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32 TESLA HYBRID MAGNET SYSTEM

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Résurné - Cette communication décrit la conception et la construction d'un système aimant hybride alimenté par 9 mégawatts de puissance électrique et destiné à produire 32T. Le système comprend un aimant supraconducteur de 11T en nobium-titane, un cryostat de 1.8K/4.2K, et un aimant Bitter de haute performance à refroidissement par eau, tous examinés dans la communication.

Abstract - The paper describes the design and construction of a hybrid magnet system to generate 32T with 9MW of electrical power. The system consists of an 11T niobium-titanium superconducting magnet, a 1.8K/4.2K cryostat, and a high-performance, water-cooled Bitter magnet, all of which are discussed in the paper.

INTRODUCTION

Together the University of Nijmegen and the Francis Bitter Laboratory at MIT are engaged in a program to bring both laboratories to the maximum fields permitted by their facilities. Hybrid systems for both laboratories are built at MIT and operating experience is shared to yield a combined data base upon which later designs rest. So far there have been built under this arrangement the Nijmegen I hybrid system and the current MIT hybrid, both of which are fully operational. Presently we are engaged in the construction of Nijmegen II which is the subject of this paper.

The goal of Nijmegen II is to provide fields of 32 T in a 33 mm bore, a standard size in both laboratories. The power supply at Nijmegen is rated for 6 MW continuous, but it has a 100% overload capability for 1 minute. One minute is more than enough time for measurements, and being denied the luxury of virtually limitless time at high field forces experimenters to work efficiently.

CHOICE OF CONDUCTOR

The choice between a conductor based on niobium-tin or on niobium-titanium defines the approach which is taken in building an 11T superconducting magnet. Niobium-tin at 4.2K, the boiling point of liquid helium at atmospheric pressure, is capable of superconducting performance which is sufficient for an 11T magnet. On the other hand, niobium-titanium performance needs to be enhanced by going to a lower temperature, such as 1.8K (Fig. 1). /1/

Two things which make working with niobium-tin difficult are its brittleness and the fact that the copper matrix in which the filaments are embedded, being fully annealed from the reacting treatment, has very little strength. Where in a niobium-titanium conductor the copper can be strengthened through cold-working, a niobium-tin conductor requires the inclusion of an electrically inert reinforcing member.

Engineering a 1.8K cryostat, while not trivial, did not entail the uncertainties notoriously inherent in developing conductors. Pioneered by the French, reduced temperature cryostats have been built successfully in Europe, Japan and the U.S., and
moreover, we had already been introduced to 1.8K technology through graduate student experience at our own laboratory.

In sum and especially in view of the scale of the project, niobium-titanium was more readily available than was niobium-tin.

Fig. 1 - Critical current density vs magnetic field for a niobium-titanium conductor at various temperature. Note the curve for niobium-tin at 4.2 K.

MAGNET DESIGN

Among other things we concluded that it is important to be able to operate the superconducting magnet at 4.2K as well as at 1.8K. With respect to the design of the magnet the two requirements are somewhat incompatible: at 1.8K high stresses arising from the higher fields are the dominant concern while at 4.2K cryostatic stability requirements are more important.

For 1.8K stability is defined on the basis that heat generation will always be less than heat removal as depicted in Fig. 2. Note that the design is actually for 2.0 rather than 1.8K.

Fig. 2 - Heat generation and cooling curves for niobium-titanium conductor exposed to a field of 11.5T.

Full cryostatic stability is not necessary in order for these magnets to operate reliably at 4.2K. Our experience has been that they are quite free of disturbances. Nijmegen II is designed for the heat flux to be 0.4 W/cm². Included is a temperature margin of 0.2K; the design is for 4.4K instead of 4.2 according to Iwasa’s critical current margin criterion. /2/

With the stability parameters established an analysis was undertaken to determine the optimum operating current based on minimum coil cost. It took account of the costs of winding pancake coils as well as of materials and yielded 2500 A as an optimum. A preference for somewhat lower current for gas-cooled leads and current feeds and power supply costs resulted in setting 2000 A as the design current. Other things being equal it is desirable for the current to be high (low inductance) for the sake of minimizing voltages when the magnet has to be discharged rapidly. Not only must one be concerned with current leads but instrumentation wiring, particular-
ly voltage taps, are sources of trouble when there are large voltages between them, especially in the connectors through which they exit the cryostat. Fig. 3 gives coil statistics.

<table>
<thead>
<tr>
<th>Statistics of Superconducting Magnet</th>
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<tbody>
<tr>
<td><strong>Coil Dimensions</strong></td>
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<tr>
<td>Inside diameter (mm)</td>
</tr>
<tr>
<td>HF/LF splice diameter (mm)</td>
</tr>
<tr>
<td>Outside diameter (mm)</td>
</tr>
<tr>
<td>Length (mm)</td>
</tr>
<tr>
<td>No. of double pancakes</td>
</tr>
<tr>
<td><strong>Coil Parameters</strong></td>
</tr>
<tr>
<td>Field on centerline (T)</td>
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<tr>
<td>Field at I.D. (T)</td>
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<tr>
<td>Current (A)</td>
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<tr>
<td>Inductance (H)</td>
</tr>
<tr>
<td>Energy (kJ)</td>
</tr>
<tr>
<td><strong>Conductor</strong></td>
</tr>
<tr>
<td>High field (mm x mm)</td>
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<tr>
<td>Low field (mm x mm)</td>
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</tbody>
</table>

The next question was what should be the working stress in the cold worked conductor. The subject of fatigue comes into the picture at this point as the stress levels are too high for repeated load cycles without regard for service life. Every time the magnet is charged and discharged the winding undergoes one normal cycle. A more severe loading cycle is imposed each time that the insert is tripped out. These occur either from a burnout or from an inadvertent trip caused by the monitoring circuitry. We assumed that over a 10 year period there would be 1000 normal cycles and 100 trip events and applied a factor of 10 as a safety margin.

For the purpose of ascertaining how the copper is loaded the conductor was modelled as a composite obeying the rule of mixtures, and we chose a working stress for the copper based on published fatigue data.

Lastly, a stress analysis was performed to determine how the magnet structure would respond to both cooldown thermal stresses and to Lorentz force loading. In this analysis the modelling took account of conductor and insulating systems. Different values of radial tensile strength were assumed, for it was determined that if the radial bonding between turns were to be too strong, radial tension would produce excessive hoop stress. Some strength is required though while the pancakes are being wound, and until they are finally in place in the completed stack, the turns must be stuck together. Afterward, the insulating spacers must still remain securely in place and not come adrift in the helium bath.

The structural design is based upon room temperature values of the mechanical properties of the materials used. To the extent that these properties are enhanced at cryogenic temperatures the design is conservative.

**CRYOGENIC SYSTEM**

Five watts of refrigeration at 1.8K would suffice for the various heat inputs and the power dissipations which are expected, but the cryostat components are designed for the 15W which is inherent in the large vacuum pump which is available. The 15W limit comes from the mass flow through the pump when the inlet pressure is 12.6 torr. The higher mass flows which attend higher inlet pressures can be used to speed the cooldown from 4.2K. The cryostat arrangement is shown in Fig. 4.

**INSERTS**

Although the cryostat will accept inserts offering a variety of bore sizes and fields and which are basically interchangeable with those of Nijmegen I, the most demanding in terms of design is the one to generate 32T. It will be similar to the one in the
MIT 30T hybrid which is a radially cooled Bitter magnet consisting of two concentric stacks connected electrically in series. Cooling water enters and exits from both ends (top and bottom), and the flow through the coils is radially outward first through the inner and then outer in grooves in the Bitter plates. Coil clamping is achieved from magnetized iron armatures at the ends of each stack. The success of these insert magnets comes in no small measure from a very careful match of material properties and cooling performance throughout the winding volume.

The duty cycle imposed by the 1 minute overload limitation of the power supply is quite compatible with normal hybrid magnet operation where the superconductor is charged and remains so throughout the test period while the insert is swept. Of course the insert can run indefinitely so that at lower powers continuous operation is possible.

An unexpected problem of filament breakage during the production of low-field conductor has set the timetable back by nearly one year. Completion of the system including testing is now set for the summer of 1984. The subject of filament breakage is worth commenting on because of the particular fact of the 1.8K operation. Ordinarily broken filaments could be tolerated, if not happily, at least to the extent that the resultant power dissipation could be met with liquid helium replenishment. However, in a reduced temperature cryostat, refrigeration capacity sets a much lower limit on the dissipation; if dissipation exceeds refrigeration, the system simply will not work.

The next hybrid will be a second MIT system, and we are studying conductor choices once again as the development of Internally Cooled Cabled Superconductors (ICCS) brings niobium-tin to an apparently credible state. If it comes to pass that niobium-tin is an irresistible choice, then we will have to address the problems of how to design and build coils with it.

REFERENCES

2. Iwasa, Y., Cryogenics 19 (1979) 705.