Proceedings of the Tenth International Conference on Cyclotrons and their Applications, East Lansing, Michigan, USA

# SUPERCONDUCTING MAGNET FRONTIERS

John R. Purcell

GA Technologies Inc.
P.O. Box 85608
San Diego, California 92138

## INTRODUCTION

Although the field of superconducting magnets has not grown as fast as many people expected in the early days, it has still grown significantly in the last twenty years. As the principles of magnet engineering become better understood, new applications will make themselves known. It looks like a field that has a bright future.

A frontier sounds like a definite point in development; however, I find it much more indefinite with a lot of fuzzy spots. For instance the 12 ft. bubble chamber magnet, the first of the very large superconducting magnets, does not look so different from the large magnets of today even though it was started in 1966 and finished in 1968. The big difference in the 12 ft. magnet and the large magnets of today is in the details and the uncertainty involved. The uncertainty was not so much a matter of the information existing as it was in finding it. In the 12 ft. magnet we had to make a large number of splices in the conductor and we wanted to soft solder them. It was a simple matter to run a few tests in the lab and determine the resistance of the soldered splices; however, the question was asked about the long term phase stability of the tin in the solder at cryogenic temperatures. This was a much more difficult question to answer because nobody wanted the magnet splices to deteriorate after 10 or 20 years. Somehow we found out that it was only pure tin that underwent a phase change at low temperatures and that alloys, such as lead-tin, were stable. The point of this little story is that the "frontier" looked different on this small matter depending on whether you could find the answer or not.

Another area of "frontier" that confronts the builder of a "one of a kind, large device" is how is the best way to do it. Once a company has built a few million cars they have done the wrong thing enough times to have a pretty good idea of the best way to go about it. Going back to the 12 ft. magnet again, a lot of soul searching went into the decision as to whether to build the cryostat so it could be taken apart to repair the magnet if necessary or to weld it together for better reliability and economy. Either way could probably be made to work, however the decision to weld it together was the right one as the magnet is still in operation after serving more than 10 years at the Argonne Laboratory in Chicago and then having been moved to the Stanford Linear Accelerator in California. After our worrying about such small seeming problems as soft solder phase transition, we completely ignored one of the major aspects of superconducting magnets and that is twisted conductor. The issue did not arise until much too late for us to consider it in the fabrication of the 12 ft. magnet. Fortunately, we had enough "ignorance" factor (some people call this "safety factor") in the magnet that it worked fine without the conductor being twisted.

The Fermi National Accelerator Laboratory bubble chamber magnet was the next big magnet that I was involved with. The frontiers for this magnet were completely different from the 12 ft. magnet. Stable soft-solder, twisted conductor, martinsetic transformation in stainless steel, cryogenic stability, and other small things were "old hat" now and our attention was focused on different problems concerning the enormous forces and stored energy. The 12 ft. magnet stored about 80 MJ of energy and operated at a modest current density of about 1,200 A/cm$^2$. The new magnet would store 400 MJ and for economy needed to operate at an overall current density of 3000 A/cm$^2$. The current density in the conductor was much higher because stainless steel had to be co-wound with the conductor to support the large hoop load. At this current density and such a large energy, the question was "how to handle the energy if something went wrong?" Four hundred megajoules is enough energy to vaporize a cubic foot of copper and the magnet would surely run low on liquid helium sometime in its life and the energy would have to be taken care of very quickly. The obvious solution is a dump resistor that can be put into the circuit in the event of an emergency and dissipate the energy. However, to get rid of 400 MJ in the few seconds before the conductor started to overheat, and at the operating current of 5,000 A, it would take a voltage of several kilovolts and a resistor that could withstand a peak power of perhaps 100 MW. Rather than follow this rather alarming route we decided instead to construct the magnet to absorb the energy within itself. To accomplish this, after many calculations, we incorporated a large (12 in.) vent pipe with a rupture disk that would blow at about 30 psi. The reasoning behind this was that if something went wrong with the magnet and a large normal region appeared, the pressure would rise very quickly. By not venting until the pressure reached 30 psi and then letting it go suddenly, the total contents of the helium vessel would be expelled in about 4 sec. Further calculations showed that the normal region would propagate very quickly throughout the coil, once the liquid was gone, and the energy would be dissipated uniformly throughout the coil. No high voltage would exist because the IR drop would equal the L di/dt in each section of the coil and the temperature would go up to about 70 K in a few seconds. All this was just theory, of course, and we didn't try to test it during the magnet startup.

After the magnet had been in operation about 6 years, sure enough the operating crew was distracted by a malfunctioning refrigerator, a liquid level indicator failed allowing a low liquid helium level, and the magnet was quenched. Everything worked as planned. The vent dumped almost all the 6,000 liters of liquid helium in 4 or 5 seconds and the normal region propagated throughout the coil. Someone had the presence of mind to measure the temperature of each pancake after the quench and they were all within 15 K of 70 K. After the excitement died down, the magnet was carefully analyzed and found to be unharmed. It was put back into service and remains in operation to this

The following is a brief description of some of the large magnets and why there were on the frontier. The list is certainly not complete, but is mostly the magnets I have been involved with.

## 12 Ft. BUBBLE CHAMBER MAGNET

Although the 12 ft. bubble chamber magnet has been mentioned before, it is worthwhile describing it a little better. The magnet winding bore is 16 ft. and it produces a 1.8 T field in a 10 ft. gap, utilizing iron for the return path. Its stored energy is 80 MJ and it operates at a current of 1800 A. The conductor is 0.1×2 in. and it contains 6 NbTi filaments untwisted. No trouble was experienced due to the untwisted filaments because it has plenty of copper for stability and the iron reduced the radial field to a small value which eliminated any mechanical problems due to the conductor twisting in the radial field. The reason I would call this magnet on the frontier is that it was the first large superconducting magnet built.

## FNAL 15 Ft. BUBBLE CHAMBER MAGNET

The Fermi Laboratory 15 ft. bubble chamber magnet[1] was completed in 1972. It is a split solenoid without iron. Each coil is about 40 in. long with a 40 in. gap between the coils. The operating current is 5,000 A at an overall current density of 3,000 $\mathrm{A/cm}^1$. In order to reduce the cost, the 0.15×1.5 in. conductor was made by soldering copper strips to the basic NbTi-copper conductor to have enough copper for stability but not having to put all the copper through the expensive process used for making superconductors. This magnet was on the "frontier" because of its stored energy of 400 MJ, along with the very large hoop loads. The hoop loads were supported by a stainless steel strip co-wound with the conductor. The stainless steel was made a little wider than the conductor so it would support the entire compressive load of the coils. This allowed the use of the relatively economical and fragile soldered conductor. The compressive force between the two coils is 12,000 tons, almost as much as the weight of a battleship.

## U-25 MHD MAGNET

The U-25 MHD magnet[2,3] was on the frontier because of its unusual support system and the method of obtaining cryogenic stability. The coils of a dipole magnet push apart and must be supported by structure in bending. Most dipoles are supported by beams in bending on the outside of the coils; bending of the U-25 was taken on the bore tube and transmitted to the

CH1996-3/84/0000-0212 $1.00 © 1984 IEEE

bore tube by banding in tension. In addition, although the magnet is cryogenically stable, it depends on heat transfer from adjacent conductors to be stable. This is accomplished by a large contact area between conductors with a thin insulation. All this effort was to keep the magnet outside dimensions as small as possible. It also has the distinction of being the only magnet to fly nonstop from Chicago to Moscow on a C5-A.

## THIRTY MEGAJOULE ENERGY STORAGE COIL

The 30 MJ coil[4] was built by GA Technologies under contract with Los Alamos National Laboratory to be used by the Bonneville Power Administration for power line stabilization. It serves as an energy sink or source for the power line and is connected to the line with a 10 MW inverting power supply. The coil normally floats at about 25 MJ and can either supply or absorb 5 MJ at a 10 MW rate.

The frontier aspects of this coil are that it can tolerate a very rapid charge or discharge (3 sec to full charge) with small losses. It was designed for $10^8$ cycles, and it is contained in the world's largest fiberglass dewar. Cabled conductor was used, supported with co-wound stainless steel strips. The compressive load of the coil was also taken by the steel straps. At its operating current of 5,000 A, the maximum terminal voltage from the power supply is 2,000 V, however a high speed dump system could run the peak voltage up to 7,000 V. The coil has an outside diameter of 133 in., a winding bore of 107 in., and a height of 48 in. It weighs 37,000 lbs.

## MFTF-B

The Mirror Fusion Test Facility at Livermore National Laboratory is certainly a magnet system that is on the frontier. Although the system is still under construction, the first Yin-Yang coil has been tested.[5] This coil is large and stores a lot of energy, however the frontier aspect is the large forces that had to be supported in difficult directions. The coils in the system are dwarfed by the immense stainless steel structure required to support them.

This magnet has a peak field of 7.68 T, operates at a current of 5,775 A, and stores 410 MJ of energy. The conductor is unusual in that it has internal cooling passages built in the conductor. The conductor is square, rather than a flat strip as in most large magnets, to facilitate winding in three axes.

## FUTURE MAGNETS

### Tokamaks

In the future, large tokamaks will utilize superconducting coils for both the poloidal and toroidal field coils. These coils will be very large; toroidal coils 15 m tall and poloidal coils 20 m in diameter. The magnets of a tokamak must operate under severe conditions. They have to be extremely reliable because replacing a failed coil is an almost impossible task after the reactor has been in operation due to activation from the neutron bombardment. In addition, the coils must operate at high fields superimposed with pulsed fields and a neutron environment that damages the materials and heats the conductors. A complete set of magnets for a tokamak might cost from 100 to 200 million dollars and weigh a thousand tons.

### SMES

Another future use of superconducting magnets is in Superconducting Magnetic Energy Storage. These coils will store surplus power generated at night, when the load is small, and then deliver the power during the day when the demand is high. A 5,000 MW-hour coil would have a diameter of about 1,500 m with 85 MA turns and be buried under the ground to support the enormous forces involved. Reference 6 describes such a magnet in detail.

### Medical Imaging MNR

Nuclear magnetic resonance has been around for some time, however the latest use to generate images of slices through the body promises to be the largest use of superconducting magnets to date. These magnets are solenoids with a 1 m room temperature bore and operate at fields from 0.5 to 2 T. In order to obtain good images, the field must be uniform to a few parts per million over a 50 cm sphere in the center of the magnet. Several companies are presently producing these magnets. They have an extremely low heat leak of 0.1 to 0.3 liters of liquid helium boiloff per hour and only need to be refilled once a month or so. Most of them operate in a persistent mode and will drift less than one part per thousand per year. In the next few years it is expected that thousands of these systems will be in operation and they will greatly improve medical diagnostics.

## REFERENCES

[1] J.R. Purcell *et al.*, “The NAL Bubble Chamber Magnet,” *Proc. 1973 Applied Superconductivity Conference* (Annapolis, Maryland, May 1-3, 1972).

[2] J.R. Purcell *et al.*, “A Superconducting Dipole Magnet for the Second Loop of the U-25 MHD Facility,” *Proc. of the Sixth International Conference on MHD Power Generation*, June 1975.

[3] R.C. Niemann and K.F. Mataya, “Design and Operating Experience of the Cryogenic System of the U.S. SCMS as Incorporated into the Bypass Loop of the U-25 MHD Generator Facility,“ *IEEE Transactions on Magnetics, Vol. Mag-15,* No. 1, January 1979.

[4] E. Hoffmann *et al.*, “Design of the BPA Superconducting 30 MJ Energy Storage Coil,” *IEEE Transactions on Magnetics, Vol. Mag-17,* No. 1, January 1981.

[5] T.A. Kozman *et al.*, “Magnets for the Mirror Fusion Test Facility: Testing of the First Yin-Yang and the Design and Development of Other Magnets,” *IEEE Transactions on Magnetics, Vol. Mag-19,* No. 3, May 1983.

[6] R.W. Boom *et al.*,, “Superconductive Energy Storage for Large Systems,” *IEEE Transactions on Magnetics, Vol. Mag-11,* No. 2, March 1975.