Pulse Magnet Development Program at NHMFL

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***Abstract*—In 1989, the NHMFL Pulsed Magnetic Field User Facility was set up at the Los Alamos National Laboratory. Two programs were initially conceived: 1) The construction of a 60 T long pulse magnet energized by the 600 MJ, 540 MW generator, and 2) a high field magnet program for the 1.6 MJ/32 mF capacitor bank with an operating range of 10 kV. These magnets are designed and built at the NHMFL. Our pulse coil development has its roots in the work accomplished by the group in Leuven which served as a starting point for our technical development programs. After having established the technology, we have focused our efforts on increased reliability. Our present user magnet design is based upon the use of distributed MP35N and Zylon reinforcement. These 60 T short pulse (5.7 ms pulse rise time) and 50 T mid-pulse (40 ms pulse rise time) magnets have become the "workhorse" magnets of the Pulsed Magnetic Field User Facility since the failure of the first 60 T long pulse magnet. Coil longevities of 1500 shots, of which half are at full field, are becoming the standard.**

Presently, the short pulse group is engaged in several programs to increase the science opportunities at our user facility. The development activities encompass fast-cool magnet systems, allowing a shot at least every 20 minutes, the production of a new generation of user coils for higher fields, and a 100 T insert. We present a technical overview of our development programs and new coil designs, including materials development and characterization, identifying those areas critical to progress toward even more reliable and stronger magnetic fields.

***Index Terms*—High magnetic field, pulsed magnet.**

I. INTRODUCTION

RESEARCH and hard-earned operational experience with pulsed magnets has spawned the recent development of national and international scientific pulsed field user facilities. The financial investments in these facilities are becoming significant. There is now a strong requirement for increased productivity in physics research using pulsed magnets. There are competing goals in these modern facilities. There is the desire for experiments at higher magnetic fields and there is the requirement that pulsed magnet performance be predictable if not totally reliable to minimize risks to scientific apparatus. Another technical objective is the pulse width or time at "useful" fields. Long pulse coil designs, $\tau_{\text{rise}} > 40$ ms, excel at achieving time at field. Short pulse coil designs, $\tau_{\text{rise}} > 10$ ms, are most suitable for high field operations. We list here three measures to qualify a pulse magnet system: 1) maximum operational field, 2) high intensity shot life, and 3) time at field or more conveniently rise time, τ_{rise}.

The operation and maintenance of a pulsed field scientific user facility presents two additional requirements: 1) cycle time between shots should be minimized to increase available time at field; 2) logistically, the magnet production capability should exceed user facility requirements to allow development of newer improved systems. Design engineering should also recognize that the facility logistics is significantly impacted by magnet reliability and production complexity.

The magnet development program for a user facility should provide a range of magnet systems to satisfy the experimental science requirements for higher fields, increased time at field, and above all reliable operation for users.

II. NHMFL CAPACITOR DRIVEN PULSE MAGNET SYSTEMS

Capacitor driven magnets remain the technical backbone supporting the scientific programs at the NHMFL Pulsed Field Facility at Los Alamos National Laboratory. The present facility is comprised by an experimental hall containing four user cells for short-pulse and mid-pulse physics. The capacitor bank is a 10 kV 32 mF bank rated at 1.4 MJ of stored energy during normal operation. The facility presently operates two short pulse magnet systems and two mid-pulse class systems. The experimental hall user cells are numbered right to left in Fig. 1 which presents an outline of the facility.

A. 50 T 24 mm Bore Short Pulse Magnet

We operate 50 T short pulse magnets in cell #1. Present NHMFL 50 T short pulse magnets are 24 mm in bore and have a rise time of 7.5 ms with the NHMFL bank at 16 mF of capacitance. The coil's conductor is a 2 mm × 3 mm Glidcop Al-15 copper wire. The internal reinforcement structure is an S2-Glass composite impregnated with CTD-101 epoxy [1]. Typical lifetimes are ~600 full field shots. The maximum operational lifetime achieved is ~1200 full field shots. The full field shot to shot cycle time is ~20 min. This design has been in operation since 1998 and 31 units have been produced over this time. Three units were built in 2003. The 24 mm bore design will be upgraded to 55 T over years 2004–2005.

B. 50 T 15 mm Mid-Pulse Magnets

The facility presently operates 50 T mid-pulse magnets in user cell #2. The mid-pulse was constructed to augment the 60 T long pulse magnet program [2]. The NHMFL 50 T mid-pulse magnets are 15 mm in bore and have a rise time of 39 ms with the NHMF bank at 32 mF of capacitance. The magnet's conductor is a 3 mm × 5 mm hard copper wire. The internal reinforcement structure is a wet lay-up zylon and L-28 epoxy composite. The full field shot to shot cycle time is ~70 min. The design has been in operation since 2002. We initially produced two units. Both have seen service. There are >600 full field shots on unit #1 and ~200 shots on unit two. Neither magnet has failed. The

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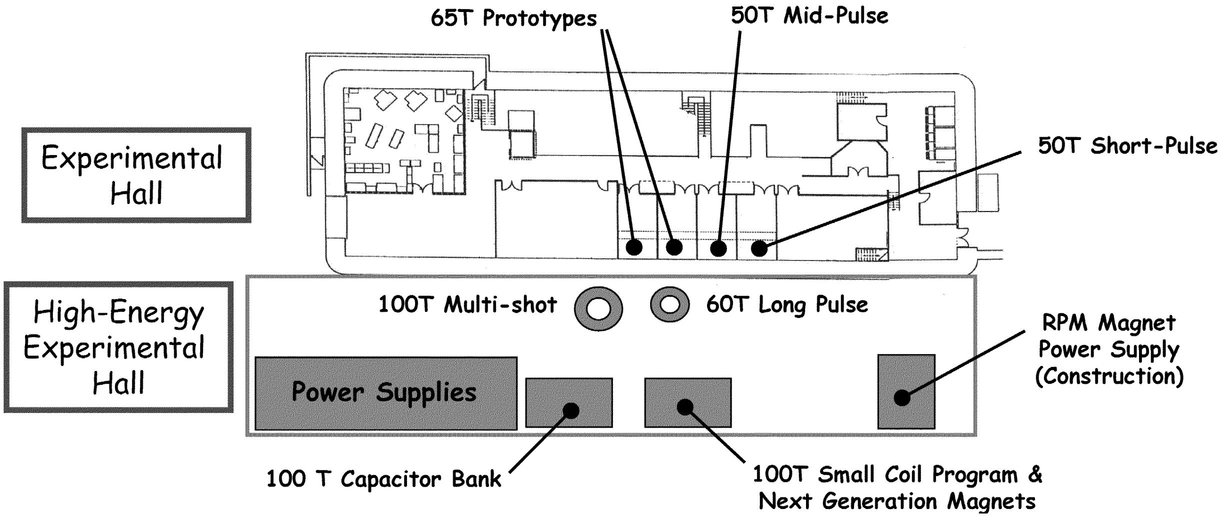


Fig. 1. Outline of the NHMFL pulsed field user facility at Los Alamos National Laboratory.

TABLE I
PRODUCTION HISTORY FOR 60 T ZM COILS

Year	Quantity	Model number
2000	4	60 T ZMA Prototype + R1
2001	6	60 T ZMB Revision B
2002	5	60 T ZMC Revision C
2003	3	60 T ZMD Revision D

15 mm bore mid-pulse design will be upgraded in conjunction with the mature gap cooling technology and a planned user capacitor bank upgrade to a 13 kV operation voltage with 32 mF.

C. 60 T-ZM 15 mm Bore Magnets

The facility presently operates 60 T short pulse magnets in user cells 3–4. The NHMFL 60 T ZM short pulse magnets are 15 mm in bore and have a rise time of 5.7 ms with the NHMFL bank at 16 mF of capacitance. The magnet's conductor is a 2.5 mm × 4.0 mm AL-15 Glidcop copper wire. The internal reinforcement structure is a wet lay-up zylon/MP35N and L-28 epoxy composite. The full field shot to shot cycle time is $\sim$34 min. Various versions of this design have been in operation since 2000. Initial production units experienced premature failures in the transition regions of the windings. The reinforcement design was altered to stabilize wire motion in the transition regions. Annual production quantities for the 60 T ZM coil models are listed in Table I. Coil longevities of 1500 shots, of which half are at full field, are becoming the standard with the 60 T ZM design. The production record illustrates the demand and reliability relationship one encounters when operating a user facility. The integration of a lower reliability higher field system may place such demands on the production that it may retard development of improved or higher fields magnets.

The 60 T 15-mm bore short pulse magnets will be gradually phased out in 2004 with an upgraded 65 T magnet design.

D. 65 T 15 mm Bore Gap Cooled Magnet

We are testing of a 3rd prototype 15-mm bore 65 T pulsed magnet [3]. The measured rise time is 9.2 ms with the NHMF bank at 32 mF of capacitance. The magnet's conductor is a 3.0 × 4.8 mm AL-60 Glidcop copper wire. The full field shot to shot cycle time is $\sim$25 min. The magnet is a nested two-coil assembly that has a cooling manifold between the inner and outer coil. The design is novel because of the cooling manifold between the nested solenoids and an integral coaxial lead. The 65 T inner coils "poly-layer" construction methodology was developed in conjunction with the 100 T insert design [4]. The features defining the nested two-coil assembly are a template for future user magnet coils.

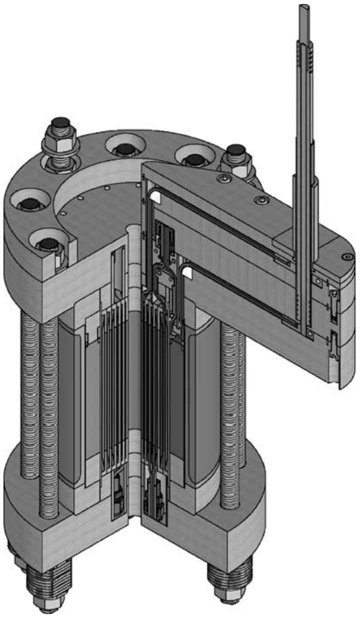


Fig. 2. NHMFL 65 T pulsed magnet. The magnet assembly is comprised by two six layer coils. The inner insert has a zylon and MP35N internal reinforcement.

Three prototypes magnet assemblies have been tested. The first two prototypes experienced soft failures in the outer monolithic coil after 11 and 16 shots at 66 T. The engineering design of the outer coil was changed for the 3rd prototype. The third prototype started testing in October 2003. The magnet passed the testing protocol accumulating 12 full shots at 66.2 T and 52 shots at 65 T. The 3rd prototype is transitioning into scientific service as a high-risk user coil.

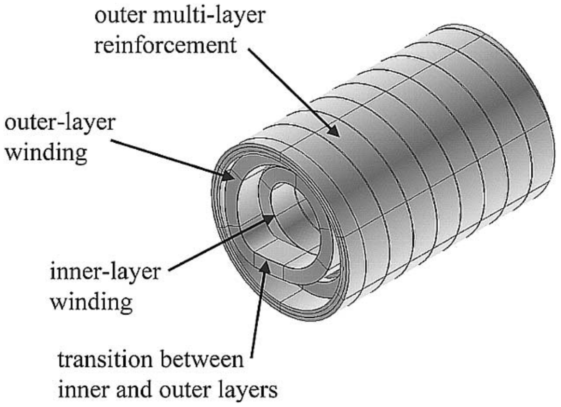


Fig. 3. ANSYS generated image illustrating stabilization of continuous wire transition with metal.

The insert coils have been recycled from the first two prototypes. Therefore the insert in prototype assembly #3 has accumulated ~80 shots above 65 T. We are presently reviewing the engineering tolerances to simplify the fabrication costs as we transition this design into a scientific user system.

III. Pulse Program Objectives and Technical Path

The NHMFL pulse magnet group is responsible for the maintenance & upgrades of the NSF user facility and the design and construction of the insert coils for the DOE 100 T nondestructive multi-coil magnet program [5]. The technology development for these two tasks is concurrent. Therefore it is desirable that the developed technologies be as common as possible.

A. NHMFL Monolithic Coil Technology

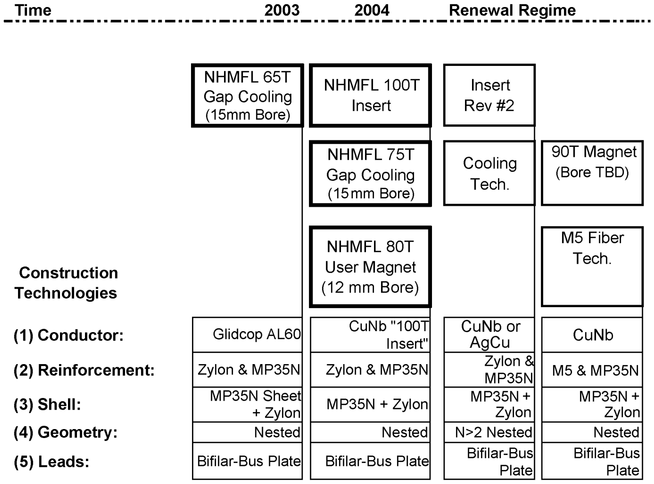
NHMFL user facility magnets have their design origin in the internal reinforcement work done by Herlach *et al.* in Leuven [1]. Continuous conductor is wound into a monolithic coil. NHMFL 60 T development, by Weiss & Liang, entailed the inclusion of MP35N and zylon as a replacement for S2 glass reinforcement [6]–[8]. Subsequent NHMFL work successfully stabilized the mechanical structure of an internally zylon reinforced transition by axially extending metal reinforcement over the transition region. However analysis of this structure indicated that such transitions are not a suitable design platform for high-field applications due to excessive conductor strain and the risk of insulation damage via shear [9]. Topologically there will always be the potential for an internal short between the layer insulation and metal reinforcement. The structure is limited by the modulus of the internal filler materials around the conductor [10]. Additionally, designs with continuous conductor limit our ability to grade conductors for each layer. We have, for these reasons, developed an alternative poly-layer coil construction technology.

B. Poly Layer Assembly Technology

The objective is to develop a magnet assembly technology with the following features:

1) the assembly technique should allow grading of conductor on a layer by layer basis by using joint interconnect technology.

Fig. 4. Poly layer coils after winding. The angular phase advance between leads is 240°.



Construction Technologies				
(1) Conductor:	Glidcop AL60	CuNb "100T Insert"	CuNb or AgCu	CuNb
(2) Reinforcement:	Zylon & MP35N	Zylon & MP35N	Zylon & MP35N	M5 & MP35N
(3) Shell:	MP35N Sheet + Zylon	MP35N + Zylon	MP35N + Zylon	MP35N + Zylon
(4) Geometry:	Nested	Nested	N>2 Nested	Nested
(5) Leads:	Bifilar-Bus Plate	Bifilar-Bus Plate	Bifilar-Bus Plate	Bifilar-Bus Plate

Fig. 5. Technical roadmap for pulse magnet development program showing the time evolution of construction technologies. We can improve our predictions of development times by an analysis of the actual time required to implement technical changes. This temporal roadmap approach allows us to predict project costs and improve our decision making process.

2) the joint leads should be free to move axially while reacting torques to the magnet support structure. The coil leads should be bifilar in nature to create a zero net force assembly allowing nested multi-coil construction.
3) the engineering features should be designed to be mechanically stable allowing their application to magnet designs for higher fields and mechanical stress.
4) the engineering system allows the inclusion of cooling gaps within any design.
5) the resulting technology should be sufficiently simple and reliable so that production logistics allow a reliable supply of magnets to the user facility.
6) development of this engineering system would focus on two and then three coil mechanics to minimize the complexity of two coil mechanics.

The first technical iteration was in the 65 T insert coils. We experienced, through the fabrication of pilot and prototype windings, the impact of tolerances on the assembly and the resulting practical limitations to the theoretical design.

C. Integration of 100 T Insert and User Magnet Programs

The 100 T insert design incorporates the novel features associated with the poly layer assembly process. We must also recognize that the insert conductor, a 1.4 GPA CuNb material developed by Bochvar Institute, is equally novel [11], [12]. The conductor material, together with the mechanical design, requires testing and long term operational data to confirm the designs robustness before operation in the 100 T system.

We are implementing a small coil test program to explore the electromechanical reliability issues associated with design space of the 100 T insert. This program will also open up test and scientific user stations to explore short pulse operation at magnetic fields in the 70 T–80 T range. The development path, after the 65 T gap cooled system, is to fabricate 75 T and 80 T magnet assemblies using CuNb conductor with the 65 T poly layer assembly template. Coil testing of the 75 T and 80 T systems will be performed in the high-energy experimental hall with the 100 T capacitor bank. User facility upgrades will allow use of these larger magnets for the short-pulse and mid-pulse magnets.

IV. CONCLUSION

The NHMFL pulsed magnet program is at a technical crossroads. We have developed and are evaluating the poly layer magnet construction technique for the assembly of pulsed magnets. This represents a shift from traditional monolithic coil fabrication techniques to that of nested series connected coils. The design requirements were derived from the needs of the user facility and the requirements of the 100 T insert program. We are presently involved in prototype testing of 65 T gap cooled prototype user magnets. Coil development is progressing and the 3rd prototype has passed the testing protocol and is transitioning to use for scientific research.

The new short pulse magnets will require more stored energy in the capacitor bank. The 5.7 ms 60 T-ZM magnets require $\sim$0.54 MJ of bank energy. The 9.2 ms rise time 65 T mid-pulse requires a capacitor bank energy of 1.3 MJ which is comparable to the 1.4 MJ required by the 39.5 ms 50 T mid-pulse. The 100 T insert, $>$4.5 ms rise time, 54 T coil is estimated to require $\sim$2 MJ. Clearly the requirements for increased fields, and more time at field will continue to increase the demands for more bank energy.

Higher reliability at these energies will also require even better engineering, materials, and improved analysis. We must recognize that our present analytic models and design tools will require refinement to avoid divergence between theory and practice as we scale up to larger magnet systems [13], [14].

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