# Power Coupler Development at Argonne National Laboratory

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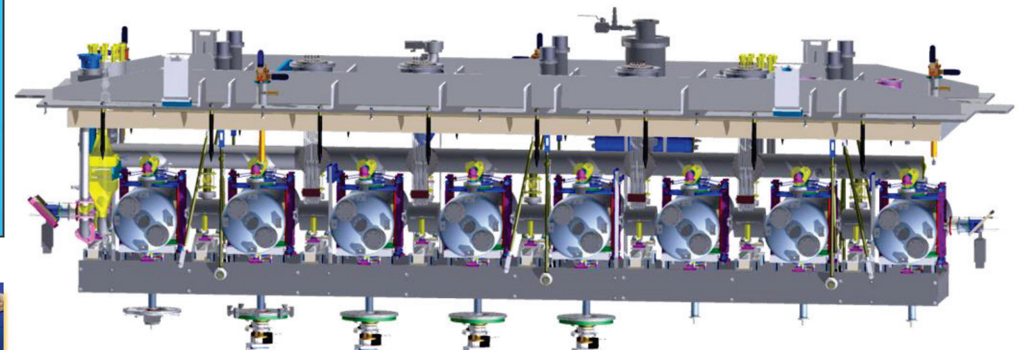
# Outline

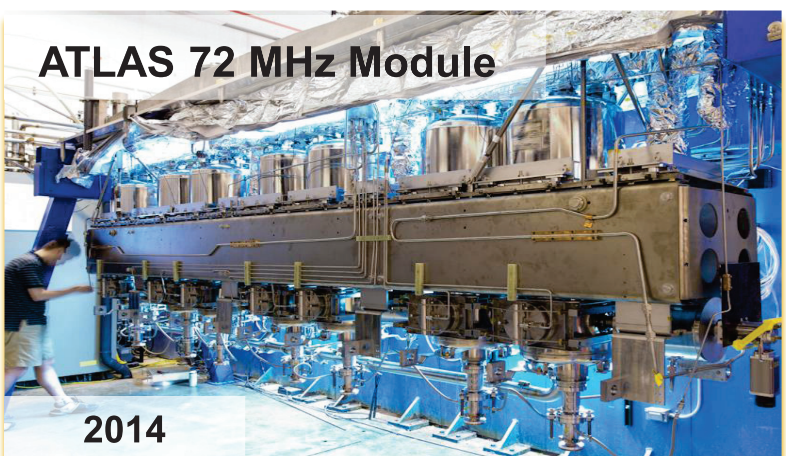
- ANL coupler applications
- Design approach
- Issues of fabrication/assembly/lifetime
- Techniques, Quality Control
- Multipacting
- Limitations/ultimate performance

# Applications for ANL Coaxial Couplers


**FRIB QWRs**

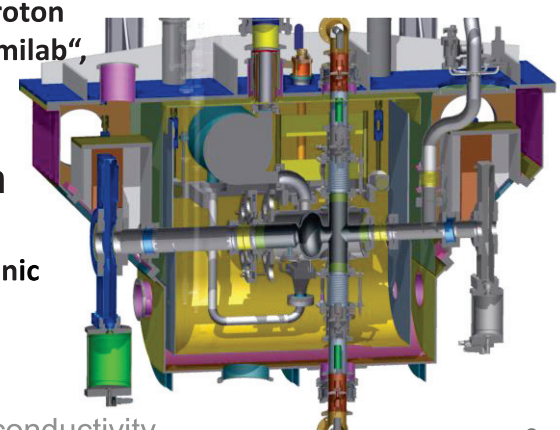
"FRIB SRF production status: cavities, ancillaries…" SRF17, T. Xu






**PIP-II HWRs**

"Half-wave Cryomodule for Proton Improvement Project 2 at Fermilab", SRF17, Z. Conway



**Advanced Photon Source Upgrade**

"A Superconducting Harmonic Cavity System for the ANL Advanced Phton Source" SRF17– Sang-hoon Kim

# ANL Coaxial Couplers for CW SRF

| Facility/ Project | Frequency | Coupler type | Outer diameter | Stroke | Qext | Power | Notes |
|---|---|---|---|---|---|---|---|
| ATLAS | 72.75 MHz | 50 Ω Coax | 4 cm | 7 cm | $2x10^6$ | 4 kW | Standing wave |
| FRIB | 80.5 MHz | 50 Ω Coax | 4 cm | 3.4 cm | $3x10^6$ | 4 kW | Standing wave |
| PIP2IT | 162.5 MHz | 50 Ω Coax | 5 cm | 2.5 cm | $3x10^6$ | 10 kW | Standing wave |
| APS-U | 1408 MHz | 50 Ω Coax | 8 cm | 4 cm | $6x10^5$ | 20 kW | Travelling wave |

**Cost range from ~$15 to $50 K per complete coupler**

# Design Approach

## Common features/issues for recent ANL SRF couplers

### Hardware notes

- Materials: 316/321 stainless, copper (OFHC), alumina, copper/gold braze alloy
- Two planar ceramic windows, one warm, one cold
- Single manufacturer for window assembly (MPF), metallized ceramic (WESGO AL300, 97.6% $Al_2O_5$)
- Copper plating(~20 micron) with nickel strike onto a formed SS bellows → adjustability and thermal transition to cavity
- Working with 3rd vendor on copper plating; adhesion has been fine; issue is purity/losses

### Operations

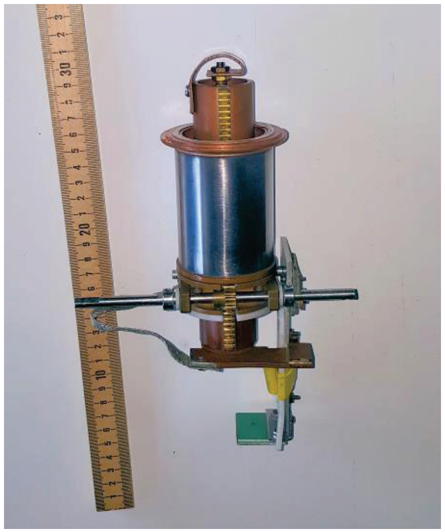
- Variable coupler → conditioning, accurate cavity measurements, optimize tuning window for cavity phase control, accommodate different beam loads, passive phase/amplitude control
- Forced flow LN2 or He gas cooling on outer diameter of cold window
- Conductive (passive) cooling of center conductor through alumina windows
- Air cooling at warm window (outside the cryomodule)
- Diagnostics based on thermometry; silicon diodes/Cernox, gallium-arsenide optical thermometers; dual directional couplers

**→Challenge: (moving) thermal transitions with lots of different materials and high power flow**

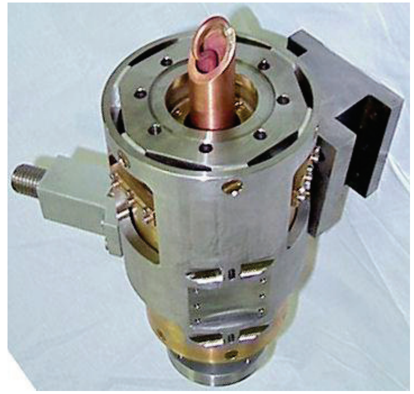
**→Experience: ~2 dozen couplers built/tested (4 different types, the first 4 kW version in operation for several years, FRIB is building >100 of 2nd 4 kW coupler)**

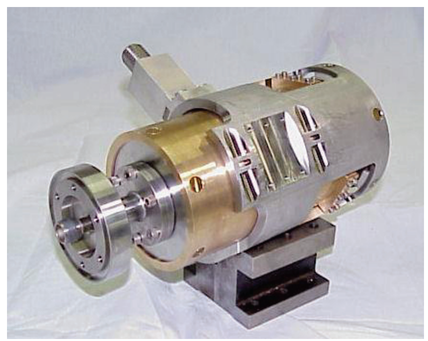
# Design Approach

## Previous ANL power couplers

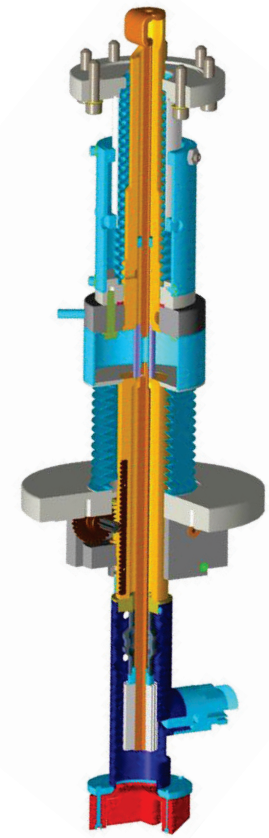


**Magnetic-loop coupler for split-ring**
*Issue: No integral RF window*





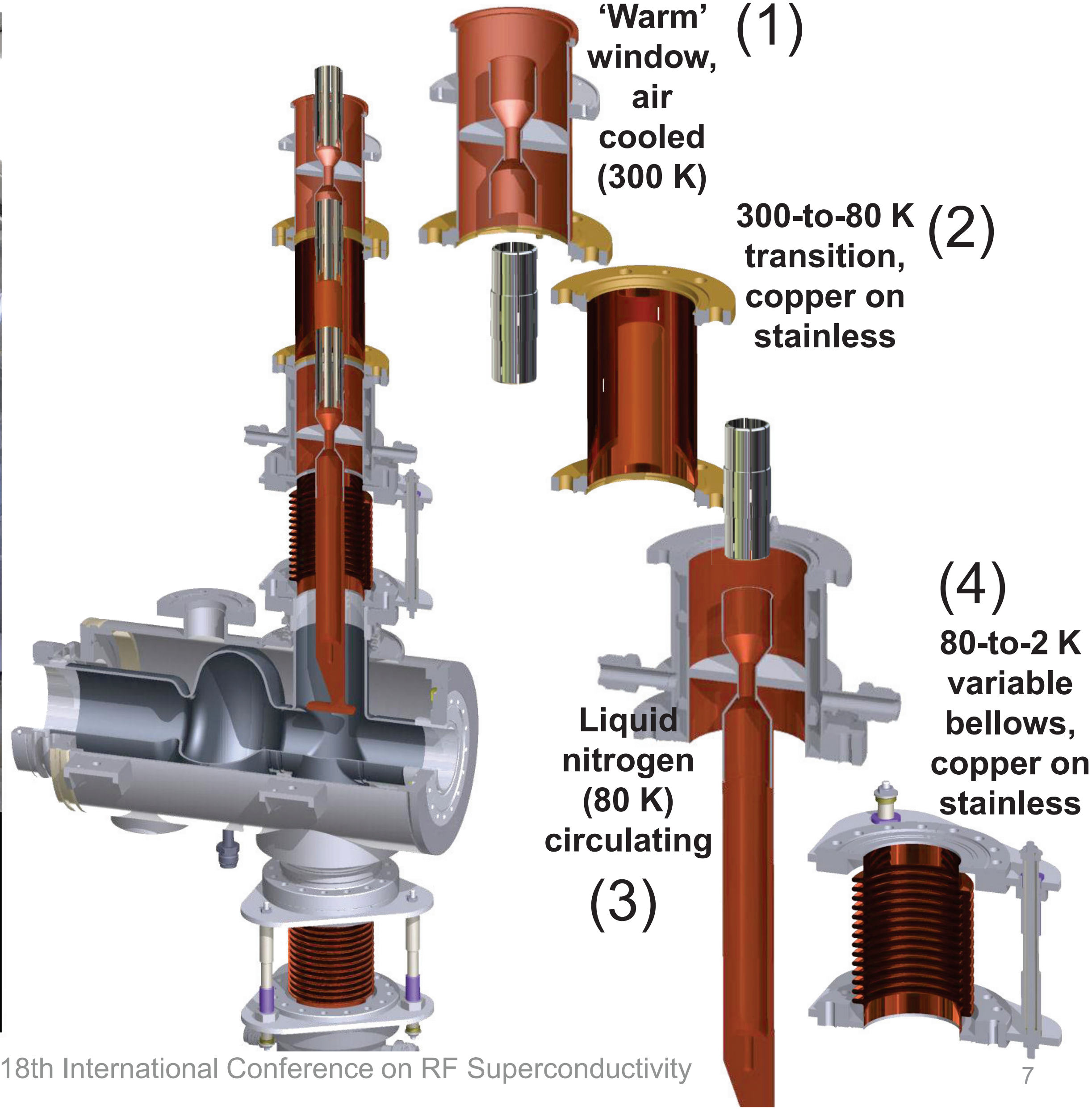
**'Clean' single-window magnetic-loop coupler for double spoke**
*Issue(s):cumbersome, fragile*



**'Clean' single-window magnetic-loop coupler for quarter-wave cavity**
*Issue(s):cumbersome, fragile, power handling*

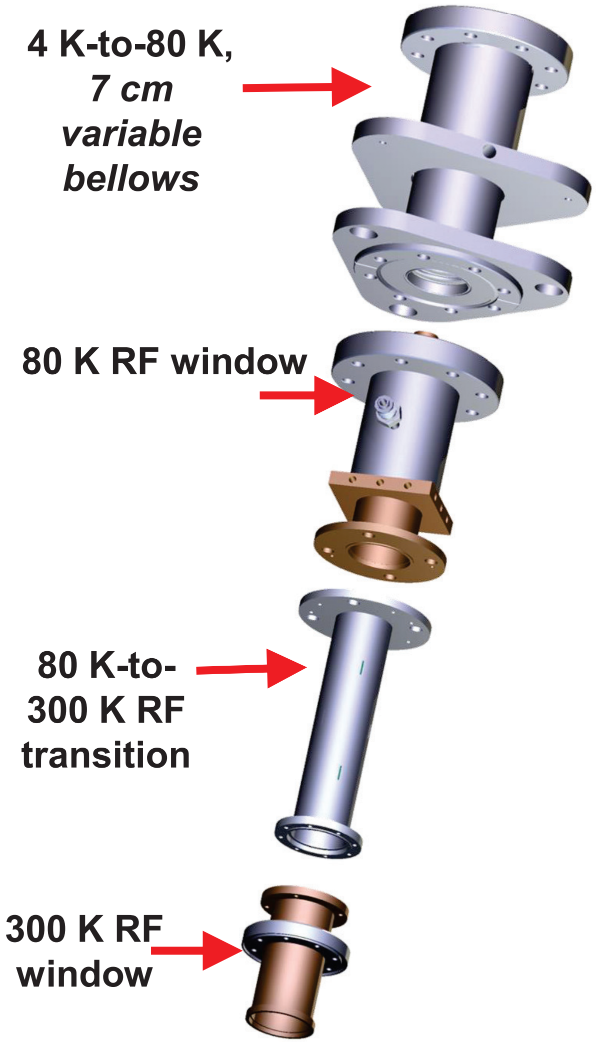
# Design Approach

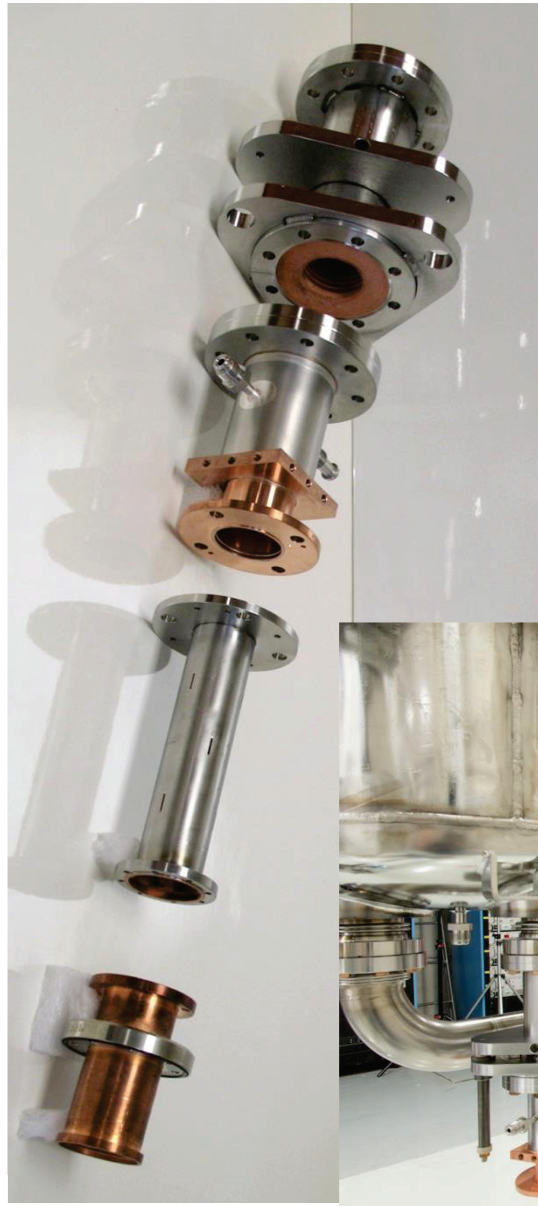
## Most recent example: 20 kW CW coupler for 1.4 GHz Harmonic Cavity



# Design Approach

## First use of 2-RF window design on ATLAS 72 MHz upgrade module



ATLAS Upgrade Production Couplers

4 kW (cold) couplers installed
FRIB design is similar

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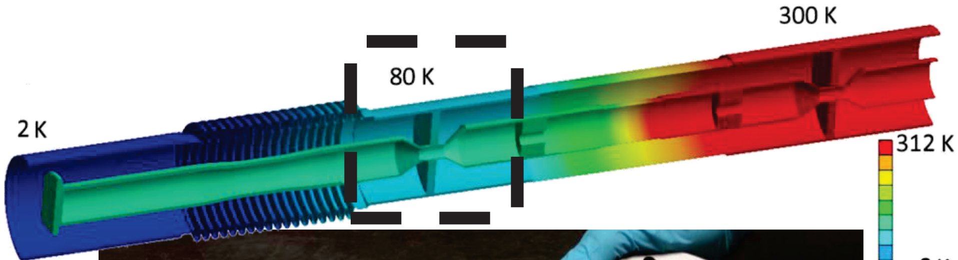
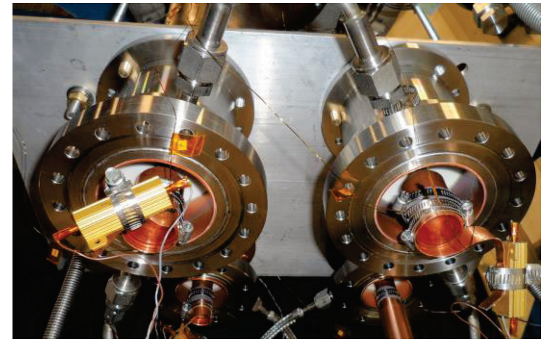
# Design Approach

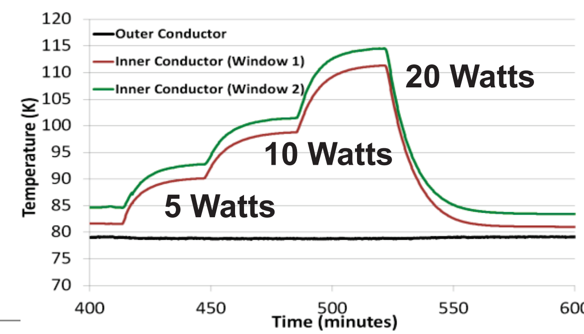
## Thermal stability based on conductive cooling through planar ceramic windows

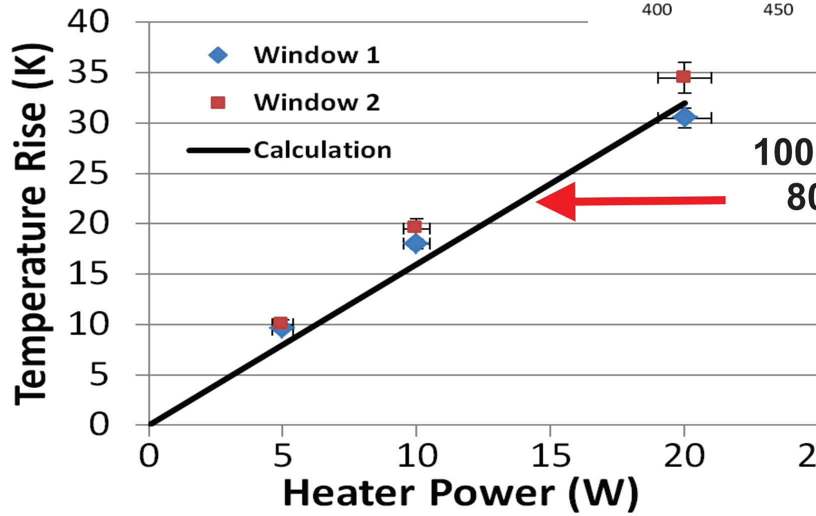






80 K test apparatus

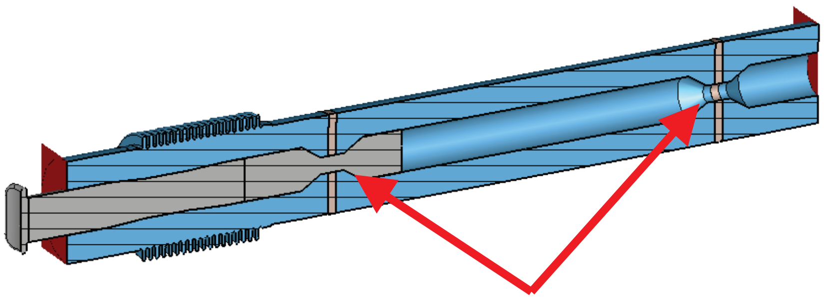


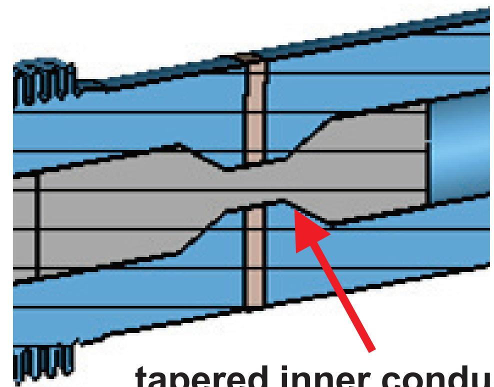

100 W/m/K in the 80 K alumina windows

# Design Approach

## Special adaptations for high-frequency/high-beam power application: Tapered inner conductor

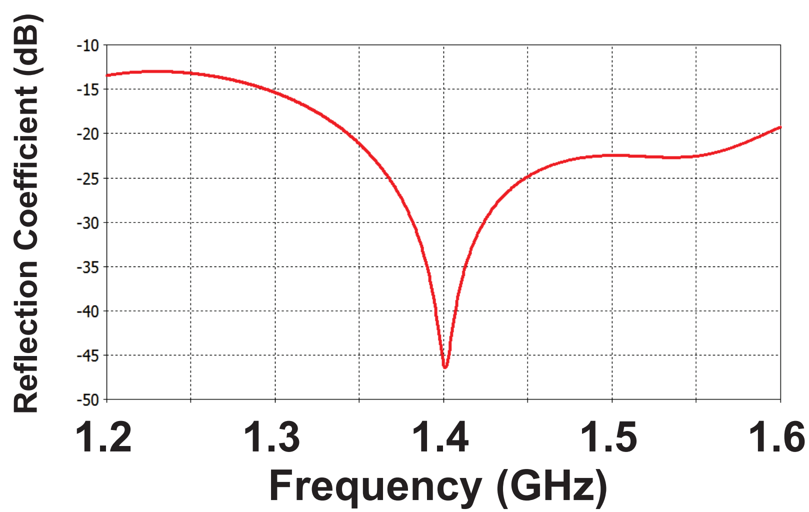


**Cold and warm RF windows**



**tapered inner conductor → 50 Ω line impedance @ 1.4 GHz**

Figures from S.Kutsaev (ANL/presently Radiabeam)

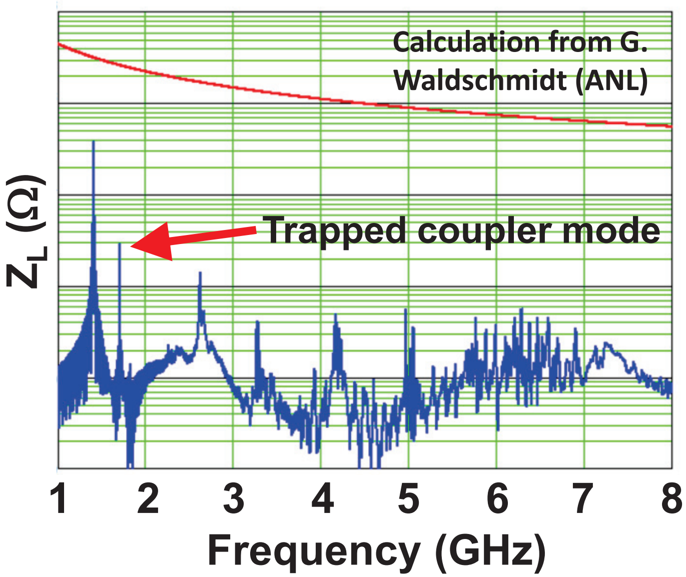


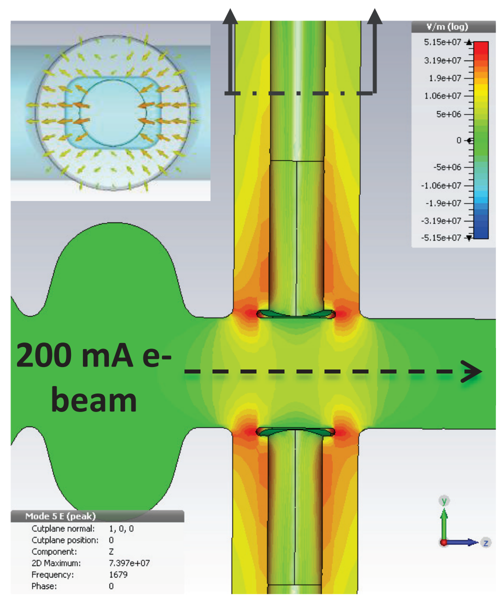
# Design Approach

## Special adaptations for higher-frequency/high-beam power application

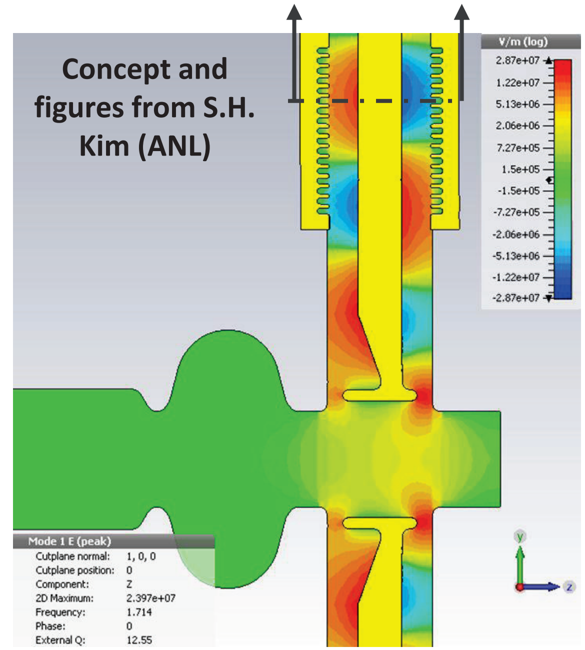
## ‘Wedge Antenna’

s

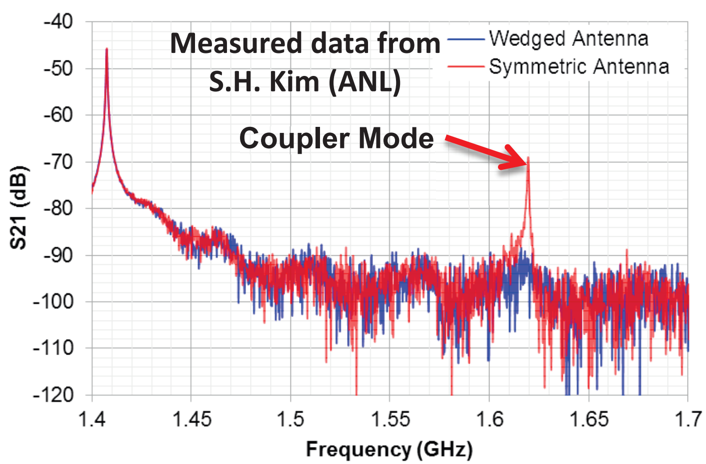


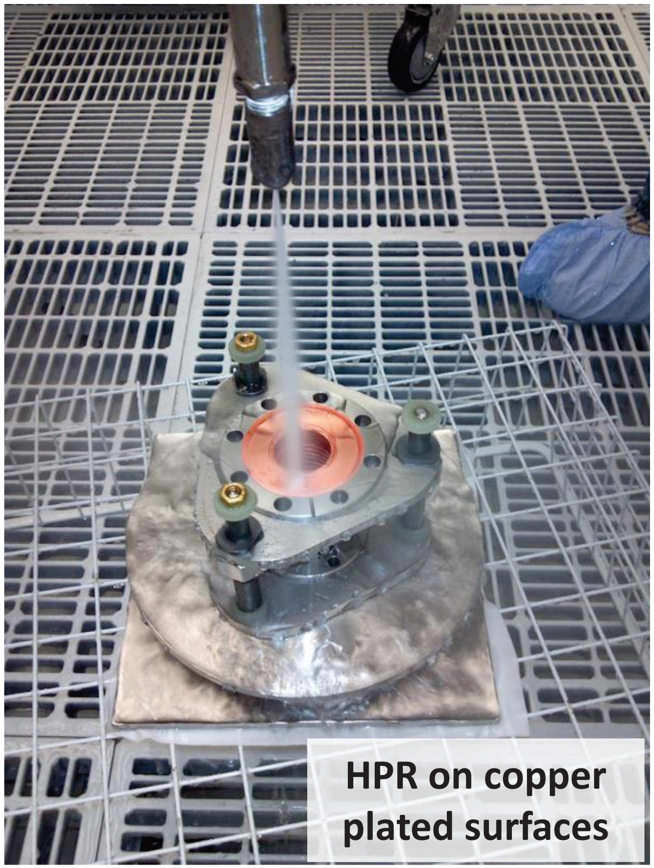

Trapped TE11-like mode @ 1.6 GHz using symmetrical antenna




Conversion to TEM mode @ 1.6 GHz using wedge antenna



# Fabrication / Assembly/ Lifetime



HPR on copper plated surfaces

# Fabrication / Assembly/ Lifetime

## Brazed alumina into OFHC copper has a finite fatigue life when cycled to 80 K

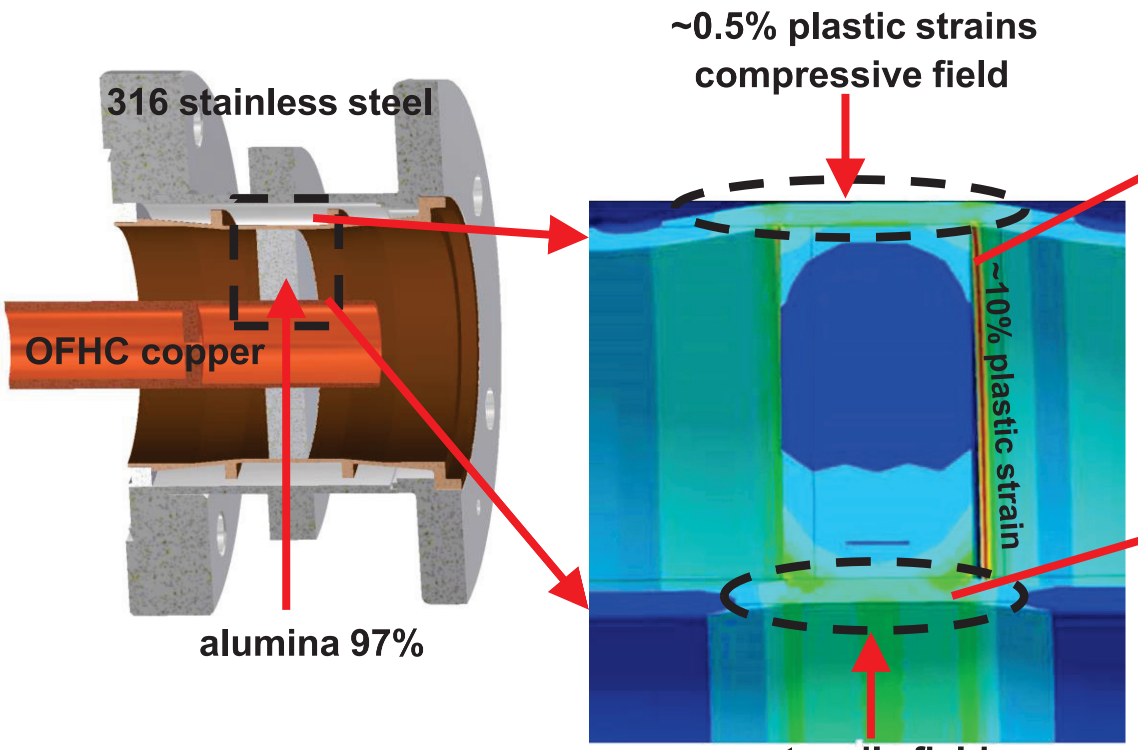
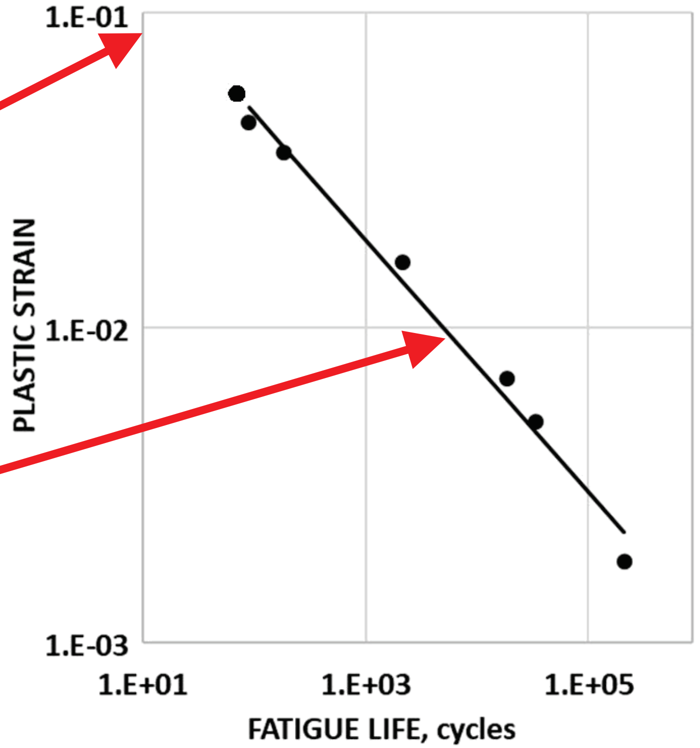



Figure from R.Fischer (ANL)

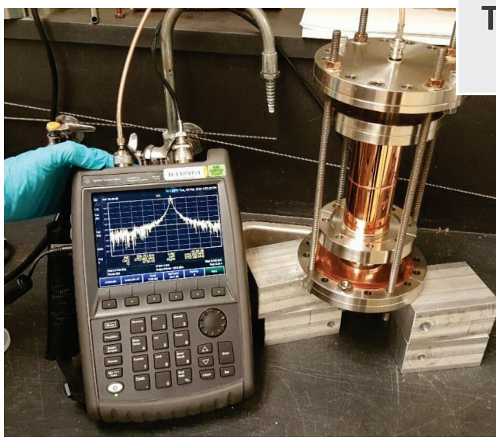
**Strain controlled fatigue life data for OFHC copper at 80 K**



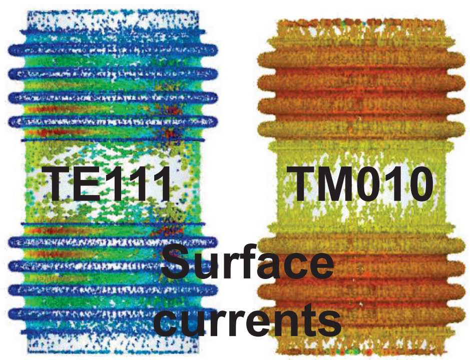

- Copper/alumina brazing cycle down to 80 K produces ~1% plastic strain → finite lifetime
- Corners can produce much higher local values, ~10%
- Chamfered or radiused corners on the ceramic with a meniscus of braze alloy mitigate local stresses/strains (experimentally several units cycled up to 100 times with no issues)

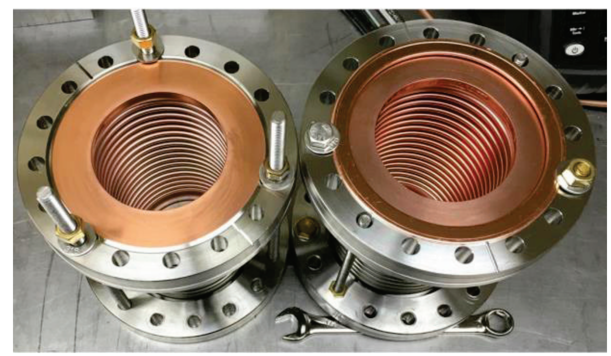
# Techniques, QA

## A pillbox cavity measurement as a test of RF losses in copper plating



| Pillbox Quality Factors/1000 | | | | | | |
|---|---|---|---|---|---|---|
| | Simulation | Bellows #1 Vendor A | | Bellows #2 Vendor A | | Bellows Vendor B |
| 80 mm diameter bellows | σ=5.8x10$^{7}$ S/m | Before Baking | Baked (500ºC, 1 hr) | Before Baking | Baked (450ºC, 1.5 hr) | No Baking |
| TE111 @ 2.4 GHz | 20 | 3.9 | 11 | 4.2 | 13 | 16 |
| TM010 @ 2.7 GHz | 10 | - | 5.6 | 1.8 | 6.3 | - |

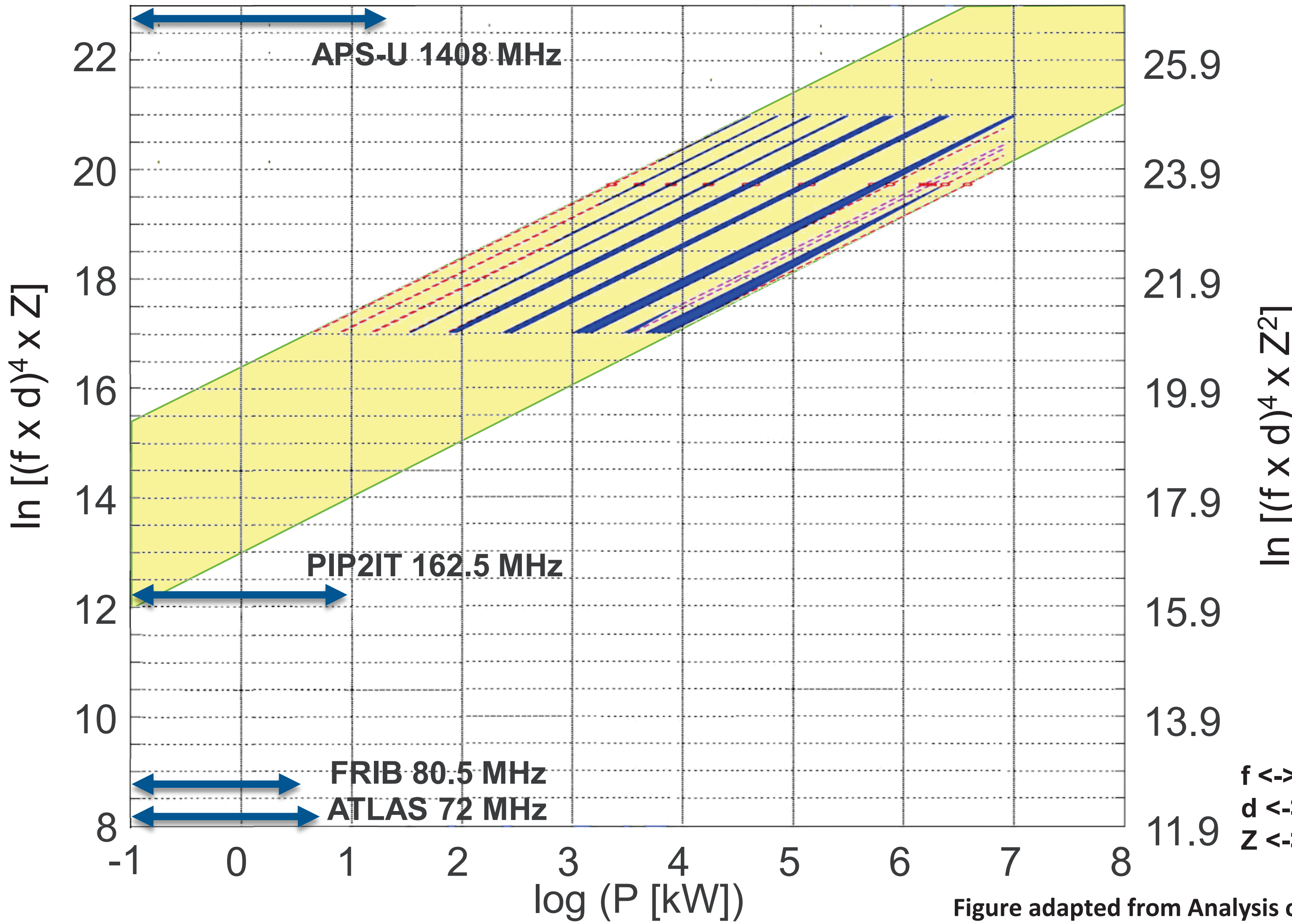


- DC conductivity (4-wire resistance) measurements seem to be a poor predictor of RF losses
- However, pillbox cavity measurements correlate strongly with losses observed in coupler testing
- Baking may improve copper conductivity; possible to get good conductivity without baking

# Multipacting

## Comparison with 1pt / 2pt Scaling Laws for Levels in a Coaxial Line



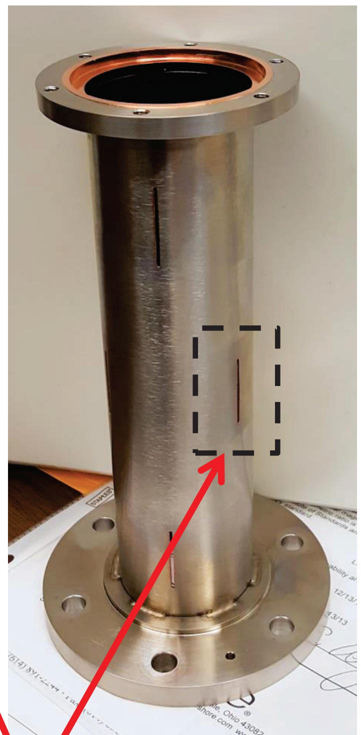

f <-> frequency [GHz]
d <-> diameter [mm]
Z <-> impedance [Ω]

**Figure adapted from Analysis of Multipacting in Coaxial Lines, University of Helsinki, PAC 1995**

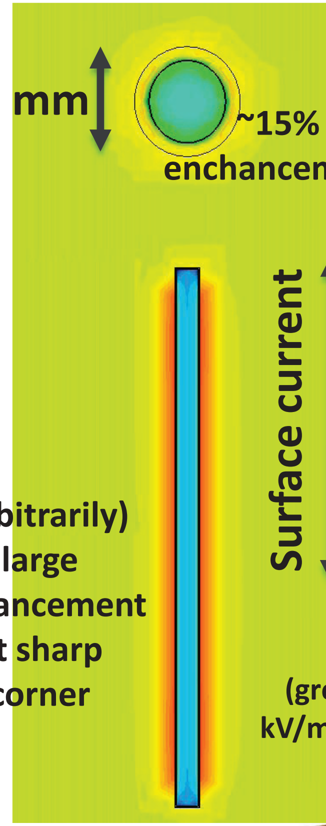
# Multipacting

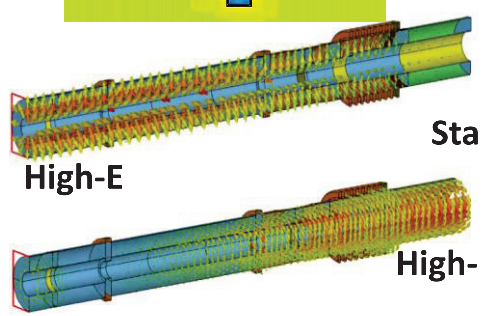
## Suppression by small geometrical improvements: Replacement of pumping 'slots' by pumping 'holes'

**Initial design for (162.5 MHz) thermal transition**



Location of damage on central conductor aligns with slot location



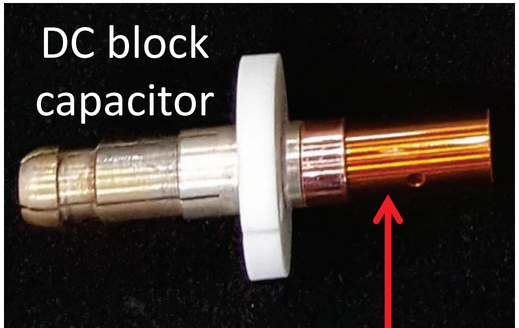




Standing wave fields

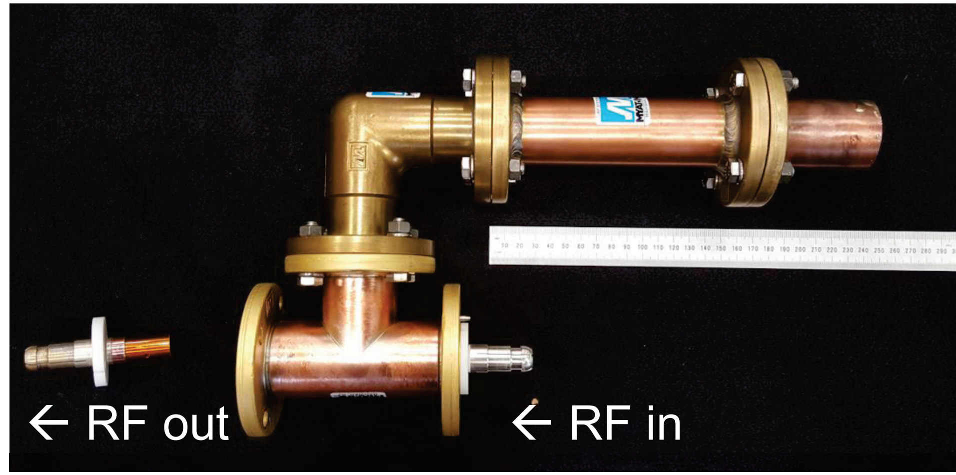
**Present design (162.5 MHz)**

# Multipacting

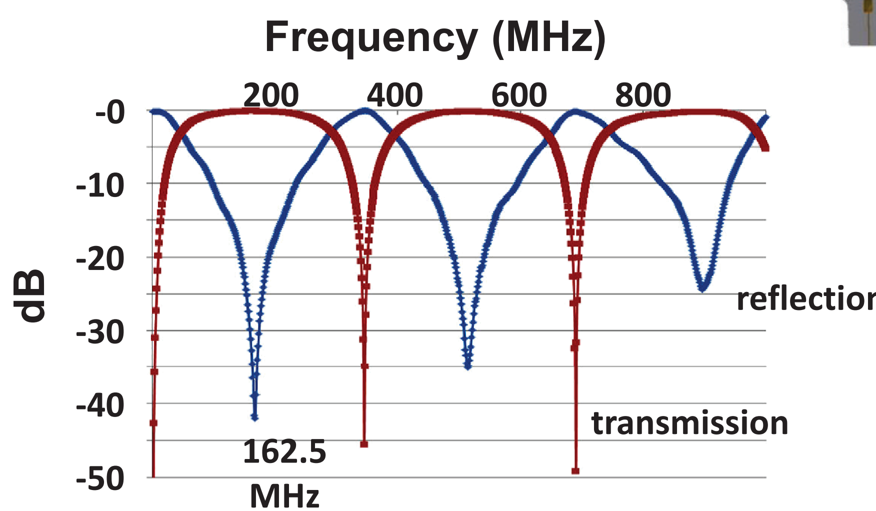
## A simple technique for suppression using a ‘DC Block’




Electrical isolation
5 micron thick Kapton film



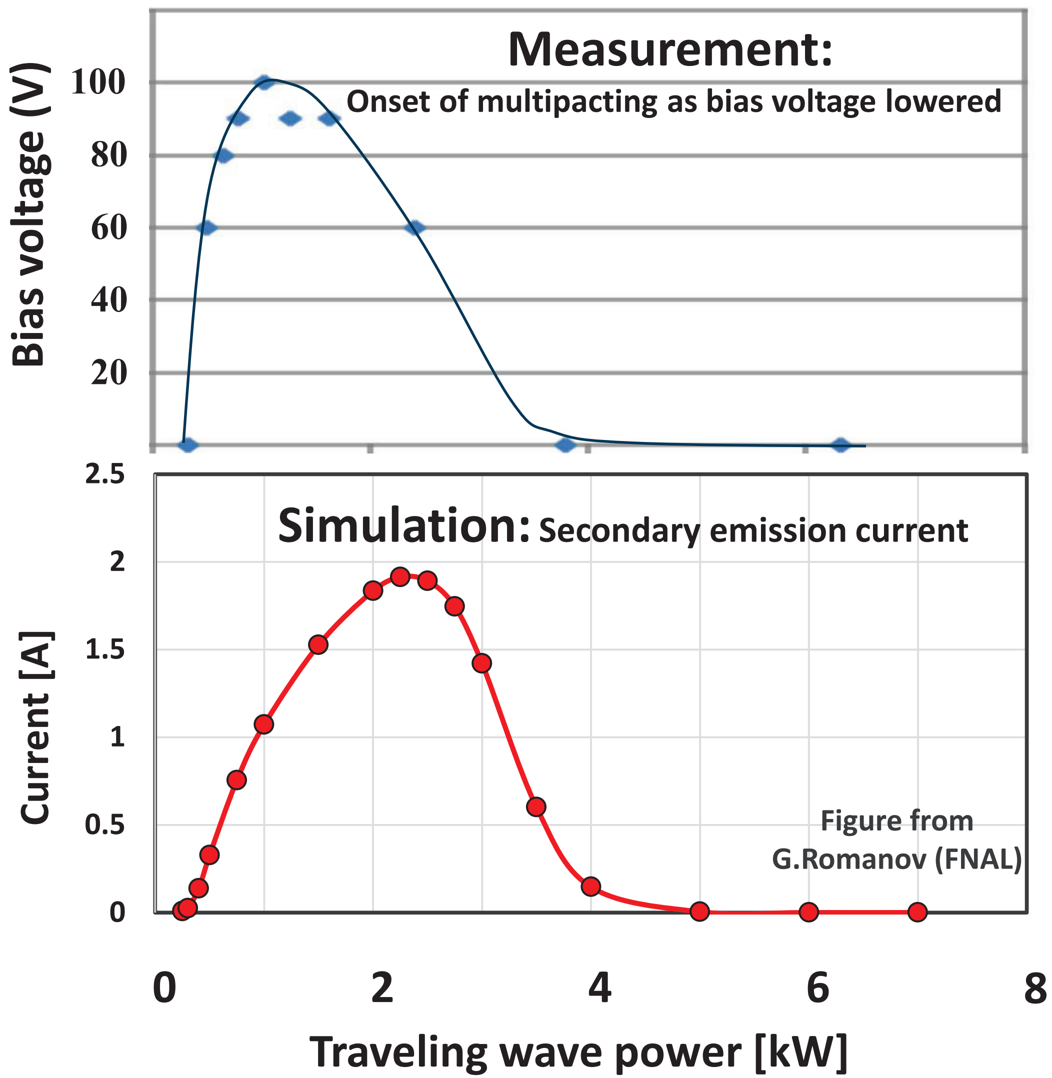





This approach suggested to us by FNAL

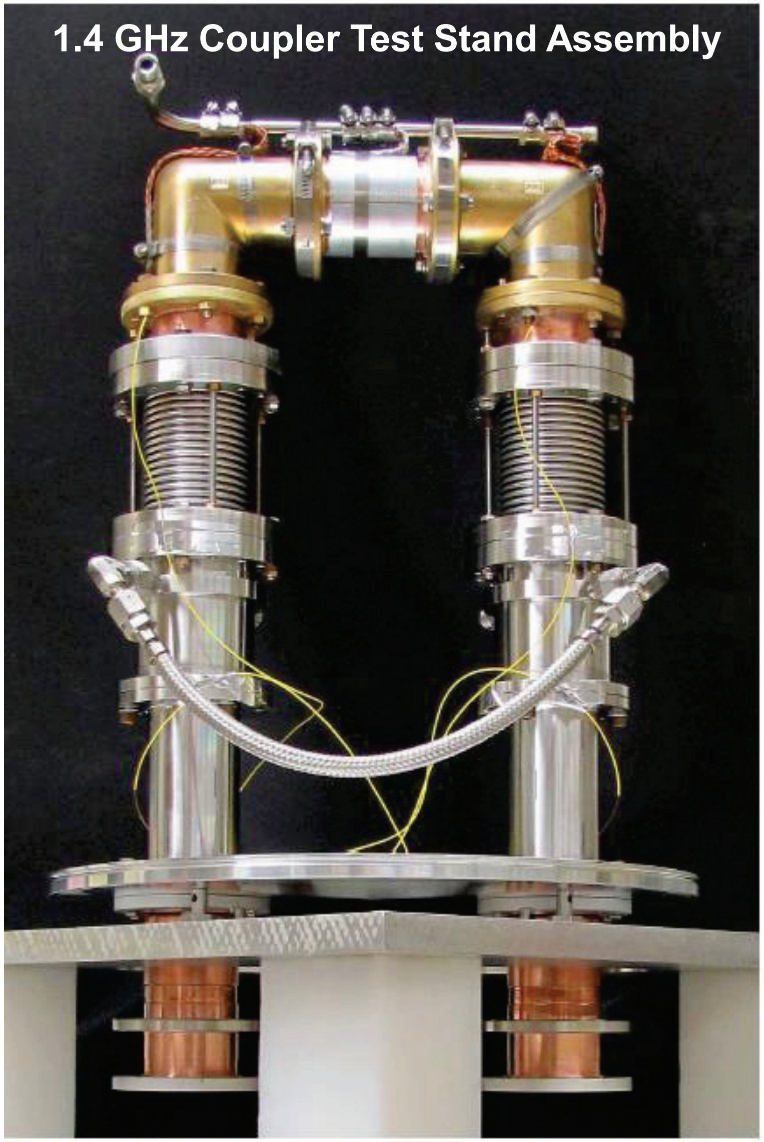
# Multipacting

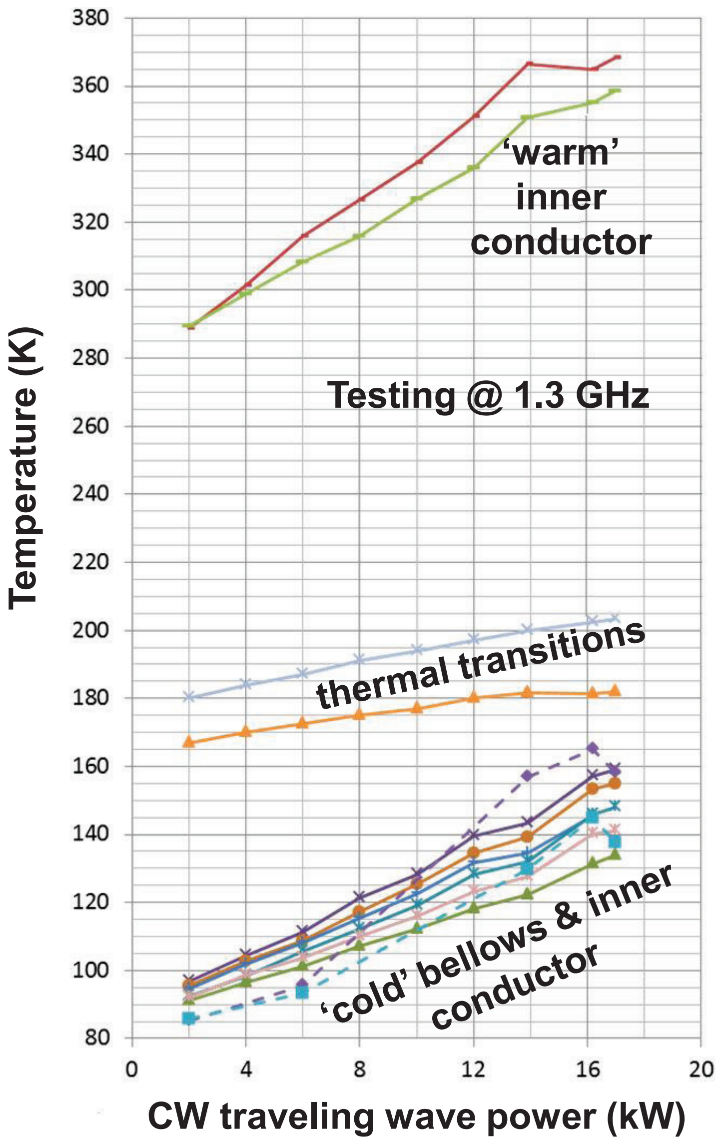
## Simulated and measured multipacting in 162.5 MHz Coupler for PIP2IT



# Limitations/ultimate performance

## CW performance to 20 kW appears reasonable



# Limitations/ultimate performance

## Thoughts on extension to 100 kW CW power and beyond

- **Several ways to extend the present approach**
  - **Have looked at double-window 160 mm diameter, 50 Ω design at SRF 2013, 75 kW with only passive cooling of cent. cond., but not at 162.5 MHz as in that study)**
- **Several examples of CW couplers demonstrated from 100 kW up to ~1 MW (*e.g.* KEKB, APT)**
  - **Further work to address future needs for use with high-power, high-gradient cavities**
- **Avoid multipacting through design choices (*e.g.* 160 mm diameter, 50 Ω, 800 MHz →avoids bands up to 1 MW)**
  - **Incorporate DC bias and active cooling of the central conductor in two window design**
- **Substantial and sustained coupler development will be needed – ADS, ERLs, FCC, CEPC…**