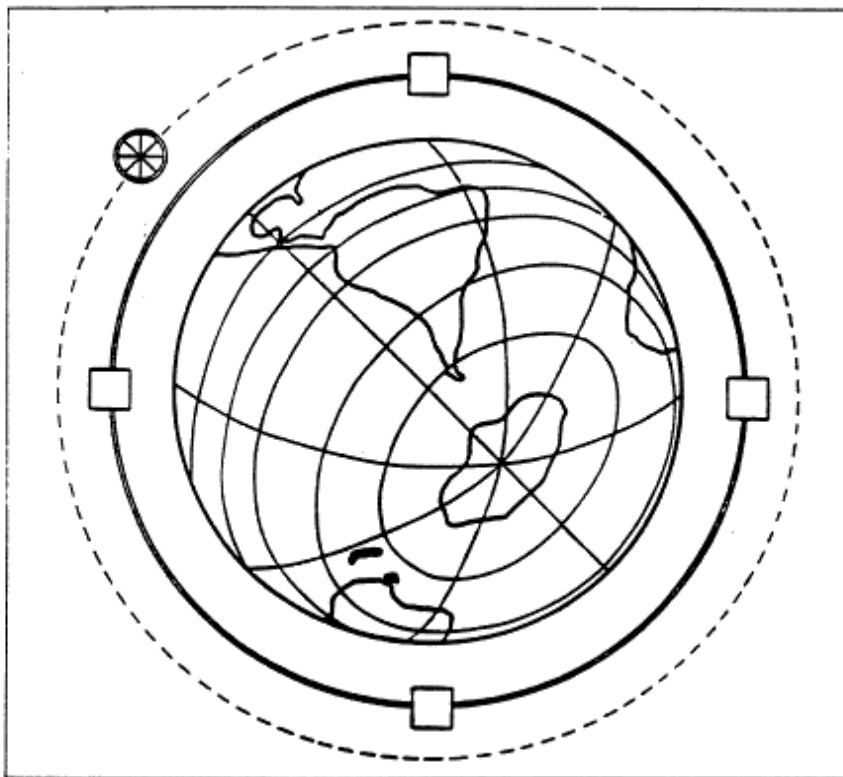


PROGRESS TOWARD THE VERY LARGE HADRON COLLIDER



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

March, 2000

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“The LHC will be a great step on the energy frontier, but it will not be the last step. Compelling questions surely lie beyond the physics reach of the LHC,” wrote the Drell panel in 1994, adding, “The technology of the LHC does not exhaust the possibilities for proton storage rings. Preliminary examination indicates that it may be technically feasible to build a proton collider with beam energies up to ten times those of the LHC with technology that could be developed during the next decade.”[†]

The efforts of various researchers looking beyond the LHC came together at the 1996 Snowmass Workshop. At Snowmass, consistent parameter tables were worked out for hadron colliders with 100 TeV center-of-mass energy and 10^{34} cm⁻² s⁻¹ luminosity, using superconducting magnets in low (2 T), high (9.5 T), or very high (12.5 T) regimes. The R&D, workshops, and other studies accomplished since Snowmass-96 support the preliminary conclusion that a Very Large Hadron Collider of order 100 TeV in the center-of-mass is clearly realizable with technology that is at hand, or nearly so. In most areas it appears that the accelerator physics issues are understood, thanks to the tremendous amount of work done for the SSC and LHC. The challenge is to make technological advances that will significantly reduce the “expected cost” of such a collider, where the “expected cost” is arrived at by simple extrapolation of SSC or LHC estimates.

In 1997 the HEPAP Subpanel report, “Planning for the Future of U.S. High-Energy Physics” recommended “... 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 1997 Subpanel also called for a report on the progress of the coordination, organization and R&D in roughly two years time. This paper is that progress report.

In response to the Subpanel recommendation the directors of Brookhaven, Fermilab, Berkeley Lab and Cornell University, and more recently the Stanford Linear Accelerator Center, established a VLHC steering committee and charged it to facilitate the R&D work at the various DOE laboratories, at universities, and in industry. The steering

[†] HEPAP Subpanel Report on a New Vision for U.S. High-Energy Physics, 1994 (Drell Report)

[‡] HEPAP Subpanel Report on Planning for the Future of U.S. High-Energy Physics, February 1998 (Gilman Report)

committee set up working groups in magnet technology, accelerator physics, and accelerator technology. Each working group organized a workshop. An annual meeting was held at Monterey, CA, June 28-30, attended by 55 interested and active participants. The present membership of the Steering Committee and the working groups, and the dates and locations of the workshops are listed in Table I.

TABLE I.

A. Steering Committee Membership

William A. Barletta, LBNL; Alexander Chao, SLAC; Gerald Dugan, Cornell; Michael Harrison, BNL; Peter Limon, FNAL; Ernest Malamud, FNAL; Stephen Peggs, BNL; James L. Siegrist, LBNL.

B. Workshops and Working Group Convenors

Magnet Technology: G. William Foster, FNAL; Ronald Scanlan, LBNL;
Peter Wanderer, BNL

Workshop: *Magnets for a Very Large Hadron Collider*
Port Jefferson, NY, November 16-18, 1998
Peter Wanderer, Chair

Accelerator Technology: Chris Leemann, TJNLF; John Marriner, FNAL;
Thomas Shea, BNL

Workshop: *VLHC Workshop on Accelerator Technology*
Thomas Jefferson national Laboratory Facility
Newport News, VA February 8-11, 1999
John Marriner, Chair

Accelerator Physics: Alan Jackson, LBNL; Shekhar Mishra, FNAL;
Michael Syphers, FNAL

Workshop: *VLHC Workshop on Accelerator Physics*
The Abbey, Fontana, WI, February 22-25, 1999
Michael Syphers, Chair

This document reports the activities of the VLHC working groups in the two years since the Gilman Subpanel Report. Initial work has concentrated on magnet design, with some effort on tunneling, accelerator physics and accelerator systems. Progress on magnets includes development of innovative designs, some of which use new superconducting materials. Progress in accelerator physics includes possible solutions for transverse instability problems. Evaluations of tunneling costs and seismic effects have begun for the Fermilab site. In the coming year, there will be continued progress in magnet and material development, and more detailed information on Fermilab geology

and tunneling issues. A select set of accelerator physics and technology problems will be studied in depth at narrowly-targeted workshops.

Although the VLHC Steering Committee is prepared to help coordinate the national VLHC R&D effort by offering guidance to the participating institutions, such guidance has not been necessary up to now. As the outlines of the different R&D programs show, there is considerable cooperation among the participants and very little overlap in the magnet designs. The steering committee has strongly supported a proposal for a national materials R&D program in industry to improve the performance and decrease the cost of Nb₃Sn superconducting wire. The first coordinated effort in support of this effort came out of the VLHC Magnet Technology Workshop of November, 1998, in Port Jefferson, NY.

A bibliography of papers and technical notes that describe in detail work referred to in this report is attached. Many of these reports can be found at the VLHC web page, <http://vlhc.org>.

Magnets

Superconducting magnets are the most costly and technically challenging components of a hadron collider, and they significantly constrain the design parameters of the VLHC. Accordingly, they have been the subjects of vigorous R&D efforts. Diverse magnet designs are being investigated. The major participants in the R&D have been Brookhaven Lab, Fermilab, Berkeley Lab, and Texas A&M University. Coordinated work in superconducting material R&D has been ongoing at Berkeley Lab, in industry and at a few universities, most notably, the University of Wisconsin.

An Overview of Candidate Magnet Technologies

Four magnet configurations aimed specifically at a VLHC have emerged as leading candidates for further work:

1. **The “Transmission Line” magnet:** A superferric 2 T design (Fig. 1) in which a single superconducting cable carrying 100 kA energizes both apertures, the current returning by a separate conductor path. The magnet uses room-temperature iron and a room-temperature vacuum system. For a beam energy of 50 TeV, the low field results in a very large ring. If the magnet and associated systems are inexpensive enough it may result in a collider that is least costly overall.
2. **A two-in-one cosine θ magnet:** A “conventional” design, extending SSC and LHC technology to Nb₃Sn (Fig. 2). This magnet is useful in its single-aperture configuration for many high-field applications. A cosine θ design is efficient in its use of steel and superconductor, and is a familiar technology used in all high-energy superconducting accelerators up to now.

3. **The “Common-Coil” magnet:** A high-field design that uses simple, flat coils (Fig. 3) to energize two gaps simultaneously. The large radius of curvature of the windings is friendly to the use of brittle Nb₃Sn and high-temperature superconductor (HTS) and may permit small coil apertures and the use of simplified react-before-winding techniques. Two designs, one for 10 T, another for 15 T are being studied.
4. **The “Stress Management” magnet:** In this design (Fig. 4), block coils are separated from each other by the support structure in such a way that the stress generated in one section of the coil is not transferred to its neighbor. This reduction in stress and advantageous block structure may allow higher magnetic field strength.

Notable by their absence are any designs of intermediate field strength, from 2 T to 9 T. Whether such designs will be useful for a VLHC is not yet known, but it is clear that extensive R&D in that regime is not needed at this time. Designs above 2 T to about 5 T are already well-understood due to the extensive successful construction of magnets for the Tevatron, HERA and RHIC. For field strengths above 5 T, we can rely on the development for SSC and LHC. It appears that intermediate field strengths provide neither the potential cost savings of the low-field design, nor the advantages of synchrotron radiation damping, which significantly reduces the emittance of the beam, offered by the high-field designs at 50 TeV beam energy. Intermediate-field magnets could, however, offer us understood cost models for comparison studies, and might be the appropriate choice for certain staging scenarios.

Any high-field magnets that use the familiar NbTi conductor operating in superfluid helium cannot support the field strength that is the goal of the high-field R&D. Furthermore, such magnets are high in cost because they use superconducting material at the limit of its performance. Hence, Nb₃Sn and Nb₃Al, have been the focus of the R&D effort. There has been some magnet R&D using high-temperature superconductor, but the relative unavailability of high-current, compact geometry HTS cable has constrained magnet development.

Low-Field Superferric Magnet: Design Considerations

The superferric magnet uses iron to shape the magnetic field, much as a conventional magnet, but uses superconductor to carry the excitation current. The iron limits the maximum field to about 2 T. There are many possible superferric designs. The one being pursued for the VLHC is an elegant design called a “Transmission Line Magnet.” Two apertures (Fig. 1) are arranged horizontally, with room-temperature iron carrying the flux between them and excited by a single NbTi cable carrying 100 kA. The superconductor and its cryostat are basically a transmission line, hence the name. The small mass of material at cryogenic temperatures and the relatively simple construction may lead to reduced cost per Tesla-meter.

The steel pole tips of the dipoles are shaped to produce a “combined function” magnet (dipole and quadrupole together), eliminating the need for separate quadrupoles. The return path for the current, and the supply and return for the helium, are contained in a utility structure underneath the magnet. The conductor (Fig. 5) is an arrangement of superconducting cable and Invar support pipes clamped at the magnet ends. Invar is

chosen because of its low temperature coefficient of expansion. The spiral arrangement of the conductor permits it to contract independently of the Invar. The simplified design allows the magnets to be made quite long, perhaps over 100 m, reducing the number of magnet interconnections.

Low-Field Superferric Magnets: R&D Progress

In 1998, a small cryogenic test loop was built and a first one-meter model was tested. In 1999, an extension of this test loop, 17 m in circumference, was built at Fermilab (Fig. 5) and energized to over 100 kA using a conventional magnet as the primary and the superconducting loop as the secondary of a DC transformer. This was recently used to test a sample of transmission line that meets all design requirements for the final machine. The NbTi and Invar sample carried the full 100kA current at 7.1K, substantially above the 6.5 K maximum temperature of the low-field VLHC cryogenic system design. In the next few months, this loop will be used to test several alternative conductor designs.

Optimization of the 2-D iron cross section continues, using the room-temperature test stand commissioned in 1999. The work focuses on saturation control techniques to ensure adequate field quality up to about 2.2 T (the practical limit for field strength given a 100kA drive current). A successful proof-of-principle of the “crenelation” technique was demonstrated last year, and a second technique based on judiciously placed holes in the pole tips is being built. A precision 20-element Hall probe array has been delivered and will be used for field shape measurements in the 2 cm magnet gap.

Superconducting Materials

Niobium-titanium, the superconductor that has been used in all superconducting accelerator magnets up to now, will not be able to reach fields above 10 T, even in superfluid helium. At this time Nb₃Sn is the best near-term candidate for high-field magnets. Its current-carrying capacity was significantly improved during the International Thermonuclear Experimental Reactor R&D program (ITER), but is still below what is desired for VLHC magnets. In the absence of other large customers, orders from high-energy physics are essential to keep the existing technology alive and improving.

New challenges arise when using Nb₃Sn for a magnet. This material is extremely brittle after the high-temperature reaction that forms the stoichiometric compound that becomes superconducting at liquid helium temperature. Hence, coils with small-radius bends, such as the saddle coils of a cosine θ magnet, must be wound before the cable is reacted. This requires electrical insulation that can withstand the high-temperature reactions, usually glass or ceramic fibers followed by vacuum impregnation after reaction. Coils with gentle bends, such as the “Common-Coil” design might be able to be built from pre-reacted cable, a significant fabrication simplification. Another low-temperature superconductor, Nb₃Al, is similar to Nb₃Sn but has more tolerance for strain. Some R&D on this material is being sponsored through SBIRs.

Most of the processes used for making Nb₃Sn and Nb₃Al lead to large effective filament sizes and, hence, poor field quality at low field. This is exacerbated by magnet designs that have large amounts of superconductor and small coil diameters. Although some of these problems can be relieved by judicious design, such as the use of steel

shims, it will take a significant R&D investment in superconducting materials to completely solve the magnetization issue. The “powder-in-tube” method of making Nb₃Sn conductor holds promise of yielding high current density and small effective filament size, but the technique is relatively new and needs further development.

For accelerator magnet applications, HTS entails high technical risk but has the potential for high reward. The materials of interest are BSCCO and YBCO. The current density of BSCCO is presently insufficient for a high field accelerator magnet but is increasing each year and present indications are that it will continue to increase. BSCCO development continues to attract large investments from the private and government sectors, including DOE funding of about \$30M a year. Much of this investment is directed toward obtaining more efficient electrical transmission lines and motors. The results of these efforts are likely to help create better conductor for magnets, as well.

Superconducting Materials: R&D Progress

A consortium of DOE laboratories and universities has proposed an R&D program for Nb₃Sn and Nb₃Al to be carried out in industry over the next five to ten years to encourage continued improvement in performance and cost reduction. The DOE has agreed to fund this effort at \$500,000 for the first year, starting in January, 2000. A Steering Committee comprising laboratory and university membership has written a Request for Proposals, the responses to which will soon be evaluated.

A facility for reacting and testing superconducting strand has been set up and commissioned at Fermilab. It is capable of operating up to 17 T, and from 1.8 K to 100 K. LBNL and Fermilab have collaborated with the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL, in the use of their cable-testing facility, which has the capability of putting strain on the cable during testing, which is an important parameter for Nb₃Sn.

A few hundred kilograms of excess ITER Nb₃Sn that belongs to DOE has been drawn down to useful sizes from 0.3 mm to 1.0 mm for use in mechanical models of high-field magnets. This material is not good enough to make high-field magnets but its mechanical properties are typical of Nb₃Sn, permitting early, accurate and inexpensive studies of the fabrication techniques and mechanical properties of these magnets.

In the low-field R&D, Nb₃Al strand has been used to manufacture four 4 m long transmission line test sections for use in the 100 kA inductive test loop. The advantages of Nb₃Al include a higher current density than NbTi, and the cryogenic cost savings from running at temperatures as high as 11 K, while retaining the flexibility and ductility required for a reliable field splice.

High Field Magnets: General Considerations

At high fields, high-energy proton beams emit significant amounts of synchrotron radiation. This is both good and bad. Radiation damping is beneficial as it reduces the emittance (size) of the beam, thus increasing the integrated luminosity. It may also make the beam less sensitive to the deleterious effects of field distortions, power supply and RF noise, and ground motion. However, the radiation presents an increased heat load to the cryogenic system and causes desorption of gas molecules from the beam tube, both of which require a beam-tube liner, which complicates the cryogenic, vacuum and

mechanical system of the magnets. Much progress in understanding the effect of synchrotron radiation on proton collider operation has been made since the SSC first started investigating it in 1984. Nevertheless, it remains one of the most challenging issues of high-energy, high-field colliders.

High-field magnets necessarily have a large amount of superconductor, and Nb₃Sn has a very high critical current density and relatively large filament diameters, resulting in large magnetization currents at injection field. Investigators have made progress in designs that use steel shims on the beam tube or behind the coils to partially cancel the injection field errors. At high field the steel shims are completely saturated and have no influence. This is a promising technique that will be pursued further.

High-Field Cosine Θ Magnet Design Considerations

An effort underway at Fermilab in a collaboration with LBNL and KEK focuses on obtaining the maximum performance from Nb₃Sn in a two-layer, cosine θ coil. This wind-and-react coil is designed to take advantage of numerous advances in materials and tooling; it is insulated with ceramic cloth, allowing a higher temperature reaction; the cloth has a ceramic binder that can be partially cured at moderate temperature, binding the coil together for easy handling, but which leaves no carbon residue after coil reaction; the tooling is designed to allow the coils to be wound, cured and reacted as a complete unit, shortening and simplifying the fabrication.

This design combines the high-field capability of Nb₃Sn with the large body of experience building NbTi cosine θ magnets for the Tevatron, HERA, RHIC, and the LHC. The magnet design is intended to produce an 11 T operating field with a 45 mm coil aperture. Work has included comparisons with other designs (e.g., the common-coil), field quality optimization of the coil straight section and ends, and calculations of the electromechanical forces. Ovens large enough to react Nb₃Sn conductor in the form of a coil have been installed, a facility for measuring the critical currents of Nb₃Sn wires has been brought into operation, and measurements of material properties have been made. The initial R&D models have a single aperture, but the design of a two-in-one version was completed in December, and will be fabricated in 2001.

High-Field Cosine Θ Magnets: R&D Progress

Most of the tooling infrastructure for making shell-type magnets is in hand because of Fermilab's long tradition of making magnets of this kind, and because of the recent LHC R&D program. Additional infrastructure specific to Nb₃Sn magnets is in place and is being used, including small ovens for sample preparation and a large oven for reacting model magnets up to one meter in length. The goal of the Fermilab cos θ program is to build and test a working single-aperture magnet in fiscal year 2000. The magnetic and engineering design are complete and most of the tooling is in hand or has been ordered. Oxford Superconducting Technologies, Inc. has made and delivered high-performance strand to Fermilab for the first model. IGC Advanced Superconductors, Inc. and Shape Metal Innovation, BV (The Netherlands) are making superconducting strand for future models. Coil samples for the mechanical models (Fig. 6) are being wound, cured, and reacted from spare ITER cable using ceramic insulation made by Composite Technology Development, Inc. Two mechanical/electrical models will be made from ITER cable in

February and March, followed by fabrication of a magnet from high-performance cable made at LBNL. Investigators expect tests of the first high-field model in August.

High-Field Common-Coil Magnet Design Considerations

A common-coil dipole uses flat racetrack coils, arranged to produce uniform dipole fields in two apertures in a single magnet. (Fig. 3). Racetrack coils, in contrast to saddle coils, bend the conductor in only one plane. Furthermore, in the common-coil design, the radius of the bends is of the order of the aperture spacing rather than the size of the aperture. Thus these coils are “conductor friendly” and more suitable to the brittle A15 or HTS materials required for high field.

Brookhaven, Fermilab and LBNL are all working on one or another variant of a common-coil magnet. Brookhaven is pursuing the design with the intention of eventually using high-temperature superconductor for very high field and low operating cost. The goal at LBNL is to build a very high-field dipole ($B > 15$ T) from Nb_3Sn or Nb_3Al , possibly using react-and-wind techniques. Fermilab’s plan is similar, except that the goal is a 10 T dipole with the inner coils made of Nb_3Sn , the outer of $NbTi$. A major choice in the design is whether to use “auxiliary coils,” that is, coils separate from the main coils, to enhance the field. Such designs are more difficult to fabricate but are considerably more efficient in their use of superconductor.

High-Field Common-Coil Magnet: R&D Progress

Two 1 m-long common-coil dipoles have been successfully tested in the last year, one at Brookhaven, one at Berkeley Lab. Both models used existing superconductor to obtain a relatively fast check of design and construction methods at moderate field. The LBNL magnet (Fig. 7) performed well, reaching the 6 T limit of the ITER superconductor without training. The LBNL group is now well along in its design of a common-coil magnet able to reach 14 T. The LBNL and Fermilab staffs are working together on the field quality aspects of this design.

The other common-coil dipole was built at BNL using $NbTi$ left over from the SSC, to generate a 6 T background field in a yoke designed for easy changing of additional test coils. The intention is to use this magnet to test HTS coils, but in the absence of available HTS materials, test coils were made from industry-donated pre-reacted Nb_3Sn tape, which has strain characteristics similar to Nb_3Sn . The quench performance of both the $NbTi$ and the Nb_3Sn coils was satisfactory. The coil manufacturing and assembly techniques used for the Nb_3Sn coils are now being used to build coils made from pre-reacted BSSCO HTS. The BNL staff also made a successful short (30-cm) common-coil magnet coil using BSSCO tape. (Fig. 8)

Small purchases of BSSCO material have been made by BNL, LBNL and Cornell in order to provide manufacturers with feedback about its use in high field magnets. In 1998, HTS coils were ordered jointly by BNL, Cornell and Fermilab from two vendors, Intermagnetics General Corporation (IGC) and Applied Superconductivity Company (ASC). Meanwhile, a quadrupole suitable for the Cornell Electron Storage Ring was designed. Using a winding mandrel made at Fermilab, ASC wound two quarter-coils (Fig. 9), which tested successfully at their facility and at BNL. Late in 1999, IGC also completed two quarter-coils, which are currently under test at BNL.

The magnetic design of the Fermilab common-coil magnet is complete, and finite element analysis and tooling design is proceeding. Since the goal is to make a Nb₃Sn react-and-wind magnet, investigators are paying considerable attention to the cable design. Cables with strand diameters of 0.3 mm, 0.5 mm and 0.7 mm are being made at LBNL with and without a central stainless steel core. This core prevents the strands from welding during reaction, and also decreases the AC losses. The cables are being reacted at Fermilab for strain tolerance tests. Tooling is being procured, and magnet coil winding will follow quickly on the heels of the cosine θ coils. Fermilab expects to test a magnet in early 2001.

High-Field Stress-Management Design Considerations

In this approach (Fig. 4), the magnet is designed so that the large electromagnetic forces produced by high fields do not accumulate in a coil and degrade the performance of the brittle superconductor. Instead, the coil is constructed of a series of blocks of conductor supported by a system of Inconel ribs and plates. The stainless steel structure carries the force on each coil block to an external support structure. At the magnet end, the coil is wound over the beam pipe in a region of relatively low field.

The subdivision of blocks makes it natural to use a “graded conductor” design in which the costly high-field materials are only used in the coil that is closest to the beam, with cheaper materials such as NbTi in the low field regions. Also, the Cu-to-SC ratio can be different in the different blocks. Stress-management designs for both 16- and 12-T magnets have been developed. Electrically, there are three independent coils in each magnet. Field quality is maintained through the ramp by varying the currents in each coil as needed. The design of the magnet shields the beam from the magnetization currents at injection field, increasing the range over which the magnet can be operated. Proper support of the coil block under all conditions requires a novel spring to make up for changes in the relative sizes of the coil block and its support structure. It also requires a slip plane and electrical insulation between the coil and the support structure.

Accelerator Physics

The major work in the area of accelerator physics has focused on aperture and its relationship to both single-particle dynamic aperture, particularly at injection, and collective effects. This is appropriate at this stage of the VLHC studies because magnet cost is strongly dependent on physical aperture. Other important issues have been discussed at workshops, and have been left to future studies and experiments. These will be discussed in the section on future work.

Single-Particle Effects—Dynamic Aperture

The design and development of the SSC and the LHC significantly advanced the understanding of the dependence of beam lifetime and emittance growth on magnet field quality, correction systems and cell length, and the dependence of field quality on magnet physical aperture. They need to be revisited for the VLHC because technological and theoretical advances and anticipated design changes, such as the use of Nb₃Sn magnets,

and the influence of synchrotron radiation damping, have changed some of the underlying assumptions.

Magnet field quality and aperture

For superconducting magnets, decreasing the inner coil radius can lower the cost. On the other hand, single-particle stability and collective effects suggest that the coil radius and the beam pipe radius be as large as possible. The choice of optimal single-particle aperture depends on injection energy, injection errors, orbit distortions, lattice mismatches, power-supply ripple, correction schemes and half-cell length in the arcs. It is important in setting the aperture of the magnets that we understand the expected distribution of systematic and random field errors in the arc magnets.

For conductor-dominated (high-field) magnets, single-particle considerations at injection usually set the lower bound on coil aperture, where magnetization effects and large beam size conspire to make the effects most damaging. For superferric magnets, the field quality at injection is not likely to be a concern since the field is shaped by iron pole tips and the magnet is insensitive to persistent currents in the superconductor. The field-quality challenges for the low field magnet occur at peak field, when the iron enters saturation. At peak field, however, the dynamic aperture requirements have dropped by a large factor due to the adiabatic damping of the beam size. Thus the minimum workable aperture of superferric magnets will likely be set by other considerations

During the design of the SSC magnets it was expected that random errors would be larger than systematic errors. Experience with RHIC dipoles, as well as with the last SSC dipoles built, has shown that random errors were much smaller than expected. Some of this overestimate may have been due to simplifications of the initial mechanical model, but most of the improvement was achieved by better tooling, better control of manufacturing processes, and reduction of measurement errors. Systematic errors have also been reduced by improvements in the design of NbTi magnets, but magnets with Nb₃Sn coils will probably have much worse magnetization effects at injection. Some of this can be moderated by the judicious use of steel shims and by aggressive R&D to reduce conductor filament diameter. Even with good results in those areas a complete set of correctors and the right choice for cell length and injection energy will be necessary to optimize the injection aperture and the cost of the collider.

Optimum cell length

One of the key cost drivers is the cell length. Longer cell length implies fewer quadrupoles, sextupoles and other correctors, but it also increases the beam size and makes the beam more sensitive to field errors. How the transverse and longitudinal beam parameters scale with cell length depends on the distribution of field errors and how they affect the dynamic aperture. Where the dynamic aperture is dominated by chromaticity correction sextupoles, longer cell lengths are favored, as this reduces the required sextupole strengths. In other circumstances—either when systematic errors are large or when random errors are dominant—shorter cell lengths would lead to a larger dynamic aperture.

Collective Effects

The strongest instabilities expected in the VLHC are the single-bunch transverse mode coupling instability (TMCI—sometimes called the “fast head-tail instability”), and a low frequency transverse multi-bunch instability. Both effects are most severe at injection energy. The multi-bunch instability is driven primarily by the resistive wall impedance; the TMCI instability is driven primarily by the resistive wall impedance in the low field case, and by the broadband impedance in the high field case. Thus, the low-field design, with its much larger circumference and room-temperature vacuum chamber, has the lowest threshold for the single bunch TMCI and the most rapid growth rates for the multi-bunch instability.

Transverse Mode Coupling Instability (TMCI)

The frequencies of coherent bunch motion (mode 0) and head-tail motion (mode -1) are shifted towards each other by the transverse impedance. At some threshold current, the mode frequencies become equal, and the bunch becomes unstable, with a very rapid growth time (on the order of the synchrotron period). As noted above, this is particularly an issue for the low-field design because of its large impedance. The situation is clouded by the fact that this instability has only been observed in electron machines (which have much shorter bunch lengths) and has never been seen in proton machines. Nonetheless, if the instability formulae are valid and if no further measures are taken, this instability has the potential for limiting the achievable luminosity.

Calculations up to now indicate that the TMCI does not limit the luminosity below $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, but this is still controversial. Several methods of raising the beam-current limit due to the TMCI in the low-field design have been proposed to avoid the straightforward but costly solutions of raising the injection energy or increasing the beam tube diameter. These include rf quadrupoles or coalescing beam at higher energy than injection to reduce bunch intensity at low energy. Some of the proposed methods are unproven, requiring further R&D. Of the various schemes, conventional feedback systems have been shown to increase the instability threshold in the electron machines PEP and VEPP-4M and may work in the VLHC, although that is controversial at this time. Nevertheless it is worth studying the different schemes in some detail to see which leads to the lowest-cost solution and increases the instability threshold.

Transverse multi-bunch instability

The multi-bunch instability is most severe at injection energy; the growth time is proportional to the total beam current. It is driven by the low-frequency transverse impedance resulting from the finite conductivity of the beam pipe walls. At 3 TeV, the instability growth time in the low-field VLHC varies from 0.4 to 4 turns (depending on lattice parameters), and is about 300 turns in the high-field case. The instability can be damped with use of a distributed feedback system. This system senses the beam position error and generates an amplified kick 90 degrees in phase advance from the pickup. Of course, the kick is slightly out of phase with the error, due to electronic propagation delays, but the correction works anyway due to the slow nature of the change in position error. Spacing a number of such systems around the ring will decrease the damping time considerably. It is estimated that ten such feedback systems in the ring would be

sufficient to create a damping time of less than a third of a turn and eliminate this as a luminosity-limiting effect. This needs to be confirmed by detailed simulations.

Beam Loss and Energy Deposition

Stored energy in the beams is very high in the VLHC: about one gigajoule for the high-field option and about 10 GJ for the low-field case, compared to 0.33 GJ in the LHC. Measures must be taken to protect people, the environment, and the accelerator from the consequences of beam loss. This is not a fundamental accelerator physics issue, but it will require care to cope with both operational beam loss and accidental beam loss.

Operational loss refers to the relatively slow and steady loss resulting from halo particles interacting with limiting apertures. It results in reduced luminosity lifetime, potential vacuum problems, activation of components and other unpleasant consequences. There exists a preliminary design of a two-stage collimation system to deal with operational beam loss similar to one used at HERA and an LHC design.

Accidental losses might occur, for example, due to the misfire of one of the abort kickers, resulting in a large amount of beam hitting part of the collider. The high stored beam energy could destroy a magnet or a detector. A system of three appropriately placed absorbers has been designed for the LHC to protect interaction-ring magnets from unacceptably large increases in temperature as a result of these kicker misfires. A similar design should also work for the VLHC, but alternative ideas could be more cost effective over the long run.

Accelerator Technology

Civil Engineering

The construction of the collider enclosure is an important cost driver for the VLHC, especially for the low-field version. Therefore, investigators are studying the development of new tunneling technologies. Two important advantages to building the VLHC at Fermilab are the existence of the injector chain and the excellent geology. At a depth of 150 m, below the nearly flat Illinois surface lies a 50 m thick dolomite layer. This relatively homogenous rock mass is ideal for siting the VLHC and its injector. It is seismically stable and vibration free, with a very low rate of infiltration of groundwater.

The two main components in the tunnel construction are mining and muck removal. The standard approach is to use tunnel-boring machines (TBM) for mining and a conveyor belt for muck removal. The Kenny Construction Company has made a study of a 34 km tunnel in the dolomite near Fermilab and has shown that a major cost driver is the number of people underground. The mining industry is exploring new ideas and is moving in the direction of more automation in tunnel construction.

Cryogenics

The cryogenic issues for every superconducting accelerator are threefold: operating temperature, temperature gradients, and temperature stability. Since all of the high-field magnets use Nb₃Sn at the present time, in which J_c does not have much temperature dependence below 4 K, the high-field magnets all operate at about 4.2 K. Therefore, the

cryogenic systems for these magnets will closely resemble those of the SSC. One significant difference comes from the increased synchrotron radiation power (several watts per meter) deposited in the cryogenic beam screen. It is desirable to intercept this at the highest possible temperature consistent with obtaining adequate beam vacuum and RF impedance. This will require significant R&D in the coming years.

Of particular note is a cryogenic design for the low-field case that uses the fact that the superconductor in the superferric magnet is in a low-field region, permitting the coolant temperature to rise to the critical point or even higher. This may permit the use of a cryogenic system that effectively uses the sensible heat of the cryogen, thereby eliminating heat exchangers in the magnet system and greatly simplifying the controls.

Vacuum

The vacuum system of the low-field machine is not cryogenic, and is expected to have a gas load from photo-desorption and outgassing similar to or less than LEP. Although it will not be trivial, there is a demonstration that such a system will work. The high-field machines all have beam tubes at cryogenic temperatures. Although no existing collider actually has a beam-tube liner, all high-energy high-field collider designs (SSC, LHC, VLHC) include a beam-tube liner inserted between the beam and beam-tube. This liner operates at a higher temperature than the magnets, from 20 K to 80 K, and has holes punched in it to allow desorbed gas (mostly hydrogen) to escape and stick to the beam-tube wall. The higher-temperature liner reduces the cryogenic load, but the temperature of the beam tube of VLHC (4.2 K), is not low enough to reduce the residual hydrogen vapor pressure to acceptable levels. It is believed that this can be dealt with by coating the wall with some form of adsorbant material to increase its effective surface area. This problem has been studied at light sources in the U.S., France, and most recently and extensively at Novosibirsk, Russia. This issue, which was one of the most troublesome during the design phases of the SSC and the LHC, is still a thorn. Studies must continue.

Ground Motion

Ground motion can vibrate magnets, leading to emittance growth if the resulting coherent motion is not corrected over its decoherence time. Measured ground vibrations in deep Illinois dolomite tunnels are smaller than the tolerances for both the low- and the high-field options. The “cultural” noise level (i.e., arising from human activities such as nearby traffic) measured in the shallow Tevatron tunnel is several times above the VLHC tolerances but small enough to be suppressed by the multi-bunch damper system discussed above.

Plans for the Coming Year

Magnets

As in the past, most of the R&D effort for the VLHC nationwide will be devoted to magnet development. Our extensive experience with existing or soon-to-be-existing superconducting colliders indicates that eight to twelve years is a realistic estimate of the time it will take to develop cost-effective and proven magnets for the VLHC. The present level of effort produces no more than one short model magnet per year at each of the laboratories. It will soon become necessary to make several short magnets per year to

optimize fundamental design features, to permit a systematic and scientific approach to the R&D, and to allow each program to take some technical risks in its pursuit of the best design. Thus, we envision that the budget will continue to have modest growth in the coming three to five years. At a later stage, full-scale magnets will have to be built and tested. This will require greater growth, and selection among the various designs to concentrate our resources.

Each of the participating DOE Laboratories has a detailed plan for R&D that projects one or two years. The goals of the individual laboratories' programs and their approach to the development challenges have surprisingly little overlap at this time. For example, even though three laboratories are interested in developing the two-in-one common-coil concept, the actual goals of each of the programs are so different that the resulting designs have very little resemblance to each other. It is because of the promise of a less costly VLHC that this particular concept has attracted so much attention.

In broad outline, the goals for 2000 are:

- 1. BNL—high-field, common-coil magnet:** The first HTS coils designed for the common-coil magnet will be tested using NbTi coils to provide a 6 T background field. Since this will be the first time HTS coils are operated in this environment, many basic measurements will have to be made to characterize their performance. In addition, work will start on a second-generation HTS common-coil magnet, which will be designed to operate at 12 T, and which will be used to investigate issues such as field quality, magnetization, eddy currents.
- 2. Fermilab—superferric, transmission line magnet:** Make and test a magnet on the room-temperature facility using the second-generation cross section; make a 10 m magnet and test it using the induction loop at the transmission line test facility; increase the capability of the induction loop to electrically and cryogenically operate longer magnets; start the engineering design of a 50 m magnet; make and test various support and superinsulation designs for the transmission line; start to design tooling for welding, splicing, and other installation operations; finish the design of 100 kA power leads.
- 3. Fermilab—high-field cosine θ magnet:** Fabricate, possibly test, and dissect one or two mechanical models; build and test the first one-meter, 11 T model using high-performance superconductor; start to build the second model; order superconductor for two more models to be built and tested in 2001. Start the engineering and tooling designs for the first two-in-one models.
- 4. Fermilab—high-field common-coil magnet:** Continue the investigation of strain tolerance of various cables for react-and-wind technique, using spare ITER conductor, and select a strand and cable design; complete the tooling design and order tooling for delivery in mid-2000; react the selected ITER cable and make and test practice coils using real tooling; assemble and test a mechanical model using ITER cable; order high-performance strand for the first high-field (10 T) magnet to be made in 2001.
- 5. LBNL—high-field common-coil magnet:** Continue the current program based on a high-field, Nb₃Sn, common-coil design, paying particular attention to

fabrication issues related to brittle conductor, especially cost-related issues. The fabrication of this second-generation magnet has already begun. It is designed to reach 14 T, limited by the performance of available superconductor. The outer coils will be tested in the spring in a background field. The inner coils will be assembled with the outer coils and tested in the fall.

Accelerator Physics

Fundamental limitations to ultimate hadron collider luminosity, such as the beam-beam effect, intra-beam scattering, collective effects and instabilities, and synchrotron radiation, will continue to be important in the VLHC parameter regime. In addition, the magnet R&D program continues to need feedback from accelerator physics about important issues such as field quality, aperture, and time-dependent effects.

Emittance damping from synchrotron radiation enhances the equilibrium beam density by an order of magnitude compared to the nominal injection value. The dynamic evolution to denser beams leads to stronger and more complex beam-beam interactions. Although the damping times are long compared to those in electron machines, an additional potential increase in luminosity comes from the flat beams that ensue if the linear coupling terms are small enough. Since interaction region optics designs are strongly influenced by the beam size and shape, it is important to understand this new beam dynamics regime.

The VLHC will confront some or all of these fundamental physics limitations to its ultimate luminosity, many of which are amenable to beam studies and experiments that can be performed at the Tevatron and RHIC, and eventually at LHC. Such experiments, that are actively being pursued, will be of benefit to all hadron colliders. In these efforts, the VLHC Steering Committee can be useful in supplying a natural venue for organizing and coordinating mini-workshops on topics of mutual interest within the hadron collider accelerator physics community.

Three different accelerator physics mini-workshops are planned for the coming year, on the topics of collective effect limitations on bore size, synchrotron radiation and flat beams, and beam dynamics experiments.

Accelerator Technologies

Civil Engineering

Investigators are pursuing a number of avenues aimed at lowering the cost per meter of collider tunnel. Greater automation of the tunneling machines will reduce the labor component as well as increase the advance rate. A 17-ft TBM in operation on a 4000-ft tunnel under Chicago (part of TARP) has been instrumented by Fermilab to understand more quantitatively the factors governing the efficiency of TBM utilization. These data are being collected in real time and being analyzed. In addition, the possibility is being considered to write contracts with industry to study innovative concepts in tunneling and muck removal.

A major effort in the coming year will be to understand more exactly the geology in the Fermilab area. This work has already been started at Fermilab, with the formation of a

Siting Study Group that is concerned with all siting aspects of possible new machines located at or near Fermilab. A first step will be connecting with the Illinois Geologic Survey to get detailed maps of the underground and surface conditions that will be encountered by tunneling in northern Illinois. It might be necessary to make additional surveys. A mini-workshop on the subject will be held in the next twelve months.

Seismic measurements to date cover three ranges: 2×10^{-3} to 1 Hz, important for alignment; 1 - 100 Hz, important for orbit stability; and above 100 Hz, important for emittance growth. Measurements are being extended this year to lower frequency, near 10^{-7} Hz, to understand if dynamic alignment will be necessary.

Workshops

Because of the amount of R&D, we will again have a rather large magnet workshop, this year scheduled to be near Fermilab in the spring. Instead of two large workshops in accelerator physics and accelerator technologies, we plan to organize a larger number of smaller, more focused workshops on specific subjects, trying to bring together the most interested and expert scientists in each area. Examples might be beam stability and feedback; ground motion; simulation of dynamic aperture; and perhaps some focused magnet workshops, as well, such as cancellation of magnetization effects with steel shims.

Mini-Workshop on Beam Dynamics Experiments	Feb., 2000	BNL
Workshop on Superconducting Accelerator Magnets	May, 2000	Fermilab
Mini-Workshop on Limitation Due to Collective Effects		
Mini-Workshop on Synchrotron Radiation Damping		
Mini-Workshop on Fermilab Regional Geology		
VLHC Annual Meeting	Sept., 2000	BNL

Acknowledgements

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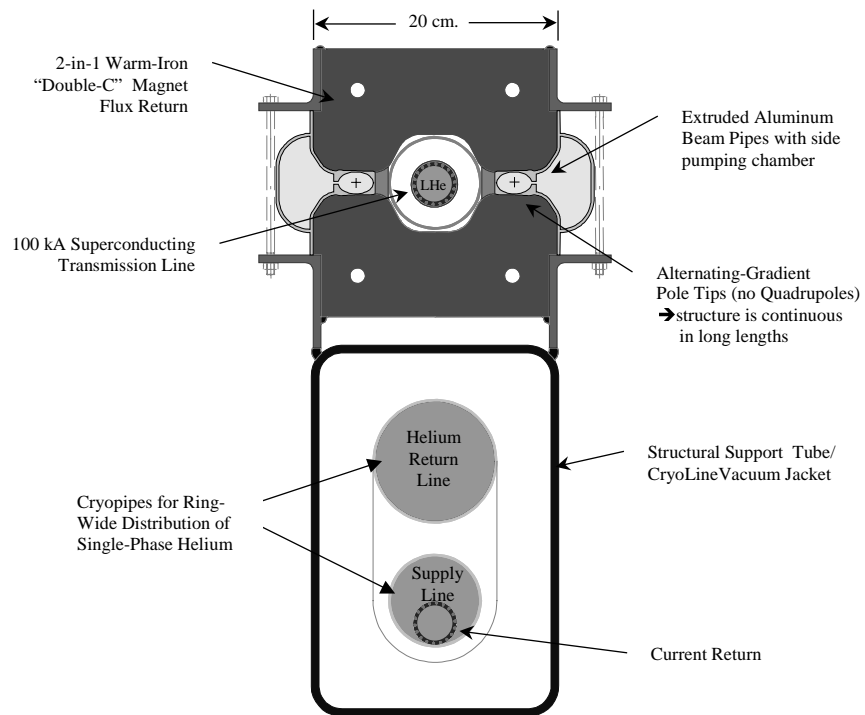


Figure 1. A cross-section of a “transmission-line” magnet. Current flowing down the central conductor excites a magnetic field in the surrounding iron and the two gaps. The maximum field attainable is approximately two Tesla. The simplicity of the design may result in low-cost magnets and accelerator systems.

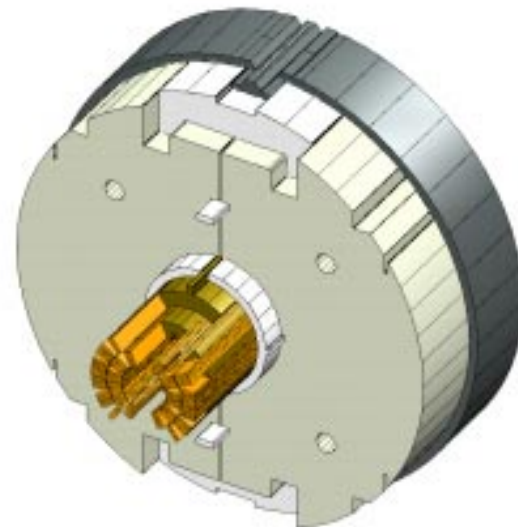


Figure 2. A single-aperture version of a “cosine θ ” design. The Roman arch coil configuration results in mechanical stability without internal support, and is similar to all high-energy collider superconducting magnets used until now. This design is for R&D. The collider magnet will have a double aperture, and can sustain fields up to about 13 T.

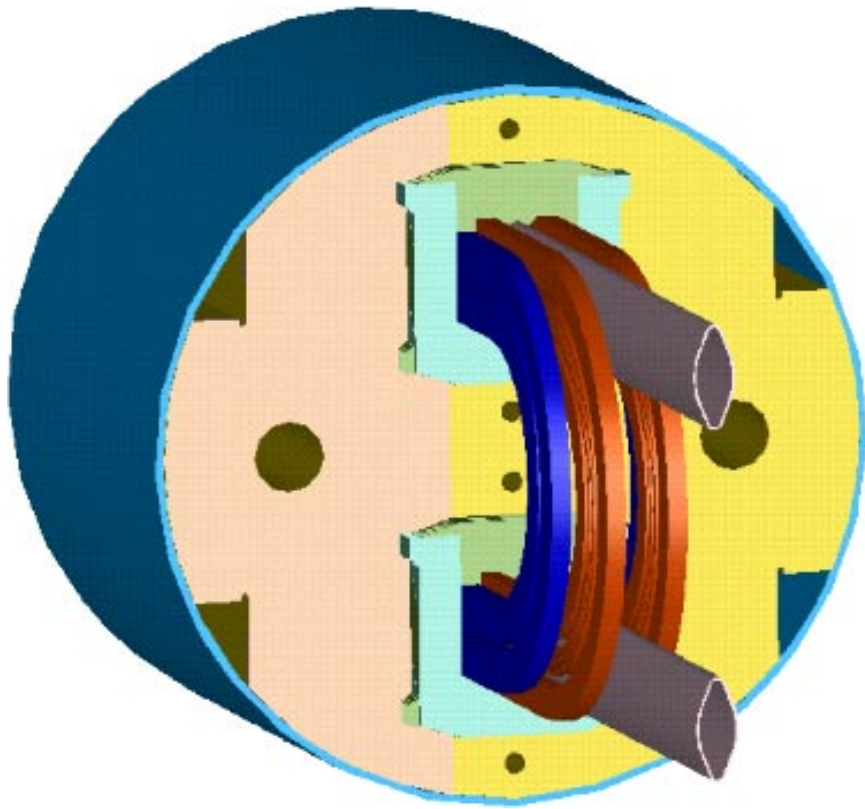


Figure 3. The “Common-coil” magnet has simple, flat coils with gentle radii of curvature friendly to brittle conductors such as pre-reacted Nb_3Sn and high-temperature superconductor. The coils require internal support for mechanical stability, but their simplicity suggests a less-costly high-field magnet. Attainable field

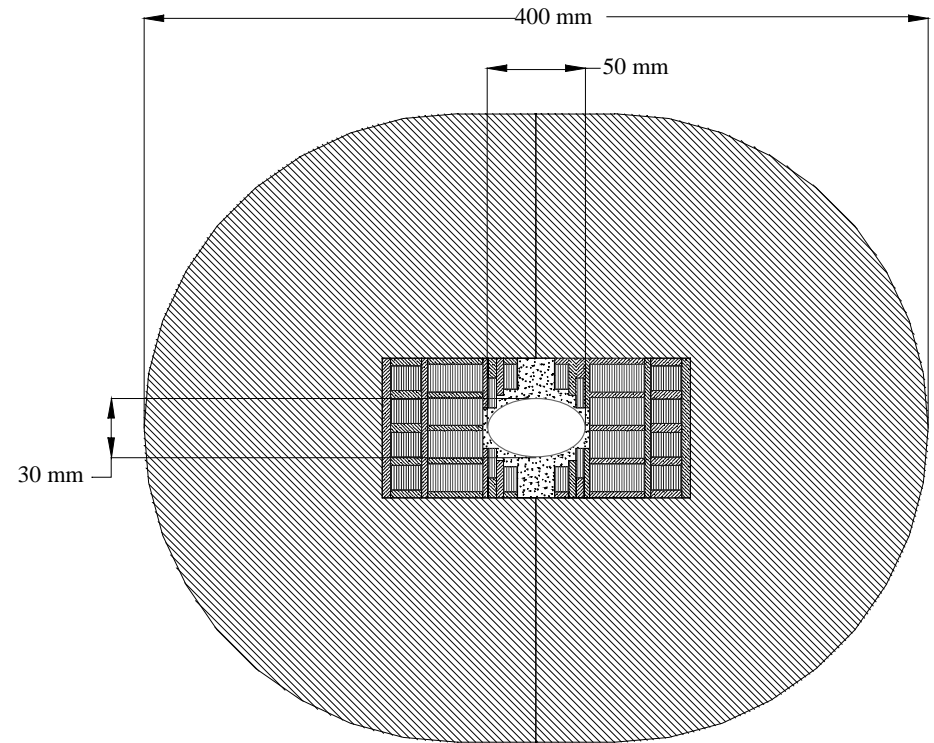


Figure 4. A concept for a “stress-management” magnet, in which the outward forces from the inner coils are transferred directly to the yoke without acting through the other coils, reducing stress on the superconductor. Block configurations of this type may be necessary to attain very high magnetic fields, greater than 15 T.



Figure 5. The Fermilab Transmission-Line Test Facility. The conventional magnet is configured as a DC transformer; the secondary is a superconducting loop. This facility has been energized to over 100 kA, and has a four meter long replaceable section used to test various conductor and splice configurations.



Figure 6. Coils for a mechanical model of the cosine θ magnet. The Nb_3Sn cable is insulated in ceramic cloth (left) sized with a material that binds the coil when cured at moderate temperature (right), but which leaves no carbon residue when reacted. This greatly simplifies assembly.

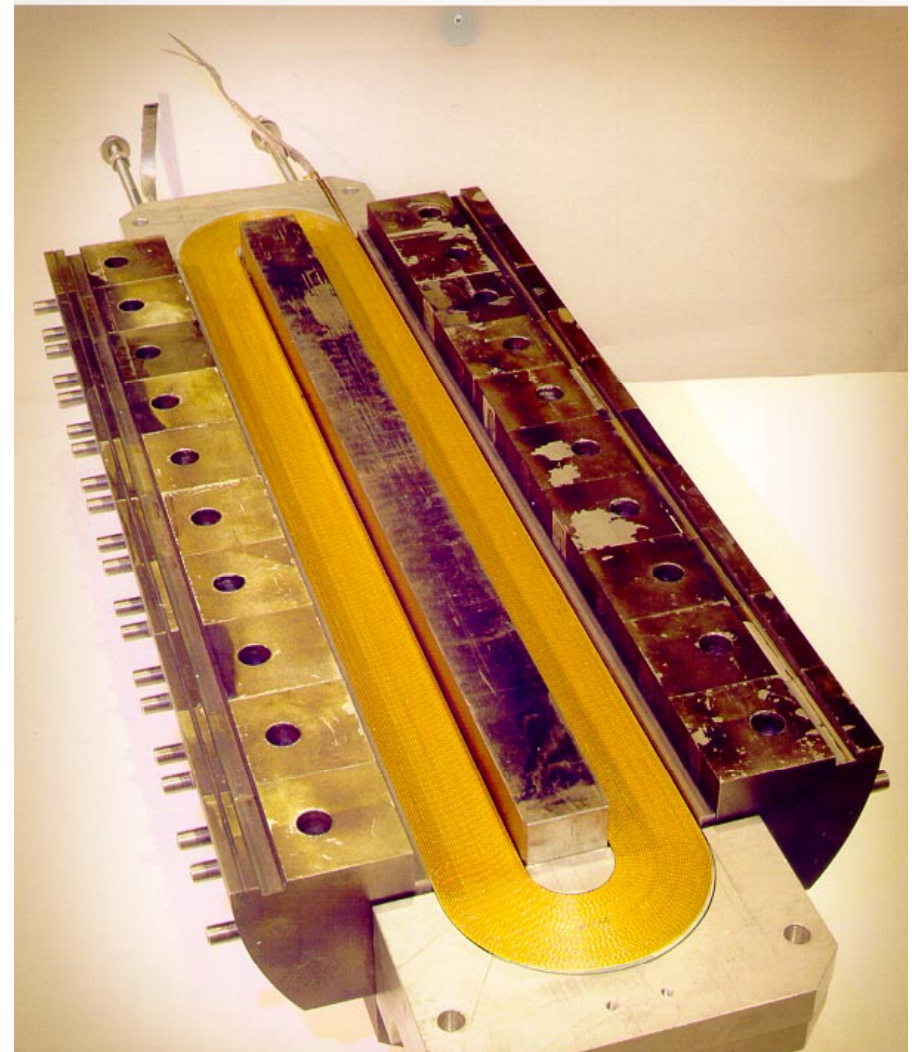
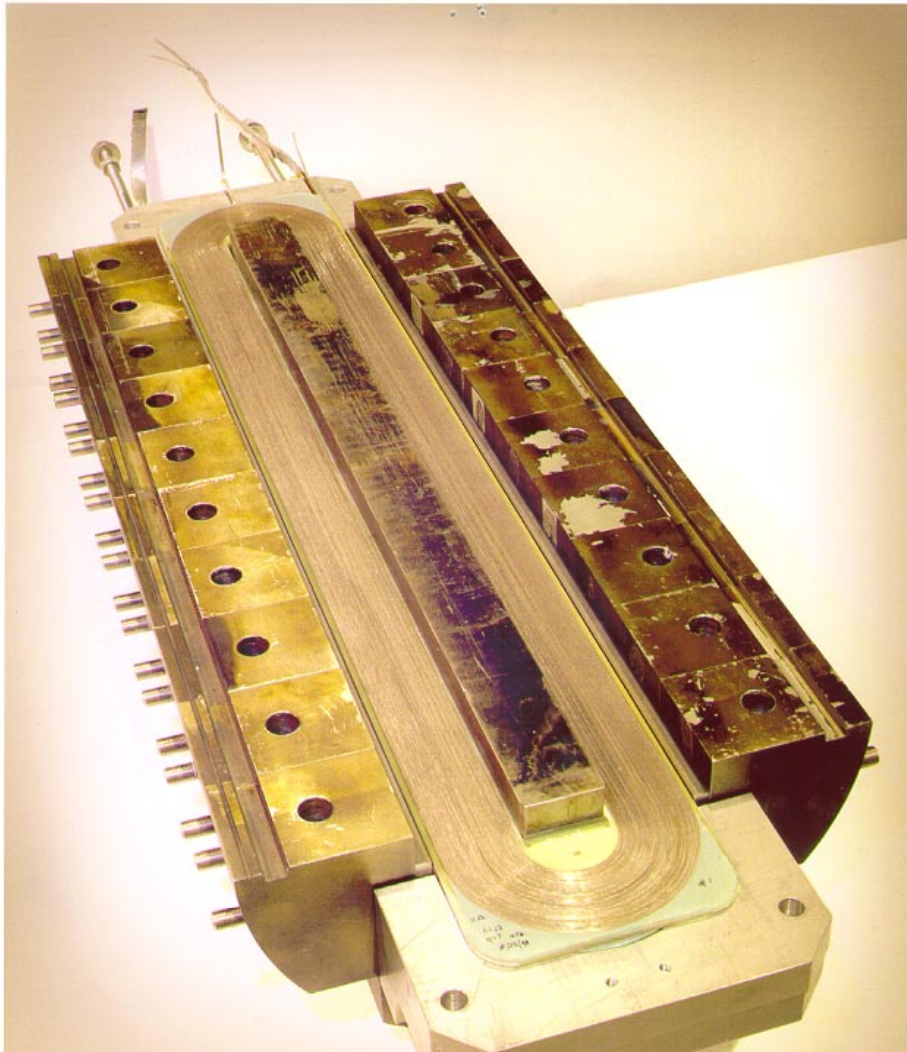


Figure 7. Apparatus used at BNL for testing HTS coils in a common-coil configuration and in a background field. The background field is supplied by outer NbTi coils (right), and the inner coils are various HTS coils (left). This easily modifiable setup allows fast turn-around in testing different materials and geometries at high field.

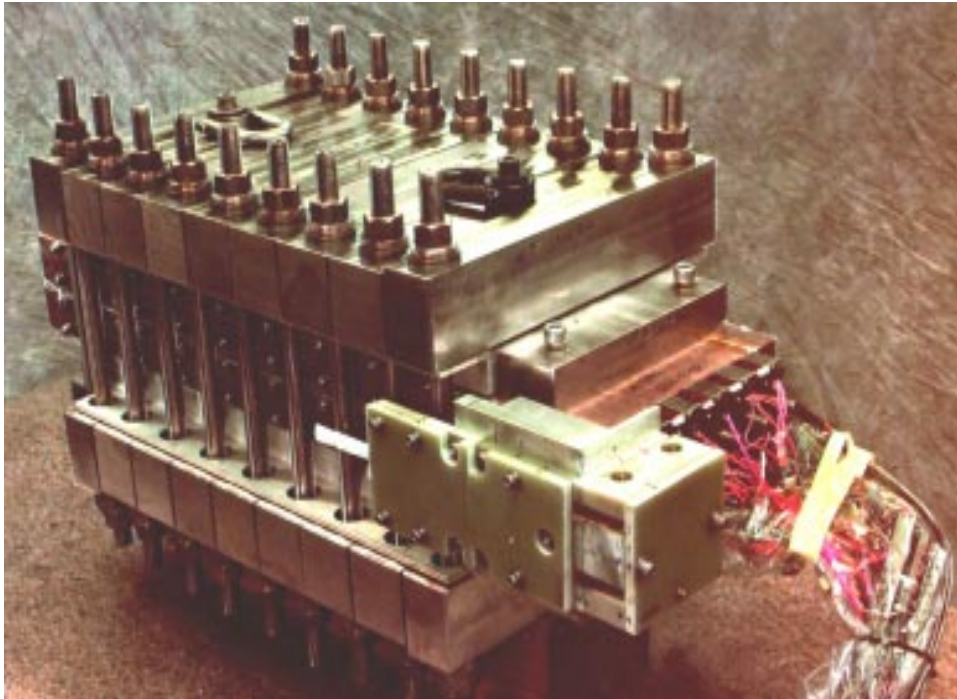


Figure 8. The first example of the LBNL common-coil magnet. This magnet was easily and quickly assembled, and attained its moderate short-sample limit without training. The field strength was limited by the poor quality of the available conductor, but the ease of assembly suggest possible cost-reduction capability of this concept.

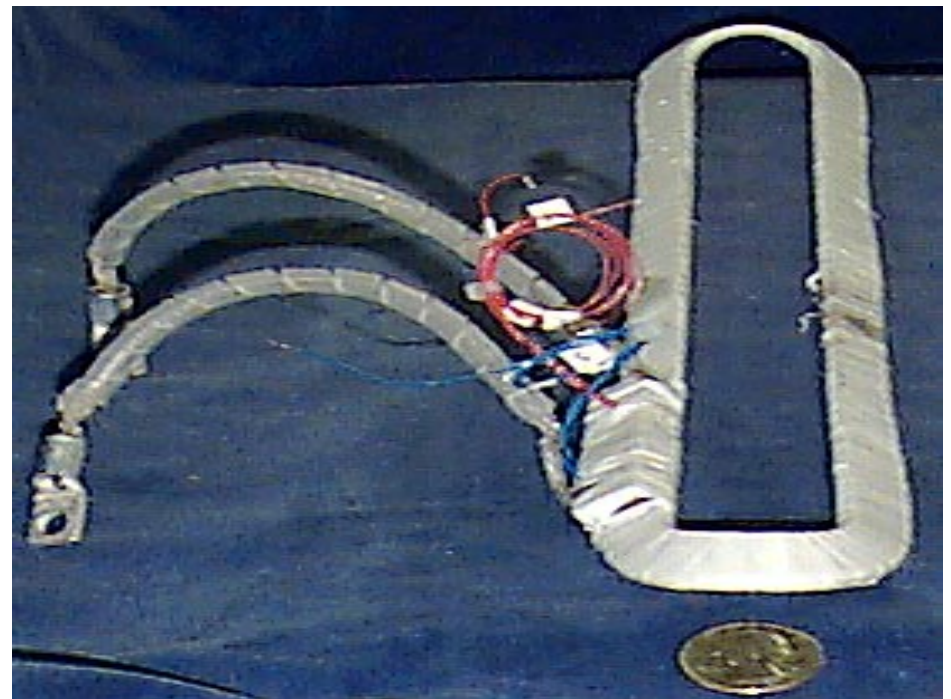


Figure 9. These HTS coils from IGC Advanced Superconductors, Inc. are two of four made in industry for Cornell University to verify the concept of a moderate-gradient quadrupole that can operate at 30 K and which takes little space. Two other coils have been successfully made by the American Superconductor Corporation.