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# PERFORMANCE OF AN INTERNALLY COOLED SUPERCONDUCTING SOLENOID*

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## INTRODUCTION

Not long ago, cable-in-conduit type conductors cooled by forced flow supercritical helium were proposed as alternatives to bath cooling large superconducting magnets.[1] The rationale behind this design was to use the large cooled surface of the cable strands and turbulent flow to ensure good heat transfer to the coolant. The price one expected to pay for forcing supercritical helium through the cable in the turbulent regions was the high pumping power loss resulting from high pressure drop. Subsequently, however, experiments on samples up to several meters long showed that because of the existence of high conductive transient heat transfer a reasonably high stability margin could be obtained with very low or no flow.[2-3] Furthermore, under proper conditions, heat transferred to helium from the initially quenched superconductor could induce a transient flow which produces locally very high heat transfer.[4] Thus, very high stability margins, limited only by the available helium enthalpy, could be observed with no net flow. If it could be shown that these phenomena hold in a magnet, then high pumping power loss may not be necessary in this type of Internally Cooled Superconductors (ICS).

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Another concern on ICS is the vulnerability to strand motion in a magnetic field. This could cause degradation of the magnet. Experiments on samples with short, straight sections in high fields[5-6] again alleviated this worry.

A superconducting solenoid constructed of ICS with NbTi composite strands has been completed and tested a couple of times. Details of the design, construction, and preliminary testing have been reported elsewhere.[7] The performance of this solenoid and, in particular, its stability margins as a function of operating fields is reported here.

## SOLENOID CONSTRUCTION

We used NbTi-ICS for the construction of this solenoid. The cable, enclosed in a stainless steel jacket, consists of 12 triplex units of NbTi/Cu composite wires cabled around a core of 7 triplex units of copper wire. Thus, the superconducting strands are fully transposed. A cross section of the conductor is shown in Fig. 1b. The round stainless steel conduit provides a cable space of 7.36 mm in diameter, where the void fraction for helium flow is about 0.43.

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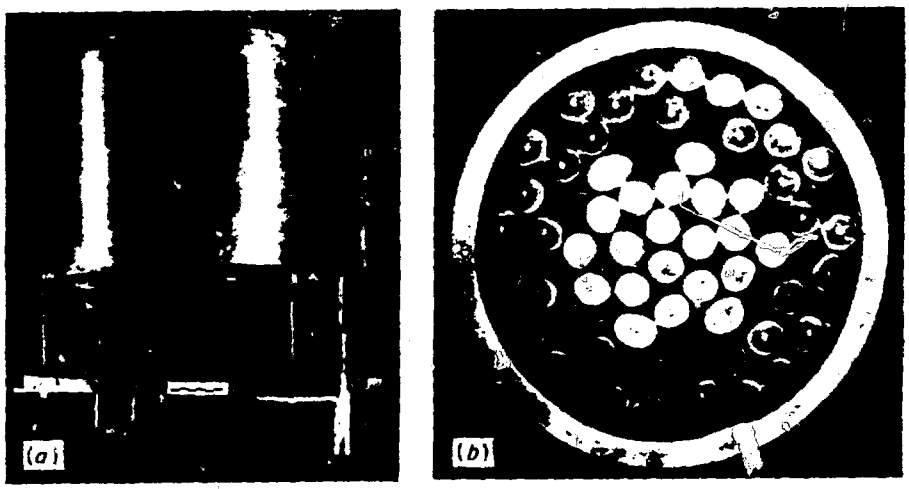


Fig. 1. (a) Finished solenoid and (b) Conductor cross section. The solenoid was mounted in the position shown (upside down).

The solenoid was designed to produce the maximum field achievable with the available length of conductor (about 360 m). Consideration of not overbending the conductor led to a winding

bore of 113 mm. The coil was layer wound in 19 layers with an average of 21 turns per layer. A wrap of Nomex* braid was applied for standoff. Vacuum impregnation with epoxy resin, after winding, completed the insulation and provided insurance against leaks. A "Saddle Tee" was soldered to the end of each layer to make possible various series-parallel combinations of flow paths. Figure 1a shows the finished coil with flow manifolds and electric current junctions. A brief list of the conductor and coil parameters is given in Table I.

Table I. Conductor and coil parameters

| | |
|---|---|
| Cable pattern | 12 x 3 NbTi composite around 7 x 3 Cu core |
| Strand size | 0.72 mm |
| Cu:SC ratio | 1.8:1 in composite strands; 3.4:1 overall |
| Conduit ID x OD | 7.36 mm x 8.56 mm |
| Void fraction in cable space | 0.43 |
| Winding ID x OD x height | 113 mm x 414 mm x 203 mm |
| Total number of turns | 399 |
| Total conductor length | 340 m |
| Coil inductance | 23 mH |

## INSTRUMENTATION AND TEST SETUP

One of the primary objectives of building this test solenoid was to investigate the stability of an ICS in a magnet. Since the innermost layer of the solenoid sees the highest field, we instrumented it for stability testing. Four induction heating coils, each extending about 26 cm, were wound on the conductor at the middle of this layer. They were driven by a capacitive discharge circuit similar to that described elsewhere.[8] Cowound voltage leads were placed over this heated zone to observe the response of the conductor following a pulse discharge.

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Quenching of the magnet was monitored by the balanced voltage signal of the inner 12 layers against the outer 7 layers, since they have approximately the same self-inductance. The quench protection circuit had a room temperature dump resistor of 0.1 Ω, which made a discharge time constant of about 0.23 s.

A helium pump[9] was available for flowing helium through the magnet and was housed in the same dewar with the magnet. Hydraulic connections to the magnet in this series of tests were made in such a way such that the inner two layers had the shortest paths and thus received the most flow. The outer layers, having several layers in series, received very little flow. This arrangement forced helium to flow through the parts of the coil where it was most needed.

The solenoid was mounted (upside down) with the current junctions facing the bottom of the dewar. With the final heat exchanger located at the bottom of the dewar, the magnet could be operated with its main body suspended above the helium bath.

## MAGNET PERFORMANCE

### Quench Field

At a bath temperature of 4.2 K, quench currents of about 4800 A were observed on the first and several subsequent charges. This corresponds to a maximum field at the winding of about 7.65 T. During these tests the liquid helium level in the dewar was either high enough to immerse the whole magnet or had fallen below the bottom of the magnet. No difference in performance was observed. The helium inside the conductor conduit was maintained at pressures from 1.1 to 2.5 atm. It was either stagnant or given flow of up to about 0.6 m/s through the innermost layer. Comparison of the magnet load line with the short sample critical current as shown in Fig. 2 indicated that the critical current limit was reached. When the dewar helium temperature was lowered to 3.9 K, a quench current of 5100 A or a maximum field of about 8.13 T was achieved. Scaling of critical current measured at 4.2 K to 3.9 K, shown as the broken curve in Fig. 2, also indicates that the achieved quench current is very close to the critical current limit.

### Stability Margins

Stability margins of the magnet were measured by discharging a capacitive voltage into the induction heating coils. All four coils with a total heating length of about 1.1 m were used in the present experiment. Pulse currents decayed in about three cycles, indicating that the initial capacitive energy was dissipated in the conductor and the pulse coils themselves in about

3.5 ms. In the field range of 5-7 T studied, there was no measurable difference in the decay time constant. Thus, the total effective resistance of the coupling circuit remained constant, but the fraction of energy dissipated in the primary (pulse coil) circuit varied as the pulse coil resistance varied with the field. In consideration of magnetoresistance of the pulse coil windings, it was determined that the fraction of energy deposited directly into the conductor ranges from 46% at 5 T to 32% at 7 T. Furthermore, since the magnetic diffusion time constant of the stainless steel sheath is much shorter than the cable strands, essentially all of this energy went to the strands.

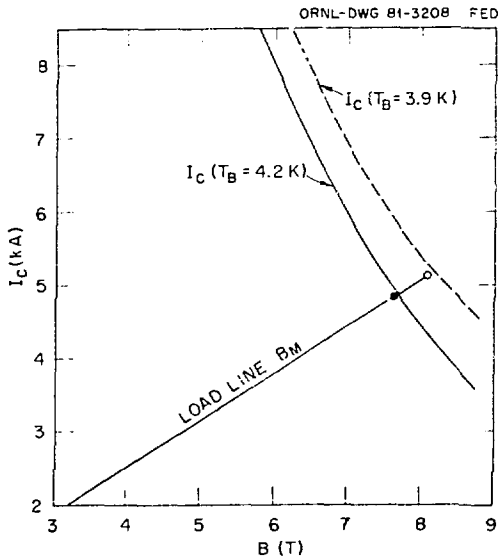


Fig. 2. Short sample critical currents and magnet load line at the winding. The data points are measured quench fields (currents) at 4.2 K and 3.9 K.

The measured stability margins as a function of the magnetic field or magnet current are shown in Fig. 3. Similar to the results of short sample stability experiments,[4-10] it exhibits regions of high stability margin and regions of low stability margin. For fields below 5.8 T, stability margins of 300-600 mJ/cm$^3$ were observed, while margins of 120 mJ/cm$^3$ or less were found for fields of 6.1 T and above. There is a clear discontinuity in the stability margin between 5.8 and 6.1 T. Because of the similarity of this stability curve to that observed in short samples,[4-10] we infer that multiple stabilities could exist in

this region. Based on the results of short samples and the scaling relationships developed,[11] we have calculated that the low stability margin should disappear at fields below 5.7 T for 5.0 atm helium and no flow operation. Although we do not know precisely how this limiting current (field) scales with helium pressure or flow rate, earlier results[4-10] showed that both the lower pressure and the flow used in the present experiment should push this limit higher. Therefore, we view the present results as excellent agreement between the performance of an ICS in a magnet and the scaling relationship developed on the basis of earlier short sample results.

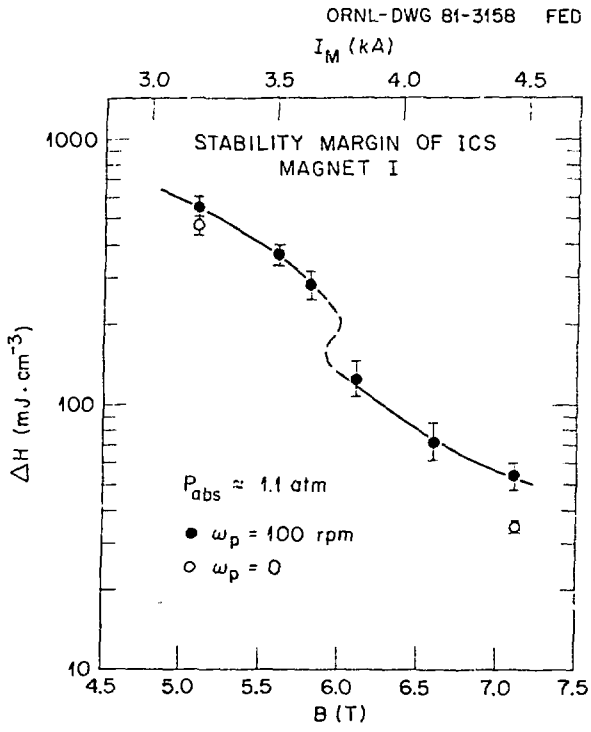


Fig. 3. Stability margin of the solenoid as a function of the magnetic field or magnet current. Data point limits are measured quench and recovery levels. $\omega_p$ is the pump velocity. At $\omega_p$ = 100 RPM, an estimated maximum flow of 0.6 m/s is applied to the first layer.

Two data points with no helium flow are also shown in Fig. 3. The slightly lower stability margin at 5.1 T indicates that the coil temperature was probably a little bit high when there was no flow, since this high stability margin is limited by the available helium enthalpy. The larger difference at 7.1 T is probably due to both the elevated temperature and the degraded heat transfer at no flow.

Pulse Fields

During the pulse discharge for stability testing, the peak pulse field on the conductor generated by the pulse coils ranged from 0.34 to 1.14 T. Within 0.6 ms, pulse coil current was swept from positive peak to negative peak current and the negative peak had decayed to about half of the positive peak value. Thus, pulse field rates of 900-3000 T/s were experienced by the conductor in the high field region of the magnet, and recovery was observed for fields of 7.1-5.1 T. Table II summarizes the coil performance characteristics described above.

Table II. Coil performance characteristics

| | |
|---|---|
| Maximum current/field attained @ 4.2 K | 4815 A/7.68 T |
| Maximum current/field attained @ 3.9 K | 5100 A/8.13 T |
| Magnetic stored energy @ 7.68 T | 267 kJ |
| Current density over the cable space @ 7.68 T | 11.3 kA/cm$^2$ |
| Maximum charge rate (limited by power supply) | 45 s to 7.1 T |
| Stability margins @ 1.1 atm 4.2 K | 56 mJ/cm$^3$ @ 7.0 T |
| | 590 mJ/cm$^3$ @ 5.0 T |

CONCLUSION

A superconducting magnet constructed of ICS has been produced and tested. Particular emphasis was placed on measurement of the stability margins of the magnet. Test results showed that this magnet has demonstrated the following merits:

1. *It reached short sample critical current limit with no* training.
2. No degradation due to strand motion in fields was apparent.
3. It can be charged and discharged to high current densities and high fields at a fast rate.
4. It has reasonable stability margin up to 90% of the critical current.

5. Stability measurements verify the scaling relationship for a limiting current below which there is single valued high stability margin.
6. It is not really necessary to have bulk helium flow to ensure high stability.
7. Very high pulse field changes can be accommodated as long as the energy deposition is within its stability margin.

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