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Hadron Colliders Working Group Report

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I. CHARGE AND ORGANIZATION

A long-term goal of the U.S. high energy physics program is to regain the energy frontier after the start of LHC operation. A very high energy, high luminosity hadron collider is the only sure way to accomplish this goal. The Working Group on Hadron Colliders should develop a vision and a long-term plan for the US hadron collider program. In particular, it should examine the physics and technology issues central to the design of very high energy, high luminosity hadron colliders and specify the most critical accelerator physics and engineering issues that determine the performance of the machine; identify the technology developments and accelerator physics experiments needed to prove the machine feasible, and evaluate and estimate the technological and physics limitations on ultimate energy and luminosity in hadron colliders. The results of the recently completed VLHC study of a staged collider in a large-circumference tunnel should be evaluated and compared with other potential approaches to building and operating very large hadron colliders. Finally, an R&D plan that will accomplish the goals set out above should be developed. This plan should prioritize the areas of technology R&D that will provide maximal benefit to a future VLHC in terms of performance and cost-effectiveness, and should include an estimated cost and schedule for the R&D.

To this end, the 50+ participants of the Working Group divided themselves into six main sub-groups. These six groups, and their respective leaders, are listed below:

Design Study Review & Alternative Approaches	*P. McIntyre, V. Yarba, J. Strait, G. Foster*
Luminosity & Energy Scaling	*P. Bauer*
Superbunches	*K. Takayama*
Lattice Issues	*J. Johnstone*
Collective Effects	*A. Chao, R. Baartman*
Beam Experiments	*T. Sen*

II. EXECUTIVE SUMMARY

Luminosity and energy scaling. The VLHC Design Study examines one point in a parameter space rich in technologically possible VLHCs, in an extrapolation from designs that already work and are well understood. It studies a "2 stage" scenario in which two colliders occupy a single 233 km circumference tunnel, with beam energies of 20 TeV and 87.5 TeV, and with dipole fields of approximately 2 T and 10 T. Because the VLHC is unlikely to be built for several years, there is ample opportunity for further cost and performance optimization, through a focused research and development plan.

The low field ring performance is close to being limited by collective instabilities. In the high field ring the product of luminosity and energy has a maximum value, limited by the total synchrotron power that can be deposited in the cryogenic system. Beyond the Design Study, it is expected that most of the stage 2 ring synchrotron radiation can be absorbed in room temperature "photon stops". This is a very exciting development, because it breaks the nominal total synchrotron radiation power constraint, and potentially allows an order of magnitude increase in the stage 2 luminosity. With or without photon stops, 75% or 80% of the protons are "burnt off" in a typical store, so that the peak luminosity scales linearly with the number of protons stored, and therefore also linearly with the stored beam energy, and with the collision debris power at each interaction point (IP). The Design Study stage 2 luminosity of 2×10^{34} cm^{-2}s^{-1} corresponds to a stored energy of 3.9 GJ and a collision debris power of 73 kW per IP, values that are well beyond current experience and LHC parameters. When photon stops are assumed, the high field ring luminosity is (softly) limited by the ability to engineer beam dumps, and interaction regions magnets. Photon stops, beam dumps, and energy deposition resistant interaction region magnets are all topics which need further research and development.

The VLHC tunnel geometry is compatible with an unpolarized Very Large Lepton Collider (VLLC). (In contrast, the tunnel is not compatible with the Very Large Muon Collider.) This enables e^+e^- collisions with a nominal center of mass energy of about 400 GeV, a luminosity of about 10^{34} cm^{-2}s^{-1}, and good energy resolution. Electron-proton collisions are also possible. The VLLC luminosity and energy scale with circumference like $L \sim C$ and $E \sim C^{1/3}$.

VLHC design study and alternative approaches. The beam energies can be scaled around the Design Study by ±50% simply by changing the tunnel circumference. Roughly 2/3 of the project costs scale linearly with the beam energy. A higher energy stage 1 may be crucial in placing its physics program sufficiently far beyond the LHC to assure a vigorous research program. While the 2 stage concept seems the most reasonable to provide a multi-decade program of energy frontier physics, single stage scenarios should also continue to be studied, as parameters and costs are further optimized. Therefore, the vicinity of at least two other points in parameter space, cases A and B (below), also deserve further study.

Case A (2 stage): 3 T, 50 TeV center of mass; 10-13 T, 150-200 TeV center of mass. The cold-iron super-ferric 3 T stage 1 collider makes it possible to reduce the overall circumference while increasing the collision energy. The cold bore significantly reduces the resistive wall impedance, possibly allowing significantly higher luminosities. A large dynamic range (~30:1) would allow a beam energy as high as 30 TeV, still using the Tevatron as injector. The stage 2 collider uses 13 T Nb_3Sn dipoles to produce 200 TeV collision energies. This is a very aggressive goal; however, even a 10 T field would provide a collision energy of 150 TeV.

Case B (1 stage): 5 TeV injector; 150-200 TeV center of mass collider. A 5 TeV injector is built in a new 15 km circumference tunnel on the Fermilab site, using 11 T fast cycling magnets. (This field and the injector energy could be somewhat lower.) The injector tunnel could also house a double ring polarized Giga-Z e^+e^- collider, supporting high luminosities at the Z pole. The case B collider is identical to the case A stage 2 ring, but with a dynamic energy range of ~20:1, not ~4:1.

HERA and the LHC face difficulties with dynamic ranges of 20:1 and 16:1, respectively, due to persistent current and snap back effects at injection and at the beginning of the energy ramp. Exciting new superconducting magnet design developments suggest that it is possible to suppress these effects, with a very positive impact on VLHC design if dynamic energy ranges greater than 20:1 become feasible. Research and development into persistent current and snap back suppression should be encouraged.

Superbunches. The Superbunch concept from KEK uses induction acceleration modules with an average gradient of 25 kV/m to create very long bunches bounded by "barrier buckets", in a high current, high luminosity scenario. This is potentially very interesting for stage 1, but may be inappropriate for stage 2, due to the very high synchrotron radiation load. The superbunch idea needs to be tested experimentally, for example in the KEK 12 GeV proton synchrotron. Although the experiments prefer a conventional bunched beam structure, superbunches are acceptable. Superbunch collective effects and the potential of stochastic cooling both need further study.

Lattice design. If photon stops are used, the ultimate VLHC performance is limited by challenges associated with the beam dump, and with energy deposition in the interaction region magnets. Optical solutions have been found for the high field abort, and for the seamless transition from triplet (round beam) optics to doublet (flat beam) optics. More research and development is needed, integrating these optical solutions with technically feasible components, such as energy deposition resistant interaction region magnets.

Accelerator Physics. The VLHC physical beam sizes are so small – especially in stage 2 – that discussing the dynamic aperture (in units of the beam size) is less relevant. New paradigms, such as the operational aperture required during the energy ramp, need exploration and development. For example, the closed orbit must be held constant to 0.1 mm in the stage 1 resistive wall feedback pick ups, and perhaps to 1 mm accuracy near the stage 2 photon stops. Operational issues (such as beam based "single particle" feedback on closed orbits, tunes, and chromaticities) need thorough investigation, in order to relax component tolerances such as magnet field quality, and to enable rapid commissioning. Recent and continuing developments in beam instrumentation and diagnostics need to be incorporated in the VLHC design, in order to get a better machine at less total cost. Particle tracking studies, and energy deposition simulations, need to be performed.

Collective effects. Both magnet costs and beam impedances are strong functions of the beam pipe aperture. Close attention must therefore be paid to collective effects, when optimizing cost and performance. The large circumference and small aperture of the VLHC serve to increase the transverse impedance, and to focus attention on the Transverse Mode-Coupling Instability (TMCI), Resistive Wall (RW) instabilities, and Laslett space charge tune shifts.

TMCI: The nominal stage 1 single bunch intensity is 50% higher than the TMCI instability threshold. This can be overcome by bunch coalescing techniques. Electron Cloud simulations indicate that neither the heat load nor the e-p instability growth rate appear to be a problem. However, simulations also suggest that the electron cloud can enhance the TMCI by a large factor. This research needs to be continued.

RW: The skin depth of the lowest RW mode is much smaller than the stage 1 warm beam pipe thickness, resulting in an instability growth time of less than one turn. Several "trailing bunch" feedback systems are therefore required, with the potential for slow emittance growth (although calculations predict otherwise). Additional feedback simulations, and beam demonstrations, would improve the design of these novel stage 1 systems. Resistive wall effects are effectively suppressed in stage 2 by including a 0.5 mm thick copper layer on the cold beam pipe liner.

Laslett space charge tune shifts: These tune shifts are strong while beam is being accumulated in the stage 1 ring. Amelioration techniques need further study.

Beam experiments. Well prepared beam experiments investigating both fundamental physics and also new technologies will also help in designing a less expensive and better VLHC. Since beam time is a precious resource, it is necessary for such experiments to be clearly motivated by vital VLHC issues, and for these motivations to be clearly communicated to accelerator staff and management at the hadron colliders where such time would be requested. Assuming that the community endorses beam experiments motivated by the VLHC design effort, then a 3 to 5 year program should be formally organized.

Collaborative beam experiments provide a natural context in which to make a prototype test of the Remote Operations aspect of a Global Accelerator Network.

There are 6 main beam experimental areas: 1) feedback systems to damp the resistive wall instability, 2) control of orbits, tunes, and chromaticity, 3) superbunch demonstration, 4) slow diffusion, 5) long range beam-beam compensation, and 6) beam-vacuum interactions. The first 3 topics have already been discussed, above.

Slow diffusion: The operational scenario for the Design Study high field ring assumes that the beam emittances decrease by an order of magnitude or more from their injection values (typical of current colliders), with a damping time of order 2.5 hours (10^7 turns). Our present understanding of the catalog of slow diffusion mechanisms – including intra beam scattering, modulational diffusion, and beam-beam induced diffusion – does not guarantee that this is possible. While significant theoretical and simulational advances are possible, beam based diffusion experiments are the most promising avenue for further research.

Long range beam-beam compensation: The dynamic aperture of the VLHC at collision may be dominated by long range beam-beam interactions, which may also limit the lifetime of "Pácman" bunches et the bunch train ends. Beam studies using the Tevatron electron lens compensator would help to establish the expected performance of the present VLHC interaction region design, and will point in the direction in which more R&D is required.

Beam-vacuum interactions: Photon stops are very promising, but need to be tested "under fire" to confirm their beam impedance and vacuum characteristics. Beam experiments should also be performed to test secondary electron production rates under various conditions in a superconducting collider environment.

III. THE VLHC DESIGN STUDY

Much of the discussion at Snowmass concerning future hadron colliders was centered around the recently completed VLHC Design Study. This six-month study for a future high energy hadron collider was initiated by the Fermilab director in October 2000. The request was to study a staged approach where a large circumference tunnel is built that initially would house a low field (~2 Tesla) collider with center-of-mass energy greater than 30 TeV and a peak (initial) luminosity of $10^{34}\text{cm}^{-2}\text{sec}^{-1}$. The tunnel was to be scoped, however, to support a future upgrade to a center-of-mass energy greater than 150 TeV with a peak luminosity of $2 \times 10^{34}\text{cm}^{-2}\text{sec}^{-1}$ using high field (~10 Tesla) superconducting magnet technology.

In a collaboration with Brookhaven National Laboratory and Lawrence Berkeley National Laboratory, a report of the Design Study was produced by Fermilab in June 2001 [1]. The fundamental parameters of the Design Study VLHC staged scenario are given in Table I. In Stage 1, a 233 km circumference tunnel would be built, and a low-field storage ring would be installed using the transmission line, 2 Tesla, combined-function magnets that are being developed at Fermilab [2]. Stage 1 would support an initial experimental program of p-p colliding beams at 40 TeV collision energy with luminosity $10^{34}\text{cm}^{-2}\text{s}^{-1}$. In Stage 2, a second ring of high-field (~10 T at 175 TeV collision energy) dipoles would be installed in the tunnel, using the low-field ring as injector, achieving the design collision energy and luminosity. In the transition from Stage 1 to Stage 2 operation, the experiments will remain centered on the same interaction points. At the same time it is envisaged that they will

	Stage 1	**Stage 2**
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	±20	±30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

TABLE I: VLHC Design Study Parameters.

be upgraded to take up more space along the beam line, increasing the distance from the IP to the first magnet, L^*, from 20 to 30 m. It is therefore necessary to allow for a bypass to keep the low field ring beams well clear of the experiments. This must be done without changing the total low field ring circumference. The lattice is generated using modular construction, with the advantage that low and high field lattices are guaranteed to have almost identical footprints, and therefore to fit in the same tunnel, so long as corresponding low and high field modules are placed on top of each other. The maximum deviation is only a few millimeters, easily allowing one ring to be placed on top of the other at all locations in the VLHC tunnel.

The Tevatron is assumed as the injector for the 20 TeV (beam energy) Stage 1. The straight section regions of the design are clustered such that all facilities – interaction regions, injection and beam abort regions, RF and major instrumentation, *et cetera* – can be fit onto the Fermilab site, as shown in Fig. 1. The first stage, operated at 10 TeV, is the injector for the anticipated second Stage collider.

Details of the accelerator physics issues, design philosophy, and beam physics calculations of the Design Study can be found in [3]. The Hadron Colliders Working Group concluded that the staged approach to a VLHC design, as outlined in the Design Study, is a viable approach, and agreed that the accelerator physics and technical issues are in hand today. Most members, though not all, agreed that a two-stage approach is the best option for the long-term, providing a clear upgrade path to very high energies. The working group agreed that if there is a "Stage 1," it must be a machine which can explore the energy frontier ($\geq 3-5\times$ LHC).

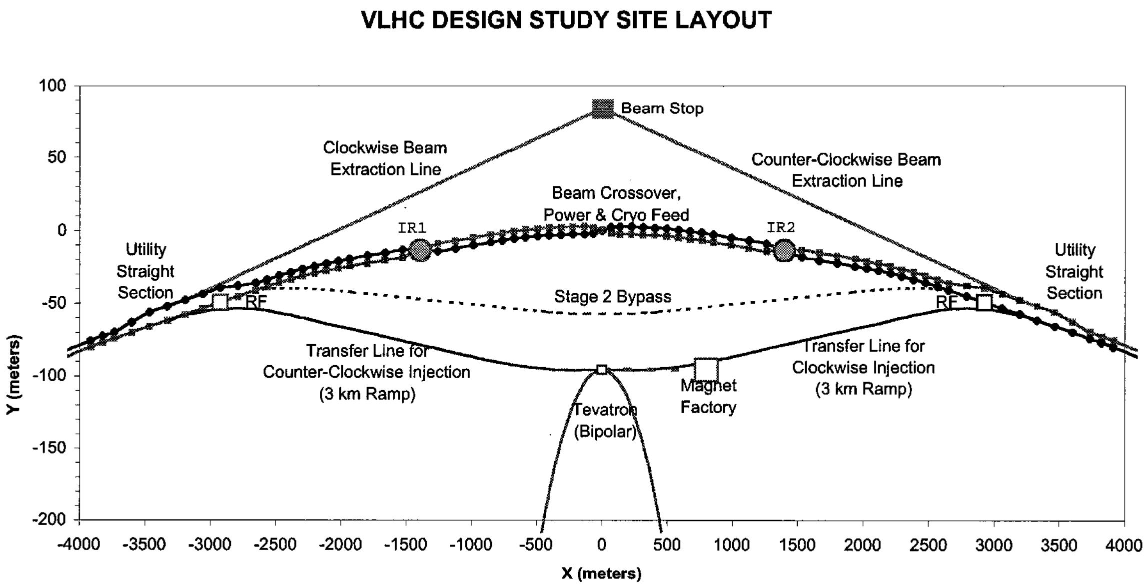

FIG. 1: VLHC Design Study Fermilab site layout.

While the Design Study looked at a single "point design" in detail, one can question whether other magnetic fields, other circumferences, or other major parameter choices are optimized. One sub-group at Snowmass looked at this question in more detail, as described below.

IV. ALTERNATIVE APPROACHES

The beam energies can be scaled around the Design Study by ±50% simply by changing the tunnel circumference. Roughly 2/3 of the project costs scale linearly with the beam energy. A higher energy Stage 1 may be crucial in placing its physics program sufficiently far beyond the LHC to assure a vigorous research program. While the two stage concept seems the most reasonable to provide a multi-decade program of energy frontier physics, single stage scenarios should also continue to be studied, as parameters and costs are further optimized. Therefore, the vicinity of other points in parameter space also deserve further study.

The sub-working group considered a range of possible alternatives to this baseline scenario in an effort to identify those alternatives that might provide a more cost-effective path to the physics goal. The group also tried to identify collateral physics capabilities that might be supported within the VLHC plan. Alternatives considered include:

- higher field magnets for the Stage 1 and Stage 2 rings;
- an injector located on the existing Fermilab site;
- a Giga-Z collider sharing the tunnel with such an on-site injector;
- a ∼400 GeV center of mass e^+e^- collider ring sharing the tunnel;
- acceleration of superbunches of protons using induction acceleration devices.

The superbunch proposal of KEK, discussed elsewhere in this report, looks interesting as a path towards very high luminosity in the Stage 1 machine, and needs to be experimentally tested. This can be done at the 12 GeV PS at KEK or at the Fermilab Main Injector. After additional R&D this idea may be incorporated into the VLHC project.

The two-stage concept and the large circumference tunnel are the most reasonable to provide a multi-decade program of energy frontier physics. On the other hand, single-stage scenarios should also be considered as parameters and costs are optimized. Therefore two specific scenarios were considered in some detail that appear to merit further study. In both of these scenarios one can accommodate a 400 GeV e^+e^- collider ring sharing the tunnel as one of the stages.

Scenario A: modified version of the Design Study.

For Stage 1, a 3 Tesla cold-iron superferric ring [4] could be installed in a 200 km circumference tunnel, producing 50 TeV collision energy. For Stage 2, a 13 Tesla Nb_3Sn magnet ring would produce 200 TeV collision energy. This is a very aggressive goal; however, even a 10 Tesla field would provide a collision energy of 150 TeV.

The 3 T magnets in Stage 1 would make it possible to reduce the overall circumference of the VLHC ring, and at the same time to increase the collision energy in the initial phase. The simplicity of design should result in a total cost per TeV that is comparable to that for the 2 Tesla design. The cold bore beam tube significantly reduces resistive wall impedances and might make possible significantly higher luminosity. The large dynamic range ($\sim$30:1) of this magnet may allow as much as 30 TeV per beam using the Tevatron as the injector.

The 10 – 13 T dipoles of the Stage 2 ring need a dynamic range of $\leq$10:1 if the Stage 1 ring is limited to 10 TeV when used as an injector, although one could inject at a higher energy and reduce the required dynamic range. This modest dynamic range should ensure that persistent current effects are minimized, and a dipole with an aperture as small as $\sim$20 – 30 mm should be sufficient. An example design was presented that demonstrates that such a reduced aperture requirement could be realized with a significant reduction in the amount of expensive Nb_3Sn superconductor that is required in the Stage 2 dipoles.

The parameters for Scenario A are summarized below:

	Stage-1	Stage-2
E_{beam} (TeV)	25	75 – 100
E_{inj} (TeV)	0.9	10
B_{coll} (Tesla)	2.99	10 – 13
B_{inj} (Tesla)	0.11	1.30
R_{bend} (km)	27.9	25.6
Arc packing factor	93%	85%
R_{arc} (km)	30	30
C_{arc} (km)	188	188
$L_{straights}$ (km)	13	13
C_{total} (km)	202	202

Scenario B: single stage VLHC with 150-200 TeV collision energy and $\sim$5 TeV injector.

The tunnel for the injector could also accommodate a high-luminosity e^+e^- collider operating at the Z-pole, a so-called Giga-Z facility. The 5 TeV injector could be built in a 15 km circumference tunnel on-site at Fermilab. The VLHC itself would then become a single stage project. The injector would use $\sim$11 Tesla fast-cycling magnets. Certainly, this field and the injector energy could be somewhat lower at the expense, however, of requiring a larger dynamic range in the collider. Construction of the injector as an initial project would enable an early transition into manufacture for high-field Nb_3Sn magnets, and also would stimulate the industrialization of Nb_3Sn superconductor into mass production, hopefully engendering a substantial reduction in its unit cost. This construction would thereby likely have a beneficial impact on the budgetary cost for the collider. The parameters for Scenario B are summarized here:

	Injector	Collider
E_{beam} (TeV)	5	75 – 100
E_{inj} (TeV)	0.9	5
B_{coll} (Tesla)	11	10 – 13
B_{inj} (Tesla)	2.0	0.65
R_{bend} (km)	1.5	25.6
Arc packing factor	85%	85%
R_{arc} (km)	1.75	30
C_{arc} (km)	11	188
$L_{straights}$ (km)	4	13
C_{total} (km)	15	202

The peak energy and field of the VLHC would be similar to that in Stage 2 in the first alternate scenario. A collateral benefit from such a 15 km injector tunnel could be the staging in the same tunnel of a Giga-Z collider.

With an arc length half that of LEP, and comparable total straight section length, an e^+e^- collider could be configured there using LEP technology to make separated e^+ and e^- rings. This configuration could support polarized beams and high luminosity of $5 \times 10^{33}\text{cm}^{-2}\text{sec}^{-1}$ at the Z pole.

In addition to the staged scenarios, it has been suggested that a single-stage p-p collider with energy comparable to Stage 1 in the Design Study or in the first scenario discussed above could be constructed for lower cost if it were optimized as a single stage project and not part of a plan that allows for a second, much higher energy ring to be installed in the same tunnel. Such a machine might use intermediate field magnets of ~5 T in a ring considerably smaller than envisioned in the staged approaches. This alternative was not examined in detail, but should be addressed to determine what cost, if any, is incurred in Stage 1 to provide an upgrade path to very high energy.

V. LUMINOSITY AND ENERGY SCALING

The VLHC Design Study examines one point in a parameter space rich in technologically possible VLHCs, in an extrapolation from designs that already work and are well understood. It studies a "2 stage" scenario in which two colliders occupy a single 233 km circumference tunnel, with beam energies of 20 TeV and 87.5 TeV, and with dipole fields of approximately 2 T and 10 T. Because the VLHC is unlikely to be built for several years, there is ample opportunity for further cost and performance optimization, through a focused research and development plan.

The low field ring performance is close to being limited by collective instabilities. These issues are discussed in Section IX. In the high field ring the product of luminosity and energy has a maximum value,

$$L_{ave}\, E \;<\; P_{cryo} \left(\frac{1}{N_{IP}\sigma_{tot}}\right)\left(\frac{T_0}{T_{store}}\right) ,$$

limited by the total synchrotron power that can be deposited in the cryogenic system. For some time, this has been seen as the limiting factor for ultimate performance of any future high-energy hadron collider. The next leading issue for performance of such colliders is the debris power emanating from the interaction regions toward the detector and IR magnet system. Other limiting effects include the total stored energy of the beam, the tolerable number of events per crossing for the detector systems, and the beam-beam tune shift limit. With these limiting factors in mind, an examination of various possible VLHC scenarios can be performed, as described below.

A. Synchrotron Radiation Power

The cryogenic environment of a superconducting accelerator strongly complicates the removal of the power deposited by synchrotron radiation. However, the extensive experience with synchrotron radiation absorbers in lepton machines and light sources should give confidence that extraction of synchrotron radiation power on the scale of 100 W/m/beam from a cryogenic magnet system in a proton collider is manageable at minimized costs using "photon stops." Fermilab and Argonne National Lab are currently involved in R&D aiming at testing the first photon stop system in a cryogenic environment in the Tevatron. However, as long as photon stops remain a speculative technology, and to account for accelerator scenarios in which photon stops cannot be used, it is more reasonable to limit present-day calculations to much lower levels. Preliminary calculations, done in the context of the recent VLHC Design Study, indicate that 10 W/m/beam peak radiation power can be handled by a beam screen installed in a ~40 mm magnet aperture [5].

B. IR Debris Power

The LHC accelerator at CERN is projected to produce ~1 kW of debris power per IR. The Stage 1 of the VLHC Design Study would produce 2-3 kW of debris power, which can be absorbed by a succession of shields much like in the LHC. However, Stage 2 of the Design Study would generate a level of up to 50 kW per beam. A detailed analysis of possible shielding scenarios has not been made as yet. Preliminary analysis predicts the need of absorbers in the bores of the interaction region magnets together with a series of collimation shields at the end of the detector and interspersed between the IR magnets to cope with the neutral debris (~30%).

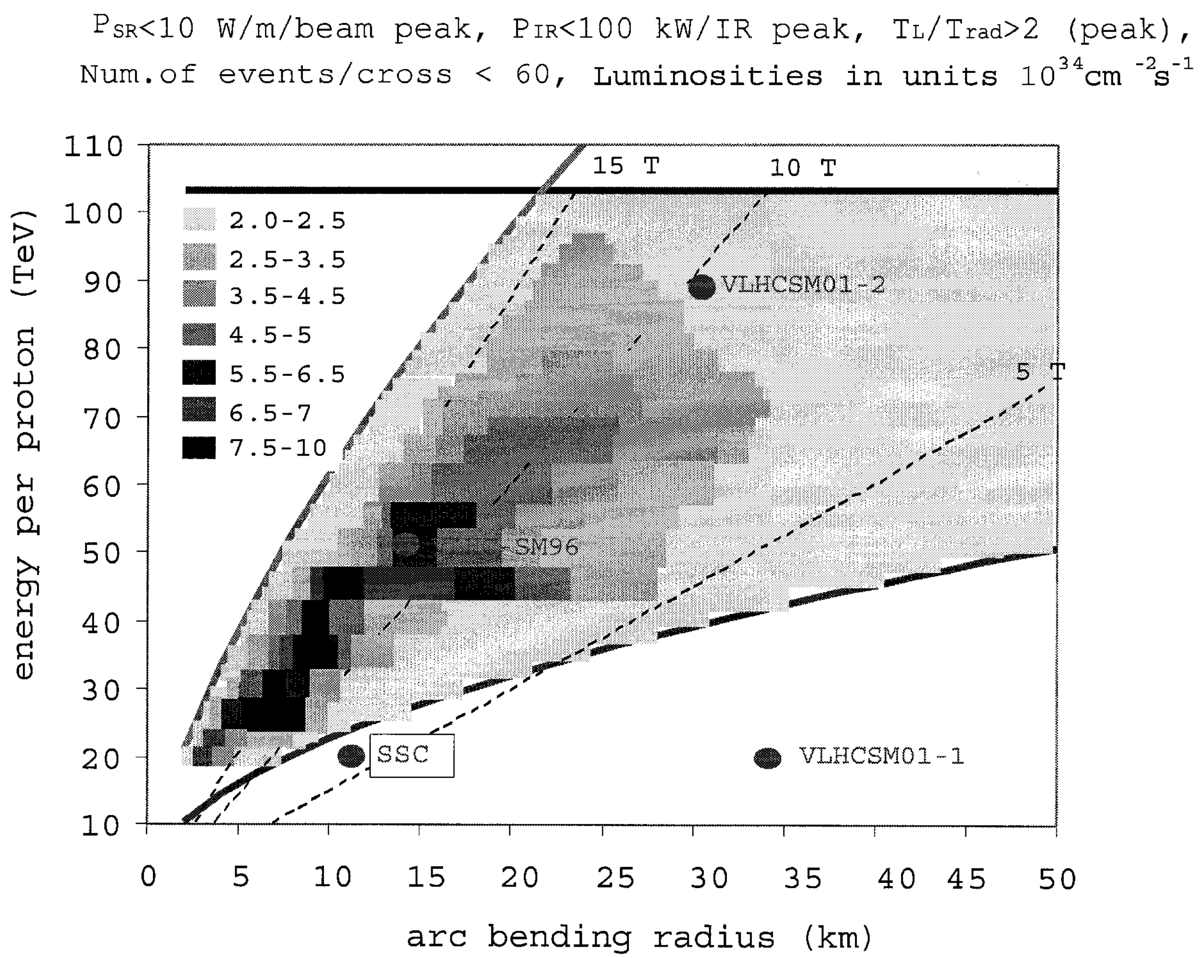

FIG. 2: Maximum luminosity in the "possible" VLHC region, in units of $10^{34}\text{cm}^{-2}\text{sec}^{-1}$. See text for further explanation.

C. Other limitations

The Tevatron operates with several events taking place per bunch crossing on average, and the LHC will operate near 15-20 events per crossing. The VLHC Stage 1 has been designed with a similar number (19), while Stage 2 would have up to 60 events per crossing at maximum luminosity at the bunch spacing of the Tevatron, ~19 ns. Bunch spacings of 10-12 ns for hadron colliders are not out of the question for future machines.

Experimental and simulation data for lepton colliders suggest that for a synchrotron radiation dominated hadron collider, such as Stage 2 in the VLHC Design Study, a maximum allowable beam-beam tune shift of 0.008 at a damping decrement of $\sim 10^{-7}$ is a reasonable limit to achieve.

The beam stored energy in the LHC is approximately 0.5 GJ. In the VLHC Design Study, both the low field and high field stages have stored energies of about 4 GJ per beam. When examining further VLHC options, a limit of 5 GJ per beam has been assumed.

D. Exploring further VLHC options

By combining the limiting factors described above, a map of possible future hadron colliders has been generated by Bauer [6]. The result is shown in Fig. 2. In this figure, energy per proton is plotted against the bending radius of the arc of the accelerator. The shaded region is bounded below by the constraint that the accelerator have significant synchrotron radiation, *i.e.*, that the radiation damping time is less than half the luminosity

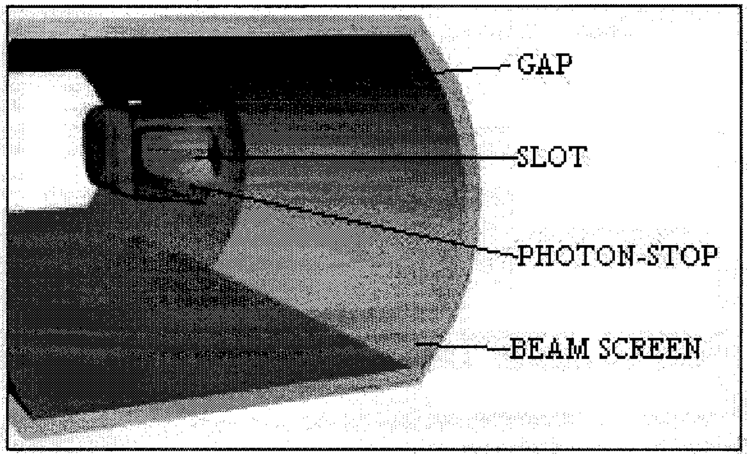

FIG. 3: A photon stop design, from VLHC Design Study [1].

lifetime. The region is bounded above, and to the left, by the constraint that the synchrotron radiation power is below 10 W/m/beam at its peak. It is ultimately bounded above by the constraint that the IR debris power be below 100 kW/IR. Along all these boundaries, the luminosity is $2 \times 10^{34}\text{cm}^{-2}\text{sec}^{-1}$. Lines have been drawn to indicate 5 T, 10 T, and 15 T bend fields, and locations of the SSC design, the Snowmass VLHC design of 1996, and the VLHC Design Study (Stages 1 and 2) are indicated. As can be seen, the highest luminosities are generated in regions toward higher bend field and smaller bend radius.

E. Comments on Photon Stops

Beyond the Design Study, it is expected that most of the Stage 2 ring synchrotron radiation can be absorbed in room temperature "photon stops." (See Fig. 3.) This is a very exciting development, because it breaks the nominal total synchrotron radiation power constraint, and potentially allows an order of magnitude increase in the Stage 2 luminosity. With or without photon stops, 75% or 80% of the protons are "burnt off" in a typical store, so that the peak luminosity scales linearly with the number of protons stored, and therefore also linearly with the stored beam energy, and with the collision debris power at each interaction point (IP). The Design Study Stage 2 luminosity of 2×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ corresponds to a stored energy of 3.9 GJ and a collision debris power of 73 kW per IP, values that are well beyond current experience and LHC parameters. When photon stops are assumed, the high field ring luminosity is (softly) limited by the ability to engineer beam dumps, and interaction regions magnets. Photon stops, beam dumps, and energy deposition resistant interaction region magnets are all topics which need further research and development.

F. Comments on Other VLHC Options

It has been suggested that a large circumference tunnel for use in a VLHC could also be used for a large lepton collider [7]. The lepton collider could be considered a "first stage" device, or the tunnel could be built to support both options. During the Snowmass study, the lepton collider was explored in more detail, and it was found that the VLHC Design Study tunnel geometry is indeed compatible with an unpolarized Very Large Lepton Collider (VLLC). (In contrast, the tunnel is not compatible with a Very Large Muon Collider.) This enables e^+e^- collisions with a nominal center of mass energy of about 400 GeV, a luminosity of about 10^{34} $\text{cm}^{-2}\text{s}^{-1}$, and very good energy resolution. Electron-proton collisions are also possible. For parametric studies, it should be pointed out that the VLLC luminosity and energy scale with circumference like $L \sim C$ and $E \sim C^{1/3}$.

VI. SUPERBUNCHES

The Superbunch hadron collider concept [8] was presented and discussed at Snowmass by K. Takayama, et al. The scheme, depicted in Fig. 4, consists of the formation of very long "superbunches" in the upstream booster rings which are maintained and brought into collision in the VLHC. Induction acceleration devices generate essentially square waveforms for acceleration and for barrier bucket confinement during storage. A large beam occupation ratio has been shown to result in a larger luminosity – by a factor of 15 – than is found in the more conventional hadron collider based on RF technology. It has been demonstrated that innovative hybrid "inclined crossing" techniques can be used to substantially suppress or control a large beam-beam tune spread. Immediate concerns associated with superbunch acceleration and collision were addressed and discussed at Snowmass. Possible superbunch schemes based on the VLHC Design Study have been seriously considered, together with a wide variety of applications such as a long base-line neutrino oscillation experiment.

A. Feasibility

From a beam dynamics point of view, the beam-beam effects including long range interactions of particles with the on-coming superbunch are most serious. Extensive computer simulations indicate that the beam-beam tune spread can stay within a tolerable level without any emittance blow-up, assuming the same line density as the averaged line density of an RF bunch in the corresponding conventional collider, and assuming an inclined crossing scenario. In addition, the Pacman effects in the superbunch collision have been simulated. In contrast to a conventional collider where the bunches located in the head and tail of the bunch train never change their relative positions in the train, particles in the head and tail of a superbunch will exchange positions due to the (long-period) synchrotron oscillation within the bunch. This suggests that mismatching due to the long-range beam-beam interactions is adiabatically induced and will not result in emittance increase. Simulations bear this out.

The stored energy in the superbunch accelerator is quite high. However, synchrotron radiation power is still small in the first stage of the VLHC Design Study employing the superbunch scheme. Resistive wall loss is substantially reduced due to the small high frequency components in the wall current compared with that of an RF bunch in a conventional collider. Furthermore, it is noted that the magnitude is negligibly small compared to the synchrotron radiation loss.

A scenario for producing superbunches in the existing Fermilab accelerator complex and in the low energy VLHC has been proposed. A microsecond-long barrier bucket is painted with chopped H^- beams to generate a superbunch in the 8 GeV Booster and eventually injected into the Main Injector. After filling one accelerator, adjacent superbunches can be combined by bringing the trigger signal of the barrier voltage for the latter superbunch forward. Using this process, eventually 334 superbunches can be accelerated up to the collider energy. As the number of protons captured in the 8 GeV Booster is assumed to be 4.3×10^{12}, the number of protons in each superbunch of the Stage 1 VLHC would be 5.2×10^{13}. This intensity gives a luminosity of $1.5 \times 10^{35}\text{cm}^{-2}\text{sec}^{-1}$.

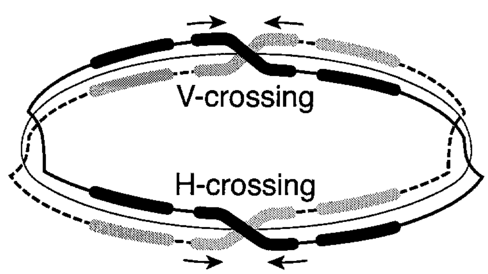

FIG. 4: Schematic of the superbunch concept. The long bunches are brought into collision at two points, with crossing angles in the horizontal and vertical planes.

B. Required R&D – Present and Planned

Required induction accelerating devices, which use the nanocrystalline magnetic material such as Finemet, and a modulator triggered by a fast switching device using FET elements – or Static Induction Thyristor (SIT) – are being developed at KEK under a close collaboration with the Tokyo Institute of Technology and with industry. A prototype has been assembled and successfully operated with an output voltage of 4 kV and a pulse width of 400 nsec at 100 kHz. Recently its operation at 800 kHz was demonstrated. From the initial operation of the prototype device essential important features, such as switching performance and heat deposit, have been determined. The second prototype using the SIT as a switching element, by which 96 FET's used in the first prototype can be replaced, was assembled and its capability demonstrated with an output voltage of 3 kV and a pulse width of 200 nsec at 200 kHz. A unit cell, which is currently designed, is specified by an output voltage of 2.5 kV, a pulse width of 450 nsec, a maximum repetition rate of 800 kHz, a physical length of 0.1 m, and a maximum core loss of 3 kW. CW mode operation of the device with complete core and switching element cooling is urgently required. Programmed switching and switching of the device with feedback must be demonstrated as soon as possible. By the end of 2002 a proof-of-principle experiment of superbunch acceleration is expected in the KEK 12 GeV PS. In addition, a similar experiment in the Fermilab Main Injector introducing the induction accelerating devices from KEK should be considered. Funding for this effort may be sought from the Japan-US collaboration program.

C. Unsolved Issues

Collective instabilities of the superbunch scheme are a concern because of the particular feature of an extremely long bunch length, and a very low synchrotron frequency. The preliminary analysis assuming a rectangular distribution in longitudinal phase space indicates that the mode coupling instability in the transverse direction is serious for the resistive wall impedance. A more realistic model for the superbunch is required to estimate the growth rate and to design a required damper system. Adiabatic motion of the barrier bucket is critical to the bunch combining process. To avoid the undesired particle diffusion, a maximum step of gate pulse signal change must be confirmed.

Another major concern is the stored energy of a high luminosity superbunch beam. The magnitude of the stored beam energy would force one to re-examine beam collimation systems, beam absorber systems, and IR protection schemes.

D. Superbunch Summary

The superbunch hadron collider scheme is potentially very interesting for a Stage 1 VLHC, though it may be inappropriate for a high energy Stage 2, due to the very high synchrotron radiation load. In order to convince the accelerator community of its capability, barrier bucket acceleration must be tested experimentally in an existing accelerator.

It was also pointed out that with the very long bunches of the superbunch option, bunched-beam stochastic cooling may be possible in such a collider. This would have the added benefit of reducing the emittances and enhancing the luminosity. To reach Stage 1 luminosity requirements, it may be that the combination of stochastic cooling of long bunches, with a reduced total beam intensity may be feasible. Superbunch collective effects and the potential of stochastic cooling both need further study.

VII. LATTICE DESIGN

If photon stops are used, the ultimate VLHC performance is limited by challenges associated with the beam dump, and with energy deposition in the interaction region magnets. Optical solutions have been found for the high field abort, and for the seamless transition from triplet (round beam) optics to doublet (flat beam) optics. Fig. 5 shows two IR designs. They both use the same magnets, but the optics on the left produces a flat beam, while the optics on the right produces a round beam. The IR can be tuned smoothly from one arrangement to another, so that an initially equal-emittance (horizontal and vertical) beam can be tuned from round to flat as the vertical and horizontal emittances damp to their unequal equilibrium values.

More research and development is needed, integrating these optical solutions with technically feasible components, such as energy deposition resistant interaction region magnets.

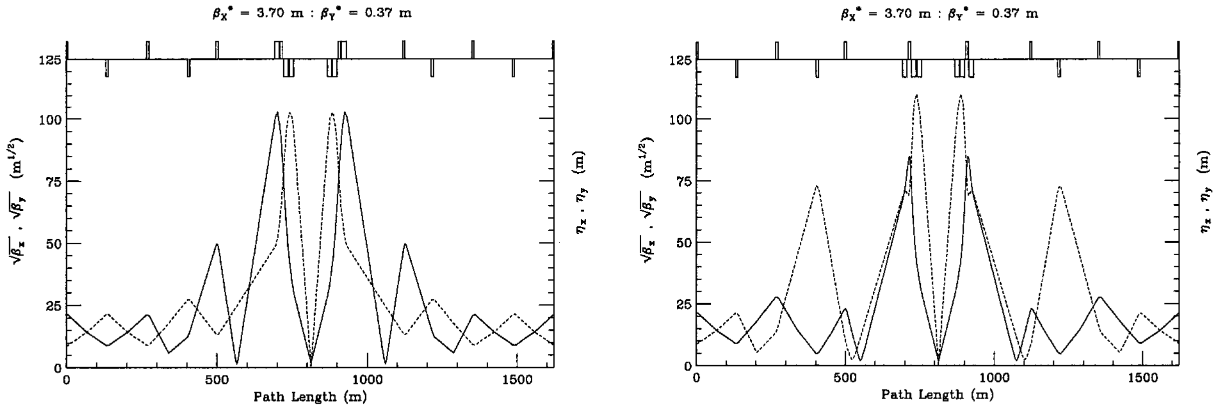

FIG. 5: Round beam (triplet) and flat beam (doublet) optics using identical magnetic elements. (J. Johnstone, FNAL)

VIII. ACCELERATOR PHYSICS

The VLHC physical beam sizes are so small – especially in Stage 2 – that discussing the dynamic aperture (in units of the beam size) is less relevant. New paradigms, such as the operational aperture required during the energy ramp, need exploration and development. For example, the closed orbit must be held constant to 0.1 mm in the Stage 1 resistive wall feedback pick ups, and perhaps to 1 mm accuracy near the Stage 2 photon stops. Operational issues (such as beam based "single particle" feedback on closed orbits, tunes, and chromaticities) need thorough investigation, in order to relax component tolerances such as magnet field quality, and to enable rapid commissioning. Recent and continuing developments in beam instrumentation and diagnostics need to be incorporated in the VLHC design, in order to get a better machine at less total cost. Particle tracking studies, and energy deposition simulations, need to be performed.

IX. COLLECTIVE EFFECTS

Both magnet costs and beam impedances are strong functions of the beam pipe aperture. Close attention must therefore be paid to collective effects, when optimizing cost and performance. The large circumference and small aperture of the VLHC serve to increase the transverse impedance, and to focus attention on the Transverse Mode-Coupling Instability (TMCI), Resistive Wall (RW) instabilities, and Laslett space charge tune shifts. As a result of a VLHC Instability Workshop held at SLAC, March 21-23, 2001 [9], most other instability issues are not expected to be serious concerns for the VLHC.

TMCI.

The nominal Stage 1 single bunch intensity is 50% higher than the TMCI instability threshold. This can be overcome by bunch coalescing techniques. Electron Cloud simulations indicate that neither the heat load nor the e-p instability growth rate appear to be a problem. However, simulations also suggest that the electron cloud can enhance the TMCI by a large factor. This research needs to be continued.

Resistive Wall.

The skin depth of the lowest resistive wall mode is much smaller than the Stage 1 warm beam pipe thickness, resulting in an instability growth time of less than one turn. Several "trailing bunch" feedback systems are therefore required, with the potential for slow emittance growth (although calculations predict otherwise). Additional feedback simulations, and beam demonstrations, would improve the design of these novel Stage 1 systems. Resistive wall effects are effectively suppressed in Stage 2 by including a 0.5 mm thick copper layer on the cold beam pipe liner.

Coherent tune shifts

The very low revolution frequency of the VLHC Design Study collider leads to a variation in the magnetic image Laslett tune shift when the ring is partially filled during the injection process. The variation is due to the fact that the revolution period is comparable to the magnetic diffusion time through the beam pipe. As the accelerator is filled with bunch trains, the eddy currents induced in the beam pipe by the passing bunches generate a magnetic field distribution which has a strong quadrupole moment, as can be seen in Fig. 6.

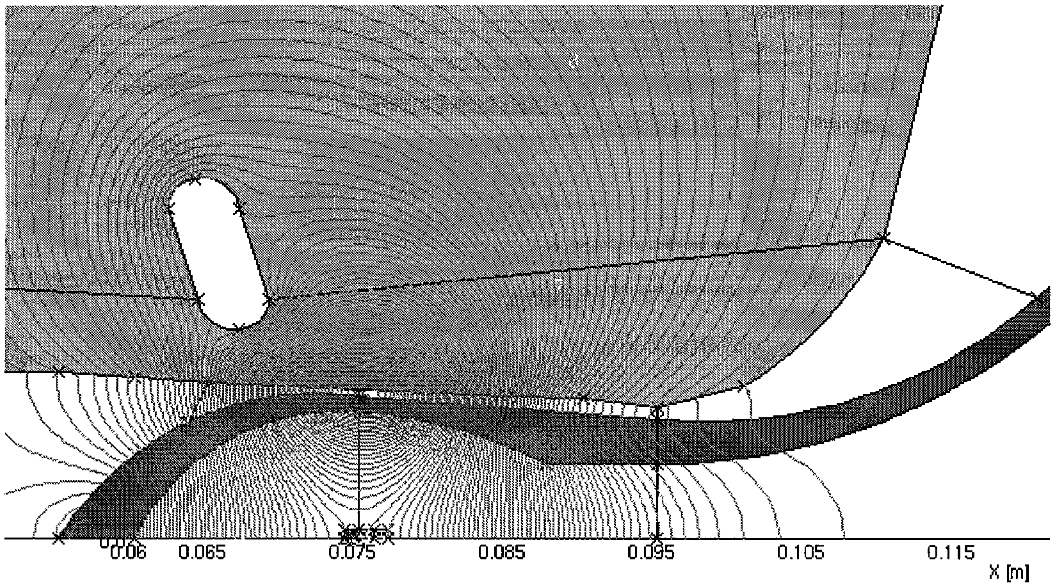

FIG. 6: Magnet field distribution caused by beam pipe eddy currents after ten bunches with current 0.19 A pass by. (V. Kashikhin, FNAL.)

Initial estimates show a DC tune shift on the order of 0.5 units, with an AC component of about 0.1 units due to the time dependence of the magnetic diffusion into the beam pipe. The DC tune shift can be compensated for by adjusting the normal tune correction circuits. Additionally, increasing the vacuum pipe thickness and/or radius could reduce both of these problems. Increasing the dipole magnet gap can reduce the DC Laslett tune shift while the variation in tune along the bunch train could be reduced by quadrupoles running at multiples of the revolution frequency. It is envisioned, however, that injecting beam in an appropriately symmetric manner, with bunches entering the ring far apart from each other and gradually filling in between the already injected bunches, the AC tune variations can be reduced to a tolerable level.

X. BEAM EXPERIMENTS

Well prepared beam experiments investigating both fundamental physics and new technologies will also help in designing a less expensive and better VLHC. Since beam time is a precious resource, it is necessary for such experiments to be clearly motivated by vital VLHC issues, and for these motivations to be clearly communicated to accelerator staff and management at the hadron colliders where such time would be requested. Assuming that the community endorses beam experiments motivated by the VLHC design effort, then a 3 to 5 year program should be formally organized.

Collaborative beam experiments provide a natural context in which to make a prototype test of the Remote Operations aspect of a Global Accelerator Network.

There are 6 main beam experimental areas: 1) feedback systems to damp the resistive wall instability, 2) control of orbits, tunes, and chromaticity, 3) superbunch demonstration, 4) slow diffusion, 5) long range beam-beam compensation, and 6) beam-vacuum interactions. The first 3 topics have already been discussed, above.

Slow diffusion:

In Stage 2 of the VLHC, the design beam emittances are very small and therefore the beam brightness is much higher than in present or future hadron colliders such as the LHC. The beam emittances decrease by an order of magnitude or more from their injection values (typical of current colliders), with a damping time of order 2.5 hours (10^7 turns). Our present understanding of the catalog of slow diffusion mechanisms – including intra beam scattering, modulational diffusion, and beam-beam induced diffusion – does not guarantee that this is possible. IBS in particular will cause significant emittance growth and reduce the luminosity. Other sources of diffusion such as power supply ripple, ground motion, etc., may combine with IBS to cause unacceptably large emittance growth. At present RHIC is dominated by IBS effects when operated with gold ions and is an ideal accelerator to test the present theories of IBS against measurement. Beam behavior with externally introduced sources of diffusion such as quadrupole strength modulation should also be studied. These measurements could be used to determine the expected emittance growth rate when scaled to the VLHC.

Long range beam-beam compensation:

Tracking studies both for the Tevatron (Run IIa) and the LHC have revealed that the dynamic aperture at collision is completely dominated by the long-range interactions. The dynamic aperture in both cases is close to or smaller than the physical aperture determined by the primary collimators. This may strongly limit the lifetime of most bunches and in particular those of the Pacman bunches. Studies of the compensation scheme with the electron lens proposed for the Tevatron together with the complementary electromagnetic wire compensation proposed for the LHC would be extremely useful to determine whether these compensation schemes suffice to provide enough lifetime. If these schemes are not adequate, then either other compensation schemes have to be invented or the beams have to be separated more quickly to reduce the number of long-range interactions. In any event, these experiments will either establish the feasibility of the present VLHC design or will point the direction in which more R&D is required.

Beam-vacuum interactions:

Photon stops are very promising, but need to be tested "under fire" to confirm their beam impedance and vacuum characteristics. Beam experiments should also be performed to test secondary electron production rates under various conditions in a superconducting collider environment.

XI. VLHC ACCELERATOR PHYSICS R&D

The accelerator physics R&D plan for the next few years will need to include work in the areas of beam instabilities, diffusion effects, optics, simulation and modeling, and beam experiments. As for instabilities studies, one must carefully consider an impedance budget for the colliders and generate estimates of the impedances of the major items which the beam will encounter along its trajectory. Photon stops are a good example of a new device whose impedance needs to be studied in detail. Work must continue to understand the TMCI threshold, including experimental measurements (using the Tevatron electron lens, for example). Collective feedback system specifications must be developed in order to understand their feasibility. Closed Orbit tolerances in the vicinity of feedback pick-ups must also be studied.

The area of diffusion includes further ground motion studies, modulational diffusion studies, and continued investigations into Intra-Beam Scattering effects, especially for the high energy rings. Beam-Beam induced diffusion, etc., will continue to be investigated as well.

Lattice design work must continue in the following areas: interaction region optics (doublet & triplet), vertical dispersion suppression, beam abort system, beam collimation systems, crossing angles generation (including optimization of crossing planes), and continued development of the optimum half cell length.

Simulation and scaling efforts will need to continue in the areas of particle tracking, energy deposition, and dynamic optics. Is operational aperture (measured in mm) more critical than the dynamic aperture (measured in beam sigmas)? Feedback systems on closed orbits, tunes, and chromaticities must be investigated for optimal performance of these future colliders. Arc and IR correction schemes will continue to be developed, with much input coming from the operational experience of RHIC and the LHC. IR debris distributions should be generated to understand the requirements of radiation shielding of the magnetic elements of the interaction region.

Further study of luminosity versus energy, cryogenic power load, IR energy deposition, the number of events per crossing, and capital or operating costs of future hadron colliders must be conducted.

And, as mentioned previously, beam experiments will play a major role in the further optimization of a VLHC design.

XII. SUMMARY

The "point design" studied this year shows that a staged VLHC (40, ~200 TeV) is feasible, with no insurmountable challenges. Further work can provide a more optimized design, by studying various alternative field strengths (e.g., superferric magnets for Stage 1) for improvements to vacuum, wall impedance, and other major performance parameters. It may be that a "single-stage" scenario for accessing higher energies sooner is the correct approach. A next-step design study should be considered to look at the two cases near to and complementary to the 2001 VLHC Design Study.

The effectiveness of photon stops and their engineering design need to be addressed in the near future to truly determine if these devices can lead this effort to even higher luminosities and energies. The superbunch approach should continue to be studied, as well as IR designs, new instrumentation and diagnostics, and beam dynamics issues. Finally, a well organized VLHC-motivated beam studies effort should become part of the national program.

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