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First 100 T Non-Destructive Magnet Outer Coil Set

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Abstract— **The controlled power outer coil set of the first 100 T non-destructive (100 T ND) magnet is described. This magnet will be installed as part of the user facility research equipment at the National High Magnetic Field laboratory (NHMFL) Pulsed Field Facility at Los Alamos National Laboratory. The 100 T ND controlled power outer coil set consists of seven nested, mechanically independent externally reinforced coils. These coils, in combination, will produce a 47 T platform field in a 225-mm diameter bore. Using inertial energy storage a synchronous motor/generator provides ac power to a set of seven ac-dc converters rated at 64 MW/80 MVA each. These converters energize three independent coil circuits to create 170 MJ of field energy in the outer coil set at the platform field of 47 T. Each coil consists of a multi-layer winding of high strength conductor supported by an external high strength stainless steel shell. Coils with the highest magnetic loads will utilize a reinforcing shell fabricated from highly cold worked 301 stainless steel strip. The autofrettage conditioning method will be used to pre-stress the coils and thereby limit conductor and reinforcement strains to the elastic range. The purpose of pre-stressing the coils is to attain a design life of 10,000 full field pulses. The operation and conditioning of the coil set will be described along with special features of its design, magnetic and structural analyses and construction.**

Index Terms—high field, pulsed magnet, 100 tesla

I. INTRODUCTION

The 100 tesla non-destructive (100 T ND) magnet outer coil set provides a nominal platform field of 47 T (net at peak) in a 225 mm bore. The 100 T ND insert coil provides the balance of the 100 T field in a 15 mm bore. A complete description of the 100 T ND magnet is given in [1].

Many of the design characteristics of the 60 T long pulse (LP) coils have been transferred to the 100 T ND outer coil set design. The 60 T LP magnet is described in [2]. Higher magnetic pressures, however, have driven the design to utilize stronger conductor and shell materials, and a post assembly coil conditioning method referred to as autofrettaging. Other design enhancements include additional insulation between coils and an improved coil lead and busbar design.

Conductor material strength can be increased by changing the conductor material from aluminum dispersion strengthened copper UNS C15175 (GlidCop Al-15™) and UNS C15715 (GlidCop AL-60™) to either steel clad copper or copper silver, or by increasing the amount of cold working of the aluminum dispersion strengthened copper. Using highly cold worked UNS-S30100 stainless steel sheet can increase the shell material strength.

Autofrettage conditioning has been used for decades to condition artillery tubes and pressure vessels by plastically yielding the inner surface with a radially directed internal pressure. Upon removal of the pressure, the inner surface is driven into a state of beneficial compressive stress. During subsequent operation the tensile stress of the conditioned inner surface is reduced for pressures less than that which originally yielded the inner surface of the tube or vessel [3].

The analysis and preliminary design of the 100 T ND outer coil set are near completion. The primary design issues are the fatigue life and strain softening of the conductor and shell materials for the two innermost coils. Strain controlled fatigue testing of the conductor material and UNS-S30100 stainless steel overwrap at operating conditions will address these issues.

II. SPECIFICATIONS

The following specifications guided the design of the outer coil set:

1) The net platform magnetic field will be 47 T or greater at magnet peak field.

2) The maximum number of nominal pulses will be 10,000 or greater.

3) The time between nominal pulses will not exceed 1 hour.

4) The size of the magnet will be not be much greater than 1 m in diameter and 1 m long, due to manufacturing limits.

5) The voltage, current and power requirements for the magnet will not exceed that available from 7 power supply modules each rated at 64 MW or 20kA @ 3.2 kV (full load)

III. DESCRIPTION

A cross section of the 100 T ND magnet is shown in Fig. 1. The outer coil set consists of 7 coils divided into 3 separate electrical sections powered by a synchronous motor/generator through combinations of seven ac-dc converters. A coil is

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comprised of a winding inserted into a steel shell and then vacuum impregnated with epoxy. The coils are numbered 1 through 7 starting at the innermost radial coil and progressing to the outermost radial coil. Section 1 consists of coils 1 and 2 connected in series, powered by 2 converters. Section 2 consists of coils 3 and 4 connected in series, powered by 2 converters. Section 3 consists of coils 5, 6 and 7 connected in series, powered by 3 converters. The sections are energized in stages; section 3 first, followed by section 2 and finally by section 1.

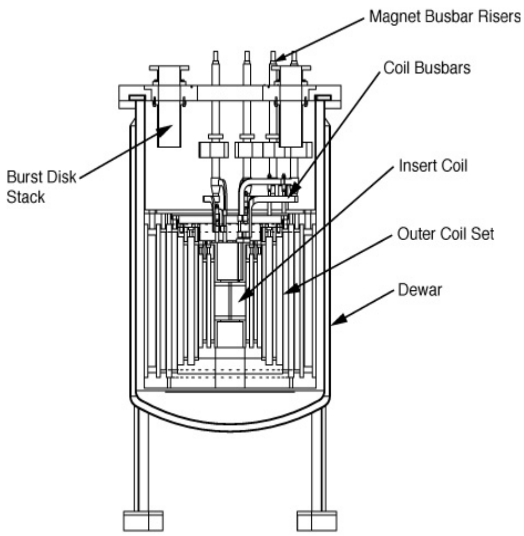

Fig. 1. Internal details of 100 Tesla Non-Destructive Magnet

A simulation of the resultant nominal magnetic field produced by the outer coil set is shown in Fig. 2. The insert coil set is energized at the peak platform field. High magnetic pressures in coils 1 through 4 have driven their design to utilize stronger materials and the autofrettage technique for prestressing the conductor.

The coils are nested and mounted in a NEMA G-10 epoxy fiberglass laminate and stainless steel frame. The frame is suspended inside a dewar (see Fig. 1) which is cooled to 77 K operating temperature. Cooling is accomplished using liquid nitrogen. The coils are free to expand and contract axially inside the dewar.

A. Coil Windings

The coil windings are basic multi-turn, multi layer solenoids. All of the coil windings are mechanically independent of each other and radially supported by a steel reinforcing shell. Coil winding details are presented in Table I.

Conductor leads are silver brazed to the winding terminations and transition to a coaxial geometry which interlocks the leads against each other. This mechanical coupling of the start and end of a winding allows a significant portion of the magnetic forces on the first and last turn to be reacted by the conductor. The busbar connections to the coaxial leads utilize hemispherical rotating and sliding/rotating mechanical joints, which will adjust for minor deviations in geometry plus assembly and manufacturing tolerances. Paired, rectangular busbars connect to the coaxial leads and rise upward and radially outward and connect to coaxial magnet busbar risers that penetrate the dewar lid (see Fig. 1). Current is provided to the electrical sections through these risers. The busbar system design allows limited movement to accommodate thermal expansion and contraction and coil deflection under magnetic loads.

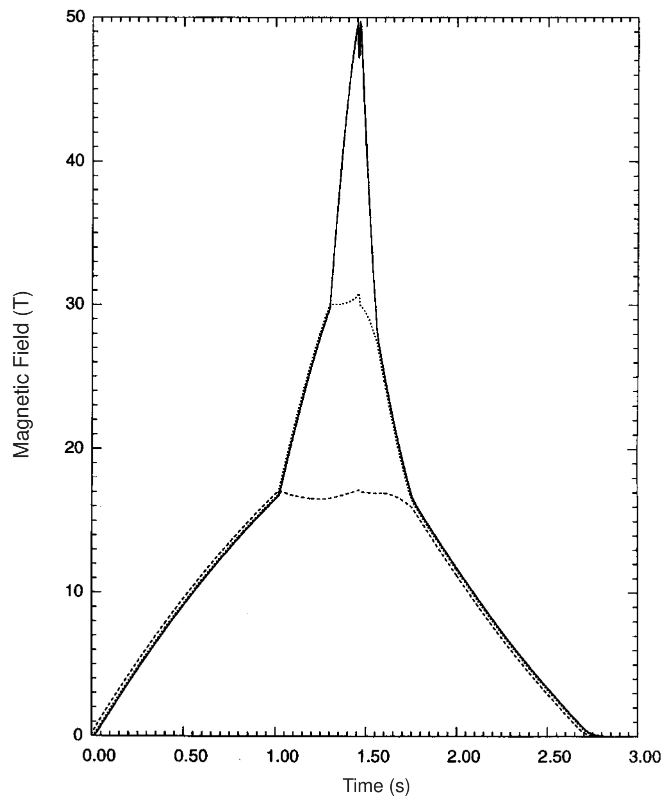

Fig. 2. Simulated 47 T platform magnetic field pulse

TABLE I
COIL WINDING GEOMETRY

Coil	Conductor Size (mm)	Turns per Layer/Layers	Coil ID/OD W/o shell	Coil Length (mm)
1	7.2 x 5.2	58 / 4	225 / 274	460
2	7.2 x 5.2	58 / 4	338 / 388	460
3	10.5 x 5.5	67 / 4	454 / 506	752
4	10.5 x 5.5	67 / 4	607 / 659	752
5	13.0 x 9.0	67 / 4	751 / 831	920
6	13.0 x 9.0	67 / 4	913 / 993	920
7	12.0 x 8.5	68 / 6	1054/1167	866

B. Shells

Each coil winding is enclosed by a stainless steel reinforcing shell. Shells 1 through 4 are each comprised of a forged steel bobbin wrapped with 60 % cold worked stainless steel sheet (see Fig 3). Sheet is needed to obtain this degree of cold working and the associated yield strength. Shells 5 and 6 are made from annealed stainless steel forgings. Shell 7 is a rolled, welded, and annealed stainless steel tube.

C. Materials

The base line materials for the conductors are Glidcop AL-60™ for windings 1 and 2, Glidcop AL-15™ for windings 3 through 6 and C10400 copper for winding 7. Steel clad copper and copper silver are also material candidates for windings 1 and 2. The primary electrical insulation system for the conductors is comprised of an epoxy (CTD 101™) impregnated E-glass™ fabric tape and Kapton™ tape.

Shell 1 through 4 bobbins are Nitronic-40™ and the overwrap sheet is extra full hard (XFH) UNS-S30100 stainless steel. Shells 5 and 6 are comprised of Nitronic-40™. Shell 7 is comprised of UNS S30400 stainless steel. Additional information on materials may be found in [4].

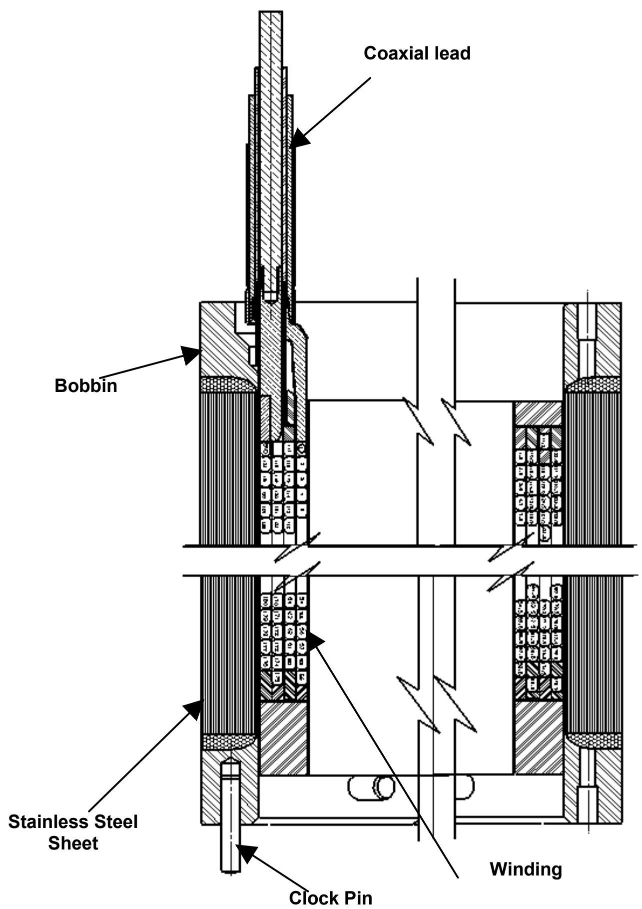

Fig. 3. Cross-section of coil 1 showing winding, bobbin and stainless steel sheet wrap.

IV. Analysis

Magnetic and structural finite element analysis was performed on the outer coil set using an axisymmetric model with mid-plane symmetry. The structural effects of the autofrettage pulse (50.92 T) and a nominal pulse (49.43 T) were examined using the analysis code, Cosmos™-M. Currents obtained from a circuit analysis code were input into the magnetic analysis. Forces obtained in the magnetic analysis and coil temperatures predicted from the circuit analysis code were used as input into the structural analysis. The structural analysis was run in non-linear mode to allow plastic deformation to occur during the autofrettage pulse. Table II shows the conductor compressive state after autofrettage (for coils 1 through 4), maximum Von Mises stresses due to a nominal pulse, and yield strength for each coil.

The high stress states in the conductors for coils 1 and 2 have driven the design to require the autofrettage of these coils. The lower stresses in coil 3 and 4 conductors have allowed the selection of a material with a lower yield strength, but higher conductivity. These coils are also autofrettaged, primarily because their contribution to the total field is needed during the autofrettage of coils 1 and 2.

The stress range for coils 1 and 2 is large and approaches a full reversal, an undesirable situation for fatigue loading and strain softening. A test is planned to cycle the coil 1 and 2 conductor material through 10,000 cycles at this stress range and at operating temperature.

The stress state of the stainless steel overwrap for coils 1 and 2 is also of concern. Von Mises stresses as high as 1950 MPa are predicted at the midplane near the winding to shell interface during a nominal pulse. The yield strength of the UNS S30100 XFH stainless steel at 77 K is 2040 MPa. The stainless steel sheet will also be fatigue tested.

The highest predicted combined stresses for the insulation occur during the autofrettage pulse. These predicted stresses are conservative due to the bonding of the insulation nodes with the shell nodes in the model. In reality, slippage can occur between the bobbin wall and the insulation. The mechanical safety margins of the insulation were checked using the Mohr-Coulomb criterion. The criterion states that in

TABLE II
PREDICTED CONDUCTOR STRESS AND YIELD STRENGTHS

Coil	Autofrettage Cond. Comp Stress (MPa)	Nom Pulse Cond. VM Stress (MPa)	Conductor Y.S. (MPa) @ 77 K
1	-485	639	725 (AL-60™)
2	-493	651	725 (AL-60 ™)
3	-20	622	660 (AL-15 ™)
4	-19	618	660 (AL-15 ™)
5	--------	502	660 (AL-15 ™)
6	--------	459	660 (AL-15 ™)
7	--------	211	400 (C10400)

order to avoid failure the following equation must be satisfied

$$\frac{\sigma_n}{\sigma_0} + \frac{\tau_n^2}{\tau_0^2} \leq 1 \tag{1}$$

where: σ_n = predicted compressive stress,
σ_0 = compressive strength,
τ_n = predicted shear stress,
τ_0 = shear strength.

Using the predicted compressive stress of 248 MPa, the compressive strength, 1250 MPa, the predicted shear stress of 68 MPa and the shear strength, 201 MPa, the summation was calculated to equal .313.

II. Fabrication

A. Coil Windings

The conductor material is pulled off of a supply spool and run through a winding train where a staggered half lap wrap of .03 mm thick Kapton™ and .13 mm thick E-glass™ tape is applied. The insulated conductor is wrapped over a mandrel under moderate tension (less than 900 N) and an automated guide positions the conductor. Windings 3 through 7 will require the brazing of several lengths of conductor material. Additional insulation is added on the ID, OD, and between layers of the winding. Coaxial lead components are brazed to the start and end of the windings.

B. Sheet Reinforced Shells

The process of winding the bobbins is described below. First, a steel wedge, which tapers from .41 mm thick to .13 mm, is glued to a bobbin. This wedge creates a gentle transition with a .13 mm step when winding rather than an abrupt .41 mm step. Next the UNS-S30100 stainless steel sheet is either welded to the wedge or glued to the bobbin. The sheet is then wound onto the bobbin under tension, to achieve a greater packing factor. The wedge and the sheet starting edge are held in place by friction. A packing factor greater than 90% is required for structural integrity. The steel sheet is terminated by plug welding the end of the sheet to the underlying layer and then cutting the material.

C. Coils

The OD of the winding is measured and the ID of the shell is machined to that dimension plus an assembly clearance. The winding and its mandrel are inserted into the shell. The shell is sealed and the winding is vacuum impregnated with epoxy. After curing the winding mandrel is removed from the coil.

D. Coils

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III. Autofrettage and Operation

Coils 3 and 4 are autofrettaged by pulsing them with more current than used in a nominal pulse. Coil 5, 6 and 7 are also active to provide a background field, but coils 1 and 2 are inactive, as they would reduce the magnetic field in coils 3 and 4. This is due to the mutual inductances. A reduction in magnetic field would decrease the amount of yielding in the coil 1 and 2 conductors. Coils 1 and 2 are autofrettaged by energizing the entire coil set.

During a normal operation, coils 5, 6 and 7 are energized first and the period these coils are energized bracket in time the period in which coils 3 and 4 are energized, which bracket the time period for coils 1 and 2. A peak platform field of 49.4 T (before interaction with the insert coil) is achieved when all coils are energized.

IV. Summary

A method of fabricating a high strength high field magnet coil has been conceived and analyzed. A complete full size prototype of coil 1 will be built. After successful fabrication, it will be used in the operational magnet outer coil set. The estimated completion date for fabrication of the outer coil set is June 2001.

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