Fermi National Accelerator Laboratory

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The Very Large Hadron Collider

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I. WHY BUILD THE VLHC?

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}.

What might be "beyond the LHC"? Design and build a vlhc, which has at least another 7x in E_{cm}. The vlhc is already technically feasible. The key issue is lowering the cost measured in $/TeV.

Here is a partial menu of potential discoveries: See Albrow [1] and references therein for more details.

New strong dynamics. If strong dynamics is involved in EW symmetry breaking, the physics associated with it will first appear at the 1 TeV scale. The VLHC will have the opportunity to explore it in more depth than the LHC. New strong dynamics as well as any phenomena associated with flavor physics would also give a rich structure in the 1-10 TeV range.

Differential parton-parton luminosities will be much greater. E.g. a vlhc at 10^{34} gives 10^5 more gg interactions at 6 TeV than the LHC.

SUSY. If LHC finds SUSY, and if it is gauge-mediated, one could then expect new gauge bosons in the 10-100 TeV range.

Scattering of two longitudinal W's could give a rich structure in analogy with $\pi-\pi$ scattering.

Exotics. Of course, beyond the Standard Model we have no idea what we will see! Here are some examples of the "reach" of the vlhc:

Scalar lepto-quarks. Tevatron-Run II will reach 250 GeV, LHC 1.5 TeV, and vlhc ~ 7 TeV

W', Z'. CDF and Dzero current limits are ~700 GeV; the vlhc can reach ~25 TeV.

Compositness scale: LHC could see effects @ Λ_c ~ 10-15 TeV; the vlhc can probe to 100 TeV -- 10^{-19} cm or one μfermi!

II. STEERING COMMITTEE FOR A FUTURE VERY LARGE HADRON COLLIDER

Background. This effort was an outgrowth of recommendations of the Gilman Panel. [14]

> *….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.*

At the initiative of John Peoples, representatives from BNL, FNAL, and LBNL met informally at Fermilab on February 25 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, LBL and Cornell University's Laboratory of Nuclear Studies to appoint representatives to a Steering Committee to organize this effort. Appointed were:

BNL: Michael Harrison and Stephen Peggs
FNAL: Peter Limon and Ernest Malamud
LBL: William A. Barletta and James L. Siegrist
Cornell: Gerry Dugan

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. Using a nominal 20x in dynamic range, injection would be from the 150 GeV Main Injector into a 3 TeV Booster, which could be either a site "filler" or a site "buster." The 3 TeV machine would inject into the 50 TeV vlhc.

Charge (excerpts): 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, and provide a mechanism for all interested parties to participate in the evaluation of the alternative technological approaches that are presently being pursued.

The focus of these efforts is on technology and cost reduction.

The Steering Committee will organize the selection of a good name and logo for the vlhc. It is for this reason that we are using lower case letters for vlhc; it is a placeholder for a better name!

Working Groups. Working Groups are being formed. They are open to all and participation is welcomed from all foreign and U.S. institutions.

These are: Magnet Technologies, Accelerator Technologies**,** and Accelerator Physics.

Charge to the working groups: Guided by the Snowmass '96 parameter sets [8] 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.

On July 25, the leaders of the three working groups met at BNL with the Steering Committee to discuss near-term plans.

Magnet Technologies Working Group

Co-convenors are Bill Foster (FNAL), Peter Wanderer (BNL) and Ron Scanlan (LBNL).

They are organizing a Workshop on Long Island November 16-18, 1998. The following topics will be discussed: cost drivers for superconductor and superconducting magnets; manufacturing tolerances and field quality; cost models for cryogenic systems at various temperatures; beam screens and synchrotron radiation.

Accelerator Technologies Working Group

Co-convenors are Chris Leemann (Thomas Jefferson Lab), Waldo Mackay (BNL) and John Marriner (FNAL).

They are organizing a Workshop near Thomas Jefferson Lab Feb. 8-12, 1999. The following topics will be discussed: rf & feeedback; diagnostics & controls; cryogenics; some aspects of the vacuum system.

Accelerator Physics Working Group

Co-convenors are Alan Jackson (LBNL), Shekhar Mishra (FNAL) and Mike Syphers (BNL).

They are organizing a workshop to be held near Fermilab Feb 22 - 25, 1999. The following topics will be discussed: high field magnet collider (lattice, synchrotron radiation, magnetic field quality at injection, lifetime at injection); low field magnet collider (lattice, aperture, magnet field quality and correction systems); instabilities; ground motion and feedback systems; longitudinal dynamics.

Annual Meeting will be held in California near the end of June 1999 and is being organized by LBNL. At this meeting in-depth reports from each working group will be presented and become the basis for our first annual report.

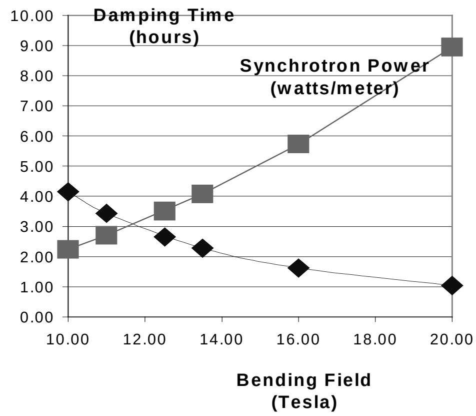
III. MAGNETS: "THE HEART OF THE MATTER"

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. Once the collider energy is chosen one can examine the role of synchrotron radiation in more detail.

For a 50 TeV + 50 TeV collider in the low-field machine damping time is too long to be helpful. However, this allows an AG structure with no problems from anti-damping.

For a high-field vlhc synchrotron radiation puts power into the cryogenics (bad) but makes the beam emittance smaller (good).

The figure shows damping time and synchrotron power in watts/meter for high-field magnets from 10 to 20 T for a somewhat artificial choice of parameters: luminosity $=10^{34}$; $\beta^* = 20$ cm; $\varepsilon=1.5\ \pi$ mm-mrad and bunch spacing = 6 m.



There are other factors that need evaluation to properly understand the role of synchrotron radiation: ground motion; quadrupole alignment (AG vs. SF); dipole field noise; intra-beam scattering; quantum fluctuations in the synchrotron radiation.

IV. MAGNET R&D PROGRAMS: "DIFFERENT PATHS TO A COMMON GOAL"

This subject is covered in detail by P. Limon [2]

Superconductors Low-field magnets will probably use NbTi. J_c of this material at low field has increased 10x since the Tevatron built due primarily to the large MRI market. Its cost is probably < $1 /kA-meter. Nb_3Al is an attractive alternative that will also be investigated. It caries higher current at low field than NbTi and can operate at higher temperatures.

High and very high field magnets will use either high-temperature materials (BSSCO, YBCO) or low-temperature A15 conductors (Nb_3Sn, Nb_3Al).

Magnet R&D programs. Fermilab has active programs on low (2 T) and high (11 T) magnets; BNL and LBNL are working on very high (> 12 T) vlhc dipoles.

V. ACCELERATOR PHYSICS CONSIDERATIONS

Transverse Mode Coupling Instability (TMCI). The strong head-tail instability appears from the defocusing effect of wake fields induced by the head of the bunch on bunch tail particles. Synchrotron motion, i.e. exchange of particles between head and tail helps to avoid the instability.

TMCI has been observed in electron storage rings but not (yet) in proton storage rings. 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.

The problem is most severe at injection (3 TeV) into the 50 TeV ring and is most severe in the room temperature vacuum chamber, large circumference superferric vlhc.

An (expensive) strategy is to increase the vertical gap since the pipe impedance varies inversely as gap^3.

We define SF = Safety Factor = $Z_{threshold}/Z_{pipe.}$ One can plot SF as a function of luminosity for various assumptions. For the low-field ring we assume a vertical half height = 9 mm with high purity aluminum on the inside of the vacuum chamber. SF remains >2 up to 4 x 10^{34}. Although operation at $>10^{34}$ is not envisioned for many years after first operation, the ring should not be limited to this luminosity. A solution is to inject with 1.7 m bunch spacing and then coalesce at (or before) E_{coll} to achieve bunch spacing desired by the experimenters. This maintains SF > 2 for L $>10^{35}$.

V. V. Danilov, V. D. Shiltsev, and A. Burov have proposed more creative solutions to the TMCI problem. [3] [4].

RF quadrupoles increase the tune of the head ($\Delta\nu$) and decrease the tune of the tail. Some possible parameters [6] are given below (ν_s is the synchrotron tune.)

$\Delta\nu/\nu_s$	1	2
500 MHz RF normal	L = 50 m Power = 6 MW Grad = 8 MV/m^2	L = 100 m Power = 12 MW Grad = 8 MV/m^2
500 MHz RF superconducting	L = 20 m	L = 40 m
TMCI Threshold Increase	2.7 x	6.2 x

Asymmetric vacuum chamber can increase the TMCI threshold by 2 - 4 x but will reduce the horizontal aperture to be approximately equal to the vertical aperture. The shape is not yet optimized.

Clearly more work is needed including experiments using the Tevatron.

Transverse Coupled Bunch Instability has a growth time (high field) ~ 300 turns (similar to LHC) whereas growth time (low field) ~ 0.4 turns! This led to previous statements that this "required a feed-back system beyond the state of the art." One solution is the undesirable step of increasing the magnet gap since $Z_{pipe} \sim b^{-3}$.

J. Marriner (see his papers in the “Turquoise Book” [10] and the “Brown Book” [11]) makes the important point that since growth times vary as $f^{-1/2}$ only <u>low</u> 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 lowest and fastest growing mode. The fastest growing modes are all below 100 kHz.

His proposed damping consists of a series of feedback systems, each one with pickup and kicker separated by about 1 km. Signal propagation need not be extremely high since it is not necessary to act on single bunches. Ten such systems around the 500 km low-field vlhc would reduce growth time to 3 turns where a “conventional” feedback system would take over. 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.

Coupled bunch instability due to the RF system will have a growth time of about ~10,000 turns. [6] 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.

VI. EXCELLENCE OF THE FERMILAB SITE

It is important to build the vlhc is where an injector chain and its associated laboratory infrastructure already exists. In the U.S. this is at Fermilab.

There is excellent geology in the region around Fermilab. The surface of the land is flat; below it are nearly parallel strata. One stratum in particular, called the Galena-Platteville, lies about 150 m below the surface, and is a thick (> 50 m) and uniform layer of dolomite. It is ideal rock for tunnel boring machines and is an aquatard minimizing ground water problems. Furthermore there is extensive experience in the area in making long tunnels in this stratum. TARP - the deep Tunnel and Reservoir Project (under the City of Chicago) already has nearly 150 km of tunnel in the same rock where we propose to site the vlhc.

The Fermilab region is seismically stable. A vibration free environment is important to minimize emittance growth problems. A Novosibirsk - SLAC - FNAL collaboration (led by V. Shiltsev) has made extensive measurements in the TARP tunnels and in a nearby dolomite mine in North Aurora. [12].

In the 1 - 10 Hz range comparison of on-surface and underground sites have shown that levels of vibrations are typically smaller in deep tunnels.

In the 50-200 Hz range they find vibrations are below the tolerance for orbit stability and emittance growth for both hi- and low- field vlhc's.

Beginning in October, 1998 the measurements will be extended to 10^{-7} Hz (one year) to understand if dynamic alignment will be necessary.

VII. CONCLUSIONS

What we agree on:

- a common goal of probing the nature to a μfermi
- a set of main working parameters: 50 TeV/beam; 3 TeV injector fed from the Fermilab Main Injector
- that the vlhc is already technically feasible; the key issue is to lower the cost/TeV

A 2.0 T (low-field) VLHC

Significant work has been done at Fermilab on a 2.0 T magnet that could be used in the 3 TeV booster and, perhaps also in the 50 TeV collider.

There is progress on exploring in partnership with the private sector ways to reduce the cost of making long tunnels, an important cost driver for the low-field vlhc.

An international effort

The vlhc is already an international effort. There are many opportunities for increasing the world community of scientists and engineers participating in the vlhc effort.

A great deal of work on vlhc magnets and accelerator physics is being done by Russians, both in the U.S. and here.

Novosibirsk, SLAC, Argonne, and Fermilab are collaborating on seismic measurements.

KEK, Fermilab, BNL, LBNL are collaborating on vlhc magnets.

There is an accord in place for future collaboration on magnets with JINR, builders of the world's first superferric synchrotron. Based on that experience they have made a conceptual vlhc design. [13]

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.

There is uncertainty in the future: which big machine to build next; where to build it; when to build it. We need to continue to pursue the VLHC option so that we can make the most informed long-term strategy.

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

New technologies and new approaches

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?

- high temperature superconductors
- 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

If there are real benefits to society from the R&D leading to this project it will help gain the necessary public support.

ACKNOWLEDGEMENTS

I am grateful for the opportunity to present this talk and to renew friendships with many J.I.N.R. colleagues and their families some whom I have known and worked with for more than 25 years.

REFERENCES

The vlhc project is moving rapidly. Recent information can be found in the compilations references [7] - [10]

However, the best source is our web page. **http://www-ap.fnal.gov/VLHC/** which also has links other vlhc related web pages. Many of the references below are on this web page or have links to them from our web page.

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