Magnets for RFMTF

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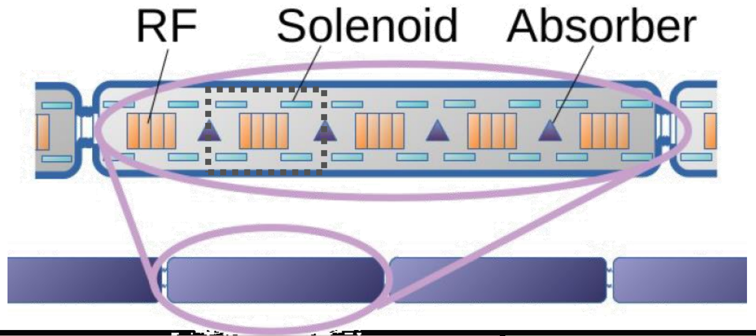
Outline

- Muon Collider 6D cooling
- Why HTS coils?
- Do we need a test stand?
- The RF Magnet Test Facility

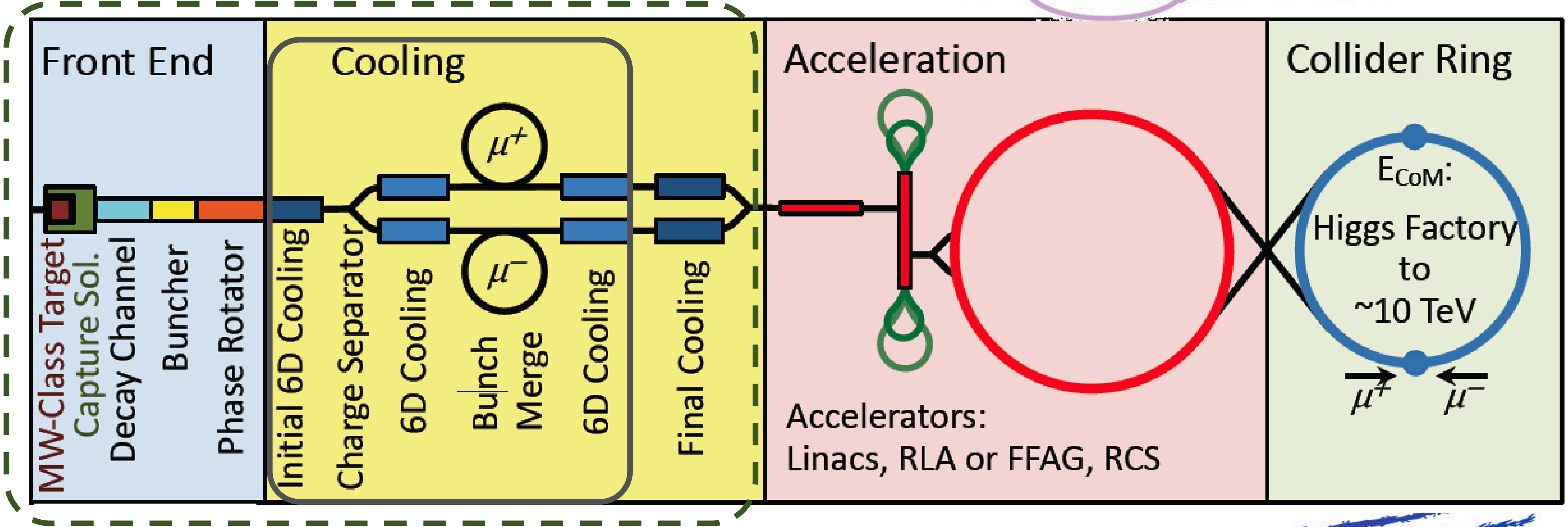
Muon Collider 6D cooling magnet

2 km of 6D cooling
2432 solenoids

6D Cooling solenoids
Field: 4 T … 14 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD



TASK 7.2

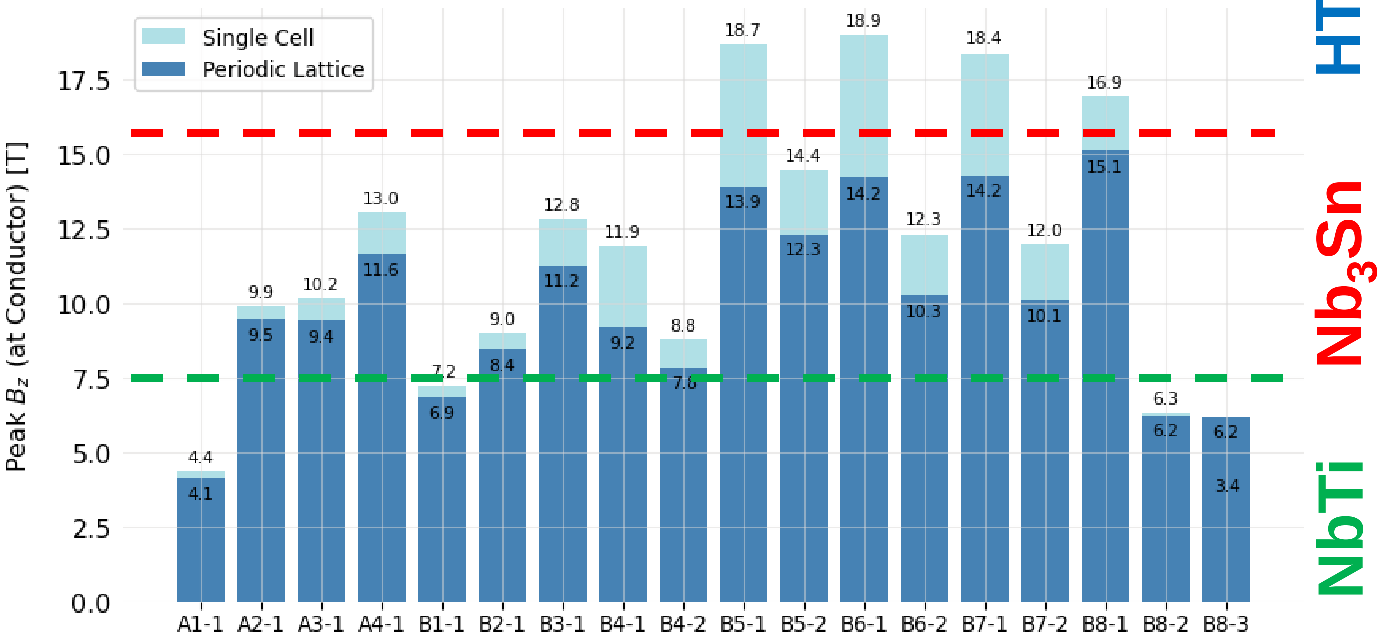


Selected features

We have a full catalogue based on US MAP original design (field on axis)

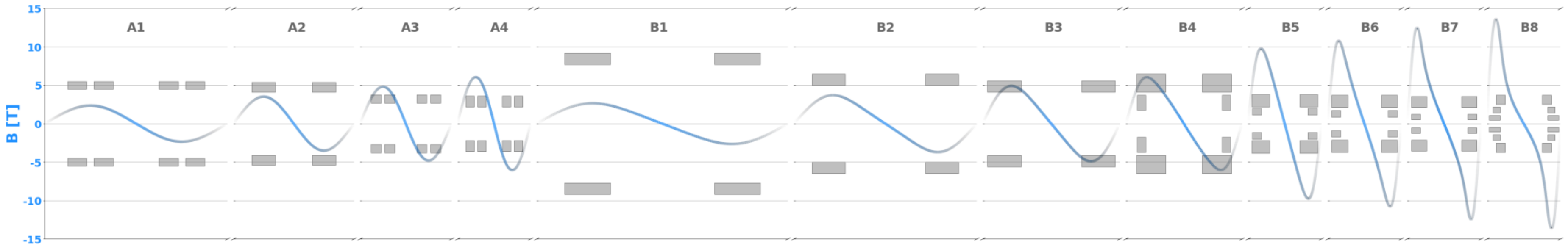
- 12 unique stages:
  - 4 cooling stages *before* bunch recombination (A1-A4)
  - 8 cooling stages *after* bunch recombination (B1-B8)
- *Each stage has a repeating series of a cell type*
- High field, very compact solenoids
- Each cell has symmetric solenoids of opposite polarity

Courtesy of S. Fabbri and J. Pavan



Some stats:

- Fields on axis: 2 to 14 T
- Cell Lengths: 0.8 to 2.7 m
- Total length of all Stages: ~ **2 km**
- Total number of solenoids: 2432

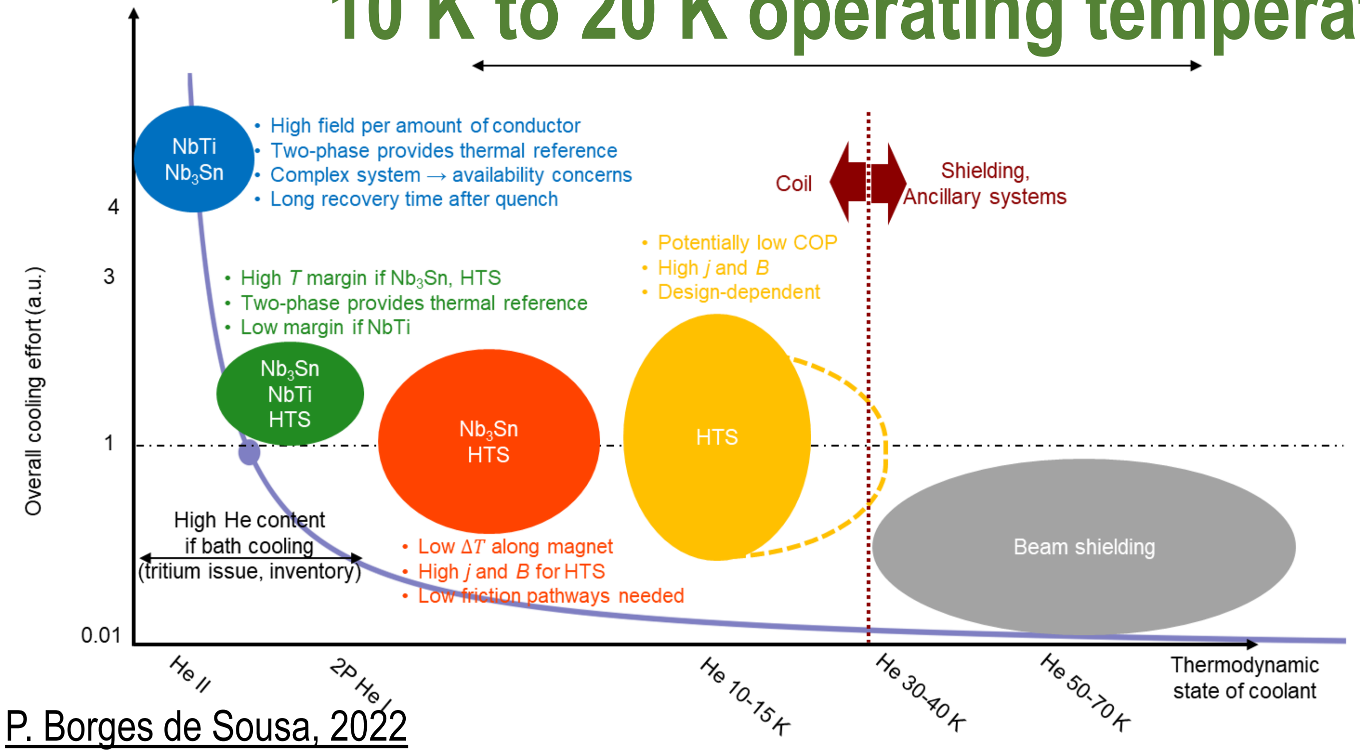


HTS conductor at 20 K

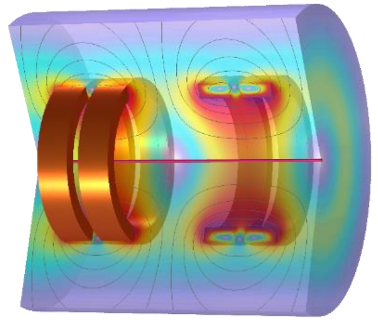
3 pillas of design:

Performance (field and field quality), Cost and Sustainability

10 K to 20 K operating temperature



P. Borges de Sousa, 2022



Technology options

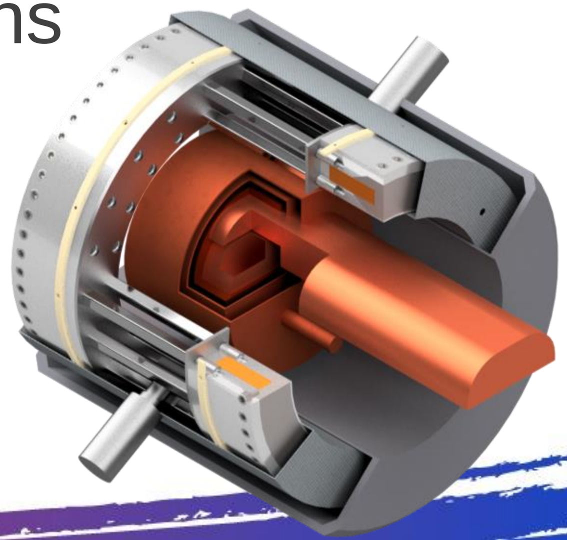
Stage	[1] Cell Length [m]	[1] Solenoids/Cell	[2] Peak Bz field on axis [T]	[2] Stored Magnetic Energy [MJ]	Coil	Technology Options: NbTi (4 K)	Nb3Sn (4 K)	HTS (4 K)	HTS (20 K)
A1	2	4	2,4	5,38	A1-1	X	X	X	X
A2	1,32	2	3,5	15,35	A2-1		X	X	X
A3	1	4	4,8	7,23	A3-1		X	X	X
A4	0,8	4	6,1	8,39	A4-1		X	X	X
B1	2,75	2	2,6	44,54	B1-1	X	X	X	X
B2	2	2	3,7	24,1	B2-1		X	X	X
B3	1,5	2	4,9	29,83	B3-1		X	X	X
B4	1,27	4	6	24,4	B4-1		X	X	X
					B4-2		X	X	X
B5	0,806	4	9,8	12,03	B5-1			X	X
					B5-2		X	X	X
B6	0,806	4	10,8	8,19	B6-1			X	X
					B6-2		X	X	X
B7	0,806	4	12,5	5,65	B7-1			X	X
					B7-2		X	X	X
B8	0,806	6	13,6	1,42	B8-1			X	X
					B8-2	X	X	X	X
					B8-3	X	X	X	X

To be investigated

We are defining technologies
- Conductor
- Operation condition, i.e. temperature an cooling method

To be investigated
- Conductor performance
- Conductor configuration
- Field quality
- Thermal/mechanical configuration

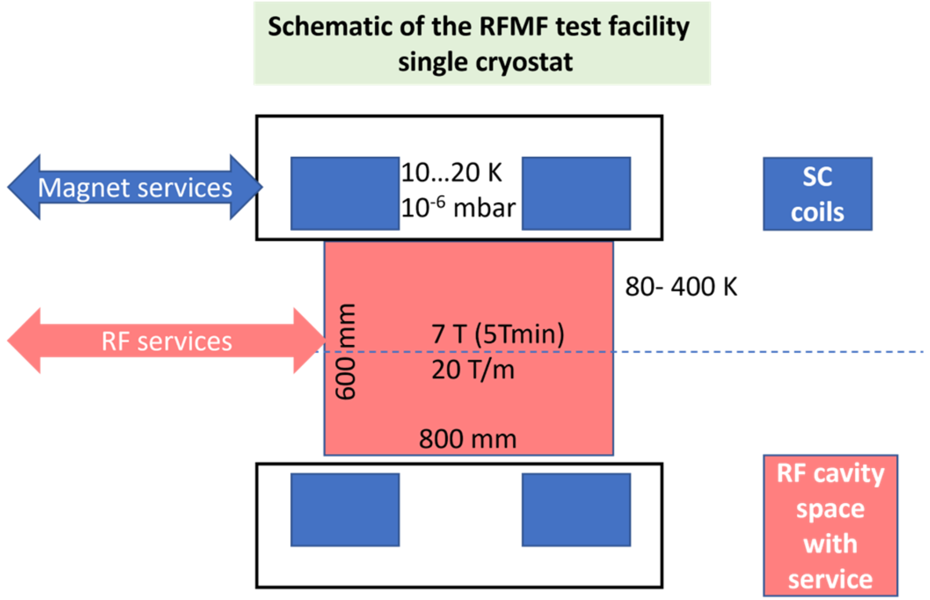
Why a test stand?
- RF test in field and in field gradient
- Develop coils technology (increase TRL)
- Test of conductor, mechanical and thermal options

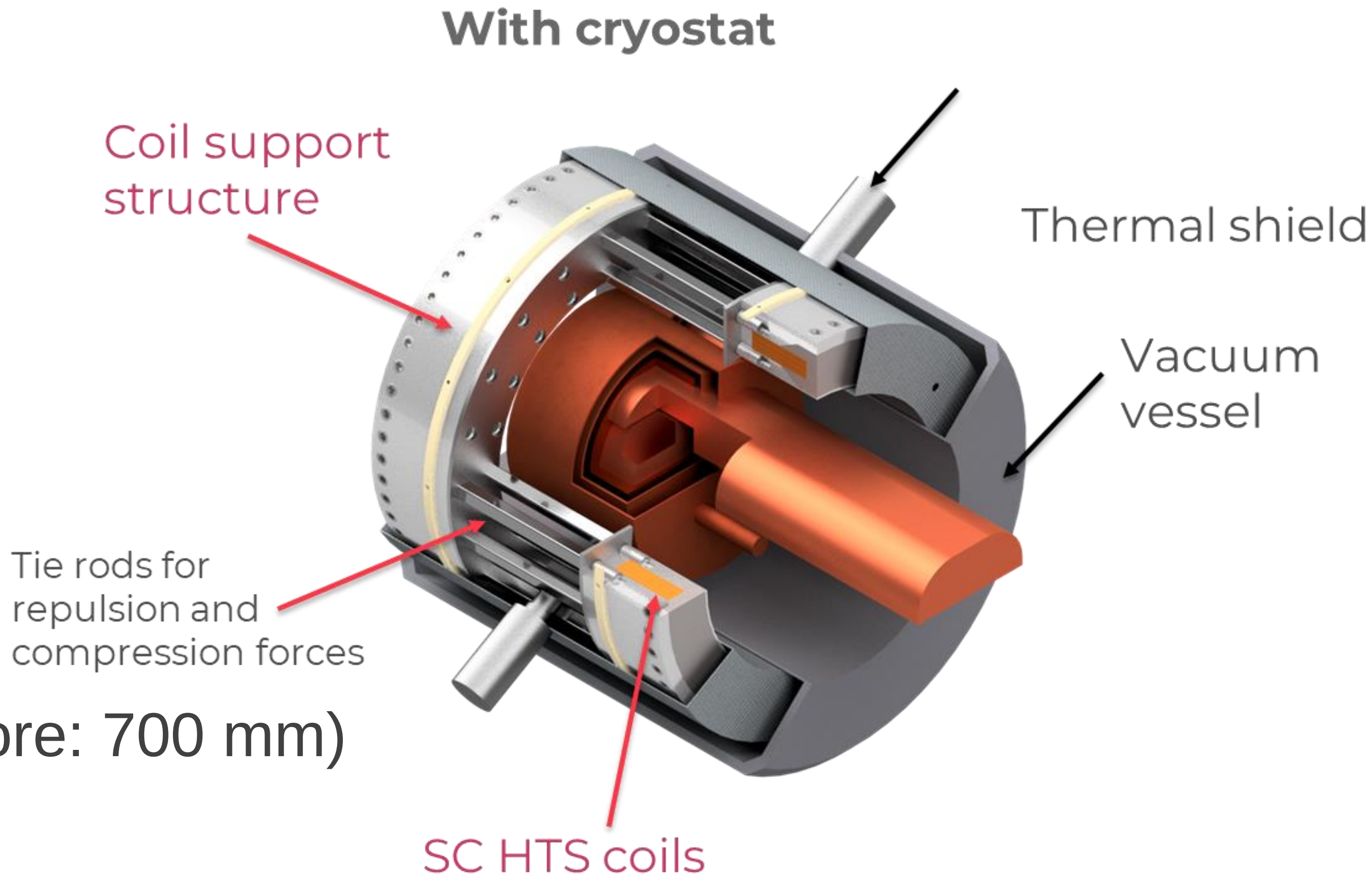


Technologies 6D cooling solenoids

Technology	Pro's	Con's
LTS	Known technology (TRL 9)	Operating temperature
HTS ReBCCO Insulated	More compact than LTS/HTS Allows for operation at higher temperature Batch above 100 m demonstrated	R&D at low readiness (TRL 4/5) Quench detection protection Production of km batches to be demostrated
HTS ReBCCO Non-insulated	Most compact magnet winding Synergies with other fields of science and societal applications Batch above 100 m demonstrated Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated Quench detection and protection Production of km batches to be demostrated
HTS BiSSCO/IBS	Round wire demonstrated for BiSSCO	R&D at low readiness (TRL 3/4) for IBS Production lengths (?)

RFMTF – initial guess





- 700 MHz to 1300 MHz and 3GHz
- Inner diameter coil 800 mm (free bore: 700 mm)
- Distance between coils 800 mm
- Field 7 T (margin up to ~10 T)
- Dual powering scheme: same and opposite magnetic field

Cost evaluation of the first design

- Cost evaluation by L. Rossi for HTS coil and by M Castoldi (INFN-LASA) and A. Kolehmainen (CERN/EN-MME) for mechanics and cooling system

- The bottom line that the HTS magnet with 800 mm dia. is expensive:
- 45 km of REBCO tapes 12 mm cost about 3 MCHF (plus taxes)!!!
- The coil manufacturing and structure > 1 MCHF; the cryostat and services about 1 MCHF
- 5 MCHF minimum total cost (crude evaluation)
- HTS remains our basic choice in view of then MC design

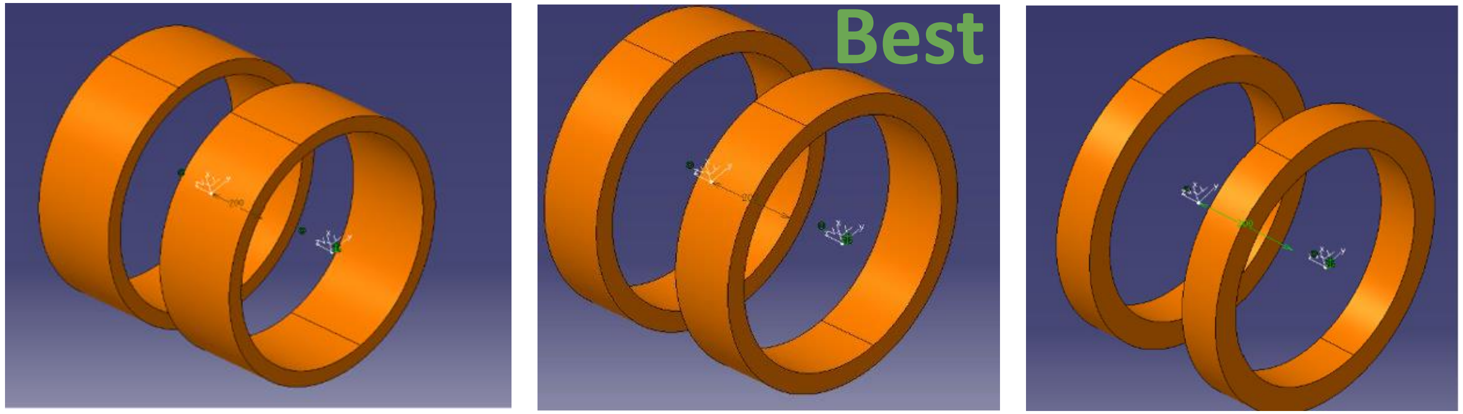
Decision summer 2023

- Redesign to 300-350 mm free bore
  - → coil dia. ~ 400 mm
  - → good for 3 GHz test or higher frequency
  - 7 T, parallele and antiparallel coil excitation
- Try to optimize solution for cost saving
- Redesign **by IMCC CM of March 2024**
  - Conclude the 800 mm dia. coil design
  - Detailed design of the 400 mm dia. System → cost target **< 2 M€**

Magnetic design

Redesign to 320 mm FREE BORE
3 coils configuration

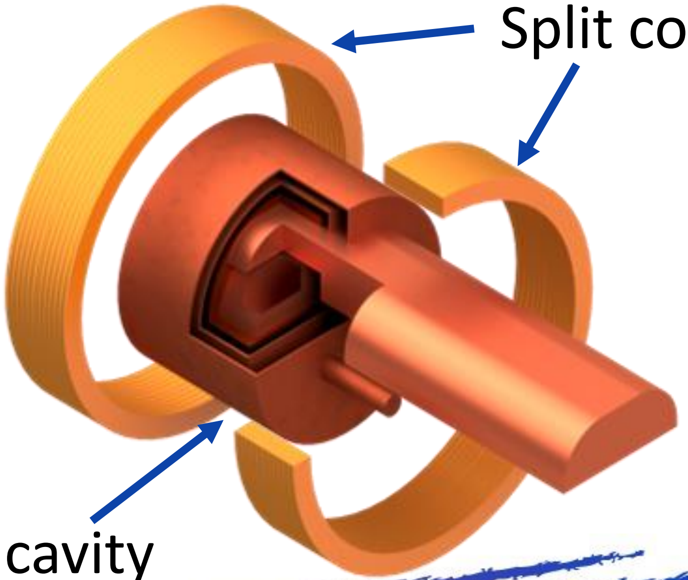
NI winding



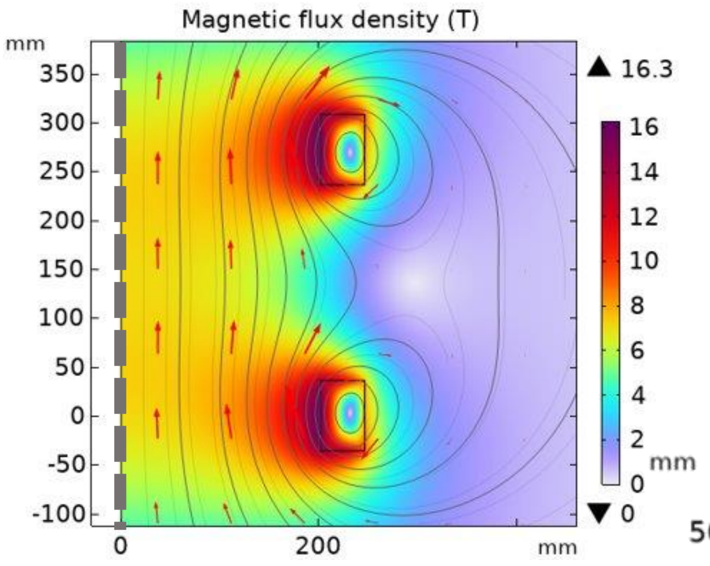
Parameter	Symbol	Value
Current density	J (A/mm^2)	621.8
Bore diameter	d (mm)	400
Coil distance	L_{gap} (mm)	200
Coil thickness	T_{hcoil} (mm)	45.56
Coil width	W_{coil} (mm)	72
Number of turns	N_{turns}	4080
Tape width	T_{width} (mm)	12
Tape thickness	T_{thick} (mm)	0.067
Tape cross section	T_{cross} (mm^2)	0.804
Radial Young's modulus	E_r (GPa)	69
Axial Young's modulus	E_z (GPa)	144
Azimuthal Young's modulus	E_h (GPa)	144

Inner diam.	**400 mm**
Coil distance	200 mm
Cross section	46x72 mm^2
turns	4080
Tape length	**11 km**

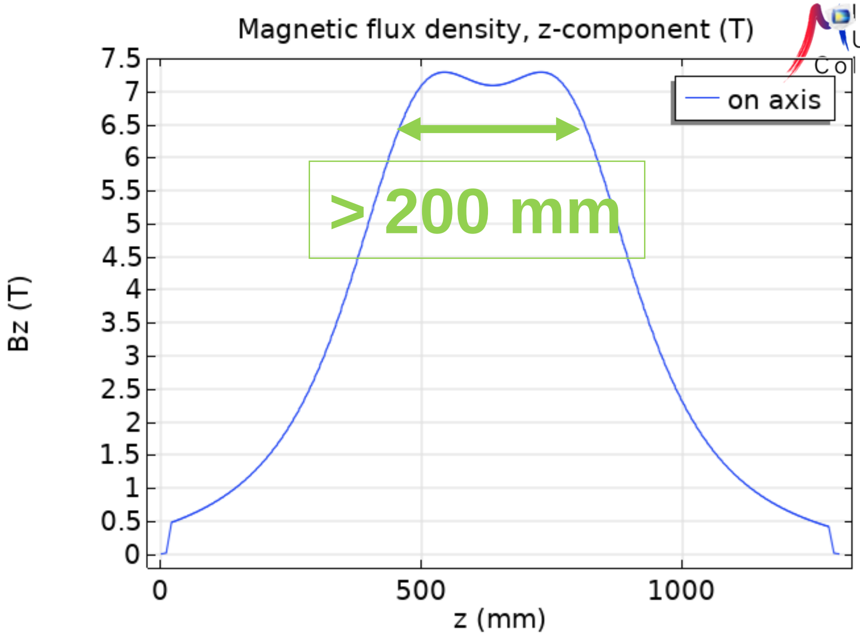
Courtesy of D. Batia



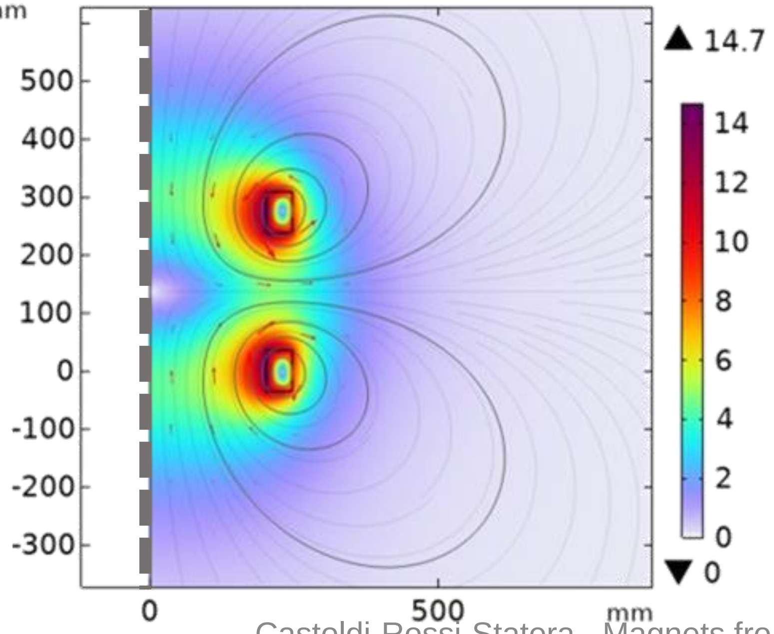
Magnetic field

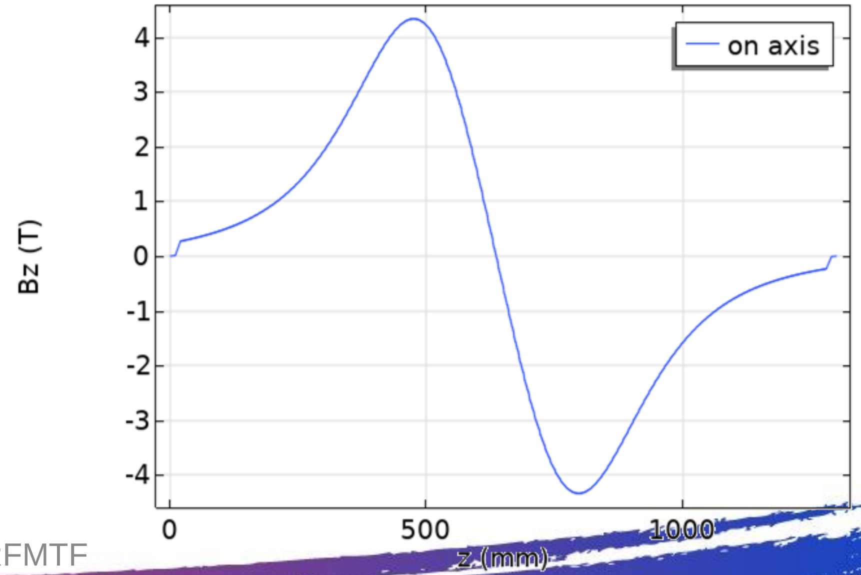


Same polarity



Opposite polarity

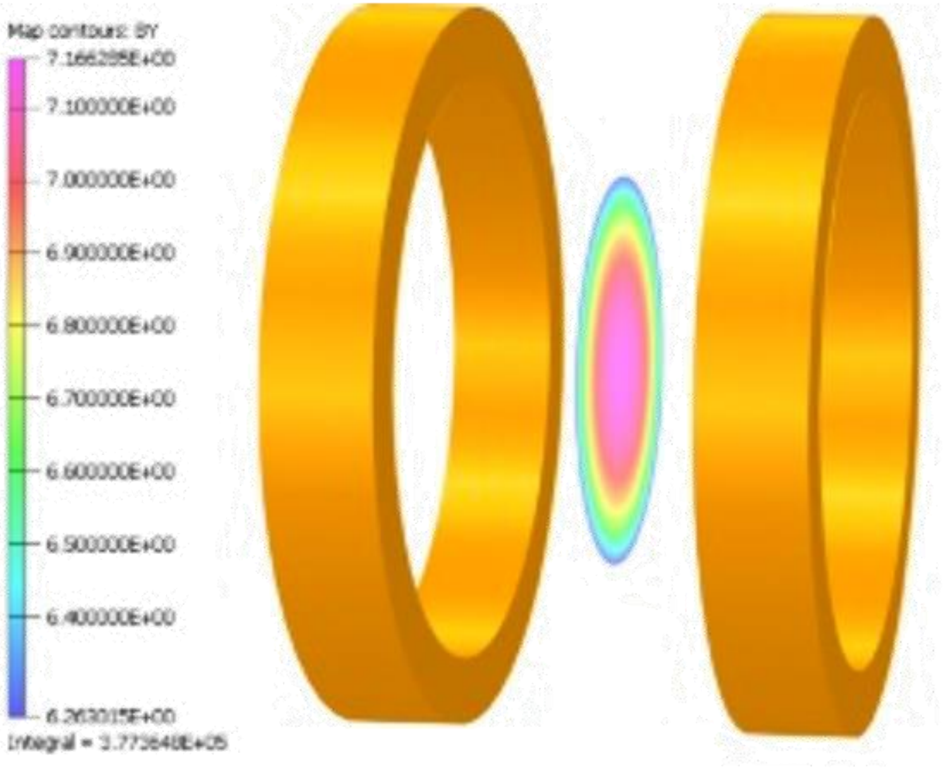




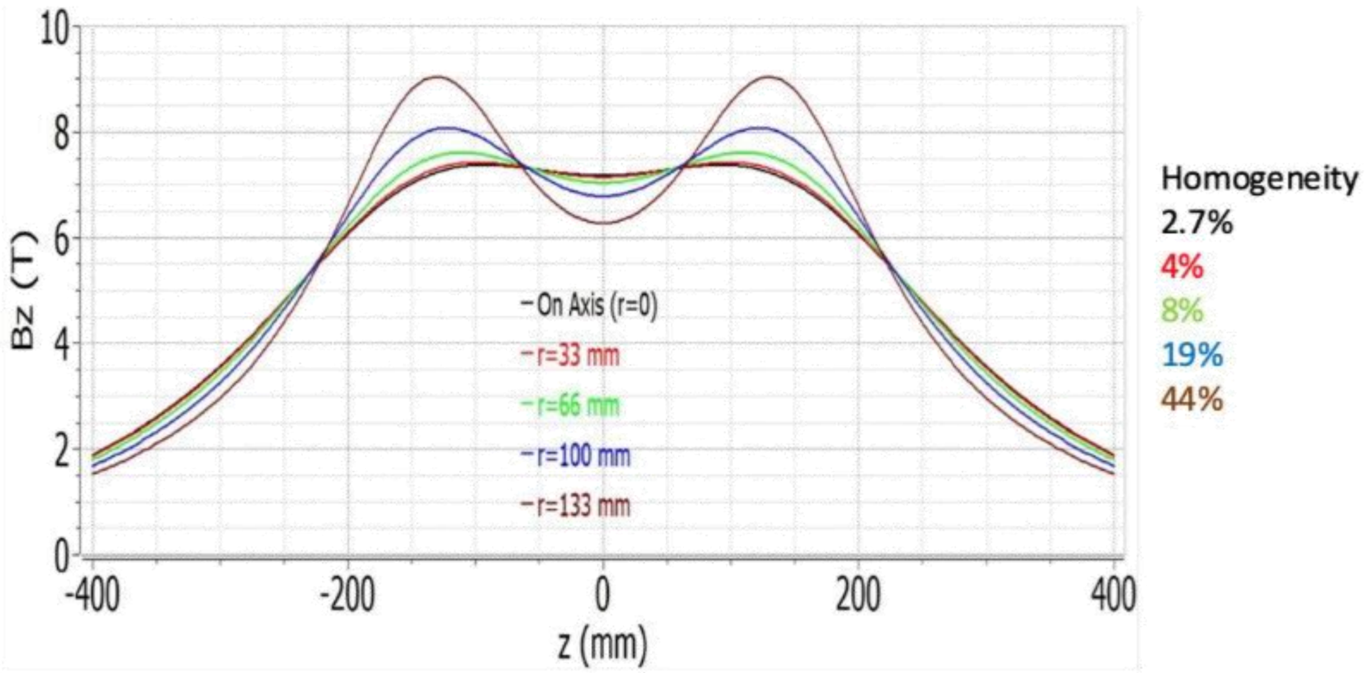
Field homogeneity

Field homogeneity calculated in the region between the two peaks of the axial component of the magnetic field

$$\frac{B_{z,peak} - B_{z,center}}{B_{z,peak}}$$



(a) *Same polarity configuration*



(b) *Same polarity configuration*

Mechanics main results

	Same polarity	Opposite polarity
B_z al centro (T)	7,09	4,34
B_max (T) (sulla coil)	16,28	14,69
Forza radiale F_r (MN)	10,2	6,37
Forza assiale F_z (MN)	2,06	2,08
Von Mises stress Max (MPa)	649,11	413,62
Von Mises stress Min (MPa)	460,11	295,65
sigma_t max (GPa)	0,62	0,42
sigma_t min (GPa)	0,44	0,27
sigma_r max (MPa)	0	0
sigma_r min (MPa)	-79,74	-80,47
sigma_z max (MPa)	0	45,05
sigma_z min (MPa)	-144,19	115,17

High forces, better manageable with one single structure

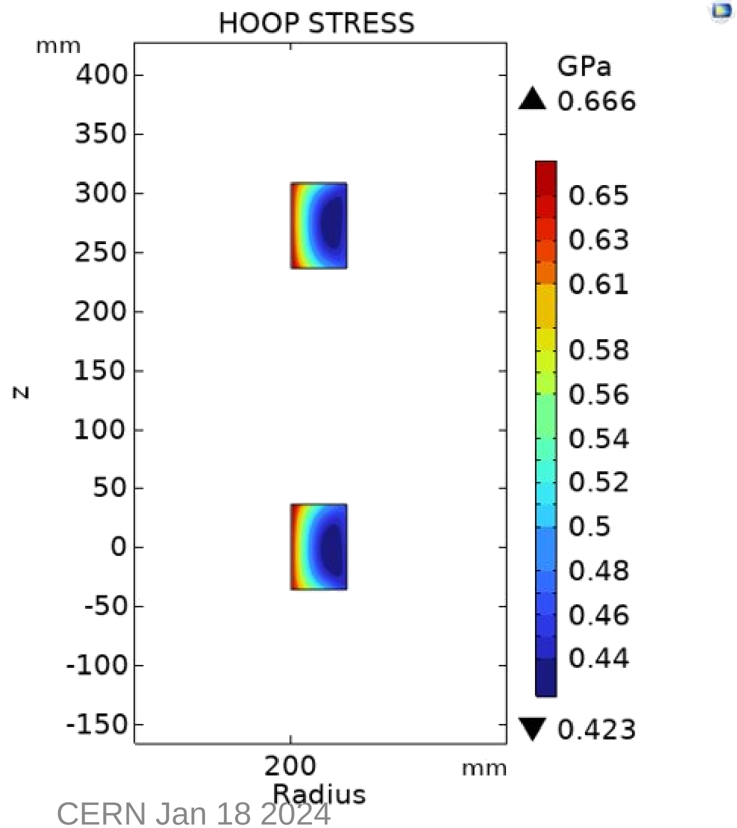
Too high for unsupported HTS tape: add an external banding. Reduce to 300 MPa

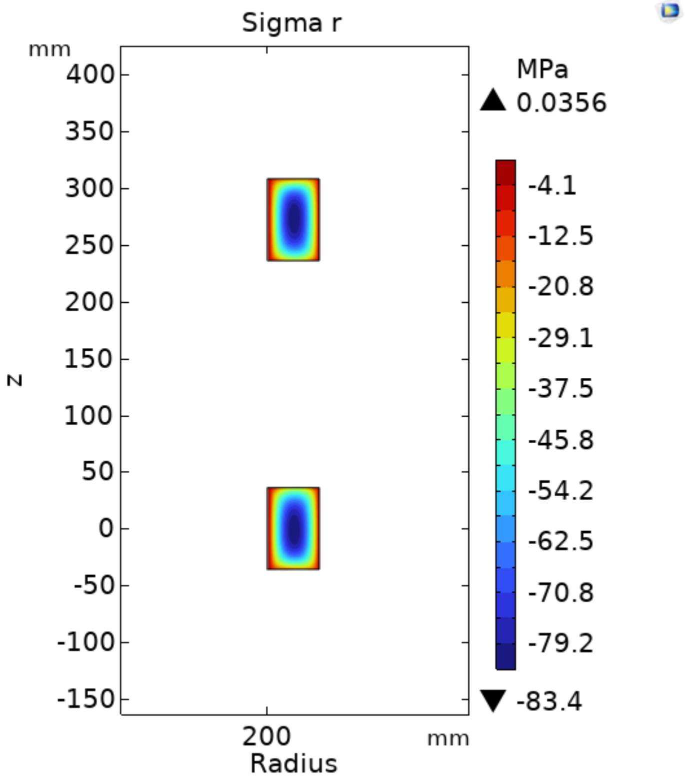
Stress on coils

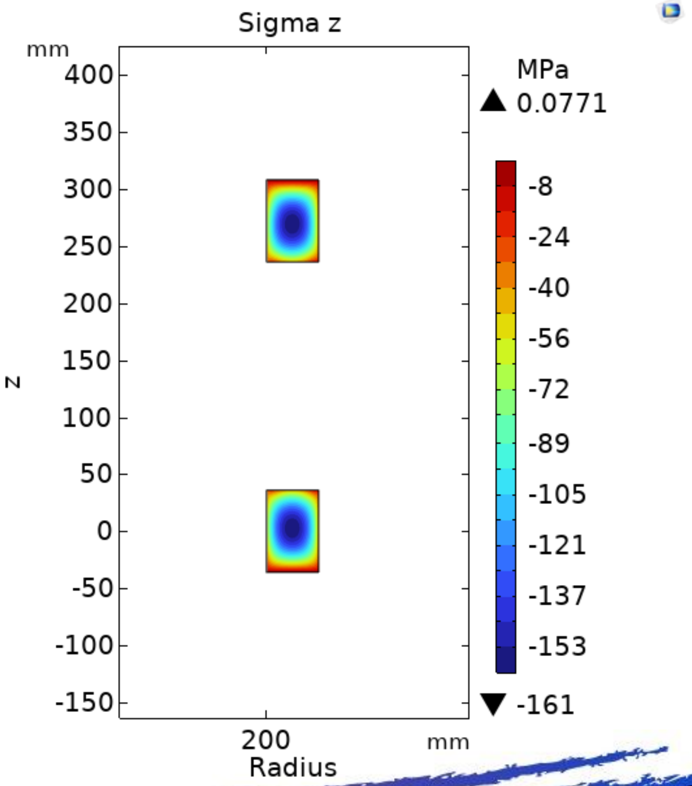
Force volume density: $\mathbf{F_L = J \times B}$

Maximum hoop stress (same polarity): **666 MPa**

Coils non-supported in the simulation, supported coils simulations ongoing

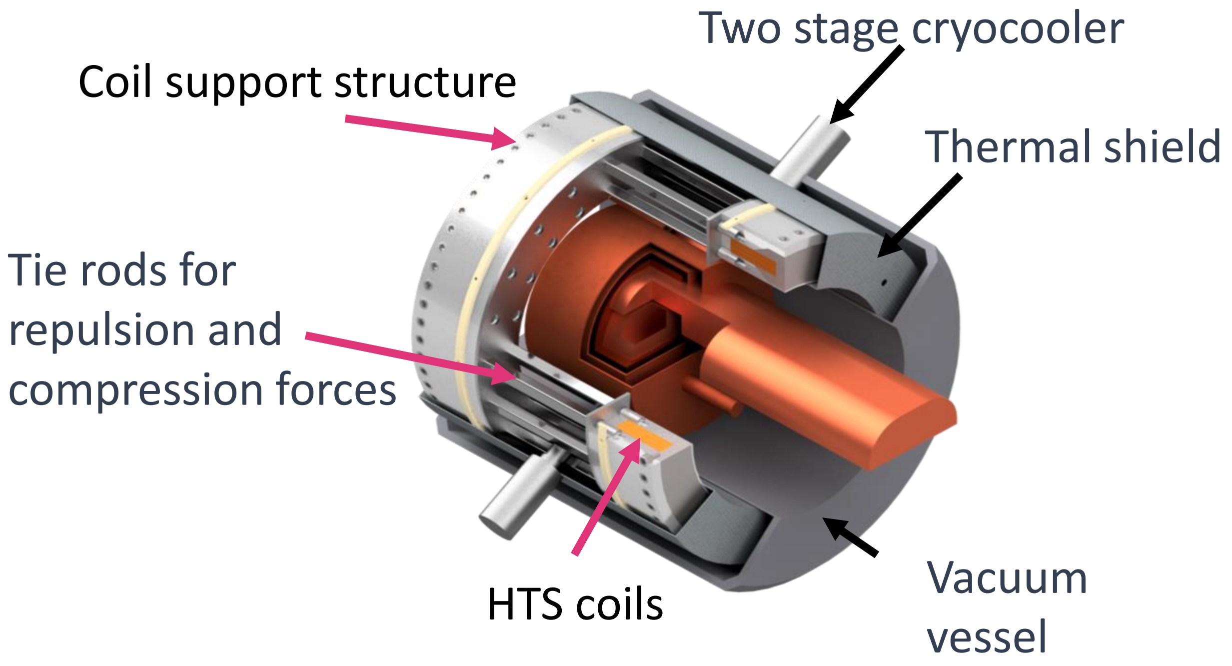


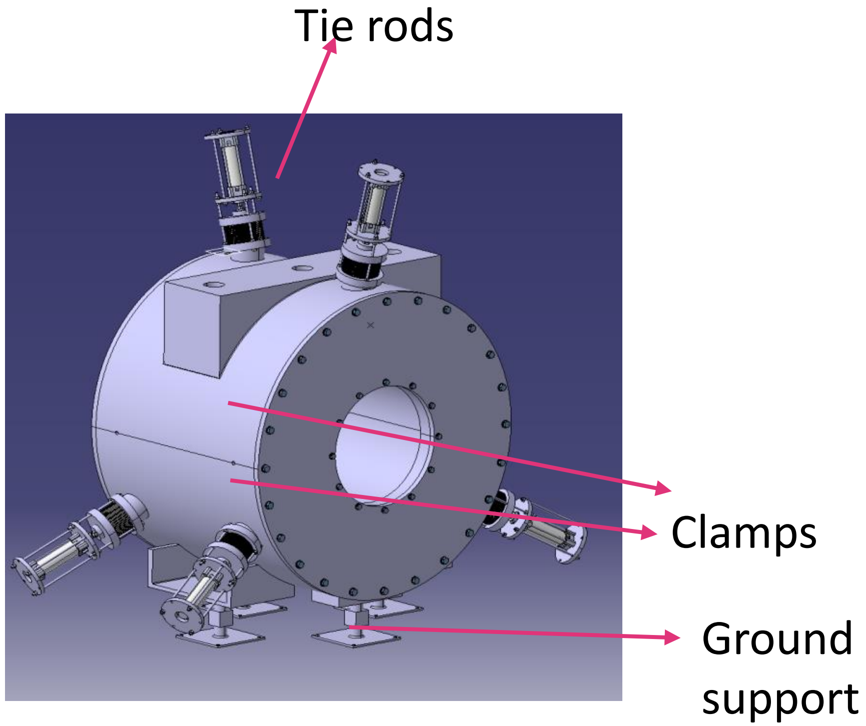




Mechanical Analysis

- Full plasticity regime (ε > 0.2 %) → reduce the hoop stress to ~ 300 MPa

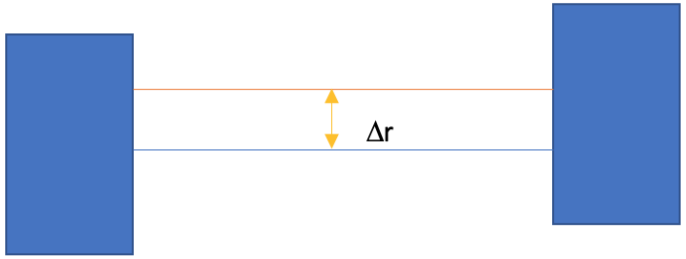




Assembly tolerances

Not aligned coils		
Current polarity	Same	
Total Radial Force/mm (N/mm)	-7840	Attractive
Total Momentum/mm (Nm/mm)	-831	destabilizing
Current polarity	Opposite	
Total Radial Force/mm (N/mm)	7840	Repulsive
Total Momentum/mm (Nm/mm)	831	Stabilizing

Tilted coil faces		
Current polarity	Same	
Total Radial Force/mrad (N/mrad)	-27	Attractive
Total Momentum/mrad (Nm/mrad)	165	Stabilizing
Current polarity	Opposite	
Total Radial Force/mrad (N/mrad)	27	Repulsive
Total Momentum/mrad (Nm/mrad)	-165	Destabilizing



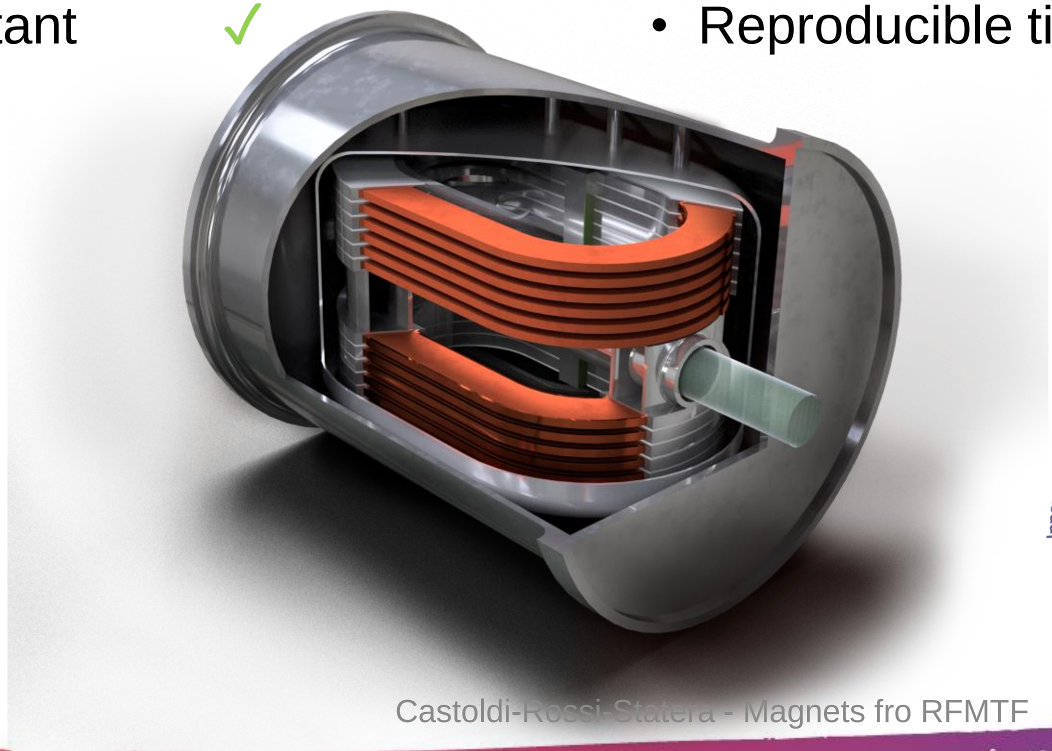
Assembly tolerances not extreme: 0.2-0.3 mm

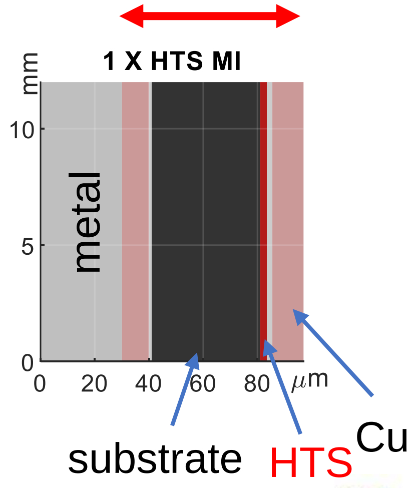
Forces and torques change direction with polarity

Non Insulated coils Vs Metal Insulated

- Higher current density ✓
- Higher thermal stability ✓
- Lower risk of Quench ✓
- Long charging time ×
- Variable time constant ✓

- Higher Joule dissipation ×
- Compatible with splices ✓
- Higher current ×
- Lower charging time ✓
- Reproducible time constant ✓





Courtesy of S. Sorti

Preliminary heat load calculation

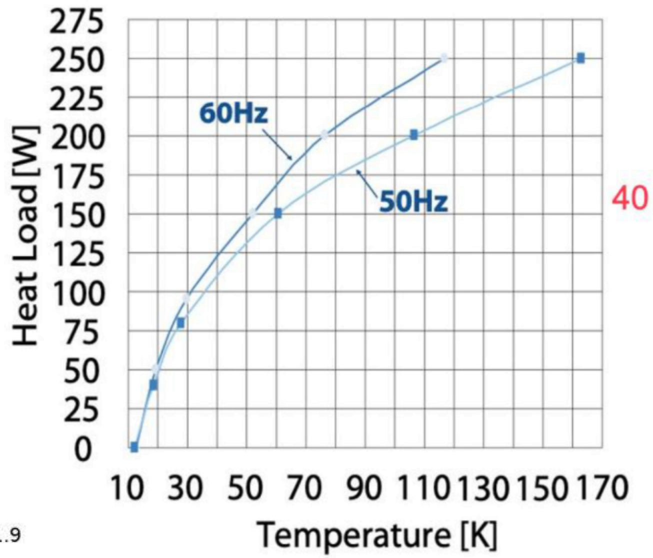
Static heat loads	Screen [W]	Coils [W]
Radiation	100	1
conduction	2	6
Current leads	110	2
TOTAL	**212**	**8**

By C. Santini, D. Batia, E. Beneduce, M. Castoldi

Dissipation during charge (20 h) = 13 W @ 20 K

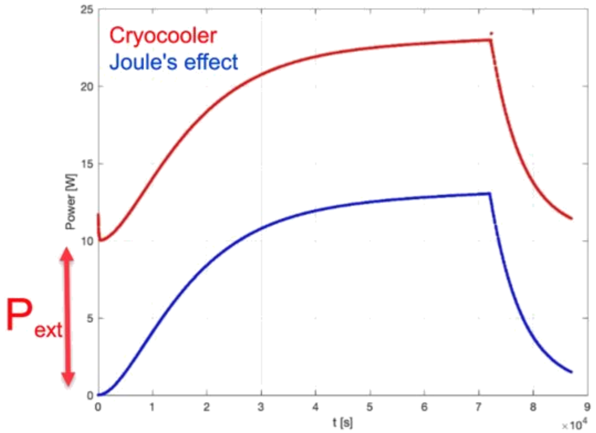
SRDK-500B Cold Head Capacity Map (50/60 Hz)

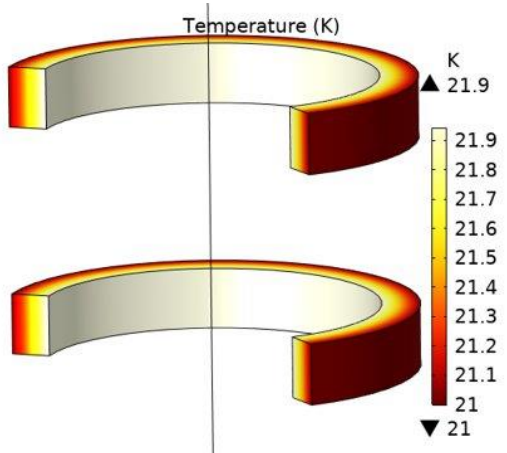
With F-70 Compressor and 20 m (66 ft.) Helium Gas Lines



40 W, T=20 K

Temperature durign a ramp (preliminary)

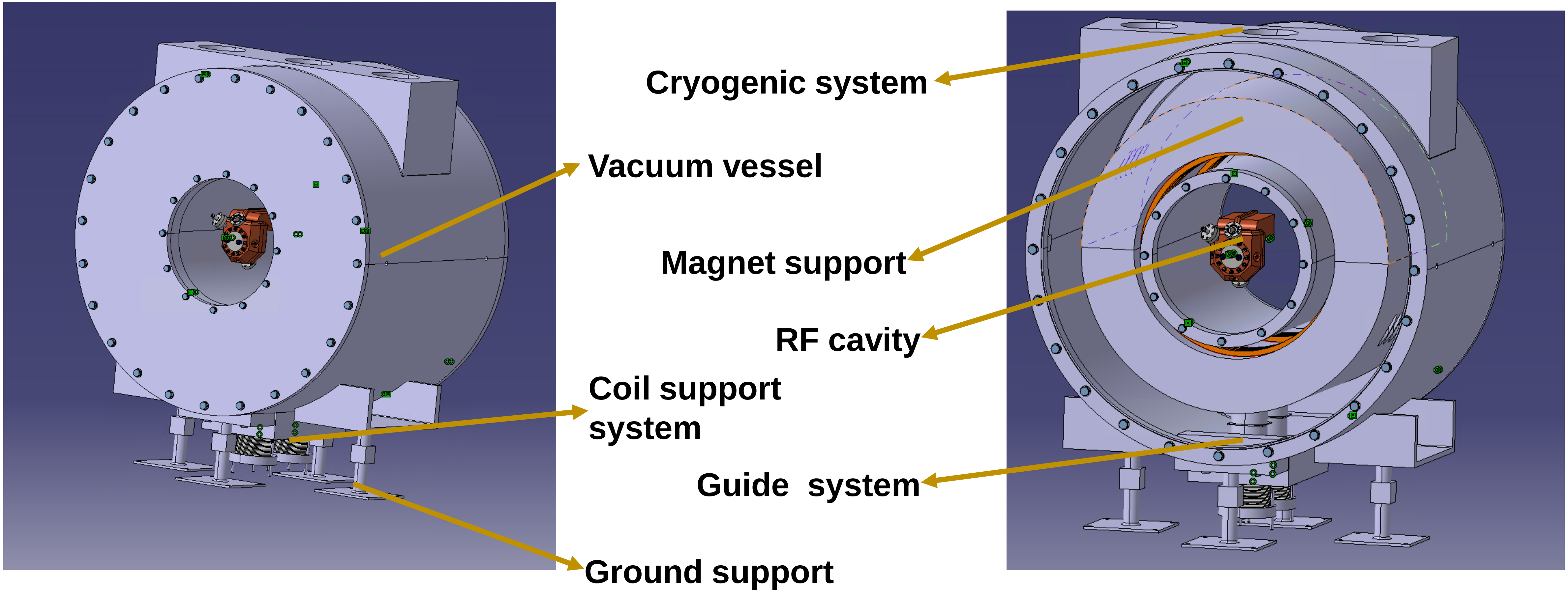




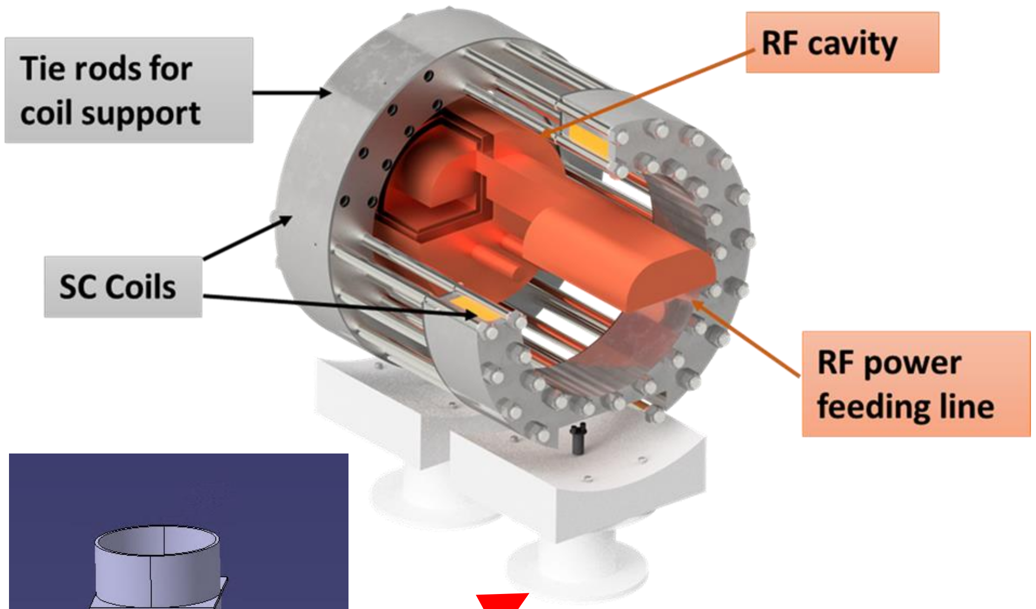
Temperature homogeity (preliminary)

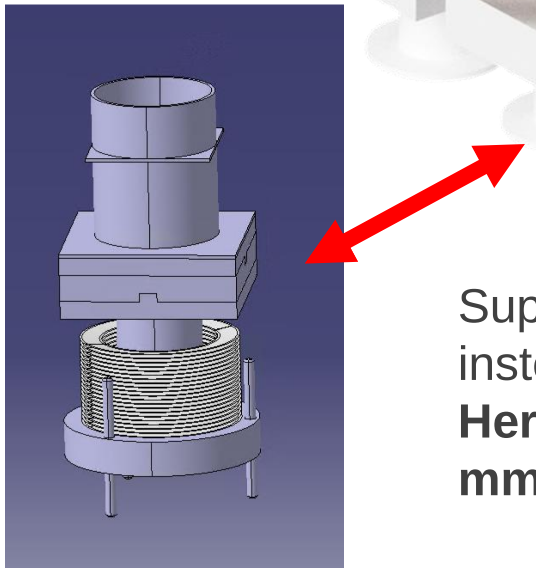
3 cryocoolers:
2 for thermal shield and resitive current leads
1 for the magnet

Mechanical design: General view



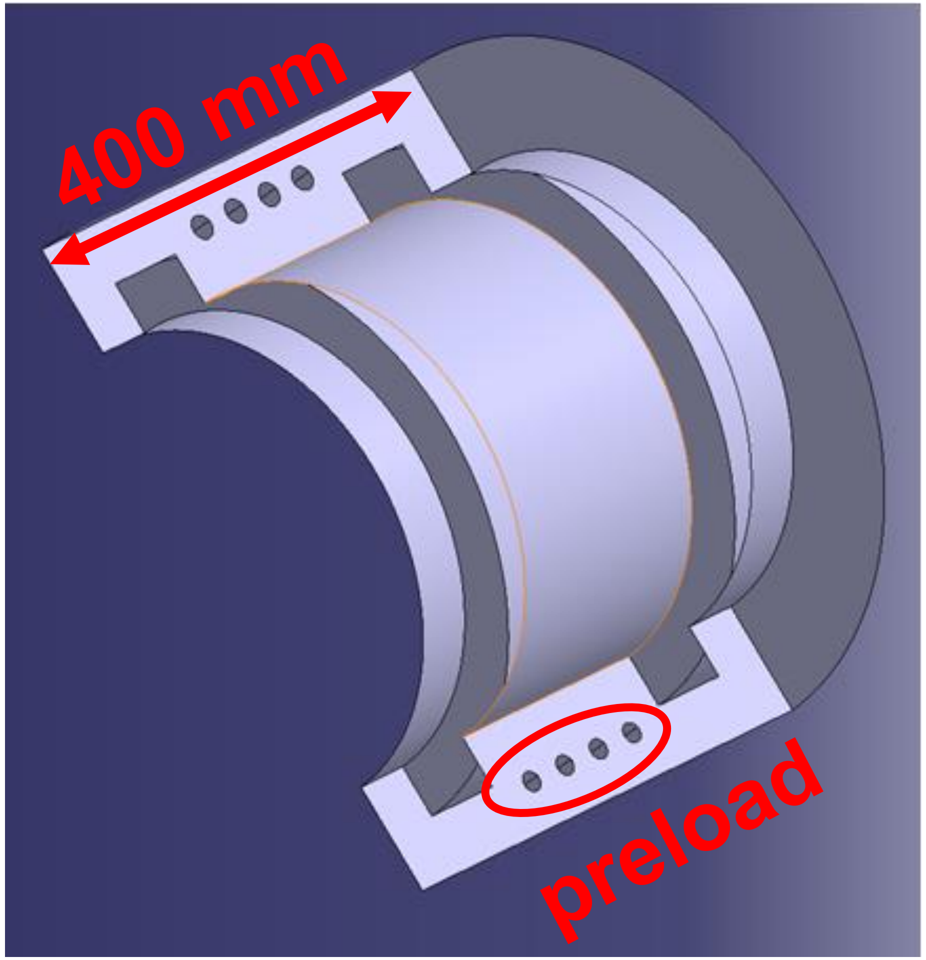
Supporting coils and cold mass



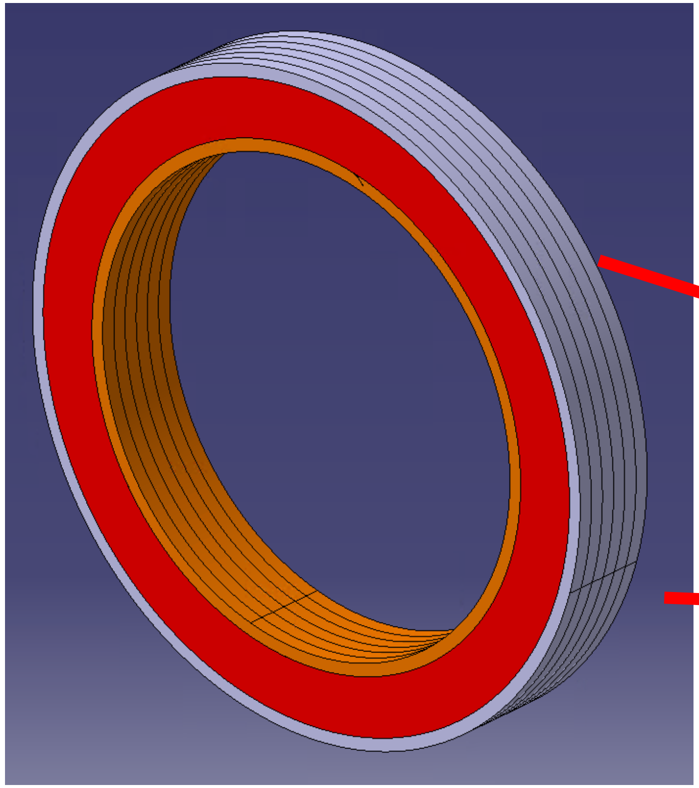


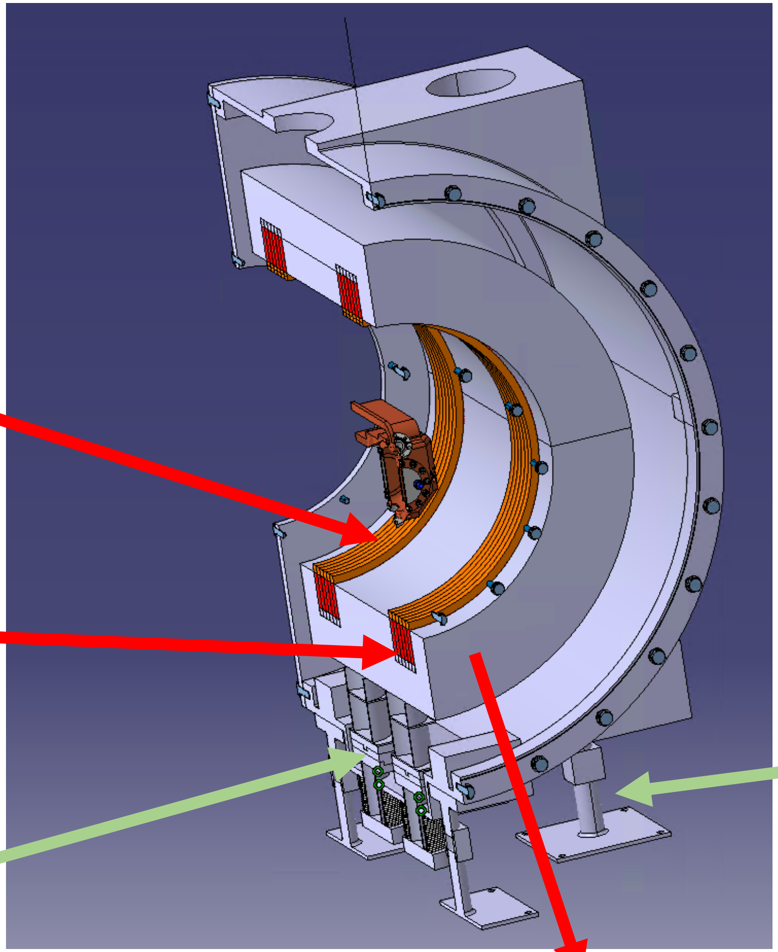
Support post (LHC like)
instead of tie rods
Here shown with the 700 mm R.T. bore

- Two half shells
- 500 kg
- Tight tolerances
- Inner 400 mm
- Outer 591 mm
- AISI 316LN
- Positioning
- Supporting (longitudinal and radial)



Updated design





Return yoke/ field shielding

To be implemented

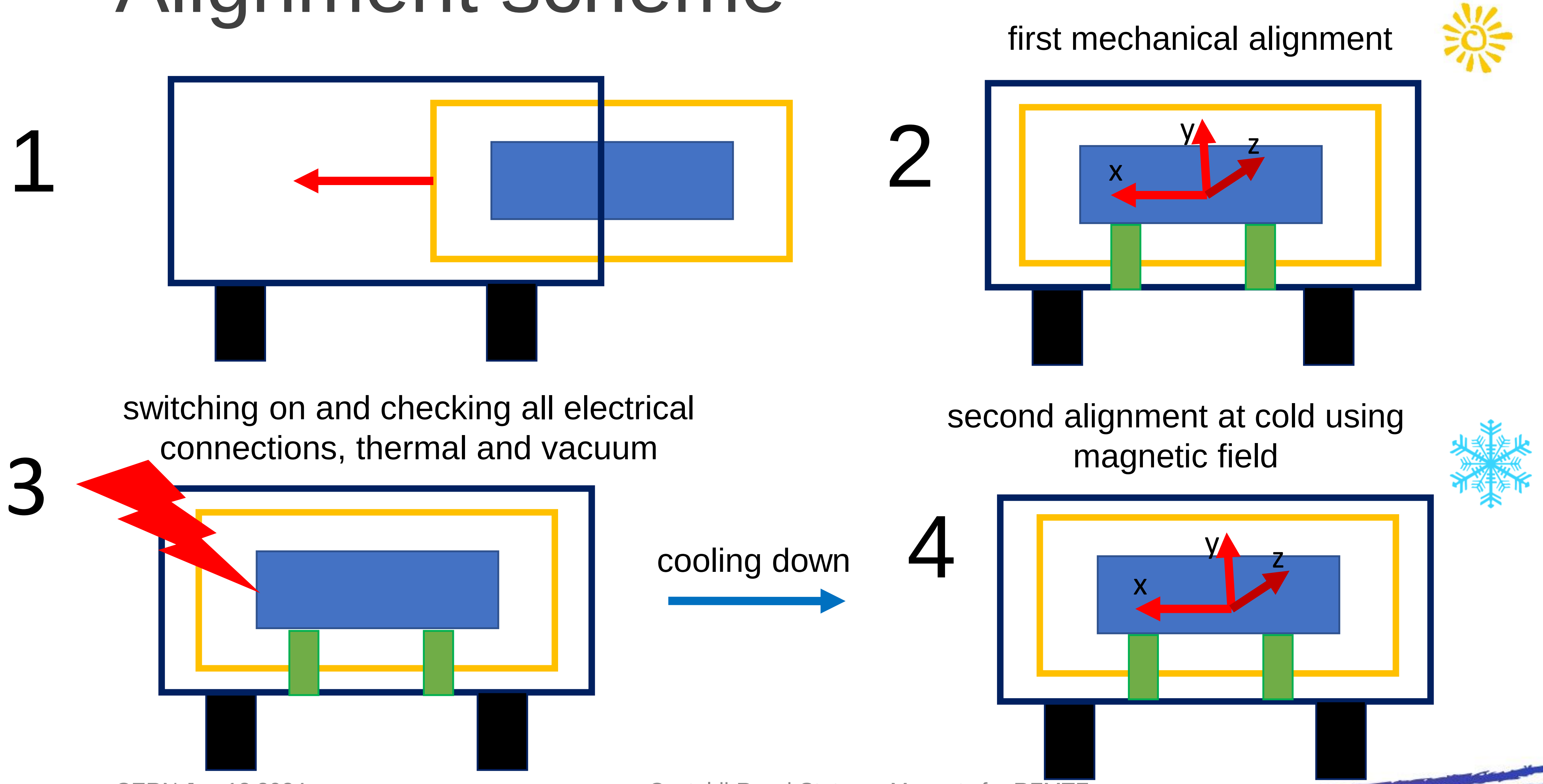
Cryostat support

Cold mass supporting

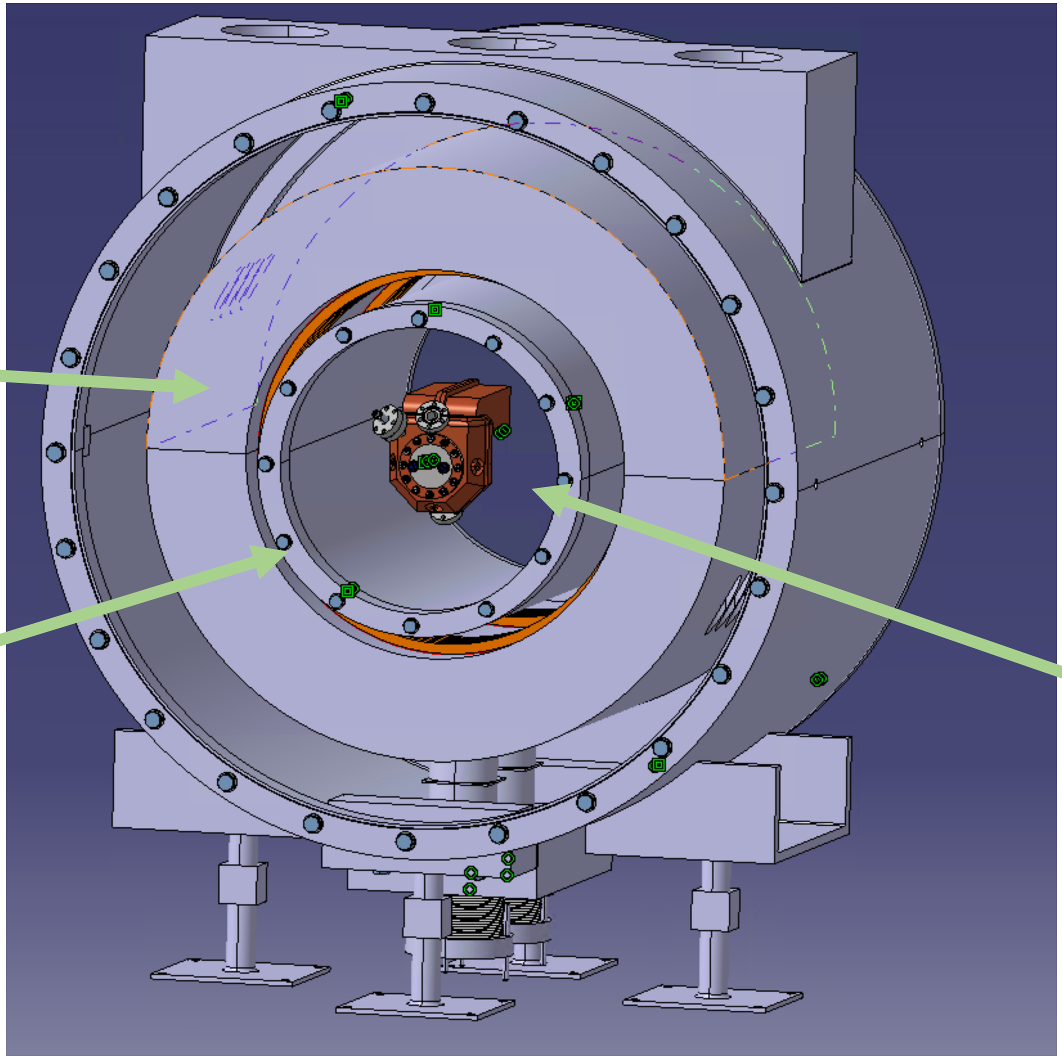
Single coil (perfectly cylindrical)
Final dimensions to be defined
Mechanical tolerances and structure to be defined

Mechanical structure capable to withstand axial forces and to reduce radial stress (down to 300 from 600 Mpa)

Alignment scheme



RFMTF



HTS coils and supporting structure

Inner warm bore 300 mm

3 GHz RF cavity

To be further analized:

- Fine tuning of coil suppporting and positioning
- Iron yoke for fringe field
- Cryogenic detailed design
- Supporting the RF cavity

Next steps and outlook

- Magnet:
  - Refine magnetic design and freeze it → **under way**
  - Calculation of field error and forces/torques due to assembly tolerances → **done! (thesist)**
  - Decide with WP7 (magnets) the acceptable stress level, the banding technology for stress reduction, MI or NI → **more critical item (depend on coil design)**
  - Quench modeling, strong synergy with WP7 and other projects (ONRR_IRIS) → **under way**
  - More detailed mechanical design → **under way**
  - Make thermal model → **under way with thesist**
  - **Order of 150 k€ for HTS tape by INFN-Mi under way**
  - **Period of 6 weeks od 1 staff (F. Broggi) at CERN to compute heat depo on Magnet and other elements of CC.**
- Integrate RF cavity in the design: services and insertion devices → **Started**
- Cost evaluation (already launched by INFN/CERN) → **under way , outlook very positive** (< 2 M€ for the magnet system, with resource also from other projects (PNRR_IRIS, CERN-HFM, EU call hopefully…)
- PNRR_IRIS is providing a building in Milano with an additional INFN bunker (see D. Giove) , it may be an ideal place do install the RFMTF

Conclusion

- The 7 T – 320 mm RT free bore RFMTF is well under way at LASA with contribution by CERN.
- If the EU-MAHTS if approved can be upgraded to 10 T
- Practical winding test and technology mockups in parallel with other programs (IRIS-ESMA dipole, IFAST HTS CCT, etc.) will start **in May 2024**
- In the second part of 2024 we are ready to launch construction if funding is available, **even partially**. Winding can start at CERN (INFN could take over later, when tooling at LASA is available)
- The RFMTF is a great opportunity to improve the TRL of HTS coils for high field magnets testing technological solutions evaluated and selected by WP7
- If so, we are confident to commission the facility in 2026, a key element to demonstrate feasibility of the MC Cooling Cells (and for initiating RF test in magnetic field) before end of the ESPP Update.
- LASA will be a ideal place to host it (but location can be discussed according to funding source)

THANKS