 IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

SUPERFERRIC MAGNET OPTION FOR THE SSC

F. R. Huson, H. Bingham, J. Colvin, M. Davidson, J. Greenough. S. Heifets, H. Hinterberger, M. Kobayashi, K. Lau, G. Lopez, P. McIntyre, W. MacKay, D. Neuffer, G. Phillips, S. Pissanetzky, P. Rajan, D. Raparia, R. Rocha, W. Schmidt, R. Stegman, D. Swenson, T. Tominaka, P. VanderArend, R. Weinstein, W. Wenzel, R. Wolgast, J. Zeigler

Texas Accelerator Center
2319 Timberloch Place
The Woodlands, TX 77380

The basic design for the SSC started at Snowmass in the summer of 1982. The premise is that a superferric SSC has the potential to be simple, reliable, inexpensive and provide future flexibility. A concentrated effort began in March of 1984 when the Texas Accelerator Center was formed. The Texas Accelerator Center is a group of about 50 people divided into three areas of research, a calculations group working on beam dynamics, an R and D group working on superconducting magnets, and an R and D group working on new accelerator ideas including a proton linac and a plasma-laser accelerator. This paper will emphasize the work on the superferric magnet R and D.

Machine Parameters

We propose an injector system with a 3 GeV linac, a 3 to 100 GeV booster, and a 100 GeV to 2 Tev high energy booster. The main ring would operate from 2 TeV to 20 Tev. We are pursuing R and D for an H^- linac capable of 30 ma of beam with an emittance of 1πmm.mr and high acceleration gradiant. The elements of this accelerator would be an H^- ion source, an RFQ, a 440mHz drift tube linac, and an undefined cavity structure.

The first booster would have a 250 meter radius with small (6''x11'') 1.5 Tesla conventional magnets. This very small magnet with a 1'' aperture is allowed because of the small beam emittance. The small beam emittance is possible because the limit on beam emittance is normally at the injection of the linac into the first circular machine. This space charge blow up is proportional to $\beta^{-2}\gamma^{-3}$ and explains the reason for the 3 GeV linac. The booster would operate at 5 Hz and thus allow construction of a conventional beam tube for vaccum. This accelerator would be capable of accelerating $3x10^{10}$ particles per bunch at 50 mHz or $3x10^{13}$ per second.

The high energy booster would use a unit of the superferric magnet from the big ring, which will be discussed below. This ring would have a radius of 2.5 kilometers, and would be an oval accelerator with straight sections on the two sides that could be used for machine functions or for interaction regions. The accelerator would be capable of a 1 minute cycle time similar to the Tevatron at Fermilab, and thus be able to load the large SSC ring in 10 minutes. It would be constructed with a 2-in-1 magnet so that beam could be simultaneously injected in each direction into the big ring. This would also permit colliding beam experiments in this ring at 2 Tev on 2 TeV. The luminosity would be approximately $10^{32}cm^{-2}s^{-1}$. There would also be extracted beams for tests or fixed target physics.

The main ring of the SSC would be made up of 1330-115 meter units, plus straight sections for machine operation and interaction regions, and have a total circumference of 162 kilometers. Each of the 115 meter units would be made up internally with 3-35 meter dipoles, 1-4.7 meter quadrupole, and 4.3 meters for a spool piece containing correction elements, position monitors, expansion joints, and heat exchangers. The 35 m unit dipoles, quadrupoles, and spool pieces would be assembled individually at various industries throughout the country. These units would be shipped to the SSC site and assembled above ground into a single 115 meter unit. This unit externally would be a 16 3/4'' diameter pipe serving as the vaccum chamber for this full unit. The insulating vacuum would be pumped and then sealed off. These units would then be inserted into the main tunnel at four locations and welded together to make up the arcs of the accelerator. The magnets would be transported by a special made self propelled vehicle that could follow a wire located in the floor. This is done routinely in industry, particularly in warehouses and manufacturing plants. Figure 1 illustrates a cross section of the tunnel with the magnet mover. The ring would be an oval with clustered interaction regions on each side. There would be a total of 6 interaction regions, each cluster of 3 interaction regions would be about 4.5 kilometers long. A more detailed report on the lattice and study of aperture and stabilities is presented in another paper at this conference.

SUPERFERRIC DESIGN

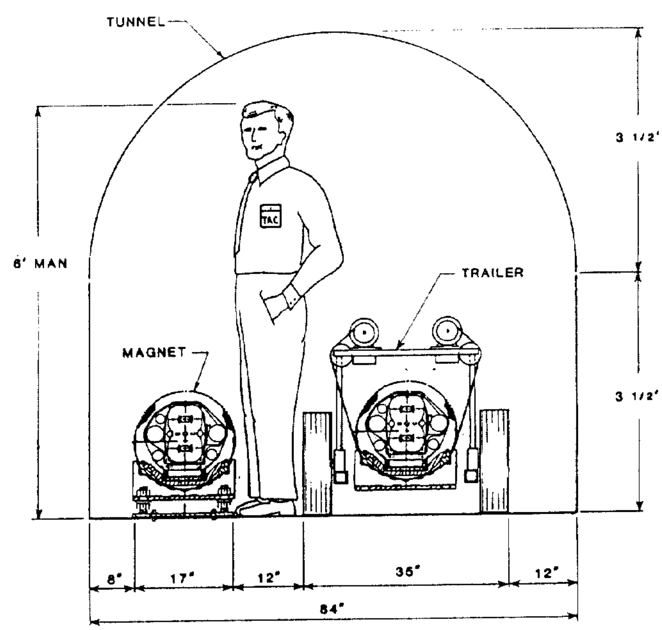

Figure 1. A cross section of the tunnel for the superferric magnet. The small magnet with no external cables or pipes allows for a tunnel of 7' dimensions. Since the cost per unit length of tunnel is proportional to the cross sectional area, it is important to minimize tunnel size.

0018-9499/85/1000-3462$01.00© 1985 IEEE

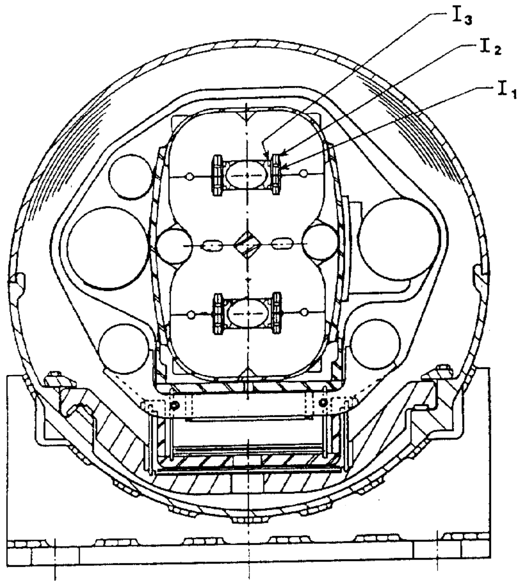

Figure 2: The 2-in-1 3 Tesla superferric magnet is enclosed in a vacuum chamber of 16 3/4'' O.D. The iron is 1/16'' laminations. The two magnet channels are magnetically independent. The gap of the magnet is 1 inch. The good field is greater than 2 cm diameter. The support in the figure is made of 2 concentric fiberglass cones, one between 10°K and 80°K and the other between 80°K and 300°K. There is a support every 24 feet. The small pipes are for liquid helium and nitrogen and the larger ones for helium gas. Sixty layers of superinsulation are between 80°K and 300°K.

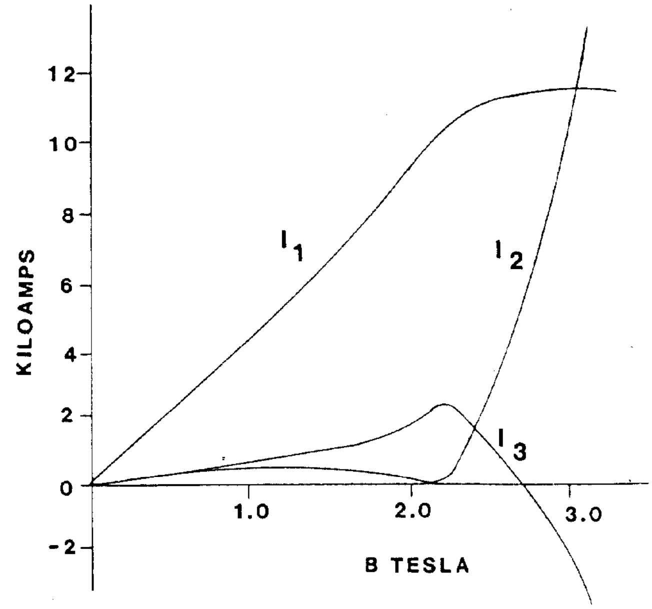

Figure 3: The 3 independent currents as a function of magnetic field.

Magnet Design

Figure 2 is a cross section of the 3 Tesla Superferric magnet. The magnet has 3 independent currents, I1 is the four turns closest to the horizontal plane, I2 is the four turns furthest from the horizontal plane, and I3 is a trim coil on the edges of the pole face. The main dipole field is set by the sum of the 3 currents, I1+I2+I3, B2 (sextapole) is adjusted to zero by the ratio I1 to I2, and B4 (decapole) is adjusted to zero by I3 (The multipoles are defined in figure caption 6). The B6 multipole is the first nonzero coeffecient for this design, and has about 1 unit which must be corrected by the correction elements at the end of each dipole. The odd B multipoles and all of the A multipoles are zero by symmetry. The rms width of the distribution of these multipoles is discussed in the next section. Figure 3 gives the current as a function of field.

The Iron of the magnet is made of 0.060'' laminated steel (1008). A unique aspect of this magnet is the iron magnetic shunt located between I_3 and I_1-I_2 in the magnet. This 0.060 steel shunt between the pole polefaces saturates immediately and helps to control the tolerances on the placement of the cable plus it reduces the flux seen by the cable by about 15%, permitting a higher current density for a given field. This allows the magnet to nominally operate above 3.5 Tesla, however the multipoles start to become observable above 3.25 Tesla.

The electric circuit for the magnets is shown in figure 4. When a quench occurs in the magnet the main current is bypassed every 105 meters of dipole. The stored energy in 105 meters of dipole is 525 kilojoules per channel. There will be 6 power supplies around the ring for each circuit. The three independent current circuits are magnetically coupled.

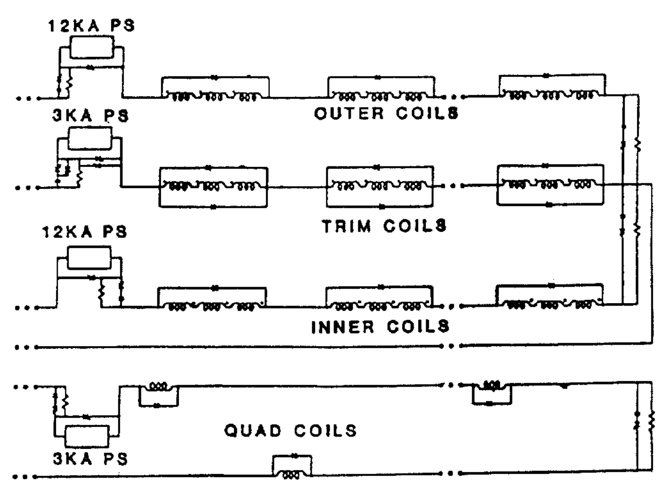

Figure 4: There are 6 electrical circuits around the ring. This figure shows 1/2 of one circuit.

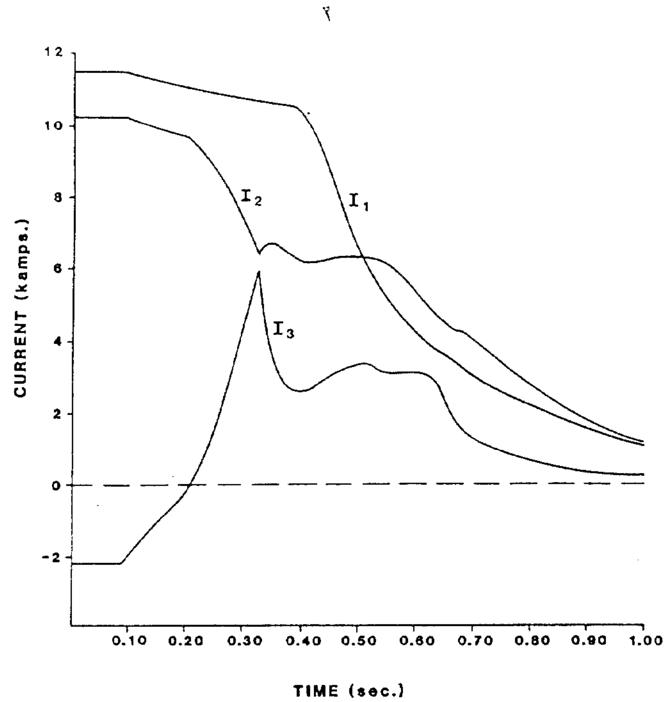

Figure 5: The quench that produces the highest temperature in any conductor occurs at full current and in I_2 (shown). Normally quenches will occur by beam loss in I_1. The quench occurs at t=0.0. The power supply is removed at t=0.1 seconds. The diode in circuit I_2 begins to bypass current at t=0.2 seconds (fires at 4V). The trim current I_3 diode fires at t=0.2 seconds and the whole I_3 circuit quenches at t=0.3 seconds. The diode in circuit I_2 fires at t=0.4. The warmest spot in I_1 is 56 ^{O}K, in I_2 472^{O}K and in I_3 40^{O}K.

Figure 5 illustrates what happens when a magnet quenches. As mentioned in the figure caption the maximum temperature experienced in the superconducting cable is 565^{O}K. This will not damage the conductor.

The cryogenic system consists of 12 refrigeration circuits around the ring. The cryogenic loads which must be taken care of are listed in table I. The liquid helium is fed down through the magnets to a distance of 1/24 of the ring. At that point part of the liquid helium is expanded through a Joule Thompson valve to cool it giving a two phase helium and the other part of the liquid is returned in a separate pipe. Between every other magnet, that is, every 230 meters, there is a heat exchanger where the returned liquid and cold gas are combined in an heat exchanger to heat exchange with the helium coming down through the magnets. In this manner, the full length of magnets is kept cool. The remaining helium at the end of the magnet string is brought along a shield between the liquid helium magnet container and the liquid nitrogen shield. This shield will be at a temperature of about 10^{O}K. When a quench occurs the warm helium in that magnet or magnets, is removed at the next spool piece where there are cryogenic valves that allow this warm helium to be put into the return lines. Recovery from a quench will take about 30 minutes. It will take about 1 week to exchange a magnet in the ring. This requires a high reliability for the magnets. This can be achieved with a vigorous R and D program.

TABLE I

Steady State Heat Loads in W/Meter

	300-80	80-10	4.5^{O}K
Radiation	.75	.066	.0124
Shield Support System	.114	--	--
Closure Bellows	.12	--	--
Magnet Supports	.63	.080	.0040
Magnet Connec	.16	.040	.0200
*Refrig. Station	.06	.031	.0800
Contact Resist	--	--	.0032
Synchrotron rad.	--	--	.0579
TOTALS	1.834	.217	.1055
TOTAL/REFRIG. STATION	23,842	2,822	1366
TOTAL FOR RINGS	286,100	33,864	16,396

*Includes allowance for valves.

Magnetic Measurements

Thus far seven magnetic channels have been measured. The Texas Accelerator Center has assembled 3 one-meter single channel magnets, 1 one-meter two channel magnet, and 1 seven-meter 2 channel magnet. General Dynamics Corporation has assembled 1 one-meter single channel magnet. Only one of these magnets has quenched below the short sample limit of the superconductor, (a TAC magnet at 90 % of full current). This was linked to a poor assembly of that particular magnet. There have been no problems with electrical shorts, we are convinced that the cable does not move, that the insulation on the cable is sufficient, and that cooling of the superconductor is very good. Therefore we are satisfied with the mechanical design of the magnet.

Figure 6 illustrates the measured magnetic multipoles for the seven magnets that have been measured. Also indicated on the figure are the RMS widths for the corresponding distribution for the 700 doubler magnets at a corresponding point. That is the multipole at 1/2 the radius of the innercoil. The width of the distributions compare very well with the doubler magnets. We believe that future magnets will have narrower distributions as we implement quality control on assembly of the magnets and improve our measurement system.

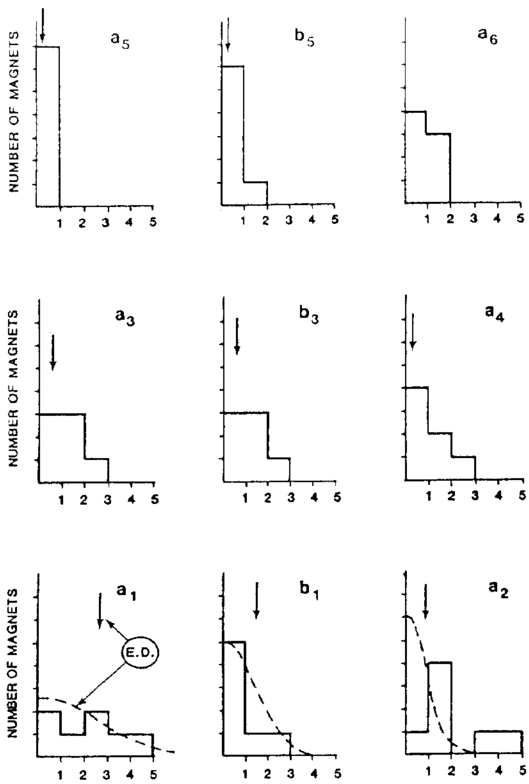

Figure 6: Measured RMS multipole coefficients in units of $10^{-4} cm^{-n}$ for the first seven Texas Accelerator Center magnets. The multipole coefficients are defined by:

$$B_y(y=0) = B_o \left(1+b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5 + ..\right)$$

$$B_x(y=0) = B_o(a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 + \ldots).$$

All a_i coeffecients and odd b_i should be zero by symmetry. B_o is adjusted by the sum $I_1 + I_2 + I_3$. b_2 is adjusted to zero by I_1/I_2. b_4 is adjusted by I_3. B_6 will be adjusted by a small trim magnet at the end of the dipole. The arrows in the figure mark the RMS width of the multipole coefficients for the Fermilab Energy Doubler. These are the coefficients evaluated at 1/2 the radius of the inner coil (1.9 cm) for over 700 magnets. Some of the width of the coefficients for our magnets is due to a systematic error caused by our measurement probe.

We have measured the quench propagation velocity in our magnets. We find that at 5 kamps the velocity is 5 meters per second, at 7.5 kamps 8 meters per second, and at 10 kamps 15 meters per second. These values are consistant with calculations and have been inserted in our quench protection calculations used in the data in figure 5. It takes about 0.10 seconds for an ajacent cable to quench.

Conclusion

We believe the design for a SSC that we have presented in this paper is workable. The magnets at this point appear to have sufficient field quality and reliability for good operation of the SSC. We have shown that industry can assemble this magnet. During the rest of this year the Texas Accelerator Center will assemble more 1 meter and 7 meter models to refine the design and better measure the magnetic field quality. General Dynamics Corp. will assemble 3 28-meter magnets to be measured at the Texas Accelerator Center. These magnets can easily be shipped over the road between San Diego California, where they are assembled, and The Woodlands, Texas where they will be measured. If these magnets are selected for the SSC then next year a string test of the order of a dozen of these magnets would be done. The full compliment of 1330 115-meter units could be assembled in industry in a period of 2-3 years.