Spectrometer Magnet for SHiP Experiment
-
Status

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7th March 2024

22nd EP Magnet Working Group Meeting

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

Already covered in a presentation during the
15th EP Magnet Working Group Meeting
by A. Devred on the 1st December 2023

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

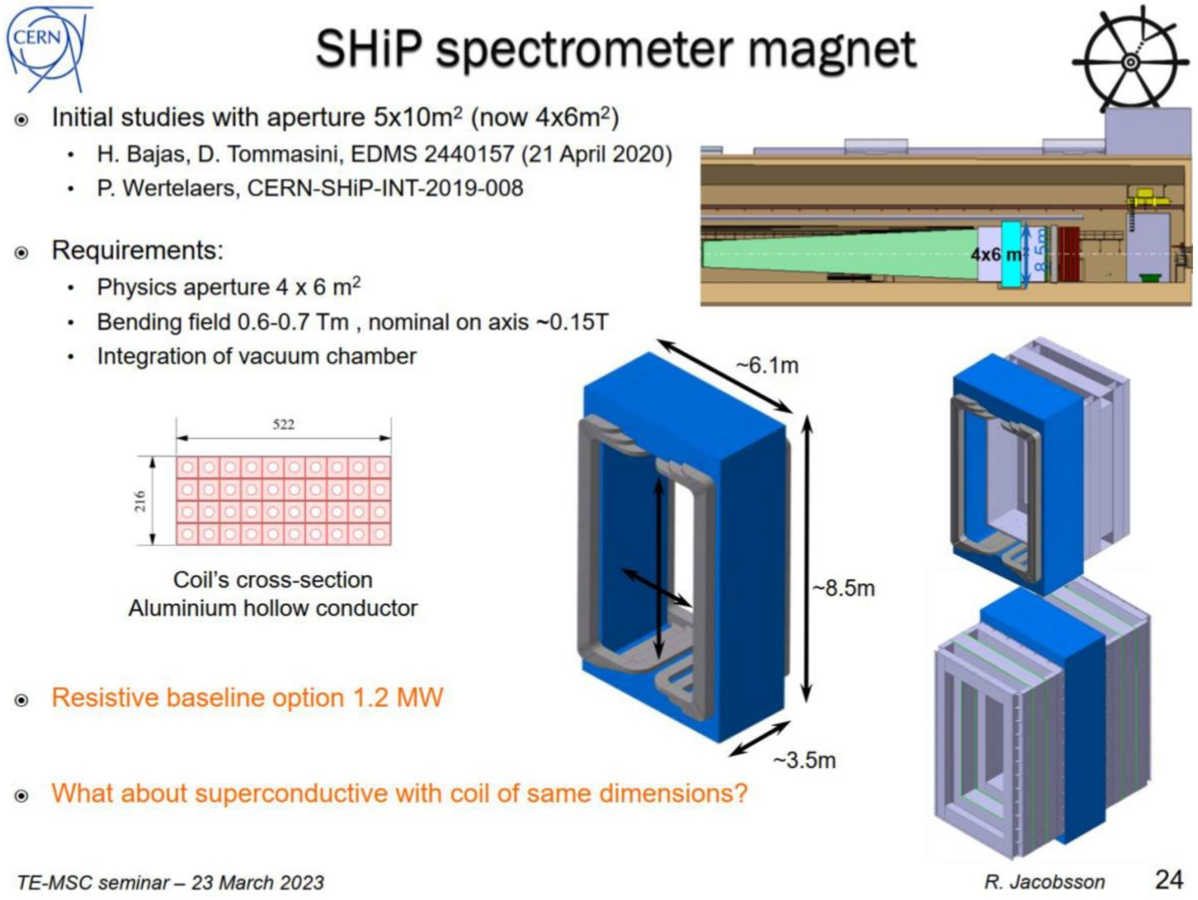
Spectrometer magnet requirements
Initial design proposals

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)

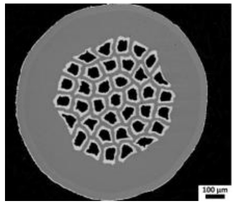
Motivations to use MgB_2 cable developed for HL-LHC WP6a

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

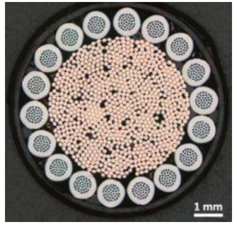
- Spectrometer magnet calls for a large number of Ampere-turns to produce a low field in a large aperture.;
- DC operation, dominated by static losses, large electrical consumption of the resistive option;
- Coil winding allowing large radii of curvature compatible with the use of MgB_2;
- Preference 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.

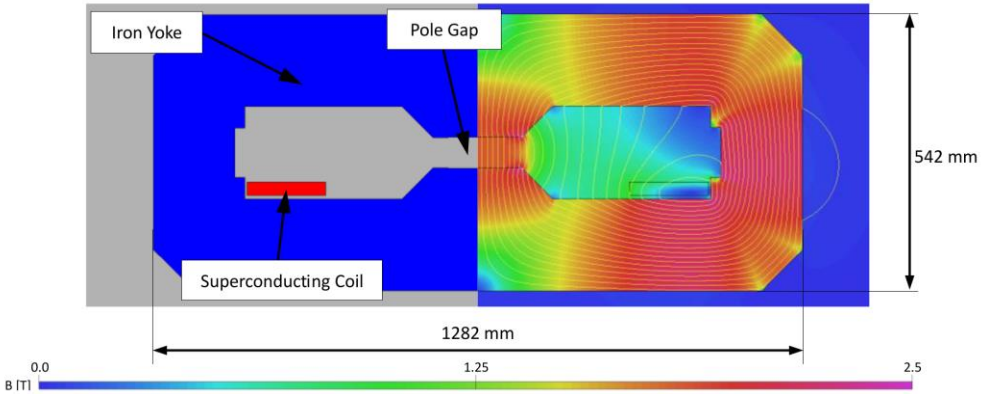
Testing Phases for Proof-of-Principle Demonstrator:

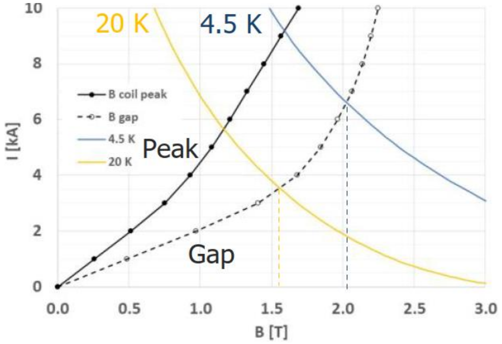
1) test in a cryogenic test station with LHe at 4.5 K;
2) test in a cryogenic test station with GHe at 20- 30 K;
3) test with warm iron and coil at 20 K in a dedicated cryostat.

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

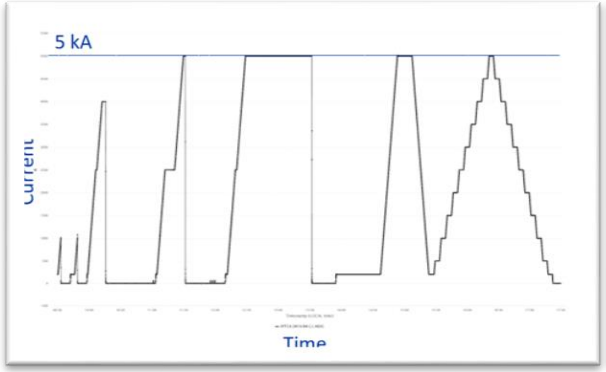
Technical specifications:

- 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)

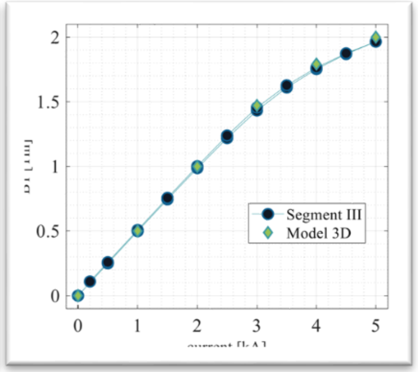
Test results:

- 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)

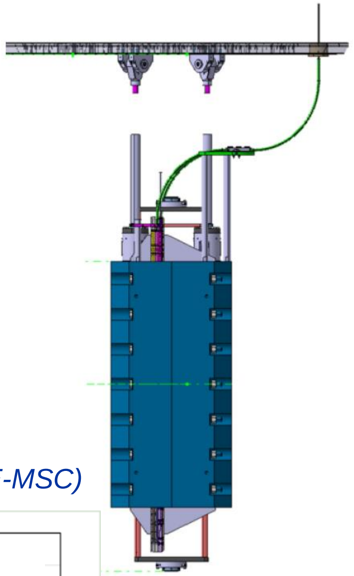
A. Devred, et al., "Proof-of-Principle of an Energy-Efficient, Iron-Dominated Electromagnet for Physics Experiments," IEEE Trans. Appl. Supercond., Vol. 34 No. 5 (2024).

Energy-Efficient Superferric Dipole: Phase 2

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

Test Results:

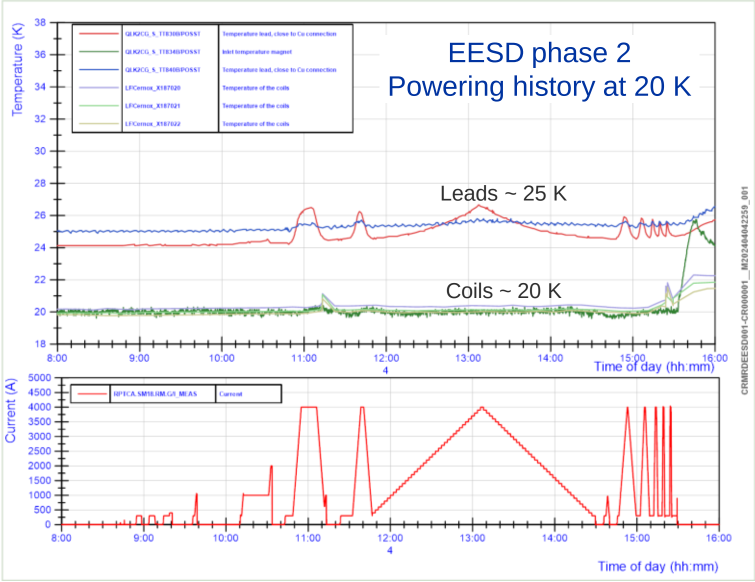
- Phase 2: Successfully carried out in gaseous helium (GHe), in January 2024.
  - Technical challenge:
    Adaptation of the HFM test station to manage a stable cryogenic operation
  - Initial Cooling:
    Cooled down to 4.5 K to reestablish previously achieved performances
  - Incremental Warming and 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).



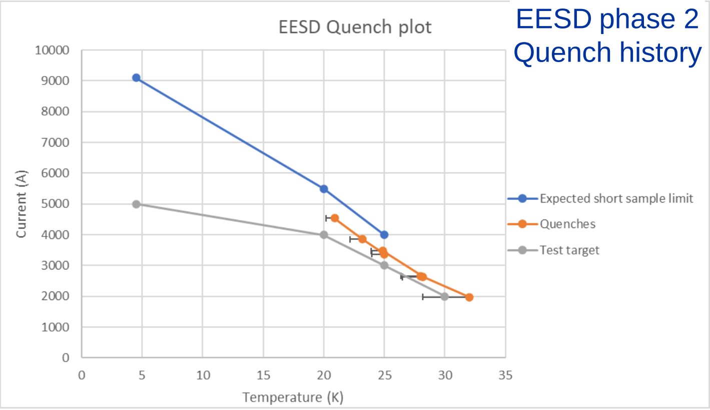
Reassembly of EESD demonstrator for Phase 2

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

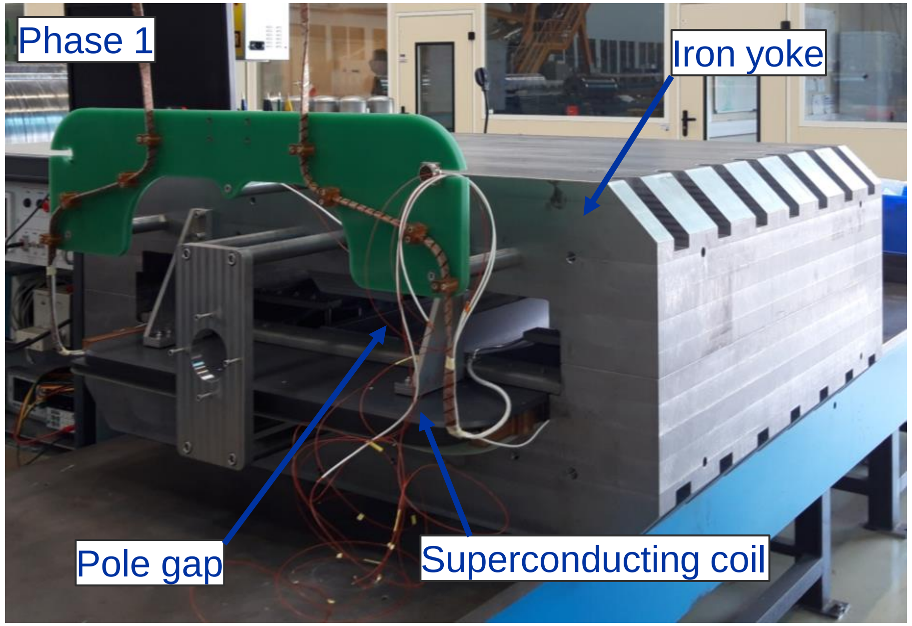


EESD phase 2
Quench history

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

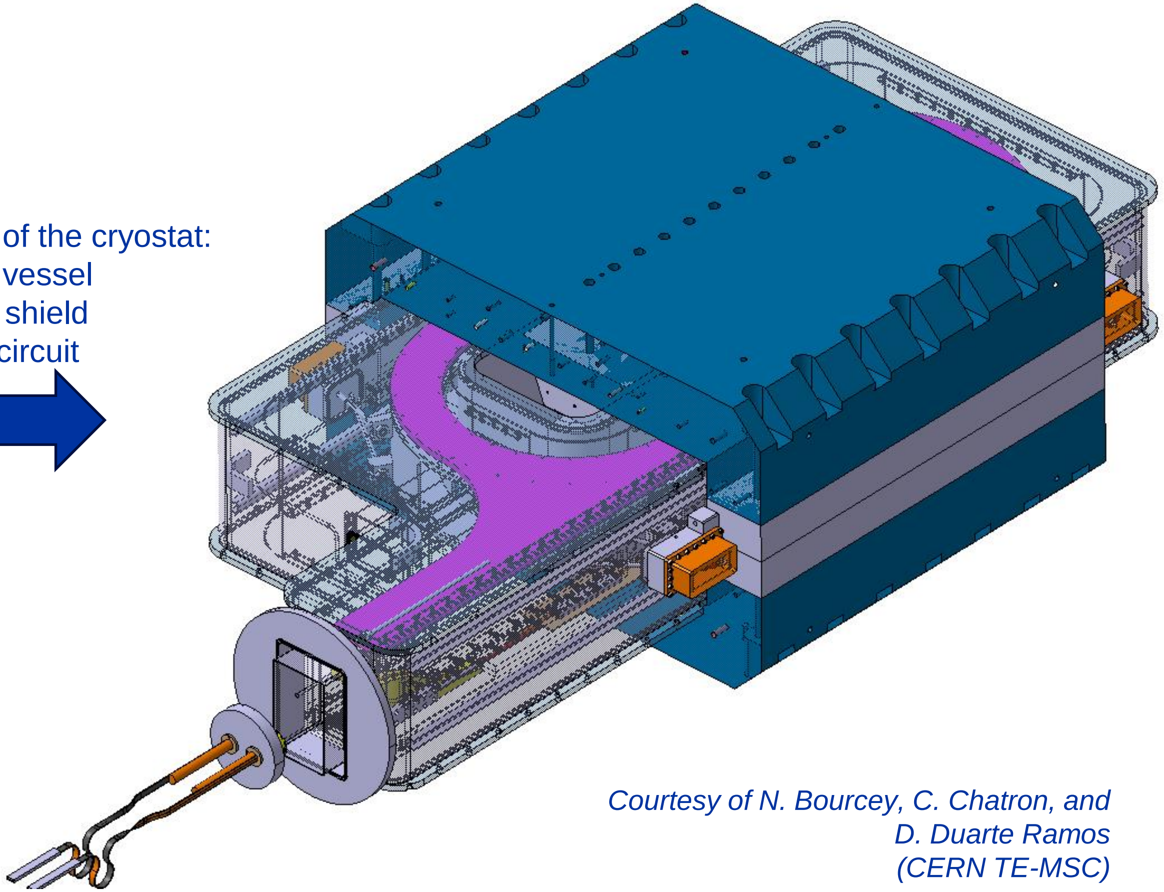
Objective:

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:

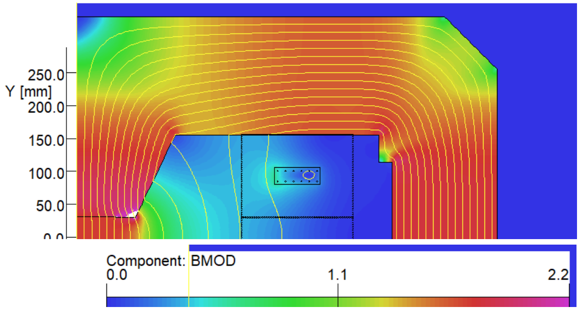
Main design concepts/parameters are:

- 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 K.

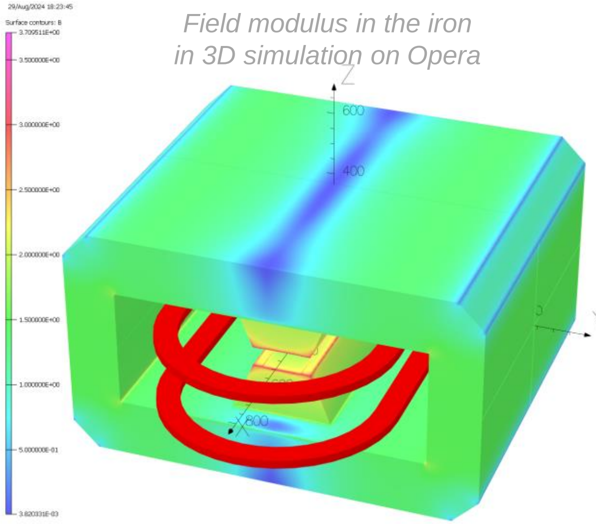
- 2 symmetric Racetrack-type coils :
  - Optimization of cryostat design
  - Lorentz loads transfer
  - Decrease of the peak field

Analysis are done
MSC Technical Note EDMS 3212397

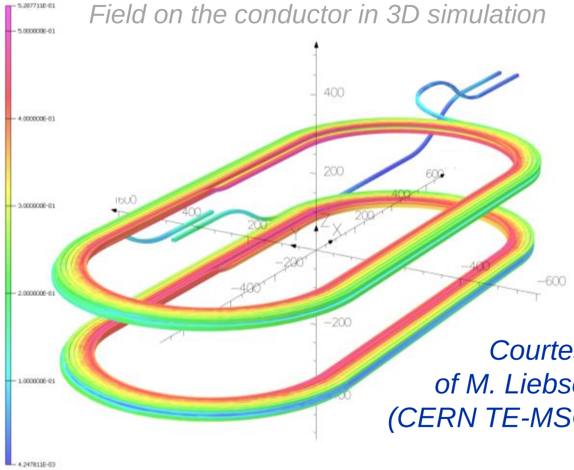
Field map and potential lines in 2D simulation on Opera



Field modulus in the iron in 3D simulation on Opera

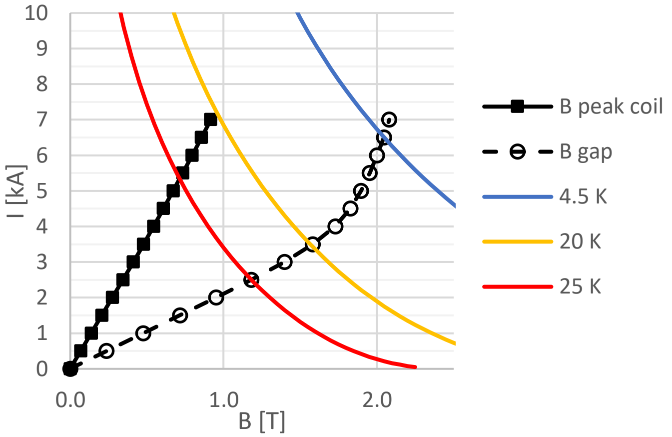


Field on the conductor in 3D simulation



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

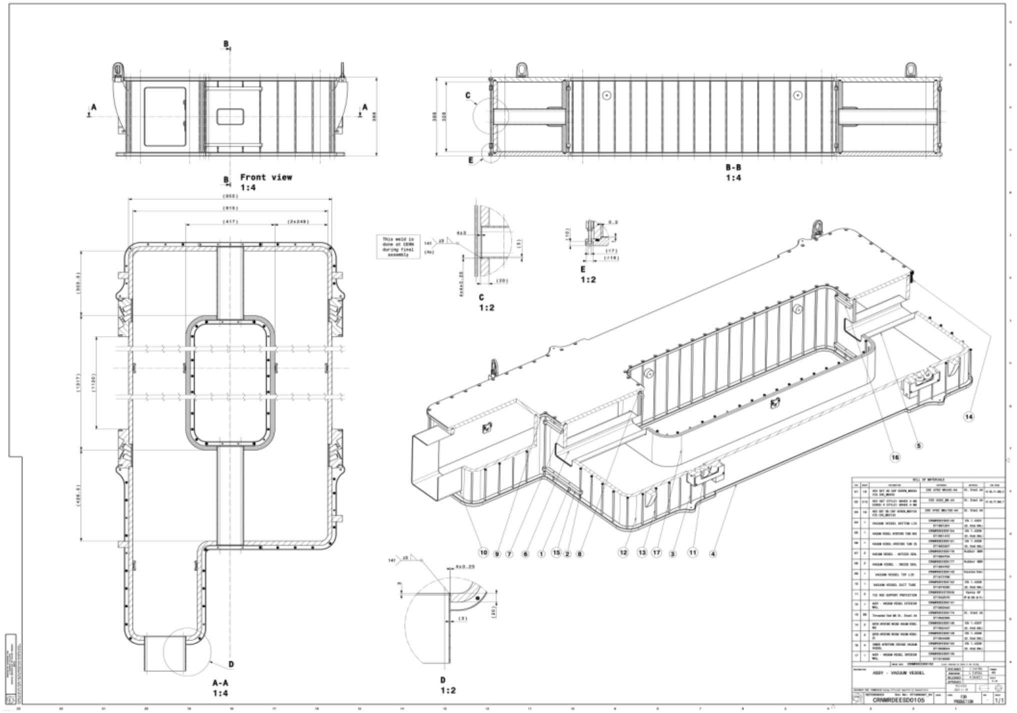


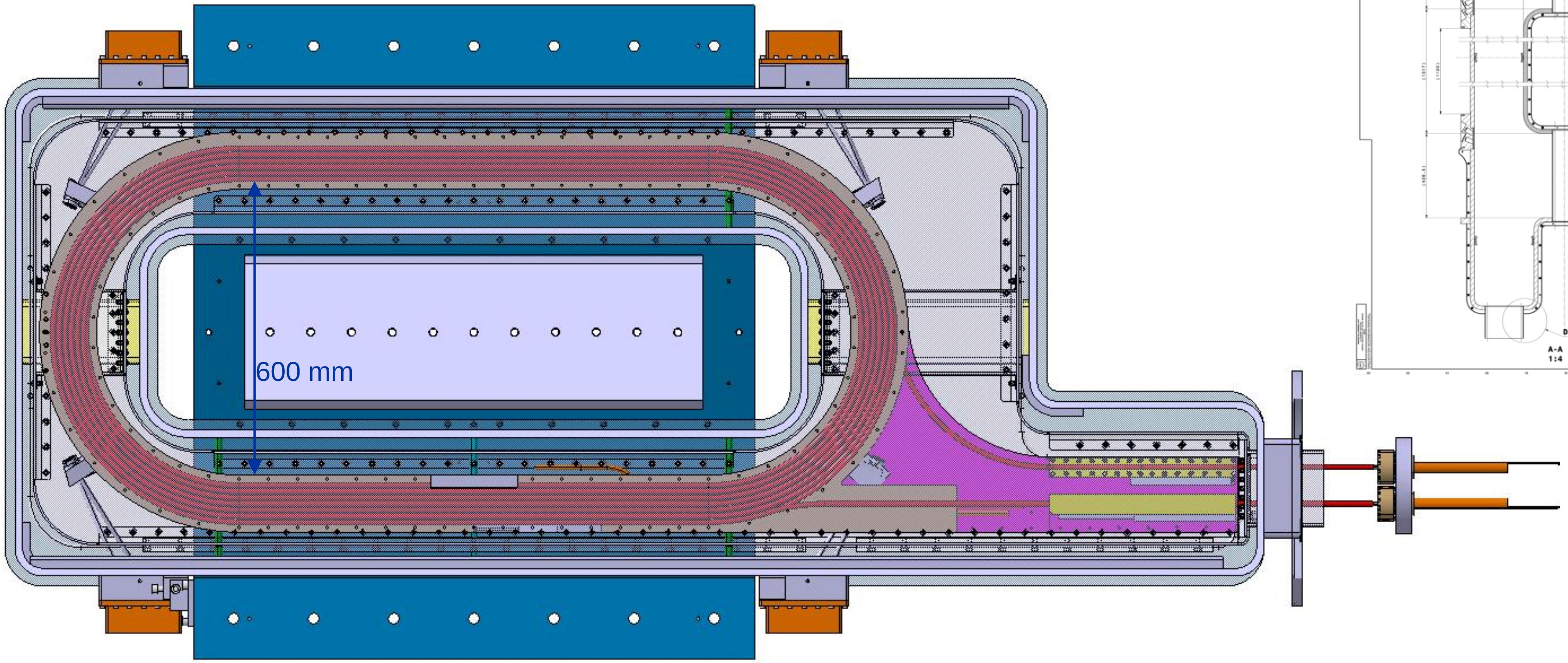
Energy-Efficient Superferric Dipole: Phase 3
Indirect cooling of the coils at 20 K

Mechanical design:

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

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





Manufacturing ongoing
Assembly planed for Q3 2025

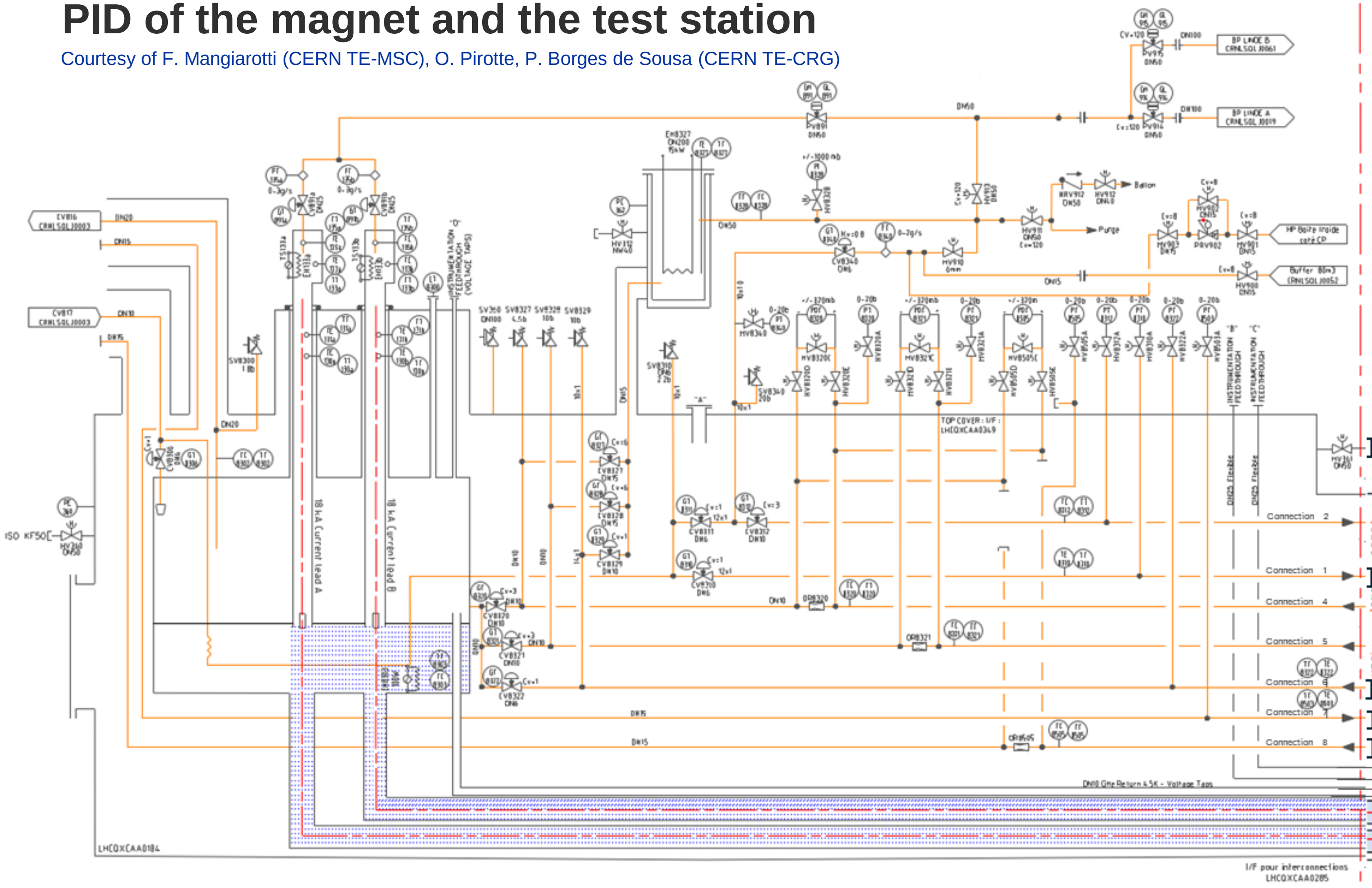
Courtesy of N. Bourcey, C. Chatron, and D. Duarte Ramos (CERN TE-MSC)

EESD Phase 3

Interconnection assembly
Connection to Cluster G
Test of EESD phase 3 Q4 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)

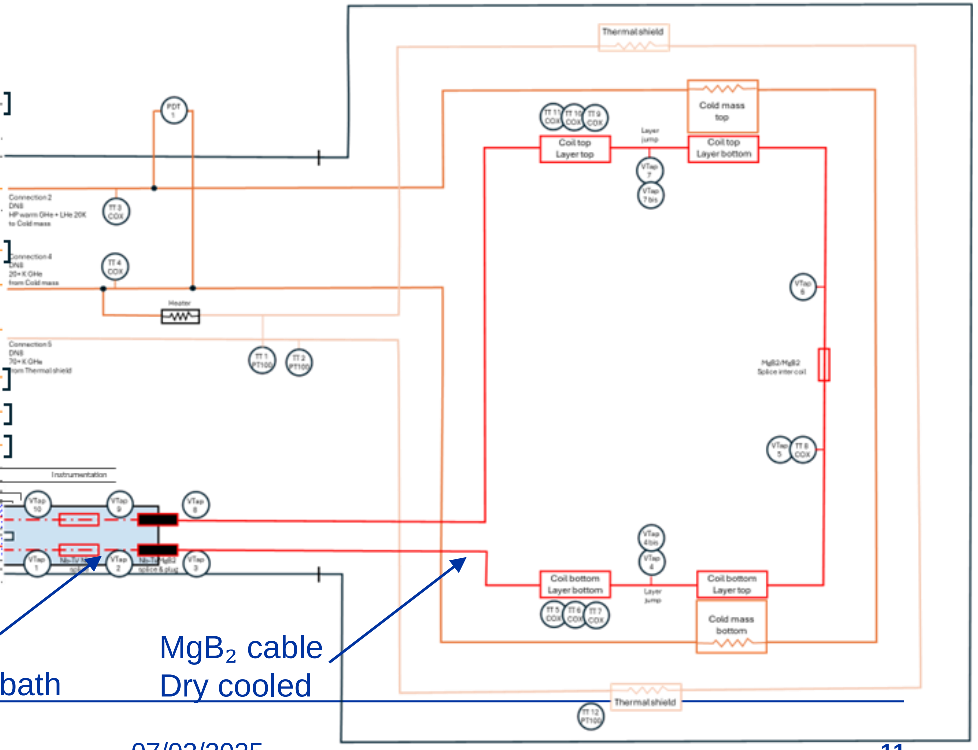


Test station in SM18: Cluster G
(Nota: optimization of cooling architecture of the coils and current leads by cryocoolers won’t be assessed by the demonstrator)

<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

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 by Q4 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:

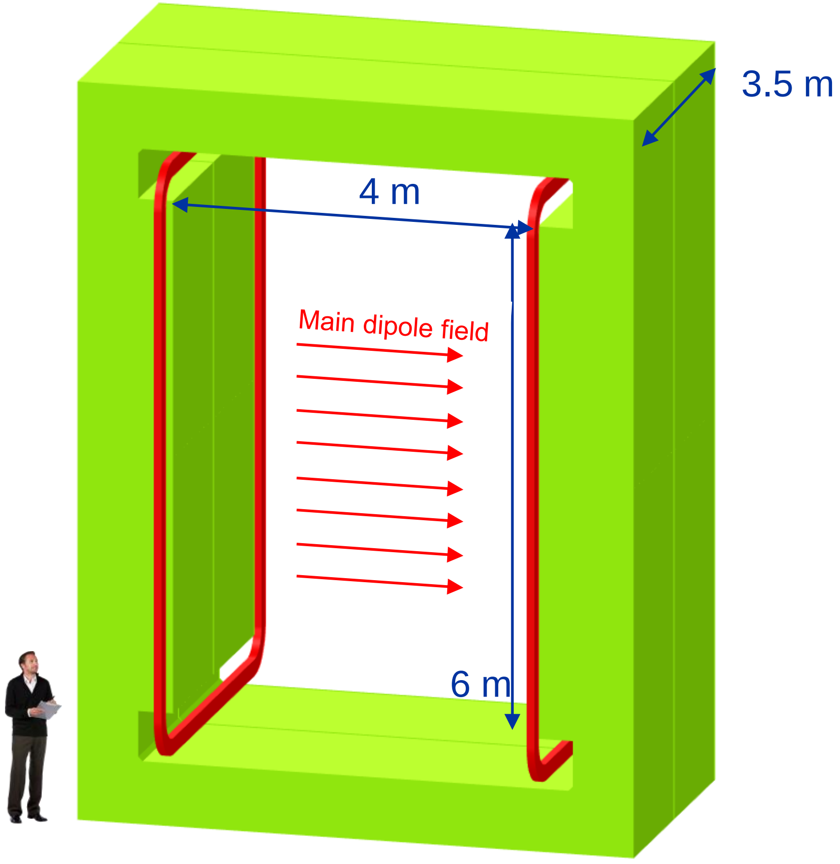
- Superferic = iron dominated magnet;
- H-type iron yoke;
- 2 symmetric coils;
- Double-pancake, racetrack-type coils = flat coils;
- Pole gap: 6000 x 4000 mm;
- Target central field: 0.15 T at 3 kA and 20 K.

Requirements for physics point of view :

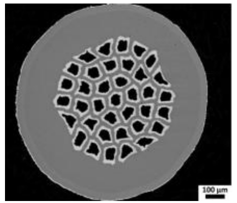
- Integrated field strength;
- Field homogeneity;
- Time stability.

Conceptual design of the magnet has started and must include:

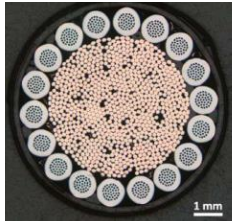
- Electromagnetic design;
- Conceptual and mechanical design of the coil's structure and the cryostat;
- Cooling architecture;
- Current leads, "cryogenics satellite" and superconducting link between the two coils;
- Assembly procedure;
- Technical infrastructure interfaces…



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)

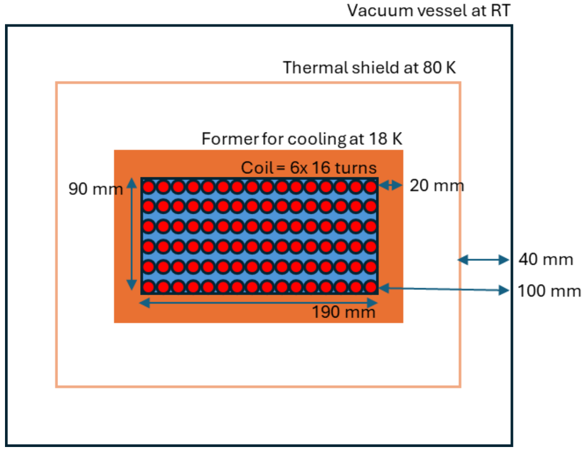
Courtesy of A. Ballarino (CERN TE-MSC)

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 unit 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

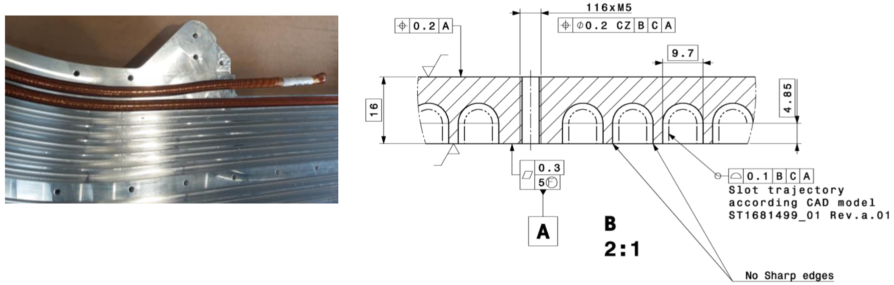


Schematic cross section of the coil and the cryostat

Coil:

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

Extract from former bottom plate drawing CRNMRDEESD0005



Cryostat:

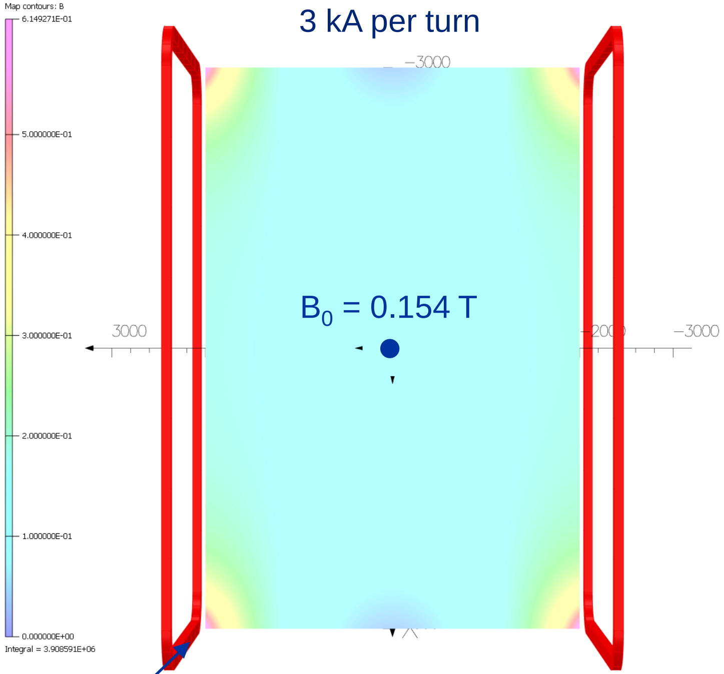
- One coil per cryostat (different to EESD/FCM);
- Thermal shield and vacuum vessel like “rigid” cryostat (similar to EESD/FCM).

Inputs for electromagnetic simulations
Static heat loads computations

Preliminary electromagnetic design

Magnetic simulations and output on baseline geometry

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



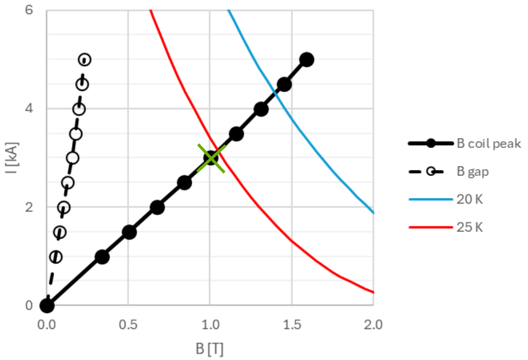
B_0 = 0.154 T

B_p = 1 T

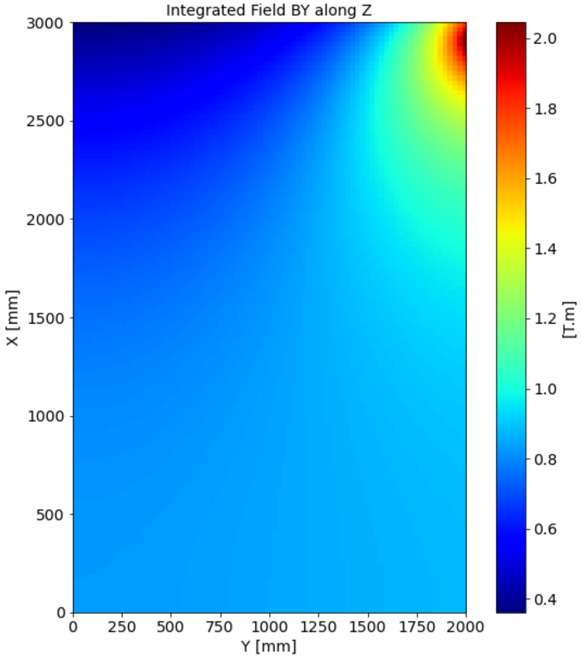
Int *B.dl* [-2.5 m; 2.5m] = 0.630 T.m
Stored energy: ~ 2.75 MJ

Main parameters of the electromagnet design proposed as V01 in EDMS 3168589

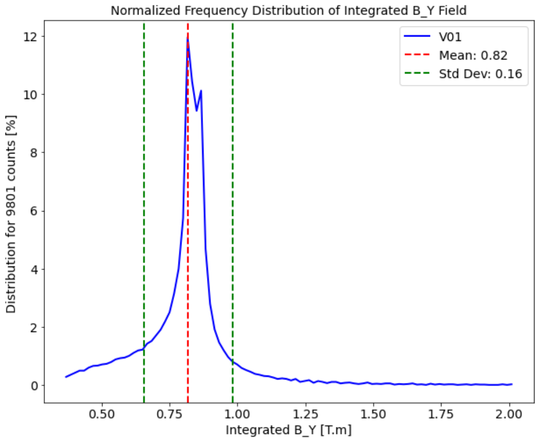
Operating point:
B_{op} = 1 T
I_{op} = 3 kA
28% margin on load line
Temperature margin: 6 K



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



Integrated field on the longitudinal direction on the top right quadrant of the spectrometer magnet aperture
Electromechanical design V01



Histogram of the integrated field on the longitudinal direction
Electromechanical design V01

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

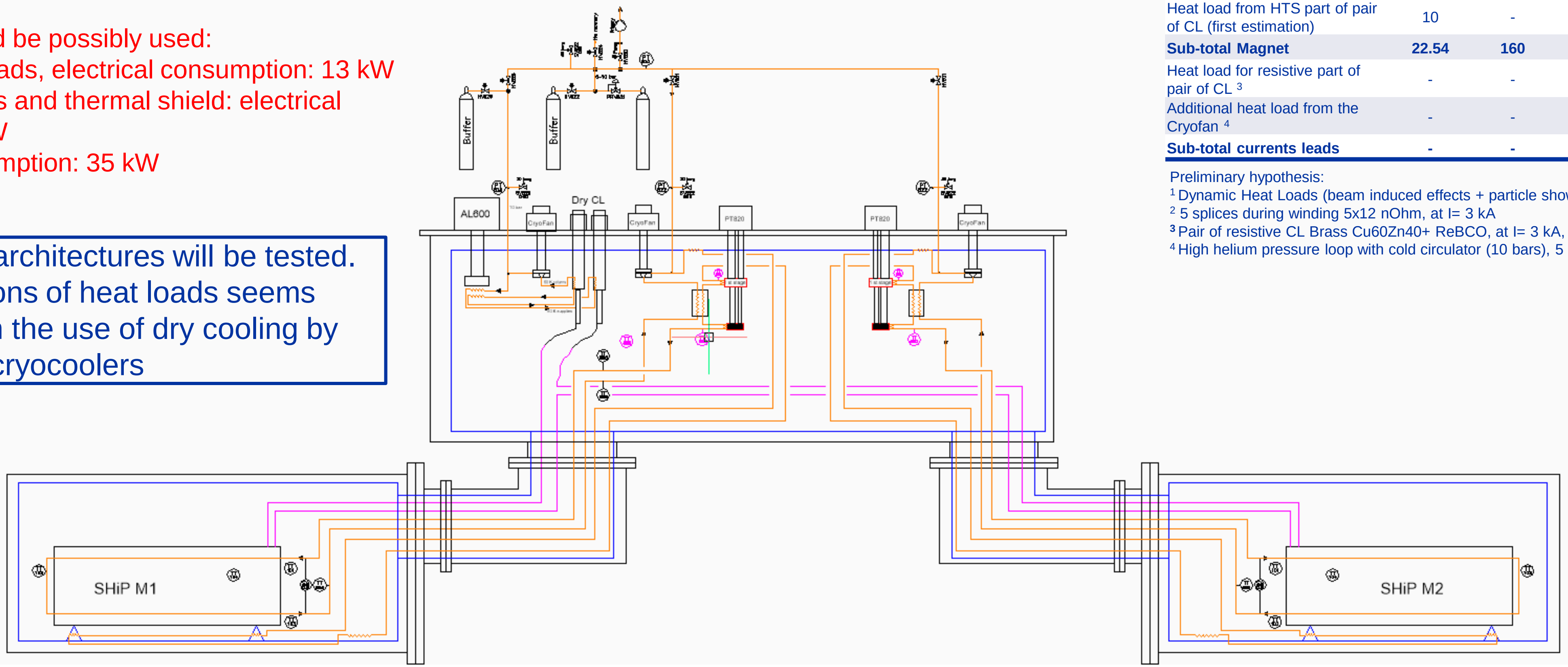
Cryogenic study of novel cooling schemes: Updated values

Two separate circuits: Current leads & magnet
Highly efficient heat exchangers with fluid circulation loop cooling are being developed to cool down the current leads

Requirements for temperature of the magnet coldmass: 18 K
(to keep a margin on the temperature of the cable expecting a gradient on such large coil)

Cryocoolers that could be possibly used:
1 AL600 for current leads, electrical consumption: 13 kW
2 PT840 for cold mass and thermal shield: electrical consumption: 2x11 kW
Total electricity consumption: 35 kW

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



Source [1]	$\dot{Q}$ at 18 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]	0.54	-	-
Heat load from HTS part of pair of CL (first estimation)	10	-	-
Sub-total Magnet	**22.54**	**160**	**-**
Heat load for resistive part of pair of CL [3]	-	-	245
Additional heat load from the Cryofan [4]	-	-	30
Sub-total currents leads	**-**	**-**	**275**

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

Technical infrastructures

Preliminary consideration for assembly, transport and integration in ECN3

Direction of insertion of longitudinal TiRods

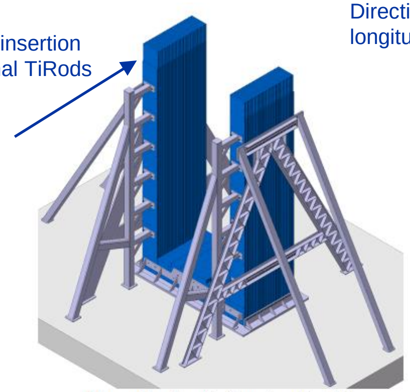


Figure 55 – Step 10 : Grow the entire "U".

Direction of insertion of longitudinal TiRods

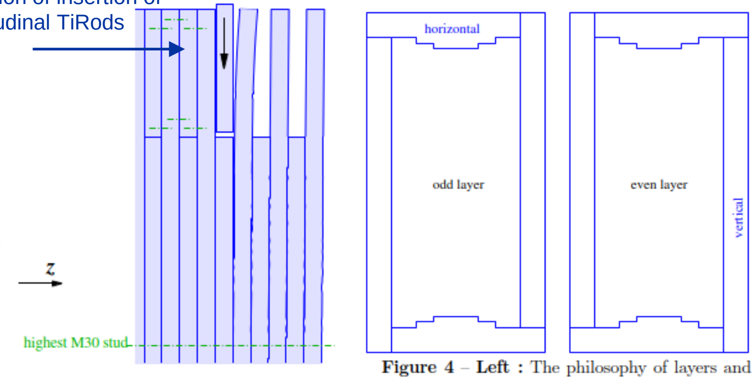
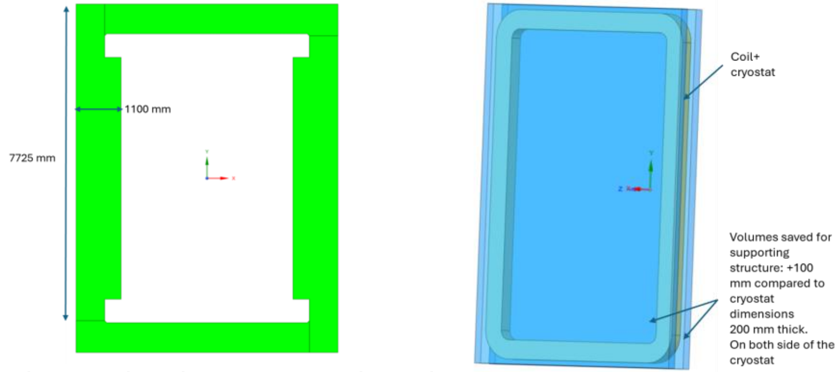


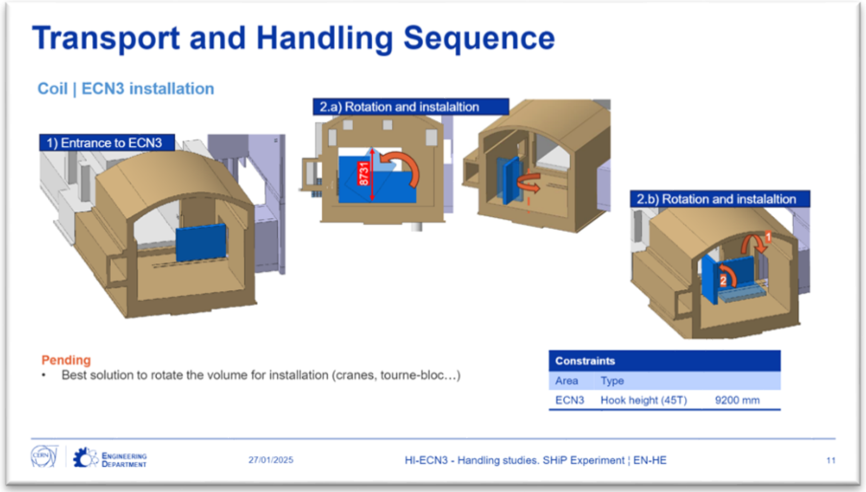
Figure 4 – **Left :** The philosophy of layers and sheets.

3D model view of the yoke during its assembly & schematic views of the yoke plate assembly
Courtesy of P. Wertelaers and A. Perez (EP-DT) in 2019, CERN-SHiP-INT-2019-008



Update on the plate geometry based on the V01 electromagnetic design

Status of 19/02/2025 Courtesy of HI-ECN3 WP4 – SHiP Experiment
C. Duran Gutierrez, R. Rinaldesi (EN-HE)



Transport and Handling Sequence

Coil | ECN3 installation

Pending

- Best solution to rotate the volume for installation (cranes, tourne-bloc…)

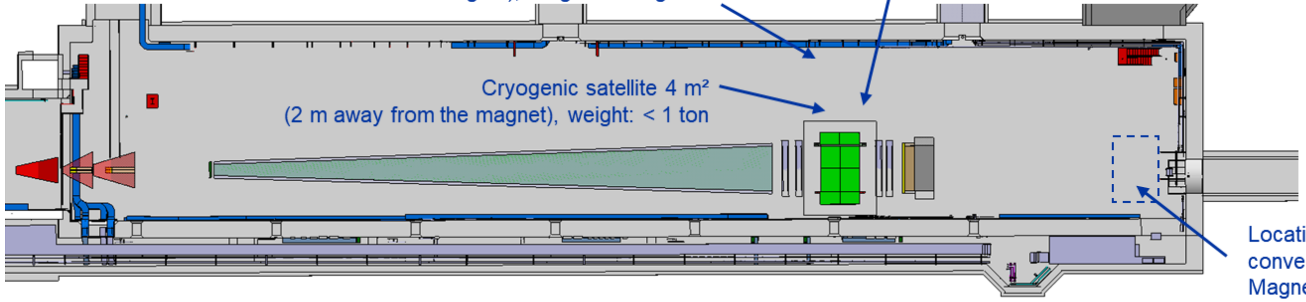
Constraints		
Area	Type	
ECN3	Hook height (45T)	9200 mm

27/01/2025 HI-ECN3 - Handling studies. SHiP Experiment ¦ EN-HE 11

Compressors 3 m²
3 compressors (10 m away from the satellite box, 15-20 m from the magnet), weight: 190 kg each

Point to connect the DC supply cable to the current leads and cryogenic satellite

Cryogenic satellite 4 m²
(2 m away from the magnet), weight: < 1 ton



Location for power converter spectrometer Magnet ?

Construction strategy – first thoughts

Technology and Practical Feasibility

We are confident in our ability to manufacture the coil and magnet, benefiting from the knowledge, expertise, and support from CERN's teams (MSC, EP experts, MME, Transport).

Participation from industry in the engineering design phase, including development of dedicated tooling, can be an option

Key Next Steps: Identify a suitable location for:

- Coil winding
- Cryostat assembly
- Test bench installation
- Preassembly of the full-scale system at the surface

Qualification campaign and production of the full-scale will be done at CERN

Winding machine operated in building 181, by TE/MSC-NCM, for the manufacturing of the resistive coils of the SPS MBB magnets (coil are 6.5 m long)

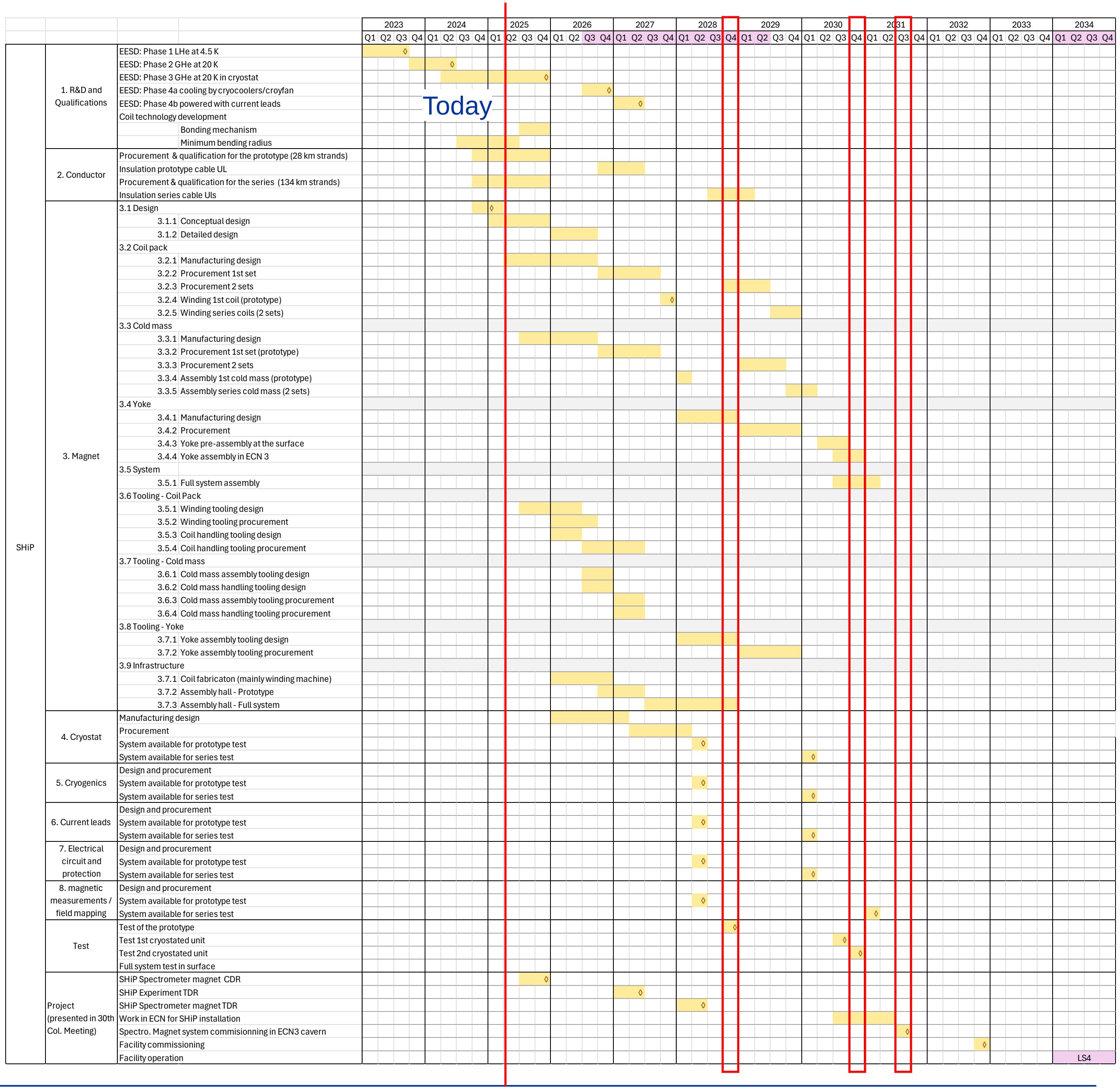
Tentative timeline

Key milestones:

- Test of the prototype coil: Q4 2028
- Test of the series coils Q4 2030
- System commissioning in the ECN3 cavern: Q3 2031

No time to lose: engineering design to start spring 2025 (i.e., main parameters must be fixed Q2 2025)

High co activities with HL-LHC installation during LS3 for most of the teams involved in SHiP project



SHiP	1. R&D and Qualifications	EESD: Phase 1 LHe at 4.5 K	
		EESD: Phase 2 GHe at 20 K	
		EESD: Phase 3 GHe at 20 K in cryostat	
		EESD: Phase 4a cooling by cryocoolers/croyfan	
		EESD: Phase 4b powered with current leads	
		Coil technology development	
			Bonding mechanism
			Minimum bending radius
	2. Conductor	Procurement & qualification for the prototype (28 km strands)	
		Insulation prototype cable UL	
		Procurement & qualification for the series (134 km strands)	
		Insulation series cable Uls	
	3. Magnet	3.1 Design	
		3.1.1	Conceptual design
		3.1.2	Detailed design
		3.2 Coil pack	
		3.2.1	Manufacturing design
		3.2.2	Procurement 1st set
		3.2.3	Procurement 2 sets
		3.2.4	Winding 1st coil (prototype)
		3.2.5	Winding series coils (2 sets)
		3.3 Cold mass	
		3.3.1	Manufacturing design
		3.3.2	Procurement 1st set (prototype)
		3.3.3	Procurement 2 sets
		3.3.4	Assembly 1st cold mass (prototype)
		3.3.5	Assembly series cold mass (2 sets)
		3.4 Yoke	
		3.4.1	Manufacturing design
		3.4.2	Procurement
		3.4.3	Yoke pre-assembly at the surface
		3.4.4	Yoke assembly in ECN 3
		3.5 System	
		3.5.1	Full system assembly
		3.6 Tooling - Coil Pack	
		3.5.1	Winding tooling design
		3.5.2	Winding tooling procurement
		3.5.3	Coil handling tooling design
		3.5.4	Coil handling tooling procurement
		3.7 Tooling - Cold mass	
		3.6.1	Cold mass assembly tooling design
		3.6.2	Cold mass handling tooling design
		3.6.3	Cold mass assembly tooling procurement
		3.6.4	Cold mass handling tooling procurement
		3.8 Tooling - Yoke	
		3.7.1	Yoke assembly tooling design
		3.7.2	Yoke assembly tooling procurement
		3.9 Infrastructure	
		3.7.1	Coil fabricaton (mainly winding machine)
		3.7.2	Assembly hall - Prototype
		3.7.3	Assembly hall - Full system
	4. Cryostat	Manufacturing design	
		Procurement	
		System available for prototype test	
		System available for series test	
	5. Cryogenics	Design and procurement	
		System available for prototype test	
		System available for series test	
	6. Current leads	Design and procurement	
		System available for prototype test	
		System available for series test	
	7. Electrical circuit and protection	Design and procurement	
		System available for prototype test	
		System available for series test	
	8. magnetic measurements / field mapping	Design and procurement	
		System available for prototype test	
		System available for series test	
	Test	Test of the prototype	
		Test 1st cryostated unit	
		Test 2nd cryostated unit	
		Full system test in surface	
	Project (presented in 30th Col. Meeting)	SHiP Spectrometer magnet CDR	
		SHiP Experiment TDR	
		SHiP Spectrometer magnet TDR	
		Work in ECN for SHiP installation	
		Spectro. Magnet system commisionning in ECN3 cavern	
		Facility commissioning	
		Facility operation	

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 Q3 2031

home.cern

Comparison with resistive option

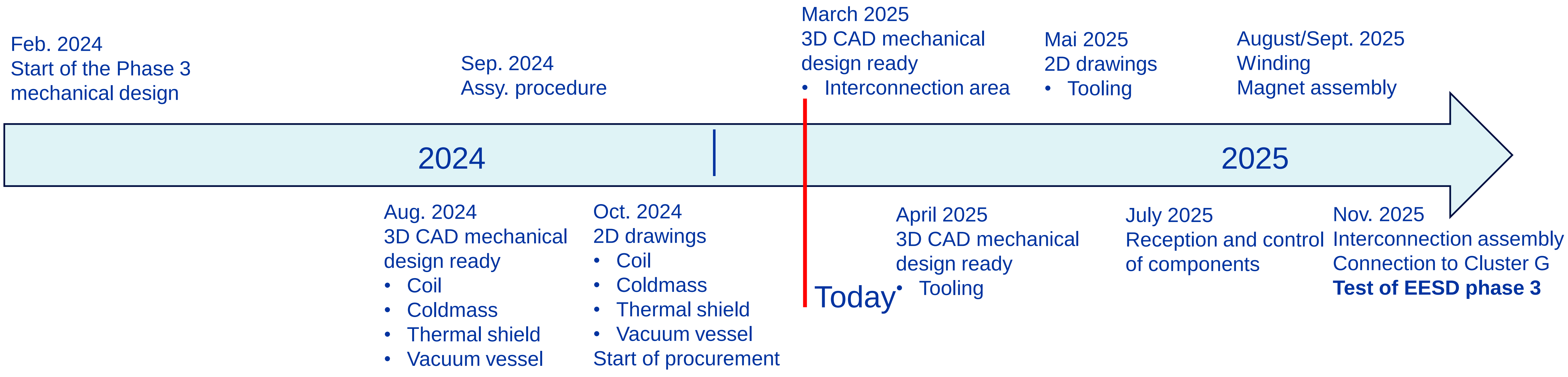
Initial cost vs operation cost

Component	Cost of MgB_2 option [kCHF]	Cost of Normal conductive
Conductor	908	125 (for aluminium)
Coil pack	660	
Vacuum vessel	1200	
Cryo-satelitte	515	
Quench protection	200	
Cooling		100
Power convertor		+100
Initial extra-cost	**3483**	**425**
Electricity consumption	40	650
Cost of electricity for one month operation (140CHF/MWh)	4	66

The initial extra cost of the Superconducting MgB_2 option is compensated after 50 months of operation

F. Savary, et al. / 32nd SHiP Collaboration Meeting / SHiP Spectrometer Magnet Status 13/03/2025 22

Timeline for EESD demonstrator Phase 3



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

March 2025
3D CAD mechanical design ready
- Interconnection area

April 2025
3D CAD mechanical design ready
- Tooling

Mai 2025
2D drawings
- Tooling

July 2025
Reception and control of components

August/Sept. 2025
Winding
Magnet assembly

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

Validation of the technology choice Q4 2025:
- use of MgB_2 cable developed for WP6a
- winding in grooves machined in a radial plate
- cooled by indirect cooling

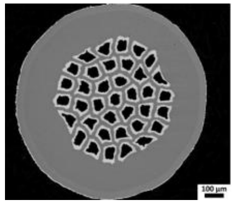
Procurement of MgB_2 strands

Estimation of the cable and strands needs for the project based on conceptual electromagnetic design V01:

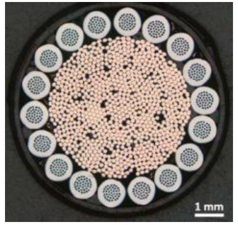
Hypothesis for the calculation of the cable unit length:

- Estimation of cable length for one coil based on current 3D magnetic simulations: 2200 m
- 2 +1 spare coils
- 1 double pancake (1/3 of coil) for prototyping margin
- Must include winding margin
- + 10% twist pitch
- + 10% losses during cable production
- 18 strands per cable

The 28 km of strand has been ordered

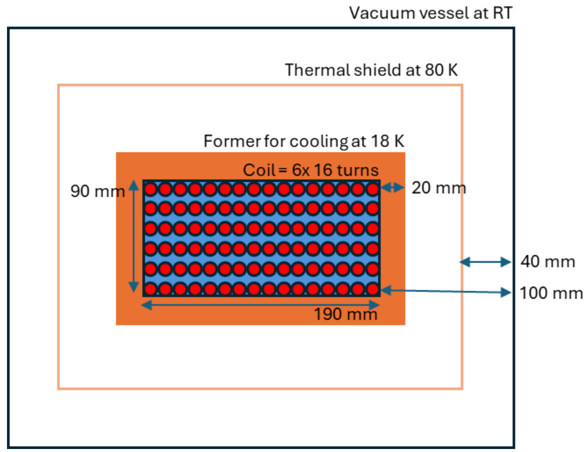


MgB_2 wire for HL-LHC superconducting link (over 1000 km produced)



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

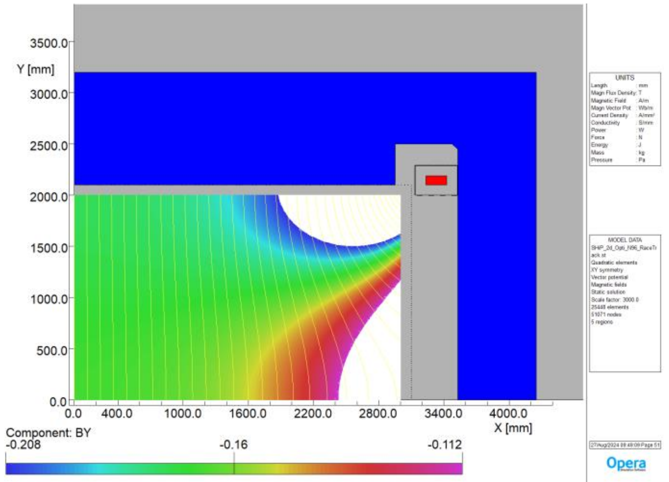
Unit length one coil for one double pancake	750 m
Number of double pancake :	
Three coils (2+1) x 3 + 1 prototype	10
+ 10% twist pitch	1.1
+ 10% cable prod. losses	1.1
18 strands/cable	18
Total	**162 km**

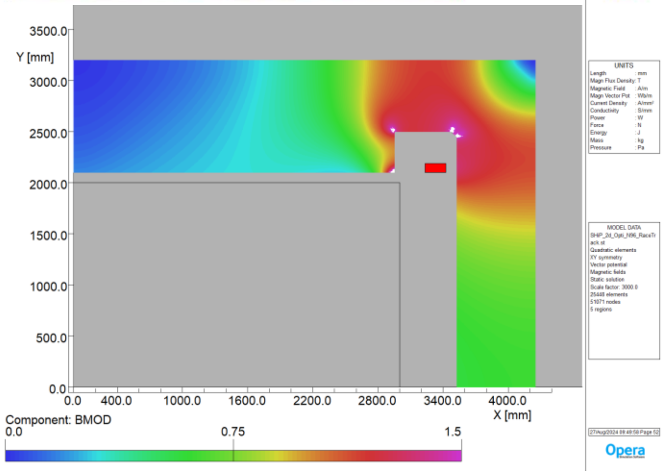
Preliminary magnetic simulations

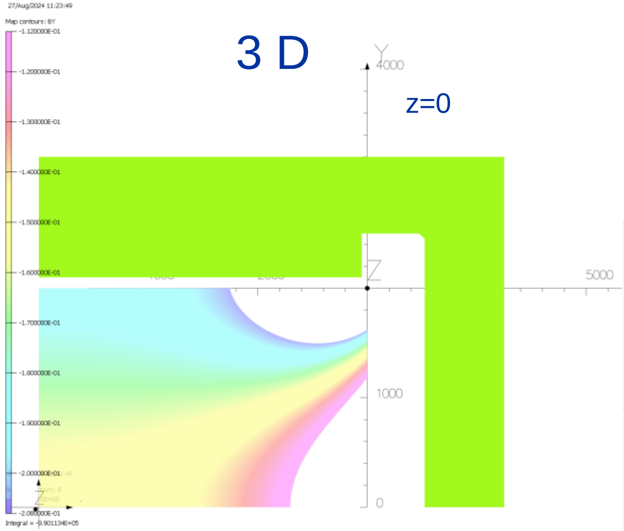
Simulations on a reference geometry

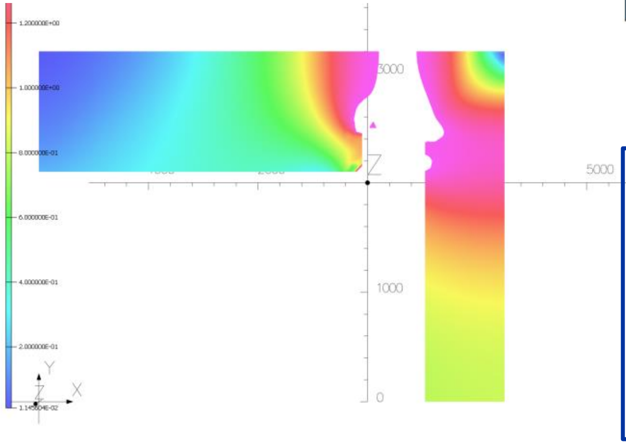
2 D

3 D



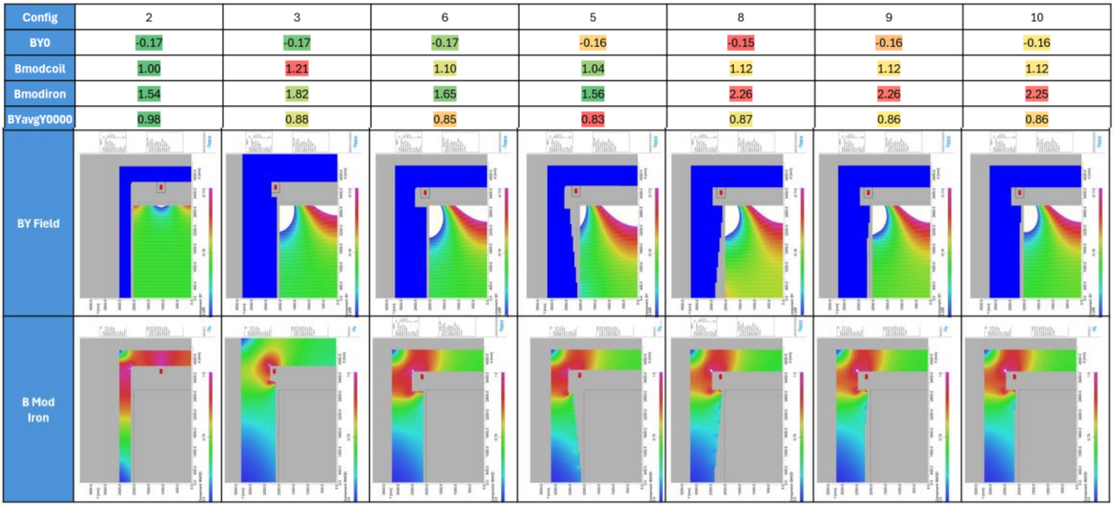






Benchmark Opera/Roxie on going

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:

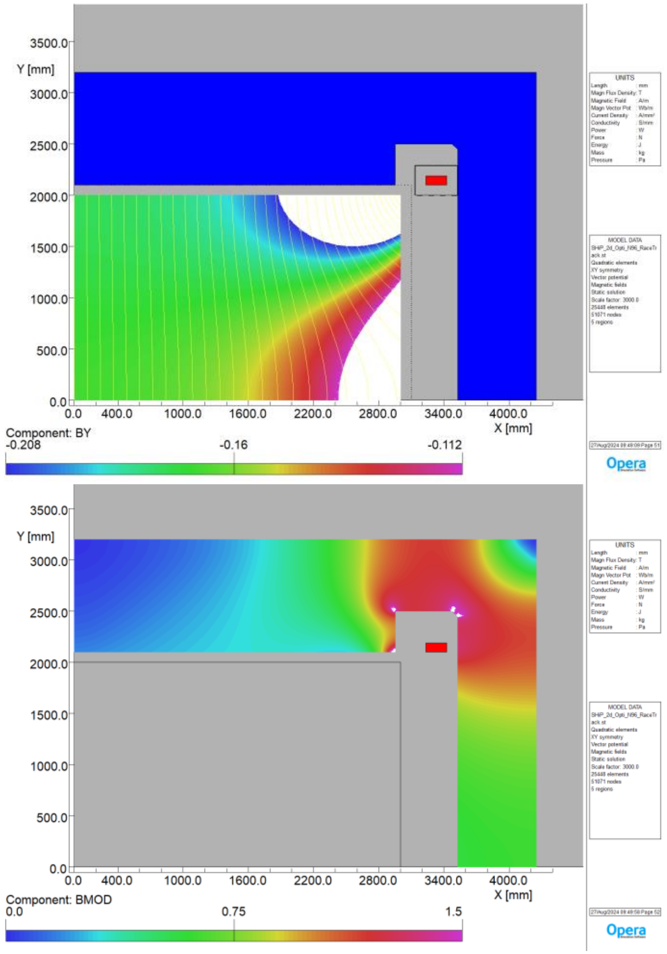
- Identification of the optimisation challenges
- First estimation of the coil’s characteristics
- First estimation of the electromechanical forces

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

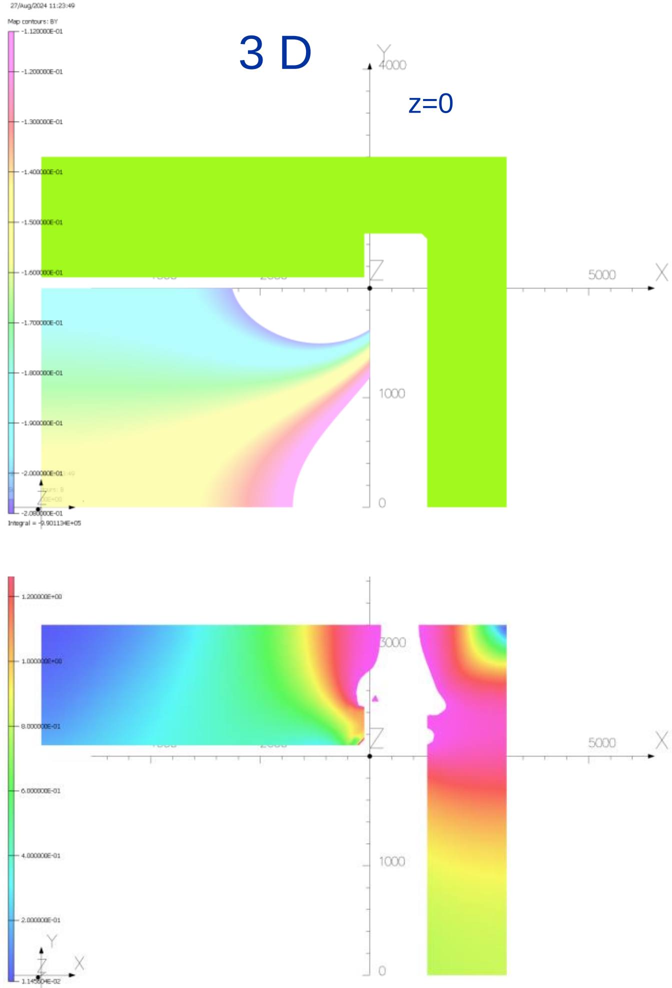
Benchmark Opera/Roxie

Simulations on a reference geometry

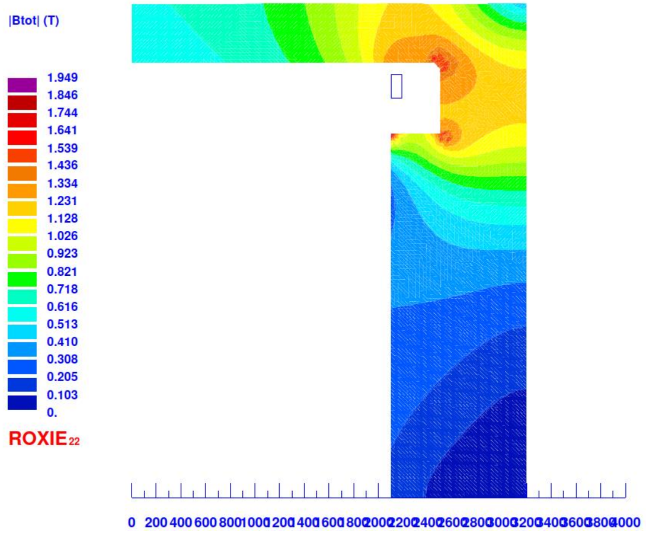
2 D



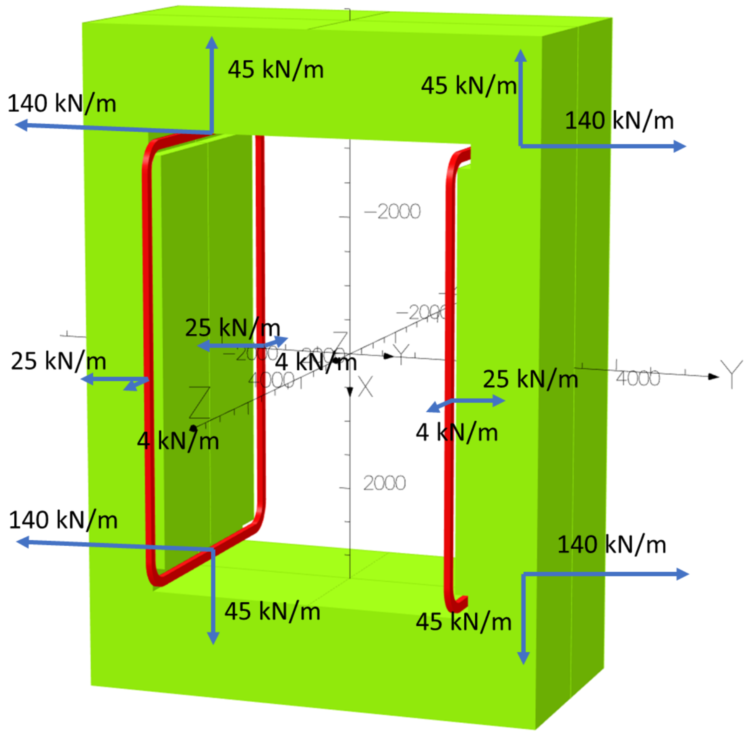
3 D



					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



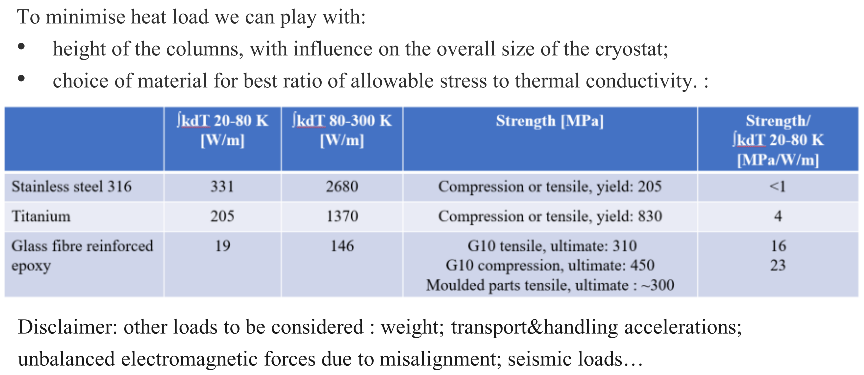
First consideration on cryostat design and coil supporting system



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



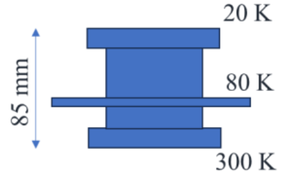
To minimise heat load we can play with:

- 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. :

	$\int kdT$ 20-80 K [W/m]	$\int kdT$ 80-300 K [W/m]	Strength [MPa]	Strength/ $\int kdT$ 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.

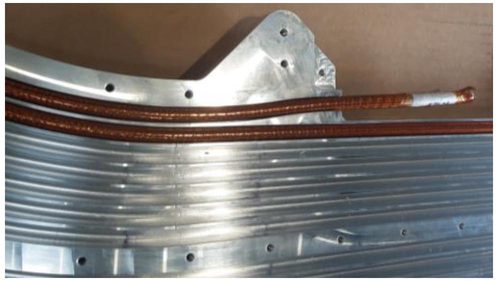
Technology development

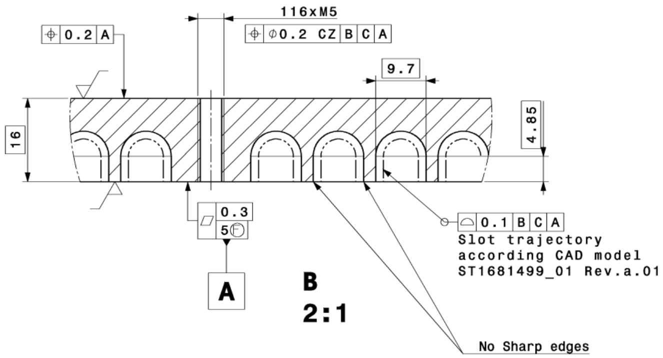
Assessment of the thermal contact resistance between the isolated MgB_2 cable and the radial plate :

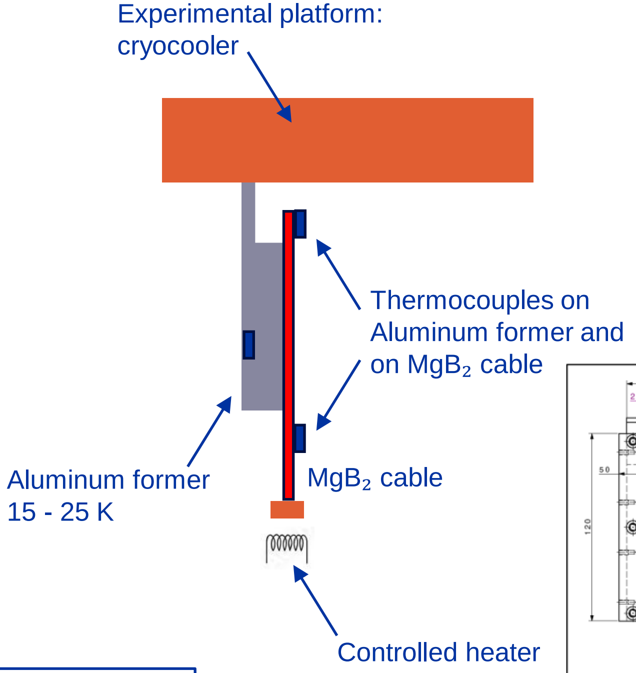
- Mechanical adjustment:
  - As build in EESD in phase 3:
    mechanical adjustment relying on differential thermal contraction and mechanical tolerances;
  - Addition of a counter former made of aluminum to increase of contact surface and contact pressure.
- Impregnation? Wet winding?
  discussions 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
Q2 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)