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Design of an HTS demonstrator coil for a superconducting toroidal magnet for a particle physics experiment in space

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The HTS Demonstrator Magnet for Space (HDMS) project

External project collaborators:

- The Italian Space Agency (ASI)
- University of Trento
- TIFPA
- University of Milan

agenzia spaziale italiana

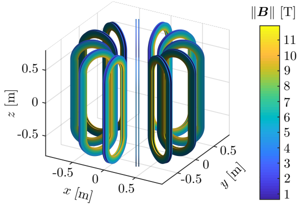
UNIVERSITÀ DI TRENTO

Trento Institute for Fundamental Physics and Applications

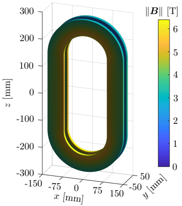
UNIVERSITÀ DEGLI STUDI DI MILANO

Project goals

1) Make a conceptual design of a toroidal HTS magnet for a magnetic spectrometer in space



2) Design and manufacture a demonstrator coil pack for the toroidal magnet



Part 1: Conceptual design of a toroidal HTS magnet for a magnetic spectrometer in space

Rigidity and bending strength

Rigidity:

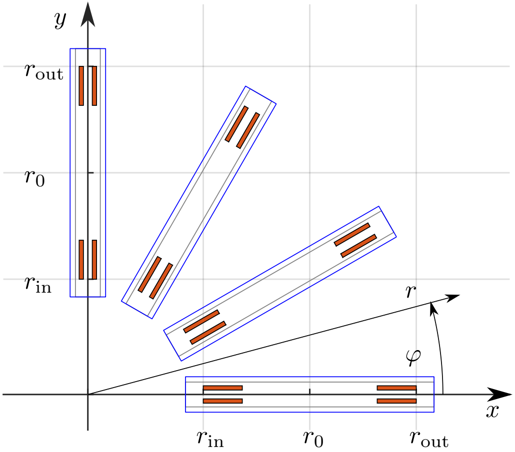
$$R = c\,\frac{p}{q} \quad [\mathrm{V}]$$

Bending strength:

$$\overline{B}_\varphi L(\varphi) = \int_0^L B_\varphi(r,\varphi)\,dr$$

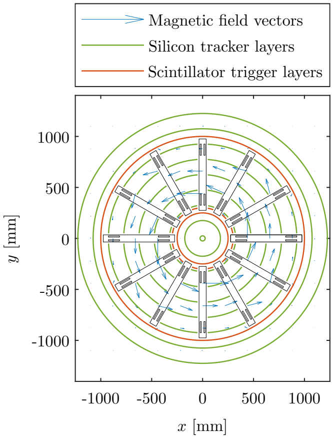
Average bending strength:

$$\langle \overline{B}_\varphi L \rangle = \frac{N}{\pi} \int_0^{\pi/N} \overline{B}_\varphi(\varphi) L\, d\varphi$$



Requirements for the toroidal magnet

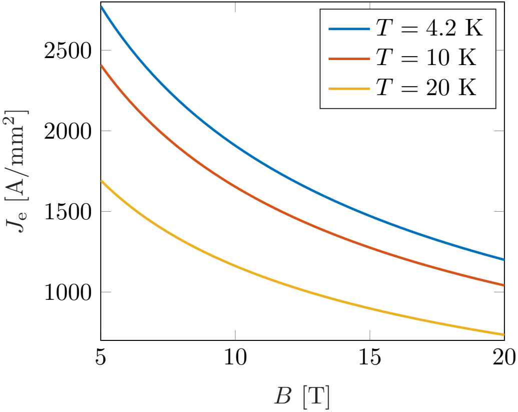
- Average bending strength: 3 T m
- Inner toroid diameter: 500 mm
- Outer toroid diameter: 2000 mm
- Straight coil segment height: 1000 mm
- Operating temperature: 20 K
- Conduction cooled by a cryostat
- Lightweight structure
- Sufficient space available for detectors



Conductor requirements for the toroid

HTS ReBCO tape:

- 12 mm wide, 100 µm thick
- $J_e = 1200\,\mathrm{A/mm^2}$ at 4.2 K and 20 T
- Angle dependence: worst case conditions
- Field dependence: Fitting function



0D circuit models

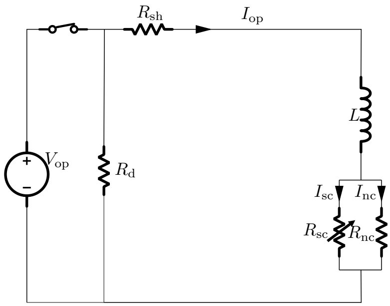


Figure: Equivalent circuit for insulated coil.

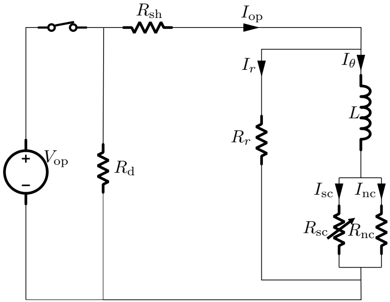


Figure: Equivalent circuit for metal insulation coil.

0D circuit model solutions

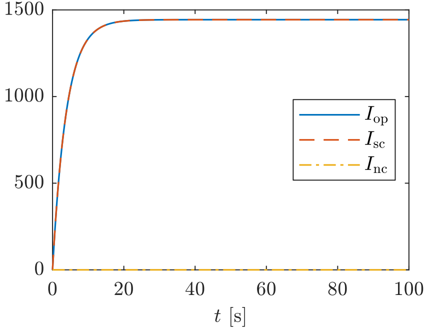


Figure: Current in insulated coil during charging.

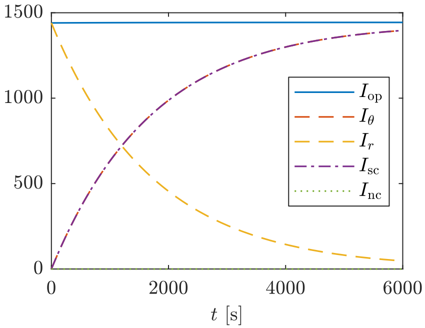


Figure: Current in metal insulation coil during charging.

Quench protection if insulated

After a quench, the temperature of the hot spot increases according to the power equation

$$\frac{C_\mathrm{m}(T)}{\rho_\mathrm{m}(T)}\frac{dT}{dt} = \frac{I_0^2}{A_\mathrm{cd}^2} e^{-2t/\tau}$$

Symbol	Description	value
T_i	Initial temperature	20 K
T_f	Final temperature	200 K
A_cd	Conductor cross sectional area	2.4 mm^2
I_0	Initial operating current	2052 A
τ	Current decay time constant	0.33 s
R_d	$\approx L/\tau$, Dump resistance per coil pack	4.8 Ω
V_max	$\approx R_\mathrm{d} I_0$, Voltage drop over dump resistor	9.8 kV

Table: Parameters for one toroidal coil pack.

Insulated coil approach discarded:

- It is difficult to insulate for more than $V_\mathrm{max} \approx 1\,\mathrm{kV}$
- The dump resistor would add to the total mass of the spectrometer
- Higher risk of damaging the coil in case of a quench (very difficult, time consuming, and expensive to do repairs in space)

Quench protection if non-insulated

Discharging the coil internally increases the specific enthalpy of the conductor material by

$$h_{p_{\mathrm{Cu}}}(T_{\mathrm{f}}) - h_{p_{\mathrm{Cu}}}(T_{\mathrm{op}}) = \frac{E_{\mathrm{m}}}{m_{\mathrm{coil}}}$$

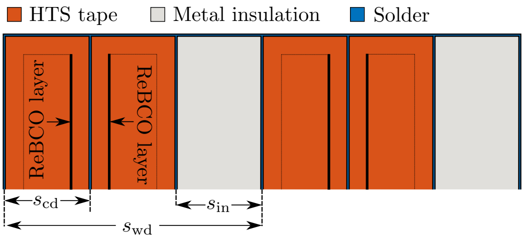
Final temperature: $T_{\mathrm{f}} \approx 166\,\mathrm{K}$. However, distributing the energy over the entire coil quickly enough might be challenging.

Cable configuration

Soldered metal insulation coil:

- Solder added to tape surfaces during winding
- Entire coil heated to melt the solder after winding
- Self-protected againsts quenches
- Long charging and discharging times

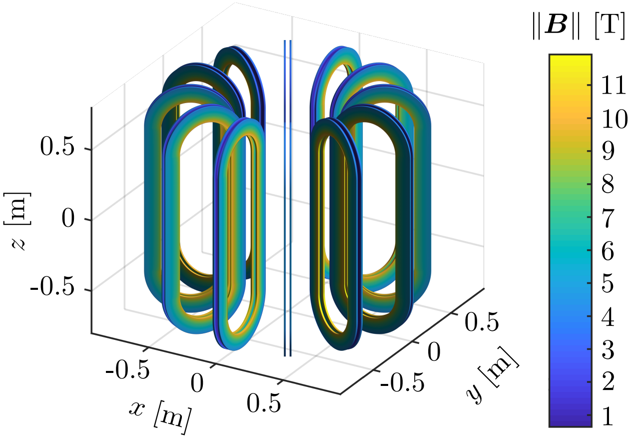
Two HTS tapes (face-to-face) and one stainless steel tape



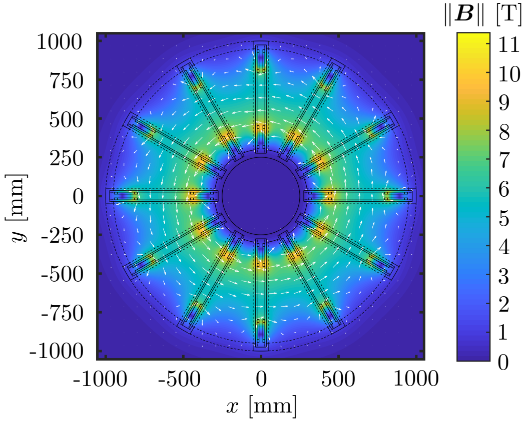
Cable thickness: $s_{wd} = 300\,\mu m$

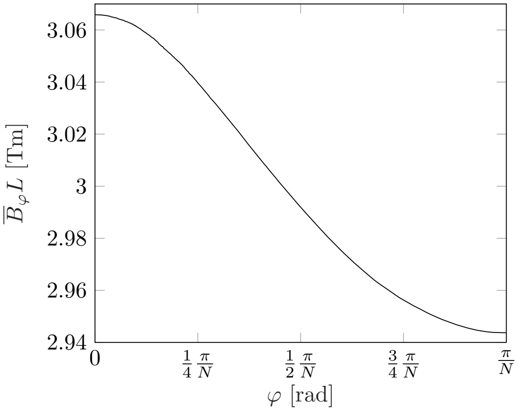
Toroidal magnet design

- 12 racetrack coil packs
- 2 winding layers per coil pack
- Engineering operating current density: 855 A/mm^2
- Peak magnetic field: 11.9 T
- Total HTS tape length: 62 km
- Stored magnetic energy: 39.6 MJ



Field characterization



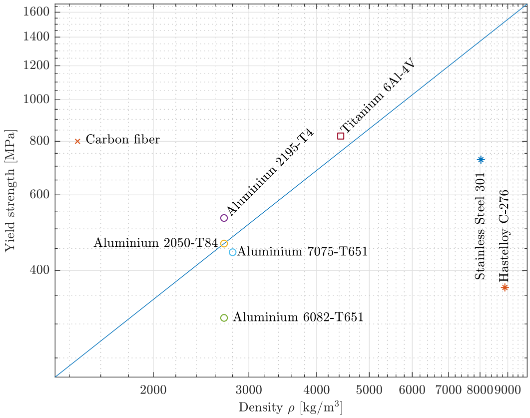


Structural material: Strength vs. density

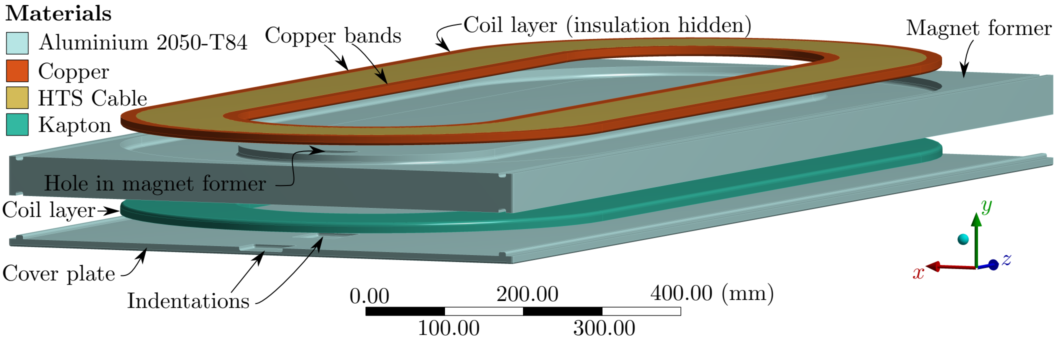
A strong and light material is desired for space launch.

The metals with highest specific strength (strength divided by density) are

- Aluminum alloys
- Titanium alloys



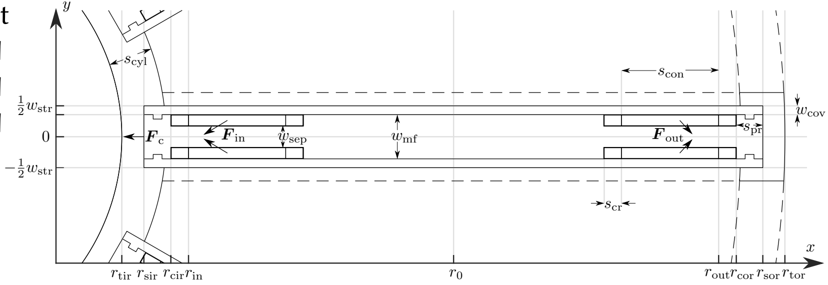
Coil mechanical structure



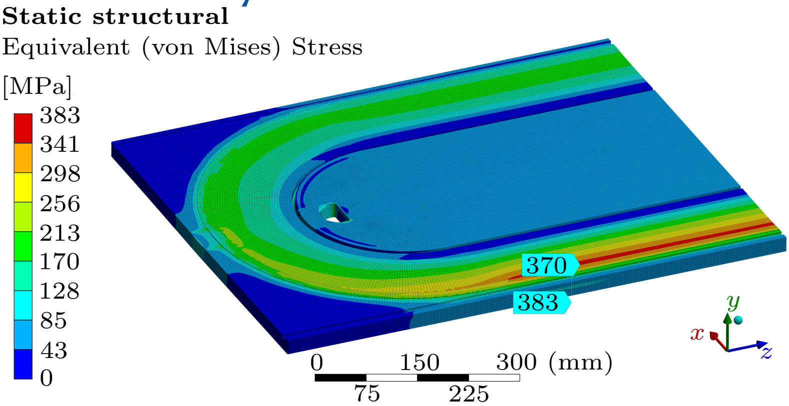
Note: Upper cover plate and insulation of upper winding layer are hidden in the figure.

Force analysis

Symbol	Value	Unit
F_{in}	5.5	MN
F_{out}	4.0	MN
F_{c}	4.0	MN

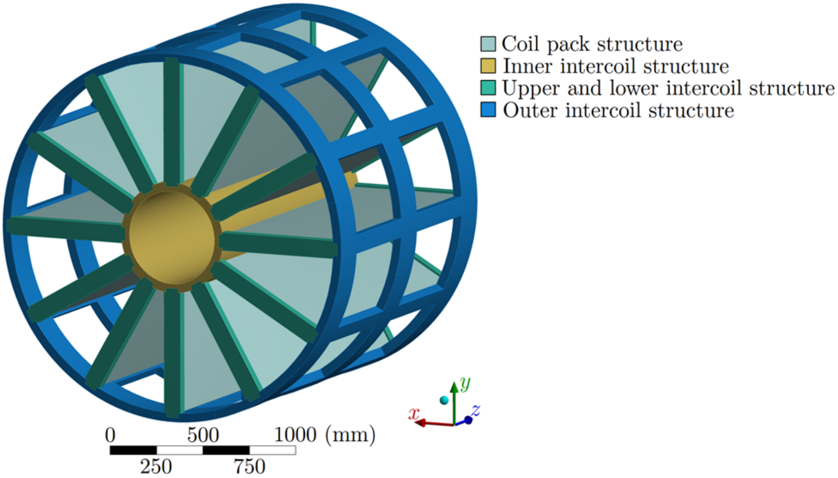


Mechanical analysis

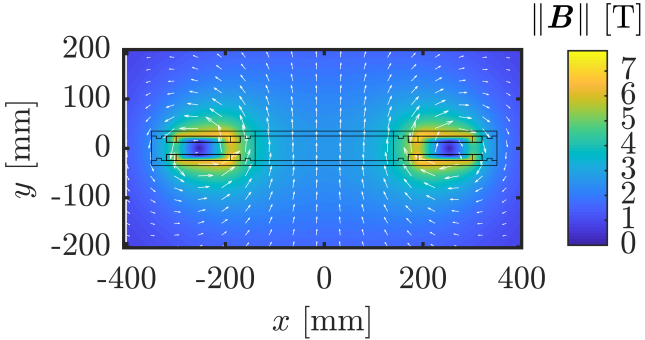


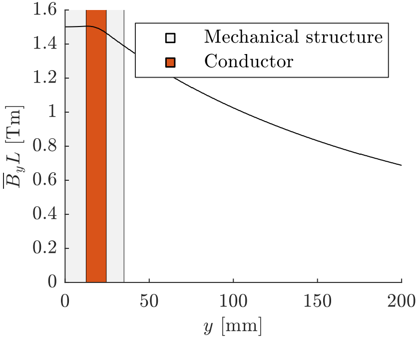
Note: Due to symmetry only one quarter of a coil pack is shown. The cover plate and insulation are hidden in the figure.

Intercoil structure



Single coil pack characterization





$$\overline{B}_y L(y) = \int_{-d_{\text{out}}/2}^{d_{\text{out}}/2} B_x(x, y) dx.$$

Part 2: Design and manufacture of a demonstrator coil for the toroidal magnet

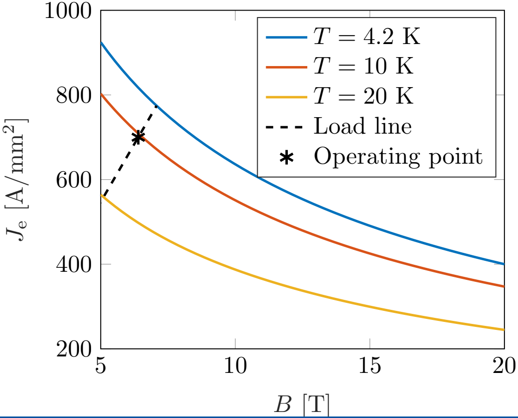
Demonstrator main goals

- Copper bands as current leads and layer jumps
- Test medium sized soldered metal insulation coil
- Test design of aluminum structure

Conductor requirements for demonstrator

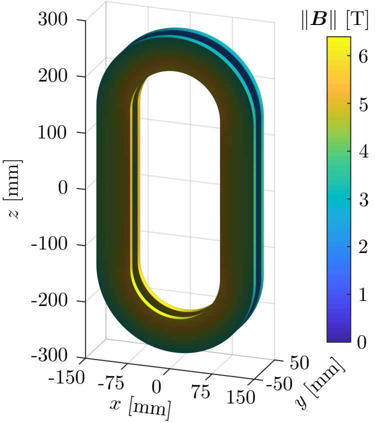
HTS ReBCO tape:

- 12 mm wide, 100 µm thick
- $J_e = 400\,\mathrm{A/mm^2}$ at 4.2 K and 20 T
- Angle dependence: worst case conditions
- Field dependence: Fitting function

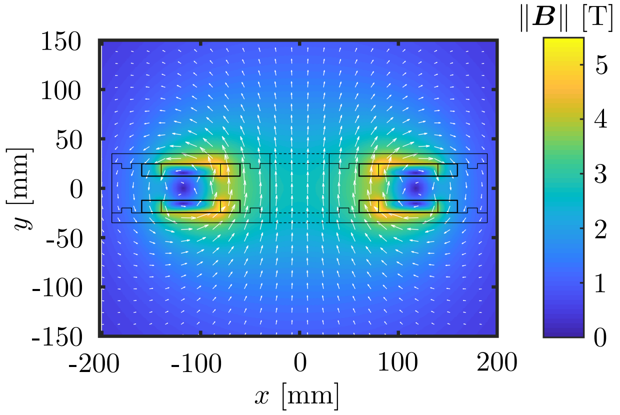


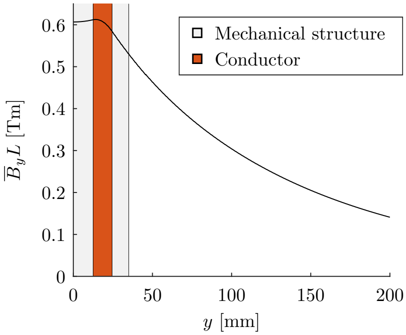
Demonstrator coil design

- Racetrack, about 1/2 outer width and 1/4 outer height of toroidal coils
- Soldered metal insulation coil
- Two HTS tapes (face-to-face) and one copper coated stainless steel tape
- Engineering operating current density: 700 A/mm^2 at 4.2 K, and peak field of 6.4 T
- Total HTS tape length: 1 km
- Stored energy: 106 kJ



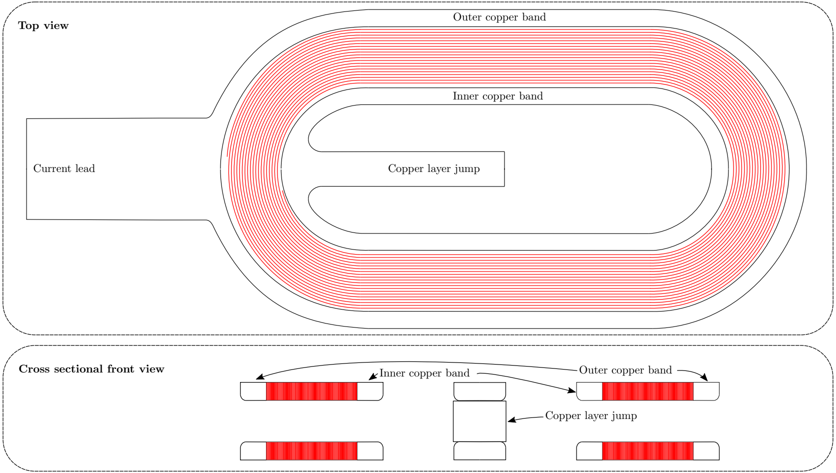
Demonstrator coil characterization



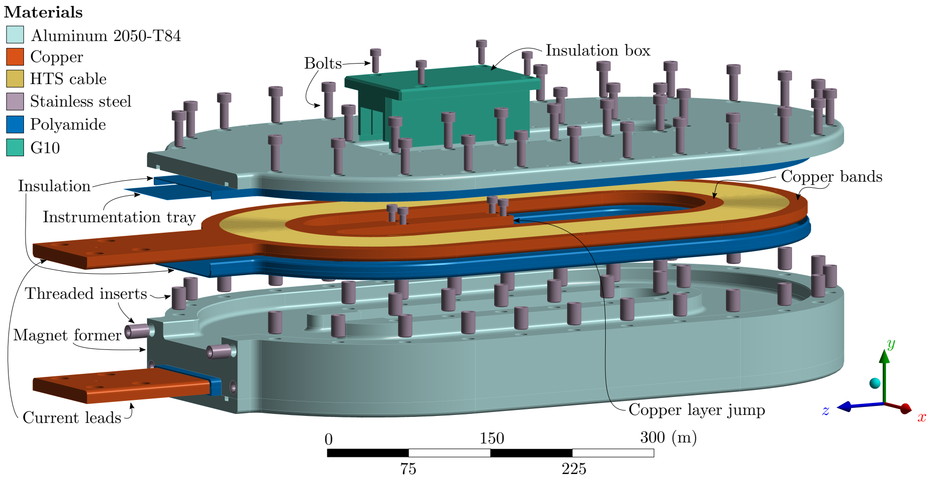


$$\overline{B}_y L(y) = \int_{-d_{\text{out}}/2}^{d_{\text{out}}/2} B_x(x, y) dx.$$

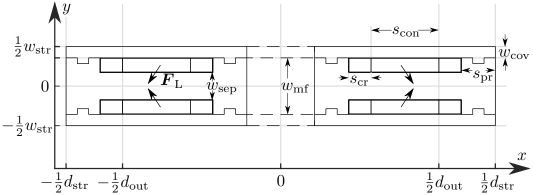
Copper bands



Mechanical structure for demonstrator coil

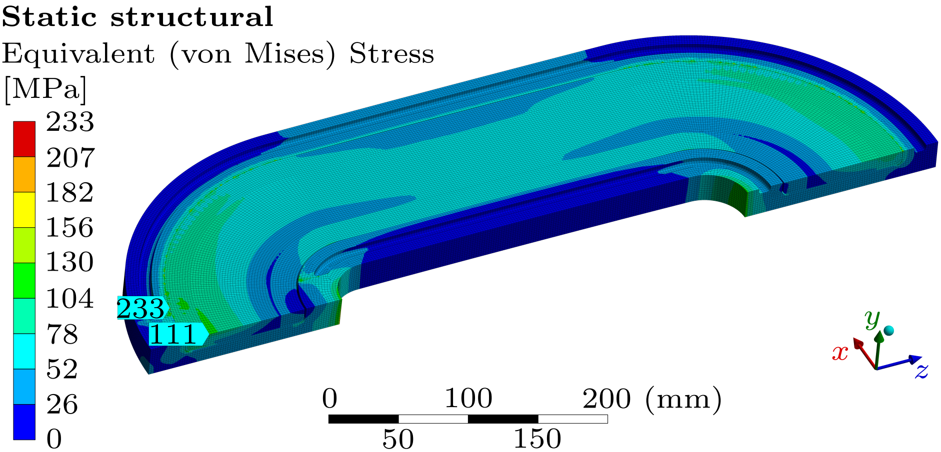


Force analysis



Symbol	Description	Value	Unit
F_x	Lorentz force x-component	$\pm$181	kN
F_y	Lorentz force y-component	$\pm$272	kN
F_z	Lorentz force z-component	0	kN
F_L	Lorentz force magnitude	327	kN

Demonstrator coil mechanical analysis

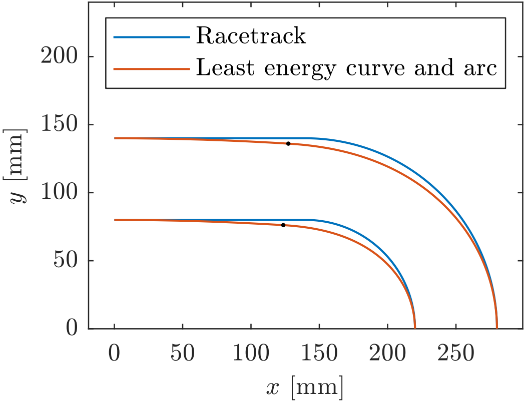


Racetrack shape

A series of winding tests showed problems with obtaining a tight winding on the straight part of the racetrack.

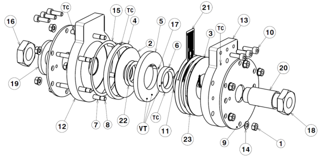
The end segments were replaced by curves of least energy (obtained by calculus of variations) and the straight parts were replaced by circular arcs with a large radius of curvature (smoothly connected).

The resulting shape has a strictly positive curvature everywhere.



Manufacturing plan

1) Small solenoids: Several configurations to test various cable and solder configurations and charging/discharging behavior. Each coil uses 50-60 m of HTS tape



2) AMaSED-0: Dummy coil using copper coated stainless steel tape instead of HTS tape. Cable consists of three identical tapes. The winding turns are soldered together.
3) AMaSED-1: Single pancake practice coil using 500 m of low performance HTS tape. Cable consists of two HTS tapes and one stainless steel tape. The winding turns are soldered together.
4) AMaSED-2: Final demonstrator coil using 1000 m HTS tape. Same cable configuration as AMaSED-1.

AMaSED: **A**dvanced **M**agnetic **S**pectrometer **E**xperimental **D**emonstrator

Summary of the HDMS project

Part 1: Conceptual design of a toroidal HTS magnet for a magnetic spectrometer in space

- 12 racetrack-shaped coil packs
- Bending strength: 3 T m, peak field: 11.9 T
- Lightweight aluminum structure

Part 2: Design and manufacture of a demonstrator coil for the toroidal magnet

- About 1/2 in outer width and 1/4 in outer height of one toroidal coil pack
- Soldered metal insulation coil
- Status: Manufacturing of small test solenoids has started and the dummy coil pack (AMaSED-0) will soon be manufactured

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