THE CHALLENGES OF A SUPER ACCELERATOR

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In early June the U.S. Department of Energy formally received a reference design for a Superconducting Super Collider (the SSC). The design is summarized in 27 pounds of paper. Without giving away the price, the calibration seems to be a hundred million dollars per pound.

The reference design is an important document. It provides some assurance to DOE that the SSC is not strictly a wild blue sky proposal. There is a technical possibility for building it and for a price that is close to the stated price. The reference design shows that the SSC doesn't require radical new inventions that might never be made. More important, the reference design forces people to think very seriously about the SSC and to begin to optimize features and make compromises.

Probably no one is foolish enough to believe that the high-energy physics community is going to build a machine of this size or this price out of its back pocket. The project is going to take continued industrial help, possibly by a new avenue that hasn't been explored yet.

Very large superconducting accelerators are under construction in several other places in the world. In Germany, the DESY High Energy Physics Laboratory now has approval to bore a tunnel roughly the same size as the Fermilab tunnel under a populated area (Fig. 1). This will be used to collide circulating electrons against protons in a project called HERA. They will use superconducting magnets to put together a proton ring of 820 GeV. With certain design changes that they are now discussing, the energy might even be higher, perhaps 1000 GeV. The work that DESY is doing on magnets is logically connected to the work going on at Fermilab. Naturally, with the passage of time and additional thinking, there have been improvements, and they are still learning and modifying their plans. Fermilab is developing close ties to DESY and will be able to learn from their work. At the same time, DESY will be able to profit from the operating experience at Fermilab.

Another real project is underway at CERN, in Europe. They are boring a tunnel under France and Switzerland through solid rock to hold a large electron-positron collider, LEP (see Fig. 2). The tunnel has a circumference of 27 kilometers or roughly four times the circumference of the Fermilab ring. LEP as it stands will use conventional magnets. Since it's a machine that stores electrons, there is an incredible energy burden due to synchrotron radiation from the electrons that forces them to go to weak magnetic fields. As a result, they have to build a

Fig. 1. Environs of DESY showing the future location of an accelerator under a populated area.

large diameter tunnel. Naturally it offers the future potential for a large proton machine somewhat along the lines of the SSC. There are going to be severe problems in installing a superconducting proton machine in a tunnel that will be chock full of magnets and experimental apparatus. Whether this is a credible alternate to an American SSC or even an International SSC remains to be seen. However, this tunnel is being bored, LEP will be built, and some experience will be gained on a very substantial project.

The SSC is a large undertaking. But just how large? The existing machine at Fermilab, the Tevatron, is a circle a mile and a quarter in diameter (Fig. 3). The experimental areas stretch out for more than a mile. The Tevatron might serve as an injector for the SSC at one twentieth of the main machine energy. So, although Fermilab is a good size piece of real estate, it's really pretty small on this scale. The SSC is going to be a big machine.

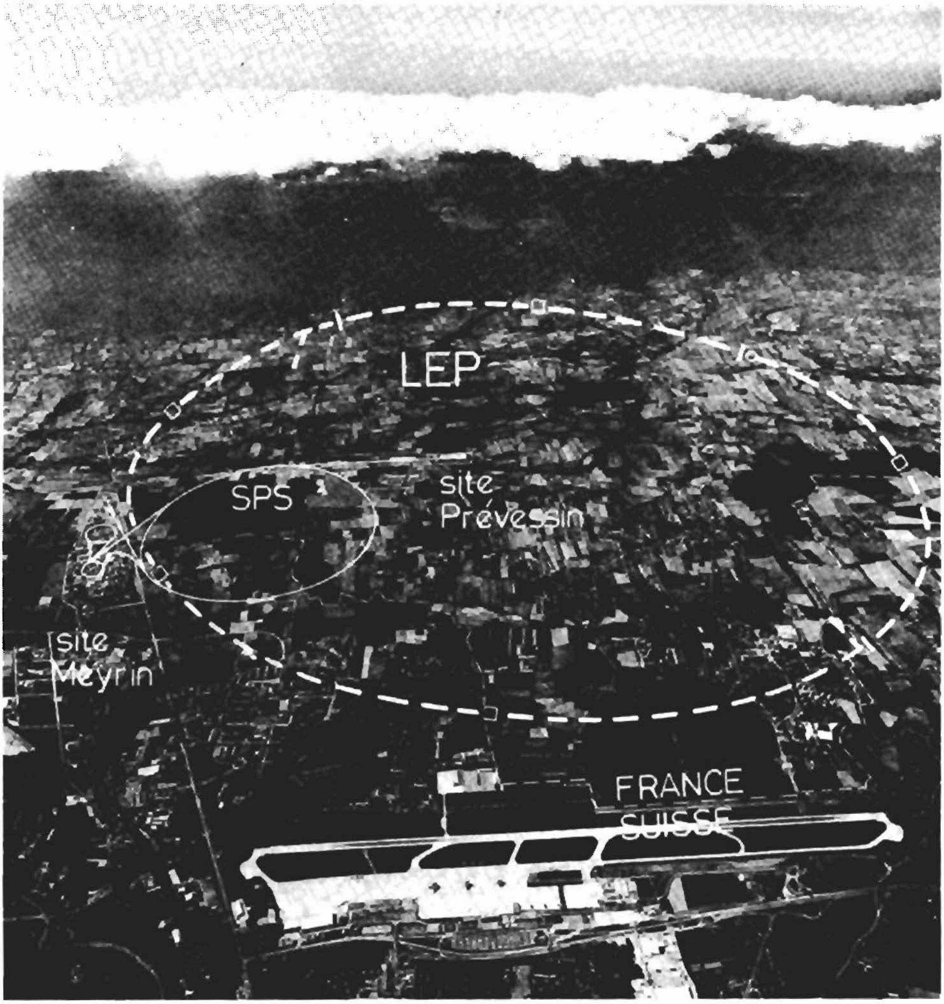

Fig. 2. LEP tunnel location at CERN in Geneva, Switzerland. Note the airport in the foreground. France is in the upper portion of the figure, Switzerland in the lower part.

Some people think that the center of the world is Washington, D.C. There is a beltway around it that could just about hold the smallest proposed SSC ring (Fig. 4). No one appears to be seriously considering the beltway as a site. Now consider another scale and a more reasonable location. The smallest proposed ring for the SSC is 20 miles in diameter. This

Fig. 3. Aerial view of Fermilab. Note the experimental areas extending away from the ring.

is the ring for the highest field magnet. The ring would fit comfortably into some area west of Fermilab. For a lower magnetic field and correspondingly larger diameter the accelerator ring could go east under the Sears tower in the center of Chicago; however, once the geology is understood it is likely that a proposed Illinois site will be to the west of Fermilab in Kane and DeKalb counties. Figure 5 shows the northern part of Illinois with a typical SSC ring sketched in.

The Reference Design

The reference design treats three fairly different magnet approaches, each with a different field. The different fields lead to different tunnel lengths and the costs vary from design to design. In what follows, reference design B, largely based on Tevatron concepts, will receive the most emphasis. At the moment it happens to have the highest cost. This should be taken with a

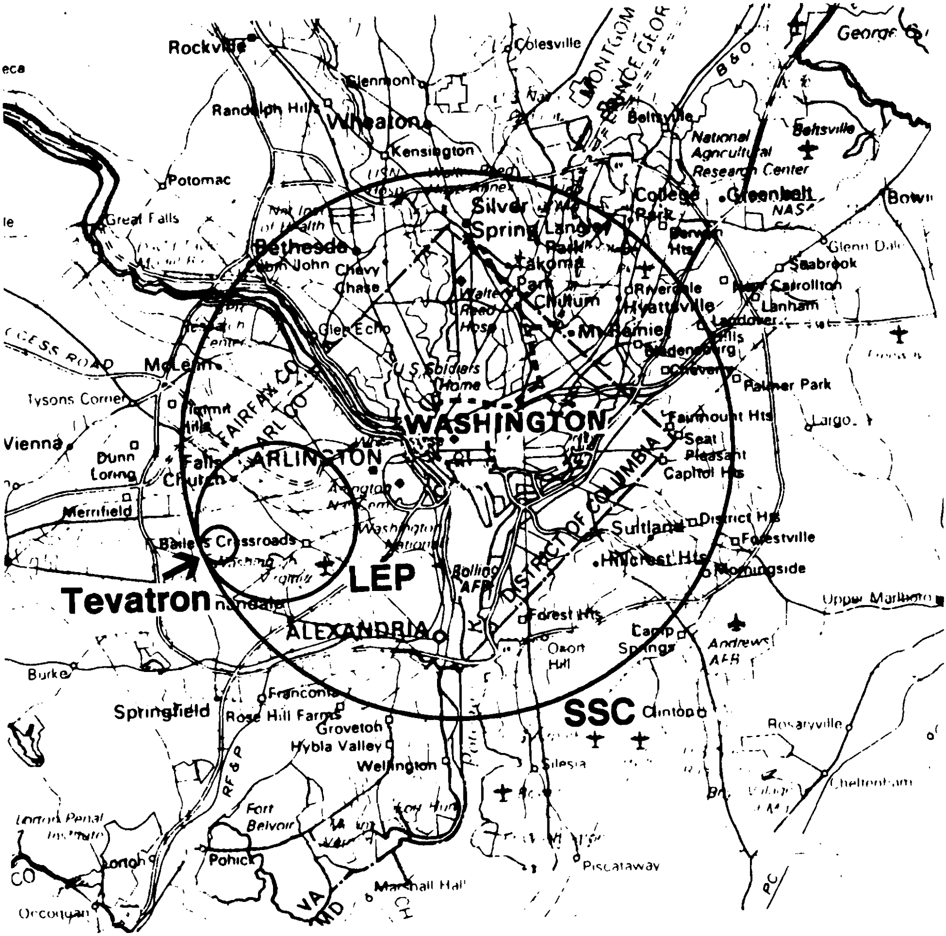

Fig. 4. The smallest diameter version of the SSC along with two smaller colliders, LEP at CERN and the Tevatron at Fermilab, superimposed to scale on the environs of Washington, D.C.

grain of salt. The machine won't be built by following any of these designs, and it won't cost the amount mentioned in the reference design, but these prices are still good guidelines (see Table I). It is a big cost and what is scary about it is that a small overrun on a project this big is an embarrassing sum. Now two things have to be folded into a design like this. The cost must be known, and it must be possible to deliver it for something on that order or preferably less. And, the design had

Table I. Comparison of Reference Design A and B Dipole Magnet Costs.*

	B	A
No. of dipoles	14,880	3,870
Total costs (M$)	719.2	590.9
Cost per dipole (K$)	48.3	153.0
Dipole length (m)	12	18
Dipole aperture (cm)	5.0	3.34
Maximum field (T)	5.0	6.5
Number of apertures/magnet unit	1	2

*Costs in FY 1984 dollars.

better work because if a machine is built at this price tag with this much attention and it fails to actually run physics for a good fraction of each year, it would certainly be embarrassing and possibly fatal to the future of high-energy physics. With

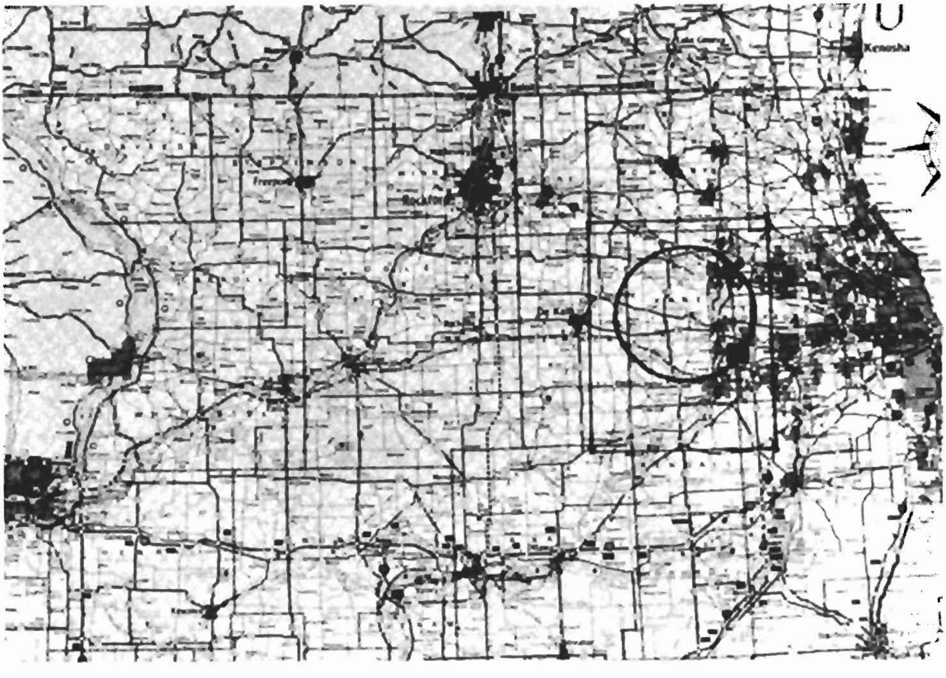

Fig. 5. Map of northern Illinois showing a schematic view of one possible SSC location.

these kinds of stakes it is doubtful there would be a second chance.

Table II provides more financial breakdown. A lot of different parts go into an accelerator. There is the radiofrequency accelerating system (rf), there are controls, there is cryogenics, and, of course, magnets. The focus of the discussion here will be on the dipole magnets which comprise 70 to 80 per cent of the total magnet cost. They'll serve as an adequate illustration of the challenge. The three magnet designs in the reference document represent a diversity of opinion about what is the best magnet to build, what's the most reliable kind, what could go into production on a minimum time scale, and what the cost of the three designs are. These three designs represent the popular magnet concepts at the moment. All were costed and analyzed as to the impact on the whole project. There are also some more radical designs that have not been included. They will receive attention at a later stage. The three designs have been labeled A, B, and C in the reference design report.

Table II. Collider Ring Facilities
Cost Summary--SSC Reference Design B
(FY 1984 M$)

Collider Facilities			1664.1
Conventional Construction		496.1	
Land Improvements	18.8		
Main Ring Tunnel/Encl.	419.9		
Cryogenic Facilities	8.0		
Support Buildings	1.7		
Utility Distribution Syst.	47.7		
Collider Accelerator Systems		1168.0	
Magnets	955.3		
Cryogenics	115.9		
Vacuum	12.2		
Main Power Supplies	21.0		
Correction Element PS	13.4		
RF System	7.7		
Injection System	2.9		
Abort System	8.0		
Beam Instrumentation	7.0		
Controls	19.3		
Safety Systems	5.3		

Design A, the one that is featured in the reference design, pushes niobium-titanium conductors pretty much to the present state of the art. Figure 6 shows the design A cross section. Design A incorporates a 6.5 tesla magnet (65 kilogauss). The

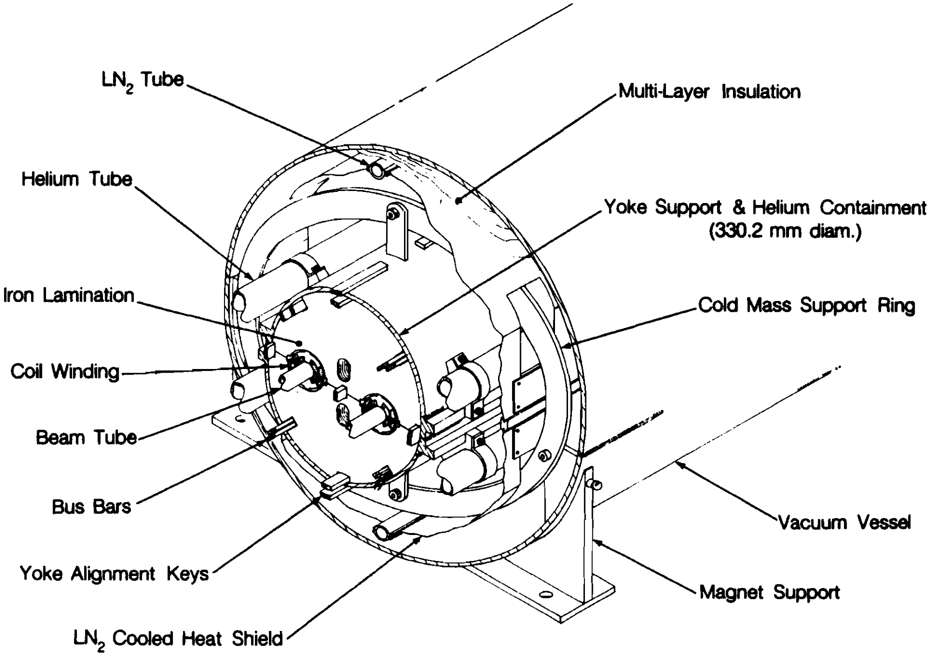

Fig. 6. Cutaway perspective view of the 6.5 T, 2-in-1 SSC dipole magnet.

magnet uses cold iron to generate some portion of the field. It takes advantage of a trick; the iron is not saturated in the central region between the apertures where the two dipoles with fields in opposite directions share the iron. In order to keep cost down the magnets are made long, close to 18 meters. It is only necessary to build about 4000 dipoles that way, but remember each dipole is dual, it has two superconducting coils inside. There may be some problems with that magnet that are not yet anticipated. At the moment probably not more than two or three magnets of this geometry have ever been built and tested. But that will change soon.

This magnet design is the outcome of a collaborative effort on the part of Lawrence-Berkeley Laboratory (LBL) and Brookhaven National Laboratory (BNL). General Dynamics, one of the firms represented on the Round Table, made some of the cost estimates. There are two vacuum pipes for a beam in which protons circulate going in opposite directions. There are two cosine theta superconducting windings close to the vacuum pipes to generate the dipole fields. Iron is wrapped around those windings to return the magnetic flux and to shield the two apertures from each other. As usual there are a lot of cryogenic pipes to make things cold and carry the fluids around the long refrigeration circuits. There are fiber glass epoxy resin rings to support the assembly inside a vacuum vessel using low heat leakage technology.

A strong group based in Berkeley and Brookhaven will be experimenting with this magnet. As an offshoot of this design, a group primarily at Brookhaven is considering even smaller apertures. Instead of an aperture of four centimeters they are considering one something like three centimeters. They would use niobium-tin, which is a much higher field conductor. As a result, they will try for fields of 8-10 tesla. If the BNL group succeeds in that, the tunnel would get smaller, certain civil engineering costs and other length-related costs would go down and to some extent the number of site possibilities might even expand because it's not possible to fit a 5-tesla circle on Long Island. Note that a 10-tesla magnet made with niobium-tin and wire bending radii of an inch or less is a challenge.

Design B, the Fermilab proposal, is closely related to the Energy Doubler because that is what has just been done, and it is known how to do it. It pushes the conductor a little less hard to give a field of 5 tesla. It essentially derives no field from the iron. Each aperture is put into a separate cryostat. That way it's possible to think of building only one ring and going to a proton-antiproton option initially. Figure 7 shows the design B cross section. Design B has a modest length of 14 meters. That may change; it may get longer or shorter. A lot more units are needed, close to 16,000 separate dipole magnets with a correspondingly larger number of quadrupoles. Naturally, the tunnel gets longer going from a 90 kilometer circumference in design A to 113 kilometers in design B. Initially the system was designed with the two apertures one above the other instead of side by side (the figure should be rotated by 90 degrees). This design, which has two independent dipoles with 5 centimeter apertures, uses a cosine theta superconducting winding and a set of aluminum collars to take the Lorentz forces. Again, there is a lot of piping to carry the cryogens around. But now there is just enough iron to make a vacuum vessel and to prevent the magnetic field of one dipole from influencing the beam in the other.

Fermilab Doubler magnets would cost something like a factor of three or four more than design B, because of their more restricted design. They would also have a much higher heat leak than the proposed design B. That would lead to refrigerator costs which would be ten times higher. The Doubler magnets use superconductor less efficient, and they do a lot of other dumb things that seemed smart six years ago.

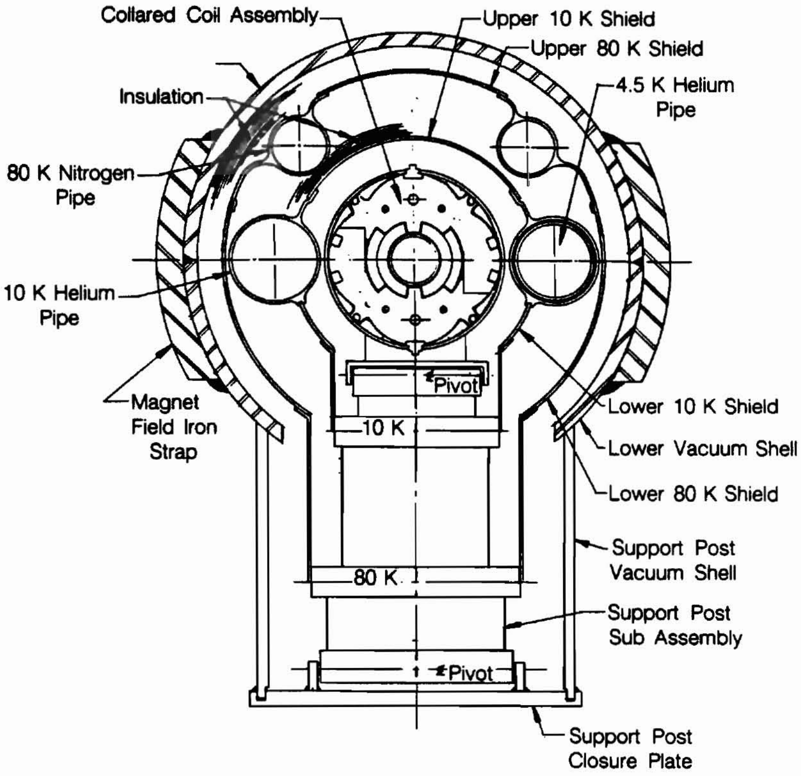

Fig. 7. Reference Design B cryostat cross section showing major components.

Design C was developed by a group from Texas where Russ Huson, Peter McIntyre, and others have picked up on the idea of a superferric magnet. This is a magnet operating in the 2-3-tesla region in which iron forms the main component in the magnetic circuit, and superconductors are chosen as a clever way to excite that iron without a great deal of power investment. Figure 8 illustrates the magnet. What's radical about that magnet? Well the aperture is fairly small. Naturally, since it's an iron magnet, more of that aperture is uniform field than any of the others. The length, 140 meters, is designed to minimize the cost of the ends and of other features. One hundred and forty meters is long, a football field and a half. A lot of light airplanes land and take off in a distance less than that. No one has ever made an accelerator magnet even approaching that length. It would be a tour de force to learn how to build them, but only a thousand would have to be built.

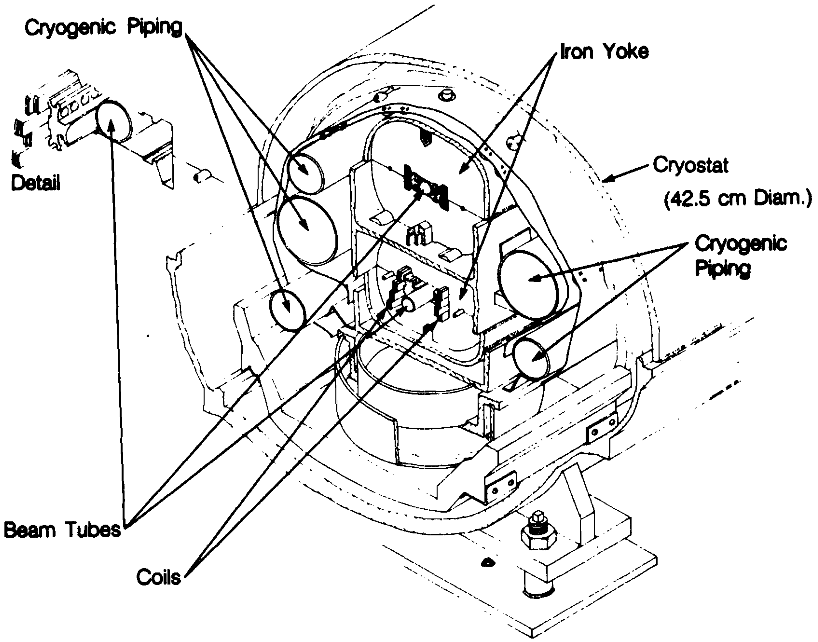

Fig. 8. Cutaway perspective view of the 3T, superferric dipole magnet.

The superferric magnet for design C has a rectangular aperture excited by superconducting windings similar to a classical copper and iron dipole. This leads to a small beam tube. The two apertures are located one above the other. Now a six meter magnet loses about 3/4 of an inch of length when it shrinks. A 140 meter long magnet will have substantial shrinkage. As a result, the ends of this device have to be capable of moving several inches without breaking. There are some substantial engineering challenges involved in that.

In what follows the primary concentration will be on design B. What are some of the technical and logistical challenges with design B? The beam pipe may have to be copper plated inside for low conductivity. Aluminum collars will be used to hold the magnetic forces. Stainless-steel pipe will be employed in conjunction with the beam pipe to form an annular vessel for liquid helium. Heat shields at various temperatures will be needed to help minimize the heat load of the structure. A set of posts made out of epoxy fiberglass will be used to hold the coil mechanically and not introduce a large heat leak. A carbon steel vacuum vessel is part of the thermal insulation. Iron is required to help return the magnetic flux and shield one aperture from another.

There is the problem of putting together sixteen thousand magnets in a period of four years. At Fermilab it was a struggle to build a thousand magnets in four years and this is 16 times more. This will require industrial help. One of the topics that the Round Table will explore is how to translate a design developed by the Laboratory or by the Laboratory with industrial help into an industrial environment. One must get reliable magnets yet cut costs by making changes to simplify production. Once something works, no one usually wants to change it; however, to achieve the economies that industry can offer, changes will probably be necessary. I hope the Round Table discussion will shed some light on this point.

Costs

A central element of any discussion about the SSC is costs. The magnet issue is crucial to the cost. Table III, the magnet cost summary, is one of many pages of costs developed for the

Table III. Magnet Design B Cost Estimates and Contingency Developed by the RDS Group (Baseline) and the Review Committee (Recommendation) (1984 $M).

		Baseline		Recommendation	
		Cost Estimate	Contingency (25%)	Cost Estimate	Contingency (25%)
1.	Tooling (Use 2 shifts/ day, 5 days/ week operation)	21.3	5.3	36.0	9.0
2.	Dipoles	719.0	179.8	719.0	179.8
3.	Quadrupoles	60.8	15.2	60.8	15.2
4.	Special Devices	75.5	18.9	75.5	18.9
5.	Special Magnets	20.0	5.0	11.2	2.8
6.	Installation	58.5	14.6	58.5	14.6
7.	Factory Supervision (Included above)	N.A.	0.0	N.A.	0.0
	Subtotal	955.1	238.8	961.0	240.3
8.	EDI (WBS 1.6.2)	95.5	28.7 (30%)	96.1	28.8
	Total	1050.6	267.5	1057.1	269.1
	Grand Total	1318.1		1326.2	
	Recommended Change		+8.1		

reference design. A number of interesting things go into the $955 million magnet bill (of which $719M would be for dipoles). Of that $719 million, only 20% or $130 million would be for labor. Obviously it's important to minimize the labor but with only a 20 per cent fraction, cutting the labor in half will only cut the cost 10 per cent on the magnet. A better motive for minimizing the labor is probably that the less labor that is used, the more reliable the end product will be. Simple blocks of metal that have never been touched hardly ever fail. It's the parts that are worked a lot that can break and fail. So the design minimizes labor and probably increases reliability at the same time. This ratio is approximately the same for all the designs. Of the $719 million for materials, $318 million is for superconducting insulated cable ready to wind into a coil.

Is there enough superconducting material for the project? Well, at least one gentleman that sits on large piles of niobium says that there is an adequate supply of feed stock at a more or less constant price. The existing U.S. industry (and that's discounting the rest of the world which shouldn't be discounted) is capable of producing at the rate needed for this project. Remember that these magnets use less superconductor than the Fermilab Doubler magnet. There is perhaps fifteen million dollars worth of superconductor imbedded in the Fermilab magnets. Only a factor of twenty more is needed for the SSC.

The cost of superconductor is almost half the magnet cost, so it's an important fraction of the total costs. In design B this is particularly true; one could say it is wasteful of superconductor since none of the field is from the iron. However, this avoids all of the problems that come with saturating iron. It also opens the window to one area in which advances may occur in the next few years. Nobody expects the saturation field of iron to improve but the ability of superconductor to achieve high current densities could improve dramatically. If it does, the same design might become not a 5-tesla magnet but a 6 or 7-tesla magnet. Steps have been taken in design B to avoid building anything into the magnet that would limit its field performance. Since the iron plays virtually no role, changes in the field level are not influenced by that. The size of the force restraining collars can be made large enough at this time to handle bigger forces. For design B, it would be possible to either cut the cost or improve the performance. Since superconductor cost is such a large fraction it's possible to concentrate attention on a fairly narrow technical area with the hope of producing large yields.

Cable

This cable, so-called Rutherford Cable, shown in Fig. 9, consists of of 23 or 25 individual strands. Each strand is about 30 mils in diameter. The strands are twisted and each strand has

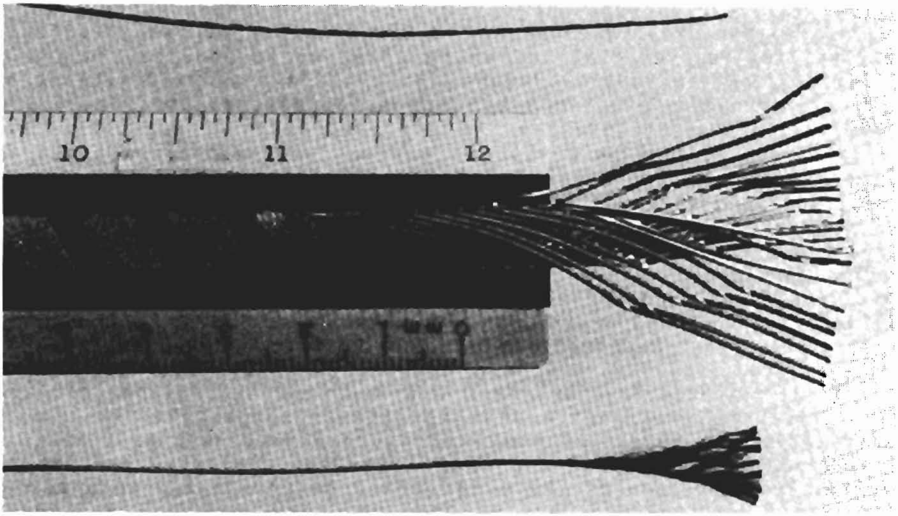

Fig. 9. Rutherford-style superconducting cable.

an internal structure that contains about 500 small filaments of niobium titanium. This is similar to the cable that is used in the Energy Doubler with very small dimensional changes. The quantity is staggering; something close to 100 million feet of this have to be provided. The wire is a simple component, but it's a crucial one. Table IV gives the superconducting cable specifications. There's nothing very important in this table

Table IV. Superconducting Cable Specification.

Conductor type	Nb - Ti (47.5%Ti)
Copper to superconductor ratio, (by volume)	2.0/1 (inner), 3.0/1 (outer)
Number of filaments	710 (inner), 533 (outer)
Filament size	16.5µm
Strand size	0.0298 in.
Number of strands in cable	25 (inner) 23 (outer)
Cable dimensions	
With insulation	0.053×0.369×0.065 in^3 (inner) 0.053×0.340×0.065 in^3 (outer)
Bare metal	0.048×0.364×0.060 in^3 (inner) 0.048×0.335×0.060 in^3 (outer)
Cable short sample current (5T, 4.2K)	6650 amps (inner)
Miits to 500K	15.4 (inner), 12.5 10^6 amp^2-sec

except one number. The superconductor that went into the Energy Doubler had a current density of something like 1800 amps per square millimeter at 5 tesla and 4.2K. This was almost an industry standard for the late 70's and early 80's. All of the designs in the reference design are assuming 2400 amps per square millimeter under the same conditions. There are good reasons to think that could be achieved. There is some evidence that it's possible to go even higher. The more the current density goes up, the fewer dollars it takes to build the machine or the more beam energy that will be available. So it's worth working hard on the current density that can be achieved in a superconductor, and the subject has got to be attacked very vigorously in the next few years.

Magnet Assembly

Once the superconductor is as good as one can make it, it has to be put into cable. The cable has to be wound into long coils of semi-cylindrical cross section. Each cable turn has to be very accurately placed. The cables have to be placed to an accuracy of 2 mils or better and held there against strong magnetic forces. If this can be done, the magnet will have a suitable field quality for the accelerator, tolerances of one part in ten thousand. It's not possible to see the keystoning as it's called in this wire, but to put this package together these cables have to be thinner at one edge and thicker at the other. If that is carried to extremes, the superconductor is damaged and the premium density that has been fought so hard for is lost. A compromise is reached by tilting some of the current elements and filling in with inert wedges. The same trick can also help with the field uniformity. The insulation, winding, compaction, and collaring of this coil are all very tricky steps. A failure to maintain the dimensional tolerances or the pre-load on the cable will lead to a useless magnet.

It will surely require many prototypes to prove out the particular technique. In the Energy Doubler 100 to 200 prototypes were needed. For the SSC it should be possible to get by with something like 100 prototypes. These will test not only the aspects mentioned above but other design features.

Magnetic quality is important. A radius of 2/3 of the aperture is the usual place to specify the field quality. The dipole field will have a strength of something like ten thousand times any of the non-dipole multi poles. These are given in Table V. Since they are high harmonics they increase rapidly at larger radii. At 1 centimeter they are very small. That makes a very uniform magnet, and uniform magnets make accelerators like the Tevatron that are easy to turn on and operate. One would be ill-advised to compromise on the field quality here for economy, since one might end up building a machine that could never really operate.

Table V. Multipole Coefficients
(As Calculated for a Mechanically Perfect Magnet).

	R=1cm	R=1.7cm(2/3 aperture)
B_0	10^4	10^4
B_2	0.07	0.20
B_4	-0.07	-0.55
B_6	0.09	+2.14
B_8	-0.14	-9.49
B_{10}	0.01	+2.78
B_{12}	0.00	-0.56
B_{14}	0.00	-0.03

It would be nice if only geometric placement influenced the field quality in superconducting magnets, but that's not the case. Particularly, at low fields where the beam is injected, superconductivity stabs one in the back with the problem of persistent currents. These are currents produced inside the superconductor filaments by the changing magnetic field. These persistent currents at low excitation lead to error fields, such as sextupoles, that spoil the perfection of the magnet. The bigger the filaments, the worse the persistent current effects. At low fields the persistent current magnitude is set by the short sample performance of the superconductor, just the thing that one has been trying to maximize. If the short sample current distribution in such a conductor is different from the distribution at high field persistent current, terms will be present in the magnets that will vary in an irregular fashion. That would be very bad. Therefore, it's important to learn on a production basis how the very low field short sample valves in these niobium titanium conductors are determined and to control both the temperature of the magnets and all the other factors that influence the error fields. That's true of both designs A and B. Design C side-steps this problem by using the iron to short out these error fields to a large extent.

The superconductor has to be held in place in spite of the Lorentz forces that amount to hundreds of tons on these coils. Fairly strong aluminum collars have been incorporated to take the force.

The design also provides space to put in electrical heaters. These heaters will be used for the rapid warm-up that is desirable. One of the features of design B is the flexibility to handle magnet failure and replacement quickly by warming up a magnet string. In this case a magnet string is 5 kilometers long. It will be possible to warm-up a string in a 24 hour period, change a magnet, and cool the string back down in 24 hours.

At Fermilab the present experience is that it takes 36 hours to warm-up and eighteen hours to cool-down. Those fast rates put large thermal stresses on components. The SSC design has to be proven to be invulnerable to those kinds of thermal cycles. To break something, just warm it and cool it. Big forces are involved. Parenthetically, in design B there are 16,000 magnets. They all have to work all of the time to make the beam go around.

The choice of a high strength aluminum alloy and design of dies to produce enough collars for 60 miles of magnets is a nice challenge. The DESY effort is using aluminum collars, and it seems to work quite well.

As a cost cutting feature, it is proposed to make all of the heat shields out of extruded aluminum. They would be welded together with automated welding techniques to make the longitudinal joints. Aluminum is a good thermal conductor; its mass is low and it has a lot of other good features. In the past Fermilab has always used stainless steel and manual welding. New welding techniques must be learned. The Japanese at KEK have utilized automated aluminum welding.

The suspension system in the design B magnet consists of a G10 post every three or four meters sitting on the vacuum vessel floor. It's a nested set of cylinders with heat intercepts at intermediate temperatures. Different contraction coefficients must be accounted for so that parts can slide back and forth. There is experience on how to do all that; it's just necessary to find the cheapest and most reliable way to do it.

The end detail of the magnet is something that affects installation cost. Every effort should be made to simplify the ends. Figure 10 shows a plan view of a magnet interface. At the end of the magnet, the fins are trimmed away on the extruded aluminum pipes that are part of the heat shields. Aluminum bellows are welded on and welded to the next magnet. There are big bellows on the outside to complete the vacuum vessel. The 100,000 or more welds had best be done by machine to get a high degree of reliability. Note that the Doubler was not welded together but instead put together with mechanical clamp seals. It's probably fair to say that each seal was made at least twice in order to get one leak-tight joint. Welding the joints for the SSC implies a good reliable magnet since taking out a welded joint is a little tougher than unclamping one.

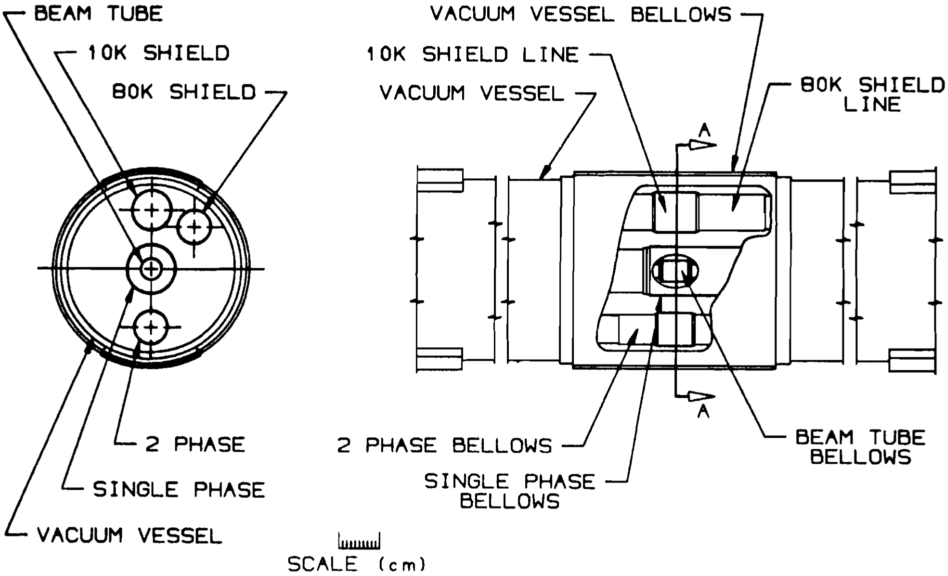

Fig. 10. Plan view of the magnet interface for design B.

R&D Challenge

A nice technical challenge is compensating the persistent field in a reliable way. Measuring all these magnets is another tough problem. It won't be possible to measure 15,000 magnets one by one the way it was done in the Energy Saver where each magnet was individually cooled and measured. The hope is that every magnet can be measured with warm techniques and perhaps one in ten or even one in a larger number will be sampled cold. What that means is that 90 per cent or more of the magnets will be installed in the tunnel, cooled and ramped to full field in the tunnel. Magnets not capable of full-field operation will be removed and replaced.

There are many other R&D challenges. Surveying devices to a fraction of a millimeter in such a large ring is not exactly a proven technique. Quench protection, that is the ability to save the magnet if it inadvertently stops working as a superconductor, has to be made reliable and simple. Table VI contains a complete list of these challenges for design B.

Quality control will be an important part of producing these superconducting magnets. At Fermilab, paper records were kept of who did what to each magnet, what they did it with, and where the parts came from. A computer-based system has been developed with a terminal at every technician work station. This system is now

Table VI. List of R&D Challenges.

- Developing methods to extend to large quantities the industrial production capability of improved Nb-Ti superconductor, and cable with higher critical current density.
- Improving the mechanical cabling process to increase cable performance.
- Developing methods to correct for the effects of persistent currents at low magnetic fields, including both self-energized and externally energized correction coil systems.
- Developing rapid and economical methods for measuring magnetic fields to accuracies of about 10^{-4} in long magnets.
- Developing accurate, labor-efficient methods for magnet alignment.
- Developing a simple and fail-safe quench protection system.
- Developing special superconducting magnets, such as high-gradient quadrupoles and large-bore dipoles for the interaction regions.
- Developing tooling that is appropriate to producing magnets at the required rate.
- Developing coil winding and collaring methods that can eliminate the coil pre-forming step.
- Investigating techniques that allow smaller diameter coils to be fabricated.
- Designing optimized thermal shields to eliminate distortion due to thermal gradients.
- Investigating the behavior of aluminum collars, and the cost/benefit of using more aluminum parts.
- Optimizing the cold-mass support structure.

in use for building some complex assemblies which are part of the TeV I antiproton source. This is just an illustration of the method. The assembly is a one-meter long set of microwave cavities, pick-up loops, nitrogen cooling lines and a delay line combiner board that puts all the rf signals in phase. This is to provide a 1 gigahertz low noise signal indicating the antiproton bunch properties in the machine so that various rf dampers can work on those properties. About 100 of these have to be built to tight tolerances. To do this, a computer terminal is put at each work station and a set of instructions somewhat like a Heathkit manual is loaded in the computer by a supervisor. If someone can read and can recognize part numbers, they can build an assembly by walking into the laboratory and following these instructions.

The point of this is that fairly unskilled labor can be used. When requested, they make measurements on the assembly. They enter those measurements into the computer rather than using pencil and paper. The supervisor sitting in his little cubby hole somewhere can call up any relevant information. He may ask "Where is sub assembly number such and such and how far down the production chain has it got?" The supervisor can also quickly get determinations of the measured properties as a function of serial number or anything else. It doesn't take much computer power to put this work control system in place. A small machine will do it. A system like this will be very useful in the SSC production phase. It provides a quick way of changing the work flow in that new instructions can be inserted without going back to the engineering department and saying "I have to change all these blueprints because I want to change a 10-32 screw to an 8-32."

Summary

Construction and operation of the Fermilab Energy Doubler as well as intensive DOE studies over the last year indicate a Superconducting Super Collider can be built. There will be many challenges. Many people and many institutions will face and solve these challenges. This Round Table was organized to discuss ways whereby the parties could work together to solve the challenges expeditiously and frugally and meanwhile produce a superb accelerator. It is our hope that some progress has been made in that direction.