Input Power Coupler Development
for Low-Beta Superconducting Cavities

Jon Wlodarczak
USPAS
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Overview

- Background
  - Introduction
  - Types
  - Windows
- Project motivation
  - Application
- Methodology
  - Design
  - Conditioning
  - Testing

Cornell 500 MHz storage ring SRF cavity
Introduction

• Necessary for (nearly) all cavities
  – Fundamental power couplers (FPCs) transfer RF power from the generation system to the cavity, and thus to the beam
  – HOM couplers remove energy from cavity
• Commercial couplers are quite expensive
  – High power
    • 805 MHz medium beta elliptical cavities were 10 kW CW and $30,000 each.
• Failure is expensive
• Challenging design
  – Multi-disciplinary design
  – Trade-offs
Electrical Function

- Couple power from amplifiers to cavity
- Designed for CW or pulsed operation
- Impedance match to source
Mechanical Function

- Vacuum feed through
  - Separates cavity vacuum from atmosphere
  - Seals cavity from potential contamination

- Thermal isolation
  - Separates room temperature from cryogenics
  - Withstand repeated thermal cycles
    - Contraction rates
Coupler Types: Coaxial

- Transmission line
  - Coupling
    - Electrical
      - Probe
    - Magnetic
      - Loop
  - Impedance
    \[
    Z_o = \frac{\eta_o}{2\pi} \ln \left( \frac{r_{oc}}{r_{ic}} \right)
    \]
    - Ratio for 50 Ω
      - \( r_{oc} = 2.3 \ r_{ic} \)
Coupler Types: Waveguide

- Waveguide
  - High power
  - Large size
  - $\text{TE}_{01}$

$$f_c = \frac{\eta}{2b\sqrt{\mu\varepsilon}}$$

- width $\approx$ 1.9 meters
  @ 80.5 MHz
Power Coupler Comparison

- **Waveguide**
  - Large
  - Simple
  - Larger heat load
  - Complex variability
  - High pumping speed
  - Fixed frequencies

- **Coaxial**
  - Compact
  - Complex
  - Small heat load
  - Less complex variability
  - Low pumping speed
  - All frequencies
Window Types

- Warm window
  - Outside module
  - Further from cavity

- Cold window
  - Inside module
  - Increase thermal stress
  - Vacuum on 2 sides
  - Seals cavity before module assembly

- Planar
  - Waveguide

- Coaxial
  - Disc
  - Conical
  - Cylindrical

Coaxial disc, planar and cylindrical windows
Potential Problems

- Barrier faults
  - Cracked windows
    - Mechanical
    - Thermal
  - Bad brazement
  - Leaky bellows
  - Flange seal

- Transmission faults
  - Multipacting
    - Heating
    - Arcing
  - Ceramic metallization
  - Gas condensation
  - $Q_{ext}$ shift
    - Fixed couplers
Motivation

- Create an affordable power coupler for the QWR that is robust and capable of handling the power requirements.
Application: QWR Cavities

\[ \beta_{opt} = 0.041 \quad 80.5 \text{ MHz} \]
\[ \beta_{opt} = 0.085 \quad 80.5 \text{ MHz} \]
\[ \beta_{opt} = 0.16 \quad 161 \text{ MHz} \]
\[ \beta_{opt} = 0.285 \quad 322 \text{ MHz} \]
\[ \beta_{opt} = 0.425 \quad 322 \text{ MHz} \]
# More on QWR Cavities

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda/4$</th>
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<tbody>
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<td>$\beta_{opt}$</td>
<td>0.041</td>
<td>0.085</td>
<td>0.160</td>
<td>0.285</td>
<td>0.425</td>
</tr>
<tr>
<td>$V_a$ (MV)</td>
<td>0.46</td>
<td>1.18</td>
<td>1.04</td>
<td>1.58</td>
<td>2.51</td>
</tr>
<tr>
<td>$I_{beam}$ (pµA)</td>
<td>10.6</td>
<td>10.6</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>$&lt;Q&gt;$</td>
<td>28</td>
<td>28</td>
<td>73</td>
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<td>89</td>
</tr>
<tr>
<td>$P_{beam}$ (W)</td>
<td>118</td>
<td>350</td>
<td>510</td>
<td>784</td>
<td>1610</td>
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<tr>
<td>$Q_{beam}$</td>
<td>$4.2\times10^6$</td>
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<td>$1.6\times10^7$</td>
<td>$1.9\times10^7$</td>
</tr>
<tr>
<td>$P_g$ (W)</td>
<td>236</td>
<td>700</td>
<td>1020</td>
<td>1570</td>
<td>3210</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>$1.4\times10^6$</td>
<td>$3.2\times10^6$</td>
<td>$1.9\times10^6$</td>
<td>$5.3\times10^6$</td>
<td>$6.2\times10^6$</td>
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<td>Control bandwidth $\Delta_{allowed}$ (Hz)</td>
<td>54</td>
<td>23</td>
<td>81</td>
<td>56</td>
<td>47</td>
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<td>$&lt;\phi&gt;$ (deg)</td>
<td>-30</td>
<td>-30</td>
<td>-35</td>
<td>-35</td>
<td>-30</td>
</tr>
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</table>
Design Methodology: Mechanical

- **Size**
  - 3-D model
  - Fitment
- **Assembly**
- **Thermal analysis**
  - Vacuum side O.C. Plating
- **Material specification**
Design Methodology: Electrical

- **Coupler type**
  - Cavity placement
- **Modeling**
  - Fields
  - S-parameters
    - Reflection
    - Transmission
Electrical Parameter Measurements

- Measuring
  - S-parameters
    - Reflection
    - Transmission
- Coupling
  - $Q_{\text{ext}} = 2 \times 10^6$
Prototype

- Ultrasonic Cleaning
  - Micro-90 solution
    - 20 minutes
  - Ultra pure water
    - 40 minute rinse
- Assembly
- Class 100 Clean room
Prototype cont.

- Bake-out
  - 200° C
  - 36 hours
Bake-Out: Temperature & Pressure
Bake-Out RGA Readings

Before

2 hrs. after

2 days after
Conditioning Assembly

- Two couplers at a time
  - Shorted
Conditioning Stand

- Standing-wave
  \[ P_{sw} = P_{in} + 20 \text{ dB} \]
Conditioning

- Sliding shorts
  - Full wave
    - 3.7 meters
  - Moved in 3” increments
Conditioning Sweep
RGA Before, During, and After

During conditioning
@ 63” (near window)
Pressure ≈ 8.5x10^{-6} Torr

After bake-out
Pressure ≈ 1.4x10^{-8} Torr

After conditioning
Pressure ≈ 9.4x10^{-9} Torr
Conditioning Issues

- Over-heating
  - Possibly due to non-plated O.C.
    - Melted solder
    - Vacuum breach
    - RGA failure
    - Turbo pump destroyed

- Replaced soft solder (m.p. = 249°C) with silver braze (m.p. = 635°C)
Future Work

- New flange design
  - Thicker tubing on diagnostic ports
- Implement IR pick-up
- Determine how much reconditioning is necessary after “sitting” in clean room
- Determine if canted springs are necessary
  - Simplify design and assembly
  - Better RF match at window
- Test couplers on new prototype QWR
- Measure copper plating thickness
Conclusions

- Conditioning process drove out residual contaminants from window.
  - 10 kW standing-wave
  - Slow, approx. 8 days
- Window able to withstand non-ideal operation
  - Solder failure
  - Mechanical stress
- Assembly capable of operating at 1 kW CW for 7 days.
- Comparatively affordable, prototype cost was about $6,000 each
Resources

- J. Delayen, Couplers, USPAS, Maryland, June 2008
- B. Rusnak, “RF Coupler and HOM Coupler Tutorial,” 11th Workshop on RF Superconductivity, 2003
- National Superconducting Cyclotron Laboratory, “Isotope Science Facility at Michigan State University: Upgrade of the NSCL rare isotope research capabilities,” NSCL, East Lansing, MI, 2006
Questions?
### Table 5.10: Electromagnetic and cryogenic parameters.

<table>
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<td>$f$ (MHz)</td>
<td>80.5</td>
<td>80.5</td>
<td>161</td>
<td>322</td>
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<tr>
<td>$T$ (K)</td>
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<td>4.5</td>
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<tr>
<td>$R/Q$ (Ω)</td>
<td>424</td>
<td>416</td>
<td>381</td>
<td>199</td>
<td>210</td>
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<tr>
<td>$G$ (Ω)</td>
<td>15.7</td>
<td>19.0</td>
<td>35.0</td>
<td>61.0</td>
<td>86</td>
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<tr>
<td>$G\cdot R/Q$ (kΩ²)</td>
<td>6.66</td>
<td>7.90</td>
<td>13.3</td>
<td>12.1</td>
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<td>$E_g$ (MV/m)</td>
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<td>20</td>
<td>20</td>
<td>25</td>
<td>30</td>
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<td>$V_s$ (MV)</td>
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<tr>
<td>$J$ (A/m²)</td>
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<td>6.19</td>
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<td>$R_{c}$ (nΩ)</td>
<td>2.5</td>
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<td>10.1</td>
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<td>$R_{min}$ (nΩ)</td>
<td>5</td>
<td>5</td>
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<td>$Q_{max}$</td>
<td>$2.1 \times 10^9$</td>
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<td>$Q_{design} = Q_0$</td>
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<td>$P_{design}$ (W/cav) = $P_0$</td>
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<td>4.3</td>
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### Table 5.12: Beam loading requirements by cavity type for uranium at 400 kW and 200 MeV/u. ($I_{beam}$ denotes beam current, $<q>$ denotes average charge state, $<\phi>$ denotes average synchronous phase.)

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\[ \beta_1 = \frac{1 - 10^{(S_{11}/20)}}{1 + 10^{(S_{11}/20)}} \]

\[ \beta_2 = \frac{10^{(S_{21}/10)}}{1 - 10^{(S_{11}/10)} - 10^{(S_{21}/10)}} \]

\[ Q_o = (1 + \beta_1 + \beta_2) \times Q_L \]

\[ Q_{ext2} = \frac{Q_o}{\beta_2} \]

\[ BW = \frac{f_r}{Q_{ext2}} \]

\[ Q_L, S_{11}, S_{21} \text{ are measured values} \]