chine.... One of the problems with using antiprotons is their extreme rarity. As we go to much higher energies, there's a real question as to whether the technology for making enough antimatter to fill such a big machine will suffice to produce the reaction rates we need. So it's not obvious that Dr. Lederman's idea solves the problem at a single stroke. I wish it could."

If the exchanges at the House hearing left questions about the future of SSC, the discussion at the 6 November meeting of DOE's Energy Research Advisory Board was even more unsettling. During a 90-minute debate on the wording of statements about SSC in a report, *DOE Long-term Civilian Research and Development*, William Carey, executive director of the American Association for the Advancement of Science and a former budget official in the Kennedy and Johnson Administrations, argued forcefully against its support. Though SSC is "a magnificent concept in high-energy physics," said Carey, "the department was not created to advance high-energy research at the expense of mission-related R&D programs. It would be unwise [for DOE] to fund SSC while competing research is on short rations.... You all seem to be saying this machine should be treated as a funding irregularity, that new money needs to be found so that other research can go forward unthreatened. It cannot be put in a special category. It cannot be put against the social security budget or the defense budget or the welfare budget. It will have to come out of the science budget."

In the end, ERAB, whose 21 members represent a wide range of interests in energy research and production, agreed to say that "increased funding of SSC must not preempt other DOE civilian R&D priorities, as there are important, less expensive projects to fund in the near term." To get even that statement required some strong support of the supercollider by two ERAB members, Norman Ramsey of Harvard and Mildred Dresselhaus of MIT. Before they made their case, ERAB had wanted to say there were "more important" projects for DOE to support and that SSC "poses a particularly significant issue regarding the provision of adequately balanced support for basic research *across the sciences*."

—Irwin Goodwin

Selection panel opts for stronger SSC magnets, shorter ring

From among five proposed magnet designs for the Superconducting Super Collider, the SSC Magnet Selection Advisory Panel has chosen its preference. On 9 September, the panel, headed by Frank Sciulli (Columbia), submitted the report of its deliberations and final, unanimous recommendation to Maury Tigner, director of the SSC Central Design Group at Berkeley. "This formal selection process is unusual," Sciulli told the House Subcommittee on Energy Development and Application at a hearing on 29 October, "reflecting the importance attached by the US high-energy-physics community to securing the best and most cost-effective possible technology for the SSC design."

Before a particular superconducting magnet design was chosen, one could discuss the overall design of the SSC proton–proton storage-ring collider only in rather general terms. Because the proposed bending-field strengths ranged from about 3 to 6 tesla, the circumference of the proposed ring for 20-TeV colliding protons ranged correspondingly, from 120 to 60 miles. Sixty extra miles involves, of course, a prodigious additional civil-engineering cost. But it was thought the extra cost of the larger ring might well be more than offset by the lower cost of the simpler low-field magnets.

Having now concluded that such a tradeoff would not be cost effective, Sciulli and his fellow panel members have opted for the high-field, smaller-ring alternative. From among the five magnet designs originally submitted for their consideration, the panel chose a high-field, "cosine θ, one-in-one, cold-iron" type developed by a Brookhaven–Fermilab–Berkeley collaboration. A test model of this "style-D" design at Brookhaven was successfully run up to 6.6 tesla last spring, and the panel concluded that "it has been shown that the style-D magnets can operate with a reasonable safety margin at 6.4 T with presently producible superconducting materials."

Cosine θ magnets are so designated because the superconducting coils running axially along the outside of the magnet's beam pipe are arranged such that the current density varies approximately as the cosine of the azimuthal angle. The coils are concentrated near the horizontal plane, with current density tapering off to zero at the top and bottom of the pipe. If the current density running along the walls of a horizontal cylinder has precisely a $\cos\theta$ distribution, the resulting magnetic field inside the cylinder will be perfectly vertical and uniform: the ideal field configuration for a bending magnet.

The field configuration of a superconducting $\cos\theta$ magnet is determined primarily by its coil geometry. The iron in the structure serves mostly a mechanical function. The style-D magnet's principal competitor during the panel's four-day meeting in Berkeley at the end of August, the style-C design, works on a quite different concept: It is a low-field, "superferric, two-in-one" magnet. The style-C magnet, proposed by a group at the Texas Accelerator Center, is something of a hybrid between conventional and superconducting magnets. Like ordinary electromagnets, its field configuration is largely determined by its iron yoke. The idea is that this mass of ferromagnetic material will give an additional boost to the field intensity produced by the superconducting coils, permitting the construction of a relatively simple and inexpensive 3-T superconducting magnet. Conventional room-temperature electromagnets are limited to about 2 T by the saturation of the iron.

The Texas design, requiring a storage-ring circumference of about 120 miles to bend 20-TeV protons in a full circle, is very much in the spirit of the original "Desertron" proposed by Leon Lederman and Robert Wilson—inexpensive low-field magnets arrayed on lots of inexpensive real estate. It is easy to imagine that Texas, with more room than most, would find this alternative attractive. By the end of the August meeting, at which the various magnet proponents put their cases before the panel, styles C and D had emerged as the only surviving contenders.

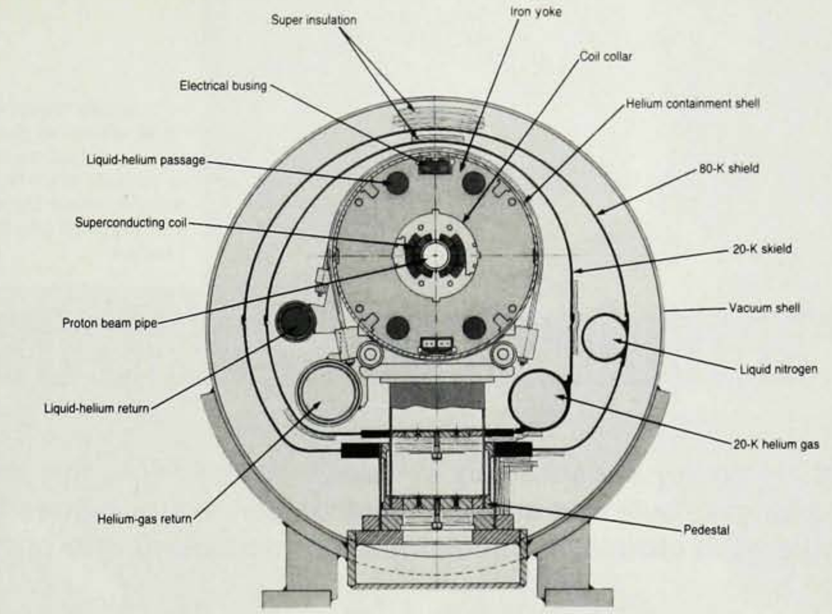
Mechanical tolerances are a crucial issue for ensuring adequate magnetic-field uniformity. The superconducting coils of a 6-T $\cos\theta$ magnet, despite being subjected to enormous magnetic forces, must not be allowed a displacement of more than about 25 microns, lest the field configuration become unacceptably distorted. The D design is in fact mechanically configured to hold the coils adequately in place even if the magnet is run at 7 T. Such demanding mechanical rigidity and manufacturing precision are of course costly.

When the Texas group began work on the superferric design, it was hoped that the weaker magnetic stresses of 3-T operation would permit significantly looser tolerances and corresponding savings. As the superferric design evolved, however, it turned out that its mechanical tolerances were not much looser than those of the $\cos\theta$ design.

The anticipated simplicity of the superferric design is also undermined by the problem of variability in the iron yoke from one magnet to the next. At a given current the field of a superferric magnet depends crucially on the permeability of the iron, which can vary from one batch to the next. One can take measures against this variability. But they are all costly complications of a design whose principal virtue is supposed to be its simplicity.

"The Texas group has performed a considerable service in evolving and testing a specific superferric design," Sciulli told us. "The superferric idea was an attractive alternative, and one couldn't judge the relative costs until the details had been worked out." But in the end, the panel determined that the savings involved in the C design would not compensate for the added civil-engineering costs. The overall cost of an SSC based on the superferric magnets is estimated to be about \$83 million more than that of the $\cos\theta$ design.

"The promise of two years ago, that the superferric design would provide a simple, cheaper SSC, has not come true. [Its] complexity has increased with time," Sciulli told the House subcommittee. To counteract field nonuniformities introduced by the saturation of the iron, the Texas magnet requires three separately programmable coils of differing geometry. The 3-T maximum field of this design is due essentially to the limited capacity of something as simple as a three-coil configuration to cope with iron saturation, not to the intrinsic limits of the superconducting cable itself.



The cosθ bending magnet design preferred by the SSC magnet selection panel.

The field-strength limitation in the $\cos\theta$ magnet design, by contrast, is the critical current the superconducting cable can tolerate before going normal. Both the C and D designs contemplated by the panel employ a niobium–titanium alloy as the superconducting material. Five years ago, when mass production of niobium–titanium $\cos\theta$ magnets began for the Tevatron at Fermilab—the first of the superconducting particle accelerators—this limited the Tevatron magnets to 4.5 T (see page 23).

The critical current density depends crucially on the processing of the tiny individual Nb–Ti filaments, imbedded in a copper matrix, that make up the superconducting cable. By repeated extrusion and drawing of Nb–Ti rods in a copper billet, the superconducting filaments in the Tevatron cable were drawn to diameters of 10 microns, with a critical current density of 1.8 kA/mm^2. Since then, thanks largely to the efforts of David Larbalestier and his colleagues at the University of Wisconsin's Applied Superconductivity Center, in collaboration with groups at the Lawrence Berkeley Lab, Intermagnetics General, Superon and Teledyne Wah Chang, much progress has been made in the art of Nb–Ti-cable production. With metallurgical advances and improved fabrication techniques, the critical current density has now been improved by a factor of almost two, making it possible to run the proposed $\cos\theta$ magnets confidently beyond 6 T. "It's been rather painless to transfer our lab-scale advances to industrial scale," Larbalestier told us.

At the low end of the magnetic-field cycle, recent advances in making still finer filaments (2–5 microns wide) yield an additional blessing. The protons that are to be accelerated to 20 TeV enter the SSC ring at the much lower injection energy of 1 TeV. Thus, the superconducting bending magnets must run at $\frac{1}{20}$ of their maximum transport current during the first stage of the acceleration cycle. It turns out that when the current in a superconducting cable is drastically reduced, one is plagued by persistent magnetization currents running along the edges of the filaments and degrading the magnetic-field configuration. The thinner one can make the filaments, the weaker the persistent currents will be. Whether one ultimately chooses to deal with these persistent currents by employing compensating coils or ultrathin-filament windings will depend on the cost of 2–5-micron cable produced in quantity.

The considerable experience the high-energy community has had with $\cos\theta$ magnets weighed heavily in their favor. The superferric concept is much more of an unknown quantity, the panel concluded. The 800 $\cos\theta$ bending magnets of the four-mile-long Tevatron ring are very similar to the D design proposed for the SSC, and they have been operating successfully for two years now. "The recent R&D on the $\cos\theta$ magnets has been addressing engineering and cost issues rather than fundamental superconductor problems," stresses panel member Alvin Tollestrup (Fermilab). "It's not at all like ten years ago when we were first developing the Tevatron and Isabelle magnets. The old problems are now very well understood."

The "one-in-one" D design has separate cryogenic systems for each of the two countercirculating proton rings. Unlike an antiproton–proton collider, a pp machine requires two magnet rings of opposite bending polarity. The diameter of the beam pipes that will thread the 17-meter-long bending magnets is 4 cm. Although the beam itself is only a few millimeters across at injection, one wants at least a 2-cm width of very uniform field at the center of the pipe. "You can't guarantee that the beam will always go right down the middle," Tollestrup told us. "Remember, this ring will be 60 miles around."

Recently Fermilab Director Leon Lederman broached the suggestion that one might save money by running the SSC as an antiproton–proton collider, requiring only a single ring of magnets. This would of course significantly reduce the machine's design luminosity below its target of 10^{33} events per cm^2 per second. The community would thus have to consider a tradeoff between cost and lowered event rate. Lederman believes that the reduction in luminosity may be no worse than a factor of ten. Reduced luminosity is not altogether without redeeming virtues: At 10^{33} $\mathrm{sec}^{-1}\mathrm{cm}^{-2}$ the detectors will have to sift through a fearsome avalanche of almost a hundred million high-multiplicity events per second.

—Bertram Schwarzschild ☐