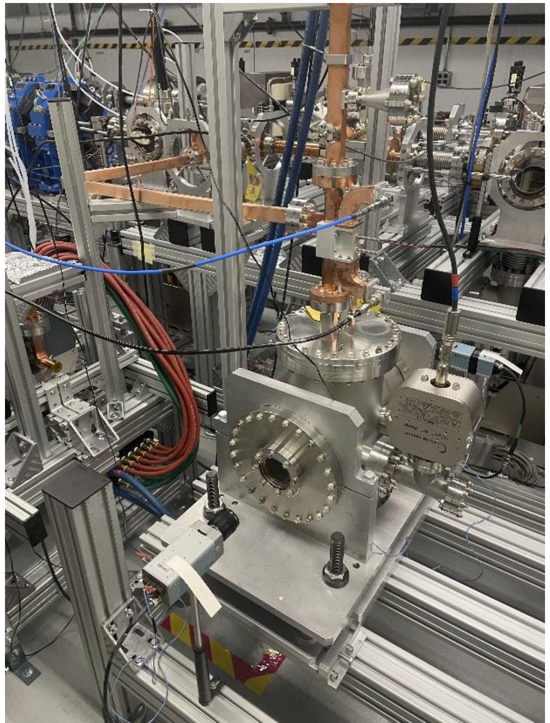
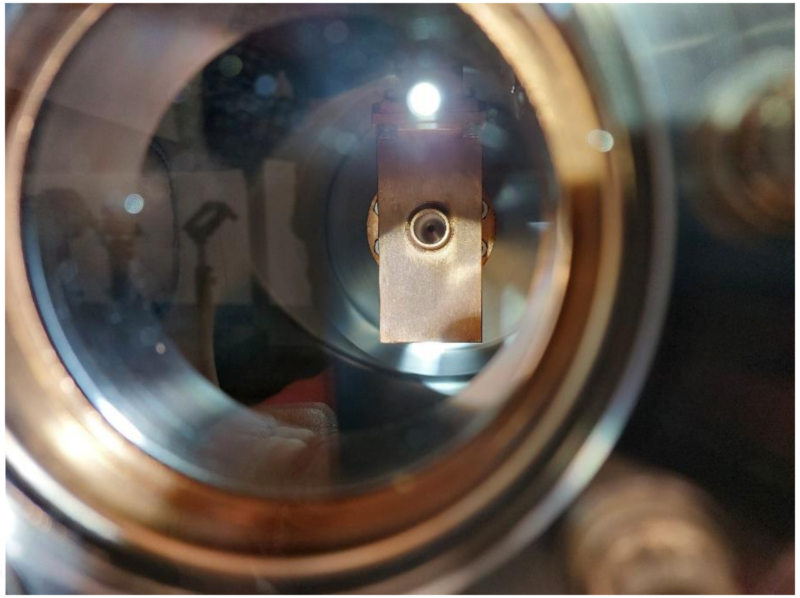
High Power Test Results of X-Band Dielectric Disk Accelerating Structures



Ben Freemire
for Euclid Beamlabs &
Argonne Wakefield Accelerator



AAC'22 Advanced Accelerator Concepts Workshop
November 6 - 11, 2022
Hyatt Regency Long Island, NY

Motivation

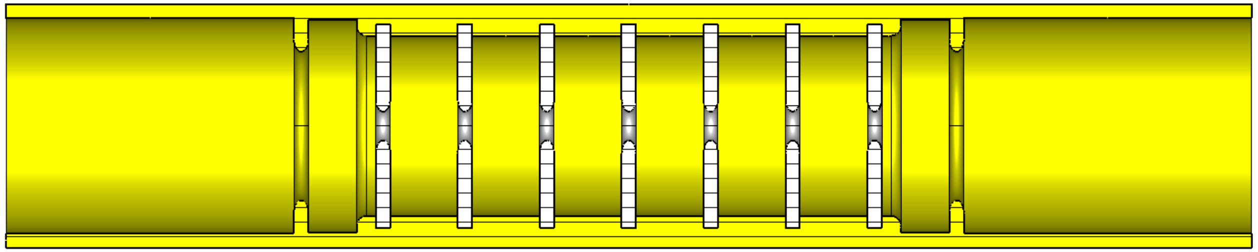
- Develop enabling technologies for TeV-scale linear colliders
- Support demonstration of 500 MeV electron beam energy gain using Two Beam Acceleration approach at Argonne Wakefield Accelerator
- Improve RF-to-beam efficiency
  - High shunt impedance and r/Q
  - High group velocity
- Short pulse – high gradient acceleration
  - Capitalizes on RF breakdown rate ∝ RF pulse length

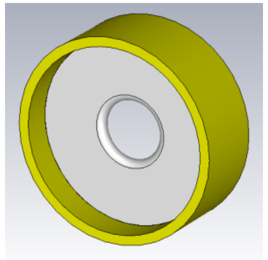
Dielectric Disk Accelerators

- 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

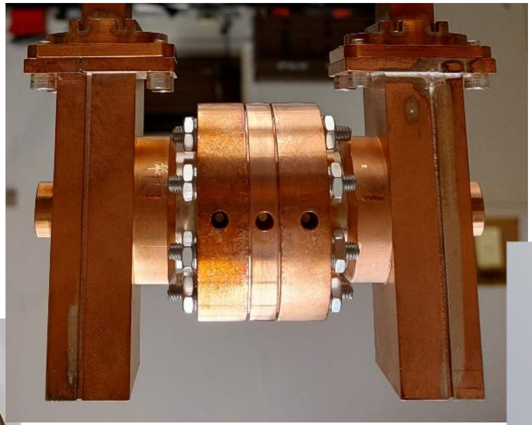
*Constant impedance 2π/3 structure, not suitable for short RF pulse acceleration due to low group velocity

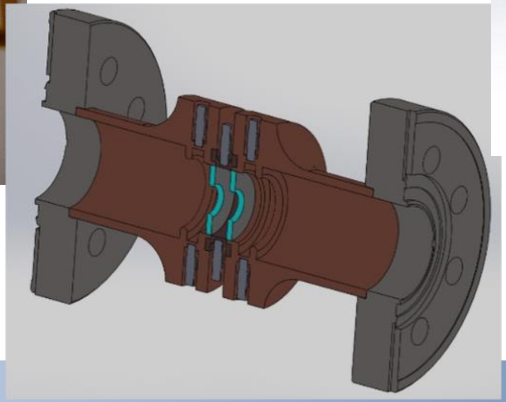


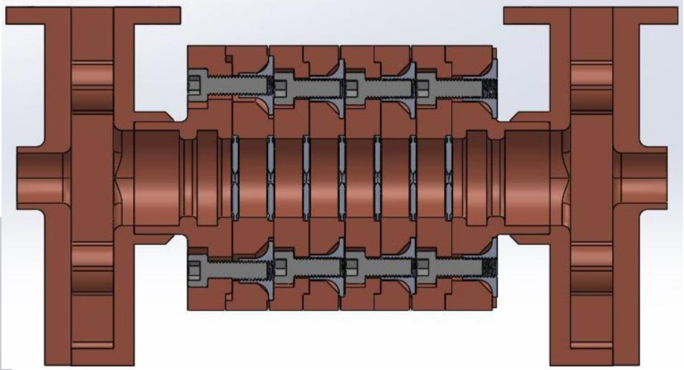


Euclid-AWA DDA Testing History

- 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: upcoming 2022

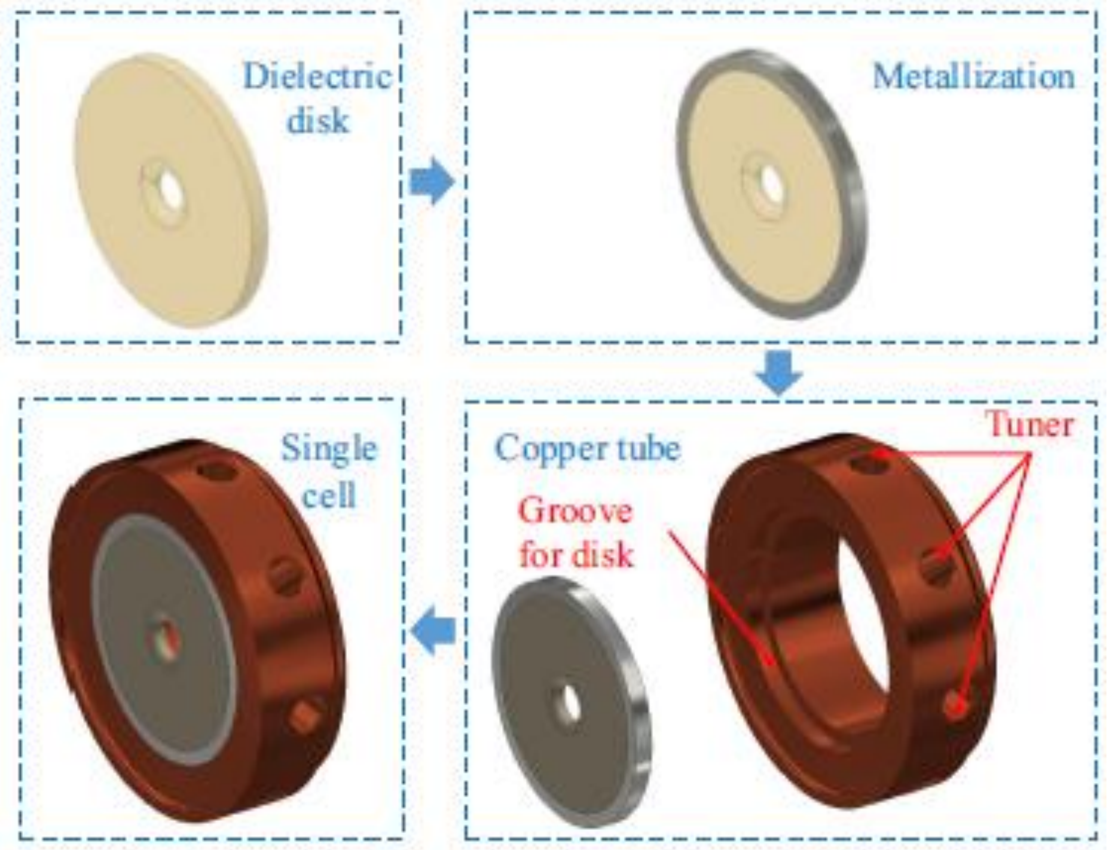






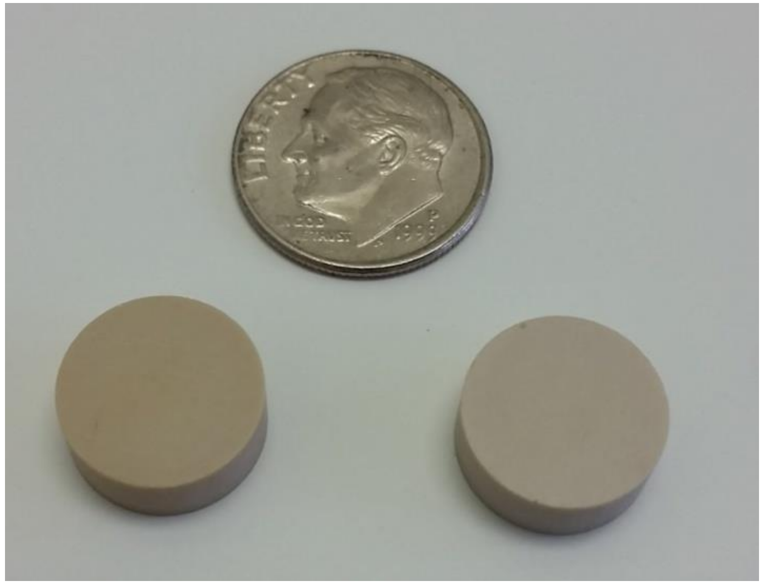
Fabrication Challenges

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



Dielectric Material Characterization

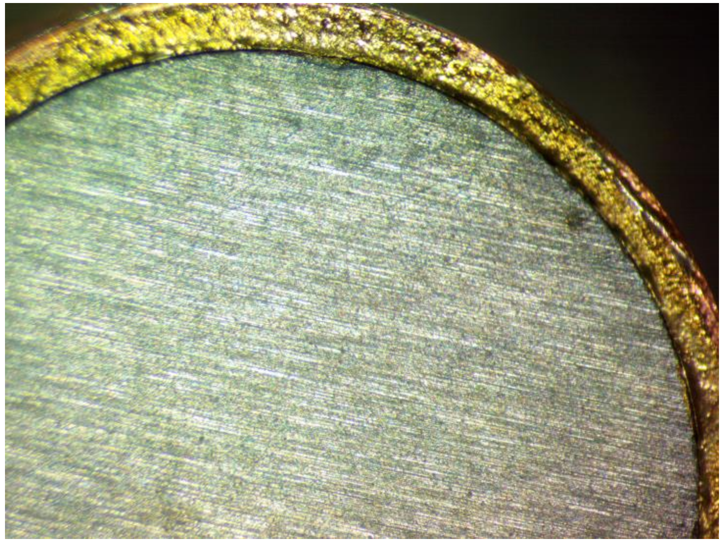
- Prototype I & II:
- $BaTiO_x$ ceramic (D-50) from Skyworks (Trans-Tech)
- 10 coupons measured (4 GHz):
  - ε_r = 50.14 ±0.35
  - tan δ = 8.00e-5 ±0.32e-5



- 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-4

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*

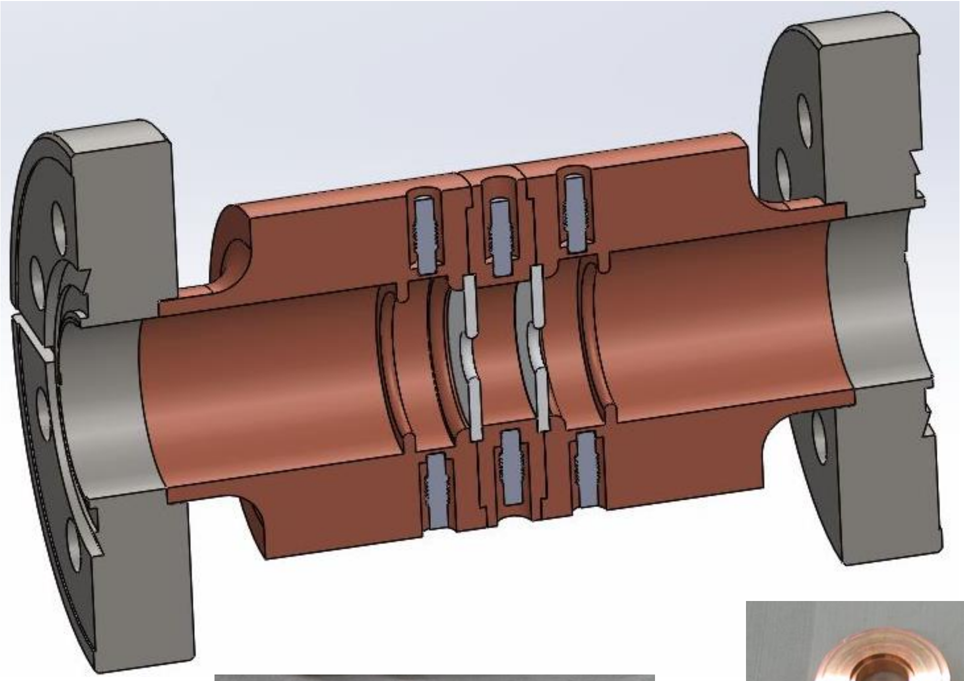


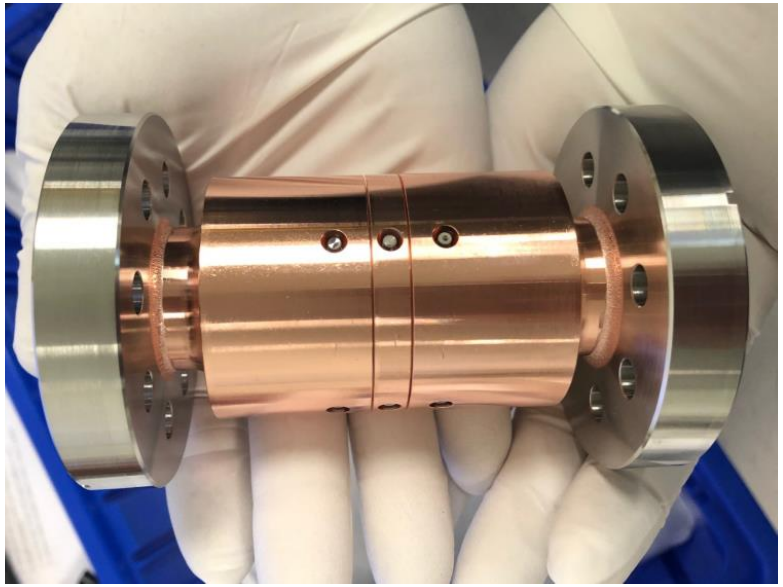
	Temp.	Time	ε_r	**tan δ**
Original	-	-	50.2	8.15e-5
Post-Braze	835	N/A	49.7	1.43e-2
Post-Bake 1	800	60 min.	49.3	7.17e-4
Post-Bake 2	800	60 min.	49.3	1.03e-4

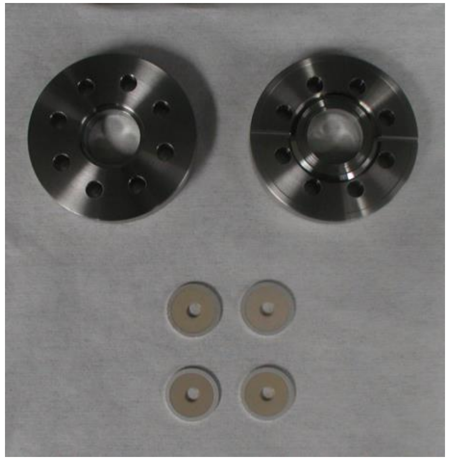
Choice of Brazing Method

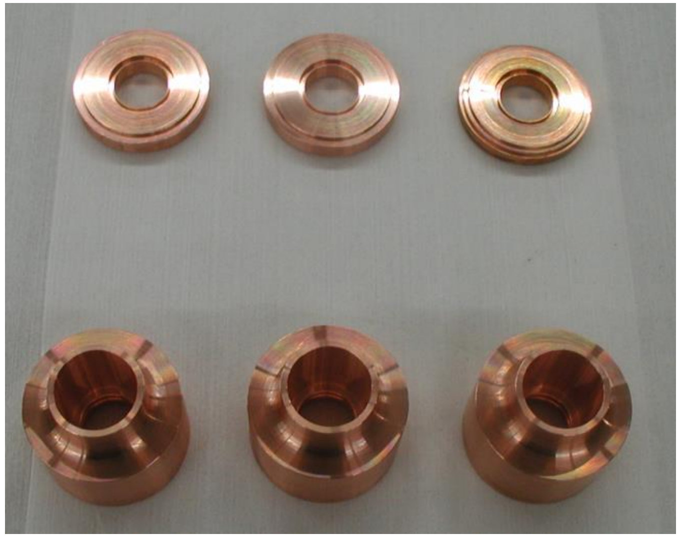
- Low temperature solder (Au-Sn, 350°C) with silver-metallized disks chosen for Prototype I
  - Metallization @ 850°C in air, preserved dielectric properties
- High temperature ABA (InCuSil, 850°C) with nude disks chosen for Prototype II
  - Leaked after first braze cycle
  - Second braze cycle improved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

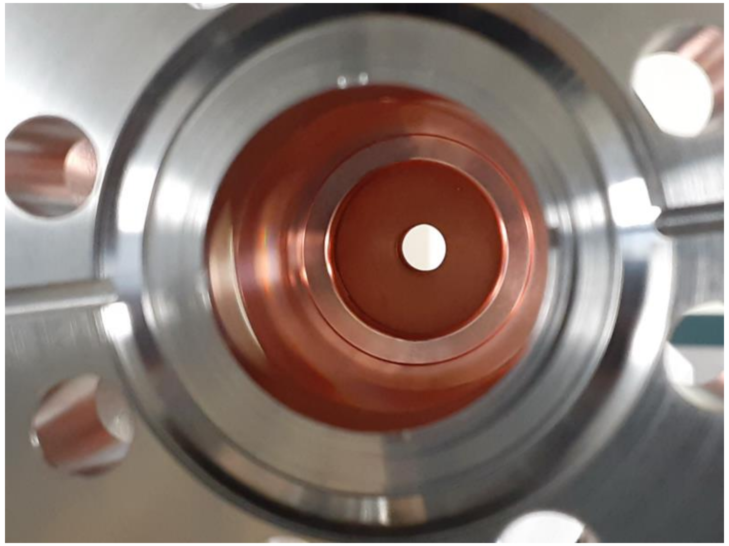
Brazed Prototype Fabrication





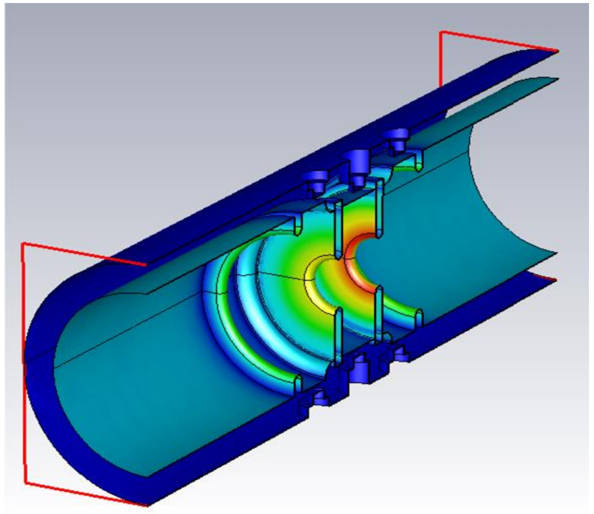


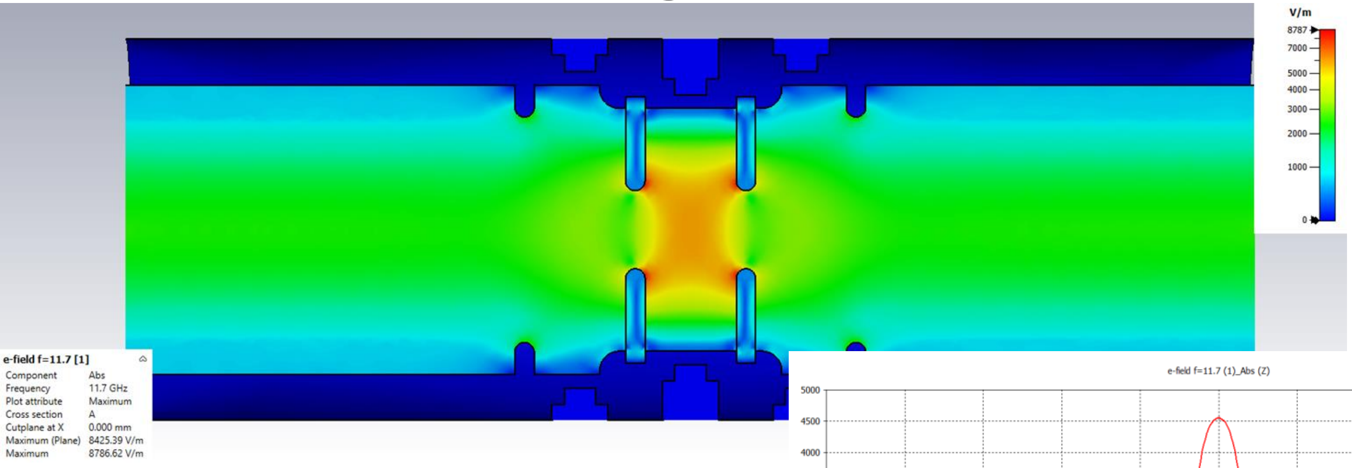


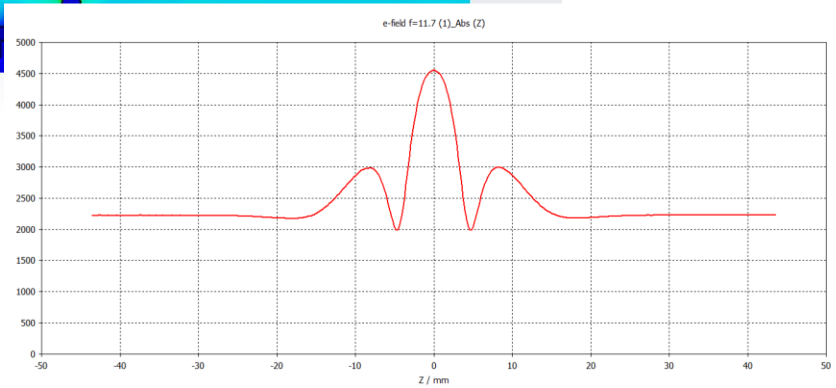


Brazed Prototype RF Design

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



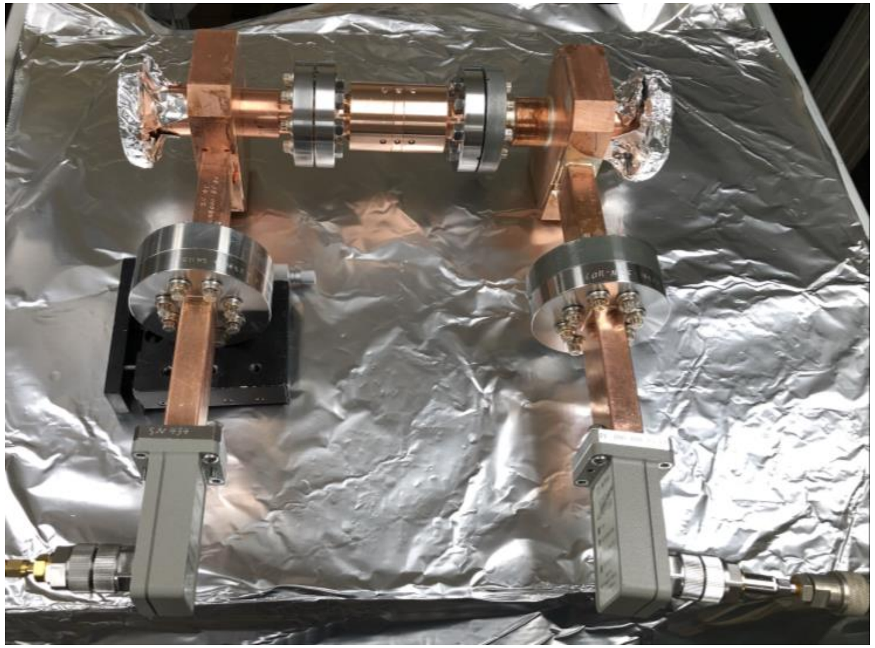


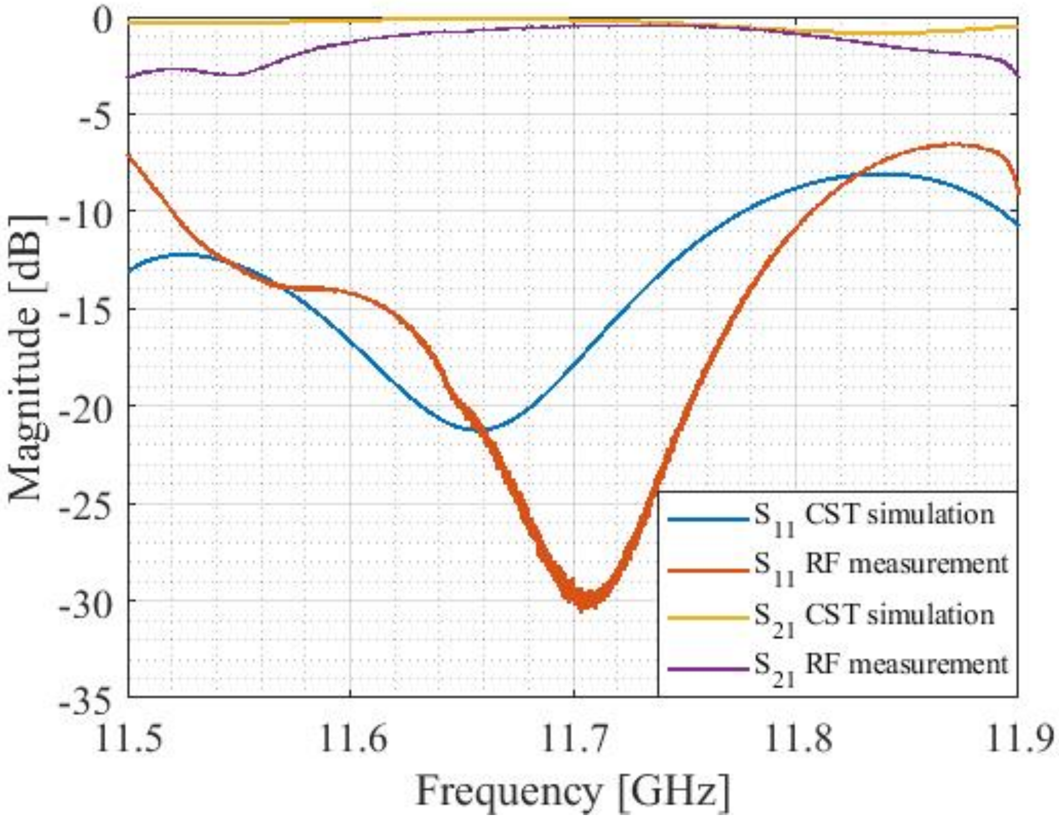


Dielectric constant	50.1
Loss tangent	8e-5
Q	10,300
Shunt impedance	176 MΩ/m
Group velocity	0.345c
Phase advance	2π/3
E_{acc} (P_{in})	100 MV/m (280 MW)
E_{max} / E_{acc}	1.84

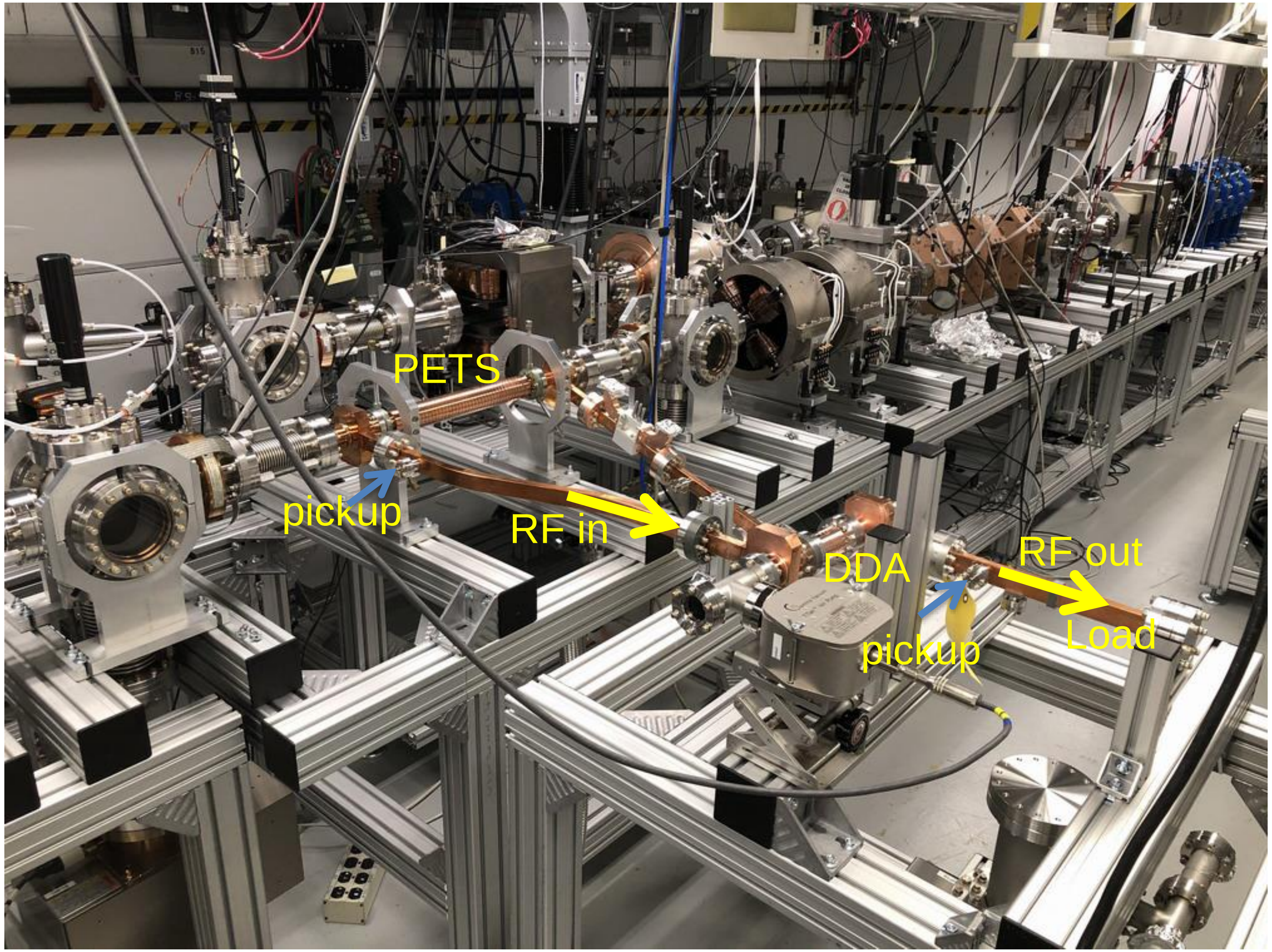
Brazed Prototype Bench Test

- 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





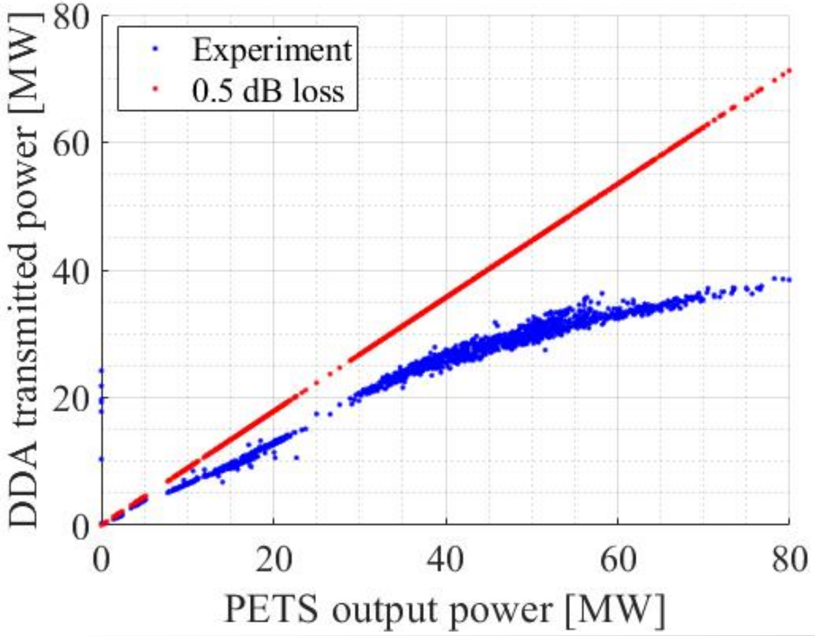
High Power Test Setup

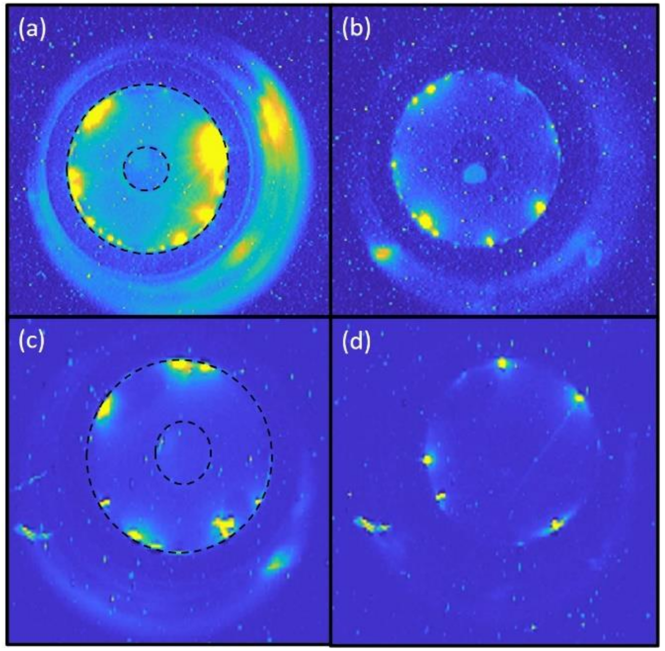


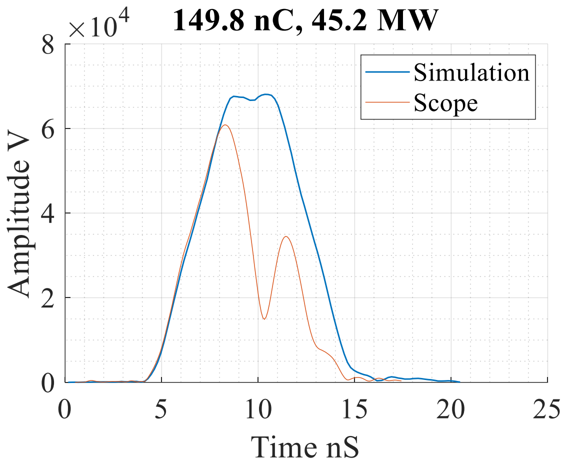
- Power provided by Power Extraction and Transport Structure (PETS)
- ICTs measure beam current for power generation
- Directional couplers at DDA input & output
- Instrumentation to look for multipacting/breakdown
  - Ion pump & vacuum gauge
  - Cameras on both ends of DDA

Brazed Prototype High Power Test Results

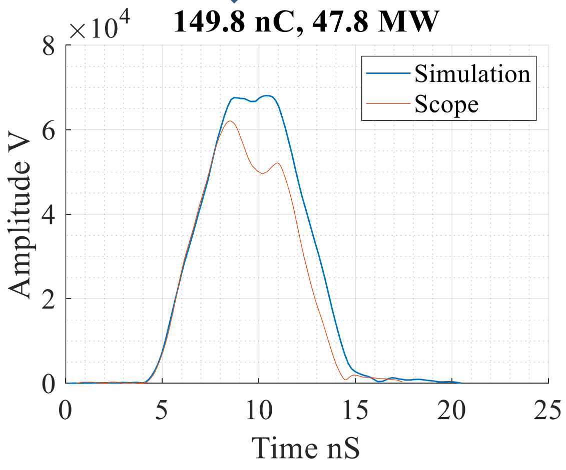
- Significant multipactor/breakdown activity observed
- Light emission from circumference of both ceramic disks
  - No light visible from irises
- Conditioning improved power transmission & light emission somewhat; never eliminated
- Run aborted at 80 MW input power





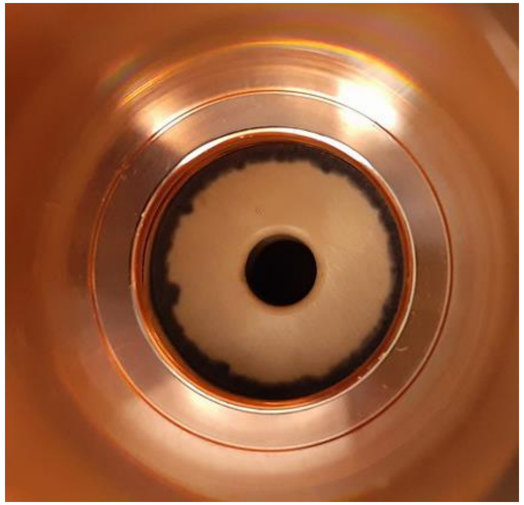


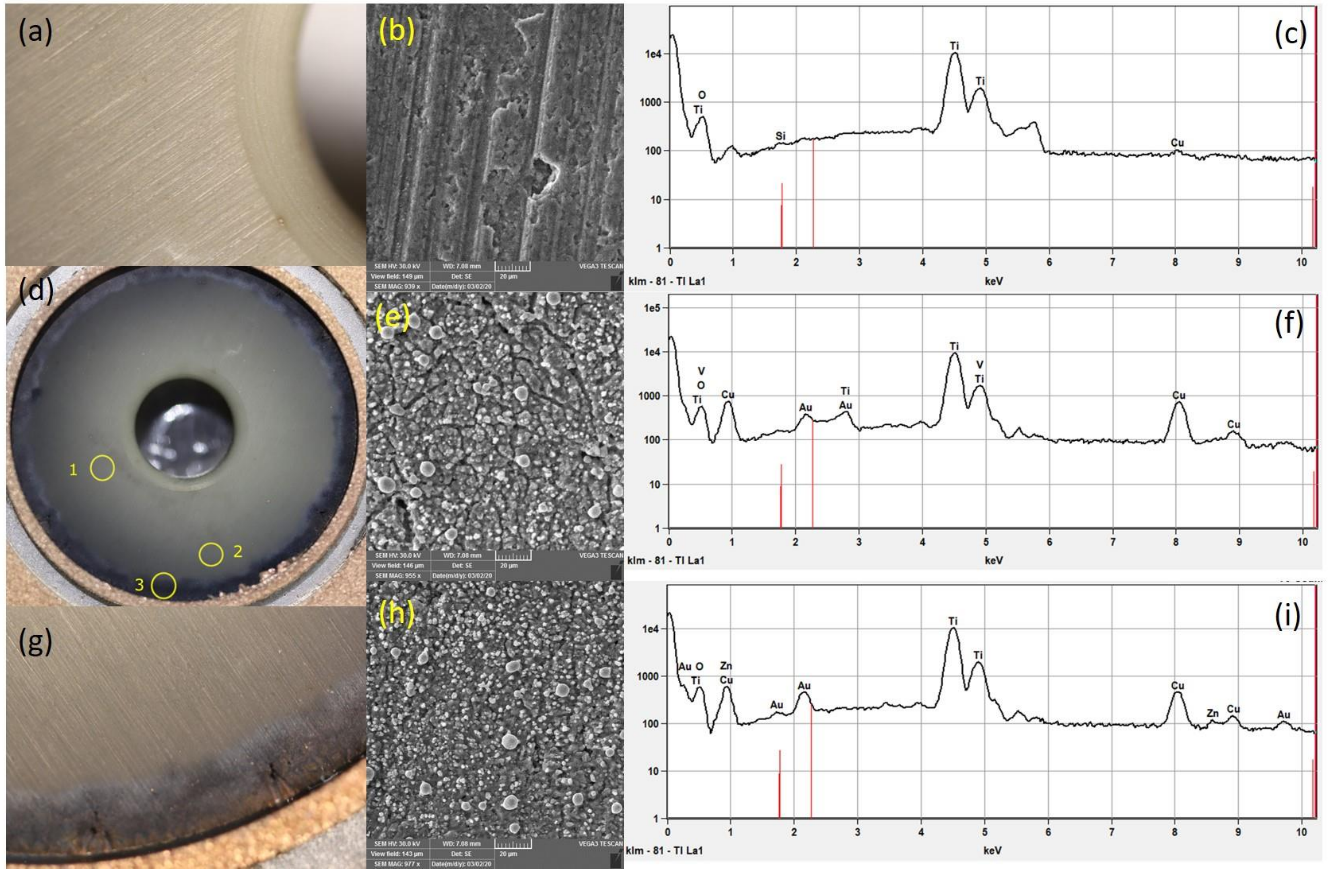
Conditioning



Brazed Prototype Autopsy

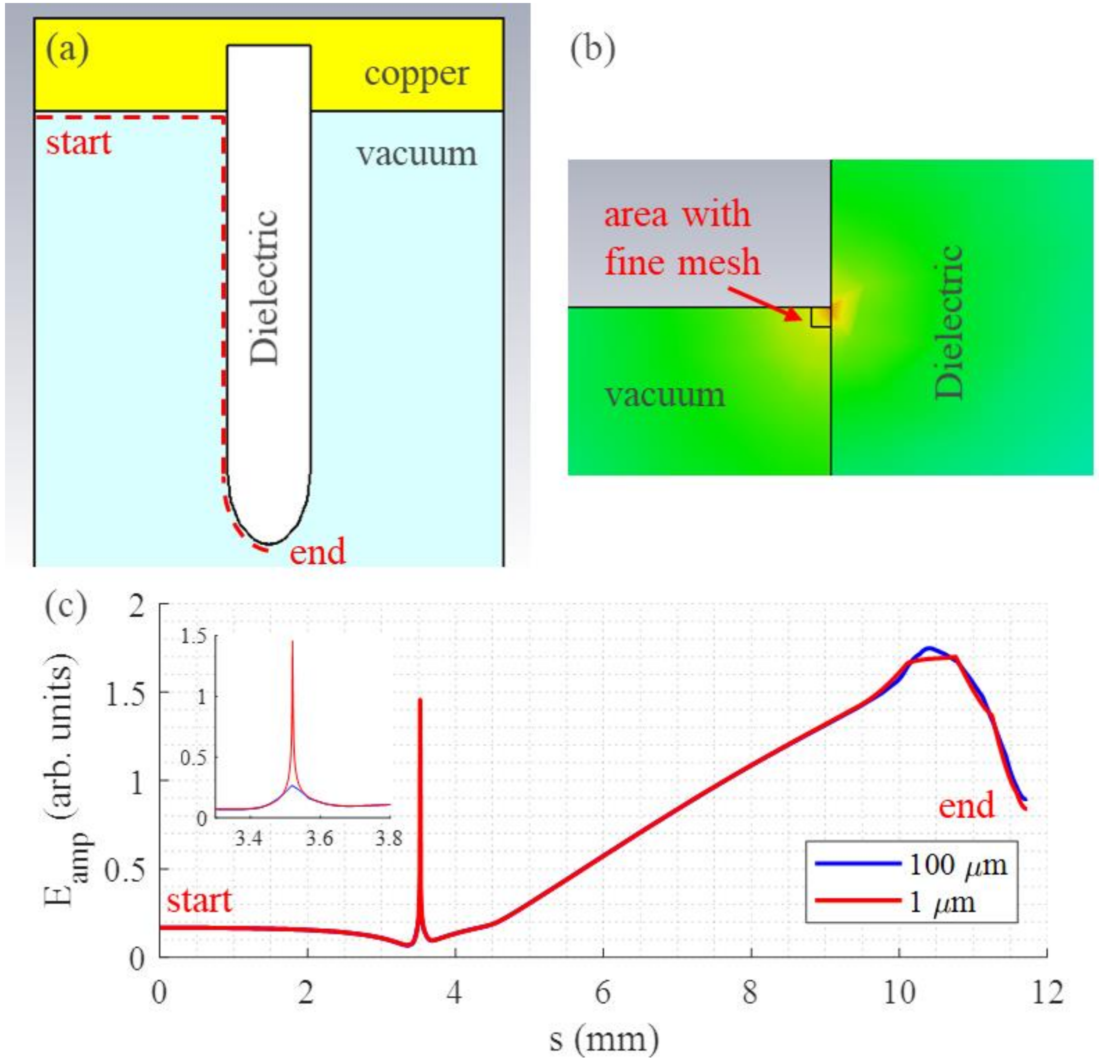
- Damage around ceramic circumference
- SEM & EDX results reveal pitting and presence of gold (braze alloy) and copper near outer radius of disks
- Iris & surrounding area free from damage or contamination
- Breakdown/ multipactor confined to triple junction region





Brazed Prototype Conclusions

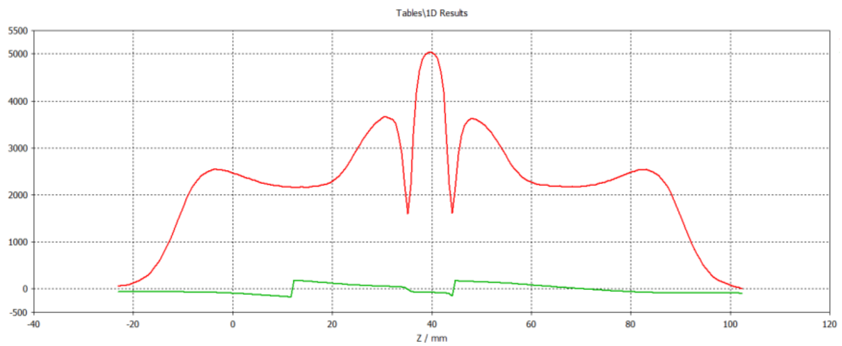
- Finer mesh revealed field enhancement at triple junction
- No evidence of problems stemming from iris or ceramic material
- Engineering challenge to overcome, not fundamental

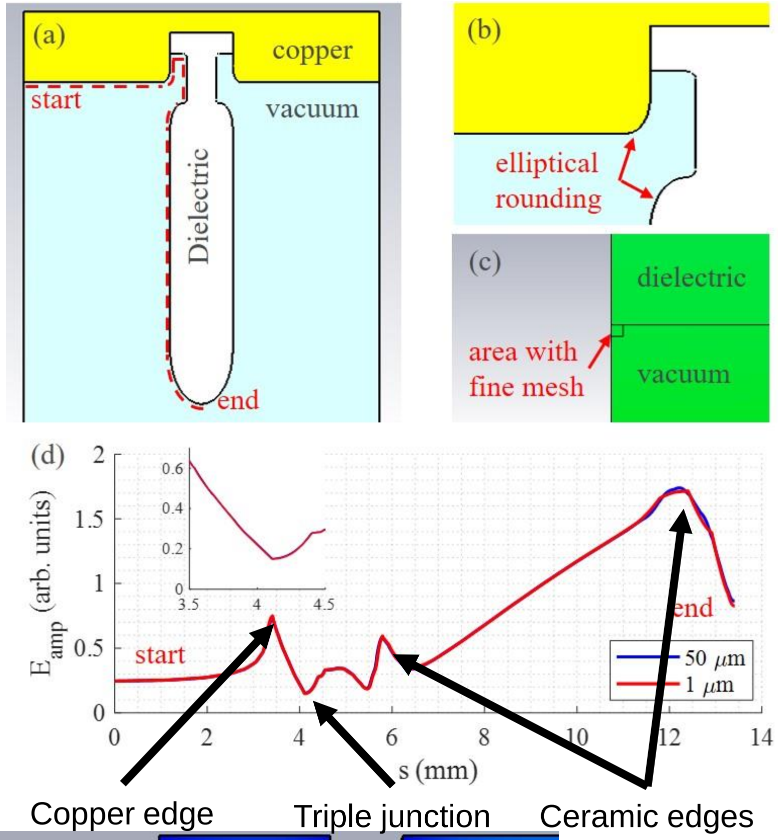


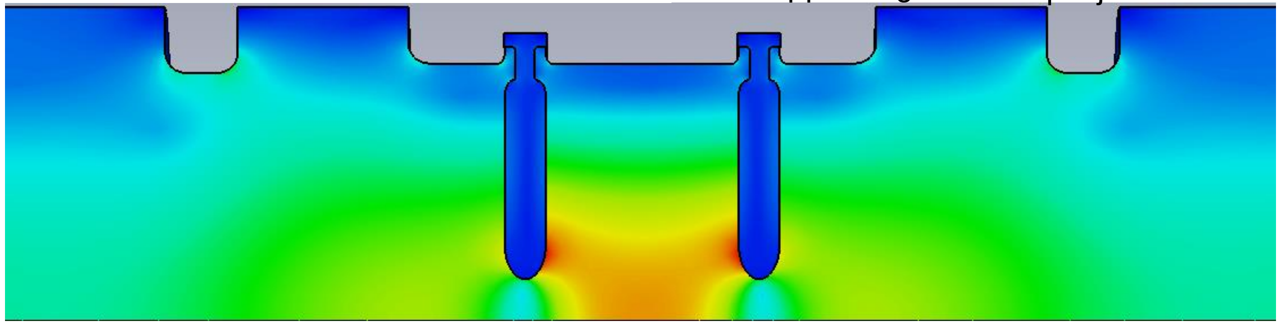
Clamped Prototype RF Design

- 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

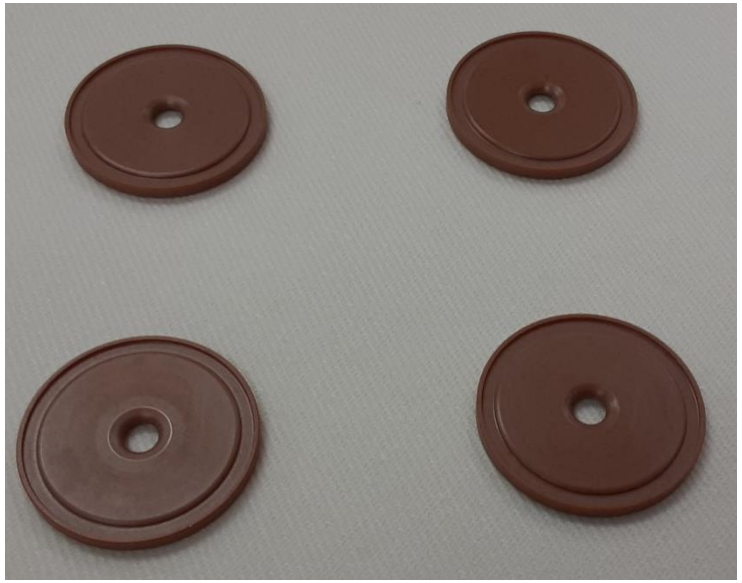


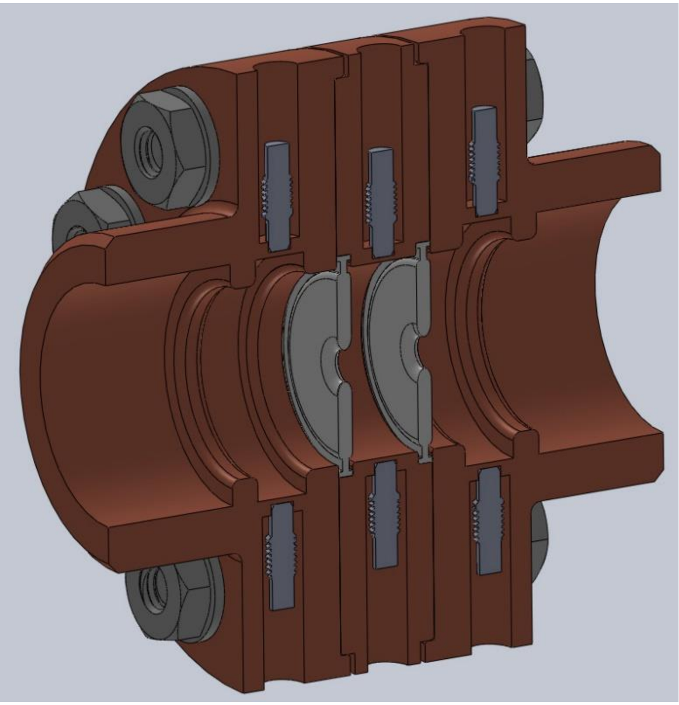


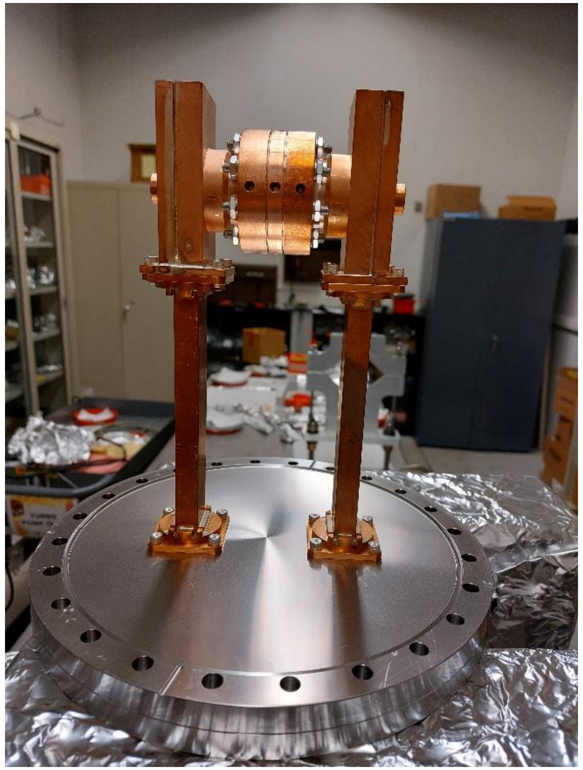


Clamped Prototype Fabrication

- 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

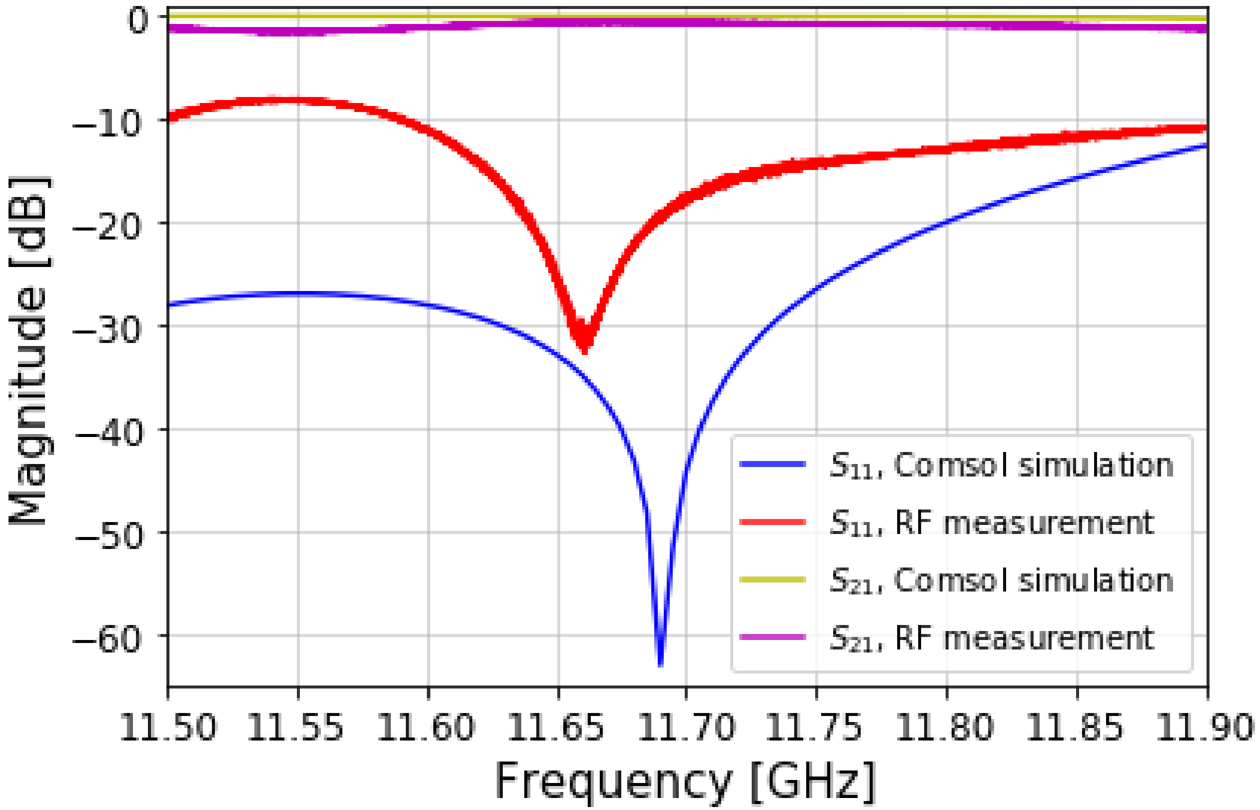






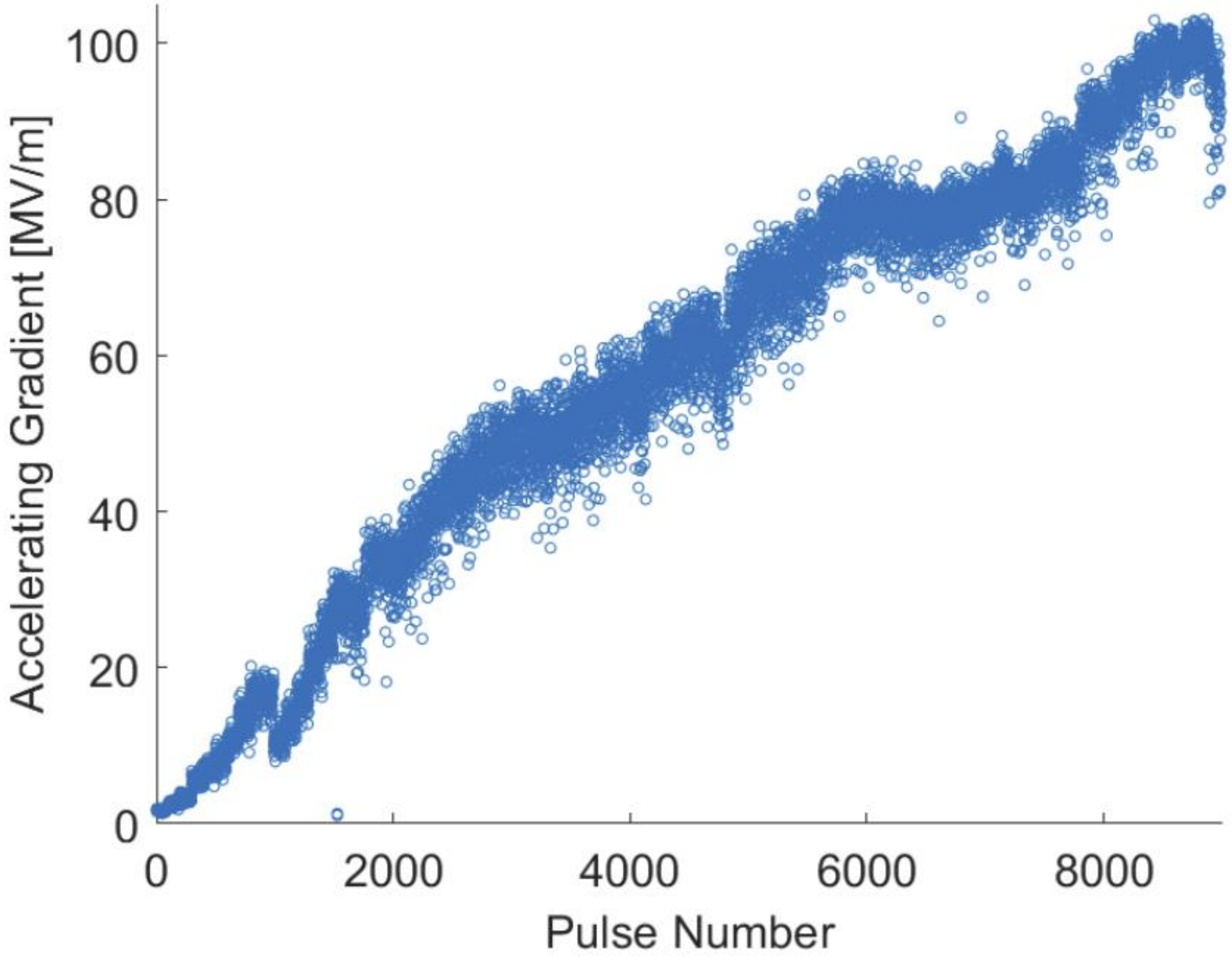
Clamped Prototype Bench Test

- 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



euclid BEAMLABS

Clamped Prototype High Power Test History

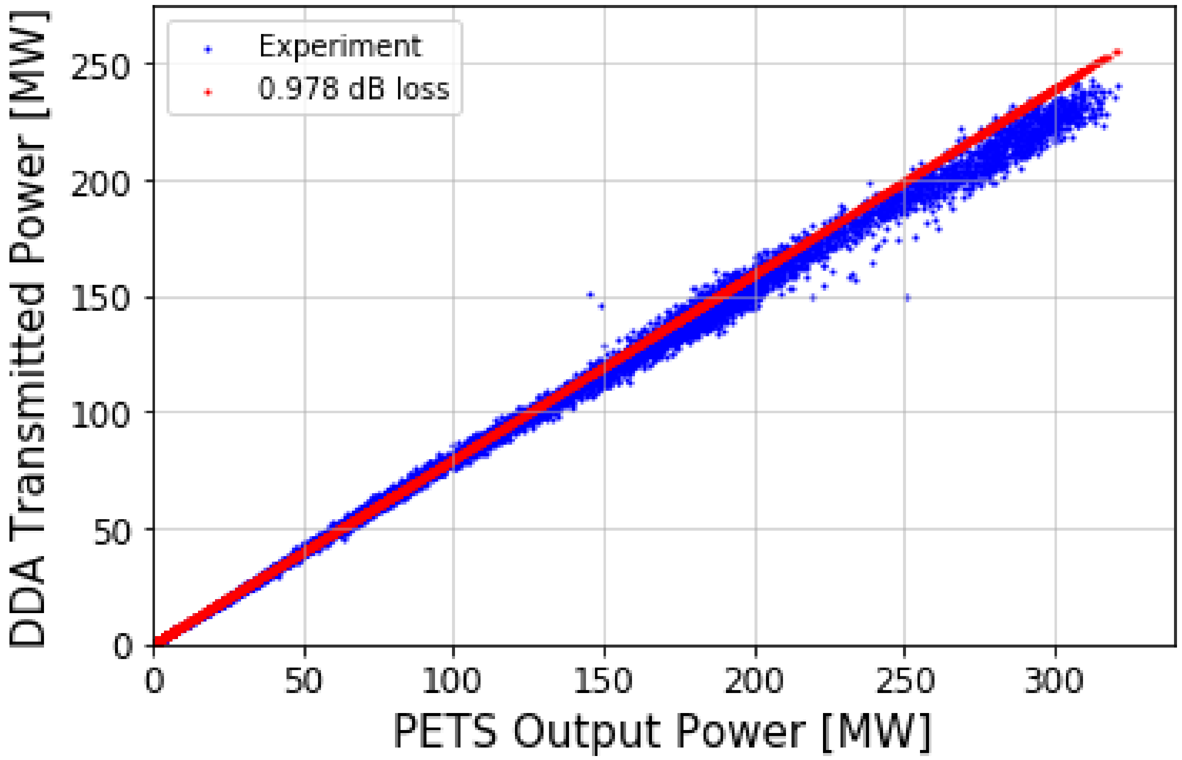


- > 250k RF pulses delivered at 2 Hz rep. rate over 8 days
  - > 9k pulses recorded
- Vacuum & light monitored for multipacting/breakdown
- Input power increased once vacuum settled down & became steady
- Last data points = attempts to adjust laser for larger drive beam bunch charge

Clamped Prototype High Power Test Results

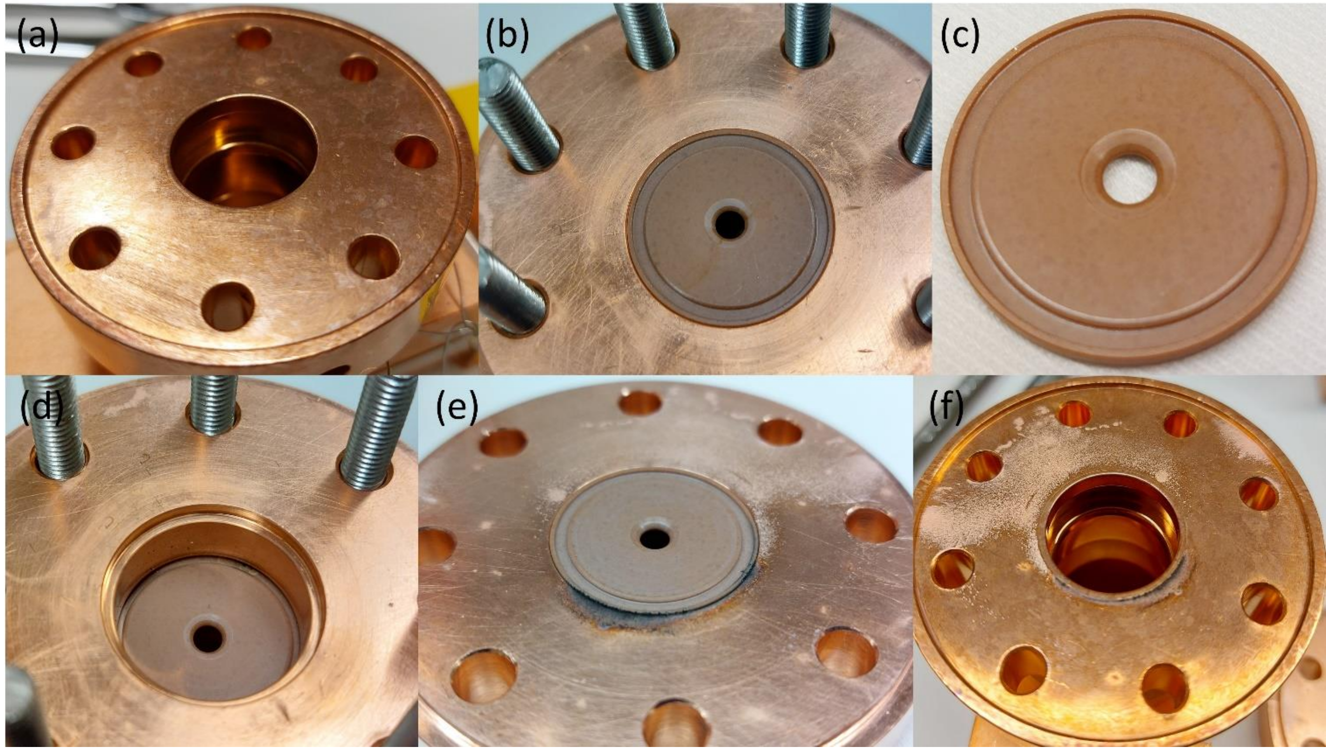
- No evidence (RF or light) of breakdown or multipacting
- Brief period of faint light from interior of structure at highest power conditioned away
- Transmitted power agrees very well with measured transmission loss from DDA+waveguide
- Limited by available input power!

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



Clamped Prototype Conclusions

- No multipactor or RF breakdown observed at high gradient
- Redesigned triple junction solved problem with brazed prototype
- 102.3 MV/m new accelerating gradient record for dielectric disk accelerator!
- Fundamental limit for DDAs still not reached

Outlook

- Issues yet to be addressed:
  - Are these positive results confined to clamped DDAs?
    - Another brazed DDA in fabrication
  - What engineering challenges arise from “real” accelerating structures?
    - Multicell DDA already designed
  - How to properly stage DDAs to accelerate beam
    - Planned for 2023-2024

Acknowledgements

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