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**A Pulsed Superconducting Magnet for a Static Magnetic Refrigerator
Operating between 1.8 K and 4.5 K**

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Abstract - Superfluid helium is increasingly used as a technical cooling medium in large-scale research projects involving high-field superconducting magnets, such as the CERN Large Hadron Collider (LHC). For refrigeration cycles operating below the normal boiling point of helium, a potentially interesting alternative to vapour compression is magnetic refrigeration, pioneered decades ago. In the framework of development for an industrial-size 1.8 K magnetic refrigerator using a static active material, we have designed, built and tested a pulsed superconducting magnet producing up to 3 T at a ramping rate of 6.5 T/s. The solenoid-type coil, wound with low-loss superconducting wire (small-filament Nb-Ti in a composite Cu/Cu-Ni matrix), is internally cooled by normal boiling helium, and installed inside a toroidal yoke, made of tapered laminations of commercially pure iron. After describing design and construction of the magnet, we present test results and measurements of performance, field quality and pulsed-operation losses.

I. INTRODUCTION

CERN, the European Laboratory for Particle Physics, is conducting development work in preparation for its next major research facility, the Large Hadron Collider (LHC). This machine, to be installed in the 26.7 km-circumference tunnel of the existing LEP collider, will make intensive use of high-field superconducting magnets operating in pressurized superfluid helium at temperatures below 2 K [1]. In spite of the technological difficulties imposed by the low saturation pressure of helium in this temperature range, the reference solution for large-capacity refrigeration remains helium vapour compression by means of subatmospheric cold compressors [2], [3] or vacuum pumps. Magnetic refrigeration, in which the compression and expansion of a process fluid is replaced by adiabatic magnetization and demagnetization of a suitable working medium, appears as a potentially interesting alternative, provided it can be incorporated in a practical and efficient thermodynamic cycle. As pioneer work in CEA Grenoble, France, has demonstrated a decade ago [4]-[6], paramagnetic single-crystal gadolinium-gallium garnet (GGG) appears a good working material for designing magnetic refrigerators

operating on quasi-Carnot cycles between 1.8 K and 4.5 K. We are working on such a prototype refrigerator [7], with a nominal capacity of about 20 W, generated in a static core made of 10.1 kg single-crystal GGG when cycled between 0 and 3.5 T. Magnetization and demagnetization of the core is produced by a pulsed-field, low-loss superconducting magnet operating in normal boiling helium at 4.5 K, a technology made possible by the recent development of fine-filament, resistive matrix a.c. superconductors. In the following, we describe the design and construction of the pulsed superconducting magnet and present results of tests and measurements of performance, field quality and losses.

II. DESIGN AND CONSTRUCTION

The adiabatic magnetization and demagnetization phases of the refrigeration cycle are non-productive for heat exchange and their duration should therefore be kept minimum in order to maximize the average cooling power of the machine. The basic design challenge of the magnet then resides in its capacity to generate the nominal field in the desired volume, at the maximum ramping rate permitted by limitations in current (heat load due to feedthroughs) and voltage (dielectric breakdown of ground and interturn insulation). The design compromise yields the set of parameters listed in Table I.

TABLE I
DESIGN PARAMETERS OF THE PULSED SUPERCONDUCTING
MAGNET

Coil inner diameter [mm]	150.0
Coil outer diameter [mm]	211.2
Coil axial length [mm]	120.5
Nominal central field (in vacuum) [T]	3.0
Nominal central field (in GGG) [T]	3.5
Nominal current [A]	400
Inductance [H]	0.17
Number of turns	914
Stored energy at nominal field (in GGG) [kJ]	13
Mass of conductor [kg]	6.31
Mass of magnetic circuit [kg]	115

The nominal current appears well matched to the current-carrying capacity of industrially-available, low-loss Nb-Ti superconducting wires, while the maximum inductive voltage at the magnet terminals remains well below 500 V, thus allowing use of conventional electrical insulation techniques.

The magnet geometry, shown in Fig. 1, primarily aims at confining the field volume to that of the GGG core, while preserving sufficient homogeneity and allowing for circulation of liquid helium through the core, alternatively from the 1.8 K and 4.5 K baths. The solenoid-type coil, which surrounds the GGG core, is enclosed in a toroidal magnetic circuit for flux return.

The coil consists of 6 bilayers of 2×82 turns each¹ of close-wound, enamel-insulated superconducting wire, interspaced with 120 cooling channels parallel to the coil axis, each 2.5 mm x 10 mm in cross-section (Fig. 2). In this fashion, every layer is in full contact with liquid helium over 38 to 50 % of its circumference (depending upon radial position), while the remaining fraction ensures mechanical support against wire motion. The coil was wound on a glassfiber-epoxy composite mandrel, with a wire tension of 6 daN, applied by a frictionless brake (weight-loaded capstan) to avoid damage to the enamel insulation. Glass-fiber band, preimpregnated with B-stage epoxy resin, separates each layer and was finally wrapped around the completed winding for external insulation to ground. After installation of removable aluminium-alloy filler shims in the cooling channels, the coil assembly was vacuum-and-pressure impregnated with low-viscosity ARAIDITE F epoxy resin at 50°C, and cured for 48 hours at 80°C.

Fig. 1: Geometry of the superconducting magnet, showing calculated field lines. The layered structure of the coil is apparent. The core is divided in 4 regions of different permeability. Dimensions are in meters.

¹ Except the outer layer which only has 12 turns.

Fig. 2: View of the coil during winding, showing axial cooling channels and insulation system (photo).

The magnetic circuit snugly fits around the coil and core package. It is made of tapered laminations of commercially pure ("Armco") iron, machined in two passes on a magnetic table, surface-insulated by phosphatization and preassembled to form epoxy-glued quadrants. The quadrants were finally assembled around the coil (Fig. 3) and held in place by stainless-steel retaining rings.

The first series of tests, reported in the following, were performed on the magnet alone, without the GGG core, thus giving access to the useful region for field measurement and mapping.

The main characteristics of the superconducting wire are listed in Table II, and its measured short-sample d.c. performance is plotted in Fig. 4, together with the load lines of the magnet, as calculated using the POISSON program [8] for "vacuum" and GGG-core configurations and measured during the tests. The relative permeability of the GGG core enhances the central field by a factor of about 1.3 with respect to vacuum.

Fig. 3: Coil and magnetic circuit assembly.

TABLE II
CHARACTERISTICS OF THE SUPERCONDUCTING WIRE

Material	Nb-Ti in Cu/Cu-Ni matrix
Volume ratio [%]	18.1/60.4/21.5
Diameter (uninsulated) [mm]	1.35
Critical current @ 5 T, 4.22 K [A]	627
Filament diameter [mm]	4.5
Number of filaments	20298
Twist pitch [mm]	14
Insulation	PEI Duromid enamel
Insulation thickness [mm]	0.05

Fig. 4: Measured characteristic of the superconducting wire and load lines of the magnet.

III. TESTS AND MEASUREMENTS

The superconducting magnet was installed in the cryostat which will house the magnetic refrigerator. The electrical connections were done using self-regulated vapour-cooled current leads, and the tests were performed in a bath of saturated liquid helium at 4.3 K. Fig. 5 shows the experimental setup. Measurements include coil current, voltage and magnetic field, as well as helium level and boil-off rate. Detection of resistive transitions is done by comparing the voltages developed between coil terminals and "mid-point". If an imbalance between these voltages occur, the power supply is immediately shut down and the magnet energy discharged into a 1 Ω resistor. The thyristor pulsed power supply is capable of delivering a maximum current of 500 A under ± 500 V. It is driven in current control mode and the output current follows the signal of an arbitrary waveform generator. The coil current and voltages were measured by fast voltmeters (up to 2000 readings per second) or a 4-channel digital oscilloscope. The magnetic field was measured by integrating the voltage developed during current ramps across a set of calibrated pick-up coils with a diameter of about 10 mm.

Fig. 5: Experimental setup used for tests of the s.c. magnet.

The magnet was powered with a maximum current of 400 A, thus producing a central field of 3.1 T, and no resistive transition was observed. The magnetic field inside the coil was mapped along its central axis in steps of 10 mm, for currents ranging from 50 to 400 A (Fig. 6). Although the measured field inhomogeneity shows good agreement with the result of calculations, the latter tend to overestimate saturation effects and thus underestimate the field strength at high current. No hysteresis effect is measurable.

Fig. 6: Field map along the magnet axis.

The inductance and a.c. losses were measured by sweeping the field in the magnet along quasi-triangular cycles at ramping rates ranging from 0.5 to 6.5 T/s, and with varying amplitudes. The dependence of the inductance on ramping rate appears in Fig. 7. Losses were measured using a calorimetric technique. Such measurements are made difficult by the long settling times (of the order of 30 minutes) required for establishing steady temperature and vapour flow-rate conditions in the cryostat. The self-losses of the cryostat, which strongly depend on the vapour flow-rate, were measured separately by means of a calibration heater. Insufficient precision of our apparatus made direct measurement of losses by the electrical method impossible. The results, shown in Fig. 8, separate the frequency-dependent eddy-current dissipation from the hysteresis losses, which dominate in the range of interest. They do not allow, however, to disentangle the superconductor losses from those of the magnetic circuit. For quasi-triangular cycles with a peak-to-peak amplitude of 280 A, the losses of the complete magnet can be approximately represented by the empirical formula:

$$Q = 15.0 + 6.2 f$$

where Q is the energy loss per cycle (J) and f the cycle frequency (Hz).

Fig. 7: Frequency dependence of the magnet inductance at 200 A.

Fig. 8: Measured a.c. losses of the superconducting magnet.

IV. CONCLUSIONS

We have designed, built, and tested successfully the pulsed superconducting magnet for a prototype magnetic refrigerator operating between 1.8 K and 4.5 K. The measurement of the field level and inhomogeneity, as well as the estimation of the pulsed-operation losses, are essential information for the precise calculation of the thermodynamic cycle and the optimization of the process. The now qualified magnet is being incorporated into the magnetic refrigerator for operational tests.

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