DESIGN, FABRICATION, AND TESTING OF NOVEL HIGH POWER RF INPUT COUPLERS

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Abstract

A novel high power RF coupler was developed and designed by AMAC to reliably operate at an average power level over 200 kW and to exceed the present specification requirements for the SNS accelerator project. CPI performed the manufacturing optimization and the fabrication of prototypes. The RF couplers were conditioned and tested at the Jefferson Laboratory.

An innovative feature consisting of a compression ring was incorporated to reduce the tensile forces on the ceramic by pre-stressing the ceramic and increase the reliability of the ceramic window. Watercooling is used to remove the dissipated power at the window and the antenna. Extensive calculations were performed to optimize window design using MAFIA, HFSS, ANSYS, multipacting program. Based on the above efforts, an innovative RF surfaces design (AMAC-2) was developed to remove the chocks used in AMAC-1 and provided the following advantages: better vacuum, easier cleaning, and less secondary electron-multipacting. The simulation, design consideration, engineering design and results of the RF high power qualification were briefly discussed in this paper.

1 INTRODUCTION

The RF window problem has grown as the power required for waveguide and coaxial operating systems has exceeded prior design margins [1, 2, 3, 4]. Failures of windows generally occur in three categories: (1) excessive heating, (2) arcing, and (3) weak mechanical designs. In the first case, power lost in transmission through the window has not been adequately removed and the resulting stress build-up within the window exceeds the tensile strength of the material. In the second case, failure is a result of charges building up on one side of the window developing an electrical gradient, which exceeds the dielectric strength of the window material. The resulting breakdown arc causes a puncture through the window and a loss of vacuum. In the third case, the mechanical design of the window is so weak that small variation in thermal gradients (cases due to waveguide arcing) cause the window to crack.

AMAC was awarded by the US Department of Energy the SBIR [1] grant to develop the high RF power input coupler AMAC-2 to resolve some of these challenges [5, 6]. AMAC-2 aims to replace the AMAC-1 design [7] to improve the multipacting characteristics, vacuum properties, and to allow for easier cleaning and fabrication procedures. After extensive RF calculations, using MAFIA and HFSS programs, the design was further analyzed for multipacting resonances with a program implemented at the University of Helsinki [7]. The calculation results support the selection of this design for 200 kW average RF power operation. An innovative feature consisting of a compression ring was incorporated to reduce the tensile forces on the ceramic by pre-stressing the ceramic and increase the reliability of the ceramic window. Watercooling is used to remove the dissipated power at the window and the antenna.

For further commercialization of the innovative technologies, the frequency and cryomodule dimensions are chosen to develop the high RF power couplers: a coaxial 805 MHz, 50 Ohm coupler design with a waveguide transition, an inner conductor bias voltage of 2.5 kV, and the installation of the RF ceramic window in a –30° standing wave phase angle position. CPI fabricated three AMAC-2 window-couplers. The fabrication is described in more detail in a separate presentation in this workshop. The coupler windows have been conditioned and RF qualified at the Jefferson Laboratory as part of a CRADA [8] collaboration agreement. Figure 1 shows the complete coaxial coupler assembly.

1.1 Design Specification

The main specification parameters for SNS prototype couplers are:

- VSWR for window assembly: 1.05 or lower at 805 MHz
- Power input: 550 kW peak traveling wave, Average power: 53 kW (with 10 % margin)
- Beam on pulse length: 1.0 ms, RF on pulse length: 1.3 ms

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Pulse repetition rate: 60 Hz, RF active duty factor: 8.7%
Standing wave in full reflection: 4 MW (for up to 150 µs)
Maximum radiative heat loss to 2.1K circuit: 1 W
Operating pressure: <5 × 10⁻⁹ torr, Radiation resistance at tip of antenna: 4 × 10⁹ rads

2 COUPLER RF DESIGN

We chose a typical door-knob design for the waveguide-co-axial transition. The coupler RF geometry was modeled using the HFSS program. Figure 2 shows the plot of calculated electric fields, and Fig.3 shows the geometry of the window area.

2.1 Window RF Design
Extensive calculations were performed for this window design using the MAFIA algorithm and the finite element analysis code HFSS. The MAFIA results are more accurate for the fields and losses calculations, but the simulation times become extremely long for larger number of mesh points. After verifying the agreement between the results of the initial calculations using both methods, we used only the HFSS program for detail parameter optimization. Figures 4 to 11 show the electric and magnetic field distributions, and the losses in the ceramic window.
Fig. 5 Magnetic fields along the surface of the ceramic window

Fig. 6 AMAC-2 Magnetic Field Amplitude Along Surface of Reduced Inner Conductor

Fig. 7 Contour plot of magnetic field in AMAC-2 at 1/2W incident power

Fig. 8 Contour plot of electric field in AMAC-2 at 1/2W incident power

Fig. 9 Radius dependence of electric field at the ceramic center plane of AMAC-2 at 1000 W of incident power

Fig. 10 Contour plot of dielectric loss of ceramic in AMAC-2 at 1/2W of incident power
3 MULTIPACTING CALCULATIONS

The vacuum side of the ceramic window is coated with 10-15 Angstrom Titanium Nitride to reduce the secondary electron emission activity at the Alumina ceramic window. The multipacting calculations take into account the properties of this coating, and use secondary emission data for copper and copper plated surfaces extended to 50 eV on the lower energy side.

These calculations were performed at the University of Helsinki [7, 9] using a program that tracks electron trajectories in various wave reflection conditions and determines their enhancement possibility for different power levels. These calculations are considered a reliable indication of multipacting occurring due to secondary electron emission on the coupler surfaces in the vacuum region, and are used to validate the coupler geometry in the design stage. The description and results of the calculations are shown in Fig.12. R is the reflection coefficient (R=1 corresponds to full reflection (standing wave) with an electric minimum at the center of the window, and R=0 corresponds to a traveling wave condition). F is the phase angle position of the window in the reflected wave (F = 0° is when the center of the window is at the position of minimum field at full reflection).

The results show low multipacting activity at several phase angle positions. The F=+30° phase angle position shows the lowest multipacting activity, but F=-30° was used for the design because of SNS cryostat constraints.

It is evident from the comparative results for up to 1.2 MW peak power levels (104 kW average power), that the AMAC-2 version shows a much lower multipacting activity than the AMAC-1 version in all reflection and power level conditions. Further calculations for were performed for AMAC-2 at higher power levels up to 4 MW peak power (648 kW average power) for F=-30°. Figure 13 shows the results for the total reflection (R=1) and the traveling wave case (R=0) for up to 4 MW peak power levels.
4 COOLING

The antenna and the inner and outer edges are water-cooled. The circuit is designed for up to 150 psi water pressure and the water circuits are not in direct contact with the thin copper cylinders attached to the ceramic to avoid the risk leaks into the vacuum system in case of eventual corrosion. The water velocity was limited to less than 1.2 m/s also to reduce the possibility of radiolitic corrosion. The calculated temperature increase in the water circuit is approximately 2°C and depends on the actual losses on the ceramic.

The maximum calculated temperature difference on the ceramic along the surface is 15°C for 200 kW average power and loss tangent value 0.0006.

5 COMPRESSION RING AND STRESS ANALYSIS

A stainless steel compression ring was added to AMAC-2 to reduce the thermal tensile stresses in the ceramic during high power operation [6]. For a case of 500 kW input power with symmetric cooling, the compression ring reduces the maximum tensile stress in the ceramic to 2.7 kpsi (the maximum stress occurs at the outer brazing edges). This is only 47% of the corresponding stress without the compression ring.

A check of alternate materials for the compression ring (Berillium Copper and Aluminum) showed no significant stress differences for this application.

Table 1 lists the calculated tensile stresses in the ceramic for different average power levels.

<table>
<thead>
<tr>
<th>Average Power (kW)</th>
<th>Max. Tensile Stress (ksi)</th>
<th>Bulk Tensile Stress (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no CR</td>
<td>with CR</td>
</tr>
<tr>
<td>Symmetric cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>5.7</td>
<td>2.7</td>
</tr>
<tr>
<td>200</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>53</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Asymmetric cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(32°C inner edge, 62°C outer edge)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>7.2</td>
<td>3.7</td>
</tr>
<tr>
<td>200</td>
<td>5.2</td>
<td>3.1</td>
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<tr>
<td>53</td>
<td>4.3</td>
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<td>Asymmetric cooling</td>
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<td>(62°C inner edge, 32°C outer edge)</td>
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<td>500</td>
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<td>200</td>
<td>5.1</td>
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<td>53</td>
<td>3.8</td>
<td>2.2</td>
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</tbody>
</table>

Figures 14 to 17 show some typical ANSYS plots for the stresses and temperatures.
6 RF TEST RESULTS

The tests were not completed at this time because of a klystron failure at the test facility. The presented results are mainly for the traveling wave condition, and it is expected that the standing wave tests will be completed in the next two months. Figure 18 shows the test fixture.

6.1 Preparation Procedure (Pressure Rinse, Bakeout, Ultimate Vacuum, RGA, Etc.)
6.2 RF Conditioning On The Test Stand (Vacuum Response Vs. Power And Pulse Length, And Vacuum Residual Gas Analysis)

Conditioning and testing at room temperature was performed at JLAB using the 1 MW RF system consisting of a klystron, waveguide distribution system, terminating load or variable short circuit, directional couplers and associated RF power meters, electronic racks for klystron controls, coupler instrumentations, interlocks, software for RF processing and data acquisition. Coupler No1 was on the klystron side, coupler No2 on the RF terminating load (Short circuit). The process consisted in starting conditioning in TW mode with low RF power amplitude and duty cycle and increasing the RF power amplitude and duty cycle to the specifications (our capabilities were limited by RF system to 1 MW, 6% duty cycle. After reaching maximum RF power, the RF was cycled between different power levels, or maintained constant for an extended period of time (similar with machine operation). During conditioning and high power RF testing, vacuum, electron activity, arcing events, temperatures and flows on the cooling water, and RGA were continuously recorded.

6.3 Conditioning Times

In TW mode, the time to reach 1 MW (1 ms, 30 Hz at the end) was about 24 hour of RF conditioning.

6.4 Water Temperature Rise, Flow Rate And Pressure Drop At Maximum RF Power.

The flow was maintained constant at about 0.3 gpm (actually it was at the control limit of out valves), antenna and the border of the ceramic windows being “cooled” in series by the same water circuit on the same coupler. No T change on temperature readings (under our measurement conditions) or water flow were identified during long term constant power tests on both versions of window. Temperatures at the windows were always about 32 Celsius degrees (temperature of the cooling water).

6.5 Electron Activity

During conditioning, the maximum electron activity in excess of 200 nA was measured on both windows, starting with RF power of 250-300 kW.

6.6 Power RF Results (Power, Vacuum And Other Limitations Or Result)

In TW mode up to 1 MW (1 ms, 30 Hz), test “CW” at 800 kW for about 100 minutes O.K. In TW mode CW test at 400 kW (1 ms, 40 Hz - due RF system limitations) for 3 hours. In SW mode up to 800 kW local peak power. Tests stopped due to klystron problems.

7 ACKNOWLEDGMENTS

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8 REFERENCES