A 3 T High Temperature Solenoid Design for the IDEA detector project

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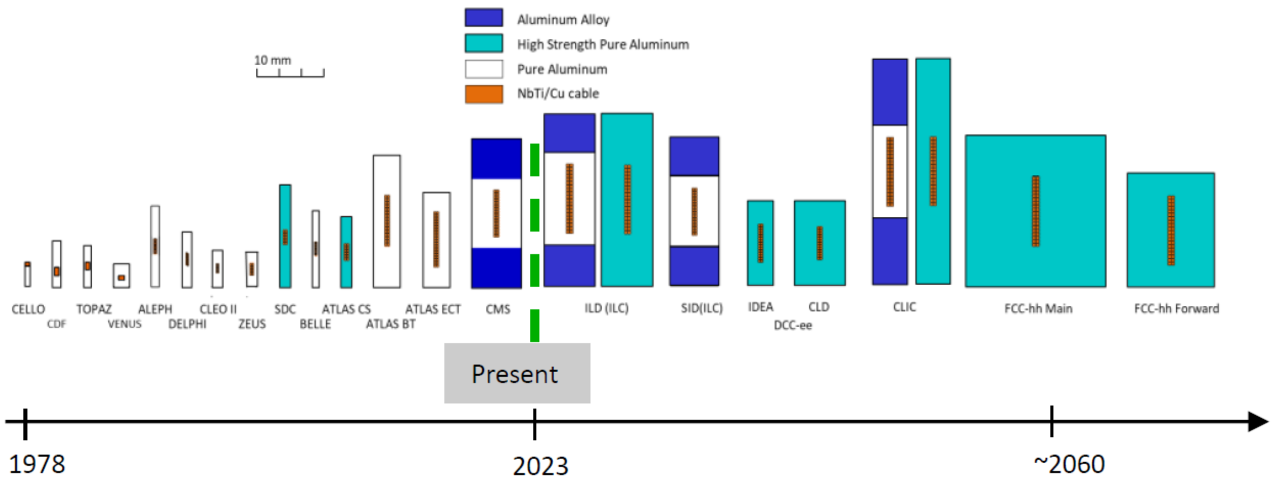
Current Technology for Detector Magnets

Detector magnets are all based on historically proved aluminum-stabilized NbTi Rutherford cables:
Well understood technology, affordable and good mechanical properties



Aluminum-stabilized Nb-Ti conductors: Courtesy of A. Yamamoto

1. **NO Commercially available nowadays**
   - Re-establishing conductor technology in industry
2. **Required low temperature operation (< 5 K)**
   - Large energy consumption (low sustainability)
   - Large inventory of LHe (limited resources)

«M. Mentink et al 2023 JINST 18 T06013»

Table 4. The proposed design parameters for the detector solenoids for future projects.

Projects	Magnet	B_c (T)	InnerR (m)	Length (m)	E/M (kJ/kg)	Stored energy (GJ)
FCC-hh		4	5	20	11.9	13.8
CLIC		4	3.65	7.8	13	2.3
ILC	ILD	4	3.6	7.35	13	2.3
	SID	5	2.5	5	12	1.4

Property	IDEA	CLD	Unit
	Coil		
Inner radius	2.235	4.02	m
Length	5.8	7.2	m
Weight	12.5	49.5	t
Number of turns x layers	530 x 1	300 x 1	
Support cylinder thickness	12	25	mm
Total coil thickness	53	102	mm
Central field	2		T
Stored energy	170	600	MJ
Energy density	14	12	kJ/kg

FCC-ee Detector Magnets, CDR

IDEA Detector

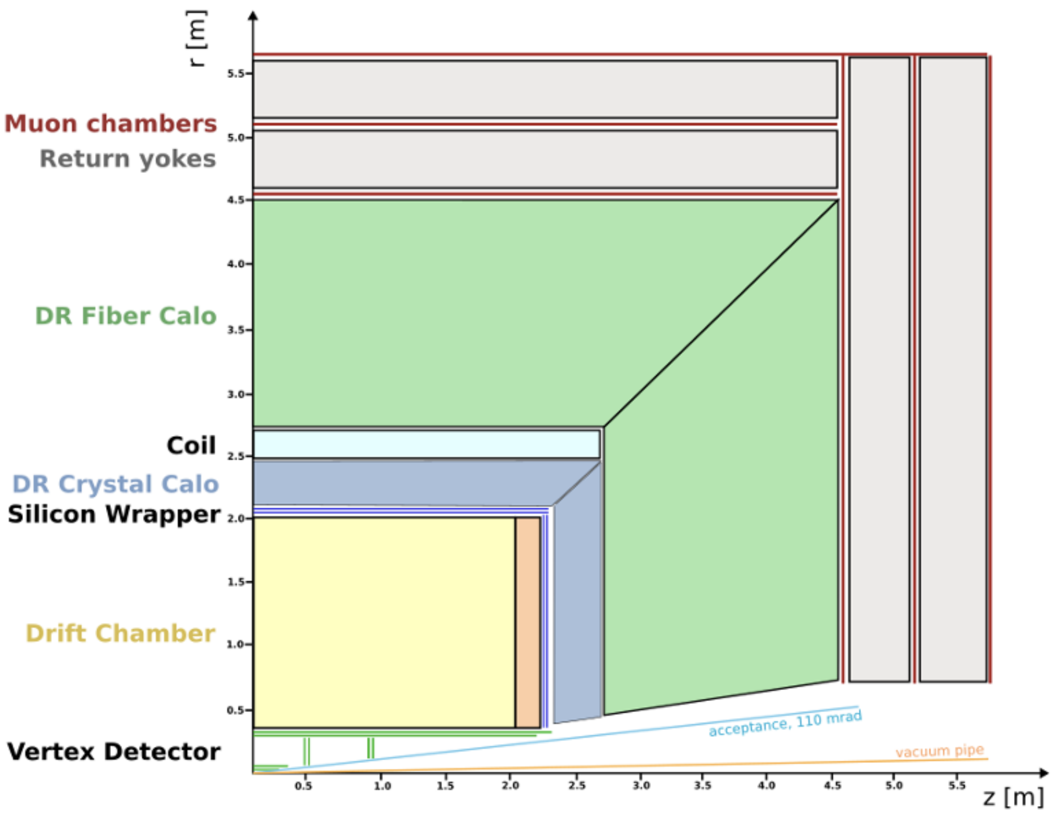
Innovative Detector for e+e- accelerator

1. Silicon vertex detector
2. Short-drift, ultra-light wire chamber
3. **Dual-readout calorimeter options**
    1. Longitudinal unsegmented dual-readout fibre calorimeter (combined EM+HAD)
    2. Dual-readout crystal (EM calo) + dual-readout fibre calorimeter (HAD calo)
4. **Thin and light solenoid coil between two different calorimeters**
5. Muon system: 3 layers of μ-RWELL detectors in return yoke

Main Advantages for the Solenoid:

- **Relaxed constraints on solenoid's material components in terms of X_0**
- Still compact and cost effective (for operation)

Innovative proposal to move the EM calo inside the solenoid!



Courtesy of P. Giacomelli

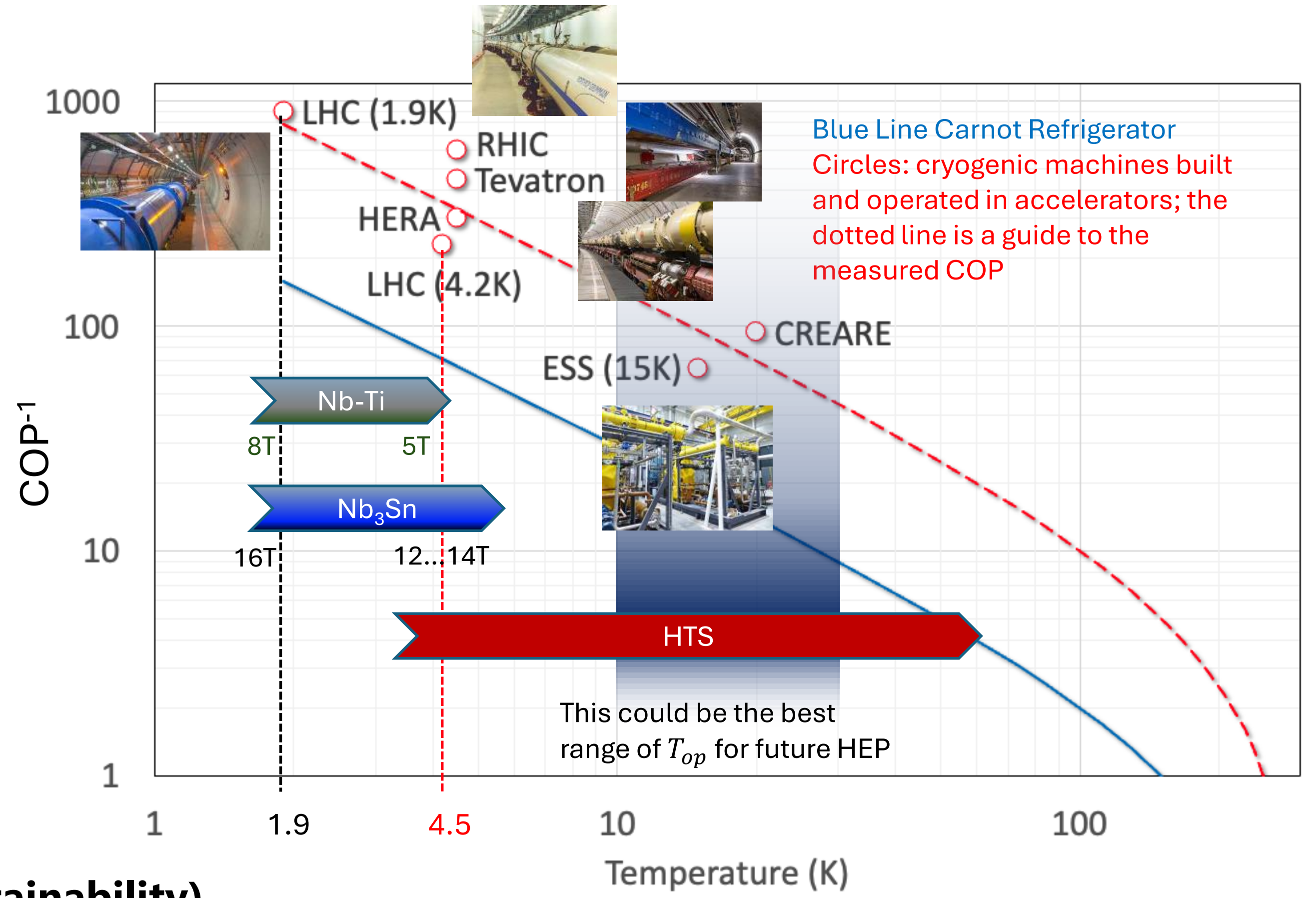
Operating Costs

Cryogenic Efficiency

- **Conductor technology used in a superconducting magnet is heavily affected by operating temperature**
- **Energy efficiency of cryogenic implant is characterized by a Coefficient of Performance (COP)**

$$COP_{Carnot} = \frac{T_{cold}}{T_{hot} - T_{cold}} \qquad COP_{REAL} = \frac{Q_{cold}}{L}$$

- Advantages of high cryogenic temperatures:
  - Reduction **of He inventory**
  - Reduction of **power consumption** (**higher sustainability)**



Increasing T_{op} from **1.9 K** to **15-20 K** would increase the **Cryogenic** system **efficiency** by **one order of magnitude!!!**

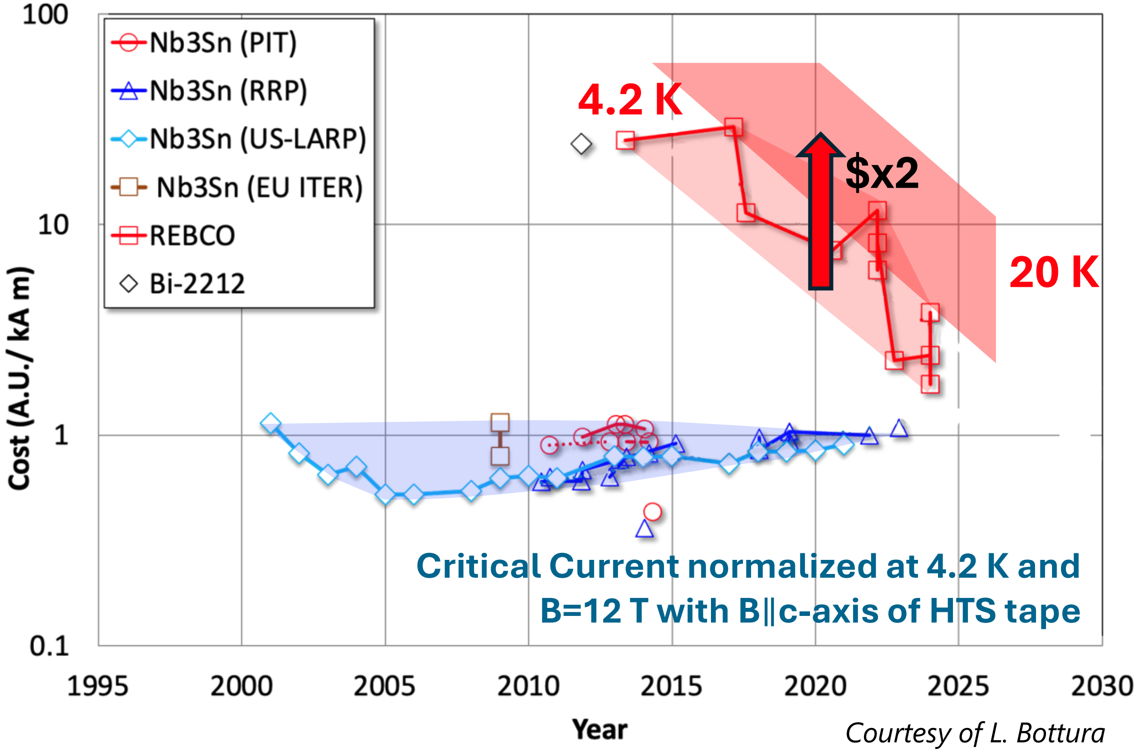
Why HTS Technology?

Fast-growing Technology with rapidly decreasing costs

- Massive production of **HTS for Fusion Reactors**
- Huge R&D and production quality effort in industry
- 5 qualified vendors world-wide (more are coming)

- **LTS is still the most advanced superconductor (restricted to low T = 1.9-4.5 K)**
- **HTS possible alternative with T > 10 K (but require R&D)**

Cost per unit length and current for Nb3Sn and HTS purchased at CERN, US labs and ITER



Courtesy of L. Bottura

MAIN GOAL of the proposal:

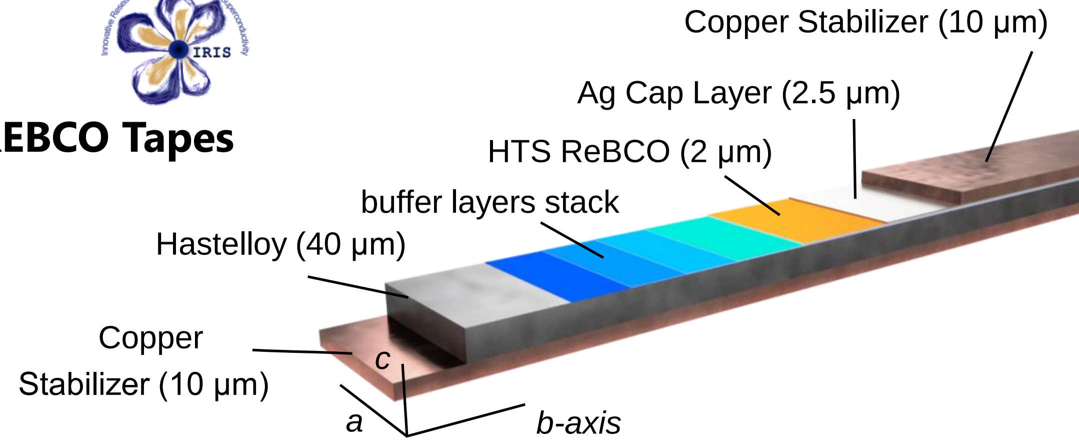
(B= 3 T, T= 20-50 K) HTS solenoid for IDEA detector

- HIGHER FIELD for better resolution (Designed to reach 3 T and operate at 2 T at the Z peak energy)

Cable Technology

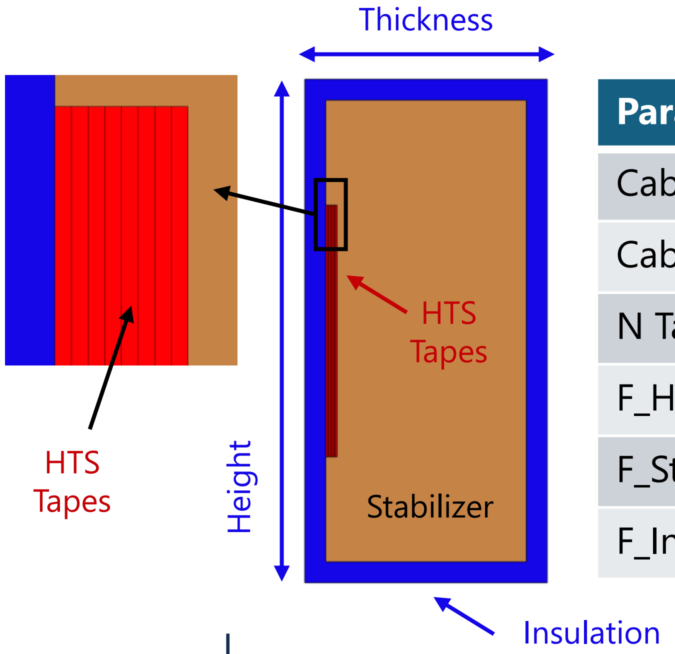
Cable concept: **U Shape channel cable** with **Faraday Factory HTS REBCO Tapes**

- Critical current depending on cable orientation along field lines
- Aluminum stabilizer for thermal conductivity and protection

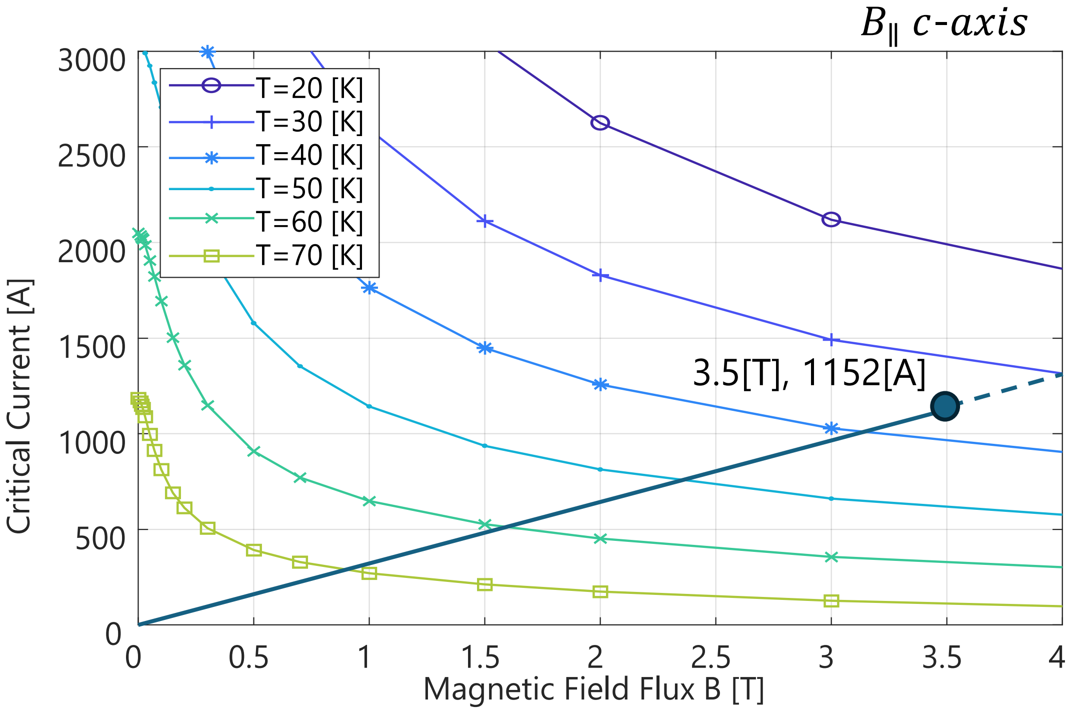


Stabilizer Material under study:

1. **Pure Aluminum** (99.999%)
2. **Al2.0%wtNi** (RRR=170, Yield Strength=170 MPa @ 4.2 K)



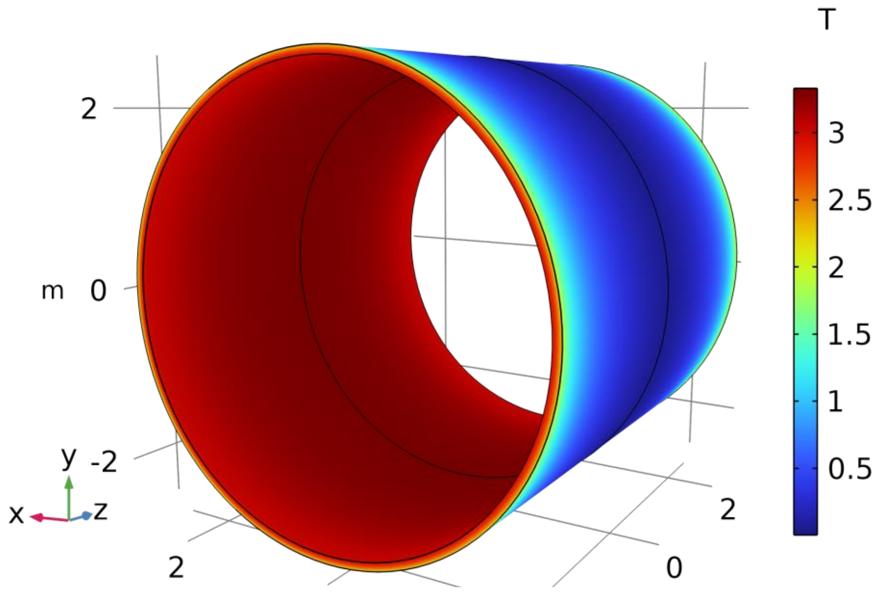
Parameter	Value
Cable Thickness	11.47 $[mm]$
Cable Height	24.0 $[mm]$
N Tape	7
F_HTS	2.32%
F_Stabilizer	73.45 %
F_Ins	24.23 %

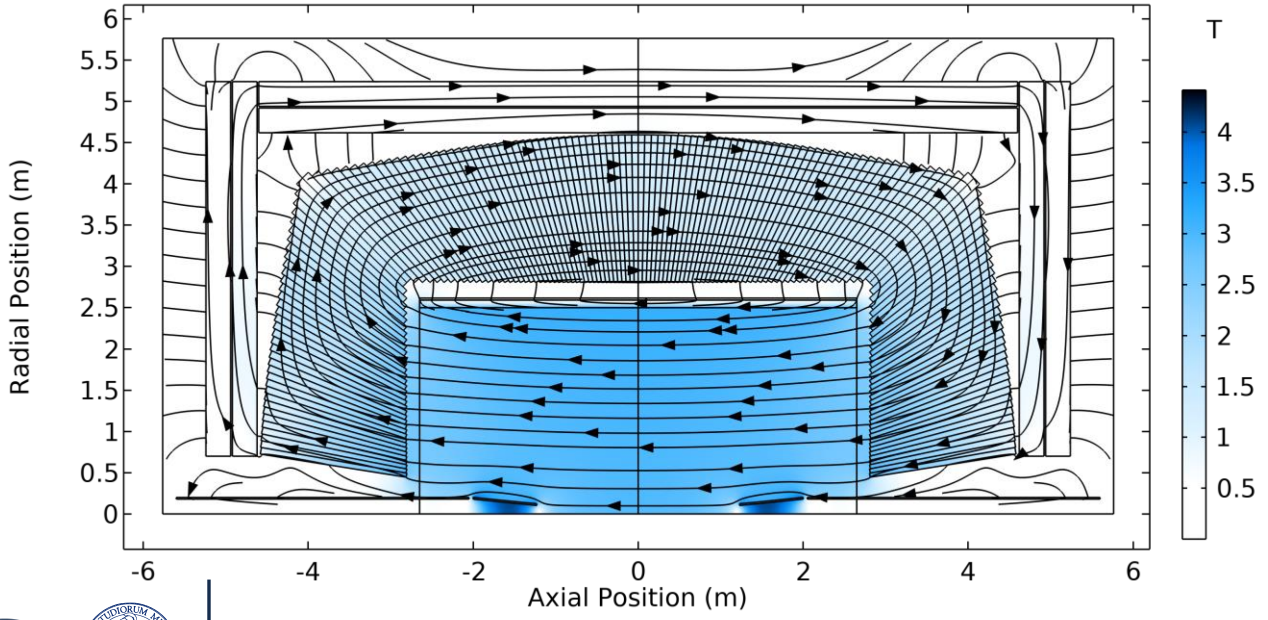


First Considerations: Magnet

From analytical evaluations:
- B= 3 T, R_i=2.5 m e L=6 m → **18.65 MA-turns**

Peak field on the conductor equal to **3.37 T**
2D Rotational Symmetry Simulation in COMSOL
- Internal radius increased to allow for EM Calorimeter
- Coil thickness limited stress on conductor (100 MPa)
- Dual readout ferromagnetic HCal **implemented in the computation model!**



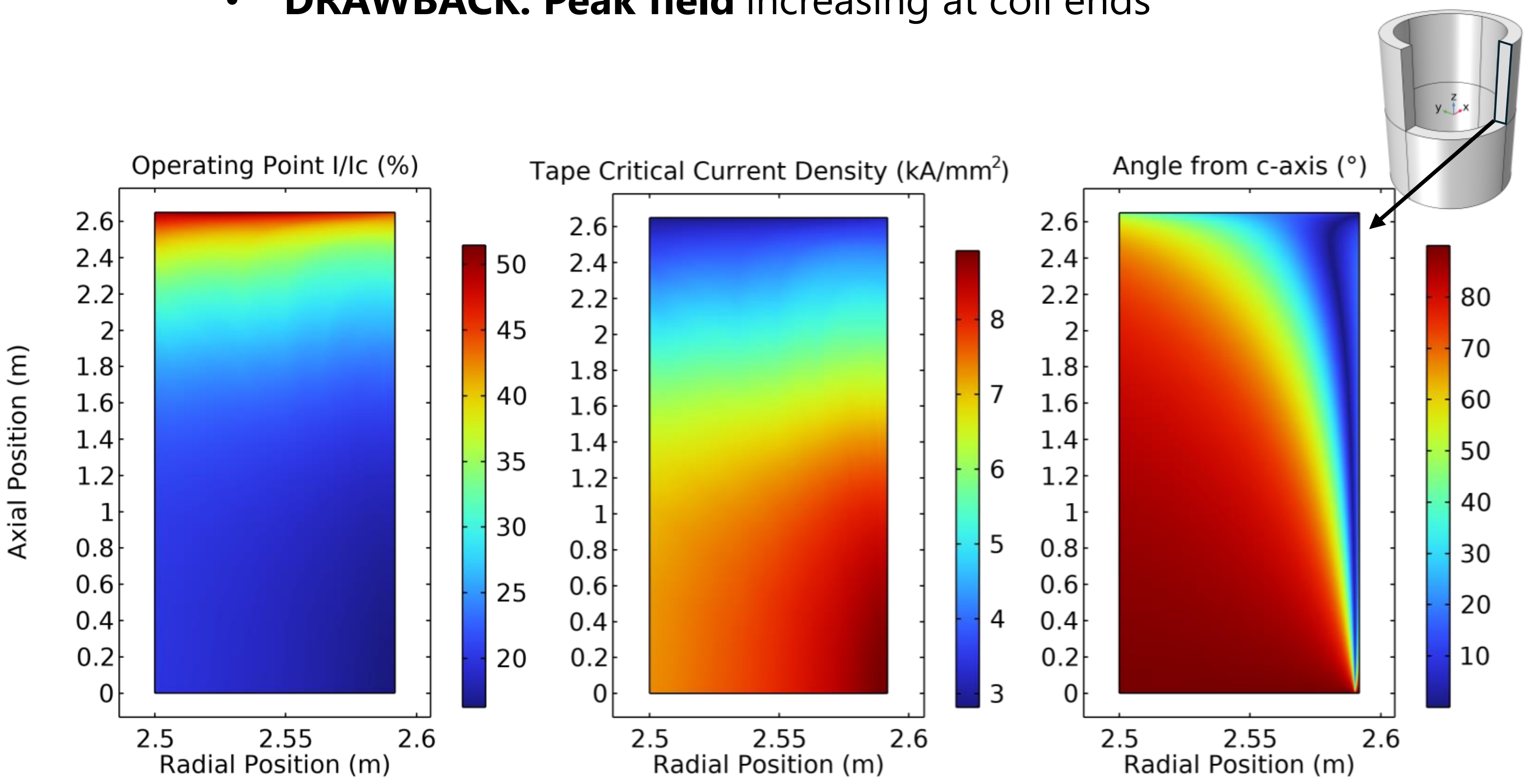


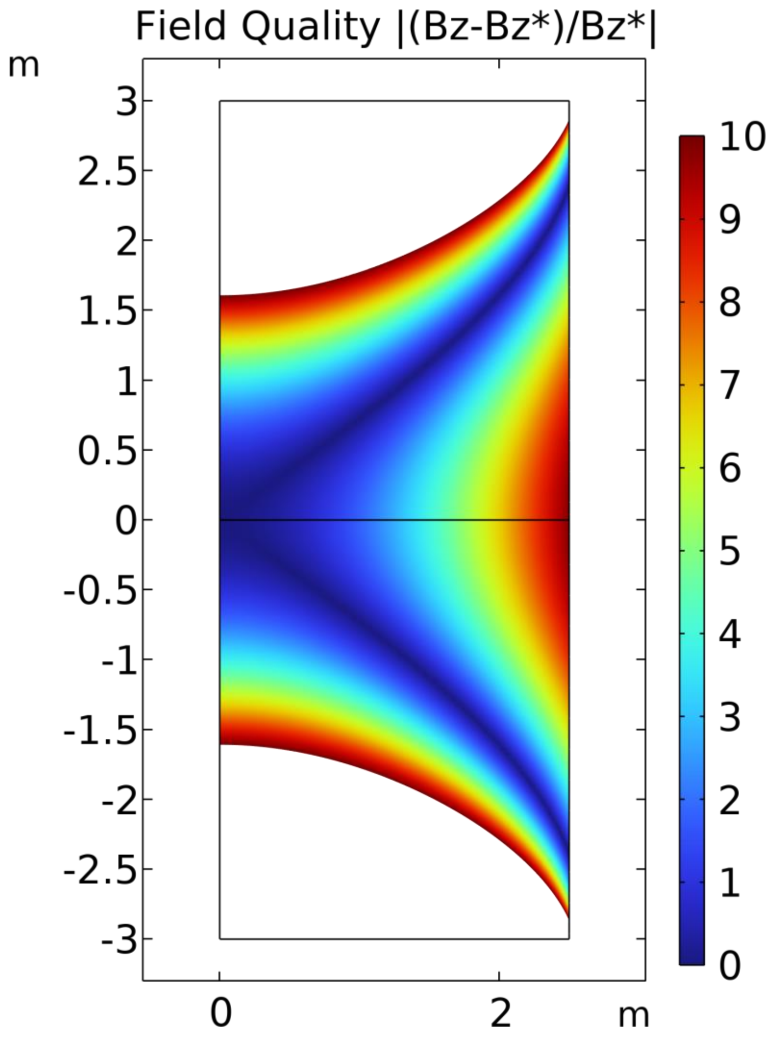
Parameter	Value
Bore Field	**3 [T]**
I_{nom}	8068 [A]
Coil Thickness	91.7 [mm]
Turns	1760 (220x8)
Inductance	12.4 [H]
Stored Energy	402 [MJ] 19.41 [kJ/kg]
Operating Temperature	**20 [K]**

Field Quality and Margin

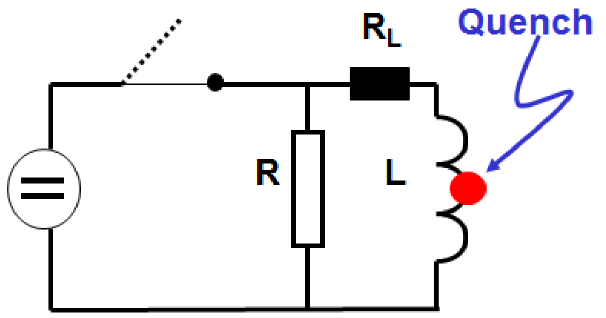
Superconducting coil operates at **- MAX 50.5% I/I_c (coil edges)**

- Equivalent **temperature margin of 15 K (T_c = 35 K)**
- Possible idea to uniform the margin: grading of conductor **density**
  - **DRAWBACK: Peak field** increasing at coil ends





Magnet Protection and Stability

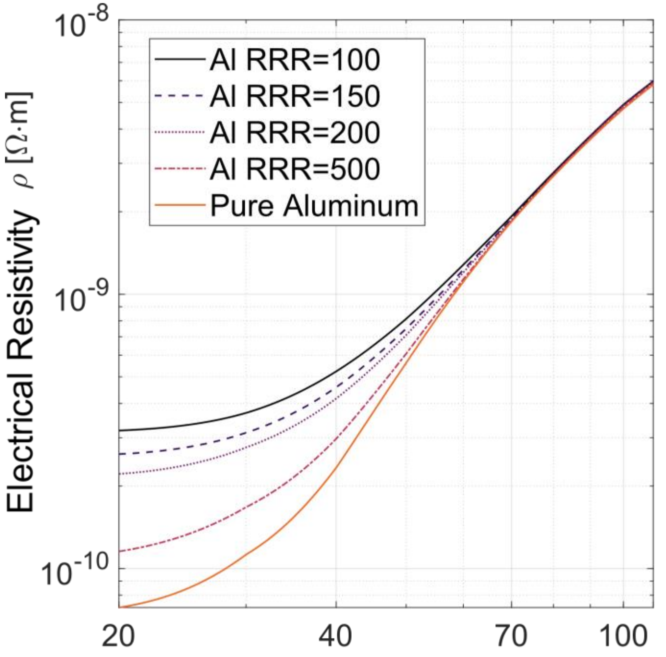


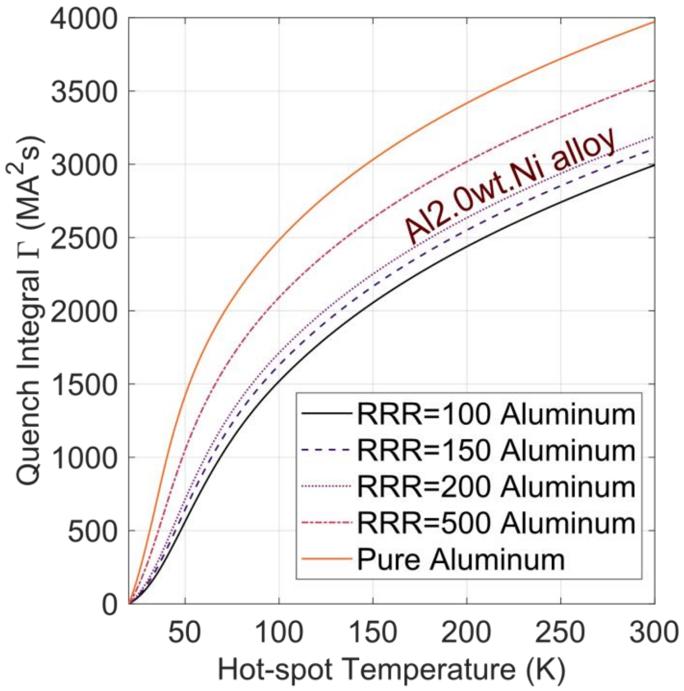
In case of quench, dissipation is localized in small portion of conductor volume:

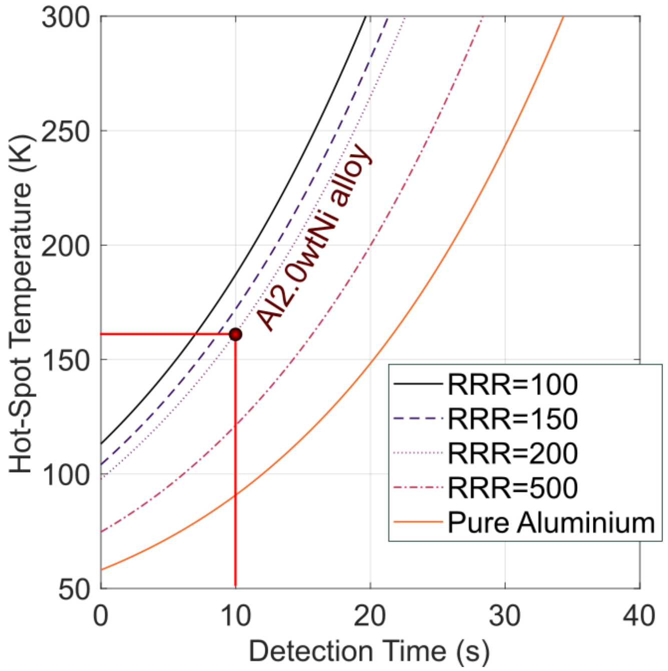
- **Energy of the magnet is absorbed by the cable material**
- Need of **Energy Extraction method** for protection:
  1. V_{MAX} to ground during magnet discharge**: 2kV**
  2. External resistance of 0.2 Ω
  3. **Maximum temperature 160 K** (10 s detection time)

To be further investigated:

- Detailed simulation at conductor level for quench propagation analysis and detection accuracy
- **Charge/Discharge magnet time: 65 s acceptable?**



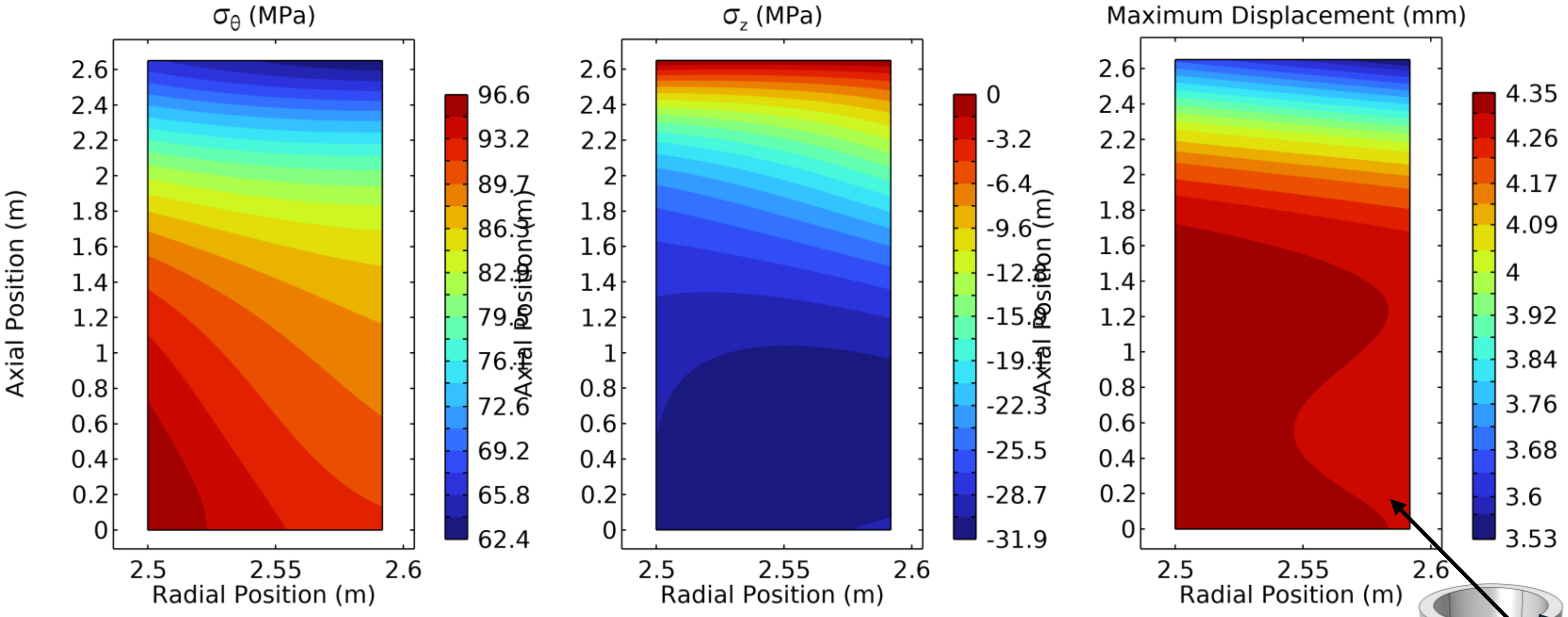


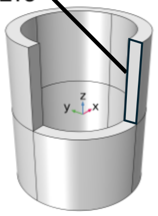


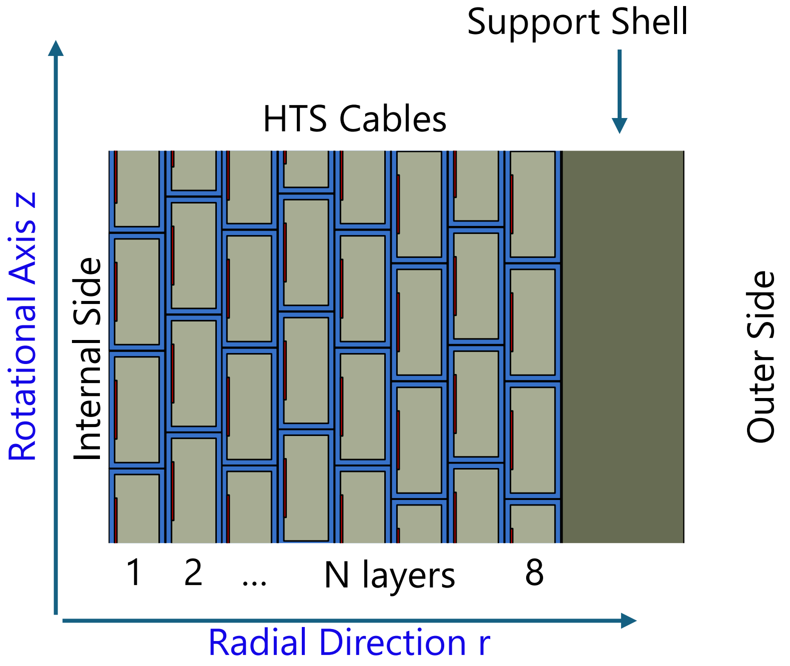
Preliminary Mechanical Performances

Coil simulated as an **ortotropic material** with averaged properties on the material fraction and cable geometry

- Maximum stress (only Lorentz Forces): **97 MPa (well below 500 MPa limit)**
- Longitudinal Strain on the cable: 0.18% (no HTS degradation)







Parameter	Value
HTS Tape (E_r, E_ϕ, E_z)	$[70,180,180]\ [GPa]$
Cable (E_r, E_ϕ, E_z)	$[51,61,54]\ [GPa]$
Poisson Ratio	0.33

Aluminum alloy 5083 (25 mm) shell as support for the coil

- Maximum hoop stress of 120 [MPa] (Tensile Strength 400 [MPa])

Coil Transparency

Coil Transparency dominated by HTS tape, Cable Stabilizer (Al2.0%wtNi for currently considered configuration) and Shell

Pure HTS tapes within the Coil

- Thickness dominated by Hastelloy material ($\rho = 8.61\ g/cm^3$)

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i} = \frac{1}{12.44\ g/cm^2} \qquad X_0[cm] = 1.40\ cm$$

Stabilizer: Al2.0%wtNi

- Material density ($\rho = 2.82\ g/cm^3$)

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i} = \frac{1}{23.59\ g/cm^2} \qquad X_0[cm] = 8.35\ cm$$

External Support Shell Al5083

- Material density ($\rho = 2.65\ g/cm^3$)

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i} = \frac{1}{23.81\ g/cm^2} \qquad X_0[cm] = 8.99\ cm$$

Hastelloy C276

Material	f_i	Radiation Lenght
Ni	59%	12.68 [g/cm^2]
Cr	22%	14.94 [g/cm^2]
Mo	13%	9.80 [g/cm^2]
Fe	4%	13.84 [g/cm^2]
W	2%	6.76 [g/cm^2]

Coil Total Normalized Radiation Length

Material	Total Thickness	X/X_0
HTS Tape	4.0 mm	0.296
Al2.0%wtNi	72 mm	0.862
Insulation	16 mm	0.056
Shell	25 mm	0.278
TOTAL	**117.3 mm**	**1.492**

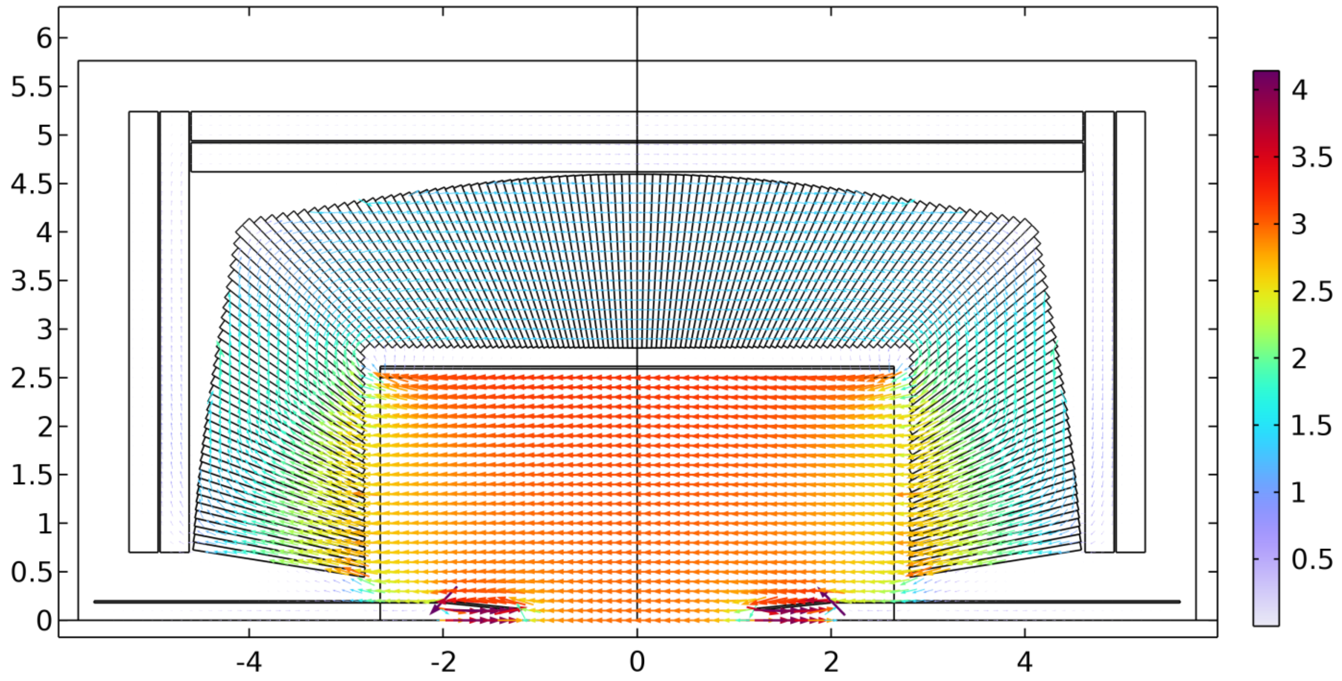
If we want to use Cu as stabilizer: X/X_0 = 5.646

Field Maps

Generation of detailed magnetic field maps for subdetectors and particle simulations for other WP or collaborators

- Implementation of **different magnetic components** for unified magnetic field simulation of IDEA Detector
    - Main Solenoid
    - Muon Chambers
    - HAD Calo
    - **Local/Non local correction scheme of antisolenoids**
    - **Main focusing magnet of MDI region**

Common geometry Implemented: GitHub k4geo IDEA



Field Map Example:

- **Radial Grid**
  (0< r <6.5 [m], -6.5 [m]< z < 6.5 [m])
  Binning distance: 1 cm
  Dimensions: 845k points (80 MB)
- **3D Grid (X,Y,Z)**
  Work in progress

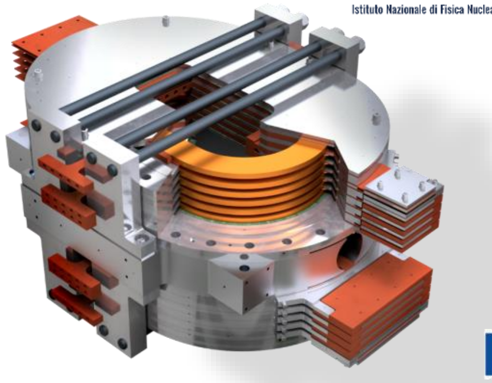
Synergies with LASA activity

LASA Superconducting Magnet research group involved in several **R&D projects on HTS and major international collaboration for collider magnet design: HFM program, FCC, MuonCollider**

10 T HTS Dipole Magnet: ESMA

New Development project (PNRR-IRIS) 2022-2025
“Innovative Research Infrastructure on Applied Superconductivity”

- Improvement of 6 National research infrastructures and university laboratories to perform cutting-edge technology research activity on superconductivity



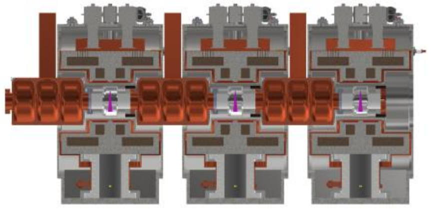
Courtesy of S. Sorti and L. Balconi, University of Milano and INFN-Milano, LASA

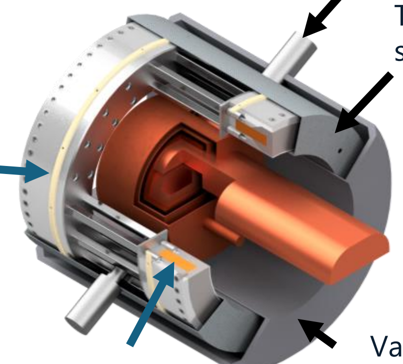
Central field B0 (min. accept)	tesla	10 (8)
Free aperture	mm	Ø70
Good field region uniformity	N/A	±1.5%
Good field region	mm	H50xV30xL350
Operating temperature	K	20
Critical current margin	N/A	>20%

Split Coil – RFMTF
Magnet Test Facility for RF

10 T gradient split coil design

- (300 mm warm bore)
- Operation @ 20 K
- Conduction cooled cryogenic system





HFM Program for HTS Magnets

Common **R&D program** to increase the TRL of HTS magnet technology for next generation future colliders and accelerator sustainability

Conclusions and Next Steps

Preliminary design evaluations did not identified any showstopper for the feasibility of an HTS compact solenoid design operating @ 3T and 20K

1. **Magnetic Design and Quench Protection**
   - Field quality enhancement
   - Margin optimization with coil grading
   - Detailed quench analysis and failure estimation
2. **Detailed Mechanical Assembly and Cool-down**/energization stresses on conductor
   - Optimization of coil/cryostat thermal and mechanical supports
   - Cryostat losses and cooling technologies evaluation
3. **Cable manufacturing and characterization**
   - Properties of HTS aluminum stabilized cables at cryogenic temperatures
   - Joints: LASA facility equipped with necessary infrastructure for cable testing (ATLAS Cable joints)
4. **Field Maps for subdetector and MDI working groups under development**
   - IR region magnetic elements and beam pipe
   - Fringe field analysis for Booster accelerator beamline

Thank you for the attention