# 50 TEV HIGH-FIELD VLHC WITH A LOW FIELD INJECTOR*

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*Abstract*

The 50 TeV very large hadron colliders studied at the 1996 Snowmass workshop were taken to have an injection energy of 3 TeV. As the injection energy increases, the cost and complexity of the final injector increases, while that of the collider decreases. In this paper, we would like to consider the extreme case of a full energy injector. Presumably, this produces the maximum benefit, in terms of technical simplification and cost reduction, for the collider, at the cost of having to build a rather large injector. We consider the specific case of a 50 TeV high-field radiation-damped collider (12.5 T magnets), whose injector is a 50 TeV low-field (2 T magnets) machine. We discuss the general advantages and disadvantages of this approach.

## 1 INTRODUCTION

The 50 TeV very large hadron colliders studied at the 1996 Snowmass workshop were taken to have an injection energy of 3 TeV. With this injection energy, the 50 TeV ring must have a dynamic range of about 16; this is a reasonable, conservative choice. Existing hadron colliders have dynamic ranges varying from 7 (Tevatron) through 20 (HERA); LHC is planning to have about 16 also. The implicit assumption is that, to minimize the total costs, one should have as low an injection energy as possible. This strategy certainly minimizes the cost of the injector, but the cost of the collider may be higher, since it must operate over an extended dynamic range. It is not obvious that minimizing the cost of the injector serves to minimize the cost of the total project.

If one begins to consider a higher energy injector, it is natural to consider an injector which shares the same tunnel as the collider. This approach was considered in some early SSC studies[1]. Let us consider a 50 TeV high-field collider, with dipoles operating at 12.5 T. The injector will have an energy equal to 50 TeV times the ratio of its dipole field to that of the collider. For example, an injector made using SSC dipoles (6 T field) would provide about 25 TeV injection energy; an injector made using 2 T superferric magnets would provide 8 TeV injection energy. The collider dynamic range requirement is reduced to 2 or 6, respectively, in these cases. Some of the generic benefits of this approach are considered in [1].

In this paper, we would like to consider the extreme case of a full energy injector. Presumably, this produces the maximum benefit, in terms of technical simplification and cost reduction, for the collider, at the cost of having to build a rather large injector. We shall consider the specific case of a 50 TeV high-field radiation-damped collider (12.5 T magnets), whose injector is a 50 TeV low-field (2 T magnets) machine. (See Fig 1.)

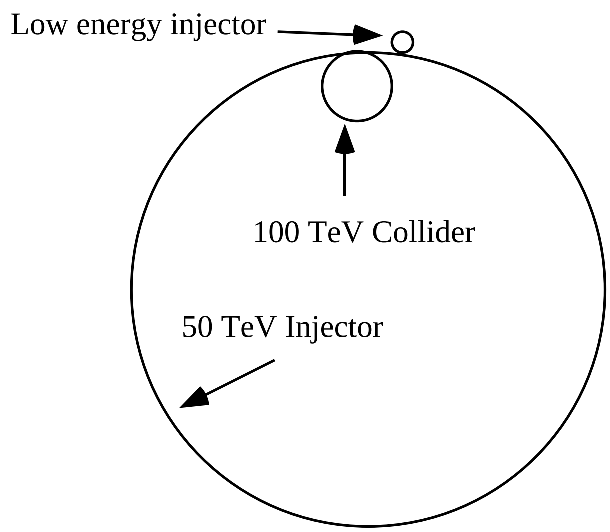


Figure 1: Layout of full-energy injector and collider.

## 2 ADVANTAGES AND DISADVANTAGES

There are several significant advantages to the collider with this approach. First of all, the magnet aperture can be made significantly smaller. The beam size at injection is quite small (see below), and if the closed orbit errors can be kept under control, the coil diameter may be able to be reduced to as small as 12-15 mm. The reduction in the beam emittance due to radiation damping, together with the fact that the machine's dynamic aperture will be determined in collision by the interaction region optics, should greatly ease the field error tolerance for the arc dipoles. The high field magnets will be able to be realized with lower currents, and the forces correspondingly will be reduced. Moreover, since the collider has a fixed field, persistent current problems will be absent: this may be particularly important for magnets that use high temperature superconductor. The magnets need only be optimized for one operating point, which could substantially ease their design.

Since acceleration is not necessary, the rf system is only needed to supply the energy lost through synchrotron radiation, and to provide the voltage needed for the required bunch length. This could result in a simpler rf system. Beam stability issues will be eased, despite the small aperture, since the beam is always at full energy. The beam

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abort system will be simpler, as it will operate at a fixed energy.

The collider will also be able to be filled very rapidly. In fact, the collider can be "topped off" periodically, which means the luminosity need never go to zero (except when the beam is lost), which will result in higher integrated luminosity.

The obvious disadvantage is the need to build a very large 50 TeV injector (together with its very large tunnel), and full energy transfer lines and injection systems. However, the 2 T magnets can be very simple: only one beam tube is required, so a simple C-magnet design may be the best approach, perhaps driven by a transmission line as in the Foster design[2]. The field quality requirements should not be very severe, as the beam emittance is not crucial, due to the radiation damping in the collider. The aperture could be small, since some multibunch stability issues are mitigated due to the low current needed for the final machine: only a fraction of the circumference needs to be filled. Single-bunch stability issues will remain important, although they may be minimized if a bunch coalescing scheme is adopted. The vacuum requirements should not be severe, since the beam does not stay in the ring for a very long time. The low-field machine would also be available for a 50 TeV fixed-target program between collider fills.

## 3 COLLIDER MAGNET APERTURE

The required aperture in a collider is typically determined by the beam size and the closed orbit deviations; in addition, an allowance is usually also made for injection errors. The maximum rms beam size at injection is given by

$$\sigma_x^2 = \frac{\epsilon\beta_{max}}{\gamma} + (\hat{\eta}\ \sigma_\delta)^2. \quad (1)$$

Here $\epsilon$ is the normalized rms emittance, $\gamma = E_{inj}/mc^2$, and $\sigma_\delta$ is the rms relative momentum spread. For 90° cells of length $2L$, we have $\beta_{max} = 3.41\ L$ and $\hat{\eta} = 2.71\ L^2/R$, where $L$ is the half cell length and $R$ is the ring radius. Using the beam parameters $\epsilon = 1$ mm-mrad and $\sigma_\delta = 50 \times 10^{-6}$, and with $R$ = 16.7 km, $L$ = 150 m, we have $\sigma_x$ = 208 $\mu$m. The closed orbit deviation due to $N$ random angular deviations of rms amplitude $\sigma_\theta$ is given by

$$\sigma_{co} = \frac{\sqrt{N\beta_{max}\bar{\beta}}}{2\sqrt{2}|\sin\pi\nu|}\ \ \sigma_\theta \quad (2)$$

in which $\bar{\beta}$ is the average amplitude function at the locations of the errors, and $\nu$ is the betatron tune. Angular deviations may arise from quadrupole alignment errors (taken to have an rms value of 200 $\mu$m), the roll angle of the dipoles (rms value 250 $\mu$rad), and the relative dipole field errors in the dipoles (rms value $3 \times 10^{-4}$). The total rms closed orbit deviation (quadrature sum of the contributions from these three sources) is about 10 mm without correction. Assuming the orbit is corrected perfectly at the beam position monitors (located at focusing quadrupoles), the rms residual orbit error (including defocusing quad locations) would be about 60 $\mu$m. We assume this is within the monitor resolution. The required beam pipe aperture would thus be dictated by the position monitor alignment with respect to the quadrupole centers, which is taken to be about 200 $\mu$m. Adding this to the beam size contribution gives about 400 $\mu$m; allowing a factor of five to encompass the entire distribution results in a required radial aperture of 2 mm.

Allowing an additional 1 mm radial aperture for injection errors and other miscellaneous effects brings the total radial aperture to 3 mm. The beam-stay-clear diameter is thus 6 mm. This could be accommodated in a 15 mm diameter magnet coil bore; the good field region is required to be 40% of the coil diameter, and a radial space of 4.5 mm is available for the implementation of the required beam screen/cryosorber system to pump the gases desorbed by synchrotron radiation.

The meaning of "good field region" in this case requires considerable study. The presence of synchrotron radiation damping means that emittance growth mechanisms with a time scale greater than the damping time (about $3 \times 10^7$ turns) will not be important. This may allow a more tolerant requirement on the field errors. The motion within the "good field region" may not need to be completely linear. The SSC CDR tracking studies found a dynamic aperture of 12 mm with a 40 mm coil diameter[3]. If the aperture scales with the square of the coil diameter, a 20 mm coil diameter would be required to obtain a 3 mm dynamic aperture. Study will be required to determine whether the field errors associated with a 15 mm coil diameter would be tolerable in the presence of synchrotron radiation damping.

There is considerable current interest in common-coil, block designs for high field magnets. Such designs should be able to more easily accommodate smaller apertures than cos-theta designs. In addition, the simplicity of the block magnet design should minimize the random errors, which must be extremely well controlled for small aperture magnets.

## 4 INJECTION

The simplest injection scheme loads the full-energy injection with a bunch train of the same length as the collider. This bunch train is then accelerated to full energy and transferred in a single turn into the collider. For the counter propagating beam, the polarity of the injector is reversed, the beam is accelerated, and transferred using a separate injection line into the collider.

For a low-field injector with a warm beam tube, it is important to limit the injected beam current because of potential stability issues related to the large resistive-wall impedance. Since only a fraction of the circumference is filled, multibunch stability problems are somewhat alleviated. Single bunch stability, which depends on the magnitude of the peak current, can also be enhanced by coa-

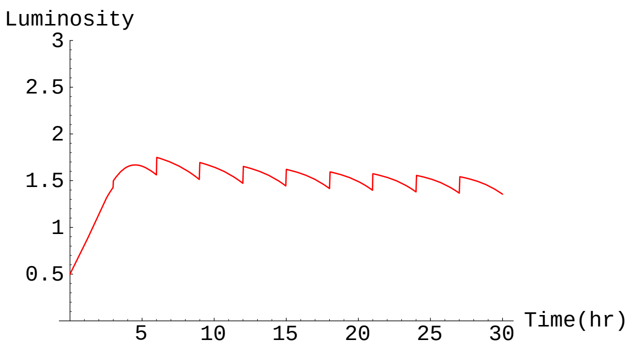


Figure 2: Topping off.

lescing. The injected beam can be distributed into a large number of bunches, with reduced intensity in each bunch, and accelerated to full energy in this form using a high frequency rf system. At full energy, before beam transfer, the bunches can be coalesced into a smaller number of bunches with the correct time structure, and then transferred to the collider. This limits the peak current per bunch at injection and raises the stability thresholds.

Although a conventional full-aperture kicker can be used in the collider, there may be a significant advantage in the use of a partial-aperture shuttered kicker at a point of high dispersion. In this scheme, additional beam may be injected while circulating beam is already in the machine; this is similar to the "topping-off" procedure used in electron colliders. In principle, a significant gain in integrated luminosity may be realized, since the beam need never be dumped, and the topping off can be used to replace the beam lost through interactions at the IP.

One possible arrangement to achieve this is the following. The beam is injected with a small relative energy offset $\delta = \Delta E/E$; the kicker is located at a point of dispersion, $\eta$. The distance between the on-energy beam and the injected beam is $\eta\delta$; this distance is made sufficiently large that a shutter can be inserted between the injected beam and the circulating beam. When the kicker fires to put the injected beam onto the closed orbit, the shutter is closed, and the circulating beam does not see the kicker field. The shutter is then opened. Due to the synchrotron radiation, the beam damps and eventually $\delta = 0$. During the damping time, because of the synchrotron oscillations, the injected beam will (longitudinally) miss the circulating beam at the IP, and so some reduction in luminosity will result. However, after a couple of damping times, the injected beam will merge with the circulating beam, resulting in full luminosity. This process can then be repeated. By adjusting the amount of beam injected each time, the luminosity may be maintained at a relatively constant level until a failure causes the loss of the stored beam. (See Fig. 2.)

# 5 CONCLUSION

In this paper we have considered some of the features of a high-field very large ($E_{cm}$ = 100 TeV) hadron collider with a low-field full-energy injector. Probably the principal advantage of such an approach is that the collider's high field magnets can be designed and operated at a fixed field, and may have a small aperture. Such magnets, which would be free from persistent current effects, could be smaller and less expensive than in the conventional approach, in which dynamic ranges greater than 10 to 1, and apertures sufficient to handle the low-energy injected beam, are required. Additional advantages include simplifications in auxiliary systems (abort, rf, focusing insertions) due to the fixed energy of the ring. The injection process can take place during collider operation, utilizing radiation damping to bring the beam onto the reference orbit. This could allow the machine to be "topped off," as is done with existing electron-positron colliders; an increase in the integrated luminosity could result.

The disadvantage to this approach is the need to build the low-field injector, and its very large tunnel. The key question regarding the economic viability of this scheme is whether the simplifications afforded in the collider result in sufficient savings to more than offset the cost of the large injector. A detailed trade study would be needed to answer this question.

# 6 REFERENCES

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