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HOM DAMPING PROPERTIES OF FUNDAMENTAL POWER COUPLERS IN THE SUPERCONDUCTING ELECTRON GUN OF THE ENERGY RECOVERY LINAC AT BROOKHAVEN NATIONAL LABORATORY*

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Abstract

Among the accelerator projects under construction at the Relativistic Heavy Ion Collider (RHIC) is an R&D energy recovery LINAC (ERL) test facility. The ERL includes both a five-cell superconducting cavity as well as a superconducting, photoinjector electron gun. Because of the high-charge and high-current demands, effective higher-order mode (HOM) damping is essential, and several strategies are being pursued. Among these is the use of the fundamental power couplers as a means for damping some HOMs. Simulation studies have shown that the power couplers can play a substantial role in damping certain HOMs, and this presentation will discuss these studies along with measurements.

INTRODUCTION

The requirements for several future accelerator projects at the RHIC all involve the use of ERLs. These projects require high-current, high-charge operating parameters making effective HOM damping essential. They include the development of an experimental 703 MHz ERL [1]; the study of superconducting cavities for a polarized electron-ion collider (eRHIC) [2]; and the development of coherent electron cooling [3].

The experimental ERL aims to operate with an average beam current in the range of 500 mA, combined with very-high-efficiency energy recovery. The facility is comprised of a five-cell superconducting LINAC plus a ½-cell superconducting, photoinjector RF electron gun, both operating at 703.75 MHz [4].

This paper focuses on the use of the fundamental power couplers (FPCs) to damp higher-order modes in the gun. The gun is designed to generate a 2 MeV beam with a bunch charge of 1.4 nC as well as bunch length of 1.0 cm, requiring an average RF power of ≥ 1 MW and very strong coupling ($Q_{ext} \sim 4\text{-}5\times10^4$). A schematic of the design is shown in Figure 1. The gun features two coaxial FPCs with curved, oval-shaped ("pringle") tips (Figure 2) originally designed for the Cornell ERL injector [5] with a contour radius of the beampipe. The dual couplers minimize the destabilizing effect of non-zero fields on axis and half the RF power required for each coupler.

The goal of this study was to determine whether the FPCs provide significant HOM damping. A ferrite-loaded HOM damper will be placed downstream of the gun cavity and is intended as the main HOM absorber for the gun (described elsewhere in these proceedings [6]). However, the effectiveness of this damper depends upon the ability of the cavity modes to reach it ~66 cm from the center of the cavity. Modes below the cutoff of the beam-tube may not be damped by the ferrite. In such cases, one avenue for HOM damping might be through the FPCs. Therefore, simulations and room-temperature measurements using the niobium gun cavity and "mock" FPCs, designed to simulate the actual FPCs, were conducted.

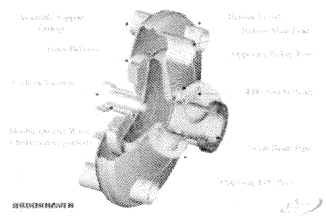

Figure 1: Schematic of ERL superconducting electron gun. Note opposing FPC ports.

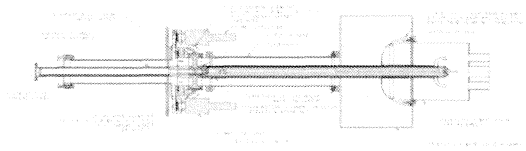

Figure 2: Schematic of FPC showing "pringle" tip at left and waveguide transition feeding power to coupler at right.

SIMULATION STUDIES

Cavity and FPCs

To establish the spectrum of HOMs in the gun cavity as well as the effect of the FPCs on the spectrum, a model of the gun in two different configurations was created using CST Microwave Studio [7], and eigenmodes were calculated. In one configuration, only the superconducting cavity and the beampipe were included. The length of the beampipe was determined by the space between the cavity iris and the position of the ferrite. In a second configuration, the FPCs were added to the model, and both couplers were inserted as shown in Figure 3. Frequencies and Q_{ext} values were calculated and compared.

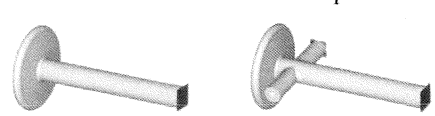

Figure 3: Models of cavity with only beampipe (left) and with beampipe and FPC couplers attached (right). Red rectangles indicate waveguide ports (perfect termination).

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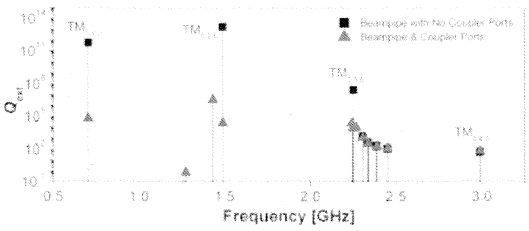

Figure 4: Plot of Q_{ext} for monopole modes from models with terminated beampipe only and from terminated beampipe and FPCs with well-defined cavity modes indicated.

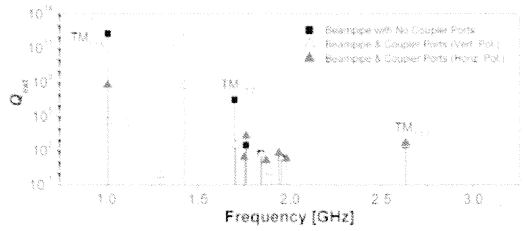

Figure 5: Plot of Q_{ext} for dipole modes from models with terminated beampipe only and terminated beampipe and FPCs for horizontally and vertically polarized modes with well-defined cavity modes indicated.

The results indicate that the Q_{ext} values for monopole modes below 2.25 GHz of the model with FPCs are significantly lower than the corresponding modes in the model with a beampipe only, suggesting that the FPCs couple strongly to these modes, tending to damp them by orders of magnitude. By 2.25 GHz, the damping diminishes, and above this frequency, no damping due to the FPCs is observed.

This is explained by the 5.08 cm radius of the beampipe with a TM_{01} cutoff frequency of 2.26 GHz. For the terminated beampipe only, modes below this frequency are attenuated outside the cavity and effectively remain trapped. The FPCs couple to these modes and energy flows out, accounting for the greatly reduced Q_{ext} values. Above 2.26 GHz, energy now flows along the beampipe and the FPCs have little effect.

For dipole modes, the situation is similar, but the orientation of the dipole modes must also be taken into account. The TE_{11} mode is 1.75 GHz, and below this frequency there is strong damping. Furthermore, modes aligned with the FPCs show substantially more damping than rotated modes.

Shunt impedances for the full model with beampipe and FPCs were also calculated. None of the frequencies lie on any of the beam harmonics, suggesting that the likelihood of exciting these modes is small.

Waveguide Transition

For effective HOM damping, the transition from the coaxial FPC to the waveguide that feeds the couplers must allow the energy from the HOMs to flow through the transition back to a circulator that ultimately shunts power to the dump. The transition is a "doorknob"-type transition designed by Advanced Energy Systems [8]. In the studies above, only the coupling of the FPC to the cavity was considered without regard to the transition. The transition was simulated using the frequency solver of Microwave Studio. The model appears in Figure 6, and the results are plotted in Figure 7.

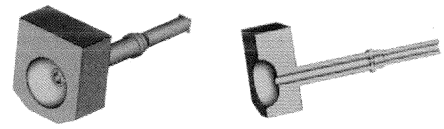

Figure 6: Microwave Studio model of doorknob transition. Red rectangles indicate ports (left). Port 1 is on the waveguide side of the transition. Right shows cutaway view.

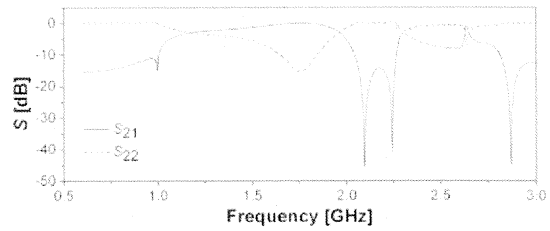

Figure 7: S_{21} (black) and S_{22} (red) simulation results for doorknob transition.

The results show that signal transmission at frequencies below 1 GHz is rather low (< -10 dB), but increases sharply above 1 GHz. Transmission falls off again rapidly around 2 GHz. The S_{22} signal shows full reflection up to 1 GHz and then reflection decreases above 1 GHz, allowing signal to flow out. Taken together, this behavior will allow for the damping seen in the cavity data above. However, it remains to simulate the mode of the cavity joined to the waveguide transition.

MEASUREMENTS

Next, room-temperature measurements on the niobium cavity probed the spectrum of HOMs for the cavity by itself and in various configurations including "mock" FPCs meant to simulate the physical dimensions and impedance of the actual FPCs, which were unavailable. The mock FPCs were designed from EIA-type couplers (RLA150-NF manufactured by Electronics Research, Inc. [9]) with 50 Ω impedance. An aluminum rod was attached to the "bullet" of the connector with the same diameter as the inner conductor of the actual FPC so that when the mock probe was inserted into the gun port, the 50 Ω impedance of the arrangement was preserved. A rounded tip was also attached to the end of the probe similar to that of the actual FPC with the same radial dimensions and curvature. The EIA connector and the entire mock probe are shown in Figure 8.

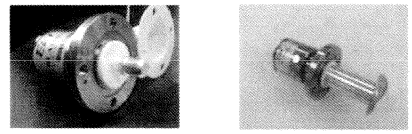

Figure 8: EIA connector and mock FPC probe showing coupler with inner conductor and "pringle" tip attached.

HOMs of Cavity Without FPCs

To characterize the HOM spectrum of the bare cavity, S_{21} measurements were conducted using a network analyzer and Q-values were collected using the 3-dB method. Two measurement configurations were used: in the first, a probe was inserted in the cathode port of the cavity (see Figure 1) and another probe was inserted in one of the pickup ports. All other ports were covered with shorting plates. In a second configuration, probes were inserted in both of the FPC ports. The results show good agreement with simulation. Several modes are missing from both measurement configurations, possibly due to low Q-values for these modes, making it difficult to clearly resolve and identify the modes.

HOMs of Cavity With FPCs Inserted

Several measurements were conducted with the mock FPCs inserted into the cavity. For these, a probe was inserted into the cathode port and a second probe was inserted into the pickup port and the cavity was attached to a short section of beampipe (~25.4 cm) with the same radius as the beamport opening of the cavity (5.08 cm) to simulate the cavity in the accelerator. For each measurement, all open ports were covered with shorting plates. Q-values were compared for various measurement configurations: a "reference" structure with all ports covered with shorting plates and the same structure in which the FPCs were inserted and terminated in 50 Ω. Monopole and dipole modes were identified by comparison to simulation and the results of the measurement are shown in Figure 9. In a second set of measurements, plotted in Figure 10, the Q-values for the cavity, attached to a short stretch of beampipe were measured for FPCs unterminated (open), both FPCs shorted, and both FPCs terminated in 50 Ω.

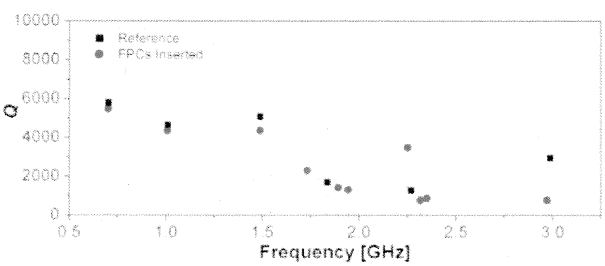

Figure 9: Plot of monopole and dipole Q-values for bare cavity (reference) attached to beampipe and cavity with FPCs inserted and terminated in 50 Ω.

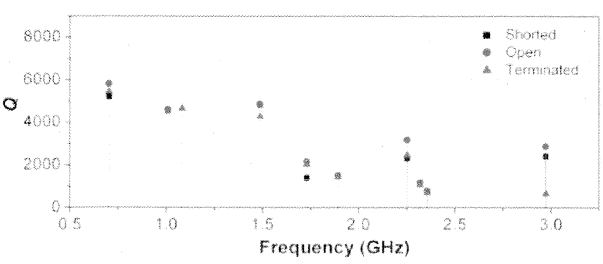

Figure 10: Plot of monopole and dipole Q-values for FPCs shorted, open, and terminated in 50 Ω.

An external Q-value of 8.79×10^4 was found for the FPCs at 703.75 MHz. The design value is $4\text{-}5\times10^4$, so the coupling of the mock FPCs is somewhat weaker than the design value, likely due to impedance mismatch and geometrical imperfections. The virtue of the mock FPC design is that it is based on an EIA connector that easily mates with the center conductor whose dimension is critical to assure impedance matching. However, errors are introduced if the coupler is not perfectly centered on the port. Furthermore, the orientation of the pringle relative to the beampipe is important and may have a significant impact on the measurement. Errors in the alignment of the pringle through twisting could contribute to changes in coupling.

Comparison of reference to fully terminated FPCs indicates that modest damping can be expected from the FPCs at low frequencies. In the case of the shorted, open, and terminated FPCs, a similar pattern of modest coupling at low frequency is also evident. For certain isolated modes, there appear to be higher-Q modes when the FPCs are inserted. These modes may be due resonances of the FPC port and the beampipe.

CONCLUSIONS

While simulation results show strong damping of higher-order modes particularly below 2.25 GHz, measurement results are more modest. The measurements show that some damping is expected, particularly at frequencies below ~2 GHz, which is important because these modes are otherwise effectively trapped in the structure. As simulation of the waveguide transition shows, these modes may also pass through the doorknob transition. However, the change in Q-value for room temperature measurements is rather small. Fortunately, none of the modes appear to lie on the beam harmonics and are unlikely to be strongly excited by the beam. One issue that has yet to be explored is the simulation of the cavity with the waveguide transitions attached to the cavity. Furthermore, cold measurements remain to be performed.

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