OPTICS IMPLICATIONS OF IMPLEMENTING Nb3Sn MAGNETS IN THE LHC PHASE I UPGRADE*

J.A. Johnstone†, V.V. Kashikhin, N.V. Mokhov, A.V. Zlobin, FNAL, USA

Abstract

CERN has encouraged the US-LARP collaboration to participate in Phase I of the LHC luminosity upgrade by analyzing the benefits gained by using Nb3Sn technology to replace the functionality of select NbTi magnets that CERN is committed to construct. Early studies have shown that the much higher gradients (shorter magnetic lengths) and temperature margins (quench stability) of Nb3Sn magnets compared to their NbTi counterparts is favorable -- allowing the insertion of additional absorbers between Q1 and Q2, for example. This paper discusses the relative merits of the NbTi and Nb3Sn options.

INTRODUCTION

In the LHC Phase I luminosity upgrade β* is reduced from the baseline 55cm to 25cm and CERN intends to replace the 70-mm NbTi high luminosity triplets with long, low-gradient NbTi quadrupoles [1]. In this paper the advantages and feasibility of employing shorter, stronger Nb_3Sn magnets in Phase I are briefly explored. The Nb3Sn quadrupoles assumed here are modeled to be interchangeable with either the NbTi Q1 or Q3 in whatever optics scheme is eventually adopted. 'Interchangeable' in the sense that they would have the same slot length, same integrated field at a given current, and the same interconnects as the NbTi magnet they replace, and require minimal retuning of the IR matching quads. A sampling of options using 90 or 110mm aperture quads are discussed, where the Nb3Sn Q1/Q3 comprises either a single long magnet or two short modules.

PHASE I OPTICS

The two triplet configurations considered here are based on the NbTi 'LowBetaMax' (LBM) and 'Symmetric' (SYM) lattice designs developed by Riccardo de Maria [2], with additional space allocated for correctors, BPMs, absorbers, etc. The relevant NbTi magnet parameters are listed in Table 1, and the corresponding collision lattice functions for β* = 25cm in the LBM model are shown in Fig. 1 (SYM optics are similar).

Table 1. Magnet parameters for the NbTi LBM and SYM triplet configurations.

	LBM			SYM		
	Coil ID mm	Lmag, m	Gnom, T/m	Coil ID mm	Lmag, m	Gnom, T/m
Q1	90	7.060	167.21	130	9.200	121.86
Q2a	130	7.787	-121.37	130	7.800	-121.86
Q2b	130	7.787	-121.37	130	7.800	-121.86
Q3	130	8.711	121.37	130	9.200	121.86

LBM is characterized by Q1 and Q3 having unequal lengths, and Q1 has a 90mm coil ID whereas Q2/Q3 have 130mm. In the SYM lattice Q1, Q3 are equal lengths and all magnets have 130mm apertures. In both designs, the overall triplet length is ~10 m longer than in the baseline – pushing the D1/D2 dipoles and Q4, Q5 towards the arcs.

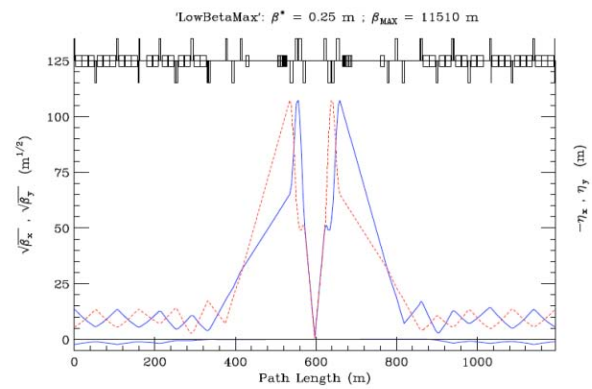

Figure 1. LBM collision optics with β* = 25cm.

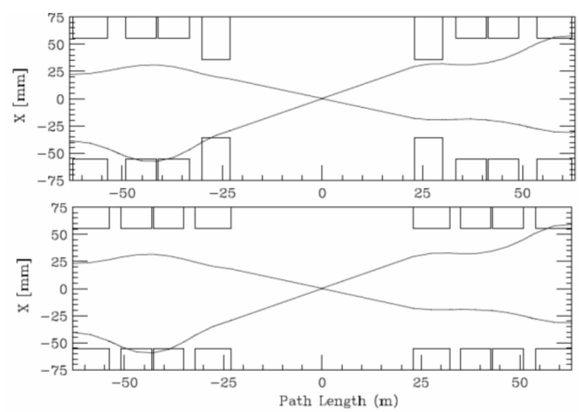

Figure 2. Magnet apertures and 9σ beam envelopes for LBM (top) and SYM (bottom) in the crossing plane, with a 225 μrad half-crossing angle.

Magnet apertures and beam envelopes for these two models are shown in Fig. 2 for the horizontal crossing plane (IR5). Physical apertures have been reduced from the coil diameter by a total of 18.6mm to correct for beam pipe, beam screen, etc. The 9σ beam envelope reflects a 450 μrad crossing angle (10σ beam separation at the first parasitic crossing) and is inflated via the prescription given in [3] to account for optical mismatches, beam jitter, momentum errors, etc. With these corrections, the beam touches the 90mm Q1 and 130mm Q2, Q3 in LBM, and the 130mm Q2's and Q3 magnet apertures in SYM.

* This work was supported by the U.S. Department of Energy.
†jjohnstone@fnal.gov

Nb3Sn MAGNET OPTIONS

High-field Nb3Sn quadrupoles are being developed and, for Phase I, preliminary design parameters exist for 90, 110, and 130mm coil IDs with corresponding gradients ranging from 208 to 156 T/m. Details can be found in these conference proceedings [4].

LBM with a Nb3Sn 90-mm Q1 or 110-mm Q3

Replacing the 7.05m NbTi Q1 with a 206T/m, 5.65m Nb3Sn quad with 90mm aperture, and shifting the Q1 focusing center towards the IP, opens an additional 1m of space between Q1 and Q2a. The earlier focusing also results in improved clearance between the beam and Q1/Q2/Q3 than in the corresponding NbTi solution. Alternatively, two 3.00m, 176T/m Nb3Sn magnet modules with 110mm apertures can replace the NbTi Q3. Splitting Q3 into two modules and keeping the focusing center fixed accurately reproduces the original optics. The 9σ beam envelope and magnet apertures for the Nb3Sn Q1 and Q3 cases are shown in Fig.3.

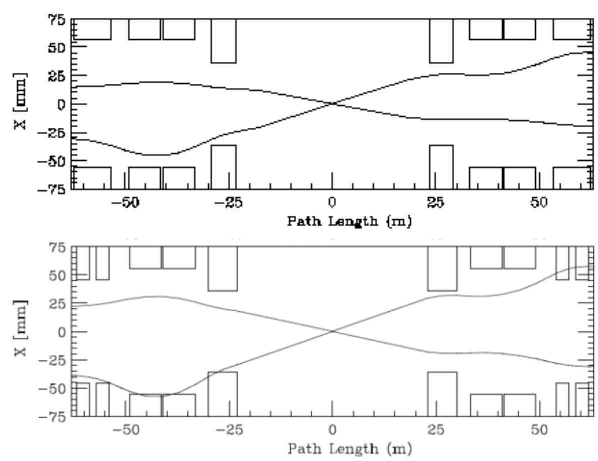

Figure 3. Magnet apertures and 9σ beam envelopes in the crossing plane for LBM with a 90mm Nb3Sn Q1 (top), and 110mm Nb3Sn Q3 (bottom).

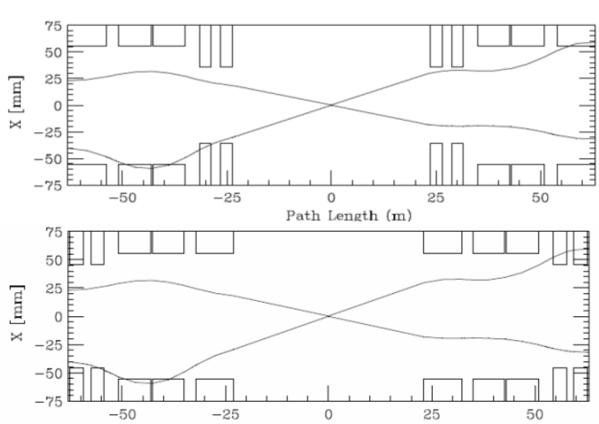

Figure 4. Magnet apertures and 9σ beam envelopes in the crossing plane for SYM with a 90 mm Nb3Sn Q1 (top), and 110mm Nb3Sn Q3 (bottom).

SYM with a Nb3Sn 90-mm Q1 or 110-mm Q3

In SYM optics either the Q1 or Q3 is replaced with 2 Nb3Sn magnet modules. By replacing the 9.20m NbTi Q1 with two 2.75m long, 204 T/m Nb3Sn modules the beam envelope slightly overlaps the aperture of Q1b (Fig. 4 top), but is no worse than in the NbTi LBM optics. With the higher heat margin of Nb3Sn this is not expected to be a problem. Two 3.19m long 110mm Q3 modules with gradients ~176 T/m replace the NbTi Q3. Beam overlap with the Q3 aperture (Fig. 4 bottom) is worse than in the original NbTi design but, due to the very generous allowance for beam errors, this might be acceptable.

HEAT DEPOSITION AND OPERATION MARGIN

Simulations are performed with MARS15 (2008) [5], using DPMJET-3 as an event generator for 7x7 TeV pp collisions at 2.5×10^{34} $cm^{-2}s^{-1}$ in the IP5(R) region. Segmented stainless steel and tungsten absorbers cooled at LN2 temperature are implemented [6]. Three of the Nb3Sn triplet configurations are studied: LBM with 2 Q3 110mm modules (LBM-1); a 90mm aperture Q1 (LBM-2), and SYM with 2 Q1 90mm modules (SYM-1) Figs. 5 and 6 illustrate the MARS model with a 55mm TAS aperture.

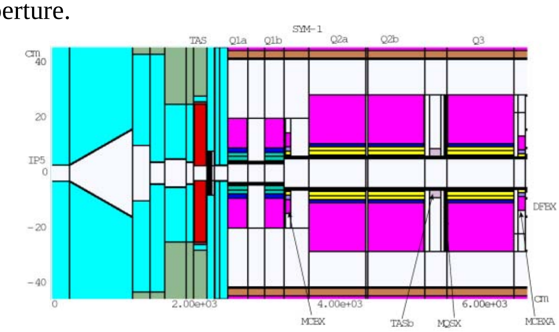

Figure 5. SYM-1 longitudinal MARS model.

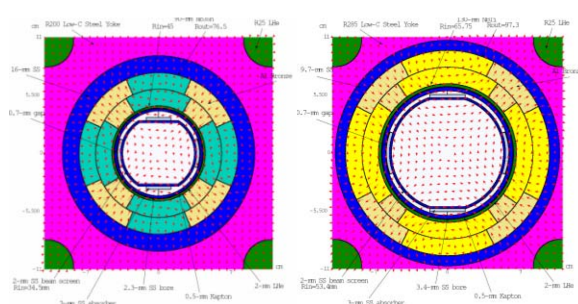

Figure 6. 90-mm Nb3Sn and 130 mm NbTi quadrupole cross-sections, with beam screens, absorbers, cold bore, kapton, LHE, coils, collar, yoke and cryostat in MARS15.

Calculations qualitatively confirm our earlier results: four pronounced peaks in the longitudinal distributions of maximum power density in the first SC cable (averaged over the cable area at the azimuthal maxima) – close to the Q1 non-IP end, Q2a IP end, Q2b non-IP end, and Q3 IP end (Fig. 7), taking place in horizontal and vertical mid-planes (Fig. 8).

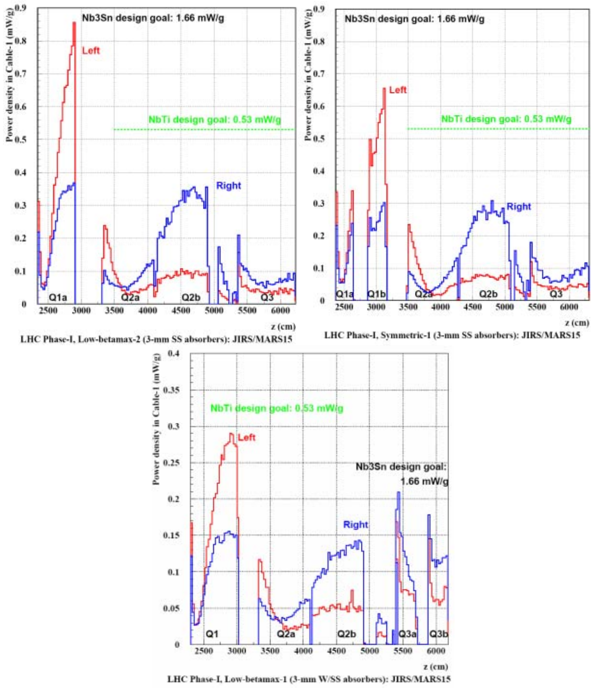

Figure 7. Peak power density in inner cable vs z: LBM-2 (top left) and SYM-1 (top right) with 3mm SS absorbers, and LBM-1 with 3mm W/SS absorbers (bottom).

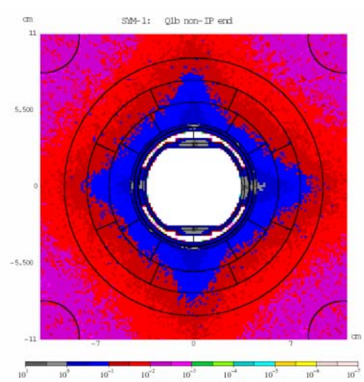

Figure 8. Power density profiles at the non-IP end of Q1b in SYM-1 optics.

Table 2. Peak power density with respect to design limits.

Optics	Absorber		TAS ID 55 mm	
			NbTi. mW/g	Nb3Sn, mW/g
		Design limit	0.53	1.66
LBM-1 Nb3Sn Q3 110 mm	3 mm/W	Q1	0.29	
	3 mm/SS	Q2	0.15	
		Q3		0.21
LBM-2 Nb3Sn Q1 90 mm	3 mm/SS	Q1		0.88
	3 mm/SS	Q2	0.33	
	3 mm/SS	Q3	0.21	
SYM Nb3Sn Q1 90 mm	3 mm/SS	Q1		0.66
	3 mm/SS	Q2	0.31	
	3 mm/SS	Q3	0.18	

For the configurations considered here, all the peaks are safely below the design limits (Table 2). The 3-mm tungsten absorber in Q1 reduces the peaks by a factor of about 3 and 2 in Q1 and Q2, respectively, compared to the stainless steel ones. The peak in Q3 is practically insensitive to the configuration.

The pp-interactions result in 2.24 kW of power per beam carried out from IP1 and IP5. About 1/3 of this power is deposited in the TAS and triplet. Power dissipation in the TAS scales with the luminosity and decreases with aperture increase, thus giving rise to the power deposited in cold components. The heat loads in LBM-2 optics (Watts) are: 109 (Q1), 20 (MCBX), 74 (Q2a), 84 (Q2b), 25 (MQSX), 7 (TASB), 80 (Q3), 11 (MCBXA), 27 (DFBX), and 17 (vessel).

Table 3. Heat load balance (Watts)

	LBM-1	LBM-2	SYM-1
LHe (bore, SC, collar, yoke)	264	306	292
LN2 (beam screen & segmented absorber)	173	101	104
Room T (vessel)	20	20	23
Total	457	427	419
Grand total (TAS included)	740	710	702

CONCLUSIONS

With the preliminary IR triplet layouts and Nb3Sn configurations considered here it appears that there is sufficient aperture for shorter, higher gradient 90mm Q1s. In LBM two 110mm Nb3Sn Q3 modules also appears to be acceptable, and this is likely to be true for the SYM optics but requires further study.

Compared to the baseline case, dynamic heat loads to the SC quads are certainly higher at 2.5×10^{34} cm^{-2} s^{-1} but seem to be manageable due to larger quad apertures and the use of absorbers – especially high-Z absorbers – cooled at LN2 temperature. Using Nb3Sn for Q1 or Q3 instead of NbTi substantially increases operational margins, frees space for additional instrumentation between quads, and provides verification of this new technology for Phase II.

REFERENCES

[1] J.-P. Koutchouk, L. Rossi, E. Todesco, "A Solution for Phase-One Upgrade of the LHC Low-Beta Quadrupoles Based on NbTi", LHC Progress Report 1000 (2007).
[2] R. de Maria, "LHC IR Upgrade Layouts", website: cern.ch/rdemaria/layouts/ (2007).
[3] T. Sen, et al., "US-LARP Progress on LHC IR Upgrades", LARP-DOC-103 (2005).
[4] A.V. Zlobin, et al. "Nb3Sn Quadrupoles in the LHC Phase I Upgrade", EPAC'08, Genoa, WEPD037, June 2008.
[5] N.V. Mokhov, http://www-ap.fnal.gov/MARS/
[6] N.V. Mokhov, I.L. Rakhno, "Mitigating Radiation Loads in Nb3Sn Quadrupoles for the CERN LHC Upgrades", PRSTAB 9 (2006) 101001.