A Cost Optimized Small-Aperture 2-in-1 VLHC

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I. INTRODUCTION

The costing algorithm used here was started at the time of the SSC proposal, was updated and presented[1] at the Port Jefferson VLHC meeting in October 2000, and has been slightly modified again for this study. The method starts from a specified central field and aperture, and uses approximate formulae to design the dipole magnet cross sections. The required masses of superconductor, stabilizing copper, support stainless steel, and yoke are calculated, and the surface area of the cold mass determined. Costs per unit weight, or area/temperature, are assigned for each item and a linear cost added to cover the tunnel, supports, magnet ends, correctors, quadrupoles, survey etc. The unit costs were originally extracted from the SSC estimates, but have been inflated and modified since. They have no Intersection Point magnets, detectors, detector halls, EDIA, contingency, R&D or escalation. The assumed linear cost, including magnet ends, with the inflation factor, is 22 k$/m.

If the aperture is small, as in the pipeatron, the magnets can be long, end costs reduced, and the packing factor improved. This expectation is confirmed by the recent Fermilab VLHC study[2]. Using the total estimate from this study, the algorithm has been modified to include these effects.

Beam pipe apertures are scaled to maintain a fixed beam impedance. This scaling requires the apertures r to increase as the cube root of the circumferences and thus: $r \propto B^{-1/3}$. The proportionality is normalized to either: a) the LHC, with a beam shield radius of 2.2 cm at a field of 8.3 T; or b) a transmission Line Magnet (also known as the Pipeatron), with a beam tube radius of 9 mm at a field of 2 T. This case has approximately 30 times the impedance of case (a). Stability in this case, with appropriate feedbacks, is discussed in the VLHC Study[2] and in the proceedings of a VLHC workshop at SLAC[3]. We will assume here that it can indeed be done.

TABLE I: Optimum Fields and Minimum ring costs per TeV (relative to SSC)

	NbTi 4 deg		NbTi 1.8 deg		Nb_3Sn 4 deg		HTS 20 deg		NbTi Pipeatron	
	cost	B	cost	B	cost	B	cost	B	cost	B
a) LHC Z	.91	5.9	.9	6.6	.86	7.1	.78	8.0	1.89	2.0
b) Pipeatron Z	.54	5.2	.55	5.9	.53	6.0	.50	6.4	1.00	2.0

II. COSTS VS. FIELDS

Figures 1a and b show the cost of rings assuming a) apertures with LHC impedances, and b) pipeatron impedances . Table I gives the fields that minimize the costs, and those costs relative to the SSC. In the "SSC" example two rings of one-in-one magnets is assumed. In the "Pipeatron" case a simple circular model is used (see figure 2d). In all other cases, two-in-one designs are assumed. The cost of Nb_3Sn or "HTS" conductor is assumed to be twice that of NbTi. The current in the "HTS" is assumed equal to that in Nb_3SN at 7T, but with a critical field of 20 T (this is a lot better than any currently available HTS conductor). We note:

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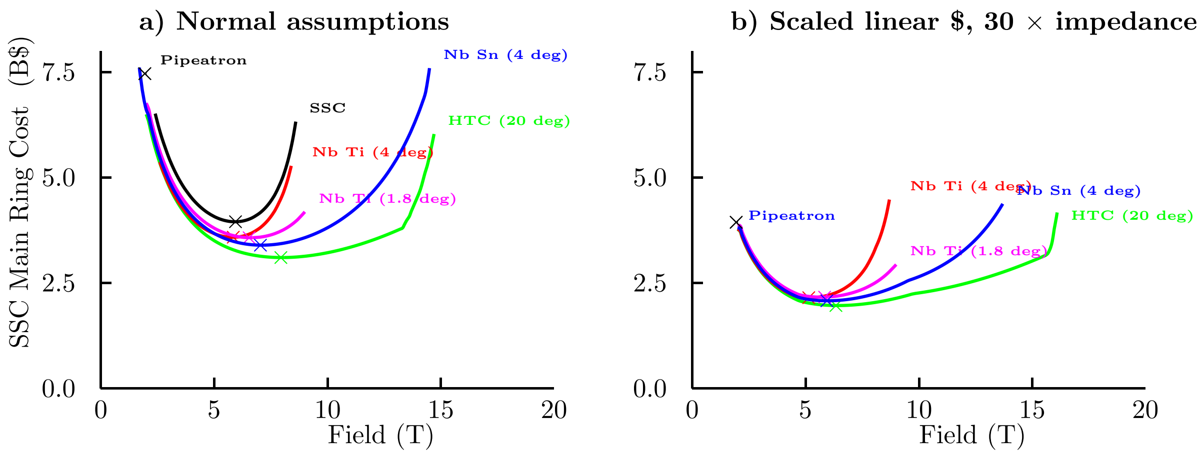

FIG. 1: Cost vs. bending magnet fields;a) Normal assumptions b) Scaled linear costs, and 30 × impedance

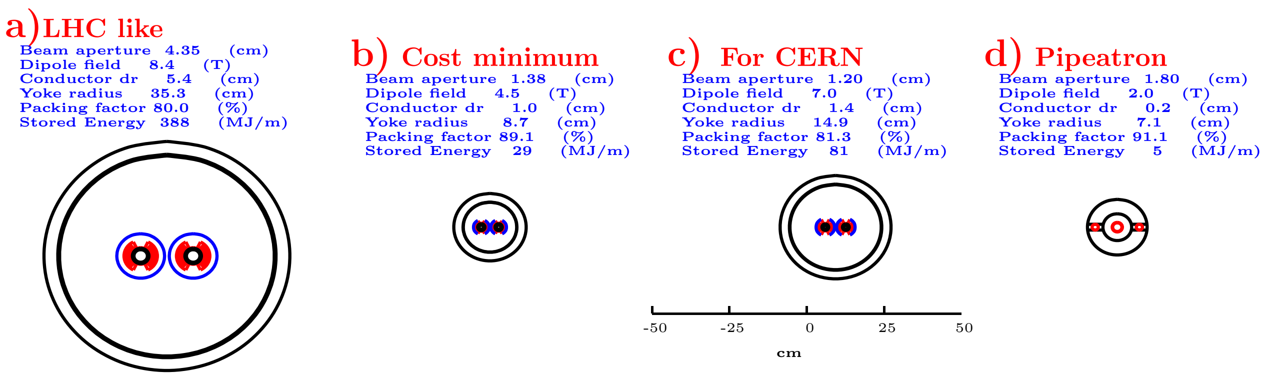

FIG. 2: Comparative Cross sections: a) LHC like: high field, large aperture; b) Proposed: low field, small aperture; c) For CERN: higher field small aperture ; c) Pipeatron: very low field, small aperture.

- The cost minimum two-in-one design is 9% cheaper than the SSC one-in-one.
- The use of 1.8 degrees or Nb_3Sn raises the field for minimum cost, but does not significantly reduce that cost. An "LHC" ring at 8.4 T and 14 TeV is estimated at 1.22 B$.
- HTS conductor does not reduce the cost by more than 15%.
- The "pipeatron" with an aperture radius of 3.5 cm, costs almost twice the SSC.

With the Pipeatron impedance assumptions, the best fields drop by about 10%, and the costs come down almost a factor of two. Once again there is little advantage in using the more exotic superconductors.

III. A 50 TEV COST MINIMIZED VLHC

Assuming that at full energy the impedance problems can be handled, we can now discuss some parameters of a small aperture two-in-one cost optimized collider. We pick 25 + 25 = 50 TeV for the energy. At Fermilab, we assume that a pre-accelerator is required and pick 2.5 TeV (1/10) for its energy. Using the program, we conclude that it would be cheaper to build it at low field (6 T) in a new tunnel, than use 12 T magnets in the existing TeVatron tunnel. The program gives 0.2 B$ for the single ring plus tunnel cost, but this should be increased somewhat to allow for the smaller size of the project.

At Fermilab, one might pick a collider operating field a little below that of the cost minimum, to allow for the possibility of a later higher field ring. The minimum is at 5.2 T. At 4.5 T the cost would be little higher. The ring circumference would be 103 km + 4 km (for the intersections). The ring cost is given as 2.75 B$;

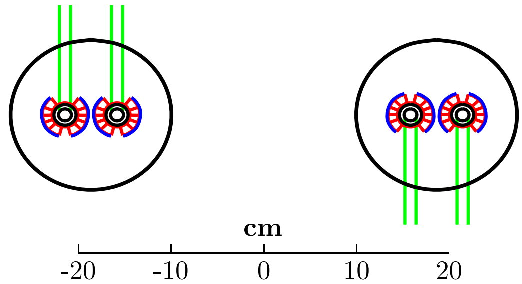

FIG. 3: Proposed magnet with continuous large busses, and combined function by alternately raising and lowering the conductors.

compared with 3.95 B$ for the 20 + 20 TeV 2 T pipeatron of the Fermi study (note that the Fermi Study cost of 4.1 B$ includes some intersection costs not in this estimate).

If built at CERN, LHC would provide an excellent pre-accelerator: 7 TeV is clearly better than 2.5 T and the cost is saved. In view of the geology, one might pick a higher and slightly less optimum field, such as 7 T and keep the circumference down to 70 Km. In this case the cost estimates for NbTi at 4 deg, NbTi at 1.8 deg, and NbSn at 4 deg. are 3.1, 2.8, and 2.65 B$ respectively. We note that in this case there appears to be an advantage in using Nb_3Sn, but this depends in detail on our assumptions, and may, or may not, be real.

Fig. 2 compares the cross sections and some parameters of four magnet types. The small size of the small aperture medium/low field magnets compared with the larger aperture higher field LHC-like design are apparent. For total project costs, in either case, we must add for transfer lines, detectors and detector halls. For US accounting the costs must then be approximately doubled. The totals are about the same as those for TESLA or NLC.

IV. DESIGN DETAILS

The 4.5 T magnets could be RHIC like, with a conventional separate function lattice with correctors. But the cost should be less if we use an idea from the pipeatron concept: continuous busses. The use of 5 continuous 100 kA busses (see figure 3) on either side of continuous magnets could eliminate magnet ends. Saturation correction can now be applied by controlling the individual bus currents. Focusing could be provided by alternating the vertical locations of all busses, thus generating alternating skew quadrupoles. Corrections would be applied by attaching floating trim supplies across half cell lengths of bus.

V. CONCLUSION

Although one must recognize that parametric studies like this are not equivalent to real cost estimates, one can draw some probable conclusions. Clearly, in all cases, there is a cost optimum: at higher fields, magnet costs rise disproportionally; at low fields tunnel and other linear costs are excessive. Fields above 10 T and bellow 3 T appear to be uneconomic. Field in the 4-6 T range seem optimum. Better superconductors raise the optimum field, but by surprisingly small amounts, and offer only small savings. On the other hand, reducing the magnet apertures yield large savings. In particular, we find that a collider with SSC like energy could cost about half that of the SSC if built with 5 T magnets and apertures yielding an impedance equal to that for the proposed transmission line magnet ring. It would also be about half the cost of a ring made with those transmission line magnets.

[1] http://pubweb.bnl.gov/people/palmer/magnet/pjmagopt.pdf
[2] "Design Study for a staged VLHC"; Fermilab-TM-2149 (June 2001)
[3] http://www.slac.stanford.edu/ achao/VLHCworkshop.html