BEYOND THE LHC: A CONCEPTUAL APPROACH TO A FUTURE HIGH ENERGY HADRON COLLIDER*

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Abstract

The concept of a post LHC hadron collider operating in the radiation damping regime was discussed in the DPF workshop on future hadron facilities[1]. To date hadron colliders have all operated in a state of insignificant damping, where phase space dilution from any source results in a costly degradation of instantaneous and thus integrated luminosity. The concept of using radiation damping to enhance the integrated luminosity results in an effective decoupling of the machine performance from the initial beam parameters. By relying more heavily on the damping mechanism, the requirements for tight emittance control through the injector chain and during the collider fill process can be relaxed allowing for less stringent injection field quality and the possibilities for looser tolerances in many other aspects of the machine. In this paper we present some generic parameters and machine characteristics before examining options for lengthening the standard cell (quadrupole and spool piece reduction) and highly lumped correction schemes (correction element reduction).

Table I
30 TeV Collider Parameters

Parameter	
Beam Energy (TeV)	30
Peak Luminosity ($\times 10^{33}$ cm^{-2} sec^{-1})	10
Injection Energy (TeV)	1
No. of IR's	2
Dipole Field (T)	12.5
Circumference (km)	60
β^* (cm)	20
Init. Trans. Emittance (rms, mm-mr)	1.5π
Init. Long. Emittance (rms, eV-s)	0.1
Bunch intensity (10^{10})	2.4
No. of bunches	2030
Bunch spacing (ns)	100
No. Events per crossing (@60mb, 10^{34})	60
Init. beam lifetime – burn off (hr)	16
Syn. Rad. power / length / ring (W/m)	0.56
Rad. transverse damping time (hr)	4.3

I. PARAMETERS

Radiation damping implies synchrotron power with the associated problems of cryogenic heat load and gas desorbtion. Constraining the latter to a tractable range while maintaining the former as a useful feature argues for a collision energy in the range of $25 \rightarrow 40$ Tev with a corresponding dipole field of 12.5 ± 2.5 T. We have chosen to use a parameter set based on a 30 Tev design (T30) since this looked a reasonable energy for a post LHC machine and demonstrates the necessary parametric behavior. We have also used a 12.5 T dipole magnet, since this appeared to represent a reasonable goal for a next generation superconducting magnet. A range of dipole fields can be accommodated in this approach.

A partial parameter list is shown in Table I. Minimizing the synchrotron power resulted in a reduced number of protons and beam bunches. The total number of protons was determined largely by the desire for ~ 10 hr stores in spite of significant particle burn-off with 2 IR's operating up to a luminosity of 10^{34} cm^{-2}s^{-1}. The maximum credible cryogenic heat load is considered to be 3 W/m. This parameter set is well below this value. We estimate an average of ~ 60 events per bunch crossing.

The time evolution of the luminosity, transverse emittance, and bunch intensity is shown in Fig. 1. A parameterization of intra-beam scattering (IBS) is used to provide a beam heating mechanism. The luminosity increases by a factor of 2 during the first several hours of a store until the IBS and radiation damping mechanisms come into equilibrium, from which point the luminosity decreases as the bunch intensity is depleted from the interactions. The peak to average luminosity is a healthy ~ 70%. We have assumed a standard FODO cell lattice with an "SSC-like" footprint of 2 IR's and 2 long arc regions. Dipoles occupy 90% of the machine circumference. The machine operating characteristics do not exhibit any undue sensitivity to the details of the assumed parameters but rather are defined primarily by the damping regime itself. This is demonstrated in Fig. 2, which shows the 10 hour integrated luminosity versus the initial transverse emittance. Unlike a conventional hadron collider, the performance is only weakly correlated to the initial beam parameters, but is defined primarily by the equilibrium condition between heating and cooling mechanisms. It is this robust nature of the performance that allows the kind of speculation in the balance of this report which involves simplifying the lattice, and contemplating inferior magnetic field quality, in a more agressive manner than was deemed prudent for the SSC.

II. LATTICE ISSUES

Drawing upon the lessons from the SSC, the number of different types of components must be minimized, long cable runs for correctors are to be avoided, and the number of power leads minimized. This philosophy leads one to a design with "sparse/lumped" correctors, and to have power and vacuum hardware physically attached to the main quadrupole magnet cryostat, avoiding having "spool pieces" in every half-cell.

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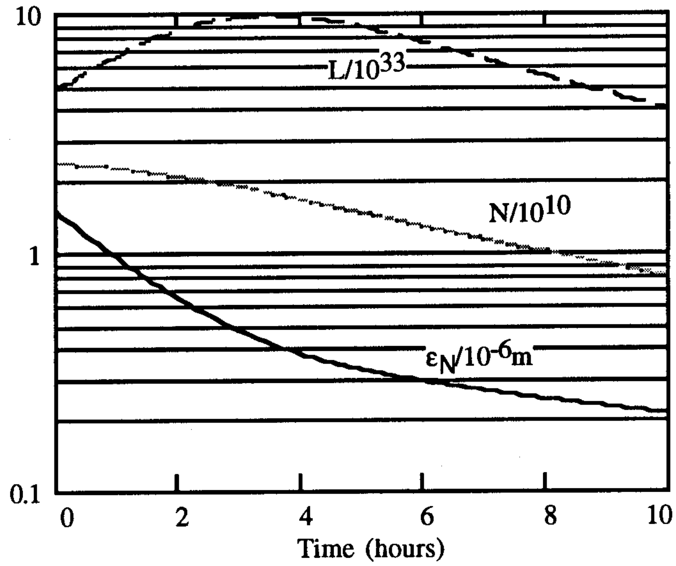

Figure 1. Emittance, luminosity, and bunch intensity vs. time during store.

A. Cell Length Optimization

The optimum half FODO cell length, L, depends on a dynamic balance:

- longer cells save money through fewer quadrupoles, fewer correctors, and fewer spool pieces
- longer cells reduce chromatic sextupole nonlinearities
- shorter cells and thus smaller beams reduce magnetic field quality demands

The magnetic field quality in the arc dipoles dominates the dynamic aperture at injection, the most critical time. The half cell in T30 can become quite long, if the historical trend to improved field quality continues, and the dipole bore is large enough. Figure 3 plots the vertical magnetic field versus horizontal position in the mid-plane of dipoles for which data were available [2].

The dynamic aperture may be crudely represented by the "good field aperture," r_{GF}, in the arc dipoles. In this picture, particle motion is stable so long as the maximum field deviation $\Delta B/B \leq 10^{-3}$, which occurs at a horizontal displacement of r_{GF}. In practice, of course, there are many complications to attach to this simple model, which is nonetheless useful in the spirit of this paper.

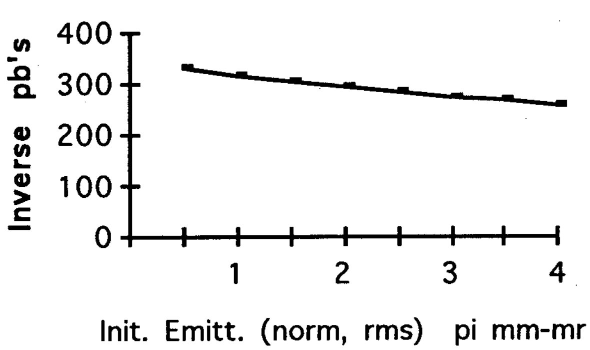

Figure 2. Integrated luminosity (10 hr store) vs. initial transverse emittance.

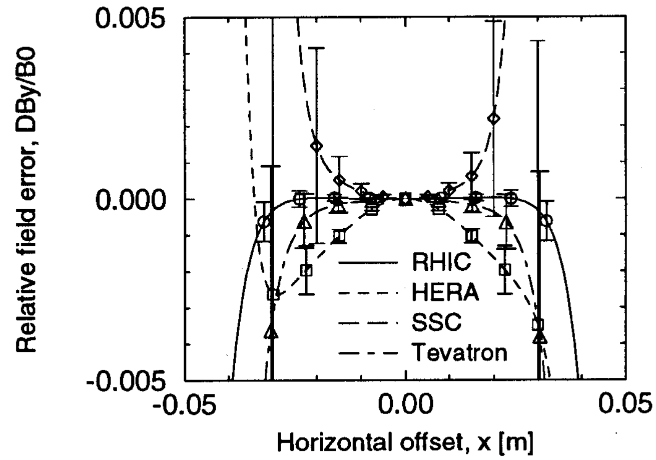

Figure 3. Field profiles of arc dipoles at injection.

For $90°$ FODO cells the maximum beta function is given by $\widehat{\beta} = 3.41\ L$. The maximum transverse rms beam size at injection, $\widehat{\sigma} = \sqrt{\epsilon\widehat{\beta}/\pi\gamma_I}$, therefore increases with increasing cell length. The maximum allowable beam size occurs when the beam fills the good field aperture, or $r_{GF} = n\widehat{\sigma}$, where a reasonable value for n is 10. This expression ignores the beam size contribution due to finite momentum spread. It is shown, below, that with nominal parameters it is possible to reduce σ_p/p (at the expense of increased bunch length) so that the betatron size continues to dominate. Putting all this together gives a maximum allowable half cell length

$$\widehat{L} = \frac{\pi\gamma_I}{\epsilon}\frac{r_{GF}^2}{3.41\,n^2} \qquad (1)$$

Table II applies this expression to existing machines and to T30, assuming that $n = 10$ in all cases. For the SSC [3], the real half cell length appears to be conservatively small, while RHIC is close to the limit predicted by Equation 1.

Table II
Half cell length for different accelerators.

Machine	γ_I	ϵ/π [μm]	r_{GF} [mm]	$\widehat{L}$ [m]	L_{real} [m]
Tevatron	150.0	3.0	20	60	30
SSC	1000.0	1.0	10	290	94.0
RHIC(Au)	12.6	1.7	30	20	14.9
T30	1000.0	1.5	15	440	(400)

Even in a careful and detailed analysis, the good field aperture is the least well known quantity in determining $\widehat{L}$, and the most important, since it enters quadratically on the numerator of Equation 1.

Long FODO cells make $\widehat{\beta}$ unusually large, while the total arc tune $Q_{arc} \approx C/8L$ remains quite modest. The maximum dispersion $\widehat{\eta} = 2.71\,L^2/R$, and the beam width due to momentem increase quadratically with L, faster than the betatron contribution. Assuming a longitudinal rms bunch area of $S = 0.1$ eV-sec, this results in the rather small momentum spread 3×10^{-5}, determined by setting $\sigma_p/p = \widehat{\sigma}/\widehat{\eta}$ so that the two contributions are equal. The bunch is not unusually long (36 cm), because the injection energy is relatively high. The resultant synchrotron tune is in the range of conventional experience, since the slip factor (approximately $1/Q^2_{arc}$) is relatively high, while the momentum width is relatively low. This high slip factor also makes the beam acceptably resistant to collective effects, such as the microwave instability.

So long as the field quality can be maintained, a much longer half cell (few hundred meters) for this next generation hadron collider must not be ruled out.

B. Sparse Correctors

To take even more advantage of a "simplified arc," every few kilometers the normal FODO lattice is interrupted by a section of cells with free space generated by leaving out a sequence of dipole magnets as a "dispersion-matched insertion." These "free spaces" would contain "empty cryostats," which could then be converted to function as spool pieces as required. An example of such an insertion is shown in Fig. 4.[4]

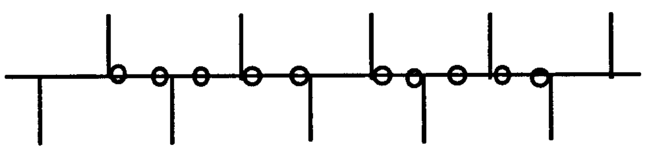

Figure 4. Dispersion-matched free-space FODO region; the circles indicate locations where dipole magnets are missing from the normal cell structure.

The adjustment of the global tunes of the accelerator can be performed by Phase Trombones – one at each end of each arc, supplemented by the placement of trim quadrupoles in the "free-space" insertions. Likewise, sextupoles are placed in these spaces as well. Naturally, the effects on dynamic aperture of such a lumped scheme will have to be studied carefully. But the analysis of the previous section has shown that long half cells help in this regard.

One primary concern of a sparse correction scheme is that of orbit correction. Suppose that "trim" dipoles are used only in our "free space" insertions to bring the orbit deviations to zero at these locations. For a distance d_{sa} between service areas, d_{rms} quadrupole alignment error, and dipole magnets with individual lengths ℓ_b, then in terms of the half-cell length L and bend radius ρ, the rms maximum displacement is

$$\widehat{\Delta x} = 4.8\ L \sqrt{\frac{d_{sa} d^2_{rms}}{L^3} + \frac{(\Delta B/B)^2 d_{sa} \ell_b}{\rho^2}}. \qquad (2)$$

Figure 5 shows the rms maximum orbit distortion and lattice functions versus half-cell length for $C = 60$ km, $d_{rms} = 0.5$ mm, $\ell_b = 20$ m, $d_{sa} = 8$ km, and $\Delta B/B = 10^{-3}$.

Some form of local orbit correction (trim coils, moveable magnets) is still necessary for any reasonable cell length. However, it is feasible that many other major correctors can be sparsely distributed, thus simplifying the arc hardware design.

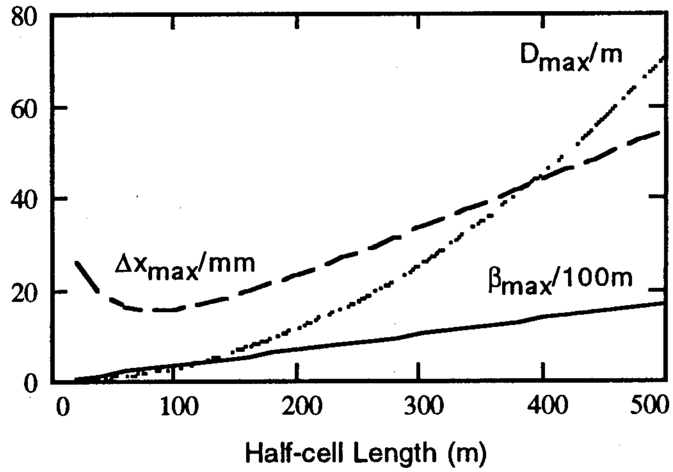

Figure 5. Maximum beta function and dispersion function, and rms maximum orbit error versus half-cell length.

III. CONCLUDING REMARKS

The goal of ≥60 TeV in the center-of-mass, with a luminosity of 10^{34} cm^{-2}sec^{-1} is reasonable for a facility following the LHC. The most interesting and promising factor of this energy regime is the utilization of synchrotron radiation to enhance the accelerator performance. Long cells and lumped correctors are an option worth pursuing, as the overall performance of the collider can be maintained or enhanced with such a simplified hardware design. Bending magnets with fields in the range of 12.5 T± 3 T will be needed to support these aims. The authors would like to thank all of the participants of the DPF Workshop for their contributions to this effort.

References

[1] "Proc. of Workshop on Future Hadron Facilites in U.S.," Fermilab-TM-1907, 1994.

[2] Tevatron and HERA data are from private communication with N. Gelfand and D. Gall, respectively.

[3] J.D. Jackson (Ed.), "SSC Conceptual Design", Berkeley, 1986

[4] A. A. Garren, reported in "Proc. of Workshop on Future Hadron Facilites in U.S.," Fermilab-TM-1907.