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PROGRESS IN SUPERCONDUCTING MAGNET TECHNOLOGY FOR ACCELERATORS/STORAGE RINGS

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The progress on the Energy Saver is briefly described. A description of some of the "hard lessons" is given, and a short comparison of the two-shell dipole versus the "cos θ" form is made.

Introduction

There is a rapidly developing commitment to superconductivity in the physics community. At this conference, papers describing magnets for the Tevatron, ISABELLE, UNK in the U.S.S.R., TRISTAN in Japan, and HERA in Germany have been heard. As a result, it is perhaps useful to review the state of the technology as it now exists. To this end, this paper will briefly review the Tevatron status and indicate some of the hard lessons that we have learned. I would then like to make a few comments comparing the two different magnet structures being pursued. The one at FNAL can be described as a two-shell, collared coil using Rutherford cable and a warm iron yoke. The other being pursued at BNL is a single shell, cos θ winding using a braided conductor with a cold iron yoke.

Present Status

Construction of the Tevatron is proceeding satisfactorily. The magnet components consisting of collared coils, cryostats, and yokes are now proceeding well after we had encountered troubles with the supports for the coil. These supports which position the coil in the center of the yoke and must span from the room temperature yoke to the 4° coil, must have high strength and a low heat leak. The difficulty with the support system was discovered after magnet production had commenced. The cryostat production was delayed while this problem was solved, and the coil production continued. During this period, quality control of the collared coil assemblies was provided by the room temperature magnetic measuring system that has been described in previous contributions to these conferences. At present, more than half of the collared coil assemblies are complete for both the dipole and quadrupole magnets. Cryostat production is now at the level of eight dipole and two quadrupole cryostats per week, and we expect to reach the level of ten dipoles per week shortly.

The refrigeration system consisting of the 3,000 liter per hour central liquefier and 24 satellite refrigerators is proceeding on schedule. Three satellites are working, and the main liquefier plant is being run in. Since reports of this nature are of transient interest, I will now leave the subject and list a few of the hard lessons that have been learned.

Hard Lessons

1. Quality control is much more difficult than expected. Magnet production is still a difficult and state of the art procedure. An extensive and sophisticated QC system is needed. It must have many small, self-correcting loops. This means local monitoring of processes or subassemblies in a manner that catch difficulties before a large backlog of deficient components is accumulated. For instance, a high voltage test of the cable insulation as it comes off the cabling machine is sensitive to bad insulation, over-size strand, and sharp corners on the conductor from the process. Such a test unables the manufacturer to catch the trouble immediately before a large amount of bad cable is made and shipped for use in the magnets. Leak checking of subassemblies is also another obvious example.

However, a second level of quality control must also exist. The magnet/cryostat system is sensitive to slow drifts in the production processes which must be monitored and corrected. Room temperature magnet measurements of the dipoles and quadrupoles and ultimately cold measurements at the Magnet Test Facility (MTF) fulfill this function. An essential feature for this system to function is that there must exist ways to make small changes in the fabrication of the magnet on the basis of these measurements. For instance, small changes in the shims that control the lower harmonics are made to correct slow drifts arising from changes in cable size, insulation thickness, etc. The normal and skew quadrupole moments are removed entirely by positioning the coil off axis in the iron yoke during its final measurements at MTF.

2. Refrigeration. Need lots! At turn-on time in a new system, as much as twice the anticipated refrigeration should be available. All troubles that are encountered with superconducting magnets such as quenches, vacuum leaks, contamination, heat leaks, human mistakes, and ignorance immediately get turned into refrigeration troubles. Later as the system is operated and better understood, the load may approach the one originally anticipated. It may be useful, for instance, to provide for temporary extra compressor capacity at turn on for a small system. Large systems will be brought on piece-meal, i.e. a section at a time, for instance, which represents a second way of achieving overcapacity of the refrigerator at turn-on time.

3. Magnet Test Facility (MTF). It is easy to underestimate the load that MTF must handle. FNAL is undersized even though the facility has six test stands, two complete measuring systems, and a large amount of refrigeration capacity. It must perform three functions. First, complete check of the vacuum integrity, cryogenic integrity, and magnetic field properties of magnets to be installed in the tunnel. Second, it is the ultimate quality control tool; and third, it is the heart of all of the R&D that is being carried on during the project.

4. Strong industrial support is necessary. Fermilab has had very strong support and close ties with many component manufacturers. Perhaps, one of the most successful (but not the only one by any means) is with the cable processing done by New England Electric Company. A quick reaction time and short turnaround time are necessary to avert expensive mistakes. The manufacturer must be both willing and able to work closely with an R&D project. I do not believe that the complete magnet assembly is suitable at this time for industrial manufacture. It is still too much of an R&D effort.

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Magnet Structure

I would now like to make some highly personal remarks on the comparison between the FNAL two-shell Rutherford cable, collared coil design, and the BNL cos θ, braided conductor, cold iron structure. I will confine these remarks to four areas:

1. Preload. In order that the coil not distort under excitation, the elastic compressive forces must exceed the magnetic JxB forces. To change the preload in a collared coil, the coil is molded to a larger size. The collars are then slipped over the coil, and the greater preload is directly applied by the collaring press when it closes the collar tightly. Any amount of change in the preload is easily accommodated, and the molded coil size is easily changed by shims in the mold. With the BNL assembly procedure, the change in preload is accomplished by molding the coil to a larger size, and then using a single or double shrink method to insert the coil package into the precision bore of the yoke. The process does not lend itself to adjusting the preload over a wide range.

2. Field accuracy. For harmonics higher than about the decapole, the errors are dominated by fluctuations in the turn-to-turn placement of the wire and are the same for all methods of construction. The lower harmonics depend on the current block positions or the key angles. The collared coils make these angles easily adjustable by means of shims that are put in place when the coil is collared (the necessary change of a few mils has negligible effects on the preloading). Thus, a given stack of coils can be made into magnets with differing multipole moments. The collar is a highly reproducible and accurate piece of stainless steel obtained by stamping with precision dies. The field accuracy is tied to the accuracy of the collar. For the cos θ structure, accurate placement of the block is necessary and must be built into the coil with great care. The large iron mass does not aid in controlling the angles of these blocks or the field accuracy. An additional advantage of the warm iron is that there is a relatively large central hole in the yoke since the iron must not saturate. It is possible by placing the axis of the coil off the axis of the yoke to completely eliminate the normal and skew quadrupole moments of the coil assembly. This is presently being done on the test stand at the time of the final measurement for the Fermilab coils.

3. Dynamic effects of the support. For each system, there are dynamic effects on the field of the support. The collars flex elastically, and the cold iron saturates. Both of these effects show up in the sextupole moments, but the effects of the collars elastically deflecting, about .002 in., is less than 5 percent of the effect of the saturation of cold iron. The advantage of the iron being close is that it makes available about 1 Tesla additional field. But it forces a greater load upon the correction coil package.

4. Cryogenics. The cold iron design entails extracting a much larger amount of heat during cooldown than is the case of the collared coil assembly. As mentioned earlier, refrigeration and turn-around time are very important when bringing up a system of superconducting magnets.

Future

In the future, answers to some of the above criticisms will undoubtedly be found. Perhaps as we go to higher fields, only magnets such as the Danby design at BNL or the ones presented at this conference by J. Perot from Saclay and Clyde Taylor from LBL will be able to stand the forces. As we go to higher energies, the question of higher field magnets must be addressed. Tom Collins, at Fermilab, has made a very strong point that the aperture must be decreased in order to save on the superconductor costs. A study of the errors in the present magnets indicate that we could go to an aperture as small as 2 in. He also points out that quadrupoles with a high gradient become increasingly hard to design. This is just the reverse of the past. Present machines have a large aperture in order to accommodate complicated beam choreography at injection and extraction times. In the future, we may not be able to afford this luxury but will have to rely much more on sophisticated beam manipulation techniques. It appears that we are going to be strongly challenged to keep the circular machine on the main line in the Livingston graph.