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Input Power Coupler Development

for Low-Beta Superconducting Cavities

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USPAS

Annapolis, Maryland, June 2008

NSCL

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Overview

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

Cornell 500 MHz storage ring SRF cavity

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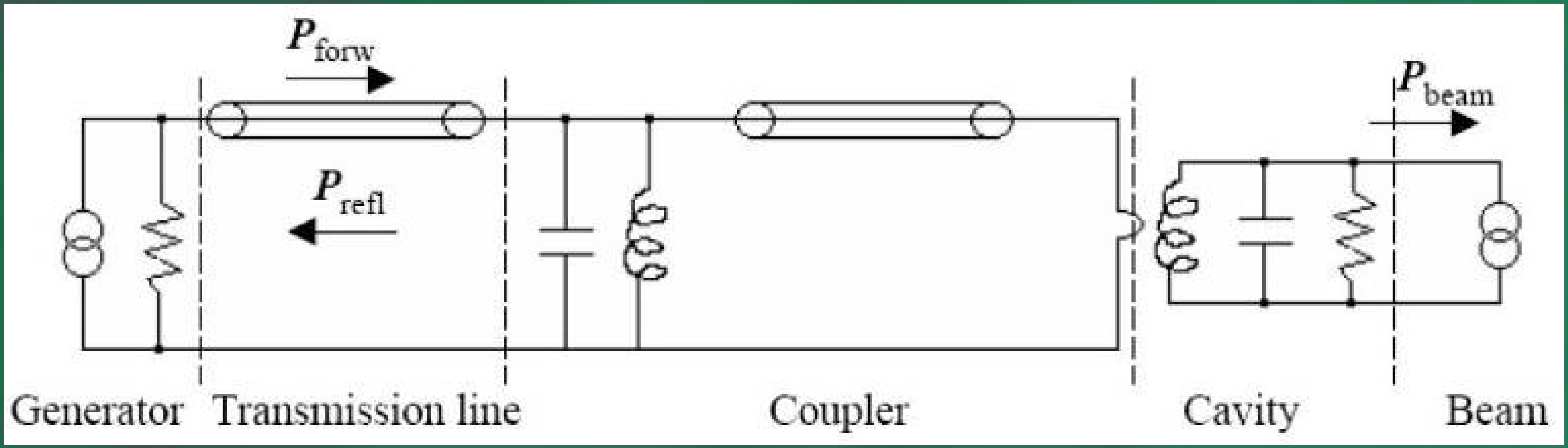
Introduction

- 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



J. Delayen, USPAS, MD 2008

Mechanical Function

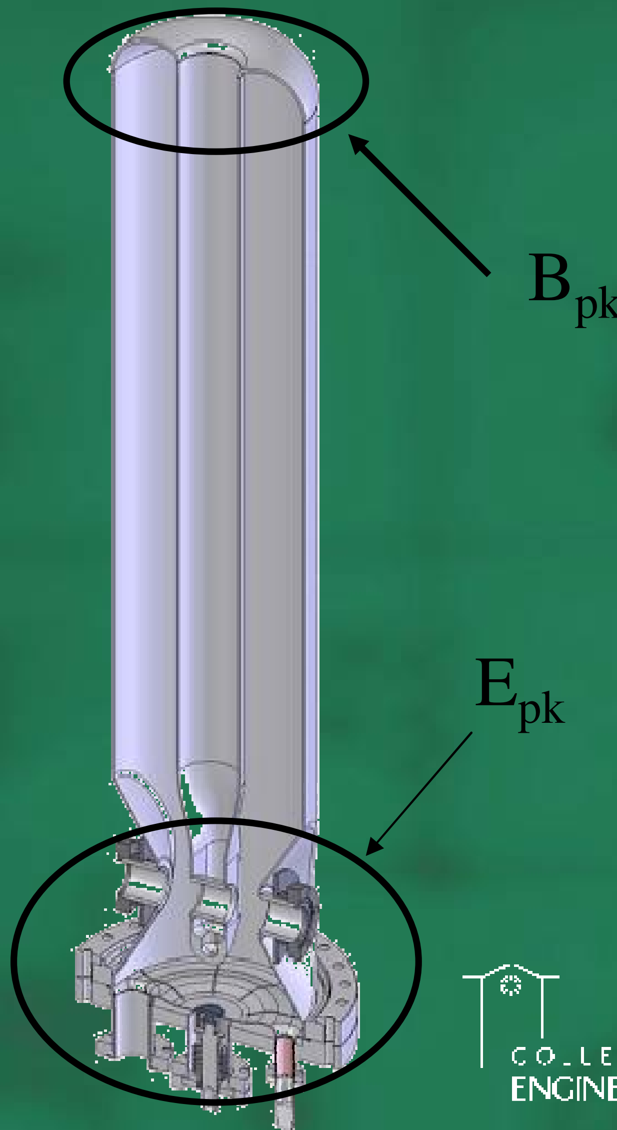
- Vacuum feed through
  - Separates cavity vacuum from atmosphere
  - Seals cavity from potential contamination
- Thermal isolation
  - Separates room temperature from cryogenics
  - Withstand repeated thermal cycles
    - Contraction rates

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
  - $r_{oc} = 2.3\ r_{ic}$

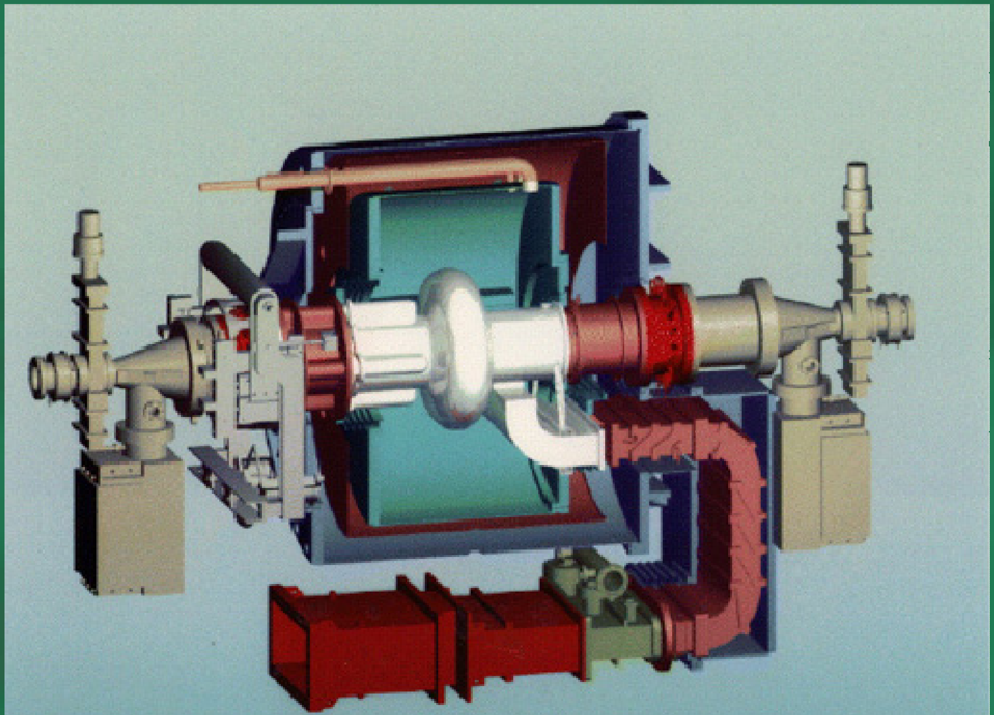


Coupler Types: Waveguide

- Waveguide
  - High power
  - Large size
    - TE_{01}

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

- width ≈ 1.9 meters @ 80.5 MHz

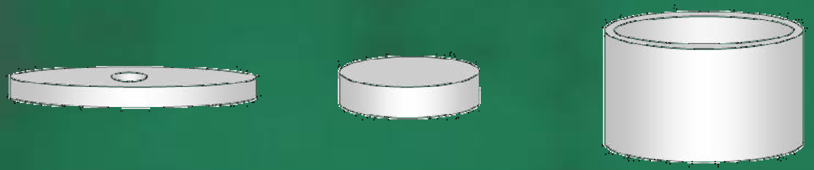

CESR Cavities

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

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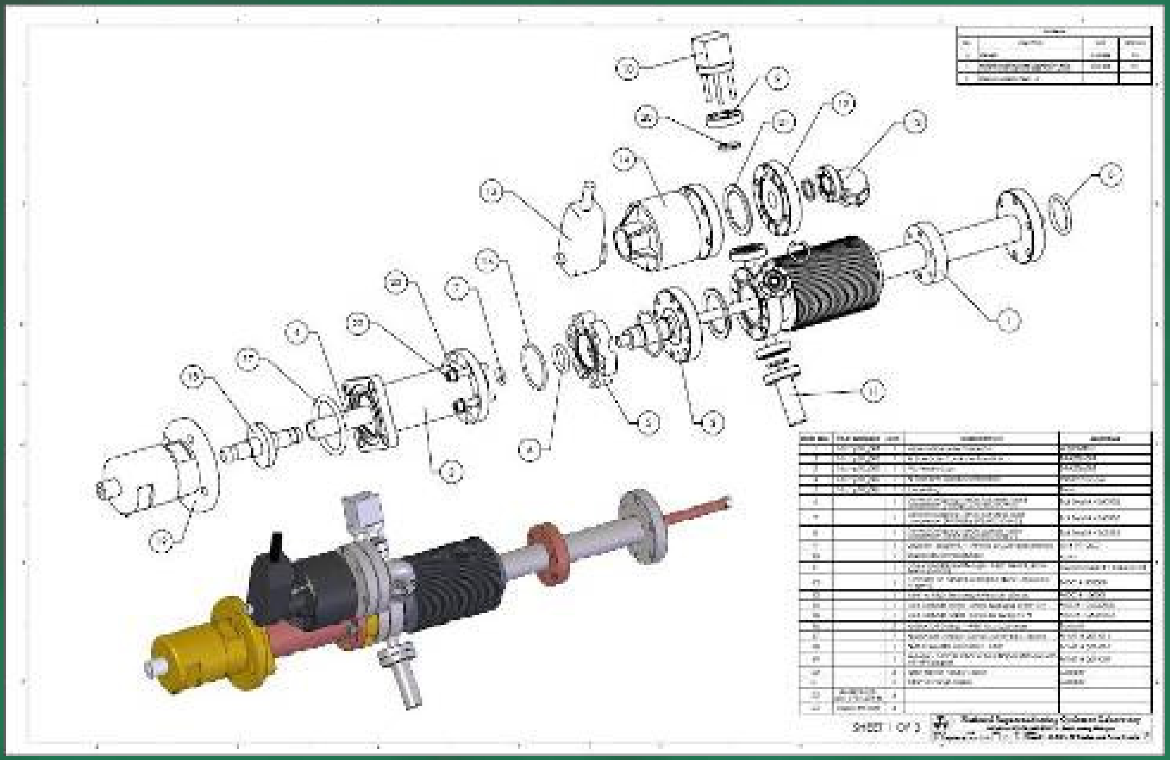
Motivation

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



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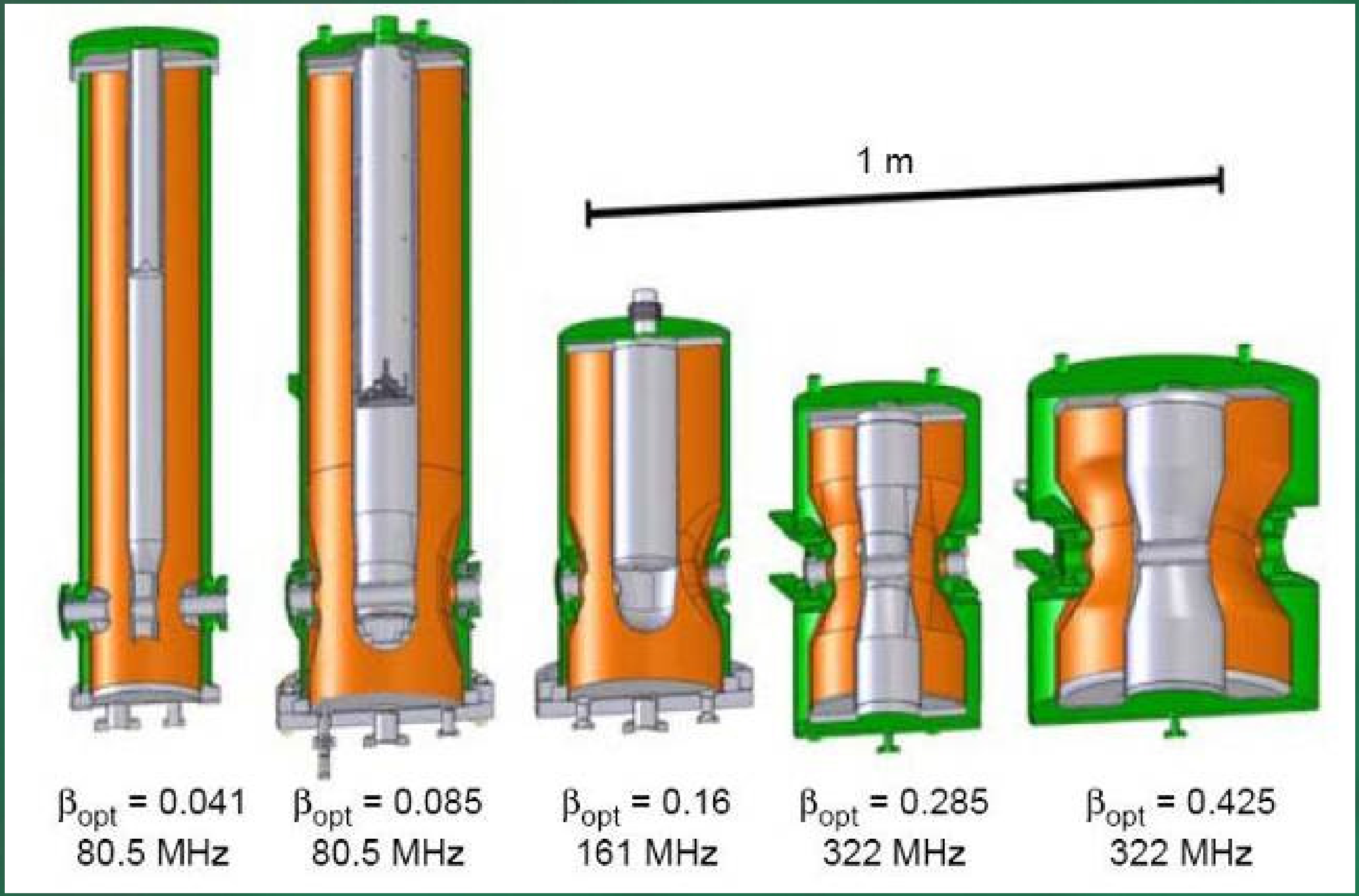
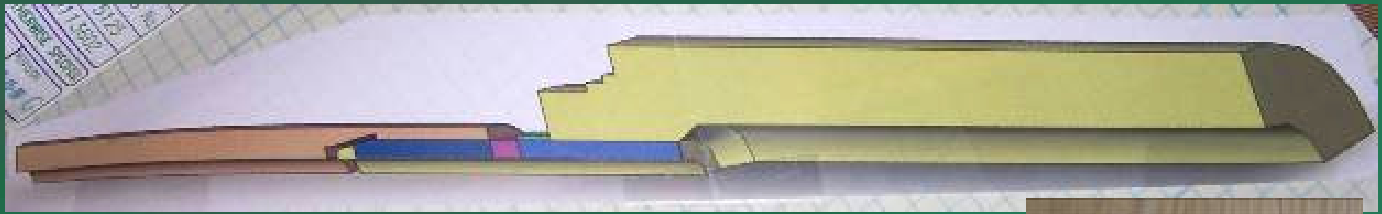
Application: QWR Cavities



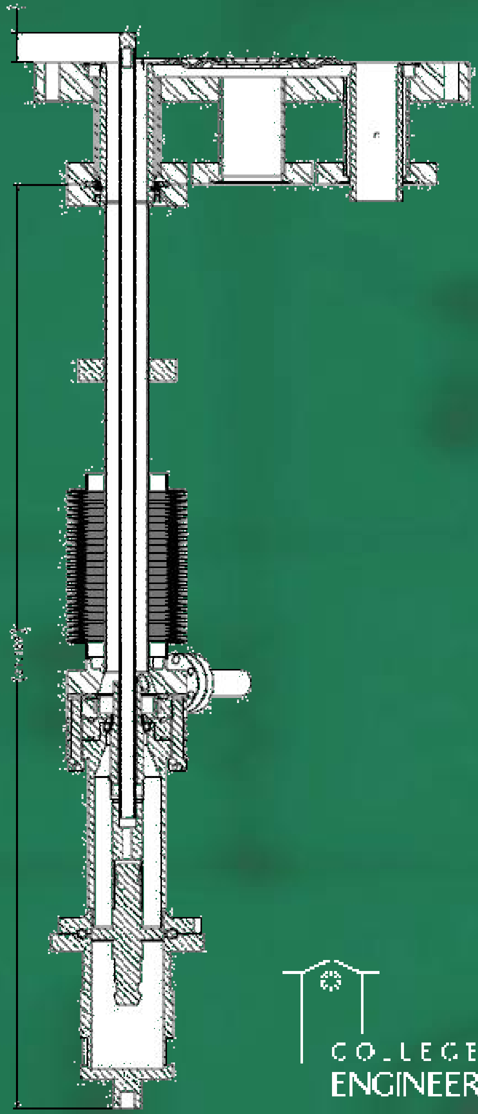
More on QWR Cavities

Type	λ/4	λ/4	λ/4	λ/2	λ/2
β_{opt}	0.041	0.085	0.160	0.285	0.425
V_a (MV)	0.46	1.18	1.04	1.58	2.51
I_{beam} (pμA)	10.6	10.6	8.3	8.3	8.3
$\langle Q \rangle$	28	28	73	73	89
P_{beam} (W)	118	350	510	784	1610
Q_{beam}	4.2×10^6	9.6×10^6	5.6×10^6	1.6×10^7	1.9×10^7
P_g (W)	236	700	1020	1570	3210
Q_L	1.4×10^6	3.2×10^6	1.9×10^6	5.3×10^6	6.2×10^6
Control bandwidth $\Delta_{allowed}$ (Hz)	54	23	81	56	47
$\langle \phi_s \rangle$ (deg)	-30	-30	-35	-35	-30

Design Methodology: Mechanical

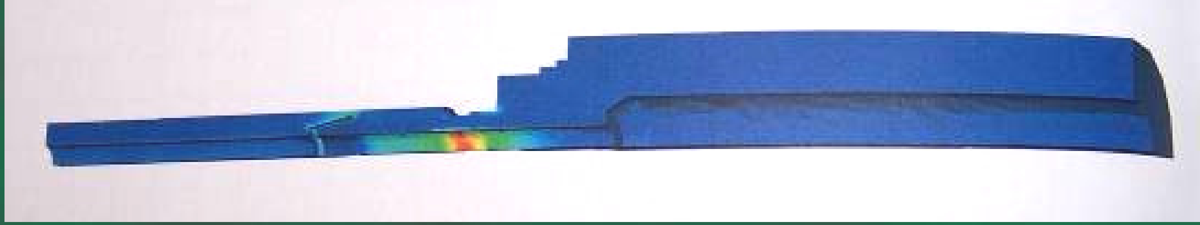


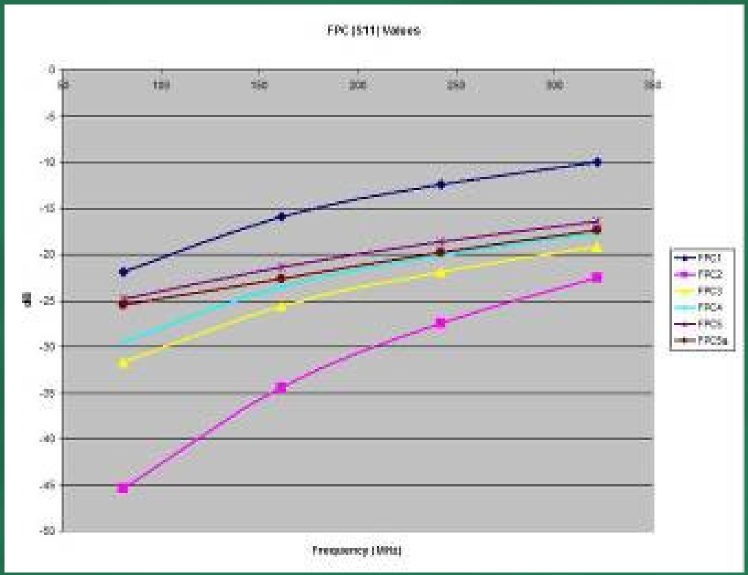
- Size
  - 3-D model
  - Fitment
- Assembly
- Thermal analysis
  - Vacuum side O.C. Plating
- Material specification



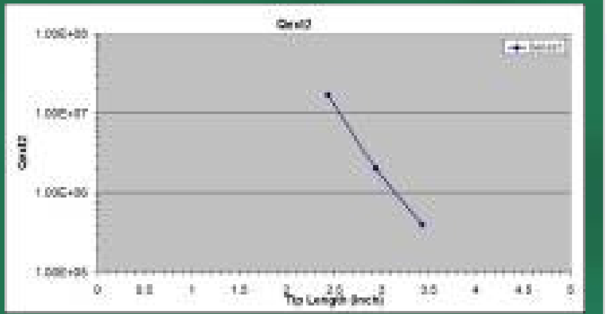
Design Methodology: Electrical

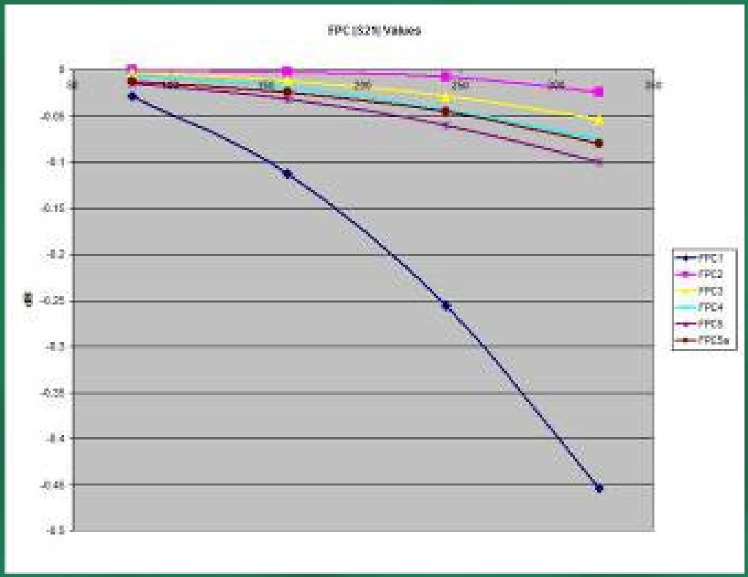
Analyst E-field model





- Coupler type
  - Cavity placement
- Modeling
  - Fields
  - S-parameters
    - Reflection
    - Transmission





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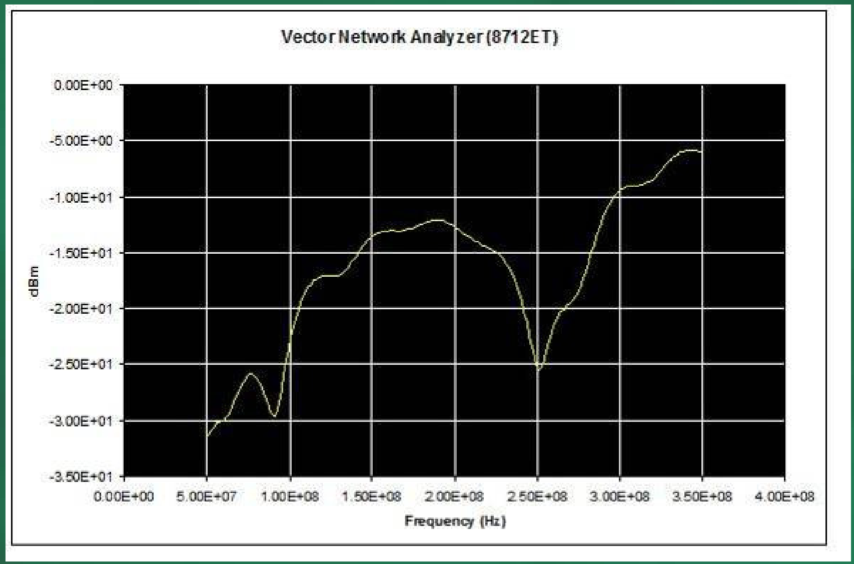
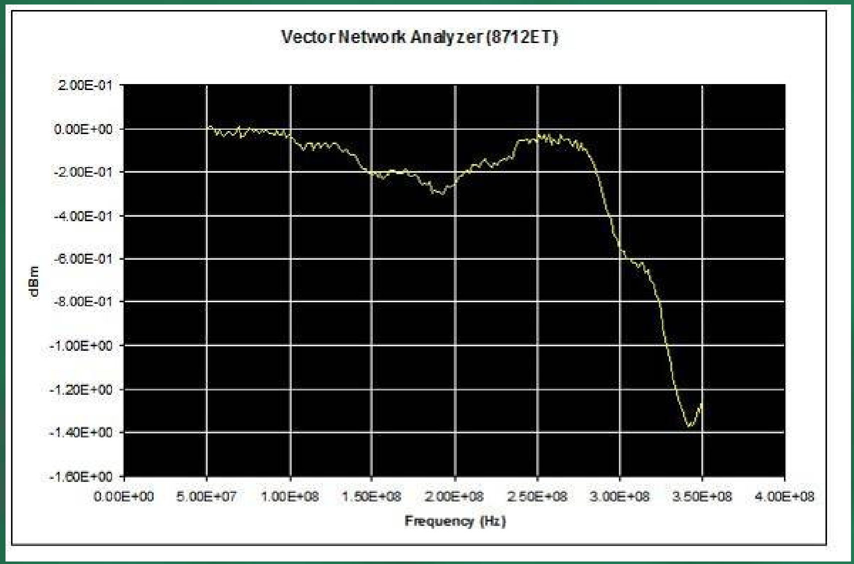
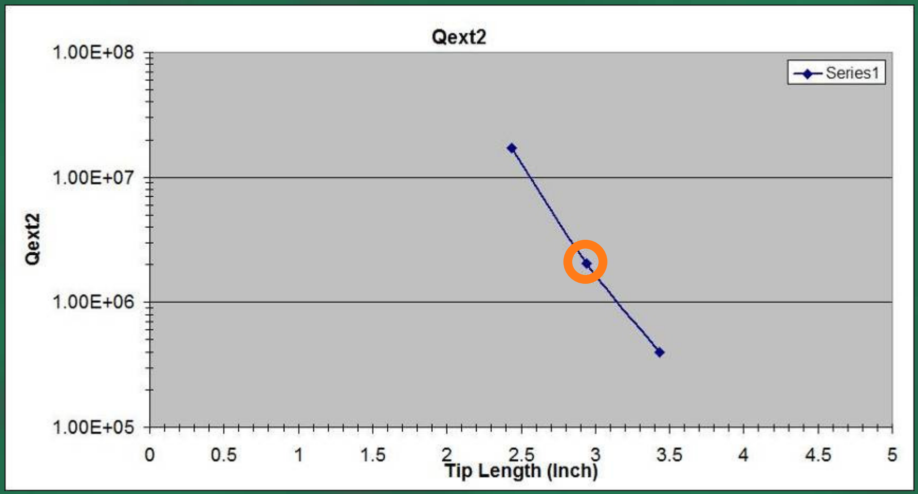
Electrical Parameter Measurements

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







Prototype

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

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Prototype cont.

- Bake-out
  - 200º C
  - 36 hours

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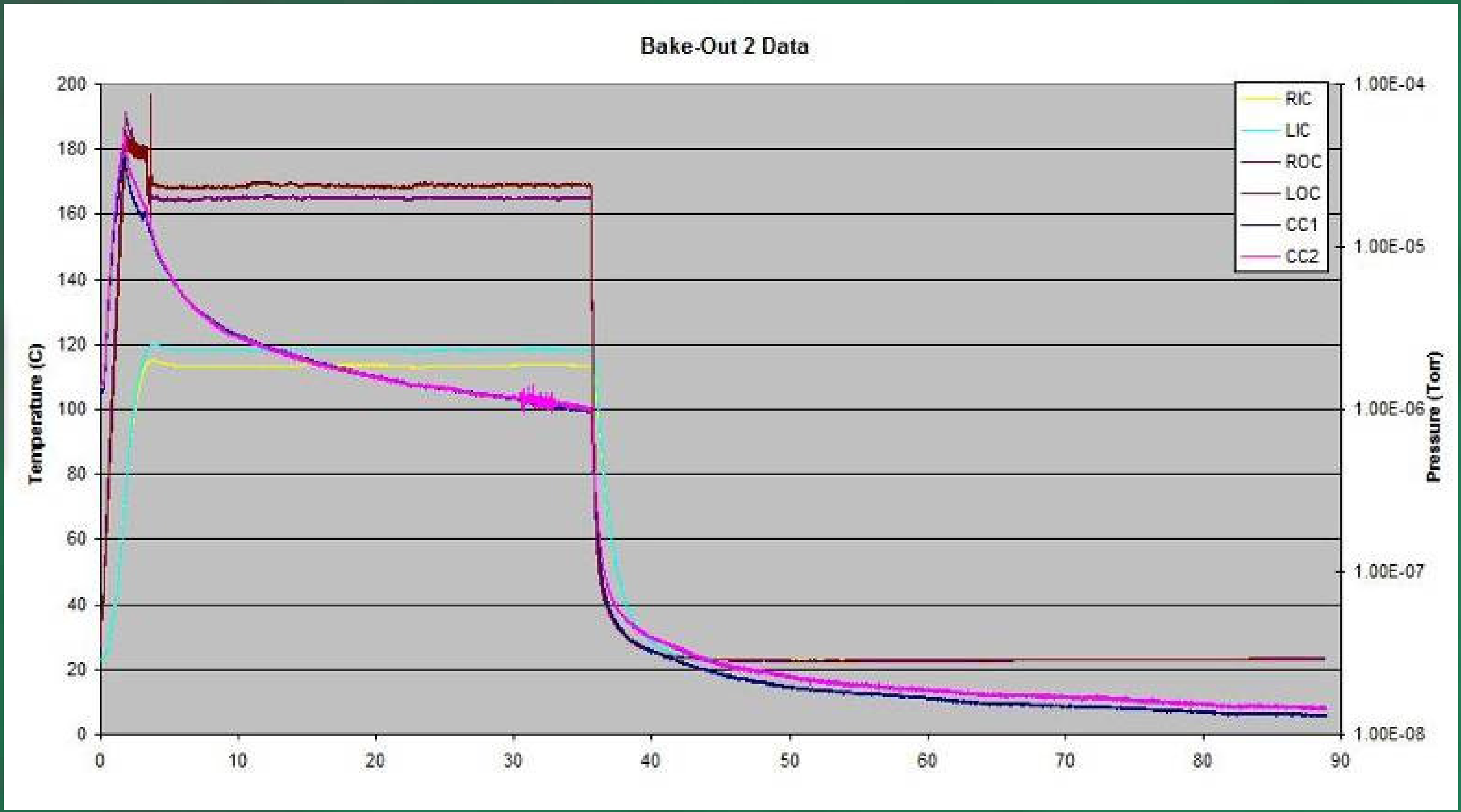
Bake-Out: Temperature & Pressure



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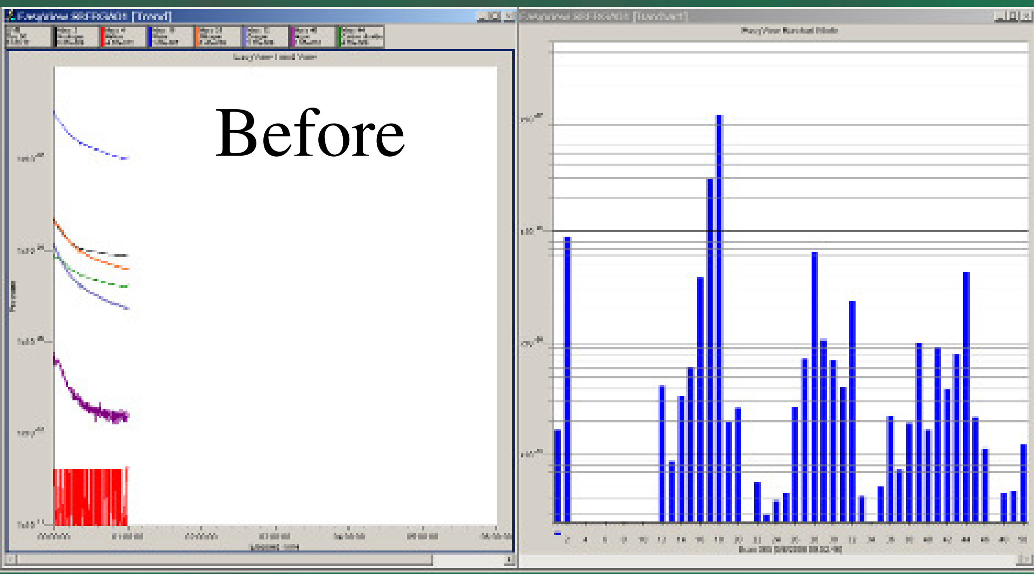
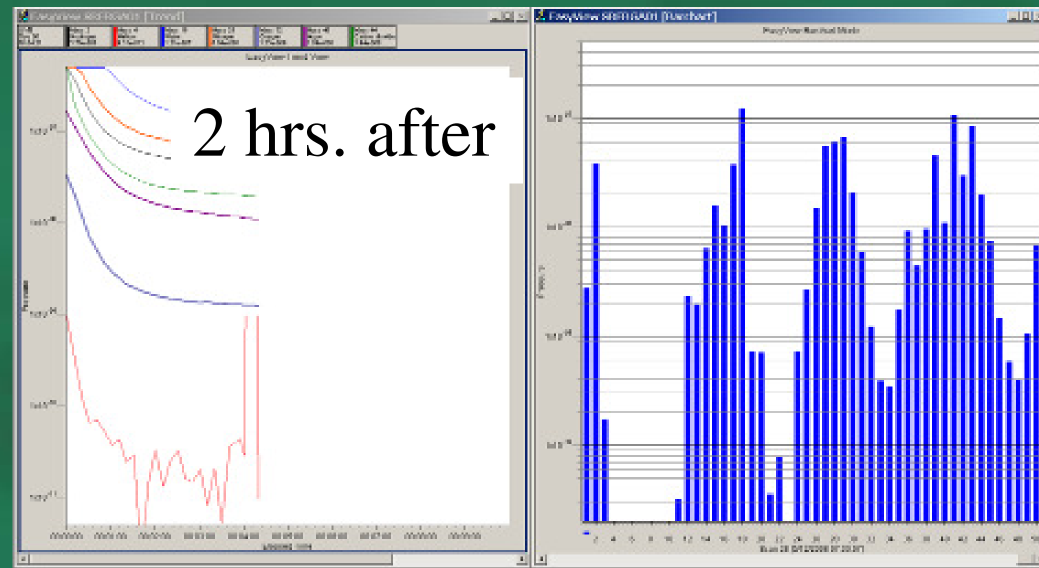
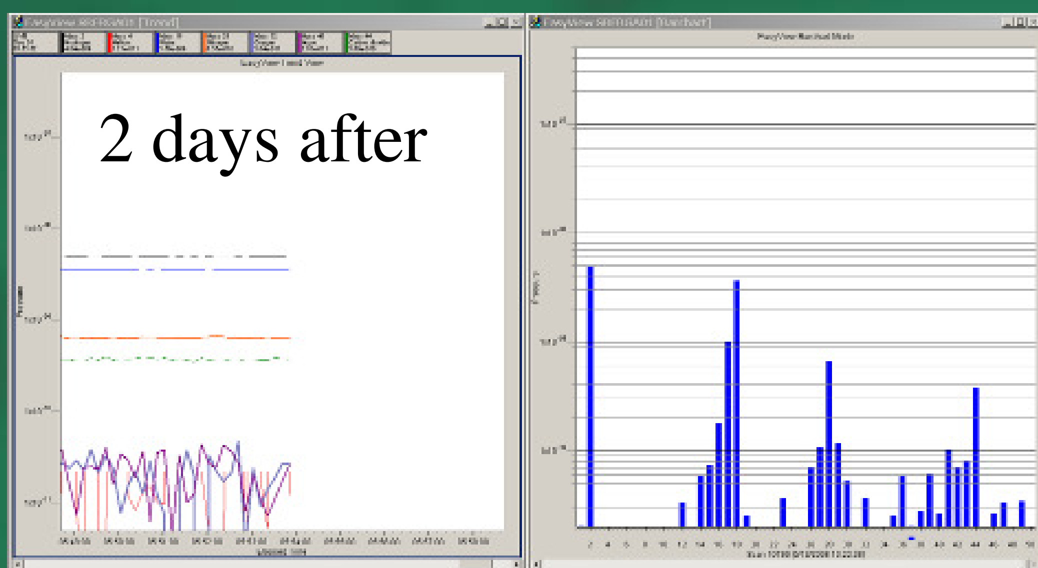
Bake-Out RGA Readings







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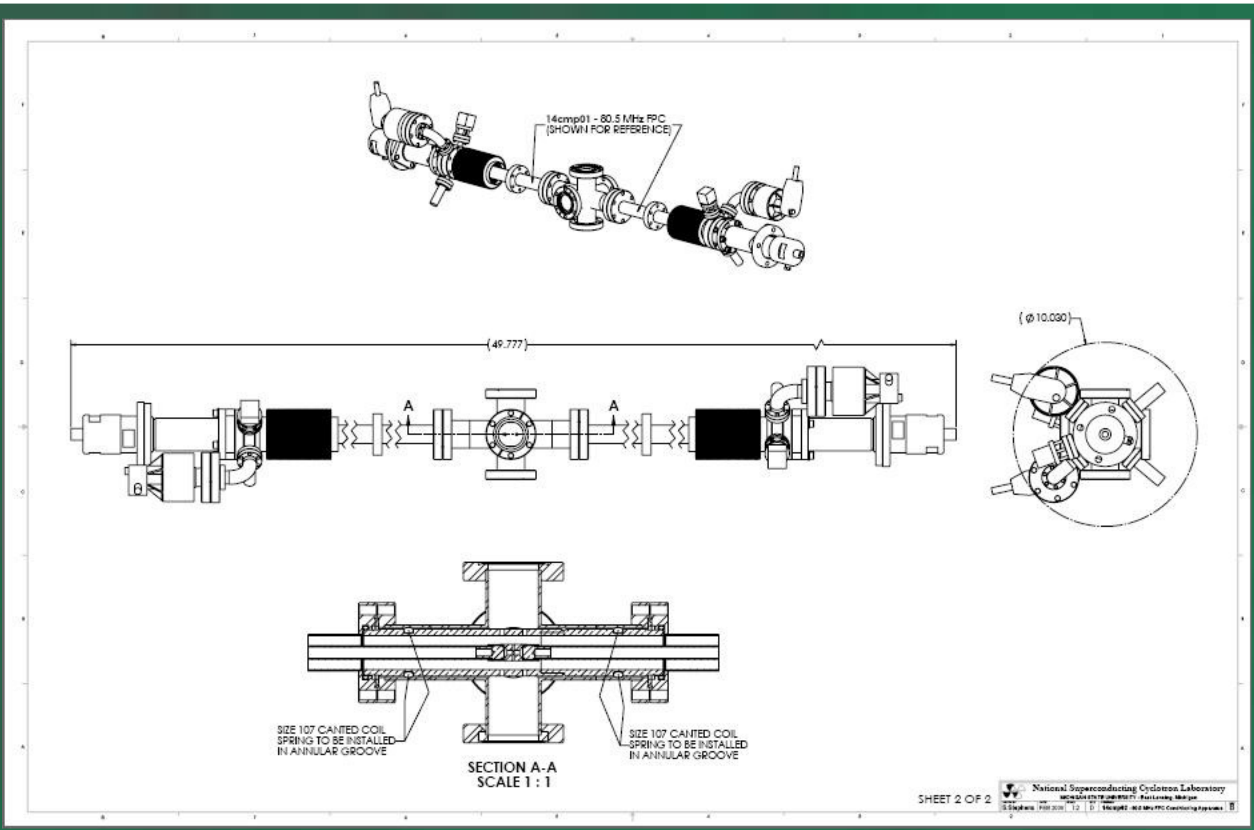
Conditioning Assembly



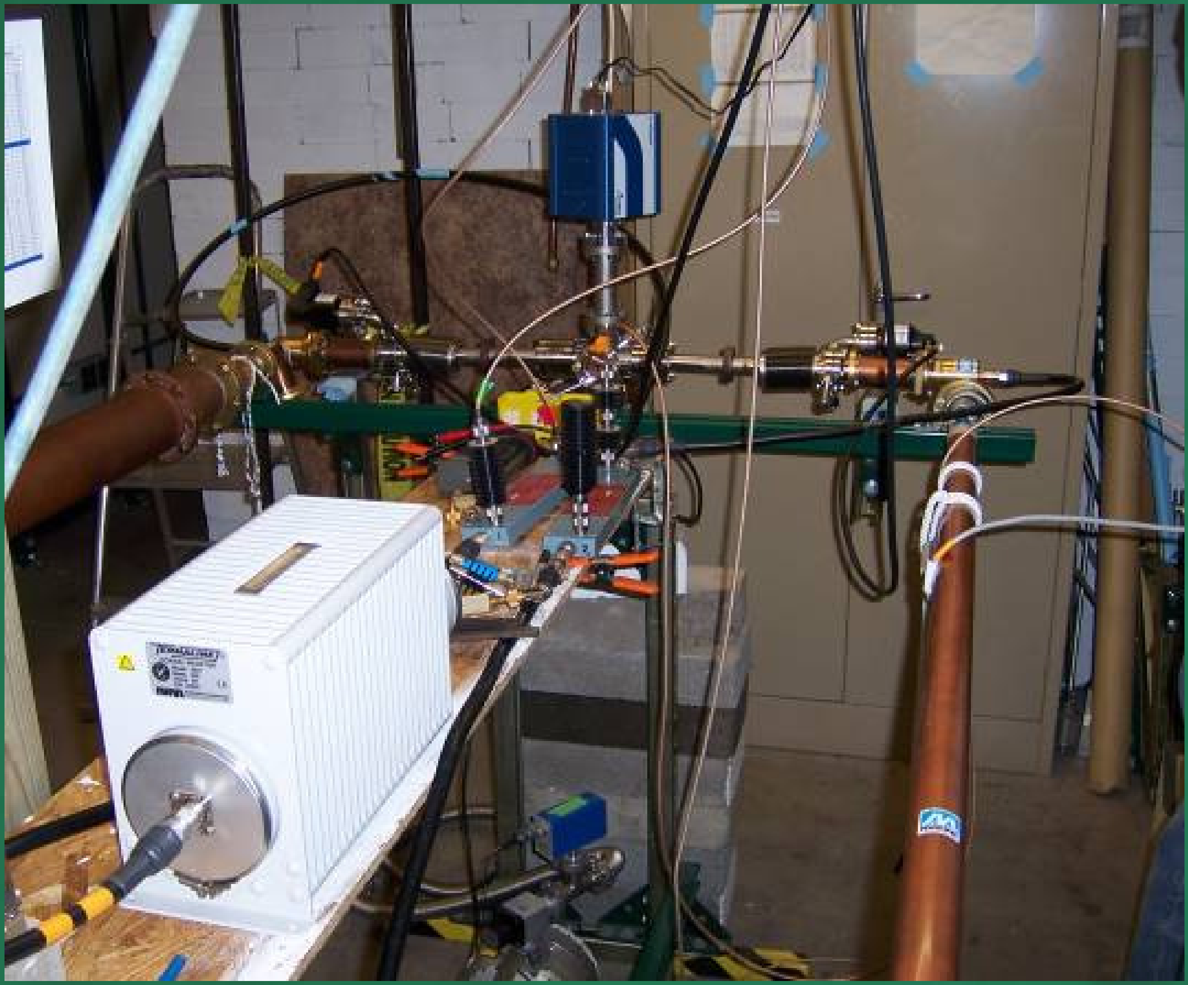
- Two couplers at a time
  - Shorted

Conditioning Stand

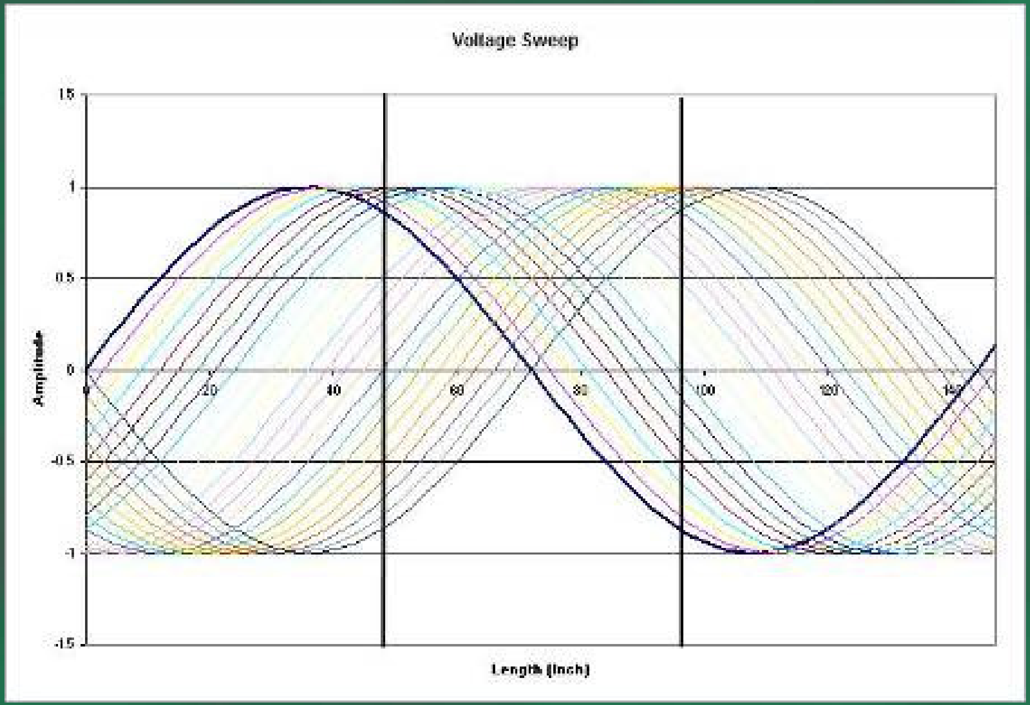
- Standing-wave
  - $P_{sw} = P_{in} + 20$ dB

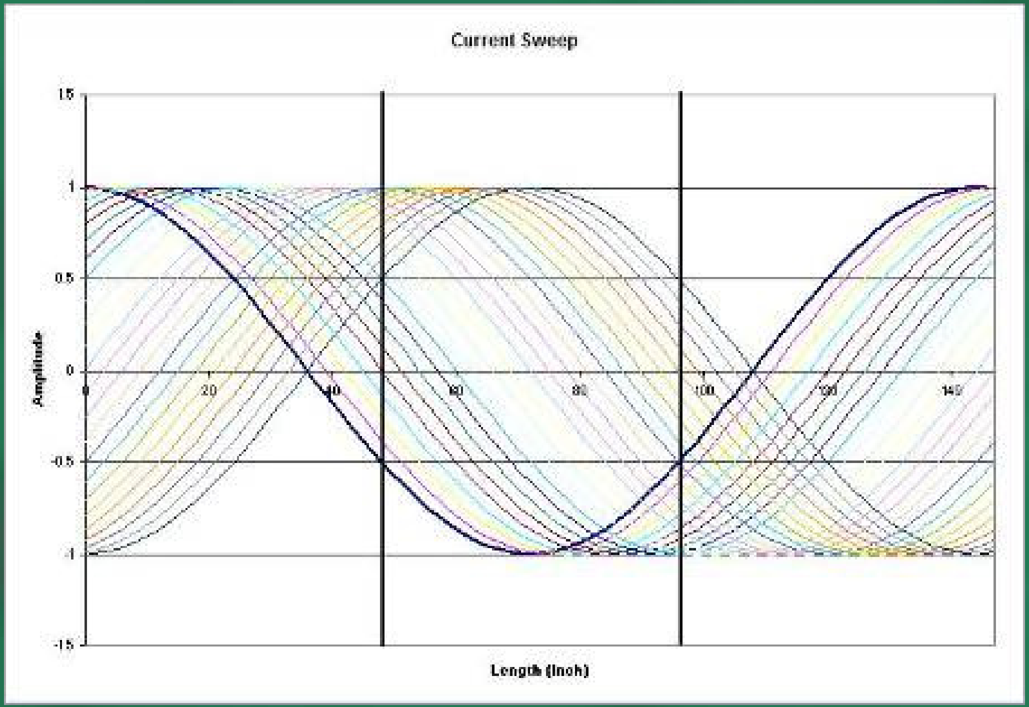
Conditioning

- Sliding shorts
  - Full wave
    - 3.7 meters
  - Moved in 3” increments



Conditioning Sweep



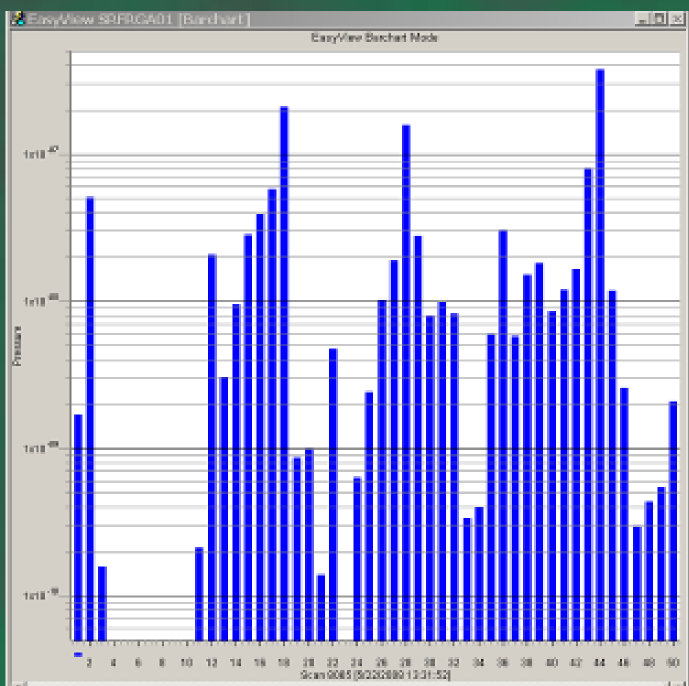


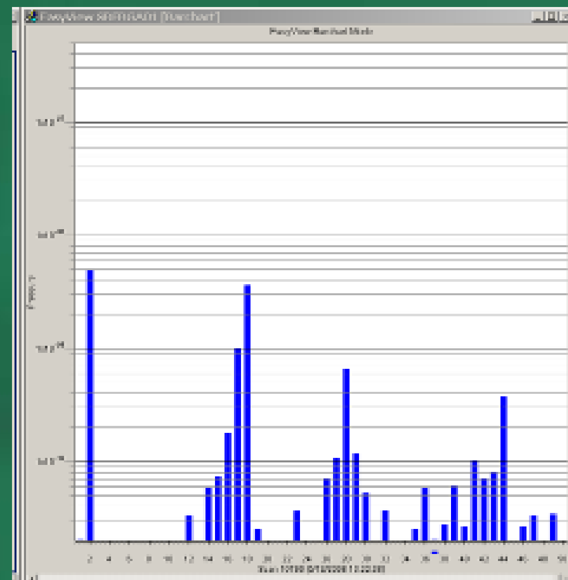
RGA Before, During, and After

During conditioning

@ 63” (near window)

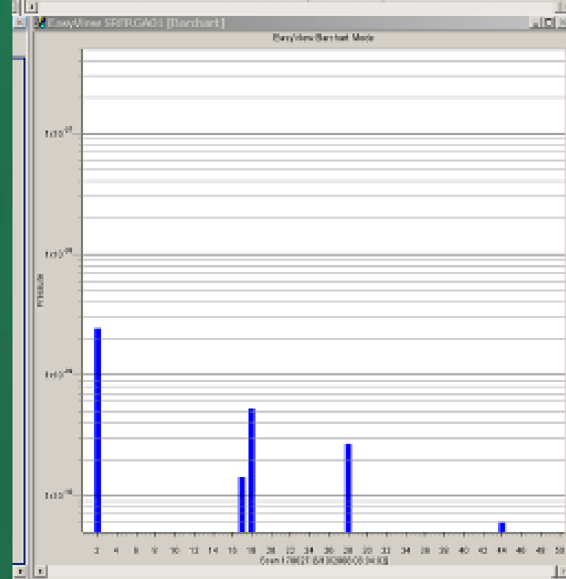
Pressure ≈ 8.5×10^{-6} Torr





After bake-out

Pressure ≈ 1.4×10^{-8} Torr

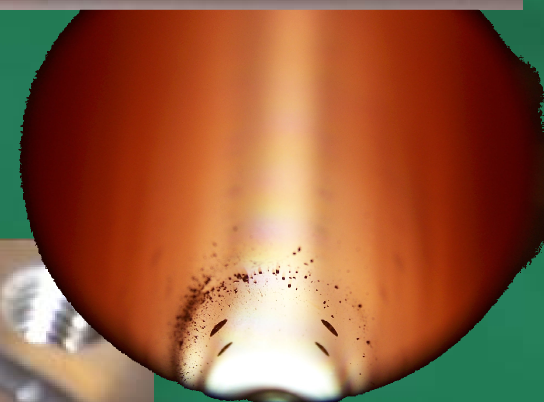


After conditioning

Pressure ≈ 9.4×10^{-9} Torr

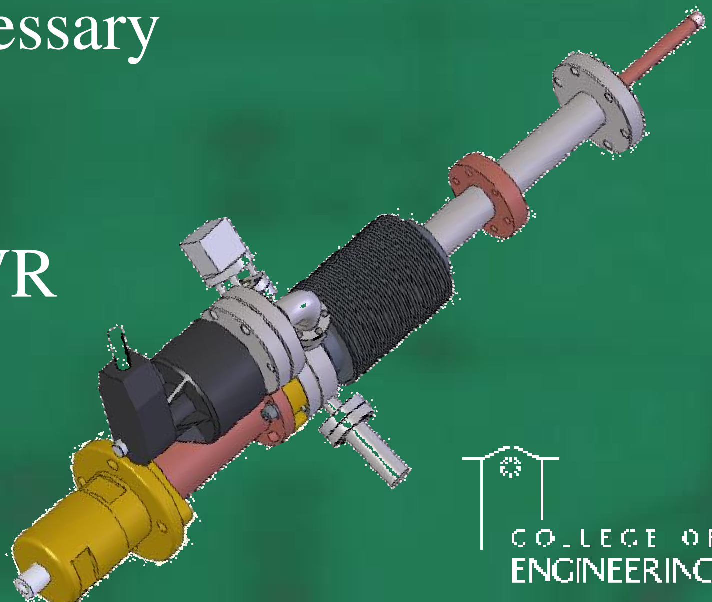
Conditioning Issues

- Over-heating
  - Possibly due to non-plated O.C.
    - Melted solder
    - Vacuum breach
    - RGA failure
    - Turbo pump destroyed
- Replaced soft solder (m.p. = 249^{o} C) with silver braze (m.p. = 635^{o} 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



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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

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Resources

- H. Padamsee, J. Knobloch, and T. Hays, "*RF Superconductivity for Accelerators*, Second Edition" Wiley-Interscience, 2008
- 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
- A.D. Moblo, *Low Beta Superconducting RF Cavity Power Coupler Development for the Rare Isotope Accelerator,* M.S. Thesis, Dept. of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, 2004

Questions?

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Bonus Charts!

Table 5.10: Electromagnetic and cryogenic parameters.

Type	λ/4	λ/4	λ/4	λ/2	λ/2
β_{opt}	0.041	0.085	0.160	0.285	0.425
f (MHz)	80.5	80.5	161	322	322
T (K)	4.5	4.5	4.5	2	2
R/Q (Ω)	424	416	381	199	210
G (Ω)	15.7	19.0	35.0	61.0	86
$G{\cdot}R/Q$ (kΩ²)	6.66	7.90	13.3	12.1	18.1
E_p (MV/m)	16.5	20	20	25	30
V_a (MV)	0.46	1.18	1.04	1.58	2.51
U (J)	0.99	6.69	2.81	6.19	14.93
$R_{BCS,min}$ (nΩ)	2.5	2.5	10.1	0.7	0.7
$R_{res,min}$ (nΩ)	5	5	5	5	5
Q_{max}	2.1×10^9	2.5×10^9	2.3×10^9	1.1×10^{10}	1.5×10^{10}
$Q_{design}=Q_o$	5×10^8	5×10^8	5×10^8	5×10^9	7×10^9
P_{design} (W/cav)$=P_o$	1.0	6.7	5.7	2.5	4.3

Table 5.12: Beam loading requirements by cavity type for uranium at 400 kW and 200 MeV/u. (I_{beam} denotes beam current, $\langle q \rangle$ denotes average charge state, $\langle \phi_s \rangle$ denotes average synchronous phase.)

Type	λ/4	λ/4	λ/4	λ/2	λ/2
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Control bandwidth $\Delta_{allowed}$ (Hz)	54	23	81	56	47
$\langle \phi_s \rangle$ (deg)	-30	-30	-35	-35	-30

Q_{ext2} Formulae

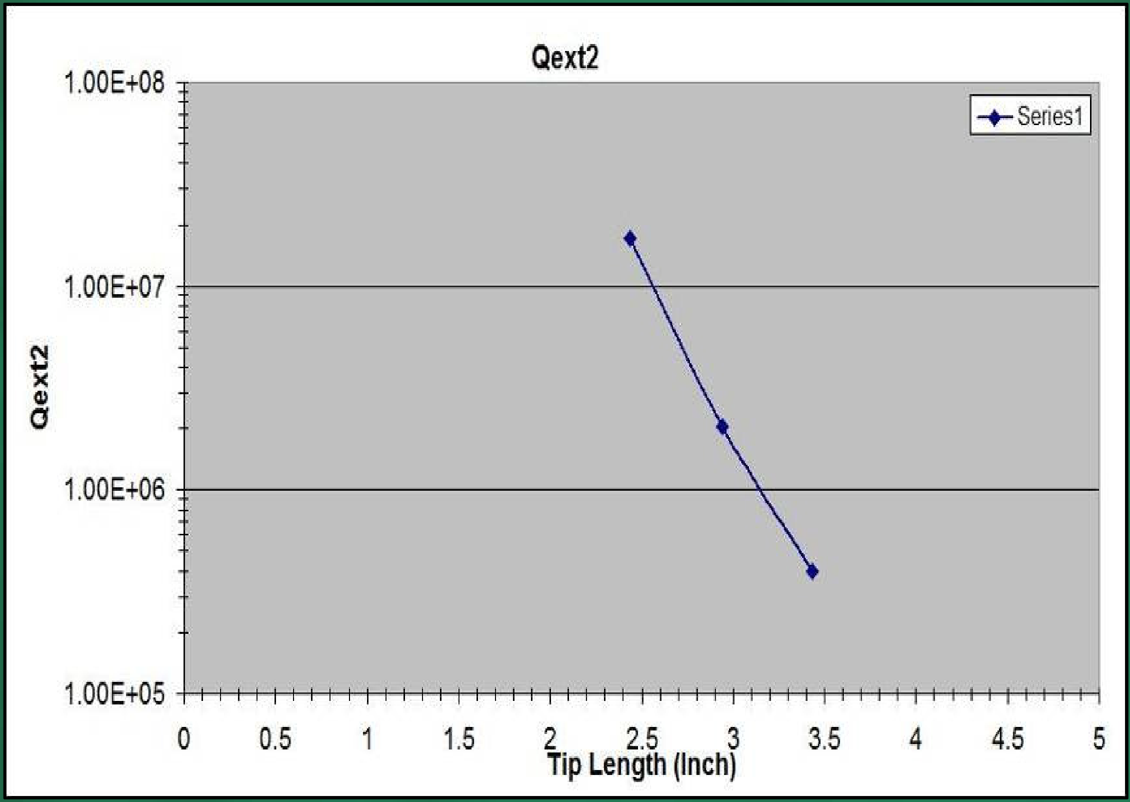
$$\beta_1 = \frac{1-10^{(S_{11}/20)}}{1+10^{(S_{11}/20)}}$$

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

$$Q_o = (1+\beta_1+\beta_2)\times Q_L$$

$$Q_{ext_2} = \frac{Q_o}{\beta_2}$$

$$BW = \frac{f_r}{Q_{ext_2}}$$



Q_L, S_{11}, S_{21} are measured values