CNPEM's First Superconducting Device Development: A Wavelength Shifter for Sirius Hard X-ray Beamline

TE-MSC Seminar

27th June 2024

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On behalf of the Technology Unit

CNPEM Brazilian Center for Research in Energy and Materials

MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

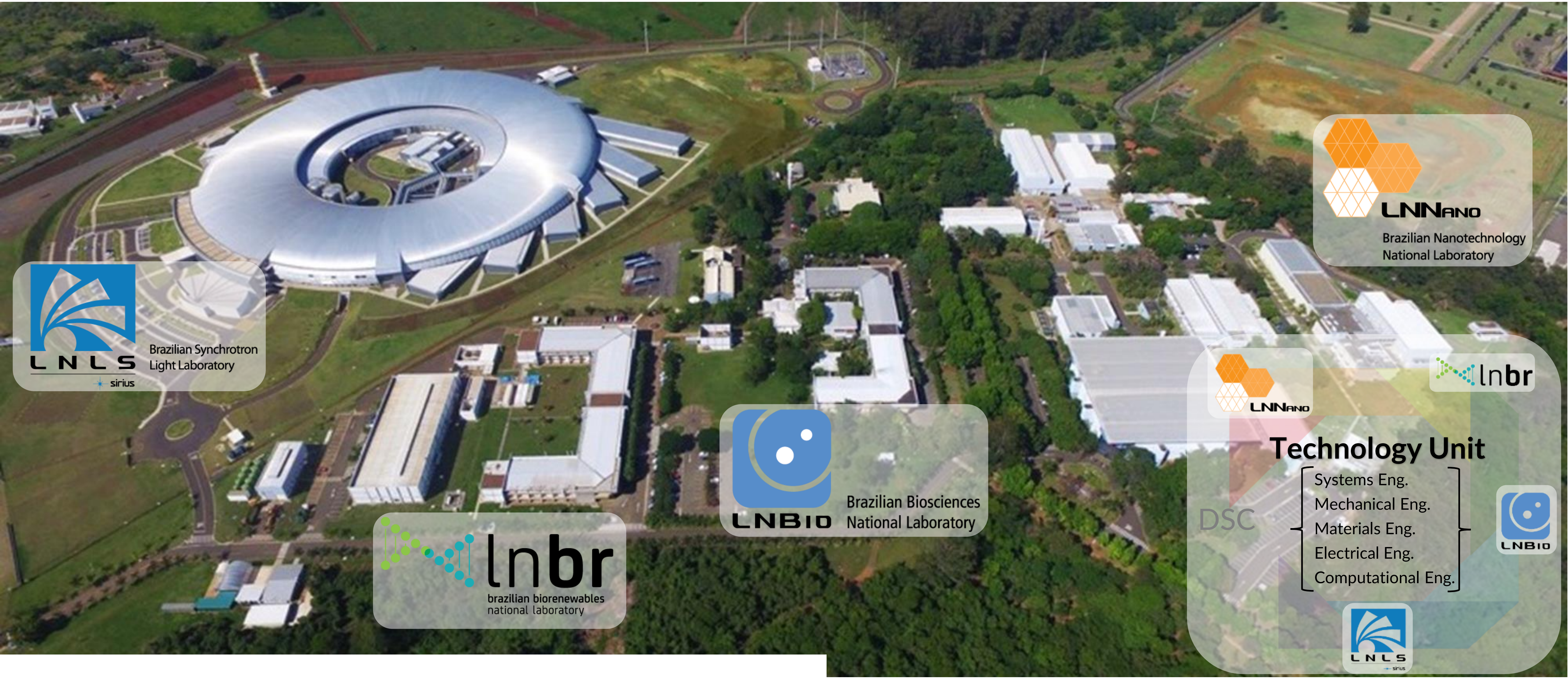
Outline

- Brief Overview of CNPEM
- CNPEM engages in superconductivity initiatives
- SWLS Overview
  - Electromagnetic design
  - Coils fabrication
  - Mechanical design
  - Cryogenic design
  - Electrical systems
  - Magnetic characterization approach
  - Assembly and Sirius Installation
  - Schedule and summarized development status

We are located at Campinas (a city of ~1.1 million people), about 100 km from Sao Paulo

CNPEM is a private, nonprofit organization, working under contract with the Brazilian Ministry of Science, Technology, Innovation (MCTI)

CNPEM



~860 employees

~450-560 trainees, pos-docs, students and outsourced personnel

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Sirius Highlights

(Some numbers only considering the storage ring)

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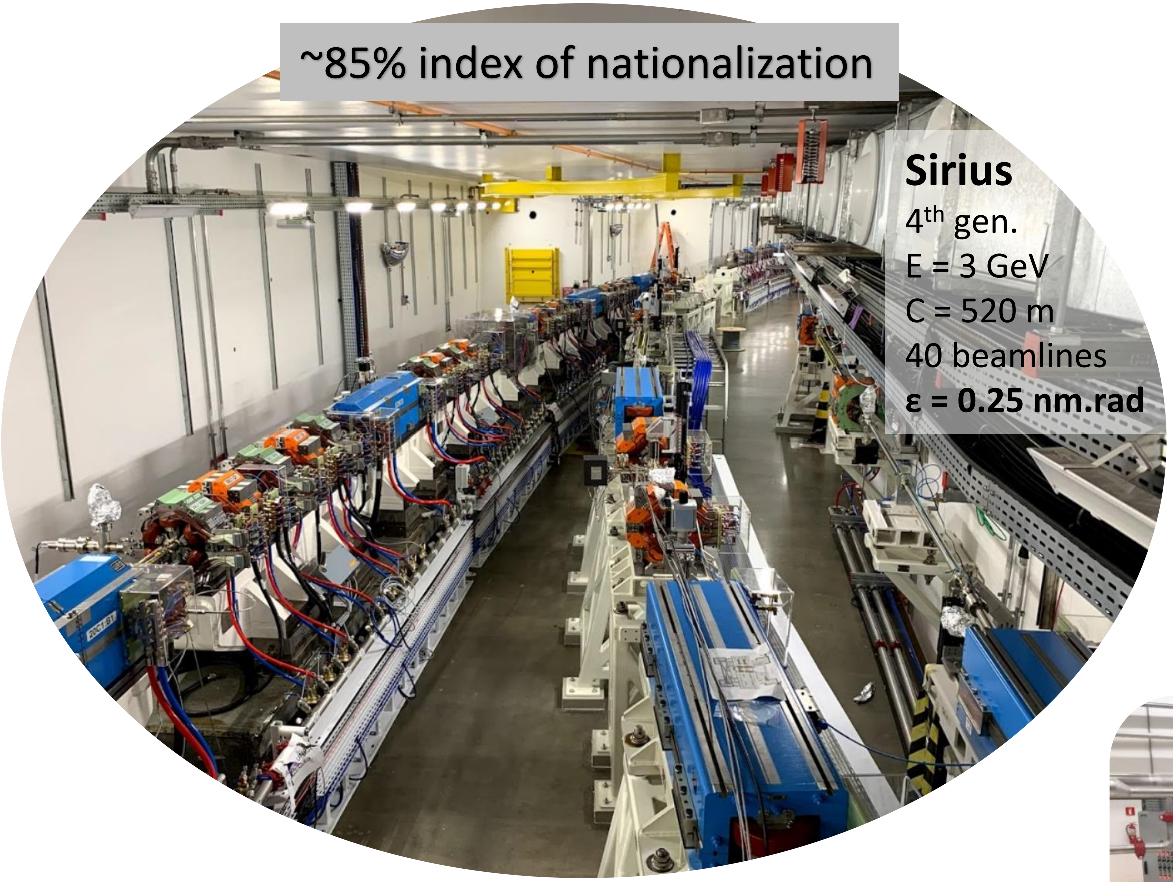
More than 1000 magnets (developed in a partnership w/ WEG)

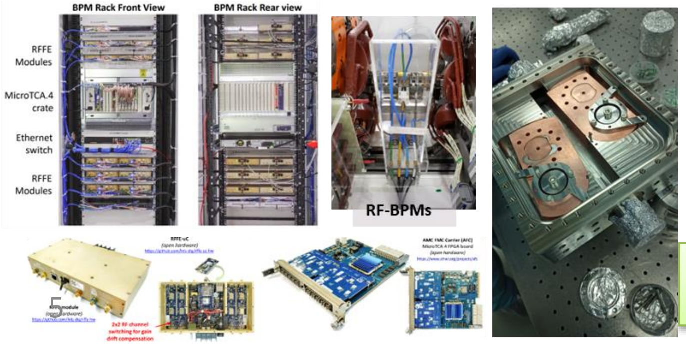
520 m of fully NEG-coated vacuum chambers (developed in-house)

~85% index of nationalization



Sirius
4th gen.
E = 3 GeV
C = 520 m
40 beamlines
ε = 0.25 nm.rad

More than 35 power Supplies powering families of magnets (developed in-house)



180 RF BPMs and electronics; beam scrappers etc. (developed in-house or w/ partnerships)

550 W module, produced by BBEF

4 towers of RF solid-state amplifier, 65 kW each (developed in-house)

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Superconductivity Initiatives

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Motivation:

late 2019 Sirius accelerators were delivered

mid 2020 The accelerator's engineering division was separated from LNLS, and the Technology Unit was created – work on other engineering projects of the center and partnerships with Brazilian industry: **Knowledge gap: lack of expertise in superconducting technology -> Need to bring this expertise to CNPEM, focusing on the center's main actuation fields**

Main fields of interest

Energy	Accelerators	Medical	Materials
Electric motors, generators, power transmission lines, SMESs	Magnets, insertion devices, RF cavities	Magnetic resonance devices (MRI and NMR), cyclotrons for therapy	Low and high temperature superconducting materials development and characterization

late 2020 An agreement was signed between CNPEM and CERN for transferring know-how and technology in superconducting magnets

2021 First initiative in superconductivity was started at CNPEM with CERN's help: build a team at CNPEM and design of the first magnet

Superconductivity Initiatives – CNPEM/CERN/Universities (USP and UFSCar) partenership

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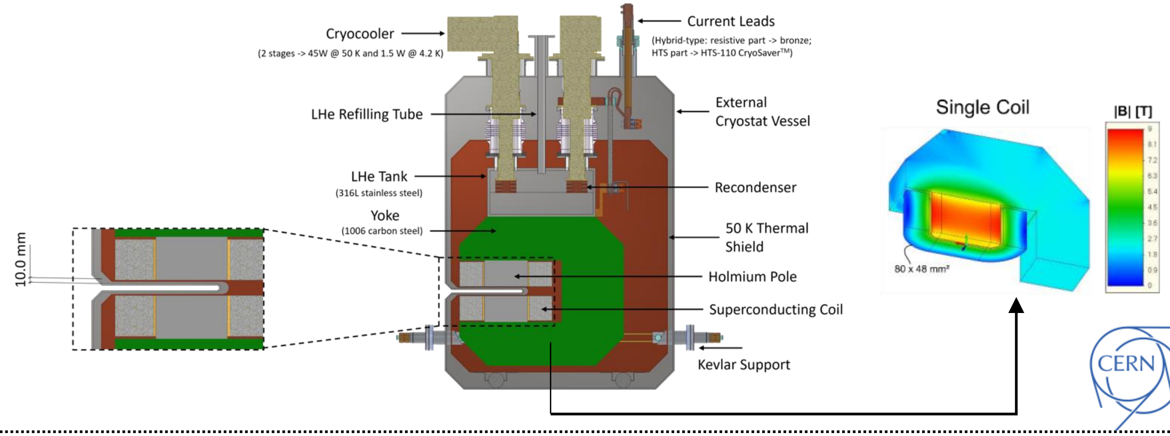
2021 Superconducting Dipole of 6.4 T (project on hold)

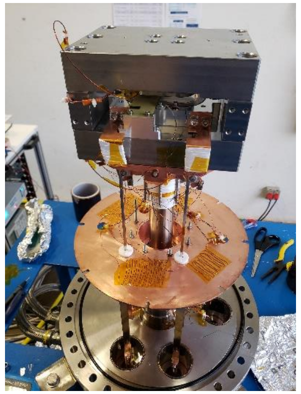


CERN

2022 Vertical Cryostat for Testing Superconducting Coils

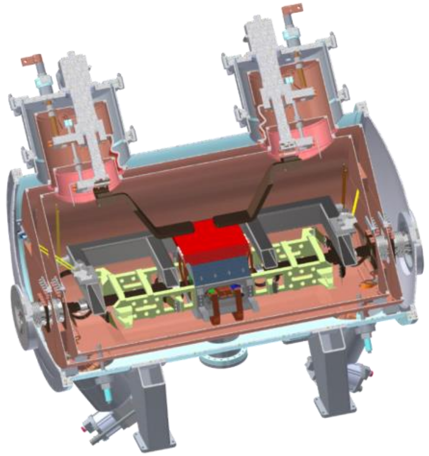
CERN

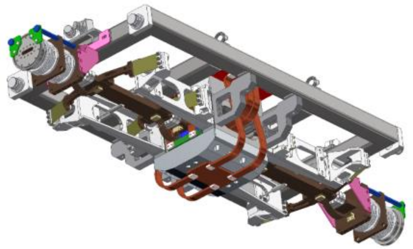
Setup for testing coils

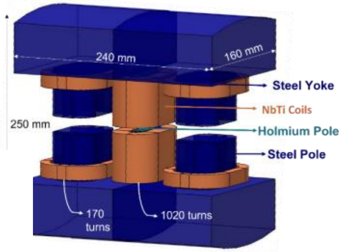


2021 *Superconducting Wavelength Shifter of 6.6 T*

(ongoing project – FDR phase)







CERN

2023 Manufacture and Characterization of NbTi Wires

(ongoing project) – CNPq InovaNióbio Project

Superconductivity Initiatives – CNPEM/CERN/Universities (USP and UFSCar) partenership

CNPEM

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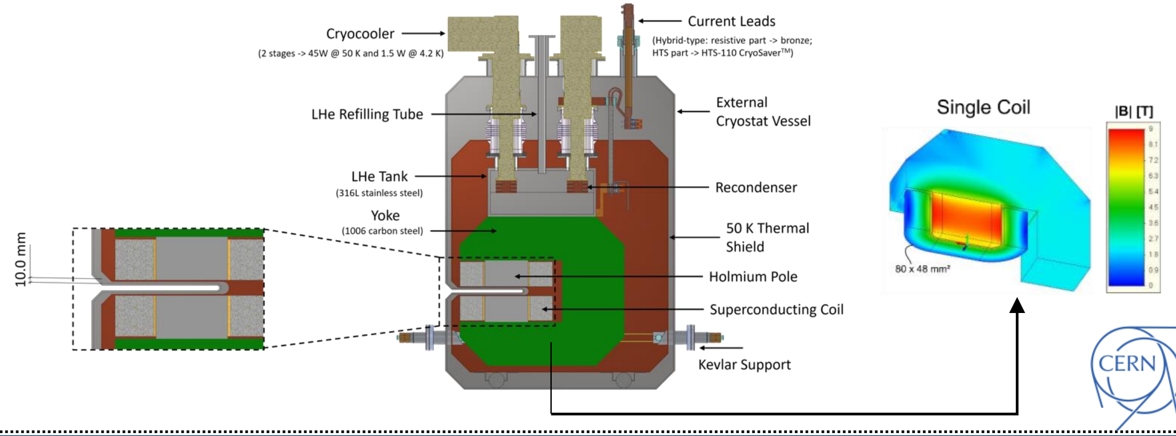

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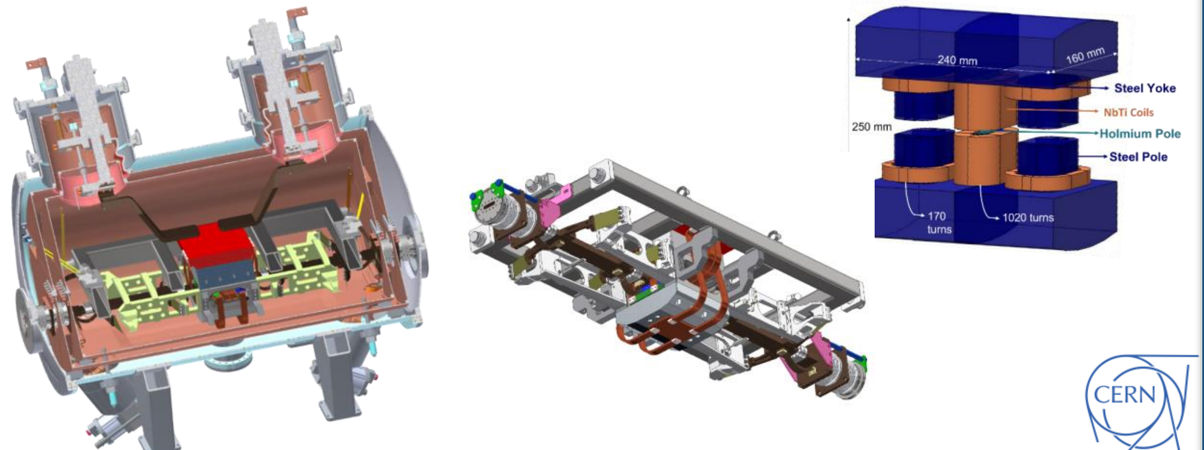

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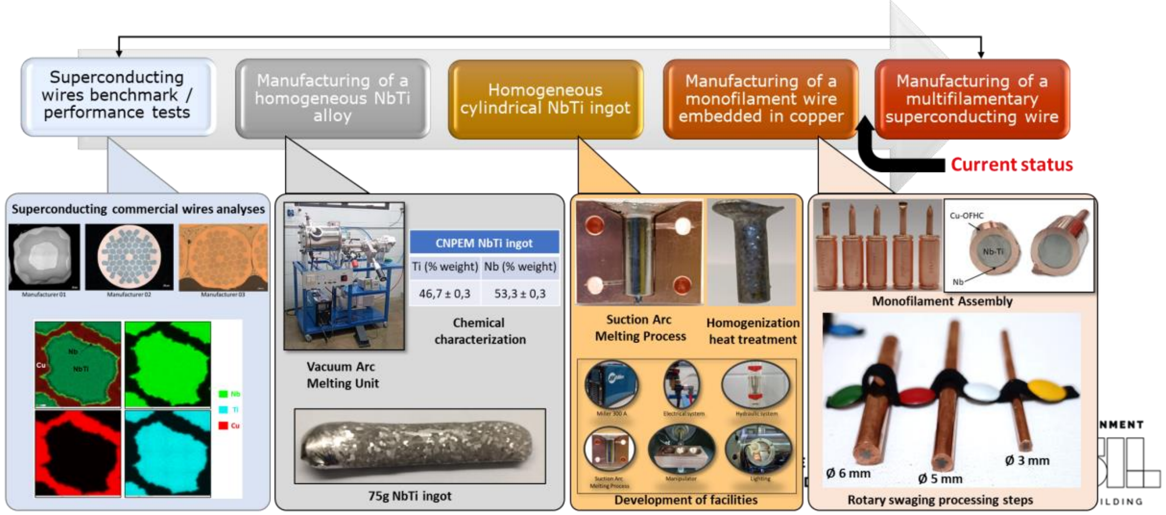


SWLS - Motivation

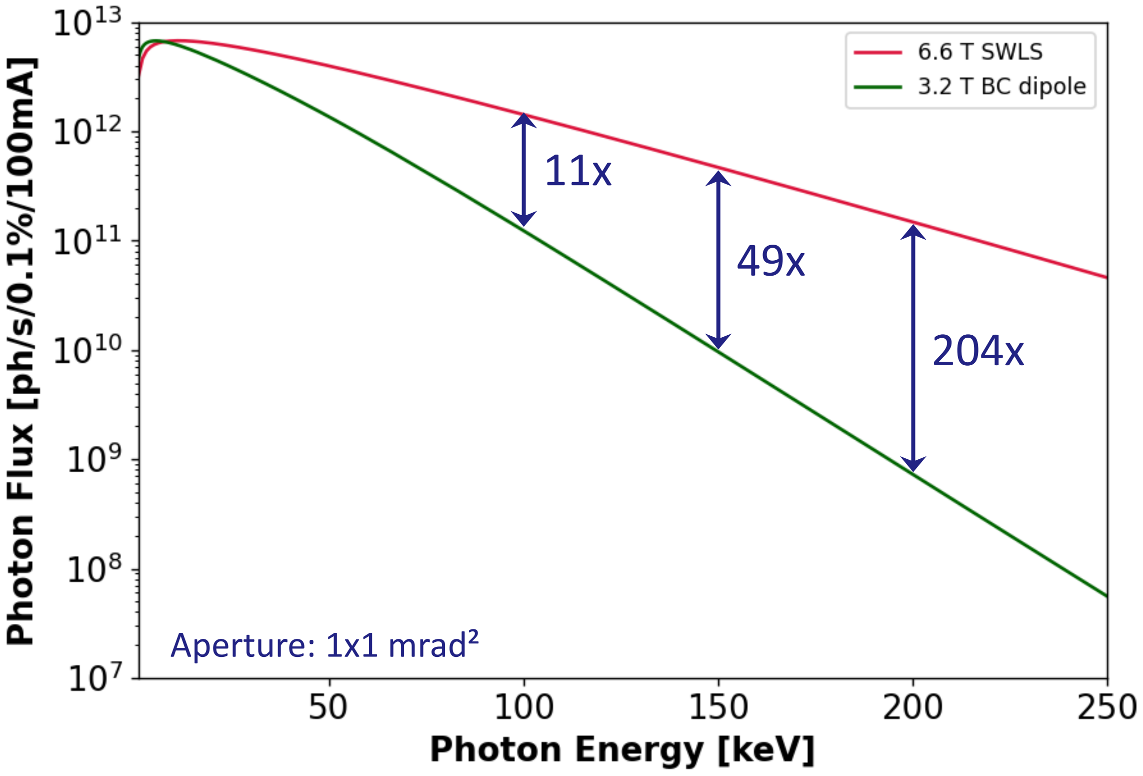
- Sirius phase 2 - new hard X-ray beamlines -> Need for high energy photons

Two beamline candidates

Beamline	Exp. Technique	Energy Range [keV]
SUSSUARANA	X-ray Diffraction	30 - 200
MANATI	X-ray Tomography	80 - 150

(current beamlines focus on photon energies below 70 keV)

- Current non-superconducting magnets of **3.2 T do not produce** reasonable photon flux above **100 keV**



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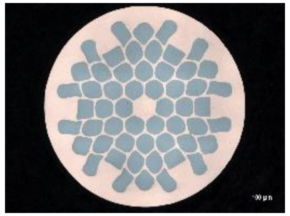
SWLS – Design Premises

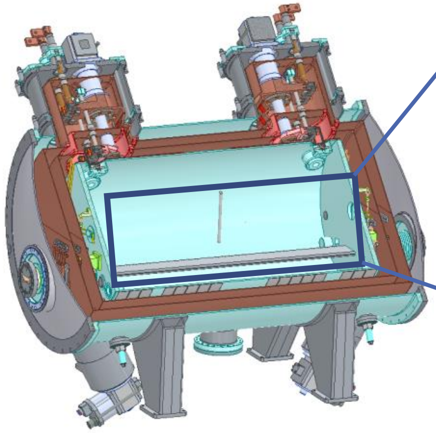
- Build a superconducting magnet, **cryogen-free**, with **magnetic field higher than 6 T and compatible with one of the Sirius low-beta straight sections**
- The **magnet** must not **impact** the **Sirius emittance and beam dynamics**
- Use **NbTi wires**
- **Reuse** components from a deactivated **4 T Superconducting Wiggler**

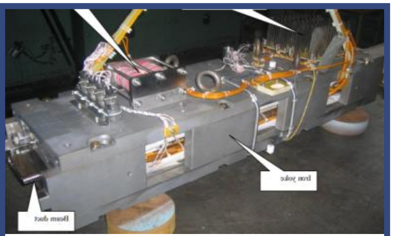


SWLS NbTi wire
Ø = 0.90 mm
Cu/NbTi = 0.97

Nova estrutura eletromagnética

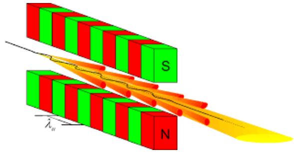
4 T SCW





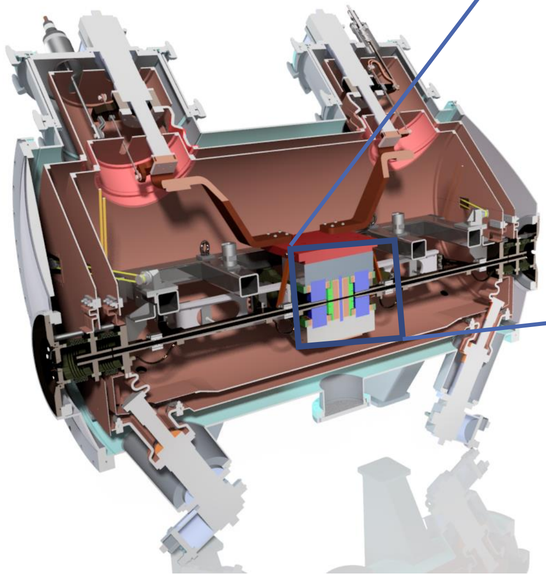
Cold mass
(In LHe bath)

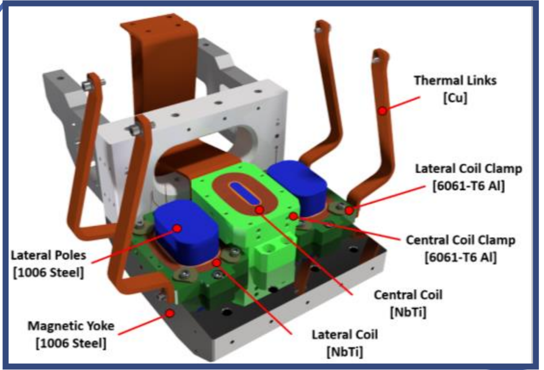
Bought from Budker Institute of Nuclear Physics



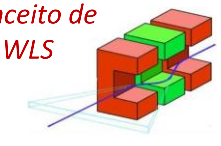
Schematic of a Wiggler

SWLS





Conceito de WLS



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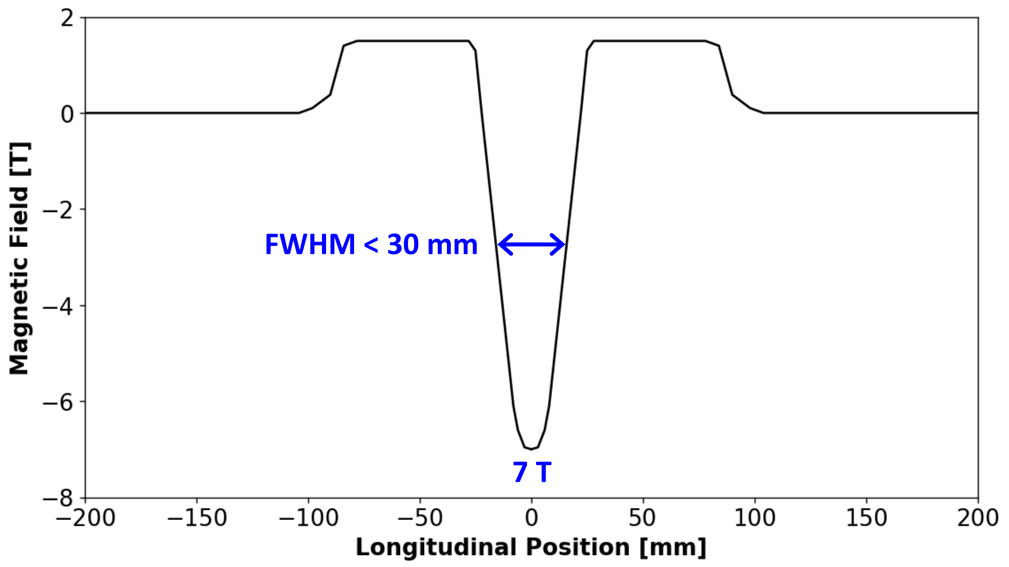
Electromagnetic Design

Target magnetic field profile (Accelerators Physics group)

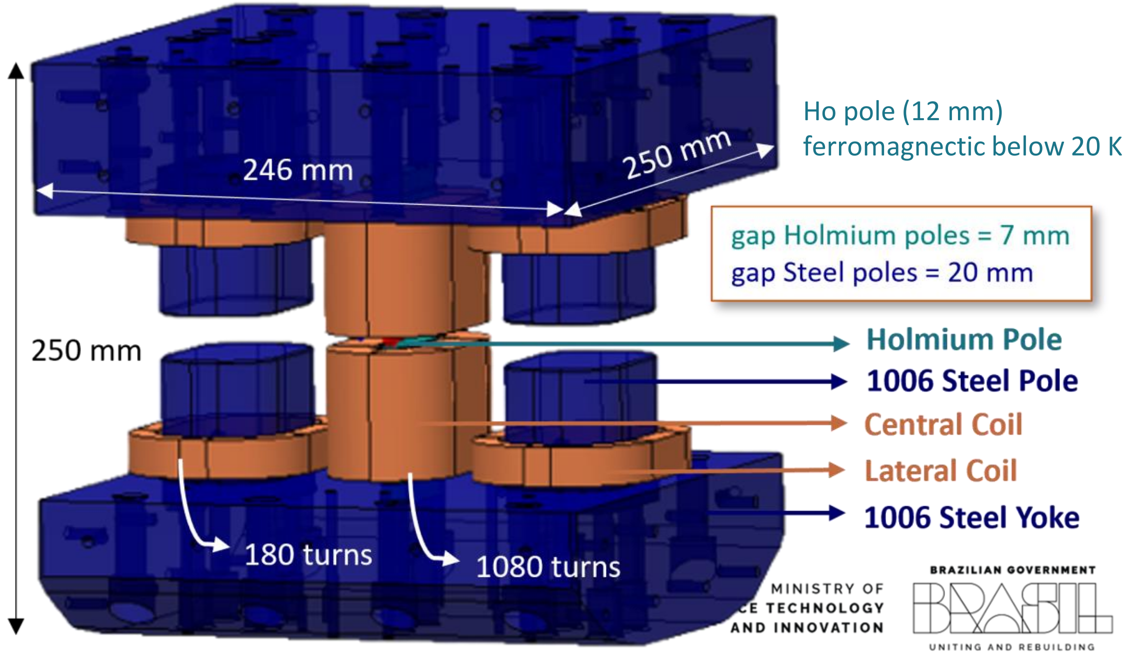


A very narrow central peak field not to **impact the beam emittance**

Basic Parameters

Parameters	Targets
Current	< 300 A
Peak field	> 6 T
FWHM of central peak	< 30 mm
1st magnetic field integral	< 200 G.cm
Margin @ 5.0 K	> 20%

Proposed electromagnetic model



Electromagnetic Design

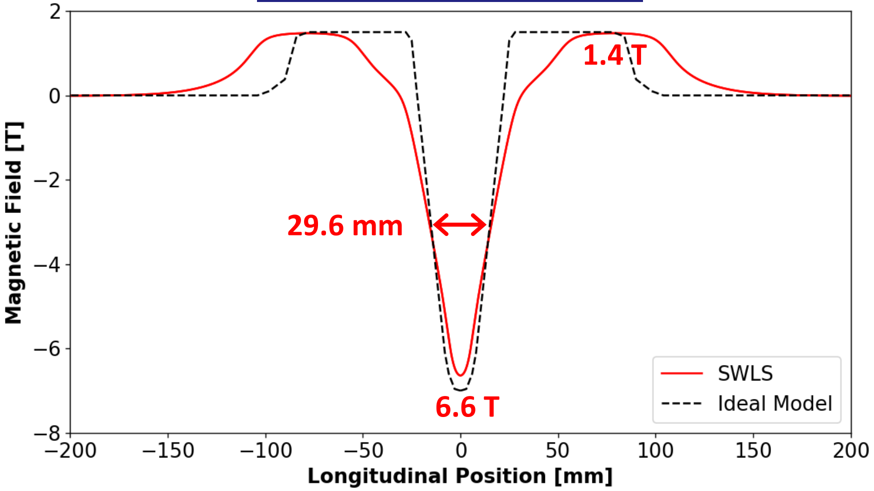
Electromagnetic Design Analysis and Optimization:

- Geometry of the model
- Magnetic field plots
- Field integrals and multipoles
- Fabrication errors
- Load line operating margin
- Energy Losses
- SME and Inductance
- Photon flux emission

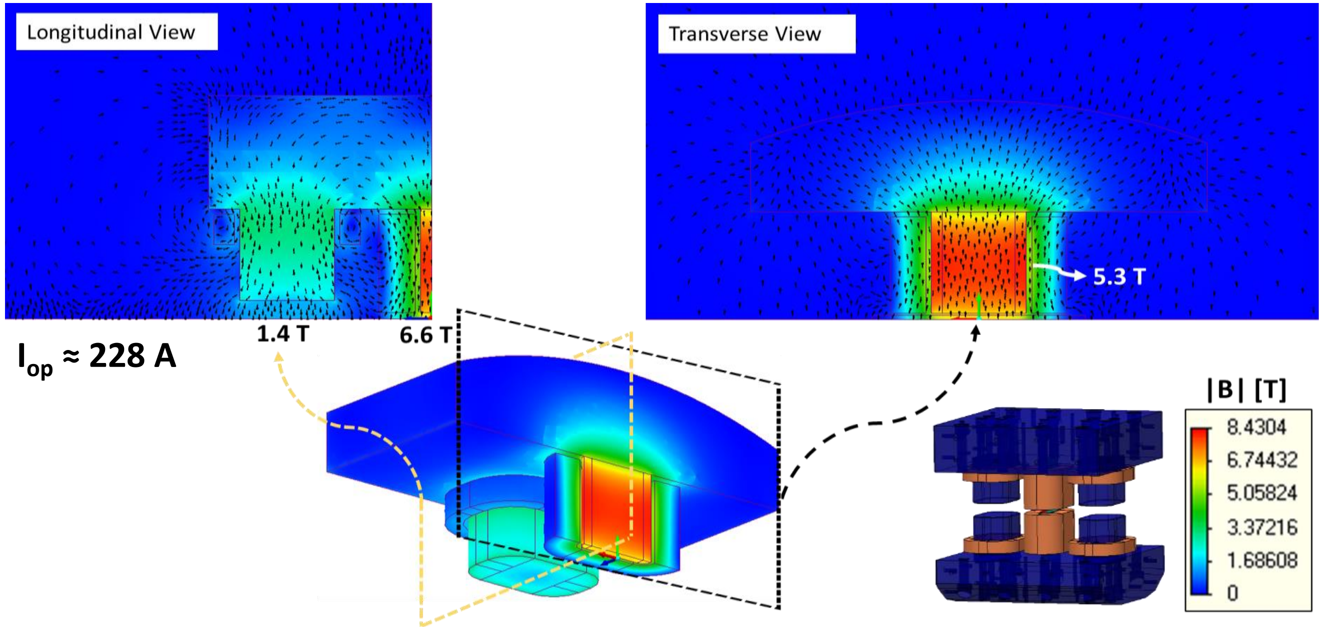
Main results

Parameters	Targets	Results
Current	< 300 A	228 A
Peak field	> 6 T	6.6 T
FWHM of central peak	< 30 mm	29.6 mm
1st magnetic field integral	< 200 G.cm	72 G.cm
Margin @ 5.0 K	> 20%	24%

Simulated field profile



Field maps



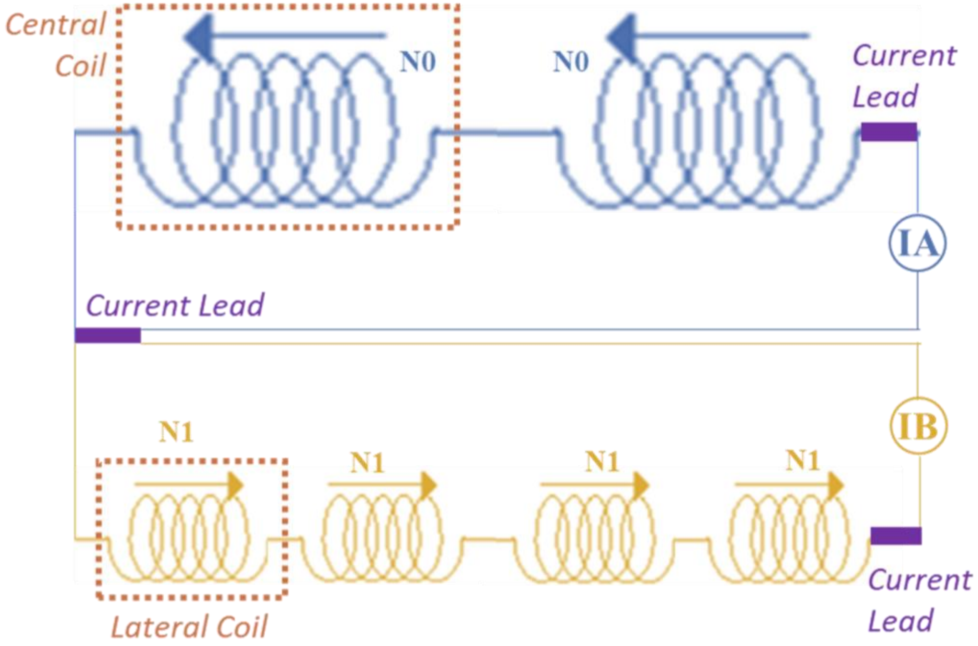
Additional results

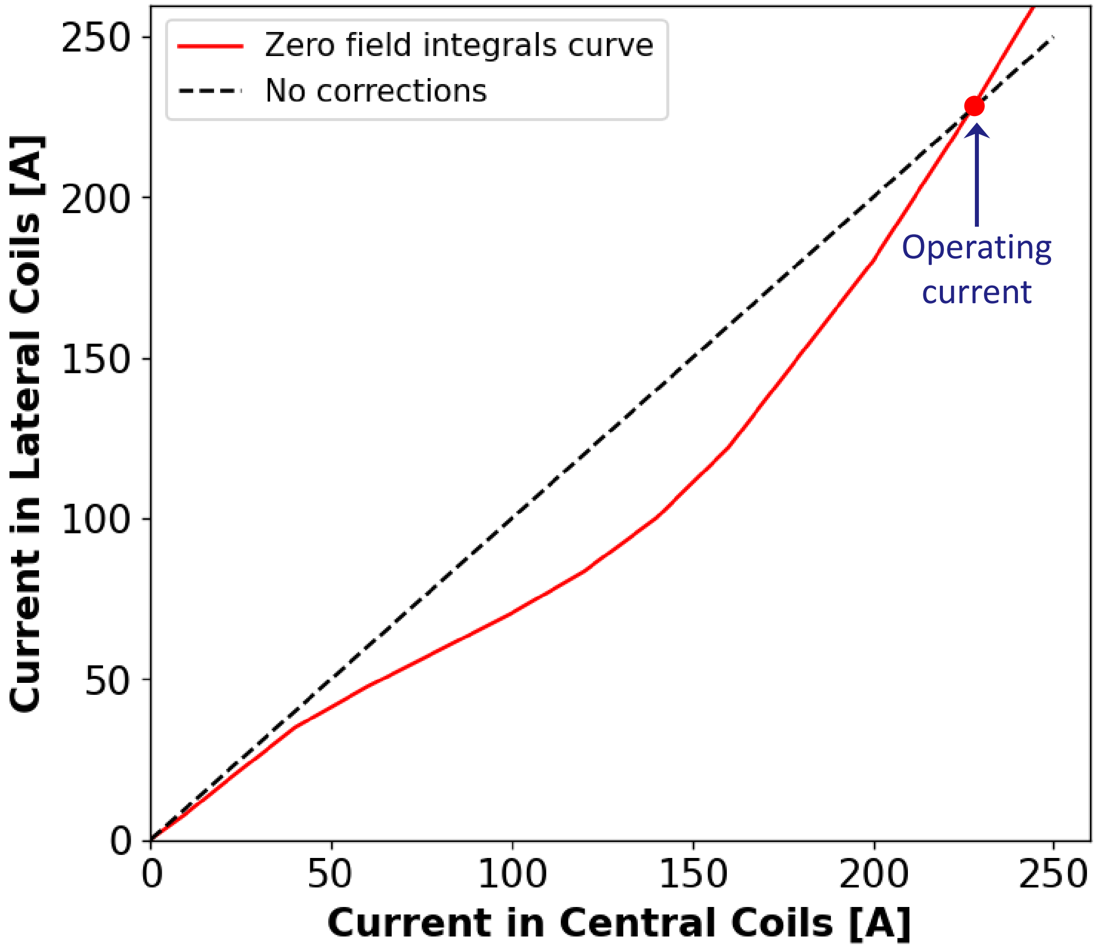
Parameters	Results
Roll-off of peaks (± 5 mm)	0.16%
2nd magnetic field integral	6.7 kG.cm²
Total integrated quadrupole	0.13 T
Total integrated sextupole	5.7 T/m
Current sharing temperature	6.1 K
Total AC loss during ramp-up (time = 5 min)	0.314 W
Stored magnetic energy	3.37 kJ
Inductance	130 mH

Electromagnetic Design – Current ramp-up

Independent power supplies used to central and lateral coils:

- Allows correction of the field integrals during the current ramp-up
- Minimize perturbations on the beam





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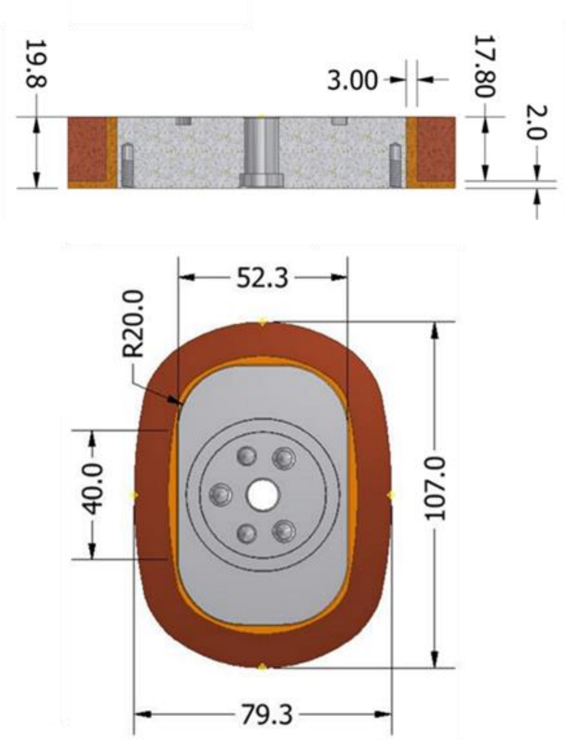
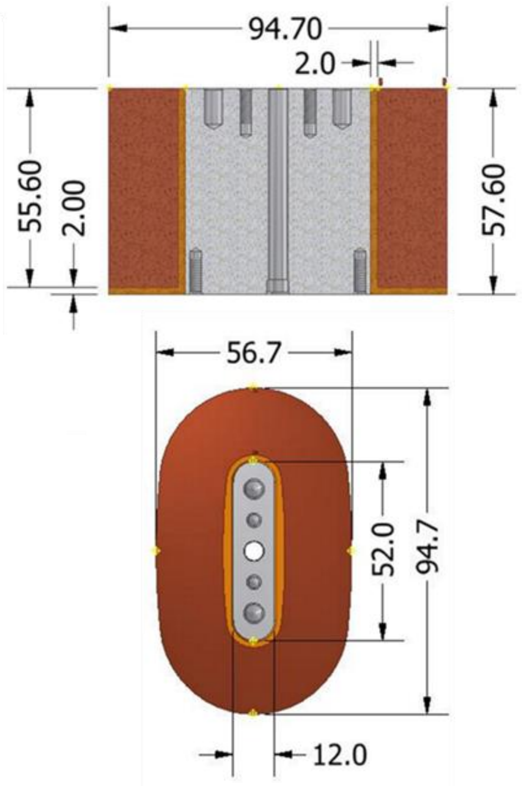
Coils fabrication

The **coils** have slightly **oval shape** to better maintain the **tension on the wires** during winding process

Geometry and dimensions

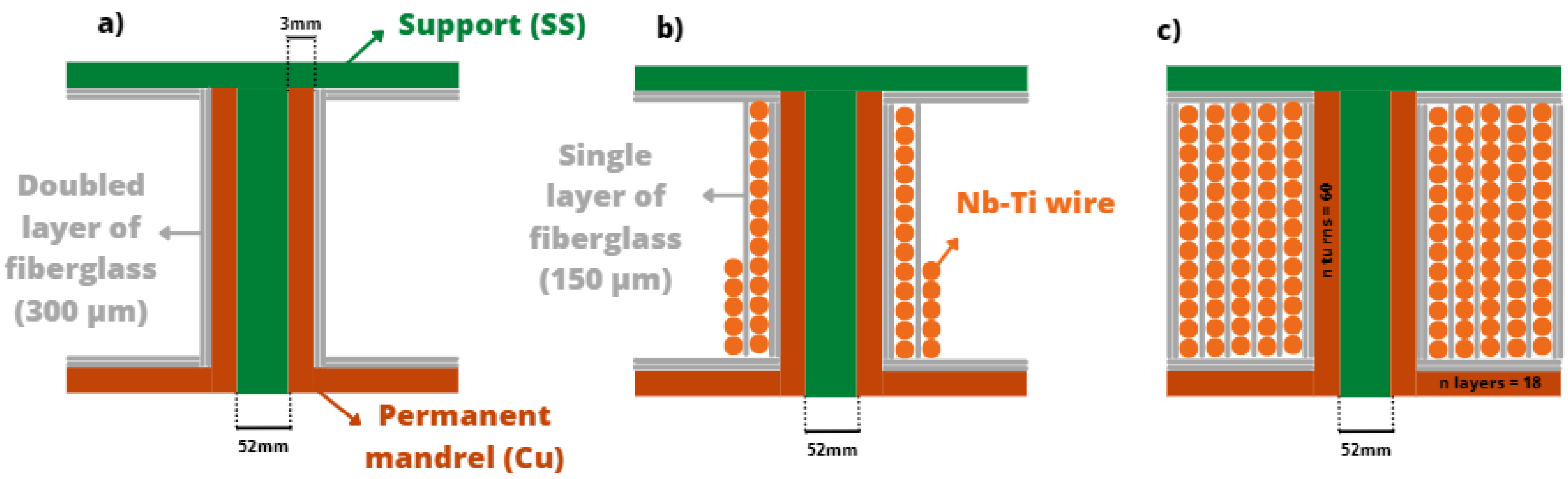


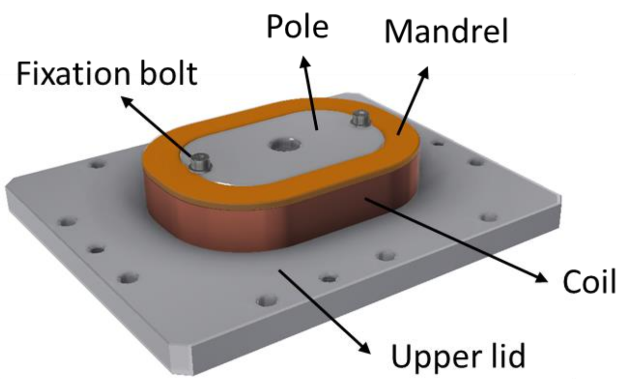
Lateral coil (180 turns)

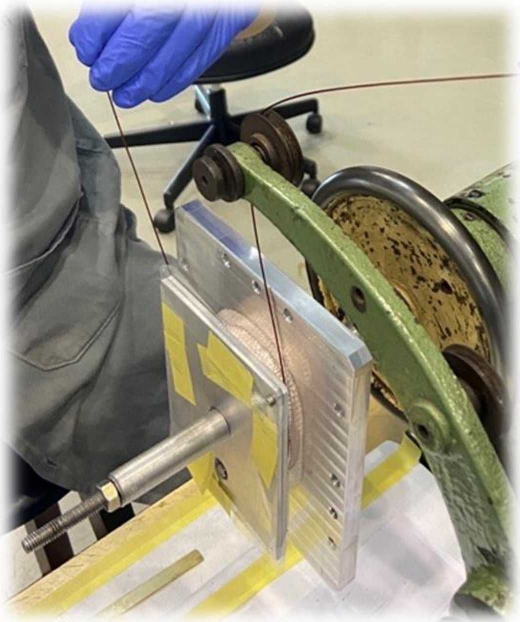


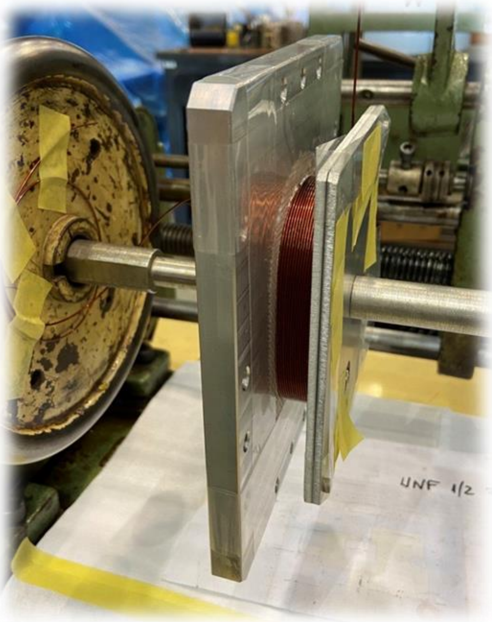
Central coil (1080 turns)

Coil prototyping – winding process









- **Winding structure:** Mandrel + pole + support (Upper lid)
- **Edges insulation:** 300 µm fiberglass
- **Winding process:** layer by layer
- **Interlayer insulation:** 150 µm fiberglass

Coils fabrication – impregnation setup and procedure

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Pre-impregnation process:

1. Room temperature pump down (24h) and bake-out (24h@80°C): pressure 10^{-2} mbar
2. Resin overnight at room temperature with vacum pump

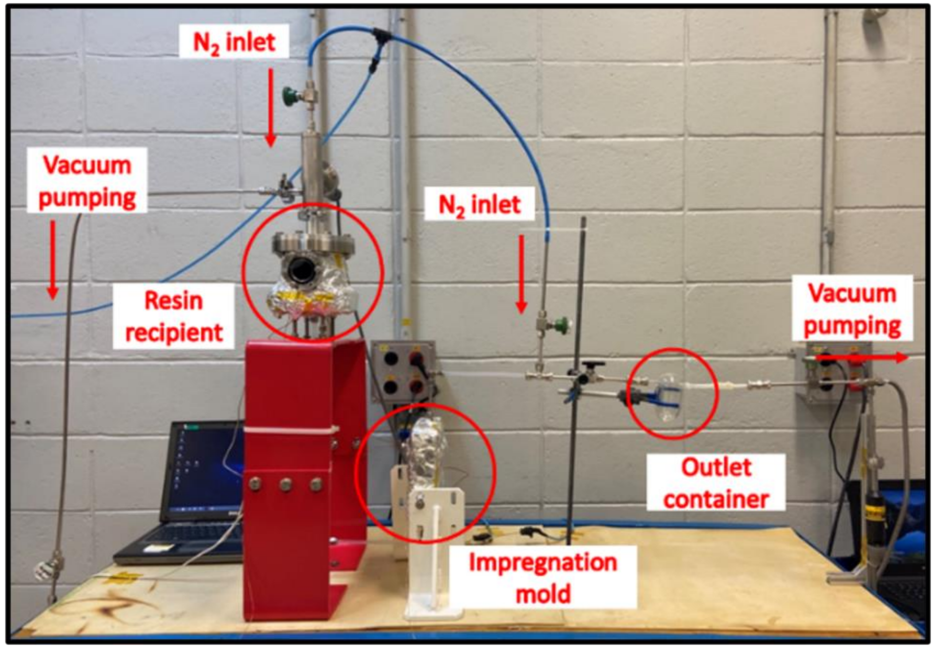
Impregnation process:

1. Degass the resin: 1h@50°C
2. Open valve and apply 100 mbar nitrogen pressure to control the velocity of the flow
3. Milking and reversed milking with 1 atm pressure (about 5 – 7 times)

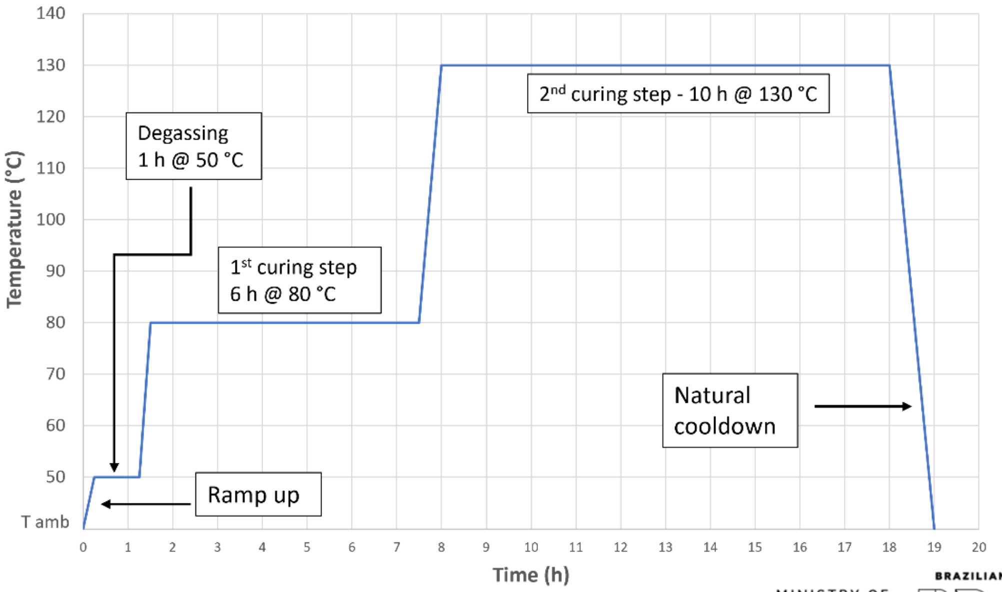
Used resin:

- Araldite F (100 pbw)
- Hardener HY 905 (100 pbw)
- Flexibilizer DY 040 (10 pbw)
- Accelerator DY 062 (1 pbw)

(pbw = parts by weight)



Resin curing process



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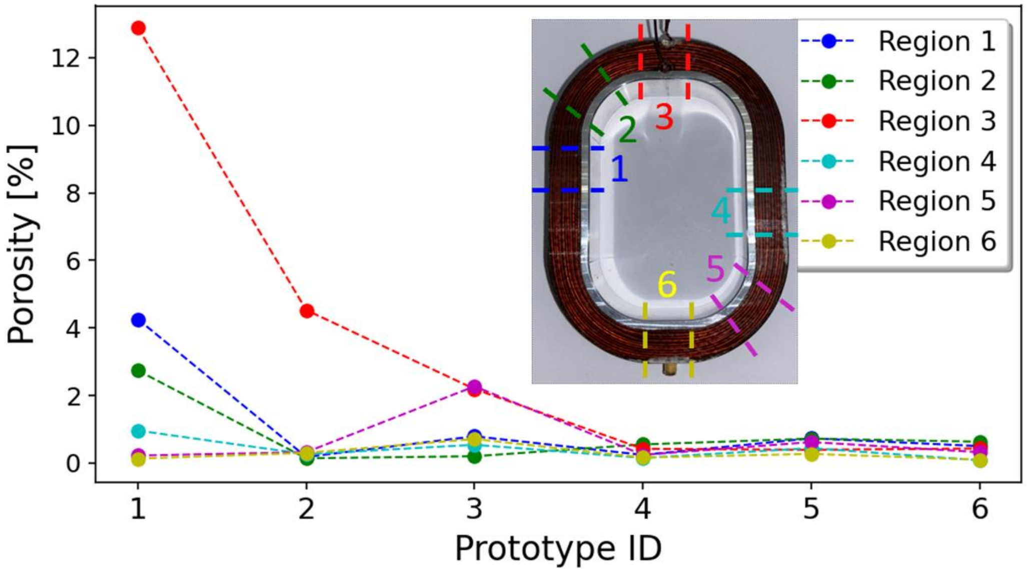
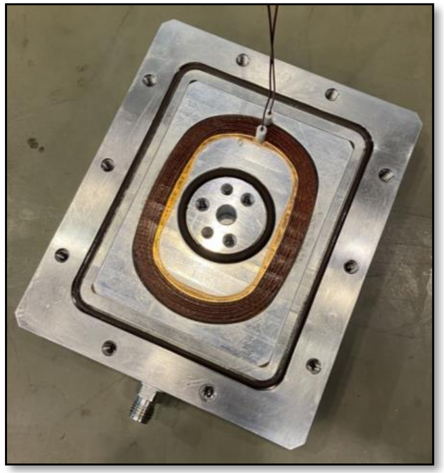
Coils fabrication - prototypes

- Impregnation process was optimized using copper prototypes
- **After** few **copper prototypes**, NbTi coils were successfully prototyped
- **Prototyped coils** were **successfully tested** at the vertical cryostat

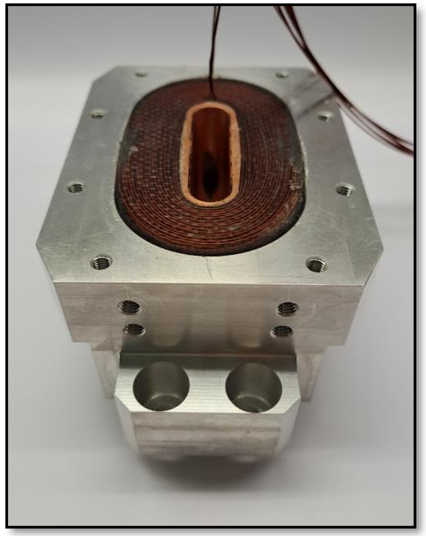
Copper prototyoes – porosity evolution



NbTi lateral coil prototype



NbTi central coil prototype



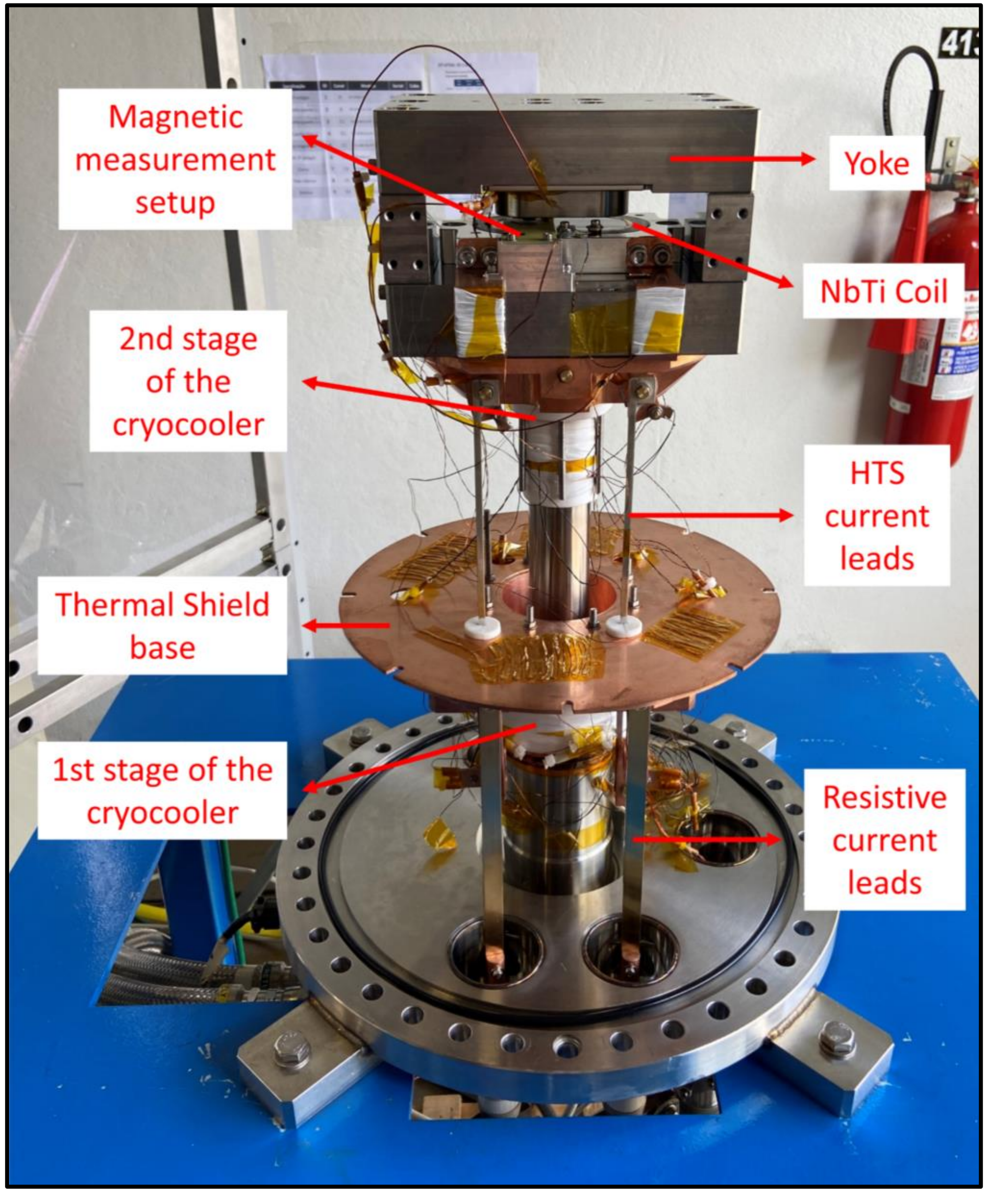
Vertical Cryostat

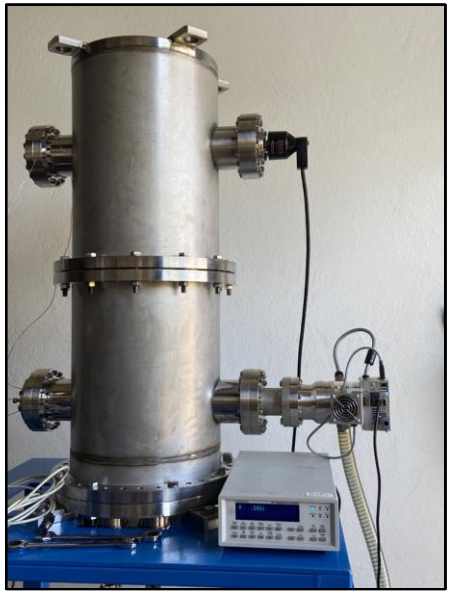
Cryostat Design and Features:

The cryostat follows the same principles as the SWLS: conduction cooling, current leads, thermal shield, etc.

Applications and tests planned

- Thermal and magnetic tests of superconducting coils
- Thermal performance of components at cryogenic temperatures
- Mechanical component fixation at cryogenic temperatures
- Splice box performance evaluation
- Quench protection system testing
- Control system testing and evaluation

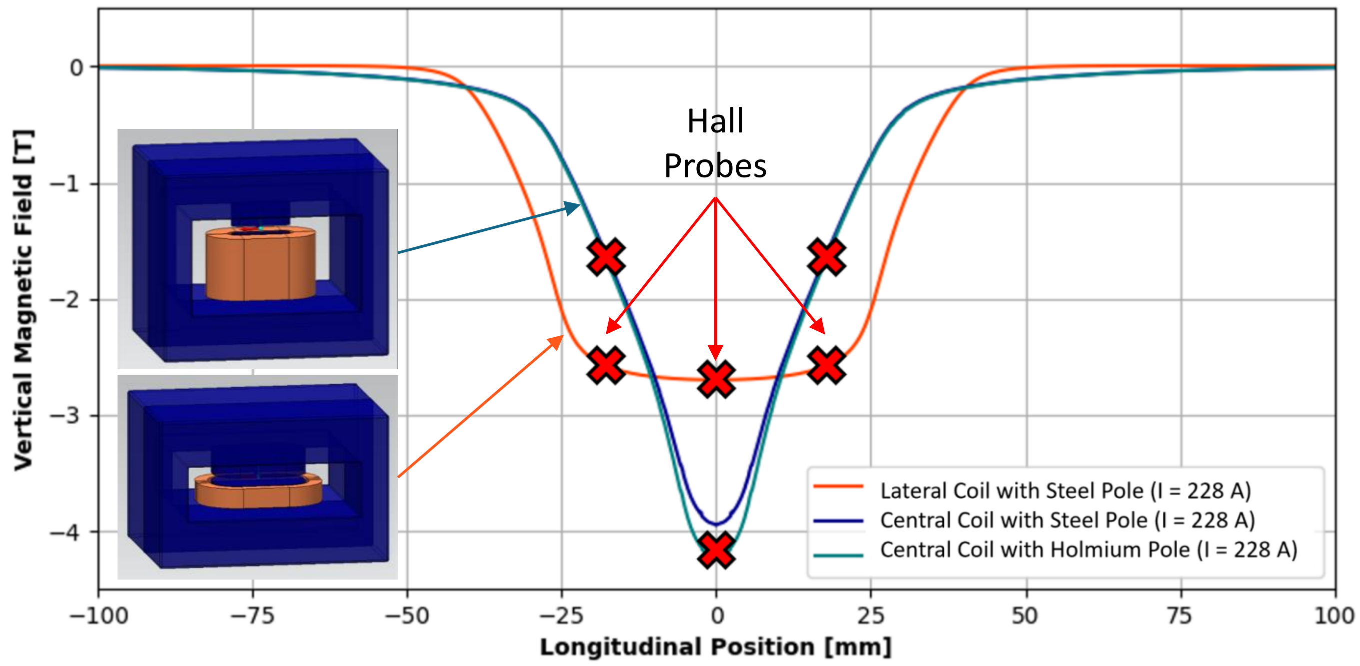




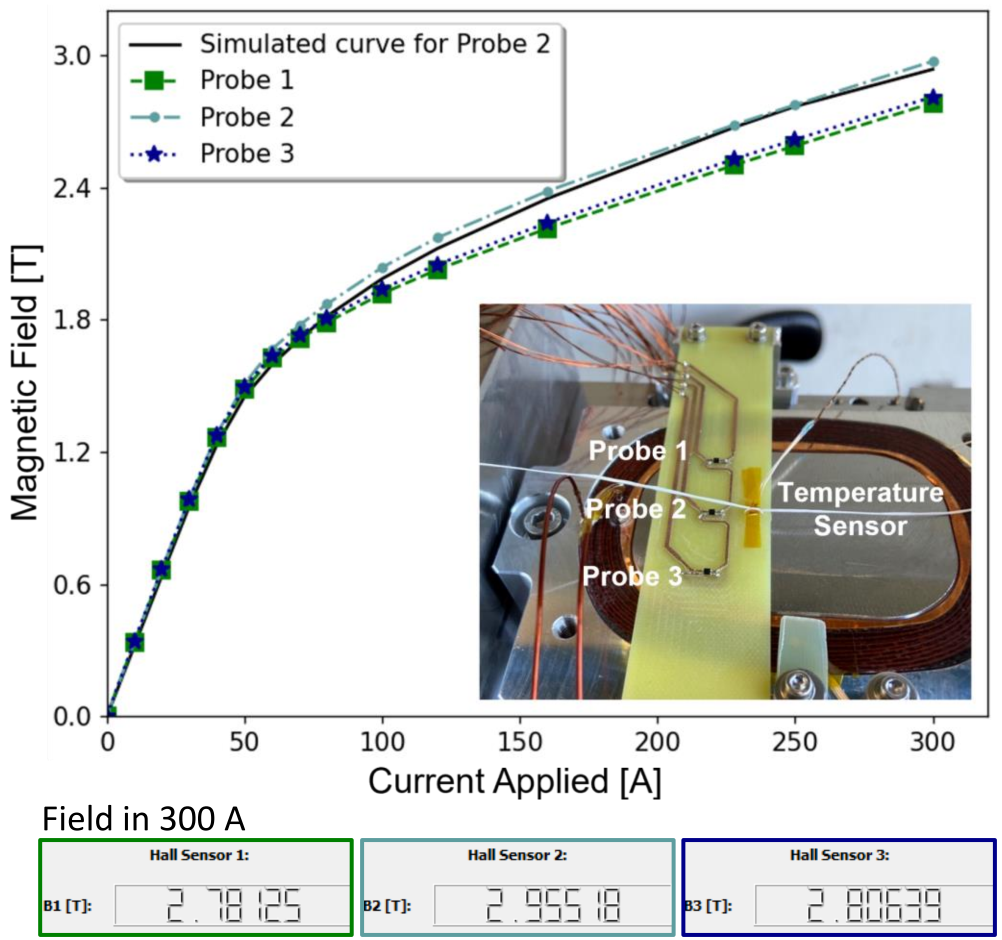
Coils fabrication – tests in the vertical cryostat

- **Mirror yokes** were designed to test the coils
- PCB boards with **3 Hall sensors** (HGT-2101) were used to **measure the magnetic field**

Simulated magnetic profile for the mirror yokes



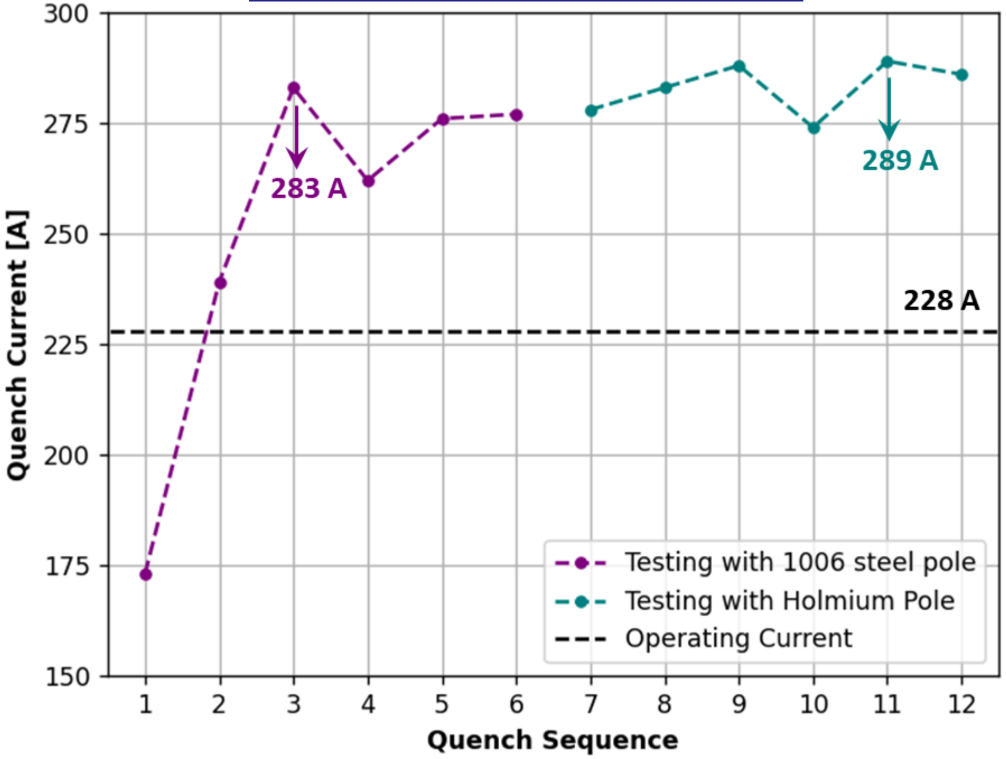
Results: Lateral coil



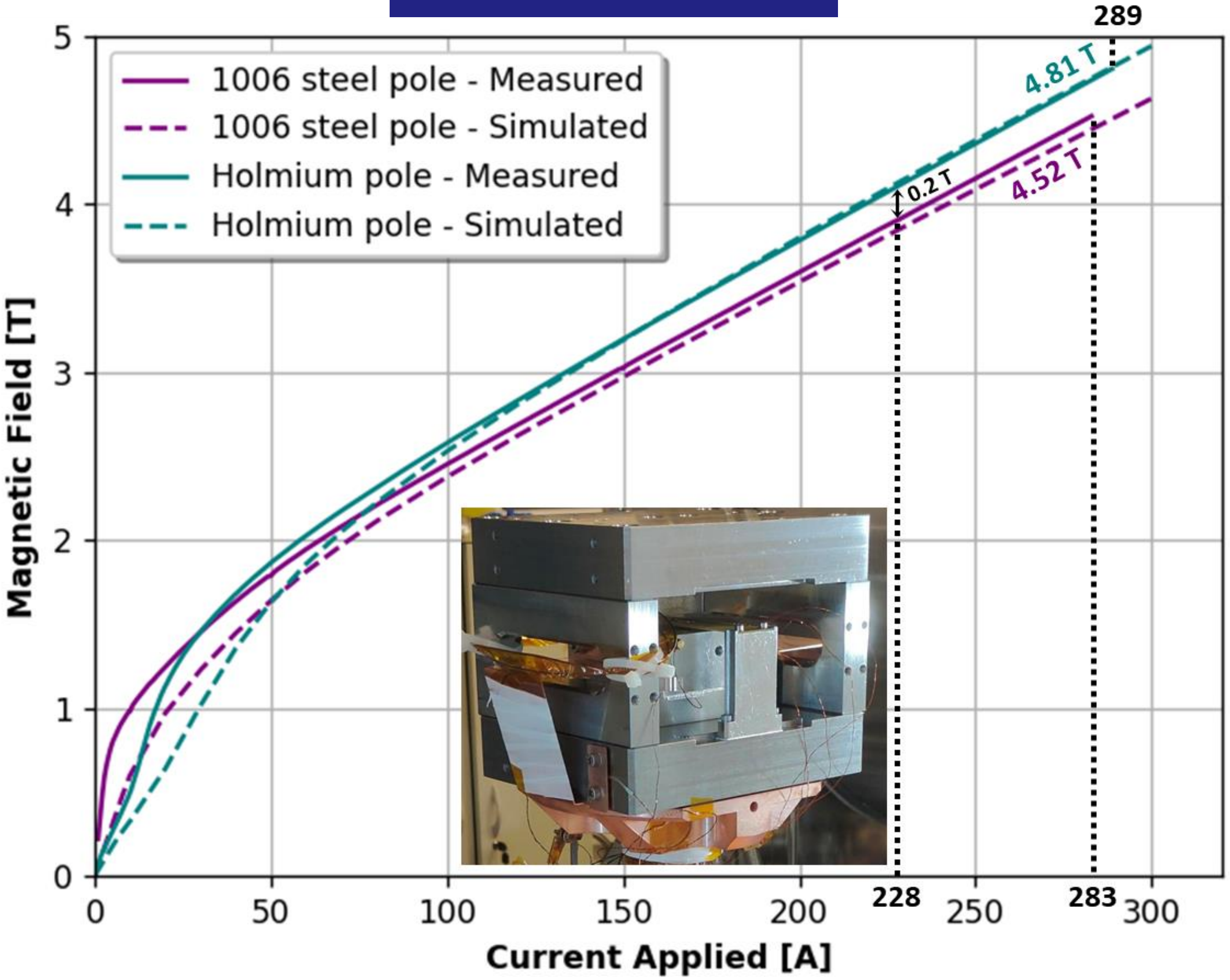
Coils fabrication – tests in the vertical cryostat

- **1006 steel** and **Holmium poles** were tested
- **Quench protection** was also **tested** and **validated**

Quench training: central coil



Results: Central coil



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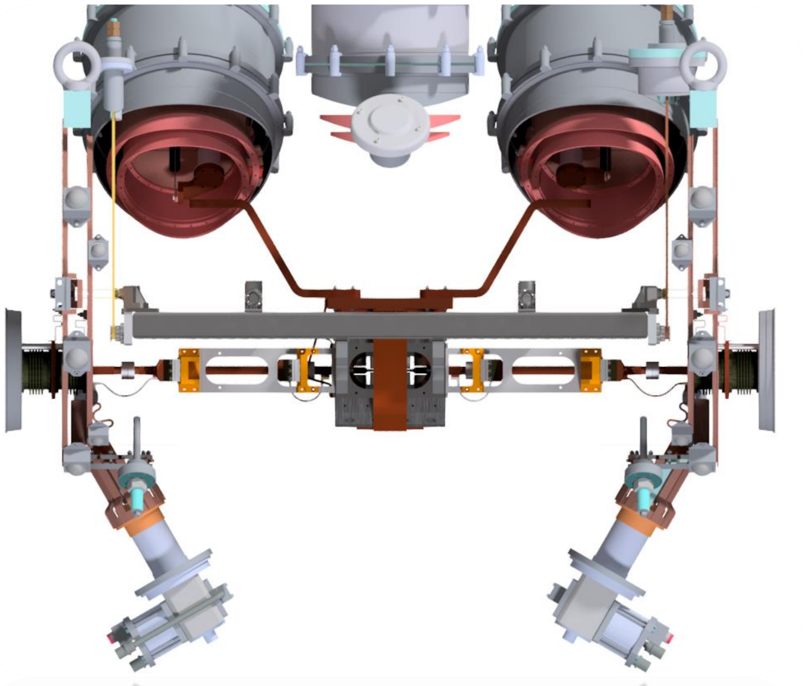
Mechanical design

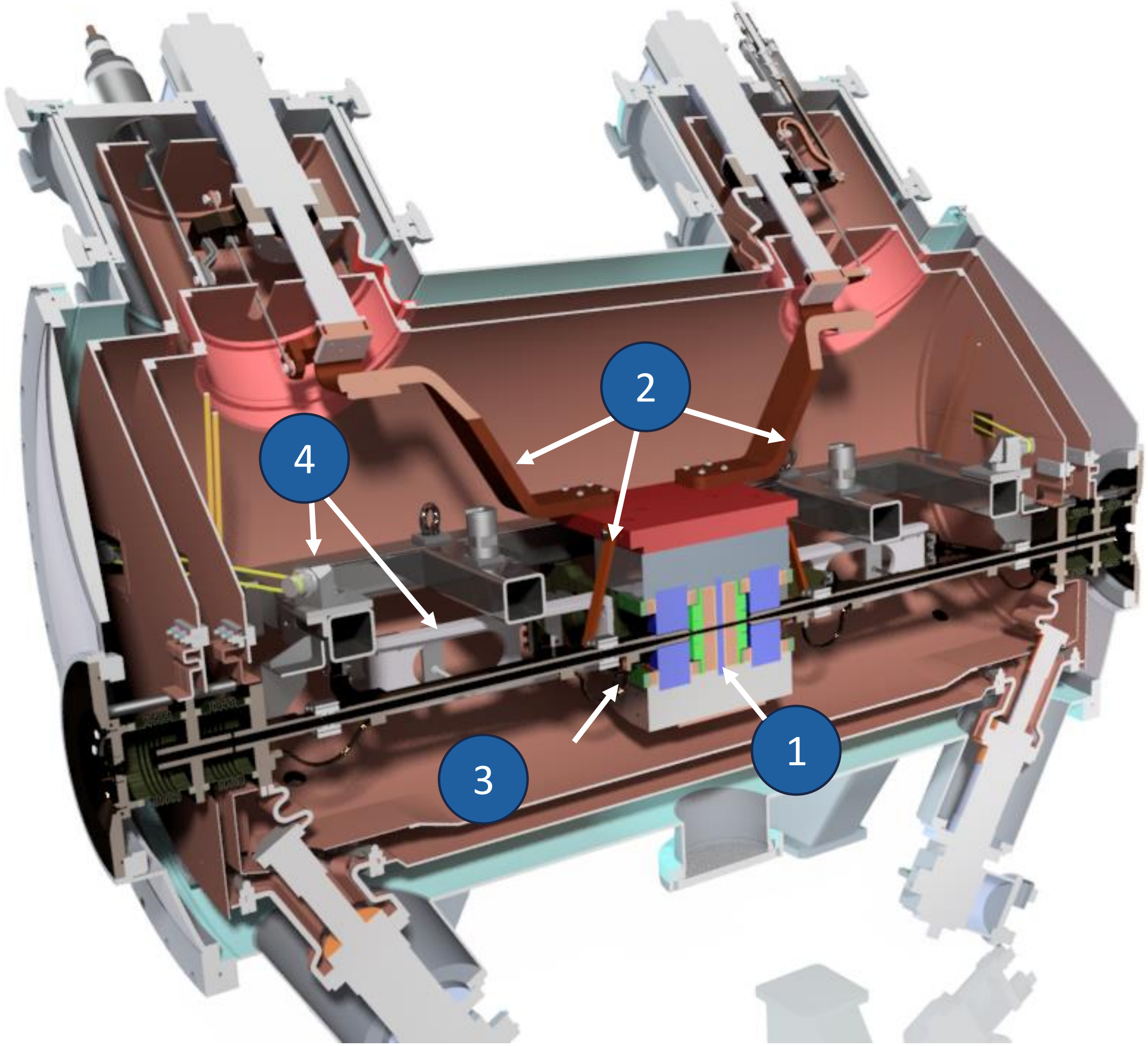
1 Electromagnetic structure

3 Electron beam vacuum chamber

2 Thermal circuit

4 Supports



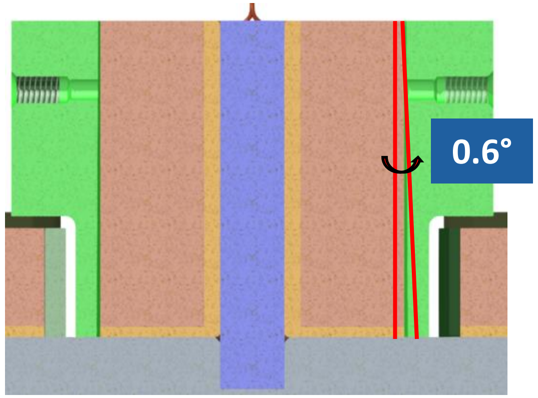


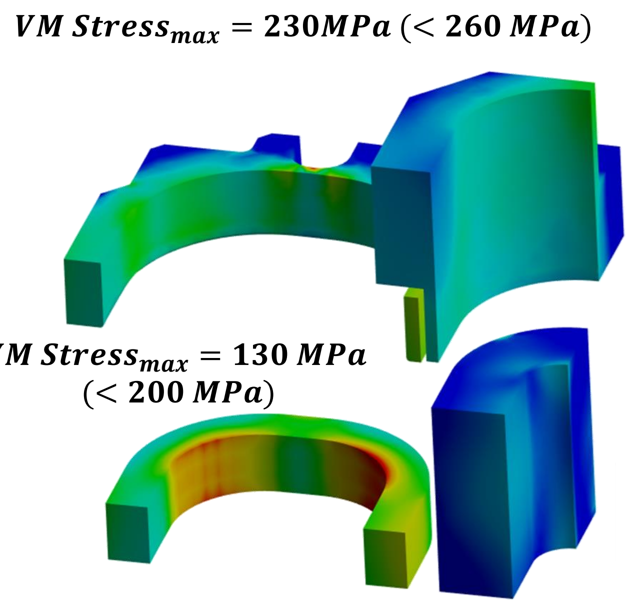
Mechanical design – electromagnetic structure

Main Concepts

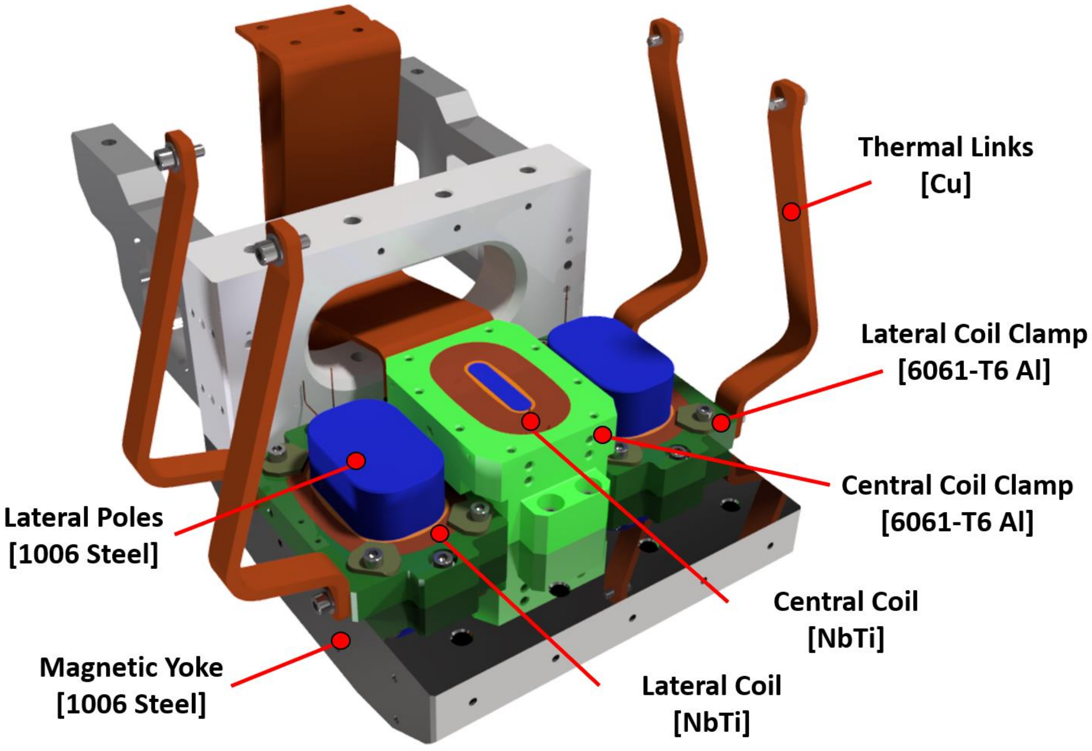
- Large thermal contraction of **Al clamps** to **pre-load the coils**
- **Central coils' clamps with conical shape** to prevent magnet's gap closing
- **Invar washers** to prevent bolt loosening

Central coils' conical clamps





Simulation Results of Thermal Contraction and Magnetic Forces for Coils and Clamps

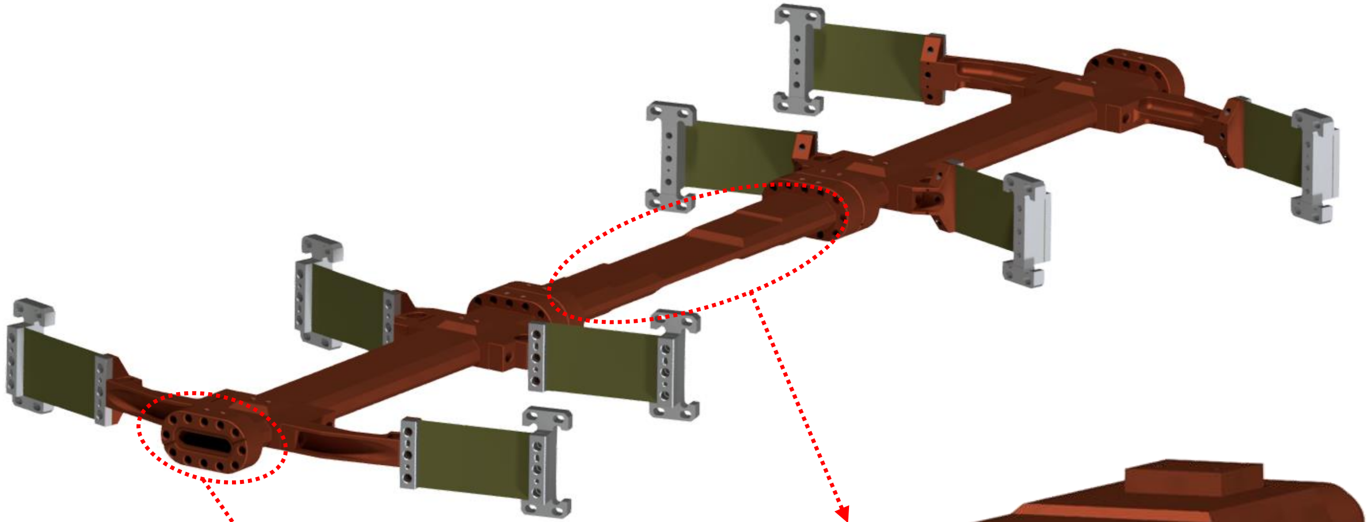


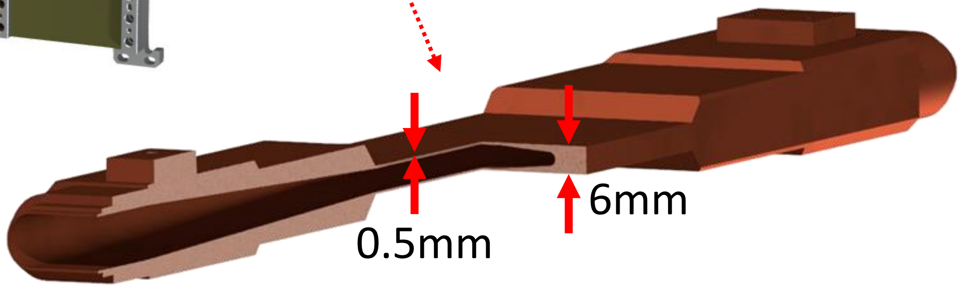
Mechanical design – vacuum chamber

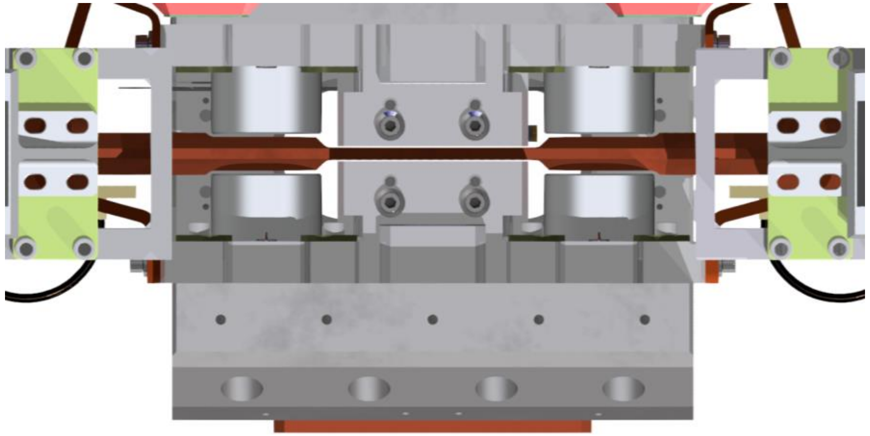
CNPEM

Main Concepts

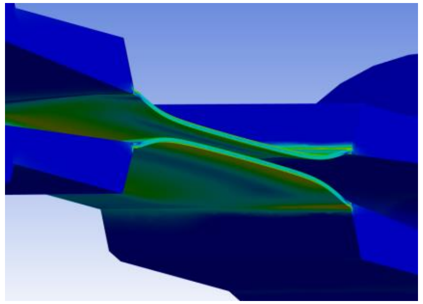
- **Tripartite CuCrZr** chamber
- Total length of **1.2m**
- Very thin central part (**5mm** vertical aperture; **0.5mm** wall)
- **Optimized internal profile** to withstand the pressure difference at the central part







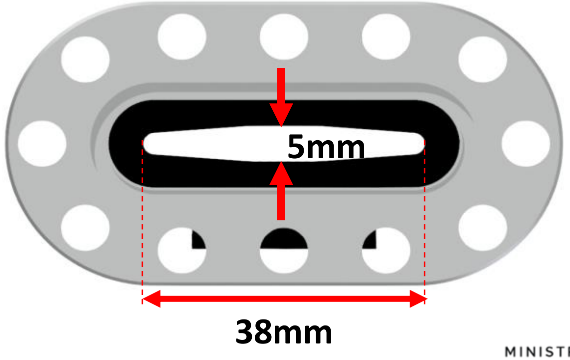
Longitudinal external profile in the assembly



Pressure gradient simulation for optimization of the internal profile

$Deformation_{max} = 40\mu m$ **(each side)**

$VM\ Stress_{max} = 56MPa$



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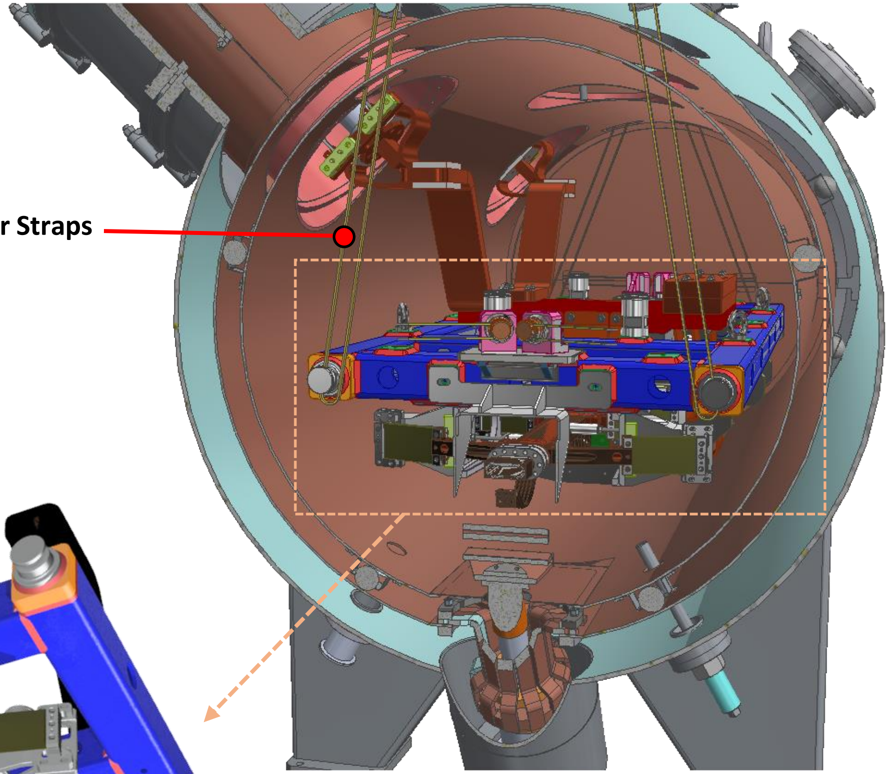
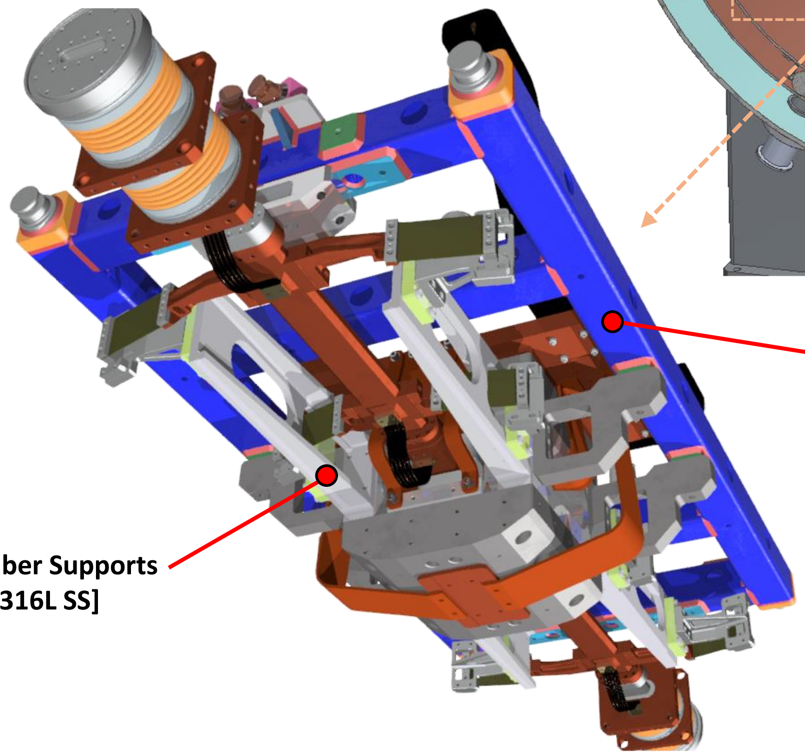
Mechanical design – structure supports

Main Concepts

- **Base frame** supports the whole structure
- **Kevlar straps suspension**:
  - Minimize thermal conduction with low thermal contraction
  - Provide vertical (adjustable out of vacuum) and horizontal alignment
- **Lateral Yoke** serves as an anchoring point for the supports (unique connection between base frame, vacuum chamber and yoke)

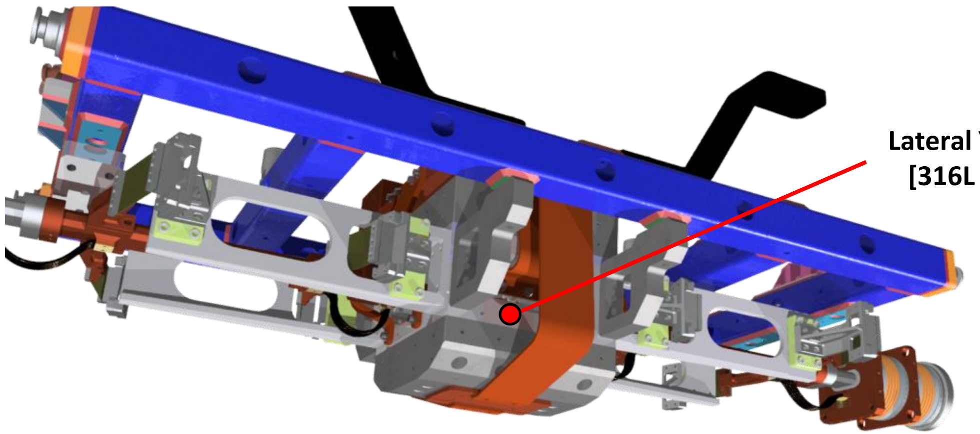


Kevlar Straps



Base frame
[304 SS]

Chamber Supports
[316L SS]



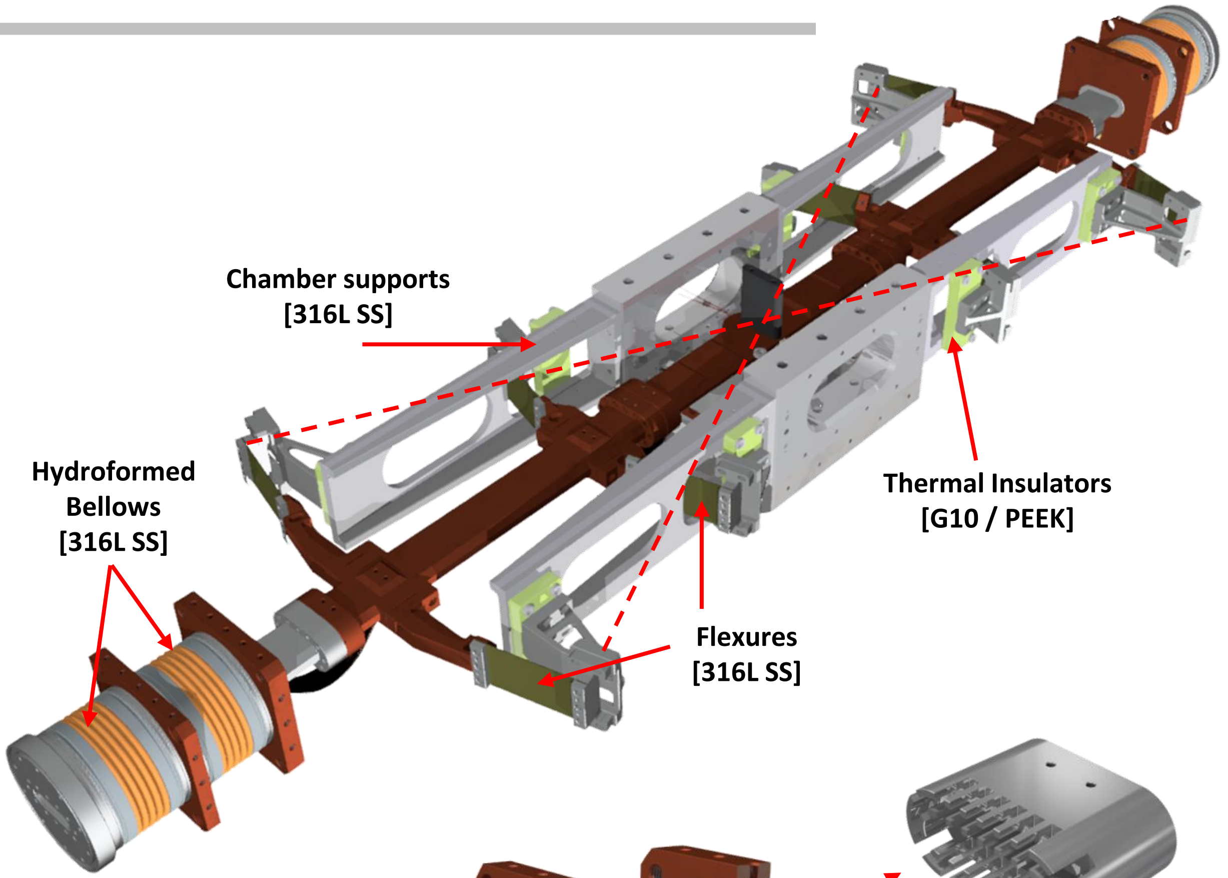
Lateral Yoke
[316L SS]

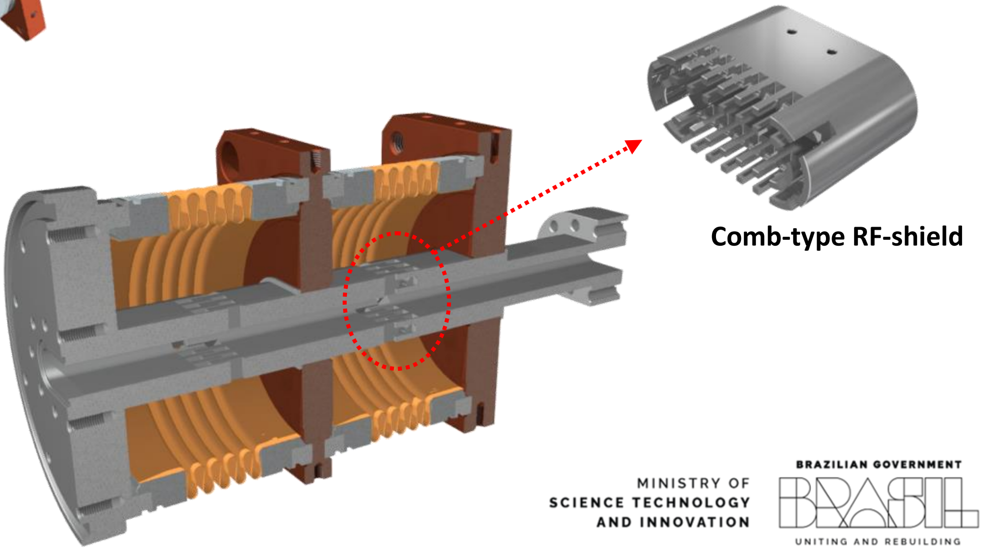
Mechanical design – chamber supports

CNPEM

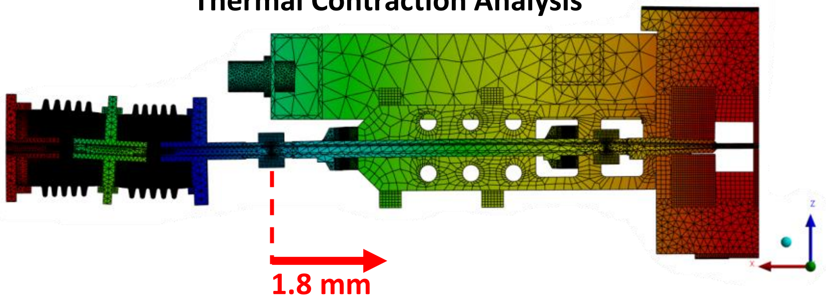
Main concepts

- **Flexures** ensure high transversal stiffness and low longitudinal stiffness (to accommodate thermal contraction)
- **Flexures' anchoring points** forms perpendicular lines pointing to the magnet's center avoiding its displacement
- **Materials:**
  - **316L SS** provides good mechanical strength with relatively low thermal conductivity and low heat capacity (improving cooldown)
  - **G10** minimizes heat transfer between 4K and 20K circuits due to its low thermal conductivity
- **Hydroformed bellows with modified comb-type RF shield:**
  - Isolate the vacuum (cryostat/beam)
  - Provide longitudinal elasticity for thermal contraction
  - Minimize heat transfer between chamber (20K) and cryostat (300K) with low machine impedance impact





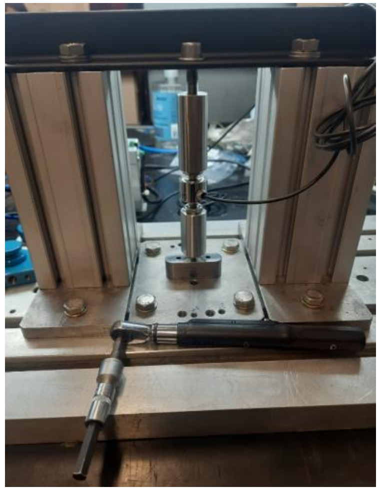
Thermal Contraction Analysis



Mechanical design – validations and next steps

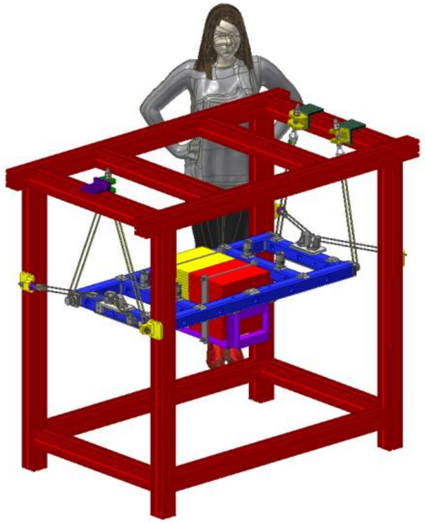
Validations already carried out

✓ Kevlar straps mechanically characterized

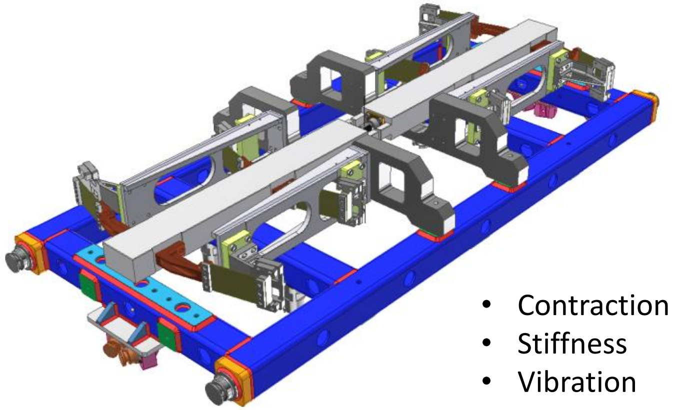


✓ Mechanical detachment tests of Ho poles and clamps

Supports validation (static and dynamic studies)



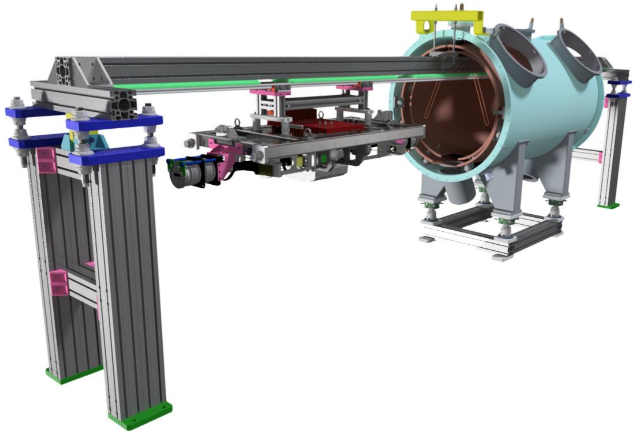
- Alignment procedure
- Suspension stiffness
- Vibration



- Contraction accommodation
- Stiffness
- Vibration

Disassembly and inspection of the 4T SCW

Assembly and fiducialization → More details in the following slides



Outline

CNPEM

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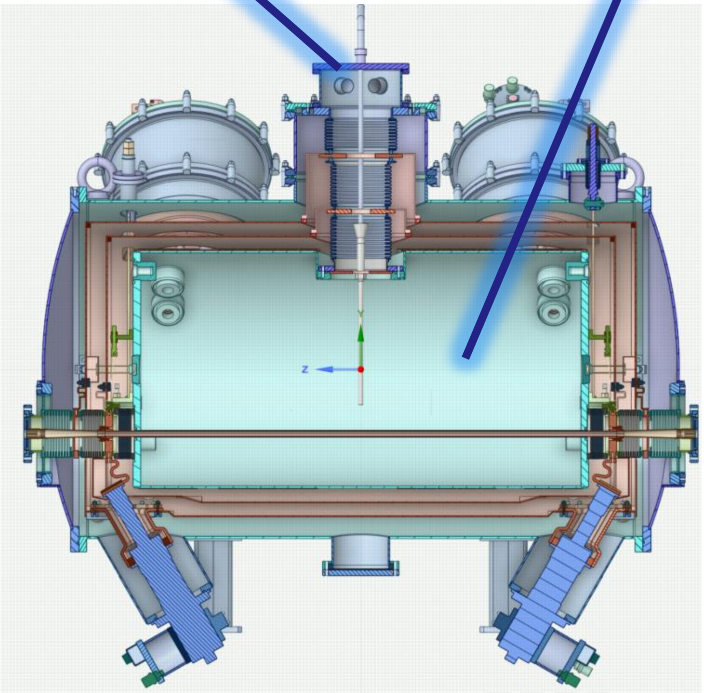
Cryogenic concept

Central flange – access to the central Lhe tank

LHe tank for the coils ~4.2 K



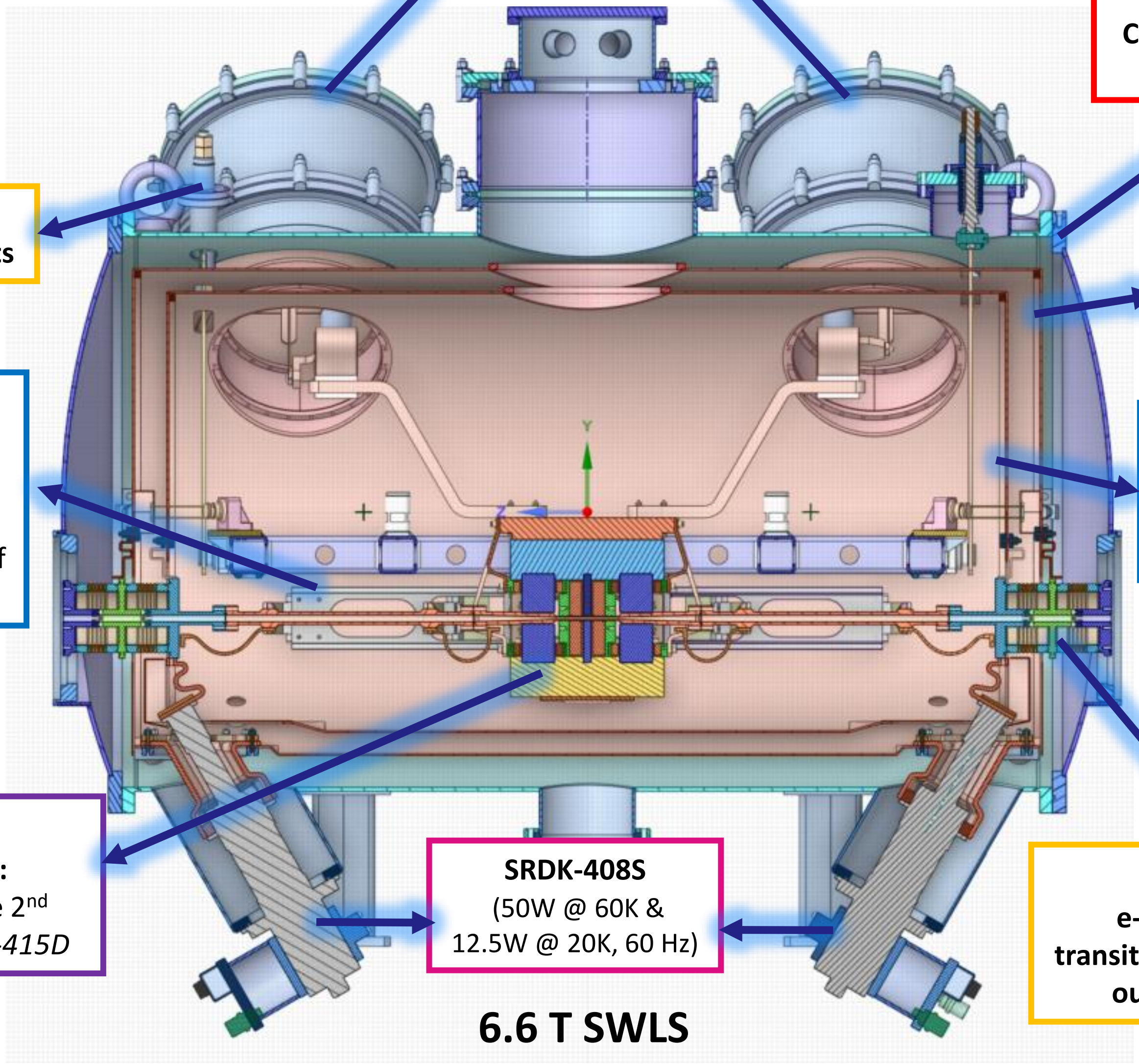
4 T SCW
(in bath cooling)

SRDK-415D
(55W @ 60K & 1.5W @ 4.2K, 60 Hz)

Kevlar supports

20K
E beam vac. Chamber and supports: Cooled by the 2^{nd} stages of *SRDK-408S*

4K
Cold mass: Cooled by the 2^{nd} stages of *SRDK-415D*



SRDK-408S
(50W @ 60K & 12.5W @ 20K, 60 Hz)

6.6 T SWLS
(cryogen-free cooling)

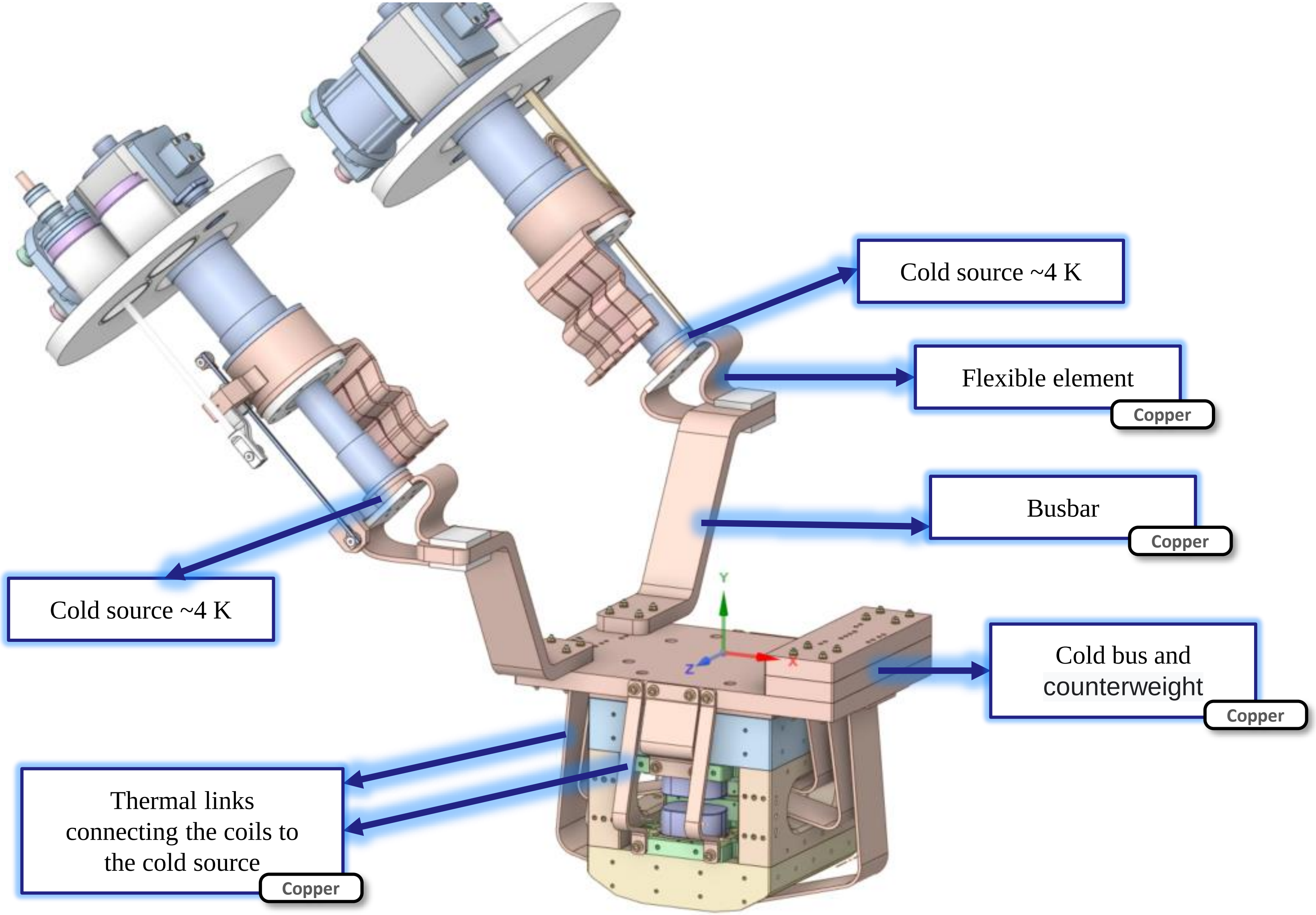
300K
Cryostat Vac Vessel
10^{-6} ~ 10^{-8} mbar

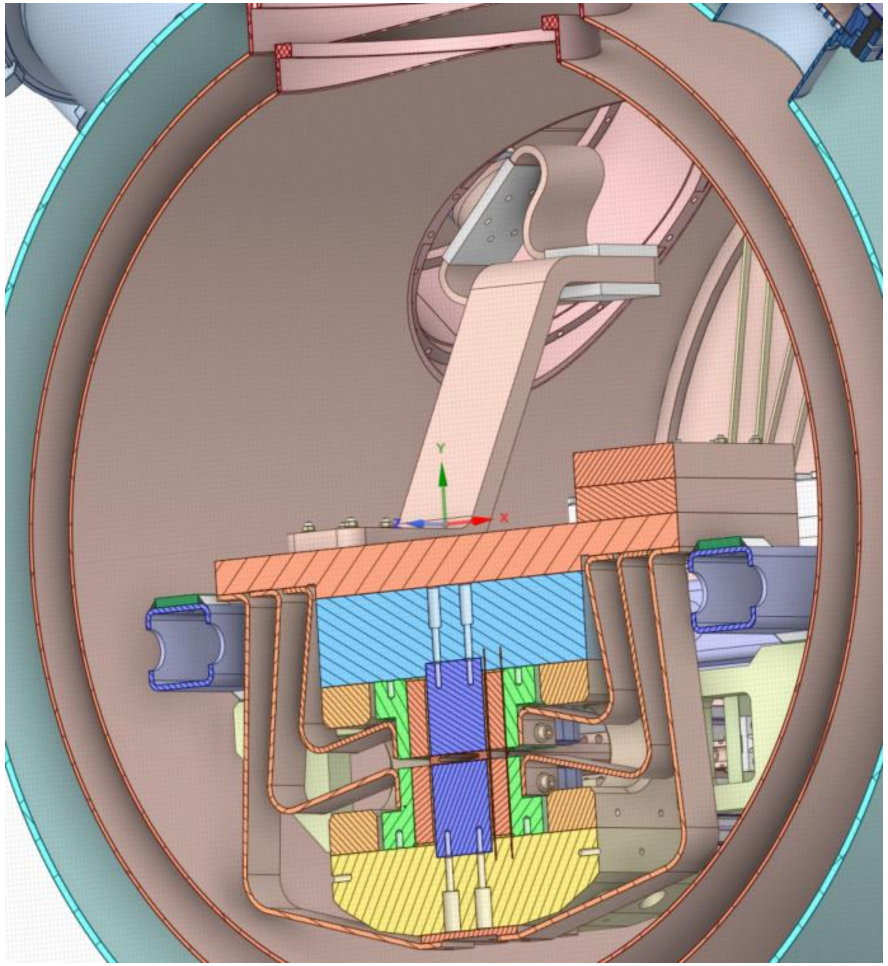
60K
1^{st} Thermal Shield: Cooled by 1^{st} stage of the 4 cryocoolers

20K
2^{nd} Thermal shield: Cooled by the 2^{nd} stage of *SRDK-408S*

300K – 20 K
e- beam chamber transition inner: 10^{-10} mbar
outside: 10^{-8} mbar

Thermal links





Heat Loads and Cooling Circuits

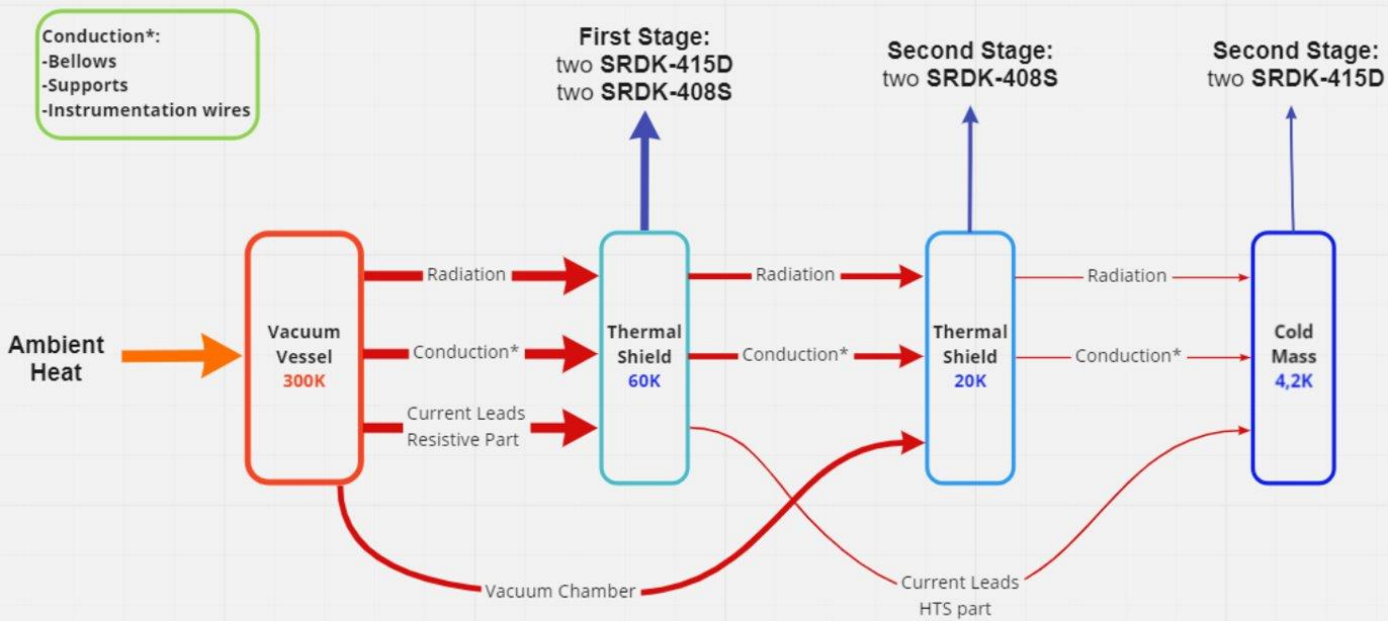
Heat loads

Design Temperatures

Heat Source	60 K [W]	20 K [W]	4 K [W]
Radiation	7.95	0.3	0.007
Conduction	13.82	0.77	0.17
Current leads@228A	39	-	0.65
Beam Chamber	37.2	8.65	-
Total	**97.97**	**9.72**	**0.827**
Cooling Capacity	210	25	3

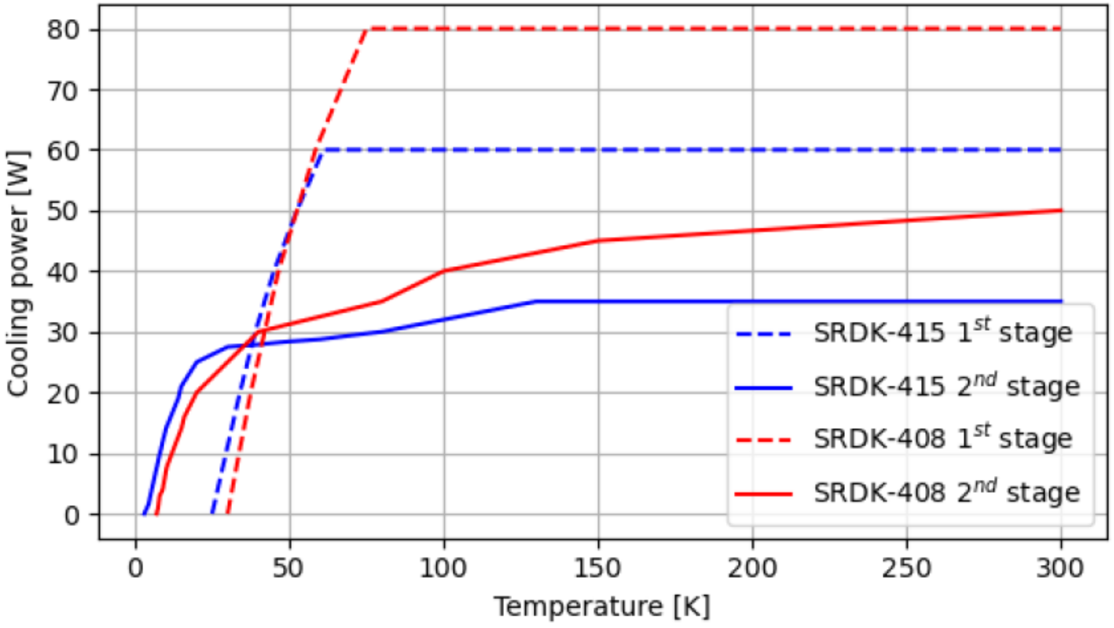
Cooling capacity higher than the heat loads

Cooling Circuits

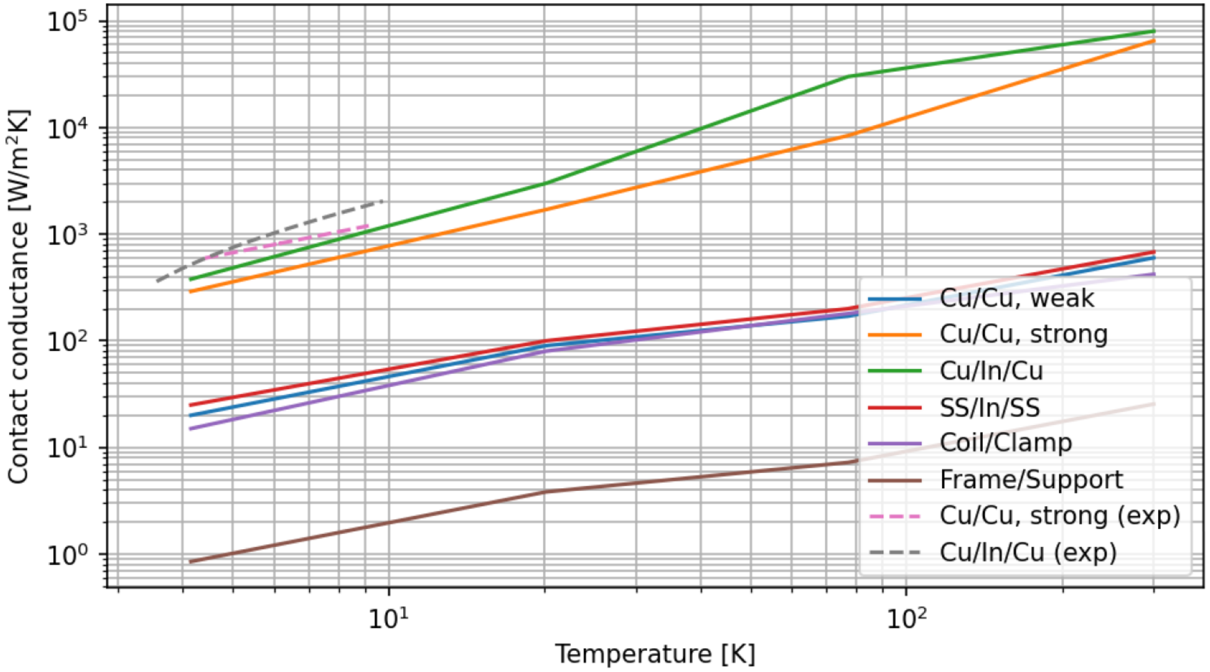


Thermal Simulaitons – main considerations

The cooling power of the cryocoolers' stages as a function of their temperatures (based on the models' load map)

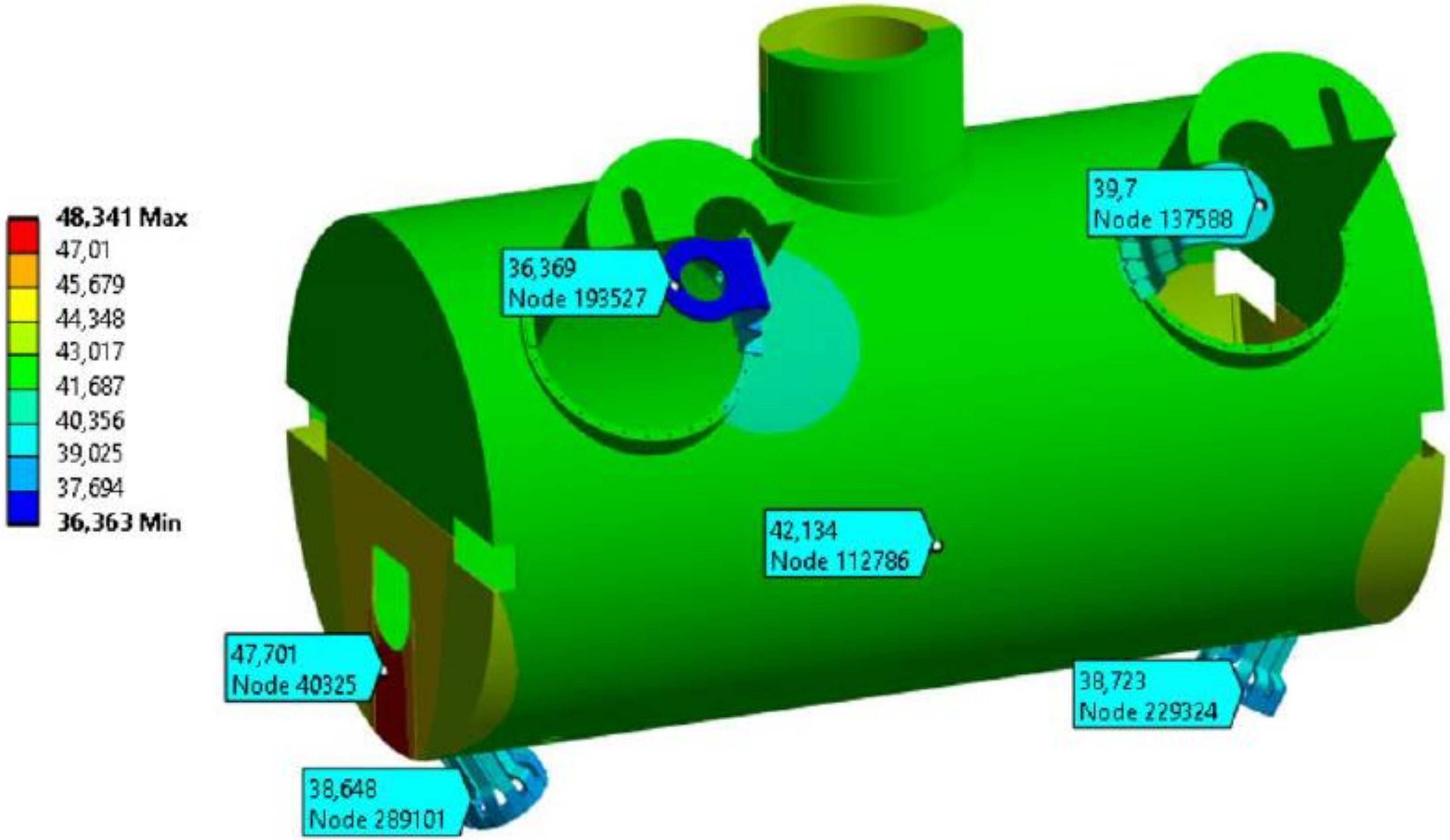


Thermal Contact Conductances considered in the simulations (literature and measured values)



The heat loads were considered in the model with their calculated values and locations along each thermal circuit

Temperature distribution – 60K Circuit



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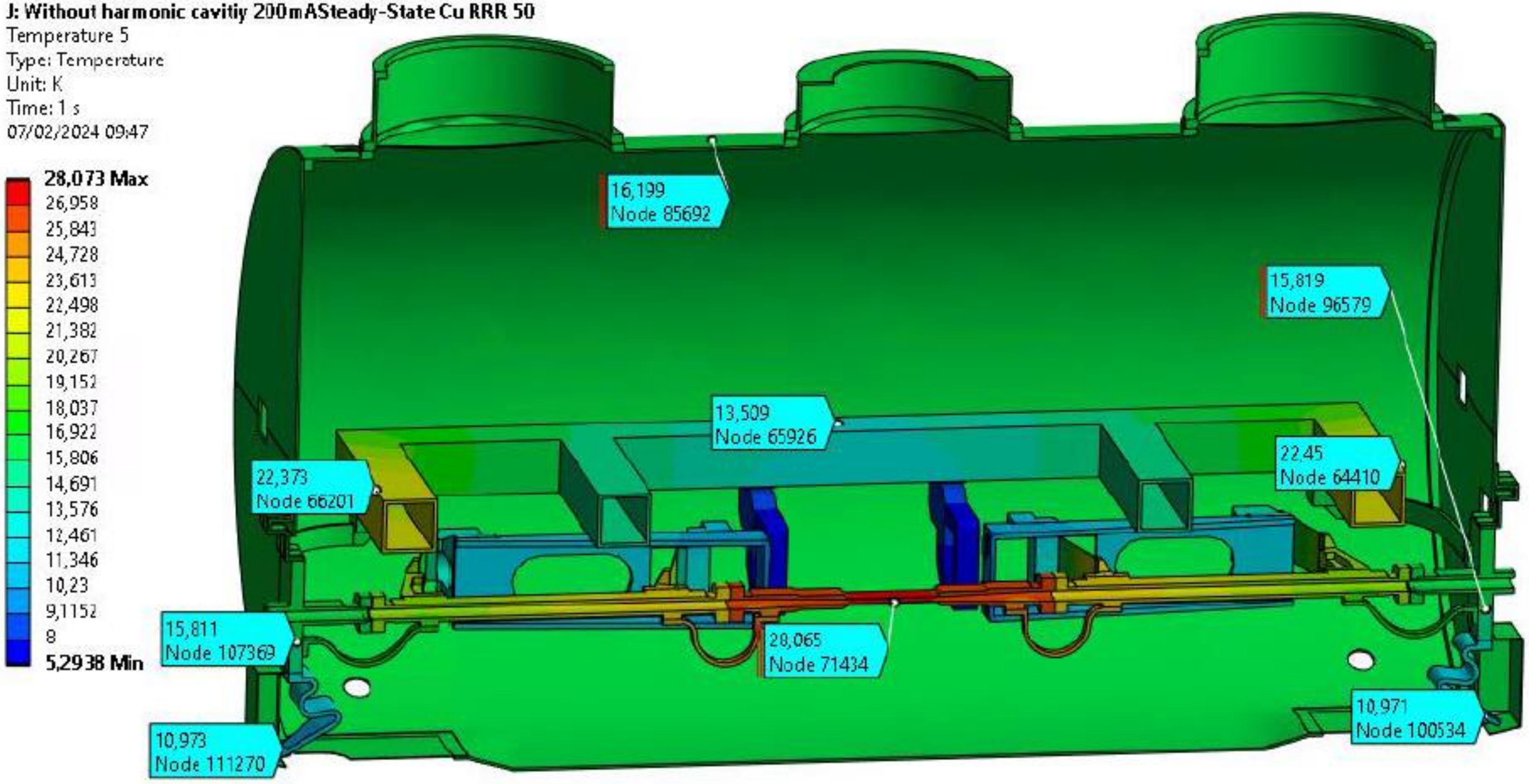
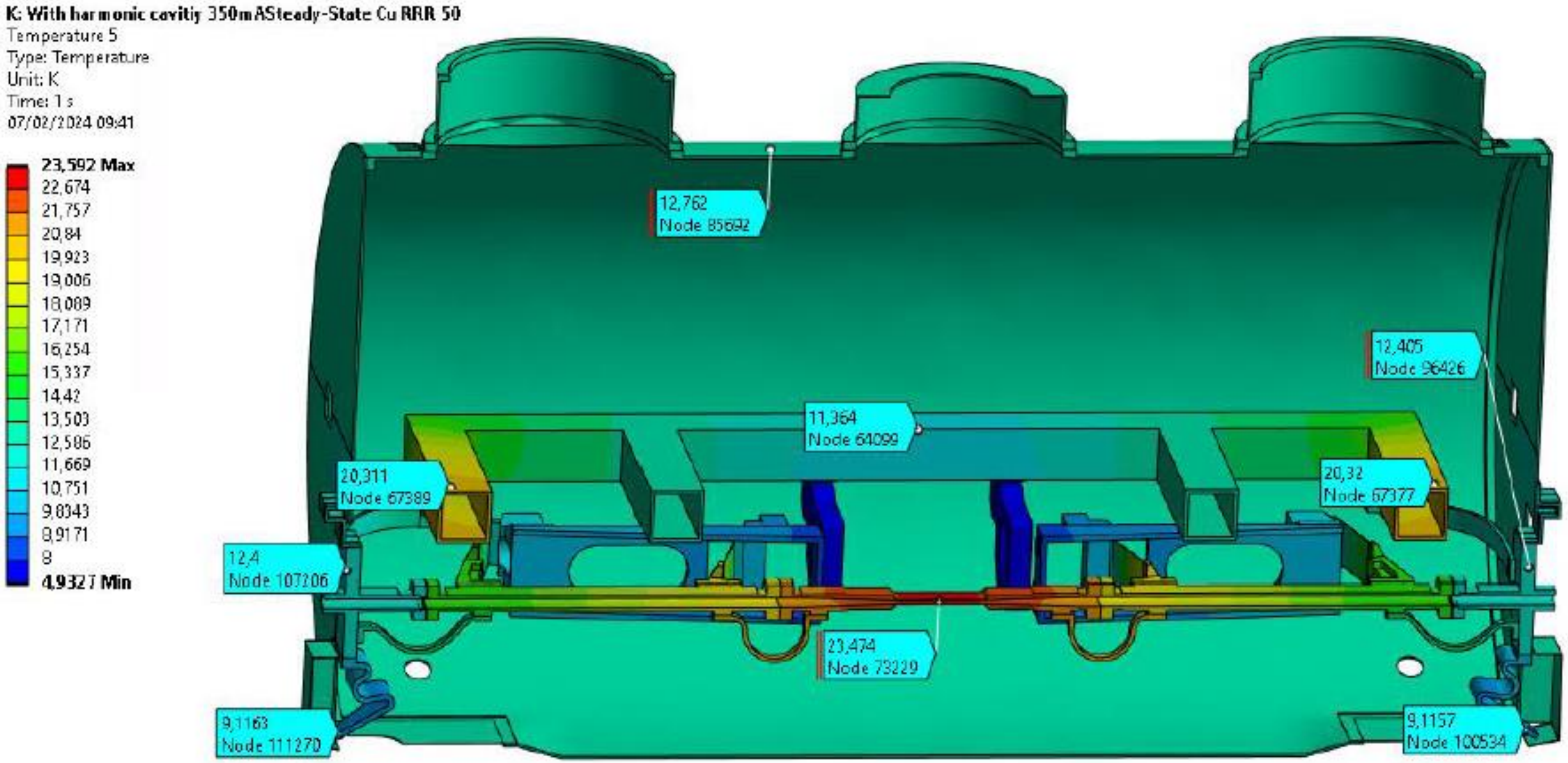
Temperature distribution – 20K Circuit



Without 3rd Harmonic cavity – short e- beam bunch
(Power dissipated in the chamber: **~15 W**)

Temperature distribution – 20K Circuit



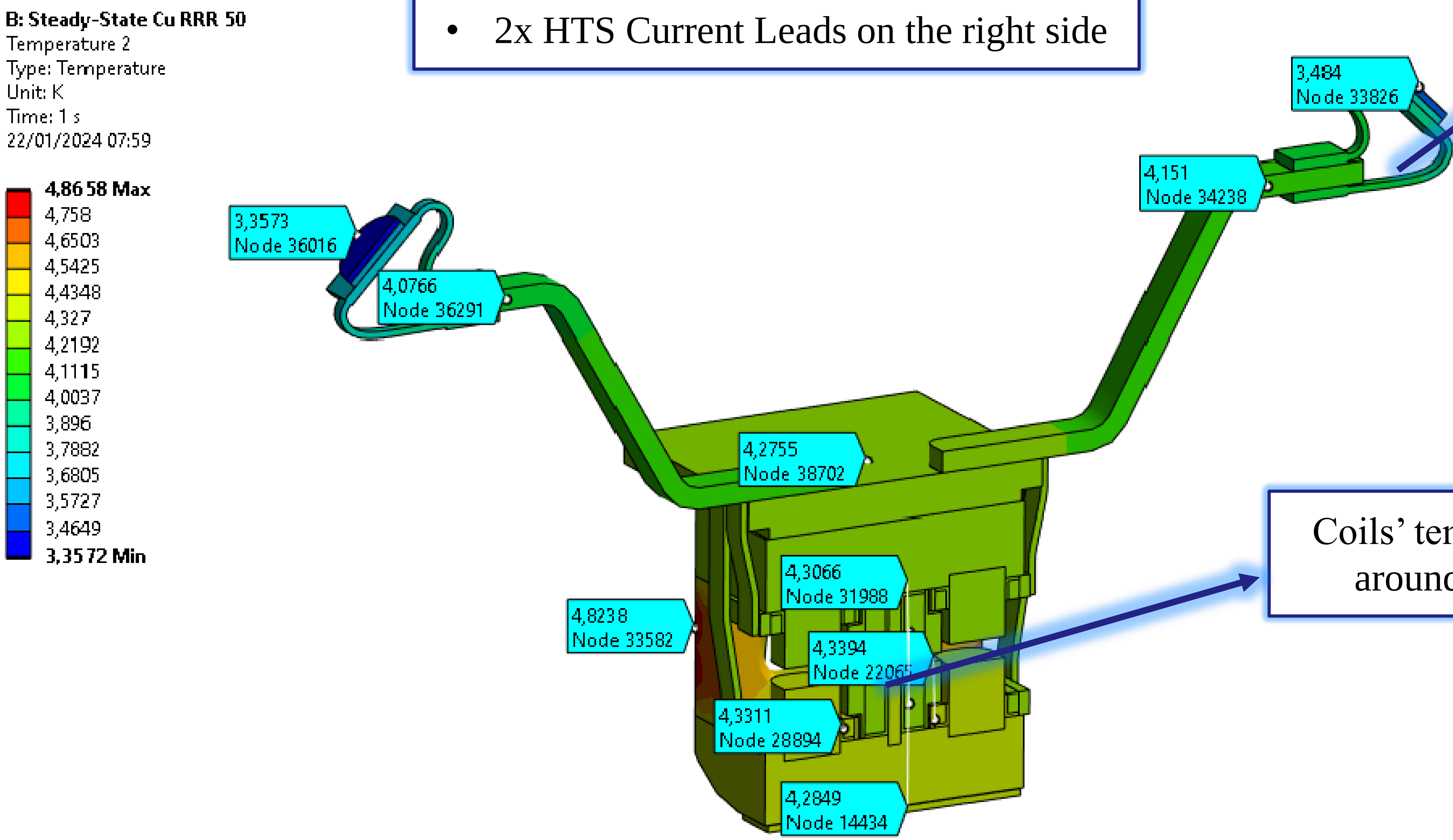
With 3rd Harmonic cavity – long e- beam bunch

(Power dissipated in the chamber: **~1.75 W**)

Temperature distribution – 4K Circuit

Assymetric thermal load:

- 1x HTS Current Lead on the lef side
- 2x HTS Current Leads on the right side



High ΔT, under evaluation to be improved*

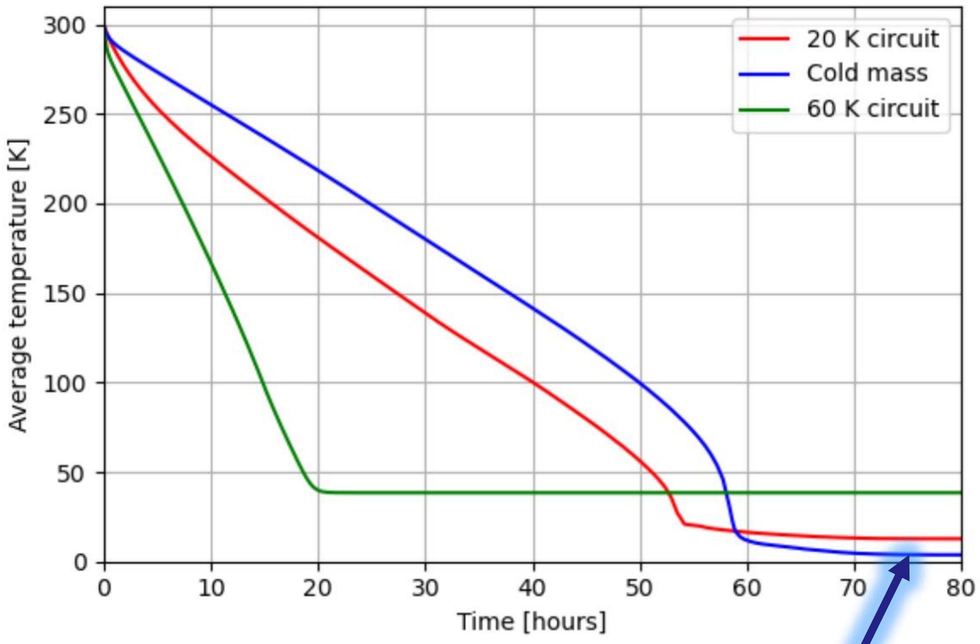
* By increasing the section and improving the quality of the contacts by brazing, without compromising flexibility, assembly, and manufacturing

Coils' temperature around 4.3 K

Cooldown and warm-up time

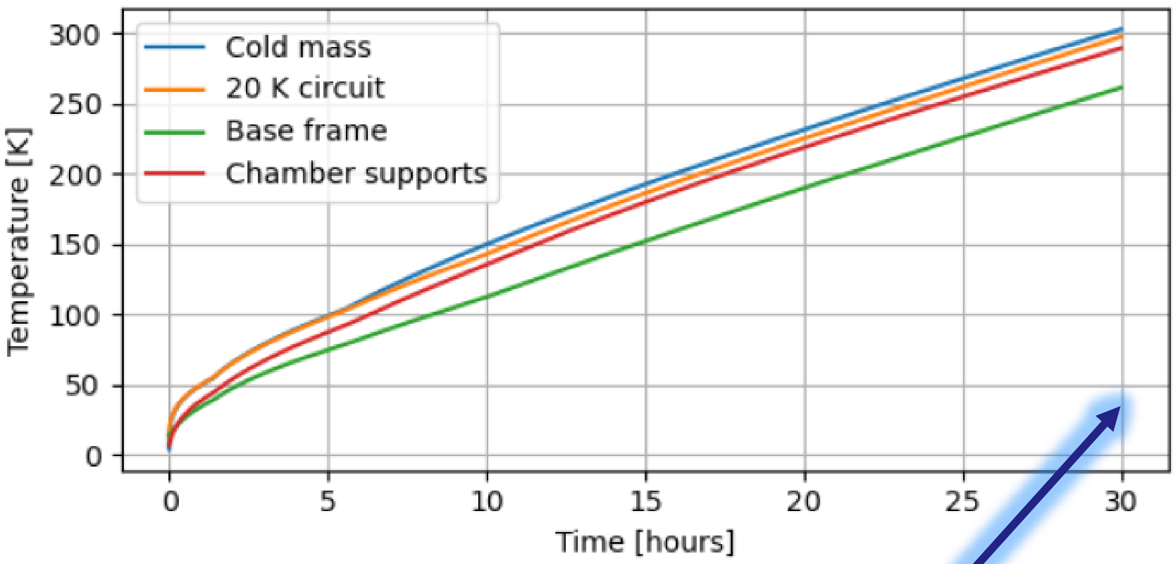
CNPEM

Cooldown



About **75 hours** to achieve operating temperature

Warm-up

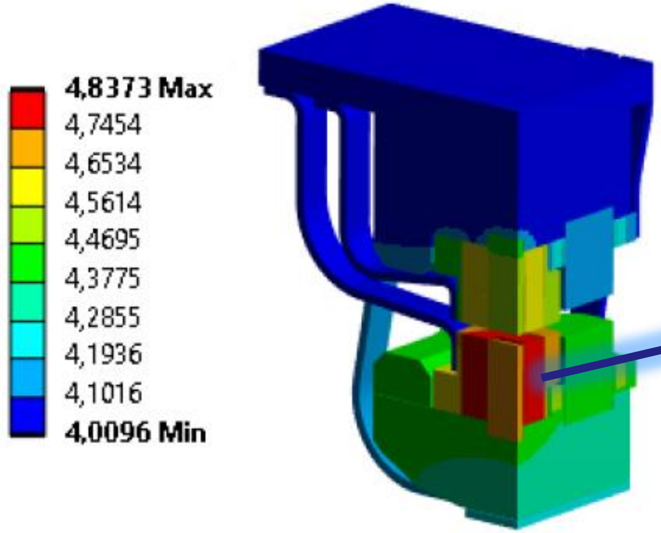


About **30 hours** for complete warm-up

Total time for a shutdown needs to fit in one week!

Coils temperature after current ramp-up

Temperature distribution after 10 minutes current ramp-up

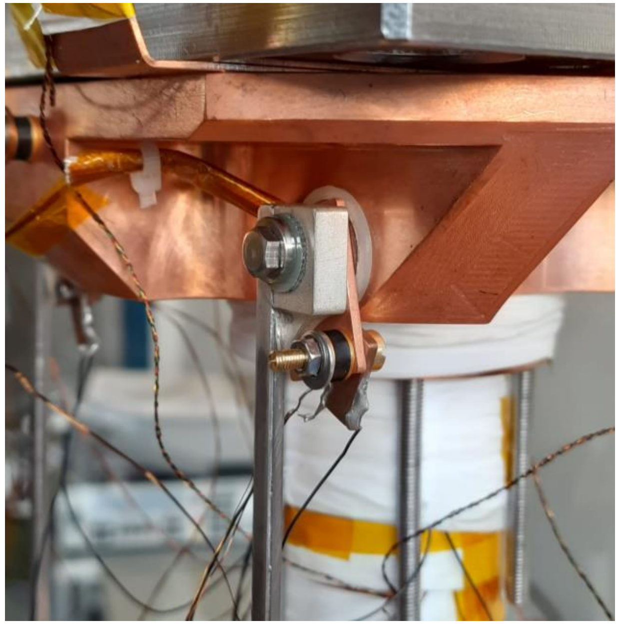


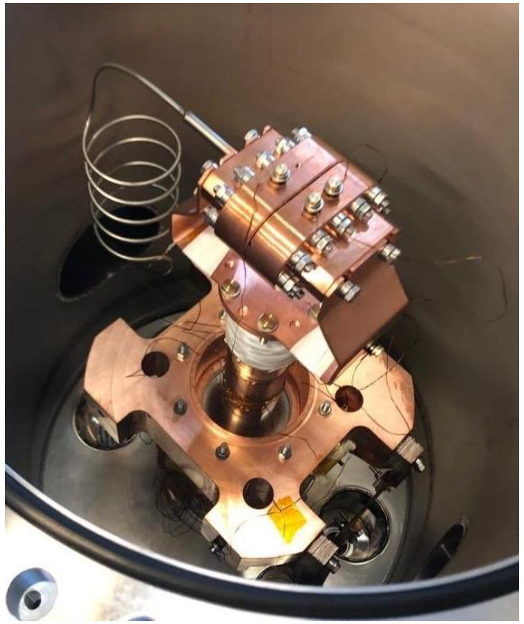
AC losses heat up prevents current ramp-up shorter than 10 minutes

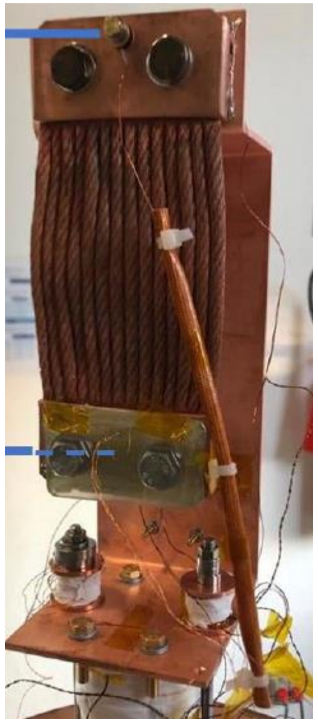
Ramp-up time	5 minutes	10 minutes	15 minutes
Central coils max. temperature	5.54 K	4.84 K	4.54 K
Ramp rate	0.76 A/s	0.38 A/s	0.25 A/s

Tests and validations already carried out

CNPEM







- ✓ Validation of fastening and tightening methods at cryogenic temperatures
- ✓ Vacuum sealing concept of the CuCrZr flanges at cryogenic temperatures
- ✓ Characterization of thermal elements and their contacts at low temperatures

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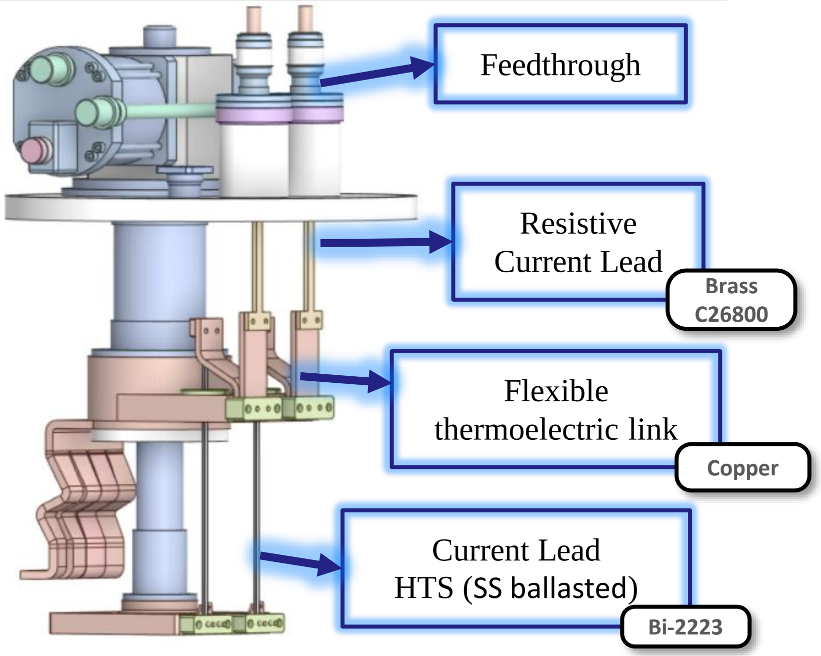
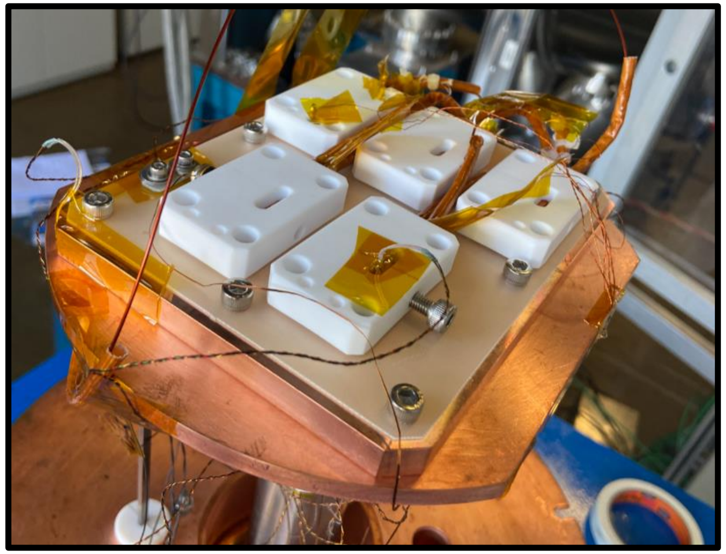
Current leads and cryogenic electrical circuits

CNPEM

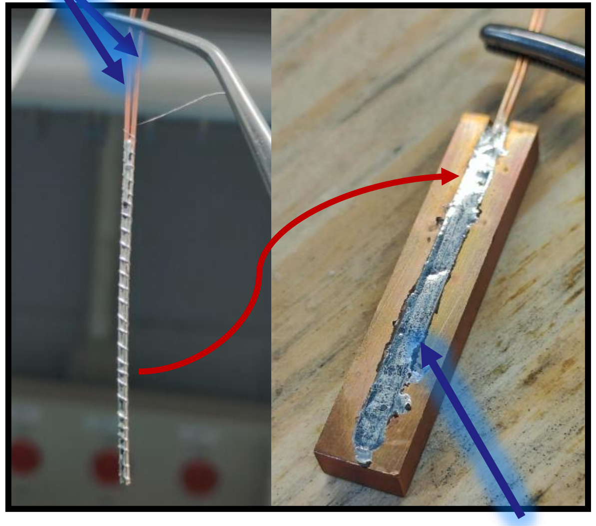
- **Current Leads**: 300K – 4K
  - ➢ Main heat load in the cryogenic system
- **Links**: between SC wires and coils
  - ➢ Coils wound with long extensions
  - ➢ Minimize connections
- **Splices**: electrical connection between coils
  - ➢ Connections located at good cooling capacity regions
  - ➢ Unique resistive part between coils
  - ➢ Pre-requisite: R < 500 nΩ @ 4 K





Splice box installed at the vertical cryostat

SC wires



Preliminary results: R < 10 nΩ @ 4 K

Next steps:
- Test the new mechanical fixture of the current leads

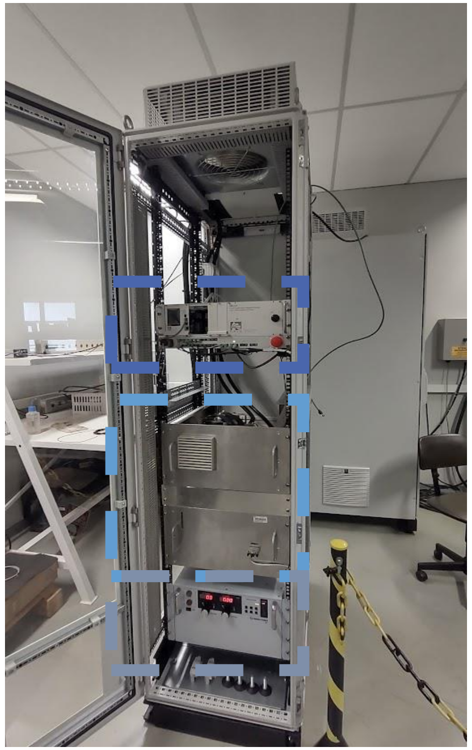
Power supply

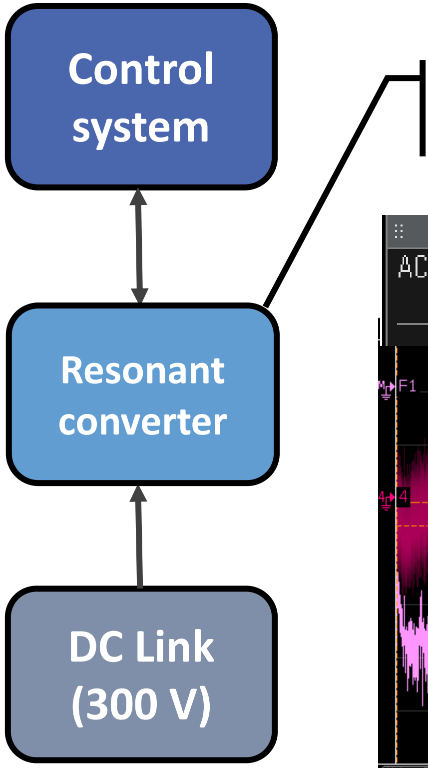
Plan A **Resonant converter** (discontinuous parallel resonant converter): in-house development

- **3 kW, 300 A, and 10 V**, and **ripple** lower than **10 ppm**

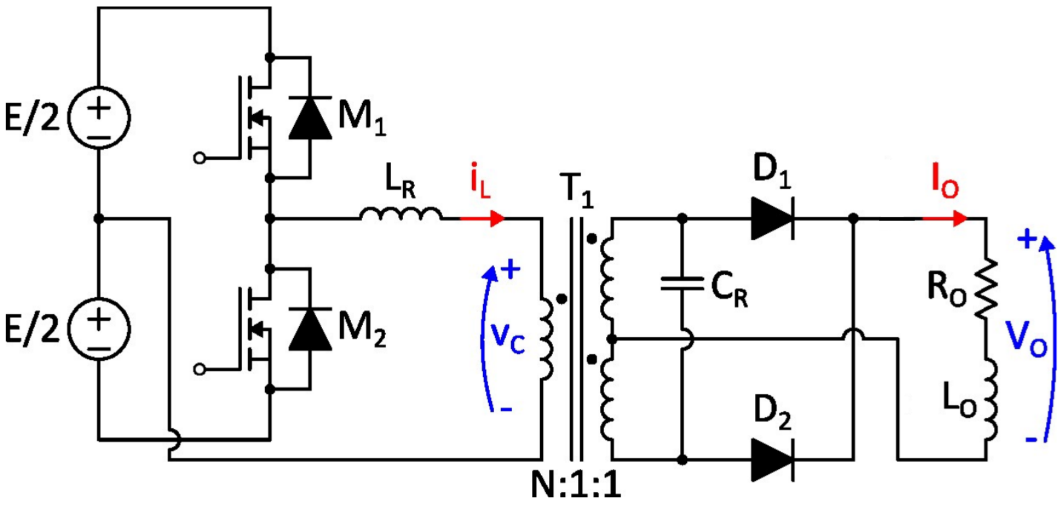
Plan B **4T SCW power supplies:** Danfysik MP8443

- **3 kW, 300 A** and **10 V**, **ripple** of **25 ppm**
- Obsolete hardware and software
- No technical support anymore



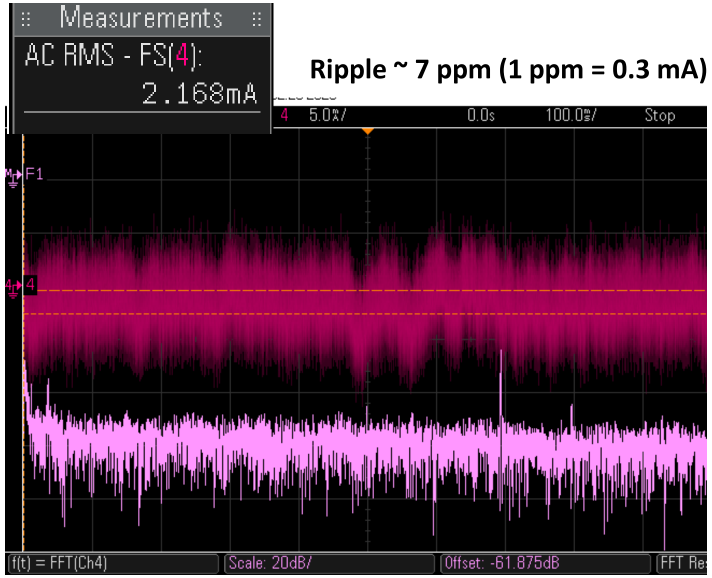


- **Can operate with the load in short-circuit**



Topology of the developed resonant converter

Ripple ~ 7 ppm (1 ppm = 0.3 mA)



Next steps:
- Final test of the developed power supply in the vertical cryostat with SC coils

Quench protection

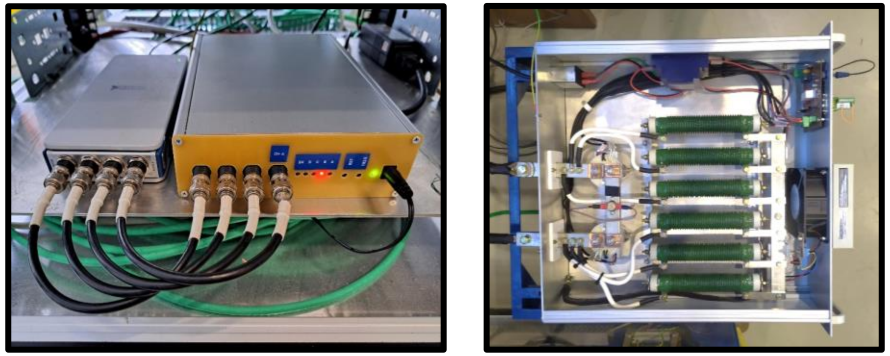
- **Premises**:
  - ➢ Provide redundant detection and protection
  - ➢ Design to keep max hot-spot temp < 100 K

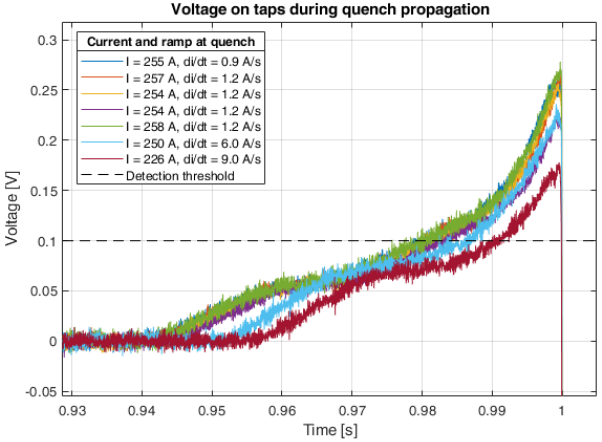
  Redundant voltage taps
  Detection by overvoltage and coil unbalance
  Redundant extraction switches
  •••

- **Detection**: voltage measurement – voltage taps
  - ➢ Detection circuit: Analog vs Digital using FPGA:
    - ➢ FPGA can be scalable and optimizable for the SWLS

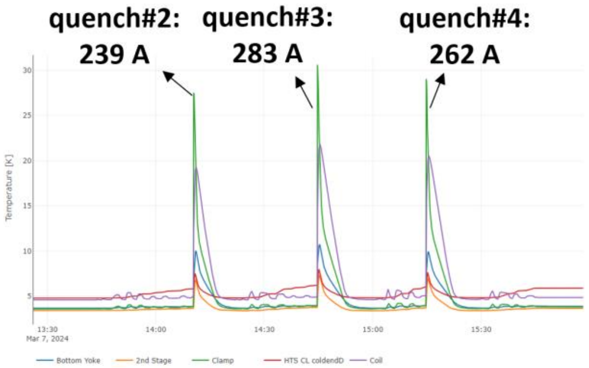
- **Protection: Active method with external energy extraction**
  1. The detection circuit sends a signal to the extraction circuit
  2. The power supply is turned off, and the contactors are activated
  3. Dump resistors in the extraction circuit dissipate the stored energy

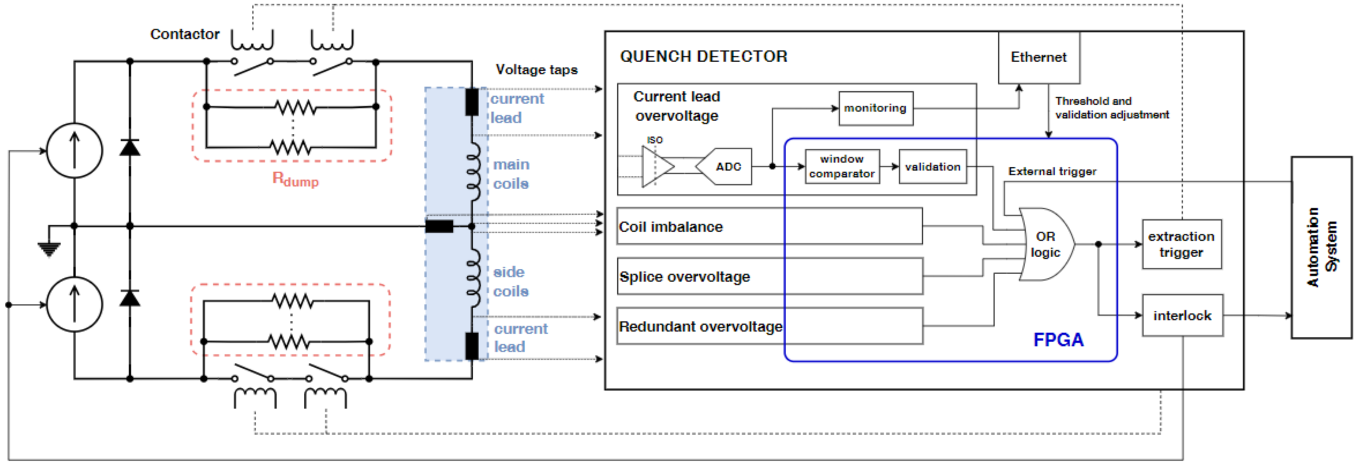
Quench Detection prototype (analog circuit) and Extraction circuit





Detected quench during tests of the coils





Quench protection archtecture

Next steps:
- Validate the FPGA prototype in the vertical cryostat
- Robustness and reliability of the FPGA concept for the SWLS

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Magnetic characterization plans

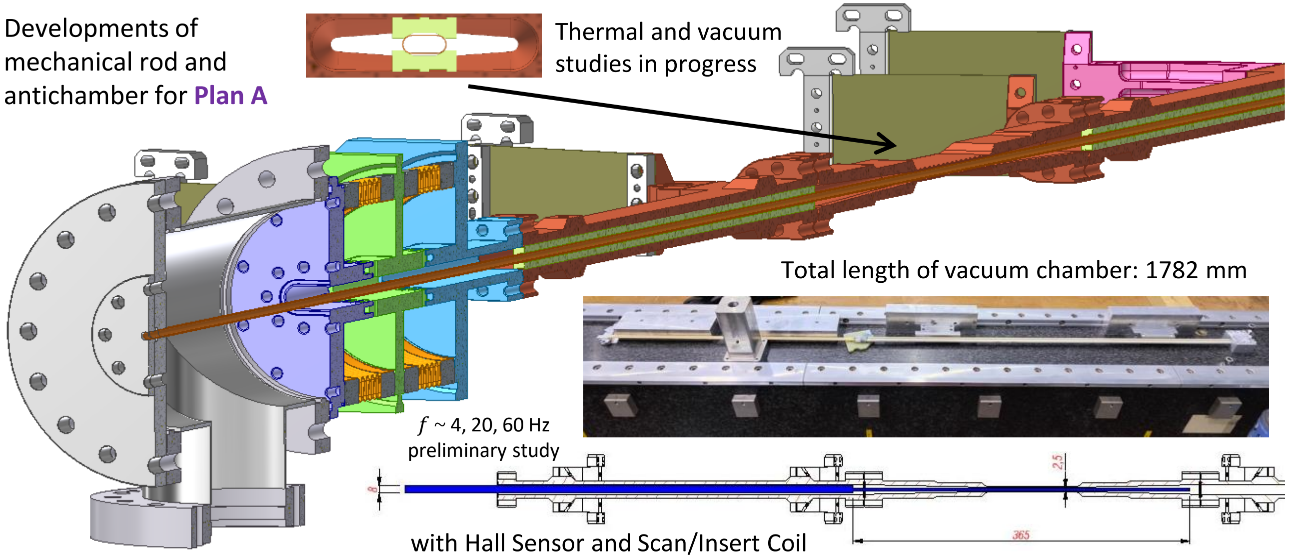
- **Challenges**: Small gap; cold vacuum chamber; high field calibration
- **Two proposed solutions**: Characterization in air (“**Plan A**”); Characterization in vacuum (“**Plan B**”)
- **Measurements**: Mapping of the magnetic field profile; measurement of field integrals

Plan A	Plan B
Antichamber for RT* measurements	Measurements inside SWLS vacuum chamber
Hall sensor setup adaptations	New Hall sensor setup and calibration at CT**
Mechanical rod or Hall sensor carriage	New vacuum actuation system
Stretched wire for field integrals measurements	PCB coils for field integrals measurements

* Room Temperature

** Cryogenic Temperature

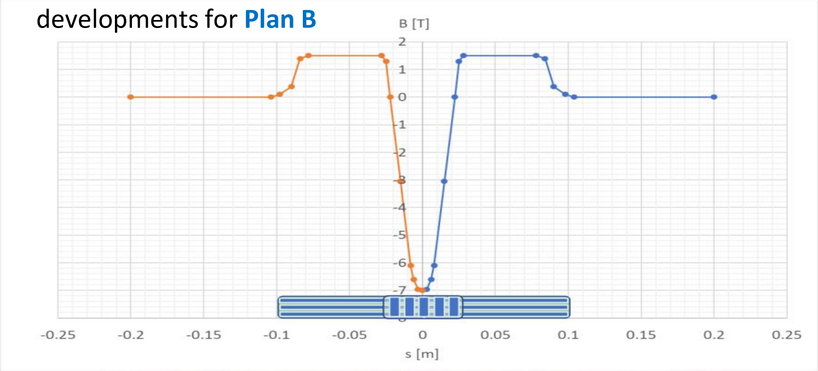
Developments of mechanical rod and antichamber for **Plan A**

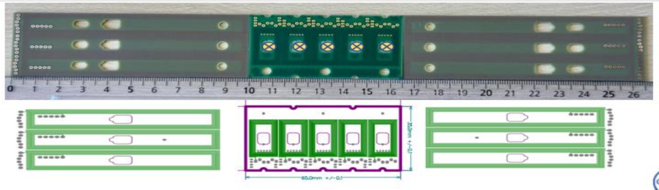


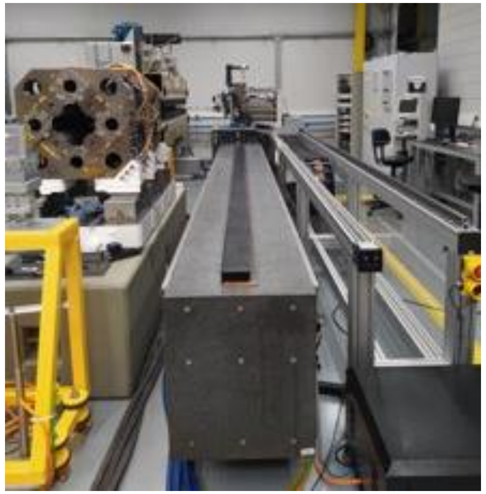
Total length of vacuum chamber: 1782 mm

with Hall Sensor and Scan/Insert Coil

PCB coils and Hall sensors developments for **Plan B**







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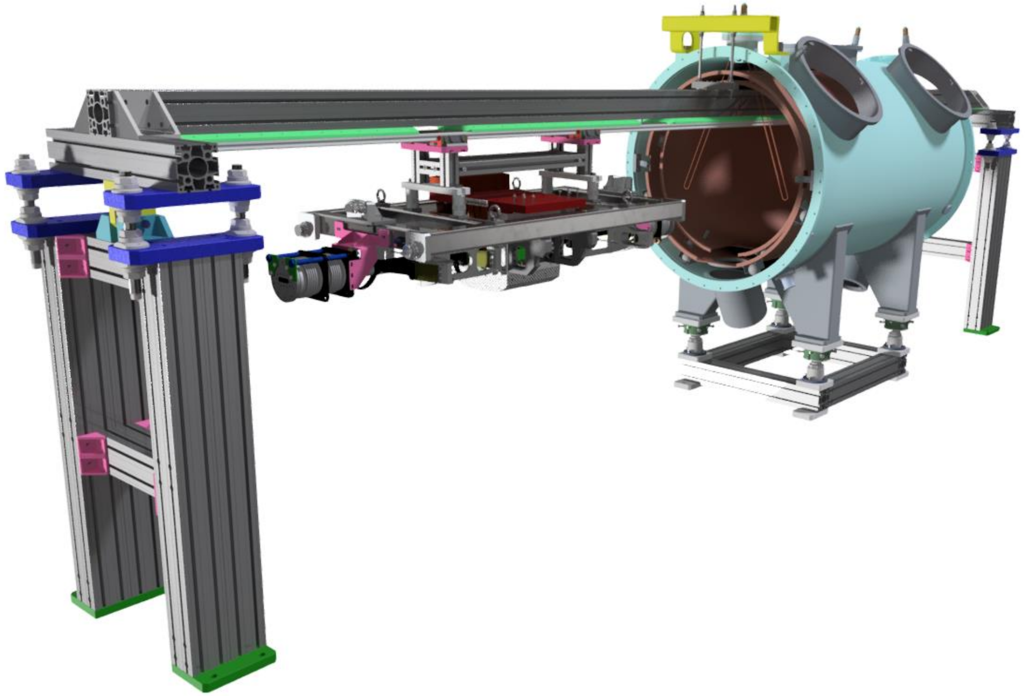
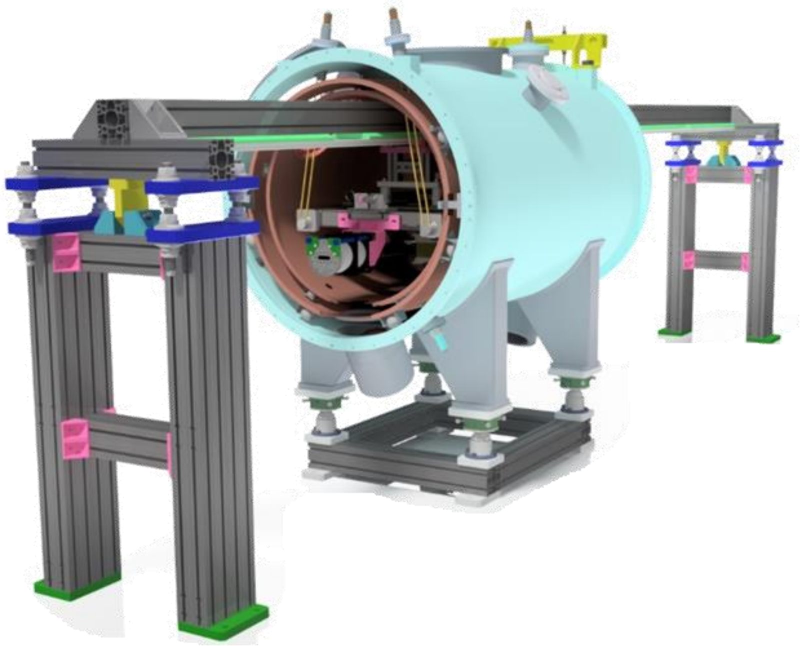
Assembly

Challenges

- **Centering the magnetic field:**
  - Before cooldown: ensuring precise alignment with geometric references
  - After cooldown: maintaining precise positioning with limited access for correction
- **Cabling and thermal links integration:** Planned assembling sequence to simplify the connections

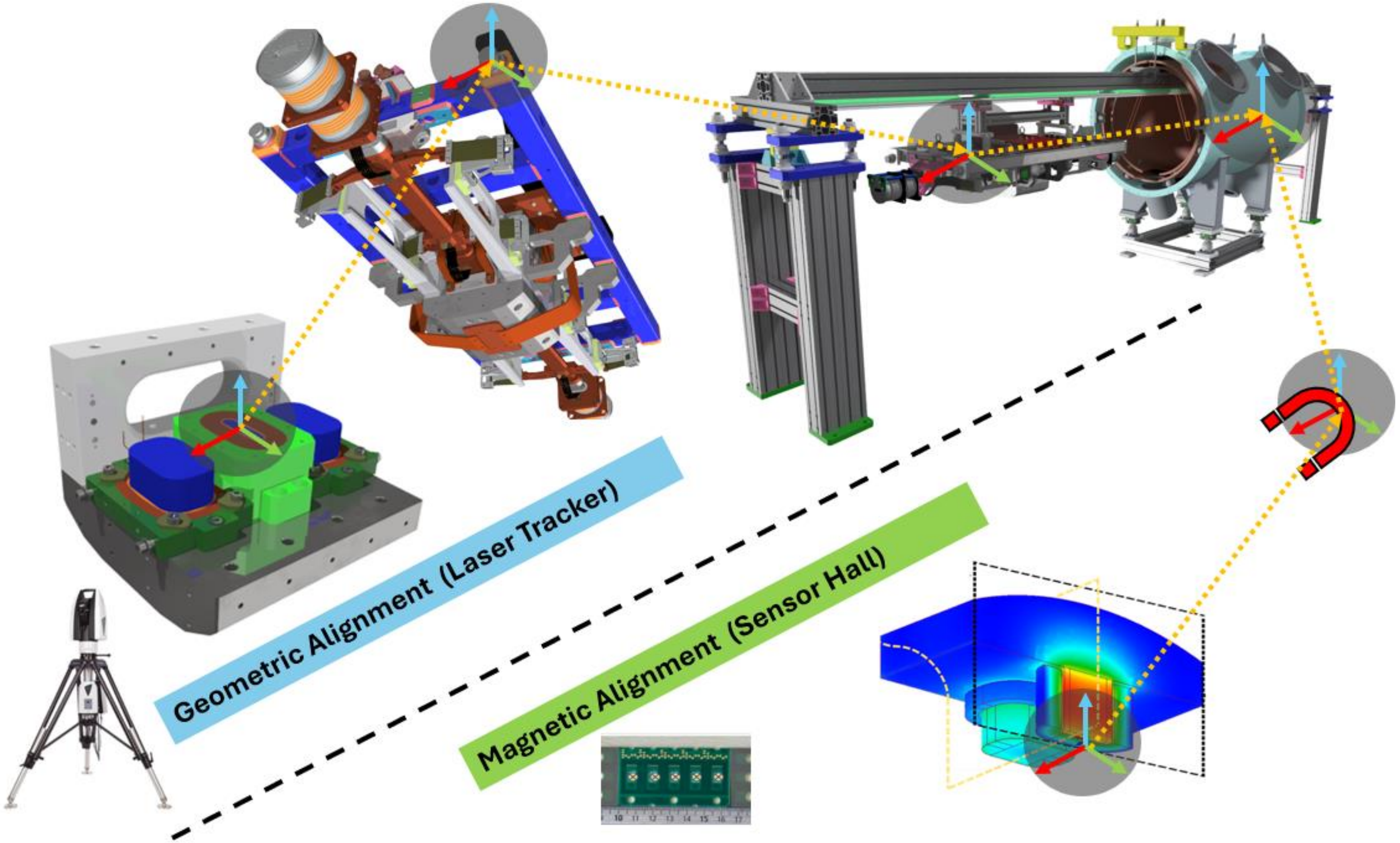




Assembly

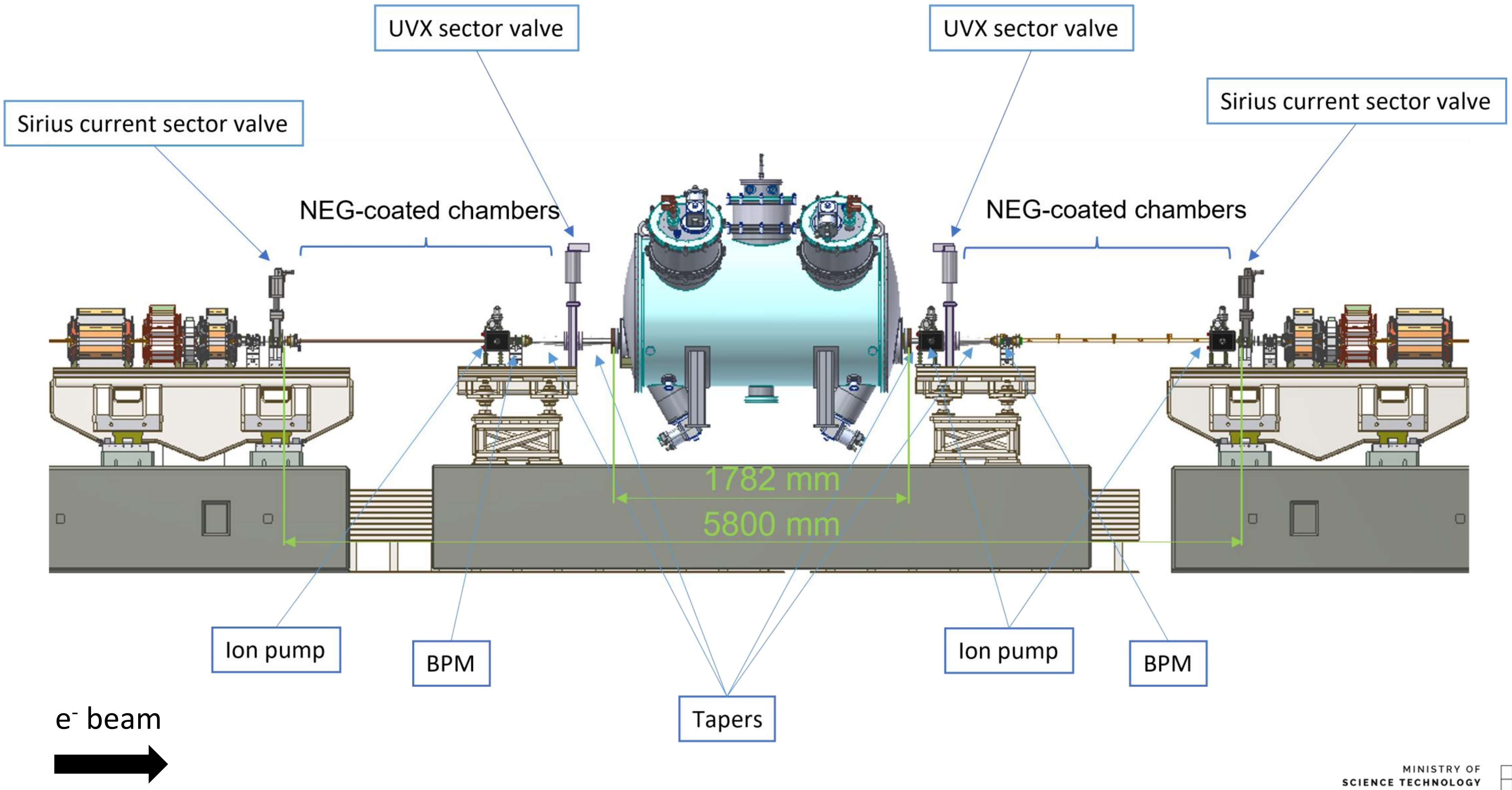
Main Concepts

- **Measurement-assisted alignment concept (before cooldown):**
  - **Geometric center alignment:** assembling and measuring components in respect to fiducial points – reference points transferred from the electromagnetic structure to the external cryostat
  - **Magnetic center alignment:** the measurement of permanent magnets center, located in fiducial points outside the cryostat, allows to correlate the magnetic center with the geometric reference – using the same magnetic measurement system
- **Accommodation of thermal contraction (after cooldown):**
  - Position the structure considering simulated thermal contractions (validation needed)
  - Vertical alignment can be adjusted using screws outside the cryostat (validation needed)



Alignment tolerances are still being defined together with the Accelerator Physics Group

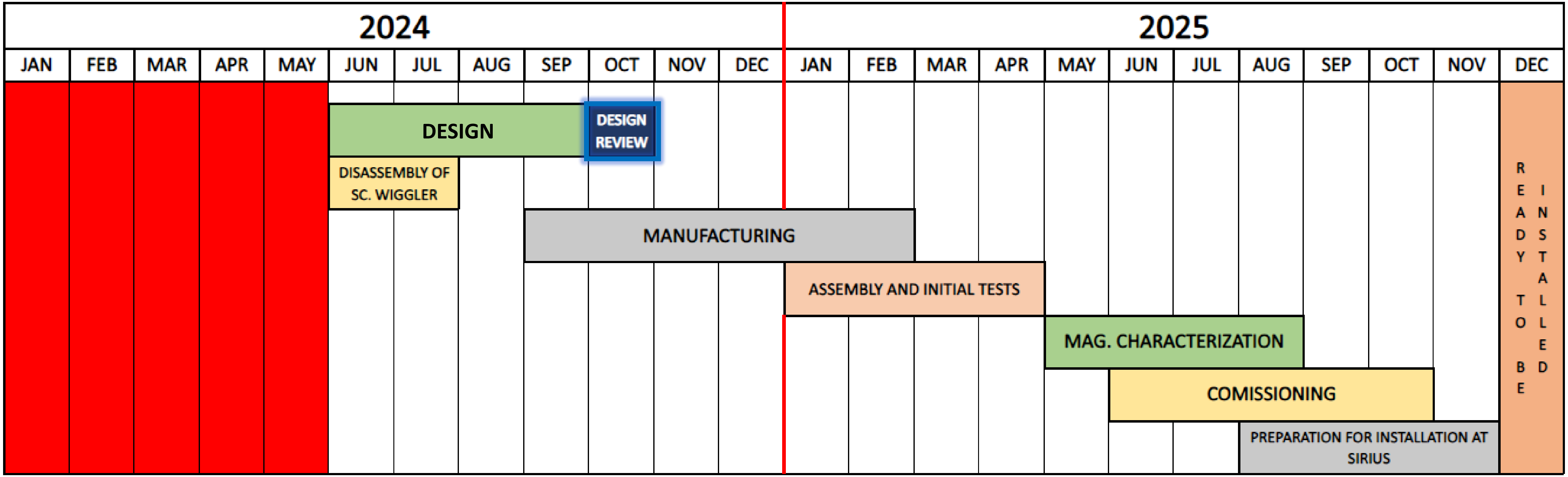
Sirius installation



Outline

- Brief Overview of CNPEM
- CNPEM engages in superconductivity initiatives
- SWLS Overview
  - Electromagnetic design
  - Coils fabrication
  - Mechanical design
  - Cryogenic design
  - Electrical systems
  - Magnetic characterization approach
  - Assembly and Sirius Installation
  - Schedule and summarized development status

Schedule



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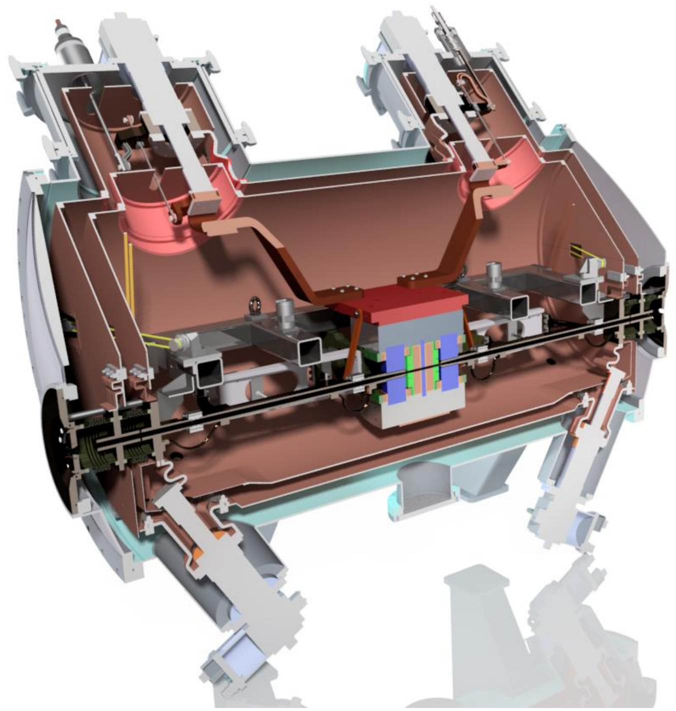
OCT
NOV
DEC
DESIGN
DESIGN REVIEW
DISASSEMBLY OF SC. WIGGLER
MANUFACTURING
ASSEMBLY AND INITIAL TESTS
MAG. CHARACTERIZATION
COMISSIONING
PREPARATION FOR INSTALLATION AT SIRIUS
READY TO BE INSTALLED

Summarized development status



PROGRESS

Electromagnetic Design

1. Simulations and analysis of the magnetic field profile
2. SC coils fabrication
3. Testing of the coils in the vertical cryostat
4. Final validation of the electromagnetic design of the SWLS
5. Development of hor/ver correctors

70% completed

Mechanical and Cryogenic Design

1. Simulations and analysis of temperature distribution
2. Simulations and analysis of force distribution in mechanical elements
3. Validation of refrigeration concepts using the vertical cryostat
4. Development of electron chamber components
5. Evaluation and inspection of the superconducting wiggler structure

60% completed

Electrical Systems

1. Development, testing, and validation of cryogenic electrical circuit
2. Manufacturing, improvement, and testing of resonant power converter
3. Development of quench detection and protection system
4. Development of hardware and software for control and monitoring

70% completed

Validations and Characterizations

1. Development of setup for magnetic characterization
2. Integration, assembly, and fiducialization strategy
3. Evaluation of the impact of device vibration on the machine
4. Final magnetic characterization of the SWLS

30% completed

Thank you!

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CNPEM Brazilian Center for Research in Energy and Materials

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BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING