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CONDITIONING OF LOW-FIELD MULTIPACTING BARRIERS IN SUPERCONDUCTING QUARTER-WAVE RESONATORS*

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Abstract

Multipacting (MP) barriers are typically observed at very low RF amplitude, at a field 2 to 3 orders of magnitude below the operating gradient, in low-frequency (<~100 MHz), quarter-wave resonators (QWRs). Such barriers may be troublesome, as RF conditioning with a fundamental power coupler (FPC) of typical coupling strength (external Q = 10^6 to 10^7) is generally difficult. For the FRIB β = 0.085 QWRs (80.5 MHz), the low barrier is observed at an accelerating gradient (E_{acc}) of ~10 kV/m; the operating E_{acc} is 5.6 MV/m. Theoretical and simulation studies suggested that the conditioning is difficult due to the relatively low RF power dissipated into multipacting rather than being a problem of the low barrier being stronger than other barriers. We developed a single-stub coaxial FPC matching element for external adjustment of the external Q by one order of magnitude. The matching element provided a significant reduction in the time to condition the low barrier. We will present theoretical and simulation studies of the low MP barrier and experimental results on MP conditioning with the single-stub FPC matching element.

INTRODUCTION

Coaxial multipacting appears at very low RF amplitudes (2-3 orders of magnitude lower than operating E_{acc}) in low-frequency (<~100 MHz) coaxial cavities [1]. This sometimes causes operational issues because it requires a relatively long conditioning time. It is claimed that a stronger coupling and/or a broad loaded-bandwidth helps faster conditioning. Accelerator facilities equipped with low-frequency QWRs such as ATLAS at ANL, ISAC-II at TRIUMF and ALPI-PIAVE at LNL use variable couplers to condition MP [2-4]. In the case of INFN – LNL linac, MP conditioning usually starts when the cavities are still warm [4].

In FRIB β = 0.085 80.5 MHz QWRs, the low-field MP appears at E_{acc} of ~10 kV/m whereas the operating E_{acc} is 5.6 MV/m [5]. We found that this MP barrier requires a long conditioning time such as ~1 day or longer, which is not favorable from operation cost standpoints. We thus have been using an alternative method to conditioning: turning on RF with an initial amplitude higher than the MP band such that it passes through the MP band during the RF rising time before MP is built up. This technique has been working well and the downtime due to this MP issue has been negligible so far. However, operational complexities still remain particularly because the low-field MP can be enhanced by field emission from neighboring cavities. We recently revisited low-field MP and performed R&D using the ReA6 cryomodule, one of the FRIB β = 0.085 80.5 MHz QWR cryomodules, installed in the ReAccelerator linac of FRIB [6].

Figure 1 shows MP conditioning in one of the β = 0.085 80.5 MHz QWRs in the ReA6 cryomodule. The forward RF power P_{fwd} was kept constant at 2 W. The accelerating gradient E_{acc} was initially stuck at ~6 kV/m but gradually increased and eventually jumped up at ~14 kV/m after 26 hours of CW conditioning. The vacuum activities were observed on the beamline cold-cathode gauge (green) during conditioning. The reflected RF power P_{rev} (magenta) gradually decreased as the MP was getting conditioned. Multipacting simulation using the CST PIC Solver confirmed that this is coaxial multipacting; for example, at 12 kV/m E_{acc}, the dominant multipacting is 1st order two-point multipacting between the cavity inner and outer conductors, as shown in Fig. 2.

Since the conditioning time of ~1 day per cavity is not favorable for operation, we investigated possibility of improvements of the conditioning time with higher P_{fwd} and/or stronger coupling. We will present theoretical prediction and experimental results.

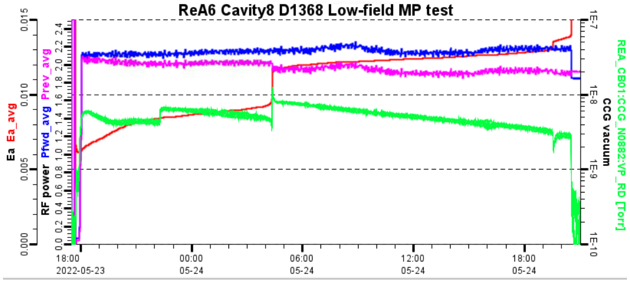

Figure 1: CW conditioning of the low-field MP barrier. This shows trends of P_{fwd} (blue), P_{rev} (magenta), E_{acc} (red), beamline cold-cathode gauge pressure (green) for ~26 hours.

THEORETICAL PREDICTION

When a coupler is coupled to a cavity, the time-dependent amplitude of the reflected wave can be represented by [7]

$$V_{-}(t) = V_{+}\left[\left(1 - e^{-\frac{t}{\tau}}\right)\frac{2\beta}{1+\beta} - 1\right], \qquad (1)$$

where τ is the RF filling time and β is the coupling coefficient, equal to Q_0/Q_{ext}. The first term in Eq. (1) can be interpreted as the wave radiated from the cavity whereas the

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second term can be interpreted as the wave directly reflected from the coupler-cavity interface [7]. According to this theory, if MP is excited in the cavity such that the cavity field is kept at a constant level while the forward RF is increased, the steady-state reflected voltage can be represented by

$$V_{-} = V_{0+}\frac{2\beta}{1+\beta} - V_{+}, \tag{2}$$

where V_{0+} is equivalent to the forward voltage at the MP level and thus it is a constant while the forward voltage V_{+} varies as the input RF power changes.

In the FRIB β = 0.085 80.5 MHz QWR, if the MP is excited such that E_{acc} is stuck at 6 kV/m, P_{rev} changes to the blue curve from the red curve (no MP case), as shown in Fig 3. The differences in the powers of those two cases are supposed to be the power absorbed by multipacting electrons. Figure 4 shows these MP-absorbed power in two different Q_{ext} cases: nominal Q_{ext} of 2e6, a stronger coupling Q_{ext} of 1e5. Presumably, MP conditioning time is proportional to the absorption power by MP. Therefore, this theoretical analysis predicted a stronger coupling together with a higher RF power will reduce the conditioning time, in agreement with common experience.

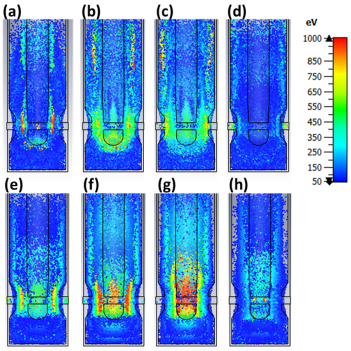

Figure 2: Plots of electron position-energy from the simulation (a): t = 300 ns, (b) – (h): time is evolved from (a) with an incremental step of 1.55 ns, an eight of the RF period. Only electrons with the energy in the range from 50 eV to 1 keV are shown in these plots and the other electrons are hidden.

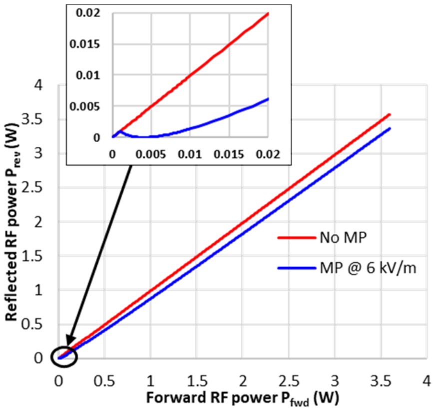

Figure 3: Calculated changes of the reflected RF power when MP is excited at E_{acc} = 6 kV/m. The reflected RF power differences between no-MP and MP cases are the power dissipated on the multipactors.

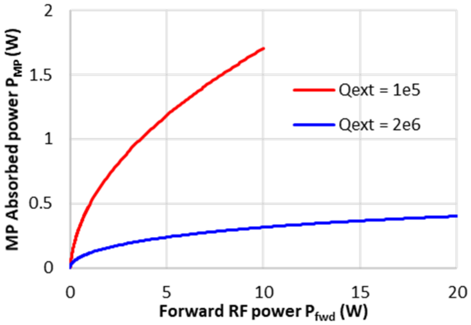

Figure 4: Calculated dissipation power on the multipactors in the nominal coupling condition (blue) compared to a stronger coupling condition (red).

CONDITIONING WITH EXTERNAL MATCHING ELEMENT

Since FPC coupling is not adjustable in the FRIB β = 0.085 80.5 MHz QWR cryomodule once the cryomodule is fully assembled and cooled down, we conceived a method to adjust it from outside of the cryomodule. Figure 5 shows a simplified FPC model with straight coaxial waveguides. Here we introduced a single-stub tuner and found that Q_{ext} is significantly reduced when the single-stub tuner combined with the FPC meets a quarter-wave resonance condition, as shown in Fig. 6.

The next step was to implement a single-stub matching element in the real cryomodule. As we found such a quarter-wave resonance condition if a coax tee with a short stub is attached to the end of the FPC warm window, we built and installed the single-stub matching element as shown in Fig. 7 and achieved Q_{ext} of 1.6e5, compared to 2.3e6 before the matching element was inserted. As an intermediate step of changing the stub, we also had 5e5 for comparison.

MP conditioning was performed in 8 cavities in the ReA6 cryomodule in different conditions:

- No matching element Q_{ext} = 2e6, P_{fwd}: 2 to 20 W,
- Matching element Q_{ext} = 5e5, P_{fwd}: 2 and 4 W,
- Matching element Q_{ext} = 1.6e5, P_{fwd}: 2 and 10 W.

The results are as shown in Fig. 8. a stronger coupling together with a higher P_{fwd} is more efficient in conditioning MP. The conditioning time was reduced to less than 2 hour and there is still a room to further reduce with higher forward RF power.

The experimental setup contains another normal-conducting resonant structure formed by the single-stub combined with FPC, whereas theoretical calculation was done with a single superconducting cavity (Qext << Q0) model. The wall losses in the stub-FPC resonant structure were not negligible such that Q0 were 2e6 and 5e5 when Qext were 5e5 and 1.6e5, respectively. However, once the MP is excited the ‘stub-FPC’ field is kept at a constant level as well as the cavity field while Pfwd in increased. The wall dissipation power at the center of the MP band, 10 kV/m, is calculated to be 30 – 40 mW, the contribution of which to the total absorbed power could be negligible if Pfwd is high enough such as at the level of 10 W.

CONCLUSION

In the FRIB β = 0.085 80.5 MHz QWR cryomodule, the theoretical analysis suggested a stronger coupling and higher RF power for efficient MP conditioning. As adjustment of FPC coupling is not available in the FRIB β = 0.085 80.5 MHz QWR cryomodule, a single-stub matching element was developed which allows to improve the coupling strength by one order of magnitude. With such strong coupling together with a higher RF power, we achieved <2 hour conditioning time, which originally took longer than 24 hours when attempted with a few Watt forward RF power.

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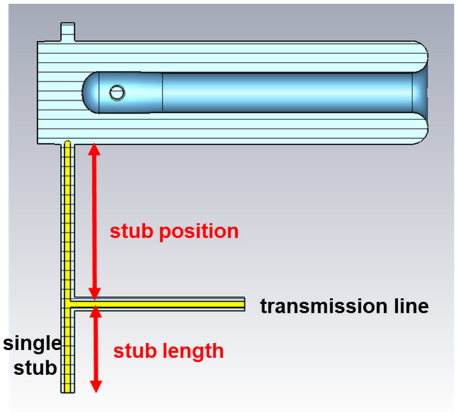

Figure 5: A single-stub tuner is introduced as a matching circuit in a simplified FPC model.

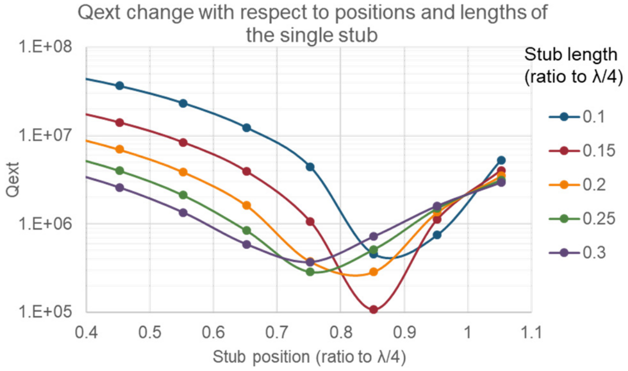

Figure 6: Simulation results of Q_{ext} changes with respect to the stub position and stub length. Note that minimum Q_{ext} happens when this condition was met: (stub position) + (stub length) = λ/4.

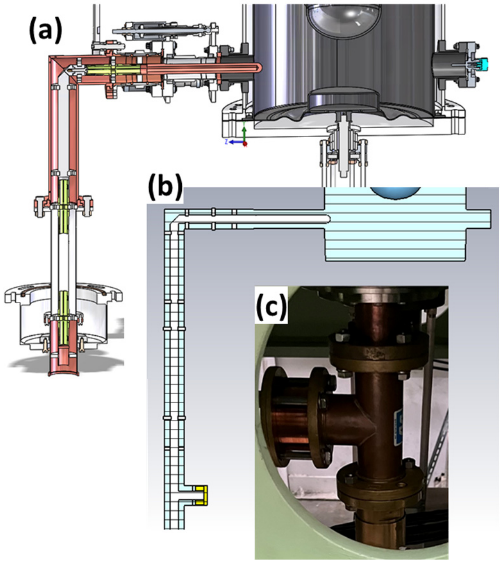

Figure 7: A single stub matching element installed in the real cryomodule. (a): mechanical model of the FPC integrated with the cavity, (b): RF model with the single-stub matching element, (c): the single-stub matching element inserted between the FPC warm window and transmission line.

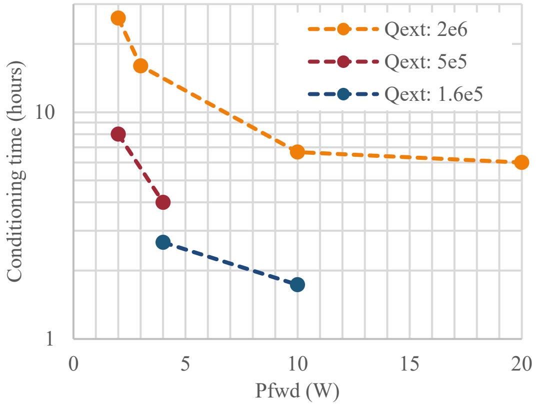

Figure 8: Experimental results of low-field MP conditioning time in eight cavities of the ReA6 cryomodule.

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