HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

REQUIREMENTS FOR SEPARATION DIPOLES

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30 November 2012

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HILUMI LHC

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MILESTONE REPORT

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In this document we summarize the main requirements for the separation dipoles, and a baseline for the layout with possible options

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Delivery Slip

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Executive summary

In this report we give an overview of the requirements for the inner triplet quadrupoles stemming from beam dynamics and we compare with the present status of the development of Nb_3Sn *models built by LARP.*

1. INTRODUCTION

The High Luminosity LHC (HL- LHC) design study has to produce a baseline for the layout of magnets in the Interaction Regions (IR). The new lattice has the main goal of having larger aperture inner triplet quadrupoles to allow squeezing the beam up to ~15 cm. The lattice also includes larger aperture separation dipoles, recombination dipoles, and two-in-one quadrupoles. The separation dipoles D1 will rely on Nb-Ti technology. The main challenges of this magnet are the large aperture, the high level of saturation, and the good field quality.

Here we give the main requirements for the separation dipoles, and a baseline for the layout with possible options.

2. SEPARATION DIPOLE REQUIREMENTS AND DESIGN TARGETS

2.1 PERFORMANCE

In July 2012 the aperture of the triplet has been fixed to 150 mm diameter coil-to-coil [1], based on a first estimate of the shielding necessary to cope with radiation damage and heat loads, and on the beam dynamics requirements. The aperture of D1 has been required to be 10 mm larger than the triplet, i.e. 160 mm.

Integrated field is 40 T m, i.e. 50% more than present value of 26 T m, to reduce the space between D1 and D2, making room for crab cavities and reducing the number of parasitic encounters. This specification could be possibly lowered by 5-15% in 2013.

We specify a relatively large margin on the loadline of 30%. The following targets will be used to evaluate the dipole performance:

- First training to nominal gradient: less than four quenches.
- Training to ultimate gradient: less than ten additional quenches.
- Training after thermal cycle: nominal gradient reached with one quench or without quench.

These targets are based on the experience of the LHC magnet production.

2.2 FIELD QUALITY

- Reproducibility of the Transfer Function (TF): must be of the order of 1 unit or better along the whole operational range.
- Geometric multipoles: the target errors are given in Table 1.
    - The random component is estimated on a tentative cross-section (see next section) with 40 μm standard deviation in the coil positioning for odd normal multipoles, 40 μm for even skew multipoles, 15 μm for odd skew multipoles, and 10 μm for odd skew multipoles. This ambitious target is based on the experience of the dipole productions of LHC, HERA, RHIC and Tevatron.
    - The systematic component is optimized at high field. The saturation component in b_3 is minimized by shaping the iron. The residual 0.9 units of saturation is compensated by -1.8 units of geometric.
- Persistent currents: the present estimate is -14 units of b_3 and -1 units of b_5.

Table 1 Target field errors

	Separation dipole field quality version 1 - November 6 2012								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	0.000	0.000	0.000	0.000	0.000	0.200	0.200	0.200	0.200
3	-1.800	0.900	-14.200	-16.000	-0.900	0.727	0.727	0.727	0.727
4	0.000	0.000	0.000	0.000	0.000	0.126	0.126	0.126	0.126
5	0.500	-0.500	-1.000	-0.500	0.000	0.365	0.365	0.365	0.365
6	0.000	0.000	0.000	0.000	0.000	0.060	0.060	0.060	0.060
7	1.600	-1.200	-0.700	0.900	0.400	0.165	0.165	0.165	0.165
8	0.000	0.000	0.000	0.000	0.000	0.027	0.027	0.027	0.027
9	-0.680	0.090	0.020	-0.660	-0.590	0.065	0.065	0.065	0.065
10	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.008	0.008
11	0.440	0.030	0.000	0.440	0.470	0.019	0.019	0.019	0.019
12	0.000	0.000	0.000	0.000	0.000	0.003	0.003	0.003	0.003
13	0.000	0.000	0.000	0.000	0.000	0.006	0.006	0.006	0.006
14	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001
15	-0.040	0.000	0.000	-0.040	-0.040	0.002	0.002	0.002	0.002
Skew									
2	0.000	0.000	0.000	0.000	0.000	0.679	0.679	0.679	0.679
3	0.000	0.000	0.000	0.000	0.000	0.282	0.282	0.282	0.282
4	0.000	0.000	0.000	0.000	0.000	0.444	0.444	0.444	0.444
5	0.000	0.000	0.000	0.000	0.000	0.152	0.152	0.152	0.152
6	0.000	0.000	0.000	0.000	0.000	0.176	0.176	0.176	0.176
7	0.000	0.000	0.000	0.000	0.000	0.057	0.057	0.057	0.057
8	0.000	0.000	0.000	0.000	0.000	0.061	0.061	0.061	0.061
9	0.000	0.000	0.000	0.000	0.000	0.020	0.020	0.020	0.020
10	0.000	0.000	0.000	0.000	0.000	0.025	0.025	0.025	0.025
11	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.007	0.007
12	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.008	0.008
13	0.000	0.000	0.000	0.000	0.000	0.002	0.002	0.002	0.002
14	0.000	0.000	0.000	0.000	0.000	0.003	0.003	0.003	0.003
15	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001

2.3 PROTECTION

- Compensated voltage used for magnet protection (difference between two poles) should be stable within 100 mV during the ramp at nominal ramp rate.
- We set a target for the maximum hotspot temperature of 300 K.

2.4 RADIATION DAMAGE AND HEAT LOADS

The current design targets for the triplet are a peak radiation dose of less than 40 MGy over the operational lifetime of HL-LHC (3000 fb^{-1} integrated luminosity). This will be probably reviewed in 2013, and could be further lowered by optimization of the shielding and aperture. Heat loads are of the order of 10 W/m on the magnet and the same on the beam screen. The same values can be assumed for the separation dipole. A simulation of the actual layout will be available in 2013.

2.5 MECHANICAL STRUCTURE

We aim at having less than 150 MPa during assembly cool-down and powering to avoid damage to insulation.

3. DESIGN OPTIONS FOR THE SEPARATION DIPOLE

3.1 A POSSIBLE BASELINE

We chose a one-layer coil with the 15 mm width cable used in the LHC main dipole, inner layer (see Fig. 1). With this cable one obtains

- 5.44 T operational field;
- 7.35 m magnetic length;
- 13.9 kA operational current;
- 1495 A/mm^2 current density in the non-Cu (see Fig. 2);
- 600 m long cable for manufacturing one pole.
- 48 mT fringe field just outside the cryostat.

The unit length is longer than the LHC dipole inner cable unit length (480 m) therefore new cables should be made, with new strand ordered with the specifications of LHC main dipole inner layer. This could take up to two years, but the short model could be already manufactured with existing lengths. The alternative is to have a splice between the first and the second block. Cable dimensions are already well known and therefore engineering design could start without additional delays.

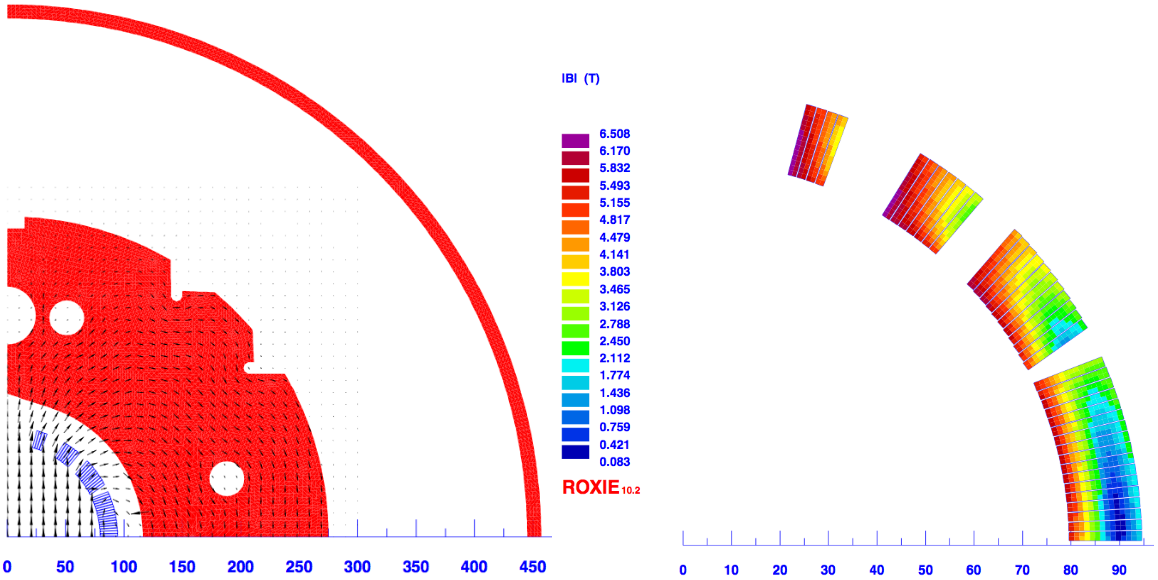

Fig. 1 Cross section of the magnet (left) and of the coil (right)

Pro:

- Cable is well known, both in terms of width and windability. Reduced time for development of engineering design.
- Operational current within the limits of KEK test station (15 kA), possible to reach 90% short sample.
- Quench protection could be viable without heaters.

Cons:

- New order of strand and cabling to get the required length for manufacturing the series magnets or internal splice;
- Not fitting the length of the vertical test station.

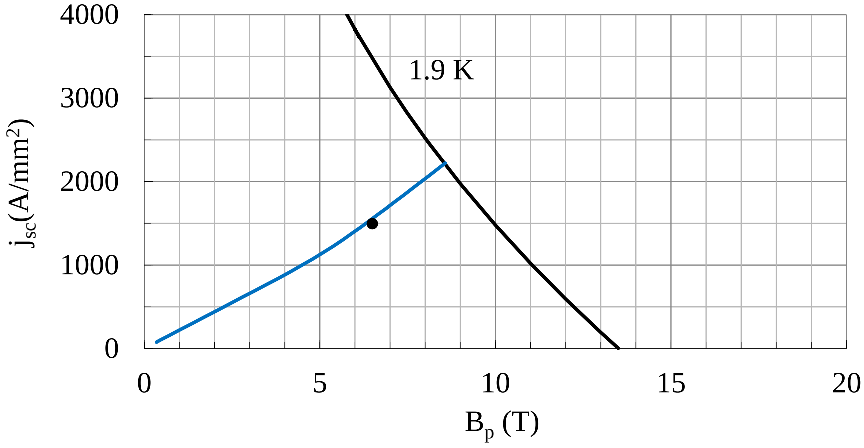

Fig. 2 Non-Cu critical current density (triangular markers), loadline for the peak field in the coil (solid line) and operational point (round marker).

3.2 FIRST VARIANT: OUTER LAYER DIPOLE CABLE

If we choose the outer layer of the LHC dipole the field is reduced by 5% (5.23 T), length is increased of the same percentage (7.65 m).

- 5.23 T operational field (-5%);
- 7.65 m magnetic length (+5%, +30 cm);
- 11.0 kA operational current;
- 1710 A/mm^2 current density in the non-Cu;
- 750 m long cable for manufacturing one pole.
- 40 mT fringe field just outside the cryostat.

Pro:

- Cable is ready and well known, both in terms of width and windability;
- Unit lengths are available;
- Current within the limits of test station (15 kA), possible to reach 100% short sample.

Cons:

- Not fitting the length of the vertical test station with present requirements;
- Heaters needed for quench protection

3.3 SECOND VARIANT: 20 MM WIDTH CABLE

If we choose to increase the cable width to 20 mm, the field is increased by 5% (5.90 T), length is reduced of the same percentage (6.78 m).

- 5.90 T operational field (+10%);
- 6.78 m magnetic length (-8%, -50 cm);
- 15.8 kA operational current;
- 1290 A/mm^2 current density in the non-Cu;
- 554 m long cable for manufacturing one pole.
- 80 mT fringe field just outside the cryostat.

Pro:

- Lower loadline, lower current density.

Neutral

- Not fitting the length of the vertical test station with present requirements, but just at the limit.

Cons:

- Cable to develop, delays in engineering design;
- Current above the limits of test station (15 kA);
- Larger fringe field.

3.4 RADIATION DAMAGE

The weakest component of the magnet is the insulation of the coils. An assessment of the radiation damage level should be given, and an estimate of the expected dose will be provided through FLUKA simulations in 2013.

3.5 MECHANICAL DESIGN

All options have stress lower than 150 MPa in assembly, cool down, and powering. The favorite structure is an option where collars are spacers and stress is given by the yoke, as in MQXA. This has the advantage of reducing the collar thickness, giving more space for iron and reducing the fringe field. An alternative option would be the self-standing collars as in MQXB and MQXC.

4. CONCLUSIONS AND FUTURE PLANS

The magnet is built with a large margin. The critical aspects are field quality and fringe field. The optimization of engineering constraints as test station length, cable and strand availability, magnet weight, margin and protection will allow to choose between the different options in a few months. An essential ingredient is the heat load and the radiation dose, which need a full model rom the IP to D1, including the corrector package.

5. REFERENCES

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ANNEX: GLOSSARY

Acronym	Definition
LHC	Large Hadron Collider
HL-LHC	High Luminosity LHC
IR	Interaction Regions
LARP	LHC Accelerator Research Program
DOE	Department of Energy
US	United States (of America)
PIT	Power In Tube (type of Nb3Sn conductor)
RRP	Restack Rod Process (type of Nb3Sn conductor)
RRR	Residual Resistivity Ratio (ratio between 300 K and 1.9 K resistivity of copper)
HQ	High field Quadrupole: 120 mm aperture, 1-m-long quadrupole built by LARP
TQ	Technological Quadrupole: 90 mm aperture, 1-m-long quadrupole built by LARP
LQ	Long Quadrupole: 90 mm aperture, 3.4-m-long quadrupole built by LARP
MQXA,MQXB	Inner triplet quadrupoles currently installed in the LHC
MB	Main Bending: main dipoles of the LHC
MQXF	Nb3Sn quadrupole for the HL-LHC inner triplet