The Very Large Hadron Collider Overview

Ernest Malamud
Fermi National Accelerator Laboratory

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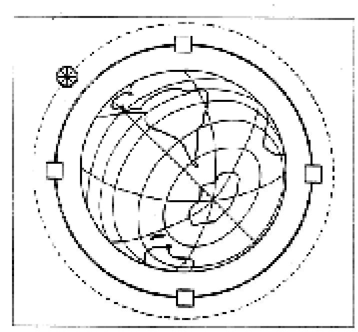
1. Introduction

This overview was presented at two vlhc workshops held at Lake Geneva, Wisconsin. The first, "VLHC Accelerator Physics" was organized under the auspices of the Steering Committee for a future very large hadron collider. The second workshop was part of a continuing series on superconductors sponsored by the Applied Superconductivity Center at the University of Wisconsin and the Superconducting Magnet Group at LBNL.



The logo from a 1954 slide by Enrico Fermi showing an accelerator circling our planet symbolizes the international nature of our field and my belief that the vlhc will, when it is built, be an international effort.

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2. Steering committee for a future very large hadron collider

From recommendations of the HEPAP Subpanel Report [1]

……….recommends an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC. These efforts should be coordinated across laboratory and university groups with the aim of identifying design concepts for an economically and technically viable facility.

The Steering Committee was formed in response to this recommendation. At the initiative of John Peoples, representatives from BNL, FNAL, and LBNL met informally at Fermilab on February 25, 1999 to discuss the formation of an organization to coordinate and bring coherence into the U.S. efforts on a very large hadron collider. Present were people from BNL, FNAL, and LBNL leading the U.S. LHC Accelerator Project together with additional representatives from FNAL working on the local vlhc effort.

Following this meeting John Peoples asked the Directors of BNL, LBNL and Cornell University's Laboratory of Nuclear Studies to appoint representatives to a Steering Committee to organize this effort. Appointed were:

BNL: Michael Harrison (harrison@bnl.gov), and Stephen Peggs (peggs1@bnl.gov)
FNAL: Peter Limon (pjlimon@fnal.gov) and Ernest Malamud (malamud@fnal.gov)
LBNL: William A. Barletta (WABarletta@lbl.gov) and James L. Siegrist (JLSiegrist@lbl.gov)
Cornell: Gerry Dugan (dugan@lns62.lns.cornell.edu)

This group met at Fermilab April 24 and adopted a Mission statement and a charge.

Mission Statement

The Steering committee for a future very large hadron collider coordinates efforts in the United States to achieve a superconducting proton-proton collider with approximately 100 TeV cm and approximately 10^{34} cm^{-2} sec^{-1} luminosity.

The U.S. site of the vlhc is assumed to be Fermilab. We will keep this working hypothesis unless political or other reasons rule it out. Using a nominal 20x in dynamic range in the magnets the newly completed Main Injector at 150 GeV would inject into a 3 TeV vlhc Booster that in turn would inject into the 50 TeV (per beam) vlhc.

Charge (excerpts)

The Steering Committee for a future very large hadron collider has been established to coordinate the U.S. effort towards a future, post-LHC, large hadron collider.

The Steering Committee does not manage the work of the individual institutions.

The Steering Committee will

- encourage the exchange of personnel between participating institutions
- promote coordination in planning and sharing of research facilities
- provide a mechanism for all interested parties to participate in the evaluation of the alternative technological approaches that are presently being pursued.

The Steering Committee will organize the selection of a good name and logo for the vlhc.

The focus is on technology and cost reduction.

The Steering Committee has appointed Working Groups and asked each of them to organize at least one workshop/year. Workshops and meetings are open to all and participation is welcomed from all foreign and U.S. institutions.

The three working groups, their co-convenors, and the first workshop held by each are:

Magnet Technologies
Co-convenors: Bill Foster, Ron Scanlan, Peter Wanderer
"Magnets for a Very Large Hadron Collider,"
Port Jefferson, LI, NY, Nov. 16-18, 1998,
Peter Wanderer, Chair

Accelerator Technologies
Co-convenors: Chris Leemann, Waldo Mackay, John Marriner
"VLHC Workshop on Accelerator Technology,"
Thomas Jefferson National Accelerator Facility,
Newport News, VA, Feb. 8-11, 1999
John Marriner, Chair

Accelerator Physics
Co-convenors: Alan Jackson, Shekhar Mishra, Mike Syphers
"VLHC Workshop on Accelerator Physics,"
The Abbey, Fontana, WI, Feb. 22-25, 1999
Mike Syphers, Chair

Charge to working groups

Guided by the Snowmass '96 parameter sets explore and develop innovative concepts that will result in significant cost reductions.

Review progress in magnet R&D. Develop bases including costs for comparing different designs.

Monitor, encourage and coordinate progress in materials development.

Explore the viability of the various parameters sets implied by the major magnet options.

Foster dialog and partnerships with industry.

An **Annual Meeting** has been scheduled for Monday-Wednesday, June 28-30, 1999 in Monterey (California). The agenda is still being developed but will include in-depth reports from the three Workshops that have been held.

- *What is vlhc; evolving parameters; collaboration structure*
- *Overview - high field option*
- *Overview - low field option*

Accelerator Physics
Single particle dynamics issues
Multi-particle dynamics issues
Energy deposition issues
Magnet Technologies
Field quality and related accelerator requirements
Magnet construction techniques and tooling design
Superconductor status and prospects
Cost drivers for magnets
Accelerator Technologies
Cryogenics
RF and feedback
Instrumentation, control, alignment

- *Physics at 100 - 200 TeV*
- *Detector issues at 100 TeV*
- *Summary and future perspectives*

The proceedings from the Annual Meeting will become the basis for the first vlhc annual report.

Several compilations of reports and transparencies trace the development of the vlhc over the past 3 years. [2-6]. Much of this material is on the Fermilab web page (http://www-ap.fnal.gov/VLHC).

The scientific programs and proceedings of the first three workshops can be found on the vlhc web page (http://vlhc.org).

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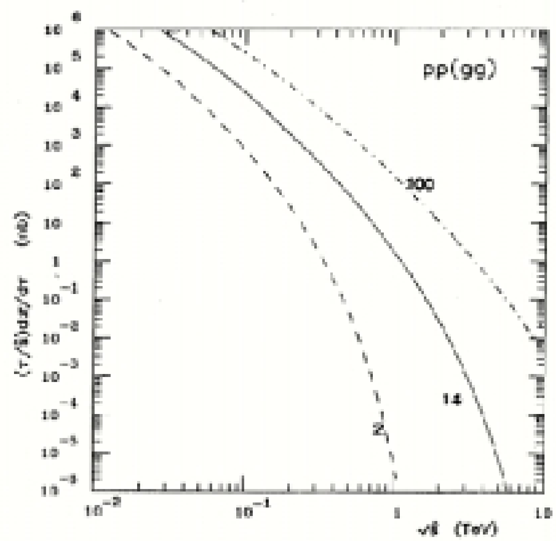
3. Why build the vlhc?

There is a rich physics menu for a 100 TeV cm vlhc running at a luminosity of 10^{34}. If **SUSY** exists, the VLHC might be the best place to study it in detail; but sectors of the theory may well lie at the multi-TeV scale. The so-called **messenger particles** make a new spectroscopy, perhaps at 10 TeV, and provide a window into the world of SUSY breaking.

Strong WW scattering can be studied; if the Higgs bosons do not exist the WW interaction is expected to become strong in the 1-2 TeV region, reminiscent of $\pi\pi$ scattering around 1 GeV.

Multiple W production could also result from the fascinating phenomenon of QCD Instantons, resulting from tunneling between different vacuum states. If such a tunneling occurs the result would be, from a single quark-quark collision, production of all the quark flavors.

One example of the reach of the vlhc is in the **differential parton-parton luminosity**. As a gluon-gluon collider the vlhc at 10^{34} gives 10^5 more gg interactions at 6 TeV than LHC.



The case for a very rich physics menu was made for the SSC at 40 TeV E_{cm} and 10^{33} [7]. A 100 TeV vlhc is a factor of $(2.5)^2 = 6.25$ in s. Thus 10^{34} is the appropriate figure to set as a working parameter. In my opinion the LHC luminosity was chosen to compete with the SSC and is not based on 1/s scaling.
The discovery "reach" of a 100 TeV vlhc based on **L** = 10^{34}, 1- year at 30% efficiency, 100 fb^{-1} can be made by extrapolating from Eichten, Hinchliffe, Lane, Quigg [7].

At 10^{34} a 100 TeV vlhc can "see" contact interactions at a scale of >32 TeV [7], perhaps as high as the E_{cm} or 100 TeV (2×10^{-19} cm) [8]. At LHC Λ^* will be ~10 TeV.

The reach in TeV for heavy quarks or scalar lepto-quarks is 7 TeV [7] compared to 250 GeV for Tevatron-Run II and 1.5 TeV expected at LHC.

The reach for new heavy bosons, W' and Z' can go up to 14 - 25 TeV[7, 9] far greater than the current CDF/DØ limits of 0.7 TeV.

For SUSY particles that are best studied in strong interactions such as gluinos or squarks the reach is 3-4 TeV.[7]
One can list many other physics justifications for a 100 TeV collider operating at this luminosity.

Today the luminosity of 10^{34} is detector limited. If history is a guide, then one or two decades after the machine has operated at 10^{34}, major detector and accelerator upgrades will take place raising the luminosity to 10^{35} or even 10^{36}. The main accelerator upgrade that will be required will be to the abort system because of the large stored energy in the beam; however, by then it is likely that brighter beams will be achieved by new cooling methods, making this problem easier to cope with.

4. Magnets: "The Heart of the Matter"

The Snowmass parameter sets were proposed 3 years ago and there has been evolution from them. In particular, high-field magnets using NbTi conductor and operating at 1.8K (extrapolation of LHC) are not being pursued. Nor are medium field SSC type magnets being considered as an option for the vlhc.

There are several factors in choosing the magnet strength:

- collider energy
- accelerator physics issues
- superconducting material availability and cost
- magnet and R&D costs
- amount of synchrotron radiation

Choosing the collider energy allows one to examine the role of synchrotron radiation in more detail. For a 50 TeV + 50 TeV collider

Low-field (2.0 T superferric):

- Damping time too long to be helpful
- However, an alternating gradient structure is allowed with no problems from anti-damping

High-field:

- synchrotron radiation puts power into the cryogenics (bad).
- synchrotron radiation makes the beam emittance smaller (good).

There are additional factors that need evaluation to properly understand the role of synchrotron radiation:

- ground motion
- quadrupole alignment: alternating gradient and separated function
- dipole field noise
- intra-beam scattering
- quantum fluctuations in the synchrotron radiation

- emittance preservation during fill and ramp times before synchrotron radiation comes into play

Superconductors:

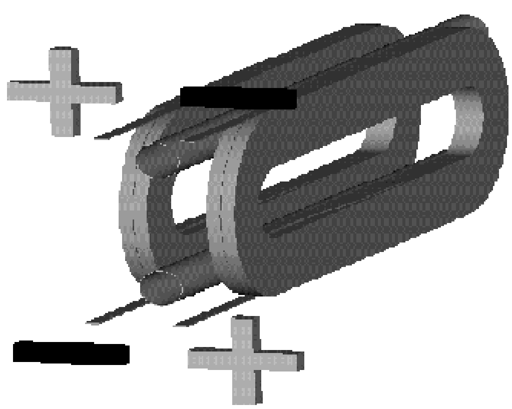
- Low-field magnets will probably be made from NbTi. Its properties are ideal for the low-field vlhc. J_c at low field has increased by 10x since Tevatron built (driven by MRI market) and its cost is probably < $1 /kA-meter.

- High and very high field will use other materials: HTS: BSSCO, YBCO, or LTS: (A15 Conductors) Nb_3Sn, Nb_3Al

Magnet R&D programs: "Different Paths to a Common Goal"

There are four programs underway in the three national laboratories. In addition McIntyre at Texas A&M is using concepts of stress management to strive for even higher magnetic fields. [10]

Fermilab Low-field NbTi superferric B ~ 2 T (Nb_3Al interesting alternative material)	Brookhaven Very high field B ~ 12.5 T Goal: based on future development of YBCO "conductor friendly" common coil
Fermilab High-Field Nb_3Sn cosθ B ~ 11 T	Lawrence Berkeley Lab Very high field B > 13 T various materials being tried: Nb_3Sn, Nb_3Al, BSCCO "conductor friendly" common coil

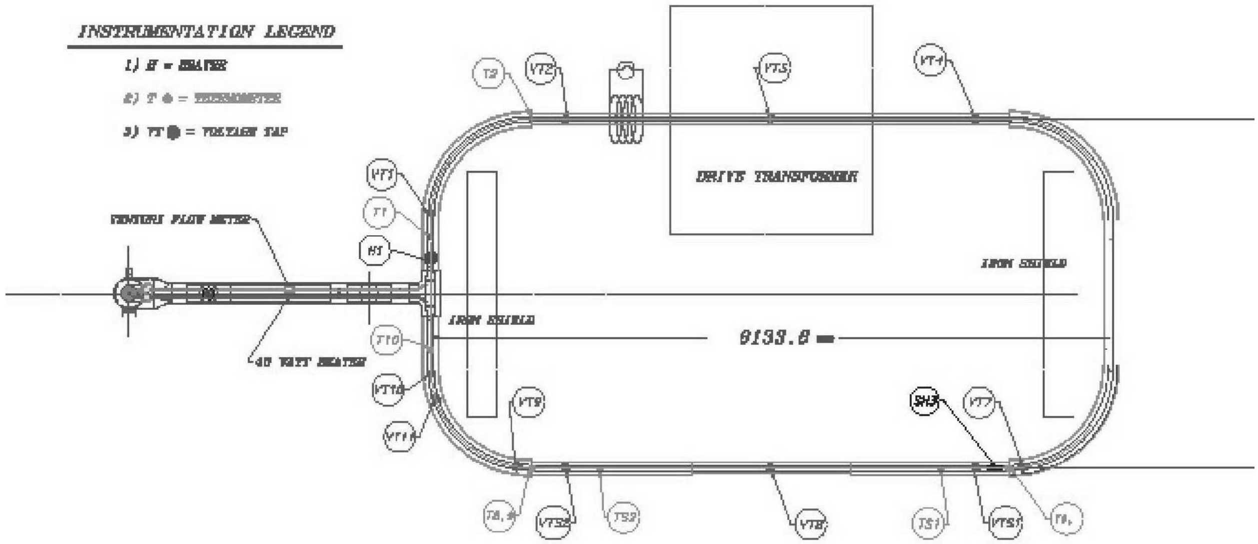


All the high field approaches use brittle materials. Thus the Gupta invention of the common coil approach [11] was an important step for the eventual use in accelerator magnets of HTS or A15 materials. The common coil magnet pictured conceptually in a figure from Gourlay [12] shows how the difficult 3-D bends of saddle coils are avoided. The bending radii are of the order of the bore spacing rather than the bore dimensions which also eases demands on the coil winding process.

Common coil designs for high-field magnets are being pursued at both BNL and LBNL.

The decision at Fermilab for a high field magnet program was to make the field high enough to take advantage of synchrotron radiation damping but no higher than that to minimize cryogenic load. [13] Fermilab in collaboration with KEK and LBNL is designing and building cosθ magnets using Nb_3Sn to operate at 11.8 T at 17.6 kA.

The Fermilab low field (2.0 T, transmission-line magnets) program [14] is making rapid progress. Nearing completion is a test loop in the MW-9 building built using surplus SSC conductor. The loop has a removable 4-m section in which various designs of the transmission line can be tested. Most of these will be made from NbTi conductor, but we have ordered lengths of Nb_3Al transmission line from Sumitomo Electric. [15] This material can operate at higher temperature. Since the magnet is one turn only and built in long straight lengths the insulation problem of A15 high field magnets does not have to be confronted.



The main issues in magnet development can be summarized.

- Materials (Nb_3Sn, Nb_3Al, HTS) development (and cost reduction) is essential for the high field approach. These materials might also apply to the low-field vlhc although probably it will use NbTi.

- How small can the aperture be? Dynamic aperture ~ equals the physical aperture for low field. Dynamic aperture < physical aperture for the high field; in general it appears that the space outside the usable dynamic aperture and the inside of the coils is about right for the necessary beam screen.

- Dynamic range -- how far can this be extended? There is a serious issue on persistent currents in magnets built with A15 or HTS materials

Interesting new approaches to the vlhc emerged at the November Magnet Technologies workshop:
- Gupta combines the advantages of good low field performance in an iron-dominated gap with a conductor-dominated gap to achieve high fields and synchrotron radiation damping at collision energy. [16] The result is a 4-gap magnet with large dynamic range.
- Dugan proposed a full energy injector. [17] This would, of course, require two tunnels. The 50 TeV injector would be built from simple, single aperture, superferric devices where injector performance is not crucial because of radiation damping in the collider. In the collider a smaller high-field magnet aperture is possible. A dynamic aperture of 6-mm (diameter) would suffice. This would mean lower currents and smaller forces. Perhaps most important, the high-field magnets are dc. This minimizes persistent current fields; there are no ac loss problems and the field can be optimized at a single operating point.

5. Excellence of the Fermilab site for the vlhc

Two important advantages to building the vlhc at Fermilab are the existence of the injector chain and the excellent geology.

Two possible 3 TeV layouts have been examined: a 15-km circumference site “filler” and a 34-km site “buster.” Depth is 150 m below the nearly flat Illinois surface and completely within a thick dolomite layer called the “Galena-Platteville.” The rock and tunneling conditions are predictable. There is extensive local experience from building the TARP tunnels (Tunnel And Reservoir Project). Over a hundred miles of tunnel in these dolomite layers now exist under Chicago in this relatively homogenous rock mass (called “competent” rock). We have been able to draw on this local experience in laying out a ring and obtaining accurate estimates on construction costs using current technology. [18] There are no settlement problems at the depths being considered. The rate of movement of groundwater in the dolomite layer we are considering for the collider is very small (called an "aquatard").

Two long (2-3 km) transfer lines from MI-62 and MI-40 bring the 150 GeV beams down to the 3 TeV Booster. These lines are straight over most of their length and can be constructed with a simple FODO lattice using permanent magnet quadrupoles. We have chosen the depth so that the 3 TeV and 50 TeV machines are in the same layer of dolomite. This is deliberate to avoid large vertical bends in the 3 TeV transfer lines. The direction from Fermilab for the 50 TeV ring is not yet determined and needs more geology information over a wide geographic region. The 150-meter depth is comparable to the deeper of the LEP/LHC shafts.

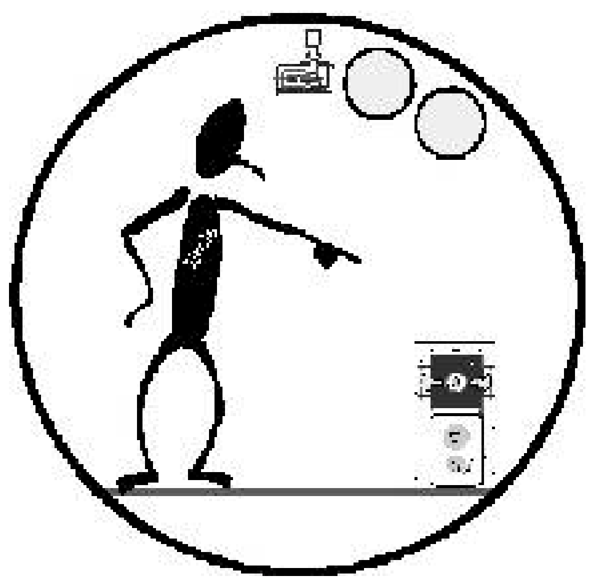
In nearby North Aurora there is a dolomite mine. Material from the Galena-Platteville layer is excavated and sold. Conco Western Stone, the mine owners, have been helpful in allowing us to take rock samples and ship them for testing to various companies to explore possible rapid excavation methods. We have been able to place seismometers in the mine to make noise measurements in the same layer where we propose to build the VLHC. [19]

Tunnels and choice of tunnel size

The Trenchless Technology (generally < 2m diameter) and the Tunneling industries are growing in importance as a practical solution to putting infrastructure underground with minimal surface disruption. These industries are in many ways driven by concern for the environment. Thus our efforts towards lowering the cost per meter of accelerator tunnel can have benefits to society beyond our needs.

The two main components in the tunnel construction are the mining and the muck removal. The standard approach is to use tunnel-boring machines (TBM) for mining and a conveyor belt for muck removal. We have used the specific siting and depth of the 34-km tunnel as a model to investigate tunnel costs. We are using a detailed cost model from the Kenny Construction Company to understand the cost drivers.[18] It is clear from that study that a major cost reduction would come from reducing the number of people underground, i.e. automating as much as possible.

The mining industry is moving in the direction of more automation. New ideas are being explored. Safety is a major issue. The fewer the number of people underground the safer the job. So we can adopt as a goal for a tunnel R&D program: no people underground except during maintenance shifts. Work is needed to see if such a goal is achievable. New concepts have emerged both in TBM's and in Muck Removal. [20] These need evaluation by experts. If the concepts look promising one can then move to the prototype phase.



The choice of tunnel size is the one with the lowest cost (which is not necessarily the smallest) and provides sufficient room for installation, maintenance, and for other machines. Operating the machine will certainly imply the use of robotics; just how much robotics is used is a matter of economics.

The sketch shows a superferric 2.0 T transmission line magnet, a low-field magnet for an 80 GeV electron machine [21] (for ep collisions at 1 TeV cm) and a small man. The water pipes are for cooling required by the larger amount of synchrotron radiation from the electron ring.

6. Accelerator Physics Considerations

A very large hadron collider is the one machine that we know can be built today. The main issue is cost. Several different R&D paths are being followed to reduce those costs. In one approach, the warm-iron superferric, low-field vlhc, questions have been raised about beam stability. The main issues are the multibunch (resistive wall) instability and the (strong) transverse mode coupling instability (TMCI). Both high and low magnetic field approaches need to worry about noise, seismic as well as other sources, e.g. magnetic field fluctuations.

Transverse Coupled Bunch Instability

J. Marriner has designed a system for dealing with this instability. [22] The growth time for this instability in the high field case is ~ 200 turns, similar to LHC, but in the low-field machine is ~ 0.4 turns. This led to previous statements that this "required a feed-back system beyond the state of the art." One way out is the undesirable step of increasing the magnet gap since $Z_{pipe} \sim b^{-3}$.

The important point that Marriner makes is that growth times vary as $f^{-1/2}$. Only low frequencies need to be considered (higher modes will be dealt with using a "conventional" bunch-by-bunch damper with a single turn delay). Growth time is ~ 1 msec for the lowest and fastest growing mode. The signal is derived from a "difference" stripline pickup, amplified and transmitted downstream to a point 90^o advanced in betatron phase. The signal is amplified further and applied to a kicker to provide feedback to stabilize the beam. The technique is not speculative and should not be controversial. A similar system was used to damp the resistive wall instability in the Main Ring. "Foam" coax (β>0.8) can be used since the fact that the signal is applied to succeeding bunches doesn't matter much at the low frequencies we need to damp. The bandwidth is 100 - 200 kHz. The damping rate is 1/3 per turn per system (50 dB) so 10 such systems distributed around the ring will provide a damping of >3/turn.

The coupled bunch instability due to the RF system will have a growth time of about ~10,000 turns. This will be damped using a "conventional" feedback system working on single bunches. One can envision a series of feedback systems for instabilities and emittance growth.

Transverse Mode Coupling Instability (TMCI)

A great deal of recent work has been done on the strong head-tail instability. This instability is caused by the defocusing effect of wake fields induced by the head of the bunch on bunch tail particles. However, TMCI, while having been observed in electron machines has never been observed in a proton ring. For proton machines, there may be factors such as incoherent tune spread due to direct space charge or beam-beam interactions that increase the TMCI threshold. Nonetheless, it is expected that TMCI will be important at injection into the SPS when it works with LHC parameters. At the vlhc the problem is most severe at injection (3 TeV) into the 50 TeV ring.

We define SF = Safety Factor = $Z_{threshold}/Z_{pipe}$ and SF is a function of luminosity. SF is between 1 and 2 in a 10^{34} low-field collider with bunch spacing roughly 20 nsec. An expensive way to raise this "luminosity ceiling" is to increase the vertical aperture since SF goes as the aperture^3. However, there are many other solutions that will raise the luminosity ceiling to $>10^{35}$ or even $>10^{36}$, although at this time we feel that detectors limit the operation to 10^{34}. Following is a list of ways to raise SF:

1. Run with smaller bunch spacing. [23] This has the additional advantages of reducing the numbers of collisions per crossing and reducing the head-on beam-beam tune spread. But it has the disadvantage of increasing the stored energy in the beam and it is not clear that present day detectors can take advantage of the smaller spacing.
2. At injection have smaller bunch spacing, e.g. distribute the charge into all of the buckets, and then coalesce at collision (or part way up the ramp) to achieve the experimenters desired bunch spacing. [24]
3. Reduce the impedance of the vacuum pipe by a few micron thick layer of pure Aluminum, copper, or silver.
4. Use an RF quadrupole to change the tune of the bunch head relative to the bunch tail. [25]
5. Use a low frequency feedback system to damp mode "0" (coherent motion) and/or a very high frequency

feedback system for mode 1. E.g. if the bunch length is 10 cm, then putting the feedback with relatively narrow bandwidth on top of a carrier of 3 GHz will work on mode 1. [26]

6. Use alternating chromaticity around the ring. [27]
7. Make an asymmetric vacuum chamber. In an asymmetric geometry a "detuning wake" is generated which causes resonance excitation of the tail. [28] SF with an elliptical chamber will be larger than with a circular one.

More work will be done in the near future including experiments using existing machines.

Noise and emittance preservation

Integrated Luminosity vs. initial rms. emittance is a frequently shown graph. It implies that there is an apparent insensitivity to injector chain emittance in the high field case. However, we expect ε to be 1π rms (6π in FNAL units) and could be $<1\pi$ with electron cooling [29]. So it is unclear if this frequently shown graph is relevant in comparing the low and high field vlhc's.

However, what is relevant is emittance preservation in the chain, and in the collider during the fill and ramp up time before damping begins to help. Also longitudinal phase space needs to be chosen to reduce ε dilution from IBS.

The Fermilab region is seismically stable. A vibration free environment is important to minimize emittance growth problems. Recent measurements in TARP and the Aurora Mine [19] show that either high or low field machines are feasible at the chosen depth. Measurement cover three ranges: 2×10^{-3} to 1 Hz -- alignment; 1 - 100 Hz -- orbit stability; >100 Hz -- ε growth. Measurements are being extended this fiscal year to lower frequency, $>10^{-7}$ Hz, to understand if dynamic alignment will be necessary.

7. Conclusions

Hadron Colliders are the "Discovery Machines" for HEP. They reach farther and probe deeper than any other type of accelerator. The W and Z were first observed at the SppS. The top quark was discovered at the Tevatron. It may be possible to discover Light Higgs and SUSY particles at the Tevatron in Run II. LHC will extend the mass reach with 7x in E_{cm}.

So What Next?

Design and build a vlhc, which has at least another 7x in E_{cm}. The vlhc is <u>already</u> technically feasible. <u>THE</u> KEY ISSUE is to lower the cost measured in $/TeV.

What we agree on

- a common goal to probe the microworld to ~1 μfermi
- some working parameters: MI injecting into a 3 TeV machine, then into a 50 TeV/beam machine; L $\geq 10^{34}$

Why work on vlhc now?

Typically 10-15 years elapse from first R&D magnet to last machine magnet. It is not too soon to be working on a post-LHC collider although clearly construction would not begin until the first physics results come from LHC. We will need years of R&D to narrow the options, to find new, innovative ways to lower the cost. That work has begun and needs to be continued.

We are looking at cost reduction strategies that would allow the machine to be built with technology that is already understood **and at the same time** at strategies that require new technology and probably have longer time scales, and unknown cost implications.

New technologies and new approaches are required to continue the dramatic rise in collider energies as represented by the Livingston Plot

What are some of these new technologies?

- HTS
- Achievement of high luminosities in hadron colliders
- industrial robotics and remote manipulation
- Digitally multiplexed electronics to minimize cables
- Advanced tunneling technologies for burying infrastructure driven by environmental needs as the planet's population increases

Public Support

Real benefits to society from the R&D leading to this project it will help gain the necessary public support. We need to learn how to communicate to our constituencies why we want to build a more powerful microscope.

Progress

There has been significant progress in the past 3 years. Innovative approaches are being suggested. R&D is underway. Proposals for future R&D are being generated.

Acknowledgements

This note is an expanded version of the talks given on February 22 and 24 at Lake Geneva. It is an overview of the work of growing number of talented and dedicated people. I thank them for their creative conceptual work on the vlhc.

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