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Critical Beam Intensity Issues in Hadron Colliders

S.D. Holmes

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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CRITICAL BEAM INTENSITY ISSUES IN HADRON COLLIDERS

Stephen D. Holmes
Fermi National Accelerator Laboratory
Batavia, IL 60510

Introduction

I would like to discuss how some of the issues that have been talked about at this workshop (and some that haven't) are reflected in the performance of hadron colliders. Hadron colliders, be they proton-antiproton, proton-proton, or heavy ion, are typically supported by a half-dozen other accelerators each of which has its own set of performance characteristics and limitations. As a result, when designing, building, operating, or upgrading a hadron collider choices must be made that determine not only overall performance but also the ultimate configuration of the complex.

It is impossible to discuss here the full range of issues that one has to consider in projecting performance in a hadron collider. I will concentrate on a few and attempt to make some observations on how/when various effects relating to beam intensity are important. We will start with a short introduction that is intended to give the "lay of the land" in hadron colliders--what are the performance issues and what are the fundamental mechanisms that limit performance? We will then examine how choices in beam parameters can and have influenced performance, and how strategies are likely to change as we contemplate higher energy colliders. Finally, I will offer some opinions on what research directions are dictated for improving the luminosity delivered from hadron colliders.

Performance Issues in Hadron Colliders

The performance of any particle collider is characterized by two parameters--the center-of-mass energy and the luminosity. A discussion of energy limitations is beyond the scope of this presentation and, at least in hadron colliders built to date, unrelated to the beam intensity. The luminosity in a hadron collider is given by the expression:

$$L = \frac{fBN_1N_2}{2\pi(\sigma_1^2 + \sigma_2^2)} F(\sigma_z / \beta_L^*) = \frac{3\gamma fBN_1N_2}{\beta_L^*(\varepsilon_{N_1} + \varepsilon_{N_2})} F(\sigma_z / \beta_L^*) \tag{1}$$

where f is the revolution frequency of the accelerator, B is the number of bunches in each beam, N_1 and N_2 are the particle populations in each beam, σ_1 and σ_2 are the rms beam sizes (assumed round) in each beam, σ_z is the rms bunch length, β_L^* is the lattice function at the interaction point, γ is the standard relativistic factor (assumed >>1), ε_{N_1} and ε_{N_2} are the normalized beam emittances (assumed round), and $F(\sigma_z/\beta_L^*)$ is a form factor related to the ratio of the bunch length to the lattice function. The definition of emittance we use here is given in terms of the (observed) rms beam size:

$$\varepsilon_N = \frac{6\pi\beta\gamma}{\beta_L}\sigma^2 \tag{2}$$

Typical parameters leading to a luminosity of about 1.6×10^{31} $cm^{-2}sec^{-1}$ at the Fermilab Tevatron are:

$N_p = 2.3 \times 10^{11}$	$\beta_L^* = 0.35$ m
$N_{\bar{p}} = 5.5 \times 10^{10}$	$\varepsilon_{N_p} = 23\pi$ mm-mr
$B = 6$	$\varepsilon_{N_{\bar{p}}} = 13\pi$ mm-mr
$f = 47.7$ kHz	$F(\sigma_z/\beta_L^*) = 0.6$
$\gamma = 959$	

As is clear from the luminosity formula the beam phase-space density, N/ε, is a critical element determining the luminosity performance of a hadron collider.

The Collider Complex

Any hadron collider is situated within an accelerator complex in which the beam (kinetic) energy typically swings through a range of more than six orders of magnitude. Fundamental limitations to be discussed here are related to: 1)space charge (including beam-beam); 2)synchrotron radiation; and 3)beam transfers. The relative importance of each of these effects depends on the energy regime of the beam.

Beam Intensity/Density Limitations

The fundamental fact of life in a hadron collider complex is that once the beam emittance is diluted its hard to recover. This is because no natural damping mechanism exists, as in electron synchrotrons, and efforts to cool the beam utilizing stochastic cooling at high energies have so far been unsuccessful. As a result preserving a high beam phase space density is at least as big a task as producing a high beam phase space density in a hadron collider complex. This fact is illustrated in Figure 1.

Figure 1 shows the measured proton beam vertical emittance at various stages of acceleration in the Tevatron collider complex. The data points represent an average over all proton fills between July 24, 1994 and July 23, 1995. The steps indicated on the figure are:

1 Linac exit (400 MeV)
2 Booster exit (8 GeV)
3 Main Ring at 150 GeV after coalescing
4 Tevatron at 150 GeV after proton injection
5 Tevatron at 150 GeV after antiproton injection
6 Tevatron at 900 GeV after squeeze
7 Tevatron at 900 GeV in collision

The figure shows that the transverse emittance of approximately 7π mm-mr delivered from the linac at 400 MeV grows to typically 24π mm-mr by the time the protons are brought into collision with antiprotons at 900 GeV in the Tevatron. Clearly low emittance at the front end is a necessary-but-not-sufficient condition for low emittance in collision.

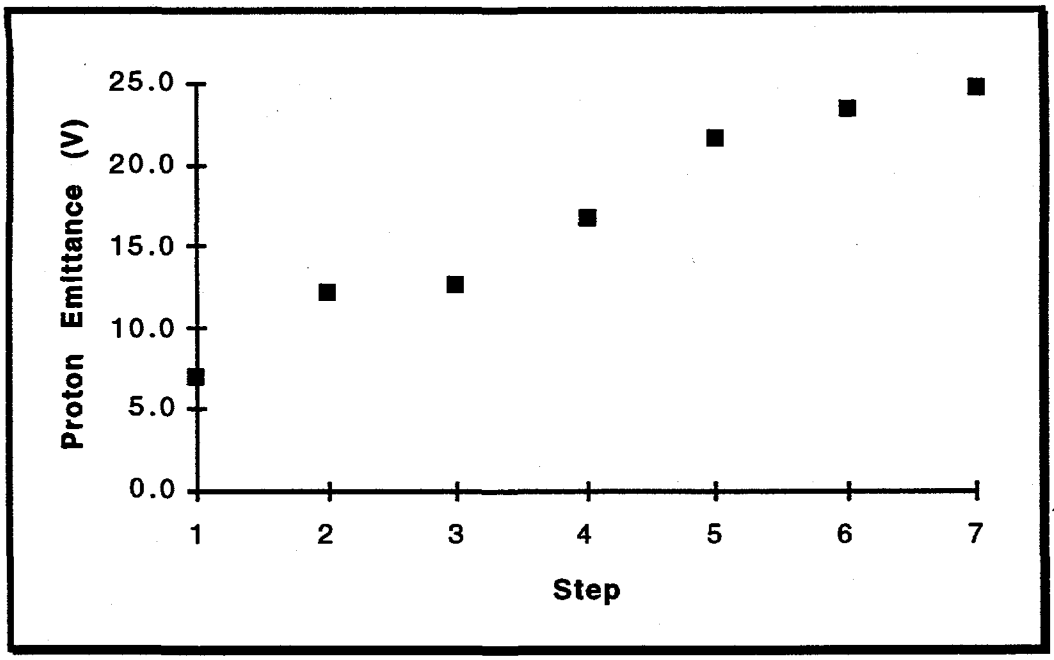

Figure 1: Proton beam vertical emittance at various stages in the accelerate-to-collision process in the Tevatron. Data points represent average of all store between 7/24-94-7/23/95.

Phase Space Density Limitations

The most fundamental effects limiting phase space density are due to macroscopic electromagnetic fields, generated by the beam, and applied to either the circulating beam itself or to its counter-rotating partner. The effect of a single beam's macroscopic fields on the individual particles making up the beam itself is called "space charge". Space charge is characterized by a net defocusing effect that is quantified in circular accelerators by the Laslett tune shift parameter:

$$\Delta\nu_{sc} = \frac{3r_o}{B_F}\frac{N_{TOT}}{\varepsilon_N}\frac{(1-\beta^2)}{\beta} \tag{3}$$

Here N_{TOT} is the total number of particles in the accelerator, B_F is the ratio of the average to peak circulating current, r_0 is the particle classical radius, ε_N is the beam emittance, and β is the beam relativistic velocity. As can be seen the size of the effect is proportional to the beam phase space density. The velocity dependence arises from the cancellation of electric and magnetic self-forces, and reduces the strength of the effect to zero as the beam becomes relativistic. For this reason space-charge is generally only a consideration in the lowest energy synchrotron in a hadron accelerator complex. This effect tends to limit the phase space density that can be achieved in low energy proton synchrotrons. Experience has shown that the value of $\Delta\nu_{SC}$ that can be achieved in practice lies in the range 0.4-1.

In a colliding beam facility one beam also feels and responds to the electromagnetic field generating by its counter-circulating partner. In this case a net focusing force is generated that again is quantified as a tune shift. The beam-beam tune shift is given by:

$$\boxed{\Delta\nu_2 = \frac{3r_o}{4}\frac{N_1}{\varepsilon_{N_1}}(1+\beta^2)} \tag{4}$$

Here $\Delta\nu_2$ is the tune shift (per crossing) of beam two caused by the particles in beam one. Again the size of the effect is proportional to the beam phase space density. The functional form of the beam-beam tune shift is similar to that of the space charge tune shift with the important exception that the electric and magnetic forces add. As a result the beam-beam tune shift can be, and often is, significant in high energy colliders and can limit luminosity performance. Experience to date has shown that a value of $\Delta\nu$ summed over all beam-beam encounters of about .025 can be tolerated.

Space charge and beam-beam effects provide fundamental limitations in our ability to increase the phase space density of proton beams at the low and high energy ends of the acceleration/storage cycle. However, as is evident from Figure 1, there are other effects that can dilute the beam emittance at intermediate energies even if a large phase space density is achieved early in the acceleration chain. The most important of these relates to dilution arising from imperfect beam transfers. If the beam is transferred from one accelerator to another and is injected off the closed orbit by an amount (Δx,$\Delta x'$) the phase space will be diluted by an amount:

$$\boxed{\Delta\varepsilon_N = \frac{3\pi\gamma}{\beta_L}\left[(\Delta x)^2 + (\alpha_L\Delta x + \beta_L\Delta x')^2\right]} \tag{5}$$

where (β_L, α_L) are the lattice functions at the injection point. The relativistic factor gives this effect considerable importance in high energy beam transfers. Emittance preservation requires injecting onto the closed orbit to a high degree of accuracy (within <100 μm at multi-TeV colliders) and/or providing feedback systems that can damp beam motion in a period less that the decoherence time. Other potential transfer mismatches, including optical mismatches, are generally more benign.

The final effect that we will mention leading to beam emittance dilution in high energy colliders is intrabeam scattering. This effect can be significant at high energy and is very sensitive to both the transverse and longitudinal emittance. Since the growth rates scale as Z^4/A^2 this effect has a huge impact on the performance of heavy ion colliders such as RHIC where operations with Au^{+79} are being planned. Intrabeam scattering growth times measured in hours are expected both in RHIC and in the Tevatron as its luminosity approaches $1\text{x}10^{32}$ $cm^{-2}sec^{-1}$.

Beam Intensity Limitations

As discussed above a variety of effects act to limit the phase space density that can be achieved in a hadron collider. In some instances limitations apply to the total beam population rather than to the density. One example is beam instabilities arising from wakefields generated by the interaction of the beam with the surrounding environment. Such instabilities are typically independent of the transverse beam emittance and (coherent motion) can be controlled by active damping systems. More fundamental limits are related to the microwave instability, which is not susceptible to control by dampers.

As hadron colliders move into the multi-TeV range, as was planned for the SSC and is currently planned for the LHC, synchrotron radiation will play an increasingly important role in determining ultimate performance. The role of synchrotron radiation ranges from irrelevant at beam energies less than 1 TeV, to a major nuisance for energies in the range 1-30 TeV, to potential ally above 30 TeV. The major impact of synchrotron radiation is the heat load generated on the refrigeration system. The heat load (at the magnet operating temperature) is directly proportional to the total beam population, N_{TOT}:

$$\boxed{P(W) = \frac{6\times10^{-14}E^4(TeV)N_{TOT}}{\rho(km)R(km)}} \qquad (6)$$

where ρ is the bend radius in the dipole magnets and R is the mean radius of the accelerator. The linear power density within the bending magnets is then given by,

$$\boxed{\frac{dP}{ds}(W/m) = \frac{6\times10^{-17}E^4(TeV)N_{TOT}}{2\pi\rho^3(km)}} \qquad (7)$$

Limiting this heat load to a level that can be extracted from a superconducting environment is a primary design criterion is multi-TeV hadron colliders and forces the designers to consider configurations in which N_{TOT} is minimized.

Strategies for Maximizing Luminosity in Hadron Colliders

A number of strategies and choices exist for ameliorating the effects described above and optimizing the performance of hadron colliders. The strategy followed in most instances depends upon what regime one is working in, i.e. whether limitations exist in the high or low energy accelerators and/or whether one is working in a regime in which the total beam population is a consideration.

Space Charge

At least two methods are available for minimizing the effects of space-charge in the low energy accelerators within a hadron collider complex. The most widely used technique involves the utilization of H^- injection into the lowest energy synchrotron. Multiple-turn H^- injection allows one to build up the beam density in the lowest energy synchrotron, thus removing the need for a very high current linac. Once this mode of operation is selected, the strategy for developing the highest phase space density possible is to inject at the highest energy possible into a synchrotron of the lowest circumference possible. Specifically, one attempts to maximize the ratio $\beta\gamma^2$/circumference (see equation 3) subject to financial and technological constraints. Figure 2 shows the impact on performance of the Fermilab 8 GeV Booster observed following an increase of the injection energy from 200 MeV to 400 MeV. The two sets of points show the dependence of the beam emittance delivered at 8 GeV on intensity for the two different injection energies. The two lines are drawn corresponding to a space-charge tune shift of about 0.4 for each of these cases. Clearly, raising the injection energy has had a highly beneficial effect on our ability to increase the phase space density delivered from this machine.

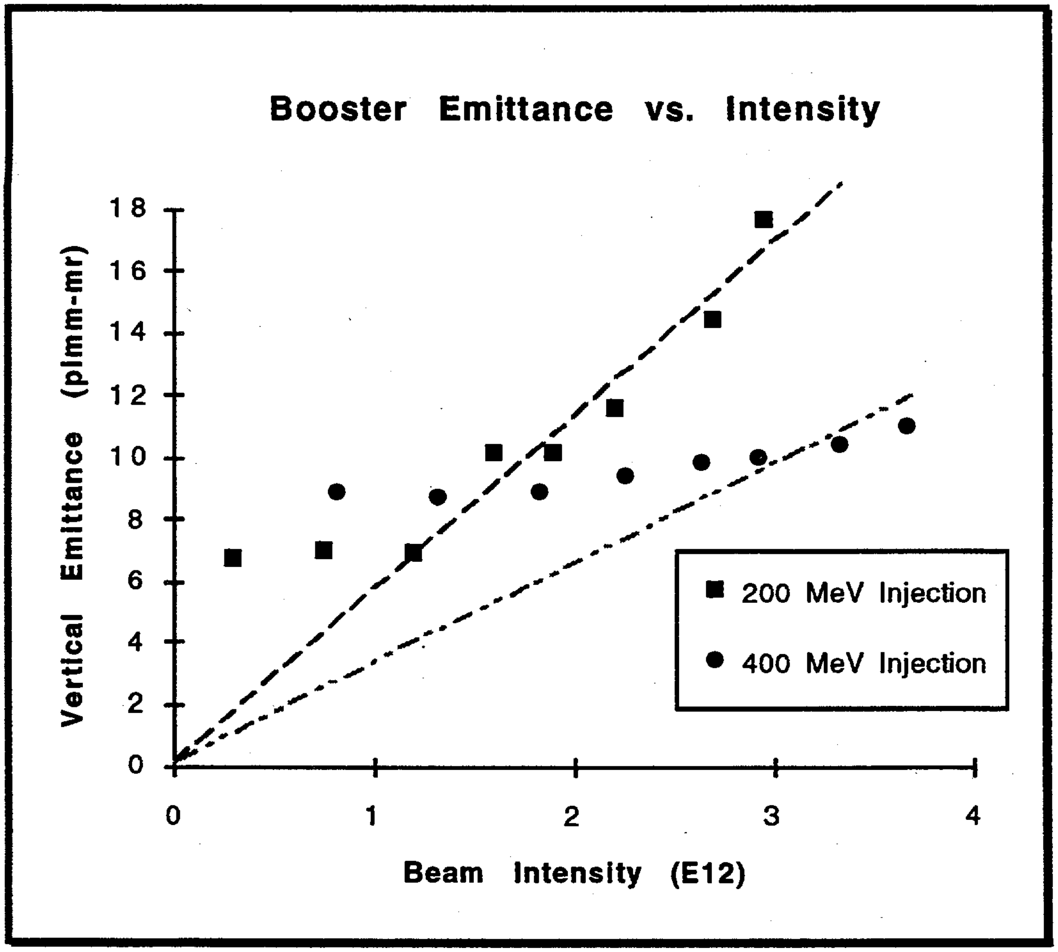

Figure 2: Vertical emittance delivered from the Fermilab Booster as a function of beam intensity for 200 MeV and 400 MeV injected beams. Contours of constant space-charge tune shift at the two injection energies are superimposed.

A second technique that is used at Fermilab to increase the transverse phase space density is called "bunch coalescing". This involves a manipulation of the beam in longitudinal phase space that combines several bunches into a single bunch. Coalescing is carried out at 150 GeV in the Main Ring at Fermilab and results in an approximate ten-fold increase in the transverse beam density. Of course, the total six-dimensional phase space must be preserved and so the longitudinal emittance of the coalesced bunch is somewhat greater than the sum of the longitudinal emittances of the (~ten) pre-coalesced bunches.

One could reasonably ask whether improvements in performance based on either of these consideration actually translate into improved performance in collision. The answer is yes. Figure 3 shows the achieved phase density of the 900 GeV proton beam in collision with antiprotons for 200 MeV linac operation and for 400 MeV linac operation. A 50-60% increase in phase space density is observed in the Tevatron for 400 MeV operations. This gain is attributed in approximately equal measure to the impact of 400 MeV linac operation and improvements in the Main Ring coalescing system. A secondary, but equally significant, impact of the improvement in beam phase space density delivered from the Booster has been to relieve some of the aperture problems present in the Main Ring and allow that machine to accelerate and deliver a significantly larger quantity of protons onto the antiproton production target. This has provided a 50% increase in the antiproton production rate and a corresponding contribution to increased luminosity.

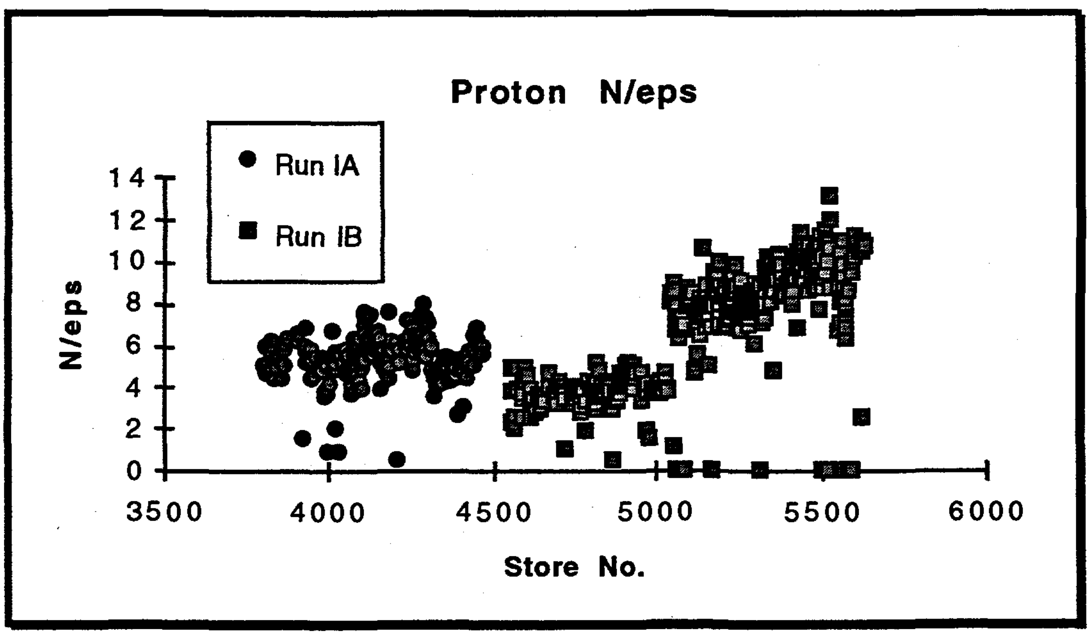

Figure 3: Proton phase space density as observed in the Tevatron before (Run IA) and after (Run IB) the 400 MeV linac upgrade. The discontinuity midway through Run IB is related to solution of a severe coupling problem in the Tevatron.

Beam-beam Effects

For a "weak-strong" scenario, such as exists in a proton-antiproton collisions, the luminosity formula can be recast as:

$$\boxed{L=\frac{2\gamma f\Delta\nu_{HO}(BN_{\bar{p}})}{r_0\beta^* N_{INT}(1+\frac{\varepsilon_{N\bar{p}}}{\varepsilon_{Np}})}F(\beta^*/\sigma_z)} \tag{8}$$

Here $\Delta\nu_{HO}$ is the head-on tune shift, summed over N_{INT} encounters, seen by the antiproton bunches. One observes that the luminosity is proportional to the allowed tune shift, inversely proportional to the number of beam-beam encounters, and actually increases as the proton emittance is raised!

One sees immediately from this expression the value of creating separated orbits in a collider that is beam-beam limited. For B circulating bunches $N_{INT} = 2B$ if the two beams are circulating on a common closed orbit. This was the situation in the Tevatron prior to the introduction of electrostatic separators in 1991. During that period the Tevatron collider operated in a beam-beam limited mode and the proton beam was intentionally diluted to raise the luminosity as indicated by the formula. The introduction of electrostatic separators allowed a reduction of N_{INT} to two, while maintaining B at six, and was accompanied by an immediate factor of three increase in luminosity.

Current operations in the Tevatron are not beam-beam limited. However, it is expected that the Tevatron will return to this regime following commissioning of the Main Injector accelerator in late 1998.

Synchrotron Radiation

Future multi-TeV hadron colliders will operate in the regime in which the total beam intensity is limited by the allowed radiated power density. In this case the luminosity can be expressed as :

$$\boxed{L\propto\frac{\rho^5 P^2}{\gamma^7 B\varepsilon_N}\propto\frac{P^2}{B_{MAG}^5 E^2 B\varepsilon_N}} \tag{9}$$

where P' is the linear power density and B_{MAG} is the magnetic dipole field. In this regime the luminosity is enhanced by: 1)lowering the emittance; 2)lowering the magnetic field (and increasing the circumference); and 3)minimizing the number of bunches (at a cost of more interactions/crossing and decreased beam lifetime due to interactions). This is the regime in which the SSC was being designed and led to a strategy based on creating and preserving a very low emittance proton beam. The LHC, now under design, will also operate in this regime.

Conclusions

The luminosity achievable in a hadron collider is inversely proportional to the beam transverse emittance, all other parameters remaining fixed. Consequently lower emittance as early as possible in the acceleration chain at a hadron collider is (almost) always desirable. However, in hadron facilities the problem of bringing low emittance beams into collision generally is not a reflection of limitations at the very low energy end of the chain. H^- injection and coalescing techniques allow an increase in the beam intensity and/or phase space density once the beam has been accelerated beyond $\beta \approx 0.5$. As a result emittance preservation is at least as important an issue as the creation of low emittance in a hadron collider complex.

Raising the injection energy of the lowest energy synchrotron in an accelerator complex has proven to be an effective approach to improving performance. Examples include the Brookhaven Booster and the Fermilab linac upgrade. However, our understanding of the role of space-charge in low energy synchrotrons is still rudimentary. Clearly, this is an area requiring continued study and attention.

Technological advances in a variety of areas will be critical to support continued improvements in the performance of high energy hadron colliders. Included are:

- Further development of beam feedback systems to minimize dilution during transfers
- Further investigation into the realization of bunched beam cooling systems capable of counteracting the effects of slow emittance growth at high energy, for example those due to intrabeam scattering, power supply and rf noise, and other mechanical motions.

- Development of medium energy electron cooling for the purposes of creating low emittance beams at a stage in the acceleration chain in which space-charge is not an important consideration.

The beam-beam interaction can limit performance in TeV scale proton-antiproton colliders. However, effects due to head-on encounters are unlikely to be important for multi-TeV proton-proton colliders because of the manner in which the parameters will tend to be chosen. What will still remain of importance however is the long-range beam-beam interaction. As bunches are spaced more closely together in an attempt to minimize the number of interactions per crossing the effects of parasitic crossings outboard of the collision point will become an important consideration.

Following the advent of hadron colliders operating with beam energies well beyond 1 TeV the premium placed on creating and preserving a small beam emittance will become much more critical. Keeping the radiation power density manageable while simultaneously generating a high luminosity will force designs to rely on a low beam emittance. In the more distant future designers of hadron colliders operating at tens of TeVs will find themselves in the happy position of enjoying the natural damping mechanism relied on in electron colliders. To gauge where we stand on that road I leave you with the following expression for the transverse damping time in a proton collider:

$$\boxed{\tau_x(hours) = \frac{1.5\times 10^3 R(km)\rho(km)}{E^3(TeV)}}$$