Technologies of the Superconducting Magnets for the SHiP Experiment

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Spectrometer Magnet

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26 September 2024

5th PBC technology mini workshop: Superconductivity Technologies

Presentation outlook

Proposal:

- Design of the spectrometer magnet of SHiP hidden sector
- Using MgB_2 sub-cables from HL-LHC WP6a,
- Operated in gaseous helium (GHe) at 20 K

Demonstrator: Energy-Efficient Superferric Dipole Program

- Achievements and results of tests already performed
- On-going work and future activities

Conceptual design of SHiP superconductive spectrometer magnet

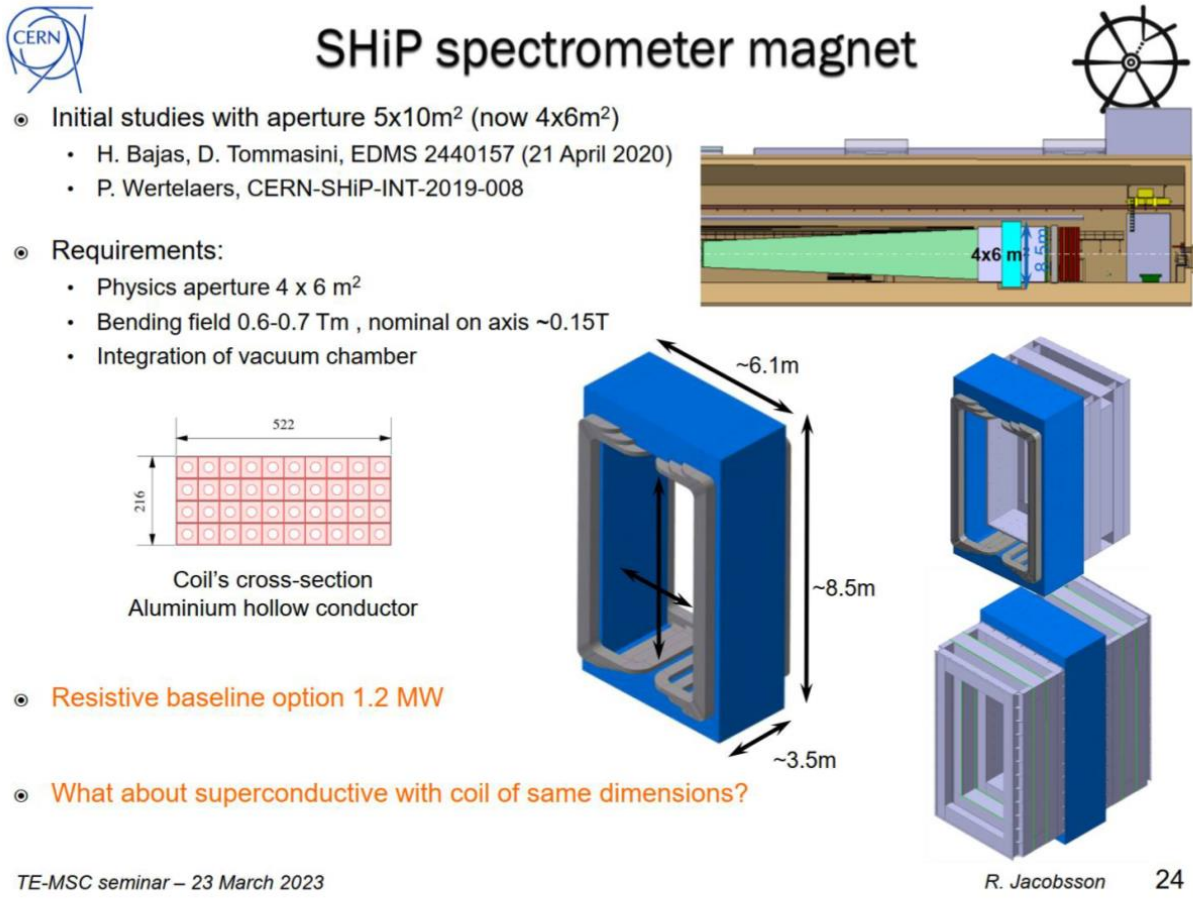
Spectrometer magnet requirements
Initial design proposals

Design requirements:

- aperture: 4 x 6 m^2;
- bending strength: 0.6-0.7 T.m;
- Integration of vacuum chamber
  (can be simplified with He option).

Initial design proposals:

- Initial design developed by P. Wertelaers and A. Perez in 2019, relying on normal conducting magnets
  - ➢ 1.2 MW power consumption!
- First study of superconducting options by D. Tommasini and H. Bajas in 2020 (incl., Nb−Ti, Nb_3Sn, MgB_2 and ReBCO)
  - ➢ all options feasible; choice to be made on cooling type, magnet protection and conductor availability.



SHiP spectrometer magnet

- Initial studies with aperture 5x10m^2 (now 4x6m^2)
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)
  - P. Wertelaers, CERN-SHiP-INT-2019-008
- Requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field 0.6-0.7 Tm , nominal on axis ~0.15T
  - Integration of vacuum chamber

Coil's cross-section
Aluminium hollow conductor

- Resistive baseline option 1.2 MW
- What about superconductive with coil of same dimensions?

TE-MSC seminar – 23 March 2023

R. Jacobsson 24

Courtesy of R. Jacobsson
(CERN/TE-MSC)

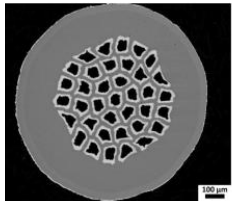
Motivations to use MgB_2 cable developed for HL-LHC WP6a

Characteristics of spectrometer magnets which motivate the use of MgB_2 cables :

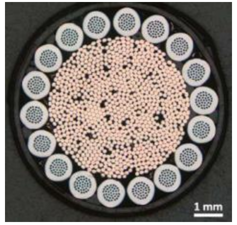
- Spectrometer magnet calls for a large number of Ampere-turns to produce a low field in a large aperture.;
- DC operation, dominated by static losses, large electrical consumption of the resistive option;
- Coil winding enables large radii of curvature;
- Preference for a cable that can be produced in long lengths;
  - ➢ Niche application for MgB_2 cables cooled by GHe at 20 K.

Courtesy of A. Ballarino
(CERN TE-MSC)

Such cables have become available thanks to the superconducting links developed within the framework of HL-LHC Work Package 6a (cold powering system). Development of dedicated ReBCO current leads also successful.



MgB_2 wire for HL-LHC superconducting link (over 1000 km produced)



MgB_2 cable made from 18 MgB_2 strands twisted around braided copper core (available in kilometric unit length)

Multi-stage MgB_2 cable for HL-LHC superconducting link (7 out of 10 unit lengths produced)

Full-size HL-LHC superconducting link prototype system successfully tested in March 2024 (transferred up to ~ 94 kA in DC mode)

Energy-Efficient Superferric Dipole: Program Overview

Objective:
Explore the potential of a superferric magnet design using MgB_2 sub-cables from HL-LHC WP6a, operated in gaseous helium (GHe) at 20 K.

First Step:
Develop a proof-of-principle demonstrator with scalable design and assembly processes for large, iron-dominated magnets in physics experiments.

The EESD program was launched by CERN/TE at the beginning of 2023, having the SHiP spectrometer (or similar applications) in mind.

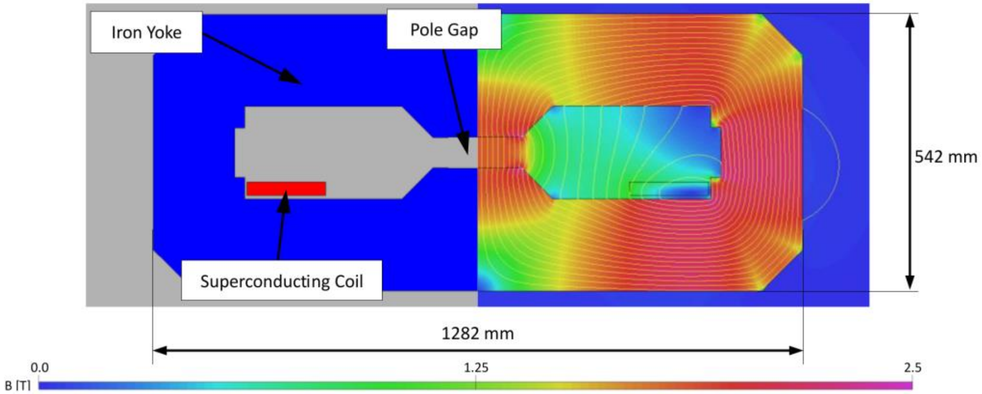
Testing Phases for Proof-of-Principle Demonstrator:

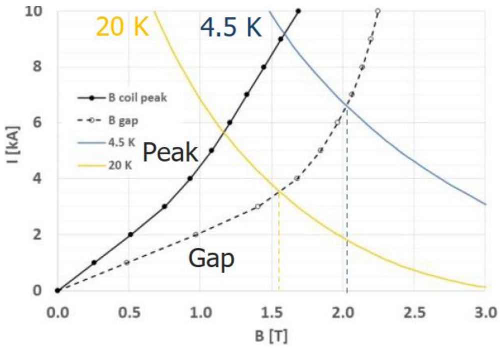
1) test in a cryogenic test station with LHe at 4.5 K;
2) test in a cryogenic test station with GHe at 20- 30 K;
3) test with warm iron and coil at 20 K in a dedicated cryostat.

Electromagnetic design:

Main design concepts/parameters are:

- H-type iron yoke;
- Single, double-pancake, racetrack-type coil;
- Pole gap: 180 x 62 mm;
- Magnetic length: 1.0 m;
- Target central field: 1.8–2.0 T at 5 kA and 4.5 T (coil peak field ~ 1.1 T).





2-D electromagnetic design and magnet load lines with reference MgB_2 cable data at 4.5 K and 20 K

Courtesy of A. Milanese (CERN/TE-MSC)

Demonstrator successfully tested in LHe at 4.5 K in Q2 2023

Energy-Efficient Superferric Dipole: Phase 1

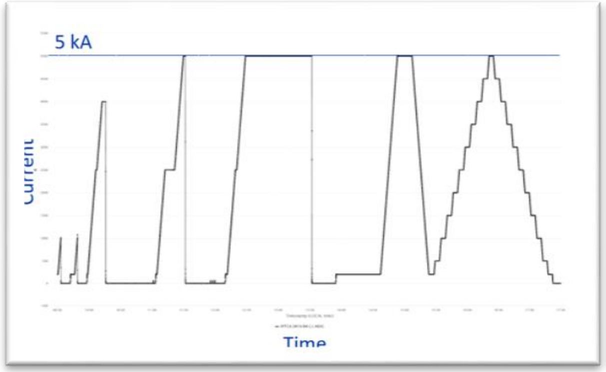
Technical specifications:

- Minimum Cable Bending Radius:
  - Set to 300 mm (lower limit under investigation)
- Double-Pancake Coil:
  - Wound without tension, with the cable positioned in half-circular grooves of aluminium alloy (grade 6082) formers (one cable per groove)
- Coil former:
  - Grooves of formers are precisely machined for a tight fit with insulated cable, supporting it during powering (similar to ITER TF radial plates)

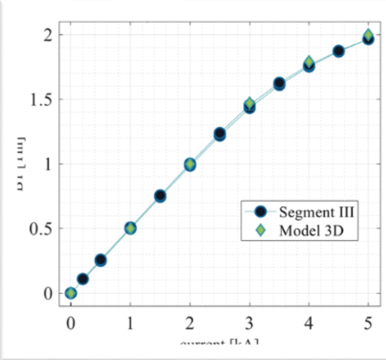
Test results:

- Phase 1: Successfully carried out in liquid helium (LHe) at 4.5 K during Summer 2023.
  - Performance:
    Powered up to 5 kA without quench or V-I issues.
  - Thermal Cycle:
    Subjected to a thermal cycle to room temperature with no impact.
  - Magnetic Measurements:
    Performed with a rotating coil magnetometer, consistent with FE simulations.
    Measured Central Field: 1.95 T at 5 kA and 4.5 K

Assembly of proof-of-principle EESD demonstrator
Courtesy of N. Bourcey and A. Milanese (CERN/TE-MSC)



EESD powering history during first test cycle at 4.5 K (Phase 1)
Courtesy of F. Mangiarotti CERN/TE-MSC)



Integral dipole field load line
Courtesy of C. Petrone (CERN/TE-MSC)

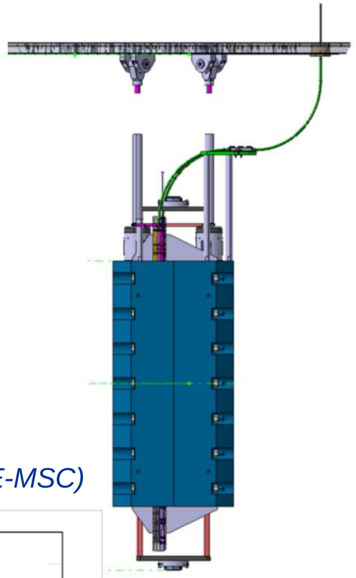
A. Devred, et al., "Proof-of-Principle of an Energy-Efficient, Iron-Dominated Electromagnet for Physics Experiments," IEEE Trans. Appl. Supercond., Vol. 34 No. 5 (2024).

Energy-Efficient Superferric Dipole: Phase 2

Demonstrator successfully tested
in GHe at 20-30 K in Q1 2024

Test Results:

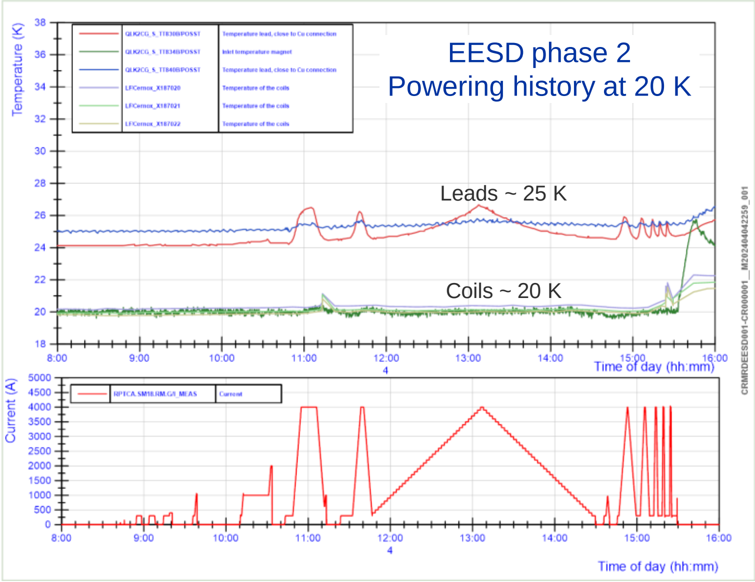
- Phase 2: Successfully carried out in gaseous helium (GHe), in January 2024.
  - Technical challenge:
    Adaptation of the HFM test station to manage a stable cryogenic operation
  - Initial Cooling:
    Cooled down to 4.5 K to reestablish previously achieved performances
  - Incremental Warming and Powering:
    - Warmed up to 20 K, 25 K, and 30 K.
    - Successfully powered up to:
      - 4 kA at 20 K
      - 3 kA at 25 K
      - 2 kA at 30 K
    - No quench or V-I observed.
  - Subsequent Testing:
    - Quench tests conducted at higher temperatures (behavior as expected).
    - AC loss measurements performed (not for SHiP applications).



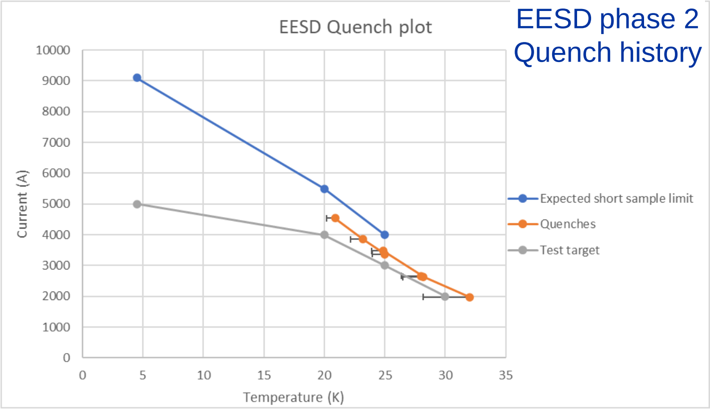
Reassembly of EESD demonstrator for Phase 2

Courtesy of N. Bourcey and A. Milanese (CERN/TE-MSC)

Courtesy of G. Willering (CERN/TE-MSC)



EESD phase 2
Powering history at 20 K

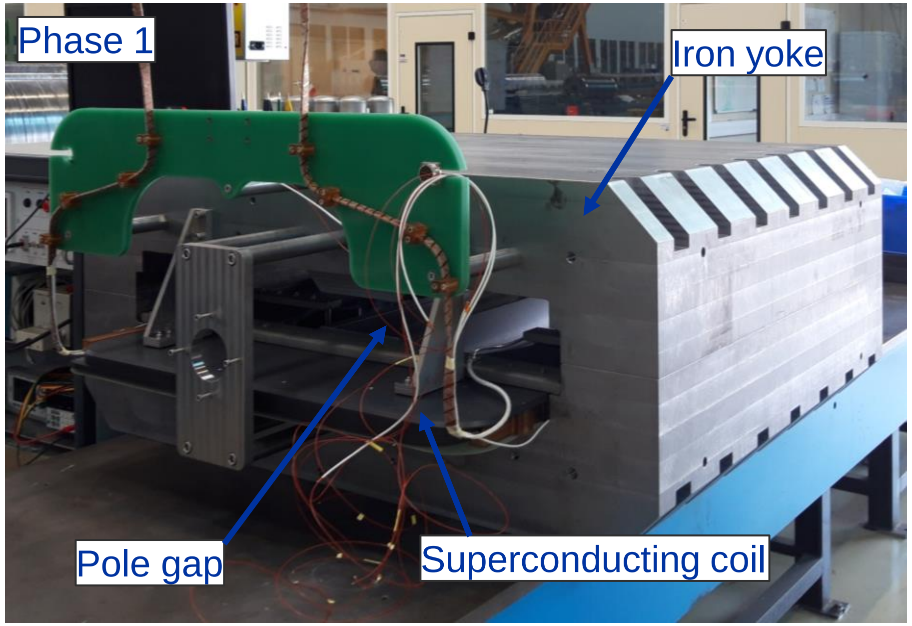


EESD phase 2
Quench history

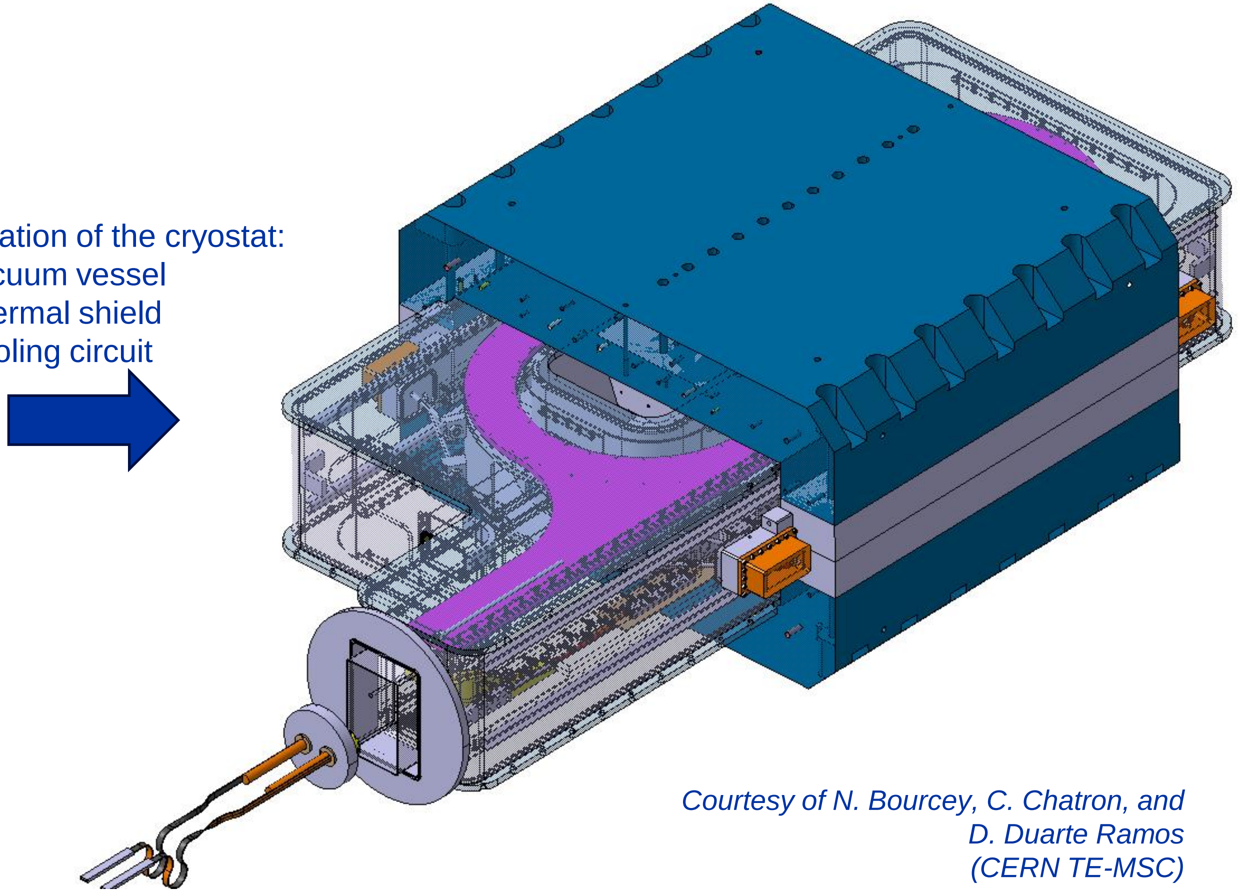
Energy-Efficient Superferric Dipole: Phase 3
Indirect cooling of the coils at 20 K

Objective:

To cool superconductive coils efficiently by circulating Gaseous Helium (GHe) through capillaries within a dedicated cryostat keeping the yoke warm



Integration of the cryostat:
- Vacuum vessel
- Thermal shield
- Cooling circuit



Courtesy of N. Bourcey, C. Chatron, and D. Duarte Ramos (CERN TE-MSC)

Cryogenic and powering tests to take place in the one of the Cluster G test station of SM18

Energy-Efficient Superferric Dipole: Phase 3
Indirect cooling of the coils at 20 K

Update of the electromagnetic design and mechanical simulations:

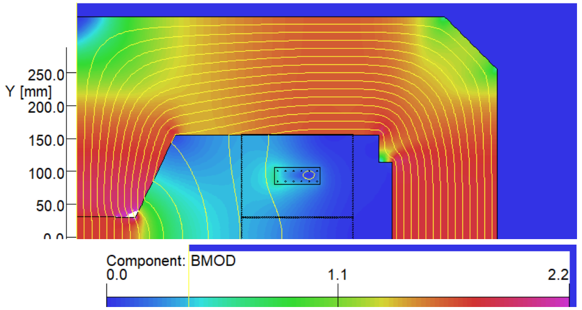
Main design concepts/parameters are:

- H-type iron yoke;
- Double-pancake, racetrack-type coils;
- Pole gap: 180 x 62 mm;
- Magnetic length: 1.0 m;
- Target central field: 1.9 T at 5 kA and 20 T.

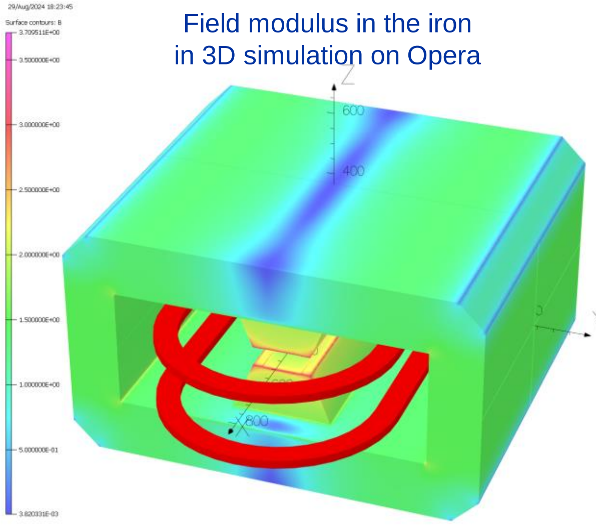
- 2 symmetric Racetrack-type coils :
  - Optimization of cryostat design
  - Lorentz loads transfer
  - Decrease of the peak field

Analysis are done
Internal Note to be written Dec. 2024

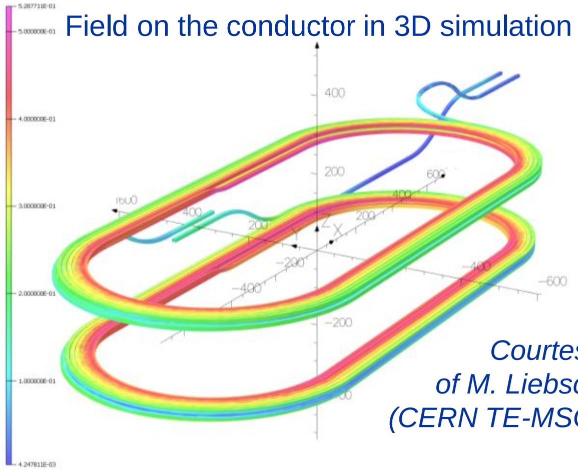
Field map and potential lines in 2D simulation on Opera



Field modulus in the iron in 3D simulation on Opera

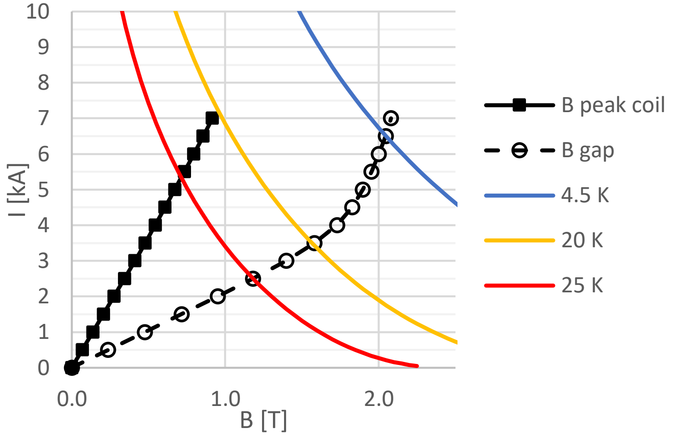


Field on the conductor in 3D simulation



Courtesy of M. Liebsch (CERN TE-MSC)

Magnet load lines based on results of 3D opera simulations with reference MgB_2 cable data at 4.5 K, 20 K and 25 K



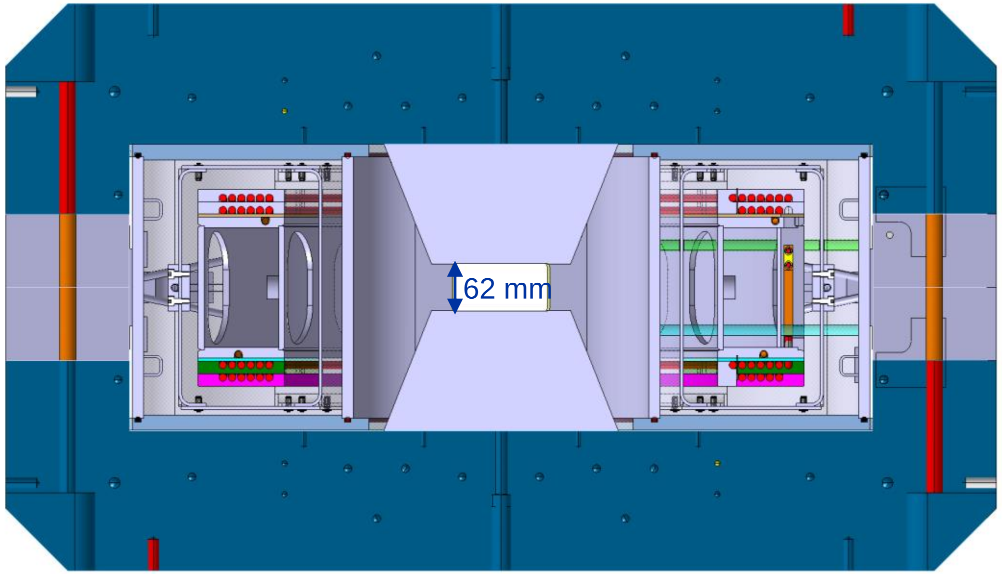
3D CAD mechanical design done
2D drawings planed for Oct. 2024
Assembly planed for Q2 2025

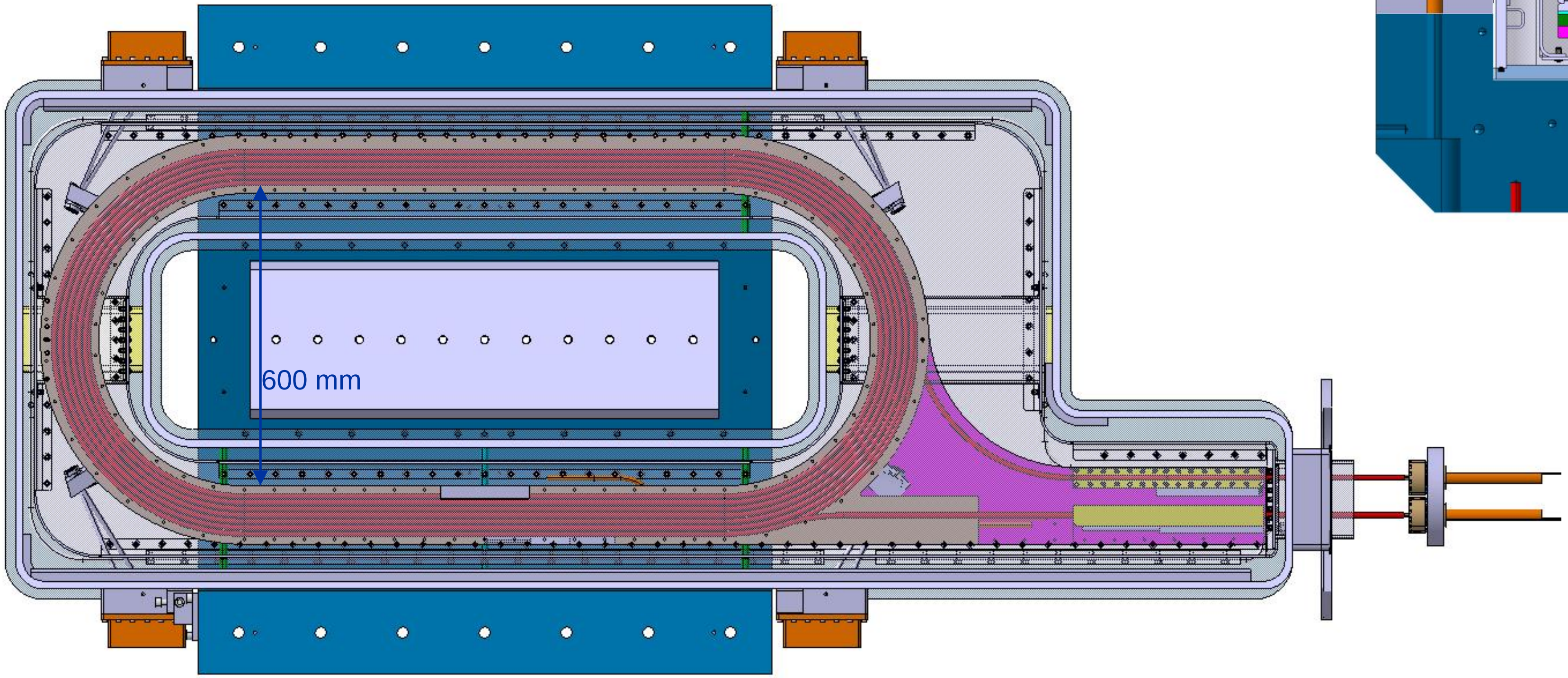
Energy-Efficient Superferric Dipole: Phase 3
Indirect cooling of the coils at 20 K

Mechanical design:

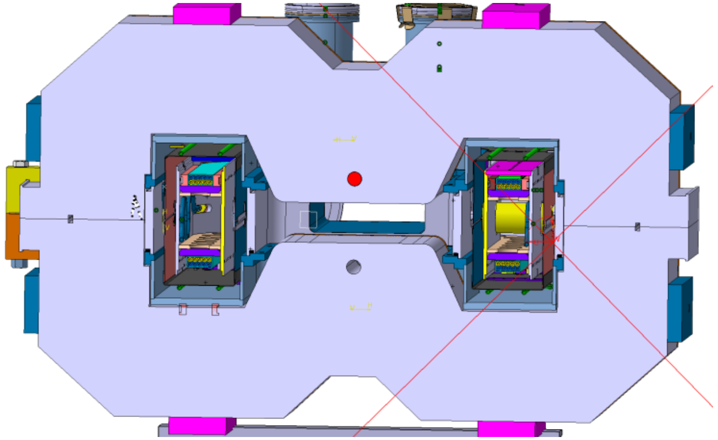
The two coils will be mounted in a common support structure and a common cryostat.

- Design of the coils, cooling formers, cryostat, coldmass, supporting system…
- Assembly procedure
- Design of the tooling





Courtesy of N. Bourcey, C. Chatron, and D. Duarte Ramos (CERN TE-MSC)



FCM Fast Cycled Magnet demonstrator program at CERN 2008-2014

Presentation outlook

Proposal:

Design of a superferric magnet

Using MgB_2 sub-cables from HL-LHC WP6a,

Operated in gaseous helium (GHe) at 20 K

Demonstrator: Energy-Efficient Superferric Dipole Program

- Achievements and results of tests already performed
- On-going work and future activities

Validation of the technology choice by July 2025:
- use of MgB_2 cable developed for WP6a in a magnet
- winding of MgB_2 cable in grooves machined in a radial plate
- Implementation of indirect cooling thanks to GHe at 20 K

Conceptual design of SHiP superconductive spectrometer magnet

Conceptual design of the SHiP Spectrometer Magnet

Main design concepts/parameters of the electromagnetic design are:

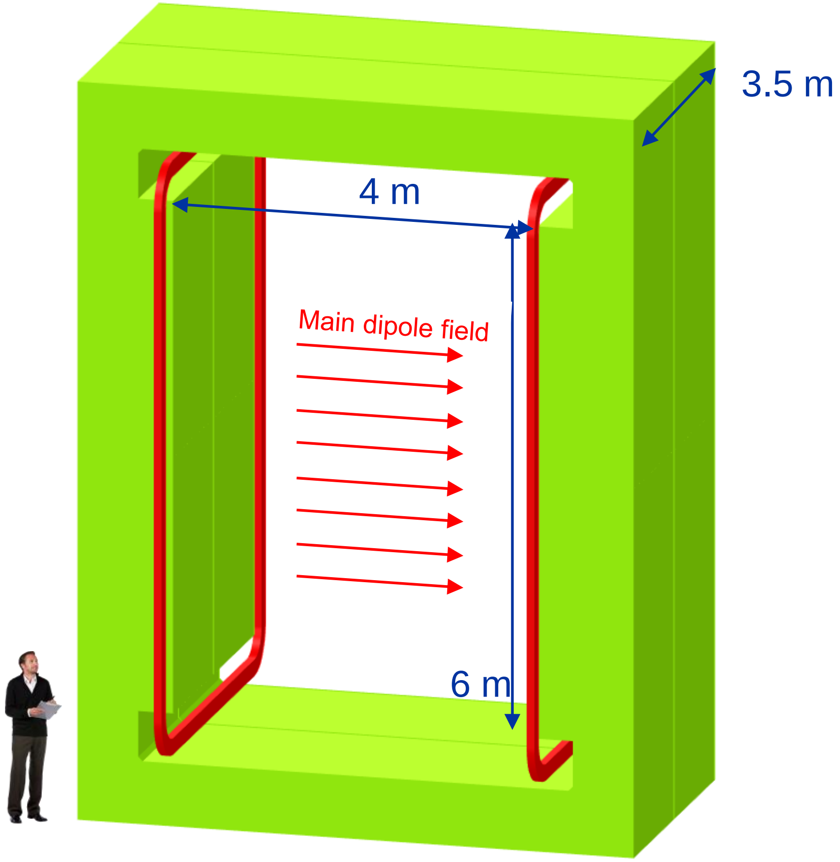
- Superferic = iron dominated magnet;
- H-type iron yoke;
- 2 symmetric coils;
- Double-pancake, racetrack-type coils = flat coils;
- Pole gap: 6000 x 4000 mm;
- Target central field: 0.15 T at 3 kA and 20 K.

Requirements for physics point of view :

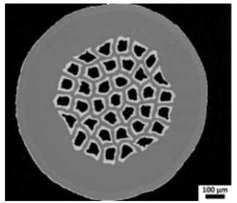
- Integrated field strength;
- Field homogeneity;
- Time stability.

Conceptual design of the magnet has started and must include:

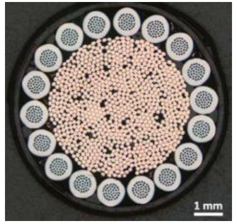
- Electromechanical design;
- Conceptual design of the cryostat;
- Cooling architecture;
- Current leads, “distribution box” and superconducting link between the two coils;
- Assembly procedure;
- Technical infrastructure interfaces…



Preliminary design: superconductor, coils and cryostat

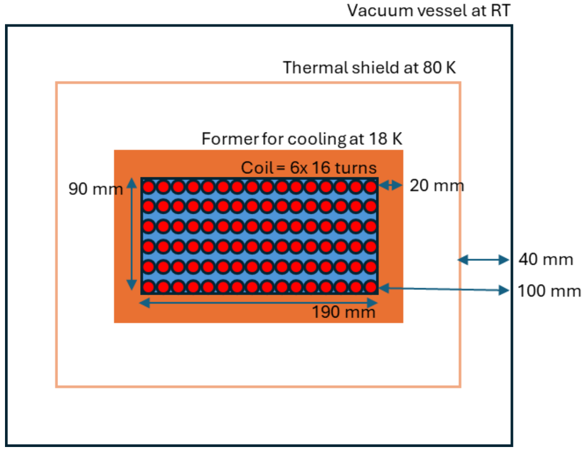


MgB$_2$ wire for HL-LHC superconducting link (over 1000 km produced)



MgB$_2$ cable made from 18 MgB$_2$ strands twisted around braided copper core (available in kilometric unit length)

Courtesy of A. Ballarino (CERN TE-MSC)



Simplified cross section of the coil and the cryostat

Superconductor:

Use of the cable available thanks to the superconducting links developed within the framework of HL-LHC Work Package 6a (cold powering system):

- Already tested and characterised included in the full-size HL-LHC superconducting link prototype system successfully tested in March 2024 (transferred up to ~94 kA in DC mode);
- Stable, "self-protected";
- Can be produced in long units lengths.

Nominal current decreased from 4000 A to 3000 A for more margin on cable operation and on the heat load of the current leads

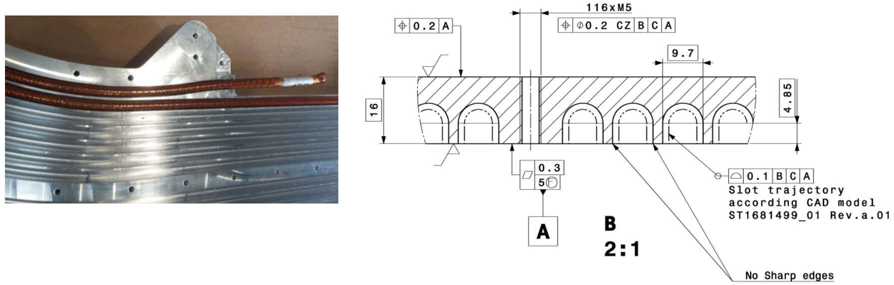
Coil:

- Winding in grooves machined in a radial plate;
- Cooled by indirect cooling.

Cryostat:

- One coil per cryostat (different to EESD/FCM);
- Thermal shield and vacuum vessel like "rigid" cryostat (similar to EESD/FCM).

Extract from former bottom plate CRNMRDEESD0005

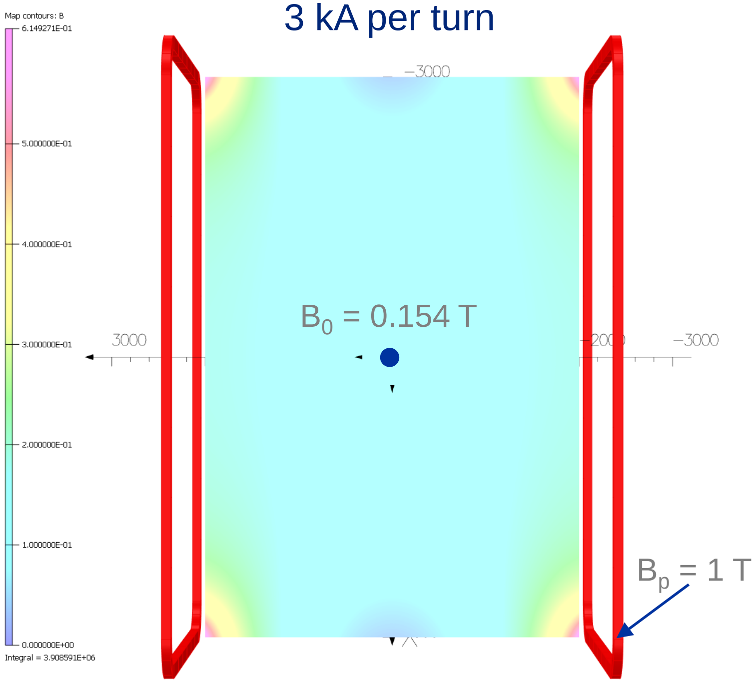


Inputs for electromagnetic simulations
Static heat loads computations

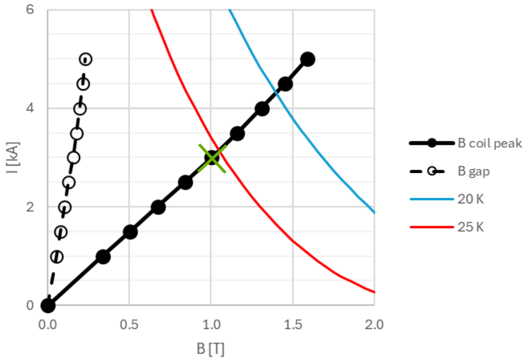
Preliminary electromechanical design

Magnetic simulations and output on baseline geometry

3 double pancakes per coil,
16 turns per layer
3 kA per turn

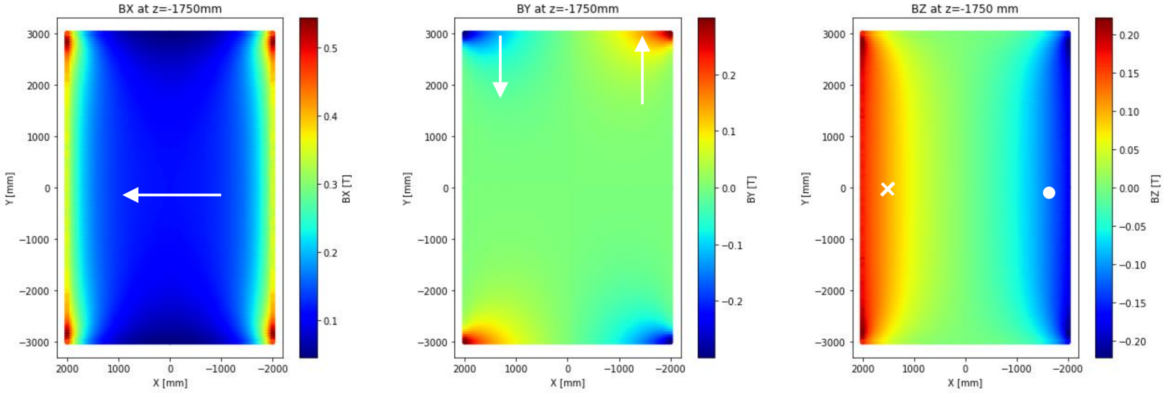


Int *B.dl* [-2.5 m; 2.5m] = 0.630 T.m
Stored energy: ~ 2.75 MJ



Operating point:
B_{op} = 1 T
I_{op} = 3 kA
28% margin on load line
Temperature margin: 6 K

Magnet load lines based on results of Opera 3D simulations with reference MgB_2 cable data at 20 K and 25 K



Field maps in the magnet aperture in vertical plan at the extremity of the iron.
The three components are shown.
The white arrows help to locally visualise the direction of the component.

Ongoing work on the electromechanical design of the spectrometer magnet:

- Iteration process for field optimisation on going
- First estimation of the coil's characteristics
- First estimation of the electromechanical forces

Benchmark Opera/Roxie done

Courtesy of P. Borges de Sousa, T. Koettig (CERN TE-CRG)

Cooling architecture by cryocoolers

HFM WP 4.6: cryogenic study of novel cooling schemes (synergies, application for other projects like EuroSIG)

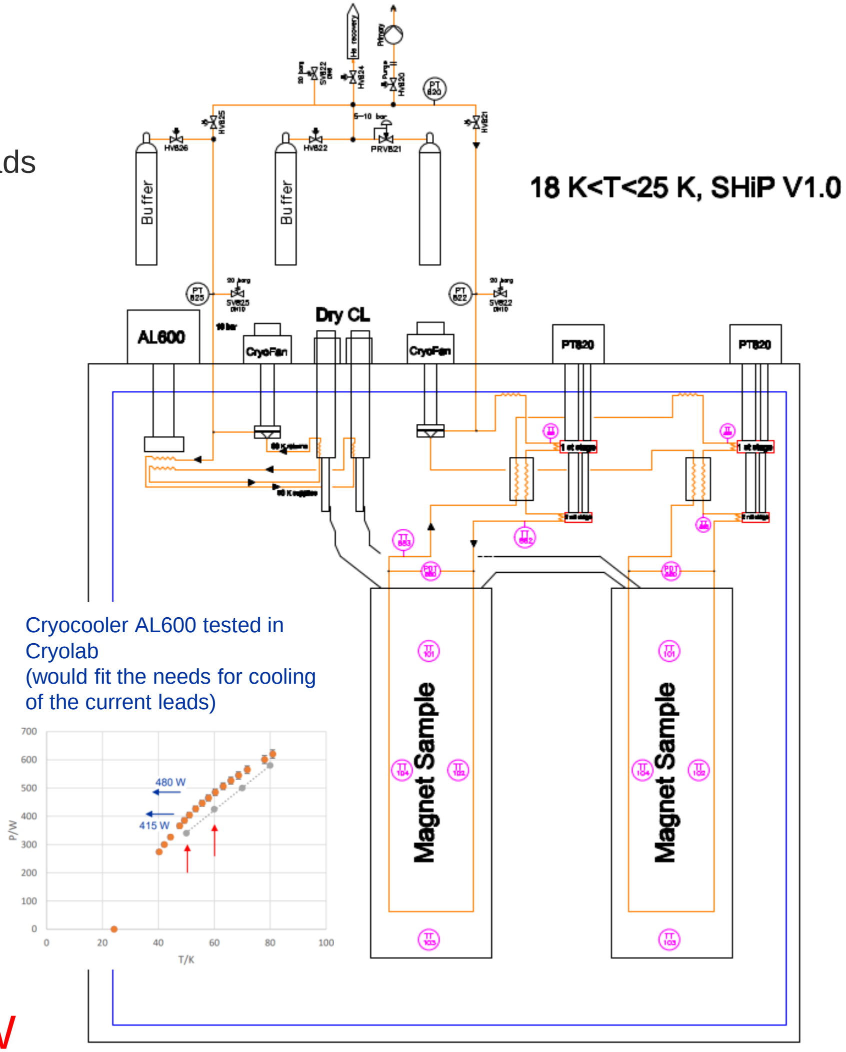
Two separate circuits: Current leads & magnet
Highly efficient heat exchangers are been developed to be used in fluid circulation loop cooling of the current leads

Requirements for cooling of the magnet: 18 K (to keep a margin on the temperature of the cable expecting a gradient on such large coil) (*not up to date in this presentation and for estimations*)

Source [1]	$\dot{Q}$ at 20 K [W]	$\dot{Q}$ at 80 K [W]	$\dot{Q}$ at 50 K [W]
Conduction through support	10	100	-
Thermal radiation	2	60	-
Splice resistance [2]	1	-	-
Sub-total Magnet	**13**	**160**	**-**
Heat load for resistive part of CL [3]	-	-	324
Additional heat load from the Cryofan [4]	-	-	30
Sub-total currents leads	**-**	**-**	**354**

Preliminary hypothesis:
[1] Dynamic Heat Loads (beam induced effects + particle showers) not included
[2] 5 splices during winding 5x12 nOhm, at I= 4 kA
[3] Resistive CL Brass Cu60Zn40+ ReBCO, at I= 4 kA, Tcold= 60 K
[4] High helium pressure loop with cold circulator (10 bars), 5 g/s

Several cooling architectures will be tested.
First estimations of heat loads seems compatible with the use of dry cooling by cryocooler



Cryocooler AL600 tested in Cryolab
(would fit the needs for cooling of the current leads)

Cryocoolers that could be possibly used:
1 AL600 for current leads, electrical consumption: 13 kW
2 PT420 for cold mass and thermal shield: electrical consumption: 2x11 kW

Conclusion on SHiP spectrometer magnet

Proposal:

Use the MgB_2 cable, originally developed for superconducting links in the HL-LHC Work Package 6a, to design the large aperture SHiP hidden sector spectrometer magnet, aiming to reduce electrical consumption.

Demonstrator achievements:

- 1st successful demonstration of an electromagnet based relying on a MgB_2 cable:
  no training at 20-30 K, no performances change after quench test.
- Quench detection and protection: the demonstrator enables data collection.
  (looking promising thanks to the presence of Monel in MgB_2 strands, which speeds up quench propagation, and of a large Cu amount in cable core).
- Next Step: Test indirect cooling using GHe circulating in capillaries.

Ongoing work on SHiP spectrometer magnet:

- Conceptual Design of SHiP hidden sector spectrometer magnet in progress:
  First iteration of electromagnetic design under verification by SHiP teams (Physics & technical infrastructures)
- Future Focus:
  Open technical points are identified (cooling architecture, current leads,...)
  They could be addressed through a dedicated R&D program and/or by constructing a reduced-scale prototype, potentially usable for other applications.
  Overall procurement strategy or inhouse production to be defined shortly

Ambitious timeline
Full-scale magnet commissioning Q4 2030

home.cern

Preliminary SHiP spectrometer magnet project timeline

			2023				2024				2025				2026				2027				2028				2029				2030			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
SHiP	EESD	Phase 1 LHe at 4.5 K	▨	▨	▨◊																													
		Phase 2 GHe at 20 K				▨	▨	▨◊																										
		Phase 3 GHe at 20 K in cryostat						▨	▨	▨	▨	▨◊																						
	SHiP R&D and tests program	EESD cooling by cryocoolers											▨	▨◊																				
		Tech. Dev. Current leads										▨	▨	▨																				
		EESD cooling by cryocoolers + current leads													▨	▨◊																		
		Tech. Dev. Winding in Radial Plates							▨	▨	▨																							
		Tech. Dev. Support System Cryostat										▨	▨	▨◊																				
		…																																
	Full Scale	Conceptual design of full scale						▨	▨	▨	▨◊																							
		Detailed design, prepa of manufacturing dossier										▨	▨	▨	▨	▨	▨	▨◊																
		Tendering, procurement and/or internal fabrication at CERN																	▨	▨	▨	▨	▨	▨	▨	▨								
		Pre-assembly in surface at CERN																						▨	▨	▨	▨							
		Installation in ECN3 cavern																										▨	▨	▨	▨		
		Magnet commisionning																															▨	▨◊
	Project	SHiP Spectrometer magnet CDR							▨	▨	▨◊																							
		SHiP Experiment TDR															▨	▨◊																
		SHiP Spectrometer magnet TDR															▨	▨◊																

Co-activities for Hi-Lumi within LMF:
MQXF's coil production, HL cold mass production, preparation of LS3 and installation.

Industrial strategy for full-scale magnet to be defined

Tentative timeline for EESD demonstrator Phase 3

2024

Feb. 2024
Start of the Phase 3
mechanical design

Aug. 2024
3D CAD mechanical
design ready
- Coil
- Coldmass
- Thermal shield
- Vacuum vessel

Sep. 2024
Assy. procedure

Oct. 2024
2D drawings
- Coil
- Coldmass
- Thermal shield
- Vacuum vessel

Start of procurement
(estimated 8 months)

Nov. 2024
3D CAD mechanical
design ready
- Interconnection area

Dec. 2024
3D CAD mechanical
design ready
- Tooling

2025

Jan. 2025
2D drawings
- Tooling

May 2025
Reception and control
of the components

June 2025
Winding
Magnet assembly

Jul. 2025
Interconnection assembly
Connection to Cluster G
Test of EESD phase 3

Validation of the technology choice July 2025:
- use of MgB_2 cable developed for WP6a
- winding in grooves machined in a radial plate
- cooled by indirect cooling

Needs for the development of a specific design of current leads

Specific design of current leads : Discussions with A. Ballarino (CERN TE-MSC), P. Borges de Sousa, T. Koettig (CERN TE-CRG)

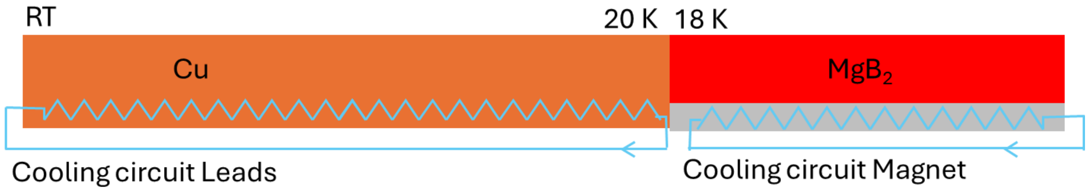
May be adapted from the current leads designed for the SC link: Resistive part - HTS tape - MgB_2 cable

The current leads (including the HTS) need to be cooled with a dry active cooling system (absence of evaporated 4.5 K He stream).

Use of cryocooler dedicated to the cooling of the current leads

Difficulties:

- Active cooling of ReBCO tape?
- Quench detection and quench protection of the HTS tape (large magnet inductance)



Difficulty:

- Mass flow needed for the Lead's cooling circuit: RT-> 20 K with I_{op}= 3.5 kA 250 mg/s ??

Persistent mode operation

Persistent mode operation:

Large contribution of the heat load comes from the current leads (see following slides)

Could the current leads be designed for persistent mode operation ??

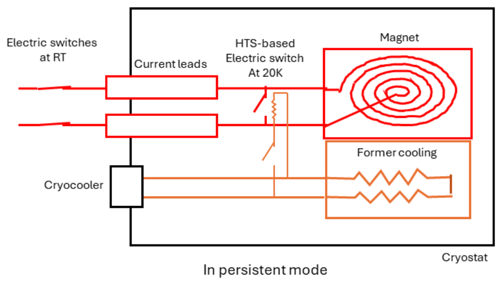
If allowed by the requirement on time stability of the magnetic field needed for the calibration of the detectors and operation aspects on cryocooler

Lmagnet = 0.6 H, strongly depending on the number of splices:

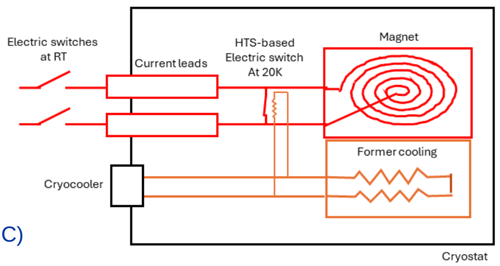
- 1 MgB_2-MgB_2 splice + 2 HTS-MgB_2 : ~36 nOhms (tbc): -14 A/day, t90%=20.3 days
- 5 MgB_2-MgB_2 splices + 2 HTS-MgB_2 : ~ 84 nOhms (tbc): -32 A/day, t90%=8.7 days

Discussions with R. Piccin (CERN TE-MSC)

When “loading”



In persistent mode



Procurement of MgB_2

Estimation of the cable and strands length based on conceptual design:

Hypothesis for the calculation of the cable unit length:

- Estimation of cable length for one coil based on current 3D magnetic simulations: 2200 m
- 2 +1 spare coils
- + prototype 1/3
- + 10% losses during cable production
- 18 strands per cable

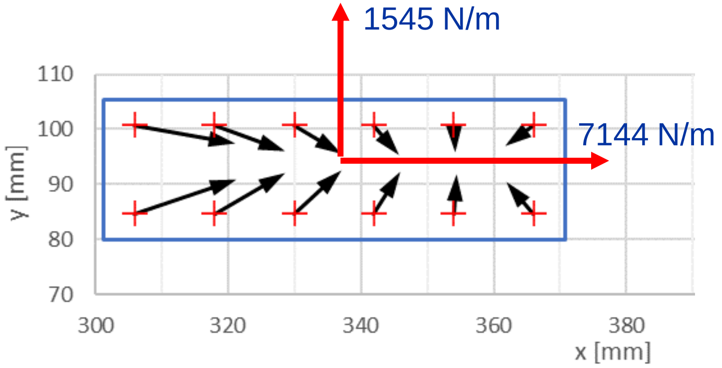
Unit length one coil	2200	m
Three coil (2+1)	3	
+ 1/3 proto	1.334	
+ 10% cable prod. losses	1.1	
18 strands/cable	18	
Total	**175**	**km**

Procurement of the cable

Procurement could be coordinated with Hi-Lumi WP6a if timelines are compatible.

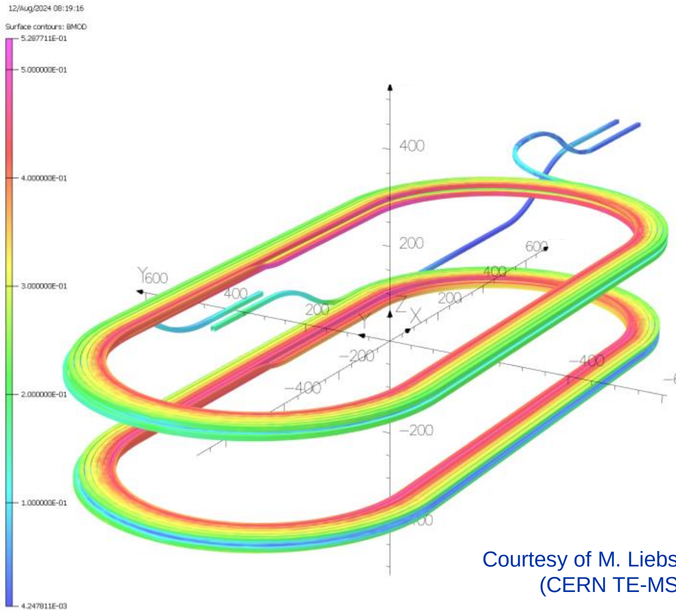
EESD Phase 3

Magnetic simulation and inputs for mechanical simulations

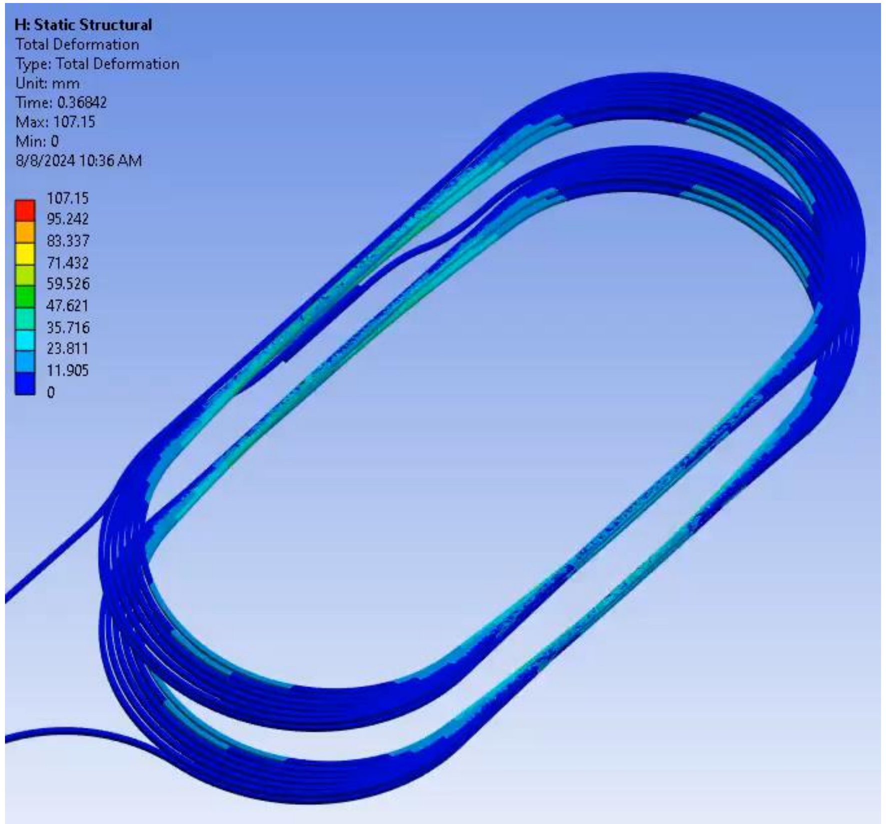


Sketch of one cross section of a coil, on vertical plan at Z=0 Top/Right quadrant compared to the center
Lorentz forces on each turn of conductor

Magnetic simulation with a detailed coil model on Opera



Courtesy of M. Liebsch
(CERN TE-MSC)



H: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 0.36842
Max: 107.15
Min: 0
8/8/2024 10:36 AM

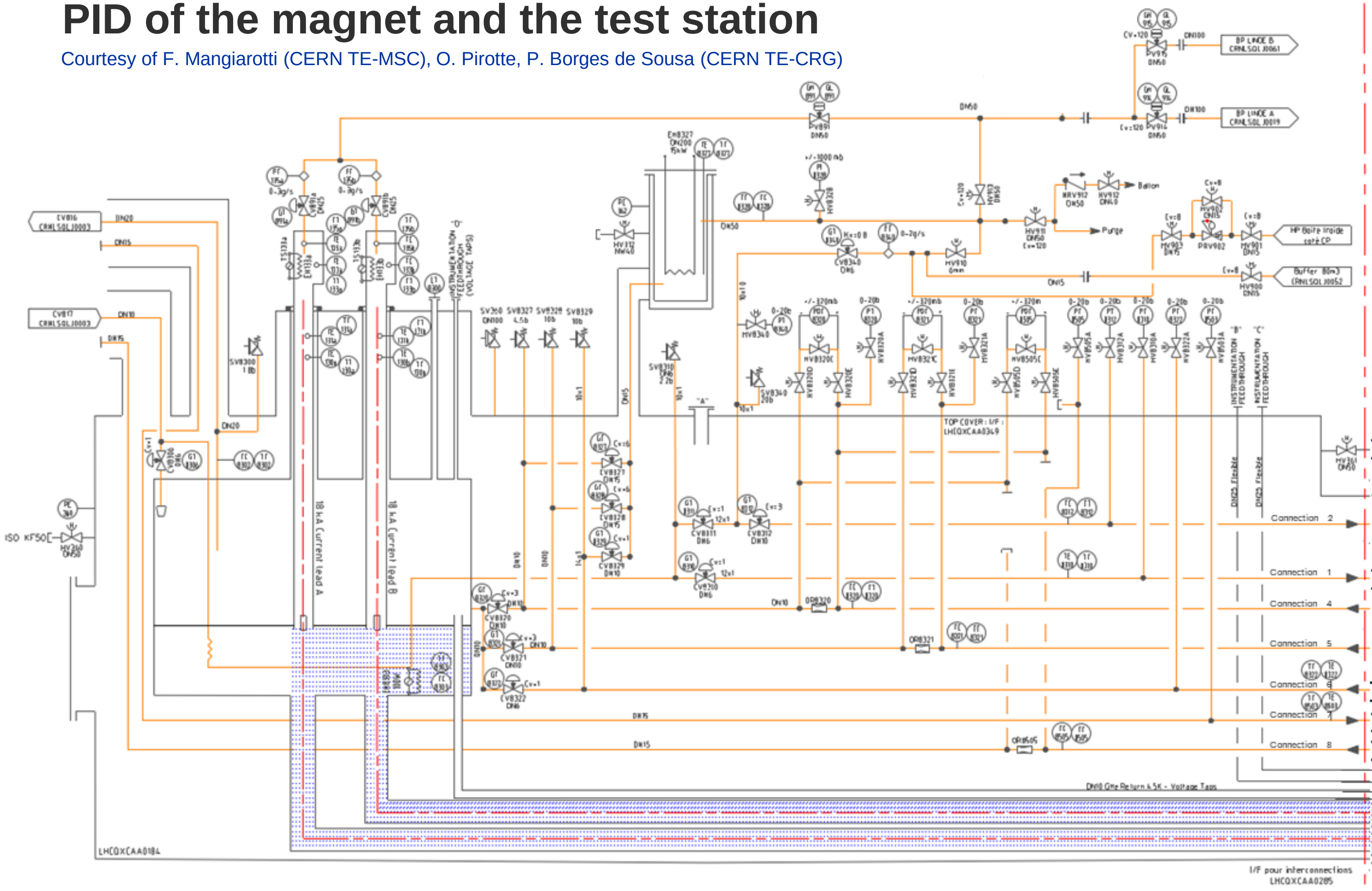
Evaluation of the Lorentz forces
Consolidation of tool and methodology transfer to mechanical simulations

EESD Phase 3

Interconnection assembly
Connection to Cluster G
Test of EESD phase 3 Jul. 2025

PID of the magnet and the test station

Courtesy of F. Mangiarotti (CERN TE-MSC), O. Pirotte, P. Borges de Sousa (CERN TE-CRG)

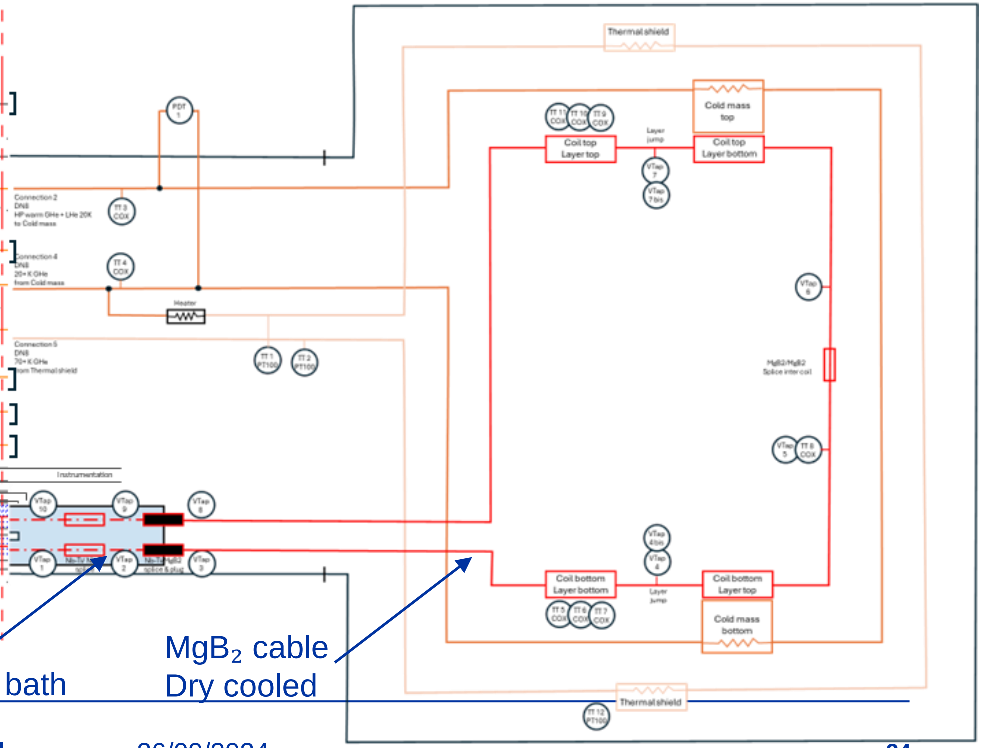


Test station in SM18: Cluster G
(Nota: optimization of cooling architecture of the coils and current leads by cryocoolers won’t be assessed by the demonstrator)

<u>Coil’s cooling circuit:</u>
GHe coming from the CFB circulates in capillaries

- Heat load estimation: 4 W @ 20 K and 20 W @ 80 K

<u>Thermal shield cooling circuit:</u>
In series with the coil’s cooling circuit
Heater to regulate the temperature of the thermal shield temperature



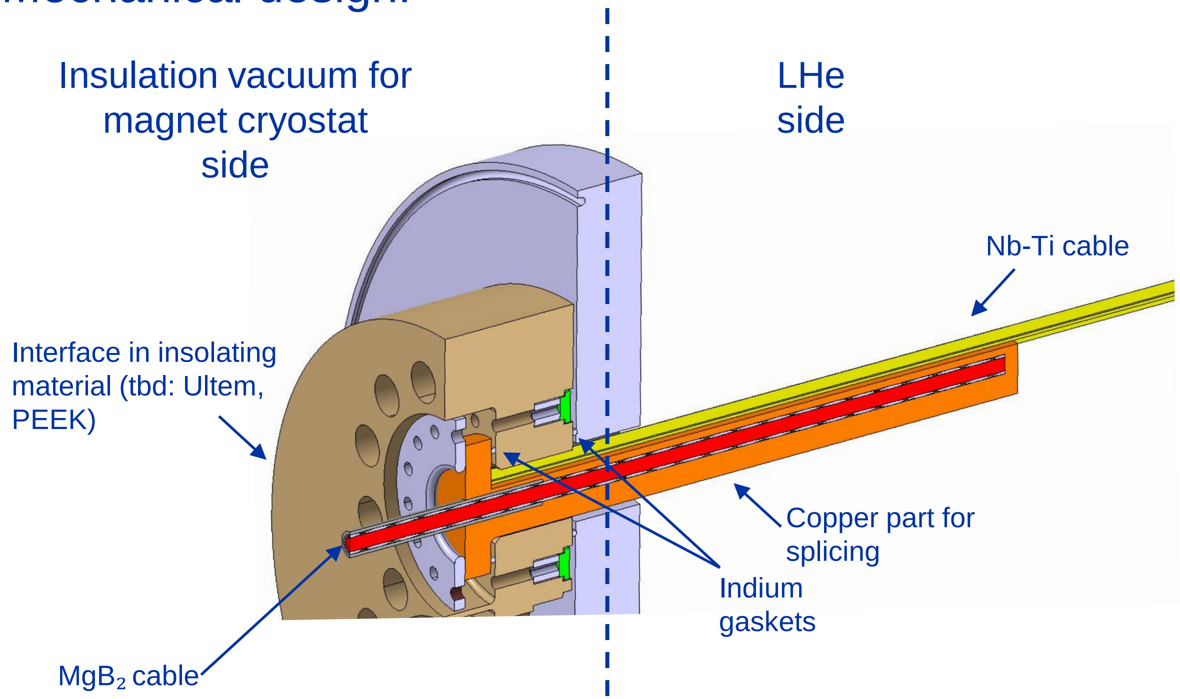
NbTi cable
cooled in LHe bath

MgB_2 cable
Dry cooled

EESD Phase 3 – Technology development

Development of a cryogenic plug (LHe/Vacuum) on a MgB_2 cable

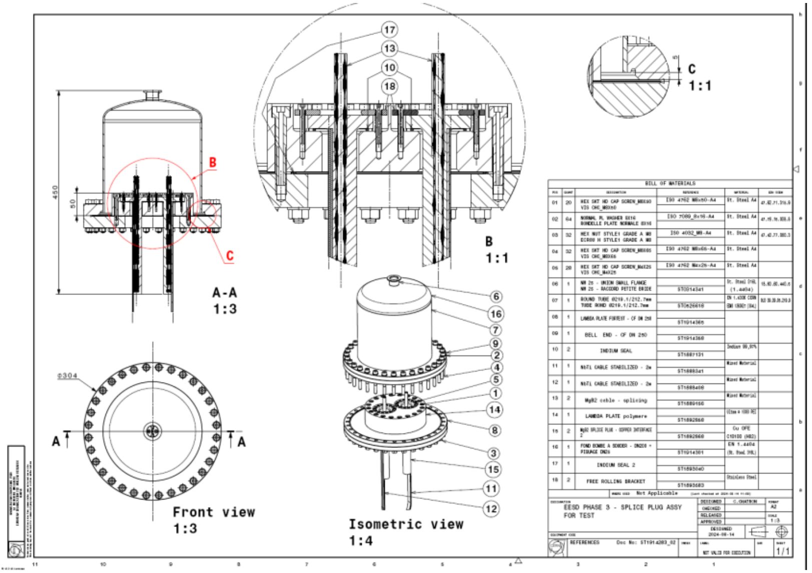
Mechanical design:



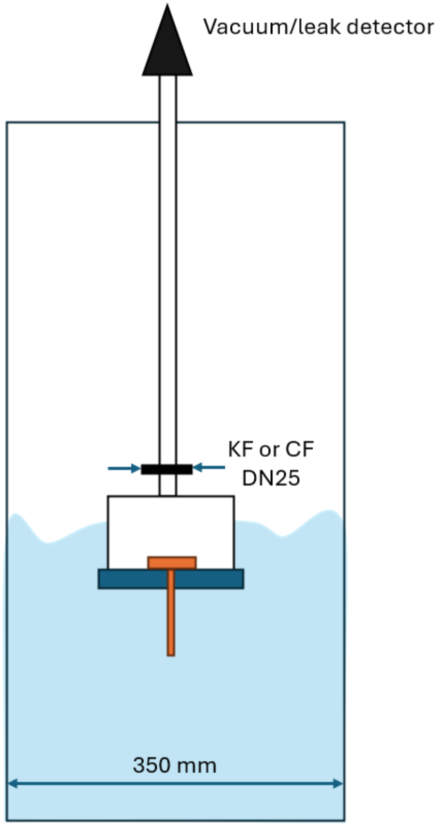
1st assembly & validation test: Sep/Oct 2024

Validation test for leak tightness at cold temperature:

At CRG cryolab:
in the 350 mm cryostat, a vacuum canister to go on the MgB_2 side of the plug – the other side directly exposed to LHe. Validation criteria pressure < 10^{-9} mbar
+
Thermal cycling in LN2 and leak test at warm or cold



Courtesy of N. Bourcey, C. Chatron (CERN TE-MSC)



Courtesy of P. Borges de Sousa, T. Koettig (CERN TE-CRG)

EESD Phase 4 – Cooling architecture

Phase 4 – 2025 Q3/Q4

Courtesy of P. Borges de Sousa, T. Koettig (CERN TE-CRG)

Source	$\dot{Q}$ at 20 K [W]	$\dot{Q}$ at 80 K [W]
Conduction through support	1.6	13
Thermal radiation	0.2	6.6
Sub-total Magnet	**1.8**	**19.6**

Test of the cooling architecture with cryocoolers in HFM test station in CRG cryolab:

- Cryocoolers
- CryoFan
- Membrane pump

Synergies with HFM WP 4.6: cryogenic study of novel cooling schemes (application for other projects like EuroSIG)

Options for cooling:

- Cold circulation high pressure supercritical fluid circulation;
- One 2-stage cryocooler + CryoFan with He circulation loop;
- One Gifford-MacMahon cryocooler for eventual test of conduction cooled current leads @ 50 K;
- Similar to baseline for SHiP.

No 4 kA electrical supply for the magnets leads available, no powering test of the magnet. The objective is to assess only the cooling architecture.

Potential for further developments

HTS version of EESD

Which cable geometry ?

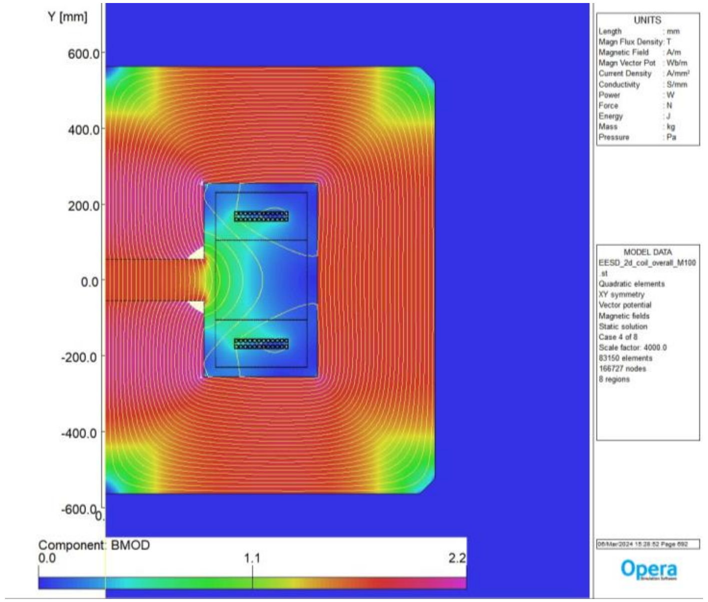
Reuse of the phase 3 yoke and cryostat?

Potential for other application than SHiP : Retro fitting of existing resistive magnets

Example: Retro fitting of a M100 resistive magnets: MBPS 01, power consumption 93 kW

Courtesy of A. Milanese
(CERN TE-MSC)

Magnetic simulations to check the feasibility of the integration of MgB_2 superconductive cable and cryostat in the M100 yoke



Full-Scale SHiP Spectrometer Magnet

Previous work on conceptual design:

- Initial design developed by P. Wertelaers and A. Perez (BE-EP) in 2019, relying on normal conducting magnets (1.2 MW electrical power consumption!);
- 1st study of superconducting options by D. Tommasini and H. Bajas (TE-MSC) in 2020 (incl., Nb−Ti, Nb_3Sn, MgB_2 and ReBCO).

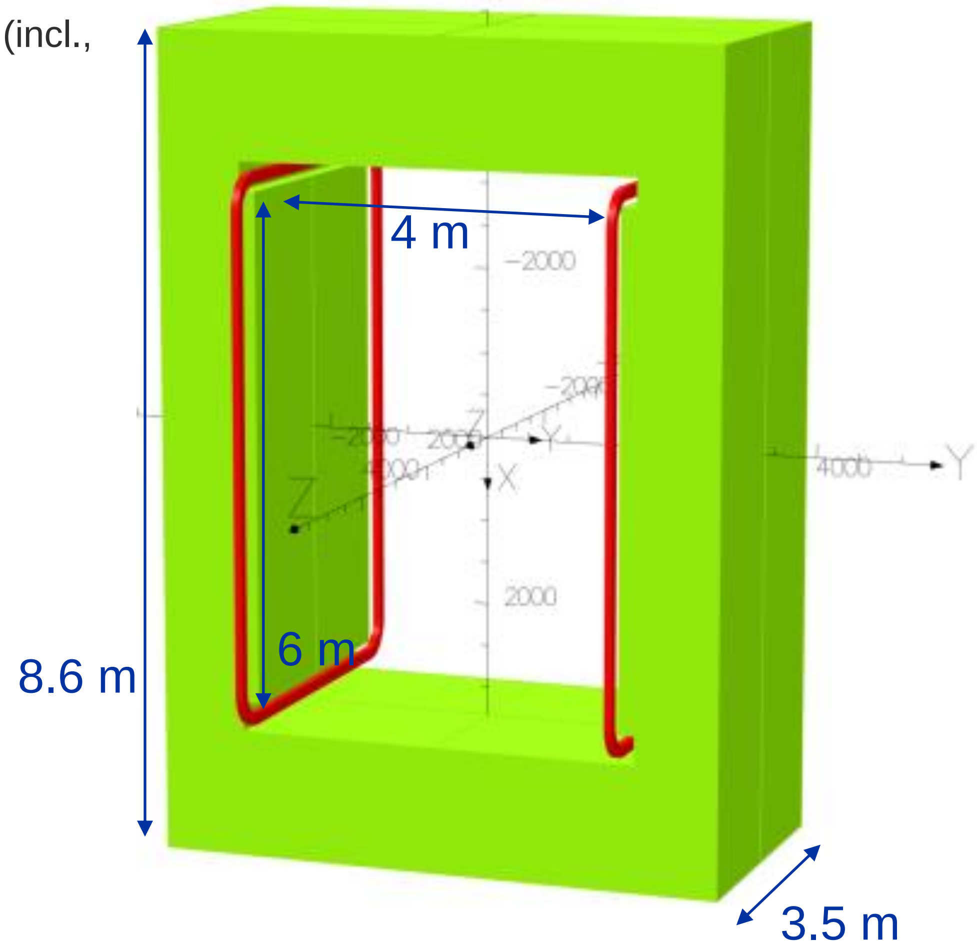
SHiP spectrometer magnet miles stone:

- CDR of SHiP spectrometer magnet Q1 2025;
- Prototype;
- TDR of SHiP spectrometer magnet Q2 2027;
- Magnet operation in SHiP in 2030.

Conceptual design of full-scale magnet has started and must include:

- Electromechanical design;
- Conceptual design of the cryostat;
- Cooling architecture;
- Current leads, “distribution box” and superconducting link between the two coils;
- Assembly procedure;
- Technical infrastructure interfaces…

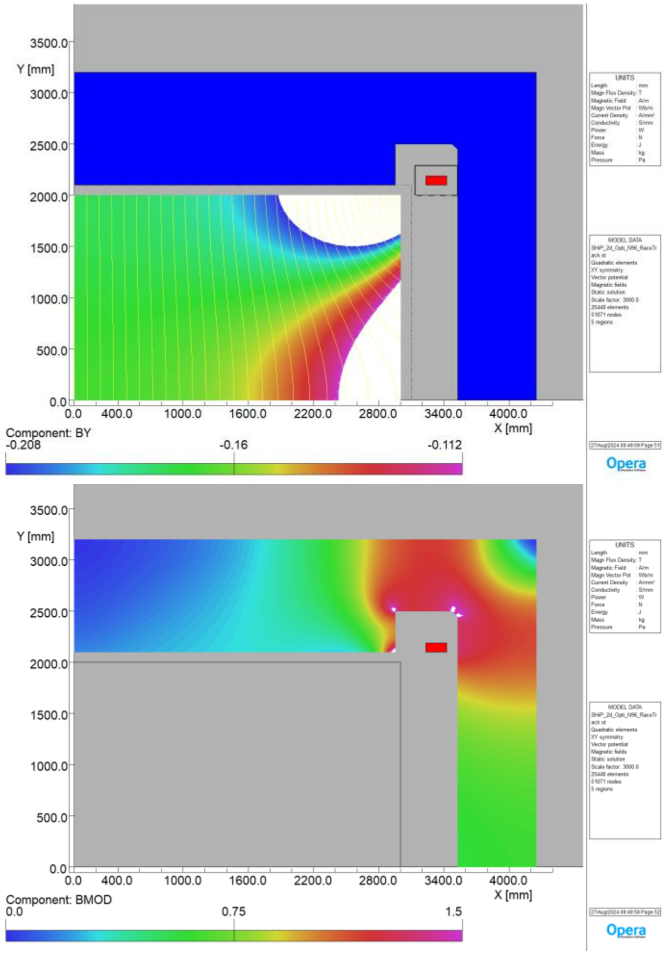
Update of the requirement
and dimension’s specifications



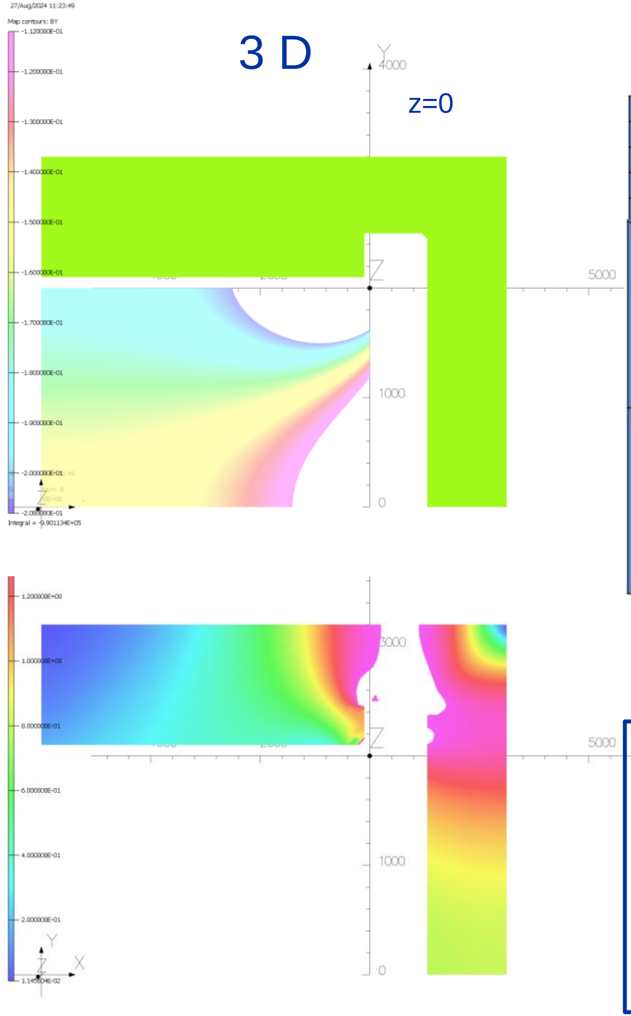
Preliminary magnetic simulations

Simulations on a reference geometry

2 D

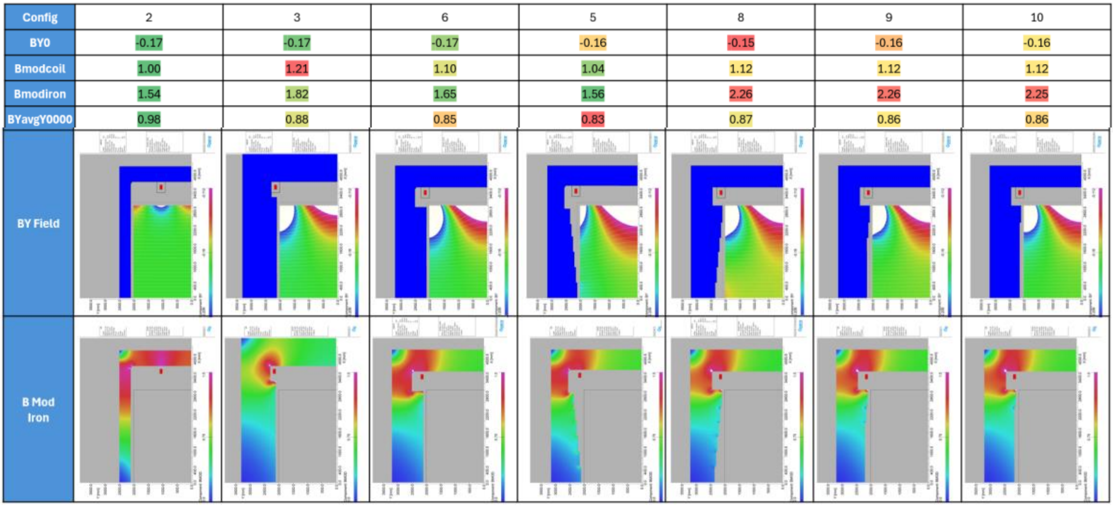


3 D



Benchmark Opera/Roxie on going

Field optimization



Config	2	3	6	5	8	9	10
BY0	-0.17	-0.17	-0.17	-0.16	-0.15	-0.16	-0.16
Bmodcoil	1.00	1.21	1.10	1.04	1.12	1.12	1.12
Bmodiron	1.54	1.82	1.65	1.56	2.26	2.26	2.25
BYavgY0000	0.98	0.88	0.85	0.83	0.87	0.86	0.86
BY Field							
B Mod Iron							

Parametric 2D simulations

Ongoing work on the electromechanical design of the full-scale magnet:

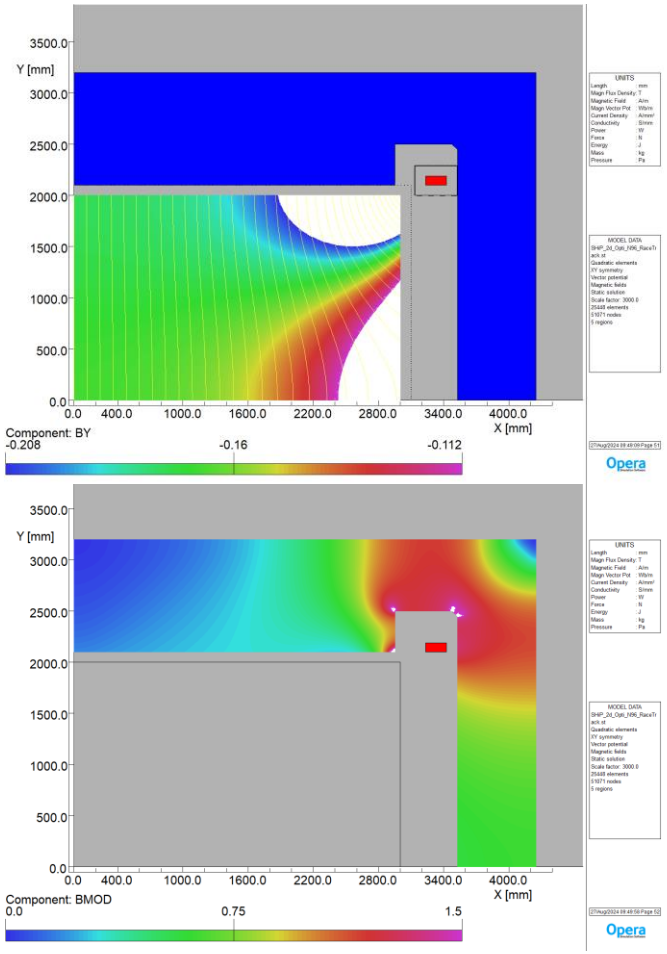
- Identification of the optimisation challenges
- First estimation of the coil’s characteristics
- First estimation of the electromechanical forces

Courtesy of S. Izquierdo Bermudez
(CERN TE-MSC)

Benchmark Opera/Roxie

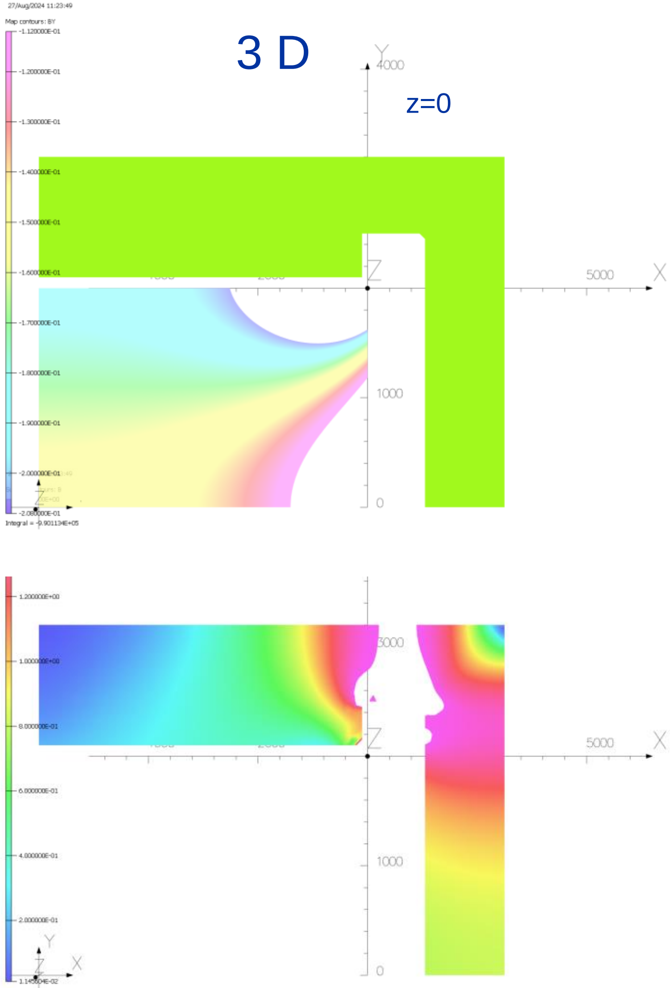
Simulations on a reference geometry

2 D

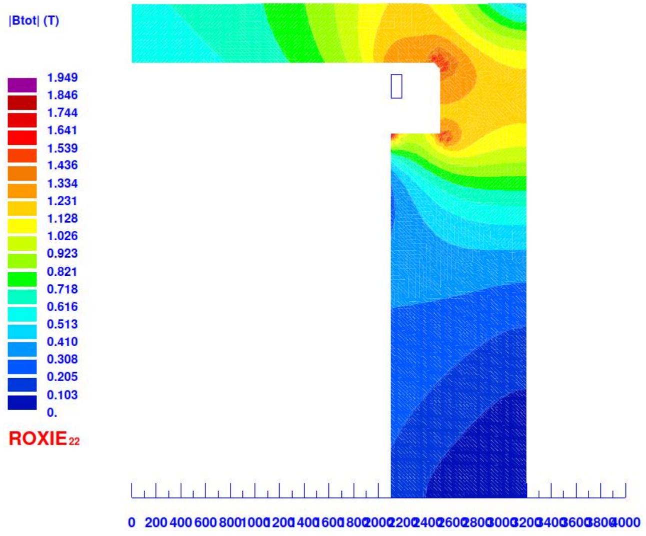


3 D

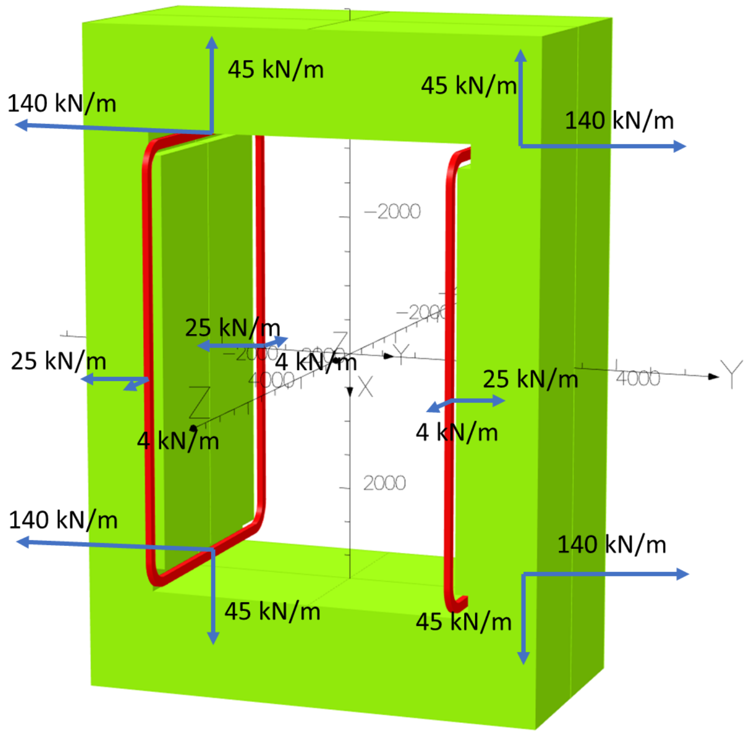
z=0



					on R=1500 mm								
	BY0 [T]	Bmod Coil [T]	Bmod Iron max [T]	Bmod Iron Z0 [T]	b3	b5	b7	Bending Field +/- 7.5m [T.m]	Bending Field +/- 2.5m [T.m]	E,stored energy [MJ]	BY Y0000 [T]	BY Y0500 [T]	BY Y1000 [T]
Roxie 3D													
Roxie 2D	0.1667	0.982	N/A	1.949	575	-223	25	N/A	N/A	N/A			
Opera 3D	-0.1539	0.9889	2.9396	1.9455	-1071	-140	-21	0.8428	0.6346	2.76	-0.1299	-0.1364	-0.156
Opera 2D	-0.1674	1.0087	N/A	2.3443	-575	-223	-24	N/A	N/A	N/A	-0.1407	-0.1452	-0.1595



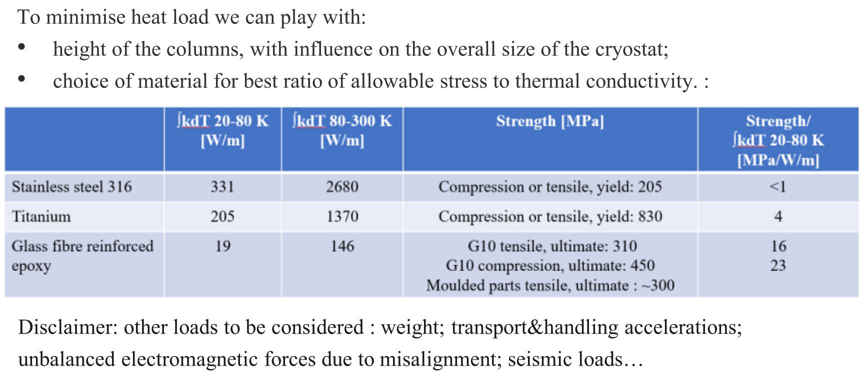
First consideration on cryostat design and coil supporting system



Total repulsive force: ~1300 kN/coil

Large coil dimensions

- Large thermal contractions, in two directions of a plan
  (thermal contraction: 24 mm aluminium coil’s former compared to the RT yoke in vertical direction)
- Large electromagnetic forces



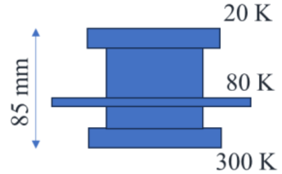
To minimise heat load we can play with:

- height of the columns, with influence on the overall size of the cryostat;
- choice of material for best ratio of allowable stress to thermal conductivity. :

	∫kdT 20-80 K [W/m]	∫kdT 80-300 K [W/m]	Strength [MPa]	Strength/ ∫kdT 20-80 K [MPa/W/m]
Stainless steel 316	331	2680	Compression or tensile, yield: 205	<1
Titanium	205	1370	Compression or tensile, yield: 830	4
Glass fibre reinforced epoxy	19	146	G10 tensile, ultimate: 310 G10 compression, ultimate: 450 Moulded parts tensile, ultimate : ~300	16 23

Disclaimer: other loads to be considered : weight; transport&handling accelerations; unbalanced electromagnetic forces due to misalignment; seismic loads…

Courtesy of D. Duarte Ramos (CERN TE-MSC)



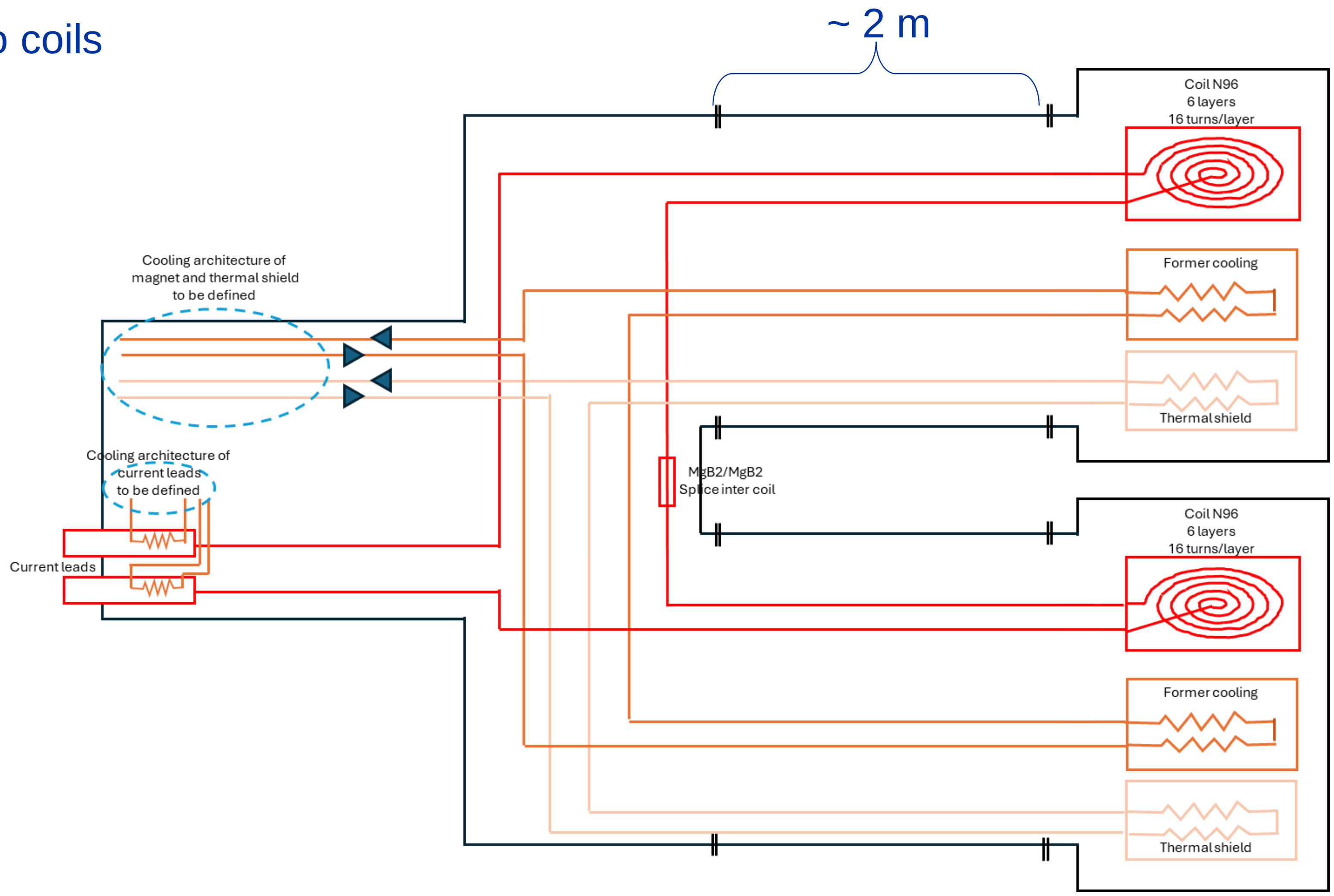
Heat load at	G10 tubes	Stainless steel
20 K level [W]	6	110
80 K level [W]	95	1700

Ongoing work on cryostat design
First estimation of the :

- space allocation for the supporting system;
- static heat load due to the supporting system of the coil.

Interconnection between coils

Same cooling circuit for the two coils
Or one cooling circuit per coil?

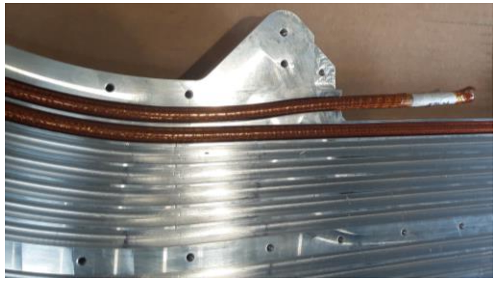


Technology development

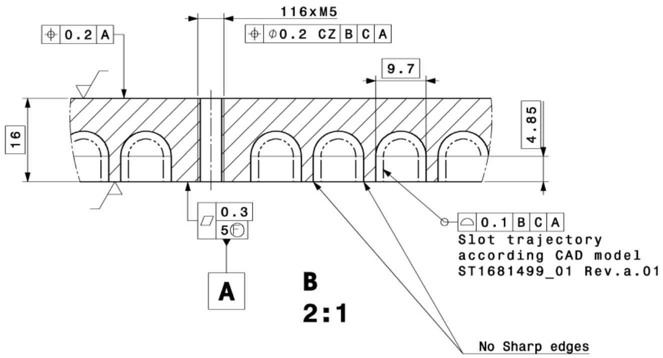
Assessment of the thermal contact resistance between the isolated MgB_2 cable and the radial plate :

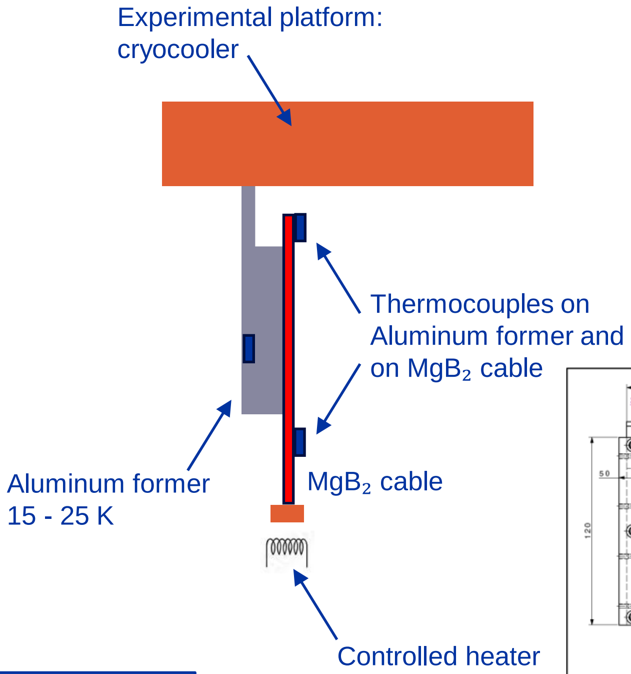
- Mechanical adjustment:
  - As build in EESD in phase 3:
    mechanical adjustment relying on differential thermal contraction and mechanical tolerances;
  - Addition of a counter former made of aluminum to increase of contact surface and contact pressure.
- Impregnation? Wet winding?
  discussions with Roland Piccin (polymer lab, CERN TE-MSC)
  - Impregnation?
  - Putty (curing in 1 day):
    - “green paste” ITER-like for the installation of TF coil case cooling pipes
    - Custom made charged epoxy for adjustment of viscosity and thermal contraction coefficient: boron-nitride (if no radiations), aluminum-nitride
  - Vacuum grease: Apiezon® like
- Isolating material for cable:
  - 2 x 55 um Kapton with tension (as build in EESD);
  - glued Kapton as LHC cable.

Tests at CRG cryolab
January 2025



Extract from former bottom plate CRNMRDEESD0005





Experimental platform: cryocooler

Thermocouples on Aluminum former and on MgB_2 cable

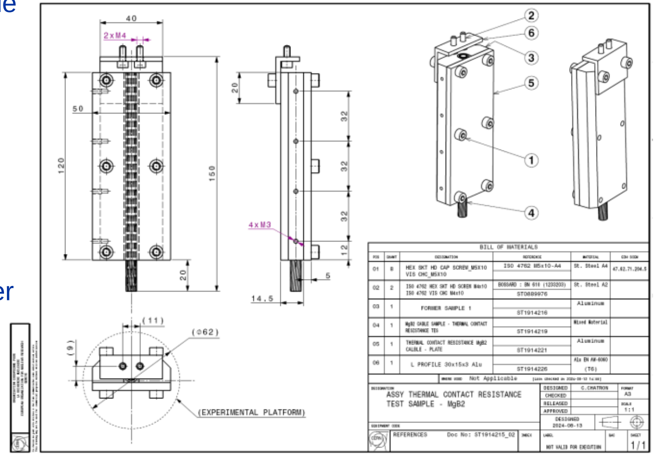
Aluminum former
15 - 25 K

MgB_2 cable

Controlled heater

Mock-up for dedicated measurement campaign

Courtesy of T. Koettig,
P. Borges de Sousa
(CERN TE-CRG)
Courtesy of N. Bourcey,
C. Chatron (CERN TE-MSC)

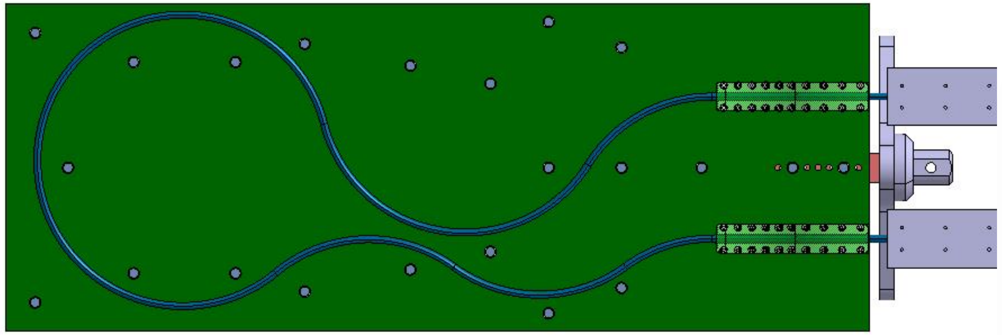


Technology development

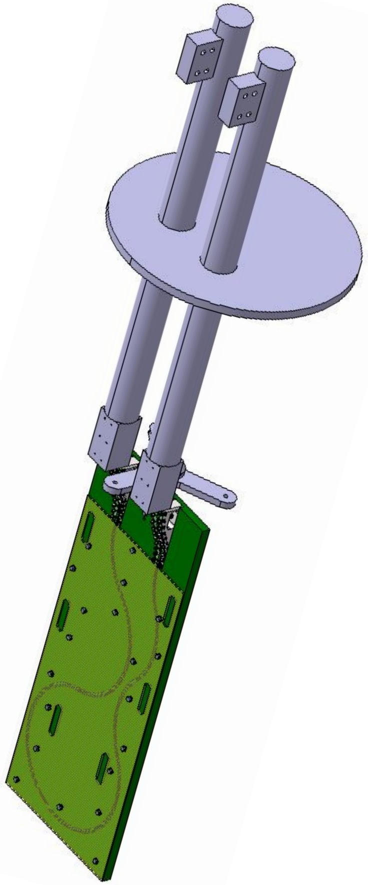
Cable test for bending radius of 200 mm

Characterizing the cable with a bending radius of 200 mm instead of the 300 mm used so far in EESD demonstrator would allow a more compact design of the SHiP spectrometer magnet coil and the routing of cables in distribution box.

Test on the Diode test station:
- at 20 K;
- without background B field.



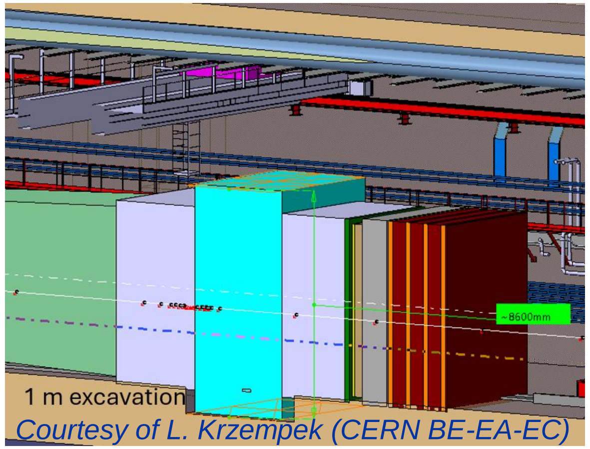
Courtesy of N. Bourcey, C. Chatron, and F. Mangiarotti
(CERN TE-MSC)



Test set-up assembly done
Test on diode test station:
Oct 2024

Technical infrastructures in ECN3

ECN3 Cavern integration



Courtesy of L. Krzempek (CERN BE-EA-EC)

Visit of ECN3 Cavern
NA62 experiment is currently operated

Constrains and requirement related to the integration:

- Civil engineering considerations: (excavation of the cavern floor, dimensions of the shaft), simplified integration model for space allocation in the ECN3 cavern
- Mechanical interfaces with other systems
  - Straw detectors
  - Decay volume Integration of vacuum chamber (reaction forces on the support i.e. the yokes) (can be down-scoped with He balloon, or even no equipment)
- Operation of electronics, and sensitive devices (detector and cryogenic equipment)

⋙ Inputs expected on:
  - Components geometry characteristics: (coil, yokes subcomponents…);
  - Assembly procedure;
  - Magnetic stray field estimation.

Power converters and electrical supply cable

Data provided:

Mainly dominated by resistance of the Cu supply cable

CIRCUIT PARAMETERS						
New Circuit Name	Magnet Type	Mode	R [Ω]	L [H]	Iop [A]	Tset [s]
Main spectrometer magnet	Super-ferric	DC	0.01	0.4	4000	30
Main spectrometer magnet (back-up option ?)	Resistive	DC	0.10	1.3	3000	30

Estimation is given :
- considering preliminary electromagnetic designs
- accounting for **100 m** of Cu supply cable, and rough estimation of the resistance in the current leads

EPC proposed:
BOREAL 4P-mini which can deliver 200 kW and 6000 Arms at output.
It means that at 4000 Arms it can provide 50 V max.

Iterations may be needed considering a more realistic value of the supply cable length and the optimised operation intensity of the spectrometer magnet.

Active exchanges and interaction with SHiP team on technical infrastructures

Open technical points

Development and optimization to be covered with a reduced-scale prototype and/or an extensive R&D/tests program:

Identified technical points :

- **Large MgB_2 coil winding;**
  - production of large-scale Aluminium former (several pieces): assembly, stiffness of the structure, mitigation of deformations
- **Coil's supporting system;**
- **Cryostat design;**
- **Yoke optimised design and assembly;**
- **Cooling architecture with cryocoolers;**
- **Design of specific current leads;**
- **Design of distribution box and link between the two coils;** (splice between coils, superconducting link (1-2 m) between the coils and the current leads)
- **Quench detection and protection;**

Attention on features of the design which should be robust enough to be built in industry (splices between double pancakes)

1/3 of full-scale size is still a large magnet! :

- ~ 0.15 T Dipole field;
- magnet aperture of 2 m x 1.5 m;
- 40-50 t yoke;
- Coils: 2.5 m x 2 m, 8 m of circumference, 400 kg each;
- 13 km of MgB_2 cable;

Constrains at building 180:

- Crane: 40 t or 2x 40 t;
- Footprint assembly area : ~ 8 m x 8 m.