US LHC Accelerator Research Program

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Nb_3Sn Substitute Quads in Phase-1 Upgrade Optics

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Outline

- Overview of the 'Substitute' Nb_3Sn Scheme
- Preliminary Nb_3Sn Quadrupole Design Parameters
- Optics Models for the IR Triplets
- Beam Envelopes & Magnet Apertures
- Summary & Conclusions

- Next Steps

Overview of the 'Substitute' Nb_3Sn Scheme

- For the Phase-1 upgrade of the LHC IR triplets CERN plans to employ long, low gradient, NbTi quadrupoles in some combination of 130 & 90 mm apertures.
- The JIRS (Joint Interaction Region Studies) group within US-LARP is exploring the advantages & feasibility of producing Nb_3Sn quads that could be easily interchanged with either the Q1 or Q3 NbTi magnets in whatever optics scheme is eventually adopted.

  'Interchangeable' means:

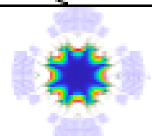
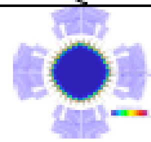
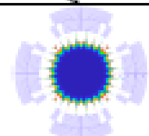
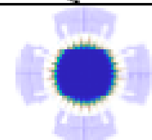
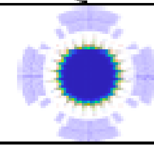
  - Same slot length
  - Same interconnects
  - $\int G_{Nb3Sn} \cdot dl = \int G_{NbTi} \cdot dl'$ at a given current
  - Minimum re-tuning of the matching section quadrupoles

Nb_3Sn Substitution Overview (cont'd)

- Advantages inherent to pursuing the Nb_3Sn replacement scheme are several:
  - Higher heat margin of Nb_3Sn relative to NbTi, allowing less shielding & smaller coil diameter
  - Higher gradients & shorter magnets for a given aperture
  - Larger aperture for a given gradient with corresponding gain in heat margin and/or a gain in the gradient margin if the aperture is also left unchanged.
  - Push Nb_3Sn R&D of 110 mm Nb_3Sn quadrupoles appropriate for a Phase-2 upgrade & the return to short(er) triplets
  - Gain operational experience with Nb_3Sn technology

***Mitigating radiation loads in Nb3Sn quadrupoles for the CERN LHC upgrades*, N.V. Mokhov & I.L. Rakhno, PRSTAB 9,101001,2006.**

Preliminary Nb_3Sn Quad Design Parameters

	TQC-90	IRQ-90	IRQ-110	HQ-110	IRQ-130	HQ-130
Coil cross-section						TBD
Strand OD, mm	0.7	0.7	0.7	0.8	0.7	0.8
Coil ID, mm	90	90	110	110	130	134
Bare cable width, mm	10.05	15.14	15.10	15.15	15.10	15.1
Number of strands	27	42	41	35	41	41
Strand Jc(12T, 4.2K), kA/mm2	2.5					
Bmax(1.9K), T	12.87	13.83	14.37	14.49	14.52	14.5
Gmax(1.9K), T/m	248.0	268.1	229.2	229.4	193.2	190
Imax(1.9K), kA	15.05	18.59	16.38	17.61	15.91	
Gnom(12.5kA)	**208.3**	**185.6**	**179.7**	**168.0**	**155.9**	**136**
Gmax/Gnom	**1.19**	**1.44**	**1.28**	**1.37**	**1.24**	**1.40**
W(12.5kA), kJ/m	358.1	383.9	674.4	595.0	923.2	702

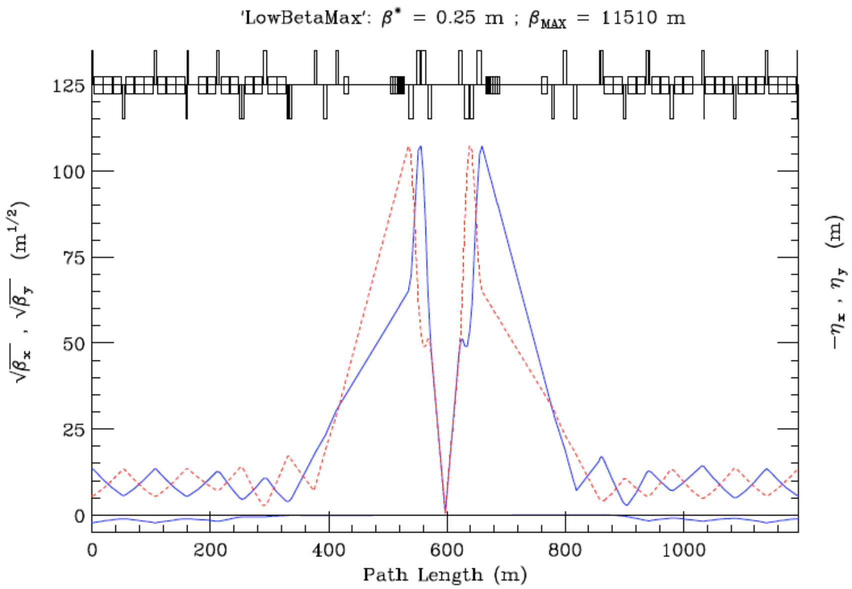
A. Zlobin

Optics Models for the IR Triplets

- The two optics models discussed here are ***very*** preliminary modifications of the NbTi 'LowBetaMax' & 'Symmetric' lattice designs developed by Riccardo de Maria.
- LowBetaMax (LBM) with NbTi Qs
  - Q1, Q2, Q3 are unequal lengths
  - Q1 is 90mm bore with G~168 T/m
  - Q2, Q3 are 130mm bore with G~122 T/m
- Symmetric (SYM) with NbTi Qs
  - Q1 & Q3 are equal lengths
  - Q1, Q2, Q3 are all 130mm bore with G~122 T/m
- Both triplet designs are ~10m longer than the baseline, pushing the D1/D2 dipoles, and Q4, Q5 quads towards the arcs

***http://cern.ch/rdemaria/layouts/*, Riccardo de Maria, 2007**

LBM Optics (version 0.1) with NbTi Quads

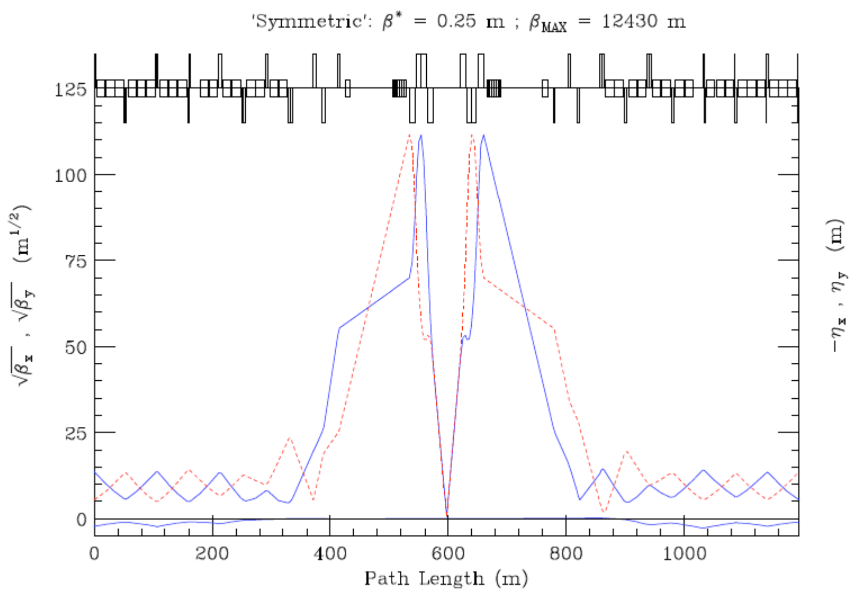


LBM 90mm NbTi Q1

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.1R5	23.000	7.060	167.207
	30.060		
MQXN.A2R5	33.226	7.787	-121.370
	41.012		
MQXN.B2R5	41.312	7.787	-121.370
	49.099		
MQXN.3R5	53.544	8.711	121.370
	62.255		

- Ample room is provided for orbit correctors, BPMs, absorbers, higher harmonic correctors, …
  - Q1-Q2A separation = 3.17m
  - Q2B-Q3 separation = 4.45m
- βmax ~ 11.5 km

SYM Optics (version 0.1) with NbTi Quads



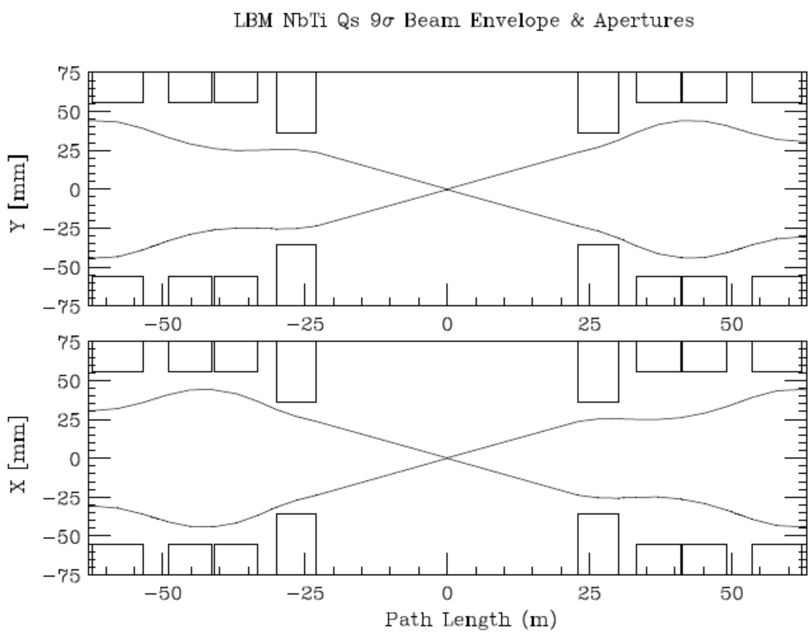
SYM 130mm NbTi Q's

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.1R5	23.000	9.200	121.863
	32.200		
MQXN.A2R5	34.900	7.800	-121.863
	42.700		
MQXN.B2R5	43.000	7.800	-121.863
	50.800		
MQXN.3R5	53.925	9.200	121.863
	63.125		

- ➢Reduced spacing for correction packages relative to LBM, but still adequate
  - Q1-Q2A separation = 2.7m
  - Q2B-Q3 separation = 3.13m
- ➢βmax ~ 12.4 km

LBM Beam Envelope & Magnet Apertures

NbTi Q1, Q2, Q3

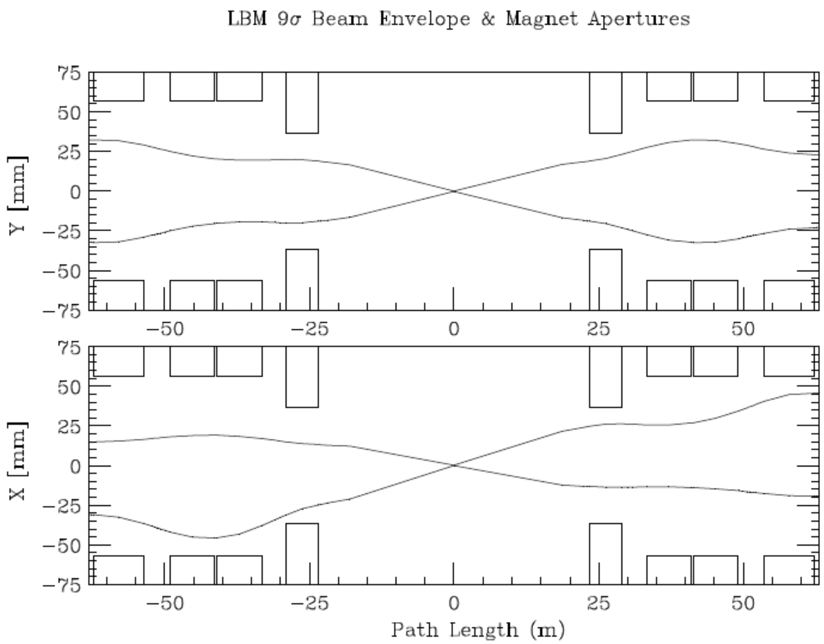


- Magnet aperture reduced from the coil diameter by:
  - 2* 3.4mm beampipe
  - 2* 2.75mm He channel
  - 2* 2mm beamscreen
  - 2* 1.2mm kapton + vacuum gap
- 9σ Beam envelope corrected for:
  - 10σ beam separation
  - 20% β-wave error
  - 8.6mm orbit distortion due to
    - ✓ 3mm on-momentum errors
    - ✓ 4mm dispersion
    - ✓ 1.6mm alignment

Nikolai Mokhov, private communication

***US-LARP progress on LHC IR upgrades*, Tanaji Sen, et al., LARP-DOC-103, 2005**

LBM Apertures for Nb_3Sn 90mm Q1

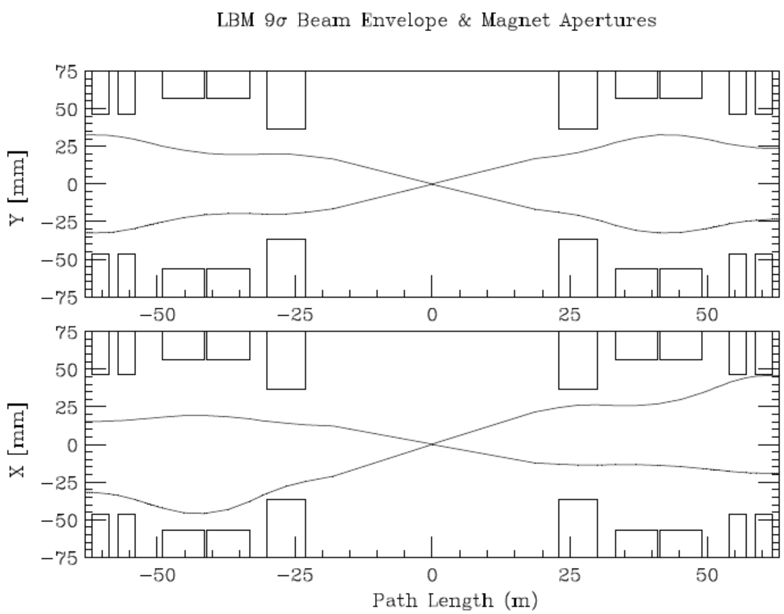


LBM 90mm Nb3Sn Q1

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.1R5	23.410	5.650	206.141
	29.060		
MQXN.A2R5	33.226	7.787	-121.146
	41.012		
MQXN.B2R5	41.312	7.787	-121.146
	49.099		
MQXN.3R5	53.544	8.711	121.146
	62.255		

- The 7.05m NbTi Q1 is replaced by a high gradient, 5.65n Nb_3Sn quad with 90mm aperture
- The focusing center of the Q1 is shifted towards the IP, opening 1m of space between Q1 & Q2A for additional absorber or correction packages
- Shifting the Q1 focusing center impacts the triplet optics and, in particular, there is more clearance between the beam & Q1 than with NbTi

LBM Apertures for Nb_3Sn 110mm Q3



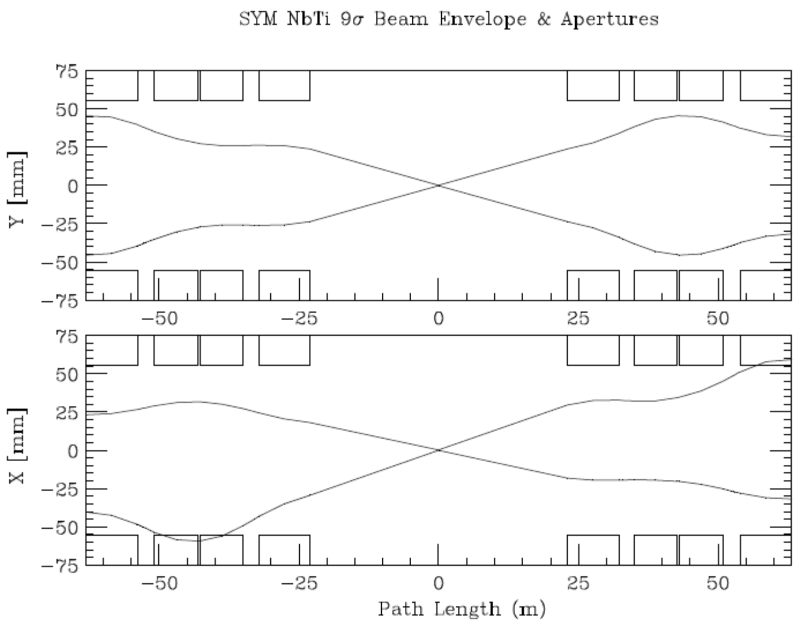
LBM 110mm Nb3Sn Q3

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.1R5	23.000	7.060	167.207
	30.060		
MQXN.A2R5	33.226	7.787	-121.370
	41.012		
MQXN.B2R5	41.312	7.787	-121.370
	49.099		
MQXN.A3R5	54.000	3.000	176.208
	57.000		
MQXN.B3R5	58.800	3.000	176.208
	61.800		

- The 8.71m NbTi 130mm aperture Q3 is replaced by higher gradient 2* 3.00m Nb_3Sn magnet modules with 110mm apertures.
- By keeping the focusing center fixed, splitting Q3 into 2 modules makes it possible to accurately reproduce the original R-matrix.
- The 9σ beam envelope approaches within 0.5mm of the Q3B aperture, but with the higher heat margin of Nb_3Sn this might not be an issue.

SYM Beam Envelope & Magnet Apertures

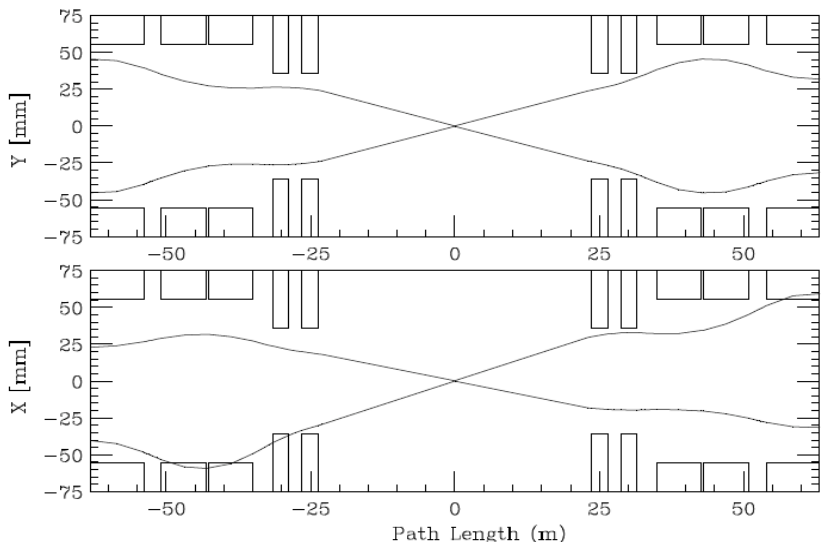
NbTi Q1, Q2, Q3



(Wait for Nikolai's analysis!)

- With the 9σ beam + beam offsets defined here (including all the orbit error terms from misalignments & optical mismatches), the beam impinges on the 130mm Q2's & Q3 magnet apertures. This is a very liberal estimate of beam slop, though, and might not be a realistic concern (?).
- The substitution of a Nb_3Sn Q1 or Q3 does not impact the result at Q2A/Q2B.

SYM Apertures for Nb_3Sn 90mm Q1



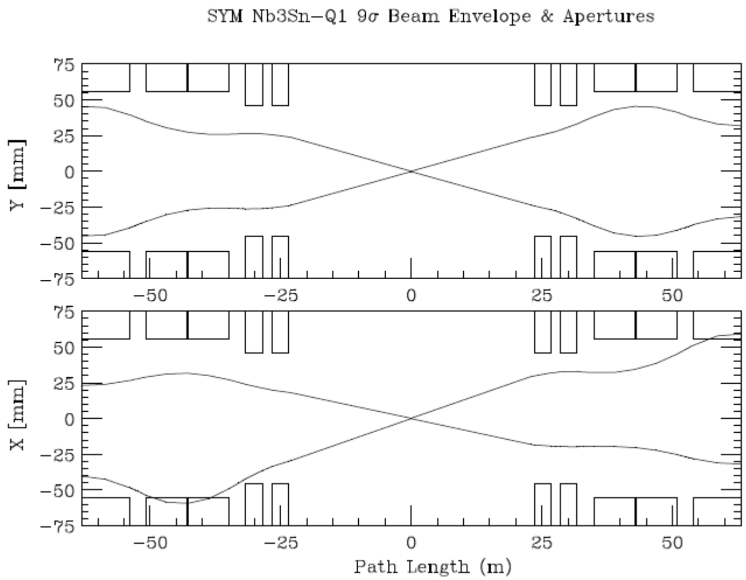
SYM 90mm Nb3Sn Q1

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.A1R5	23.690	2.750	203.844
	26.440		
MQXN.B1R5	28.760	2.750	203.844
	31.510		
MQXN.A2R5	34.900	7.800	-121.863
	42.700		
MQXN.B2R5	43.000	7.800	-121.863
	50.800		
MQXN.3R5	53.925	9.200	121.863
	63.125		

- The 9.20 NbTi Q1 is replaced by 2*2.75m, high gradient, Nb_3Sn magnet modules.

- The beam envelope closely approaches the aperture of Q1B, but is no worse than in the baseline NbTi LowBetaMax optics. With the higher heat margin of Nb_3Sn this should be even less of a problem

SYM Apertures for Nb_3Sn 110mm Q1



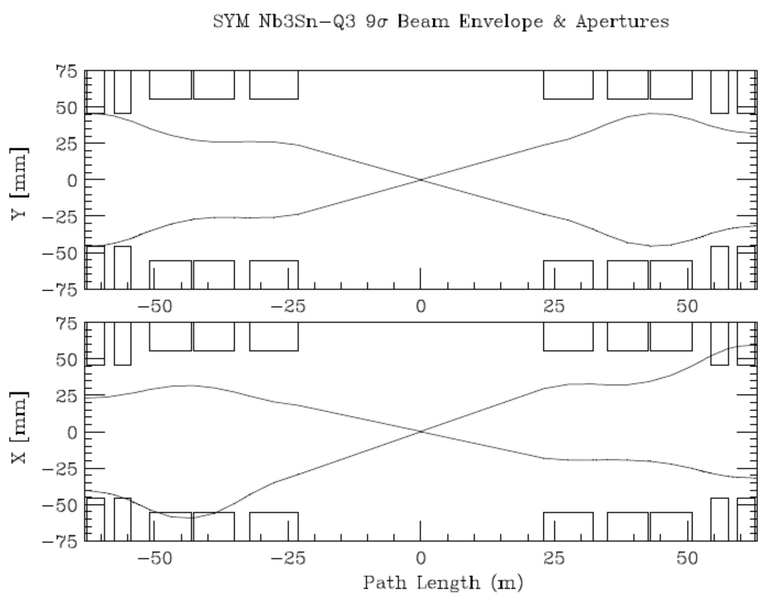
SYM 110mm Nb3Sn Q1

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.A1R5	23.510	3.190	175.727
	26.700		
MQXN.B1R5	28.500	3.190	175.727
	31.690		
MQXN.A2R5	34.900	7.800	-121.863
	42.700		
MQXN.B2R5	43.000	7.800	-121.863
	50.800		
MQXN.3R5	53.925	9.200	121.863
	63.125		

- The 130m NbTi Q3 quad with a 122 T/m field is replaced with 2*3.19m 110m Nb_3Sn quads with gradients ~176 T/m.

- The aperture constraints are less restrictive than with a 90mm aperture Q1

SYM Apertures for Nb_3Sn 110mm Q3



SYM 110mm Nb3Sn Q3

MAGNET	S(m)	L(m)	G(T/m)
IP5	0.000	0.000	0.000
MQXN.1R5	23.000	9.200	121.863
	32.200		
MQXN.A2R5	34.900	7.800	-121.863
	42.700		
MQXN.B2R5	43.000	7.800	-121.863
	50.800		
MQXN.A3R5	54.435	3.190	175.727
	57.625		
MQXN.B3R5	59.425	3.190	175.727
	62.615		

- The 9.20m NbTi Q3 is replaced by 2*3.19m 110mm Nb_3Sn Q3 modules with gradients ~176 T/m

- Beam overlap with the Q3 aperture is worse than in the baseline NbTi design. Again, because of the very generous allowance for beam errors, this situation might not be a realistic concern.

Summary & Conclusions

- Efforts are underway by JIRS to assist in development of the LBM & SYM Phase-1 optics upgrade scenarios. In particular, the implications are being explored of developing 90mm and/or 110mm aperture Nb_3Sn quads as substitutes for either the Q1 or Q3 magnets.
- With the very preliminary IR layouts & Nb_3Sn configurations considered to date it appears that:
- (1) in LBM there is ample aperture for shorter, higher gradient 90mm Q1's & 130mm Q3's. (Although not reported here, a 6.36m Nb_3Sn 110mm Q1 with gradient ~186 T/m also works. This is still shorter than the NbTi design).

Summary & Conclusions (cont'd)

- In SYM there are potentially aperture problems at the Q2's and Q3 even with 130mm NbTi magnets. The Q1 can be replaced by a higher gradient 110mm Nb_3Sn without adversely impacting aperture. Replacing the Q3 with a 110mm Nb_3Sn magnet needs further study.

➢ JIRS will recommend that US-LARP primarily pursue development of the 110mm aperture Nb_3Sn quadrupoles:
  - *Greatest flexibility for installation options*
  - Paves the R&D pathway toward accelerator-ready IR magnets for the Phase-2 upgrade.

Next Steps

- Results presented here for potential IR optics options are still in their infancy.
- The next stages of development will result from an iterative process, relying on consultation & feedback from our CERN colleagues, and guidance from Nikolai's energy deposition studies.
- The key concern to be addressed in the next phase of the IR triplet optimization is to establish that an acceptable squeeze sequence exists from injection to collision (which does ***not*** seem to exist for today's models!).

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