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High Energy
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Analysis of the proposed LHC low-β upgrades based on the Nb-Ti and preliminary conclusions on a Nb_3Sn R&D programme.

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Abstract

This preliminary analysis was requested to evaluate a situation to be discussed in the US-LARP collaboration at the beginning of October 2005. A global model of an LHC insertion with the same topology as the present one was prepared for the Arcidosso CARE-HHH workshop. Its added value is a simultaneous treatment of beam optics, beam dynamics, magnetic field at the coils and heat deposition in a simplified way suitable for the exploration of the parameter space [1]. According to this model, the recently proposed solutions based on the Nb-Ti technology [2] [3] appear not to be suitable for the LHC luminosity upgrade. The reasons for this finding are analysed and explained. This class of solutions appears to require higher magnetic fields that can be provided by the Nb3Sn technology. The overview of the MT19 [4] contributions and expert advices show clearly that the only other solution for the next 5 years seems indeed Nb_3Sn. Other classes of insertion solutions were discussed in Arcidosso, each of them requiring new beam dynamics and technical studies that need time. In this note, it is proposed to decouple the technological R&D programme from the beam dynamics studies and progress in parallel to maximize the chances for an efficient LHC upgrade and give an appropriate support to the collaborations.

Introduction

A global model of an LHC insertion [1] was prepared for the Arcidosso workshop in order to evaluate rapidly and in a consistent way the potential of various solutions for the LHC low-β upgrades and help identifying what should be the R&D lines. The solutions studied are all of the same class as the present LHC baseline layout, namely quadrupole first, small crossing angle. Provision for dipole first solutions is included. The model tackles to the magnet layout, the beam optics, the beam-beam effect, the superconductor capabilities and the heat deposition in the coils.

Brief description of the model

The model constants are:

- The inter-quadrupole distances, equal to their present nominal values.
- The *relative* lengths of Q1, Q2 and Q3, i.e. the new quadrupole lengths are obtained by multiplying the present quadrupole lengths by the same factor.
- The default gap between the beam envelope and the coil aperture, taken to be the present thickness of the cold bore and beam screen in Q2.

The model inputs are:

- The distance of Q1 from the IP.
- The β*.
- The average length of the triplet quadrupole.
- The beam intensity and pattern: bunch charge, number of bunches.
- The crossing scheme: baseline (horizontal-vertical), horizontal only, horizontal with long-range beam-beam compensation.
- The "coil oversize" factor. It allows modifying the default gap between the beam envelope and the coil aperture. Its primary purpose is the control of the peak energy deposition.

The model outputs are:

- *Performance:* the luminosity in units of the nominal value (10^{34} $cm^{-2}s^{-1}$).
- *Linear beam optics:* β_{max}, maximum betatron beam size, beam separation, contribution of the dispersion, overall extent of the beam envelope.
- *Chromatic aberrations:* percentage of the lattice sextupole strength used to correct the first and second order chromatic aberrations assuming two higher-luminosity insertions and two nominal ones.
- *Geometric aberrations:* relative sensitivity to the dominant systematic field imperfections (12 poles and 20 poles) with respect to the present case.
- *Magnet:* gradient, required coil aperture (including the optional "coil oversize" factor), field at the coil aperture.
- *Superconductor specific:* operational margins for Nb-Ti, Nb-Ti-Ta, Nb3Sn calculated from the critical field by applying rules obtained from experts.
- *Peak power deposition:* an empirical scaling law postulated from hints in the literature [2] and published tracking results [8][9][10][11] (this law is presently being evaluated by N. Mokhov).

The description of the logics of the model and of the simplifications is available at [1] and will be published as an Arcidosso contribution. Note that the quadrupole margins are calculated from the field at the coil aperture (not the peak field) and a maximum field for a given superconductor/class of design. The margin of close to 20% obtained for the present nominal triplet (see Table 1) demonstrates the overall consistency. The influence on the margins of different possible designs of the quadrupoles is expected to be in a range of 10% [5]. The uncertainty related to the hypothesis behind the peak heat deposition calculation however cannot be evaluated at this stage and the results should be considered as guidelines only.

Results for the nominal LHC

β^* [m] 0.55	N_{bunch} [10^{11}p] 1.15	k_{bunch} 2808	*Xing scheme* HV	$\{_{IP\to Q1}$ [m] 23
<{ $_Q$ >[m] 5.9	*Coil oversize* 1.04			
β_{max} [m] 4402	$\sigma_{\beta max}$ [mm] 1.49	$a_{dispersion}$ [mm] 2.35	*Xing angle* [µrad] 285	Φ_{beam} [mm] 59.
$K_2(Q')$ [%] 62	$K_2(Q',Q'')$ [%] 67	*Coef. b6* 1	*Coef. b10* 1	
Gradient [T/m] 204	Φ_{inner} *coil* [mm] 70	B_{max} *coil* [T] 7.13		
Margin Nb-Ti 17%	*Margin Nb-Ti-Ta* 23%	*Margin Nb3Sn* 46%		
Peak power dens [mW/g] 0.4				
Relative luminosity 1				

This shows that the safety factor for the aperture is about 4% under nominal conditions.

Insertion model applied to the EPAC2004 Nb-Ti solution [2]

The insertions are sufficiently similar to be comparable. The critical differences between the model estimates and the results published in [2] are underlined in red/bold.

β^* [m] 0.25	N_{bunch} [10^{11}p] 1.15	k_{bunch} 2808	*Xing scheme* HV	$\{_{IP\to Q1}$ [m] 22
<{ $_Q$ >[m] 7	*Coil oversize* 1.			
β_{max} [m] 10508	$\sigma_{\beta max}$ [mm] 2.3	$a_{dispersion}$ [mm] **5.1**	*Xing angle* [µrad] 435	Φ_{beam} [mm] **89**
$K_2(Q')$ [%] 88	$K_2(Q',Q'')$ [%] 118	*Coef. b6* 14	*Coef. b10* 79	
Gradient [T/m] 176	Φ_{inner} *coil* [mm] **98**	B_{max} *coil* [T] **8.62**		
Margin Nb-Ti **0%**	*Margin Nb-Ti-Ta* **7%**	*Margin Nb3Sn* 33%		
Peak power dens [mW/g] 1.0				
Relative luminosity				

1.5				

The model yields a significantly higher requirement on the quadrupole inner coil diameter (98 mm instead of 85 mm). The Nb-Ti technology and even a future upgrade (e.g. by adding Ta, even though this upgrade direction is much discussed by experts) offer a vanishing or insufficient margin, while the heat deposition more than doubles, i.e. requires an increased margin. These differences between the results of the model and the publication can be traced to three sources:

- The model adjusts the beam separation to be exactly 9.5σ in the middle of Q2.
- It takes into account the extra beam extent due to the vertical dispersion excited by the vertical crossing.
- The inter-quadrupole space is taken to be the present one (on average 2 m).

The aperture formula used in the 2004 publication refers to the specification of the quadrupole aperture of [6], p24, equation (5). The beam separation taken there is 7.5σ, equivalent to a crossing angle of about 220 μrad. This is not consistent with the baseline crossing angle requirements demonstrated long ago. This same formula does not include the vertical dispersion term.
Another factor is the inter-quadrupole space limited to 0.3 m in the publication. The model uses instead an average of 2 meters to accommodate the BPM's, magnetic correctors, magnet ends… The impact of the assumption on inter-quadrupole spacing is not negligible.
The relative luminosity increase is 1.5 instead of a quoted factor of 2 that one might expect from a corresponding reduction of the β^* function. This is due to the geometric luminosity factor (effective beam cross-section in the collision frame) which increases with the crossing angle, the latter increasing when β^* is reduced.

Comparison with the PAC2005 Nb-Ti solution [3]

The relative Q1 and Q2 lengths are different but the comparison between the model and the publication should still hold for the important conclusions.

β^* [m] 0.25	N_{bunch} [10^{11}p] 1.15	k_{bunch} 2808	*Xing scheme* HV	{ $_{IP\rightarrow Q1}$ [m] 23
<{ $_Q$ >[m] 8	*Coil oversize* 1.			
β_{max} [m] 12182	$\sigma_{\beta max}$ [mm] 2.5	$a_{dispersion}$ [mm] **5.8**	*Xing angle* [μrad] **453**	Φ_{beam} [mm] **97**
K₂(Q') [%] 91	*K₂(Q',Q")* [%] 126	*Coef. b6* 20	*Coef. b10* 150	
Gradient [T/m] 143	Φ_{inner} *coil* [mm] **106**	B_{max} *coil* [T] 7.59		
Margin Nb-Ti **11%**	*Margin Nb-Ti-Ta* **18%**	*Margin Nb3Sn* 42%		
Peak power dens [mW/g] 1.0				

Relative luminosity **1.46**				

The model shows that this solution might be doable would the Nb-Ti-Ta technology or equivalent become successful and if the peak power density can be reduced. It requires however a significantly larger quadrupole diameter of the order of 110 mm instead of 95 mm assumed. The differences between model and publication arise mainly from the same hypotheses as analysed in the former section. The smaller discrepancies are explained by a realistic inter-quadrupole space assumed in the publication. Note, like in the former case, the same relative luminosity increase of 1.5 instead of 2 due to the geometric luminosity factor.

A "classical" Nb3Sn solution

In this exercise, we simply replace the Nb-Ti quadrupoles of the present triplet by identical Nb3Sn quadrupoles to explore the potential of an otherwise straightforward upgrade and compare it to the former solutions.

β^* [m] 0.25	N_{bunch} [10^{11}p] 1.15	k_{bunch} 2808	*Xing scheme* HV	{ $_{IP\rightarrow Q1}$ [m] 23
<{ $_Q$ >[m] 5.5	*Coil oversize* 1.			
β_{max} [m] 9373	$\sigma_{\beta max}$ [mm] 2.2	$a_{dispersion}$ [mm] 4.6	*Xing angle* [µrad] 421	Φ_{beam} [mm] 84
$K_2(Q')$ [%] 85	*$K_2(Q',Q'')$* [%] 111	*Coef. b6* 10	*Coef. b10* 50	
Gradient [T/m] 234	Φ_{inner} *coil* [mm] 92	B_{max} *coil* [T] 10.8		
Margin Nb-Ti -26%	*Margin Nb-Ti-Ta* -17%	*Margin Nb3Sn* 17%		
Peak power dens [mW/g] 1.0				
Relative luminosity 1.54				

The model shows that the larger field of a Nb3Sn solution is necessary to minimal realistic margins. The 90mm aperture assumed so far for such an upgrade is even barely sufficient for the nominal beam current and is shown to be insufficient for the full upgrade [1]. A future improvement of the insertion model used tin this note (as proposed by N. Mokhov) will express the peak power in units of the quench level. First estimates are as well very favourable to Nb3Sn and could exclude Nb-Ti unless a much more efficient TAS can be designed.

It is shown in [1] that reducing the IP-to-Q1 distance to 19m reduces the aperture requirement to about 90 mm for the full upgrade. By the same token, the sextupole strength limit is respected as well. The latter is not an absolute requirement if only two experiments are running and the other insertions fully detuned.

Conclusions

In this note, we show that a number of approximations or simplifications made in the definition of the aperture requirements [6] for the quadrupoles of an LHC low-β upgrade seem sufficient to invalidate the conclusions of former studies concluding at the viability of Nb-Ti classical solutions. The consistent treatment of the insertion design implemented in the insertion model used shows that two additional important issues shall be treated simultaneously to validate conclusions: The peak energy deposition more than doubles when reducing β^* by a factor of two at constant beam current; the luminosity increases by about 1.5 instead of by a factor of 2 due to the increase of the luminosity geometric factor with the required increase of the crossing angle. The insertion model shows that the higher field and quench level of a Nb3Sn solution are required to arrive at a realistic solution of the same class as the present insertion. The aperture of 90 mm assumed so far in the US/LARP studies may however turn out to be too small, or the insertion has to be pushed towards the IP by at least 4 m.

In its main lines, this conclusion is probably not a surprise for the LHC designers: the low- β insertion was studied and very much pushed by three teams and there has been since then no break-thru in the Nb-Ti technology. On the contrary additional requirements have emerged over the years, all requiring a larger quadrupole aperture and hence a larger peak field at constant gradient: increase of the requirement in separating the beams at the long-range collision points, shielding in Q1 to reduce heat deposition, beam screen in all quadrupoles, criterion for the protection against accidental beam losses,…). Another important aspect to consider is the loss of integrated luminosity due to the machine stop needed to upgrade the insertion. It is estimated to be 6 months for the machine (US/LARP Oct. 2005) and at least one year for the detectors (Arcidosso Aug. 2005). This shows that an improvement of the peak performance by 1.5 would probably be hardly visible or very modest in terms of integrated luminosity.

To implement the potential of increasing the luminosity by a factor of two by the corresponding reduction of β^*, a large investment is required: either a new 1.2 GHz RF system [7] or a cheap but intrusive installation of an early separation scheme [1] requiring a modification to the experimental detectors. In both cases, it does not look that a “modest” insertion upgrade is appropriate and well tuned to such investments.

The Magnet Conference MT19 (September 2005) showed that Nb3Sn is the only alternative to Nb-Ti for the next 5 years which is the time scale for the definition of an upgrade to be operational in 2012/2015. There seems to be no show-stoppers but the progress has not been at a rate that guaranties today a Nb3Sn solution ready in time. A rapid decision on the technological first choice (not excluding others and fall-back solutions) appears therefore appropriate to focus the limited resources at CERN and in the collaborations without waiting for the demanding beam dynamic studies required for the other classes of solutions.

Finally the chromatic correction of an upgraded insertion possibly exceeds the maximum strength of the lattice sextupoles. This problem may have several solutions: its suppression by shifting the insertions by at least 4 m towards the IP, a full detuning of the two insertions not planned to be operational for the upgrade, or well chosen betatron phase advances between the two high luminosity insertion. The latter solution is a last choice as it might interfere with the minimization of the beam-beam

effects and the maximization of the performance.
I submit these conclusions to you for discussion. A consensus would eliminate a family of possible LHC upgrade solutions and help reinforcing the focus on solutions with high potential.

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