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VERY LARGE HADRON COLLIDER R&D[*]

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Abstract

This article discusses the present state of R&D for a post-LHC very large hadron collider (VLHC). Such a machine can be built with today's technology; the thrust of the R&D is to reduce the cost of the machine, through development of new ideas and utilization of new technologies. R&D issues in the areas of accelerator physics, magnets, and general accelerator technologies, will be reviewed. Finally, the outlook for future R&D will be presented.

1 INTRODUCTION

1.1 Description of the VLHC

During Snowmass'96, the concept of a post-LHC hadron collider, with a center-of mass energy of 100 TeV, and a peak luminosity of 10^{34} $cm^{-1}s^{-1}$, was explored [1]. Two distinct approaches to the problem were studied.

In one approach, which was first investigated in detail at a workshop [2] at Indiana in 1994, and discussed at the 1995 PAC [3], the machine uses high field (>12 T) superconducting magnets, and produces considerable synchrotron radiation. At these fields, and for beam energies of greater than 30 TeV, the radiation damping time can be considerably less than the luminosity lifetime; this is very beneficial for the beam dynamics. The major disadvantage of this approach is the need to absorb this radiation at cryogenic temperatures, which complicates the design of the cryogenic and vacuum systems.

The crucial R&D issue for the high-field VLHC is the development of a high-field magnet. This magnet requires a practical, low-cost conductor, able to operate at fields in the 12 T range, and a robust design that can be built with this conductor to the specifications of the collider.

The other approach, developed at Fermilab [4] in 1996, proposes the use of a low-field (2 T) superconducting magnet. The magnet is a "double-C" iron-dominated device with a warm vacuum chamber, driven by a superconducting transmission line; its simplicity offers the possibility of a very low magnet system cost per unit energy. The principal disadvantage of this scheme is the very large circumference required for a 50 TeV per beam collider with low field magnets.

The low-field VLHC has a number of challenging R&D issues in the accelerator physics area, such as emittance preservation and emittance growth limitation, beam stability, and abort and beam loss handling. The need for the development of low cost tunneling technologies, to allow an affordable large-scale ring, is also crucial.

1.2 Developments since Snowmass '96

Since Snowmass '96, considerable additional R&D has been carried out at several national laboratories, primarily Fermilab. In the summer of 1998, a steering committee was created to coordinate R&D efforts for the VLHC. The Directors of Fermilab, Brookhaven, Lawrence Berkeley Laboratory and Cornell's Laboratory of Nuclear Studies formed the committee, and its membership contains representatives from those institutions.

Under the sponsorship of the committee, three workshops have been held, on the topics of magnets, accelerator technologies, and accelerator physics. Some of the results from these workshops are presented in the sections below. The committee anticipates continued sponsorship of these workshops on an annual basis in future years. An annual meeting will also be held to summarize progress and plan for the future.

2 CURRENT R&D ISSUES

2.1 Accelerator Physics

2.1.1 Lattice design and single particle dynamics

To maximize the simplicity of the magnet system, the low-field VLHC design has adopted a combined function magnet. The high-field VLHC is generally thought of as a separated function machine. Nevertheless, a topic for further study is the possibility of achieving the correct damping partition numbers without requiring separated function magnets, such as in a non-isomagnetic configuration [5].

The major issues in the design of the lattice itself are the phase advance per cell and the cell length [6]. The cell length is a key parameter. Longer cell lengths increase reliability and may reduce costs, as the number of components decreases. However, longer cell lengths lead to larger lattice functions, which in turn imply larger beam sizes and hence increased field quality requirements on the magnets.

Detailed considerations on single-particle dynamic aperture, and its relation to magnet aperture and field errors, have yet to be undertaken. There may be an important role for nonlinear beam dynamics experiments at existing colliders, such as the Tevatron and RHIC. For the low-field magnet, beam stability considerations (see section 2.1.4) may play the most important role in determining the magnet aperture. New types of high-field magnet designs using new conductors (see section 2.2) may also have very different field errors than conventional cos-θ NbTi magnets.

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2.1.2 Interaction region design

Many of the problems in the interaction region design are common to both the high-field and low-field VLHC. However, the design of the final focus quadrupoles may be different for the two versions of the VLHC. The radiation damping present in the high-field VLHC can result in a beam which is “flat” (small dimension vertical)[7], whereas the low-field VLHC will have a conventional “round” beam. The final focus design for flat beams is less demanding than for the round beams: a quadrupole doublet, rather than a triplet, is usually adequate. For the same minimum beta, the peak value of the beta function is also usually smaller in flat beam optics, than with round beams.

2.1.3 Emittance control

Transverse emittance is a key parameter for any high luminosity, high-energy hadron collider. At fixed intensity, luminosity is inversely proportional to emittance. Any mechanism that causes an increase in the emittance will reduce the luminosity. Consequently, there is a great premium on maintaining the design emittance.

2.1.3.1 The injector

The Snowmass ’96 designs focused on an injection energy of 3 TeV. The most challenging requirement on the injector is the beam emittance.

Preserving the emittance of the beam has historically been a crucial issue in the luminosity performance of high-energy colliders. This issue will be as important for the low-field VLHC as it is in today’s hadron colliders. For the high-field VLHC, the existence of significant radiation damping shortens the beam’s memory and relieves much of the pressure for emittance preservation.

Considerable work has been done at Fermilab on the design of a 3 TeV injector[8], which would use the low-field magnet technology. This machine would be a demonstration project for that technology, as well as serving as the VLHC injector.

Higher injection energies than 3 TeV are also being examined. One possibility is to build the collider as a fixed-energy (high-field) machine [9]. This could allow much simpler, small aperture, high field magnets, which might dramatically reduce their cost. A full energy injector (low field) would be required.

Another variant is to use an 8-10 TeV injector in the same tunnel as the collider. A particularly elegant implementation of this idea is to combine the low-field and high-field magnets into a single four-aperture device [10]. The low field magnet is iron-dominated, with a 20 mm aperture; the high field insert has a 40 mm aperture. The combination could have a dynamic range of 150.

2.1.3.2. Radiation damping and beam cooling

The energy and field parameters of the high field VLHC are specifically chosen to insure that the radiation damping time is a fraction of the luminosity lifetime. There are a number of benefits to this choice.

Since the injected beam will damp to the equilibrium emittance, the luminosity does not depend sensitively on the injected emittance. The quality of the magnetic field at injection may be reduced, since some level of emittance growth can be tolerated. In collision, radiation damping will immunize the beam against some forms of long-term emittance growth.

Although significant, these benefits must be carefully weighed against the clear disadvantages that appear in magnet, cryogenic, and vacuum systems, due to the substantial synchrotron radiation load.

Partition number manipulation with Robinson wigglers, a standard technique in electron machines, should be investigated for the VLHC. It may allow significant enhancement of damping times.

Bunched beam stochastic cooling schemes have been attempted for hadron colliders, with limited success [11]. Also under study is optical stochastic cooling [12], which has great potential because of the enormous available bandwidth.

2.1.3.3 Emittance growth

Emittance growth that occurs in the collider results in a direct reduction in the luminosity lifetime, which can lead to poor integrated luminosity performance.

There are many possible mechanisms for emittance growth. All have the general feature that they drive the beam at one of its resonant frequencies. Phase space filamentation then results in effective emittance growth. Possible sources of the driving terms are power supply ripple (coupled to the beam through the dipoles) and ground vibrations (coupled to the beam through the quadrupoles).

Because of its large circumference, the beam in the VLHC will have a lower resonant frequency than beams in today’s hadron colliders. This is particularly true for the low-field VLHC. Usually, sources of vibration and ripple have power spectra that increase as the frequency decreases [13]. As a result, emittance growth from these sources will be more of an issue than in current machines.

2.1.4 Multiparticle dynamics

Because of the relatively low beam intensities, collective effects are not expected to play a limiting role in the high-field VLHC. The usual care will be required to keep the impedance of the machine low, but no special problems are anticipated. Radiation damping in the longitudinal plane will result in a rather high longitudinal density, considerably higher than required for design luminosity performance. This high density will, in fact, be a problem, resulting in severe intrabeam scattering. Consequently, it will be necessary to artificially maintain a reduced longitudinal density.

The situation is quite different for the low-field VLHC. With its larger circumference, the machine requires a much larger number of bunches than the high-field machine. In addition, the warm vacuum chamber in the combined function magnets constitutes a very large resistive wall impedance. At low frequencies, this impedance drives a strong coupled-bunch instability, with a rise time of a fraction of a turn. At the high frequencies characteristic of the bunch, despite the decrease of the resistive wall impedance as $\omega^{-1/2}$, the impedance is still large enough that the threshold for the transverse mode coupling instability can be approached with intensities a few times larger than nominal.

Although making the diameter of the vacuum chamber larger can reduce the resistive wall impedance, this increases the cost and complexity of the magnets. Consequently, other remedies for the stability problem are under investigation. A distributed damping system has been proposed to solve the coupled bunch problem [14]. The long-wavelength collective motion is sampled at several points around the ring, and feedback is applied to damp the motion.

The transverse mode coupling instability is a more difficult problem. Schemes to raise the instability threshold using radio-frequency quadrupoles (similar to BNS damping), and asymmetric vacuum chambers, are under consideration [15].

2.2 Magnet System

This is the most important accelerator system for the VLHC. For the high field variant, the principal issues are obtaining a low-cost superconductor that can carry a high current density, at as high a temperature as possible, while satisfying the demanding mechanical and magnetic requirements; and designing a magnet which can sustain the large electromagnetic forces.

2.2.1 Field quality

The question of the required harmonic purity of the VLHC magnets is a crucial ingredient for any magnet design. Contrary to expectations prior to the SSC, both the prototype SSC magnets, and the full production magnets made for RHIC, show that, with current manufacturing processes, systematic errors dominate over random errors. Mature design techniques, improved tooling, excellent cable and coil size control, better measurement techniques, and a flexible, experimental approach mean that even early prototypes can now be made with the desired (geometric) field errors. This applies to both high field and low field magnets. Systematic persistent current errors, and saturation effects, will thus be the principal sources of error fields.

In this event, relatively simple analytic estimates [16] of the tune shifts caused by systematic errors can provide some guidance for magnet designers. A key issue is the magnitude of the tune shift that the beam can tolerate [17].

2.2.2 Conductor

The conductors that are being studied for use in high-field VLHC magnets are of two general classes. The first class is A15-compound low temperature superconductors: Nb_3Sn and Nb_3Al. These conductors would be operated at 4.5°K. The second class includes copper-oxide high temperature superconductors (HTS), such as BSCCO-2212, BSCCO-2223, and YBCO-123 [18]; these conductors could be operated from 4.5°K to 20-30°K, with some reduction in critical current at the higher temperatures.

Although Nb_3Sn has a high critical field, this material has several disadvantages. Small filament diameters and high current density are difficult to achieve simultaneously in Nb_3Sn, since high-density filaments tend to grow together after reaction. Nb_3Sn is also much less strain tolerant than NbTi.

Target specifications for conductor which would be useful in high-field VLHC magnets correspond to a critical current density of about 2000-3000 A/mm^2 at 12 T, 4.2°K, with a filament diameter <20 μm. Currently available material has a critical current density in the 950-1100 A/mm^2 range, with an effective filament diameter of 7-14 μm.

Rapid-quench Nb_3Al has less strain sensitivity than Nb_3Sn, with comparable current density performance. However, the rapid-quench method has yet to be developed into a viable industrial process. Nb_3Al is being considered as the conductor for the low-field transmission line magnet [19]; this conductor would allow a higher operating temperature than NbTi.

The high temperature superconductor BSSCO-2223 is the only form of HTS commercially available in large quantities at this time. This material is made in the form of oxide-powder-in-tube tapes. Small samples can have superconductor current densities (at 1 μV/cm) in excess of 700 A/mm^2 at 10 T, 4.2°K. Long (400 m) tapes have an engineering current density of about 100 A/mm^2. These materials, being basically ceramics, do not have a great deal of stress tolerance; in this regard, they are similar to the A15 compounds.

Another high temperature superconductor, BSCCO-2212, has been fabricated in the form of round multi-filamentary strands. Cables made from this material have operated above 600 A/mm^2 at 10 T, 4°K. As is typical of the high temperature superconductors, there is little degradation with fields up to at least 30 T.

The most promising (but least developed) of the copper-oxide superconductors is YBCO-123. Thin (1-5 μm) films of this material, up to 1 m in length, have been made in the form of a copper, superconductor and buffer layer sandwich. In this form, superconductor current densities of 10,000 A/mm^2 have been observed at 20 T, 4°K.

The processes by which the buffer layer and the superconductor are deposited onto the copper are complex, typically requiring the use of ion beams. Groups at ORNL, LANL, and BNL are working to simplify these processes. The most challenging task appears to be deposition of the buffer layer, which is needed to obtain the alignment of the YBCO crystals required for high current density.

2.2.3 Magnet design and prototyping

There are four major high-field magnet R&D programs underway. BNL, LBL, and Texas A&M (TAMU) are focusing on block designs; Fermilab is studying a conventional cos-θ design. The Fermilab, LBL, and TAMU programs are concentrating on Nb_3Sn conductor. BNL is looking at BSCCO and YBCO.

2.2.3.1 Fermilab program: High field magnets

Fermilab's goal is a magnet in the 11 T range. In collaboration with KEK and LBL, they are designing a 50-mm bore, Nb_3Sn two-shell cos-θ dipole [20]. This approach is motivated by recent progress in Nb_3Sn conductor performance, and utilizes the well-understood cos-θ technology developed for the SSC and LHC.

Facilities to react and study Nb_3Sn are being installed at Fermilab. Component tests will be done in a 15 T solenoid, at 4°K. The first prototype magnet is expected in the summer of 2000. The program will also study Nb_3Al, and common-coil block designs.

2.2.3.2 LBL program

High-field magnet development, using Nb_3Sn, has been ongoing at LBL for many years. The most recent success has been the 13 T D20 dipole [21]. The conductor performed well in this magnet: an assembly flaw limited the magnet performance. The success of this magnet shows that brittle materials can be used in high-field magnets.

LBL's future plans for high-field dipoles are concentrated on common-coil [22] block magnet designs using Nb_3Sn. Such designs have a number of attractive features. They are simple, robust, and compact; the Lorentz forces are easier to contain than for a cos-θ dipole. They use flat racetrack coils, which are quite easy to fabricate. The geometry is very friendly to brittle materials, such as Nb_3Sn or the copper oxides. The design can be fully modular, with modules independently preloaded. In the development phase, the modular design allows different conductors to be tested in the inner high-field regions. Because of the simplicity of the design, tooling and labor costs tend to be moderate, and a relatively low-cost magnet may be expected.

A 1-m long prototype Nb_3Sn dipole of this form has been built, using ITER conductor [23]. It reached 6 T (short sample) with no training. Subsequent magnets will use improved conductor, with an ultimate field target of 15 T.

2.2.3.3 BNL program

BNL is also focusing their R&D efforts on a modular common-coil block dipole [24]. They plan to use the magnet as a test vehicle for BSCCO at 20-30°K, and eventually YBCO. It will be a 1m long, 4-cm bore hybrid magnet, with NbTi background field coils and HTS (or Nb_3Sn) inserts. The goals of the program are to gain experience with HTS tape conductors and the common-coil design, and to develop techniques for magnetic measurements, quench protection, splices, and joints. This will lead eventually to an all HTS magnet.

2.2.3.4 TAMU program

The high field magnet program at TAMU [25] is focused on a 16 T dipole, which will use Nb_3Sn. The dipole has a scaleable-aperture segmented block coil design (with apertures from 1-5 cm) and emphasizes stress management techniques. Laminar inconel springs are used to intercept stress, preventing it from being applied to the conductor. Shear release is accomplished through the use of mica sheets, which prevent stick/slip friction at the coil-rib interface.

2.2.3.5 Low field magnets

Fermilab's development of the combined function transmission-line dipole for the low-field VLHC is much further advanced than the high-field magnets. A short (1 m) prototype has been built and tested with a drive current of 43 kA [26]. The latest design has a 20 mm gap, NbTi conductor with a drive current of 75 kA, a peak field of 2 T, and a good field region of 18 mm at 10^{-4}. Crenellated laminations (material missing in every 10th lamination) will be used to get to 2 T without saturation [27]. This should fully suppress the saturation quadrupole and sextupole fields. Proposed transmission line magnets for the 3 TeV injector use SSC cable [28]. A long prototype magnet and string is planned for this year or the next.

A cold iron, low field magnet is being considered at JINR. It is a 2.2 T, 1-turn, dual bore combined function magnet, with a 34 kA drive current, having a window frame conductor arrangement. The cold bore has a beam screen capable of handling up to 1.5 W/m. JINR is planning to make a prototype.

2.2.4 Magnet cost issues

For the VLHC magnet system to be affordable, it must be much more cost-effective than those of past or current large hadron colliders. A systematic attack on this problem starts with an analysis of the cost drivers and the cost tradeoffs in the scalable parameters: conductor, bore, field, length, etc.

For previous superconducting magnet systems, labor has been the major part of the cost, followed by the cost of the conductor. A cost analysis [29] for intermediate field (3-10 T) magnets has been carried out, based on RHIC dipole costs. The dipole costs have been scaled to 18 m dipoles with a single 40 mm aperture, appropriate for the VLHC. This scaling gives a dipole cost of \$1400/T-m.

High-field VLHC magnets would need fields above 10 T, where either an A15 compound or a copper oxide material would be used. These materials are currently considerably more expensive than NbTi. For example, Nb_3Sn conductor now costs about \$10/kA-m at 12 T, vs. \$1/kA-m at 5 T for NbTi. Copper oxide superconductors are even more expensive. Costs of YBCO cannot be estimated, as no material is commercially available yet. For BSCCO materials at 4°K and zero field, the costs range from about \$50/kA-m (2212) to close to \$1000/kA-m (2223).

Because of its simplicity and advanced state of development, a relatively reliable cost estimate can be made for the Fermilab low-field transmission-line magnets [30]. Two-thirds of the cost is in the iron yoke. In FY97\$, the total cost for a 13 m magnet is about \$14,000. At 2 T, this corresponds to \$540/T-m.

2.3 Accelerator Technologies

A general survey of the challenging issues in the broad range of technologies needed for the VLHC were reviewed in a recent workshop [31]. The workshop covered the topics of instrumentation, alignment, cryogenics, vacuum, rf and feedback.

The cost vs. operating temperature tradeoffs for the high-field VLHC cryogenic systems were studied for the Snowmass '96 workshop [32]. For the low field VLHC transmission-line magnet, which uses NbTi conductor, the low current density and low field allow operation at temperatures above 4°K. A higher operating temperature (6.5-7.5°K) results in a much simpler cryogenic system.

Both the high field and low field VLHC have challenging vacuum systems [33]. The large synchrotron radiation load in the high field requires a beam screen intercept operating in the 10-20°K region. The screen must be integrated with a cryosorber, which pumps the desorbed gases released by the synchrotron radiation. The warm-bore vacuum system for the low field machine is much like that of a low-energy electron machine. A distributed pumping system, using an antechamber, together with frequent localized lumped pumps, will be required.

2.4 Civil construction

Both variants of the VLHC would benefit from the minimum possible tunnel costs, but this is particularly important for the low-field VLHC. Considerable work was done on this topic at Snowmass [34], and studies have continued at Fermilab. For tunnels excavated with present-day technology tunnel boring machines (TBM), the minimum cost tunnel has a bore diameter in the range of 8-10 ft.

The overall SSC main tunnel costs were estimated in 1991 at about $5500/m. Recently, a cost estimate [35] gave $4000/m for a TBM-style tunnel for a 3 TeV low-field injector to the VLHC, sited at Fermilab. This cost may be reduced with continued R&D and tunneling technology improvements in the future.

3 CONCLUSION AND OUTLOOK

A post-LHC very large hadron collider, with a center-of-mass energy of 100 TeV and a luminosity of 10^{34} $cm^{-1}s^{-1}$, can be built with today's technology, but would be unaffordable.

The principal thrust of the R&D is to reduce the cost. The R&D on magnet systems, which is the most critical, has received the most attention to date. The low-field VLHC uses a simple low-cost magnet. In the next several years, one may hope that a good low-cost candidate also emerges for the high-field VLHC magnet. During this same period, many of the other issues mentioned above, related to the accelerator physics and the technologies of the accelerator systems, will receive more detailed study.

With this information in hand, a sound and affordable baseline design, and a detailed cost estimate, could be undertaken. If this can be completed by the time that physics results from the LHC begin to become available, the high-energy physics community would then be in a position to decide if and when it makes sense to embark on this project.

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