IR Ranking Proposal and New Beam Parameter Sets for the LHC Upgrade - The View of HHH

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Abstract

We propose a ranking for the interaction-region (IR) optics based on the presentations and results from the first two days of the LUMI'06 workshop.

1 INTRODUCTION

After LUMI'05, we were still left with a multitude of, seemingly ever more expanding, optics solutions, requiring a variety of hardware developments. One aim for LUMI'06 was to narrow down the number of options, in order to better focus the hardware R&D.

2 CRITERIA

The IR ranking criteria sketched by F. Ruggiero, when he announced the LUMI'06 workshop, included the following:

- peak luminosity reach;
- energy deposition in IR magnets;
- beam lifetime & integrated luminosity;
- chromatic aberrations;
- technological difficulty, such as hardware development, experimental validation, operational implementation

In the following, we take the technological difficulty to be the decisive criterion.

3 APPROACH

We chose the pragmatic approach not to rank the optics solutions directly, but to first look at — and rank — the technological objects these solutions require.

This approach has a twofold motivation. First, the primary goal of the ranking exercise indeed is to reduce the number of hardware options. Therefore, we should consider the hardware implied by different upgrade proposals. Second, the technology assessment will simplify the ranking and lead to a natural selection which emphasizes the practical realization.

4 TECHNOLOGICAL OBJECTS

The ranking of the technological objects should take into account the present technology status, the development risk, the performance risks, and the time needed for development, validation and implementation.

We look at the technological building blocks from which all the proposed insertions can be constructed:

4.1 State-of-the-art NbTi quadrupole magnet

The magnet considered is improved with respect to the present LHC triplets and it can have a better heat transfer. In our opinion, "pushed" NbTi magnets may sustain a higher interaction rate, perhaps improved by a factor 34 compared with the present LHC IR quadrupoles. "Pushed NbTi magnets are currently being investigated at CERN by D. Tommasini and A. Siemko. An alternative also exists, based on a conservative NbTi magnet design which could be used for a "low-gradient" optics with long and weak magnets [1]. Various optics solutions involving NbTi magnets were presented in the LUMI'06 talks of O. Bruning and T. Taylor. This magnet technology involves no risk. New NbTi triplet magnets could be available within about 5 years.

4.2 Nb_3Sn high-field quadrupoles

Magnets based on Nb_3Sn could provide 30% higher gradient or aperture. These magnets are under investigation by the US-LARP colaboration; see the talks by G. Sabbi, J. Strait, T. Sen, P. Limon, R. Tomas at LUMI'06. The main risk is that no long prototype is yet available. A first one is expected by 2009. It is impossible to make a reliable prediction on the magnet performance before this date. If the long protoype is successful, new LHC triplets based on Nb_3Sn could be available by 2015.

4.3 Nb_3Sn high-field dipoles, possibly open plane

Simulation studies of solutions based on open-midplane dipole magnets closest to the IP have been performed by R. Gupta, T. Sen, and N. Mokhov. Higher-field dipole magnets are being studied by the CARE-NED joint research activity. The main risk is that funding for a NED continuation has not yet been secured. Therefore, prototyping cannot start before 2009. If the programme goes ahead as planned and is successful, strong Nb_3Sn dipoles could be avalable by about 2017.

4.4 Slim NbTi quadrupole doublet

A slim doublet would be embedded inside the detectors, e.g., at about 13 m from the collision point [2]. This solution is under investigation by W. Scandale, D. Tommasini, and E. Laface. It relies on standard NbTi technology. The main risk is the integration in the experiment. It could be available by 2015.

4.5 Detector-integrated dipole

This solution aims to separate the two beams as early as possible without unacceptable loss in geometric overlap at the main collision point. It is studied by J.-P. Koutchouk and G. Sterbini [4]. The early separation dipole is based on standard technology. As for the doublet the main risk relates to the integration in the experiment, in this case even closer to the collision point. The magnet could be available in 2015.

4.6 Wire compensation of long-range beam-beam effects

A dc wire exists and would already be beneficial for boosting the average LHC luminosity [5, 6]. An experimental verification with colliding beams is required. Several wire compensators have been produced and are installed in the SPS and in RHIC, where their performance is under investigation. The wire compensation is studied in simulations and experiments by U. Dorda, W. Fischer, J.-P. Koutchouk, T. Sen, V. Shiltsev, J. Wenninger and F. Zimmermann. The main risk is the jitter control for an ac wire. However, even a dc wire promises considerable performance gains [5].

4.7 Crab cavities

Crab cavities are being investigated by R. Calaga, J. Tuckmantel, R. Tomas, F. Caspers, R. Gupta, F. Zimmermann and others. The main risks are phase noise [6] and the synchronization at each interaction region as well as space requirements.

4.8 Electron lens

The merits of electron lenses are presently being investigated at the Tevatron. The main risks include jitter, control of electron and proton orbits in the lens region, control of the electron-beam profile, as well as coherent or incoherent electron-proton interactions. An experimental study of head-on compensation and its benefits at RHIC has been proposed by W. Fischer and V. Shiltsev. The existing electron lenses could made be available for the LHC by 2012.

5 GUIDELINES FOR OPTICS DESIGN

From the development status and risks of the technological objects described in the last section we infer the following guidelines.

- Solutions with quadrupoles placed first are preferred over (strong) dipole-first schemes, since they require less technological items. The dipole-first optics would require new higher-field dipoles in addition to high-gradient or large-aperture quadrupoles.
- For the compensation of the crossing, wires are promising. They should be considered in the main variants of future optics layouts. Crab cavities are retained only for global crabbing with small-angle crossings, possibly in conjunction with early-separation dipoles.
- Dipoles and quadrupoles embedded in the experiment can boost any future optics layout and should be further investigated together with the experiments.
- An electron lens might be considered once head-on compensation has proven to be efficient at the Tevatron or RHIC.

6 RANKING

A common investment approach balances high-risk high-return ventures with low-risk guaranteed-return investments. In the same spirit, we estimate the technology risk and the possible return for various proposed types of IR upgrades on a scale spanning from 0 (high risk, or low potential return) to 6 (low risk, or high return, respectively). The perceived risk and potential gain for each upgrade scenario are compiled in Table 1. We recommend that all schemes in bold face be retained for the moment. These are the options either with the perceived lowest risk or with the highest potential gain but still limited risk. The three schemes with excessive risk (0 rating) should be deprecated.

7 MAIN PATHS FOR FUTURE R&D

We recommend further development of “pushed” NbTi plus R&D on Nb_3Sn quadrupole 1st options. The studies of detector-integrated dipoles and quadrupoles should also be extended. Long-range beam-beam compensators are to be optimized and their feasibility to be demonstrated for colliding beams, e.g., at RHIC.

8 COMBINATION OF TOOLS

The new low-β quadrupoles and or a detector-integrated quadrupole doublet (Q0) **need** to be complemented by a wire compensator, by D0, or by small-angle crab cavity in order to realize a significant gain in luminosity.

The detector-integrated dipole D0 is efficient both for much smaller β^* **and** for higher beam current. On the other hand, the wire compensator is efficient mainly for higher beam current. A crab cavity, in conjunction with a detector-integrated dipole, D0, would allow for a larger separation at the 1st parasitic encounter.

9 NEW BEAM PARAMETER SETS

The old upgrade parameter sets presented at HHH-2004 [7] and LUMI’05 [9] raised concern about electron cloud or event pile up. Recently we concocted several additional upgrade parameter sets, inspired by Jim Virdee, Jean-Pierre

Table 1: Perceived risk and potential gain for different IR upgrade schemes. Our recommendation is to retain the schemes in bold face for the next two years.

scheme	risk	pot. gain
low-gradient large aperture NbTi magnets with large l^*	4	2
quad. 1st with pushed NbTi: tailored aperture & length, 2 × better cooling, 20% higher field	4	2
NbTi-Nb$_3$Sn hybrid scheme	2	4
quad. 1st Nb$_3$Sn	1	6
quad. 1st with detector-integrated dipole	1	6
detector-integrated quadrupole	2	6
quad. 1st flat beam	4	4
separate channel quad. 1st Nb$_3$Sn or NbTi plus crab cavities	0	2
dipole 1st options with Nb$_3$Sn	0	2
pulsed or dc long-range beam-beam compensator	4	4
electron lens	0	4

Koutchouk, and Roland Garoby. For the new sets, — the three on the right-hand side of Table 2 —, both electron cloud and pile up appear acceptable, and the strain is put elsewhere.

The parameter set with 12.5-ns bunch spacing refers to the previous baseline scenario. This scenario can be ruled out since the expected heat load, even without electron cloud, reaches the maximum conceivable cooling capacity of 2.4 W/m per beam, limited by the hydraulic impedance of the beam-screen capillaries [8].

The set with double the transverse emittance is challenging, as the beam must be blown up at top energy in a controlled way, without suffering instabilities at injection or in the pre-injectors. In addition, the total predicted heat load is still in excess of the local cooling limit. Also this scenario is not a promising one.

The second to last parameter set describes an upgrade option with essentially the ultimate beam, but a much reduced beta function of the collision point, of about 8 cm. This is an option promoted by Jean-Piere Koutchouk. The heat load is much below the limit. However, the low beta function requires a D0 dipole inside the detector, most likely together with a low-ange crab cavity, and Nb$_3$Sn low-beta quadrupoles, as well as possibly as slim detector-integrated s.c. Q0 quadrupole doublet, neither of which is without risk. The IR layout for this option is sketched in Fig. 1. We choose this to be our new alternative upgrade scenario.

The last parameter set corresponds to long and more intense bunches at 50-ns spacing. Also for this option the heat load and the number of pile-up events appear acceptable. This solution does not require any magnetic elements embedded inside the detector, and it allows for the possibility of using final quadrupoles based on NbTi. Wire compensation of long-range beam-beam effects will be necessary. Figure 2 presents a schematic of the corresponding IR layout. In view of its advantages, we tentatively propose this last parameter set as the new upgrade baseline path.

Figure 3 compares the luminosity evolution for the two options, Assuming a turn-around time of 5 h (time between the end of a collision run and the start of the next 7-TeV collisions) and for both cases the respective optimum run times, as listed in Table 2. The dashed lines indicate the time-averaged luminosities. It can be seen that the luminosity for the 25-ns scenario starts higher, but decays faster than for the 50-ns case, leading to shorter runs. The average luminosity values are nearly identical. Figure 4 shows that the average event pile up for the 25-ns option is about 20% lower than that for the 50-ns case.

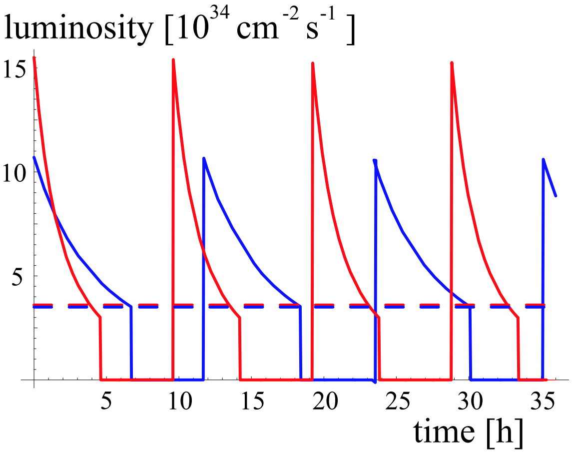

Figure 3: Ideal luminosity evolution for the new upgrade scenarios with 25-ns (alternative) and 50-ns bunch spacing (baseline), considering optimum run times for an assumed turnaround time of 5 h. The dashed lines indicate the corresponding time-averaged luminosities.

10 OUTLOOK

The first two years of LHC operation will clarify the severity of electron cloud, long-range beam-beam collisions, impedance etc. This experience is likely to decide

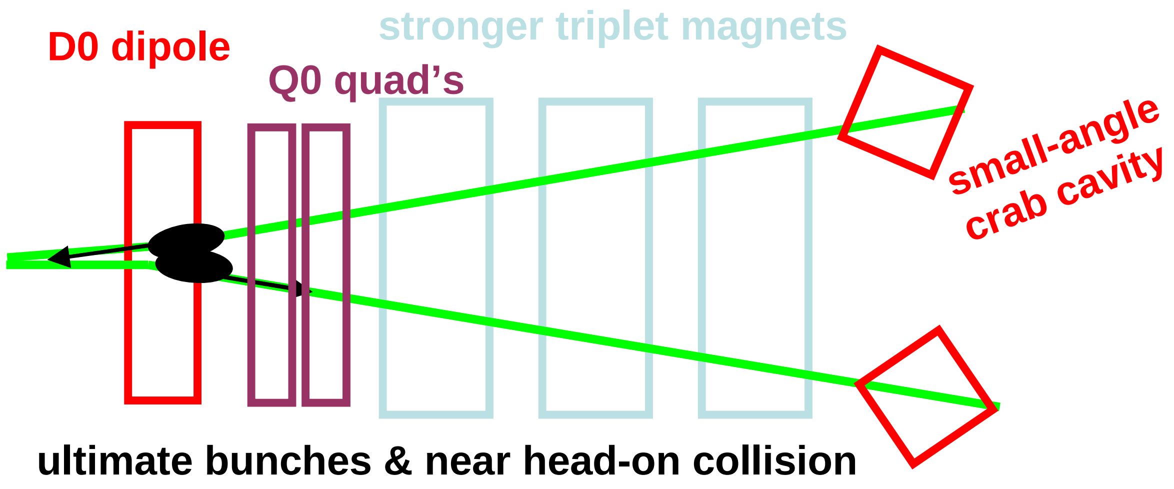

Figure 1: Interaction-region layout for 25-ns upgrade with strongly squeezed optics ($\beta^* \approx 8$ cm), involving stronger triplet quadrupoles, early-separation dipoles 'D0' close to the collision point, low-angle crab cavities, and, possibly, also a detector-integrated quadrupole doublet 'Q0'. Merits are negligible long-range collisions and the absence of geometric luminosity loss due to a crossing angle at the collision point. Challenges are the D0 dipole deep inside the detector (e.g., 3 m from the IP), the integration of the Q0 doublet in the detector, the first ever use of crab cavities for hadron beams, the noise of which may lead to emittance growth, and the luminosity reduction from the hourglass effect.

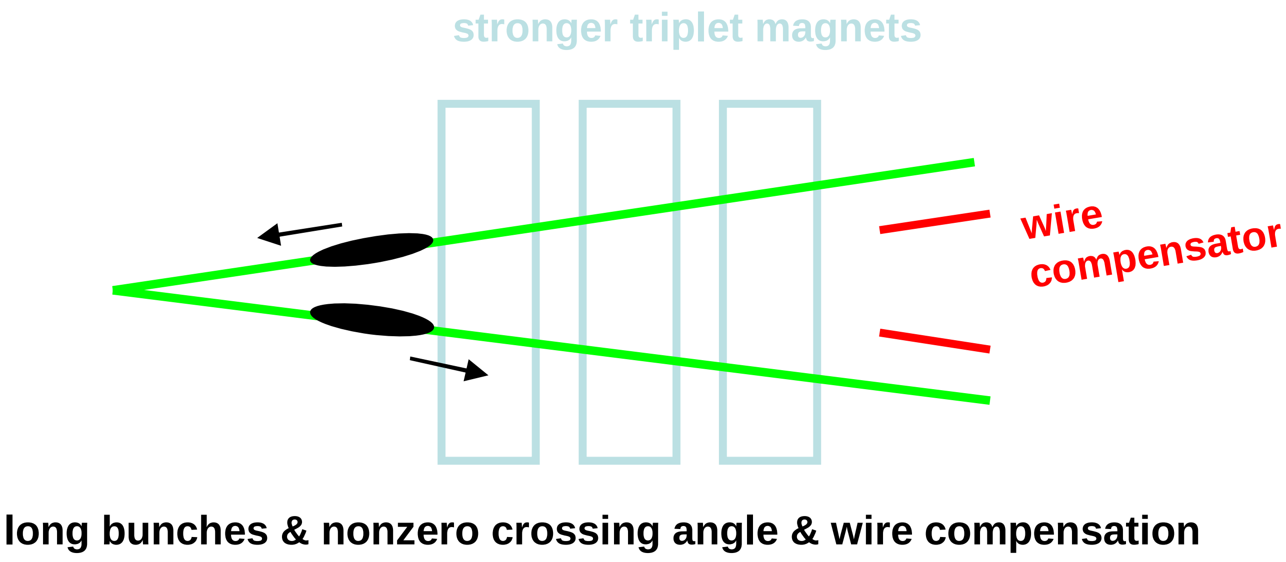

Figure 2: Interaction-region layout for 50-ns upgrade with an IP beta function of 0.25 m, involving stronger triplet quadrupoles and a wire compensation of long-range beam-beam effects. Merits of this scheme are the absence of magnetic elements inside the detector, the unnecessity of crab cavities, and a lower chromaticity compared with the alternative 25-ns low-beta scenario. Challenges are the novelty of operating a hadron collider in the regime of large Piwinski angle, the high bunch charge, and the large total beam current.

Table 2: Parameters for the ultimate LHC compared with those for four upgrade scenarios with (1) shorter bunches at 12.5-ns spacing [old baseline], (2) bigger more intense bunches at 25-ns spacing [not recommended], (3) more strongly focused ultimate bunches at 25-ns spacing [new alternative], (4) longer intense bunches at 50-ns spacing [new baseline].

parameter	symbol	ultimate	“short”	“big”	“low β”	“long”
no. bunches	n_b	2808	5616	2808	2808	1404
protons/bunch	N_b [10^{11}]	1.7	1.7	3.4	1.7	4.9
bunch spacing	$\Delta t_{\rm sep}$ [ns]	25	12.5	25	25	50
average current	I [A]	0.86	1.72	1.72	0.86	1.22
norm. transv. emittance	$\gamma\epsilon$ [μm]	3.75	3.75	7.5	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian	Gaussian	uniform
rms bunch length	σ_z [cm]	7.55	3.78	3.78	7.55	11.8
beta function at IP1&5	β^* [m]	0.5	0.25	0.25	0.08	0.25
crossing angle	θ_c [μrad]	315	445	630	0	381
Piwinski parameter	$\theta_c\sigma_z/(2\sigma^*)$	0.75	0.75	2.75	0	2.01
hourglass factor		1.00	1.00	1.00	0.86	0.99
peak luminosity	$\hat{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	9.2	9.2	15.5	10.6
events/crossing		44	88	176	294	403
rms length of luminous region	$\sigma_{\rm lum}$ [mm]	43	21	21	53	37
initial lumi. lifetime	$\tau_{\rm L}$ [h]	14.3	7.2	7.2	2.2	4.5
eff. luminosity ($T_{\rm ta} = 10$ h)	$L_{\rm eff}$ [10^{34} cm^{-2}s^{-1}]	0.9	2.7	2.7	2.4	2.5
opt. run time ($T_{\rm ta} = 10$ h)	$T_{\rm opt}$ [h]	17.0	12.0	12.0	6.6	9.5
eff. luminosity ($T_{\rm ta} = 5$ h)	$L_{\rm eff}$ [10^{34} cm^{-2}s^{-1}]	1.2	3.7	3.7	3.6	3.5
opt. run time ($T_{\rm ta} = 5$ h)	$T_{\rm opt}$ [h]	12.0	8.5	8.5	4.6	6.7
e-cloud heat load	$P_{\rm ec}$ [W/m]	1.04	13.3	2.6	1.0	0.4
for $\delta_{\rm max} = 1.4$	(1.3)	(0.6)	(7.9)	(2.1)	(0.6)	(0.1)
SR heat load at 4.6–20 K	$P_{\rm SR}$ [W/m]	0.25	0.5	0.5	0.25	0.36
image-current heatload at 4.6–20 K	$P_{\rm ic}$ [W/m]	0.33	1.85	3.70	0.33	0.70
1.9-K gas scattering heat load for 100 h lifetime	$P_{\rm gas}$ [W/m]	0.06	0.11	0.11	0.06	0.08

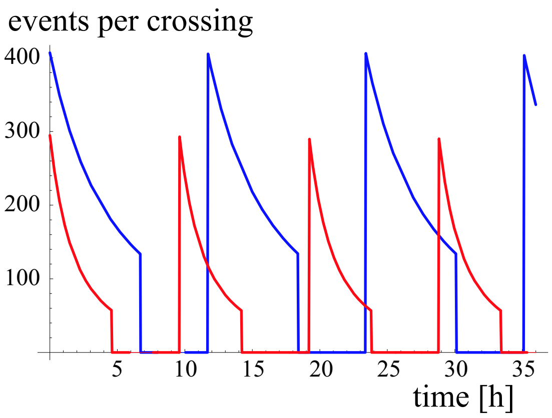

Figure 4: Number of events per crossing as a function of time for the same two upgrade scenarios and luminosity time evolutions as in Fig. 3.

the final upgrade path. In the same line, we need to wait for the first physics results for a decision whether we can integrate any magnetic elements inside the detectors or not. The accelerator R&D results until then will be important. For the moment, it is clear that with both physics and precise LHC performance limits unknown we should keep a few options open.

11 “FORWARD-LOOKING BASELINE SCENARIO”

As forward-looking baseline upgrade, we propose choosing a hybrid scheme like that suggested by Tom Taylor and Ranko Ostojic at this workshop [10], where one (or two) quadrupole(s) per triplet are made of Nb_3Sn and the others from NbTi.

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