THE OPTIMUM ENERGY OF THE REALLY LARGE HADRON COLLIDER SITED AT FERMILAB

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ABSTRACT

It is shown that, starting with the Fermilab Main Injector, a likely maximum energy for the RLHC is 100 TeV in the center of mass, with a single intermediate high-energy booster (HEB) of 3 TeV. The Tevatron is not used in the injector sequence. The implications for the HEB of some different magnet technologies is discussed.

I. INTRODUCTION

For an RLHC built at Fermilab, it is a straightforward exercise to determine the maximum energy and the sequence of injection accelerators. Fermilab is a logical site for the RLHC because of the infrastructure in its accelerators and laboratory facilities, its expertise in hadron colliders, the flatness of the terrain, and the excellent geology for drilling and tunneling.

II. THE INJECTION SEQUENCE

A. The Energy Increase Factor–the Rule of Twenty

In sequential synchrotron accelerators it has been the practice to increase energy from injection to maximum in each accelerator by a factor less than 20. In conventional machines with steel and copper magnets like the SPS or the Fermilab Main Injector, this factor is set by the low-field and saturation properties of steel. The Fermilab Main Ring violated this tradition and has a notoriously short beam lifetime at its injection energy of 8 GeV. Superferric magnets have the same field properties as conventional magnets and hence the same energy increase factor limitations. In high-field superconducting machines, this ratio is set even more stringently by the eddy current and hysteretic behavior of the large amount of superconductor in the magnets. The HERA proton ring is the only one with an energy increase factor as large as 20. The Tevatron has an energy increase factor of 6.67; the SSC would have had an energy increase factor of 10, although 20 was planned in the early design; the LHC will have an energy increase factor of about 15.

B. The Tevatron as an Injector into the RLHC

The Tevatron as the HEB of an RLHC may appear to be the least costly choice, but it is not the best one, nor is it necessarily the least expensive, because:

1. The Tevatron energy is too low for our current vision of the RLHC, which should have significantly higher energy than CERN's LHC. A 1 TeV injector would limit the RLHC energy to about 20 TeV per beam without extraordinary and expensive measures to increase the injection aperture of the RLHC or reduce the emittance of the beam at injection.
2. An injector should be rapid cycling, to minimize the dwell time of beam in the collider at low energy, where beam stability and dynamic aperture are issues. The Tevatron cycle time of 40 s. is long, although not disastrously so.
3. The difficulties caused by the low Tevatron energy are particularly apparent for low-field RLHCs (for example, the Pipetron). Such a machine takes a longer time to fill, lacks synchrotron damping to restore emittance, and has a small aperture beam tube, which causes beam instabilities that are worse with a low-energy injector.
4. Because of specifics of its design Tevatron magnets have a high heat load compared with modern superconducting magnets. Its operating costs are high relative to more modern machines.
5. The RLHC project may start 10–15 years from now, will take many years to build, and will operate for decades. The Tevatron, already operational for 13 years, may very well become unreliable by the time the construction of the RLHC is completed.

Use of the Tevatron as an injector into another injector seems unlikely, since such a high-energy injector is unnecessary and redundant. This leads to the conclusion that the Tevatron will not be used in the RLHC injection chain at Fermilab, and we will revert to a chain in which the Fermilab Main Injector injects directly into an HEB which, in turn, injects into the RLHC.

C. The HEB Energy

The Fermilab Main Injector is a 150 GeV conventional synchrotron. The Rule of Twenty limits the energy of the HEB to approximately 3 TeV. This could be slightly higher at the cost of additional aperture in the HEB, sophisticated correction schemes, or beam cooling. In any case, an energy increase factor of 20 will not be significantly exceeded.

The least costly way to increase the limits imposed on the RLHC energy by the injector is to increase the energy factors between the smallest machines in the injector chain. Whatever sophisticated or expensive methods are used, they are less expensive on smaller machines. Hence, for a 50 TeV per beam RLHC, starting from the 150 GeV Fermilab Main Injector, it is less expensive to have a factor of 20 or more between the Fermilab Main Injector and the HEB, and a lower factor between the HEB and the RLHC, than the other way around. This allows RLHC to have smaller aperture magnets and a simpler correction scheme, saving money where cost multipliers are large. The extra requirements on the HEB are imposed where cost multipliers, though not trivial, are much smaller.

D. The RLHC Maximum Energy

A 3 TeV HEB dictates that the maximum energy of the RLHC be less than about 60 TeV per beam. In reality, a factor of 20 in energy between the HEB and the RLHC may be difficult to achieve. We have concluded that 50 TeV per beam, or 100 TeV in the center-of-mass is a likely maximum energy of RLHC at Fermilab.

III. TECHNOLOGIES FOR THE MAGNETS OF THE RLHC INJECTOR

Once 3 TeV is chosen as the HEB energy, we can apply likely magnet technologies to its design. These considerations are restricted to the HEB, where the number of magnets is much smaller than in the RLHC. The optimization criteria for the RLHC are probably quite different.

A. Superferric Magnets

With a 2 T field, a 3 TeV HEB would be about 40 km in circumference. This has the disadvantage of being much larger than the Fermilab site. Other disadvantages are potential stability problems that make an energy gain factor of 20 more difficult, and a bigger RF system to realize a short cycle time. A major advantage is that a superferric design is one of the most likely to be able to use high temperature superconductor (HTS), which might greatly reduce the cost of the cryogenics system and its operation, not to mention stimulating nascent industry. Another advantage is the possible upgradeability of the energy of the HEB, and hence the RLHC, by replacing low-field magnets with high-field magnets, if, at some time, high-field magnet construction and operation become more economical.

B. Cosine-Theta NbTi Magnets

The state of the art of these well-understood magnets allows them to reach 7 T to 8 T at 4.5 K and up to 10 T at 1.8 K. A rapid-cycling injector will be more economical operating at 4.5 K. It seems probable that a few years of R&D would result in a low-AC loss magnet at B ≥ 7 T at 4.5 K. At 7 T a 3 TeV HEB would fit comfortably on the Fermilab site, minimizing (not eliminating) the impact on the surrounding community and the requirements for environmental impact evaluations. This machine operating at 1.8 K could be an 8.5 TeV (cm) pbar-p collider. Other advantages of such a design are a shorter and less costly R&D period; a well-understood accelerator design; and well-known costs and mass production techniques. This particular design could essentially begin today, with R&D concentrated on cost reduction.

C. Niobium-Tin Magnets

Higher field levels can be achieved with Nb_3Sn magnets operating at 4.5 K. The state of the art for accelerator-style dipoles is 10 T in single units. Currently, R&D programs are attempting to reach 14 T, and others are investigating Nb_3Al, which is somewhat less strain sensitive. These materials, which have been around for a long time, are difficult to work with, and progress has been slow. The critical currents are low at high field, and the AC losses are high in the presently useful commercial conductors. Because of the brittleness of reacted conductor, most designs react after winding, a costly and time-consuming process. It is likely that an expensive and lengthy R&D program would have to be launched to learn how to build such magnets even as single units, much less in mass production. There is a significant advantage to attaining B ≥ 14 T, however. In that case, a 3 TeV injector could fit into the existing Tevatron tunnel, saving money in civil construction and conventional infrastructure.

D. High-Temperature Superconductor Magnets

Almost anything that can be said about Nb_3Sn can be said about HTS. Its major advantage is its promise–so little is known that its promise runs high. It has other possible advantages over Nb_3Sn, as well: an intrinsically high upper critical field makes possible very high-field magnets, greater than 20 T; its high critical temperature holds out the possibility of operation at 20 K, or even in liquid nitrogen. The major problem is that the material does not quite exist, and although progress in recent years has been stunning, it has a long way to go. Nevertheless, it probably deserves a concerted and concentrated R&D effort. One cannot but think that the return on the R&D investment might be greater in HTS than in Nb_3Sn.

IV. CONCLUSIONS

Starting with the 150 GeV Fermilab Main Injector, it appears that an optimum energy for the RLHC would be 100 TeV in the center of mass, with a single intermediate high-energy booster of 3 TeV. It does not seem likely that the Tevatron would be used as an injector into the RLHC.

The HEB could be built within a few years using slightly improved NbTi conductor in 7 T magnets. If practical and economical magnets of 14 T or greater are developed, the 3 TeV HEB could be installed in the Tevatron tunnel, saving civil construction and other conventional costs. It might be advantageous to invest R&D in superferric magnets for the HEB as a prototype for a possible low-field RLHC, but superferric magnets do not otherwise appear to be desirable for the HEB, due to the large circumference required for such a machine.