ANALYSIS AND REFURBISHMENT OF A RADIATION-DAMAGED UNDULATOR*

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Abstract

Synchrotron radiation facilities impose stringent requirements on the magnetic field quality, stability, and lifetime of undulators. During long-term operation of a beamline at the Shanghai Synchrotron Radiation Facility (SSRF), a gradual degradation of photon-beam performance was observed. To identify the cause, the cryogenic permanent magnet undulator of this beamline was warmed up and re-measured at room temperature during the summer shutdown. The on-axis field was found to be most strongly attenuated in the upstream region, with a maximum reduction of about 20% that gradually relaxed towards the downstream end. In addition, several sharp local drops of the magnetic field were detected in the central section. Visual inspection revealed pronounced melting holes in the copper foil in this area, indicating localized electron-beam impacts that likely damaged the underlying magnets and led to the abnormal field reduction. This paper presents the magnetic measurement results and the longitudinal attenuation pattern of the radiation-damaged undulator, and describes how local magnet replacement, re-shimming, and re-measurement were used to refurbish the device, providing a reference for future operation, maintenance, and radiation-protection design of similar undulators.

INTRODUCTION

Insertion devices, such as undulators, are core components of synchrotron radiation facilities and free-electron lasers. By generating periodic magnetic fields, they deflect high-energy electron beams and emit synchrotron radiation with high brightness and high coherence. Cryogenic permanent magnet undulators (CPMU), which have advanced rapidly in recent years, enable higher peak fields and smaller magnetic gaps, making them a key technology for enhancing light source performance. They have been successfully implemented at numerous synchrotron radiation facilities [1-4]. However, these devices face severe radiation environment challenges during long-term operation. In storage rings, lost electrons interact with vacuum chambers and surrounding components, generating complex mixed radiation fields comprising high-energy electrons, gamma rays, neutrons, and other particles. The interaction of this radiation with permanent magnets can cause irreversible demagnetization, leading to reduced magnetic field strength and degraded field quality in undulators, ultimately affecting the flux, brightness, and spectral stability of the output photon beams [5, 6].

During long-term operation at SSRF, a gradual decline in photon beam performance was observed from a cryogenic permanent magnet undulator installed at the fast X-ray imaging beamline BL16U2. To identify the cause and restore its performance, comprehensive off-line diagnostics and refurbishment were conducted on this undulator. This work provides important references for the operation and maintenance of similar equipment at SSRF and offers a valuable engineering case study for addressing comparable issues at other light source facilities worldwide.

UNDULATOR STATUS AND PRELIMINARY DIAGNOSIS

Basic Information of the Damaged Undulator

The undulator refurbished in this study is a cryogenic permanent magnet undulator (CPMU) installed at the fast X-ray imaging beamline BL16U2 of the Shanghai Synchrotron Radiation Facility (SSRF). Since its commissioning, this device has been in operation for many years, providing high-quality synchrotron radiation to beamline users. Its main design parameters are listed in Table 1. The undulator employs PrFeB permanent magnet material, which takes advantage of its significantly increased coercivity and remanence at low temperatures to achieve a higher peak magnetic field at a small magnetic gap.

Table 1: Main Design Parameters of the Damaged CPMU

Parameter	Value
Period length	18 mm
Number of periods	170
Minimum gap	6 mm
B_{eff}	0.86 T

Inspection and Preliminary Assessment

Figure 1 shows a photograph of the undulator placed in the magnetic measurement laboratory after warm-up.

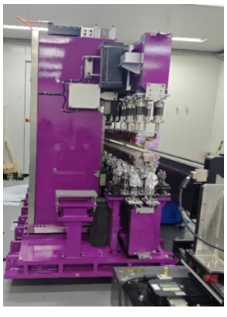

Figure 1: Photograph of the undulator in the magnetic measurement laboratory after warm-up.

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* This work was Sponsored by Shanghai Rising-Star Program (Grant No. 24YF2752400).

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Significant damage was observed on the copper foil surface of the lower girder. As shown in Fig. 2, three melted holes were found on the copper foil, distributed longitudinally along the undulator. The edges of these holes exhibited melt-solidification characteristics, indicating localized extreme heating. Given that the magnet blocks and poles are located directly beneath the copper foil, such localized electron or photon impacts likely caused a sharp temperature rise in the underlying magnets, potentially exceeding the Curie temperature or inducing microstructural damage, thereby triggering local demagnetization and resulting in magnetic field anomalies.

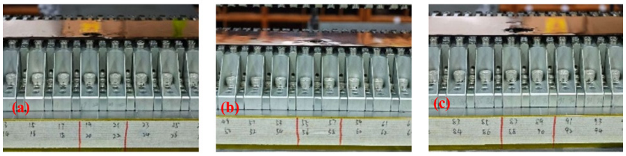

Figure 2: Photographs of melted holes on the copper foil and schematic diagram of damage locations.

To further assess the actual damage to the magnets, the copper foil was removed, and the exposed surfaces of the magnet blocks and poles were examined in detail. As shown in Fig. 3, distinct types of damage were observed on these surfaces, primarily including:

1. Surface charring: as shown on the left side of Fig. 3, the magnet block surfaces exhibited varying degrees of charring, indicating exposure to high temperatures.
2. Pitting damage: in addition to charring, evident pits with rough surfaces were observed on some magnet blocks and poles, exhibiting typical localized ablation characteristics.

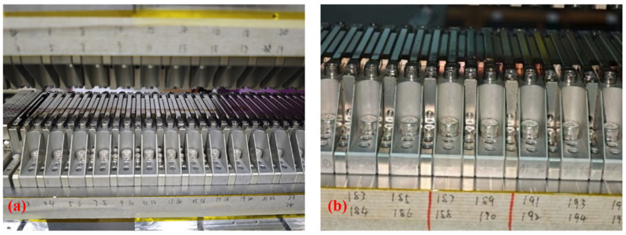

Figure 3: Damage to magnet blocks and poles: (a) surface charring; (b) pitting.

These damage characteristics clearly reveal the root cause of the magnetic field anomalies in this undulator: multiple localized, high-intensity electron or photon beam impacts occurred during long-term operation. These impacts first caused melting of the copper foil, which in turn led to thermal damage and possible microstructural destruction of the underlying magnets, resulting in an irreversible decrease in magnetization. This ultimately manifested as significant attenuation of the undulator's peak magnetic field and localized anomalies. This diagnostic outcome provides a clear basis for subsequent magnet replacement and refurbishment.

MAGNETIC FIELD MEASUREMENT AND DAMAGE CHARACTERIZATION

A Hall probe measurement system was used to measure the magnetic field of the damaged CPMU. The measurements were conducted at room temperature with a magnetic gap of 6 mm to obtain the longitudinal distribution of the peak magnetic field along the undulator axis. The peak field at each pole was extracted and plotted in Fig. 4.

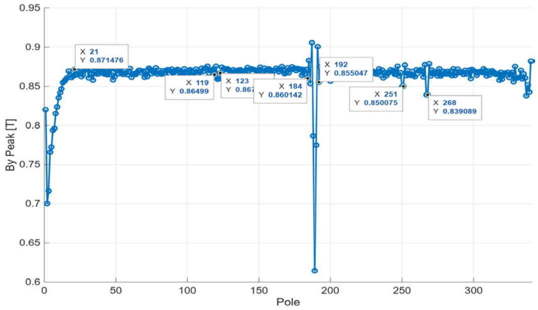

Figure 4: Peak magnetic field distribution of the damaged undulator.

Longitudinal Distribution of Field Reduction

As shown in Fig. 4, a sharp field reduction, with a maximum decrease of approximately 20%, was observed in the upstream region (poles No. 1–21), coinciding with the most severe surface charring shown in Fig. 3(a). The reduction gradually decreased along the beam direction. This longitudinal distribution pattern, characterized by strong reduction at the upstream and diminishes toward the downstream, indicates that beam losses distributed along the undulator are likely the primary cause of this overall reduction pattern.

Analysis of Local Magnetic Field Anomalies

As shown in Fig. 4, a slight reduction at poles No. 119–122 corresponded to the first melted hole (Fig. 2(a)). Located near the edge of the copper foil and away from the beam center, this hole had a minor impact on the on-axis field. The second hole was even farther from the beam center, at the edge of the magnet block near the mounting bracket, leaving the on-axis field at the corresponding poles No. 155–158 almost unaffected. The third hole (Fig. 2(c)) was the largest and closest to the magnet block center. This location exhibited the most severe damage, including pronounced pitting with a maximum pit size of approximately 6 mm, in addition to surface charring (Fig. 3(b)). Consequently, the on-axis field at the corresponding poles No. 187–190 was severely reduced (Fig. 4). The correlation between damage location and magnetic field anomaly provides compelling evidence that localized electron or photon beam impacts are the direct cause of these anomalous demagnetization points.

UNDULATOR REFURBISHMENT

Based on the magnetic field measurements and damage diagnosis, given that the damage was localized—particularly the local field anomalies and the extensive upstream attenuation—a refurbishment strategy combining selective magnet replacement and re-shimming was adopted. Owing to the urgency of the repair and the limited supply of spare magnet blocks, replacement priorities were determined by the magnetic field measurement results. Magnets exhibiting severe attenuation at the upstream end or pronounced local field reductions were replaced. Slightly elevated fields were corrected by reducing the pole height. Magnets with surface charring or edge pitting that did not affect the on-axis field or the good field region were left unchanged.

After magnet and pole replacement, re-shimming was performed to restore the phase error and electron trajectory to within design specifications. The magnetic field was then re-measured. Figure 5 compares the field distribution, X/Y trajectory standard deviations (STD), and phase error under multiple gaps before and after refurbishment (upper and lower rows, respectively). The peak-to-peak field STD was reduced from approximately 20‰ to about 4‰. The X and Y trajectory STDs dropped from maximum values of 18 and 15 to below 1.2. The phase error was reduced from over 100° to within 5°.

These results demonstrate that the undulator's magnetic field performance was successfully restored to an acceptable level. Compared with the pre-refurbishment data, the local anomalies and upstream attenuation have been effectively corrected, and the longitudinal peak field distribution has been significantly improved.

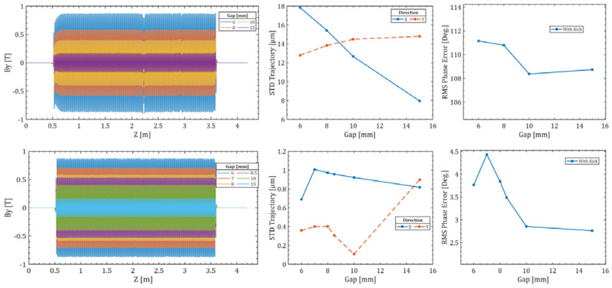

Figure 5: Comparison of magnetic field distribution, X/Y trajectory standard deviations, and phase error before and after refurbishment under multiple magnetic gaps. Upper row: before refurbishment; lower row: after refurbishment.

CONCLUSIONS

This paper presents a case study on the diagnosis and refurbishment of a radiation-damaged cryogenic permanent magnet undulator at SSRF. The damage was characterized by a longitudinal field attenuation that gradually decreased from upstream to downstream, with a maximum reduction of approximately 20%, and several sharp local drops attributable to localized beam impacts. A refurbishment strategy combining selective magnet replacement and re-shimming successfully restored the undulator's performance.

Based on the experience gained from this refurbishment, the following recommendations are proposed for future undulator design, operation, and maintenance. The observed longitudinal damage distribution indicates that the upstream end sustains the highest radiation dose. In terms of radiation protection design, the upstream end is recommended to adopt magnets with higher coercivity or enhanced local shielding to improve radiation resistance. Regarding operation and maintenance, greater emphasis should be placed on the analysis and utilization of beam loss monitor (BLM) data to establish an early warning mechanism, enabling timely detection of abnormal beam conditions that could lead to undulator damage.

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