CONF-950691--15

LA-UR-95- - 2027

Title:

Status of the NHMFL 60 Tesla Quasi-Continuous Magnet

Author(s):

Laurence J. Campbell, CMS
Heinrich J. Boenig, DX-15
Dwight G. Richel, DX-15
Josef B. Schilling, DX-15
James R. Sims, DX-15
Hans J. Schneider-Muntav, Florida State University

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Submitted to:

Conference on Magnet Technology
Tampere, Finland
June 11-16, 1995

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Form No. 896 RS
ST 2828 10/81

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Status of the NHMFL 60 Tesla Quasi-Continuous Magnet

L. J. Campbell, H. J. Boenig, D. G. Rickel, J. B. Schillig, J. R. Sims
National High Magnetic Field Laboratory (NHMFL), Los Alamos National Laboratory,
MS-E536, Los Alamos, NM 87545, USA.

H. J. Schneider-Muntau
NHMFL, 1800 E. Paul Dirac Drive B-223
Tallahassee, FL 32306-3016, USA

Abstract—All components of the National High Magnetic Field Laboratory's (NHMFL) 60 T quasi-continuous magnet are now under construction, with complete delivery and installation expected in early 1996. This research magnet has a cold bore of 32 mm and will produce a constant 60 tesla for 100 ms plus a wide variety of other pulse shapes such as linear ramps, steps, crowbar decays, and longer flat-tops at lower fields. Fabrication and testing of prototype coils are described along with the layout, construction status, and protection philosophy of the 400 MW power supply. Examples of simulated pulse shapes are shown.

I. INTRODUCTION

In the pantheon of research magnets, 'quasi-continuous' or 'controlled power' pulsed magnets, energized by commercial power or mechanical energy storage, produce higher fields than hybrid or resistive magnets and longer fields than capacitor-driven or explosive-driven magnets. Relatively little attention has been given to their development – in fact, only one magnet currently exists, at the University of Amsterdam. The rationale for this type of research magnet and the design philosophy and specifications of the NHMFL version are given in [1].

The NHMFL quasi-continuous magnet will have a field 50% higher than earlier versions and, consequently, its construction and power source are notable. The fabrication and testing of prototype coils are discussed first, then the electrical engineering issues of the power supply and examples of pulse shapes available to the user. Finally, we mention feasible upgrades, including a route to non-destructive 100 T magnets.

II. COILS

A. Description

The 60 T quasi-continuous magnet consists of nine mechanically independent, nested coils which are individually reinforced by high strength, stainless steel outer shells. Table I gives basic mechanical data on the coils. Coil conductors are drawn from high strength, high conductivity, aluminum oxide dispersion strengthened coppers C15715 and C15760 (SCM Metal Products, Inc. trade names GlidCop AL-15™ and AL-60™). The conductors are insulated with 0.13 mm thick E-glass fabric tape and 0.025 mm thick Kapton™ tape, applied

TABLE I
MECHANICAL DATA

coil # - ID (mm)	layers	turns per layer	cond. hwx (mm)	shell thck. (mm)
1 - 33.0	2	16	9.2x4.3	3.0
2 - 69.4	2	25	9.2x4.3	5.9
3 - 110.0	2	41	8.6x5.2	6.8
4 - 156.0	2	56	8.6x5.2	9.6
5 - 207.6	4	77	8.6x5.2	32.2
6 - 330.0	4	85	11.0x6.7	20.6
7 - 445.0	6	85	11.0x6.7	26.5
8 - 603.6	6	74	12.5x7.5	15.0
9 - 750.5	6	74	12.5x7.5	16.5

half-lapped and staggered. A 0.17 mm thick E-glass fabric is used between conductor layers and as a ground wrap. Coils 1-5 contain a continuous length conductor; coils 6-9 have silver brazed conductor splices at the coil ends. The coils are vacuum impregnated in the reinforcing shells with an anhydride cured, epoxy resin (CTD-101K™). The external reinforcing shells of the inner eight coils are made of seamless, annealed Nitronic-40™, (a nitrogen-alloyed manganese stainless steel: Fe-21Cr-6Ni-9Mn); coil nine has a welded and annealed 304 stainless steel shell. The Nitronic-40™ shells are forged, rough machined, and inspected using ultrasonic and dye penetration methods.

This design differs from that presented in [1] by having an additional coil: the outermost coil in [1] was divided to insure the magnet could be re-cooled to 77 K within one hour following a pulse. Also, a steel shell was added to the outermost coil for ease of manufacture and handling.

B. Prototypes

Prototypes of the innermost two coils were fabricated and tested. These prototype coils are identical to the final production coils with the exception of external lead details. The rectangular, large cross-section and high strength GlidCop AL-15™ conductor used for the coils wound readily about the relatively small diameter mandrel (4.3 mm radial dimension bent to a 18 mm radius). Winding error including "keystoning effect" was about 25% of original estimates. Actual radial winding error was approximately 0.17 mm per layer and axial winding error was approximately 0.08 mm per turn. Winding tension had to be maintained at all times (including during lead brazing and splicing) until the coils were inserted into reinforcing shells. Coil and manufacturing tooling design and winding procedures accommodated the need to maintain tension. Coil leads were machined from GlidCop AL-15™ bar stock and silver brazed to the conductor. The high strength and

Manuscript submitted June 13, 1995.

L. J. Campbell, e-mail LJC@LANL.gov, fax 505-665-4311.

This work was supported by US DOE and the National High Magnetic Field Laboratory through the National Science Foundation cooperative agreement No. DMR-9016241.

relatively large cross-sections of the conductors required that all conductor and lead forming be done with significant mechanical advantage provided by tooling and powered machinery; there was no significant manual forming of conductors or leads. All metal forming other than actual winding of coil turns was done prior to final insulating of the conductor due to the relative mechanical fragileness of the insulation system prior to impregnation. After winding, the coils were inserted and carefully positioned axially into closely fitted, stainless steel reinforcing shells and impregnated with epoxy resin. The coils were electrically tested at various manufacturing stages with a final electrical acceptance test upon completion.

C. Testing and Schedule

Prototype coil 2 was thermally shock tested by rapidly immersing the coil at room temperature into liquid nitrogen; after equilibrium at 77 K was reached the coil was warmed to room temperature. The thermal shock test was repeated 15 times. No externally visible degradation to the coil insulation system as a result of the shock tests was noted. Next the two coils were tested nested together, electrically in series, at 77 K with a capacitor power supply. The test voltage and current applied to the coils were gradually increased in a series of tests to produce a dielectric over-stress condition in both coils and a mechanical over-stress condition in the innermost coil. The voltage across the two coils was taken to 5.3 kV, which gave a peak current of 57.4 kA. This produced a midplane stress in the conductor at the bore of the innermost coil equivalent to 110% of the stress the conductor will experience at 60 T in the complete magnet. Over 100 such pulses were completed without coil failure or externally detectable coil degradation.

Fabrication of the production coils is well under way. The conductor and stainless steel reinforcing shell blanks have been produced and are on hand at the coil vendor. Production coils 1-4 are wound, impregnated in shells and have passed electrical tests at the coil vendor. Production coil 5 is wound. Production coil 6 is being wound at the time of writing. Completion of the entire set of nine production coils is estimated to be at the end of August 1995.

III. ELECTRICAL SYSTEM

A. Generator Power Source

The 1430 MVA Los Alamos generator provides the power and energy to the magnet through the electrical system diagrammed in Fig. 1. The installation and capability of the generator have been described previously [2,3]. Originally the generator was designed with water cooling in the stator windings and hydrogen cooling at 5.2 atm in the stator core, the rotor, and the air gap. Because the cooling capacity is not necessary in the pulsed mode of operation and to simplify the operation, it was decided to omit the water cooling in the stator windings and to replace the hydrogen cooling by air cooling. The generator manufacturer determined after extensive studies that in spite of the reduced insulation capability of air, especially at 2200 m elevation, the machine could safely operate at its original design voltage of 24 kV, provided the

machine is only energized at 24 kV for 10 s during a pulse and de-energized between pulses. The nominal operating voltage was chosen to be 21 kV, which is the highest voltage that can be assured throughout the rotor's pulse speed range.

B. Current Limiting and Interrupting Device

The current limiting and interrupting device (CLID) consists of an explosively opened main current path and a parallel fault interrupting path equipped with current limiting high voltage fuses. The peak asymmetrical short-circuit current of the generator at 21 kV is approximately 340 kA at 50 Hz. The installation of a phase isolated bus (to carry the generator power from the terminals of the machine to the power supplies) which could withstand the high short-circuit current forces would have been excessively expensive. Therefore, it was decided to install at the machine terminals a CLID, which would clear the short circuit well before the current reaches its peak value. The CLID is designed to trigger instantaneously at 40 kA, to limit the short-circuit current to approximately 90 kA, and to clear the fault within less than a cycle. The reduced peak current and fault duration results in considerably smaller loads on the bus. The CLID is the highest interrupting fuse installed in the world and consists of commercially available 27 kV units, connected in parallel. The pulse rating of the CLID is 24 kV, 25 kA, 2 s, once every 10 minutes. Although this value is lower than the generator rating, it is adequate for currents of the 60 T and proposed 100 T magnet. No high power test lab in the world has the capability to test the rating of the full CLID. Therefore, tests were performed individually on the two parallel CLID elements of a single phase (and were successful).

Fig. 1. Overall electrical system layout.

maintained to permit an emergency shut-down by short-circuiting the coils at any time in the pulse. (At 60 T the inductive energy needed to be dissipated in a fault is 90 MJ.) The coils are usually powered down at the end of useful field period by reversing the voltage and returning the remaining inductive energy to speed up the rotor of the motor-generator. Thermal stress considerations limit the maximum allowed coil temperature to about room temperature.

Flat-top pulses can be made substantially wider at lower peak fields, as shown in Fig. 2. Rising or falling linear field ramps can appear any place in the pulse, or precede a crowbar decay, as shown in Fig. 3. There are no active circuit elements in a crowbar decay (the coils are merely shorted) which makes it a desirable pulse for experiments that need a changing field without noise or ripple. A virtuoso example of steps, three up-down cycles, is shown in Fig. 4 along with typical descending steps. A larger catalog of pulse shapes is given in [4].

V. UPGRADES

The modular design of nine mechanically independent coils permits upgrades by replacing sets of coils with others having special or superior features, such as conductors with higher strength and/or conductivity. During the period 1996-2000 we propose to upgrade this magnet to 70 T and increase the flat-top period at 60 T to 200 ms with new inner coils and an additional two 80 MW power supply modules. Field reversals within a fraction of a second are also being considered.

By removing coils 1-4 and inserting a capacitor-driven magnet it would be possible to reach fields of 80 T, although the period would be limited to 10-20 ms by the capacitor-driven insert. Expanding on this concept, a 100 T non-destructive magnet has been proposed, consisting of a capacitor-driven insert and outer coils that closely resemble coils 5-9 of the present magnet in height and radius [5]. The conductor is CuAg instead of Cu-alumina. Start-up funding for this non-destructive 100 T magnet has been received from the US DOE.

Fig. 2. Flat-top pulses.

Fig. 3. Linear field ramps and crowbar decay.

Fig. 4. Descending and oscillating steps.

REFERENCES

- [1] L. J. Campbell, et al, "Design and analysis of high-field quasi-continuous magnets," *IEEE Trans. Magn.*, vol. 30, pp. 2222-2225, July 1994.
- [2] H. J. Boenig, et al, "Design, installation, and commissioning of the Los Alamos National Laboratory pulsed power generator," *IEEE Trans. Ener. Conv.*, vol. 7, pp. 260-266, June 1992.
- [3] J. B. Schillig, H. J. Boenig, J. D. Rogers, and J. R. Sims, "Design of a 400 MW power supply for a 60 T pulsed magnet," *IEEE Trans. Magn.*, vol. 30, pp. 1770-1773, July 1994.
- [4] L. J. Campbell, "Performance features preview of the NHMFL 60 tesla quasi-continuous magnet at Los Alamos," Los Alamos Report LA-UR-94-3238, pp. 1-31, (1994), unpublished.
- [5] L. J. Campbell, et al, "The US 100 T magnet project," in press. [4th Internat. Symp. on Research in High Mag. Fields, Nijmegen, August 29-31, 1994.]