Development of X-Band Dielectric Disk Accelerating Structures

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for Euclid Beamlabs &
Argonne Wakefield Accelerator

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Motivation

- Long term: develop enabling technologies for the short pulse TBA based SWFA linear collider concept.
- Near term: support demonstration of 0.5GeV electron beam energy gain at the AWA facility.
- Improve RF-to-beam efficiency
  - High shunt impedance under a high group velocity
- Short pulse – high gradient acceleration
  - Capitalizes on the correlation of RF breakdown rate and RF pulse length

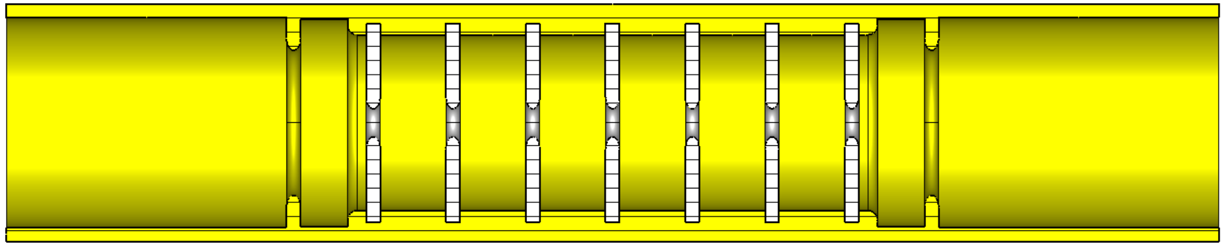
Dielectric Disk Accelerators

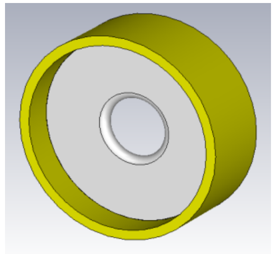
- Dielectric disk-loaded waveguides introduced in the 1940's-50's
- Modern ceramics with high dielectric constant and low loss provide opportunity to realize high shunt impedance structures

- Higher: group velocity, shunt impedance, Q
- Tuning easier than for DLAs
- Drawback: surface electric field much higher than DLAs, fabrication difficult

26 GHz Parameter	DDA	DLA	Copper-Disk*
Aperture	3 mm	3 mm	3 mm
Outer Diameter	9.23 mm	4.99 mm	9.27 mm
Thickness	0.5 mm	1 mm (wall)	0.5 mm
Dielectric constant	50	10	N/A
Loss tangent	5e-4	1e-4	N/A
Group velocity	0.16c	0.11c	0.017c
Shunt Impedance	208 MΩ/m	50 MΩ/m	139 MΩ/m
Q	6400	2300	4300
Accel. gradient	363 MV/m	363 MV/m	N/A
Surface gradient	660 MV/m	363 MV/m	N/A

*Constant impedance 2π/3 structure, not suitable for short RF pulse acceleration due to low group velocity

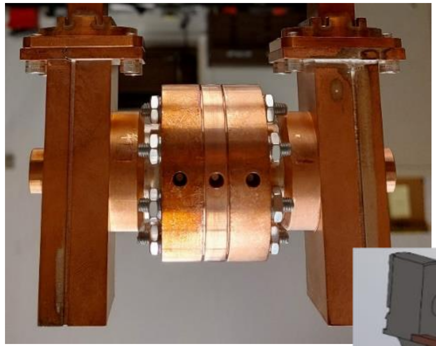
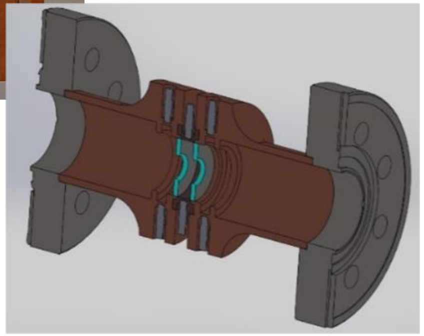
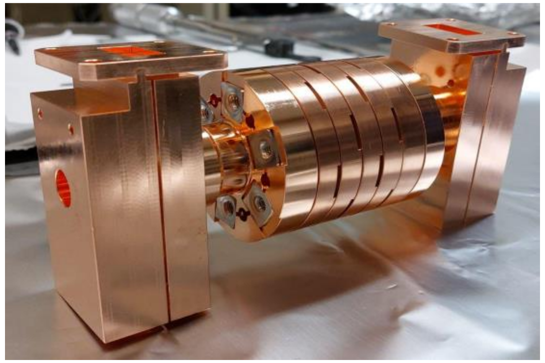
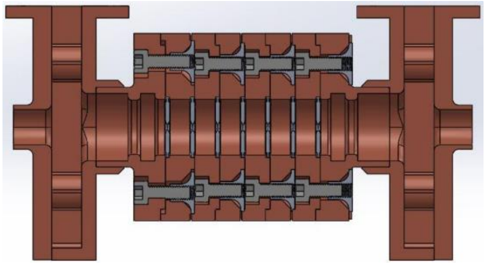




Euclid-AWA DDA Testing History

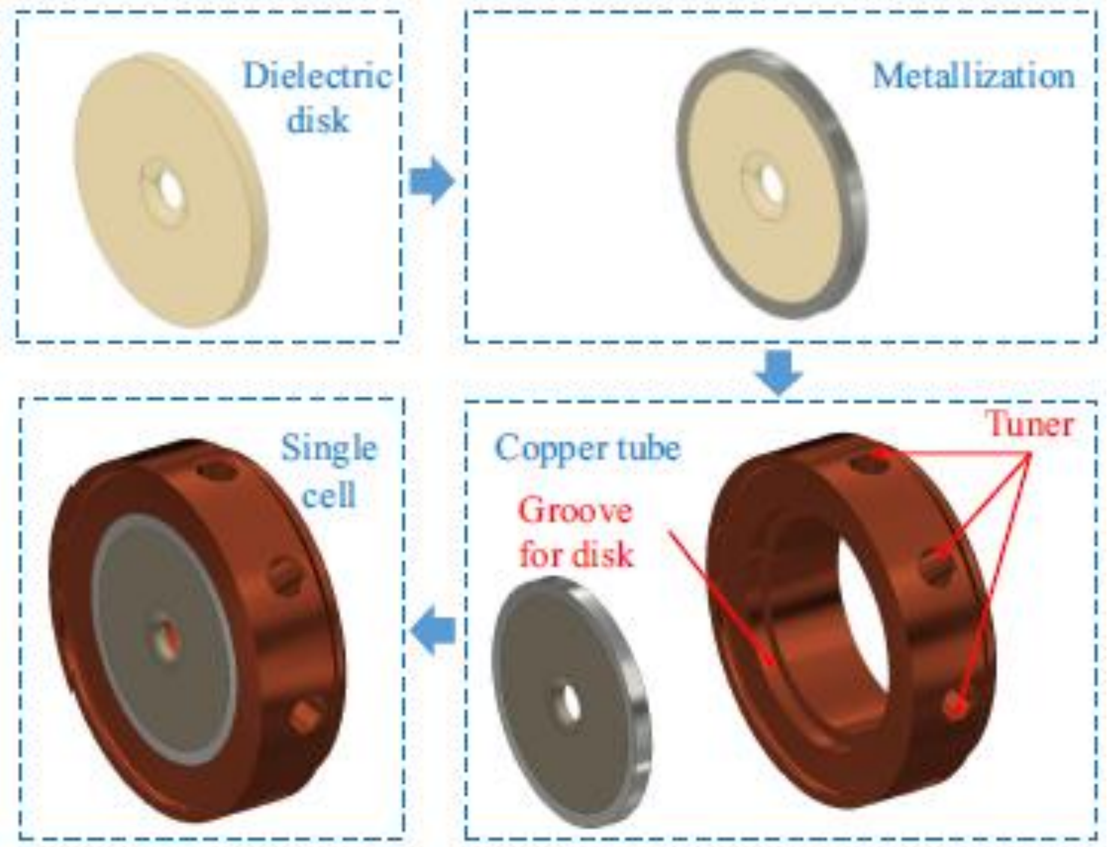
- Prototype I – Brazed: Dec. 2019-Jan. 2020
- Prototype II – Brazed: Failed during brazing
- Prototype III – Clamped: Dec. 2021-Jan. 2022
- Prototype IV – Brazed: upcoming 2023
- Multicell – Clamped: present, May 2023



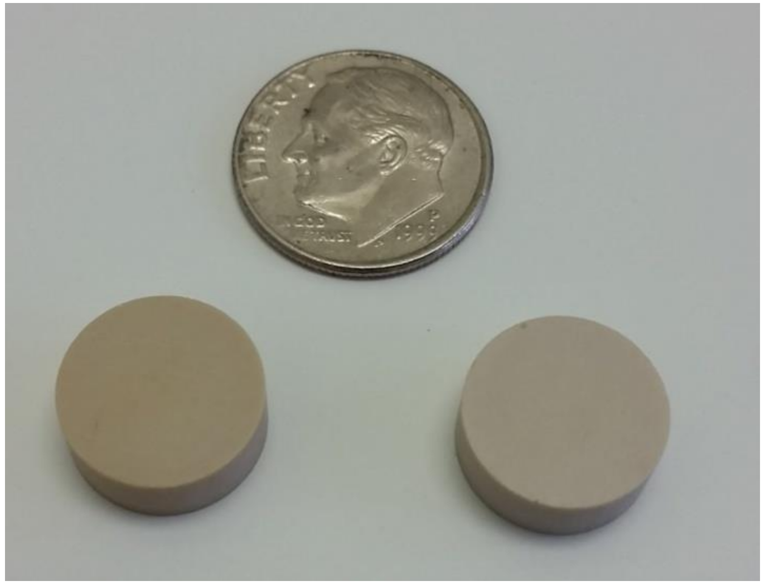
Fabrication Challenges

- Most significant challenge for program
- Precision of dielectric properties
- Machining feasibility/tolerance
- *Brazing vs. Clamping*



Dielectric Material Characterization

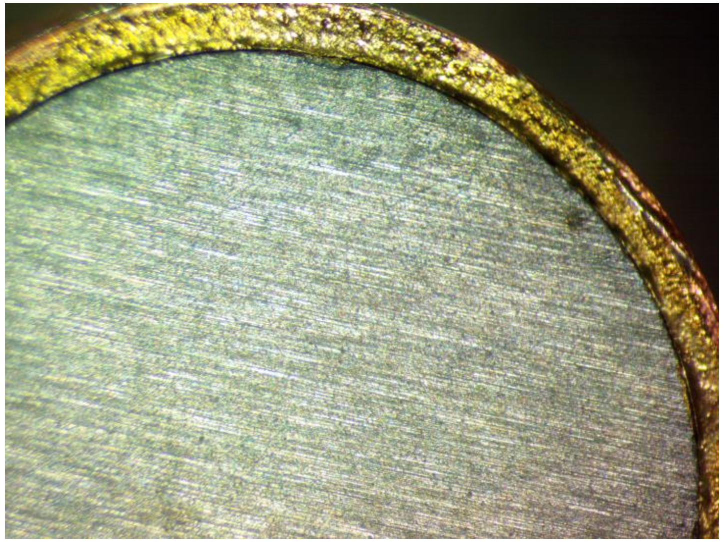
- Prototype I & II:
- $BaTiO_x$ ceramic (D-50) from Skyworks (Trans-Tech)
- 10 coupons measured (4 GHz):
  - ε_r = 50.14 ±0.35
  - tan δ = 8.00e-5 ±0.32e-5



- Prototype III:
- $Ca_vTi_wLa_xAl_yO_z$ ceramic (D-47) from Keramika
- 3 coupons measured (3.8-7.4 GHz), extrapolated to 11.7 GHz
  - ε_r = 47.7
  - tan δ = 3.44e-5

Investigation of Brazing Method

- High temperature InCuSil-ABA @835°C in vacuum furnace
- Hermetic seal successful; ceramic became lossy
- Post-braze bake in air reduced RF loss
- *Oxygen escapes in vacuum at high temperature but can be reintroduced*

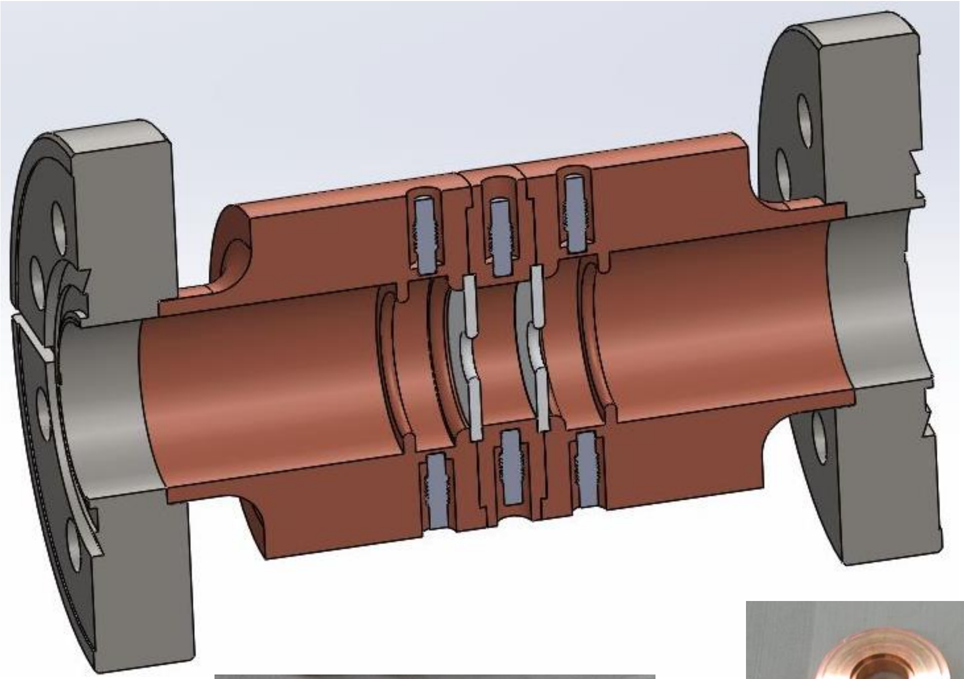


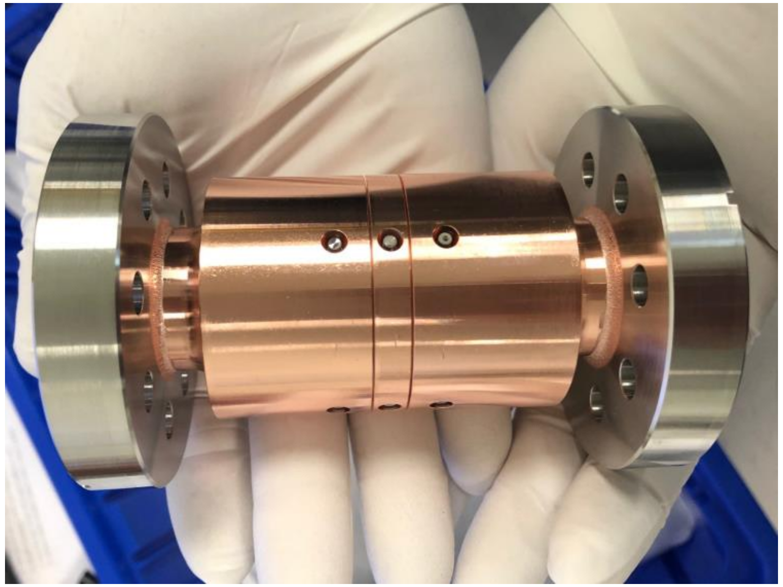
	Temp.	Time	ε_r	tan δ
Original	-	-	50.2	8.15e-5
Post-Braze	835	N/A	49.7	1.43e-2
Post-Bake 1	800	60 min.	49.3	7.17e-4
Post-Bake 2	800	60 min.	49.3	1.03e-4

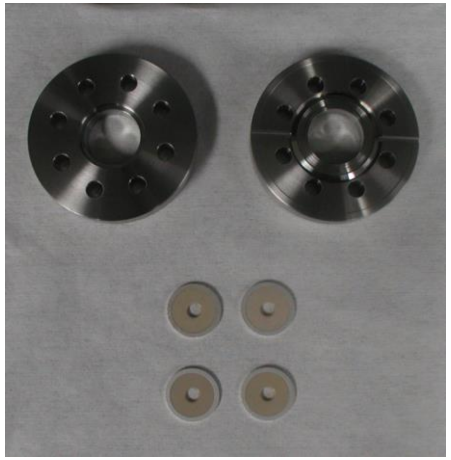
Choice of Brazing Method

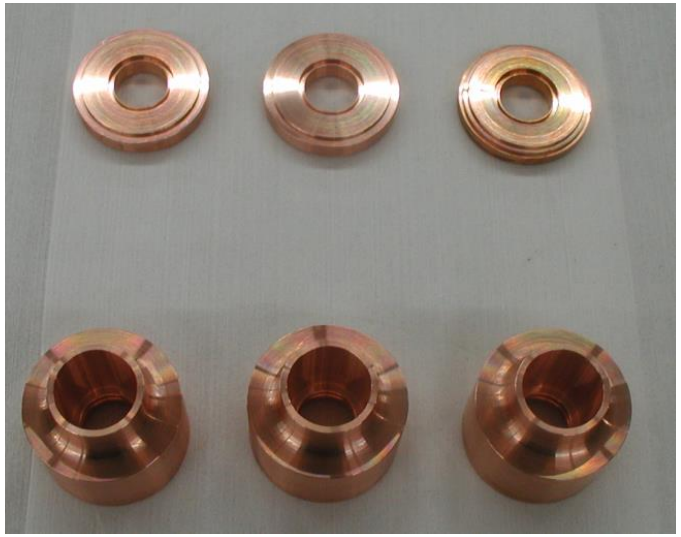
- Low temperature solder (Au-Sn, 350°C) with silver-metallized disks chosen for Prototype I
  - Metallization @ 850°C in air, preserved dielectric properties
- High temperature ABA (InCuSil, 850°C) with nude disks chosen for Prototype II
  - Leaked after first braze cycle
  - Second braze cycle improved leak
  - Third braze cycle cracked ceramic disks

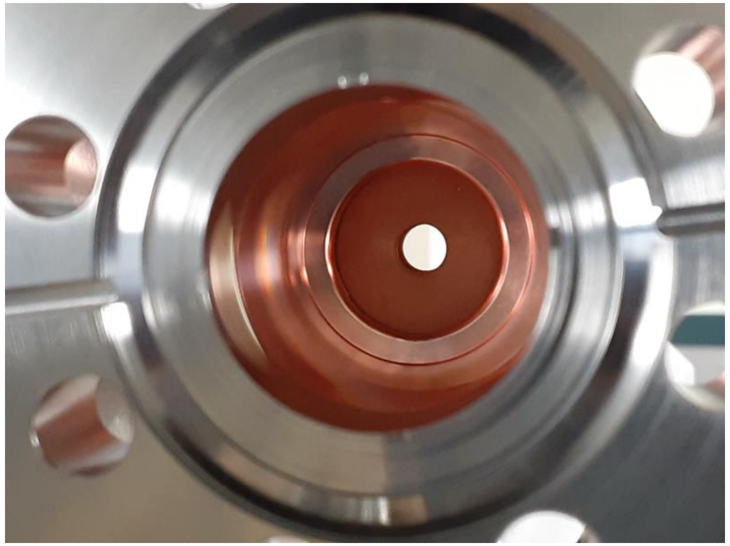
Brazed Prototype Fabrication





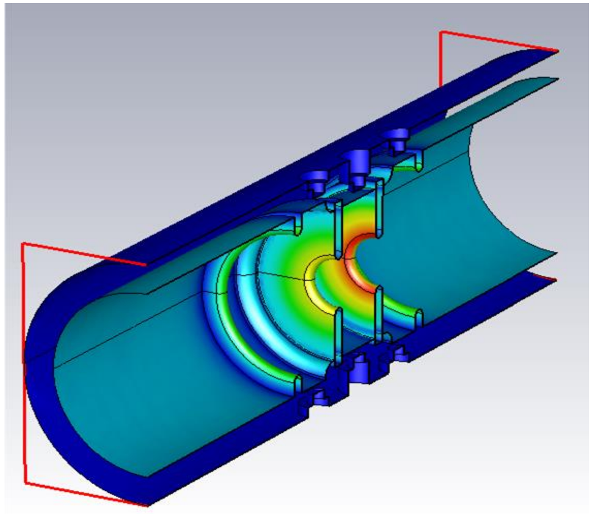


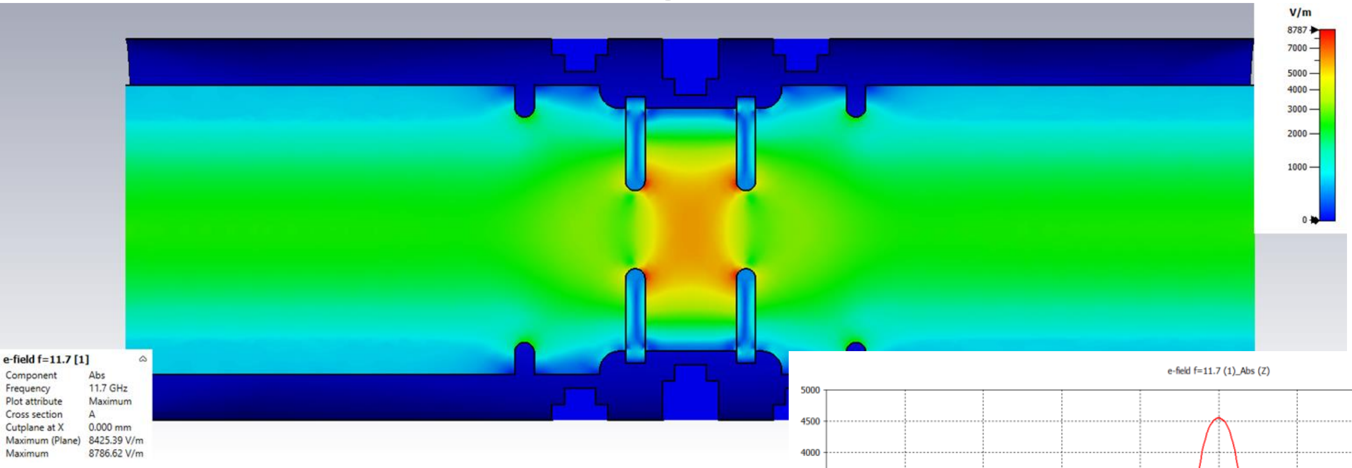


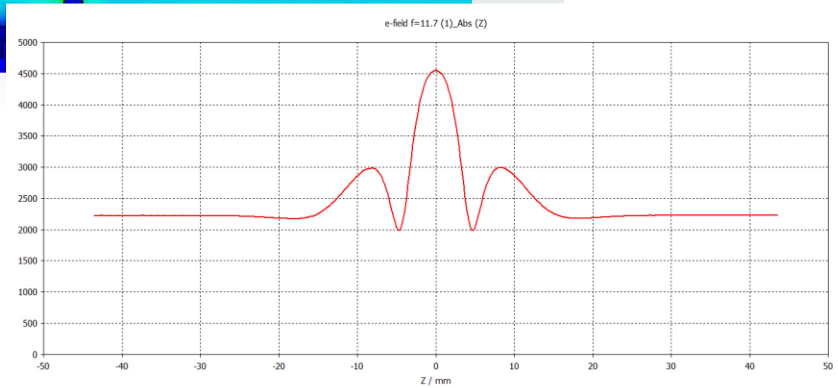


Brazed Prototype RF Design

- 1 Dielectric cell (2 disks) + 2 matching cells
- f = 11.7 GHz, three sets of 4 tuners each allow ±3 MHz range



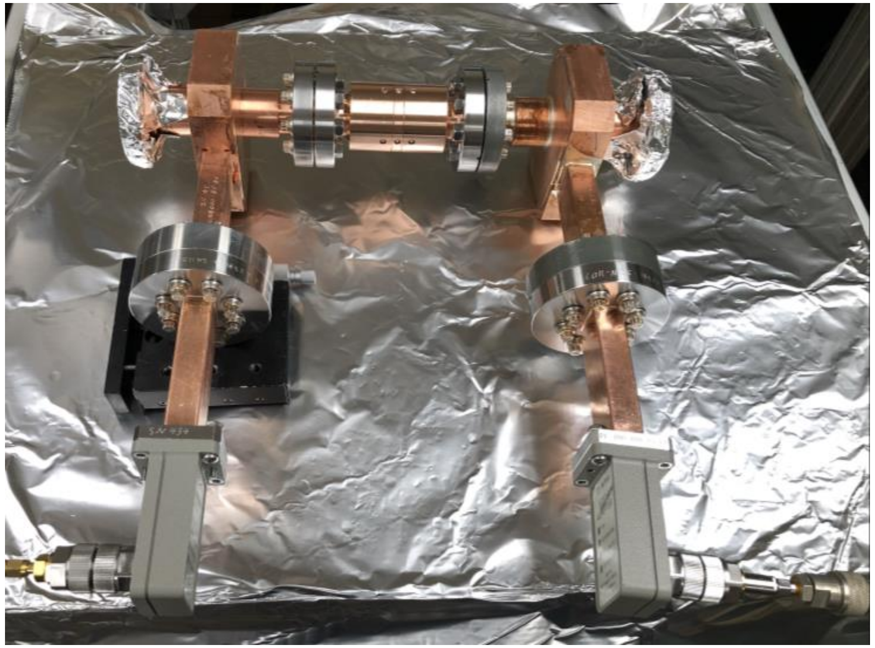


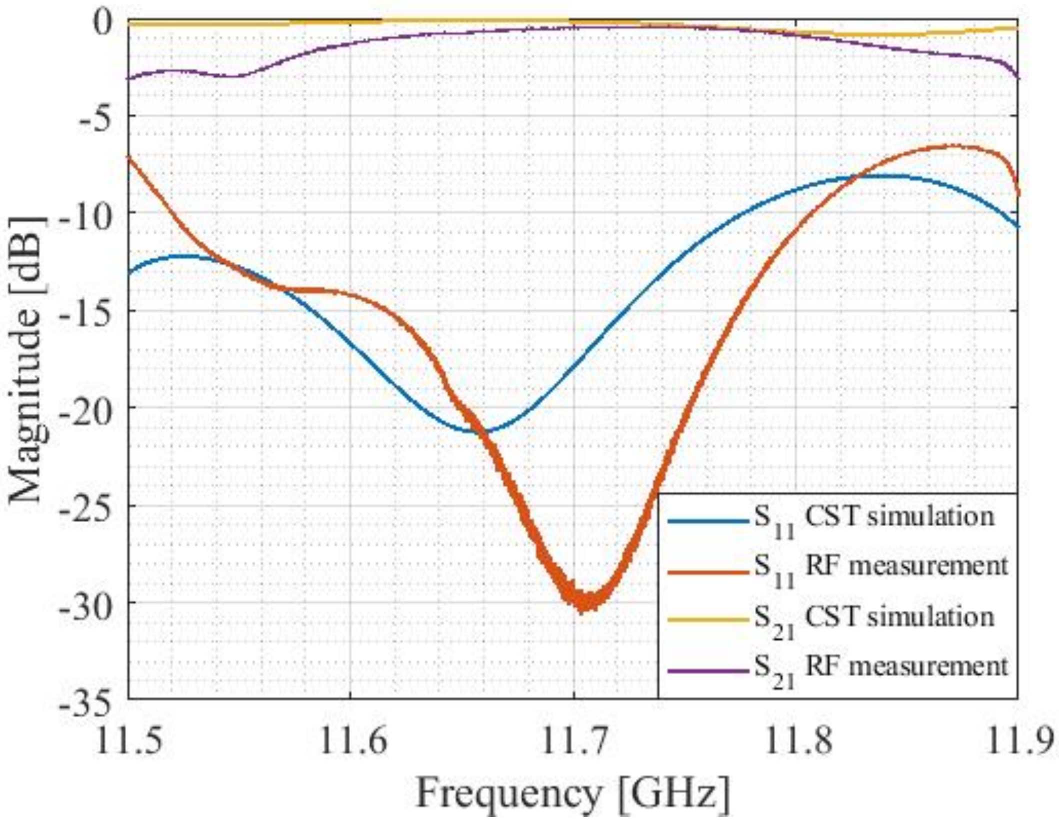


Dielectric constant	50.1
Loss tangent	8e-5
Q	10,300
Shunt impedance	176 MΩ/m
Group velocity	0.345c
Phase advance	2π/3
E_{acc} (P_{in})	100 MV/m (280 MW)
E_{max} / E_{acc}	1.84

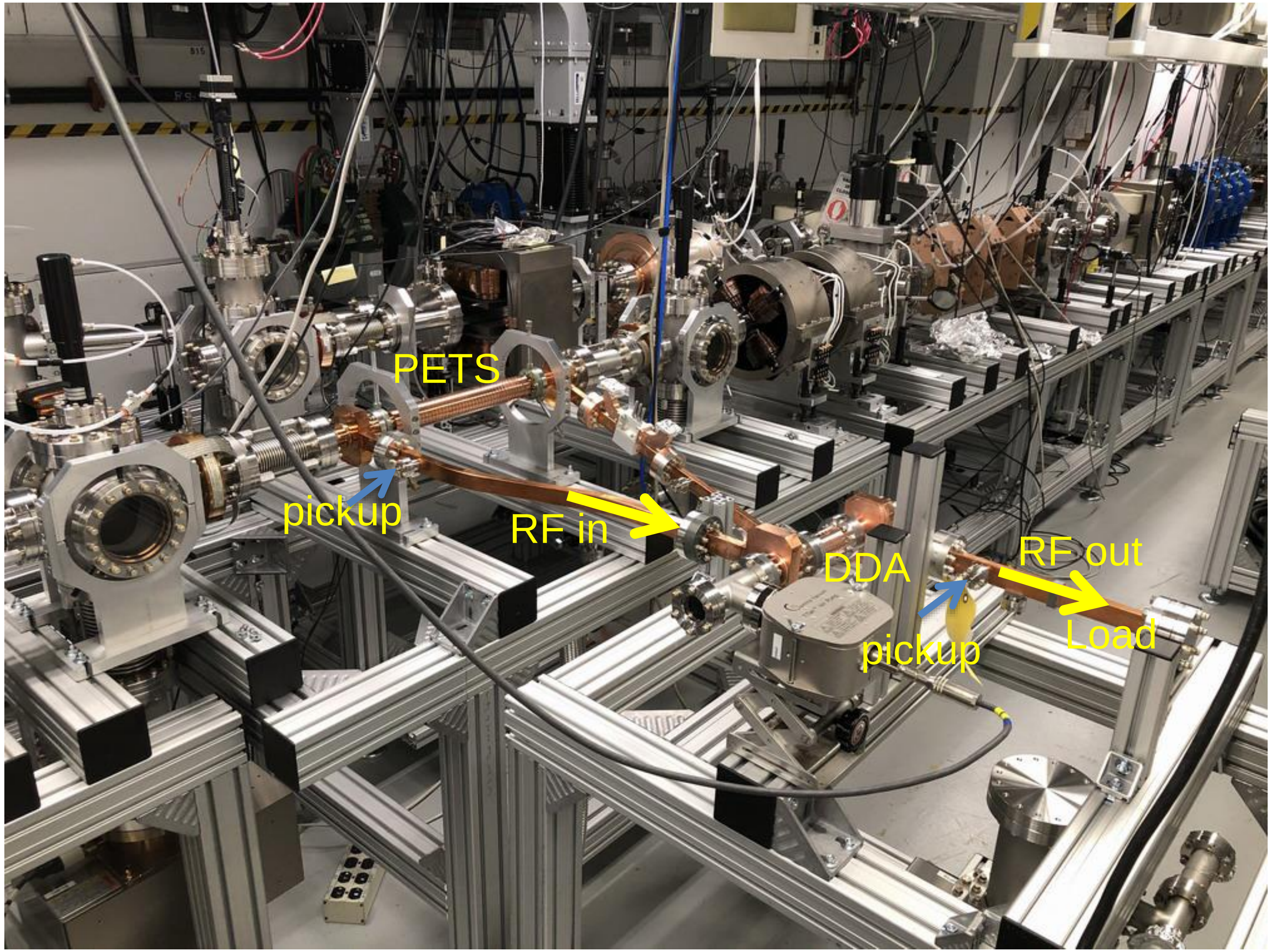
Brazed Prototype Bench Test

- Measured S_{21} = -0.50 dB & S_{11} 10 dB BW = 290 MHz
- Differences attributable to discrepancies in machined dimensions/dielectric constant
  - Couplers included in simulation
- No tuning required





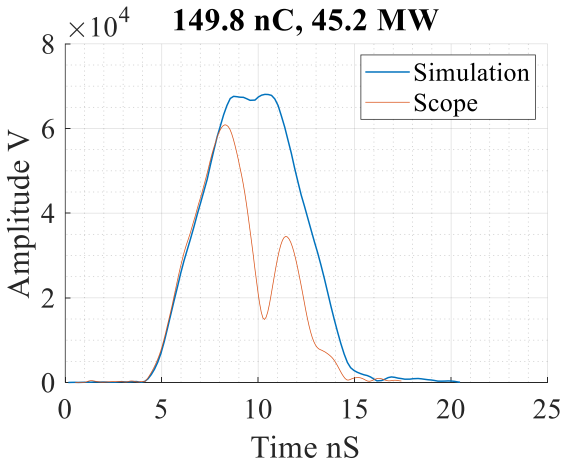
High Power Test Setup



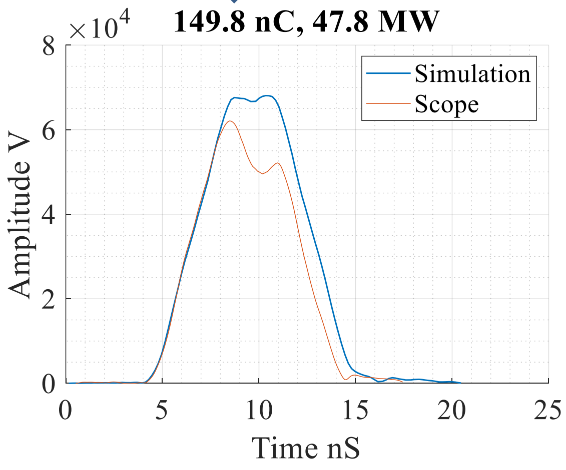
- Power provided by Power Extraction and Transport Structure (PETS)
- ICTs measure beam current for power generation
- Directional couplers at DDA input & output
- Instrumentation to look for multipacting/breakdown
  - Ion pump & vacuum gauge
  - Cameras on both ends of DDA

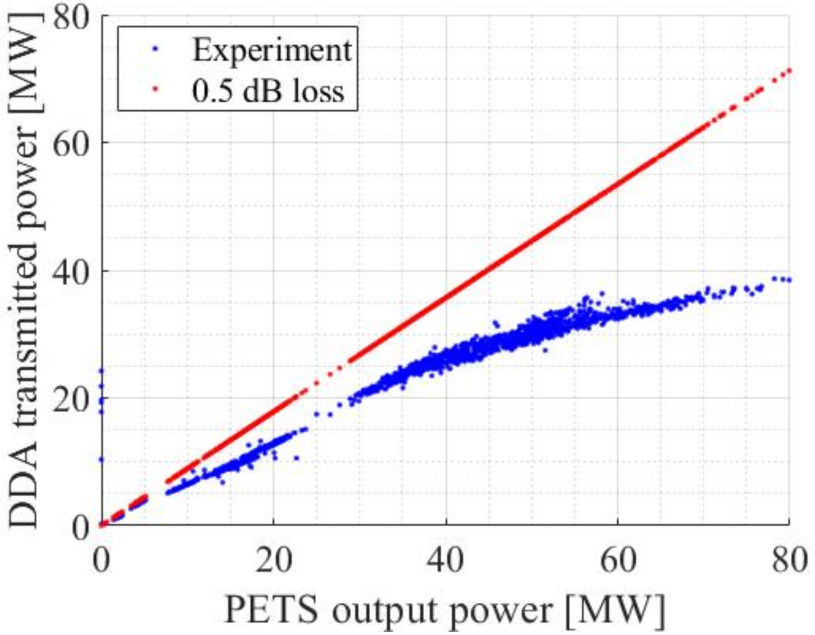
Brazed Prototype High Power Test Results

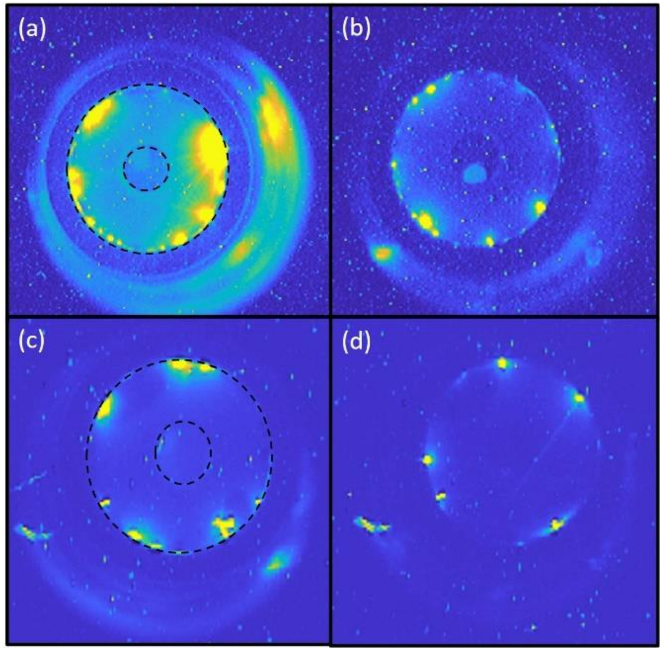
- Significant multipactor/breakdown activity observed
- Light emission from circumference of both ceramic disks
  - No light visible from irises
- Conditioning improved power transmission & light emission somewhat; never eliminated
- Run aborted at 80 MW input power



Conditioning

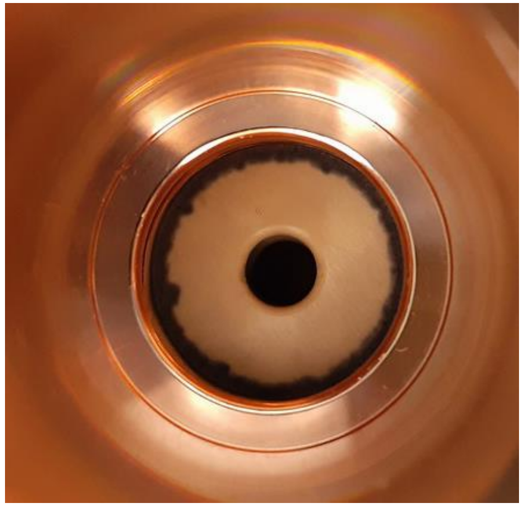


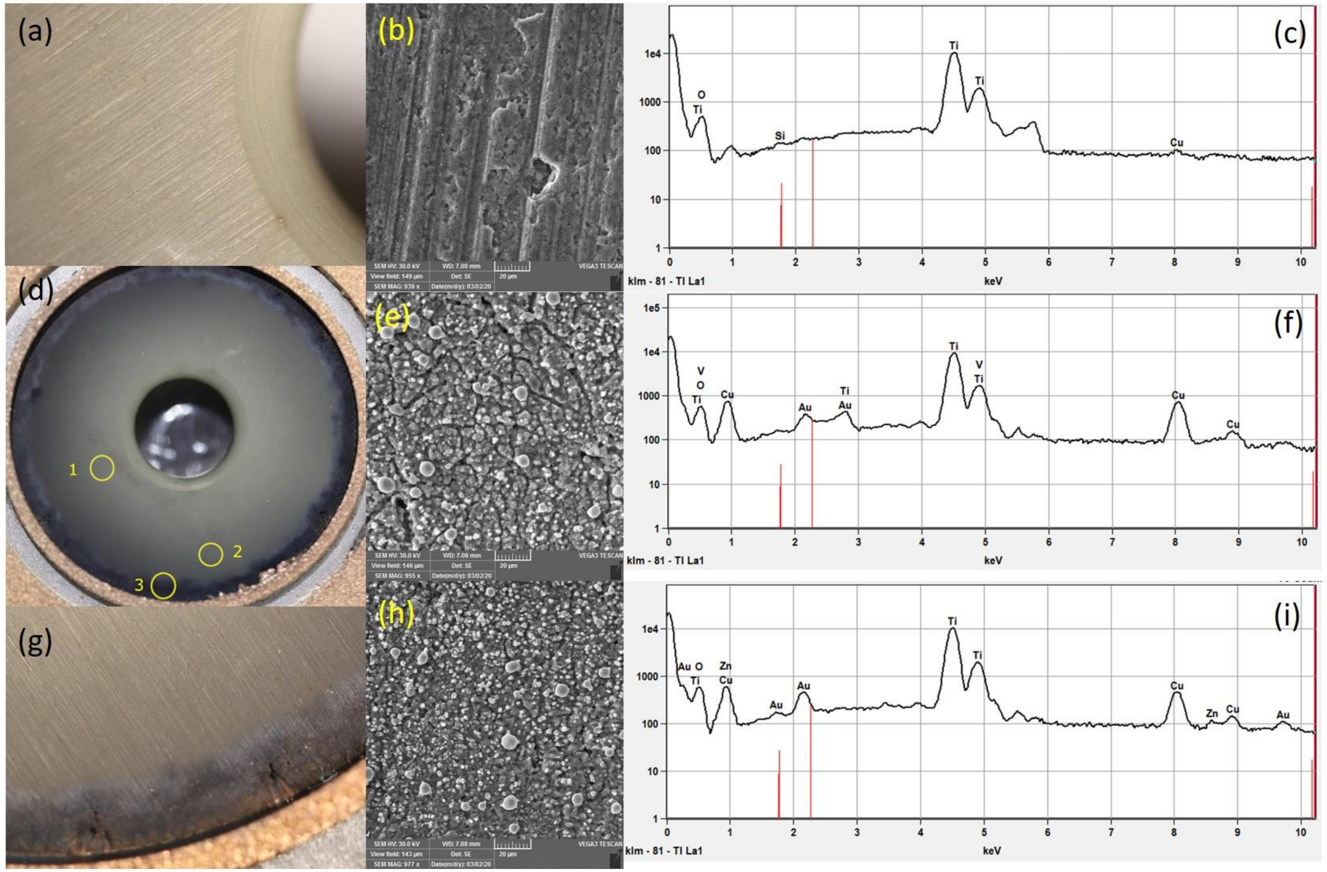




Brazed Prototype Autopsy

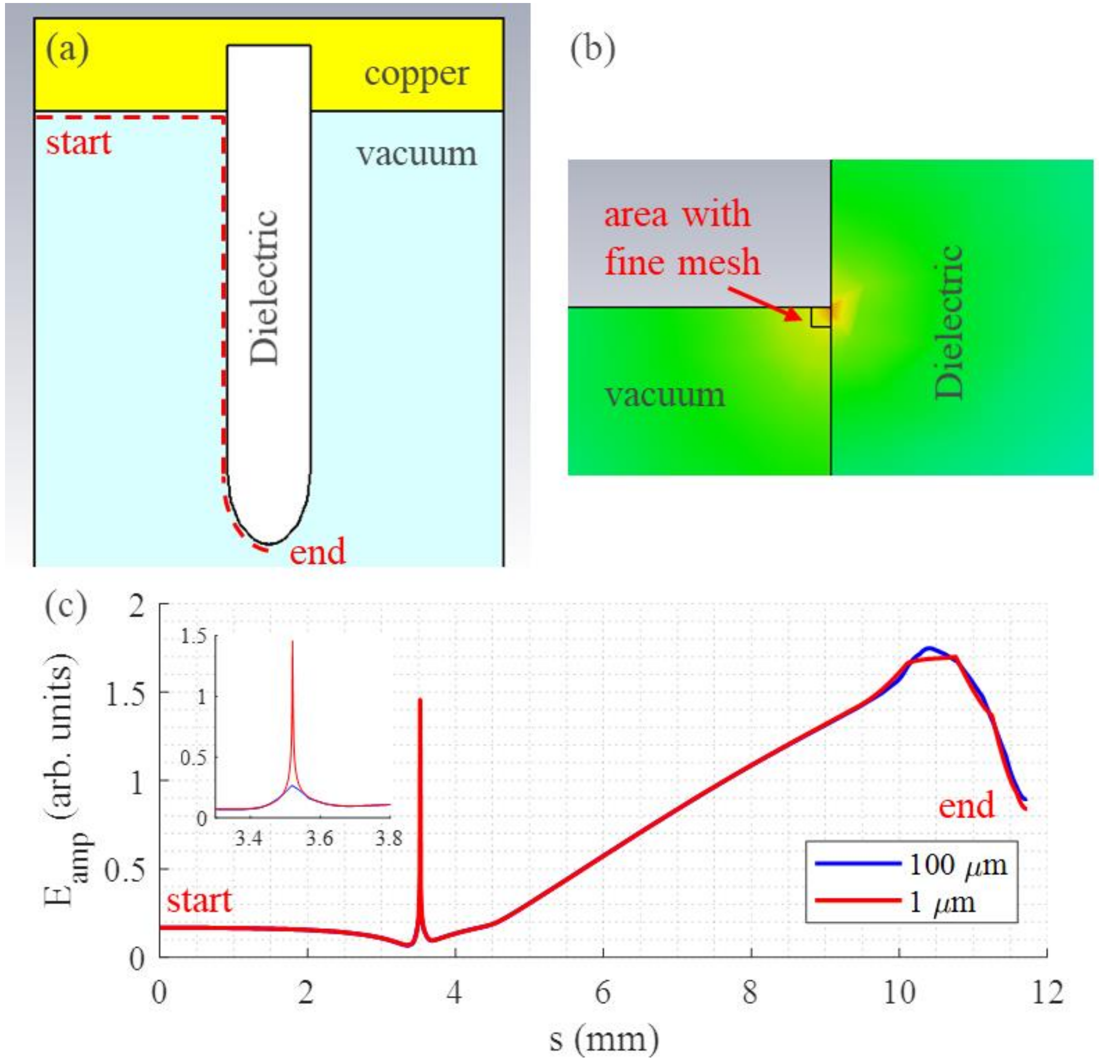
- Damage around ceramic circumference
- SEM & EDX results reveal pitting and presence of gold (braze alloy) and copper near outer radius of disks
- Iris & surrounding area free from damage or contamination
- Breakdown/ multipactor confined to triple junction region





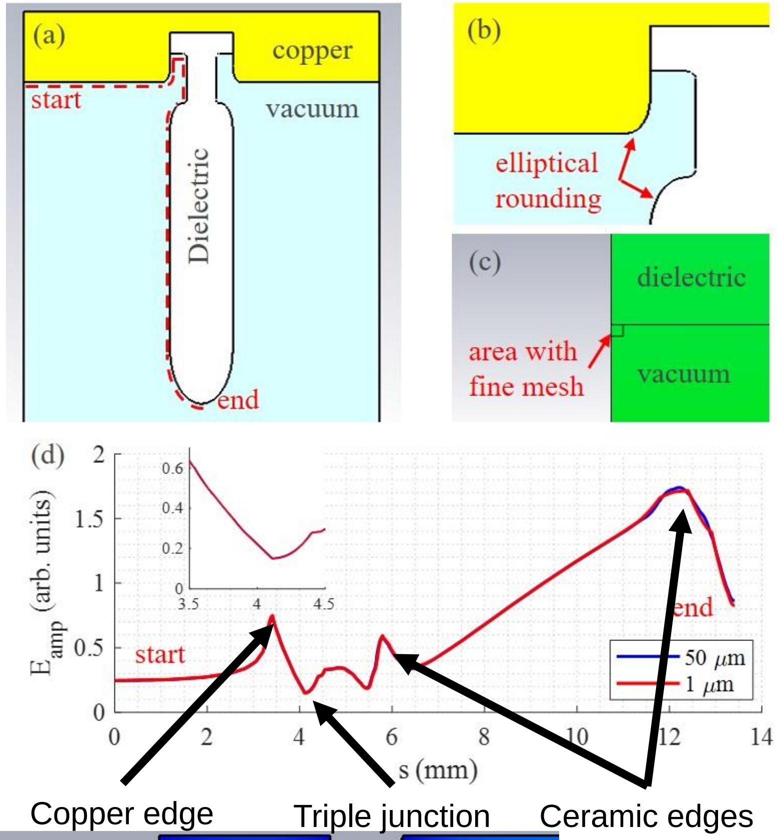
Brazed Prototype Conclusions

- Finer mesh revealed field enhancement at triple junction
- No evidence of problems stemming from iris or ceramic material
- Engineering challenge to overcome, not fundamental

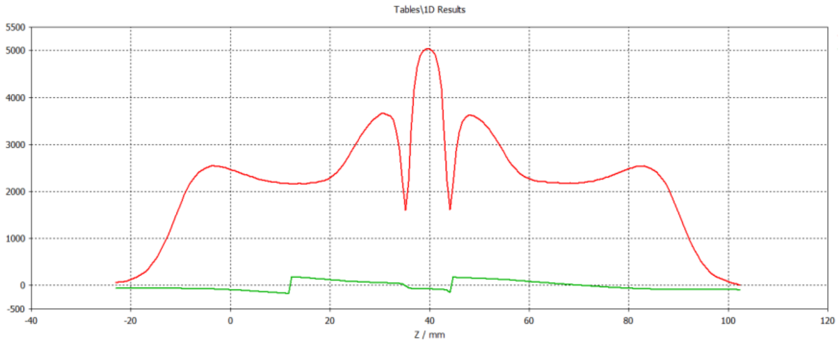


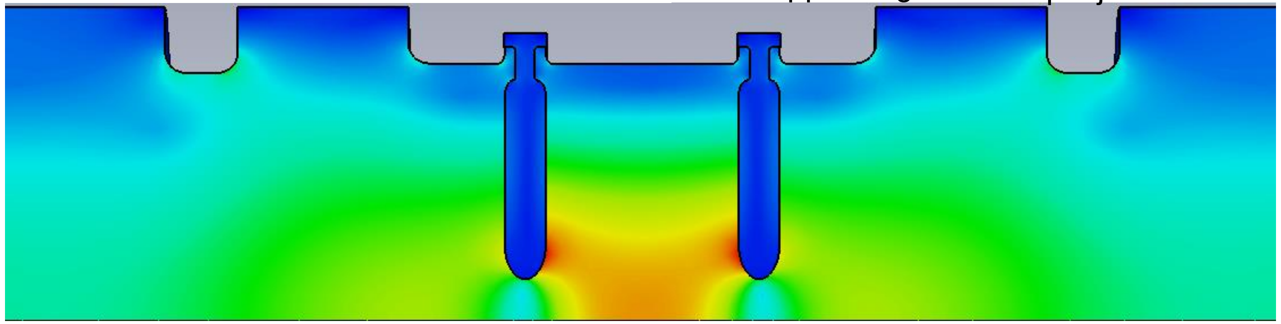
Clamped Prototype RF Design

- Triple junction redesigned to minimize E-field
- Elliptic rounding added to copper and ceramic



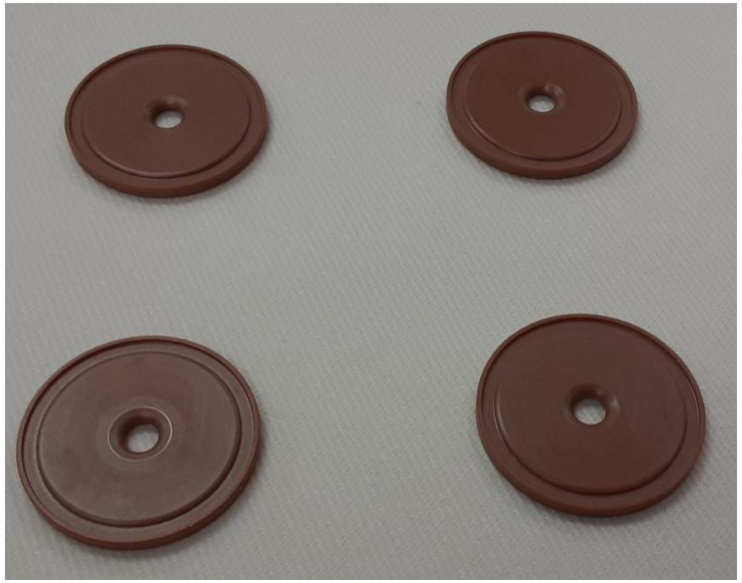
Dielectric constant	47.7
Loss tangent	3.4e-5
Q	8,500
Shunt impedance	174 MΩ/m
Group velocity	0.27c
Phase advance	2π/3
E_{acc} (308 MW)	100 MV/m
E_{max} / E_{acc}	1.44

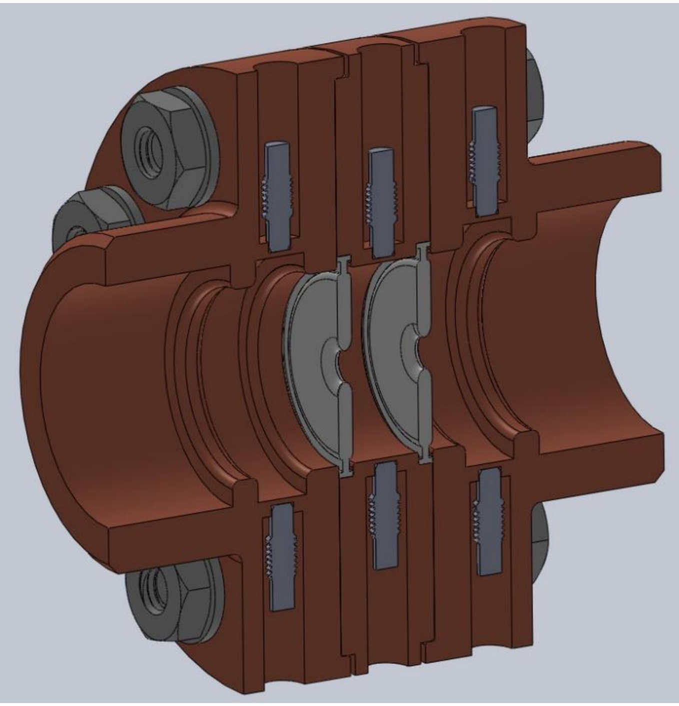


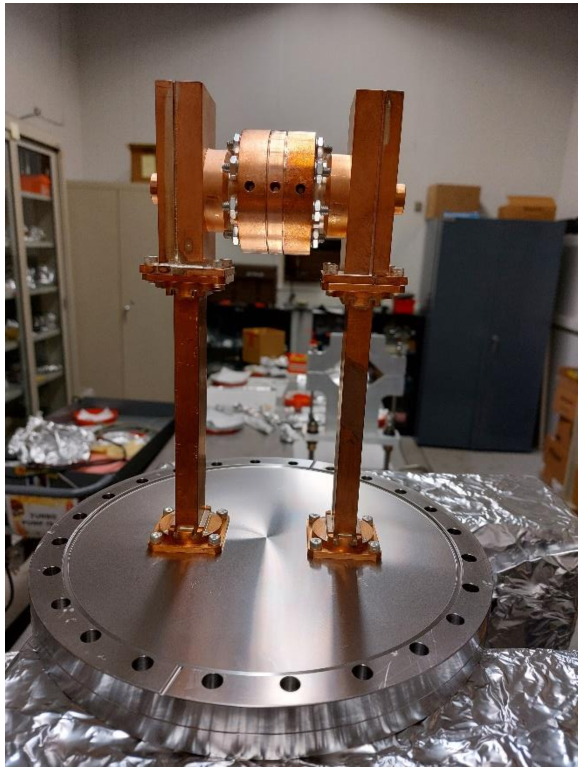


Clamped Prototype Fabrication

- Potential problem associated with braze alloy avoided
- No vacuum seal (tested in vacuum chamber)
- Outer edge of ceramic disks bite into annealed copper parts
- Ceramic design more difficult to machine

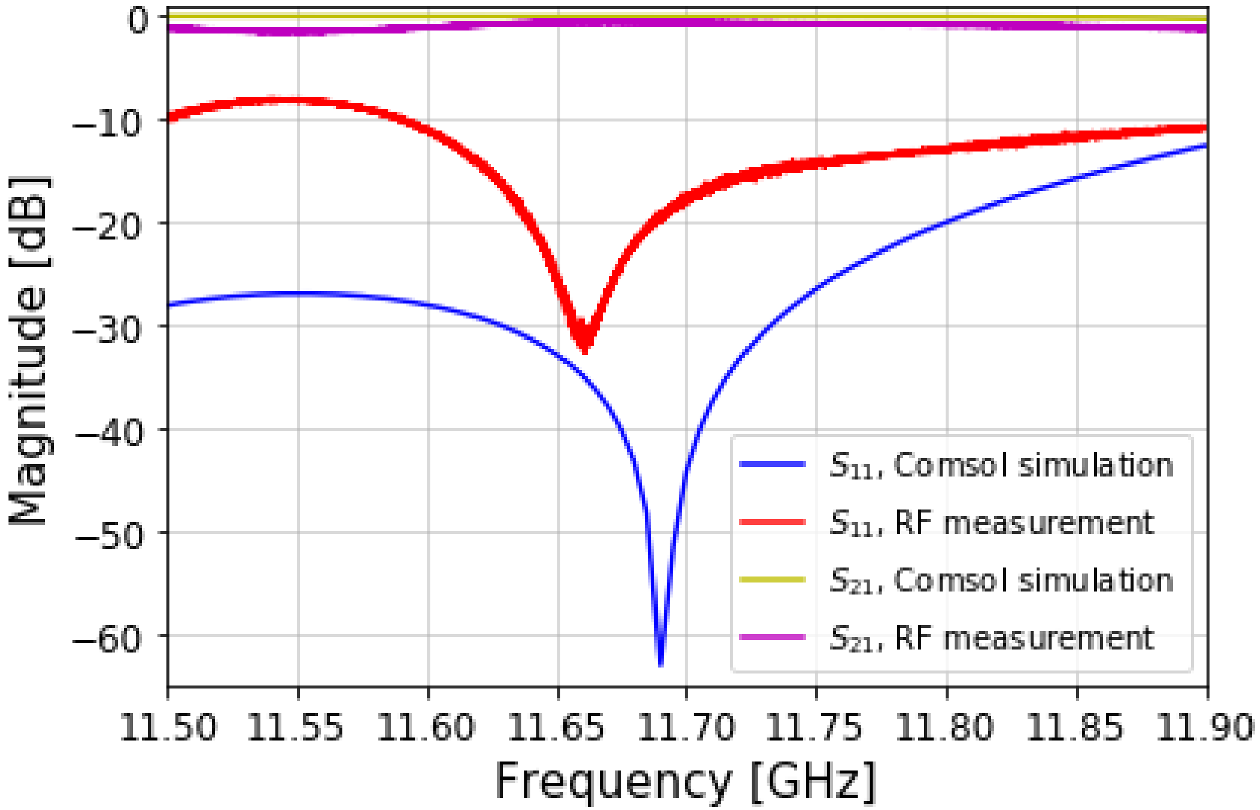






Clamped Prototype Bench Test

- Measured S_{21} = -0.652 dB & S_{11} 10 dB BW = >640 MHz
- Differences attributable to discrepancies in machined dimensions/dielectric constant
  - Couplers included in simulation
- No tuning required



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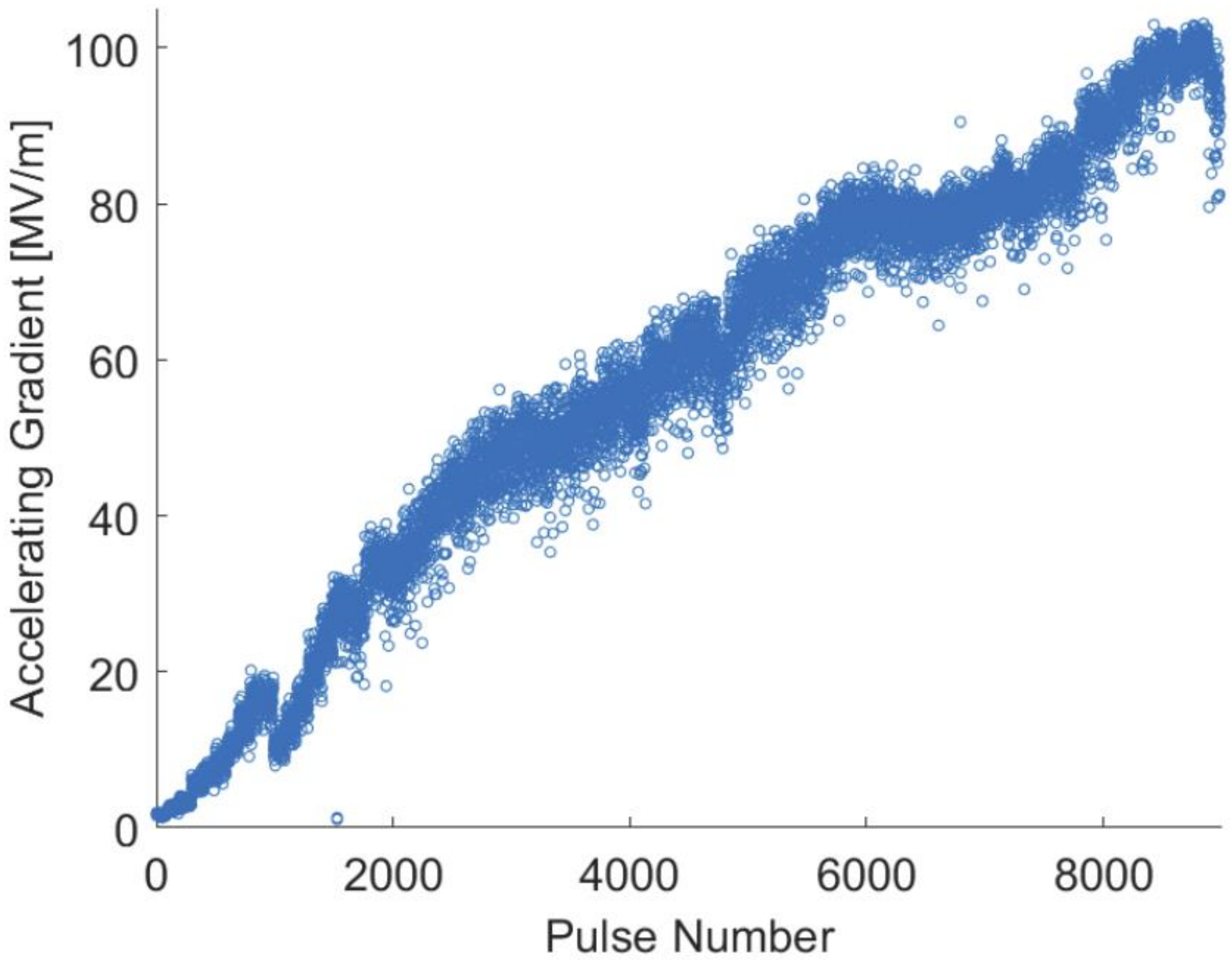
Clamped Prototype High Power Test History

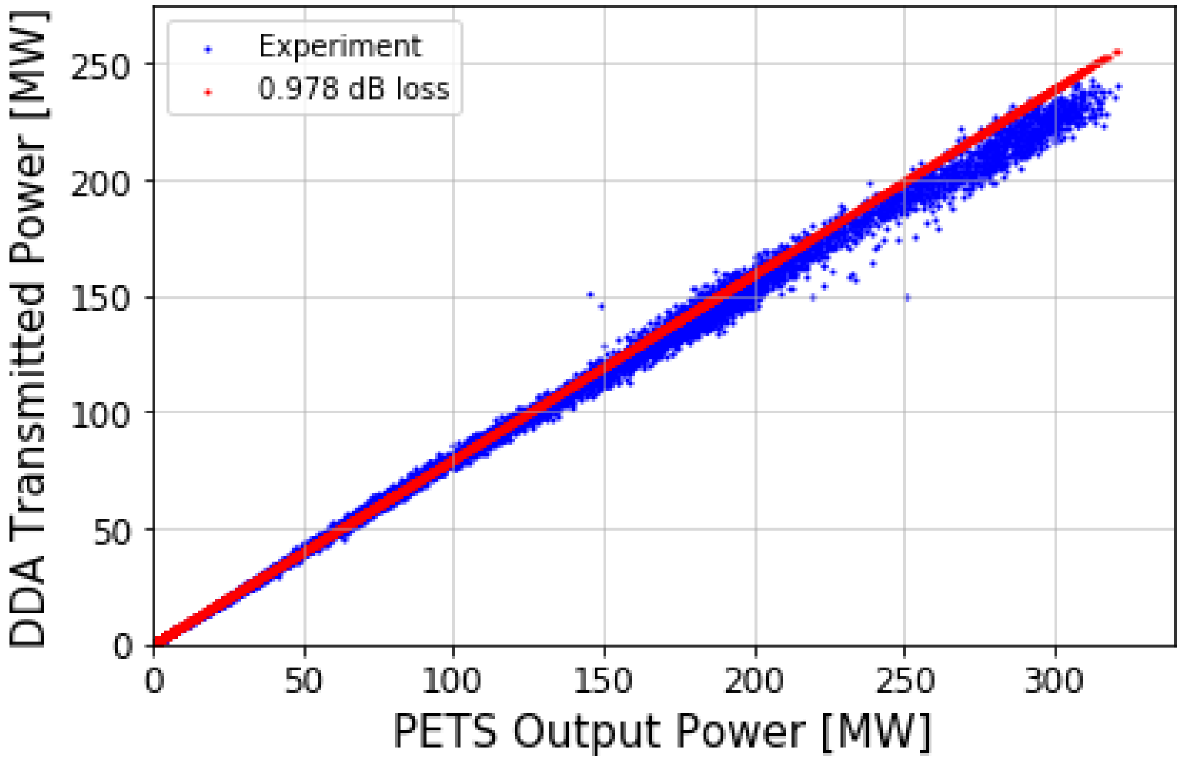


- > 250k RF pulses delivered at 2 Hz rep. rate over 8 days
  - > 9k pulses recorded
- Vacuum & light monitored for multipacting/breakdown
- Input power increased once vacuum settled down & became steady
- Last data points = attempts to adjust laser for larger drive beam bunch charge

Clamped Prototype High Power Test Results

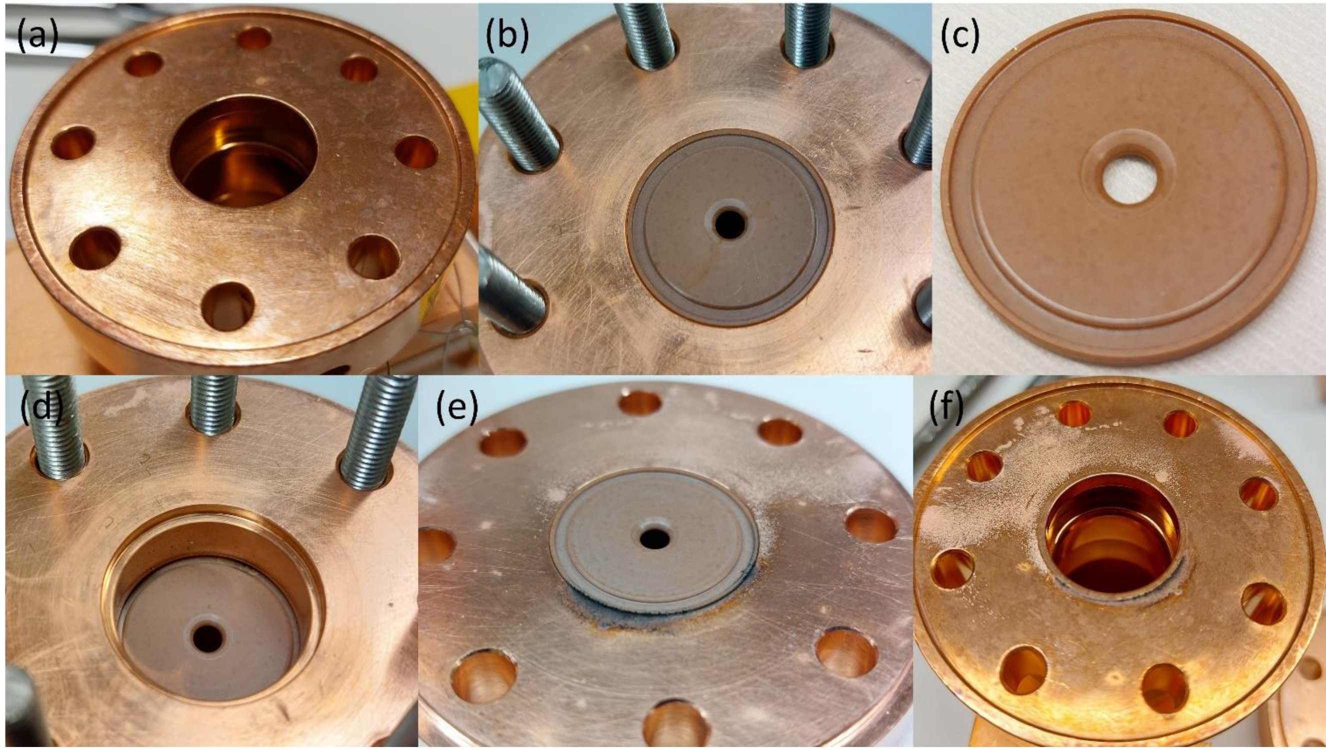
- No evidence (RF or light) of breakdown or multipacting
- Brief period of faint light from interior of structure at highest power conditioned away
- Transmitted power agrees very well with measured transmission loss from DDA+waveguide
- Limited by available input power!

320.9 MW input power
=
102.3 MV/m accelerating gradient
(147 MV/m surface gradient)

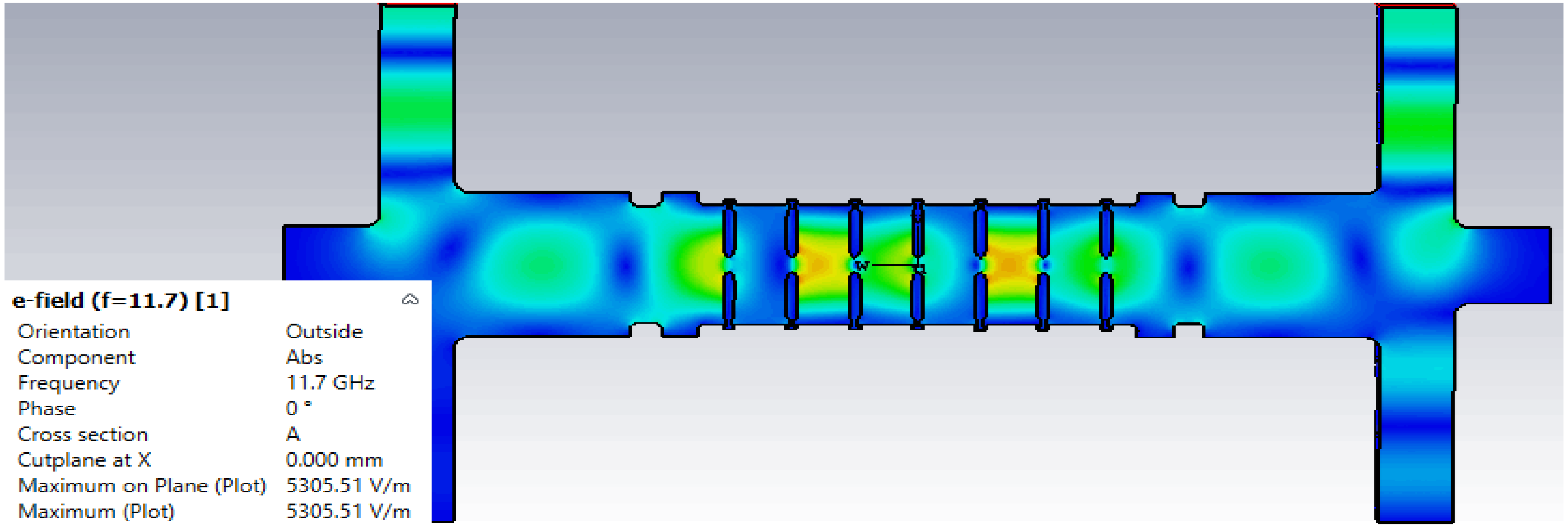


Clamped Prototype Inspection

- No damage on ceramic or copper in RF volume
- Damage on copper surface and ceramic circumference in one cell due to RF leakage caused by inconsistent clamping force
  - May have been source of brief light during high power test



11.7GHz Multicell DDA

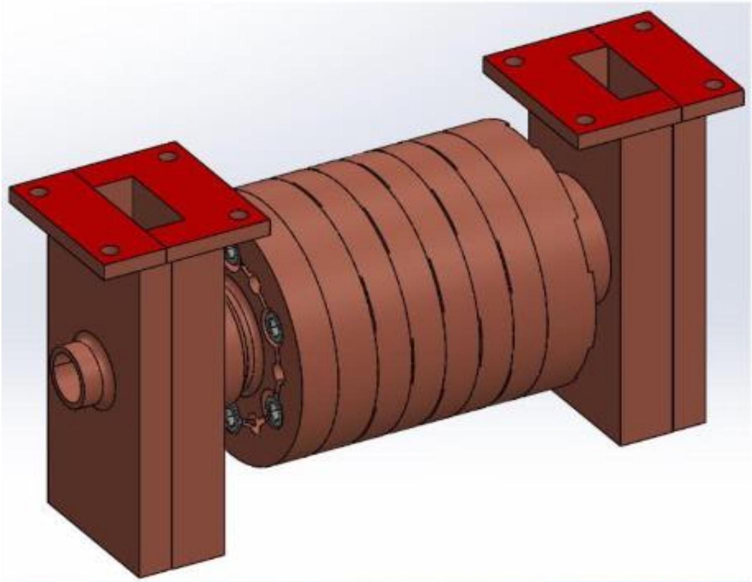
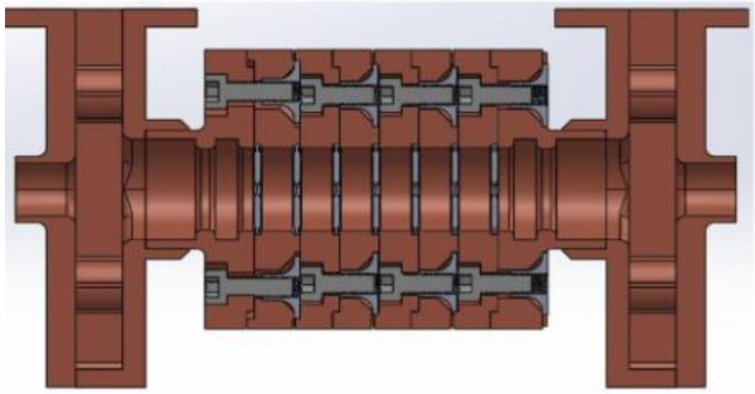


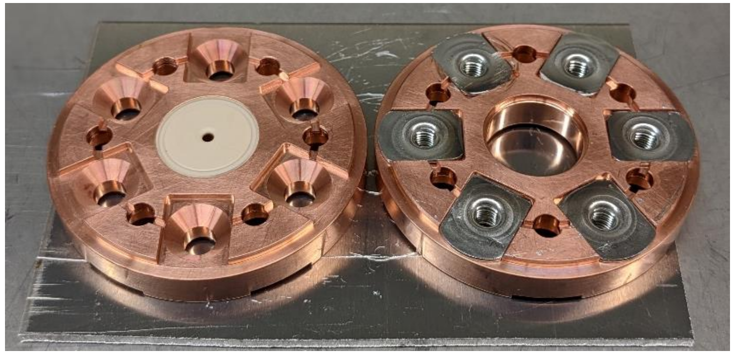
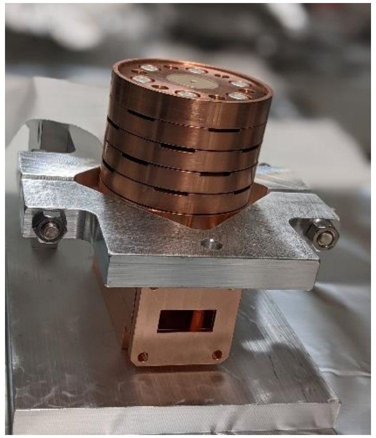
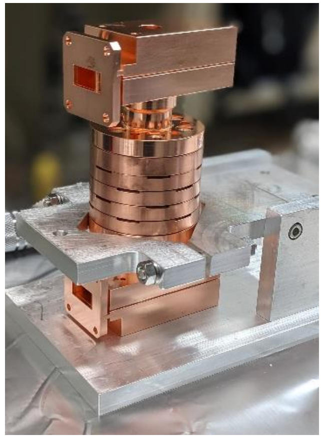
Parameter	Value
Disk Outer Diameter	20.48 mm
Disk Inner Diameter	2.239 mm
Matching Cell Iris Aperture Diameter	18.4 mm
Matching Cell Aperture Diameter	22.86 mm
Disk Thickness	1.45 mm
Dielectric Cell Length	8.541 mm
Number of Ceramics	7

Parameter	**Value**
Accelerating Gradient at 400 MW	108 MV/m
Group Velocity	0.24 c
Quality Factor	9,612
r	184.4 MΩ/m
r/Q	19.2 kΩ/m
S11 10 dB Bandwidth	> 600 MHz

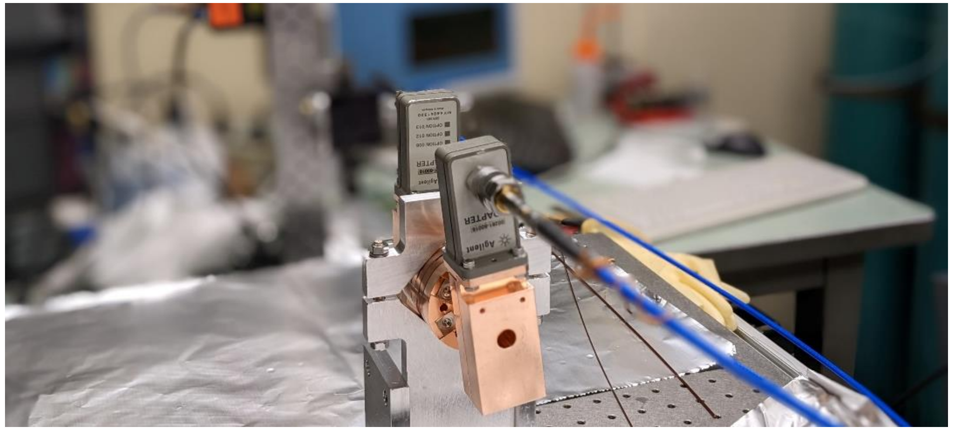
Engineering and Fabrication

- Due to clamping issues from single cell, more sophisticated clamping mechanism was designed.
- Compact enough to fit into vacuum chamber.
- Copper is annealed so that the ceramic can bite into it.

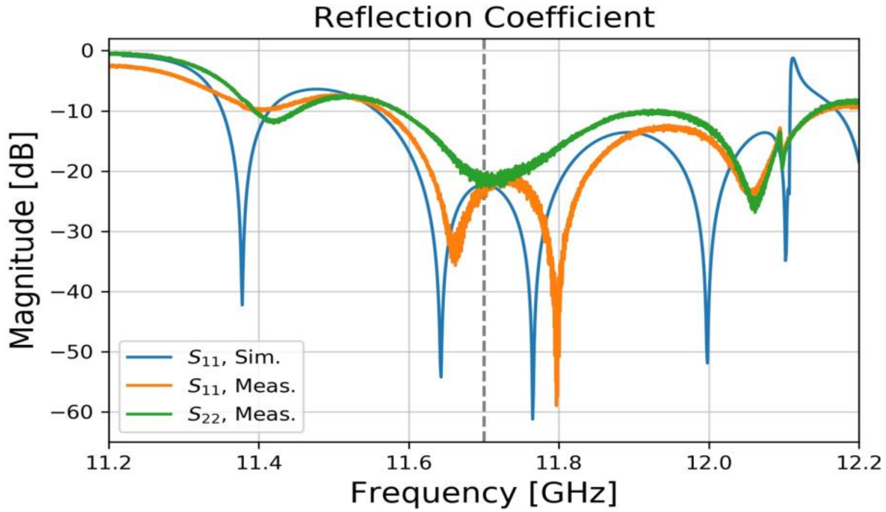



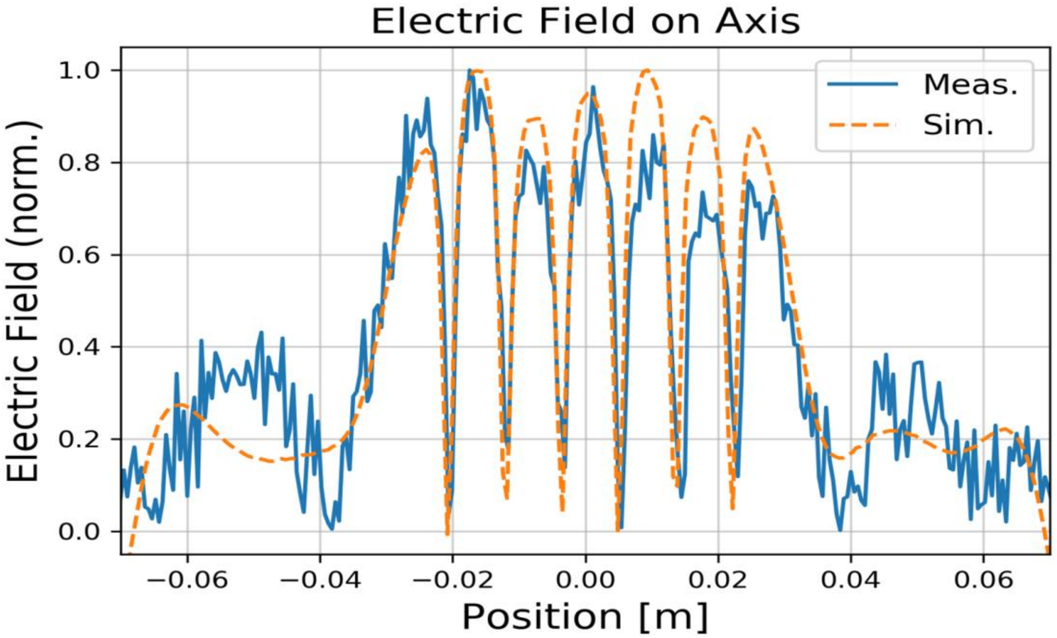
Bench Test



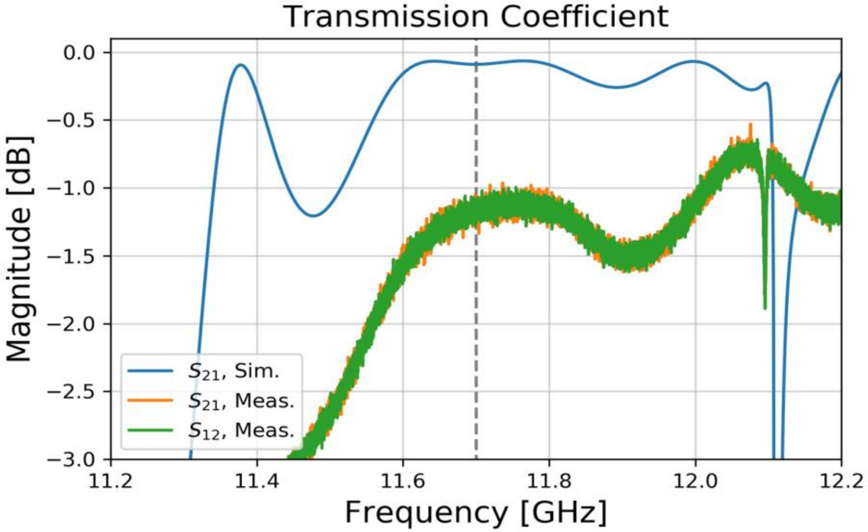
Agilent



Reflection Coefficient
Magnitude [dB]
Frequency [GHz]
0
−10
−20
−30
−40
−50
−60
11.2
11.4
11.6
11.8
12.0
12.2
S_{11}, Sim.
S_{11}, Meas.
S_{22}, Meas.

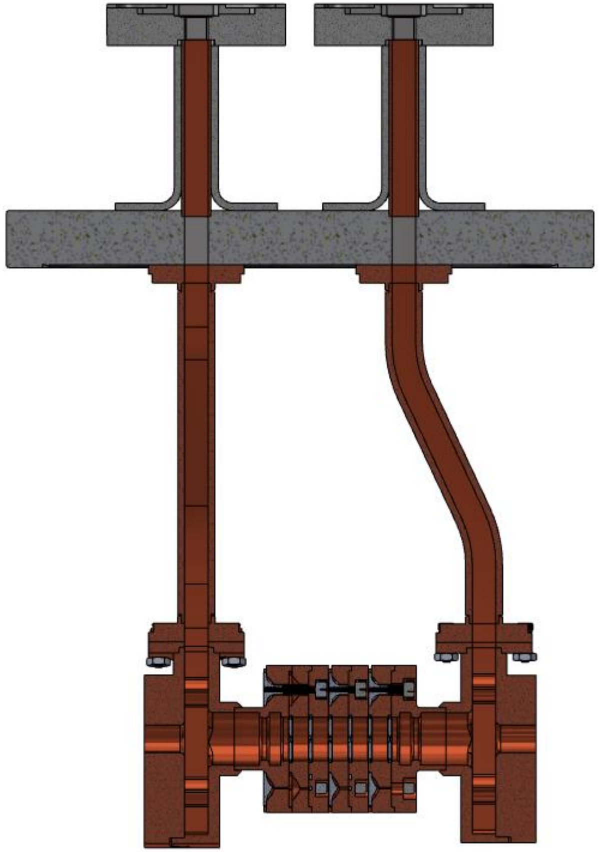


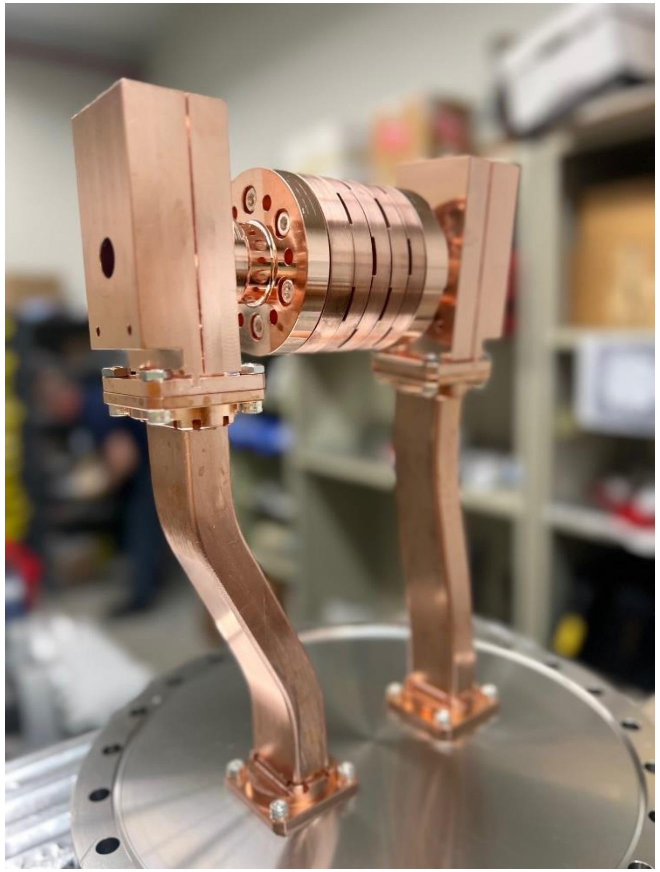
Electric Field on Axis
Electric Field (norm.)
Position [m]
1.0
0.8
0.6
0.4
0.2
0.0
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
Meas.
Sim.

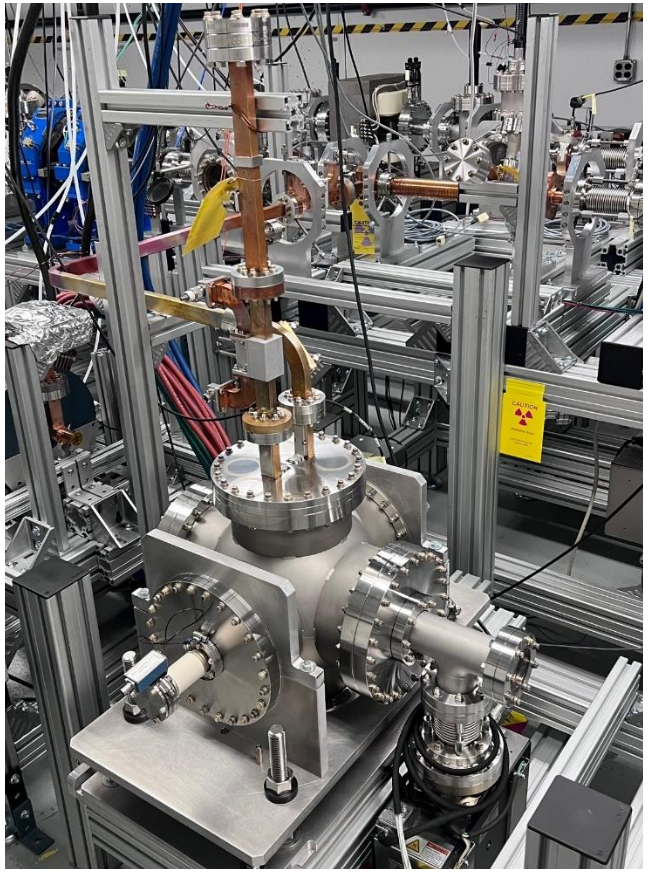


Transmission Coefficient
Magnitude [dB]
Frequency [GHz]
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
11.2
11.4
11.6
11.8
12.0
12.2
S_{21}, Sim.
S_{21}, Meas.
S_{12}, Meas.

High Power RF Test (started on May 15 2023)

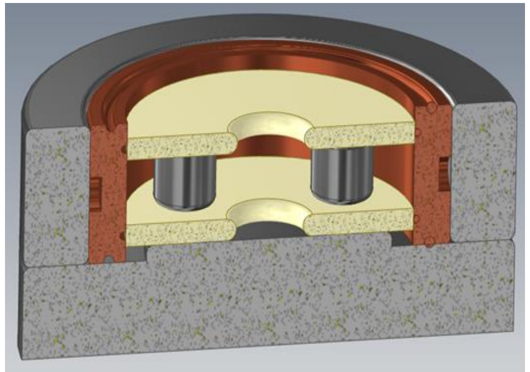


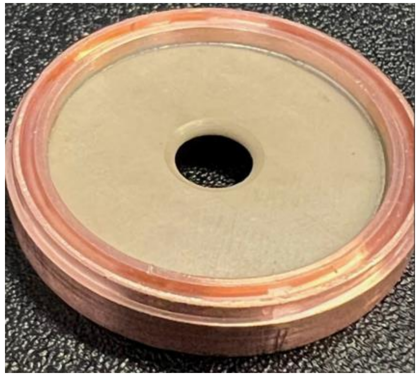


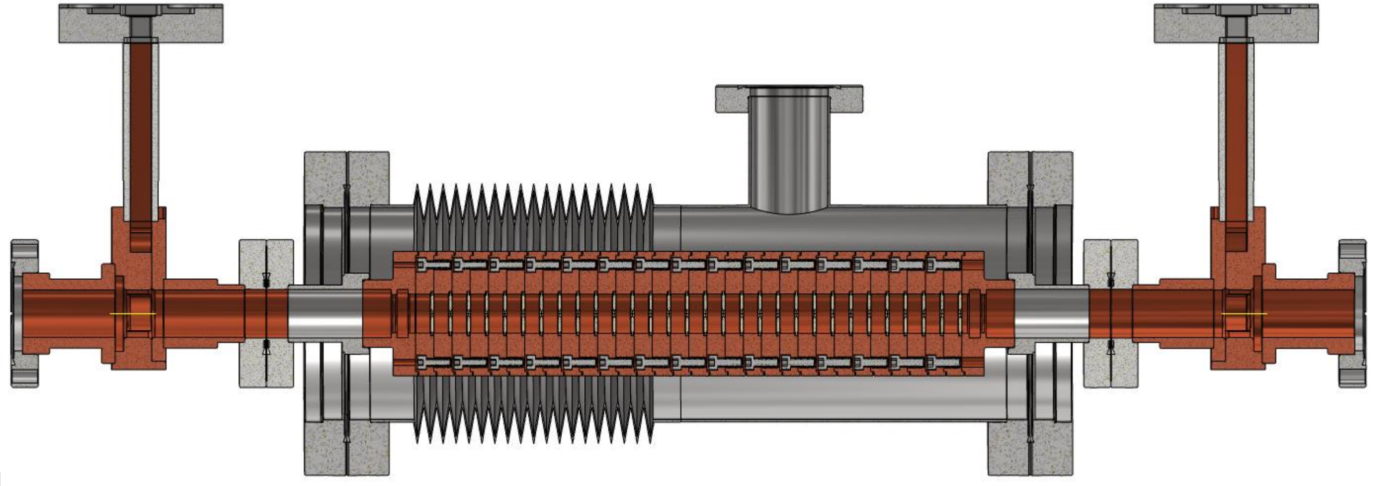


Remarks

- DDA shows an excellent properties in the role of short pulse acceleration.
- Triple junction design and implementation (clamp or braze) are key factors.
- No multipactor? To be reproduced.
- Breakdown limit to be explored.







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