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HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

REQUIREMENTS FOR NB3SN INNER TRIPLET AND COMPARISON WITH PRESENT STATE OF THE ART

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MILESTONE REPORT

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Abstract:

In this document we summarize the requirements for the inner triplet quadrupole in the HL-LHC project versus the present status of art of the Nb_3Sn magnets as developed by the US-LARP collaboration.

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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 β^*~15 cm. The lattice also includes larger aperture separation dipoles and two-in-one quadrupoles. The quadrupoles will exploit the Nb_3Sn superconductive technology, allowing a more compact triplet w.r.t Nb-Ti. The design study relies on the 10 year activity of LHC Accelerator Research Program (LARP) supported by US-DOE.

Here we give the main requirements for the inner triplet quadrupole in terms of aperture, gradient, field quality, protection, and radiation resistance. The values are based on the beam dynamics requirements in terms of particle stability and operation. The comparison is done to the wide experience gained on the quadrupole models built by LARP.

2. INNER TRIPLET 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 magnet will have QXF as generic nickname.

Nominal gradient is 140 T/m at 1.9 K operational temperature. This value is set to have ~20% margin on the load line with the specified strand of 0.85 mm diameter, a 40 strand cable, and a critical current in the non-Cu of 2000 A/mm^2 at 15 T and 1.9 K (see Fig. 1). The 20% margin is slightly more conservative with respect to superconducting accelerator magnets made with Nb-Ti used for LHC (17% for MQXB, 19% for MQXA, 14% for MB).

Peak field in the coil in operational conditions is ~12.2 T, and a current density in the non-Cu of 1700 A/mm^2. The ultimate gradient is set at 155 T/m, i.e., ~90% of short sample; this must be reached to prove that operation in nominal conditions has some margin. For this reason the mechanical structure should be able to withstand forces up the ultimate current.

The following targets will be used to evaluate the quadrupole performance:

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

These values are based on the experience of the LHC magnet production and may be modified when we will get more experience on Nb_3Sn technology..

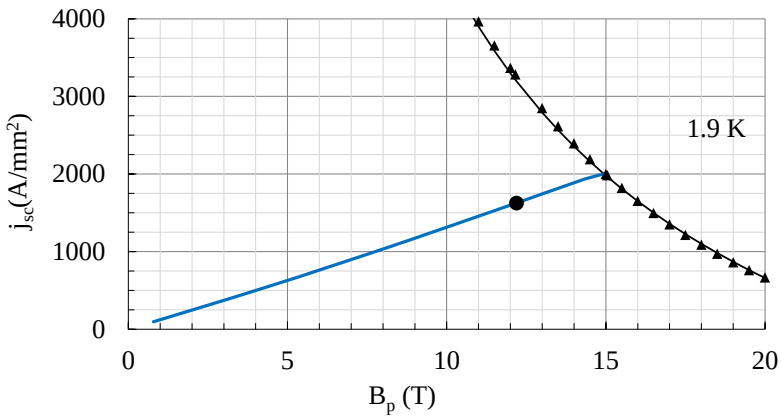

Fig. 1 Non-Cu critical current density (triangular markers), loadline for the peak field in the coil (solid line) and operational point (round marker).

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. This is a hard requirement and may be revised later based on practical experience a better evaluation of the needs.
- Geometric multipoles: the expected errors, presently used as baseline by beam dynamics team (WP2) to specify the corrector layout, are given in Table 1. This error table leads to a dynamic aperture of 9.5- 10 sigma at β^*=15 cm for the worst seeds, that is very close to target, but after minimization of the driving terms induced by all skew and normal multipoles of order less of equal to 6. Identification of the most dangerous multipoles is on-going, with possible means to mitigate their impact (e.g. sorting on the random b_6).
    - The random component is estimated on the MQXF cross-section with 30 µm stdev in the coil positioning for not allowed multipoles, and four times larger values for b_6, b_{10} and b_{14}.
    - The systematic component is optimized at high field. The large saturation component in b_6 (3.2 units) is compensated by 4 units of geometric.
- Persistent currents: the present guess of the order of magnitude is -20 units of b_6 and +4 units of b_{10}.

Table 1 Expected field errors

	Triplet field quality version 2 - November 6 2012								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
3	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820
4	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570
5	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420
6	4.000	-3.200	-20.000	-16.000	0.800	1.100	1.100	1.100	1.100
7	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190
8	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130
9	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070
10	0.150	0.000	4.000	4.150	0.150	0.200	0.200	0.200	0.200
11	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026
12	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018
13	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009
14	-0.040	0.000	0.000	-0.040	-0.040	0.023	0.023	0.023	0.023
Skew									
3	0.000	0.000	0.000	0.000	0.000	0.800	0.800	0.800	0.800
4	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650
5	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430
6	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310
7	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190
8	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110
9	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080
10	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040
11	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026
12	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014
13	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010
14	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005

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 of 15 A/s. A variable threshold (larger for lower currents) could be envisaged and will be used in the test of short models.
- We set a target for the maximum hot spot temperature of 300 K.

2.4. RADIATION DAMAGE

The current design targets a total 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.

3. REVIEW OF THE STATE OF THE ART IN NB3SN MAGNETS IN RELATION TO THE IR QUADRUPOLE DESIGN TARGETS

3.1. PERFORMANCE

The capability to approach the conductor limit and to reach the operational point with minimal training and no retraining is the main ingredient for assessing performance. The full conductor potential (based on critical current measurements of extracted strands, without accounting for stress degradation) was obtained in some of the LARP models, indicating that the coil fabrication and the assembly process is well controlled and optimized. The best models also showed fast training and no retraining (see Fig. 2). However these results were obtained after selecting the best performing coils and tuning the mechanical preload over a few cycles of assembly and disassembly.

Results from recent HQ and LQ model magnets tested at 1.9 K indicate that the operational level of 80% can be reached with fast training and no retraining after thermal cycle in three out of four assemblies [2]. On the other hand, these results must be consolidated and in addition further development is required to demonstrate that a 90% ultimate performance level can be achieved.

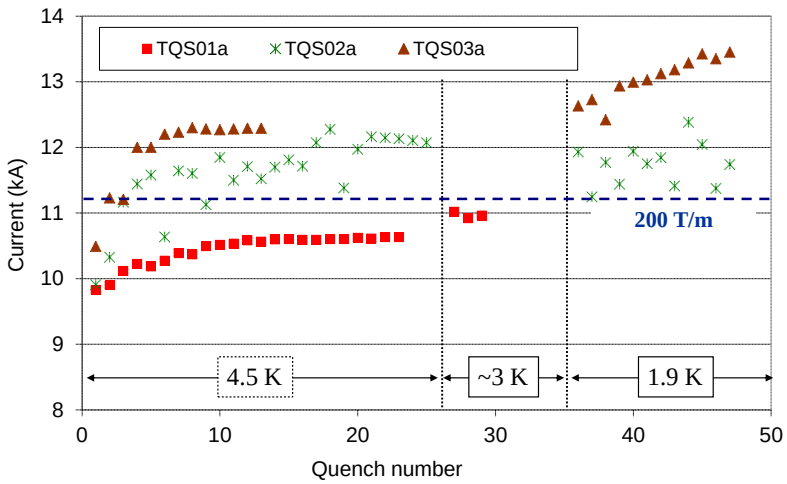

Fig. 2 Training curves for TQ models, showing improvements from each generation to the next.

3.2. FIELD QUALITY

The geometric errors are the most critical requirements and may be revised when more experience is accumulated. These values given in Table 1 are undoubtedly challenging, and magnetic shimming is probably needed to further reduce not allowed multipoles. Precise coil fabrication and structure alignment are required. The last generation of HQ models incorporates full alignment at all steps of coil fabrication, magnet assembly and operation.

Field errors at injection are in principle less critical, but need to be carefully analyzed since Nb_3Sn wires exhibit large magnetization due to high critical current density and large filament size. Simulations of HQ show good agreement with measurements (see Fig. 3) [3]. In HQ the penetration field is higher than injection current, i.e. TF and b_6 will have a non-monotonous dependence on the current (see Figs. 3 and 4). This is also why at injection the persistent components are rather similar for 54/61 conductor, with 70 μm filament, and 108/127, with 50 μm filament. Going to smaller filament would give the advantage of further lowering the penetration field and the maximum persistent current component during the ramp.

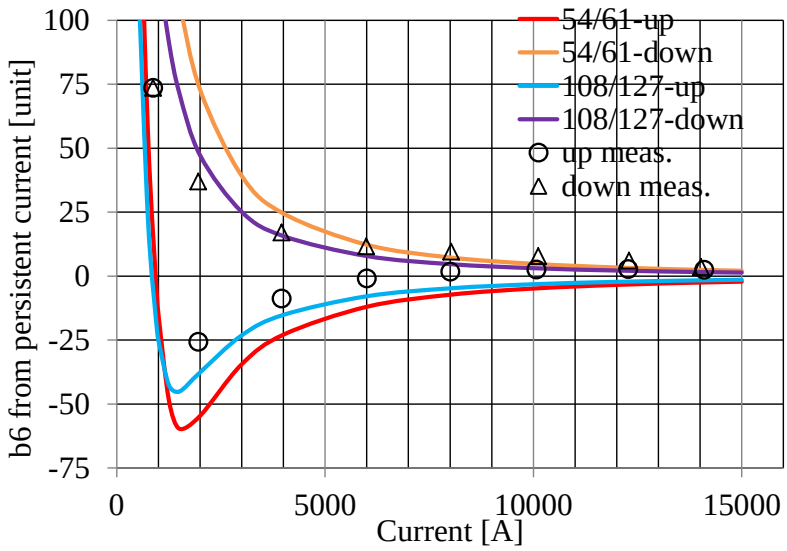

Fig. 3 Persistent current component measured and simulated for HQ, 54/61 and 108/127 strand (4.2 K).

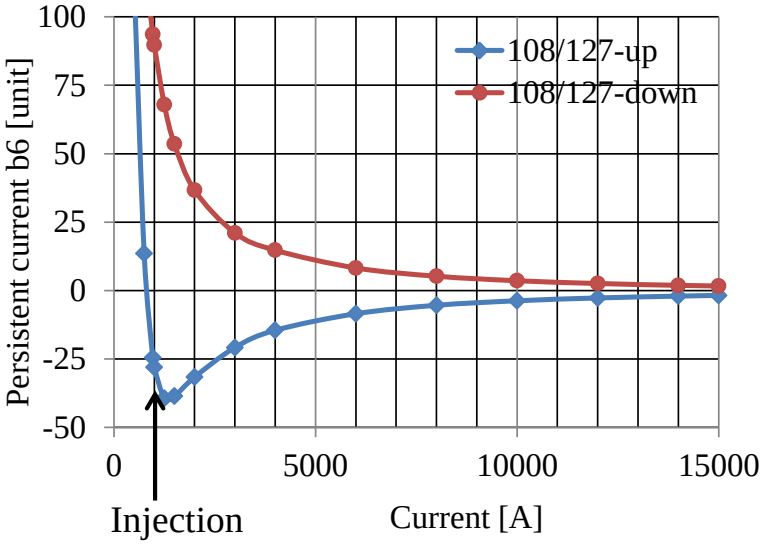

Fig. 4 Persistent current component simulated for HQ, 108/127 strand (1.9 K).

3.3. PROTECTION

According to the HQ experience [4], the 100 mV limit for flux jumps during ramp is satisfied only in the second part of the ramp (currents larger than 7 kA, see Fig. 5). The reduction of filament also aims at reducing flux jumps and associated voltage spikes. A plan B is to consider thresholds dependent on current, and it is being currently explored.

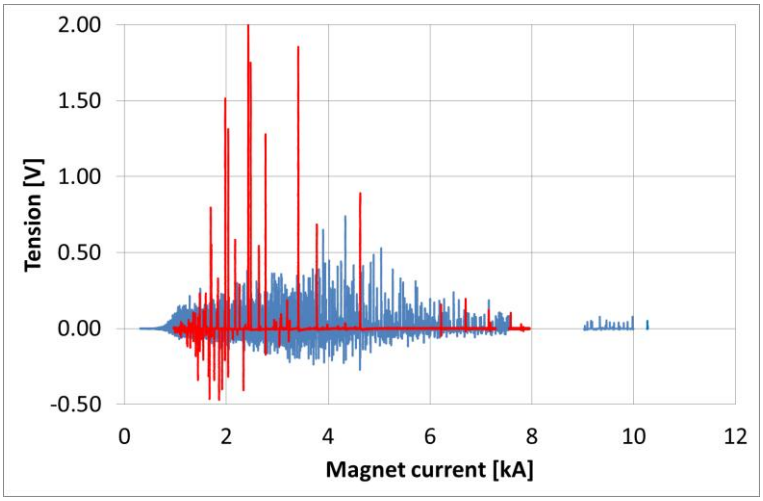

Fig. 5 Voltage spikes during ramp in HQ01e (two coils made with 54/61, two coils with 108/127) observed with 50 A/s ramp rate (red: 4.2 K, blue: 1.9 K).

3.4. STRAND

Two wire types were mainly utilized in LARP, based on RRP technology:

- Rod Restack Processed wire with 61 sub-elements (RRP 54/61);
- Rod Restack Process wire with 127 sub-elements (RRP 108/127).

The RRP 54/61 wire was used in the majority of the LARP tests to date. It delivered solid performance allowing the several models to reach their R&D objectives and performance goals. However, this design results in a rather large effective filament size (~70 μm) in the relevant strand diameter (0.7-0.8 mm). As a consequence, the threshold for flux-jump instability is only a factor of two higher than typical operating currents. This can lead to performance limitations if the stability margin is further eroded due to conductor degradation during processing or under stress. Examples of such limitations were in fact observed at low temperature (1.9 K) in second-generation TQ models.

The RRP 108/127 was first procured by LARP in 2007, when it was still considered an R&D wire by OST, to evaluate its performance and encourage further development and transition to the production stage. It provided solid performance in the TQS03 model with no signs of instability, leading to its adoption as a baseline LARP wire starting in 2009. However, further improvements to the 108/127 design are required to match the average piece length, critical current densities and RRR values obtained in the 54/61 design. A comprehensive review of conductor performance and new developments in US is provided in [5].

In Europe, PIT wire is being produced for EuCard program, with similar performances in critical current density and aiming at a filament size of 50 μm or less [6]. The 150 mm quadrupole will rely on both productions.

3.5. CABLE

LARP provided an opportunity for larger scale manufacturing, further optimization and detailed characterization of Nb_3Sn cables. To date, more than 7 km of cable of three different designs were fabricated. The current R&D effort is focused on transitioning from a three-step process (involving a first cable fabrication pass at larger size, followed by anneal and re-roll to final size) to a one-step process using pre-annealed strand. The one-step process is expected to be more robust and efficient, and is more compatible with the introduction of thin cores for control of AC losses.

The inclusion of a core aims at controlling the interstrand resistance and minimizing the ramp rate effects, which have been shown to be large (see Fig. 6) and could pose issues in operation. Several cored cables have been fabricated for the latest generation HQ models using stainless steel and fiberglass cores. Coils have been fabricated using cored cables and successfully tested in the magnetic mirror structure. In 2013 the first magnets with cored cables will be manufactured for HQ and for the 11 T dipoles, providing a first answer of the advantages of this choice.

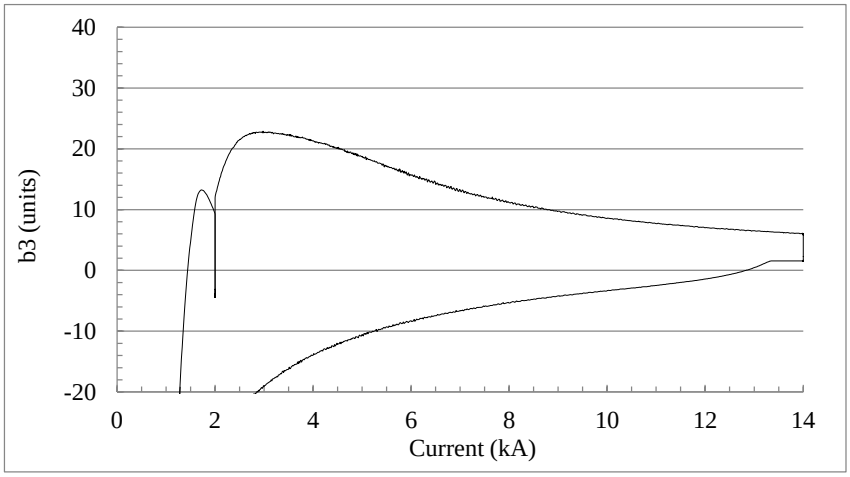

Fig. 6 Normal sextupole versus current with visible ramp rate effects in HQ01e (no cored cable).

3.6. COIL FABRICATION

Several factors contributed to a steady improvement in coil fabrication procedures throughout the program. Different experiences and methods had to be compared and integrated in order to develop tooling and procedures that would be acceptable to all collaborating groups. Robust handling and shipping tools had to be devised to allow distributed coil production lines. Careful analysis was performed in relation to the scale up to 4-m-long coils. Nevertheless, a comprehensive modeling framework is not yet available, particularly in relation to the reaction process. The coil fabrication methods are still largely based on empirical knowledge and several iterations are typically needed to optimize new designs. A recent example is given by the development of the HQ models, in which excessive compaction during coil fabrication led to high rates of coil damage in the first tests.

3.7. RADIATION DAMAGE

The weakest component of the magnet from a radiation standpoint is the epoxy resin used to impregnate and insulate the coils. A study for estimating the radiation tolerance of the CTD-101™ epoxy used for most LARP models is underway. These estimates are affected by an error which can be easily a factor two or more. Alternative resins are being tested to build additional margin for radiation damage.

3.8. MECHANICAL DESIGN

Providing adequate mechanical support in high-field magnets based on brittle superconductors requires structures that can generate large forces while minimizing stress on the conductor at all stages of magnet fabrication and operation. The bladder and key support structure is the baseline for the LARP quadrupoles. This concept is based a thick aluminum shell, pre-tensioned at room temperature using water-pressurized bladders and interference keys. During cool-down, the stress in the shell increases due to differential thermal contraction relative to the iron yoke. A series of tests were performed at CERN using the TQS03 models to better understand the Nb_3Sn stress limits and its tolerance to a large number of cycles. It was found that the magnet could perform satisfactorily up to 200 MPa average coil stress, which results in peak local stresses of the order of 250 MPa. This result considerably expands the engineering design space with respect to the 150 MPa level which

was previously considered as the limit. In addition, a cycling test involving one thousand ramps from low to high field was performed, and no degradation was found.

For the MQXF, preliminary design calculations indicate [1] that coil stresses are within the allowed range based on previous LARP experience

4. CONCLUSIONS AND FUTURE PLANS

The most critical requirement is the quench performance, especially in proving the ability of the magnet to reach the design target for ultimate gradient in operational conditions (90% of short sample at 1.9K). We keep this ambitious target, with the following plan B: (i) make use of the additional margin if LHC will operate at 6.5 TeV, or (ii) to lower the operational gradient of 5% and make the magnets longer (less 50 cm longer).

Two requirements (necessity of cored cable and small filament size) belong to the present baseline, but the experience on 2013 on HQ and 11T with 108/127 and cored cable will prove the effectiveness of these solutions. Many aspects suggest major advantages in having a magnet with small filaments and cored cable.

Field quality is challenging, the most critical aspect being the targets on the non-allowed random geometric multipoles. Magnetic shimming will be studied for MQXF and implemented on a model.

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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