The Influence of Accelerator Physics on the Magnet Design of a Very Large Hadron Collider

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***Abstract*--We present a study of the influence of accelerator physics on the design of magnets for very high energy hadron colliders. The limiting specifications of a particular VLHC model are estimated, and their effect on the design of the accelerator magnets is determined using simulations and scaling laws for magnet aperture, field quality, cryogenic and vacuum properties and cost. We show that there is a maximum useful field due to synchrotron radiation power and cost, and a minimum useful aperture due to synchrotron radiation and beam-stability.**

***Index Terms*--Very Large Hadron Collider, Accelerator Physics, Superconducting Accelerator Magnets, Synchrotron Radiation.**

I. Introduction

A recent study in the U.S. of a staged very large hadron collider [1] is based on a model in which two colliders occupy the same very-large-circumference tunnel. In this model, the specifications of which are shown in Table I, the first stage is made from 2 T superferric magnets and reaches 40 TeV in the center-of-mass. After the physics potential of the VLHC-1 is fully realized, it serves as the injector into the second stage, which reaches 200 TeV in the center-of-mass using 11.2 T magnets. Using this model, a large tunnel suitable for a very high-energy collider is built in conjunction with an inexpensive but still energy-frontier collider. This multi-decade program significantly extends the energy reach for particle physics experiments at the earliest possible time and for a reasonable investment, while significantly reducing the cost of the second stage by reusing the existing tunnel and infrastructure. This time-proven method of reducing construction costs without delaying progress in high-energy physics has been used with great success at CERN and Fermilab. There are many issues that are raised by a design that puts two colliders of very different energies in the same tunnel. For example, one must anticipate the approximate design of both stages when the civil construction begins. Because magnets are by far the most costly and difficult component of the Stage-2 collider, we are studying the way accelerator physics will influence the design of the magnets of both stages of the VLHC.

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TABLE I
THE HIGH-LEVEL PARAMETERS OF STAGE-1 AND STAGE-2 VLHC

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	200
Number of interaction regions	2	2
Peak luminosity (cm^{-2}s^{-1})	1 x 10^{34}	2 x 10^{34}
Luminosity lifetime (hrs)	24	7
Injection energy (TeV)	0.9	10.0
Initial normalized emittance, rms (10^{-6} m)	1.5π	1.5π
Dipole field at collision energy (T)	2	11.2
Average arc bend radius (km)	35.0	35.0
Initial Number of Protons per Bunch	2.6 x 10^{10}	5.4 x 10^{9}
Bunch Spacing (ns)	18.8	18.8
β* at collision (m)	0.3	0.5
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	147
Interactions per bunch crossing at L_{peak}	21	55
Debris power per IR (kW)	6	94
Synchrotron radiation power / meter (Peak)	0.03	5.7
Average power use (MW) for collider ring	20	100
Total installed power (MW) for collider ring	30	250
Total helium inventory, gas plus liquid (kg)	7.5 x 10^{4}	6.5 x 10^{5}

II. Considerations Leading to the Staged Design

One might reasonably ask whether staging is the best model for a VLHC. The answer is, as usual, "It depends." If results from LHC show that moderate energy, say less than 100 TeV is sufficient to uncover all we need to know about particle physics, then staging may not be the best solution. The existence of a higher-energy injector may also influence the choice, so the model of a VLHC sited at CERN could well be different from one at Fermilab. Our study assumed that high-energy physics will be true to its name and need the highest energy reasonably possible. We also assumed a Fermilab site, at least partially because siting a large ring at CERN is thought to be difficult, though not impossible. The issue that most motivates a staged approach is the seeming impossibility of funding a high-energy collider in one step. High-field magnets are expensive, much more so than tunnel, certainly tunnel in the Fermilab area, and, as we shall demonstrate, a simple model of magnet cost shows that it increases dramatically as their field strength increases, negating any savings gained from a smaller tunnel. In addition, it seemed logical that a large-circumference collider would be an advantage for very-high-energy because of reduced synchrotron radiation and a reduced requirement for very high magnetic field strength, which would be both technically difficult and financially punishing. Our cost analyses, coupled with previous work by the SSC Central Design Group, indicate that the cost of a 40 TeV collider depends only weakly on the magnetic field between 2 T and 7 T, provided that the technology in each field range is optimized. Hence, a low-field superferric magnet that requires a large ring to reach the energy frontier is not only no more costly than a high-field magnet and a small tunnel, at the end one is left with a large-circumference tunnel, which is far better for a very-high-energy collider.

III. Accelerator Physics Issues of VLHC-1

The innovative design of the VLHC-1 superferric magnet [2], shown in Fig. 1, appears to be low in cost, perhaps as little as one-third the cost per Tesla-meter (that is, per TeV) of a high-field cosine-theta dipole. To keep the cost low, the magnet gap is kept as small as possible, which raises issues of field quality, alignment and beam stability.

Beam stability is the overriding accelerator physics issue of VLHC-1. Dynamic aperture, beam-beam tune shift, and electron cloud and other potential vacuum problems seem to be safely away from any limits that are apparent today [3]. Synchrotron radiation and any effects from it are also moderate.

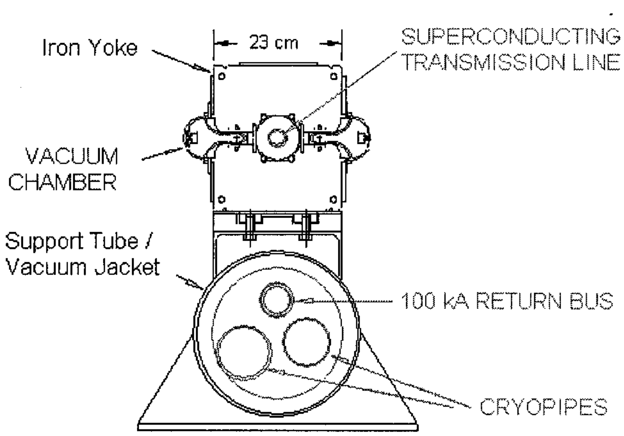

Fig. 1. Stage 1 superferric magnet, showing the 100 kA central transmission line, surrounded by the magnet yoke and the two beam pipes on the side. The current return and cryogenic lines run through the pipe underneath. The steel yoke and the vacuum chambers are at room temperature.

A. VLHC-1 Aperture and Closed Orbit

1) Alignment and ground motion

The operational and dynamic aperture is related to magnet alignment, magnetic field fluctuations and field quality in the dipoles. The VLHC has a half-cell of 135 m, making initial alignment a challenge. This is made somewhat more difficult by the combined function bend magnets, which require accurate alignment all along the half-cell length. Initial rms alignment errors of 250 ?m over a few hundred meters are adequate to attain initial closed orbit with reasonable correction strength. In rings this large, ground motion is important, and careful measurements have been made in the Fermilab tunnels and in deep tunnels in the Fermilab area [4], [5]. The spectrum is well understood, particularly for deep tunnels with very little man-made noise, and it is thought that any effects can be easily handled with relatively slow feedback systems. In addition, the ground motion results in component random walk that misaligns the rings over many months, eventually resulting in closed orbit distortions that are large enough to require magnet moves. The specified VLHC steering correctors are strong enough to limit the required realignments to only a few per year, and in only a few locations.

2) Dynamic aperture

Dynamic aperture is critical at injection when the beam is largest. Superferric magnet field shape is determined by steel, which is held at 0.1 T at the injection energy of 1 TeV. Steel has good properties at that field. Hence, the dynamic aperture of VLHC-1, modeled from simulations that include chromaticity corrections and expected systematic and random magnet errors is excellent [3], everywhere greater than 18? in both transverse coordinates.

B. Beam Stability

The small aperture of the VLHC-1 beam tube, coupled with its room-temperature resistivity may induce beam instabilities. The aperture chosen, 18 mm x 28 mm is on the verge of being too small, and will require significant R&D and beam studies to guarantee good operation. Nevertheless, in principle, all of the instabilities have solutions at hand.

The dominant beam instabilities in the VLHC are of the transverse type. They depend strongly on the magnet aperture. All of the instabilities depend on the beam current in some way; so improved emittance (and therefore fewer protons needed to reach the desired luminosity) would improve the situation. In VLHC-1, the most important instabilities are the Laslett tune shift, the resistive wall instability, and the fast head-tail, or transverse-mode coupling instability (TMCI) [6].

1) Laslett Tune-Shift

The Laslett tune-shift is a transverse space charge effect caused by the defocusing forces due to electromagnetic fields generated by the beam in the beam tube wall and the steel magnet yoke. The most dangerous tune spread in the beam occurs when the machine is partially filled during injection, and arises because the low revolution frequency of the beam, about 1280 Hz, is comparable to the magnetic diffusion time through the beam tube wall. It can be avoided by injecting beam in an appropriately symmetric manner around the ring or by using audio-frequency quadrupoles that can correct the tune in each group of bunches separately [7].

2) Resistive Wall Instability

The resistive wall instability is induced by the low frequency (of the order of the revolution frequency) transverse impedance seen by the beam, which is dominated by the resistive wall of the beam tube. It appears as a growth of the coherent betatron amplitude of the beam. Sensing the position of the beam and giving a compensating kick to the following bunches can correct the highest growth rate (low frequency) beam oscillation modes. This strategy works because of the small phase error it introduces for these modes. Since the instability growth time is of the order of one turn, there must be a number of feedback systems distributed around the ring. In addition a conventional bunch-by-bunch damper with a single-turn digital memory is required to stabilize the low growth-rate, high frequency modes [8].

3) Fast Head-Tail Instability

The fast head-tail instability (TMCI) is related to the high-frequency (of the order of the characteristic bunch-length frequency of some GHz) part of the transverse impedance spectrum. The instability appears as a resonant wiggling of the bunches, excited by wake-fields due to the protons at the head of the bunch. The cause is the sum of the impedance contributions of small-size components such as bellows and beam-position monitors. For the VLHC-1 there is also a significant contribution from resistive-wall effects. The instability threshold can be described in terms of the threshold number of particles per bunch, which, in the VLHC-1 is approximately half of the design bunch population of $2.5\cdot10^{10}$. This problem is fixed by injecting more lower-population bunches, accelerating them to a few TeV and then coalescing them into the number of bunches desired.

C. Summary of accelerator physics issues of VLHC-1

It appears that beam stability will need more study, but can be handled with a combination of actions, including feedback systems of moderate power and bandwidth; increasing the number of bunches at injection and coalescing the beam at higher energy; reducing the beam emittance with an improved injector chain or increased injection energy; or by increasing the beam tube diameter and the magnet gap. Most of these actions are moderate in cost. The sensitivity of the cost of the magnet with respect to the physical aperture has not yet been studied.

IV. Accelerator Physics Issues of VLHC-2

The Stage-2 design of the VLHC, intended to reach the highest energies and luminosities possible with today's technology, has a different set of issues from VLHC-1. Many of these could limit its performance, but none dominates the machine and magnet designs as does the presence of significant synchrotron radiation in a cryogenic environment, and we devote most of the discussion to that issue, possible ways to deal with it and the effects on the magnet parameters.

A. The interaction region

1) Inelastic-collision debris power and event rate

High luminosity and energy creates some potential problems in the interaction regions of VLHC-2. The debris power due to inelastic collisions is 100 kW, most of which goes forward and impinges on the strong quadrupoles near the detectors raising the coil temperature. This inspires one to develop magnets that use high-temperature super-conductor or the newly discovered MgB_2 in order to make quadrupoles of sufficient strength, about 400 T/m, to attain the small spot sizes required for the highest luminosity [9]. The expense of these magnets is not an important concern since there are only a few of them.

The event rate at $L=2\cdot10^{34}$ $cm^{-2}s^{-1}$ and 200 TeV is a daunting 55 events per crossing at 18.8 ns bunch spacing. Although not strictly an accelerator physics issue, there will certainly be pressure to increase the number of bunches and decrease the protons per bunch. At constant luminosity this requires an increase in the total beam current proportional to the square root of the number of bunches, thereby exacerbating the synchrotron radiation problems.

2) Beam-beam effects

Because of emittance damping from synchrotron radiation, the amount of beam in VLHC-2 is much less than would normally be required to reach the necessary high luminosity. The maximum allowable beam-beam parameter, we assume 0.008 units, determines the minimum beam emittance [3]. As the beam evaporates from inelastic collisions the emittance can be allowed to decrease, which results in a leveling of the luminosity and increased integrated luminosity over the course of a store.

B. Dynamic aperture

There are a number of possible magnet designs that could be used for VLHC-2. For the VLHC Study, we chose a so-called common coil, two-in-one design, Fig. 2, for a few reasons. First, because the cable is wound from the upper aperture to the lower, the strain on the cable is low, offering advantages in the use of pre-reacted Nb_3Sn, which seems an advantage. Second, it may allow a smaller beam tube, which is one of the attributes that we wished to study. Finally, we chose it simply because it is new and innovative. Fig. 3 shows that the dynamic aperture at injection resulting from simulations assuming a realistic placement error of coil blocks is quite adequate. The coil aperture of the VLHC dipole magnet is 40 mm. A 30 mm bore version of a different common coil type dipole was found to have acceptable field quality (systematic and random) [10]. The limiting factor to attain small coil aperture is not field quality, but the space required by a beam screen or photon stop needed to cope with the synchrotron radiation. A peculiarity of this common-coil

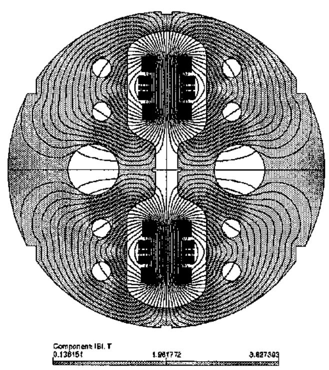

Fig. 2. The Common-Coil, two-in-one dipole design used for the high field stage in the VLHC Study [11].

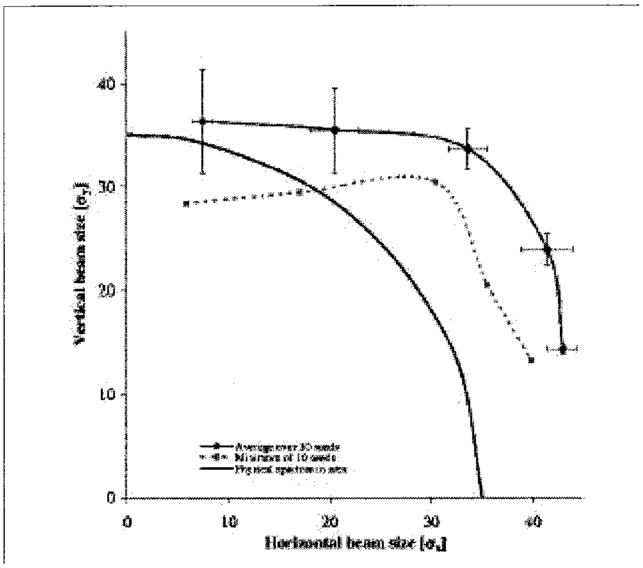

Fig. 3. Dynamic aperture at injection for a field-error model of the common-coil magnet. The available dynamic aperture is everywhere larger than the physical aperture of the beam screen.

design is that it has very small field distortions due to hysteresis. The hysteresis effects in the cosine-theta designs can be canceled by appropriate placement of steel shims [12].

C. Beam Stability

The same three beam stability issues are present in the VLHC-2 as in the VLHC-1, but much reduced in effect due to the much higher injection energy and the lower temperature, and therefore better conductance of the beam screen. Fig. 4 shows the minimum injection energy for stability, with the e-folding time constant of the resistive-wall instability being greater than one turn, assuming a 20 mm-diameter beam screen coated with copper at 100 K.

The curves delimiting the area of beam-stability in Fig. 4 do not assume any correcting schemes, which, as argued in the context of VLHC-1, can significantly extend the region of beam-stability to lower injection energies and smaller magnet apertures.

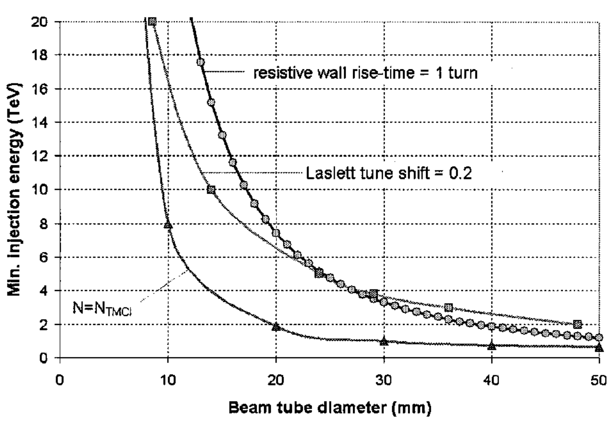

Fig. 4. Minimum injection energy in a 30 km bend-radius VLHC to remain within the Resistive Wall Instability, TMCI, Laslett Tune-Shift beam stability limitations, versus magnet aperture (luminosity = $2?10^{34}/cm^2/sec$). No corrections (feedback systems, ..etc) assumed.

D. Synchrotron Radiation

The synchrotron radiation power per unit length, per beam, in a machine with fast synchrotron radiation damping, can be formulated in terms of the beam energy, E_p, the peak luminosity, L^{peak}, and the bending radius, ?, of the proton trajectory in the bending magnets (1). In addition, (1) includes the beam current limitation imposed by the maximum beam-beam parameter, ?.

$$P_{SR}^{peak} ? \frac{4?r_p^2?^*}{?m_pc^2?^? 6??} \frac{L^{peak}E_p^3}{?^2} ?\frac{W}{m}? \qquad (1)$$

The VLHC-2 is clearly a synchrotron radiation-dominated collider, in the sense that the beam emittance is determined by the equilibrium between synchrotron radiation-damping on the one hand and beam-beam tune shift and noise sources on the other; and that the cryogenic and beam vacuum systems designs are dominated by the amount of synchrotron radiation. An important issue for the ultimate energy and luminosity of the VLHC-2 is whether one can absorb the synchrotron radiation at an elevated temperature in order to reduce the cryogenic power requirements. We are investigating two methods of dealing with this issue—beam screens, similar to the SSC and LHC designs, and photon stops, made practical by the large radius of curvature of the VLHC.

1) Beam-Screen and Vacuum

For synchrotron radiation power loads beyond 1 W/m/beam, thermodynamic efficiency requires a higher-temperature beam-screen. The VLHC-2 uses a 100 K beam-screen to extract up to 6 W/m of synchrotron radiation (Fig. 5). A more detailed description of this proposal can be found in [13]. Presently we believe that it will be difficult to handle more than ~10 W/m/beam with a beam-screen, simply because removing more heat than that requires so much cryogen flow that the beam-screen aperture becomes too small. This forces an increase in magnet aperture (and cost), as shown in Fig. 6. A room temperature beam screen is not competitive for a similar reason: the (~80 K) shield that has to be introduced between the warm screen and the cold bore to intercept the thermal radiation from the 300 K screen requires even more magnet aperture. The room temperature beam screen solution therefore becomes interesting only at a synchrotron radiation power level exceeding 20 W/m [14].

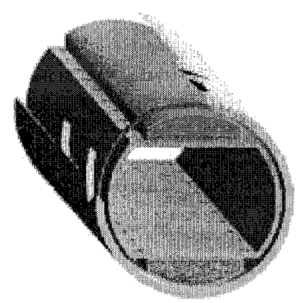

Fig. 5. A 6 W/m beam-screen as proposed for the VLHC. The large cooling channels cover 12 % of the cold bore inner cross-sectional area.

In addition, the intermediate screen interferes with the cryopumping function of the beam screen.

Magnet designs that have large vertical aperture at no additional cost, such as some of the proposed common coil designs, may permit more coolant flow without a coil-diameter penalty, solving the problem to some extent.

Fig. 6 shows the minimum physical aperture in a VLHC with a beam screen required to allow flow area for more cryogens as the radiation power increases. Shown as well is the (horizontal) aperture requirement for a photon stop in a 30 km bend radius VLHC using 14 m long magnets. The beam screen at 100 K must, of necessity, be supported without much heat flow to the beam tube, which is near 5 K. This may permit vibration of the screen, and motion of the "frozen in" magnetic field due to turbulent flow of cryogens. This effect has been measured in Tevatron magnets, which are without beam screens, and found to be very small [15]. Such effects need to be thoroughly investigated because a small motion of the field in the VLHC quadrupoles could be very destructive.

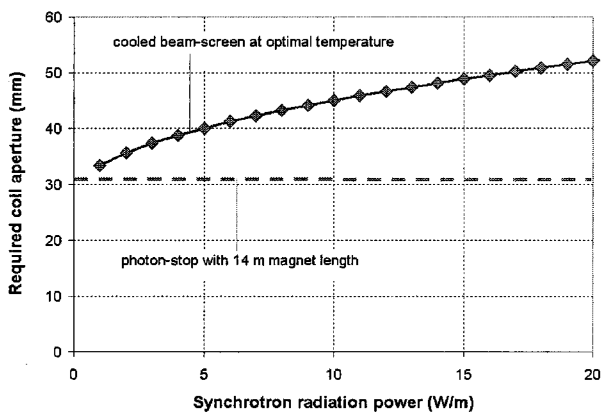

Fig. 6. Magnet aperture requirements for a beam screen and a photon stop (assuming 14 m long magnets) as function of synchrotron radiation power in a 200 TeV, 30 km bend radius, VLHC as in Table I . A 20 mm diameter beam stay clear region is assumed. The minimum distance from the tip of the photon stops to the beam is 4 mm.

2) *Photon stops*

In the context of the recent VLHC study we proposed the use of a so-called photon stop (Fig. 7), which is a water cooled finger that enters the beam tube at the end of each bending magnet and absorbs all or most of the synchrotron radiation at room temperature. There is no reason why such devices couldn't extract up to 100 W/m/beam or more as they routinely do in light sources.

There are limitations to the use of photon stops, however: 1.) The tangentially emitted synchrotron radiation should be as completely absorbed as possible without hitting on the beam tube or beam screen; 2.) At the same time, the photon stops should be sufficiently far from the proton beam orbit so that it is unlikely that the beam hit it, or that its impedance effects will disturb the beam; 3.) The beam-tube aperture and radius of curvature should be such as to allow constraints 1 and 2 to be satisfied while permitting the largest possible photon stop spacing i.e. long magnets, since the photon stops are most conveniently

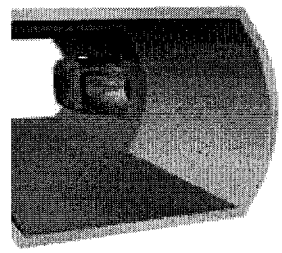

Fig. 7. Sketch of the proposed VLHC-2 photon stop

placed between magnets. The maximum permissible photon stop spacing depends on the beam-tube aperture, b, the arc bending radius, ?, and the magnet interconnect length, L_s, such that

$$L_{mag}^{\max} ? \sqrt{\frac{b?}{4?X}} ? \frac{L_s}{4?X} \quad ?m?. \qquad (2)$$

Equation 2 assumes that the radiation emitted by the (1-X)-th part of the second magnet upstream and the radiation from the |(X-1)|-th part of the magnet immediately upstream of the stop hits the photon stop. It further assumes that the magnets are perfectly straight and that the beam is centered in the magnet bore. The distance between the photon stop tip and the beam is largest for X=0 (all radiation absorbed emanates from the second magnet upstream) and becomes zero at X=1. The distance between photon stop and beam depends not only on X, but also on the magnet aperture and the arc bending radius.

The result of the geometric calculation, as shown in Fig. 8, is that for the large-circumference ring of VLHC, with X=0 and a horizontal aperture of 30 mm, photon stops could be placed as far apart as 14 m and still permit the stop to be 4 mm from the beam. This is sufficiently far at high energy to avoid being hit for a reasonable rms closed orbit variation of 1 mm, and also far enough so that its impedance contribution is negligible. The magnet, somewhat shorter than 14 m, is a convenient length, and even a bit long for over-the-road transportation. A smaller ring with small aperture magnets forces short magnets. However, for these cases, there is the possibility of shifting the magnet toward the inside of the ring, by some mm, such that the horizontal aperture on the outside, where the synchrotron radiation is emitted, is increased [16].

We consider a prudent design one in which there are both photon stops cooled at room temperature that intercept the majority of the power, and beam screens at cryogenic temperature, which need only moderate cooling power and flow, and which extract synchrotron radiation independent heat loads (multipacting, mirror currents) as well as radiation missing the stops. It also seems prudent to put in-and-out motion control on the stops so that they may be retracted during injection and at low energy. Since the photon stops significantly reduce the operating cost of the machine, one can afford to make a considerable invest in them. The photon stop makes the design and operation of the machine essentially independent of the synchrotron

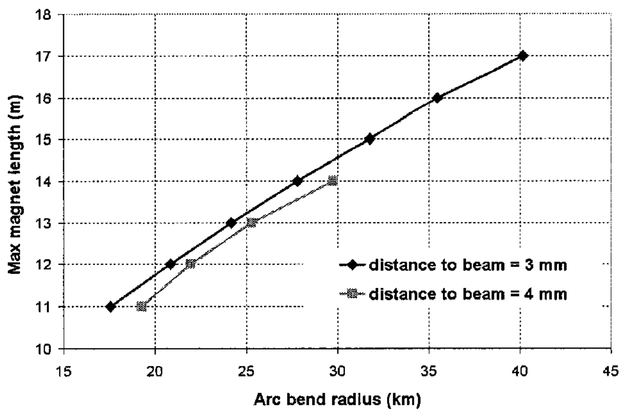

Fig. 8. Maximum magnet size versus bend radius compatible with the use of photon stops for a 200 TeV center-of-mass energy VLHC with a 30 mm horizontal beam aperture for different distances between beam and photon stop.

power, and therefore the energy and luminosity, whereas a VLHC with a beam screen is eventually limited by aperture, as shown in Fig. 6.

3) Radiation damping and luminosity lifetime

The advantage of synchrotron radiation is the resulting very efficient emittance damping mechanism. At fixed energy, smaller rings have shorter radiation damping times, and, hence, have higher integrated luminosity for fixed running time. On the other hand, longer rings have more stored beam (and, unfortunately, more stored beam energy), and therefore a longer luminosity lifetime at equivalent luminosity. Whether these balance to the advantage of higher or lower field depends on details such as reload and acceleration time. Suffice it to say that reloading and accelerating new beam is a complex process that often does not proceed as planned in the ideal world.

V. Cost Models

The final and perhaps most important aspect of magnet design is to consider costs. A simple model, although certainly not accurate in an absolute sense, can predict the general behavior of the cost of high-energy colliders [17]. All such models agree that the cost of a collider at constant energy has a broad minimum as a function of field and then rapidly becomes higher as the field is increased toward the ultimate for the material used. This is because the amount of superconductor and steel must increase dramatically, while the tunnel circumference decreases only slightly. Fig. 9 shows this effect clearly for 2-in-1 cosine-theta magnets optimized for their particular technologies. The distribution of costs among the several collider systems comes from [1]. The performance of Nb_3Sn is assumed to be 3000 A/mm^2 at 4.2 K and 12 T, and the cost of Nb_3Sn is taken to be equal to that of NbTi per unit volume. These assumptions are far from the actual today, but seem reasonable if some R&D investment is made and if the market expands, as it would if a VLHC were built. It is interesting to note that the cost-optimum magnetic field is low compared to the ultimate that can be attained using any

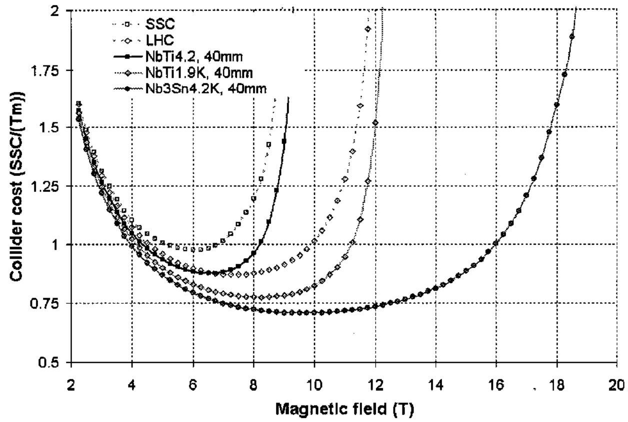

Fig. 9. A simplified model predicts the total cost of magnets plus tunnel and other collider systems vs. magnetic field for a 200 TeV collider with 40 mm aperture in units of SSC-predicted costs. Similar curves are shown for SSC and LHC configurations (40 mm aperture and for comparative purposes the actual aperture).

technology. It is also interesting to note that magnets made from Nb_3Sn can save considerable cost. This is largely because of its excellent performance at high field, a result of R&D investments during the past 10 years.

VI. Conclusions

1. The optimum magnetic field for a 200 TeV collider, and probably colliders of significantly lower energy is much less than the highest field strength that can be attained. This is due not only to synchrotron radiation, but also to total collider cost.
2. The minimum aperture of a magnet is not as small as can be obtained practically. This is due to beam stability requirements and to the need to intercept synchrotron radiation power with high thermodynamic efficiency. It applies whether one uses beam screens or photon stops to absorb the power.
3. Large-circumference rings permit lower-field magnets to reach the highest energy, have less synchrotron radiation, longer luminosity lifetime and allow greater spacing between photon stops. These advantages more than balance the tunnel costs and the shorter radiation damping time for efficient operation.

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