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Title: Completion of the US NHMFL 60 T Quasi-Continuous Magnet

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Completion of the US NHMFL 60 T Quasi-Continuous Magnet

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***Abstract*—This is a technical summary report of the 60 T controlled power research magnet that was designed, assembled, installed and recently commissioned at the National High Magnetic Field Laboratory (NHMFL) Pulsed Field Facility at Los Alamos National Laboratory. The magnet is innovative in its design, construction, size, operation and power supply. The magnet consists of nine nested, mechanically independent, free standing coils, each of which is enclosed by a steel reinforcing shell. Using inertial energy storage a synchronous motor-generator provides ac power to a set of five ac-dc converters rated at 64 MW/87.6 MVA each. These converters energize three independent coil circuits to create 90 MJ of field energy at the maximum field of 60 T, which can be sustained for 100 ms in the 32 mm bore. Prior to a pulse the 4-ton magnet is cooled to liquid nitrogen temperature, a procedure that is achieved in less than one hour by the free flow of nitrogen between the nine coils. In addition to being the most powerful of its class in the world the magnet is also the first of its kind in the US. The operation of the magnet will be described along with special features of its design and construction. A sampling of the pulse shapes that can be obtained for research will be shown.**

I. INTRODUCTION

The 60 T quasi-continuous (Q-C) magnet now being commissioned at the NHMFL at Los Alamos is designed to produce a flat-top pulse of 100 ms duration at 60 T in a 32 mm cold bore with a spatial field uniformity of 1.6 x 10^{-4} over a 1 cm sphere. The flexibility of its power supply and control system also permits the production of many types of pulse shapes. A graph of a 57 T pulse produced by this magnet is shown in Fig. 1. This magnet increases the available field in its class by 50% and the available bore size by 33%. The rationale for this type of research magnet and the design philosophy and original specifications are given in [1]. This paper describes the completed form of the magnet and its power supply. The design process, fabrication, assembly, operation, testing and commissioning to date are also discussed and summarized.

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II. MAGNET

A. Description

The magnet consists of nine nested, mechanically independent, free standing coils, each of which is enclosed by a steel reinforcing shell (Fig. 2). The nine coils with their shells have a mass of approximately 4 tons. The "as built" dimensions of the coils are given in Table I. Coil conductors are drawn from aluminum oxide dispersion strengthened coppers C15715 and C15760 (SCM Metal Products, Inc. trade names GlidCop Al-15™ and AL-60™). Each coil of coils 1 through 5 contain a continuous length conductor; coils 6 through 9 have silver brazed conductor splices at the coil layer ends. The reinforcing shells of the inner eight coils are fabricated from seamless, annealed Nitronic-40™ (nitrogen-alloyed manganese stainless steel: Fe-21Cr-6Ni-9Mn); coil nine has a welded and annealed 304 stainless steel shell. All conductor transitions and crossovers are fully supported within the coils by filler pieces machined from NEMA G-10 fiberglass epoxy laminate. The coil leads interlock to react end-turn hoop loads against each other. The coils are vacuum impregnated with epoxy within the reinforcing shells. Additional details of coil design are given in [2].

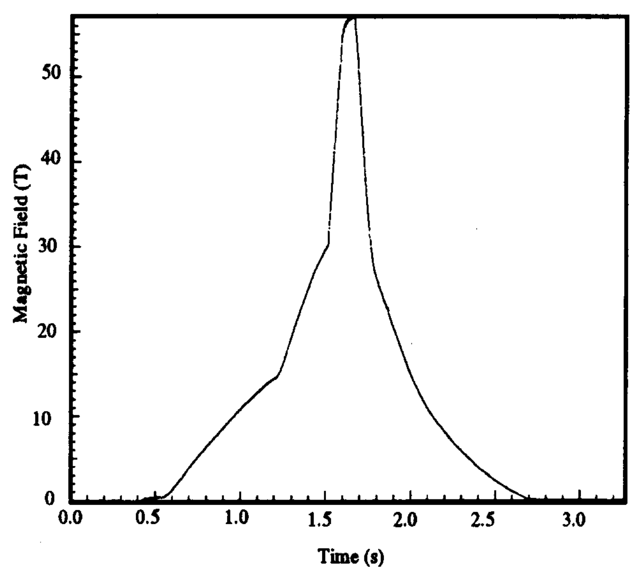

Fig. 1. 57 T pulse from US NHMFL 60 T Q-C magnet.

The magnet coils are divided into three electrical circuits. Current is supplied to each circuit by separate busbar systems consisting of paired conductors. Busbar conductors are fabricated from coppers C11000, C15715 and C15760 as required to withstand the magnetic loads. Care is taken to accommodate magnetic and thermal loads and displacements in the busbars. Provisions are made to react or null magnetic loads and also to permit free or controlled movement in the direction of thermal expansion and mechanical dilation. Busbars loads are supported by a mechanical wrapping of epoxy impregnated fiberglass tape and NEMA G-10 epoxy fiberglass laminate supports. Coils six through nine leads are joined to the busbars by screws. The leads for coils one through five are joined to the busbars using screws and low temperature Sn/Ag solder. Busbars are insulated during installation using Kapton™ film and epoxy impregnated E-glass™ tape (Fig. 3).

Paired, rectangular busbars make a transition to a coaxial arrangement and are then taken upward through the dewar lid, turned 90 degrees and extended outward away from the high magnetic field regions of the magnet. There a transition to high voltage utility cabling is made. Differential thermal expansion between the inner and outer conductors of the coaxial portion of the busbar is accommodated through the use of a movable joint in the outer conductor spanned by a flexible laminated copper sheet strap. The volume within which the flexible strap moves is kept free of ice by a combination of a dry N_2 gas purge and thermal insulation. The weight of the coaxial portion of the busbar is carried by spring mountings, loads on the busbar in excess of the weight (due to thermal expansion or coil dilation) are relieved by controlled movement of the busbar.

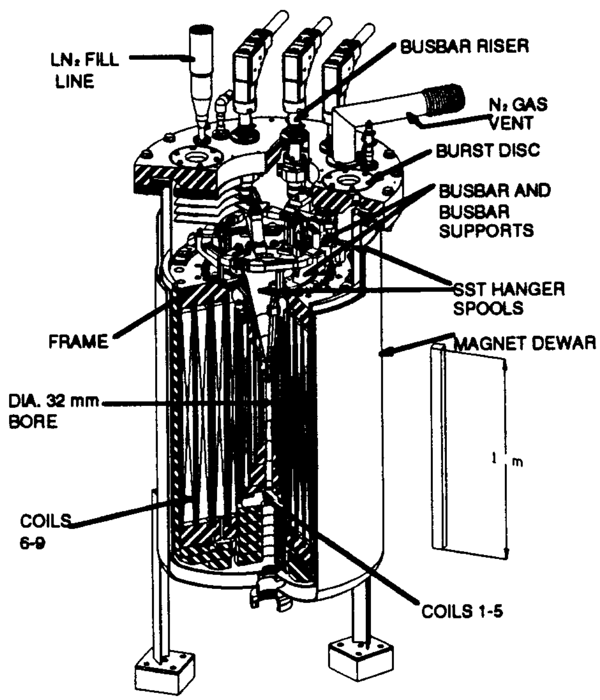

Fig. 2. Internal details of US NHMFL 60 T Q-C magnet.

TABLE I
"AS BUILT" MECHANICAL DATA

Coil	Conductor Size (mm)	Turns per layer/layers	Coil ID/OD w/o shell (mm)	Shell Thickness (mm)
1	9.2 x 4.3[a]	16/2	32/57	3.5
2	9.2 x 4.3[a]	25/2	69/92	6.1
3	8.6 x 5.2	41/2	110/135	7.4
4	8.6 x 5.2	56/2	156/182	9.8
5	8.6 x 5.2	77/4	208/157	33.8
6	11 x 6.7	85/4	331/393	21.9
7	11 x 6.7	85/6	445/537	29.1
8	12.5 x 7.5[a]	74/6	604/708	16.5
9	12.5 x 7.5[a]	74/6	751/856	15.1

[a]GlidCop AL-15™. The remaining conductors are GlidCop AL-60™.

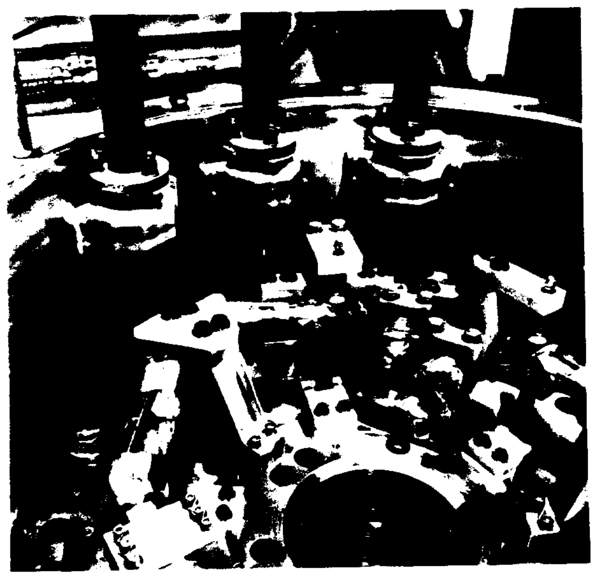

Fig. 3. 60 T Q-C magnet busbar and busbar risers.

The coil reinforcing shells are positioned and supported by a frame of NEMA G-10 fiberglass epoxy laminate plates and hub pieces and stainless steel spools. Communication for free flow of LN_2 and N_2 gas through the annuli between coils is provided by holes and slots in the hub pieces, frame plates and LN_2 displacement plates. Kapton™ and Mylar™ electrical insulating barriers are placed in the annuli between coils 5 and 6 and coils 7 and 8 to provide additional electrical insulation between the coil circuits. The magnet frame is suspended from a kinematic mount at the top of the dewar to permit vertical and lateral expansion and contraction (Fig. 2). Differential thermal expansions and mechanical dilation within the frame are accommodated by matching material thermal expansions and providing flexible structural sections. In addition, most frame and all busbar fasteners within the dewar contain a Belleville spring washer in their grip to accommodate thermal expansion and maintain fastener pre-load and are secured with lock wire or cotter pins. All critical load fasteners in the frame and busbar systems are fabricated from A-286 precipitation-hardening stainless steel, non-critical load fasteners are made from commercial grade 304 or 316 stainless steel. Stainless steel thread inserts are used in internal threads located in parts made of copper or NEMA G10 epoxy fiberglass laminate.

Heat gain to the magnet is minimized by placing it in a stainless steel dewar. The external shell of the dewar is designed to withstand combined atmospheric and magnetic pressure loads resulting from eddy currents in the shells during a pulse. The dewar inner shell is designed to withstand a 7 bar working pressure. Nominal operating pressure is 0.3 bar. The dewar is protected against over pressure by two 100 mm diameter burst disks which fracture at pressures between 0.4 and 0.8 bar depending upon their temperature. Heat loss through the top of the dewar is minimized through the use of 100 mm thick NEMA G-10 epoxy fiberglass laminate for the dewar lid, foamed styrene insulation under the lid and baffles within the gas space between the lid and top of magnet frame. Heat loss is also reduced by suspending the magnet frame from the top of the dewar with a thin wall stainless steel spool piece. Formation of ice on the portion of the busbars external to the dewar is minimized by wrapping the busbar with polyester insulation and self-fusing silicone rubber tape in a manner that produces a tapering heat gain. There are LN_2 volume displacement parts, a shell and bottom displacement plates, within the magnet dewar to minimize the LN_2 inventory. Magnet utilities are placed to one side of the top of the magnet to maximize experimental access (Fig. 4).

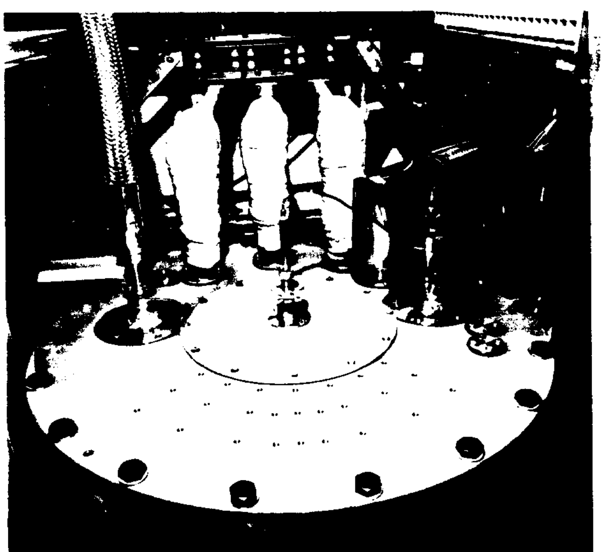

Fig. 4. Top of 60 T Q-C magnet dewar.

B. Review of Design Process and Fabrication

The magnet design is produced by a process of conceptual design, followed by numerous iterations of analysis and design modification. Important considerations for the design process are mechanical stress, material availability, magnet cooling, minimization of power required, ease of manufacture and safety. The sub-division of the magnet into mechanically independent, free standing coils permits modular construction and operation which reduce manufacturing risks and economic losses due to coil failure. It also permits optimization of conductor size, the sizing of coil reinforcing shells to match magnetic loads, and more rapid cooling of the coils.

For reasons of schedule and economy commercially available materials, stock material sizes and standard parts are used where ever possible. The GlidCop™ conductors are selected for their high conductivity, high strength, retention of strength upon heating and availability in required cross-section sizes and lengths. Nitronic-40™ is used for its good strength, toughness and fatigue properties at cryogenic conditions. NEMA G-10 epoxy fiberglass laminate is used for its good electrical insulating characteristics, good mechanical properties at cryogenic temperatures and coefficient of thermal expansion. The coils and the majority of the magnet mechanical parts were fabricated by commercial vendors from drawings provided by the magnet laboratory. Additional details of coil and magnet fabrication are given in [2].

C. Assembly

Assembly of the magnet begins with the inner cluster which contains coils 1 through 5 (coil group 1). The inner cluster is assembled inverted on the upper hanger spool and NEMA G-10 hub pieces. The hub piece diameters are match machined to the coil reinforcement shell diameters in a single setup. The transition between the bore of the upper hub pieces and the bore of coil 1 is adjusted at assembly to eliminate any steps. The coils are placed on the hub pieces and attached to the lead extensions beginning with coil 1 and progressing outward to coil 5. NEMA G-10 shims are inserted as required at assembly to maintain vertical geometric centering of coils and eliminate any looseness in the assembly.

The inner cluster assembly is fastened together by screws threaded into the top and bottom end surfaces of the coil 5 reinforcing shell. The grips of the bottom screws contain stacks of Belleville spring washers to maintain a preload and accommodate the differential thermal expansion and mechanical dilation of the NEMA G-10 hub pieces and coils 1 through 5. The insulated lead extensions are electrically tested (all insulation is electrically tested as it is installed and all coil and busbar circuits are tested systematically during assembly for continuity, grounds and insulation integrity) and mechanically fastened and soldered to the coils 1 through 5 leads. The coil lead to lead extension joints are insulated and then the lead extensions are secured with NEMA G-10 clamps to the hub pieces. When assembly is complete the inner cluster is rotated into an upright position and LN_2 displacement plates are installed on the bottom end. A fitted alignment staff is placed in the bore of coil 1 and is used to ensure centered and plumb installation (NEMA G-10 shims are used as required) of the inner cluster into the NEMA G-10 upper frame plate and inside the outer cluster coils which consist of coils 6 through 9 (coil groups 2 and 3).

The outer cluster coils are assembled into the NEMA G-10 lower frame plate and the NEMA G-10 upper frame plate is installed over the coils. Clearances between the upper frame plate and the coil shells are eliminated through the use of NEMA G-10 shims placed on the top end surfaces of the reinforcing shells of coils 6, 8 and 9 (the reinforcing shell of coil 7 is the datum). The upper and lower frame plates are connected through the reinforcing shell of coil 7 by screws threaded into the top and bottom end surfaces of the shell. The grips of these bottom screws also contain stacks of Belleville spring washers to maintain a preload and accommodate the differential thermal expansion and mechanical dilation of the frame plates and coils 6 through 9. Next the LN_2 bottom displacement plates are attached to lower frame plate.

Following coil installation into the frame the coils 1 through 5 busbar collector ring and supports are fitted, insulated and installed. Next the coils 6 through 9 busbar and busbar supports are fitted, insulated and installed. Paired busbars are mechanically secured together using epoxy impregnated fiberglass tape wrapped with polyester shrink/release tape then heat cured in place by wrapping with electrical resistance heater tape and temporary plastic foam thermal insulation. The busbar risers are installed and insulated next. Then the stainless steel spool that connects the magnet frame to the top of the magnet dewar is attached to the upper frame plate followed by installation of the LN_2 displacement shell onto the outside of the magnet. The magnet assembly is then placed in the magnet dewar and made level and plumb again using as a guide, the fitted alignment staff placed in the bore of coil 1. A final set of electrical tests are performed on the coil circuits and insulation and then the dewar lid is installed.

LN_2 and N_2 gas utilities are attached to the dewar and the first cool-down of the magnet to LN_2 temperature is completed. Electrical tests are again performed while the magnet is cold and again after warming the magnet to room temperature. These electrical tests indicated a problem with electrical breakdown between the circuits of coil groups 1 and 2. This fault is fixed by removing the magnet from the dewar and then removing the inner cluster assembly from the magnet frame. Special rigging hardware is installed on the upper frame plate to support the outer cluster coils. Then the lower frame plate and LN_2 displacement plates are removed from the bottom of the magnet. Next Kapton™ and Mylar™ electrical insulating barriers are installed in the annuli between coils 5 and 6 and between 7 and 8 and the magnet is reassembled. This operation is completed without significantly disturbing the installed coils and the fitted and insulated busbar systems located on the upper frame plate. The magnet is reinstalled into the dewar and electrically retested successfully.

D. Operation

The magnet is cold under nominal conditions and is covered with liquid nitrogen. A capacitance type sensor measures the liquid nitrogen level in the magnet dewar and an automatic fill system maintains the liquid nitrogen level. A dry nitrogen gas purge in maintained on the gas volume of the dewar above the magnet. Immediately prior to a pulse the liquid nitrogen level is lowered below the bottom of the magnet by draining the liquid nitrogen into a catch tank. Approximately 130 l of liquid nitrogen is drained during this process. After the pulse is completed the liquid nitrogen is pushed back up into the magnet dewar by pressurizing the catch dewar to 0.7 bar. The liquid nitrogen level in the catch tank is also measured using a capacitance type gauge. When the liquid nitrogen drained to the catch tank is returned to the magnet dewar the liquid nitrogen refill starts using a supply line from a remotely located liquid nitrogen storage tank (Fig. 5). The liquid nitrogen and gas handling systems are configured for automatic operation with local manual control capability. The system is protected by various electrical interlocks, pressure relief valves and burst disks. Resistance of the three coil circuits is monitored continuously (except during a pulse); these resistance measurements are used to gage the temperature of the magnet coils and are interlocked with the power supply control system to prevent the operation of the magnet when the coils are warm.

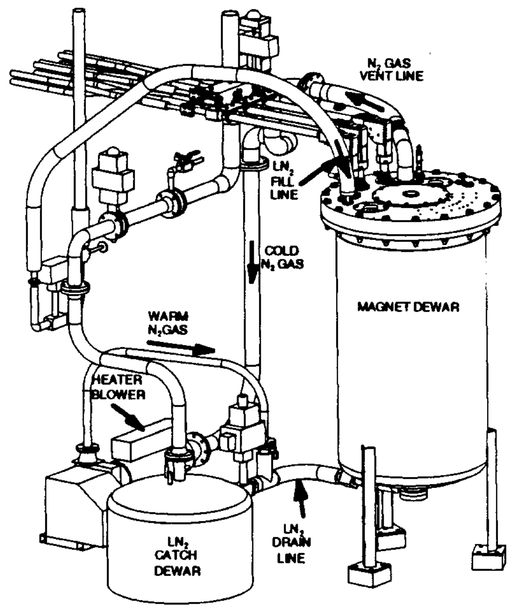

Fig. 5. 60 T Q-C magnet LN_2 and N_2 gas handling system.

III. POWER SUPPLY

The power supply and power supply testing and commissioning have been described in detail previously [3,4,5] but will be reviewed here.

A. Inertial Energy Storage Generator

A magnet pulse with a rated peak field of 60 T and a flat-top of 100 ms requires an energy of 160 MJ. The magnetic energy at peak field is 90 MJ, while 70 MJ are converted into heat in the magnet during a pulse. The necessary energy for a pulse is extracted from a 1430 MVA inertial energy storage generator (see Fig. 6.). This generator produces a terminal voltage of 21 kV and feeds power and energy to the magnet through ac/dc conversion equipment. Fig. 7 shows in block diagram form the electrical circuit. The parameters of the generator are given in Table II.

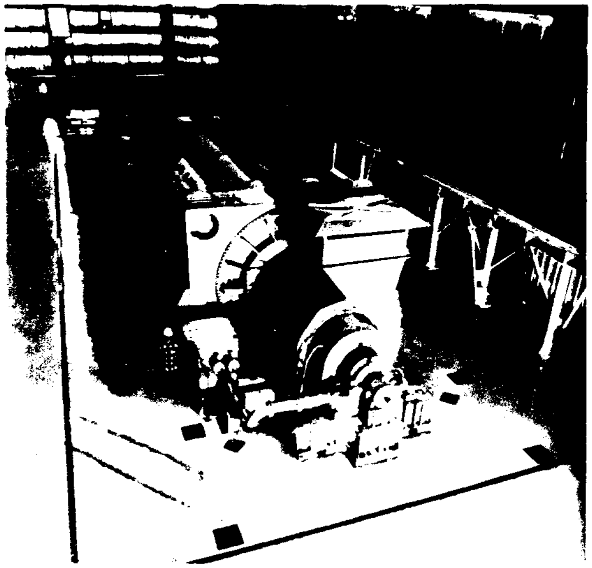

Fig. 6. 1430 MVA inertial energy storage generator.

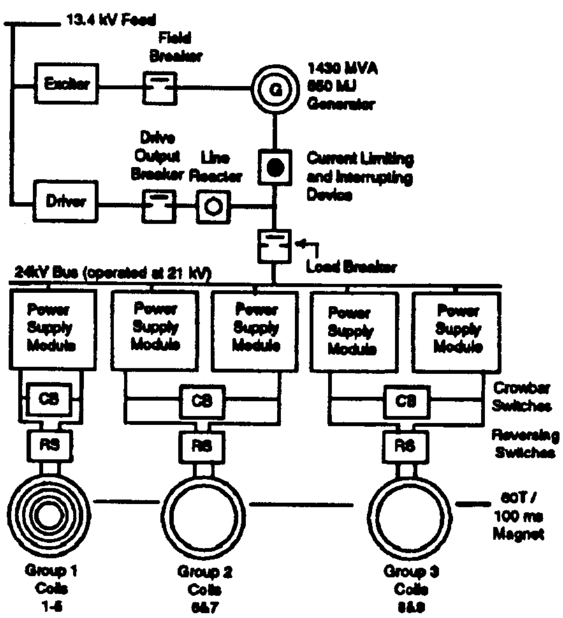

Fig. 7. 60 T Q-C magnet electrical system.

B. Power Conversion Equipment

The power conversion equipment for the 60 T magnet consists of five power supply modules, each rated with a no-load voltage of 4 kV and 3.2 kV at a rated current of 20 kA for 2 s with a repetition rate of one pulse per hour. Each twelve-pulse module consists of two parallel connected six-pulse bridges. The power supply modules use dry-type, cast coil transformers with a secondary no-load voltage of 3.1 kV. The primary voltage is 21 kV (Fig. 8). Each leg of a six-pulse bridge has two 94 mm, 5.2 kV thyristors connected in series. All the thyristors are water cooled. The two six-pulse bridges are installed in one open frame (Fig. 9). The twelve pulse converter uses an industrially proven construction. For coil groups 2 and 3 two such modules are connected in series providing 8 kV no-load and 20 kA.

TABLE II
GENERATOR PARAMETERS

Power rating	1430 MVA
Voltage	21 kV
Current	34.4 kA
Frequency	60 Hz
Synchronous speed	1800 rpm
Lower speed limit	1260 rpm
Extractable energy (1800 to 1260 rpm)	650 MJ
Pulse repetition rate	10 min.

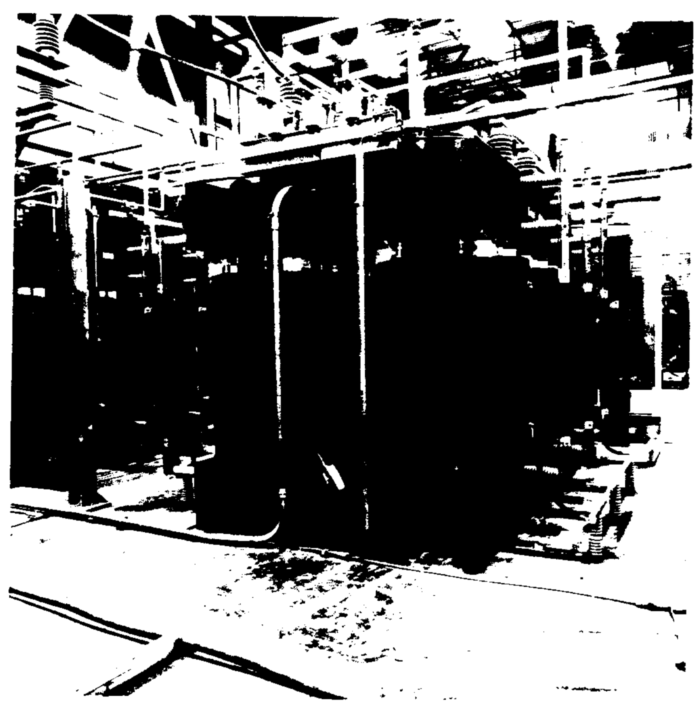

Fig. 8. 60 T Q-C magnet power supply module transformer.

C. Switches

The external mechanical high speed crowbar switches used for protection are associated with each coil group and close within 12 to 15 ms, shorting the coil group terminals. The reversing switches allow the polarity of the magnetic field to be changed as needed.

Fig. 9. 60 T Q-C magnet power supply module thyristor bridge frame.

D. Power Supply Testing and Commissioning

All power supply modules are initially tested using a 480 V source to check basic functions. Next the first three modules are tested at moderate power and currents using a 13.4 kV feed. These modules and then all others are tested using the generator operating at different voltages up to 21 kV. Finally each module is tested to its full rating of 3.2 kV/20 kA/ 2 s using a dummy load consisting of a 170 MJ/40 kV/ 40 kA variable resistor and a set of coils providing about 2 µH of inductance. All modules passed this thermal and mechanical testing. Some difficulties with the flux nulling DC-current measurement at high currents remain to be resolved.

E. Pulse Shaping

In addition to providing much longer pulses than capacitor-driven magnets and much higher fields than continuous magnets the 60 T controlled power magnet offers to the experimentalist a wider variety of pulse shapes than either. This is achieved by specifying current vs. time profiles to the controllers which adjust the voltage, with suitable amplification factors, to achieve the specified current. For each pulse 200 current points may be specified (for each of the three circuits). The physical currents are sampled every 500 µs, compared with the specified current values, and the voltages are changed accordingly. The specified currents are first tested and adjusted through computer simulations to verify that the desired field pulse can be achieved within the limitations of the ac-dc power converters and to optimize the overall pulse to minimize heating. After further testing and verification on the magnet the pulse shape is then added to the repertoire of pulses available to the experimentalist.

Some examples of possible pulses are shown in Fig. 10. The flat-top can be extended considerably for smaller fields because of the decreased heating. The wide variety of pulses includes flat-tops, linear ramps (up and down), steps (up and down), oscillating flat-tops, crow-bars, etc. Almost any shape is possible within the three constraints of a 60 T maximum field, the maximum of 200 control points, and the heating of the magnet. The latter condition also requires that an emergency crowbar be possible at any point in the pulse without overheating the magnet.

V. SYSTEM TESTING AND COMMISSIONING

Commissioning of the complete magnet and power supply began September 17, 1997. Magnetic field production per ampere of current was measured for each section of the magnet using a Hall probe rated for cryogenic service, a dc power supply and a precision shunt. Integrating the signal from a multiple turn pick-up coil centered in the bore at the horizontal mid-plane produced a measure of the field and duration generated during the pulse. Two current measurements are used. One uses a flux nulling technique and is very precise. The other uses Rogowski coils and is used as a cross check. Integrating the voltage produced in Rogowski coils placed around the power cables for each circuit produces a measure of current.

Initially each coil group was individually tested with a low current (1 kA) current pulse of short duration. Next, there were combined pulses (one pulse superimposed on another of longer duration) at low current (1 kA) supplied to combinations of coil groups. Then current levels and pulse duration were incrementally increased. A field of approximately 50.5 tesla for 50 ms was generated on September 25, 1997. Full field production tests of the outer two coils groups (coils 6-9) were completed October 3, 1997; 31.5 T for approximately 150 ms were produced. A field pulse of 57 T was produced by all coil groups October 13, 1997. Fig. 1 is a graph of this field pulse. Fig. 11 shows a field pulse of 59 T terminated by a crowbar operation produced October 13, 1997.

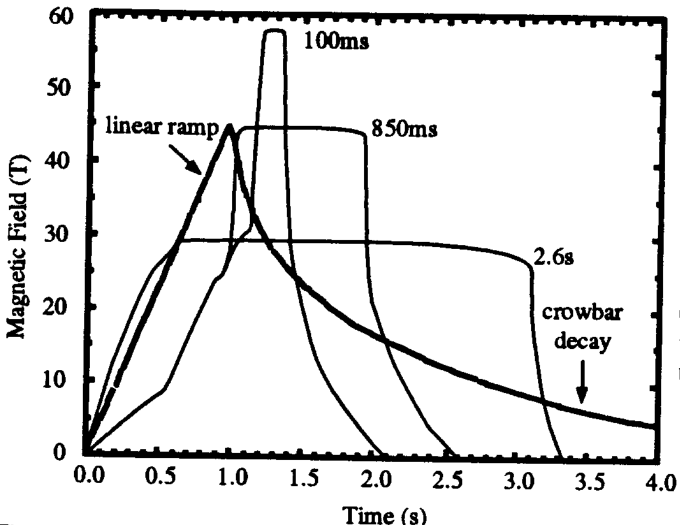

Fig. 10. Examples of possible 60 T Q-C pulse shapes.

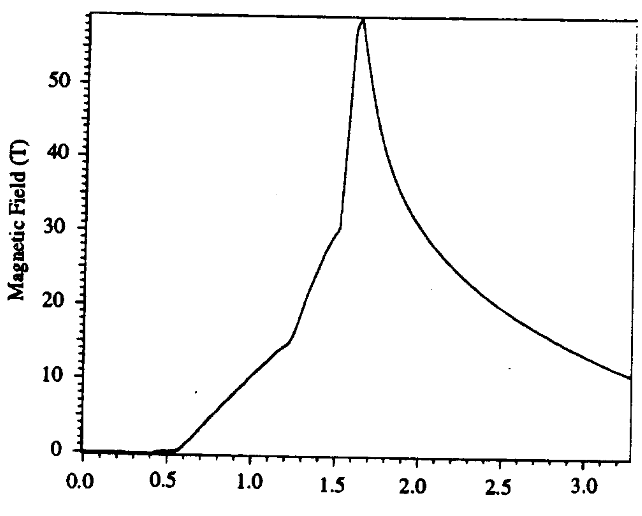

Fig. 11. 59 T pulse with crowbar at peak field.

Magnet commissioning will continue through the balance of October 1997. Numerous inductance measurements of the coil groups were made during the tests to monitor the condition of the coils. Modest increases in inductance (less than 0.2 %) were detected after the first pulses to high field levels. Subsequent inductance measurements after five full field pulses (including the crowbar from 59 T) for coil groups 2 and 3 show no changes. Coil group 1 showed an expected 0.1% increase in inductance after the 59 T crowbar pulse. Circuit resistance of coil group 3 after the 57 T field pulse (which has an I^2t value of about 90 % of a 60 T 100 ms flat-top pulse) is shown in Figure 12. Coil group 3 cools to a temperature of 80 K in 52 minutes after the 57 T pulse. Coil groups 1 and 2 cool sooner than coil group 3 due to their reduced size and radial thickness.

VI. SUMMARY

The NHMFL 60 tesla quasi-continuous magnet installed at Los Alamos National Laboratory is operating. A field pulse of 59 T has been produced in a 32 mm bore. This is the highest field in the largest bore ever achieved with this type of magnet. The magnet cools to 80 K after a full field pulse in about 60 minutes. There are no significant obstacles to attaining the specification pulse of 60 T with a 100 ms flat-top. Commissioning tests are continuing. It is planned to conduct the first experiment and make the magnet generally available to users beginning in November 1997.

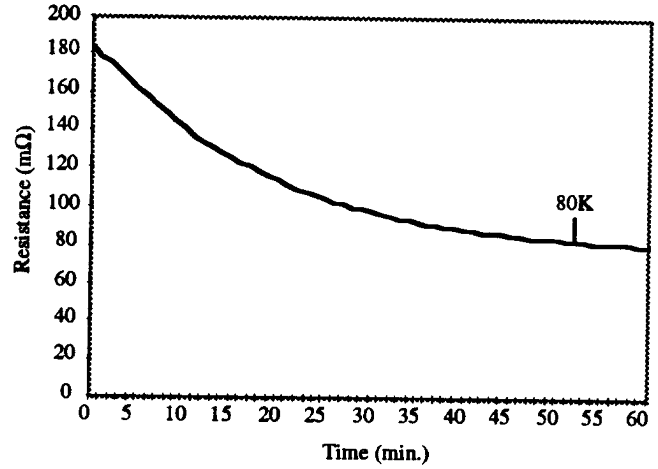

Fig. 12. 60 T Q-C magnet coil group 3 cooling rate.

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