

DOE should move forward on the "footprint" for building the machine at the site. Approval is necessary before the state begins buying land with some of the \$1 billion in general obligation bonds made available last year by voters. Six counties, including Ellis, have agreed to raise vehicle license taxes to pay for roads to the SSC laboratory around the turn-of-the-century town of Waxahachie.

Barton believes that DOE's prudent approach to the SSC was correct. He insists that Hunter had the best interests of the country in mind in being cautious. But sources in the Administration insist Hunter was really trying to micromanage the project. Most criticism centers on how Hunter sought to slow the momentum for the SSC. In January 1989, when Schwitters became SSC director, Hunter organized a separate unit within DOE's high-energy research office to keep tight control on the project.

Hunter, for his part, claimed in an interview that he hadn't been able to get a grip on SSC expenditures or get a schedule of project milestones and deliverables. "Whenever I asked for these," Hunter said, "I would get a runaround: 'We're working on those.' I wasn't getting answers about spending rates or magnet progress."

Schwitters characterizes Hunter's

grievances as "nonsense." He argues that he kept Hunter completely informed but wasn't receiving much communication from him in return.

Meanwhile, Clements and Luce complained that the project appeared to be going from bad to worse and that Hunter was causing many of the management and morale problems. On 7 September, Watkins issued DOE's management plan for the SSC, overriding Hunter, by limiting the number of officials in Washington to provide oversight to 30 and authorizing no more than 60 at the site. He restored fiscal supervision to DOE's Chicago Projects Office, which Hunter had removed from the loop.

Competing to build the SSC

Moreover, when members of Congress expressed worry that DOE would abuse its power to choose subcontractors, lawmakers clamped fetters on the department with specific language in a report by the Senate Committee on Energy and Water Development. Watkins made it clear in his memorandum that he would not tolerate the department's interference with the choice of subcontractors by SSC and Universities Research Associates, the organization of 72 US and Canadian universities that directs both the SSC and Fermilab.

Somewhat ironically, it was neither

DOE nor URA that made public the names of the three teams of industrial firms that will compete for the \$1 billion contract to manage engineering and construction for the SSC tunnel. On 6 December the news was released by Barton's office, because, says the Congressman, "the winners and losers were all calling me and so I thought the information should be made public." The finalists, from among 14 contenders for the contract, are Fluor-Daniel, the construction arm of Fluor Corporation and ICF Kaiser Engineers; Parson, Brinkerhoff, Quade and Douglas, MK Ferguson and CRSS of Houston; and a joint venture of Daniel, Mann, Johnson and Mendenhall of Los Angeles and Bechtel National Inc.

It is likely that the engineering and construction contract will be awarded this year, though there is little money in the SSC budget to begin work. Much will depend, obviously, on the fiscal 1991 budget, which President Bush will deliver to Congress on 22 January. Members of Congress from Texas say the DOE budget will contain \$393 million for the SSC. But at the White House Office of Management and Budget they speak about \$310 million—scarcely enough to get on with producing the remodeled machine at its higher new price.

—IRWIN GOODWIN

SSC DESIGN REVISIONS CALL FOR THINNER BEAMS AND FATTER MAGNETS

The Central Design Group for the Superconducting Super Collider produced its conceptual design for the proposed 20×20 TeV proton-proton collider in 1986. Since then, a specific site for the SSC has been selected in Ellis County, Texas; experimental models of the 6.6-tesla bending magnets required for the collider ring have been extensively tested; and powerful new computer codes have now made it possible to simulate the trajectories of individual protons over millions of circumnavigations of the 54-mile storage ring.

Armed with this new knowledge of how the protons stored in the ring will behave during the crucial beam-injection phase and how the unprecedentedly long and powerful superconducting bending magnets perform at operating temperature and currents, the SSC Laboratory in Dallas, which has taken over the responsibilities of the CDG, has produced a supplemental design for the accelerator. The principal changes in the revised SSC design

are a doubling of the injection energy, more focusing magnets in the ring and a 25% increase in the width of the vacuum beam pipe.

The 1986 conceptual design called for the countercirculating protons to be injected into the final ring at an energy of 1 TeV after preacceleration in a sequence of linacs and booster rings. Filling the ring with its full complement of protons will take a half hour, after which the rf cavities spaced around the ring begin accelerating the protons up to their final energy of 20 TeV. During the filling phase the protons will have to survive 10^7 trips around the ring without being lost in collisions with the walls of the vacuum beam pipe.

Beam-pipe aperture

In the original design, the aperture diameter of the vacuum beam pipe that threads its way through the thousands of bending and focusing magnets is specified as 4 cm. Was that wide enough? The larger the

aperture, the smaller is the likelihood of wayward beam protons striking the wall. But bigger apertures are also more expensive. They move the magnet coils farther away from the beam axis, making it necessary to build magnets with more superconducting cable. The unprecedentedly narrow 4-cm original design was described by the Central Design Group's director, Maury Tigner, as one of the "aggressive" specifications chosen for reasons of economy. (See PHYSICS TODAY, April 1988, page 17.)

It's not just a matter of the beam scraping the walls. Ideally the bending magnets would have perfect dipole fields. But real bending magnets are inevitably plagued with higher-multipole field components, whose adverse effects on beam quality become worse as the protons find themselves farther from the magnet axis. The beams must also be kept narrow so that the experimenters will have adequate collision rates where the beams intersect. The question is, how good can and

must the field quality be?

Traditionally, choosing a beam-pipe aperture has been something of a black art. Lacking the powerful simulation codes that have been developed for supercomputers in the last year at the SSC Lab by Yton Yan, David Ritson (SLAC) and their colleagues, accelerator designers had to rely heavily on intuition. The beam is most likely to stray beyond acceptable limits in the horizontal plane, as a result of betatron oscillation and chromatic aberration. The latter is due to the spread of particle momenta: Particles of different momentum experience different curvatures in the bending magnets. Both effects scale with beam energy like $1/\sqrt{E}$. The lower the beam energy, the greater are the excursions from the beam axis. That's one of the reasons why the half-hour injection and filling phase is the most precarious.

The simulation code

The new computer code lets the accelerator designers follow 64 individual protons on a Cray at about one or two percent of the real-time rate. That is to say, it takes a day or two of supercomputer running time to simulate 64 protons with different initial conditions making 10^7 circuits of the SSC during the half-hour filling phase. These simulations seek to determine how many of the injected protons will survive this billion-kilometer initial journey under a variety of machine parameters. The code can also simulate the acceleration phase that follows filling. But in the attempt to optimize machine parameters within cost constraints, the emphasis has been on the filling phase.

This lowest-energy phase of the SSC ring cycle is also the time at which "persistent current" magnet problems are the most severe. All cycled accelerator magnets have hysteretic problems at the low-field beginnings of their cycles. But such problems are particularly acute for superconducting bending magnets. Experience at Fermilab with the superconducting Tevatron magnets since 1986 has shown that flux creep produces persistent currents that are very hard to compensate for because they grow with time and depend unpredictably on the details of superconductor fabrication. These persistent currents introduce an unwanted parabolic (sextupole) field component whose adverse effect is worst when beam energy and field intensity are at their lowest.

In recent months the accelerator physicists at the SSC Laboratory have been running the codes assiduously to determine whether the original de-

sign parameters offered sufficient operating margin. It wasn't just a question of whether the protons survive when the machine is perfectly tuned and aligned. The machine must also be "operable"—one must allow for reasonable errors of tuning and alignment. Cost considerations and the relation of revised machine parameters to concerns about the bending magnets have also been very much on the mind of SSC Director Roy Schwitters and his colleagues.

Skinier beams, fatter magnets

The cheapest and simplest measure that offers a greater margin of injection latitude is simply to introduce more focusing quadrupole magnets into the line. The original design called for one quadrupole after every six 17-meter bending magnets. The plan now is to reduce the spacing between quadrupoles from the 114 meters originally called for down to 90 meters, with only five bending magnets between consecutive focusing magnets. This greater degree of focusing would reduce the beam width by about 40%. Incidental consequences of the revised beam optics are a reduction of the bending-magnet lengths from 17.35 to 15.85 meters and an increase of the ring circumference from 53 to 54 miles.

In addition to making the beam thinner, one can also make the magnets fatter, with similar benefits. That is to say, if one increases the beam-aperture bore that threads the magnet, a beam of given width becomes less sensitive to the undesirable higher-multipole field components of the bending magnet, because the field quality at any point depends only on its fractional distance from the magnet axis to the coils. The supplemental design increases the aperture from the original 4 cm to 5 cm, thus increasing the effective phase-space window for the injection of protons by about 60%. This will of course necessitate more superconductor in the fatter magnets, with a corresponding cost increase.

If one scales up the thickness of the cable itself, it should become easier to meet the Dipole Review Panel's call for magnets that can operate with a safety margin of 10% above the 6.6-tesla bending field required to hold a 20-TeV proton in the ring. This recommendation was one of several contained in the June 1989 report of the panel, convened by Schwitters last April to examine the progress of the SSC bending-magnet program. The panel, whose cochairmen were Tom Kirk from Fermilab and Gus Voss from DESY, concluded that the

magnet program had not yet developed a prototype bending magnet with adequate operating margin.

The SSC magnet development program, operating at Brookhaven, Fermilab and the Lawrence Berkeley Laboratory, has acquired considerable experience with short and full-length magnets of 4-cm aperture. Much of this experience will still be relevant to the new 5-cm design. But this change, if approved, will entail some disruption of the schedule envisioned for preparing a final magnet design for industrial mass production. Looking much further ahead, the 5-cm aperture should make it easier eventually to increase the luminosity of the SSC well above its design goal of 10^{33} events per second per cm^2 .

The third principal revision called for in the supplemental SSC design is the injection of the protons into the main ring at 2 TeV instead of 1 TeV. This would require a final booster ring twice as energetic as the Tevatron, the world's largest existing proton accelerator. But it would mean a thinner, better-behaved beam at injection, with higher initial magnetic fields, less plagued by persistent currents.

The computer simulations have convinced the SSC designers that all three of these changes—more quadrupoles, a larger beam aperture and higher injection energy—should be adopted. This conclusion, Schwitters told us, has been strongly endorsed by the SSC Laboratory's Machine Advisory Committee, headed by Roy Billingham of CERN. Among the economies that are being undertaken to offset these expensive revisions is a reduction and postponement of the bypass scheme of beam shunts that was recently introduced into the machine design to make it possible for some of the accelerator's four detectors to take beam while others are being worked on in a beam-free environment.

The bending magnets

The 8000 bending magnets required by the SSC ring constitute the most expensive component of the accelerator. Hence the great attention paid to the magnet program. Five 17-meter bending magnets have been completed since the Dipole Review Panel's examination of the program last spring. These new magnets have all reached the nominal operating field at 4.35 K with very little "training." Apparently the design changes introduced to constrain the magnet coils against quench-causing movements have been successful.

But the magnets still have not achieved the 10% operating margin recommended by the review panel.

One option would be to operate the magnets at 3.5 K rather than the nominal 4.35 K. At lower temperature, the superconductor can take more current before quenching, and 3.5 K is thought to be no great problem for the SSC's cryogenic system.

One reason for the Dipole Review Panel's recommendation of a 10% operating margin was batch-to-batch variation of the superconducting niobium-titanium wire fabricated for the experimental magnets. The SSC Lab could ill afford to have a goodly fraction of the ring's 8000 magnets quench during operation because of such a spread in wire quality. But in recent months, Schwitters told us, the industrial suppliers of the superconducting wire have achieved a signifi-

cant improvement in quality control, so that one could probably make do with a lesser margin. "In any case," Schwitters went on, "we could certainly run in the first year at 90% of the nominal SSC energy without any loss to the physics. The Tevatron, after all, is considered a great success, even though it runs at only 90% of its nominal 1000-GeV beam energy."

In recent months the magnet program has been concentrating on the achievement of adequate dipole-field quality. This problem is of course closely linked to the changes that have now been made in the overall SSC design. Adequate field uniformity should be easier to achieve with wider magnets and narrower beams.

—BERTRAM SCHWARZSCHILD

though, Roe's investigators have come up with few leads and even less evidence, say subcommittee sources.

Tripped on the SSC

Neither the problems over fusion nor the congressional investigation was the main reason for Hunter's sudden departure, however. He was tripped up by something altogether different—the Superconducting Super Collider. It seems that Texans in Congress and back home had made no secret to DOE and the White House that they wanted Hunter to cease his resistance to hiring certain scientists for the laboratory and to desist interfering with decisions by SSC managers. One particular irritant was Hunter's opposition to approving a "footprint" (see page 45) produced by the SSC team for locating the collider ring around the town of Waxahachie. Until DOE approves the precise location of the 54-mile racetrack-shaped ring and other components and buildings, the state is unable to purchase the 16 000 acres on which to construct the giant project.

Informed of Hunter's disagreements with SSC scientists, some of Texas's most prominent figures began bashing Hunter in front of President Bush, Secretary Watkins and others. As the Administration grew more exasperated and embarrassed, it became clear that Hunter's days at DOE were numbered.

Finally, in early October, John C. Tuck, DOE's under secretary, who maintains strong connections to influential Republicans in Congress and to important White House officials, reportedly ordered Hunter to leave the agency. On 16 October, Hunter sent a hand-penned letter of resignation to Watkins. "As we have discussed," Hunter wrote in his characteristically cramped hand, "it is now time for you to pick a person for the Bush Administration. Several weeks ago I took steps to ensure that the work of the office would be smoothly conducted, and my presence is not now required. Therefore, I would like to resign, effective immediately."

Ironically, though Hunter is gone from DOE, his ideas have not been forgotten. In the next weeks Watkins intends to name a blue-ribbon panel to examine the country's entire program of controlled fusion. He also is maintaining a vigil on the SSC.

With Hunter's departure, James F. Decker is once again acting director of DOE's research office. He filled in for a year and a half after the departure of Hunter's predecessor, Alvin W. Trivelpiece, in 1987.

—IRWIN GOODWIN ■

HUNTER DEPARTS DOE AFTER RILING KEY LAWMAKERS AND TOP TEXANS

Rumors had circulated almost every month since last April that Robert O. Hunter Jr would soon be out on his ear as the Department of Energy's director of energy research. After all, he had angered influential members of Congress in his efforts to realign DOE's fusion program. He had proposed to reduce the funds available for magnetic fusion research and to fatten the budget for inertial confinement fusion at the expense of magnetic fusion.

When Hunter's strategy was made known, many plasma physicists exploded. Hunter had argued that ICF research with lasers, as practiced at Lawrence Livermore and Los Alamos, needed far greater support from DOE and Congress if it was ever going to show any commercial feasibility. It didn't escape the notice of fusion researchers and members of Congress that Hunter's former company, Western Research in San Diego, did ICF work under contracts with the Defense Department. Nor did they ignore Hunter's ambitious plans to make both fusion technologies compete for funds in DOE's constrained R&D budget.

Among those scrutinizing the plans was Representative Robert A. Roe, a New Jersey Democrat who heads the House Science, Space and Technology Committee. At hearings and in private, Roe fumed at Hunter's proposal, which would have the effect of curtailing work at the Princeton Plasma Physics Laboratory in New Jersey. Roe took his complaint directly to Hunter's boss, Energy Secretary James D. Watkins. Other antagonists included Senators Bill Bradley and



Hunter: Gone but not forgotten.

Frank Lautenberg, both New Jersey Democrats. During one call Bradley demanded that DOE officials "stop messing with Princeton."

In the meantime, Capitol Hill was rife with tales about the sale of Hunter's company, which took place before he was confirmed by the Senate last year for the DOE job. The stories led Roe to unleash the staff watchdogs on his House Subcommittee on Investigations and Oversight to determine their accuracy. Staff lawyers and outside experts scoured the financial accounts of Hunter's old firm, interviewed former employees about Pentagon contracts dealing with large excimer lasers such as those used by Los Alamos for ICF research and reviewed patents held by Hunter that might suggest a conflict of interest. For all their efforts,