SUMMARY: LHC IR UPGRADE AND BEAM CHOICES

S. Peggs, BNL, O. Brüning, CERN

INTRODUCTION

The spectrum of potential upgrade scenarios shown in Table 1 holds the possibility of boosting the LHC luminosity by as much as a factor 10 beyond the nominal value of $1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. All scenarios incorporate new IR magnets that go beyond the present state-of-the-art, such as stronger or larger-aperture low-beta quadrupoles, or specialized beam separation dipoles. Some of them also have significant implications for other hardware sub-systems, such as beam-beam compensators, crab cavities, acceleration cavities, collimators, cryogenics, and beam dumps. Significant upgrade requirements may even extend back up the injector chain.

The presentations made in Session 3 of the workshop investigated these implications in some depth. This summary merely introduces the major themes and issues, leaving the reader to find the details in the Session 3 papers contributed to these proceedings [1, 2, 3, 4, 5, 6].

scenario	L $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	ΔT [ns]	N_i
nominal	1.0	25	23
ultimate	2.3	25	54
IR upgrade	4.6	25	108
super-bunch	9.0	9×10^4	9×10^5

Table 1: Luminosity L, bunch spacing ΔT, and the number of events per bunch crossing N_i, tabulated for a selection of different LHC scenarios [6].

REPRESENTATIVE UPGRADE LAYOUTS

At least 5 plausible upgrade layouts are currently under discussion [1]. Three of the most representative layouts are shown in Figure 1.

The “quadrupole first” layout (with a small crossing angle) is shown at the top of Figure 1. Both beams go through a single bore of a quadrupole triplet in this layout, which is the nominal implementation of the LHC as it will first be run. Stronger quadrupoles would allow the focusing center to move closer to the interaction point (IP), allowing a smaller β^* and more luminosity for a given number of bunches, and bunch intensities, et cetera. Or, larger bore quadrupoles with the same gradient would hold the slot lengths constant, allowing a quadrupole-by-quadrupole progressive upgrade. In either case the beams will suffer a relatively large number of parasitic long range beam-beam interactions, until the beam reach the first beam separation dipole, approximately 60 meters from the IP.

The “dipole first” layout shown in the middle of Figure 1 separates the beams into separate triplet quadrupole

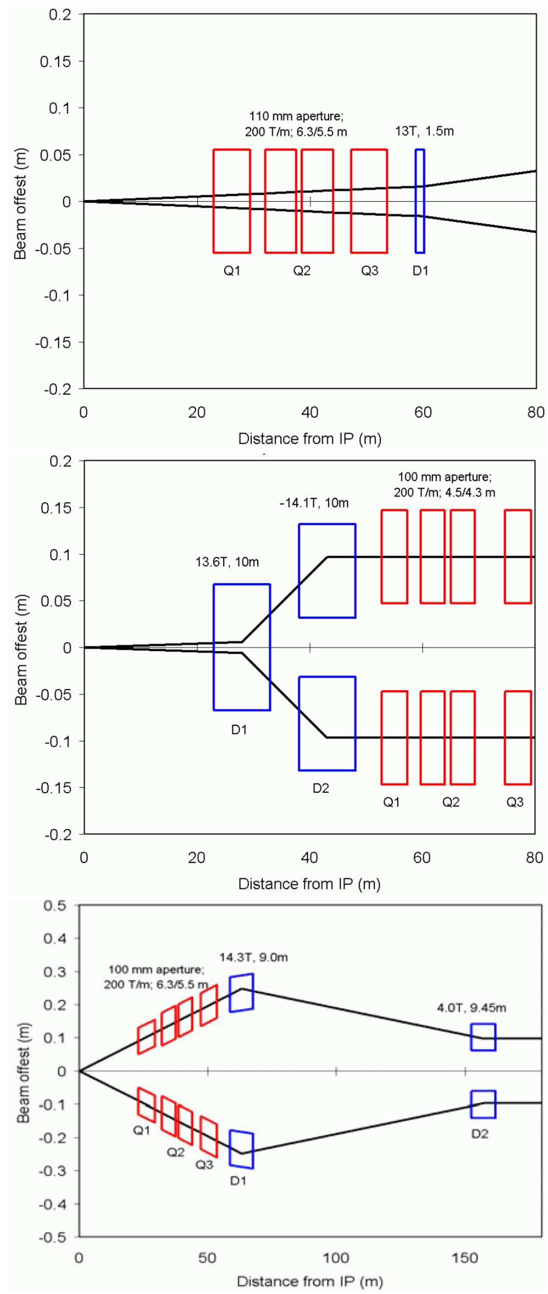

Figure 1: Three representative potential upgrade layouts [1]. TOP: quadrupole first. MIDDLE: dipole first. BOTTOM: large crossing angle, quadrupole first.

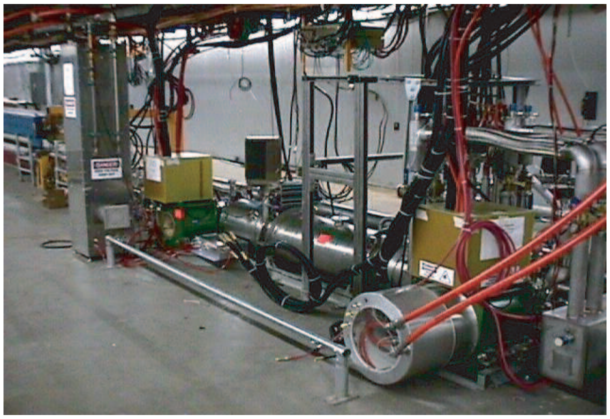

Figure 2: The first generation prototype Tevatron Electron Lens, installed for head-on beam-beam compensation and abort gap beam cleaning in the Tevatron [2].

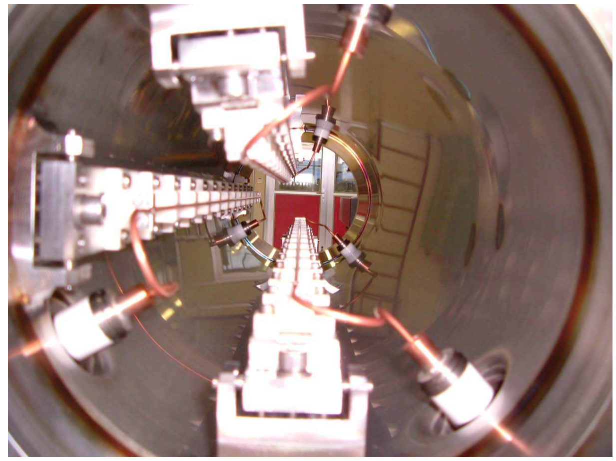

Figure 3: The second generation prototype "BBLR" long range beam-beam wire compensator, installed for tests in the SPS [2].

bores. This scheme has the advantage of eliminating the long range beam-beam collisions beyond about 23 meters from the IP, but it has the optical disadvantage of moving the triplet focusing center further from the IP. The question of where and how to absorb the many kilowatts of luminosity debris power is a significant challenge in all scenarios [1]. One suggestion is to use magnetized absorbers in the middle of the IR optics. The dipole first layout has the simultaneous advantage and disadvantage of not needing magnetic absorbers, since the first dipole will absorb much of the debris power.

Finally, the "large crossing angle" scenario shown at the bottom of Figure 1 has the dual advantages of almost completely eliminating long range beam-beam interactions, while maintaining a relatively close triplet focusing center. However, it has the disadvantage of requiring a large number of crab cavities. This in turn stresses the need to reduce the transverse size of the first focusing quadrupoles, in order to reduce the crossing angle (and unburden the crab cavity system) as far as possible.

BEAM-BEAM COMPENSATION

The nominal bunch spacing of $\Delta T = 25$ ns leads to one long range beam-beam interaction every 3.75 m up to a distance of L_{sep} from the IP, when the first beam separation dipole is encountered. Thus there are as many as 30 interactions per IR [2]. Each IR generates a long range beam-beam tune shift of

$$|\Delta Q| \approx \frac{2L_{sep}}{c\Delta T} \frac{\xi}{(\theta/\sigma'^*)^2} \qquad (1)$$

where ξ is the (head-on) beam-beam parameter, θ is the total crossing angle, and σ'^* is the RMS angular size of the beam at the IP. The plane of the crossing can be alternated between the 4 IRs in the LHC, leading to a significant cancellation of the net tune shift. This cancellation even works for PACMAN bunches, near bunch pattern gaps, that experience non-standard beam-beam collision sequences.

However, the complexities of the beam-beam interaction cannot be reduced to one or two simple quantities such as net head-on and long range tune shifts. Instead, a more sophisticated analysis is required, for example in terms of transverse diffusion rates, frequency maps, and diffusive (dynamic) apertures [2]. Nonetheless, Equation 1 accurately indicates that, if initial operating experience shows that long range beam-beam interactions are a fundamental limit to luminosity performance, then one can respond by reducing L_{sep} (for example by going to a dipole first layout), or by increasing θ (for example by going to a large crossing angle layout).

Another response is to compensate for the head-on beam-beam interactions. Figure 2 shows the prototype Tevatron Electron Lens (TEL) installed at Fermilab for head-on beam-beam compensation of anti-protons. The electron current must vary from bunch to bunch, enabling a secondary role for the TEL as an abort gap beam cleaner. The TEL is not yet in routine operation for beam-beam compensation – tests continue.

Figure 3 shows the BBLR device installed for tests in the SPS. The round water-cooled "wires" carry currents to induce magnetic fields that mimic the spatial dependence of the force-field of a round beam. The current must vary from bunch to bunch, at about 20 MHz, in order to cope with PACMAN bunches. It is possible that a BBLR prototype will be installed in RHIC, testing its long-term effects on stored beams.

CRAB CAVITIES

When the crossing angle is larger than the natural aspect ratio of the bunch, $\theta \geq (\sigma^*/\sigma_s) \sim 1$ mrad, then a lot of luminosity is lost because the head of one bunch does not collide with the tail of the other. Figure 4 illustrates the principle by which transverse deflecting mode RF crab cavities fix this problem, inducing a localized perturbation in

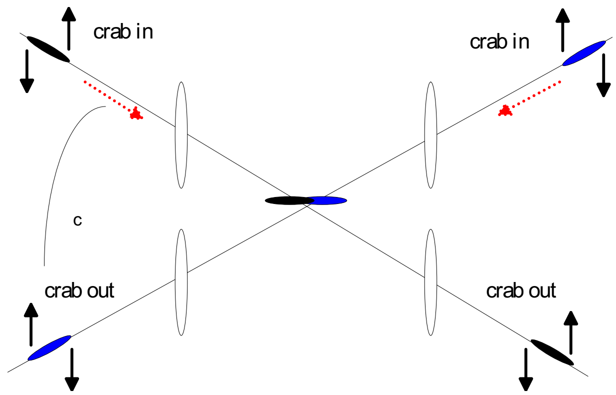

Figure 4: The crab crossing principle. Incoming bunches are tilted by transverse deflecting mode crab cavities on the extremities of the IR so that they collide head-on. The tilt is removed on exit by another set of RF cavities [2].

the closed orbit as a function of longitudinal displacement from the center of the bunch.

A single crab cavity will begin engineering tests in one of the KEK B factory rings in late 2005, followed by an operational test with one cavity in each ring in 2006 [3]. Table 2 compares KEK B crab cavity parameters with sample LHC parameters, showing that the LHC implementation is much more extreme. The total RF voltage required is given by

$$V = \frac{cE}{2\pi e} \frac{\tan(\theta/2)}{f_{RF}\sqrt{\beta^* \beta_{crab}}} \quad (2)$$

If the total crossing angle is $\theta = 8$ mrad, then the beams are only separated by about 18 cm at a distance of 23 m from the IP, the closest approach of the first (side-by-side) quadrupoles.

Crab cavity phase errors generate transverse displacements at the IP which, when coupled with the beam-beam effect, can lead to unacceptably large emittance growth rates. This effect is unimportant in electron colliders like KEK B, where it is suppressed by synchrotron radiation damping. Figure 5 shows emittance and luminosity evolution from a short timescale simulation, also including simulations of acceleration cavity phase noise for comparison [3]. It remains an open issue whether acceptably small emittance growth rates are possible. For this reason it has been suggested that, if the 2006 KEK B crab cavity tests are successful, then a crab cavity should be installed and tested in a hadron machine to demonstrate a level of RF phase noise compatible with acceptable emittance preservation.

		KEK B	LHC
crossing angle	θ [mrad]	22	8
beam energy	E [TeV]	0.008	7
collision beta	β^* [m]	0.33	0.25
crab beta	β_{crab} [km]	0.1	2
RF frequency	f_{RF} [GHz]	0.51	1.3
RF voltage	V [MV]	1.4	46

Table 2: Comparison of KEK B crab cavity parameters with those typically required for an LHC upgrade [2, 3].

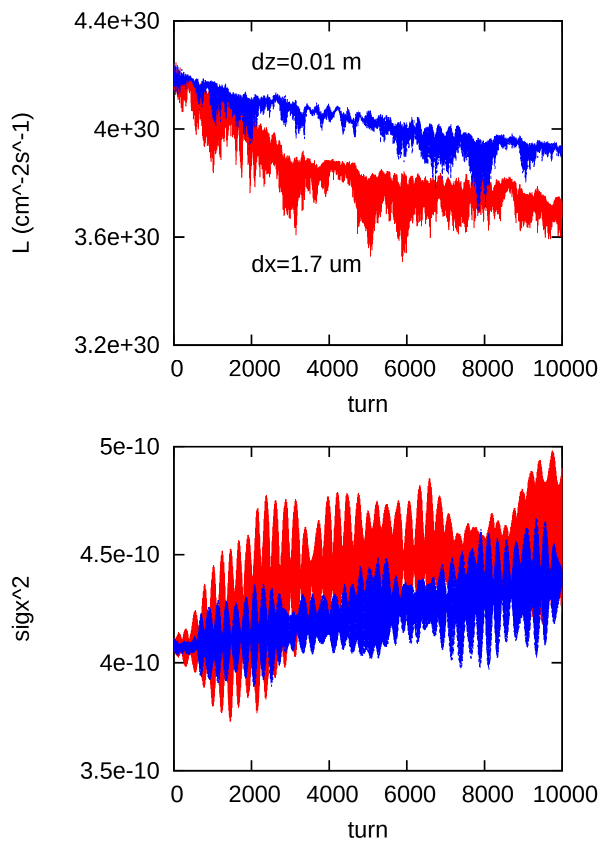

Figure 5: Evolution of luminosity and horizontal beam size due to phase jitter in the crab cavities coupling to the beam-beam interaction [3]. The effect of phase noise in the acceleration system is also included, for comparison.

LONGITUDINALLY FLAT BUNCHES

It is predicted that, under a set of conditions and assumptions including a large crossing angle θ and operation at the beam-beam limit, the luminosity with longitudinally flat beams is $\sqrt{2}$ larger than with longitudinally gaussian beams [2, 5]. Figure 6 illustrates the extreme case, in which a single flat super-bunch extends around almost all of the circumference, contained (and accelerated) by barrier bucket induction cavities. Induction acceleration has recently been demonstrated at the KEK proton synchrotron [4].

A single full length super-bunch is not optimal. Figure 7 predicts that under some conditions the optimal total bunch length is about 280 m, divided into a convenient number of bunches. Some suggest that the technology for confin-

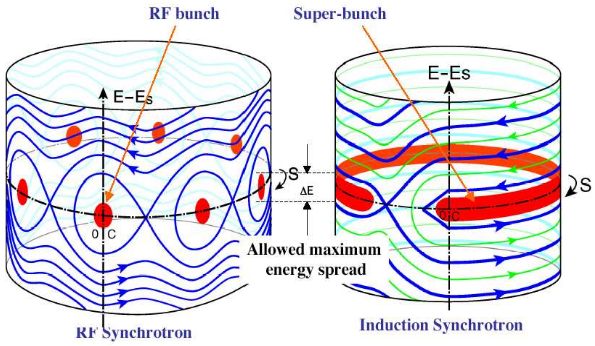

Figure 6: Bunch confinement and acceleration using conventional resonant RF and induction cavity RF systems. LEFT: many bunches in a conventional system. RIGHT: a single long super-bunch under the influence of barrier pulse voltages generated by an induction system [4].

ing "intermediate length" bunches using a conventional RF system operating at harmonics of 40 MHz is more appropriate than an induction RF system [5]. A larger number of shorter bunches is also favored by the experimentalists, who are daunted by the extraordinary event pile-up difficulties that arise for super-bunches (see the last row in Table 1). Figure 8 shows that sufficiently flat beams are produced using only a 3 harmonic system, whatever the fundamental frequency [5].

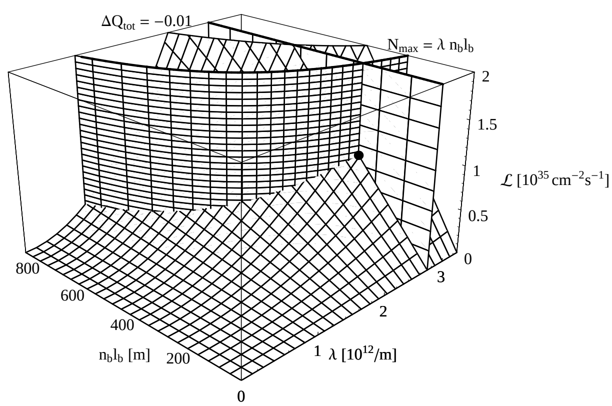

Figure 7: Luminosity in the LHC versus total beam length $n_b l_b$ and line density λ. The vertical surfaces represent constraints imposed by a maximum total beam-beam tune spread of 0.01 (flat surface) and a maximum average current of 1.1 A (curved surface) [5].

CONCLUSIONS

There is much activity exploring a spectrum of potential LHC upgrades that have the potential to enhance the luminosity by as much as an order of magnitude. Many technologies in different arenas need investigation. Nonetheless, all scenarios incorporate new IR magnets that go beyond the present state-of-the-art, whether these magnets use NbTi conductors (arguably more appropriate in the near term), or $\mathrm{Nb_3Sn}$ conductors (in the medium term). In any case, some years of initial operation of the LHC will be required before settling on the optimum upgrade scheme. This does not obviate the need to pursue further studies and R&D *now*, so as to be ready *then*. It is also possible that there will be multiple (perhaps modest) upgrades in sequence, and not one single monolithic upgrade.

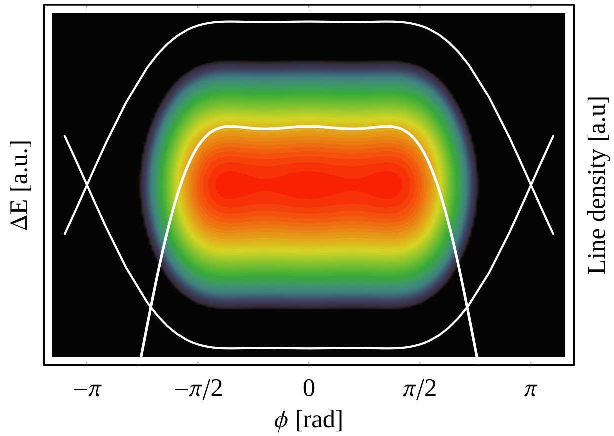

Figure 8: Longitudinal phase space and line density of a bunch held by three RF systems, for example 40, 80, and 120 MHz. The distribution is flat enough to reap the predicted advantages of longitudinally flat beams [5].

ACKNOWLEDGMENTS

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