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MEGAGAUSS FIELDS DURING MILLISECONDS

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Abstract

A non-destructive, one megagauss magnet is now being designed in cooperation between Los Alamos and the National High Magnetic Field Laboratory (NHMFL) through joint funding by the US Department of Energy and the US National Science Foundation. The design combines two types of pulsed magnet now in use at the NHMFL: a capacitor-driven 'insert' magnet with a total pulse width of order 10 ms and a much larger 'outsert' magnet with a total pulse width of order 2 seconds that is driven by a controlled power source. The insert and outsert produce approximately 1/2 megagauss each.

Although the design uses CuAg as the principal conductor further design efforts and materials development are exploring CuNb and stainless steel-clad copper as possible future alternatives.

A crucial innovation was to employ wound steel strip (sheet) as a reinforcement in both insert and outsert coils. This gives extra strength due to the higher degree of cold-work possible in strip materials. For this leading edge magnet a key role is played by materials development.

A major component, the 7 module 560 MVA controlled dc power supply required for the outsert, has been installed and commissioned.

Introduction

The promise and possibility of non-destructive 100 tesla (one megagauss) research magnets have been discussed for several years.[1, 2]

Here we present progress on the NHMFL/DoE design proposed in 1995 that combines two distinct types of pulsed magnets: a small capacitor driven magnet that requires high power, and a large controlled power magnet that requires high energy.[3]

The yield strength of known conductors is much less than the magnetic pressure associated with the energy density of a 100 T field region, $B^2/2\mu_0 = 3.98$ GPa. This pressure can be related to the hoop stress on a wire element at radius r carrying current I in a field B , which is proportional to rIB . Therefore, the hoop stress (or differential magnetic pressure) can be reduced by using a small r or small I , which imply a small bore or a large magnet, respectively. However, bore size has a lower limit for experimental usefulness and magnet size has an

upper limit for a practical power supply. Existing energy sources and available materials permit a solution to these problems for 100 T in a bore of 15 mm.

Design

Since 1995 many aspects of the NHMFL/DoE design have been considered.[4] Not only was the original concept confirmed but the availability of better materials and the use of more accurate design tools have increased the level of safety and design confidence.

The 100 T insert produces 53 T and is similar to high field pulsed magnets commonly found in research laboratories in the pulse length, the bore size, the reinforcement tailored for each layer, the LN pre-cooling, the weight, and the limited lifetime. The principal difference is the magnetic stress, which is more uniformly distributed over the volume of the insert due to the high background field from the outsert. The high level of this stress calls for greater innovation, design optimization, material strength, and fabrication quality, which will also benefit conventional pulsed magnets. The insert design will continue to evolve.

The mechanical data for the first insert are given in Table I.

Table I
Mechanical Data for Insert Magnet

Layer	Conductor Size (mm)	Turns per layer	Cond. Layer ID (mm)	Reinforcement (mm)
1	3.4 x 6.0 ^a	31	15	3.5 ^c
2	3.5 x 6.6 ^b	28	28.8	3.8 ^c
3	"	"	43.4	5.6 ^c
4	"	"	61.6	7.5 ^c
5	"	"	83.6	9.3 ^c
6	"	"	109.2	11.0 ^c
7	"	"	138.2	12.0 ^c
8	"	"	169.2	14.5 ^d

^aGlidCop Al-15™; ^bCuAg; ^cMP35N strip and Zylon; ^dMP35N strip.

Table II
Mechanical Data for Outsert Magnet

Coil	Conductor Size (mm)	Turns per layer/layers	Coil ID/OD (mm)	Shell Thickness (mm)
1	5.2 x 7.2 ^a	58/4	210/258	27.7 ^d
2	"	"	320/368	29.3 ^d
3	5.5 x 10.5 ^b	"	432/483	35.8 ^d
4	"	"	562/613	31.9 ^d
5	8.5 x 11.4 ^b	66/4	685/759	36.0 ^d
6	"	"	841/916	24.9 ^d
7	8.5 x 11.4 ^c	66/6	976/1087	38.1 ^e

^aCuAg, ^bGlidCop Al-15™, ^chard Cu, ^d301HYSS strip, ^e304SS

The outsert magnet produces 47 T and has many similarities to the NHMFL 60 T quasi-continuous magnet that was recently commissioned.[5] The outsert's salient features are seven free-standing, mechanically independent coils, divided into three electrical circuits that are sequentially energized. The coils are cooled in LN before a pulse and are predicted to reach LN temperature again in less than one hour following a pulse. The 60 T magnet is a forerunner of the outsert.

The mechanical data for the outsert are given in Table II. The cross-section for the full magnet is shown in Fig. 1 and the stress distribution in Fig. 2.

Figure 1. Cross-section of 100 T magnet, with expansion of insert.

Materials

The materials properties needed for a 100 T magnet are unprecedented, and achieving these has consumed a large fraction of the effort to date. The conductor wire posed the greatest challenge, and required a joint collaboration between staff metallurgists and manufacturers to achieve a product that permitted a feasible design. Suitable wires must have high strength and high electrical conductivity, sufficient dimensions (up to 5 mm x 8 mm cross-section and 120 m length), and acceptable fabricability, joinability and service life. Possible conductors include Cu-Ag, Cu-Nb, and stainless steel clad Cu (Cu-SS). The fabrication and properties of such wires are discussed in these proceedings (see J. D. Embury and K. Han) and elsewhere.[6,7]

The principal wire of choice now for both the insert and outsert is a cold-drawn, co-deformed Cu-(16 at.%)Ag composite, although both Cu-Nb and Cu-SS remain important candidates for upgrades and new insert designs.

As a result of employing strip winding for the reinforcement shells, mentioned earlier, it became possible to employ the 'super alloy,' MP35N, as a reinforcement material in the insert (YS = 2.5 GPa, UTS = 2.7 GPa, at LN temp.). Likewise, strip winding takes advantage of the cold-worked strength of 304SS for outsert reinforcements. Zylon fiber is also used in the insert because it is strong, stiff, and an insulator.

Figure 2. Stress distribution a) in the insert and b) in the outsert.

Power Supplies

The capacitors and switches for the insert's power supply are ready for assembly. For flexibility in accommodating future inserts this bank is configured into four independent 6 kV units that can be connected to give either 6, 12, 18, or 24 kV with a maximum energy of 2.4 MJ. The bank can be divided to power duplex coils, if necessary, but the present insert only requires a single 12 kV source.

The outsert will use 7 ac-dc power converters and controllers which have individual full-load ratings of 3.2 kV, 20 kA, and 64 MW. These are powered by a 1.4 GVA motor-generator that can deliver 600 MJ from stored inertial energy. The outsert coils are grouped into 3 independent, series-connected circuits (coils 1 & 2, 3 & 4, and 5 through 7). Correspondingly, the 7 converters are grouped into

3 circuits: 2, 2, and 3 series-connected converters, respectively. The outsert contains 140 MJ of magnetic energy at peak field.

Figure 3. Reference pulse shape of combined insert and outsert.

Fabrication

For both the insert and outsert a different approach to reinforcement was taken with the use of wrapped metal strip. The advantages of wrapped strip include: a wider range of materials and processing are available; greatest cold working strength is parallel to the greatest stress; fabrication is facilitated by winding strip as needed; eddy currents can be reduced if the strip layers are insulated; transfer of axial forces to the reinforcement occurs; crack propagation is interrupted; uniform loading is improved; easier to place multiple metal reinforcements in one magnet; thickness of strip can be chosen for various purposes (ease of winding, cold work strength, precision of overall thickness, etc.).

In particular, the insert reinforcement for each layer is a combination of Zylon fiber and wound MP35N strip, 5 mil thick. The outsert reinforcing shells will be produced by winding highly cold worked, extremely high strength, 304 stainless steel sheet onto a less strong but very tough Nitronic 40™ bobbin.

The method of 'autofrettage' will be utilized in the more highly stressed outsert coils to achieve reduction of conductor stress during routine magnet operation. This is achieved by allowing the conductor to strain soften as required during routine magnet operation or by a subjecting the coils to a deliberate one-time overstressing pulse to produce permanent plastic deformation in the

conductor and the accompanying beneficial state of compressive pre-stress. Improved articulation and adjustability of connections between coil leads and busbar, and within the busbar, will be obtained by incorporating and fingerstock fittings (Multilam™). These changes will provide relief to the coil and busbar manufacturing tolerances and will speed assembly and disassembly by reducing the amount of manual fitting required. The use of double wrapped Kapton LT tape in place of half-lapped and staggered Kapton and e-glass fabric tape is being investigated.

Conclusion

A non-destructive 100 T research magnet has been designed and funded, and is now following a well-defined engineering plan to completion. Within the next year an insert prototype will be built and tested, a prototype of the smallest outsert coil will be built, and delivery will be taken on the final CuAg wire. The insert's capacitor power supply is on hand and the huge 560 MVA dc supply for the outsert has been commissioned.

The next millennium will begin with a research tool that seemed a dream only a decade ago.

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