WP5 HL-LHC Hollow Electron lens magnet system status

HL WP5 HEL Review kick-off meeting, 13td April 2021

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Alexey Bragin and BINP Magnet group.

Indico Link

Outline

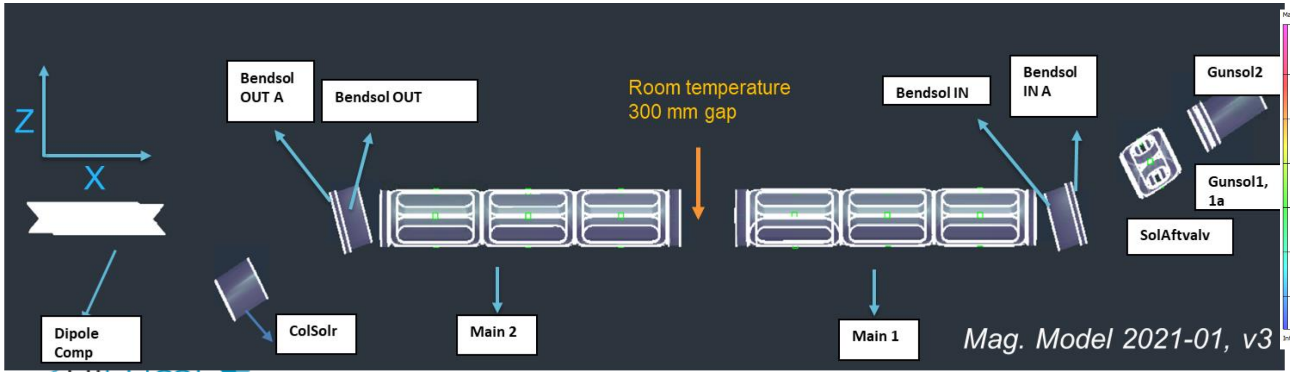
- Status
- HL-WP5 HEL Magnet system
- Functional magnet specifications
- Scope of collaboration with BINP
- HEL SC Magnet system CAD model
- HEL engineering magnet interfaces
- Preliminary magnet specifications
- Schedule, Resource plan on HEL magnet system
- Cold test strategy
- Summary
- References

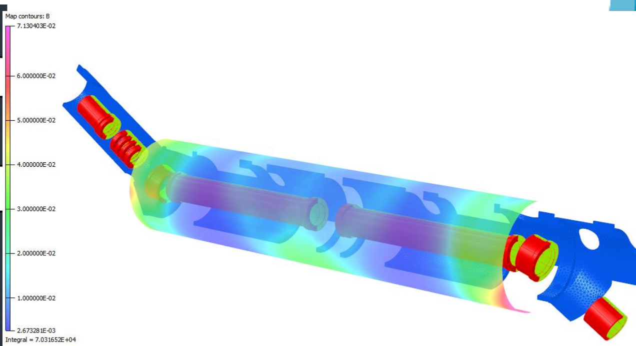
Status

- **Magnet functional specification under finalisation**
- **Preliminary conceptual study well advanced, need finalisation of functional specification**
- **First contact with BINP initiated. Need to define the detailed scope of the in-kind contribution.**
- **Since Dec. 2020, when magnet group took in charge the magnet system, PBS and WBS have been set up.**
- Crucial that BINP establishes a continuity on CERN site activity to support the finalization of the conceptual design
  - thereafter to perform the engineering design in collaboration with the other concerned teams.

HEL superconducting magnet system

- The Hollow Electron Lens ensures transport, guiding and position tuning of e-electrons (See D. Perini's slides)
- The Magnet system is composed of :
  - *Guiding e-beam:*
    - 2 Main solenoids, 2 bending solenoids, 4 solenoids after valve, e-gun, collector solenoids
  - *Correcting system:*
    - 6 correctors (H,V) per main solenoid, 4 for bending, 2 for the e-gun, one orbit dipole compensator



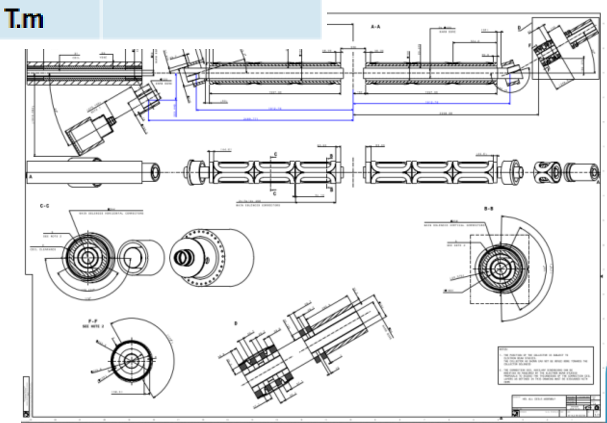


Functional magnet specification

- Magnet specification in line with HEL functional specification
- All magnet design meet specified hot spot temperature T_h < 120 K, Vmax < 500 V at operating 4.2K temperature.

SC magnets	Main Solenoid without trims	Gun Solenoid 2	H,V dipole correctors (saddles)		Orbit dipole compensator	After valve gun solenoids (AVS)
Magnetic field orientation	Axial 2 Main	Axial	Horizontal 3 per main Solenoid	Vertical	Vertical	Axial
Inner coil radius, mm	90	76	125	120	61	76
Outer coil radius, mm	111	95.95	129.4	124.4	73	102.3
Coil length, mm	1500	290.4	488	488	~1000	AVS 1,4: 39 AVS 2,3 :29 Gunsol1,1a: 29
Maximum design current I, A	350	350	120	120	350	350
Central field, T (self)	5	0.2 - 4	0.08	0.08	Int B.dl > 0.7 T.m	3.2

SC magnets	Bent Solenoids	Gun Solenoid 1	Collector solenoid	e-gun correctors
Magnetic field orientation	tilted @ +/- 16.7 deg 2	Axial @ 30 deg	Axial	H,V
Inner coil radius, mm	113	76	91.5	102.3
Outer coil radius, mm	111	98.2	106.5	107
Coil length, mm	150	290.4	200	250
Maximum design current I, A	350	350	120	120
Central field, T (self)	3.2	4.4	0.4	0.16



HEL engineering functional drawing magnets space and location

Scope of collaboration with BINP

- Support to finalisation of the functional specifications
- Engineering design performed by BINP team on CERN site
- In-kind supply of three HL-LHC WP5 Hollow electron Lens (HEL) assembly units (one spare, two series).
- The supply consists of :
  - manufacture of the magnet system, cold masses, vessels parts, QC coils cold tests at BINP.
  - Assembly of cold masses at BINP/CERN and in-cryostating at CERN site,
  - Support to commissioning cold acceptance test of each final HEL assembly on surface at CERN
  - Support to tunnel installation at LHC IR4 point .

List of in-kind supplies

Items	Components *	Spare	Series
Magnet System	Gun solenoids (4 T)	2	4
	Solenoid After valves	4	8
	Bending solenoids (~ 3.5 T) (incl trims)	2	4
	Main solenoids (5 T) (incl. trims)	2	4
	Correctors at the gun [H+V]	2	4
	Correctors along the main (dipole) [H+V]	12	24
	Dipole corrector for bending solenoids	1	2
	Collector solenoid	1	2
	Cryostats (He vessels), piping	5 + 1	10 + 1
	Magnetic shielding * (under evaluation)	1	2
	Leads high current (in & out), nominal 350 A	14	28
	Leads low current (in & out), nominal 120 A	30	60
	Magnet support external structure, chassis.	1	2
	Magnet instrumentation wiring (V-taps, SC busbars)	Per design	
Cold test	Fabrication **cryogenic tests at BINP** on sub magnet	8 tests per unit (24)	
Tooling	Cold mass and cryostat dedicated on CERN site assembly tooling	Per design	

* About 108 individual windings to be built by BINP. Dedicated magnet manufacture cryo tests are planned for each magnet at BINP

Open procurement items

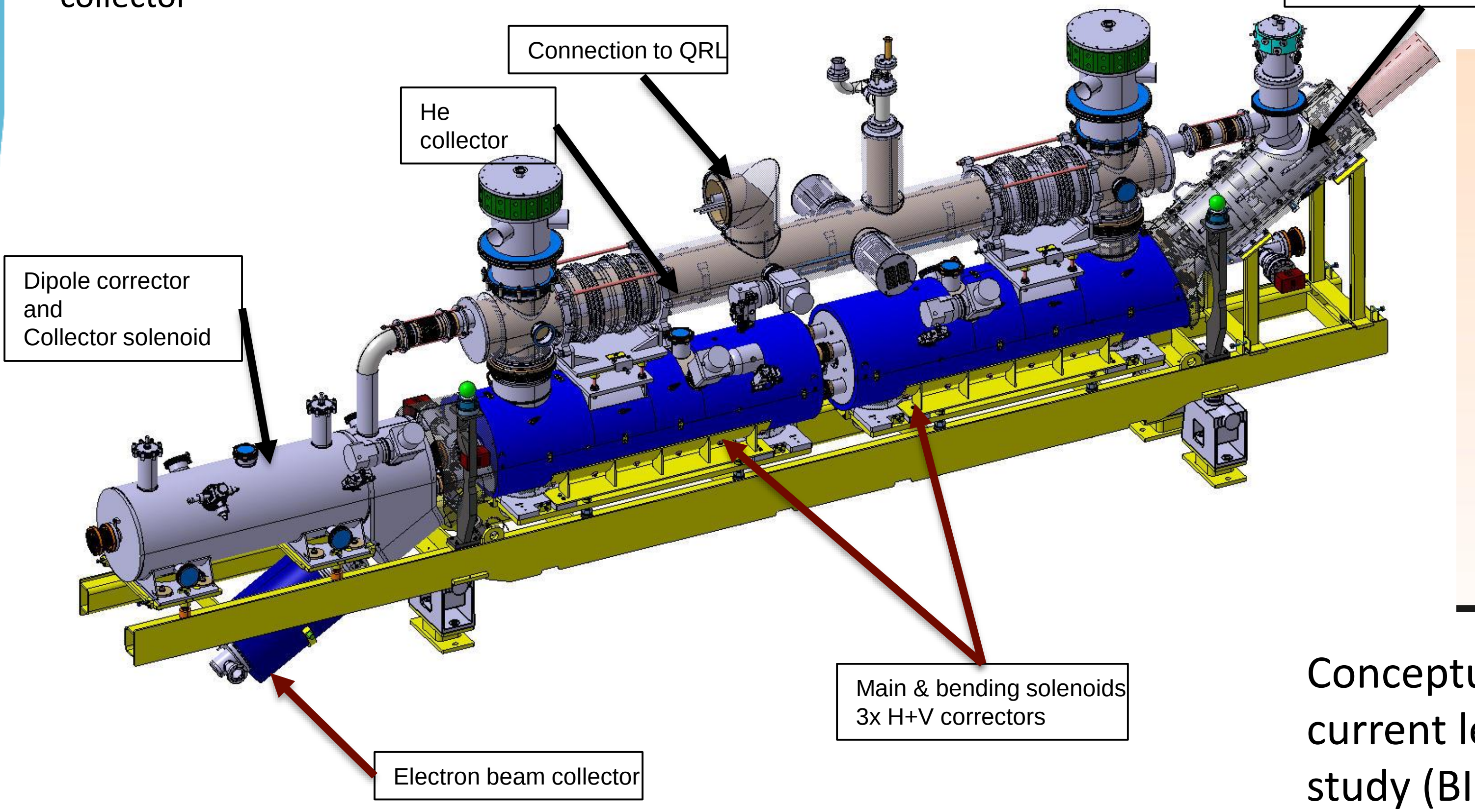
- LHe pressure cold masses vessels design and cryostating by BINP shall be performed per PED 2014/68/EU requirements (EDMS 1891856), EN:13445 code.

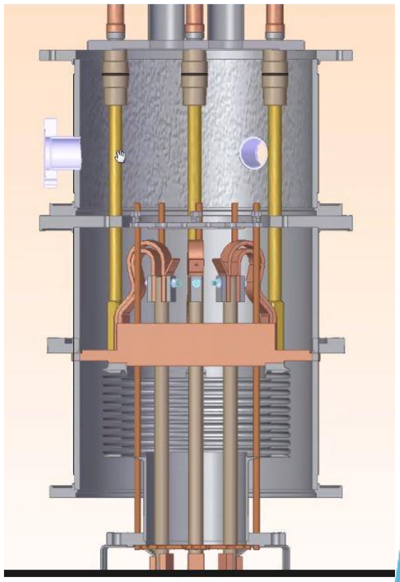
- The present baseline is that the manufacture of the cold masses and assembly are performed by BINP on CERN site. We are exploring if part of these activities can be performed on the BINP site.

- In that case, the BINP activities on CERN site would focus on cold masses **alignment & integration into cryostats**, **magnetic axis transfer**, final unit assembly

HEL SC Magnet system CAD model

HEL **superconducting magnets cooled at 4.5K to tune the size and steer the** electron beam ring from cathode to collector





Conceptual gas- cooled current leads cluster under study (BINP). Height envelop per integration (WP15)

Number of 22 circuits recently shown that three multi leads cluster envelops are needed.

HEL engineering magnet interfaces

Electromagnetic model, CAD model — TE MSC, WP5, WP2
- Field profile, beam optics ✓
- Magnet specification parameters, (inductance, load table) ✓
- Shielding simulation, baseline with 30% efficiency (in work)
- SC conductors choice, operating Iss margins, specification in work
- Current leads layout, functional integration space (in work)
- Definition of Magnetic measurement requirements

Magnets Protection — TE MPE, WP7
- Protection baseline, modelling
- Energy extraction on individual coils (up to 30%), hot spot temperature < 100 K, maximum voltage < 500 V
- Start of mutual coupling assessment, back up pick up coils

Magnet circuits — SY EPC, WP6
- Equipments code names, Circuit layout, choice of PCs✓
- Main circuit parameters baseline (MCF) ✓
- Update baseline as function of protection simulations

Busbars & Instrumentation — MSC, MPE
- Magnet quench detection scheme proposal
- Internal SC busbar specification (in work)
- HV feedtroughs, placeholder
- Magnet mechanical instrumentation, T sensors
- Cryogenic operation instrumentation pre-list

Metrology — BE-GM, EN-MME
- Magnet metrology steps, criteria (under evaluation)
- Alignment process, survey marks needs
- Final achievable targets (in work)

Cryogenics — TE CRG, (WP 9)
- Internal HEL cryogenic piping sizing ✓
- Assessment of operating He pressure, safety valve devices (P< 4.5 b) ✓
- Overpressure in case if quench and vacuum loss ✓
- Integration of cryo jumper, lines
- Integration of HEL magnet cold test cryogenic station (pending)

Work in progress

Integration — WP5, HL ATS (WP15)
- HEL unit envelop CAD model ✓
- Transport tooling assessment, process (in work)
- Integration space in tunnel, HEL interface specification

Vacuum system, diagnostics — TE-VSC (WP12), SY-BI,
- Access space for assembly of BGC diagnostics (on going)
- Layout of vacuum pumps vs magnetic field (in work)
- Access to LHC vaccum port

Cold mass and cryostat — BINP, MSC
- Functional space definition, CAD model (in progress)
- Detail assembly procedures, dimensioning, drawings, QC (BINP phase I & II, pending)

Mechanics, structure — TE MSC, EN MME
- Inter coil structure predimensionning (in work)
- External structure, girder, stabilisers, chassis compliance with integration

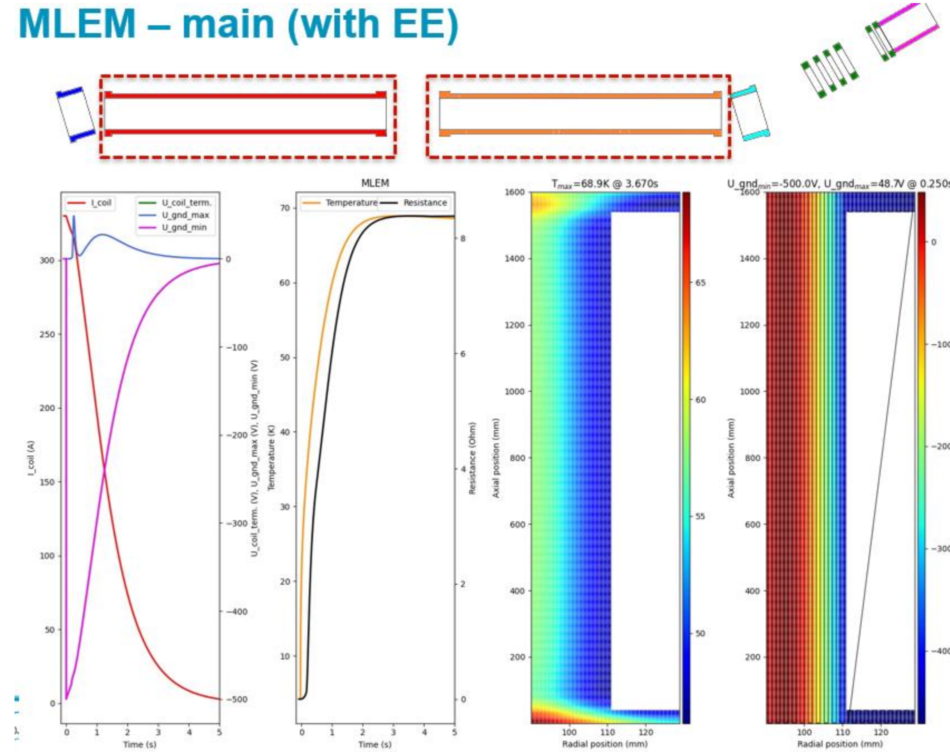
Preliminary magnet parameters

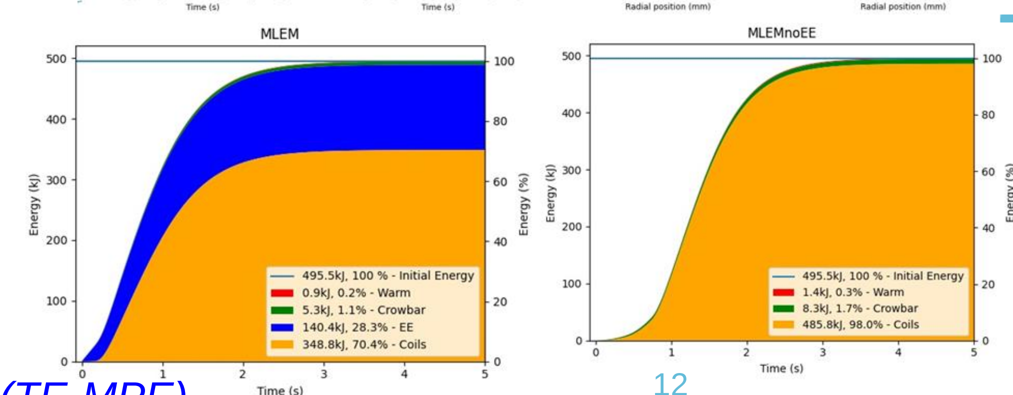
SC magnets	Main Solenoid without trims	Gun Solenoid	H,V dipole correctors (saddles)		Orbit dipole compensator (Canted Coils)
Magnetic field orientation	Axial	Axial	Horizontal	Vertical	Vertical
Bare conductor size, mm / Cu:nCu ratio	1.63 x 1.03 / 4:1	1.63 x 1.03 / 4:1	1.63 x 1.03 / 4:1		OD 0.825 / 1.95:1
Insulation system (film thickness)	Formvar Enamel 25 μm	Formvar Enamel 25 μm	Formvar Enamel 25 μm		Polyimide film (30 μm)
Inner coil radius, mm	**90**	**76**	**125**	**120**	**61**
Outer coil radius, mm	**111**	**95.95**	**129.4**	**124.4**	**73**
Coil length, mm	**1500**	**290.4**	**488**	**488**	**~ 1000**
Layers number	20	30	4	4	2
Turn number/layer	909	18	24	24	10
Total turn number	18180	540	96	96	150
Operating current I, A	**330**	**9-257**	**120**	**120**	**220-300**
Central field, T (self)	5	0.2 - 4	0.08	0.08	0.74
Max field in coil B_m, T	5.4	4.5	0.3	0.3	1.4
Stored energy, kJ	455	28	0.053	0.053	2.8
Inductance, H	7.73	0.833	0.00739	0.00734	0.115
Critical current density (6T, 4.5 K), A/mm2	2300	2300	2300	2300	2450
RRR in Copper	> 100	> 100	> 100	> 100	> 100
Critical temperature (B_m, I), K	6.5	6.5	> 8.5	> 8.5	> 8

Quench protection scheme

- **HEL circuits inteface and protection scheme baseline reviewed in MCF 79 meeting.**
- **Main solenoids quench protection analysis by MPE shown maximum 30 % dumped energy in external resistor of 1.4 Ohms (E_t = 500 KJ per Main).**
  - **Hot spot temperature Th ~ 70 K < 120 K limit ✓**
  - **Tau ~ 1.5 sec, 500 V max design to ground. ✓**

MLEM – main (with EE)





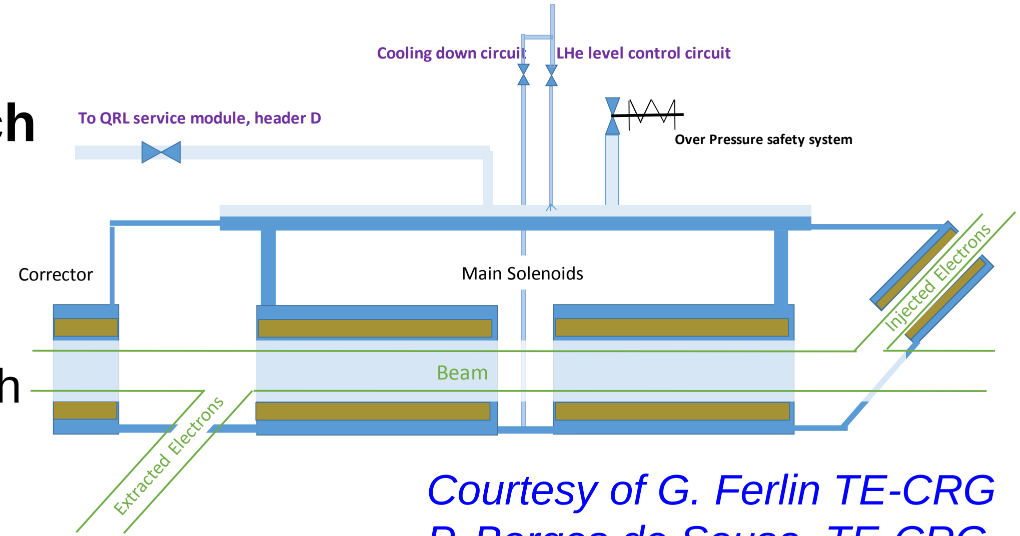
- Next, **detailed coupled simulations vs. alternative pick up coil, optimisation of small inductance circuit protection, circuits discharge scenarii.**

Courtesy of M. Woszniak (TE-MPE) , MCF meeting, 23-04-21

Each MLEM magnet stores almost **0.5 MJ**
With **EE**, **70%** (**0.35 MJ**) of magnet energy is dissipated in coils, and during **2s** from quench

Cryogenic safety interface

- Preliminary overpressure estimate by CRG during **quench Energy adiabatic released** of total 1.2 MJ in 2 sec and **air inleak cases**.
  - Initial boiling film heat transfer h of 2 W/cm2
  - Required safety system of 1600 mm^2 (inlet diameter) or >= DN50

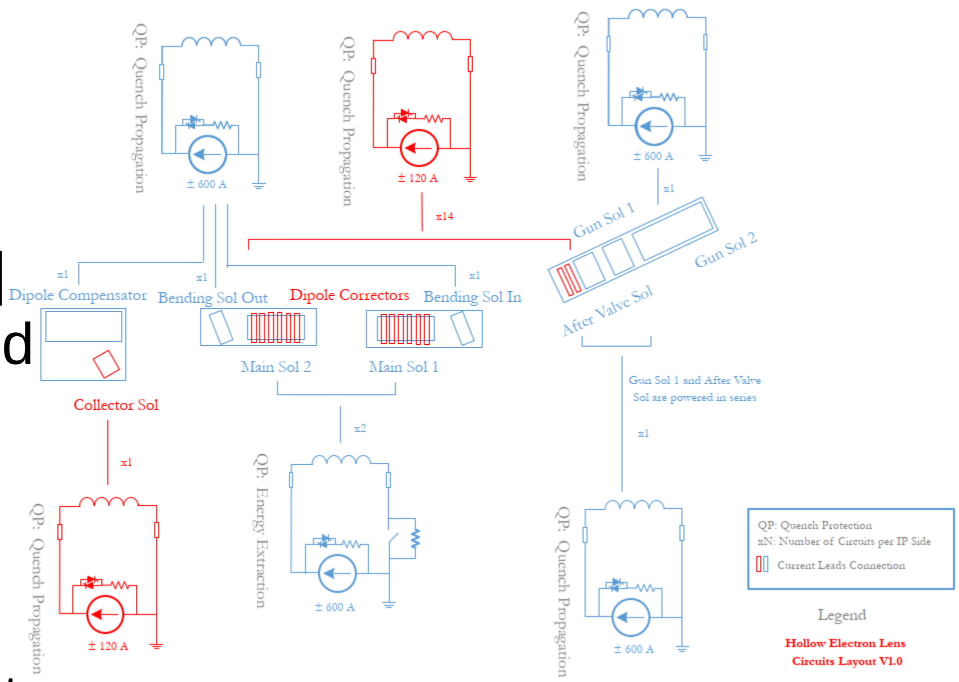


Courtesy of G. Ferlin TE-CRG
P. Borges de Sousa, TE-CRG
Ref. MCF meeting 23th March

- ✓ **Overpressure mass flow of 3.6 kg/s to evacuate** ✓
- ✓ **Design cryostat pressure update up to 4/5 bara** ✓
- ✓ Amount of helium released in the tunnel similar with neighboring DFBA or RF cryostat.

Power interfaces

- 22 HEL circuits per IP side: 7 x 600 A circuits (5 with energy extraction, 2 without) and 15 x120 A corrector circuits. [2]-[6]
- circuit layout baseline confirmed after the protection studies by WP7.
- Next magnetic coupling scenario, power converters control performance and stability (WP6B)



Courtesy of S. Yammine, M.Martino

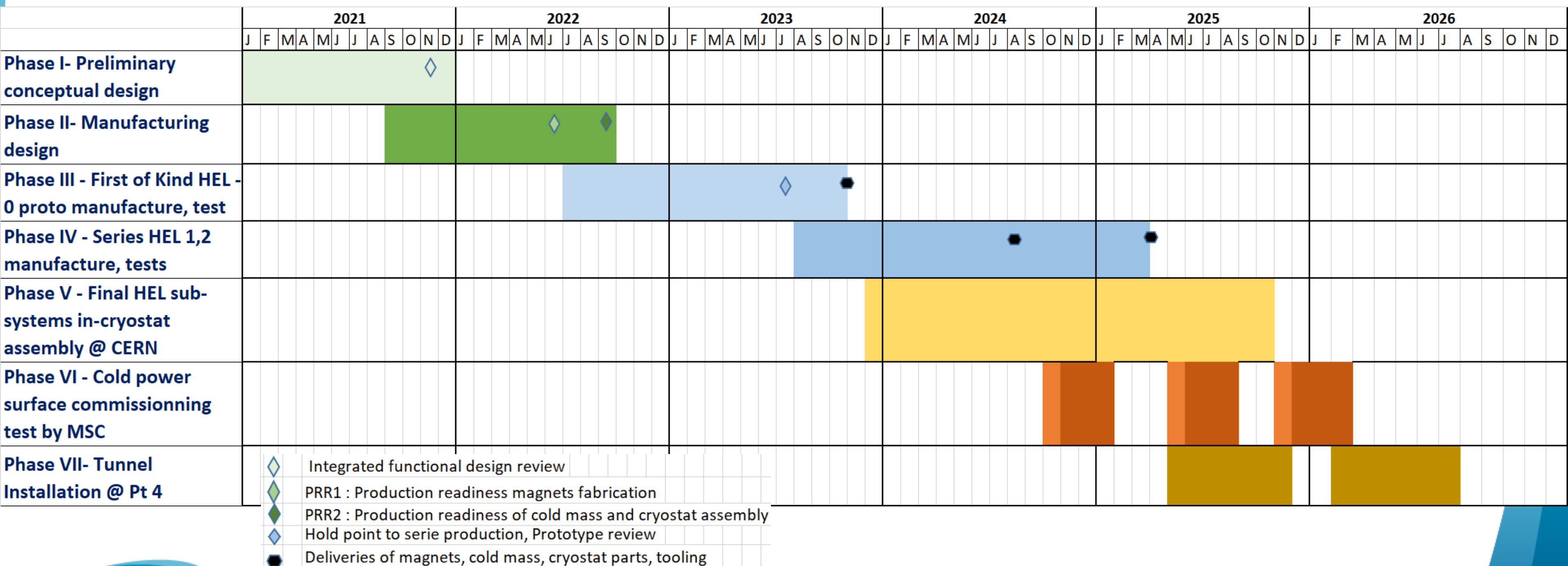
Circuits for HEL	Magnet Type	Circuit Name	Number of circuits per IP side	Total number of circuits	I_nominal [A]	I_ultimate [A]	Required Precision Class of PCs	Required ramp rate [A/s]	Required acceleration rate [A/s2]	Ramp Up Time [s]
Gun Solenoid 2	MLEG	RLEG	1	2	257	tbd	tbd	1	1	257
Gun Solenoid 1 and After Valve Solenoid	MLEA	RLEA	1	2	320	tbd	tbd	1	1	320
Bending Solenoid	MLEB	RLEB[1,2]	2	4	335	tbd	tbd	1	1	335
Main Solenoid	MLEM	RLEM[1,2]	2	4	330	tbd	tbd	0.7	1	472
Dipole Compensator	MCBEC	RCBEC	1	2	220	tbd	tbd	5	1	44
Collector Solenoid	MLEC	RLEC	1	2	100	tbd	tbd	1	1	100
Electron Gun Corrector - Vertical and Horizontal	MCBEG	RCBEG[V,H]	2	4	110	tbd	tbd	5	1	22
Main Solenoid Orbit Correctors	MCBEM	RCBEM[V,H][1,2,3,4,5,6]	12	24	120	tbd	tbd	5	1	24

Open technical items

- Integration **conceptual design space for inter-coils structures**, for **diagnostics**, access for mountability (ex: BGC, vacuum port, gun isolating valve..).
- **Multi current leads** (44 off) **clusters** design space within specified heat loads.
- **Iron shielding need** (max. efficiency assessed of 30%), check need mu-metal local shielding
- Pressure **vessels predimensionning** at newly operating 4.5 b and 5.6 b test He pressure,
- **Assembly, alignment sequence conceptual study** (See in appendix) of highly compact HEL unit magnet

Schedule

- *Detailed Magnet schedule with phases, deliverables, milestones, approved by BINP, since Dec. 2020*
  - *EDMS 2446949, WP5 HEL Magnet working schedule (see appendix)*
  - *Assumed BINP design support resources at CERN from Q1-2021.*
- *We need to define a detailed resource loaded BINP schedule.*



Resource plan on HEL magnet

- CERN resource are very limited (table below) to steer, monitor the project and CERN is relying on the support of BINP.
- BINP PJAS support resources expected on CERN site for design support (phases I, II) from 2021 and during assembly phases (III-V)
- This does not include design and assembly project resources at BINP site estimated up to ~ 25 FTEs.

HL-LHC HEL Magnet project phase	Period	TE/MSC	TE/CRG	TE/MPE	TE/VSC	SY/EPC	EN-MME	SMB	SY/BI	*Total FTE.y*
Phase I- Preliminary conceptual design	2021	0.4	0.5	0.4	0	0.06	0.9	0.3	0.2	**2.76**
Phase II- Manufacturing design	2021-2022	0.4	0	0	0	0	0.5	0	,	**0.9**
Phase III - First of Kind HEL -0 proto	2023	0.1	0	0	0	0	0.6	0	,	**0.7**
Phase IV - Series HEL 1,2 manufacture	2023-2024	0.6	0	0	0	0	0.5	0	,	**1.1**
Phase V - Final HEL sub-systems in-cryostat assembly @ CERN	2022-2025	0.9	0.4	0	0	0	0.8	0.1	,	**2.2**
Phase VI - Cold power surface test at CERN	2023-2025	1.3	1.9	1.1	0.1	0.6	0.2	0.1	0.2	**5.5**
Phase VII- Tunnel Installation @ Pt 4	2023-2025	0.9	1.9	0.9	0.2	0.8	0.5	0.6	tbd	**5.8**
total FTE.y per group		**4.6**	**4.7**	**2.4**	**0.3**	**1.46**	**4**	**1.1**	**0**	**18.56**

2021-2025

Cold test strategy

- Manufacture factory cold test of each coil at BINP, (8 sub-assemblies / unit, 1 week per test, see appendix)
- Commissioning final acceptance cold test at 4K on integrated HEL unit at CERN.
    - *Preliminary HEL Magnet test manufacture and cold acceptance specification, (Draft) EDMS 2509117. in discussion within MSC, WP5*
    - *Magnet training performance, design limits, various quench operational regimes, Field quality, test in stray field of equipments*
    - *Expected max. 12 weeks test duration per unit incl. cooling*
- On going proposal to upgrade 4th cryo line on existing FAIR test station, to be released, approved for assessment and budgeted during 2021
    - *Benefit from existing infrastructures, electrical equipments (PCs and protection system), upgrade procurement needs.*
    - *Assess the operation team resource and HL magnets test schedule during 2024-2025*

FAIR cold test station

Courtesy of CRG

Summary

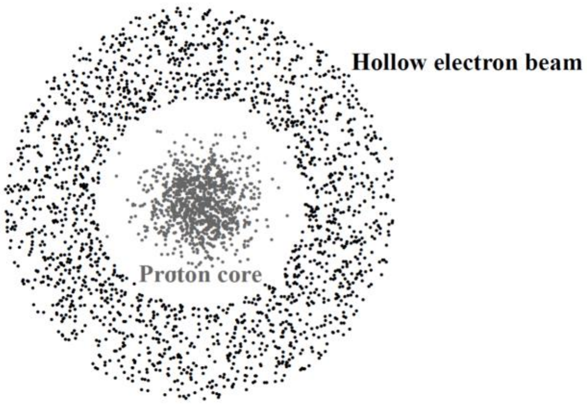
- Magnet functional specification under finalisation. The preliminary engineering conceptual design specifications, and the drawings are started, based on integration and performance requirements (end by September 2021).
- Need to define the detailed scope of the in-kind magnet contribution. Some important option on Pressure vessel construction site, to be confirmed.
- Pending technical issues to be closed for design specification completion (inter spaces, diagnostics access, magnetic shielding)
- Need of BINP resources on site to complete Phase I conceptual design and start of engineering detail design (phase II) to keep schedule

- Detail scope of supply and resource loaded baseline schedule by BINP to be confirmed through all phases.
- Commissioning cold test roadmap to be approved and test station proposal to be assessed for integration study, and test station upgrade.

References

1. Main parameters of HEL electrical circuits, EDMS 2036694
2. Magnet circuit diagram v0.2 , https://espace.cern.ch/project-HL-LHC-Technical-coordination/MCF/HEL_Circuits_Tabl
3. Magnetic model magnets geometry, EDMS 2467472
4. Magnet Load table in nominal operating conditions (BINP Opera), EDMS 2479912
5. HEL Magnet Instrumentation table, EDMS 2507516,
6. HL-LHC Hollow Electron Lens Circuits Table V0.1, MCF, S. Yammine.
7. WBS 1.0 HEL Magnet PBS and Project Tasks Items EDMS 2507886
8. WP5 HEL Magnet working schedule, EDMS 2446949
9. HL WP5 HEL Magnets resource plan, EDMS 2469326, (Draft)
10. HL WP5 HEL Estimate of support CERN groups resources on HEL WP5 Magnet project, EDMS 2515894, (Draft)
11. Preliminary HEL Magnet test manufacture and cold acceptance specification, EDMS *2509117* v.1 (Draft)
12. Center plane BGC field table from Opera model (with iron), EDMS 2492784
13. Naming conventions for functional position codes in the new HL-LHC buildings and underground galleries, EDMS 2349917
14. MCF meeting, 23td March 2021: https://indico.cern.ch/event/1020639/
    a) First Estimations of the Quench Energy Dissipated in the HEL Cold Masses of the Main Solenoids - Mariusz Wozniak,
    b) Proposal of the Design Cryogenic Pressure for the HEL Magnets - Gerard Ferlin

Thank you



for your attention

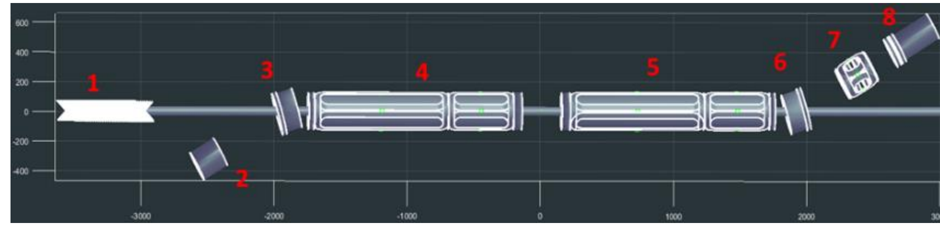
Do you have any questions …?

BACK UP SLIDES

BINP factory cold tests plan

Large magnets to be tested in long BINP cryostats. ~ up to 2 weeks per magnet, incl magnetic measurement .

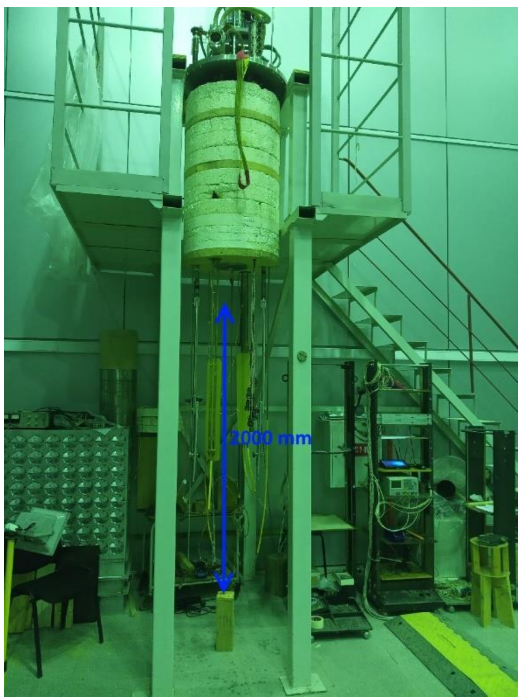
Available space in LHe vertical cryostat
∅ 700 mm, L ~ 2000 mm
Magnetic field measurements:
Hall sensors scanning along the axis.

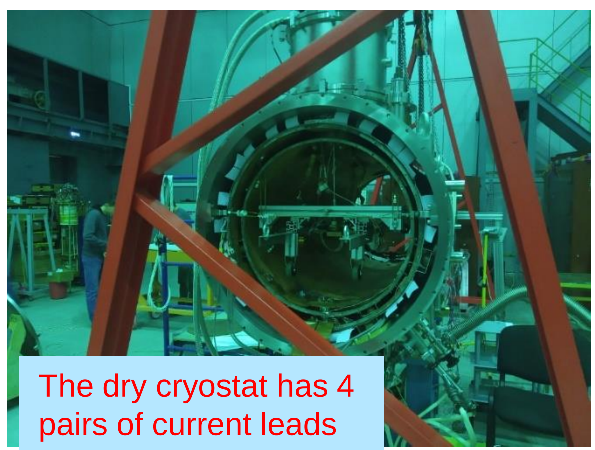


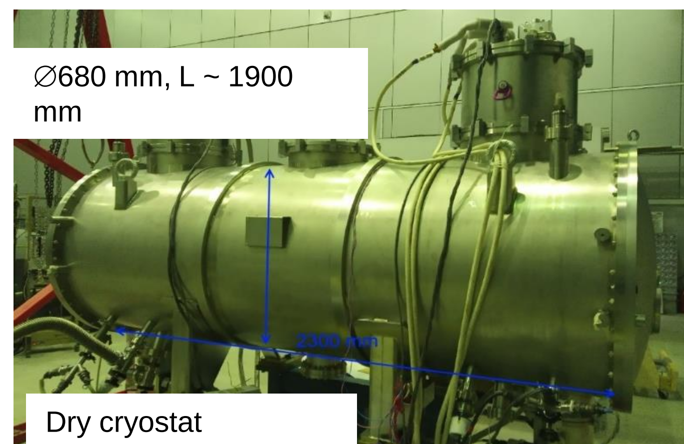
Horizontal dry cryostat
∅ 680 mm, L ~ 1900 mm
More possibilities for magnetic field measurements, but longer cooling down time (heat pipes to increase cooling power.)

Vertical dry cryostat:

- ∅410 mm, L ~ 1600 mm – LHe volume
- ∅300 mm, L ~ 500 mm, LHe test cryostat





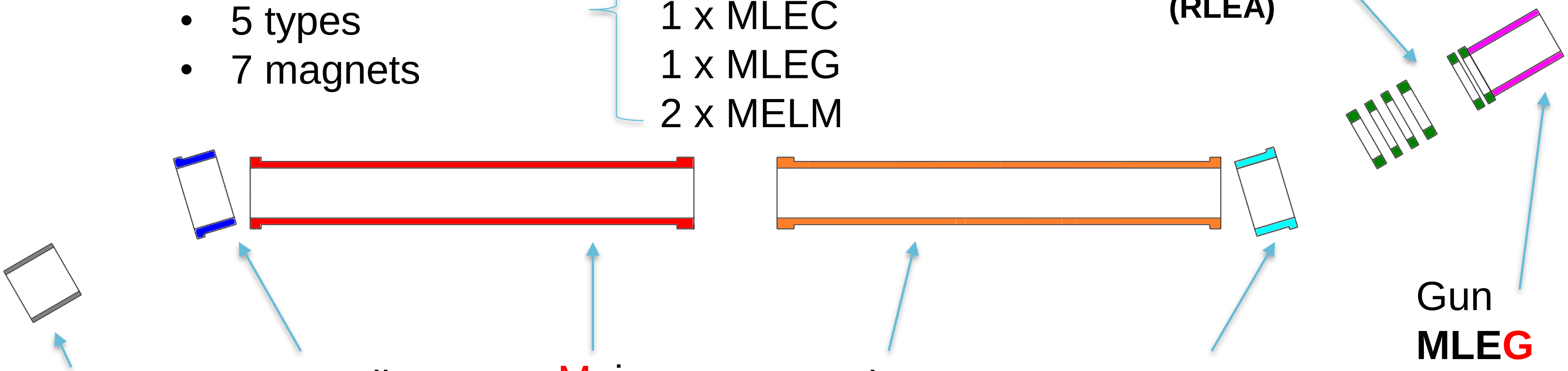


HEL solenoid magnets equipment codes

Magnet Solenoid E-lens (MLE…)

HEL solenoid magnets:
- 5 types
- 7 magnets

1 x MLEA
2 x MELB
1 x MLEC
1 x MLEG
2 x MELM

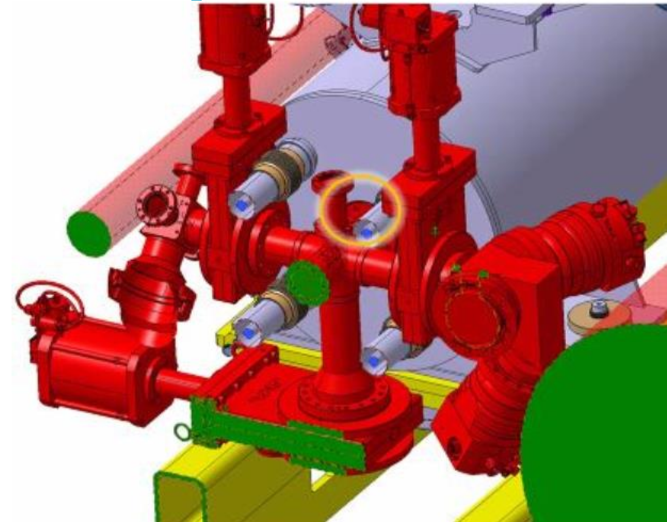


Magnet name	MLEC	MLEB	MLEM	MLEA	MLEG
Wire length (km)	1.055	1.771	13.033	2.406	2.021
		1.771	13.033		
Total (km)	35.090				

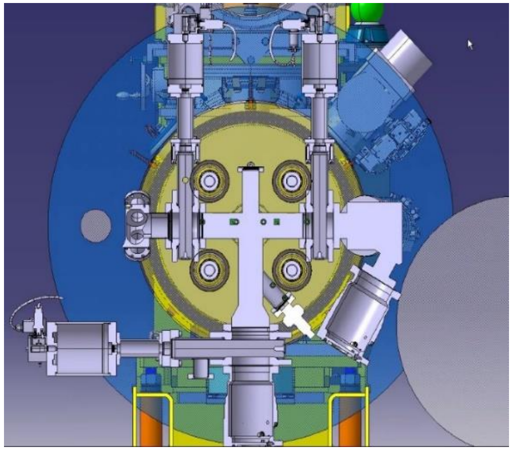
*** Markus Zerlauth, MCF 79th HEL Circuit and Magnet Naming Proposal**
https://indico.cern.ch/event/1006067/

Functional Design item
BCG inter solenoids region

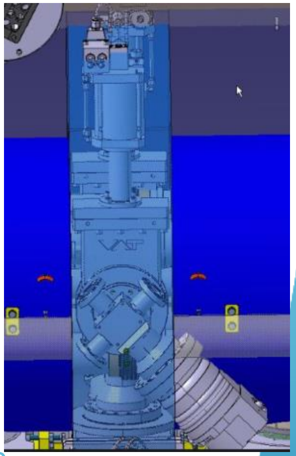
- On going design of both **Beam curtain Gas diagnostics and inter-coil reacting structure** in tight gap (~260 mm) requires an integrated design approach considering assembly steps.
  - Design of accessible vacuum flanges, bolted vs welded.
  - Discussion with SY on assembly sequence study, building of 1:1 mock-up



2019 BGC gap with inter solenoid structure

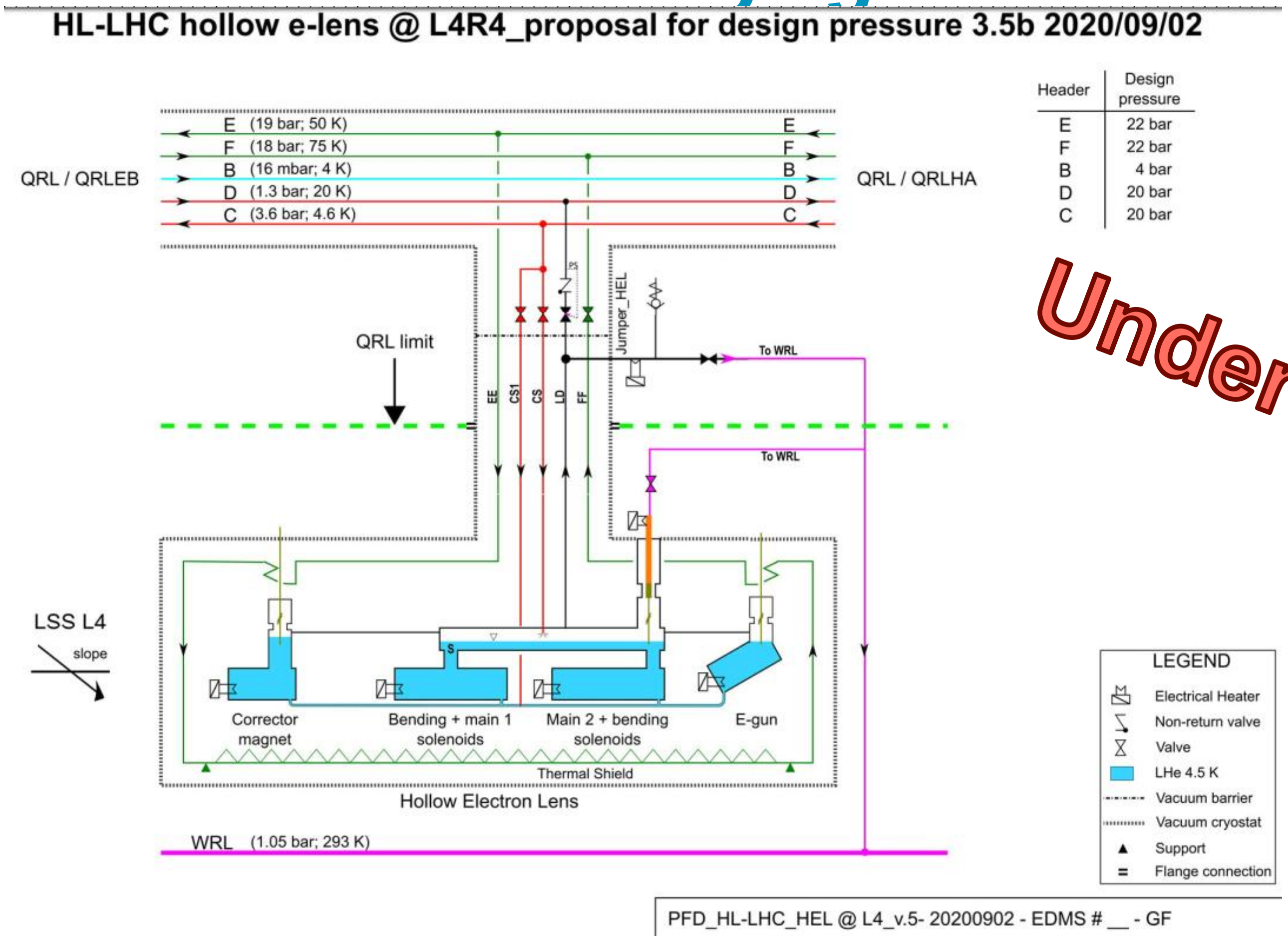


2020 inter solenoid structure



View of inter solenoid gap

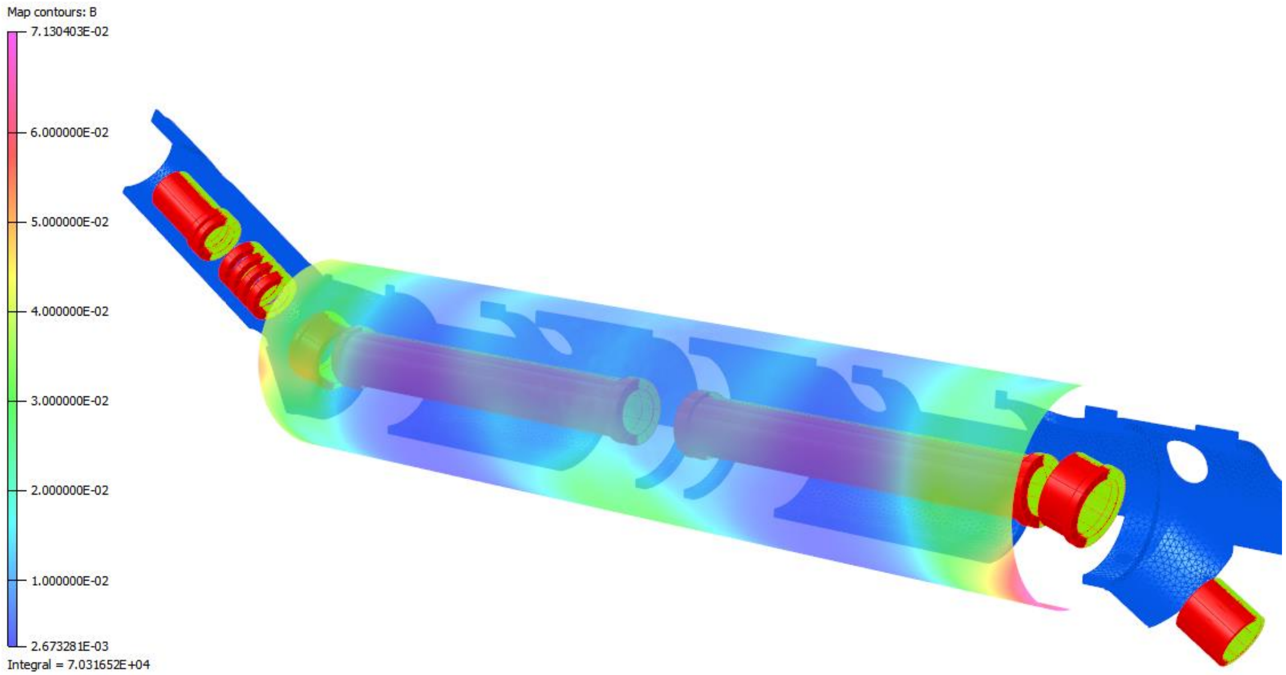
Functional Design item
HEL unit cryogenic PFD



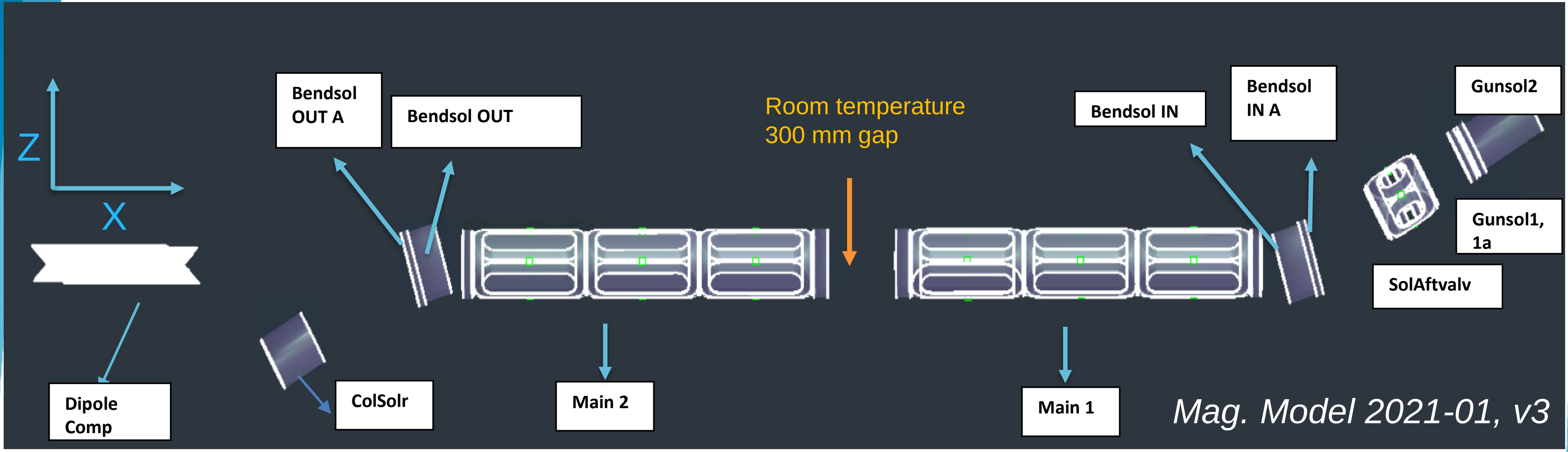
- Next PFD update depending on on-going design technical discussion with BINP on all gas current leads.

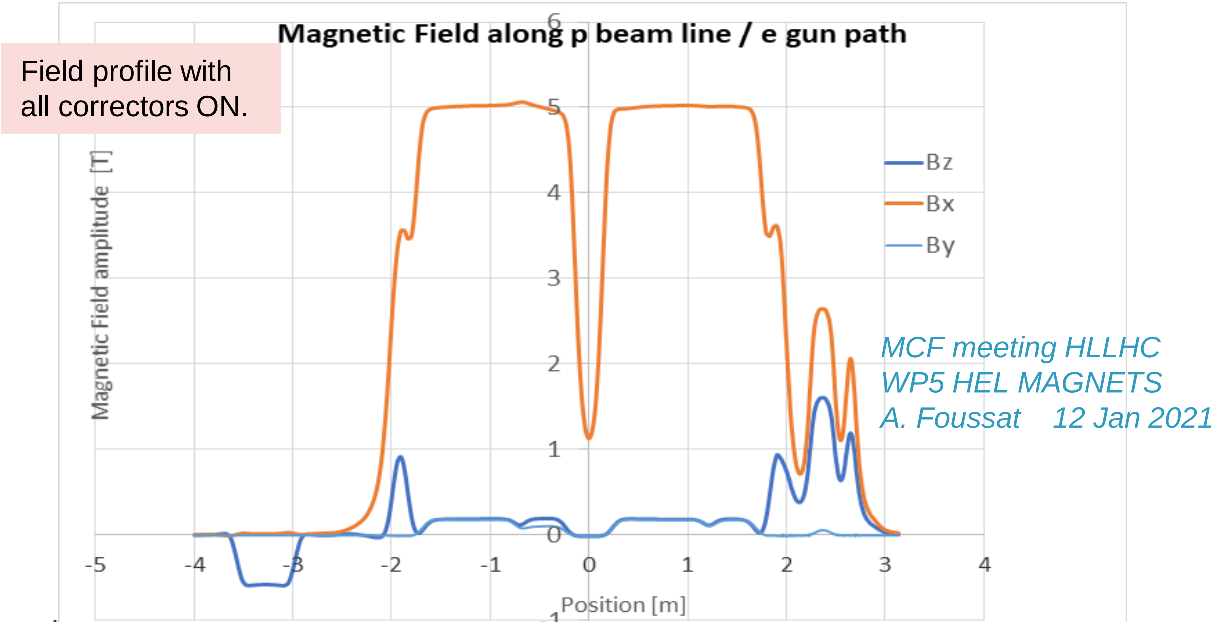
Functional Design item
Magnetic model with Iron shield

- Recent detail magnetic model with shield shown a maximum efficiency $\eta = (B0-Bs)/B0$ of 30%
- Shielding strategy to be confirmed as any improvement would have large design impact.
- Check needs of individual local HEL equipments shielding (mu metal)



Electromagnetic design

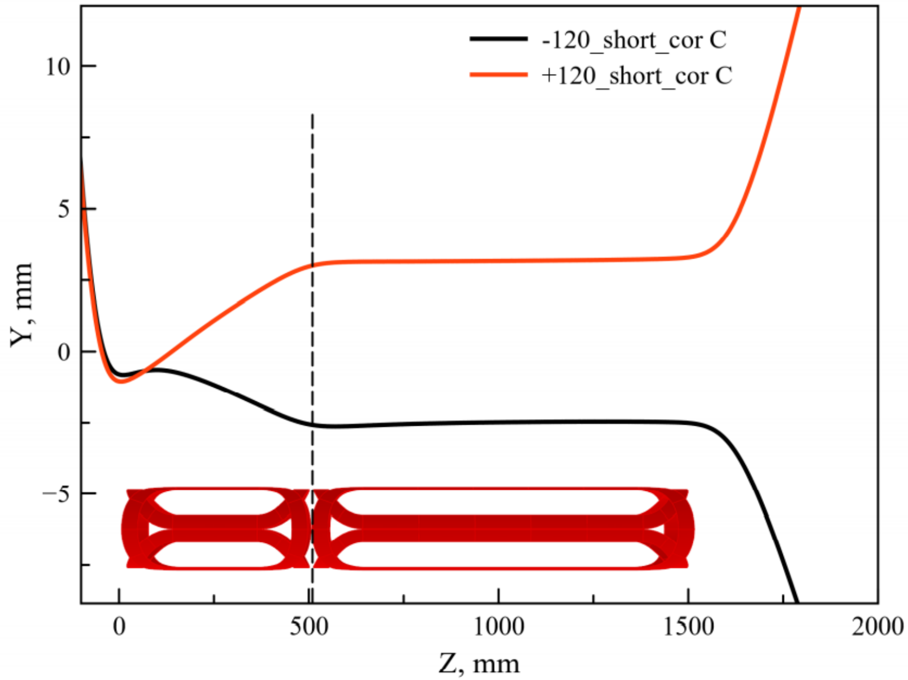




Parameter Main Sol.	Value
Insulated conductor size LxW	1.65 x 1.05
Cu/Nb-Ti	4:1
I_c(5 T, 4.2 K)	>= 750 A
I_{nom}	330 A
L_{nom}	7.8 H
$B_{nom,max}$	5 T
Je	191 A/mm^2
V_{Rleads} @ I_{nom}	1 V
N_{turns}	18180
RRR	>=100

Functional Design item
Beam optics correctors interfaces

- Updated saddle correctors design, 4 layers, 28 turns, 13440 A.turns, maximum current of 120 A
  - Increased bore field of 0.11 T allows beam deflection over +/- 4 mm
  - **Specified corrector strength of 0.166 T.mm/A** in 5 T background field
- **Pending study of e beam inlet correctors layout to reduce entrance trajectory bump. (in progress at BINP)**

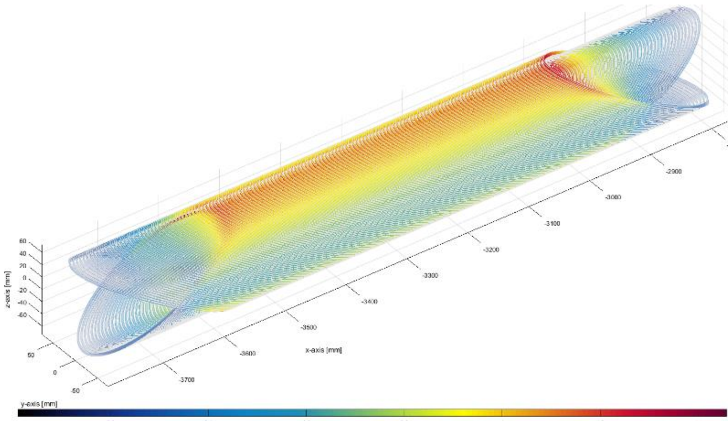


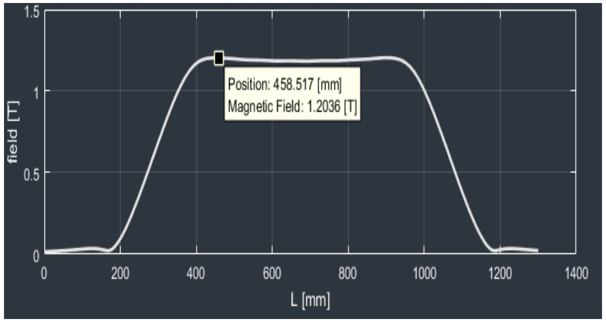
Dec 2020 to be updated
Case with bore field
0.055 T

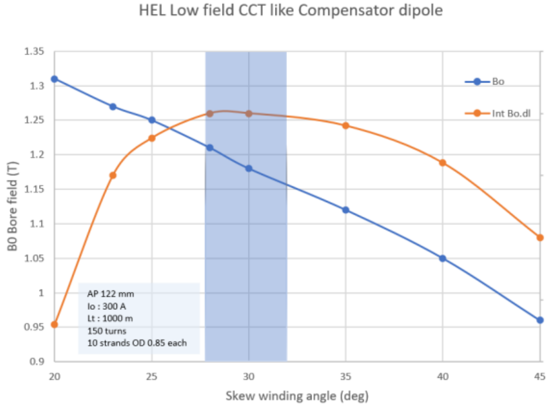
Vadim Pavlyuchenko and
Danila Nikiforov, BINP

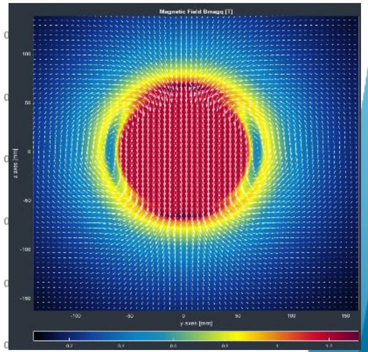
Orbit dipole compensator (CCT based)

- Orbit dipole space of 1 m to compensate the net residual vertica dipole kick seen by the proton beam from both bent solenoids up to ∫ B.dl = 0.34 T.m.
- Conceptual design based on CCT dipole using LHC NbTi ∅ 0.85 mm strand
- Optimised coils at 300 A, B0 = 1.2 T with 0.92 T.m, int_field margin factor of 2.7
- BINP shall confirm the dipole technology









Thanks to Glyn Kirby’s advices

Magnet system specifications

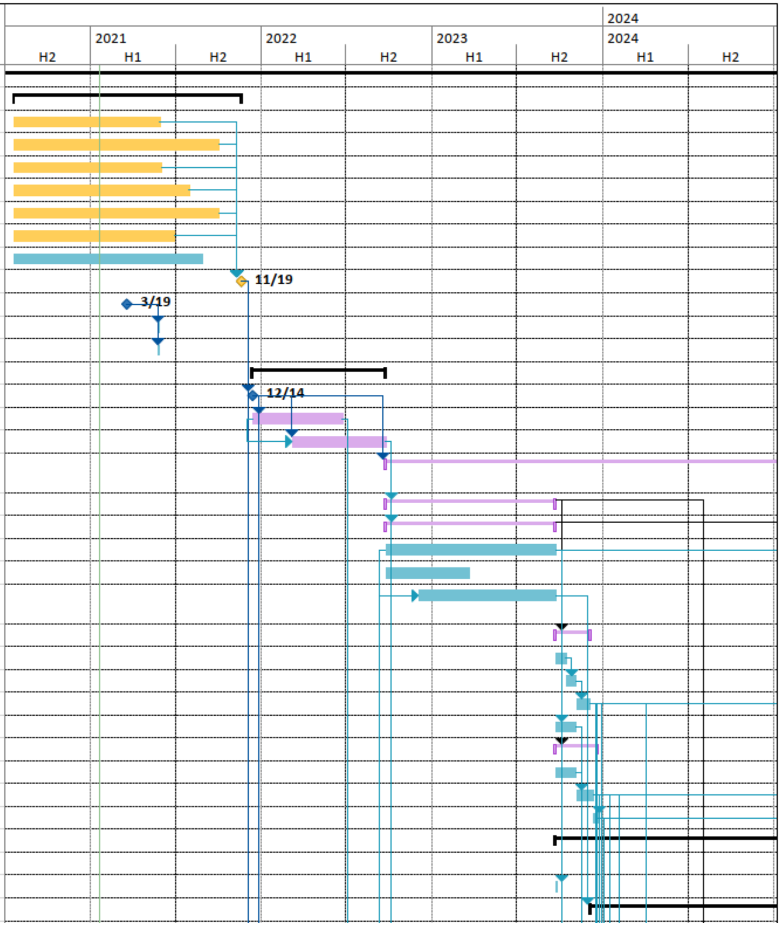
- Two 5 T main solenoids, with a 180 mm bore inner diameter split in two sections of 1.5 m length (see Fig. 1) to allow some space at the centre of the straight beam for diagnostics (300 mm separation) as well as to reduce the individual stored EM energy to less than 500 KJ
- Two tilted solenoids are used for the e-beam bending, in an “S” shape design that minimizes the effects on the proton beams from asymmetries at the e-beam entrance and exit
- Hollow electron lens magnet system is housed in a common cryostat designed to operate at nominal 3.5 bars pressure and 4.2K saturated LHe II.
- requirement of field quality straightness of the solenoid field lines set to ΔX ~ 0.2 m allows to prevent deviation of electrons trajectory off-center from a given fraction of the proton transverse beam size imposing a very small transverse field deviation of 10^{-4}.
- dipole compensator for the net residual vertical kick seen by the proton beam up to an integrated dipole field of 0.4 T.m.
- The strength requirements of each of the six longitudinal individual dipole corrector is currently set at 0.125 T.mm/A with a self peak field at 76 mT allow to move the e- beam trajectory by +/- 4 mm in the 5 T main solenoid field. (under study)

Key schedule phases

- ***Phase I - Functional design:*** Review of **magnet cold mass vessels** (PED compliance, construction features), **cryostats design and assembly sequence design**
- ***Phase II - Manufacturing design phase***: review of HEL construction design, QA, assembly jig **manufacture design files**
- ***Phase III-IV – Manufacture of HEL magnets and intermediate tests.*** Monitoring and approval of magnets, cold mass vessel, cryostat parts **manufacture documents**, inspection sheet. factory cold and magnetic acceptance test
- ***Phase V – Cold mass construction In-Cryostating*** : Cold mass manufacture, qualification (manufacture place under evaluation). Magnetic measurements, alignment and In-cryostating of cold masses at CERN with BINP assembly team
- ***Phase VI – Commissioning acceptance Cold test:*** nominal operation test of cryostated magnets HEL assembly , final acceptance
- ***Phase VII - Tunnel installation:*** approval of HEL magnet cryostat interface connections in tunnel, operation release.

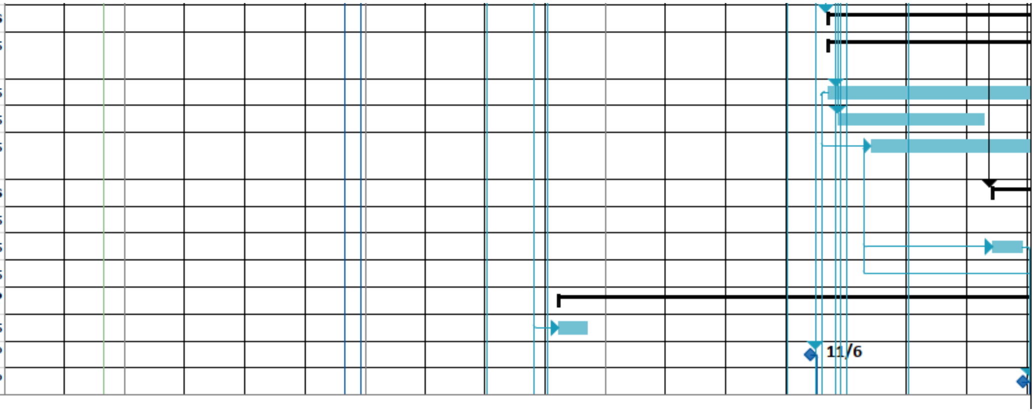
Baseline WP5 HEL Magnet Project v3.0

Nombre de tarea	Start	Finish	Duration	Predecessors
HEL Magnets production schedule	**Thu 11/1/18**	**Thu 9/18/25**	**93.13 days?**	
10- PHASE I FUNCTIONAL DESIGN	**Tue 7/21/20**	**Fri 11/19/21**	**89.38 days?**	
10.1- Magnetic model	Tue 7/21/20	Fri 5/28/21	182.13 days	
10.2- Mechanical structure design	Tue 7/21/20	Thu 9/30/21	254.38 days	
10.3- Instrumentation	Tue 7/21/20	Tue 6/1/21	184.13 days	
10.4- Quench Protection design file	Tue 7/21/20	Thu 7/29/21	225.13 days	
10.5- Electrical power interfaces	Tue 7/21/20	Fri 10/1/21	255.25 days	
10.6- Cryostat design	Tue 7/21/20	Mon 6/28/21	202.63 days	
10.7- Integration report	Tue 7/21/20	Sat 8/28/21	230.88 days	
10.8- Functional specifications	Fri 11/19/21	Fri 11/19/21	0 days	3,4,5,6,7,8
KoM CERN BINP collaboration	Thu 3/18/21	Fri 3/19/21	1 day?	
Preliminary BINP production, assembly schedule	Tue 5/25/21	Tue 5/25/21	1 day?	11FS+40 days
Preliminary BINP Quality insurance, procurement plan	Tue 5/25/21	Tue 5/25/21	1 day?	11FS+40 days
20- PHASE II DESIGN MANUFACTURING	**Mon 12/13/21**	**Fri 9/23/22**	**71.75 days?**	
20.1- KOM production CERN BINP	Mon 12/13/21	Tue 12/14/21	1 day?	10FS+15 days
20.1- Tooling manufacturing drawings for final review	Tue 12/14/21	Wed 6/22/22	120 days	15
20.1- Magnet manufacturing drawing	Mon 3/7/22	Fri 9/23/22	120.5 days	15,16SS+50 days
30- PHASE III - FIRST OF A KIND HEL-0 PROTOTYPE MANUFACTURING AND TESTING	Fri 9/23/22	**Fri 2/14/25**	581 days?	**15**
30.1 - Manufacturing, quality and reception	Fri 9/23/22	**Fri 9/22/23**	230 days	**17**
30.1- Magnet parts manufacturing and reception tests @ BINP	Fri 9/23/22	**Fri 9/22/23**	230 days	**17**
30.1 components manufacture and toling assembly	Fri 9/23/22	Fri 9/22/23	230 days	
30.1- Material reception and quality	Fri 9/23/22	Tue 3/21/23	120 days	
30.1- Cold power factory tests of sub assemblies magnets, validation test	Fri 12/2/22	Fri 9/22/23	180 days	21SS+50 days
30.2 Quality assurance review	**Fri 9/22/23**	**Mon 12/4/23**	**50 days**	**19**
30.2- Manufacturing plan review	Fri 9/22/23	Fri 10/13/23	15 days	
30.2- As-built 3D CAD manufacturing drawings review	Fri 10/13/23	Fri 11/3/23	15 days	25
30.2- Compilation of Phase III results and report (HP)	Mon 11/6/23	Mon 12/4/23	20 days	26
30.2- Shipment, pack list of HEL-0	Fri 9/22/23	Fri 11/3/23	30 days	23
30.3 HEL-0 Magnets commissionning tests @ CERN	**Fri 9/22/23**	**Thu 12/21/23**	**63 days**	**20**
30.3 Cool down test	Fri 9/22/23	Fri 11/3/23	30 days	
30.3 Power integrated test	Mon 11/6/23	Mon 12/11/23	25 days	30
30.3 Magnetic measurements	Mon 12/11/23	Thu 12/21/23	8 days	31
30.5 ITEMS AND SERVICES PROVIDED BY CERN	Fri 9/22/23	**Fri 2/14/25**	351 days?	
30.5- Magnetic Measurement Equipment	Fri 2/14/25	Fri 2/14/25	0 days	20,31,59
30.5 - NbTi busbar 600A	Fri 9/22/23	Mon 9/25/23	1 day?	21
40- PHASE IV - SERIES HEL-1-2 MANUFACTURING AND TESTING	**Mon 12/4/23**	**Thu 3/27/25**	**330 days**	**23**



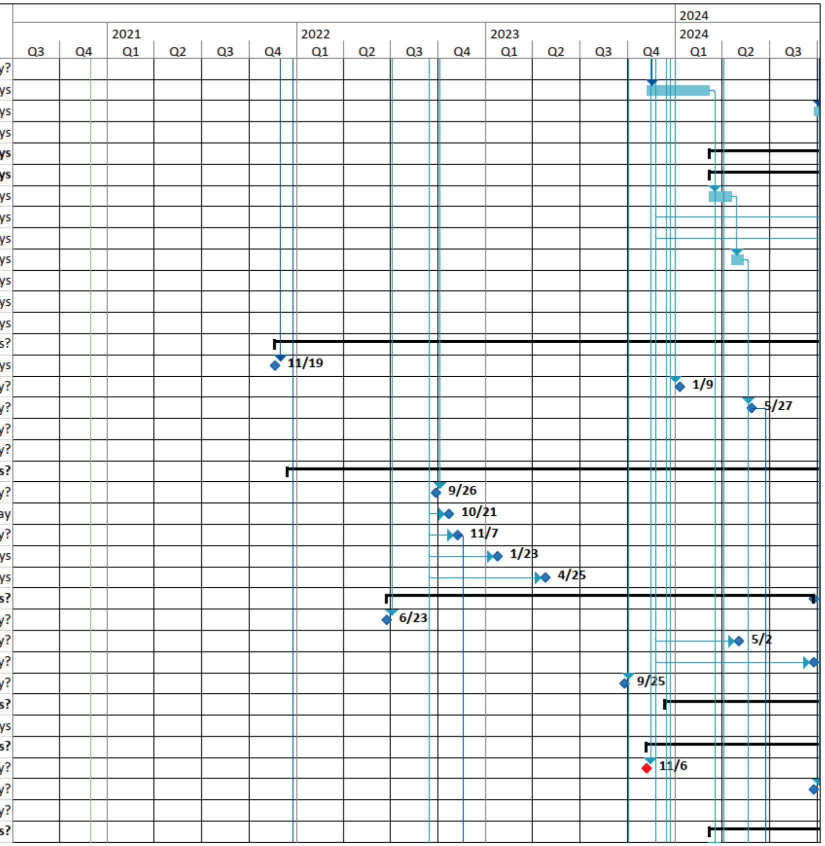
Baseline WP5 HEL Magnet Project v3.0

40- PHASE IV - SERIES HEL-1-2 MANUFACTURING AND TESTING	**Mon 12/4/23**	**Thu 3/27/25**	**330 days**
40.1- Magnet parts manufacturing quality and reception tests @ BINP	Mon 12/4/23	**Thu 2/27/25**	310 days
40.1 Magnet components manufacture for HEL-1, HEL-2	Mon 12/4/23	Thu 2/27/25	310 days
40.1- Material reception and quality	Mon 12/18/23	Fri 7/26/24	150 days
40.2- Cold power factory tests of sub assemblies magnets, validation test	Tue 2/6/24	Thu 2/13/25	260 days
40.2 Quality assurance review	**Fri 8/9/24**	**Thu 3/27/25**	**160 days**
40.2- Compilation of Phase IV results and report (HP)	Thu 2/27/25	Mon 3/17/25	12 days
40.2- Shipment, pack list of HEL-1	Fri 8/9/24	Mon 9/23/24	30 days
40.2- Shipment, pack list of HEL-2	Thu 2/13/25	Thu 3/27/25	30 days
50 - Phase V - Final HEL sub-systems in-cryostat assembly @ CERN	**Thu 10/20/22**	**Tue 6/24/25**	**651 days?**
Assembly of in cryostat tooling, building preparation	Thu 10/20/22	Fri 12/2/22	30 days
Reception of HEL-0 subassemblies, jigs, supports	Mon 11/6/23	Mon 11/6/23	1 day?
Reception of HEL-1 subassemblies, jigs, supports	Mon 9/23/24	Tue 9/24/24	1 day?



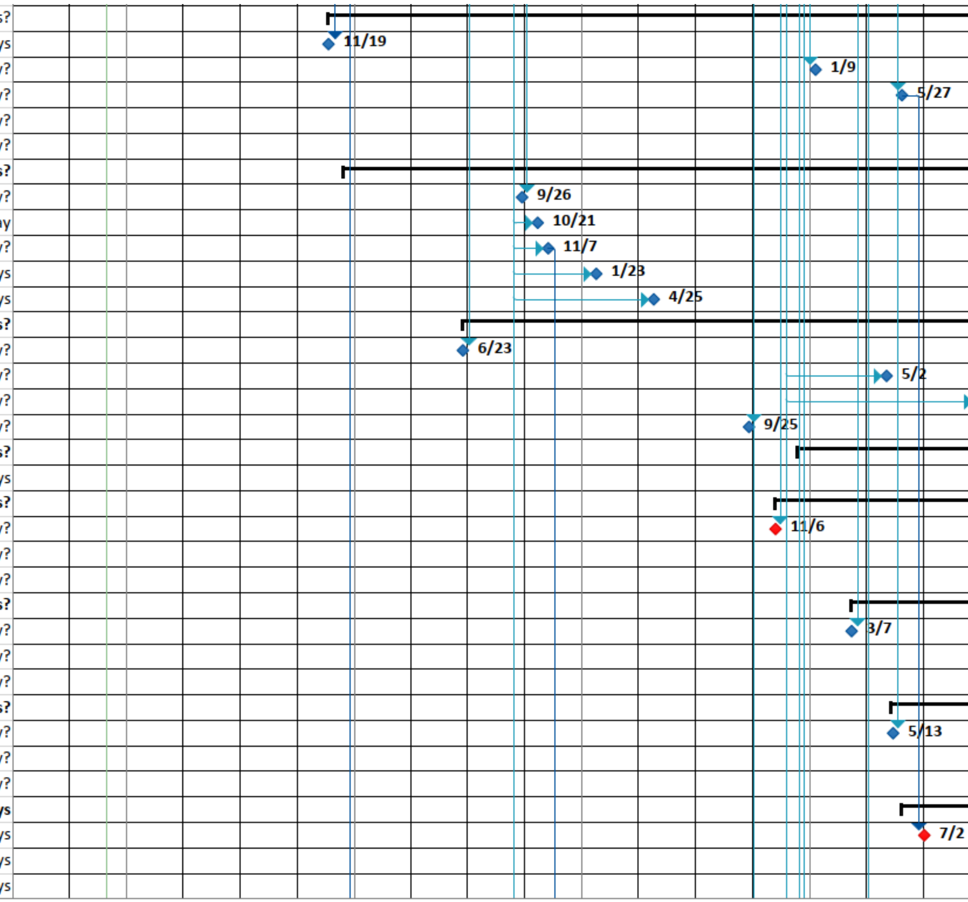
Baseline WP5 HEL Magnet Project v3.0

Nombre de tarea	Start	Finish	Duration
Reception of HEL-2 subassemblies, jigs, supports	Thu 3/27/25	Fri 3/28/25	1 day?
In cryostating operation, assembly of HEL-0	Tue 11/7/23	Wed 3/6/24	80 days
In cryostating operation, assembly of HEL-1	Tue 9/24/24	Thu 12/19/24	60 days
In cryostating operation, assembly of HEL-2	Mon 3/31/25	Tue 6/24/25	60 days
60- Phase VI - Cold power surface test by MSC	**Thu 3/7/24**	**Mon 9/1/25**	**378 days**
60.2 HEL-Series Magnets commissionning tests @CERN	**Thu 3/7/24**	**Mon 9/1/25**	**378 days**
60.2 - Cool down test HEL-0	Thu 3/7/24	Thu 4/18/24	30 days
60.2 - Cool down test HEL-1	Thu 12/19/24	Thu 1/23/25	25 days
60.2 - Cool down test HEL-2	Tue 6/24/25	Wed 7/30/25	25 days
60.2 - Power integrated test of HEL-0	Thu 4/18/24	Fri 5/10/24	15 days
60.2 - Power integrated test of HEL-1	Thu 1/23/25	Fri 2/14/25	15 days
60.2 - Power integrated test of HEL-2	Wed 7/30/25	Wed 8/20/25	15 days
60.2 - Magnetic measurements	Wed 8/20/25	Mon 9/1/25	8 days
MILESTONES	Fri 11/19/21	**Thu 8/21/25**	98.75 days?
M10 HEL 2D functional drawings sending by CERN	Fri 11/19/21	Fri 11/19/21	0 days
M11 Series Manufacturing Production readiness review	Tue 1/9/24	Tue 1/9/24	1 day?
M12 HEL-0 Readiness for Pit P4 installation	Fri 5/24/24	Mon 5/27/24	1 day?
M13 HEL-1 Readiness for Pit P4 installation	Fri 2/14/25	Mon 2/17/25	1 day?
M14 HEL-2 Readiness for Pit P4 installation	Wed 8/20/25	Thu 8/21/25	1 day?
PROGRESS MILESTONES	**Tue 12/14/21**	**Thu 9/18/25**	**02.75 days?**
M20- Integrated Engineering readiness review meeting	Fri 9/23/22	Mon 9/26/22	1 day?
M21- Completion of Practice HEL-0 solenoid mock up	Thu 10/20/22	Fri 10/21/22	1 day
M22- Completion of Practice HEL-0 Corrector coils mock up	Fri 11/4/22	Mon 11/7/22	1 day?
M23- Completion of HEL-0 Solenoid 01 and correctors	Mon 1/23/23	Mon 1/23/23	0 days
M24- Completion of HEL-0 Solenoid 02 and correctors	Tue 4/25/23	Tue 4/25/23	0 days
M25 - Assembly of HEL Magnets components	**Wed 6/22/22**	**Tue 9/24/24**	**31.63 days?**
M25.1 - Assembly complete of HEL-0 Magnets components	Wed 6/22/22	Thu 6/23/22	1 day?
M25.2 - Assembly complete of HEL-1 Magnets components>	Thu 5/2/24	Thu 5/2/24	1 day?
M25.3 - Assembly complete of HEL-2 Magnets components	Mon 9/23/24	Tue 9/24/24	1 day?
M26- Cryostating assembly	Fri 9/22/23	Mon 9/25/23	1 day?
M27- Completion of HEL cold power test in test-cryostat	**Mon 12/11/23**	**Thu 8/21/25**	**427 days?**
M28- Final magnetic measurements	Mon 9/1/25	Mon 9/1/25	0 days
M29-Packing and transport	**Mon 11/6/23**	**Fri 3/28/25**	**351 days?**
Shipment of HEL-0	Mon 11/6/23	Mon 11/6/23	1 day?
Shipment of HEL-1	Mon 9/23/24	Tue 9/24/24	1 day?
Shipment of HEL-2	Thu 3/27/25	Fri 3/28/25	1 day?
M30- Cryostating at CERN	**Thu 3/7/24**	**Wed 6/25/25**	**331 days?**



Main milestones

MILESTONES	Fri 11/19/21	**Thu 8/21/25**	98.75 days?
M10 HEL 2D functional drawings sending by CERN	Fri 11/19/21	Fri 11/19/21	0 days
M11 Series Manufacturing Production readiness review	Tue 1/9/24	Tue 1/9/24	1 day?
M12 HEL-0 Readiness for Pit P4 installation	Fri 5/24/24	Mon 5/27/24	1 day?
M13 HEL-1 Readiness for Pit P4 installation	Fri 2/14/25	Mon 2/17/25	1 day?
M14 HEL-2 Readiness for Pit P4 installation	Wed 8/20/25	Thu 8/21/25	1 day?
PROGRESS MILESTONES	**Tue 12/14/21**	**Thu 9/18/25**	**02.75 days?**
M20- Integrated Engineering readiness review meeting	Fri 9/23/22	Mon 9/26/22	1 day?
M21- Completion of Practice HEL-0 solenoid mock up	Thu 10/20/22	Fri 10/21/22	1 day
M22- Completion of Practice HEL-0 Corrector coils mock up	Fri 11/4/22	Mon 11/7/22	1 day?
M23- Completion of HEL-0 Solenoid 01 and correctors	Mon 1/23/23	Mon 1/23/23	0 days
M24- Completion of HEL-0 Solenoid 02 and correctors	Tue 4/25/23	Tue 4/25/23	0 days
M25 - Assembly of HEL Magnets components	**Wed 6/22/22**	**Tue 9/24/24**	**31.63 days?**
M25.1 - Assembly complete of HEL-0 Magnets components	Wed 6/22/22	Thu 6/23/22	1 day?
M25.2 - Assembly complete of HEL-1 Magnets components>	Thu 5/2/24	Thu 5/2/24	1 day?
M25.3 - Assembly complete of HEL-2 Magnets components	Mon 9/23/24	Tue 9/24/24	1 day?
M26- Cryostating assembly	Fri 9/22/23	Mon 9/25/23	1 day?
M27- Completion of HEL cold power test in test-cryostat	**Mon 12/11/23**	**Thu 8/21/25**	**427 days?**
M28- Final magnetic measurements	Mon 9/1/25	Mon 9/1/25	0 days
M29-Packing and transport	**Mon 11/6/23**	**Fri 3/28/25**	**351 days?**
Shipment of HEL-0	Mon 11/6/23	Mon 11/6/23	1 day?
Shipment of HEL-1	Mon 9/23/24	Tue 9/24/24	1 day?
Shipment of HEL-2	Thu 3/27/25	Fri 3/28/25	1 day?
M30- Cryostating at CERN	**Thu 3/7/24**	**Wed 6/25/25**	**331 days?**
HEL-0	Thu 3/7/24	Thu 3/7/24	1 day?
HEL-1	Thu 12/19/24	Fri 12/20/24	1 day?
HEL-2	Tue 6/24/25	Wed 6/25/25	1 day?
M31- Cold commisionning test at CERN	**Fri 5/10/24**	**Thu 8/21/25**	**326 days?**
HEL-0	Fri 5/10/24	Mon 5/13/24	1 day?
HEL-1	Fri 2/14/25	Mon 2/17/25	1 day?
HEL-2	Wed 8/20/25	Thu 8/21/25	1 day?
M32- Installation of two HEL units in LHC tunnel Pt4	**Mon 5/27/24**	**Thu 9/18/25**	**335 days**
HEL-0	Mon 5/27/24	Tue 7/2/24	25 days
HEL-1	Mon 2/17/25	Mon 3/17/25	20 days
HEL-2 availability	Thu 8/21/25	Thu 9/18/25	20 days



In-kind deliverables proposal

Project deliverables	Date
D1.1 - Manufacturing design files HEL-0 Magnets, cryostat	Thu 6/23/22
D1.2- One practice solenoid coil (trial full-scale coil built) with complete MTF traveller	Fri 10/20/23
D1.3 - One practice corrector coil (trial full-scale coil built) with complete MTF traveller	Mon 11/27/23
D1.4- Main solenoids assembly with complete MTF traveller	Mon 1/8/24
D1.5- Gun and collector solenoids assembly with complete MTF traveller	Tue 2/6/24
D1.6 - Assembly design files HEL-0 Magnets	Wed 8/28/24
D1.7 - Commissioning test summary report of HEL 0 main tooling	Fri 8/9/24
D1.8 - Completed HEL-0 Manufacturing and inspection plan	Wed 8/28/24
D1.9 - Commissionning test report of HEL-0 system	Fri 9/29/23
D1.10- Production readiness review outcome report approval	Fri 10/27/23
D1.11 - Assembly procedure report of HEL-0 system	Mon 11/27/23
D1.12 - Quality control and test reports	Wed 8/28/24
D1.13 - As-built 2D and 3D CAD manufacturing drawings of the HEL-0 magnet	Wed 8/28/24
D1.14 HEL Magnets complete MTF traveller and shipment file	Mon 10/9/23
D2.10 - Updated detailed schedule	Tue 12/14/21
D3.10 – Updated Quality Assurance plan	Fri 9/22/23

TE MSC resources

2021-2025

- MSC resource table (EDMS: 2469326) was revised since dec 2020 to include mandate of **coordination of HEL magnets construction and test** (details in back up slides). **Total estimate of 4.6 FTEs**

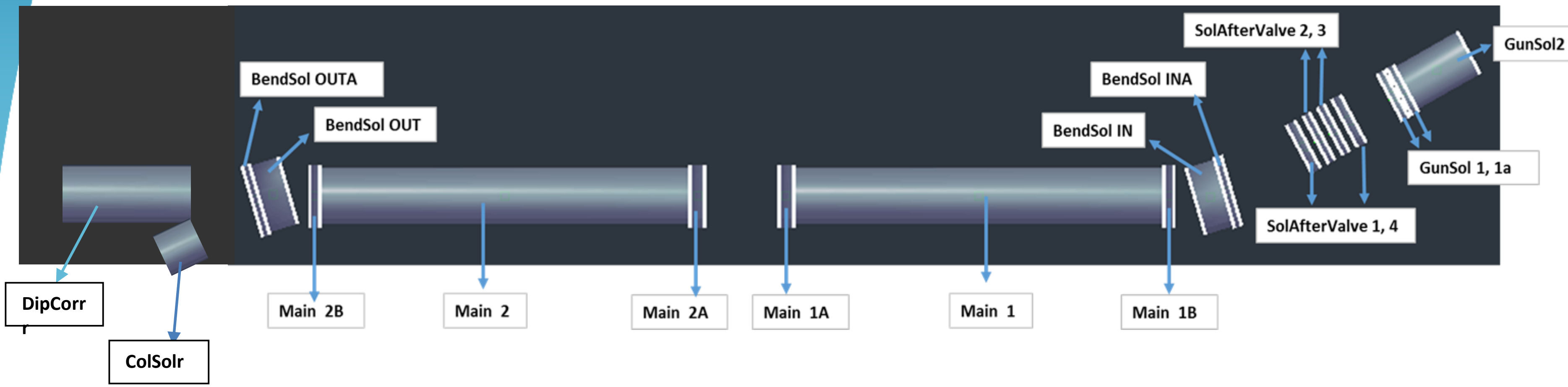
		2021	2022	2023	2024	2025	TE/MSC
Phase I- Preliminary conceptual design	CERN	**0.4**	-	-		-	0.4
Phase II- Manufacturing design		-	**0.3**	**0.1**		-	0.4
Phase III - First of Kind HEL -0 proto manufacture		-	-	**0.1**	**0**	-	0.1
Phase IV - Series HEL 1,2 manufacture		-	-	**0.2**	**0.3**	**0.1**	0.6
Phase V - Final HEL sub-systems in-cryostat assembly @ CERN		-	**0.2**	**0.2**	**0.3**	**0.2**	0.9
Phase VI - Cold power surface commisionning test @CERN		-	-	**0.5**	**0.6**	**0.2**	1.3
Phase VII- Tunnel Installation @ Pt 4		-	-	**0.4**	**0.3**	**0.2**	0.9
	total CERN FTE.y in TE	**0.4**	**0.5**	**1.5**	**1.5**	**0.7**	**4.6**
Input Eng.1 :	***total Russian PJAS FTE.y***	***0.6***	***0.5***	***2***	***2***	***1.5***	**6.6**

EDMS: 2469326

- Assumed BINP PJAS supervision at CERN site (~ 6.6 FTEs). **On site assembly team manpower estimate ~7-8 p for 3 years, to be confirmed by BINP**
- TE MSC eng.1 is in charge to coordinate the **HEL magnet functional specification, monitor the BINP design, the production packages, main deliverables and test interfaces**.
- TE MSC eng,tec.2 estimate (to be confirmed per mandate) in support as experts from sections (CMI, SCD, SMT, LMF, TM), involved in **approval of key procurements, procedure review, link persons, building assembly site coordination, magnetic test**.

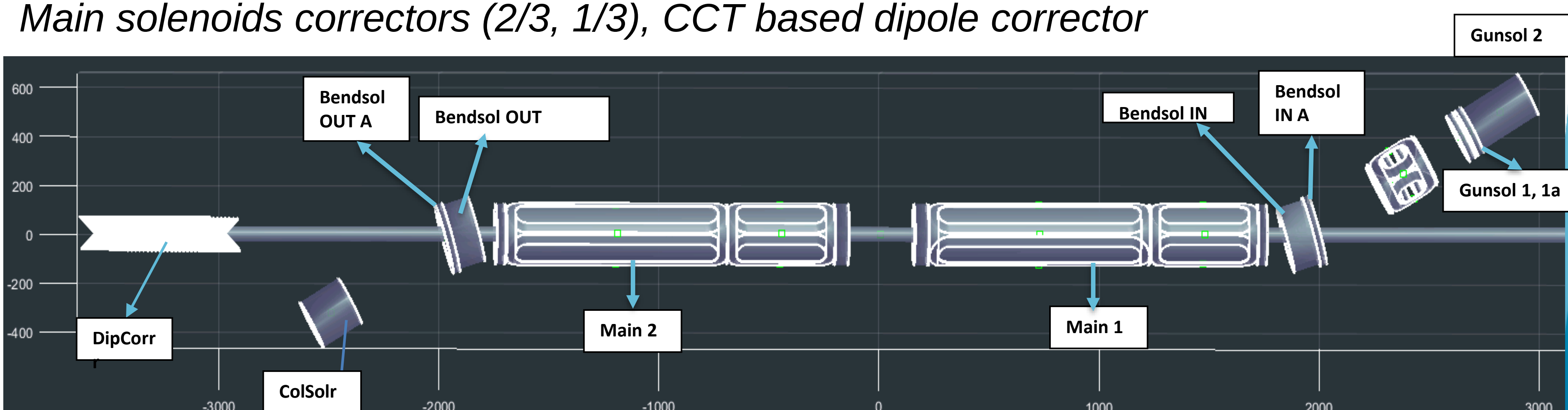
Update of magnetic model

2019 Magnetic model v.2

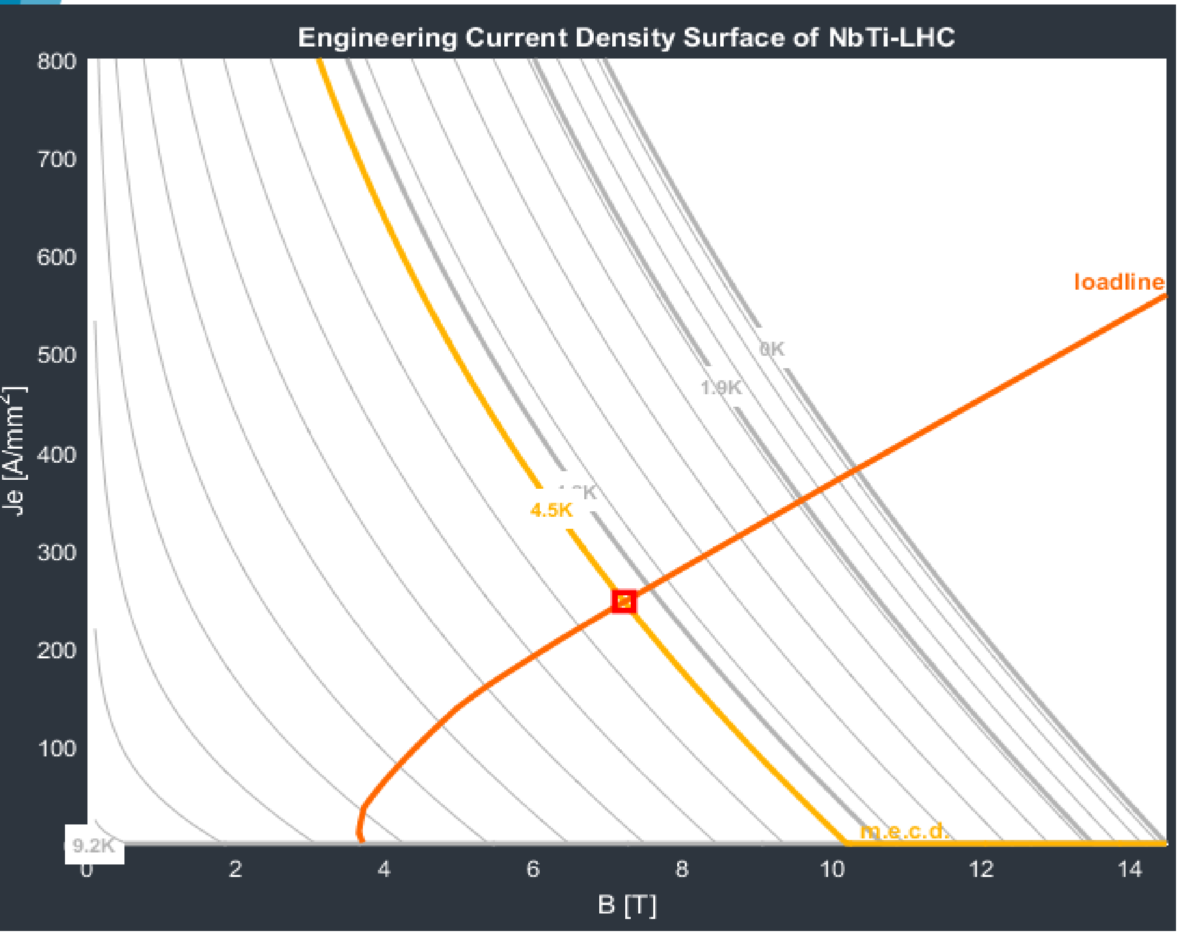


2020 Magnetic model v.3, (FIELD Package, A. Foussat)

Main solenoids correctors (2/3, 1/3), CCT based dipole corrector

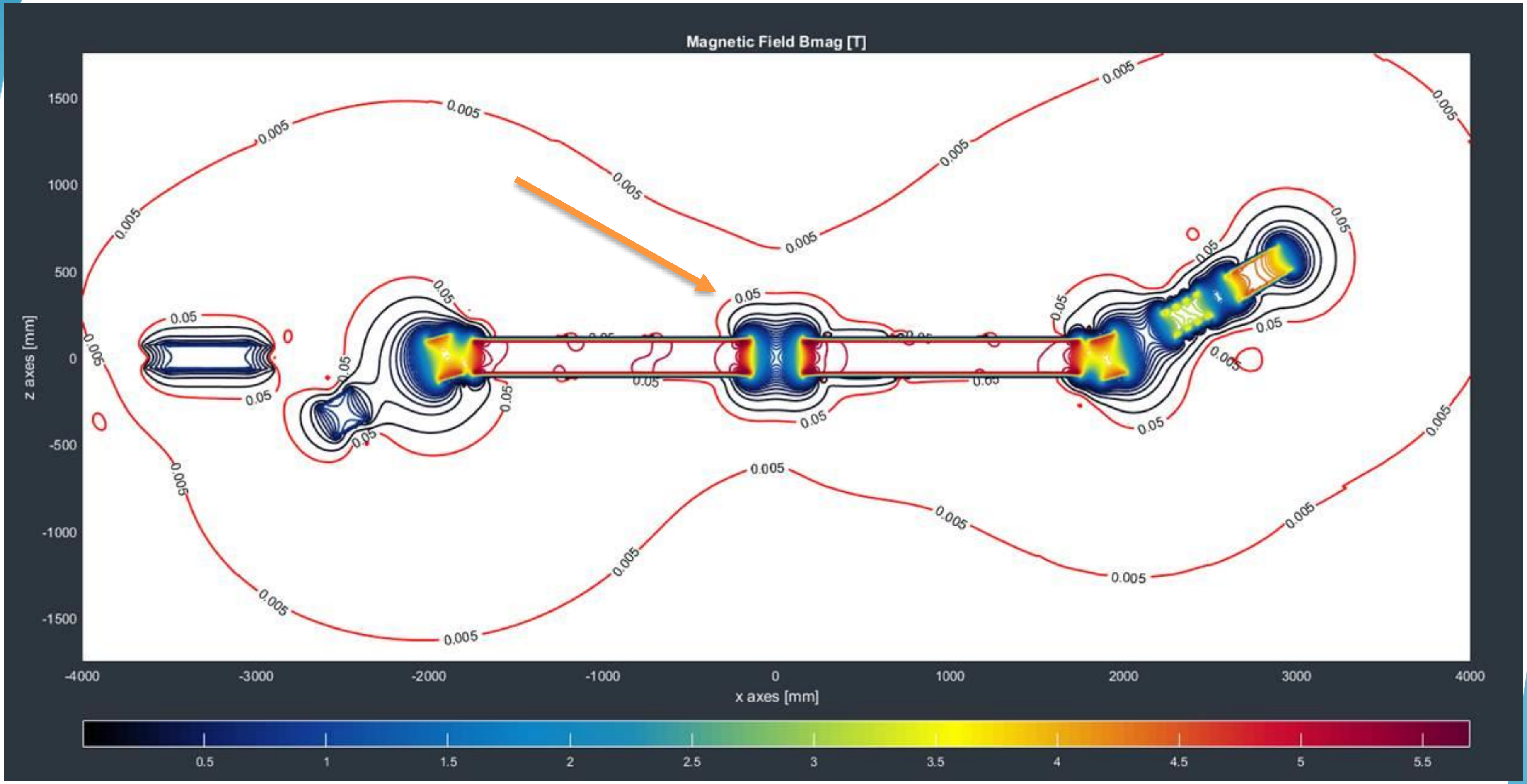


Main trim 1A (head of solenoid)



- NbTi 1.65 x 1.05 mm^2
- Jc (4.5K, 5T)= 2800 A/mm^2
- insulation thickness ~ 20 μm
- Cu/nCu ratio: 4:1
- In = 330 A
- Je = 191 A / mm^2
- Bp = 5.84 T
- Operation at I_{ss} at around 80 %.Iss
- Reduction of operating margin by 5% due to trim coil field enhancement

Stray magnetic field

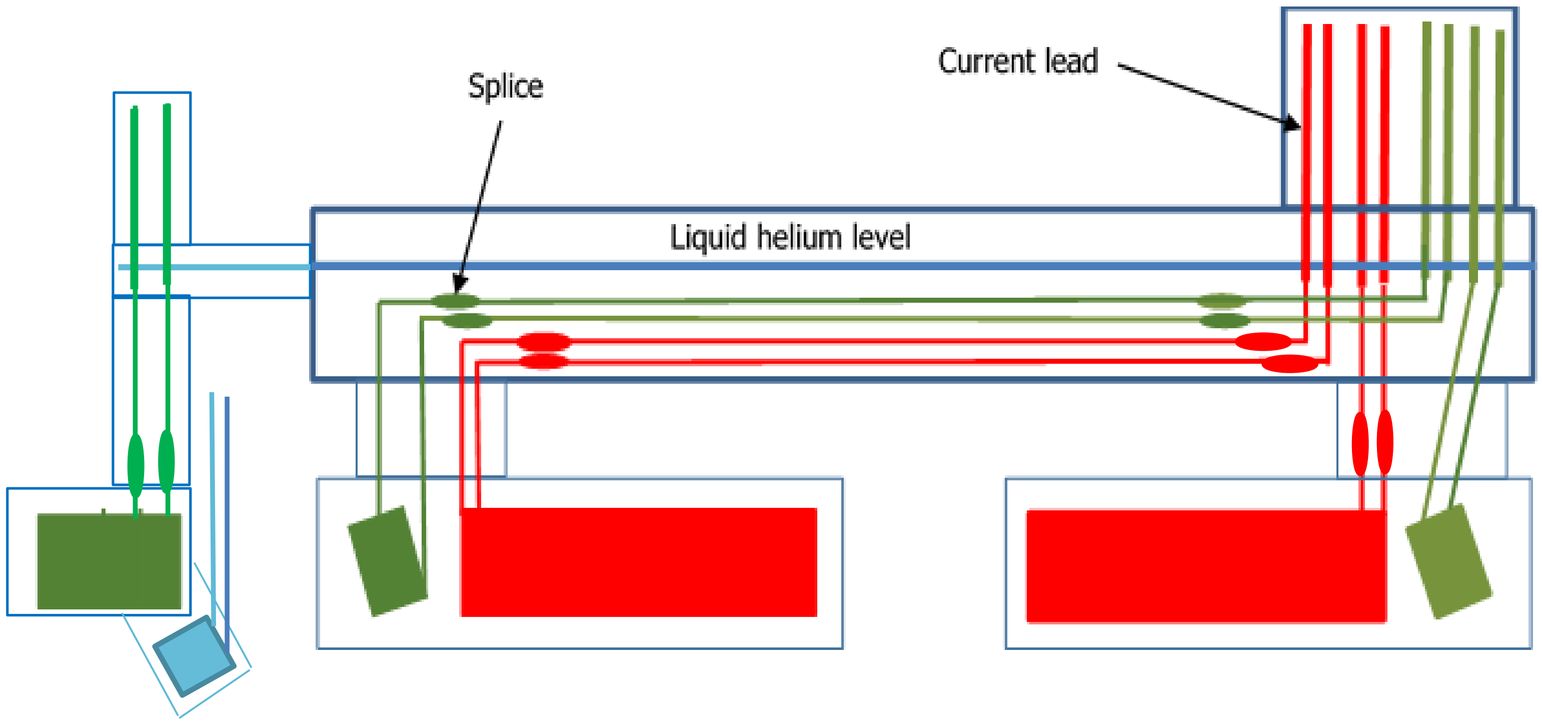


- The 5 mT limit line to be checked by WP5 HEL team wrt. Integration of Operating equipments

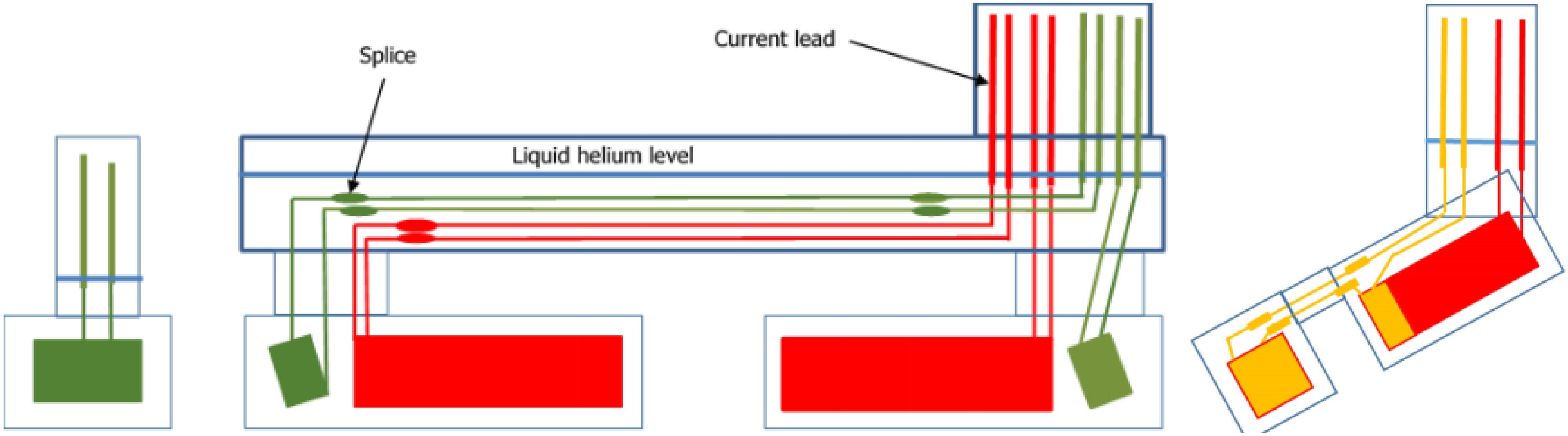
HiLumi HL-LHC PROJECT

Circuit definition as per 2019-2020

- **Main circuits** of the straight part (red) with the two main solenoids, I=350 A, the two tilted bending solenoids (green)



Updated Main Circuits per 2021

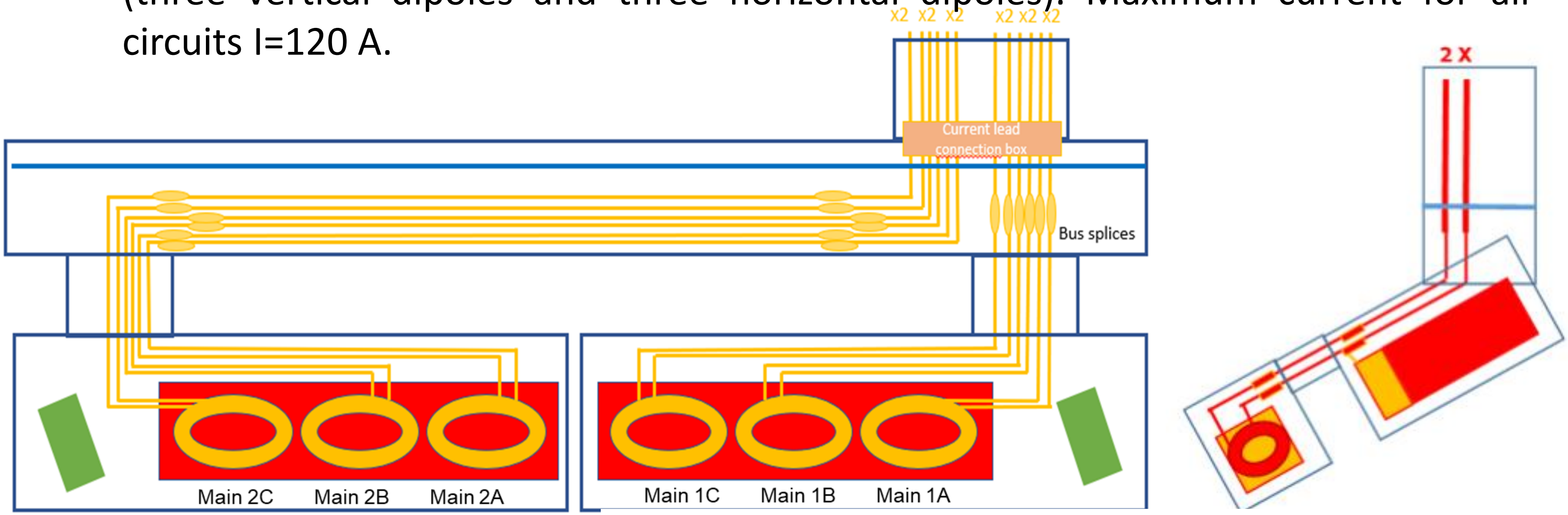


	Nominal current [A]	Inner bore diameter [mm]	Length [mm]	Inductance [mH] [2]	Number of turns	Insulated Cable size L [mm] x h [mm] / Cu:Sc, 15 microns insulation thick.
Main 1, 2	330	180	1500	**7728.5**	18180	1.65 x 1.05 / 4:1
Main 1A, 2A	330	180	61	**430.6**	1221	1.65 x 1.05 / 4:1
Main 1B, 2B	330	180	40	**206.6**	792	1.65 x 1.05 / 4:1
BendSol IN, OUT	335	226	120	**673.6**	1679	1.65 x 1.05 / 4:1
BendSol INA, OUTA SolAfterValve 1, 4	335 320	226 152	30 40	**125.5** **119.6**	576 744	1.65 x 1.05 / 4:1 1.65 x 1.05 / 4:1
SolAfterValve 2, 3	320	152	30	**72.4**	558	1.65 x 1.05 / 4:1
GunSol 1, 1A GunSol 2	320 9 - 257	152 152	30 290	**67.8** **833.9**	540 3344	1.65 x 1.05 / 4:1 1.65 x 1.05 / 4:1
ColSol	0-100	100	200	**382**	1731	1.65 x 1.05 / 4:1

*A Foussat, D, Perin: Main parameters of HEL electrical circuits, 2020, EDMS **2036694**

Updated Correctors Circuits per 2021

- Corrector circuits in the straight part. Six circuits in main solenoid one (three horizontal dipoles and three vertical dipoles), six circuits in main solenoid two (three vertical dipoles and three horizontal dipoles). Maximum current for all circuits I=120 A.



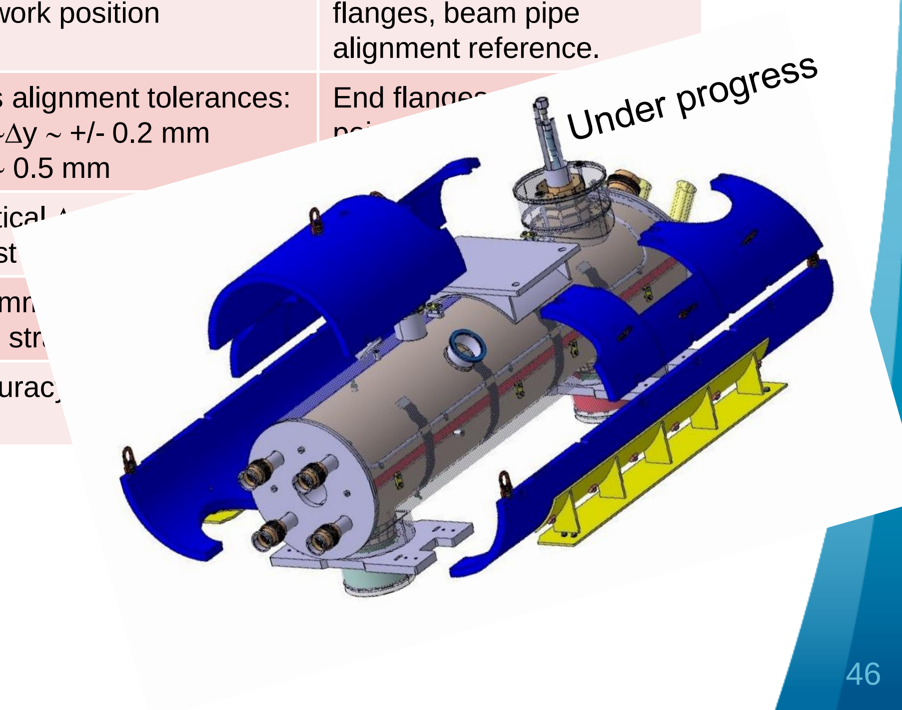
Main solenoids dipole H-V correctors
Main solenoids
Bent solenoids

	Maximum current [A]	Inductance [mH] [2]	Insulated Cable size L [mm] x h [mm] / Cu:Sc, 15 microns insulation thick.
M. Sol 1 – A hor. Dipole	120	3.8	1.65 x 1.05 / 4:1
M. Sol 1 – B hor. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 1 – C hor. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 1 – A vert. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 1 – B vert. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 1 – C vert. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – A hor. Dipole	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – B hor. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – C hor. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – A vert. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – B vert. dip.	120	3.8	1.65 x 1.05 / 4:1
M. Sol 2 – C vert. dip.	120	3.8	1.65 x 1.05 / 4:1
e-gun 2 – vert. dipole	120	27	1.65 x 1.05 / 4:1
e-gun 2 – hor. dipole	120	27	1.65 x 1.05 / 4:1

Built to specifications Survey criteria

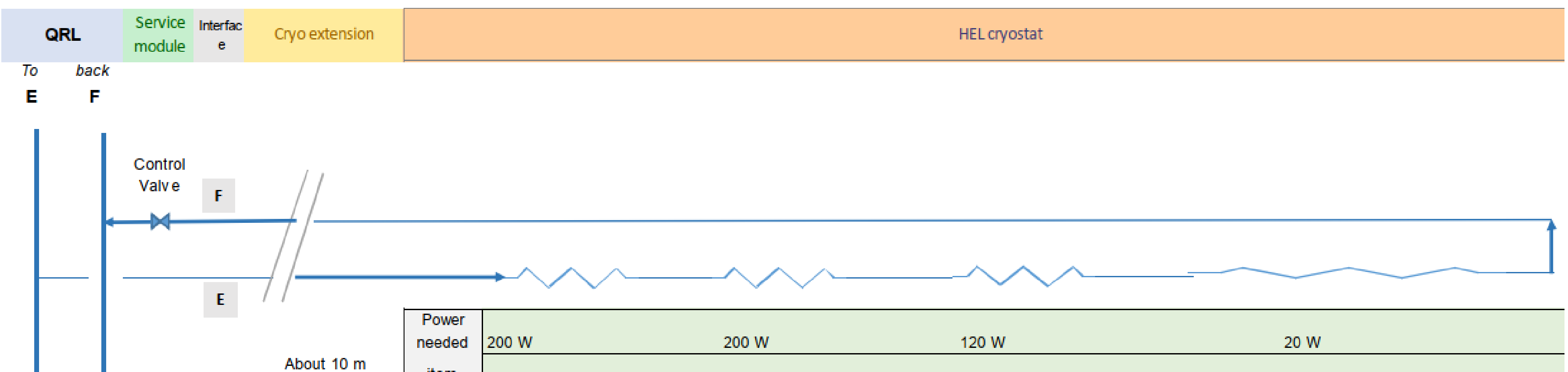
WGA meeting, on 31st March 2021. Preliminary discussion

Main step actions	Responsible of survey exécution *	Criteria	Design features
Individual solenoid, sub assemblies end flanges, former geometry	BINP	Assembly tolerances : +/- 0.2 mm	Marks on coil former ends and global survey
Individual solenoid, sub assemblies **RT magnetic axis measurement,**	BINP	+/- 0.1 mm field lines straightness	Marks on coil former ends (3)
Cold mass assembly interfaces, **RT magnetic axis transfer**	BINP	+/- 0.2 mm transfer accuracy	Marks on cold mass ends (3), shells (2).
Cryostating, **warm MM axis measurement check, axis transfer**	BINP, CERN	+/- 0.1 mm accuracy network position	Marks on cryostat end flanges, beam pipe alignment reference.
Assembly of HEL units on surface, **alignment of sub-cryostat virtual magnetic axis**, adjustment jacking.	CERN	Axis alignment tolerances: Δx ~Δy ~ +/- 0.2 mm Δz ~ 0.5 mm	End flang
Check of assembly girder deformation	CERN	Vertical Twist	
MM cold test of HEL unit	CERN	0.2 mm axis str	
Construction of HEL unit survey network for installation	CERN	Accurac	



Cooling circuit heat load technical specification

- Total specified heat loat budget at 77 K : 500 W
- Total specified heat loat budget at 4 K : 20 W
- On going definition of 77K thermal load budget for thermal shields and gas cooled currrent lead circuit



Power needed	200 W	200 W	120 W	20 W
item	CL tower1	CL tower2	CL tower3	Thermal shielding + Multilayer (>=10 layers)

interface	Pressure [bar]			Temperature [K]			Mass flow [g* s⁻¹]		Cooling power [W]	
	Nominal	Reduced	Maximum	Nominal	Reduced	Maximum	nominal	maximum	nominal	maximum
E	18	15	19	70	60	80	8	10	419	524
F	17	14	18.1	~80	~70	~90				

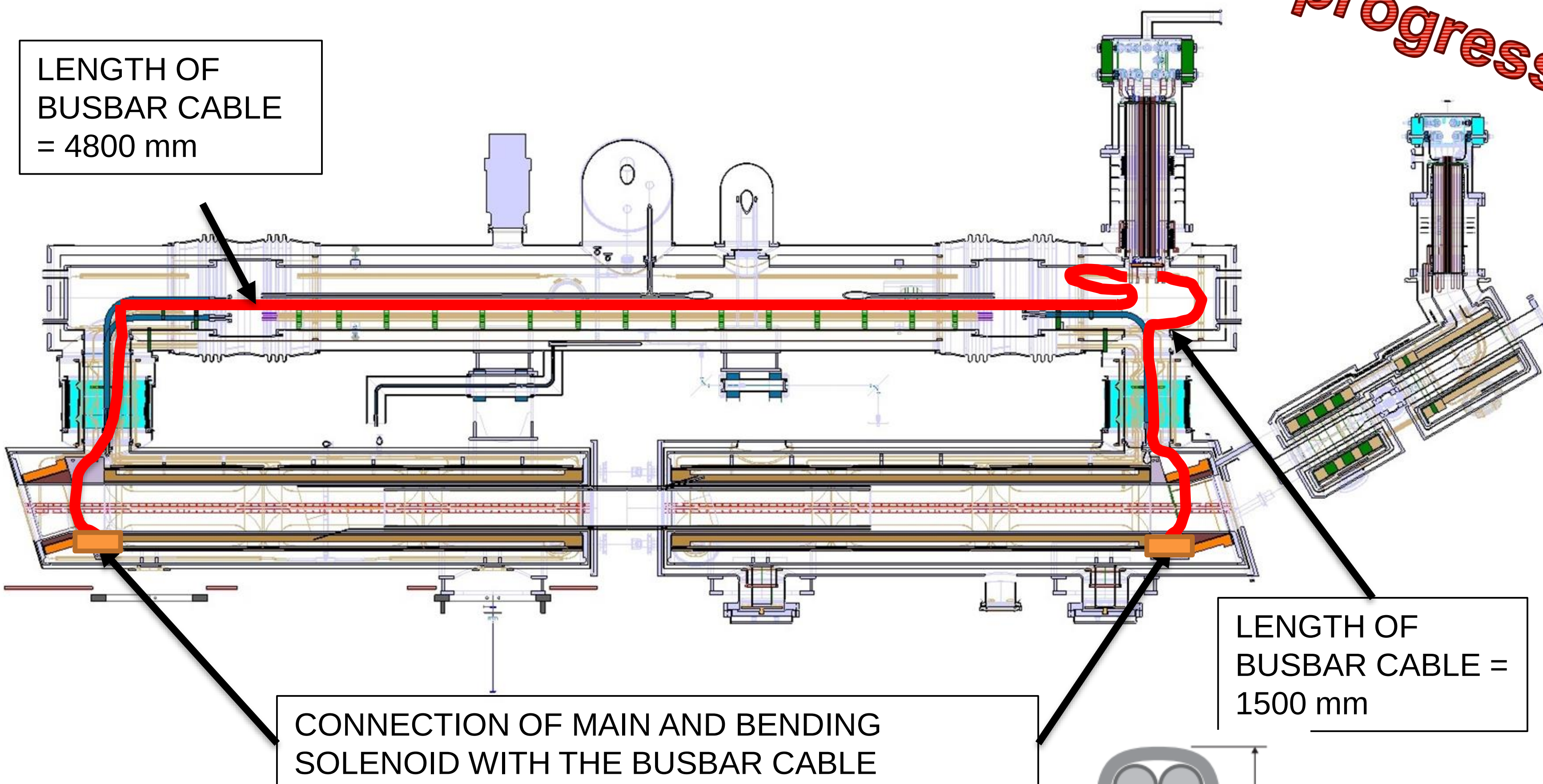
Courtesy of FG Ferlin TE CRG

HiLumi HL-LHC PROJECT

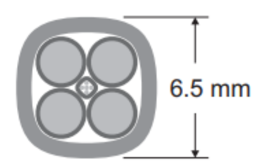
HEL electrical Mains circuit busbars

MAIN AND BENDING SOLENOID BUS ROUTING

On progress

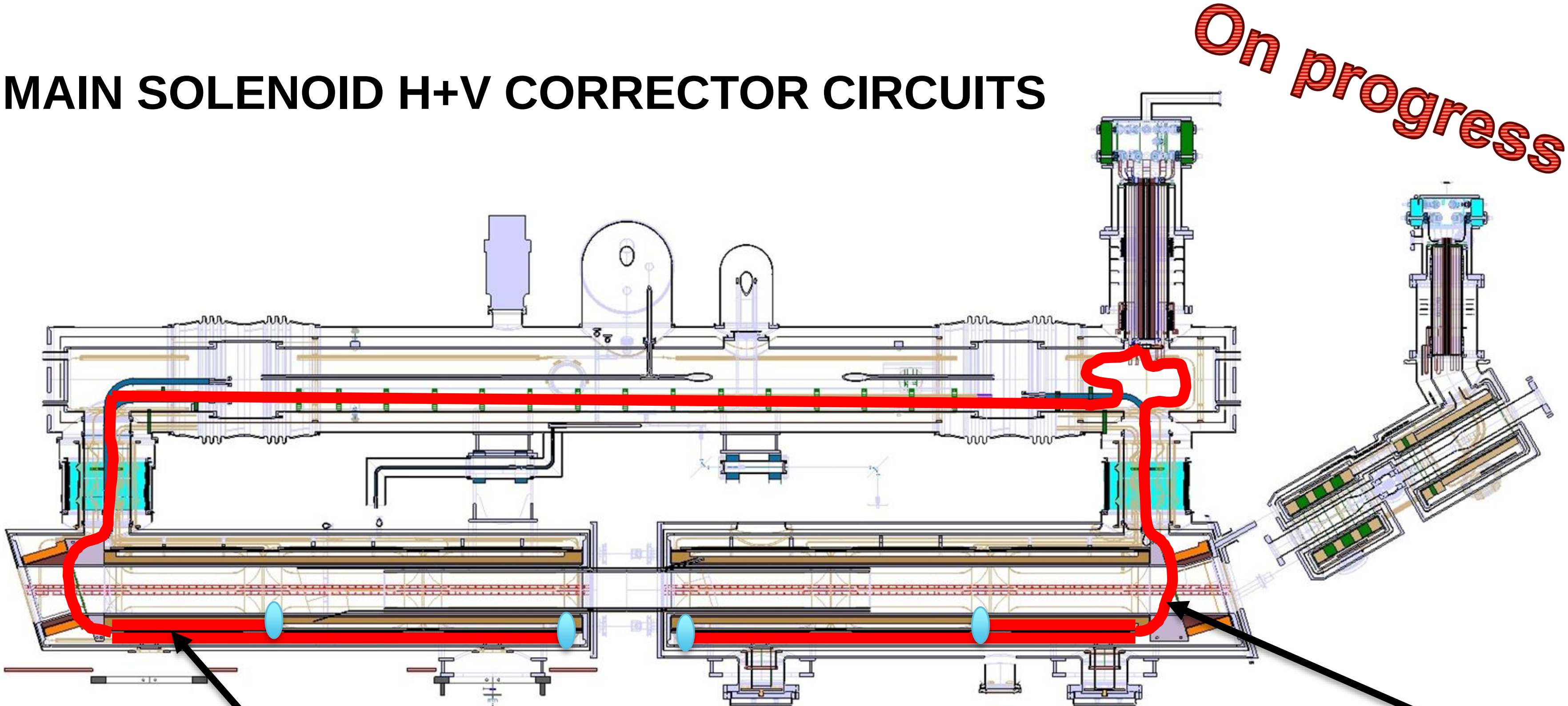


600 A LHC NbTi busbar type
Total of 80 m need.



HEL electrical Correctors circuit interface

MAIN SOLENOID H+V CORRECTOR CIRCUITS

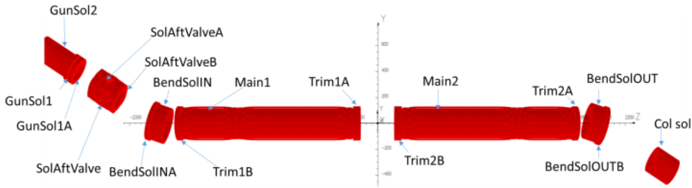


TWO BUSBAR CABLES:
- 5400 mm
- 6400 mm

TWO BUSBAR CABLES
- 2100 mm
- 3100 mm

Magnet system Load specifications

- Benchmarked nominal load table based on BINP and CERN magnetic models



EDMS 2479912

	Center of solenoid			Integral forces for coils (components and modul)				Torque for coils (for center of element)			
Name (Coil name in LP file)	X[mm]	Y[mm]	Z[mm]	Fx[N]	Fy[N]	Fz[N]	Fs[N]	Tx[N mm]	Tx[N mm]	Tz[N mm]	Ts[N mm]
Gun_Sol_L (Coil 9)	0	504.3751	-2813.15	-5.97E-12	-2450.31793	4243.89667	4900.481	172.744134	1.14E-12	-2.77E-11	172.744
Gun_Sol_S (Coil 8)	0	424.1001	-2674.11	-3.46E-11	-32414.3002	56141.9901	64827.540	1328.25473	-4.58E-09	2.86E-09	1328.255
Gun_Sol_1 (Coil 5)	0	401.75	-2635.39	-4.68E-11	28202.494	-48848.3572	56405.165	1447.80599	1.22E+00	-5.10E-09	1447.807
Gun_Sol_2 (Coil 1)	0	299.4251	-2458.16	1.84E-10	-31165.0956	53990.8811	62340.023	1438.68647	3.82E-10	-8.26E-09	1438.686
Gun_Sol_3 (Coil 18)	0	263.5501	-2396.03	-6.09E-11	-2221.13298	3869.36145	4461.546	965.666663	6.59E-11	-2.61E-11	965.667
Gun_Sol_4 (Coil 17)	0	230.1501	-2338.17	5.32E-11	2177.26234	-3714.41275	4305.500	370.872938	-4.87E-10	-3.39E-10	370.873
Gun_Sol_5 (Coil 16)	0	194.2751	-2276.04	6.37E-12	32298.5143	-55726.39	64409.817	-1514.92296	6.98E-09	3.08E-09	1514.923
				9.54E-11	-5.57E+03	**9956.96938**					
Bending_Sol_1_S (Coil 15)	0	17.3451	-1970.57	-2.22E-10	-69363.5848	250443.677	259871.781	-52072.5423	-2.59E-08	-4.10E-08	52072.542
Bendimg_Sol_1_L (Coil 3)	0	-4.2371	-1898.64	1.16E-09	81541.8398	-121630.896	146434.786	-70879.6697	1.02E-08	1.16E-08	70879.670
				9.42E-10	1.22E+04	**128812.781**					
Trim_IN_Main_1 (Coil 11)	0	0	-1730.75	-2.31E-10	-1972.96793	162785.213	162797.168	-768902.826	9.02E-09	-7.20E-12	768902.826
Main_1 (Coil 6)	0	0	-960.95	-6.64E-09	-4597.59347	19143.2498	19687.607	-3514428.09	2.50E-08	6.02E-12	3514428.090
Trim_Out_Main_1 (Coil 7)	0	0	-180.425	4.40E-10	-4.53141725	-295153.785	295153.785	-5846.59764	-5.63E-08	-6.34E-12	5846.598
				-6.43E-09	-6575.09282	**-113225.323**					
Trim_IN_Main_2 (Coil 13)	0	0	180.525	9.28E-11	2.6486951	295137.221	295137.221	-1968.27528	2.06E-06	-1.14E-11	1968.275
Main_2 (Coil 12)	0	0	961.05	-5.76E-09	5059.81021	-20756.5268	21364.341	-3864397.29	-2.44E-08	-2.60E-10	3864397.290
Trim_Out_Main_2 (Coil 10)	0	0	1730.85	-6.40E-10	2239.29286	-163251.745	163267.102	-803896.135	3.21E-08	-5.84E-12	803896.135
				-6.31E-09	7301.75176	**111128.949**					
Bending_Sol_2_L (Coil 14)	0	4.2458	1898.608	1.07E-09	-78959.33	117271.165	141375.747	-174087.888	1.28E-08	-1.89E-09	174087.888
Bending_Sol_2_S (Coil 4)	0	-17.3278	1970.517	5.28E-11	71093.2619	-253017.304	262815.540	-100660.373	-4.07E-08	2.91E-10	100660.373
				0.0	**-7866.1**	**-135746.1**					
Colector_Sol (Coil 2)	0	-323	2498.996	1.63E-10	531.534708	-927.33387	1068.867	1241.40866	-1.44E-10	-2.68E-11	1241.409