Experimental Study on Online Whole Machine Demagnetization of High-Q SHINE Modules

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Abstract

Cryomodules are key systems in SHINE. To achieve a high quality factor Q0 for the superconducting cavities in cryomodules, it is essential to provide a weak magnetic field operating environment. Efficient magnetic shielding for superconducting cavities effectively shields against background magnetic fields; excessive background magnetic fields significantly reduce the effectiveness of cryogenic Permalloy magnetic shielding. During manufacturing, installation, integration, testing, and transportation, cryomodules acquire residual magnetic fields B of varying degrees, necessitating online whole machine precision demagnetization of the entire cryomodule to reduce the background magnetic field for magnetic shielding. Taking the SHINE cryomodule as an example, this paper presents the procedure and experimental results. The study shows that after online demagnetization of the entire SHINE module, the magnetic field B inside the superconducting cavity is less than 1.0 mGs when the superconducting cavity Q0 reaches 2.7 × 1010 to 5.3 × 1010. These results provide a reference for the demagnetization of cryomodules in similar free-electron laser facilities worldwide.

Full Text

Preamble

Experimental Study on Online Whole Machine Demagnetization of High-Q SHINE Modules

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Cryomodules are critical systems in SHINE. To achieve a high quality factor Q_0 for the superconducting cavities within cryomodules, it is essential to provide a weak magnetic field operating environment. While efficient magnetic shielding for superconducting cavities effectively mitigates background magnetic fields, excessive ambient fields significantly compromise the performance of cryogenic Permalloy magnetic shielding.

During manufacturing, installation, integration, testing, and transportation, cryomodules acquire residual magnetic fields of varying magnitudes, necessitating online whole-machine precision demagnetization to reduce the background field and optimize magnetic shielding effectiveness. Using the SHINE cryomodule as a case study, this paper presents the demagnetization procedure and experimental results. The study demonstrates that after online demagnetization of a complete SHINE module, the magnetic field B inside the superconducting cavities is reduced to less than 1.0 mGs when the superconducting cavity Q_0 reaches 2.7×10^{10} to 5.3×10^{10}. These results provide a valuable reference for demagnetization protocols in similar free-electron laser facilities worldwide.

Keywords: cryomodule, whole machine demagnetization, weak magnetic field, quality factor Q_0

Introduction

The Shanghai High-repetition-rate XFEL and Extreme Light Facility (SHINE) is designed to operate 75 large-scale cryogenic superconducting accelerator modules incorporating 600 standard 1.3 GHz nine-cell elliptical superconducting cavities [1-5]. Achieving the design quality factor Q_0 of 2.70×10^{10} at 16 MV/m for these cavities—while reducing thermal load on the SHINE cryogenic system and minimizing costs in construction, equipment development, integration testing, and operational maintenance—requires a weak magnetic field operating environment [6–8]. Lower residual magnetic flux density B (hereafter referred to as residual magnetic field B) inside the superconducting cavities directly correlates with higher Q_0 values [9–11]. Previous studies indicate that when the residual magnetic field B inside the cavity is reduced to approximately 3.00 mGs, the cavity Q_0 reaches 2.7×10^{10}; further reduction of B to 0.50 mGs enables Q_0 to approach 4.0×10^{10} [12–14].

According to the SHINE high-Q module full-machine online demagnetization technical standard, after online demagnetization of a standard 1.3 GHz module, the magnetic field readings from two fluxgate probes located between the magnetic shielding layers must satisfy the following requirements:

1. At the ground-level horizontal test position, the average absolute value from the two fluxgate probes shall be below 0.60 mGs.
2. At the underground tunnel operation position, the average absolute value shall be below 1.00 mGs.

The weak magnetic field environment required for superconducting cavities critically depends on magnetic shielding effectiveness. Such shielding is typically constructed from high-permeability materials—often formed into geometric shapes such as spherical rings, frames, or cylinders—to divert ambient magnetic field lines and establish a magnetically clean background, as illustrated in Fig. 1 Figure 1: see original paper. The fundamental principle of low-frequency static magnetic shielding employs high-permeability materials such as pure iron, silicon steel, and Permalloy to provide a low-reluctance path for interfering magnetic fields, thereby substantially reducing the residual field in the equipment' s working volume [15, 16]. Based on static magnetic shielding principles, two key conclusions emerge: First, the greater the permeability µ of the ferromagnetic material and the larger the cross-sectional area S of the magnetic shield, the lower the magnetic reluctance R of the magnetic circuit, which results in a greater fraction of magnetic flux Φ being confined within the shielding material and significantly reduces leakage flux in the air. Second, magnetic shields made of soft magnetic materials should avoid openings or gaps oriented perpendicular to the magnetic field lines, as such gaps force field lines to traverse air, increasing magnetic reluctance and degrading shielding effectiveness.

The permeability µ of cryogenic Permalloy used in superconducting cavity magnetic shielding exhibits strong dependence on the background magnetic field H. Experimental characterization demonstrates that optimal shielding performance is achieved when the background field is maintained in the range of 0–50 mGs (see Fig. 1(b)), where the material retains high permeability. Consequently, establishing a weak magnetic environment (low H) that matches the permeability characteristics (µ) becomes essential for maximizing shielding effectiveness. This relationship reveals that the magnetic shield surrounding the superconducting cavity alone provides insufficient protection against stronger ambient fields. Therefore, creating a further reduced magnetic field environment external to the shield itself is necessary to establish the fundamental conditions required for achieving high shielding performance [17, 18].

The background magnetic field environment surrounding the superconducting cavity magnetic shielding is influenced by several key factors:

Inherent geomagnetic field orientation: The overall module orientation creates directional dependence in the background field, with east–west orientation exhibiting significantly lower field strength compared to north–south direction. SHINE cryomodules are aligned east–west at the ground-level test station but oriented north–south during underground tunnel installation and operation.

Magnetic shielding design: The 1.3 GHz cryomodule employs a double-layer magnetic shield exterior to the helium vessel, constructed from Chinese-developed cryogenic permalloy 1JL0. This material achieves a relative permeability $\mu > 30{,}000$ at temperatures ≤ 77 K, with a sheet thickness of 1.3 mm.

Building magnetic shielding effectiveness: The magnetic shielding performance of test facilities varies significantly. In Hall 1 of the SHINE ground test station, two test stations provide moderate shielding, maintaining an axial background field of 150–250 mGs. Hall 2 test stations offer poorer shielding, with axial fields of 250–350 mGs. The underground north-south tunnel, constructed with reinforced concrete, exhibits the highest background field of 400–550 mGs at module installation positions.

Magnetic hygiene control: Strict magnetic hygiene protocols were implemented throughout manufacturing, assembly, and testing. All components within 100 mm of superconducting cavities (including couplers, tuners, flanges, and bellows) were fabricated from non-magnetic materials (316 stainless steel, titanium alloy, or aluminum alloy) with permeability μ < 1.1 and remanent field < 1 Gs. Assembly tools and fixtures were controlled to < 2.5 Gs remanent field, with mandatory demagnetization when exceeded. The vertical test background for bare cavities was maintained below 2.0 mGs [19, 20].

Whole machine demagnetization precision: Despite strict magnetic control during cryostat installation, subsequent processes (integration, debugging, welding, and conditioning) introduce magnetization. Online whole machine demagnetization is therefore essential to reduce the cryostat' s background field environment [21–23].

The alternating current (AC) demagnetization method employs a gradually decaying AC current to eliminate residual magnetism in ferromagnetic materials. As the current amplitude decreases cyclically, the material' s hysteretic behavior drives magnetic domains through progressively smaller B-H loops, effectively reducing the remanent field to near zero when the current approaches zero [24, 25]. This well-established technique has found extensive application in engineering domains including ship degaussing and pipeline demagnetization [26, 27]. Significant advancements in superconducting cryomodule demagnetization have been achieved internationally. For the IFMIF project, CEA-Saclay implemented a comprehensive magnetic hygiene strategy involving replacement of magnetic components with non-magnetic alternatives and offline demagnetization of susceptible components to minimize internal magnetic fields [28]. At FRIB, validation of the local magnetic shielding scheme demonstrated attenuation of the cavity wall field below 15 mGs while achieving cost reduction through material optimization. Their research further established that controlled cooldown conditions eliminate the need for additional demagnetization after solenoid excitation cycles [29]. Fermilab researchers have developed a systematic theoretical framework for whole machine demagnetization and successfully implemented it on LCLS-II cryomodules, achieving residual fields below 2 mGs [30, 31]. In China, research at Beihang University has focused on low-frequency demagnetization techniques for magnetic shielding rooms, resulting in proposed methods for estimating shielding coefficients and residual magnetism [32–34]. However, systematic investigation of whole machine demagnetization for large-scale accelerator superconducting modules remains underdeveloped domestically. Bridging this technological gap is essential for achieving world-leading performance in superconducting accelerator module technology. This paper presents experimental results from online whole machine demagnetization of high-Q modules and multiple engineering cryomodules, demonstrating the creation of ultra-low magnetic field environments necessary for optimal superconducting cavity performance.

II. Experimental Method

The demagnetization of the SHINE cryomodule essentially involves demagnetizing the vacuum cryostat [35, 36]. Components such as the tuner, coupler, flange, and support pieces around the superconducting cavities inside the module cannot have their residual magnetic fields reduced through whole-module demagnetization [37, 38]. As previously described, these components can only be managed through material selection and individual component demagnetization. Therefore, the demagnetization system and process for the entire module are almost identical to those for the cryostat. The SHINE module whole machine demagnetization uses the demagnetization system IPS-403E jointly developed with Hunan United Information Security Technology Co., Ltd. The demagnetization system for the whole module consists of two parts: the demagnetization power supply system and the load coil system. The demagnetization power supply system has a total power of about 33 kW, with a demagnetization output current ranging from 6.5 mA to 130 A and a demagnetization frequency of 0.1–1.0 Hz. The switching frequency is switchable between 5 kHz and 10 kHz. It includes an industrial computer, a low-frequency power supply, and a resistor box.

The load coil system has a total length of about 1300 m and a total resistance of about 2.0 Ω when connected in series. It uses 12 mm^2 lightweight, high-temperature, and radiation-resistant cables. It includes a 100-turn coil at the module end, 20 groups of coils in the middle (10 turns per group), and output/input leads.

During the SHINE module whole-machine demagnetization process, operations such as vacuum pumping, heating, RF conditioning, and welding—all of which can interfere with demagnetization to varying degrees—must be avoided [39-41]. The Q_0 values of individual or groups of eight superconducting cavities are measured before and after demagnetization using the flowmeter-small range method, and the results are compared with vertical test data. The physical setup of the SHINE cryomodule prepared for demagnetization is shown in Fig. 2 Figure 2: see original paper. To monitor magnetic field transients and final demagnetization results during online demagnetization of the SHINE high-Q module, 13 Bartington Instruments fluxgate probes were installed at strategic positions inside the module [42, 43], as illustrated in Fig. 2(b). The fluxgate probes were distributed as follows: CH1, CH12, and CH2 were placed between the two magnetic shielding layers outside the titanium jackets of the first, fourth, and fifth cavities, respectively; CH4 was mounted horizontally atop Cell 5 of Cavity 1; in Cavity 4, CH6 and CH7 were installed at a 45° angle on top of Cell 9 and Cell 1, respectively, while CH13 and CH14 were positioned vertically along the axis at the bottom of Cell 9 and Cell 1; for Cavity 5, CH8 was placed at a 45° angle on Cell 9, with CH9 arranged vertically at the bottom of the same cell; finally, in Cavity 8, CH10 and CH11 were both oriented at 45° on Cell 9 and Cell 1, respectively, and CH15 was mounted vertically on top of Cell 9. To capture more extreme field conditions in this experiment, all internal fluxgate probes except CH4 were located at both ends of the magnetic shield—regions identified by simulation as having the strongest magnetic field. Simulation results indicate that if the field at the shield ends meets expectations, the field uniformity in the central region will be even more favorable. Similarly, for the engineering module tests, two Bartington fluxgate probes were installed between the two magnetic shielding layers outside the titanium jackets of the first and fifth cavities to monitor field variations and demagnetization effectiveness during online operation.

Unlike demagnetization of cryomodules under well-insulated and isolated conditions, the online whole-machine demagnetization of the entire SHINE module—in both the horizontal test station and underground installation states—requires numerous signal cables for data acquisition. Additionally, the conductive and magnetic support platform lacks insulation design, resulting in extensive leakage currents at test and installation sites. These leakage currents cause unpredictable interference during the demagnetization process. Theoretically, disconnecting the leakage current grounding path before demagnetization could prevent demagnetization interruption. However, this approach is impractical in operation, as it would compromise the safety of the module, equipment, and personnel. In early 2024, online demagnetization of the SHINE high-Q prototype module used a non-timed balance mode, which frequently triggered leakage current protection, causing unexpected interruptions. This mode proved unsuitable for general cryomodule demagnetization. To address this, subsequent demagnetization adopted two alternative modes—timed exponential decay (TED) and timed linear decay (TLD)—that are less likely to trigger protection. The low-frequency power supply switching frequency was also reduced to minimize interruptions.

The TED mode current waveform follows:

$$I_t = I_a \left(K^{2f}\right)^{\left(t-\frac{1}{\sin(2\pi f t)}\right)} + I_{dc}$$

where I_t is the real-time current, I_a is the amplitude of the initial peak current, K is the decay coefficient (fixed at 0.95 in this mode), and I_{dc} is the DC offset. The output termination condition is met when the total operating time reaches the preset duration T.

The current waveform of TLD mode is determined by the following equation:

$$I_t = I_a \left(\frac{t}{\text{[equation incomplete in original]}}\right) - \frac{1}{\sin(2\pi f t)} + I_{dc}$$

The current waveforms for the TED and TLD modes during SHINE high-Q module demagnetization are shown in Fig. 3 Figure 3: see original paper and Fig.

3(b), respectively. The corresponding magnetic field waveforms measured by two fluxgate probes located outside the superconducting cavity are presented in Fig. 3(c). Analysis of these waveforms reveals distinct decay characteristics: in the TED mode, both current and magnetic field exhibit a sharp exponential decay after reaching the initial peak, whereas in the TLD mode, they demonstrate a gradual linear decay following the initial maximum.

During Q_0 testing of the cryomodule, the cooldown procedure was executed as follows. The system was first cooled from 300 K to 160 K at a controlled rate of 4–7 K/h. Subsequently, the temperature was further reduced to 45 K at a rate of 10–20 K/h. A 12-hour holding period was implemented at 45 K to ensure temperature stabilization. Following this, a rapid cooldown phase with a rate \$ \$10 K/min was initiated to reach 4.5 K. Finally, the saturated helium vapor pressure was reduced to 31 mbar to establish the operational state of superfluid helium at 2 K.

The accelerating gradient E_{acc} of the superconducting cavity is determined by the following equation:

$$E_{acc} = \sqrt{\frac{r/Q \cdot Q_t \cdot P_t}{L_{eff}}}$$

where L_{eff} refers to the effective accelerating length of the cavity, r/Q denotes the shunt impedance, Q_t is the quality factor derived from the pick-up probe, and P_t is the power measured at the pick-up port. The accelerating gradient E_{acc} can be calculated following the calibration of Q_t and the measurement of P_t. A direct comparison of the intrinsic quality factor Q_0 between vertical and horizontal tests is ensured by evaluating them at an identical E_{acc}.

III. Experimental Results

Table 1 summarizes the demagnetization status of the SHINE high-Q prototype module across different workstations at the installation and test site, including position, demagnetization current, temperature, and orientation. Fig. 4 [Figure 4: see original paper] shows the magnetic field measurements inside and outside the superconducting cavities before and after demagnetization of the prototype module. For the three external fluxgate probes (CH1, CH12, CH2) at the Hall 1 test station, the magnetic fields before 60 A demagnetization were 0.51 mGs, 2.76 mGs, and 7.59 mGs, respectively. After demagnetization, these values decreased to 0.14 mGs, −0.43 mGs, and −1.09 mGs. After cooling the module to 2.0 K, the fields increased slightly but remained lower than the pre-demagnetization levels. When the module was moved to a north-south orientation in Hall 1, the magnetic fields at these probes increased significantly, except for CH1 which provided faulty data. Relocating the module to an east-west position away from the Hall 1 test station reduced the fields compared to the north-south orientation; however, due to environmental field differences from the position change, they remained higher than immediately after demagnetization. Moving the module from ground to the north-south oriented underground tunnel again increased the fields significantly, though demagnetization again reduced them. Finally, after moving the module from the underground tunnel to a ground-level east-west position, the magnetic fields decreased dramatically following demagnetization, showing a substantial difference compared to pre-demagnetization values.

For the ten internal fluxgate probes at the Hall 1 test station, the magnetic fields measured at CH6, CH7, and CH15 exceeded 5.0 mGs prior to demagnetization at 60 A. After demagnetization, these values decreased to -1.16 mGs, 0.22 mGs, and 0.14 mGs, respectively, with the remaining probes also exhibiting reduced field levels. Following cooldown to 2 K, the magnetic fields experienced a slight overall increase but remained below pre-demagnetization values. When the module was reoriented to a north-south alignment within Hall 1, nearly all probes showed a significant increase in magnetic field strength. Subsequent relocation of the module to an east-west position away from the Hall 1 test station resulted in lower field readings relative to the north-south orientation; however, due to differences in the ambient magnetic environment, field levels remained elevated compared to the immediately post-demagnetized state. Transferring the module from ground level to the north-south oriented underground tunnel again produced a substantial field increase across most probes. Although demagnetization at 75 A again reduced field strengths, certain probes continued to register fields exceeding 5.0 mGs. Finally, after moving the module from the underground tunnel to an east-west ground-level position and performing 75 A demagnetization, internal magnetic fields decreased dramatically, with all cavity-internal fluxgate probes measuring below 1.0 mGs. These results confirm the efficacy of the demagnetization process in reducing magnetic fields both inside and outside the superconducting cavities, successfully establishing the required weak-field environment for the SHINE high-Q module.

From these results, several key observations emerge: (1) Full-module demagnetization significantly influences magnetic fields both inside and outside the cavities. Importantly, the module should not be relocated after demagnetization, as substantial variations in the ambient background field can compromise the demagnetization effect. (2) Temperature reduction following demagnetization induces non-equilibrium thermal currents and related effects, resulting in a slight increase in the magnetic field. (3) Overall demagnetization efficacy is strongly correlated with module orientation. For identical demagnetization currents and process parameters, the north-south orientation—characterized by a higher background field—exhibits less effective demagnetization compared to the east-west orientation. (4) Magnetic field variations recorded by fluxgate probes inside and outside the cavities show general consistency before and after demagnetization. Since in-situ probe placement within the cavity is infeasible during operation, external probes can serve to monitor and track internal field changes post-demagnetization, offering valuable reference for operational maintenance.

Prior to demagnetization, the average magnetic field values measured by the two fluxgate probes (CH12 and CH2) between magnetic shielding layers were 5.56 mGs in the east-west direction at the Hall 1 test station, 16.32 mGs in the east-west direction at ground level at Well 2, and 9.42 mGs in the north-south direction at the Well 2 tunnel entrance. The ten fluxgate probes (CH4, CH6, etc.) inside the magnetic shielding cavity recorded averages of 4.03 mGs (east-west) at Hall 1, 4.12 mGs (east-west) at Well 2 ground level, and 4.35 mGs (north-south) at the Well 2 tunnel entrance.

After demagnetization, the corresponding averages for CH12 and CH2 were 0.76 mGs (60 A demagnetization, east-west, Hall 1; 1.81 mGs at 2.0 K), 0.94 mGs (75 A, east-west, Well 2 ground), and 1.90 mGs (75 A, north-south, Well 2 tunnel entrance). The internal probes (CH4, CH6, etc.) registered 0.34 mGs (60 A, east-west, Hall 1; 2.06 mGs at 2.0 K), 0.32 mGs (75 A, east-west, Well 2 ground), and 1.53 mGs (75 A, north-south, Well 2 tunnel entrance). Furthermore, probe CH4—positioned in the central region of the magnetic shield—exhibited relatively low field amplitude throughout module transfers and demagnetization cycles, never exceeding 2.0 mGs. In contrast, the nine probes (CH6, etc.) located near the shield ends, where fields are strongest, showed larger variations in amplitude, with certain locations approaching or exceeding 5.0 mGs. Following initial demagnetization, the SHINE high-Q module achieved an overall field below 1.0 mGs, outperforming comparable demagnetization results from the LCLS-II project in the United States, where the east-west oriented field remained below 2.3 mGs [23].

Figure 5 Figure 5: see original paper presents the Q_0 test results of the SHINE high-Q prototype module before and after online demagnetization. Key observations are summarized as follows: (1) For the full module, the initial Q_0 values of CAV1, CAV6, and CAV7 were 2.70×10^{10}, 2.50×10^{10}, and 2.93×10^{10}, respectively. After demagnetization, these values increased significantly to 3.27×10^{10}, 3.28×10^{10}, and 3.09×10^{10}. When demagnetization was interrupted under the non-timed balance mode (simulating re-magnetization), the Q_0 values dropped dramatically to 2.14×10^{10}, 1.11×10^{10}, and 0.76×10^{10}, respectively. This confirms the strong dependence of Q_0 on the magnetic field inside the cavity shielding structure. (2) Other cavities, including CAV5 and CAV8, also exhibited substantial Q_0 improvement after demagnetization. CAV2, CAV3, and CAV4 reached the design target of 2.7×10^{10}, with CAV2 achieving 5.36×10^{10}. This enhancement is attributed to the reduction of trapped magnetic flux and the intrinsic surface resistance of each cavity. (3) The overall Q_0 across all eight cavities at 134.5 MV increased from 2.58×10^{10} to 3.32×10^{10} after demagnetization, meeting the key acceptance criterion for the module. These results underscore the critical role of demagnetization in enhancing cavity Q_0 and the necessity of effective magnetic field management for optimal performance.

For engineering module CM01, the Q_0 variation before and after demagnetization is shown in Fig. 5(b). Nearly all cavities showed improved Q_0, though quenching during post-demagnetization testing significantly influenced the results. Cavities without quenching generally exhibited higher Q_0 compared to vertical test results.

Module CM10 underwent online demagnetization at 41 K. As shown in Fig. 5(c), the Q_0 increased from 2.41×10^{10} to 3.37×10^{10} at 112 MV. The overall performance of low-temperature demagnetization is consistent with room-temperature results. No quenching occurred during the Q_0 test of CM10 after demagnetization; however, the horizontal-to-vertical Q_0 ratio was 84%, below the expected 90%. The thermal gradients present during cryogenic demagnetization generate localized thermal currents in the module, whose magnetic fields complicate the internal magnetic environment and may influence demagnetization outcome. This effect requires comprehensive monitoring, as it may not be fully captured by only two fluxgate probes. Whether the observed Q_0 ratio discrepancy is linked to such thermal currents remains an open question. Further data collection and analysis are needed to fully understand these phenomena.

Table 2 summarizes the Q_0 test results for engineering modules CM01-CM12 following online whole-machine demagnetization. Across all twelve 1.3 GHz eight-cavity modules, the magnetic field between magnetic shielding layers was reduced to 0.15–0.50 mGs after demagnetization, suggesting even lower field levels in the central region of the superconducting cavities. With the exception of CM02, all modules satisfied the Q_0 design specification. The underperformance of CM02 is likely attributable to the relatively low demagnetization current applied, the intrinsic performance limitations of its cavities, and quenching events during testing. Of the twelve standard 1.3 GHz engineering modules, CM01-CM08 were demagnetized using the timed exponential decay (TED) mode, achieving post-demagnetization inter-layer fields of 0.20–0.50 mGs. Modules CM09-CM12 employed the timed linear decay (TLD) mode, which yielded slightly better performance, with residual fields below 0.20 mGs.

In general, horizontal Q_0 measurements exceeded vertical test results for cavities that did not experience quenching. Notably, CM01 and CM08 exhibited significantly higher Q_0 values than their vertical test baselines. Excluding CM05, all other cavities achieved horizontal-to-vertical Q_0 ratios exceeding 90%. In contrast, CM02, CM07, and CM09 underwent partial or full quenching during Q_0 testing after demagnetization, resulting in substantially degraded performance.

IV. Discussion and Conclusion

This paper presents the results of online whole-machine demagnetization of SHINE high-Q modules and demonstrates that the background magnetic field of the entire module significantly influences demagnetization outcome. Following online demagnetization, the magnetic field B inside the superconducting cavities is reduced to 0.15–0.50 mGs, with corresponding Q_0 values reaching 2.7×10^{10} to 5.3×10^{10}. These results satisfy the key performance requirements for SHINE modules and exceed reported online demagnetization performance from international counterparts. Significant variation in Q_0 among different superconducting cavities after demagnetization is observed, which may be attributed not only to magnetic field conditions but also to intrinsic cavity performance and quenching events during testing. The magnetic field variations measured by fluxgate probes inside and outside the cavities show strong correlation before and after demagnetization. This supports the use of external fluxgate probes for monitoring the demagnetization process during module installation and operation. To optimize demagnetization efficiency and results, the background magnetic field should be maintained stable after online whole-machine demagnetization. Demagnetization in the north-south orientation requires higher currents to achieve equivalent performance to east-west orientation, indicating greater difficulty in field configurations with higher ambient background. Post-demagnetization activities that may compromise results—including transport, welding, conditioning, and mechanical vibration—should be minimized, as these operations can induce partial re-magnetization of the module structure.

Further investigation is warranted to understand the underlying mechanism of occasional interruptions during online demagnetization in the non-timed balance mode, and to verify whether the timed exponential decay (TED) and timed linear decay (TLD) modes maintain interruption-free operation under more complex leakage field conditions. Compared to the TED mode, the TLD mode maintains higher current levels for a longer duration, facilitating more complete randomization of stubborn magnetic domains with high coercivity (H_c) in the cryostat material. Theoretically, this leads to more thorough demagnetization, a conclusion preliminarily supported by the results from modules CM09-CM12. Additional data from engineering modules must be accumulated and analyzed to fully elucidate the performance differences between these two timed modes.

The demagnetization effectiveness shows strong dependence on the background magnetic field characteristics of the test station or operational environment. With the exception of CM10, all high-Q and engineering module demagnetization tests were conducted at two locations in Hall 1, where background fields are lower and leakage currents are relatively straightforward. By contrast, demagnetization under the stronger background fields and more complex leakage conditions in Hall 2, or in the north-south oriented underground tunnel with its significantly higher ambient field, may yield different results. Process parameters likely require optimization under these more challenging conditions to maintain performance. Prior to demagnetization, the magnetic field in the central region of the SHINE superconducting cavities typically meets the specification of being below 3.0 mGs. However, actual Q_0 measurements indicate that this level is insufficient for optimal performance. To achieve superior Q_0, the post-demagnetization field inside the cavities must be reduced below 1.0 mGs, or even to 0.50 mGs. Analysis of the cryogenic demagnetization results from CM10 suggests minimal performance difference between low-temperature and room-temperature processes, though neither has yet achieved optimal results. Further cryogenic demagnetization data collection and detailed analysis are essential to clarify these findings.

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Table 1. Demagnetization status of the entire high-Q module of SHINE.

Status number	Module position	Demagnetization current	Measure status	Average reading of external fluxgate	Average reading of internal fluxgate
1	Hall 1 test station	60 A	293K before demagnetization	6.56 mGs	4.03 mGs
2	Hall 1 test station	60 A	293K after demagnetization	0.76 mGs	0.34 mGs
3	Hall 1 test station	60 A	2K after demagnetization	1.81 mGs	2.06 mGs
4	Hall 1 north-south direction	75 A	293K after demagnetization	37.9 mGs	12.36 mGs
5	Hall 1 east-west direction	75 A	293K after demagnetization	6.78 mGs	1.69 mGs
6	Well 2 underground north-south direction	75 A	293K before demagnetization	9.42 mGs	4.35 mGs
7	Well 2 underground north-south direction	75 A	293K after demagnetization	1.89 mGs	1.53 mGs

Status number	Module position	Demagnetization current	Measure status	Average reading of external fluxgate	Average reading of internal fluxgate
8	Well 2 ground north-south direction	75 A	293K before demagnetization	16.32 mGs	4.12 mGs
9	Well 2 ground north-south direction	75 A	293K after demagnetization	0.94 mGs	0.41 mGs

Table 2. Q_0 test results after demagnetization of SHINE engineering modules.

Module number	Position	Demagnetization mode/current	Magnetic field before/after demagnetization	Q_0@E_{acc}	H/V ratio	Whether quenching
CM01	Hall 1	TED mode/75 A	2.00 mGs/0.20 mGs	3.51×10^{10} @ 133 MV	120%	No
CM02	Hall 1	TED mode/60 A	1.00 mGs/0.30 mGs	2.63×10^{10} @ 166 MV	86%	Yes
CM03	Hall 1	TED mode/75 A	1.77 mGs/0.50 mGs	3.87×10^{10} @ 166 MV	98%	No

Module number	Position	Demagnetization mode/current	Magnetic field before/after demagnetization	Q_0@E_{acc}	H/V ratio	Whether quenching
CM04	Hall 1	TED mode/75 A	0.80 mGs/0.40 mGs	3.14×10^{10} @ 166 MV	91%	No
CM05	Hall 1	TED mode/75 A	2.00 mGs/0.25 mGs	3.13×10^{10} @ 166 MV	82%	Yes
CM06	Hall 1	TED mode/75 A	1.40 mGs/0.30 mGs	4.05×10^{10} @ 166 MV	99%	No
CM07	Hall 1	TED mode/75 A	2.40 mGs/0.20 mGs	2.87×10^{10} @ 166 MV	68%	Yes
CM08	Hall 1	TED mode/75 A	0.35 mGs/0.29 mGs	4.21×10^{10} @ 166 MV	108%	No
CM09	Hall 1	TLD mode/75 A	0.34 mGs/0.18 mGs	3.14×10^{10} @ 165 MV	78%	Yes
CM10	Hall 2	TLD mode/75 A	1.40 mGs/0.19 mGs	3.37×10^{10} @ 112 MV	84%	No

Module number	Position	Demagnetization mode/current	Magnetic field before/after demagnetization	Q_0@E_{acc}	H/V ratio	Whether quenching
CM11	Hall 1	TLD mode/75 A	0.35 mGs/0.15 mGs	3.07 × 10^{10} @ 166 MV	78%	No
CM12	Hall 1	TLD mode/75 A	0.25 mGs/0.16 mGs	3.41 × 10^{10} @ 163 MV	81%	No

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