fermilab report

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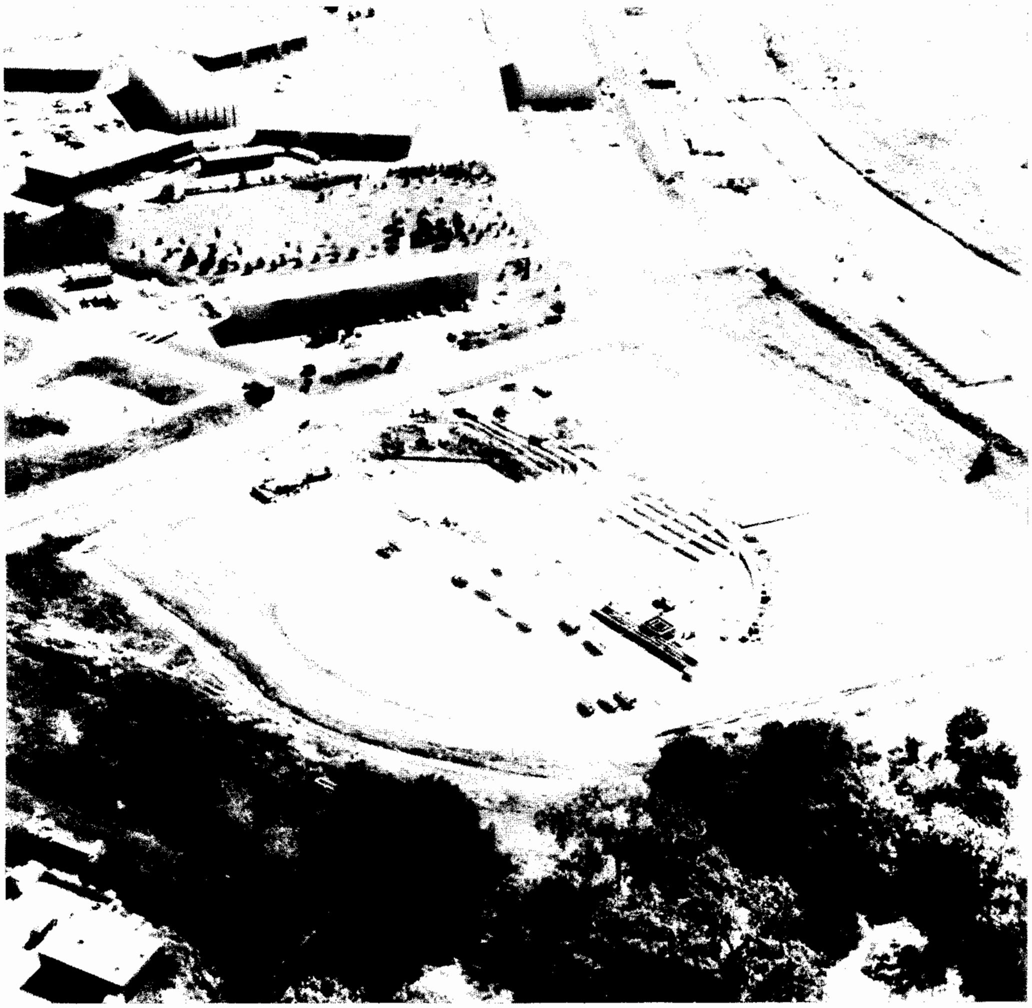

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Editors: R.A. Carrigan, Jr., F.T. Cole, R. B. Fenner
Contributing Editors: D. Beatty, M. Bodnarczuk, R. Craven, D. Green, L. McLerran, S. Pruss, R. Vidal
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87/1 **Fermi National Accelerator Laboratory** 0090.01

On the cover: Aerial view of the construction start on the new Fermilab Computer Center reveals the annular shape of the building. The photograph also shows (clockwise from project north of the Computer Center) the Helium Liquefier Facility, the Industrial Facility, and the Collider Detector at Fermilab Experimental Hall. *(Fermilab photograph 86-803-10)*

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Table of Contents

The 1987 Accelerator Startup

John Crawford and Robert Mau

In these early stages of the 1987 Collider-mode engineering run, it is perhaps appropriate to look back over the last year and assess where we have been, where we are now, and make some guesses about where we are going.

It has been 15 months since the Accelerator was shut down for a long nine-month civil construction period (time flies when . . .); that last run ended on October 13, 1985, at 0530 with the historic news that the Collider Detector Facility (CDF) had recorded 1.6-TeV proton-antiproton collisions. The euphoria was short-lived. The realization set in that there were going to be major upheavals in the Accelerator systems, that several large construction projects were beginning just as winter was making its appearance, and that we had committed to a startup schedule that left little room for miscalculation.

First, let's consider some of the major projects undertaken during the shutdown:

1. Construction of the D0 Collider Detector building.

2. Construction of a 21-ft-high overpass to carry the Main Ring beam above the B0 detector.

3. Change the Booster controls from the old Xerox 530-based system to the VAX system that the rest of the Accelerator was running on.

4. Upgrade of the 13.8-kV feeder system throughout the Accelerator.

5. Installation of Z/n plates (microwave instability dampers) at each Main Ring magnet.

6. Installation of the Booster to Debuncher beamline (the AP-4 line).

7. Installation of several "small" collider experiments in the Main Ring tunnel at B0, C0, and E0.

8. Rebuild approximately 500 Main Ring correction magnets.

9. Installation of a completely re-designed 8-GeV line (the Booster to Main Ring transfer line).

10. Construction of an experimental area at AP-50 in the Pbar Source.

11. Dismantling the entire refrigeration system between A4 and B1 (including refrigerator buildings) and then re-assembling the system once the B0 Overpass was completed.

12. Installation of 12 new transformers for the TEVATRON power supplies, and rebuilding 286 Main Ring and TEVATRON power supplies.

In addition to these major projects, literally hundreds of smaller improvements were made, each with its own requirement for de-bugging during the startup.

So, how has the startup gone? Well, we actually began bringing systems up around January 17, 1986, when commissioning of the AP4 beamline began. By the end of January, the line was being routinely used to provide protons to the Debuncher Ring. (It is worth noting that the protons were circulated in the same direction as antiprotons would normally travel, so the polarities of most devices in the ring had to be manually reversed, then reversed again for antiproton production.) Booster and Pbar Source studies continued until May 1, when installation of the new Booster control system began.

Booster and Main Ring startup began on July 18, with 8-GeV beam achieved in the Booster by July 27th. The next step was to commission the new 8-GeV line; this began on Friday, August 1, and beam was transported to the C0 abort dump by Monday, August 4. (Due to the continuing construction work, commissioning was carried out only on weekends. Because the tunnel was still open at D0 for the collision hall construction, beam had to be stopped at C0.) By August 11, a few turns of beam had been circulated in the Main Ring, but the next three weeks provided nothing but frustration for the tuners as coasting beam could not be established. Finally, a concentrated obstacle search yielded a garbage bag and a plastic beampipe cover - coasting beam followed on September 2. Main Ring beam was accelerated to 120 GeV by September 8, and cooldown of two sectors in the TEVATRON had begun.

TEVATRON power supply testing began on September 11, but all sectors were not cooled down and ramped until October 8. TEVATRON-accelerated beam was achieved on October 14 and beam was stored at 800 GeV by October 20. Antiproton stacking had begun in the Accumulator by November 12; by November 26, antiprotons had been reverse-injected into the Main Ring and accelerated to

150 GeV. On Sunday, November 30, antiprotons were accelerated to 900 GeV, stored, squeezed, and collided with 900-GeV protons.

By now, all was ready for the CDF detector to be moved into the collision hall during the week of December 15; however, a small setback occurred on December 7 when a high-field quench in the TEVATRON ruptured the cryostat of the E27-4 dipole, requiring the eventual replacement of four magnets. Once the CDF detector was in place, much work remained to be done on the gas systems; these required frequent accesses into the collision hall until about January 7. Collider commissioning began in earnest on January 10.

Where are we now and what remains to be done? The TEVATRON is now being filled twice per day. Each fill consists of three antiproton bunches and three proton bunches. Each antiproton bunch is formed by transferring a batch of antiprotons, consisting of 10 or 12 bunches, from the Accumulator to the Main Ring where they are accelerated to 150 GeV and then coalesced into a single bunch just before transfer to the TEVATRON. Three successive supercycles are used to form the X, Y, and Z bunches. On the fourth supercycle the proton bunches are formed using a similar sequence: A batch of protons, consisting of 6 to 8 bunches, is extracted from the Booster and injected in the Main Ring. After acceleration to 150 Gev, these bunches are also coalesced into a single bunch and transferred to the TEVATRON. Three successive Main Ring cycles within the supercycle form the A, B, and C bunches. Several 10-hour stores have been achieved. While luminosity and beam quality are not quite as good as we would like, there is reason to be optimistic. The set-up time for transfers also seems to be decreasing, despite glitches. The antiproton stacking rate has reached 9- to 10-billion antiprotons per hour. While this is below the 100 billion per hour called for in the design, it already exceeds the best achieved at CERN. The size and duration of the $\overline{p}$ stack is also increasing - we have attained a maximum of 150 billion antiprotons in the stack and this particular stack was stored in the Accumulator for 14 days before it was accidentally dropped. (For reference: the longest CERN has been able to maintain a stack has been 41 days.)

What does the future hold?

For the very near term, CDF will be turning on their central tracking chamber and the Accelerator will be scheduling three $\overline{p}$ transfers per day instead of two. There are on-going efforts to improve Main Ring efficiency, $\overline{p}$ stacking rate, and transfer efficiency all through the reverse injection, store, squeeze, and cogging operations. In the slightly longer term, we would like to see the whole colliding-beams operation change from a wild adventure to a somewhat dull routine.

Of course, far off in the hazy future lies another 800-GeV fixed-target run, with its own set of problems to be overcome. Stay tuned...

Superconducting Magnets

H.E. Fisk

Introduction

The TEVATRON at Fermilab, as a first-generation superconducting accelerator, has provided a working prototype for the future machines: UNK, HERA, RHIC, and the SSC. Indeed there are many areas where the designs for the new superconducting accelerators depend on improvements that are taking place. New superconducting wire gives higher current density that in turn yields higher-field dipoles. We can anticipate fine filament wire to reduce persistent current fields, although studies indicate that significant correction elements are still needed to correct systematic field errors. In response to calculations on the dynamic aperture required in accelerator designs, typical magnet coils include several wedges to generate a current distribution that is more nearly cos θ, thereby reducing higher order systematic multipoles. In the case of random errors, the available pool of measured multipole errors is beginning to give us a better understanding of how conductor placement errors vary with aperture.

The use of aluminum or stainless steel collars that constrain coil motion to negligible levels is an almost globally accepted feature of modern magnets. Cold iron surrounding the collared coil is also a feature of most recent designs. In fact, the superferric magnet is an example where the saturation of cold iron presents new challenges for the magnet designer.

Both active and passive quench protection schemes are being pursued in prototype accelerator systems tests. To meet economic demand, cryostats are being developed that have very low heat leak. An important, but not too well developed, R&D topic is high-gradient superconducting quadrupoles that are needed for the interaction regions of colliders.

Conductor

Superconducting accelerator dipoles that are now being built as prototypes all use NbTi. Over the past few years remarkable progress has been made in the critical current densities these conductors achieve at high fields. In 1983, the last 100 cable reels used in building TEVATRON magnets had an rms critical current density at 4.2K and 5T of 1700A/mm^2. TEVATRON cable purchased in 1984, made from high-homogeneity NbTi alloy, yields 2200A/mm^2. Present day SSC cables carry current densities up to 2700A/mm^2. Figure 1 (facing page) shows the history of high-current density NbTi alloy.

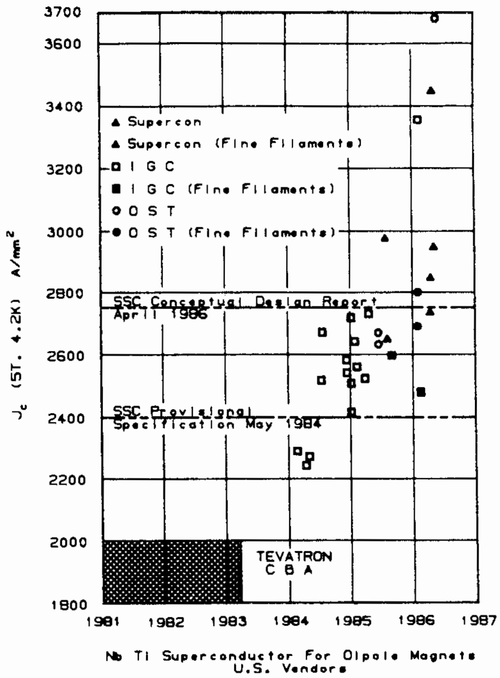


Figure 1. Progress in high-current density NbTi alloy strand.

Improvements

There are several factors that have contributed to this improvement. First, the NbTi alloy must be chemically homogeneous. Second, the formation of Ti-Nb-Cu intermetallic compounds at the filament and Cu matrix interface must be prohibited. If these intermetallics form during extrusion of the billet or in the drawing and heat treating process, they agglomerate into 1-2 μm particles that cause sausaging of the filaments and there is a consequent deterioration in critical current density as the filament diameter is reduced from 15-20 μm to 3-5 μm. Finally, it is necessary to appropriately mix heat treatments and cold work to obtain the proper microstrain in the final strand product.

Making the strand into a cable with the right mechanical properties and high current density has been a continuing R&D subject over the last few years. In addition to getting the physical dimensions and modulus of the conductor right, the cable must be made with minimal damage to the filaments. As the magnet bore radius decreases with increasing beam energy, the temptation has been to make cable with a larger keystone angle. Large keystone angle, however, leads to cable damage. With magnet designs that incorporate wedges it is possible to use cable with a small keystone angle, and this results in less than 10% reduction in J_c from strand to cable.

Cable Testing

As the critical current density has increased, the testing of cables has become more sophisticated. As discussed by Sampson in "Procedures for Measuring the Electrical Properties of Superconductors for Accelerator Magnets" (*Proceedings of the ICFA Workshop on Superconducting Magnets and Cryogenics,* P. Dahl, ed., 1986), the critical current that a cable will carry depends on whether the cable is oriented with its wide face parallel or perpendicular to the applied magnetic field. The cable self field is an especially important factor in evaluating its performance, and self field effects must be included in short sample tests on strands and cable if an absolute comparison is to be made among samples with various dimensions.

The uniformity of strands can be determined from photomicrographs of etched wire. A simpler test is to measure voltage versus current characteristics of a cable. It has been empirically established that in a transition from superconduction to normal conduction the resistivity is given by $\rho=\rho_0 I^n$. In the transition the value n measures the uniformity of the filaments. A large value of n means the filaments all make the transition simultaneously, while a small value implies necking down of the filaments or breakage that forces current to change filaments thereby generating resistive voltage. Typically a very good n value would exceed 50 while an average conductor would have an n of 30.

Fine Filaments

Largely in response to the SSC R&D considerations, wire manufacturers have developed superconductor with small filament diameter and high current density. The main motivation is the sextupole and decapole hysteresis at injection where magnetization is proportional to filament diameter times critical current density. If 3 μm filaments are desired in a 0.78 mm strand of Cu to superconductor ratio of 1.3, the number of filaments is roughly 29,000. To produce this many filaments a double stacking technique has been developed where a subelement billet is first processed and then used in a second billet. Examples produced include (19 x 1927) 36,613 filaments for inner SSC coils with J_c of 2400A/mm^2 (n=20) and outer SSC cable of (19 x 1086) 20,634 filaments with J_c of 2500A/mm^2 (n=26). Another approach is to attempt a single stacked 12-in. diameter billet with 40,000 filaments. In anticipation of this a 4-in. billet (4164 filaments) was stacked with the same elements that would make up the 12-in., 40,000-filament billet. Processing the 4-in. billet down to a 0.34 mm diameter strand where the filament diameter is 3.6

μm gave a J_c of 2700A/mm^2 (n=32). A similar billet when drawn down to 0.47-mm wire with 5 μm filaments yielded 3450A/mm^2 (n=42).

It has been known for some time that in the vicinity of one or two microns magnetization does not decrease linearly as filament size decreases. The increase in magnetization for small filament diameters is due to proximity coupling of neighboring filaments. Thus, it is important to measure magnetization to be sure that the decrease in filament size is giving the proper reduction in magnetization. Measurement is also essential in verifying similar magnetization for conductor produced under a variety of conditions, e.g., different manufacturers. Since magnetization is a property of the bulk superconductor, Sampson has noted that a measure of the integrity of the conductor is given by comparing the magnetization current density at low field (0.3T) with the current density at 5T as measured directly from transport current. Figure 2 shows this ratio versus filament diameter for a number of samples.

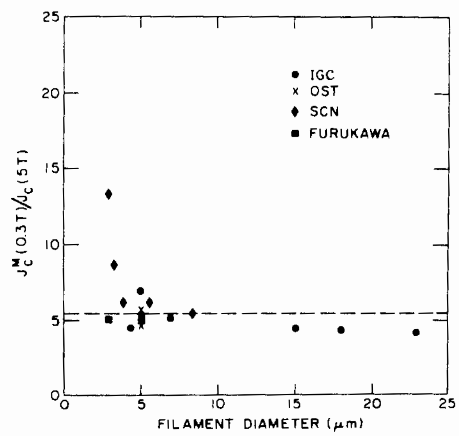


Figure 2. Critical current density ratio as determined by magnetization at 0.3T and from transport current at 5T. The ratio is plotted versus filament diameter. The data at small diameters with large ratios is caused by coupling of filaments that are too close together.

Fortunately the technical problems associated with small filaments have not been in serious conflict with the desire to obtain higher critical current density. In fact, solving the problems associated with the production of uniform small filaments has probably led to higher current density. It is, however, true that present samples of wire obtain higher current density for larger filament diameter. This tendency is shown in Fig. 3 (page 8). In the SSC program, where full-length correction coils are deemed necessary, the emphasis is to optimize current density at a filament size near 5 μm.

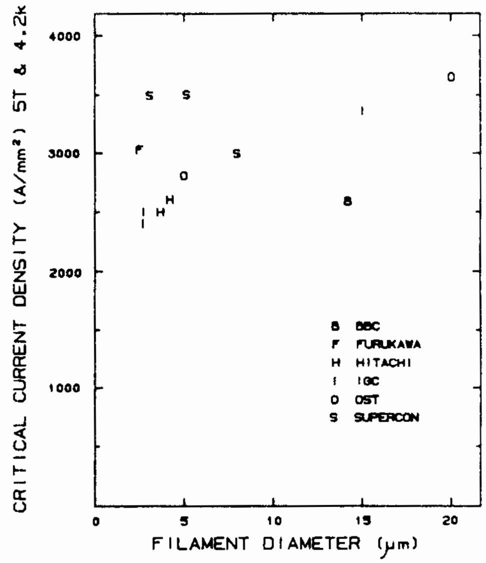


Figure 3. Critical current density versus filament diameter for recently produced NbTi strand.

Magnet Designs and Performance

Prototype dipoles have been built for UNK, RHIC, HERA, and the SSC projects. Design characteristics of these dipoles and the approximate number of constructed models are given in Table I (facing page). In addition to these, there are other recently constructed dipoles not listed in the table, such as the 9.3T and 5T magnets built at KEK with a clear aperture of 61 mm and 100 mm, respectively; a dozen 5 cm aperture, 1 m long Fermilab prototype dipoles, several 6T, 2-in-1, side-by-side BNL dipoles with 3.5 cm apertures, and a few examples of Nb_3Sn magnets. In addition, the LHC protagonists at CERN are planning a modest R&D effort to make prototype 2-in-1, side-by-side dipoles that could be employed in the LEP tunnel. The maximum field would be in the range 8 to 10T which requires either Nb_3Sn or NbTi with 1.8K operation.

All the magnets in Table I, except for the 90 mm UNK dipoles, are of the cold Fe variety. Cold Fe is chosen because it substantially increases the dipole field, typically 20 to 25% (thereby saving superconductor cost), provides a convenient mechanical structure and one that ensures the dipole field direction, provides shielding from stray fields, and costs less than a magnet with an equivalent thickness of Fe that is located outside the cryostat. On the negative side, there is more time and cost associated with warm-up and cool-down of the magnet system.

A special example of the cold Fe design is the superferric magnet that derives half of the 3.2T field from laminated iron and as a consequence requires minimal superconductor. The magnet has an almost traditional cross section (25 mm vertical

Table I.
Recently Constructed Accelerator Dipoles

	UNK	RHIC	HERA	SSC	Super-ferric
Beam Energy	3 TeV	100 GeV /amu	830 Gev	20 TeV	20 TeV
Coil i.d. (mm)	80 (90)*	80	75	40	25
Field (T)	5.0	3.45	4.65	6.6	3.2
Shells	2	1	2	2	1
Length (m)	5.8	9.48	9	16.6	28
Collar Material	SS	RX-630† + Fe Yoke	Al	Nitronic 40	Fe
No. of Prototype Dipoles	1* 6 (6m) 20 (1m)	1 (4.5m)	4 (9m)	6 (4.5m) 2 (3.5m) 8 (1m) 2 (17m)	3 (28m) 1 (7m) 10 (1m)

*Warm Iron Design †Glass-Phenolic

distance between pole tips) with the four turns nearest the mid-plane, two above and two below, on a circuit (I_1) separate from the outer four turns (I_2). The ratio

I_1/I_2 controls the normal sextupole moment as the iron saturates. There is a trim coil (I_3) on the edges of the pole face that can be used to zero the decapole. The conductor is 24 standard strands of 1.3/1 Cu/SC ratio wrapped on a Cu backing strip.

Quench Performance

The quench performance of eight BNL 4.5 m and 3.5 m SSC prototypes is shown in Fig. 4. These data are typical of UNK, HERA, and RHIC magnets. The maximum field is reached after about 4 or 5 quenches. Thus, training is not a problem. The superferric magnet also has no problem with quench performance because it achieves 3.5T before quenching.

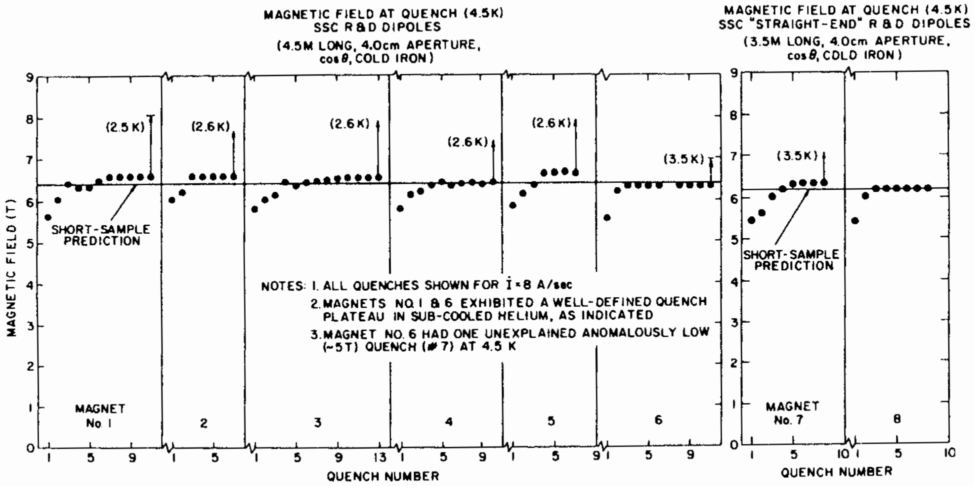


Figure 4. Quench performance of SSC 4cm prototype dipoles.

Relative to quench training there has recently been an interesting proposal and set of tests. It has been observed that a magnet can be trained to its asymptotic quench current at a given temperature, with fewer quenches, by lowering the temperature and then stressing the magnet with more current than anticipated for the asymptotic limit at the more elevated temperature. In tests at LBL, five virgin coils, i.e., with no previous quench history, have been cooled to 1.8K, powered without quenching to 7.2T which is 0.5T higher than the expected quench level at 4.2K, and then warmed to 4.2K. When quenched the first time at 4.2K, they have already reached their asymptotic quench current and further quenching does not yield a higher quench current. This phenomenona, called conditioning, has interesting applications for the SSC where it has been suggested that magnets would be quenched in strings as they are assembled in the tunnel. Conditioning would seem to be an easier process provided operation at reduced temperature is feasible without excessive costs.

There is debate about the use of aluminum (Al) versus stainless steel (SS) for collar material in the case of magnets that are not rapidly ramped for fixed-target physics where aluminum cannot endure the fatigue stress implied by millions of ramp cycles. The room temperature preload required with A1 collars is smaller than that required with SS since the A1 shrinks more than SS as the coil is cooled from room temperature to 4.5K. This means, in the case of A1 collars, the coils can be treated more gently without so much concern about cutting kapton insulation or allowing creep that causes loss of preload if the coil sits for long periods of time at room temperature. The amount of preload required for either A1 or SS is being investigated with strain gauges that can be read out either warm or cold, installed in the pole tips of the collars or adjacent to the coils themselves.

Field Quality

There are both random and systematic errors that need to be considered when designing a magnet. The random errors result from our inability to precisely locate conductor, while systematic errors come from the transport current density distribution and from persistent currents induced by the change of magnetic field encountered in ramping a magnet.

The field of these magnets is generally expressed in a two-dimensional multipole expansion since the multipoles are then easily related to dynamics in the accelerator:

$$B_y + iB_x = B_0 \sum_{n=0} (b_n + ia_n)\,(x + iy)^n$$

with $b_0=1$ and $a_0=0$. The dipole field (n=0) is given by B_0 and it is usual to suppress a factor of 10^{-4} in quoting the normal (b_n) and skew (a_n) moments. For all terms but the dipole field it is essential to choose a reference radius. Typically this is ≈2/3 of the radial distance to the inner conductor. In TEVATRON dipoles it is 1 in., while the SSC has set down 1 cm as its reference.

Random Errors

The placement errors are primarily due to the fact that azimuthally the conductor is not located exactly where it should be. As an example, one finds the normal sextupole moment for a single shell of uniform current density between radii R_1 and R_2 terminated at angle θ_0 to be

$$b_2 = \frac{1}{3}\left(\frac{w}{R_1}\right)\left(\frac{w}{R_2}\right)\frac{\sin 3\theta_0}{\sin \theta_0}$$

where w is the reference radius at which the moment is evaluated. For $\theta_0=60^0$, i.e., zero sextupole moment, $R_1=2$ cm, $R_2 = 3$ cm, and w=1 cm, we have for a small variation in θ_0, $\Delta\theta_0$, that

$$\Delta b_2 = \frac{-2}{\sqrt{3}}\left(\frac{1}{2}\right)\left(\frac{1}{3}\right)\Delta\theta_0 \ ,$$

which for an angular error of 1mr (i.e., 25 μm at a mean radius of 25 mm) gives 1.9 units of sextupole.

While the normal sextupole, decapole, 14 pole, etc., are allowed in a dipole design, they are made small by placing the conductor in blocks separated by Cu wedges. Other multipoles are not allowed unless symmetry in the magnet is violated. This means that while b_2, b_4, b_6, etc., are allowed, the existence of b_1, b_3, b_5, etc., implies a violation of left-right symmetry. Non-zero a_1, a_3, a_5 indicate up-down symmetry is broken, while a_2, a_4, a_6, etc. require both violation of up-down and left-right symmetry. In the magnet data accumulated to date, it is generally true that the rms widths get smaller as one progresses from the symmetry allowed, to up-down asymmetry violation, to left-right asymmetry violation, to breaking of both left-right and up-down symmetry.

For the higher energy machines it has been important to understand how these random errors scale with coil radius. From the multipole data on CBA and TEVATRON magnets it was anticipated that $\Delta\theta_0$ would vary as $1/\sqrt{R_1}$, where R_1 is the inner coil radius, and in this way magnet errors were scaled to the 4 cm and 5 cm possible apertures for SSC dipoles. In Fig. 5 the rms multipole width data on six 4.5 m long, 4 cm aperture magnets are presented. Also shown are predictions that indicate the measured cos θ magnet errors are safely smaller than those used in tracking calculations.

Data on seven 1-meter-long superferric magnets are also displayed in Fig. 5. The random errors that give rise to multipoles in this example include conductor placement, iron dimensions and die stamping tolerances, iron permeability variations, stacking factor variations, and up-down iron permeability mismatch. Two sets of measurement data are shown since problems at the low excitation are generally related to magnet iron, while the 2T data indicate sensitivity to conductor placement and iron saturation.

There are also multipole data from HERA, RHIC, and UNK. While these data do not change our understanding of the conclusions reached on scaling, they do confirm that superconducting magnet technology is being readily assimilated into the newer magnet programs at these laboratories. All measurements to date on random magnet errors indicate tooling and construction techniques are adequate to make coils that are good for accelerators.

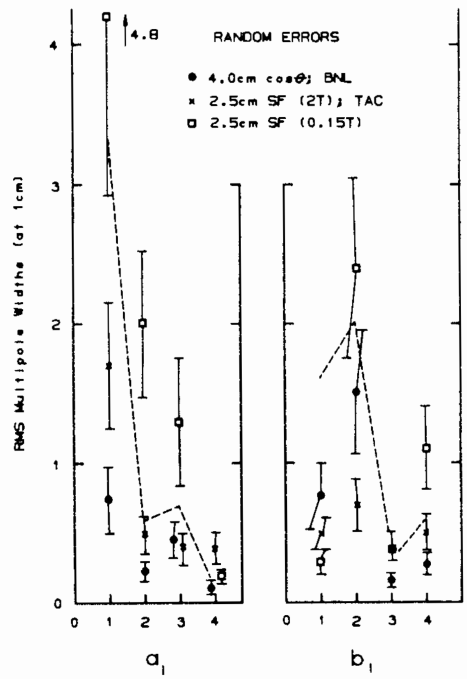


Figure 5. RMS multipole widths for 4cm cos θ and superferric dipoles. The dashed lines are a prediction of the expected sigmas for the 4cm cos θ magnets.

Systematic Errors

The cos θ magnets have three major sources of systematic multipoles: (a) deviation from a pure cos θ current distribution, (b) iron saturation, and (c) persistent current effects. As mentioned earlier, the higher order multipoles b_4, b_6, b_8, b_{10}, etc., can be designed to average zero with appropriate wedges. Iron saturation can be avoided if not too much additional field is desired from the iron. The typical dipole field enhancement due to iron is slightly more than 20%. This can give rise to a few units of saturation sextupole moment although the iron can also be shaped to reduce this level. For example, the cold Fe SSC cos θ magnet has 1.2 units of saturation sextupole moment.

Doublets of persistent current induced in the filaments of the superconductor by a change of the magnetic field give rise to systematic sextupole, decapole, etc. The problem is at injection where the external field is low and J_c is high. For example, at UNK where the injection field will be in the range 0.67 to 1T, the sextupole moment is -20 units (at 3.5-cm) for 10 μm filament wire. For HERA at injection

(.23T) the sextupole field is -30 units (at 2.5 cm) with 14 μm filaments. The 4 cm SSC prototype dipoles have a sextupole moment at injection, .33T, that is 25 units (at 1 cm) below the asymptotic sextupole built into the magnet. Since the filament diameters of the SSC prototype cables are large, ≈20 μm, the effect will be reduced significantly with finer filaments. A reduction by a factor of five to ten would still leave a substantial sextupole field. To correct these unwanted fields, all of the presently planned accelerators have long (at least half the dipole length) sextupole windings and possibly decapole windings.

There is an alternative scheme that could be used to correct the persistent current fields. In the sextupole case it employs strips of superconductor located in 4θ fashion inside the dipole aperture, perhaps in lieu of the present correction windings. No transport current is put through these strips; they produce persistent currents by induction that can be used to cancel the dipole winding persistent fields. Recently, a test at Fermilab showed that the 4 cm SSC prototype persistent current sextupole field at 0.3T was reduced by 83%. For the Fermilab test the corrector was fabricated using 45 μm filament NbTi conductor in a Cu matrix that was roughly 1.2 mm square in cross section. Figure 6 shows a picture of the corrector and the dipole winding cross section. To make a more effective correction, smaller diameter filament wire would be needed, such as 30 μm.

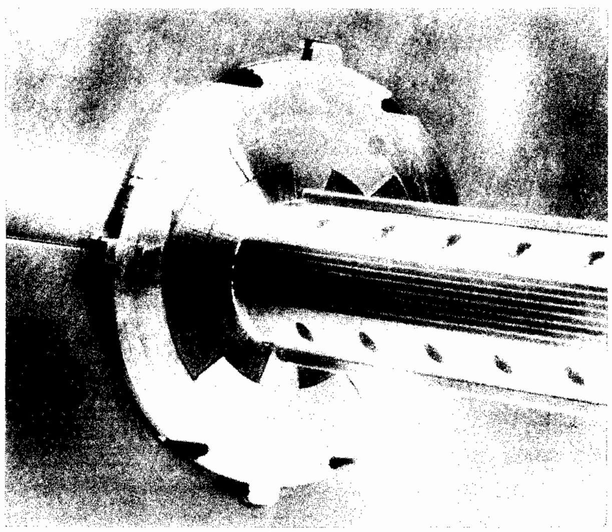


Figure 6. Passive corrector strips used to correct the persistent current sextupole field in an SSC prototype dipole. (Fermilab photograph 86-88-7)

Tracking studies that use multipole errors for magnets are becoming increasingly important in specifying both machine optical design and acceptable magnet tolerances. A.W. Chao at the Central Design Group of the SSC has suggested specifications for multipole field errors in both random and systematic categories as given in Table II.

Table II.

Specifications of multipole field error tolerances for the SSC dipole magnet. The rms specifications are given for the random field errors. The units are $[a_n]=[b_n]=10^{-4}cm^{-n}$.

	Random	Systematic
a_1	0.7	0.2
a_2	0.6	0.1
a_3	0.7	0.2
a_4	0.2	0.2
a_5	0.2	---
a_6	0.1	---
a_7	0.2	---
a_8	0.1	---
b_1	0.7	0.2
b_2	2.0	1.0
b_3	0.3	0.1
b_4	0.7	0.2
b_5	0.1	0.02
b_6	0.2	0.04
b_7	0.2	0.06
b_8	0.1	0.1

In determining the magnet's good-field region an important task is to sort the magnets on the basis of normal and skew sextupoles and place them in the ring appropriately. For the 4 cm SSC case, the aperture over which linear motion is achieved increases from 0.55 ± 0.13 cm to 0.89 ± 0.20 cm by sorting magnets in groups of 60. The dynamic aperture, defined by stable particle motion, is 1.2 ± 0.15 cm and is determined primarily by systematic higher multipoles. In the results just quoted it has been assumed that there are both sextupole and decapole correctors located on the bore tubes of the dipoles to correct the systematic average of these multipoles.

With the ability of modern programs to calculate beam dynamics on a turn-by-turn basis, there is a consequent need for accurate magnetic field data and accelerator performance data. Efforts are underway at Fermilab to understand the beam behavior in the TEVATRON vis-a-vis the Magnet Test Facility magnet data. Topics being studied include: vertical and horizontal coupling, beta function changes with low-β quadrupole tuning, and resonance width studies. Presumably, as other laboratories install measured superconducting magnets they will also want to use magnetic field data to understand the beam.

Correction Coils

Both the HERA and SSC project groups have developed correction coil windings that are attached to the beam bore tube.

In the case of HERA there are both quadrupole and sextupole coils over a length of 5.9 m on the 9.6 m long beam pipe whose outer diameter is 6.03 cm. The coils are a single layer made from 1.03 mm diameter insulated NbTi wire of Cu/SC ratio 1.8 with filaments 15 μm in diameter. The sextupole coils are made from three subcoils each having 21 turns, while the quadrupole coils are made from two subcoils of 33 windings each. The nominal sextupole (quadrupole) field is 0.030T (0.045T) at a radius of 0.25 cm for a current of 65A (85A).

The correction coils for the SSC will include sextupole, octupole, and decapole correction windings. These coils are being fabricated with a new technique in which a numerically controlled head ultrasonically embeds fine superconducting (SC) wires in a substrate coated with special adhesive. Wire can be laid at the rate of 10 meters per minute, and the transverse positional accuracy is 25 μm. The substrate is wound in its flat condition and later affixed to the beam tube. Both 0.15mm and 0.20mm wires have been used to build prototype coils. Seven 4.5 m coils of this type have been built and tested; they all give adequate performance, have small unwanted harmonics, and are adequately aligned rotationally.

The Mole

Accurately measuring the magnetic field of a long magnet with a small bore, such as the SSC prototypes, is a nontrivial problem. Brookhaven National Laboratory (BNL) has developed a 61 cm long rotating probe that is 2.5 cm in diameter which can be pulled through a warm bore tube in the magnet. The probe is driven by an air motor through a gear reducer. The measuring coil intercepts radial flux and there are also two bucking coils. The Mole assembly contains a gravity sensor to measure the dipole field angle, and there is an encoder attached to the measuring coil to readout angle. The measuring coil signals are brought out of the Mole via slip rings, and the signals from the three coils are digitally processed with voltmeters (Hewlett Packard Model 3457A). The coil rotates one revolution in 3.5 seconds.

The system has been calibrated in both large and small bore magnets. Recently, it has been used to measure a TEVATRON dipole at 4T and has also been used in warm and cold measurements of the first two 16.6 m long SSC prototypes. The data shown in Fig. 7 represent the measured warm skew and normal quadrupole moments for the second long SSC magnet. Although there are still a number of

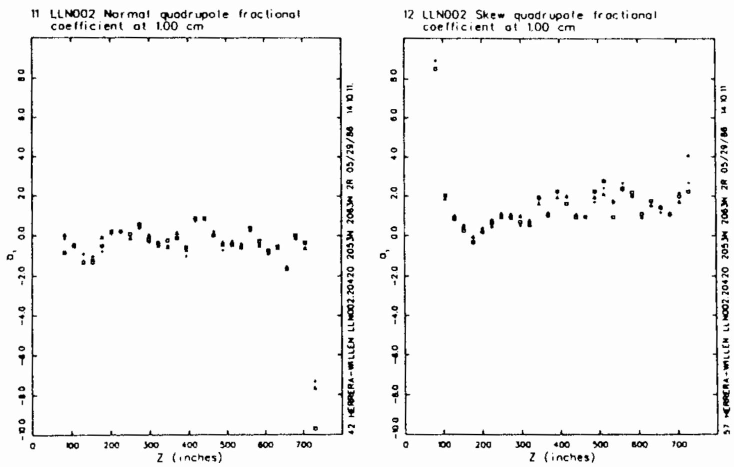


Figure 7. Normal and skew quadrupole moments for the second 17m SSC prototype magnet. The measurements are made at room temperature every 61cm with the Mole. There are three measurements at each longitudinal position.

mechanical improvements to make, the device is already being used to understand the first long SSC prototype dipoles.

Quench Protection

The protection of magnets during quenches is accomplished with current bypass circuitry that is in parallel with the magnet coils. The bypass circuit is either self-activating with diodes, or the detection of resistive magnet voltage causes normally open bypass SCR's, or thyristors, to close. These two systems are referred to as passive and active. In either case there is additional circuitry to monitor the voltage across magnet strings and take appropriate action such as the shutdown of power supplies and the firing of quench heaters located next to coils that can be used to fully distribute the quench energy throughout the coil if necessary.

The TEVATRON system is active while the passive HERA scheme uses cold diodes located in an access port on the magnet cryostat. The SSC project is slated to use warm diodes as the quench bypass switch. These warm diodes could be replaced with cold diodes if quench tests with prototype magnets are successful and if diodes can be found that are radiation resistant.

The length of magnet or magnet string that is included in a single bypass circuit depends on many factors. The stored energy in the magnet must be distributed quickly enough to keep the temperature in the coil below 450K where solder melts. The self propagation of the quench zone in the magnet, i.e., the quench velocity, is an important parameter. In general the quench propagates more quickly as the Cu content in the winding is reduced, which is good. However, the smaller cross section of Cu raises the local resistance that, in turn, raises the magnet voltage to ground. This is bad! So there is a design problem in which the adiabatic approximation to the heat diffusion equation is solved by allowing I^2 R losses to raise the coil temperature during a quench to some final value T_{max} :

$$A^2 \int_{T_c}^{T_{max}} \frac{\mu C}{\rho}\, dT = \int_0^t I^2\, dt \ .$$

Here the right-hand side of the equation, measured in 10^6 A^2 sec (Miits), is dependent on the magnet's current waveform while the left-hand side depends on density μ, specific heat C, cable area A, and resistivity ρ of the material in the cable. Several computer programs exist that can be used to make the T_{max} and voltage to ground calculations.

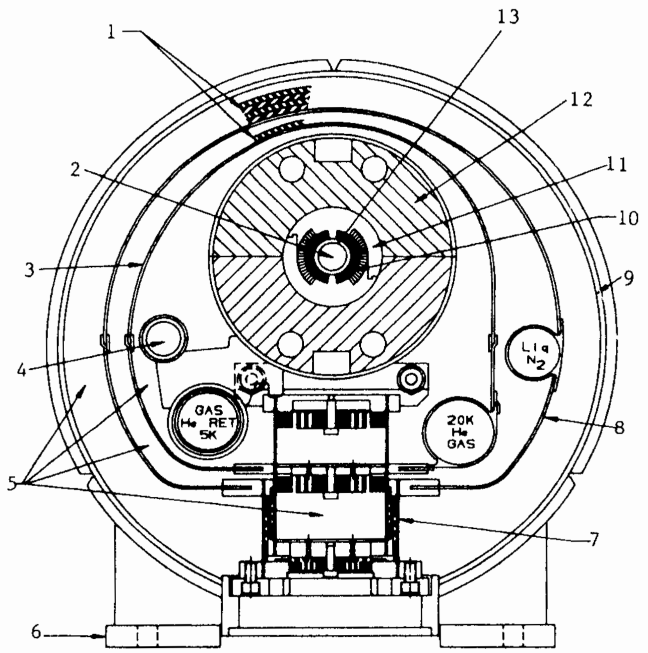
There are a few problems that may need attention. In the interconnection region between magnets, quench growth can be very slow and hard to detect. Here cables need to be completely stabilized with copper. In the new SSC-type magnets, where Cu wedges are used to reduce high-order multipoles, the delay of the quench propagation across the wedges needs to be understood. Early measurements do not indicate this to be a serious problem. The voltage to ground needs to be measured under various conditions and carefully evaluated relative to the coil insulation scheme.

Cryostats

The heat leak into the 4.5K helium system of a magnet becomes a serious economic problem for long strings of magnets. Because the heat leak in a cryostat is dominated by supports and superinsulation, there is a need to make the path length through which the heat must travel reasonably long and small in cross section. This is one of the main reasons the cold iron designs have been developed. All of the four superconducting machines mentioned here have cold iron.

The UNK/HERA design has an 80K LN_2/60K He gas-cooled radiation shield to decrease the cryogenic load at 4.5K, while the SSC and RHIC design has an additional radiation shield at an intermediate temperature (≈20K).

There are two basic suspension systems: The HERA and UNK type, and the SSC and RHIC style. Both support systems have the single-phase assembly and radiation shields inside a vacuum vessel. In the HERA design the single phase assembly is suspended with tension elements. The UNK model has titanium alloy suspension rods. The SSC and RHIC single phase assembly support is done with a folded post as shown in Fig. 8. The post, made principally of G-11CR, has thermal intercepts at room temperature, 80K, 20K, and 4.5K. It is presently built to withstand static vertical and lateral forces of 1.8g and 0.8g respectively. In addition, it will withstand seismic excitations corresponding to the vertical and horizontal shock response spectra defined in NRC Regulatory Guide 1.61, scaled to 0.3g.



1. Superinsulation
2. Beam Vacuum
3. 20K Heat Intercept
4. Liquid He Return
5. Insulating Vacuum
6. Mounting Base
7. Magnet Support Post
8. 80K Heat Intercept
9. Outer Vacuum Vessel Assembly (Fe)
10. Superconducting Coil
11. Stainless Steel Collar
12. Magnet Steel
13. Beam Tube

Figure 8. Cross section of the support system for the 4 cm SSC magnet.

Heat Leak

The design heat leak budget for the 17-meter SSC magnet is 25 watts, 2.5 watts, and 0.3 watts to the 80K, 20K, and 4.5K systems, respectively. Tests of individual posts in a dewar show that these values can be met. For example, the heat leak to 4.5K per post is measured to be ≈25mW. A 17 m-long heat leak model with a dummy thick-walled pipe to resemble a magnet coil is presently under test at Fermilab. Preliminary data indicate the 4.5K heat leak is about as expected. Data taking and analysis are still under way relative to the 20K and 80K systems.

The HERA and UNK test results are just beginning to come in. In preliminary tests the most recent 9 m-long HERA dipole has static heat loads to 4.6K and the 60K shield of 11 ± 1W and 40 ± 5W, respectively. The warm Fe UNK dipole static heat leak has been measured at 2.5 ± 0.8W/m with the calculated expectation of 2.0W/m. The cold Fe dipole is expected to have a static heat leak of 2W compared to the calculated value of 12 watts for the warm iron magnet.

The conclusion to be reached relative to cryostats is that new suspension systems and superinsulation are being developed that will allow these large magnet systems to operate economically.

Future Projects

There are a number of projects on the schedule of things to come. Prototype high-gradient quadrupoles with a 4 cm aperture are to be built for the SSC R&D effort. The anticipated gradient is 2.3T/cm. There will be production of 1m models at LBL with long 3.3 m quads being built at Fermilab. The long-term goals at the TEVATRON call for high-gradient quads that will produce a β of 1/2m at B0 and D0. The goal is to make 7.5 cm-aperture magnets with a gradient between 2 and 2.5T/cm. This can be done only with low temperature operation at 1.8K, and it is anticipated that NbTiTa alloy will be used. The ternary alloy critical current density is expected to be as much as 20% greater than NbTi at 1.8K.

Operation of magnet systems at 1.8K is an interesting new venture that is already beginning to receive attention.

The quest for higher field dipoles should go ahead. Reaching 10T and beyond will require engineering ingenuity and possibly new techniques for building magnets. It would be encouraging to find several different techniques that work.

Finally, it will be a great triumph to see most of the magnets discussed actually built and put to work in the superconducting machines that are now in the design and construction stages.

Announcements

Enrico Fermi Award Presented to Ernest Courant and M. Stanley Livingston . . .

Ernest Courant of Brookhaven National Laboratory and the late M. Stanley Livingston (1905 - 1986), a former associate director of Fermilab, were named co-recipients of the Department of Energy's Enrico Fermi Award for 1986. The proclamation, signed by President Reagan, cites Livingston posthumously "For his leadership contributions to the development of nuclear accelerators over a half-century, from his involvement in the designing of the first cyclotrons to his role in the discovery of strong (alternating gradient) focusing, now used throughout the world for the design of nuclear accelerators and particle beams of the highest energies."

Reorganizations . . .

The Director's Office has announced the following changes in the management of the Accelerator Division:

Following a five-year stint as Head of the Accelerator Division, during which time he was instrumental in the construction and success of the Energy Saver/ Doubler/TEVATRON, **J. Ritchie Orr** has, at his own request, joined the Technical Support Section where he will be involved in the Laboratory's SSC activities.

Helen Edwards, formerly Deputy Head of the Accelerator Division, is now Head of the Accelerator Division. She was recently presented with the E.O. Lawrence Award by the Department of Energy in recognition of her vital role in the construction of the TEVATRON.

John Peoples, prime mover as Head of the Pbar Source Department in the design and construction of the Pbar Source, replaces Helen Edwards as Deputy Head of the Accelerator Division. **Gerald Dugan** leaves his position as Head of Accelerator Systems for the Pbar Source to take on the responsibilities of Head of the Pbar Source.

Charles Ankenbrandt becomes Head of the Accelerator Theory Department, while **Lee Teng**, former Head of Accelerator Theory, joins the medical accelerator project which is designing a prototype medical proton-therapy accelerator for Loma Linda University Medical Center.

In addition, the following teams will rotate through the cycle of responsibility for TEVATRON and Main Ring running (with specific emphasis on the indicated areas): **Philip Martin** and **Stanley Pruss**: recommissioning of the TEVATRON and Main Ring, respectively; **Michael Harrison** and **Frank Turkot**: fixed target; and **David Finley** and **Rod Gerig**: Collider operations.

Also, **Ernest Malamud** and **Paul Mantsch** will head a group to design a new low-β for the D0 detector.

*("**Announcements**" cont'd.)*

Summer Housing Deadlines . . .

The deadline for receipt of reservations for summer on-site housing is Monday, March 3, 1987. Housing assignments will be made in April, and responses will be mailed April 10, 1987. The starting date for summer occupancy in June 1. For further information, please contact the Housing Office at (312) 840- (ext.) 3777.

Change in *Fermilab Report* Publication Frequency . . .

Beginning with this issue, *Fermilab Report* will appear bi-monthly.

Manuscripts, Notes, Colloquia, Lectures, and Seminars

prepared or presented from October 20, 1986, to February 12, 1987. Copies of technical publications with Fermilab publication numbers can be obtained from the Fermilab Technical Publications Office, Theoretical Physics Department, or Theoretical Astrophysics Group, 3rd floor, Wilson Hall. Copies of some articles listed are on the reference shelf in the Fermilab Library, 3rd floor crossover, Wilson Hall.

Manuscripts and Notes

Experimental Physics

R. Gomez et al. Experiment #557/672	Measurement of the Nuclear Enhancement in High E_t and Jet Event Production (FERMILAB-Pub-86/160-E; submitted to Phys. Rev.)
Experiment #691 J.C. Anjos et al.	Measurement of the D^+ and D^0 Lifetimes (FERMILAB-Pub-86/155-E; submitted to Phys. Rev. Lett.)
J.C. Anjos et al. Experiment #691	Measurement of the D_s^+ Lifetime (FERMILAB-Pub-87/29-E; submitted to Phys. Rev. Lett.)
R. Belusevic and D. Rein Experiment #733/649	Is There a Way to Measure the Deep-Inelastic Cross-Section Using Wide-Band Neutrino Beams? (FERMILAB-Pub-87/19-E; submitted to Z. Phys. C)

Theoretical Physics

R.D. Pisarski and J.D. Stack	Spin Dependent Potential for Heavy Fermions on the Ends of a String (FERMILAB-Pub-86/122-T; submitted to Phys. Rev. D)
St. Glazek	Light Front QCD in the Vacuum Background (FERMILAB-Pub-86/123-T; submitted to Phys. Rev.)

C. Quigg	The Superconducting Super Collider: Scientific Motivation and Technical Progress (FERMILAB-Conf-86/126-T; presented at the 6th International Conference on $\bar{p}p$ Physics, Aachen, Germany, June 30 - July 4, 1986)
S.J. Parke	Resonant Neutrino Oscillations (FERMILAB-Conf-86/131-T; presented at the 14th SLAC Summer Institute on Particle Physics, Stanford, California, August 5 - 8, 1986)
L. McLerran	Review of Properties of Quark-Gluon Plasma and Ultra-Relativistic Nuclear Collision (FERMILAB-Conf-86/134-T; presented at the IX Workshop on High Energy Physics and Field Theory, Protvino, U.S.S.R., July 1986)
R.K. Ellis et al.	Soft Radiation in Parton Parton Scattering (FERMILAB-Pub-86/141-T; submitted to Nucl. Phys. B)
H. Itoyama and T.R. Taylor	Supersymmetry Restoration in the Compactified $0(16) \otimes 0(16)'$ Heterotic String Theory (FERMILAB-Pub-86/142-T; submitted to Phys. Lett B)
C.T. Hill et al.	Ultra-High Energy Cosmic Rays From Superconducting Cosmic Strings (FERMILAB-Pub-86/147-T; submitted to Phys. Rev.D)
K. Lee	Topological Mass Terms on Axion Domain Walls (FERMILAB-Pub-86/148-T; submitted to Phys. Lett. B)
M. Soldate	Partial-Wave Unitarity and Closed-String Amplitudes (FERMILAB-Pub-86/149-T; submitted to Phys. Lett. B)
R.K. Ellis and B.R. Webber	QCD Jet Broadening in Hadron-Hadron Collisions (FERMILAB-Conf-86/151-T; presented at the 1896 Summer Study on

	the Physics of the Superconducting Super Collider, Snowmass, Colorado, June 23 - July 11, 1986)
H. Itoyama and H.B. Thacker	Lattice Virasoro Algebra and Corner Transfer Matrices in the Baxter Eight-Vertex Model (FERMILAB-Pub-86/152-T; submitted to Phys. Rev. Lett.)
W.-K. Tung	Parton Luminosities and Small-X Physics (FERMILAB-Conf-86/153-T; presented at the 1986 Summer Study on the Physics of the Superconducting Super Collider, Snowmass, Colorado, June 23 - July 11, 1986)
C.T. Hill and L.M. Widrow	Superconducting Cosmic Strings with Massive Fermions (FERMILAB-Pub-86/162-T; submitted to Phys. Lett.)
J.C. Sexton and H.B.Thacker	Scaling Studies of QCD on Asymmetric Lattices (FERMILAB-Conf-86/165-T; presented at Lattice Gauge Theory'86, Brookhaven National Laboratory, Upton, New York, September 15 - 19, 1986)
V. Baluni	Dynamical Gauge Hierarchies (FERMILAB-Pub-86/169-T; submitted to Phys. Rev. Lett.)

Theoretical Astrophysics

N. Vittorio and M.S. Turner	The Large-Scale Peculiar Velocity Field in Flat Models of the Universe (FERMILAB-Pub-86/79-A; submitted to Astrophys. J.)
A. Cavaliere and A.S. Szalay	Primeval QSOs (FERMILAB-Pub-86/119-A; submitted to Astrophys. J.)
A. Hosoya et al.	The Critical Dimension for Chaotic Cosmology (FERMILAB-Pub-86/121-A; submitted to Nucl. Phys.)

J.A. Stein-Schabes and M. Gleiser	Einstein-Kalb-Ramond Cosmology (FERMILAB-Pub-86/125-A; submitted to Phys. Rev. D)
E. Copeland and N. Turok	Cosmic String Interactions (FERMILAB-Pub-86/127-A; submitted to Phys. Rev. Lett.)
E.W. Kolb	Cosmological Phase Transitions (FERMILAB-Conf-86/128-A; submitted to the Proceedings of Gravitation in Astrophysics, Cargese, France, June 22 - 30, 1986)
T.P. Walker and D.N. Schramm	Resonant Neutrino Oscillations and the Neutrino Signature of Supernovae (FERMILAB-Pub-86/133-A; submitted to Phys. Lett. B)
E.W. Kolb	Cosmology and Extra Dimensions (FERMILAB-Pub-86/138-A; to appear in the Proceedings of the International School of Particle Astrophysics, Eriche, Italy, May 20 - 30, 1986, and presented at the 17th GIFT International Seminar on Theoretical Physics and Cosmology, Peñiscola, Spain, June 2 - 7, 1986)
M.S. Turner and L.M. Widrow	Old Inflation is Not Prevented by Large Amounts of Anisotropy (FERMILAB-Pub-86/143-A; submitted to Nature)
E.W. Kolb	Particle Physics and Cosmology (FERMILAB-Conf-86/146-A; based on lectures presented at the 1986 Theoretical Advanced Studies Institute, Santa Cruz, California, July 10-17, 1986)
M.S. Turner	Thermal Production of Not So Invisible Axions in the Early Universe (FERMILAB-Pub-86/150-A; submitted to Phys. Rev. Lett.)

M.S. Turner et al. — Double Inflation: A Possible Resolution of the Large-Scale Structure Problem (FERMILAB-Pub-86/158-A; submitted to Astrophys. J.)

J.A. Stein-Schabes — Inflation in Spherically Symmetric Inhomogeneous Models (FERMILAB-Pub-86/159-A; submitted to Phys. Rev.)

M.S. Turner — Inflation in the Universe, Circa 1986 (FERMILAB-Conf-86/168-A; to be published in the Proceedings of the GR-11, Stockholm, Sweden, July 1986)

L. Kawano et al. — Primordial Lithium: New Reaction Rates, New Abundances, New Constraints (FERMILAB-Pub-87/16-A; submitted to Astrophys. J. Lett.)

General

J.A. Carson and R. Bossert — A Technique for Epoxy Free Winding and Assembly of COS θ Coils for Accelerator Magnets (Submitted to the 1986 Applied Superconductivity Conference, Baltimore, Maryland, September 28 - October 3, 1986)

J.D. Cossairt — Shielding Design at Fermilab; Calculations and Measurements (FERMILAB-Conf-86/156; submitted to the Proceedings of the 20th Mid-Year Topical Meeting of the Health Physics Society: "Health Physics of Radiation Producing Machines," Reno, Nevada, February 8 - 12, 1987)

J.D. Cossairt and A.J. Elwyn — Personal Dosimetry in a Mixed Field of High Energy Muons and Neutrons (FERMILAB-Conf-86-157; submitted to the Proceedings of the 20th Mid-Year Topical Meeting of the Health Physics Society: "Health Physics of Radiation

	Producing Machines," Reno, Nevada, February 8 - 12, 1987)
A.D. McInturff et al.	The 5cm Aperture Dipole Studies (Submitted to the 1986 Applied Superconductivity Conference, Baltimore, Maryland, September 28-October 3, 1986)
R. Pordes	Review of the Status of the FASTBUS Standard Routine Specification (TM-1427; submitted to the 1986 IEEE Nuclear Science Symposium, Washington, D.C., October 29 - 31, 1986)
Q.S. Shu	A Systematic Study to Reduce the Effects of Cracks in Multilayer Insulation: 1 Theoretical Model (Submitted to Cryogenics)
Q.S. Shu et al.	A Systematic Study to Reduce the Effects of Cracks in Multilayer Insulation: II Experimenters Results (Submitted to Cryogenics)
Q.S. Shu et al.	Heat Flux from 277 to 77 K Through a Few Layers of Multilayer Insulation (Submitted to Cryogenics)
S. Qian and A. Van Ginneken	Characteristics of Inelastic Interactions of High Energy Hadrons with Atomic Electrons (FERMILAB-Pub-86/145; submitted to Nucl. Instrum. Methods A)
I. Gaines et al.	The ACP Multiprocessor System at Fermilab (FERMILAB-Conf-87/21; presented at the Computing in High Energy Physics Conference, Asilomar State Beach, Calif., February 2-6, 1987)
F.T. Cole and F.E. Mills	Recent Progress in Particle Accelerators (To be published in Advances in Electronics and Electron Physics)
D.A. Edwards	Accelerator Technology (Submitted to the XXIII International Conference on High Energy Physics, Berkeley, Calif., July 1986)

B. Cox et al.	Heavy Flavors (FERMILAB-Conf-86/166 [SLAC-PUB-4144, CALT-68-1411]; To appear in the Proceedings of the 1986 Summer Study on the Physics of the Superconducting Super Collider, Snowmass, Colorado, June 23 - July 11, 1986)
B. Cox and D.E. Wagoner	The J/ψ Trigger-Tag for Study of Weak Beauty Quark Decays at the SSC (FERMILAB-Conf-86/167; submitted to the proceedings of the 1986 Summer Study on the Physics of the Superconducting Super Collider, Snowmass, Colorado, June 23 - July 11, 1986)
W.S. Freeman et al.	Measurements of Neutron Spectra and Doses in the TEVATRON Tunnel for Up to 800 GeV Circulating Proton Beams (Submitted to the 20th Midyear Symposium of the Health Physics Society, "Health Physics of Radiation Generating Machines," Reno, Nevada, Feb. 8 - 12, 1987)
Y. Fukui et al.	Sources for Proportional Tube Gain Variation - What To Do About It (TM-1434; submitted to the Proceedings of the Gas Sampling Calorimetry Workshop II, Fermilab, October 31-November 1, 1985)

Physics Notes

F. Juravic, Jr.	Helium Mass Spectrometer Leak Detector Modified to Sense Neon for Cryogenic Leak Certification (FN-437; presented at the International Workshop on the Leak Detection and Repair of Leaks in Large Vacuum Systems, Baltimore, Maryland, October 31,1986)
K.-Y. Ng	Longitudinal Instabilities and Stability Criteria (FN-438; to be published in "Principles of High Energy Hadron Colliders," Part II, H. Edwards and M. Month, eds.)

K.L. Knickerbocker et al.	High Speed Video Data Acquisition System (VDAS) for H.E.P., Including Reference Frame Subtractor, Data Compactor, and 16 Megabyte FIFO (FN-439; presented at the IEEE Nuclear Science Symposium, Washington, D.C., October 29 - 31, 1986)
A.E. Baumbaugh et al.	High Speed Video Data Acquisition System (VDAS) Developed for H.E.P. Used to Study Comet Halley (FN-441; presented at the IEEE Nuclear Science Symposium, Washington, D.C., Oct. 29 - 31, 1986, and the 1986 International Electronic Imaging Exposition and Conference, Boston, Mass., Nov. 3-6, 1986)
K.-Y. Ng	Impedances of Beam Position Monitors (FN-444 [SSC-N-277])
R. K. Ellis and C. Quigg	A Pinacoteca of Cross Sections for Hadroproduction of Heavy Quarks (FN-445)

Colloquia, Lectures, and Seminars

(All at Fermilab unless otherwise noted)

J. Stein-Schabes	"Is Inflation Natural?" (October 20, 1986)
W. Smart	"Holography in Bubble Chamber Physics; Especially the 15'" (October 21, 1986)
D. Edwards	"Experimental Study of the SSC Aperture Criterion" (October 21, 1986)
P.V. Livdahl	"The Loma Linda Proton Therapy Accelerator Project" (October 28, 1986)
C. Quigg	"Discrete Physics" (October 29, November 3, 1986)
P.J. Limon	"Current SSC Research and Development" (October 29, 1986)

R. Raja	"D0 GEANT Event Generation" (October 31, 1986)
U. Baur	"Limits on Composite Isoscalar Vector Bosons from Future e^+-e^- Colliders" (November 4, 1986)
R. Siemann	"The Operation of CESR" (November 4, 1986)
R. Pasquinelli	"Low Level rf System" (November 6, 1986)
J. Klen	"$\bar{p}$ Vacuum System Performance" (November 6, 1986)
G. Krafczyk	"Baseline Subtractors" (November 7, 1986)
M. Mangano	"Introduction to String Theory" (November 10, 14, 17, 21, 24, 1986)
R. Orr	"Accelerator Division Information Meeting" (November 11, 1986)
G. Dugan	"Secondary Yields in AP-2" (November 13, 1986)
L. Bartoszek	"Li Lens History" (November 13, 1986)
J. Morfin	"Survey of Muon Physics" (November 13, 1986)
F. Mills et al.	"Report on the Conference on the Application of Accelerators in Research and History" (November 18, 1986)
T. Nash	"ACP" (November 20, 1986)
R. Niemann	"SSC Dipole Magnet Cryostat Thermal Model" (November 25, 1986)

R. Orr	"Accelerator Division Information Meeting" (December 2, 1986)
K. Dixon and R. Stanek	"Report on the Cryogenic Symposium at Miami on November 2 - 7" (December 4, 1986)
A. McInturff	"Modern Conductor Development for the SSC Magnet" (December 9, 1986)
R. Siemann	"Advanced Techniques for High Energy Particle Accelerators" (December 10, 1986)
P. Arnold	"GUTS: The How and Why of SU(5), SO(10), and Beyond" (December 10, 12, 16, 17, 1986)
H. Haggerty	"Muon Chamber Tests" (December 12, 19, 1986)
J. Morfin	"Study of Hadron Showers from Muo-production" (December 18, 1986)
H. Haggerty	"Muon Chamber Tests" (December 19, 1986)
D. Green	"Gravity for Beginners" (January 12, 14, 19, 21, 26 & 28, 1987)
M. Cornacchia	"The Berkeley 1-2 GeV Synchrotron Radiation Source" (January 13, 1987)
S. Hsueh	"Status Report on the Design of 4-8 GHz Pickup Loop" (January 15, 1987)
M. Shea	"D0 Controls and Downloading System" (January 16, 1987)
D. Rohde	"LaTeX and Graphics" (January 21, 1987)
L. Chapman and G. Mayer	"Future Control Systems Network" (January 22, 1987)

E. Malamud	"Collider Upgrade Plans" (January 23, 1987)
A. Ito	"Software Designs for Hardware Monitoring" (January 30, 1987)
M. Sokoloff	"An Experimental Study of the A-Dependence of J/ψ Photoproduction (E-691)" (January 30, 1987)
L. Gustafsson	"FASTBUS to VME Interfacing at CERN" (February 3, 1987)
H. Edwards et al.	"Status of the Division and the Machines" (February 3, 1987)
Y.C. Chao	"First Measurements of Booster Orbits" (February 5, 1987)
J. Butler	"Survey of Photoproduction" (February 10, 1987)

Index to the 1986 *Fermilab Reports*

Dates to Remember

March 3, 1987	Deadline for receipt of material to be considered at the April Physics Advisory Committee meeting
April 3 - 4, 1987	Physics Advisory Committee meeting
May 12, 1987	Deadline for receipt of material to be considered at the June Physics Advisory Committee meeting
June 13 - 19, 1987	Physics Advisory Committee meeting