UniMi: S. Mariotto, S. Sorti L. Rossi

INFN, Uni Rome: S. Busatto

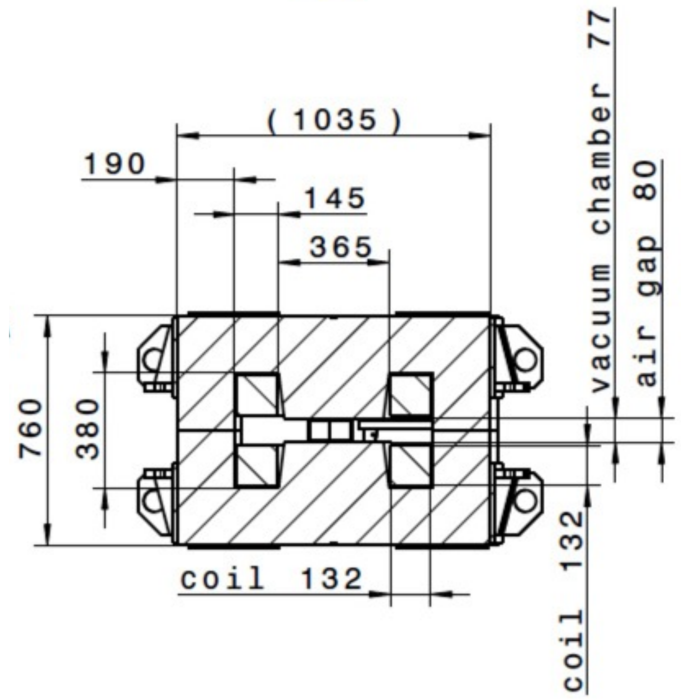
- Beam line magnets are major power consumers for R&D centres

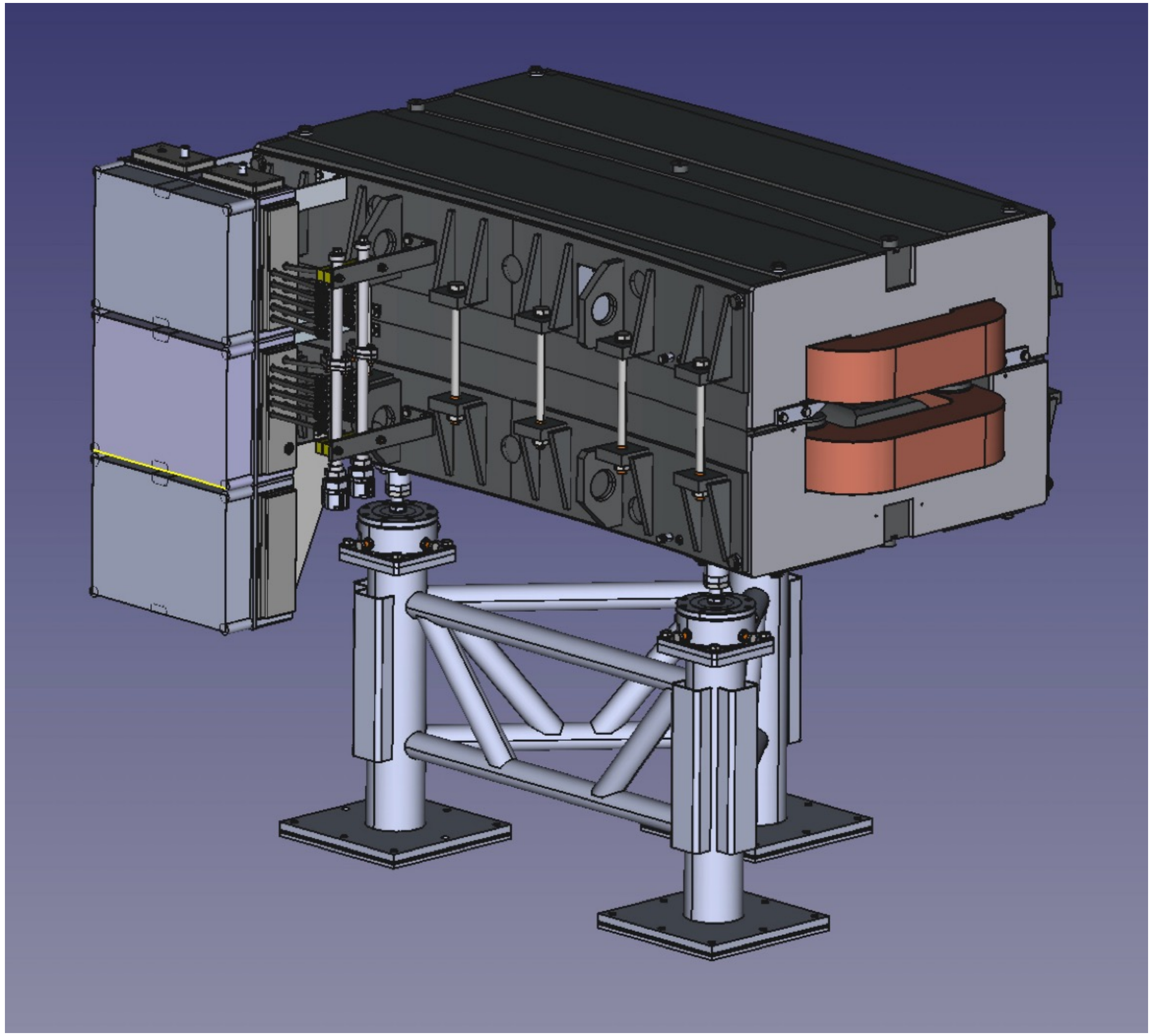
- Two examples for upgrades of normal conducting magnets from CNAO and GSI
  - Similarities:
    - Iron dominated magnet
    - Ramped operation
    - Similar power consumption (30 kW, 47 kW)
  - Differences:
    - H-Frame magnet vs Window frame magnet
    - Racetrack coil vs saddle coil
    - HTS vs. MgB_2

Example 1
HTS Upgrade of iron dominated beam steering magnet

GSI Beam Steering Magnet

- 12.5° 13 Tm normal conducting magnet
- H-Frame yoke design
- 2x 100 turn water cooled copper coils

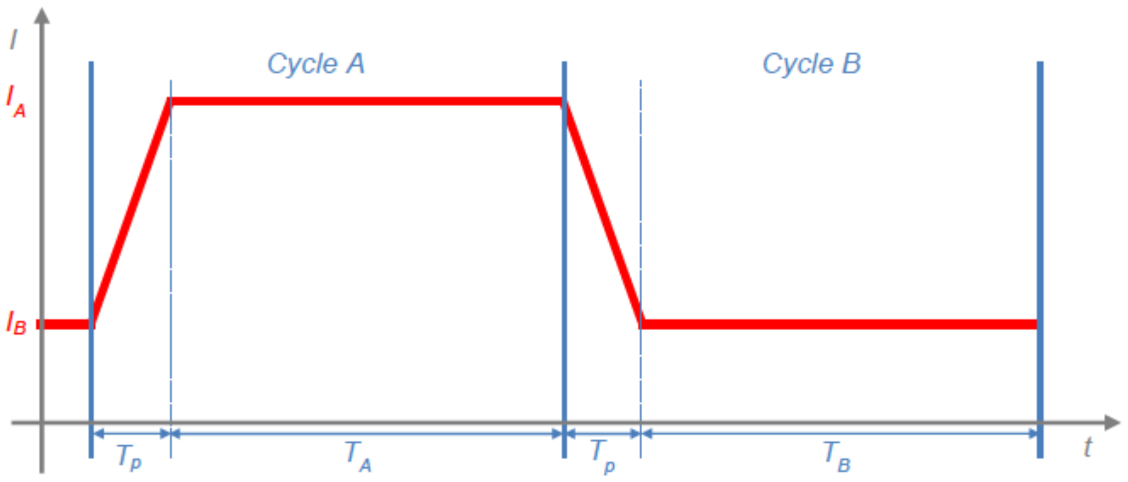




What do we want to do

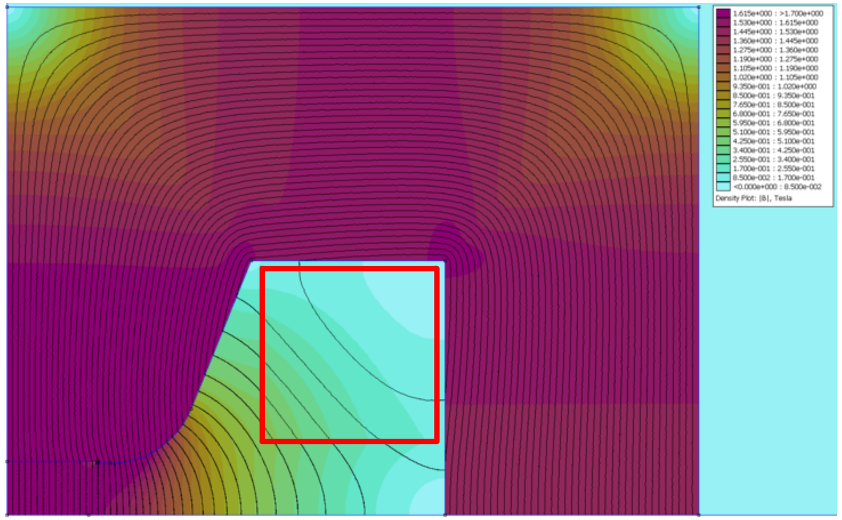
- Multiple operation modes
  - DC to 0.5 Hz
- No cryogenic fluids => dry cooling
- Reuse exiting hardware as much as possible
  - Yoke
  - Power converter
  - Cabling

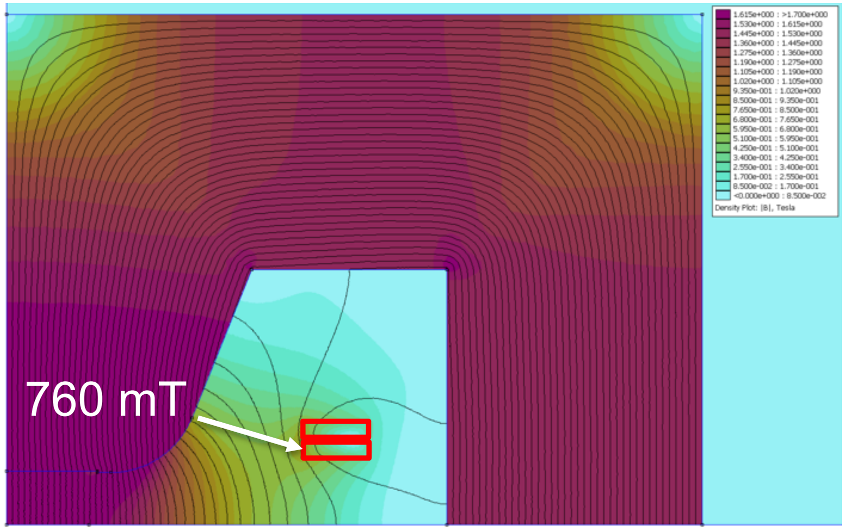
- Design concept
  - HTS racetrack coils
  - Install assembly of cryostat and coil in space of copper coils
- Challenge: Coil cooling during ramping

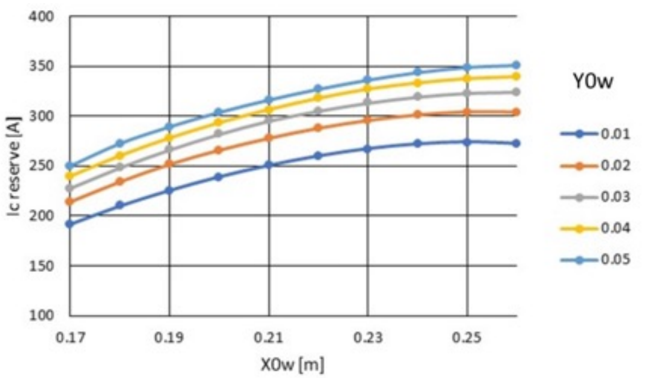


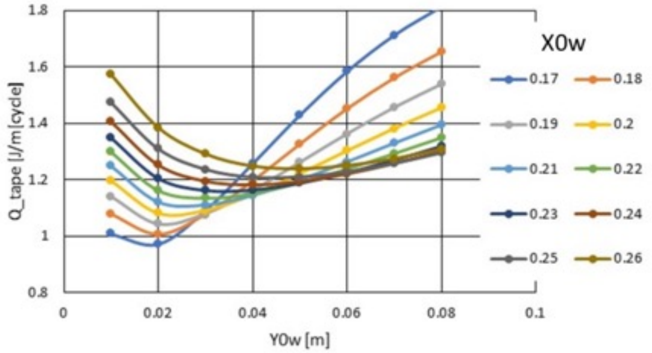
Parameter	Value
Field in Gap	1.6 T
Max Current	534 A
Ramp rate	1 T/s
DC Power	46 kW

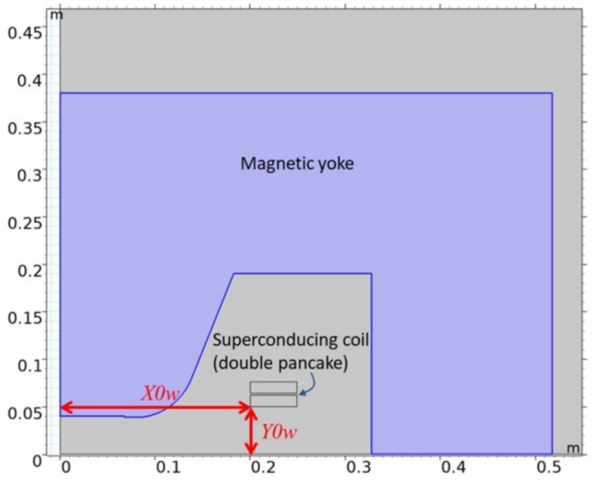
Magnetic field and AC loss

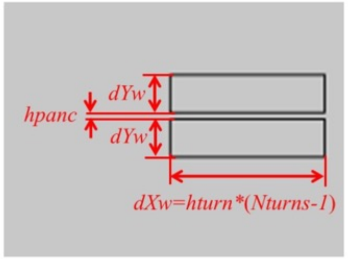












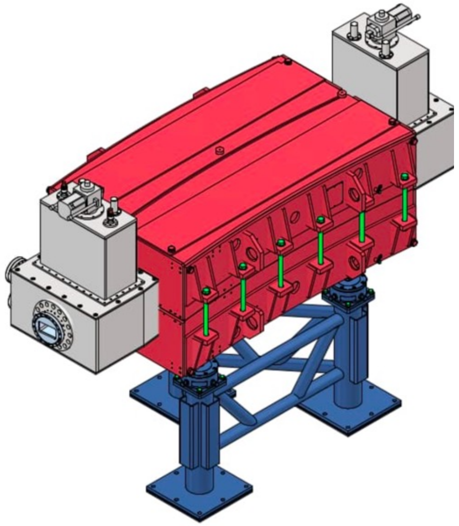
- 2D-Model in Comsol
- Parametric coil position
  - => Ic reserve and hysteresis loss
  - Verification with 3D model for two full cycle calculation shows good agreement

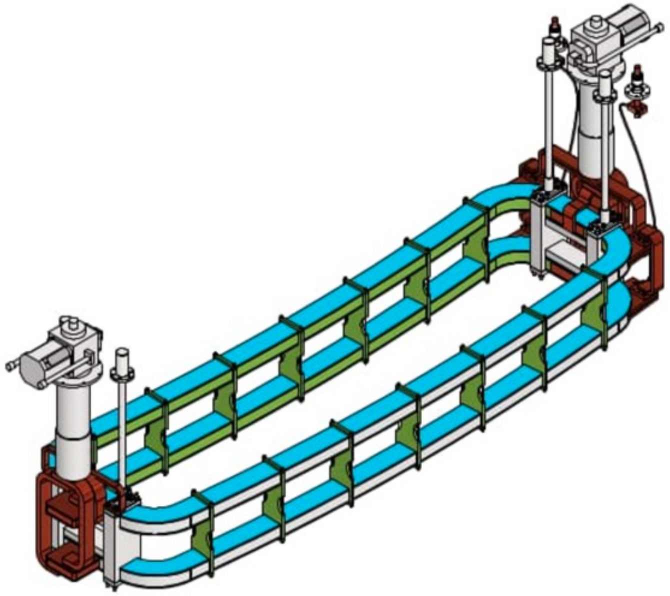
Units	Copper Coil	HTS Coil
b3	0,363	0,401
b5	0,159	0,162
b7	-0,002	-0,001
b9	-0,003	-0,002

Design

- Exoskeleton cryostat, e.g. frame with walls plated on, non-conductive contact areas to limit eddy-currents in cryostat
- No thermal shield
- Fully encased double racetrack coils
- Option for one cryocooler on each extremity, SHI SRDK-500B
- 1 mm spacing between turns to reduce AC loss in conductor

Static losses		
Support	3 W	system
Current Leads	54 W	system
Ohmic losses joints	20 W	system/coil
Radiation (ambient)	6 W	system/coil
Sensors	2 W	system/coil





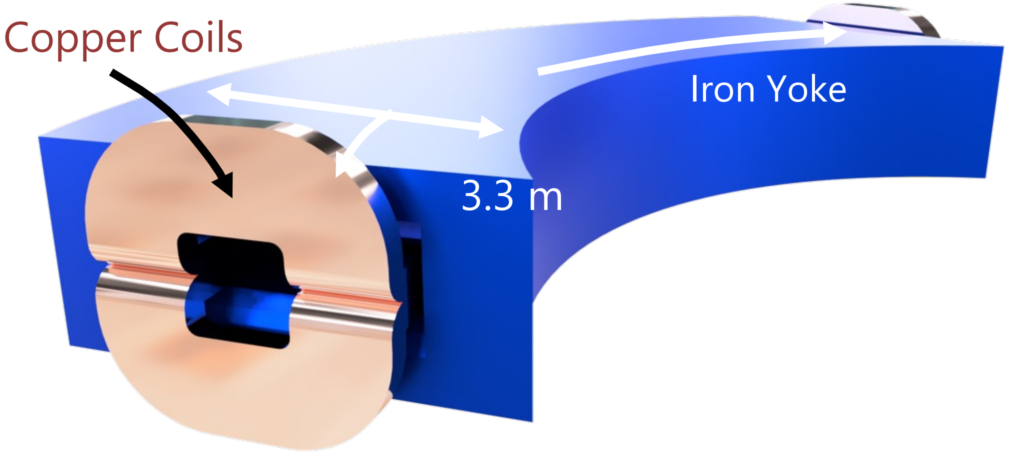
Dynamic losses		
Stainless steel components	1.76 W 0.44 W	system/coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	0.19 W 0.048 W	system/coil Mean power deposition during cycle
Thermobus	3657 W 914 W	coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	398 W 99 W	coil Mean power deposition during cycle
HTS hysteresis loss	230 J/cycle	coil Peak power deposition during 1 T/s / 0.5 T/s ramp
	25 W	coil Mean power deposition during cycle

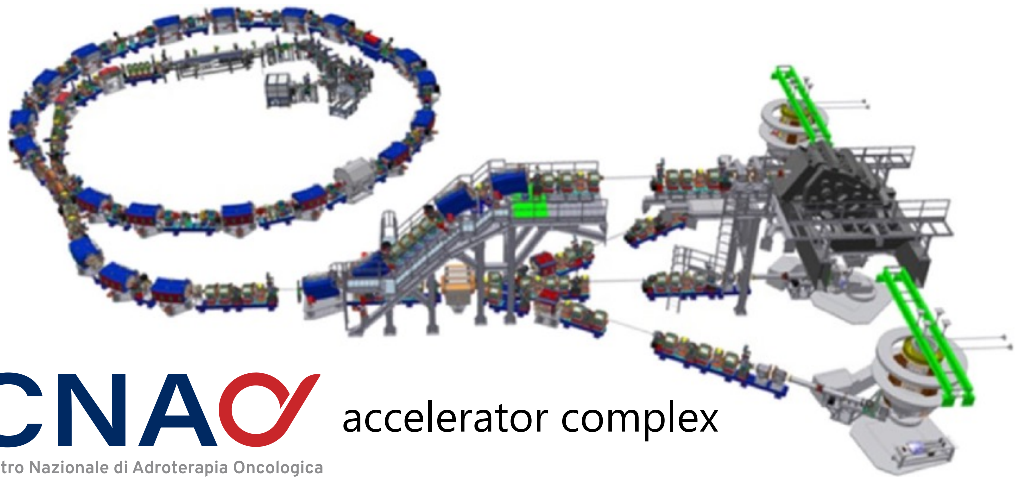
Example 2

MgB_2 Upgrade of an iron dominated magnet at CNAO

Work done by S. Mariotto, S. Busatto, S. Sorti, L. Rossi

Ramped magnet case study





CNAO Centro Nazionale di Adroterapia Oncologica 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**: $\pm$ 2E-4 $\Delta B/B_0$ in 200x200 mm^2 aperture
2. **Duty cycle** depends strongly from patient treatment

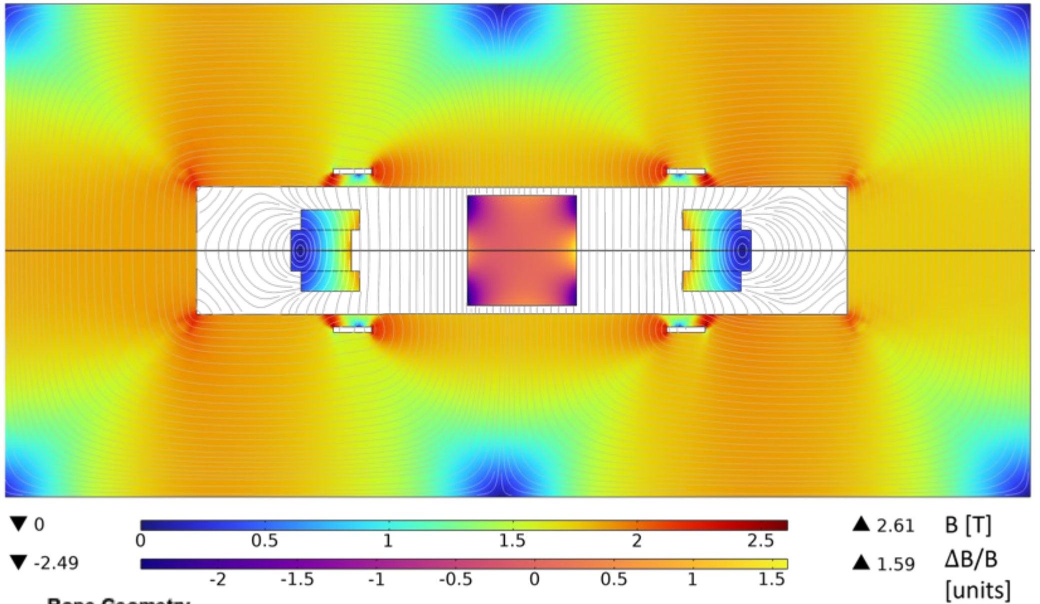
30 kW DC
262 MWh/year

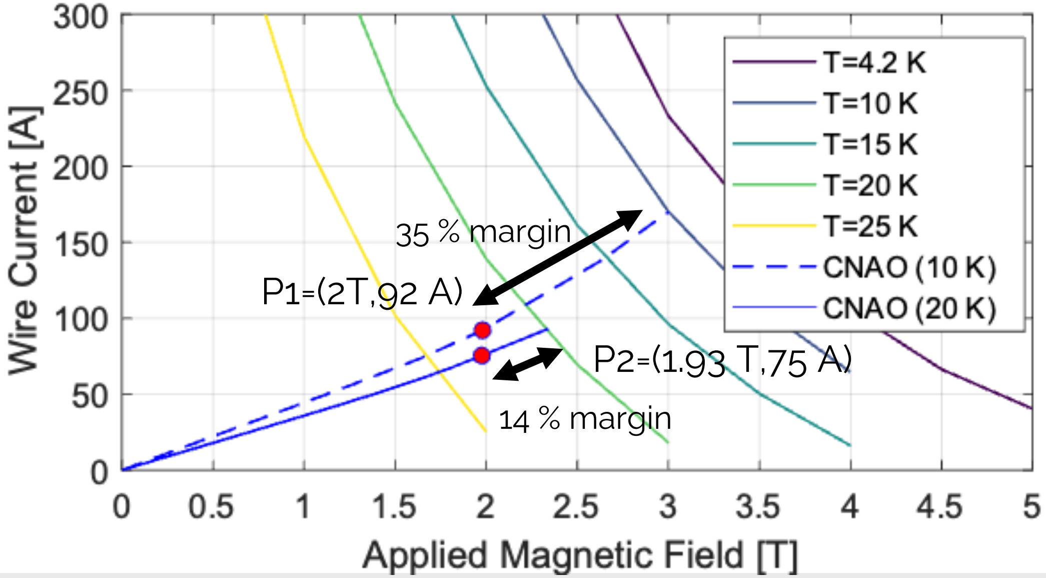
EM Design @ T=20 K

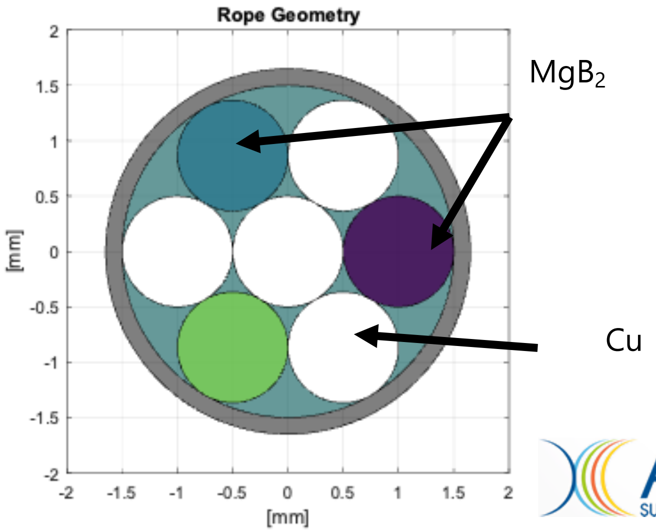
Target of the electromagnetic design optimization:
- Magnetic field of 1.74 T at center

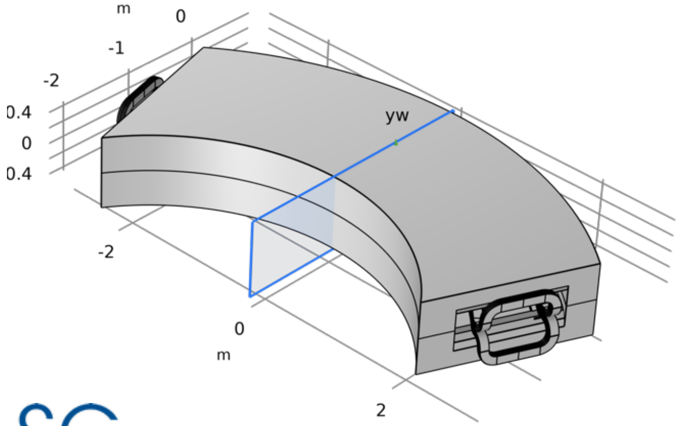
Two operating temperature considered:
- 10 K
- 20 K (shown here)

Use of a rope (3 MgB_2 conductors and 4 copper wires).
  - 756 ropes carrying 226 A @ 1.93 T
  - 14% margin LL – 3.6 K temperature margin.





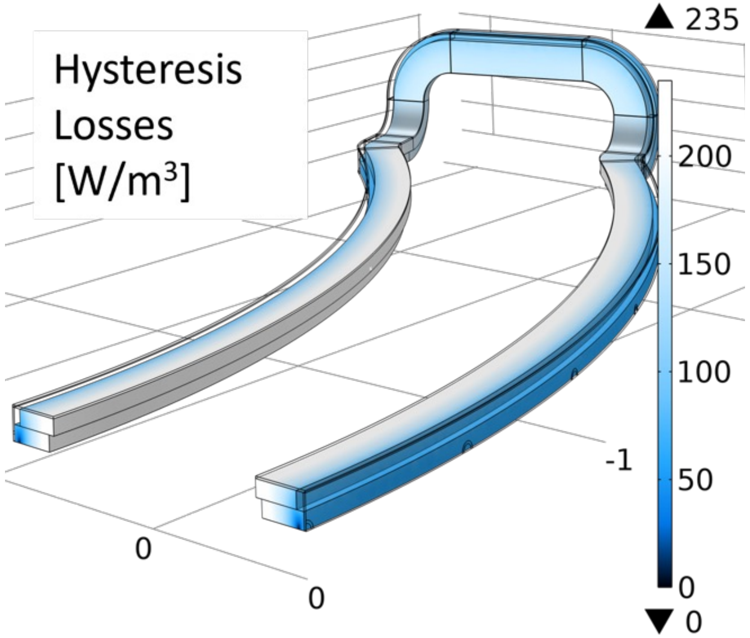




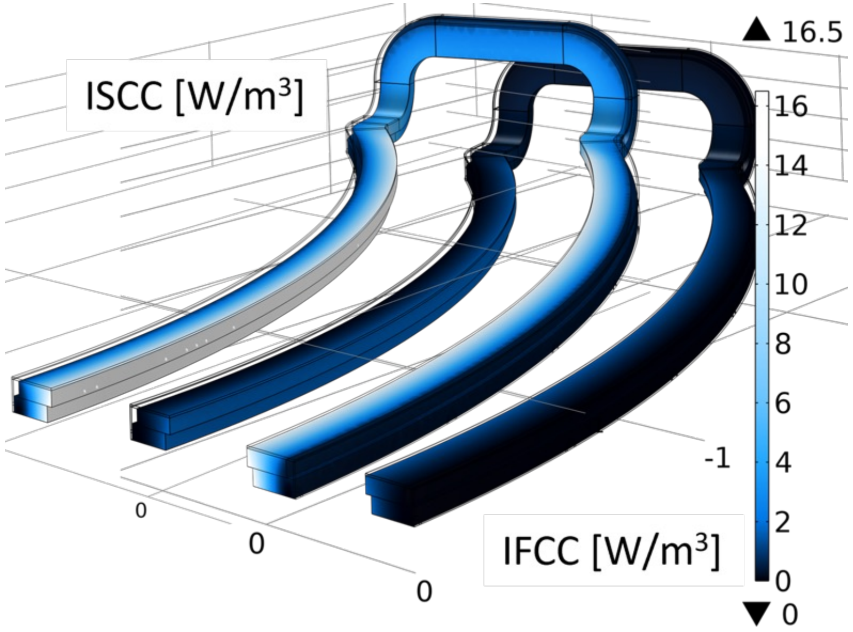
AC Loss

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

- Filament diameter equals to 55 μm
- 3D static heat map source
- Superconductor magnetization parallel to conductor has been neglected



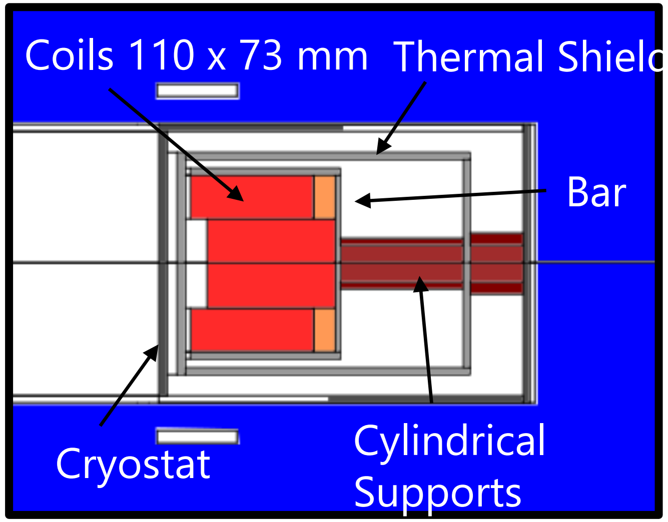
Time averaged Losses	Hysteresis
Design @ 10 K	37.2 [W]
Design @ 20 K	34.2 [W]



IFCC and ISCC: $f\,(\rho_{eff}, L_{Pitch})$

Time averaged Losses	ISCC	IFCC
Design @ 10 K	2.02 [W]	0.22 [W]
Design @ 20 K	1.55 [W]	0.17 [W]

Mechanical Design



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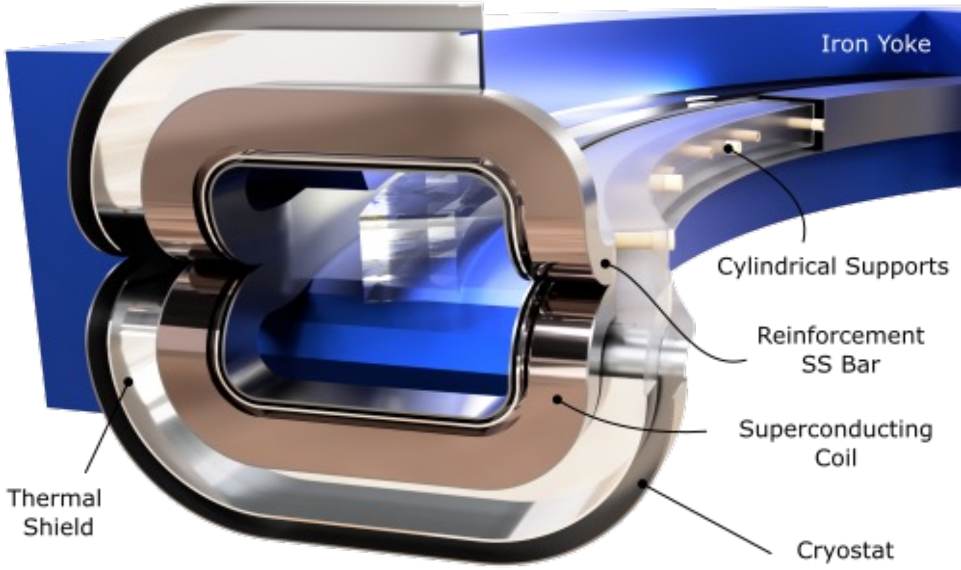


- 5-mm-thick SS 316LN **reinforcement bar** around coils to limit deformations.
- A distributed **set of 36 G10 cylindrical supports** is adopted to sustain an active aluminium **thermal shield** (@ 60 K) and coils (@ 20 K).
- Aluminum **thermal shield** (6 mm thickness) working **@ 60 K** covered with **30 MLI** layers (minimization of radiation load).

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

≈ 7 times lower

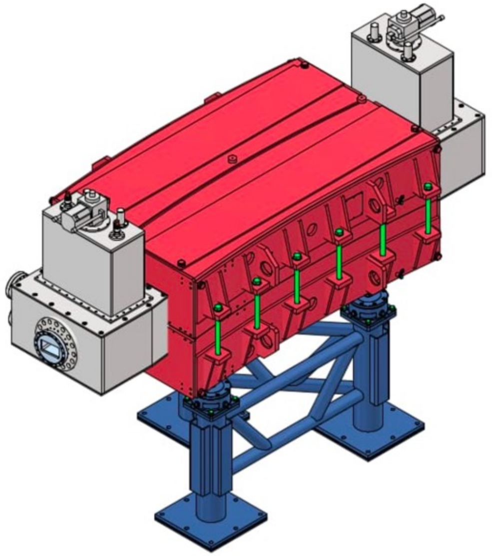
Summary and Outlook

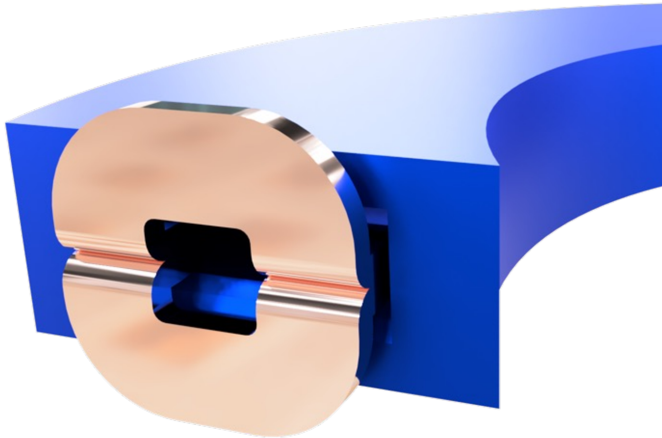
- Two examples for upgrade paths for existing ramped iron dominated magnets.
- Two very different solutions with similar properties

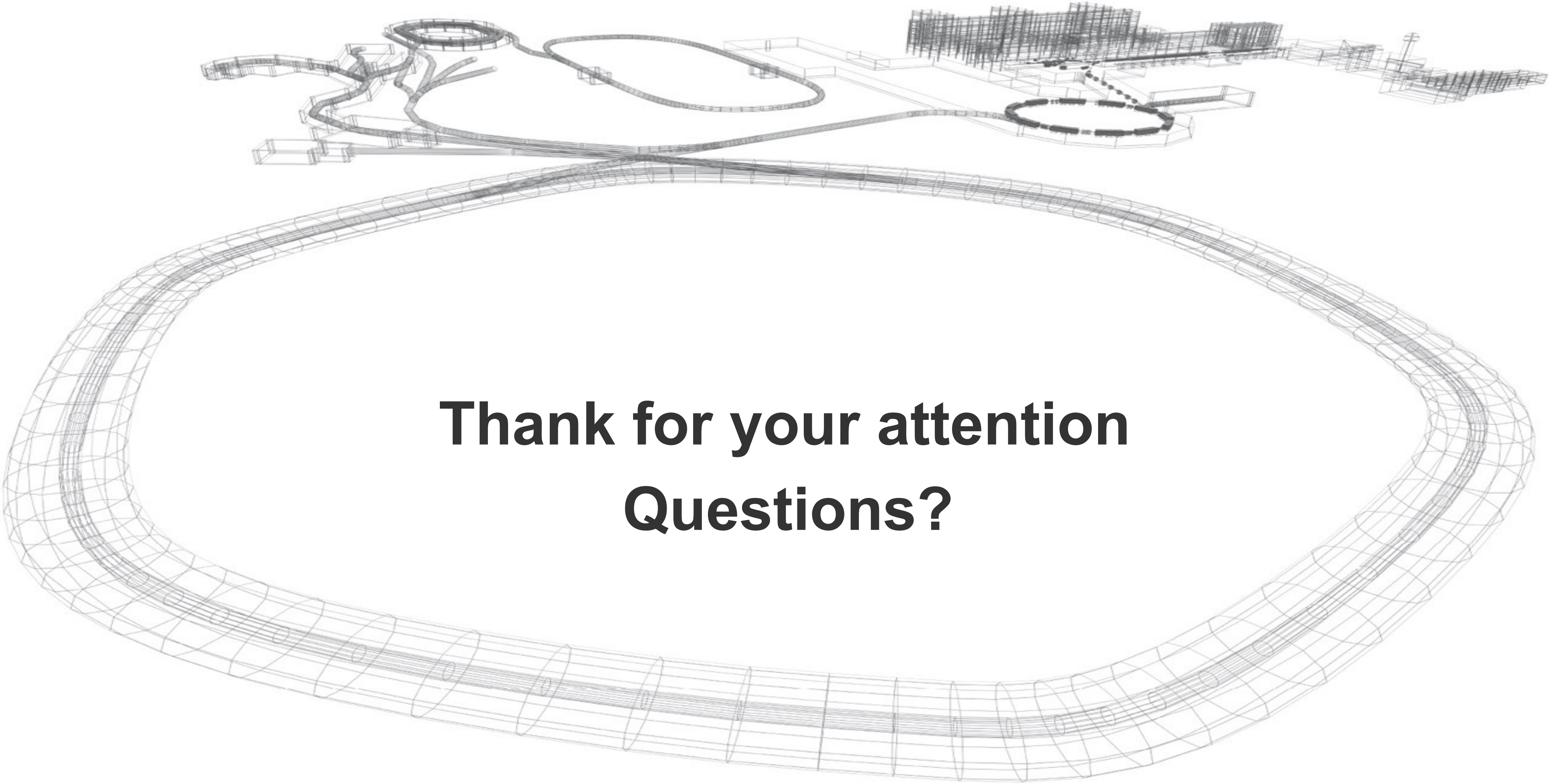
- HTS energy saving magnet at GSI:
  - Energy saving of up to 60% (DC) possible, strongly depends on the duty cycle and current
  - Possible procurement of prototype magnet planned

- MgB_2 beam steering magnet at CNAO:
  - Energy saving of up to 80% possible, again dependent on the duty cycle

- Main conclusion
  - Careful balance of duty cycle and magnet design needed, it is not a no-brainer
  - Superconductivity can reduce energy consumption but careful balancing with operation is necessary, DC operation vs. ramped operation







Thank for your attention

Questions?