Recent Magnet Developments at the Pulsed Field Facility (NHMFL) at Los Alamos

Doan N. Nguyen, *Member, IEEE*, James R. Michel, *Senior Member, IEEE*, Scott B. Betts, Jason D. Lucero, Iain R. Dixon, *Senior Member, IEEE*, and Ke Han

***Abstract*—The National High Magnetic Field Laboratory (NHMFL) – Pulsed Field Facility (PFF) at Los Alamos operates ten pulsed magnet stations that deliver magnetic fields up to 100 Tesla for user experiments. In recent years, PFF has enhanced its capabilities with upgraded magnets, enabling the generation of higher magnetic fields and an increased number of pulses. This manuscript will provide an overview of recent magnet developments at the PFF, including the performance of new systems such as the 75-T duplex and 60-T Mid-pulsed magnets. Additionally, a novel cooling technique that significantly reduces cooling time without compromising magnet lifespan or stability will be discussed. Lastly, the maintenance and upgrades for our facility's signature magnet systems, including the 100-T multi-shot and 60-T controlled-waveform magnets will be covered.**

***Index Terms*—85-T duplex magnet, 100-T magnet, capacitor bank, fast-cooling magnet, pulsed magnets.**

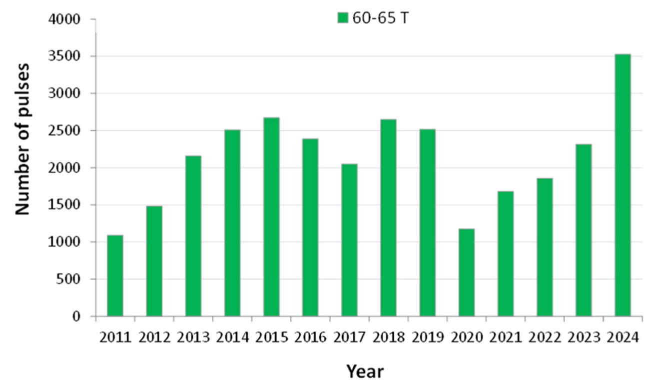

Fig. 1. Number of pulses greater than 60 Tesla delivered by 65 T workhorse magnets over the years.

I. Introduction

HIGH magnetic fields are vital tools for advancing scientific research across condensed matter physics, materials science, and related disciplines. By generating magnetic fields far beyond the limits of steady state magnets, pulsed magnets allow researchers to probe quantum phenomena, explore new phases of matter, and study complex electronic behaviors under extreme conditions [1], [2], [3], [4]. The Pulsed Field Facility (PFF) at Los Alamos National Laboratory (LANL), one of three campuses of the National High Magnetic Field laboratory (NHMFL), is one of the few leading facilities globally in this domain. For example, the Wuhan Pulsed Field Facility in China has developed and operates a wide range of pulsed magnets with varying pulse durations, providing magnetic fields of up to 95 T for user experiments [1]. Similarly, the Laboratoire National des Champs Magnétiques Intenses (LNCMI) in Toulouse, France, operates several types of non-destructive pulsed magnets capable of generating magnetic fields up to 98.8 T [2]. In Germany, the Dresden High Magnetic Field Laboratory (HLD) runs multiple magnet cells that deliver pulsed magnetic fields up to 96 T and is currently developing a triplex pulsed magnet expected to reach the 100 T level [3].

Financially sponsored by the US National Science Foundation, the PFF develops, builds and operates different types of pulsed magnets to nondestructively generate magnetic fields up to 100 T for users [5]. This paper reviews recent developments and performance of primary pulsed magnet systems and pulsed power infrastructure at PFF of the NHMFL.

II. Performance and Improvement of the Capacitor Driven Magnets

A. *Performance of the Capacitor Driven Magnets*

The PFF at LANL currently operates 16 kV–4 MJ and 18 kV–2.5 MJ capacitor banks (cap-bank) to power a variety of pulsed magnets. The five 65-T magnet cells continue to be heavily used, typically delivering approximately 8000 pulses annually, with around 2000 of those reaching 60 T or higher, as illustrated in Fig. 1. Operations were significantly impacted by the COVID-19 pandemic in 2020 and 2021, leading to a notable drop in pulse output. However, productivity has steadily returned to pre-pandemic levels over the past few years. In 2024, a new fast-cooling design (described in detail in Section II-B) was implemented, reducing the cooldown time between full-field pulses from 45 minutes to just 22–25 minutes, as shown in Fig. 2. Fig. 2 is a picture of a user monitor which shows the winding resistance of a 65 T magnet measured by simple 4-wire method. The average temperature of the magnet winding is predicted based on the measured resistance. As seen in Fig. 2, the magnet

Received 28 July 2025; revised 23 October 2025; accepted 16 November 2025. Date of publication 26 November 2025; date of current version 22 December 2025. This work was supported in part by Pulsed Field Facility (NHMFL), Los Alamos National Laboratory and PFF, in part by NSF under Grant DMR-1157490, and in part by DOE. *(Corresponding author: Doan N. Nguyen.)*

Doan N. Nguyen, James R. Michel, Scott B. Betts, and Jason D. Lucero are with the LANL, Los Alamos, NM 87544 USA (e-mail: doan@lanl.gov).

Iain R. Dixon and Ke Han are with the NHMFL, Tallahassee, FL 32310 USA.

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2025.3637789.

Digital Object Identifier 10.1109/TASC.2025.3637789

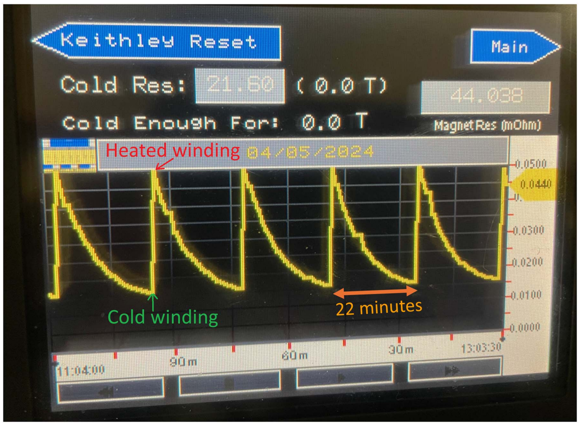

Fig. 2. Picture of the magnet resistance curve during operation of a 65-T magnet to indicate the cooling time between full-field shots is 22 minutes.

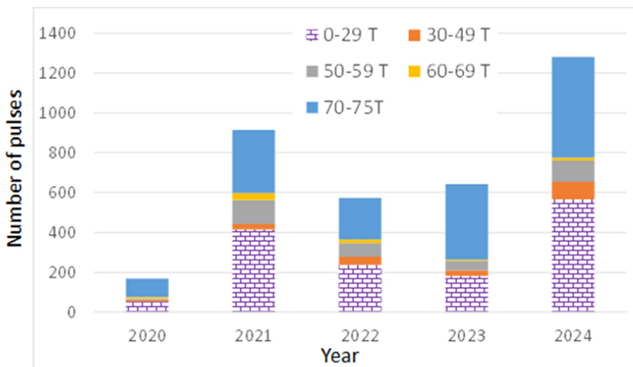

Fig. 3. Number of pulses delivered by the 75-T duplex magnet over the past few years.

resistance (or the winding temperature) vertically increases right after each full-field pulse, and it takes about 22 to 25 minutes to gradually reduce back to the base level (cold temperature). The improved cooling time, combined with the maintained magnet lifespan of approximately 1000 full-field pulses, resulted in a significant enhancement in overall performance: the 65 T magnets delivered approximately 3500 pulses at or above 60 T in 2024, representing a 50% increase over the average output of previous years.

Over the past five years, three new magnet systems have been designed and constructed at the PFF. Among them, the 75-T duplex magnet and its dedicated user cell were completed and successfully tested to 76.8 Tesla in late 2019 [6], [7]. Thanks to a newly developed fast-cooling design, the system achieves a cooling time of approximately 55 minutes for a full-field pulse. Since its commissioning, the magnet has been used extensively by the user community, as illustrated in Fig. 3. It has delivered over 1000 pulses in the 70 T to 75 T range, with demand increasing each year. Notably, in 2024 alone, the system provided approximately 440 full-field pulses to support user experiments.

Following the successful development of the 75-T duplex magnet, a new 60-T mid-pulse magnet was designed, constructed, and tested to its full field in 2021. This magnet was specifically developed to offer users access to magnetic fields

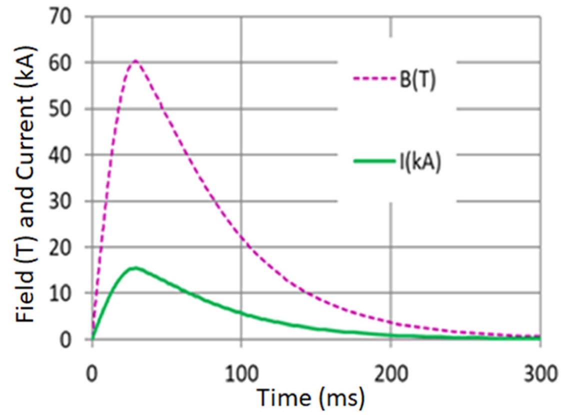

Fig. 4. Current and magnetic field profiles of the 60-T Mid-pulsed magnet.

up to 60 T with a significantly slower ramp rate. Its field profile is shown in Fig. 4. The pulse duration is approximately 300 ms, about five times longer than that of our standard 65 T workhorse magnets. The magnet draws 2.3 MJ from the 4-MJ capacitor bank and requires around 60 minutes to cool down between full-field shots.

To provide more options for users to access magnetic fields of 80 Tesla or higher, a new 85-T duplex magnet has been designed and fabricated. The inner coil of the magnet is driven by the 18 kV–2.5 MJ cap-bank and the outer coil is powered by the 16 kV–4 MJ cap-bank. The magnet requires about 5.3 MJ to reach the full magnetic field. More details on the technical design, specifications and risk mitigation approaches for that magnet can be found in [8]. The magnet and its dedicated user cell were completed and are in commissioning process. The magnet should be available for users in early 2026.

B. New Fast Cooling Design At PFF

Capacitor-driven magnets at the PFF-NHMFL are typically composed of two concentric coils, an inner and an outer coil. For mechanical robustness and simplified fabrication, the outer coil is usually wound directly on top of the inner coil. However, this configuration often results in a long cooling time between full-field pulses [5]. To address this limitation, an initial improvement involved embedding copper wires along the surface of the inner coil to enhance heat dissipation. This simple but effective method reduced the cooling time of the 65 T magnets from approximately 120 minutes to 50 minutes, without requiring significant modifications to the magnet design or fabrication tooling [5].

More recently, the magnet structure was comprehensively redesigned to further improve thermal performance. This new design - originally developed for the 75-T duplex and 60-T mid-pulse magnets - has now been implemented in the 65-T workhorse magnets. In the updated structure, the two component coils are wound separately and assembled with a 1.5 mm gap between them (Fig. 5). Liquid nitrogen flows through this cooling gap via vent holes located in the top and bottom

G10 flanges (Fig. 5), enabling more efficient heat removal from the windings. As a result, the cooling time was further

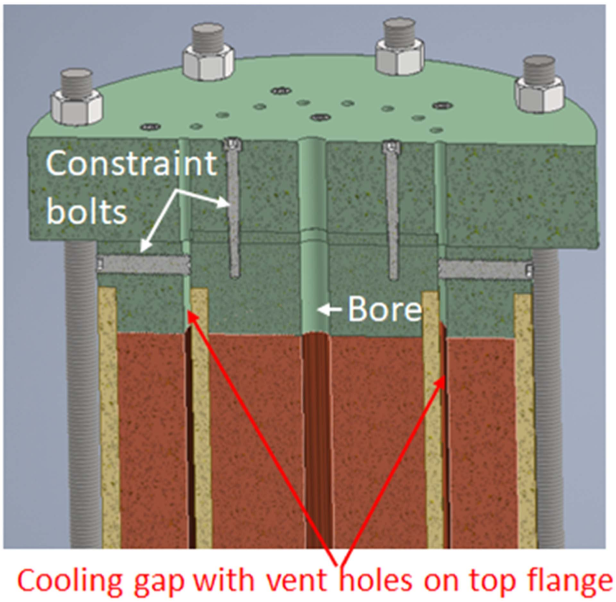

Fig. 5. Structure of a typical capacitor driven magnet with cooling gap.

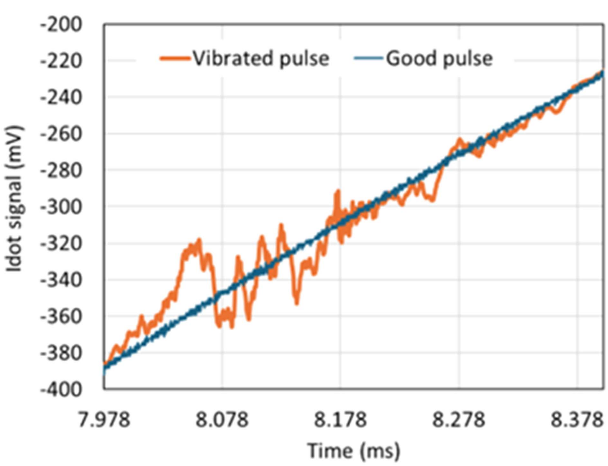

Fig. 6. Zoomed-in Idot signals for stable pulse (blue, smooth trace) and a vibrated pulse (noisy orange trace).

reduced to just 22–25 minutes (Fig. 2), effectively doubling the pulse delivery rate.

Beyond thermal efficiency, the new design also offers a significant cost advantage. In the new design, the inner and outer coils are wounded separately and installed in the magnet assembly with a cooling gap between them. Thus, when one of those coils fails during the operation, the other undamaged coil can be reused to build another magnet. This approach substantially reduces the overall cost of magnet construction for the user program. However, the introduction of a cooling gap has also introduced challenges, particularly increased magnet vibration. Fig. 6 shows zoomed-in *dI/dt* (Idot) traces comparing a smooth, stable pulse (blue curve) with a pulse affected by vibration (orange curve). The low-frequency noise in the orange trace is caused by mechanical movement between the coils during pulsing. These vibrations alter the magnet's inductance matrix, causing noisy Idot and *dB/dt* (Bdot) signals. The vibration is

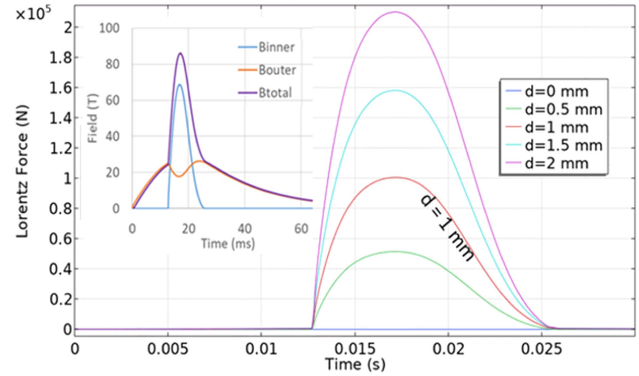

Fig. 7. Magnetic field profiles for the inner and outer coils of the 85-T duplex magnet (insert) and the force profiles for different values of field center offset *d*.

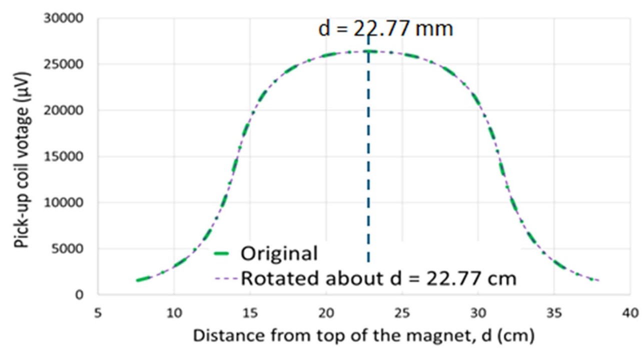

Fig. 8. Field profile along the bore of a magnet coil (green) and the curve created by rotating the original curve through the field center (purple).

therefore problematic for not only magneto-optic experiments but also electromagnetic measurements and should be mitigated.

The root cause of the vibration is an axial offset between the field centers of the two coils. When misaligned, magnetic forces attempt to realign the field centers, producing strong, transient forces which are the vector sum of Lorentz forces acting on the winding of component coils during a pulse. Those forces can be calculated easily from the distribution of magnetic field and current inside the magnet. For example, with the field profiles of component coils of the 85-T duplex magnet shown in the insert of Fig. 7, the resulting force profiles are shown in Fig. 7 for various field center offsets *d*. More details on the design and electromagnetic modeling of 85-T duplex magnet can be found in [8]. When $d = 0$ mm, the net axial force is zero as expected. However, a 1 mm offset results in a 12 ms shockwave with a peak force of approximately 100 kN on each coil, causing significant mechanical vibration. The magnitude of this shockwave is nearly proportional to the offset *d*.

To mitigate these effects, precise alignment of the component coils' field centers during assembly is essential. First, the axial magnetic field profile along the coil bore is measured (green curve in Fig. 8). A custom software tool is used to determine the coil's magnetic center by identifying the point about which the field profile is symmetric. This means rotating magnetic field profile about that point must create a new curve (purple curve) that is well superimposed to the original curve as shown in Fig. 8. This method identified the field center at $d = 22.77$ mm from the top of the coil, with an error margin of just ± 0.1 mm.

A strong yet flexible mechanical structure was also developed to enable precise alignment. Adjustable spacers (Fig. 5) allow fine-tuning of the inner coil position during assembly. The inner coil is securely mounted using constraint bolts from the sides, top, and bottom (Fig. 5), ensuring tight structural integration and correct alignment. With these improvements in design, alignment, and structural support, magnet vibrations were significantly reduced. As a result, magnets using the new cooling-gap design now deliver high-quality, low-noise magnetic fields that meet the demands of advanced scientific experiments.

III. New 30 kV Capacitor Bank and the Future Low Energy 85T Duplex Magnets

Our signature 100-T multi-shot (MS) magnet system consists of two key components: an outsert magnet driven by a generator to produce a 40-T background field, and an insert coil powered by a capacitor bank to contribute an additional 60 T [9], [10]. The outsert system comprises of seven large magnet coils, which are both expensive and time-consuming to construct. As such, it is engineered with a large safety margin and designed for long-term durability, with an expected operational life of 10 years or more.

In contrast, the insert coil is smaller, less costly, and quicker to build and replace. It is intentionally designed with a limited lifespan to maximize magnetic field strength for users. Crucially, the insert must operate with a manageable and containable amount of energy to ensure that any failure is fully contained and does not damage the outsert's high-energy, high-value coils. Therefore, developing high-field insert magnets that require less energy is a key strategy for advancing the ultra-high field frontier beyond the 100 Tesla level. This can be achieved by increasing the ramp rate of the magnet, which reduces the heating during pulsing and therefore allows higher current density to generate higher fields in with smaller magnet size and reduces energy input. The voltage required to drive a magnet coil is proportional to the time derivative of current. Thus, faster ramping magnets will require higher driving voltage. To support this approach, a new 30 kV–1.2 MJ cap-bank was recently designed and constructed to upgrade the facility's power infrastructure. The new 30-kV cap-bank features a modular design consisting of two identical units. These modules can operate independently or in parallel when the full energy is required.

To demonstrate this strategy, we have preliminarily designed a new 85-T duplex magnet using the new 30-kV cap-bank. The new design targets the same stress level as the existing 85-T duplex magnet to ensure structural safety and reliability. Details of the design and specifications of the current 85-T duplex magnet can be found in [8]. Table I provides a detailed comparison of the design and specifications for the two 85-T duplex magnets. Fig. 9 compares the von Mises stress distributions at the mid-plane of both magnets: the current system (top) and the new design using 30-kV cap-bank (bottom). As seen in Fig. 9, both designs reach the same peak stress of approximately 2600 MPa as targeted.

As seen in Table I, the outer coils in both designs utilize the same amount of energy. However, key differences arise in the inner coils. In the existing design, the inner coil operates at 15.6 kV and requires 1.9 MJ of energy. In the new design, by increasing the voltage to 27.7 kV, the required energy drops to just 1.01 MJ (nearly half). This is achieved by increasing the ramp rate to 45 T/ms, roughly three times faster than that of the current design. Importantly, while 45 T/ms is a considerable increase, it remains 3 to 6 orders of magnitude slower than the ramp rates used in single-turn or flux-compression magnets, the only currently available technologies capable of exceeding 100 T. Based on user community feedback, the fast-ramping option enabled by high-voltage cap-banks is seen as highly valuable for a broad range of experiments. This approach represents a critical step forward in building practical ultra-high-field magnets and promises to be a transformative tool for megagauss science.

TABLE I
Specifications of the Present and Future 85-T Duplex Magnet

	Present 85T Duplex	R&D 85T Duplex
Power supplier for A coils	100T bank at 15.6 kV	New 30kV bank at 27.7 kV
Power supplier for B coils	8 modules at 14 kV	8 modules at 14 kV
Winding for A coil	8 layers of CuNb wire	6 layers of CuNb wire
Winding for B coil	6 layers of CuCrZr wire	6 layers of CuCrZr wire
Maximum total energy	5 MJ	4.1 MJ
Energy of inner (A) coil	1.9 MJ	1.02 MJ
Peak training field	86T	86T
Max. ramp rate	15 T/ms	45T/ms
Bore size	10.5 mm	10.5 mm

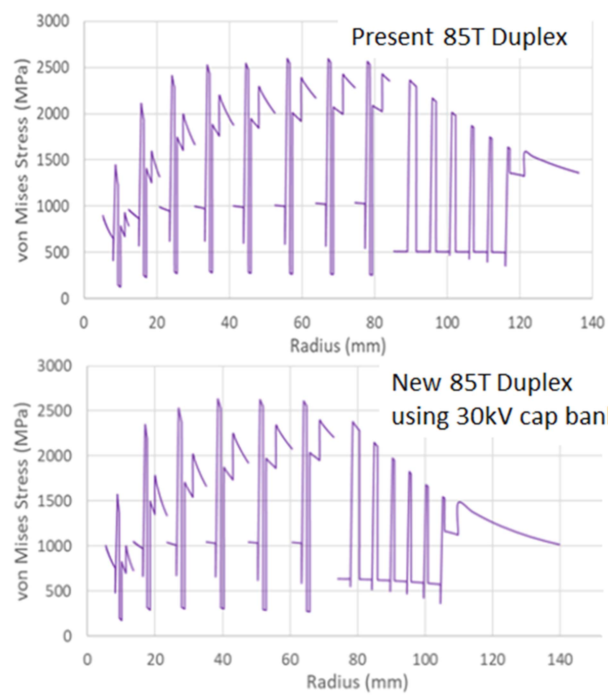

Fig. 9. Mid-plane von Mises stress along the radial direction for the present 85 T duplex magnet (top) and the new 85 T duplex magnet.

IV. Updates on Generator and Large Magnet Systems

A. *New Rotor for 1.4-GW Generator*

The 1.4-GW generator has been an invaluable asset for powering the unique 100-T multi-shot (MS) and 60-T Controlled-waveform (CW) magnets at our facility [10], [11], [12]. In 2019, the generator's rotor sustained damage during an operation

Fig. 10. New rotor for the 1.4-GW generator.

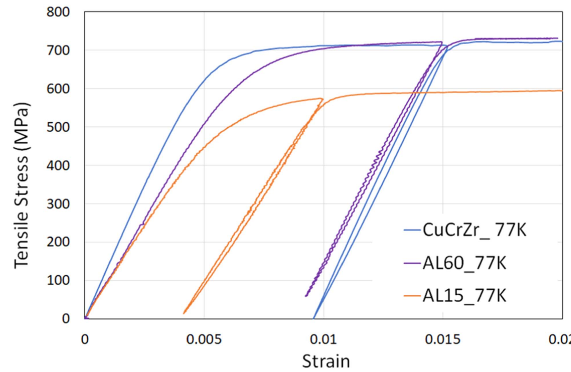

Fig. 11. Typical stress-strain curves of CuCrZr, Al60, and Al15 obtained at 77 K.

supporting the 100-T MS magnet. In response, LANL committed approximately $25 million to replace the damaged rotor. The fabrication of the new rotor consisting of a 25-meter-long magnetic steel body and its winding (Fig. 10) is now nearly completed and is in the process of acceptance testing. Installation of the rotor in our generator is scheduled for the fourth quarter of 2025, with commissioning planned for the first half of 2026.

B. Redesigning and Manufacturing Coils for Large Magnet Systems

During the generator's offline period, the NHMFL took the opportunity to redesign and fabricate several large coils for both the 60-T CW magnet and the outsert system of the 100-T MS magnet. These large coils are typically wound with either Glidcop AL-60 or Glidcop AL-15 conductors [10], [11], [12], [13]. However, Glidcop, an alumina-particle-strengthened copper alloy, poses significant challenges for large-scale, high-quality production [14]. The products we received contained large particles that led to stress concentration, leading to internal defects during the wire-drawing process. Additionally, inclusions introduced during extrusion and drawing compromised the wire surface integrity and may have triggered fractures during magnet operation.

To address these limitations, the NHMFL, in collaboration with industrial partners, recently developed and successfully produced long-length, large cross-section CuCrZr (Copper-Chromium-Zirconium) wires as a replacement for Glidcop in large magnet coils [15]. CuCrZr offers several key advantages. While its mechanical and electrical properties are comparable to Glidcop AL-60, CuCrZr material, for example, delivers five times higher production yield, making it a far more economical choice. Moreover, CuCrZr wires have been produced in single lengths greater than 600 meters, eliminating the need for brazed joints between layers, an important improvement for large coils in the 100-T outsert and 60-T CW systems. This, combined with more uniform quality along the wire length, simplified the winding process and enhanced the mechanical strength of the finished coils.

Fig. 11 shows the stress-strain curves at 77 K for typical CuCrZr, AL-60, and AL-15 conductors. As seen, CuCrZr and AL-60 wires have nearly identical ultimate tensile strengths (UTS) of approximately 720 MPa, which is roughly 20% higher than AL-15 counterpart. In terms of electrical conductivity, CuCrZr and AL-60 wires also perform similarly and exhibit slightly less conductive than AL-15 conductor. A more detailed comparison of these conductors is provided in [15]. In summary, CuCrZr conductors can match the performance of AL-60 and may even offer improved performance when replacing AL-15 in certain applications. In addition to adopting better conductor materials, the coils were also structurally redesigned to incorporate stronger reinforcing shells, as reported in [16]. By partially replacing the Nitronic-40 metal shell [17] with Zylon fibers [18], hoop stresses were significantly reduced, while the remaining metal shell retained sufficient strength to withstand axial loads. Multi-cycle simulations confirmed that this reinforced design would greatly reduce plastic deformation in the coils, thereby extending their operational lifetime [16].

The redesigned coils with CuCrZr conductors and enhanced reinforcing shells were wound and epoxy-impregnated in the large-coil winding facility at the NHMFL in Tallahassee. Final reinforcement was completed at the magnet fabrication shop at LANL's PFF. For hoop reinforcement, 3270 Dtex High Modulus (HM) Zylon fibers were wet wound onto the metal shells. To compensate for Zylon's negative thermal expansion and to increase packing density, the fiber was wound under 800 MPa pre-tension.

V. Conclusion

The Pulsed Field Facility (PFF) at Los Alamos National Laboratory (LANL) has made significant advancements in capacitor-driven magnet systems and power infrastructure, supporting the growing needs of the user community. Key additions in recent years include a 75-T duplex magnet and a 60-T mid-pulse magnet, offering user access to pulsed magnetic fields of higher amplitude or longer pulse length. The newly developed 85-T duplex magnet is in the final process of commissioning and will be available for users in late 2025.

A new structural design in the capacitor driven magnets introduced a 1.5 mm cooling gap between magnet coils, dramatically reducing cooldown time and allowing coil reuse. While this improved efficiency and cost-effectiveness, it also introduced challenges like mechanical vibration, which can degrade experimental data. The issue is mitigated through precise field-center alignment and adjustable mechanical assembly.

A new 30 kV–1.2 MJ cap-bank will enable PFF to develop high field, low energy insert magnets, paving a cost-effective and reliable way to develop magnets to go beyond 100 T.

A critical 1.4-GW generator, damaged in 2019, is undergoing a $25 M rotor replacement, with installation set for late 2025 and commissioning in 2026. During the downtime, LANL and NHMFL redesigned and manufactured large coils for the 60-T CW and 100-T MS systems. The coils of these magnets were redesigned and rebuilt using high-performance CuCrZr conductors and enhanced reinforcing shells, which combine Nitronic-40 metal and high-strength Zylon composite to better withstand both radial and axial loads.

Acknowledgment

The authors would like to express gratitude to Todd Adkins for helping in building large magnet coils, to Rongmei Niu and Vince Toplosky of NHMFL for procurement and testing magnet conductors.

References

[1] T. Peng et al., "Design and performance of the first dual coil magnet at the WHMFC," *J. Low Temp. Phys.*, vol. 170, no. 5, pp. 463–468, 2013.

[2] J. Béard et al., "Design and tests of the 100-T triple coil at LNCMI," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018, Art. no. 4300305.

[3] T. Moraine et al., "Renewal of the nondestructive pulsed magnetic fields generators of the LNCMI," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4300305.

[4] S. Zherlitsyn et al., "Coil design for non-destructive pulsed-field magnets targeting 100 T," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 1660–1663, Jun. 2006.

[5] D. N. Nguyen, J. Michel, and C. H. Mielke, "Status and development of pulsed magnets at the NHMFL pulsed field facility," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 4300905.

[6] J. R. Michel, D. N. Nguyen, and J. D. Lucero, "Design, construction, and operation of new duplex magnet at pulsed field facility-NHMFL," *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, Jun. 2020, Art. no. 0500105.

[7] Q. V. M. Nguyen, L. Torres, and D. N. Nguyen, "Electromagnetic interaction between the component coils of multiplex magnets," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018, Art. no. 4300804.

[8] J. R. Michel, S. B. Betts, J. D. Lucero, A. Bhardwaj, L. N. Nguyen, and D. N. Nguyen, "Design and construction of the new 85T duplex magnet at NHMFL-Los Alamos," *IEEE Trans. Appl. Supercond.*, vol. 34, no. 5, Aug. 2024, Art. no. 4900305.

[9] C. A. Swenson et al., "Pulse magnet development program at NHMFL," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 1233–1236, Jun. 2004.

[10] J. R. Sims, D. G. Rickel, C. A. Swenson, J. B. Schillig, G. W. Ellis, and C. N. Ammerman, "Assembly, commissioning, and operation of the NHMFL 100 Tesla multi-pulse magnet system," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 587–591, Jun. 2008.

[11] J. R. Sims et al., "The U.S. NHMFL 60 T long pulse magnet," *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 480–483, Mar. 2002.

[12] J. Schillig et al., "Operating experience of the United States national high magnetic field laboratory 60 T long pulse magnet," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 526–529, Mar. 2000.

[13] K. Han et al., "Material issues in the 100 T non-destructive magnet," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 1277–1280, Mar. 2000.

[14] J. Lu, T. Adkins, I. Dixon, D. Nguyen, and K. Han, "Nondestructive testing of high strength conductors for high field pulsed magnets," *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, Jun. 2020, Art. no. 6900405.

[15] R. Niu, V. Toplosky, and K. Han, "Cryogenic temperature properties and secondary phase characterization of CuCrZr composites," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4300405.

[16] D. N. Nguyen, D. T. Vo, J. R. Michel, I. Dixon, T. Akins, and K. Han, "Re-design of the coils for the 60t controlled-waveform magnet at NHMFL," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4300504.

[17] K. Han, R. Goddard, R. Niu, Y. Xin, and V. Toplosky, "Characterization of nitronic-40 stainless steel shells," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, Aug. 2021, Art. no. 7800105.

[18] R. P. Walsh and C. A. Swenson, "Mechanical properties of zylon/epoxy composite at 295K and 77 K," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 1761–1764, Jun. 2006.