Extracted Beam Lines and Absorbers for a 50x50 TeV Hadron Collider

N. Mokhov, C. T. Murphy, and S. Pruss
Fermi National Accelerator Laboratory, Batavia, IL 60510 USA

ABSTRACT

An extracted beam line has been designed for the 50 TeV on 50 TeV proton beams of the low-field version of RLHC, in order to kick the beams out of the machine in one turn. Two beam absorbers have been considered: a graphite-core absorber and an atmospheric pressure air-core absorber. Using the MARS13 code, the necessary absorber dimensions and beam sizes have been determined. In the case of the graphite core, it is shown that the only feasible way to make the beams big enough is to sweep the beams around the face of the absorbers during the 1.8 ms spill time. This is not needed for the air-core absorber, but an extra 8 Km of tunnel is needed.

I. INTRODUCTION

As currently designed, the low-field version of the RLHC [1] has 1.12E15 protons circulating at 50 TeV in each beam, i.e., 9 GJ per beam. This beam energy is equivalent to about 2000 kg of TNT. That is enough energy to cause severe damage to the machine and environment. The beams have sizes (σ) of typically 0.07 mm in the arcs and 0.14 mm at the center of a utility straight section (assuming a normalized emittance of 1 π mm-mrad). Obviously, if such a beam goes astray, it will melt a hole through a magnet and do further damage outside the machine [2]. The requirements for the reliability of a one-turn extraction mechanism are orders-of-magnitude greater than for the Tevatron, where a misfired extraction kicker magnet only causes a quench of the machine.

It turns out to be quite straight forward to kick the beams out of the machine towards absorbers. A scaled-up version of the LHC extraction beam lines (see Section II) calls for a mere 5 to 10 m of kicker magnets. The major difficulty lies in making the beams big enough that they will not crack a graphite absorber or reduce an air absorber to a vacuum in the center of the beam (see Section III).

II. BEAM LINES

We elected to scale up the LHC extraction line design [3] because the LHC utility straight section lattice was available, but no specific lattice exists for the RLHC. The design has not been optimized in any way. This excercise is intended merely as an "existence proof" that getting the beams out of the machine is not costly.

Like the Tevatron [4] and the SSC [5], the LHC design uses fast kicker magnets to switch the circulating beams into the other aperture of Lambertson magnets. Unlike the Tevatron and the SSC, the circulating beams go through the field-free holes in the Lambertson magnets, and the extracted beams are bent upward in the Lambertson magnets so as to clear the first quadrupoles in the downstream half of the straight section (see Fig. 1). The total length of the

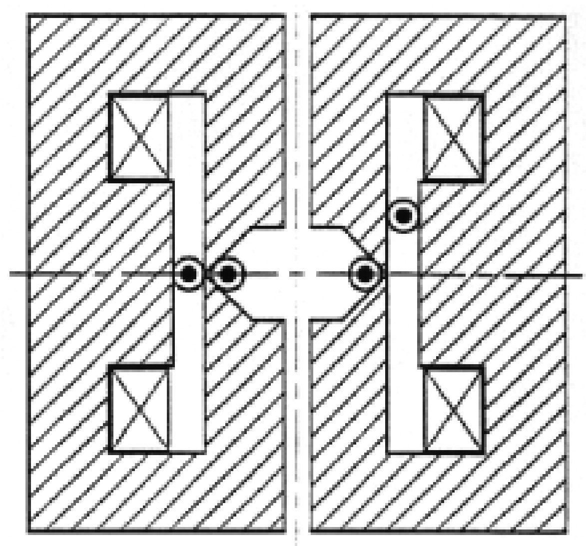

Figure 1: The LHC dual-bore Lambertson magnet.

straight section is 526 m. We have taken the length of the RLHC straight section to be 2000 m [6]. To scale the LHC straight section to the RLHC, we simply multiplied all the magnet spacings by the factor 2000/526. This leads to a layout for the RLHC straight section shown in Fig. 2. The values of $\beta_{\min}$ and the positions of the $\beta_{\min}$ in the horizontal and vertical planes were scaled up by the same factor, so that $\beta_{\min}$ = 910 m in both planes for the RLHC. These are needed to calculate the effect of blow-up quadrupoles in the extraction line.

Fast kicker magnets located between Q3 and Q4 are used to kick the beams in one turn towards the magnetic aperture of the dual-bore Lambertson magnets shown in Fig. 1. In the LHC, the separation of the circulating and extracted beams is 70 mm at the entrance to the Lambertson magnets; we have reduced that value to 25 mm, the value used at both the Tevatron and the SSC. The value needed is dependent on the beam size at injection at the

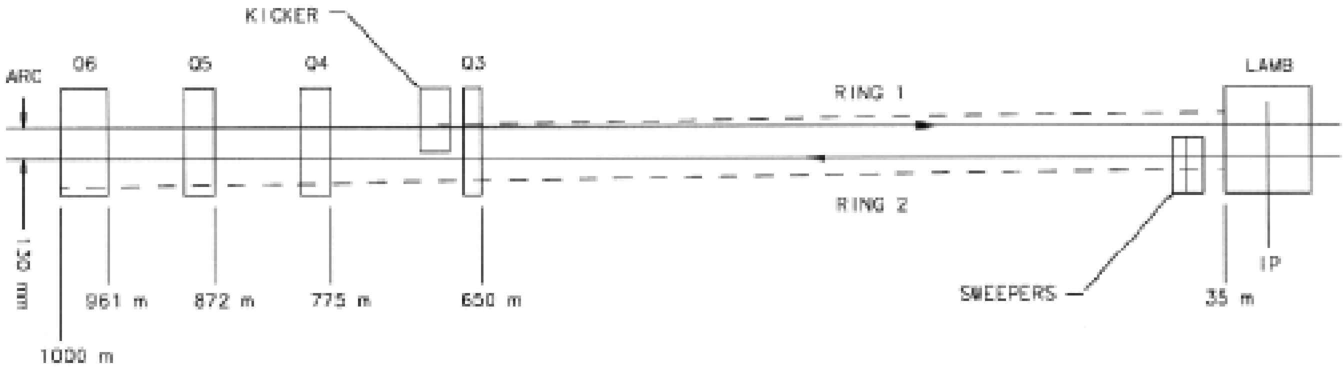

Figure 2: A possible layout of the utility straight. The dashed lines are the extracted beams.

Lambertson magnets. If the kicker magnets are placed close to Q3, 9.6 m of magnetic length are needed operating at the usual 0.6 T (the value assumed by both LHC and SSC). If the kickers are placed close to Q4, then Q3 gives an additional bend in the correct direction, and only 3.9 m of kickers are needed. Note that the LHC requires 14 m of kicker magnets.

The Lambertson magnets must bend the beams up sufficiently to clear Q3 in the downstream half of the straight section. In the absense of a real design for the RLHC quadrupoles, we have taken Q3 to have the same outside radius as the LHC Q3, reduced by half the difference in the beam separations in the two machines, so the radius is 200 mm. We then assume that the extracted beam must clear Q3 by 30 mm. The magnetic length of the Lambertson magnets, operating at 1 T, necessary for this clearance is 57.5 m. Note that the LHC requires 60 m.

III. THE ABSORBERS

The first absorber considered was the standard Tevatron type [7] graphite-core absorber, followed by aluminum with water cooling, followed by adequate steel to satisfy groundwater activation considerations. In order to determine the graphite dimensions and beam size necessary to contain the showers without cracking the graphite, shower development and energy deposition were simulated with the MARS13 code [8]. The design goal was to keep the maximum temperature rise at the axis of the graphite core per spill below 1300-1500 $^\circ$C (Tevatron experience [7] and shock-wave considerations). It was found that the graphite would need to be 10 m long and 1.5 m in radius. For a beam spill that is stationary in transverse position, the beam σ would need to be 300 mm in both x and y for a maximum temperature rise in the core of 1330 $^\circ$C. Expanding the beams to this size with blow-up quadrupoles is out of the question (see Section IV).

We immediately switched to the scheme studied by the SSC in which the beam size is effectively enlarged by sweeping the beam across the face of a square absorber in a zig-zag pattern during the 1.8 ms spill time. A vertical kicker sweeps the beam linearly from y = 400 mm to y = -400 mm, and a horizontal sweeper oscillates back and forth +/- 400 mm many times during the spill. To keep the frequency of the horizontal sweeper at a reasonable value of 7.5 KHz, the beam sigma needs to be 15 mm. This scheme was also simulated with MARS13. In this case the graphite is rectangular, with dimensions 10 x 2 x 2 m. The temperature rise is quite low at the center of the absorber (~300 $^\circ$C), but there is a pile-up at x = +/- 390 mm as the oscillating horizontal sweeper reverses the direction of the sweep, and the temperature reaches 3300 $^\circ$C. In principle, the best graphites survive at such a temperature, but the design goal for conventional pyrolitic graphites is not met. Either the sweep length needs to be increased to +/- 600 mm or a more complicated sweeping pattern needs to be explored.

Another sweeping scheme conceived by the SSC [9] is a spiral sweep. A horizontal and a vertical sweeper, 90 deg out of phase, would both oscillate with decaying amplitudes. Of course, the frequency would have to increase as the radius of the spiral decreased in order to keep the temperature rise constant, which is not easy to achieve. A suitable compromise is to limit the inner radius of the spiral to half that of the outer radius and accept a factor two higher temperature rise at the inner radius. A hand calculation indicates that an outer radius of 300 mm would be adequate to keep the temperature rise below 1500 $^\circ$C. If the beam sigma was 5 mm in both planes, the frequency of these sweepers would be 9.7 KHz.

A different idea which has been explored is to use a long tunnel of air as the primary core of the absorber. Here the principal problem is that a narrow beam will expand the air to create a partial vacuum, leaving a hole all the way to

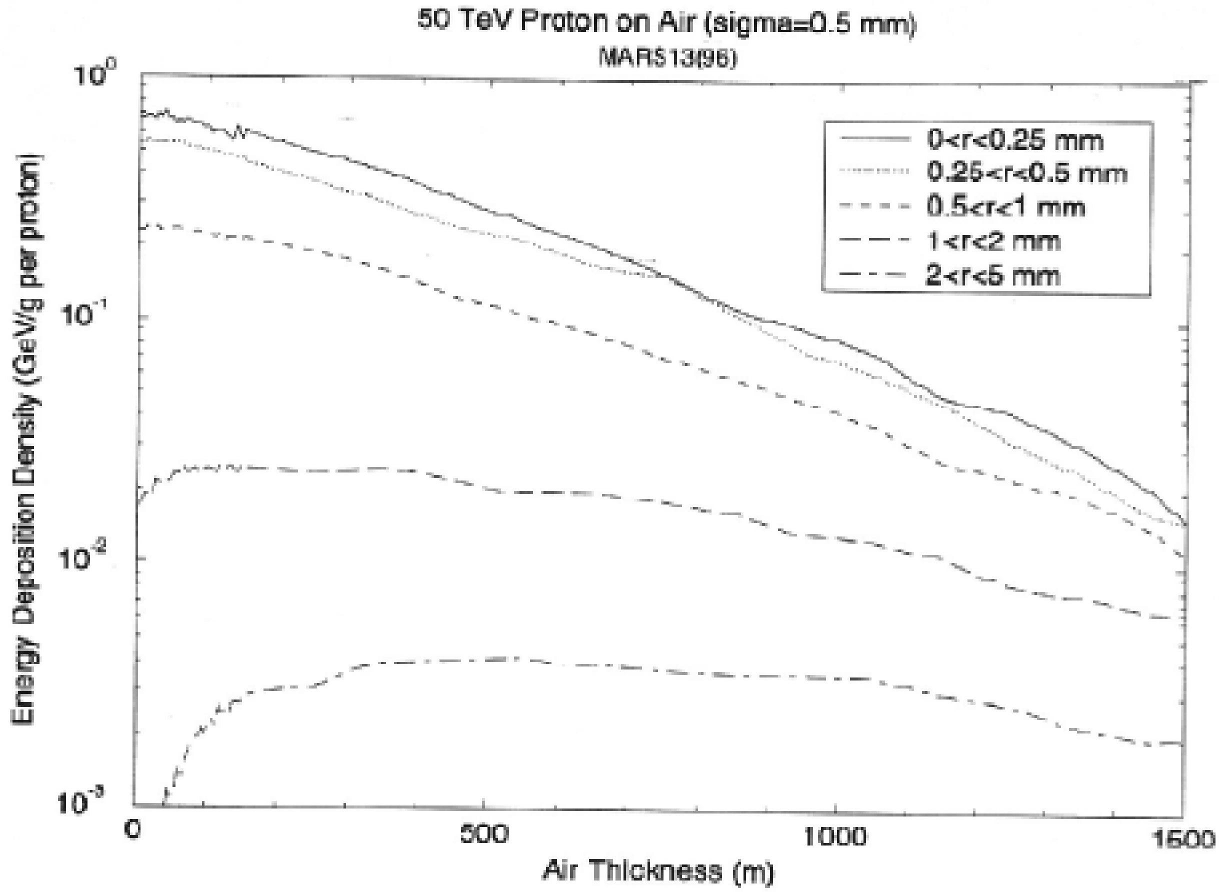

Figure 3: Energy deposition as a function of distance along an air absorber.

to twice room temperature, or 300 $^\circ$C. Again, MARS13 was used to simulate this case. It was found that the beam σ incident on the air must be 15 mm and that the air absorber needs to be 5000 to 6000 m long and 1 to 2 m flared in radius. Fig. 3 shows the energy deposition density as a function of the distance along the air core for various radial annuli.

The air core serves two functions. Some of the beam interacts inelastically with the air and distributes some radioactivity, very dilutely, along the tunnel wall. Secondly, the air multiple scatters the beam until the beam size is large enough to be absorbed on a standard graphite absorber. A graphite absorber is needed at the end of the tunnel of length 5 m and radius 2 m. Radionuclide production in air is mitigated via dilution with an appropriate ventilation scheme (e.g. see [5]). Depending on the site, groundwater activation may or may not be a problem. In the first case it is solved via standard thin concrete or isolated rock layer around the extraction tunnel.

Another thermal consideration which must be kept in mind is that a thin titanium vacuum window in the extracted beam line will melt, just from dE/dx, if the beam sigma is less than 5 mm. This condition is automatically met if the first windows encountered by the beams are just before the absorber. The beam sigma must be 15 mm for the air core absorber, and the spiral sweep spreads the beam over 300 mm for the graphite absorber.

IV. ELEMENTS TO SHAPE THE BEAMS FOR THE ABSORBERS

In the above schemes, the beam σ's need to be enlarged from their values of 0.14 mm at the center of the straight section to 5 mm or 15 mm at the absorber, which must be done with a singlet quadrupole in the extracted line. To minimize the quadrupole length, it should be positioned roughly half way between the center of the straight section and the absorber. For example, if the distance to the absorber is 5000 m, one needs 60 meters of quadrupoles operating at 40 T/m at 2500 m to bring the horizonal and vertical beam σ's to 16.1 and 14.4 mm respectively. One gains quadratically with length, so that for 10,000 m to the absorber, one needs only 15 m of quadrupoles. The optimization will be done by examining the trade-off between the economics of tunnel building and quadrupole construction and power. For instance, if tunnels cost $1500/m and quadrupoles cost $50,000/m, the optimum choice is a tunnel length of 4650 m.

To achieve the 5 mm beam σ's needed for the spiral sweeping scheme, a 3000 m distance to the absorber is needed with 50 m of quadrupoles at 1500 m.

In the scheme with beams spiraling over the face of a graphite absorber, fast sweeper magnets are needed between the Lambertson magnets and the downwstream Q3 magnet (see Fig. 2). If the distance from the center of the straight section to the absorber is 3000 m, then 37 m of sweeping magnets are needed in each plane, operating at +/- 0.6 T. Again, one needs to study the cost tradeoff between fast sweeper magnets and additional tunnel length.

V. UNEXPLORED IDEAS

In the case of the air core absorber, several ideas have not been explored which would reduce the length of tunnel needed. If the air in the absorber could be made highly turbulent (a wind tunnel), this might mitigate the effect of a small beam creating a vacuum. The beam size might be much smaller, reducing the length of the blow-up quadrupoles and the tunnel length before the air absorber. If the beam size can be reduced to below 5 mm, so that the titatium window determines the vacuum length, it is possible that a solid window might be replaced with several wire meshes which present a high vacuum impedance, and the vacuum could be maintained with massive differential pumping. It would not matter if the extracted beam burned a few more holes in the wire mesh.

Turbulent water absorbers should also be considered. Another idea suggested is a combination air and water absorber, in which the beam is deflected downward at grazing incidence on a pool of stationary water.

VI. CONCLUSIONS

We have shown that it is not difficult to kick the beams out of the tunnel towards absorbers. The minimum requirement is 4 m of fast kicker magnets in each beam, 57 m of Lambertson magnets, 50 m of blow-up quadrupoles, and 3000 m between the center of the straight section and the absorber. Two absorber schemes have been proposed. One uses a graphite core as the principal absorber and requires 37 m of fast sweeper magnets in each line to spread the beams out over the face of the graphite. The other uses air as the principal absorber, does not require fast sweeping, but needs an extra 8000 m of tunnel. If the extra tunnel costs about the same as sweeper magnets (our guestimate), then reliability would indicate that the air absorber is the favored choice. The failure of one of the two sweeper firing circuits would destroy the graphite absorber.

There are only two serious failure modes which would destroy part of the accelerator. The first is the failure of one of the many kickers to discharge during a requested extraction of the beams. This can be accommodated by making the aperture of the extraction line sufficient to tolerate the loss of one kicker. The other is more serious, the firing of one of the many kickers at some random time (this happens routinely in the Tevatron). Composite graphite shadow septa and collimators upstream of all the limiting apertures [10] is the way to protect the machine components against beam-induced destruction. More work is obviously needed to explore all these possibilities.

VII. REFERENCES

[1] G.W. Foster and E. Malamud, "Low-Cost Hadron Colliders at Fermilab", Fermilab-TM-1976, 1996.

[2] D.C. Wilson et al. In Proc. of the 1993 Particle Accelerator Conference, IEEE, p. 3090, 1993.

[3] LHC Conceptual Design, CERN/AC/95-05, 1995.

[4] M. Harrison, UPC Note 153, Fermilab, 1981.

[5] SSC Collider Utility Sections PDRR, January 1993.

[6] G. Dugan, P. Limon, and M. Syphers, "Summary of the RLHC Group", in these Proceedings.

[7] J. Kidd, N.V. Mokhov, C.T. Murphy et al. IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, 1981.

[8] N. Mokhov, "The MARS Code System User's Guide, Version 13(95)", Fermilab-FN-628, 1995.

[9] SSC Site-Specific Conceptual Design, SSCL-SR-1056, July 1990.

[10] A. I. Drozhdin et al. In Proc. of the 1993 Particle Accelerator Conference, IEEE, p. 3772, 1993.