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RF PULSE CONDITIONING TO REDUCE FIELD EMISSION IN FRIB SRF CRYOMODULES*

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Abstract

The superconducting radio-frequency (SRF) linear accelerator (linac) for the Facility for Rare Isotope Beams (FRIB) has been operating for user experiments since May 2022, using 104 quarter-wave resonators (80.5 MHz) and 220 half-wave resonators (322 MHz) operating with peak surface electric fields (E_{peak}) ranging from 27 MV/m to 33 MV/m. Field emission (FE) can limit the maximum accelerating gradients in SRF cavities and may worsen over time during long-term operation. RF pulse conditioning has been a useful technique to reduce FE in FRIB cryomodules for commissioning and user operations. In this paper, we will present RF pulse conditioning results and analysis for about 50 cavities, performed in cryomodule bunker tests and the linac tunnel. During conditioning, we observe ”electrical breakdown”, a rapid (<1 µs) collapse of the field, which usually leads to a significant reduction in FE X-rays. On the other hand, when a thermal breakdown (~ms decay time, also known as quench) occurs, opportunities for further conditioning at higher field are limited and FE X-rays may not be significantly improved.

INTRODUCTION

Field-emitted electrons from the niobium surface of superconducting radio frequency (SRF) cavities are accelerated by the RF field and strike the cavity walls, generating Bremsstrahlung X-rays. The emitters that generate the dominant field emission (FE) are likely located near the region of the peak surface electric field (E_{peak}), depending on the surface cleanliness. The FE electrons and associated X-rays can negatively impact the cavity performance by limiting the maximum achievable accelerating gradient (E_{acc}) or increasing the cryogenic heat load [1–3].

Field emission in FRIB cavities has been tracked and monitored during cavity Dewar tests, cryomodule bunker test, and linac beam commissioning [4]. In the Dewar certification tests, FE was significantly reduced in a number of cavities by repeating preparation steps (”FE reworks”) such as ultrasonic cleaning, high pressure rinsing, acid etching, and mechanical polishing [5, 6]. These FE reworks could be done relatively easily at the cavity certification stage, in contrast to the cryomodule test stage. On the other hand, RF pulse conditioning was found to be useful to mitigate FE in FRIB cryomodules. Pulse conditioning in the cryomodule is facilitated by the over-coupled fundamental power coupler (FPC), which is in contrast the matched couplers used for Dewar tests. A statistical analysis of RF pulse conditioning effects on the FE performance of FRIB cryomodules will be discussed in this paper.

PULSE CONDITIONING

In bunker cryomodule tests and in-tunnel cryomodule tests, we first measured FE X-rays as a function of E_{acc} in continuous wave (CW) mode, and then attempted pulse conditioning if significant X-rays were produced below the operating gradients. Pulse lengths of 30 to 50 ms were used (the RF fill time being a few tens of ms), with repetition rate of 1 Hz.

Electrical/Thermal Breakdown

Figure 1 shows the results of pulse conditioning in bunker tests (Fig. 1(a)) and in the linac tunnel (Fig. 1(b)). During conditioning, we observed two types of rapid drops in the transmitted RF power:

- A rapid collapse in the field, faster than 1 µs, which we classify ”electrical breakdown” (EB) [7].
- A decay taking of order 1 ms, due to ”thermal breakdown” (TB). This is faster than the normal decay dominated by the external quality factor of the FPC.

The FE onset field is significantly improved after EB, in contrast to TB. This is consistent with EB theory [7, 8]: the emitter is heated by the field emission current, leading to a local increase in pressure of vacuum and exciting a local discharge in which the emitter is explosively ”burned out.”

In TB, the emission current heats up the superconducting niobium cavity surfaces, causing a quench (transition from superconducting to normal conducting) before a local discharge can occur. This may explain why FE is not greatly improved after TB. In TB cases, if we attempt a shorter pulse (closer to the fill time) with higher peak power, we do not see a significant benefit. Generally, if pulse conditioning is limited by TB, it is difficult to induce EB after all.

The in-tunnel FE conditioning results (Fig. 1(b)) are divided into three cases: (1) during beam commissioning (2018-2021); (2) after user operation (2022-present); and (3) outliers in the statistical analysis such as non-conforming cavities in bunker tests or one case of FPC cold cathode gauge failure [9]. The FE observed in the bunker tests is likely due mainly to particulate contamination during cryomodule assembly since, in most cases, the cavities did not show significant field emission at the design field in the

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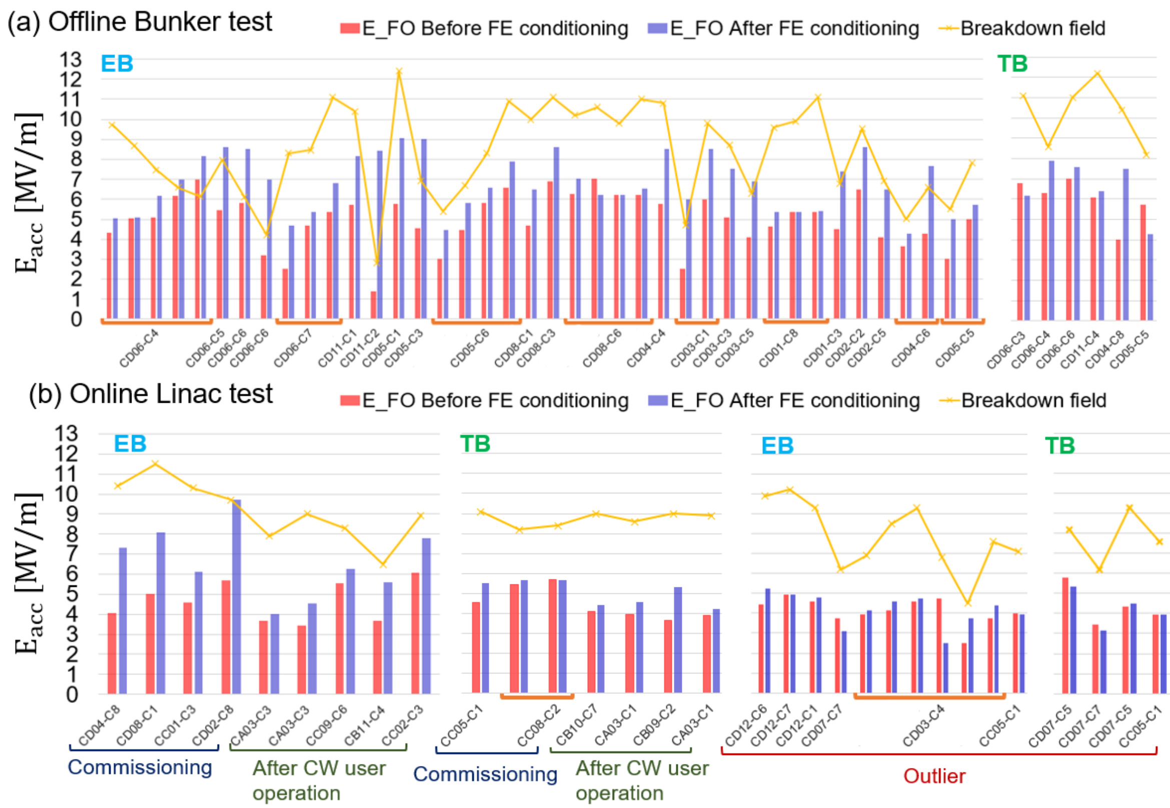

Figure 1: Results of RF pulse conditioning in (a) bunker tests and (b) the linac tunnel. The bars show the FE onset field before (pink) and after (purple) pulse conditioning. The yellow line shows the peak E_{acc} in pulsed mode when EB or TB occurred. The FE onset field (E_{FO}) is typically defined as the E_{acc} at which the X-rays cross 0.1 mR/hr, measured approximately 1 m away from the cavity [11]. If no FE X-rays are seen after conditioning, the maximum E_{acc} achieved in the CW is shown. The orange brackets indicate multiple trials of pulse conditioning in one test where the FE onset gradually increased after one or more EB events.

Dewar tests (which were done after jacketing) [5]. After installation of the cryomodules into the linac, possible FE sources include not only particulate contamination during installation but also contamination from residual gas during long-term operation or impacts by beam loss.

Fowler-Nordheim Fitting

In order to understand the physical impact on the emitters from breakdown events, we modeled the FE using the enhanced Fowler-Nordheim (FN) equation [8, 10]. The FN equation gives the FE current, but we measured FE X-rays. For simplification, we assumed that X-ray attenuation through the cavity and cryomodule walls, as well as the angular divergence of the X-rays, remained constant within the range used for FN fitting; typically a few percent of the incident FE electron energy generates Bremsstrahlung radiation.

From the FN equation, the average FE current from quantum mechanical tunneling of electrons in the alternating current (AC) case is

$$I_{\mathrm{F}} \propto (\beta_{\mathrm{FN}} E)^{2.5} \times \exp\left[-\frac{B}{\beta_{\mathrm{FN}} E}\right] \times A_{\mathrm{FN}}. \quad (1)$$

The current I_{F} depends on the field enhancement factor β_{FN}, electric field E at the emitter, the effective emitter area A_{FN}, and a constant $B \equiv 5.82 \times 10^{10}$ V/m related to the work function of Nb ($\phi = 4.3$ eV). We can infer the X-ray dose rate (mR/hr) as a power, $P_{\mathrm{F}} = I_{\mathrm{F}} E d$ [11], where d is the effective distance over which FE electrons are accelerated. Here, we used an estimated value of $d = 0.16$ m obtained from the transit time factor and the ratio of E_{peak} to the accelerating voltage for the FRIB $\beta = 0.53$ half-wave resonator.

For fitting, β_{FN} is obtained from the inverse of the slope of the FN plot; $log_{10}[P_{\mathrm{F}}/(E_{\mathrm{peak}}^{3.5})]$ vs $1/E_{\mathrm{peak}}$, assuming that the field E at the emitter is approximately equal to E_{peak} in each cavity. The field enhancement factor β_{FN} describes the increase in the local microscopic surface field relative to the ideal macroscopic surface field. The effective emitter area A_{FN} can be obtained from the $y-$intercept of the FN plot (when $1/E_{\mathrm{peak}}$ approaches zero) [12, 13].

Figure 2 shows fitted values of β_{FN} and A_{FN} for FRIB cavities before and after pulse conditioning, including bunker tests and in-tunnel conditioning. The β_{FN} values varied from 200 to 1500 before conditioning; they decreased to between 90 to 450 after conditioning. In some EB cases in particular, the FE was significantly reduced such that we could

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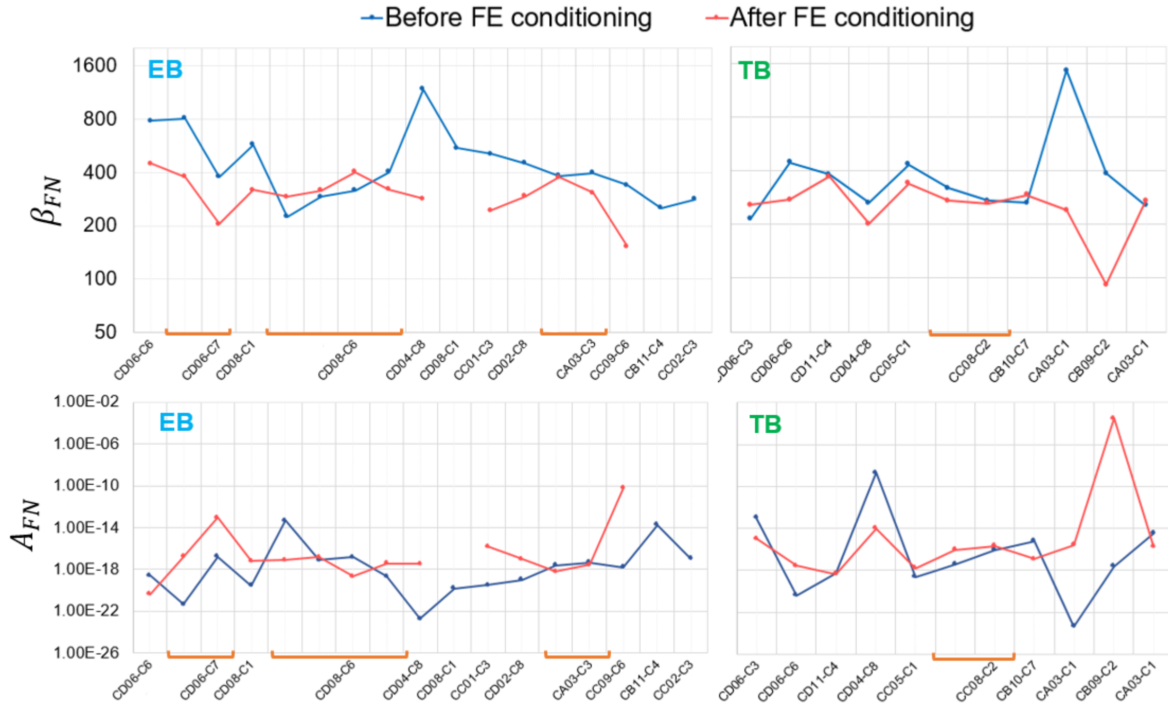

Figure 2: FE enhancement factor $\beta_{\rm FN}$ (dimensionless) and effective emitter area $A_{\rm FN}$ (arbitrary units) before and after FE conditioning for the FRIB cavities. The orange bracket is a group of multi-time trials of pulse conditioning in one test.

not measure sufficient FE X-rays for FN fitting and hence no post-conditioning FN data is shown. Along with the reduced $\beta_{\rm FN}$, we generally observed that $A_{\rm FN}$ was increased, which implies that the emitter spot might have broadened across the cavity surface. In some cases of EB, we observed an increased $\beta_{\rm FN}$ after conditioning, as the slope of the X-ray versus $E_{\rm acc}$ line became lower as we reached higher $E_{\rm acc}$. A scenario which might explain this: the emitter tip sharpens ($\beta_{\rm FN}$ increases) while the effective emitter size shrinks ($A_{\rm FN}$ decreases) with heating by the RF pulse power.

CONCLUSION AND OUTLOOK

RF pulse conditioning significantly reduced field emission X-rays and improved the FE onset fields and maximum accelerating gradients of FRIB SRF cavities after one or more electrical breakdown (EB) events. When EB was seen, the field enhancement factor was notably decreased and in some cases, FE X-rays were not measured up to the maximum accelerating gradient after conditioning.

In future work, we will consistently track the FE performance and investigate whether degradation occurs during long-term operation with high-power heavy ion beams. While RF pulse conditioning was instrumental in mitigating FE during cryomodule bunker tests and initial linac commissioning, we recently observed a few cases of FE degradation after operation, in which pulse-conditioning capability was hampered by thermal breakdown. Our strategy for long-term operation of the FRIB linac includes the use of spare cryomodules [14] and in-situ plasma processing [15].

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