DESIGN, SIMULATION AND CONDITIONING OF THE FUNDAMENTAL POWER COUPLERS FOR BNL SRF GUN*

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Abstract

The 704 MHz SRF gun for the BNL Energy Recovery Linac (ERL) prototype uses two fundamental power couplers (FPCs) to deliver up to 1 MW of CW RF power to the half-cell cavity. To prepare the couplers for high-power RF service and process multipacting, the FPCs should be conditioned prior to installation into the gun cryomodule. A room-temperature test stand was configured for conditioning FPCs in full reflection regime with varied phase of the reflecting wave. The FPCs have been conditioned up to 250 kW in pulse mode and 125 kW in CW mode. The multipacting simulations were carried out with Track3P code developed at SLAC. The simulations matched the experimental results very well. This paper presents the FPC RF and thermal design, multipacting simulations and conditioning of the BNL gun FPCs.

INTRODUCTION

The superconducting RF (SRF) gun photo-injector [1] was chosen to generate high-current, high-brightness electron beam for the ERL at BNL [2]. The 704-MHz, half-cell SRF gun requires total RF power of 1 MW in order to meet the beam current and energy specifications (0.5 A, 2 MeV). As a result, very strong RF coupling (Q_{ext} = 4.8×10^4) between the cavity and transmission line is required. A coaxial antenna coupler design was selected. To enhance coupling, the antenna has specially shaped tip – an ellipse bent to conform to the profile of the beam pipe – called "pringle". To remedy the emittance growth due to fundamental power coupler kick, two opposing FPCs are employed with an additional benefit of halving the average power through each coupler (Fig. 1).

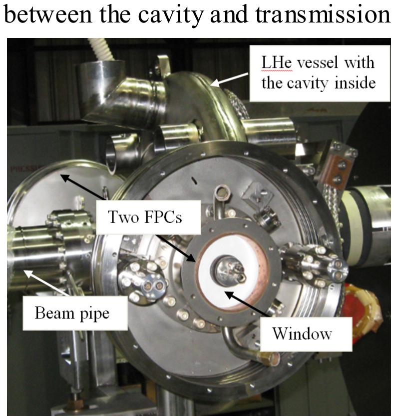

Figure 1: BNL SRF gun with two opposing FPCs attached.

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DESIGN OF FUNDAMENTAL POWER COUPLER

Design of the 500-kW fundamental power coupler is derived from the SNS power coupler [3], which in turn is based on the FPC for KEKB SRF cavities [4]. The coaxial FPC, shown in Fig. 2, is separated by a planar RF window into a vacuum side and an air side. On the vacuum side, the copper-plated stainless steel outer conductor is cooled by helium gas and the OFE copper inner conductor has a double-wall design and is cooled by water. Design modifications were implemented to allow for vacuum side of the coupler, terminated by the RF window, to be within the cryostat envelope. There are no RF-to-water seals. To enhance the coupling between the FPC and cavity, a "pringle"-shaped tip is attached to the end of the inner conductor.

Berillia was chosen for the RF window fabrication due to its better thermal conductivity and lower dielectric constant. The RF window braze joints are surrounded by RF choke joints to reduce the field (Fig. 2). Thermal and mechanical stress analyses were performed for the coupler under 1 MW RF power using ANSYS [5]. Figure 3 shows temperature and stress contours in the window area under traveling wave conditions. The maximum temperature, 61ºC, in the window area is at the inner choke. The maximum stress at the window is 6144 psi from the heat load and ambient pressure, which is approximately one third of the tensile strength of BeO. At 500 kW RF through power, the maximum temperature at the choke is 41ºC and the maximum stress at the window is 3300 psi. The cooling water temperature rise will be less than 0.1ºC with 6.9 GPM flow rate around the outer diameter of the window (entering at 20ºC). The planar ceramic window assembly has five instrumentation ports on the vacuum side: two for vacuum gauges, two for arc detectors and one spare.

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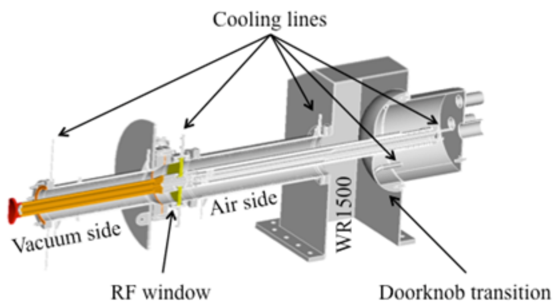

Figure 2: Design of 500-kW fundamental power coupler.

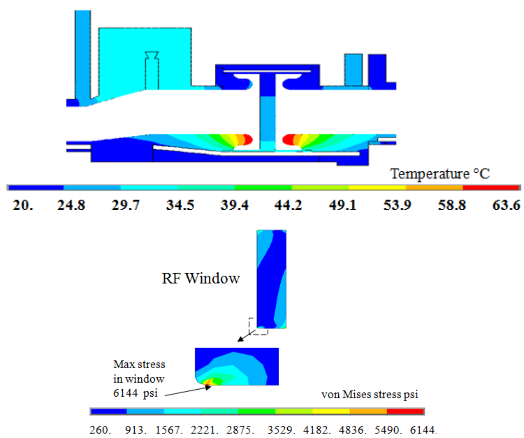

Figure 3: Temperature contours on the RF window area (top) and Von Mises stress contours (bottom) with 1MW power transmitted through.

On the air side, both the copper-plated stainless steel outer conductor and copper inner conductor are water cooled with a double-wall design. Transition between the coaxial line of the FPCs and WR1500 waveguide has a doorknob configuration. In order to obtain minimal VSWR, we optimized dimensions of the doorknob. The tolerance analysis shows that the VSWR remains below 1.1 with ±0.4 mm change of each parameter. The thermal analysis was carried out for the waveguide transition and doorknob under heat load from 1 MW RF power transmitted through. To keep the temperature rise at the doorknob smaller than 1°C, it requires cooling by a water flow of 1 GPM along the inner corner of the doorknob.

MULTIPACTING SIMULATIONS

Simulations of multipacting in the FPC were carried out using Track3P [6], a 3D particle tracking code. Figure 4 shows the side view of the FPC model used in simulations. The input power was swept from 1 kW to 250 kW with full reflection at different phases of reflection, which later allowed us to compare the simulation results directly with the actual FPC conditioning in a standing wave mode. At each power level, 50 or more RF cycles were simulated to obtain parameters of the resonant trajectories. Multipacting is possible if the final impact energy of the electrons after 50 RF cycles is in the region where SEY > 1 (120 eV to 2500 eV for copper).

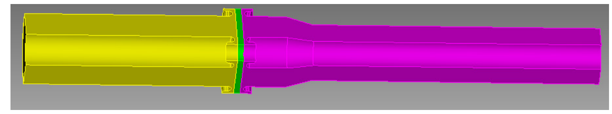

Figure 4: Side view of the FPC model for multipacting simulation: magenta – vacuum side, green – window, yellow – air side.

The simulation results show that multipacting occurs mostly in the vacuum side coaxial line. Multipacting in the RF window area was found only between 24 and 77 kW. Additionally, the multipacing zones are not sensitive to the RF phase of the reflected wave and also not sensitive to the RF frequency, although the strength of multipacting varies with the frequency change. Plots in Fig. 5 indicate strong multipacting at RF power levels of about 22 to 35 kW, 40 to 77 kW (window), 78 to 120 kW and about 135 to 205 kW. The simulations show that dominant is the two-surface multipacting. Figure 6 shows typical multipacting trajectories: in the coaxial line (left), which is a two-surface multipacting, and between the window and the choke (right).

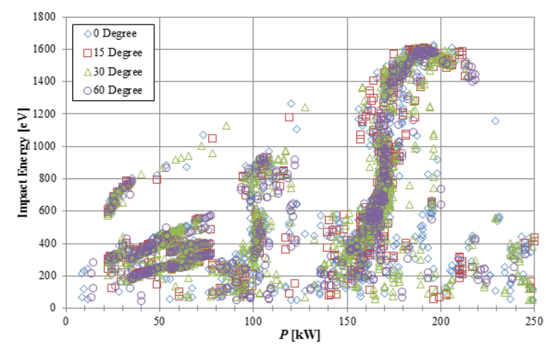

Figure 5: Multipacting simulation at different phases.

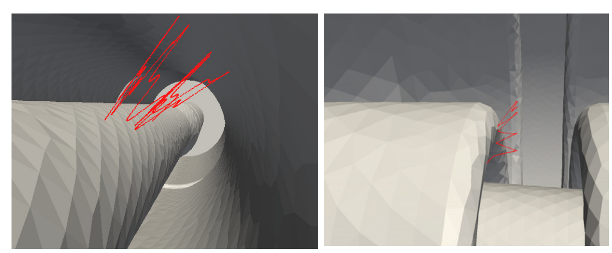

Figure 6: Multipacting at 110 kW in the coaxial line (left) and between the window and choke at 60 kW (right).

FUNDAMENTAL POWER COUPLER CONDITIONING

The FPC conditioning stand, shown in Fig. 7, is assembled on a robust, mobile aluminum cart [7]. It consists of a vacuum pump system and connecting waveguide. RF conditioning of the couplers is performed under ultra-high vacuum (UHV). UHV is maintained by a turbo-molecular pump, which is backed by a dry (oil free) mechanical pump. Vacuum near the ceramic window is measured with two magnetron gauges, providing vacuum signals for RF power level controls during the conditioning. In addition, a residual gas analyzer is provided for leak checking. A fast-response vacuum controller provides signal to the machine protection system (MPS) to shut down RF if vacuum becomes poor. Two FPCs are mounted on the connecting waveguide to be conditioned simultaneously.

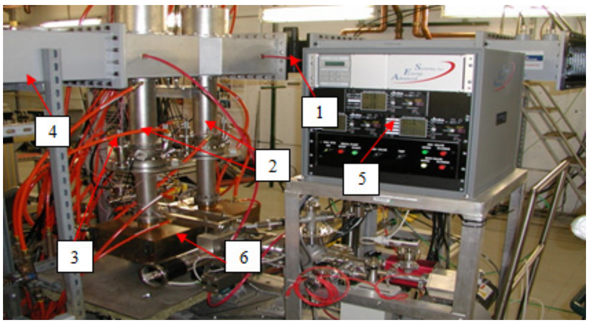

Figure 7: Assembly of the FPCs for conditioning: 1 – waveguide connecting to 1 MW klystron, 2 – two FPCs, 3 – cooling hoses, 4 – waveguide phase shifter and a short plate, 5 - vacuum instrument on the conditioning cart, 6 – connecting waveguide.

The conditioning was carried out in a standing wave mode. One FPC is connected to a circulator downstream of a 1 MW CW klystron [8], the other one is connected to a variable RF phase shifter and a short plate. Four sets of directional couplers (one before the circulator, one before the water load, one before and one after the FPC cart) are used to measure RF power levels. The Machine Protection System permission sums arc detector, vacuum, and water flow signals to enable the klystron operation. Prior to conditioning, two waveguide adapters were connected to the upstream and downstream of the couplers, and S-parameters were measured for different settings of the phase shifter. Minimum VSWR was measured at 703.9 MHz. The -1 dB bandwidth of the klystron is larger than ±0.7 MHz with the central frequency at 703.75 MHz. This allowed us to condition the coupler at 703.9 MHz.

Figure 8 compares the multipacting zones from FPC conditioning test (grey-shaded areas) and simulation results at 703.9 MHz with 0 degree (black dots). During the test, we encountered and conditioned multipacting zones at 8 to 10 kW, 16 to 25 kW, 40 to 70 kW, 85 to 120 kW and about 165 to 185 kW. Above 185 kW, there was a lot of outgassing. After FPCs were conditioned at 0 degree of RF phase, the procedure was repeated at every 10 degrees by adjusting the phase shifter. No multipacting zones other than the shown in Fig. 8 were found. It confirmed non-sensitivity of the multipacting power levels to the phase of reflection, as multipacting mainly occurs in the coaxial line, and only one multipacting zone happens at the window. For different RF phases, the processing went similar and the conditioning time was close except for the very first run, which took most of the test time to ramp up the RF power and it was much shorter time for the later runs.

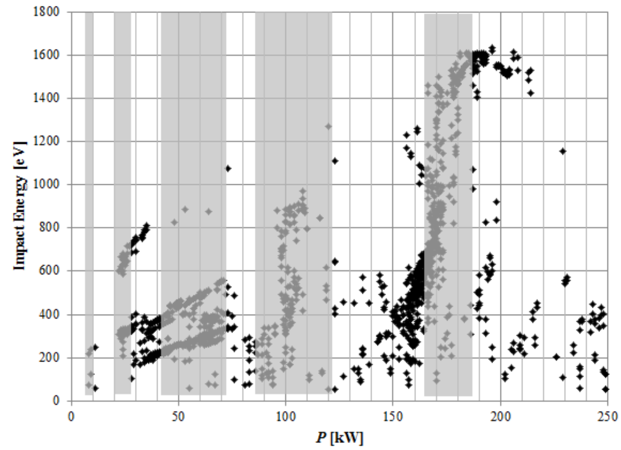

Figure 8: Comparison of multipacting zones from FPC conditioning test (grey-shaded areas) and simulation results at 703.9 MHz with 0 degree (black dots).

SUMMARY

To satisfy requirements of the SRF gun for R&D ERL, a high power CW fundamental power coupler was designed. Two FPCs were fabricated and conditioned in standing wave mode with a 1 MW klystron. The simulations of multipacting were carried out with Track3P. The simulations predicted multipacting zones that were later found during conditioning.

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