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-Chicagoland Accelerator Science Traineeship (NIU-IIT)

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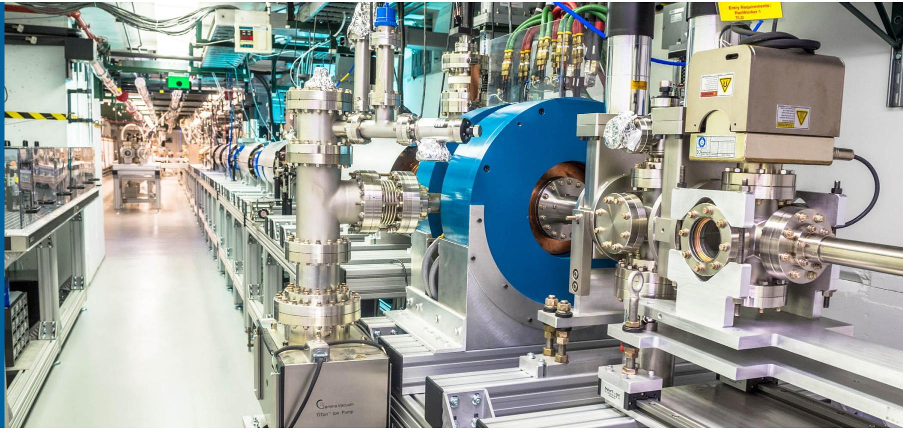
High Power Results of Dielectric Disk Accelerating Structures



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euclid BEAMLABS

ILLINOIS TECH

August 10-11, 2023

Outline of Talk

- Introduction
- Previous DDA Prototypes and Experiments at AWA
- Clamped Multicell DDA Structure
- Future Works at AWA

Introduction

Motivation for Research

- Improve RF to beam Power Efficiency
  - Better efficiency = smaller footprint = cheaper to build
  - 500 MeV Demonstrator
    - High power linear electron accelerator
    - Production of high energy beam with short footprint using Advanced Accelerator Concepts (AAC) structures.
    - Need high accelerating gradient.

- Demonstrate Short Pulse Accelerating (~10 ns)
  - High gradient production requires high power (hundreds of MW) but this can cause breakdown
    - Breakdown rate is proportional to pulse length
    - Short filling time allows structure to see flat top of pulse
      - » Large group velocity

$$t_f = \frac{L}{v_g}$$

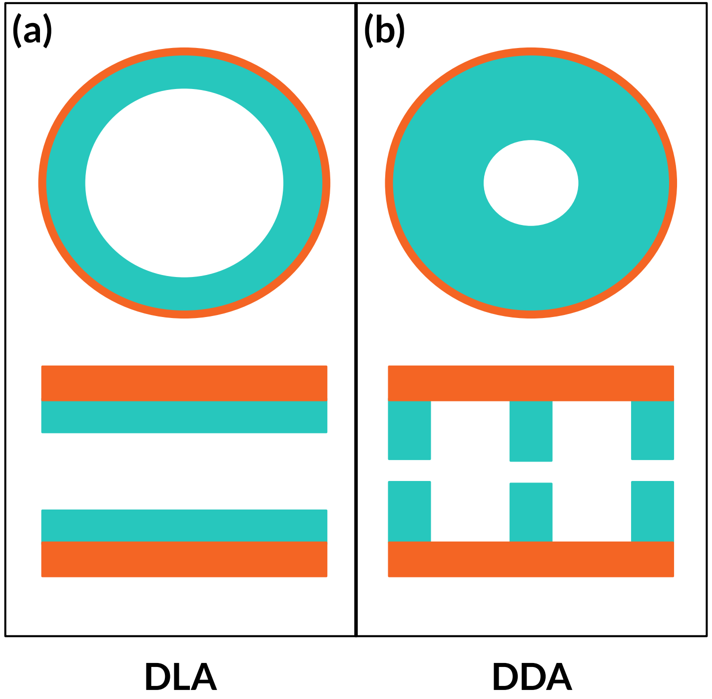
$$\frac{E_a^{30} \cdot t_p^5}{\mathrm{BDR}} = \mathrm{const},$$

A. Grudiev, et. al., "New local field quantity describing the high gradient limit of accelerating structures," Phys. Rev. ST Accel. Beams,vol. 12, p. 102001, Oct 2009.

Dielectrics in Accelerating Structures

- **Dielectric slows down speed of EM field to match it to velocity of beam**
- **Dielectric Loaded Accelerator (DLA) vs Dielectric Disk Accelerator (DDA)**

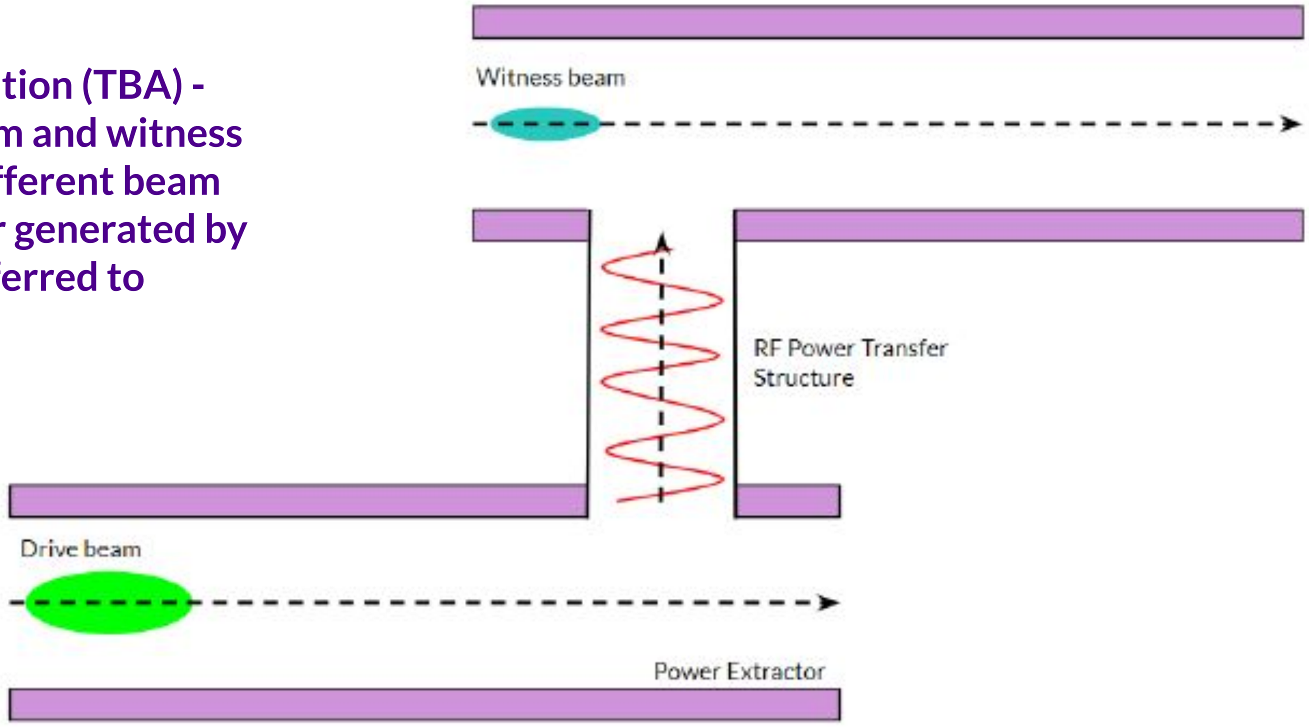
Parameter	DLA	DDA
Dielectric Constant	9.8	50
Group Velocity	0.11 c	0.16 c
Quality Factor	2295	6430
r	50.0 MΩ/m	208.8 MΩ/m
r/Q	21.8 kΩ/m	32.5 kΩ/m
Required Input Power	1.22 GW	0.96 GW
$\eta_{rf-beam}$	27%	39%
$\eta_{AC-beam}$	9%	13%
E_{max}	365 MV/m	660 MV/m



J. Shao, C. Jing, J. G. Power, M. Conde, and D. Doran, "Study of a dielectric disk structure for short pulse two-beam acceleration," in Proceedings of IPAC2018, Vancouver, BC, Canada, Summer 2018.

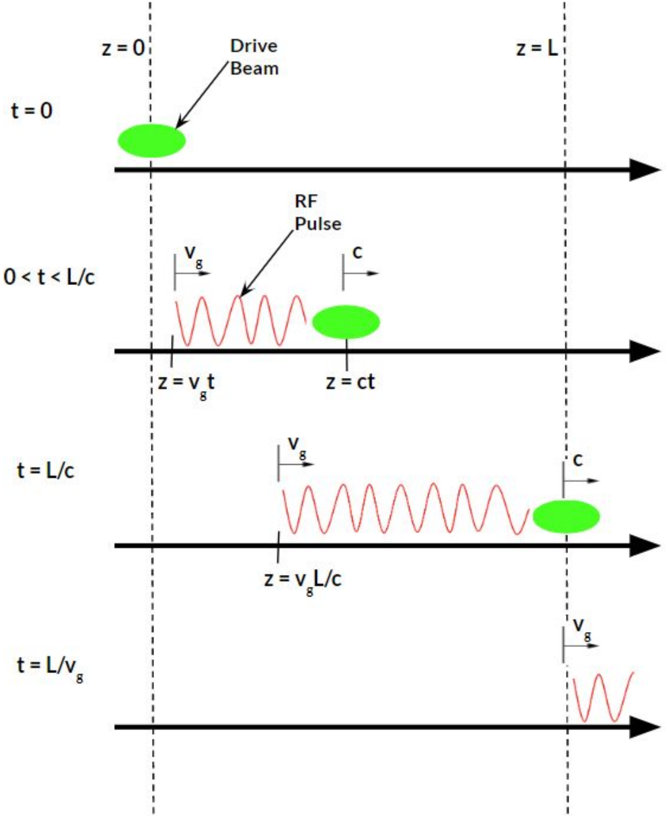
Structure Based Wakefield Accelerators

- Two Beam Acceleration (TBA) - when the drive beam and witness beam are on two different beam lines. The RF power generated by drive beam is transferred to witness beam.



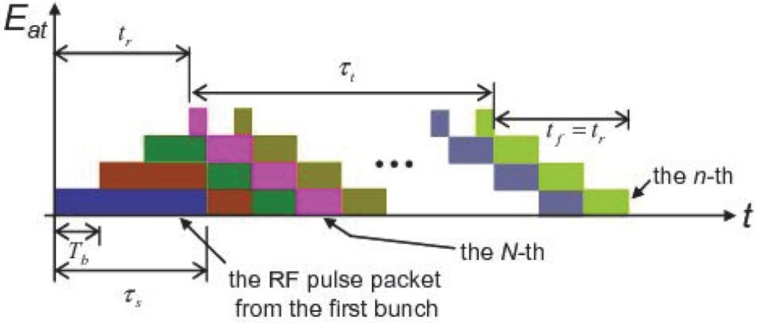
Power Extraction and Transfer Structure (PETS)

- Relativistic wakefield power extractors are made up of two parts: deceleration section and section that extracts EM wave.
- When decelerated, drive beam produces RF packet moving in same direction.
- Drive beam travels close to c while the RF packet travels at the group velocity of the structure. (vg = 0.22c)

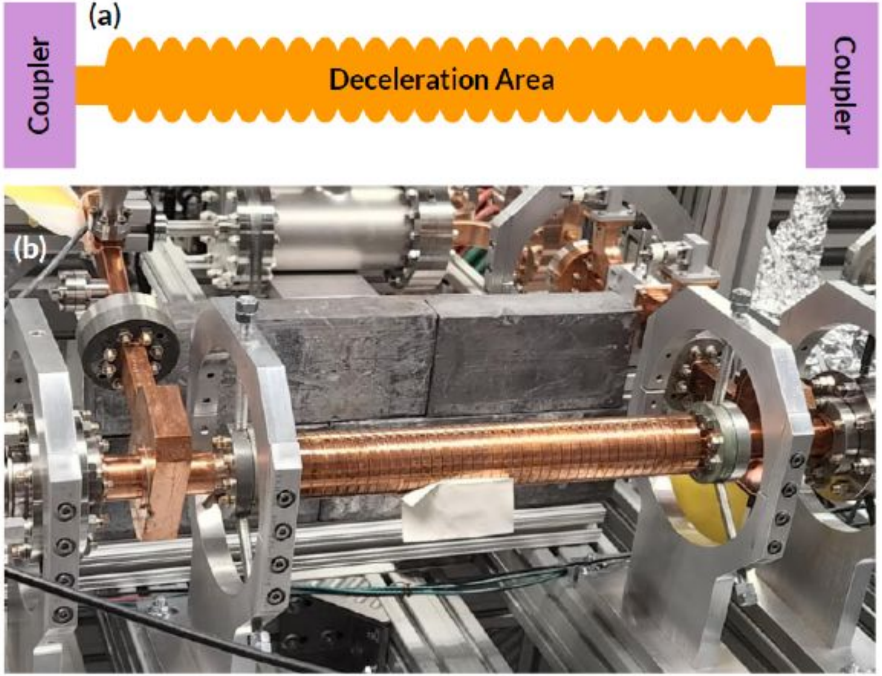


Power Extraction and Transfer Structure (PETS)

- AWA has developed and tested different types of PETS: metallic, dielectric, and metamaterial.
- Capable of generating large amounts of RF power.
- For DDA experiment, brazed metallic PETS was used to generate high power.
  - Working frequency at 11.7 GHz.



C. Jing, et al., "High frequency high power RF generation using a relativistic electron beam," in Proceedings of IPAC 2012, New Orleans, Louisiana, USA, Summer 2012.

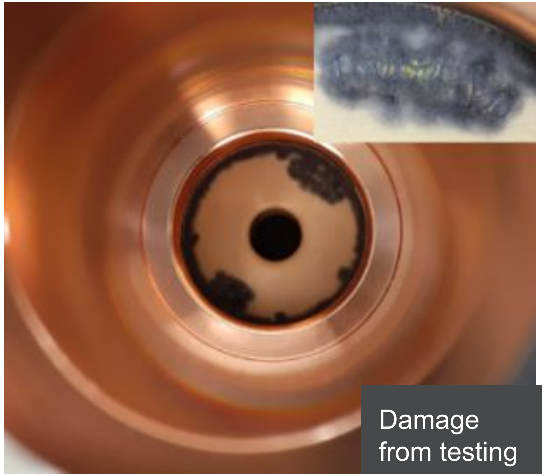


Previous DDA Structure

Single Cell Clamped DDA

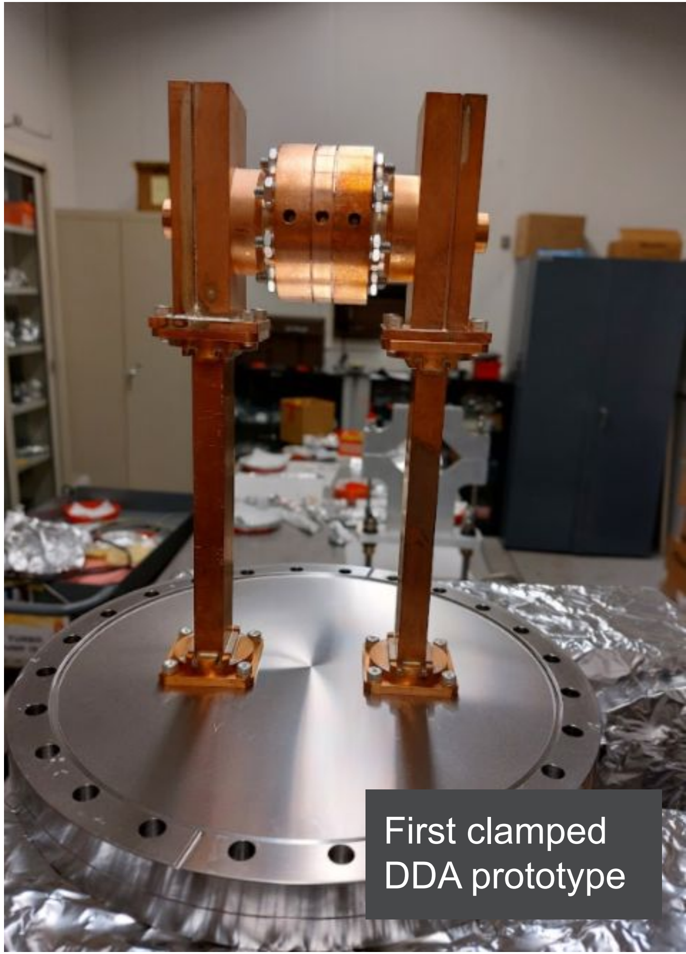
- Issues with brazing (damage to structure in oven/ possible breakdown around braze joint) led to developing a clamped DDA structure

Damaged in oven



Damage from testing

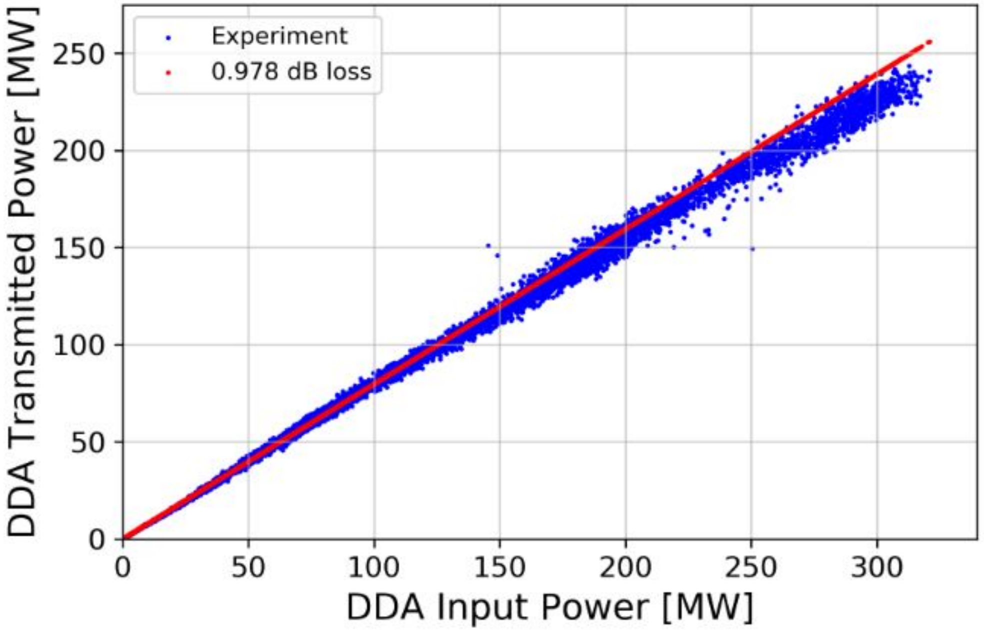
- A clamped single cell structure was high power tested at AWA in early 2022



First clamped DDA prototype

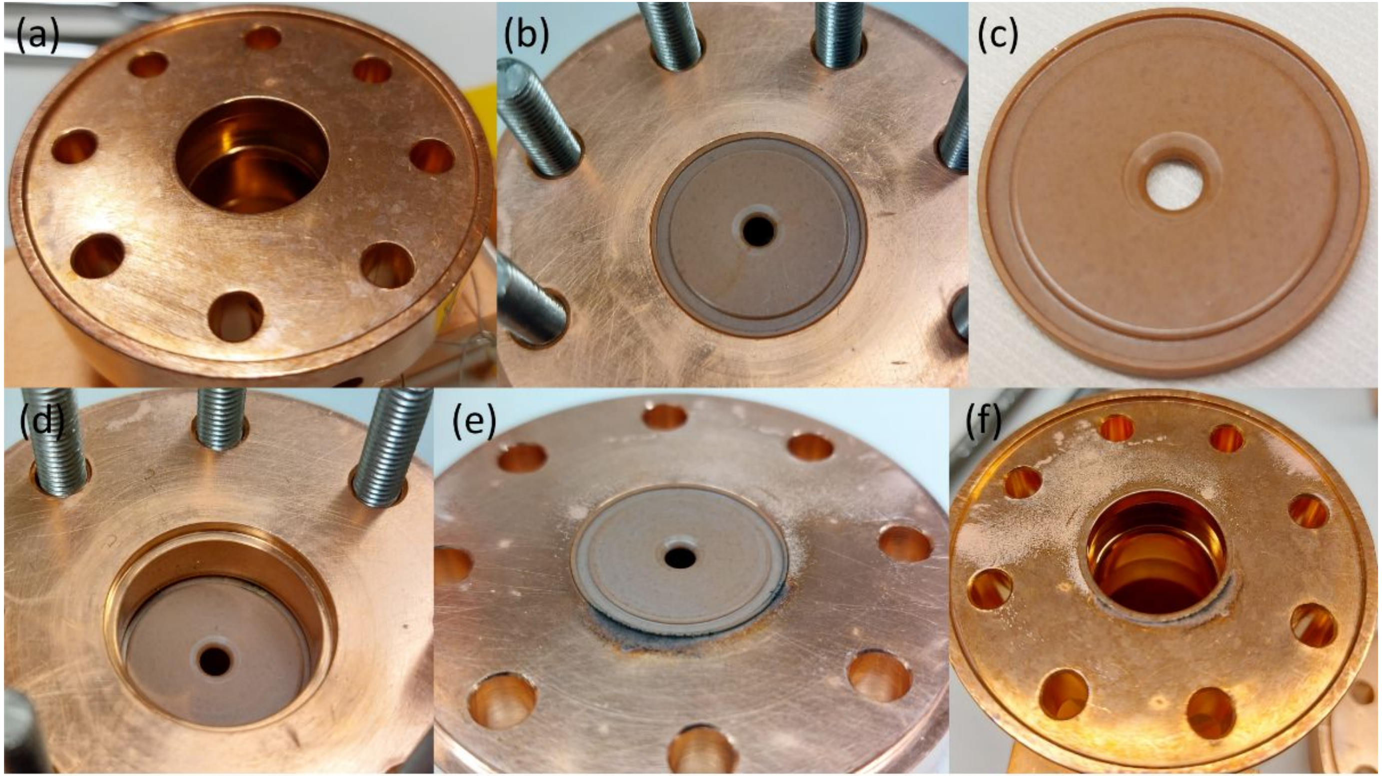
Results from Single Cell High Power Experiment

- Reached 320.9 MW of effective input power
  - 171 RF pulses above 300 MW
  - Accelerating gradient of 102 MV/m
- Linearity sign of no breakdown or multipacting.
- No RF, vacuum, or optical signals of breakdown observed
- Successfully ran up to maximum available RF power.
- PRAB paper published on results



Single Cell Clamped Post-Experiment Visual Inspection

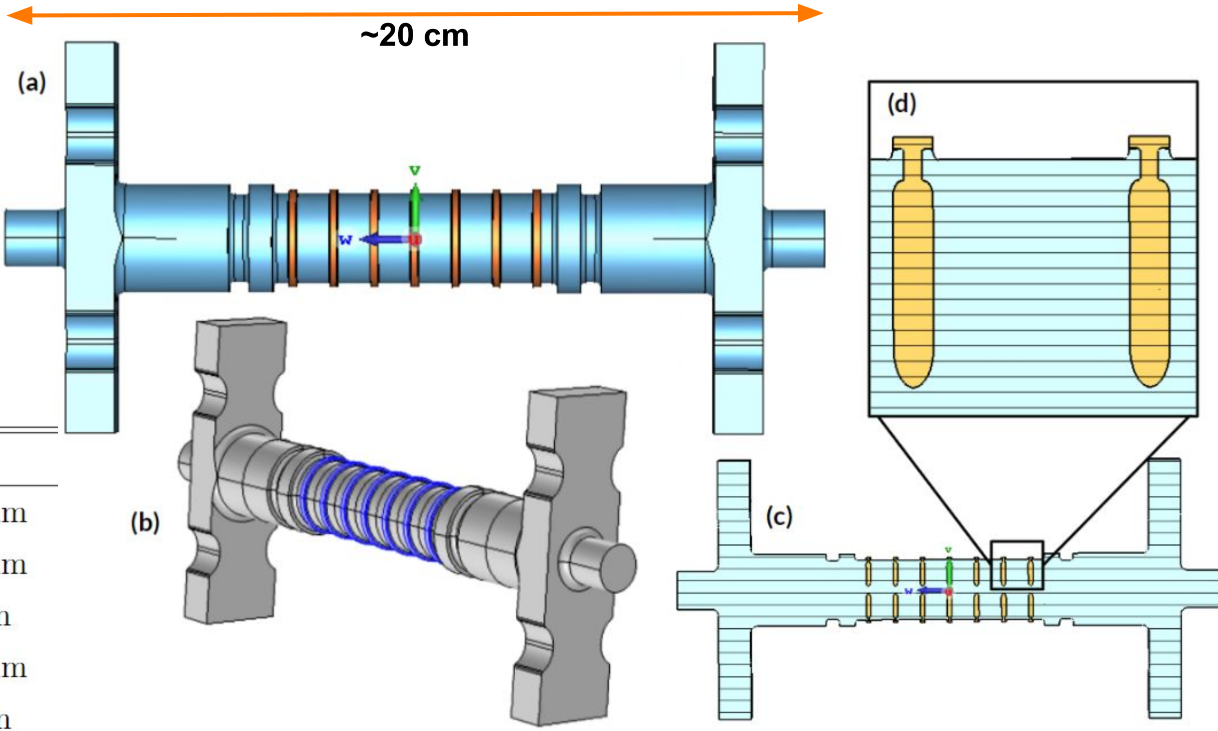
Damage found outside of RF volume of structure, potentially due to RF leakage from uneven clamping.



Multicell Dielectric Disk Accelerator

Clamped Multicell Structure

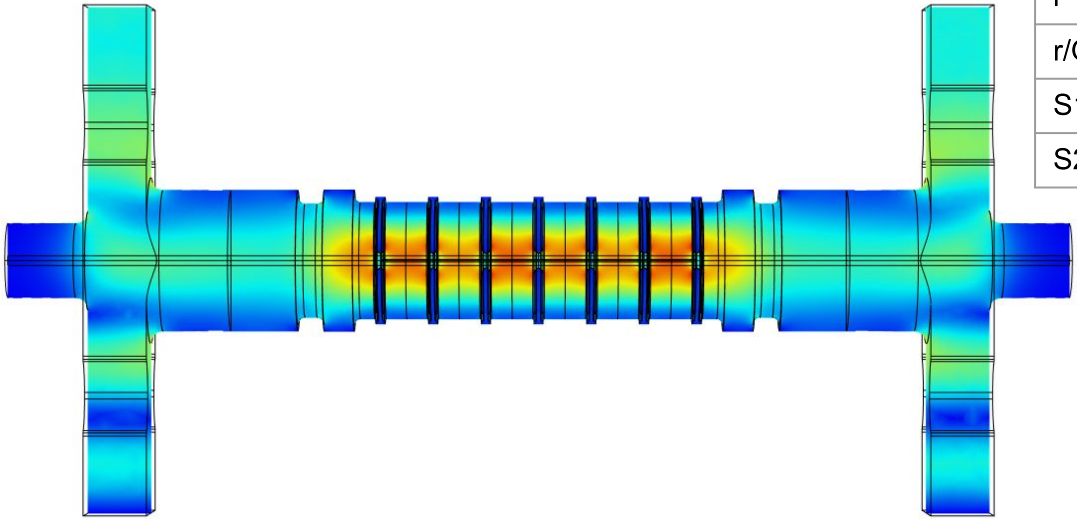
- Due to success of first clamped structure, multicell will also be clamped
- Special head detail similar to clamped single cell
- 7 ceramic = six dielectric cells

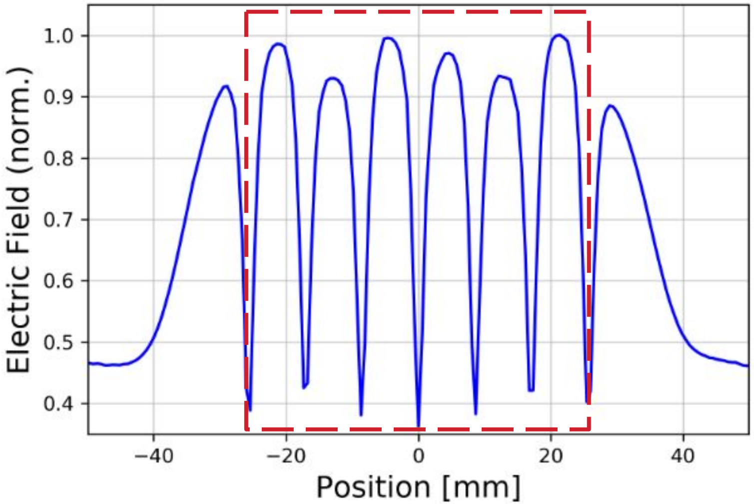


Parameter	Value
Disk Outer Diameter	20.48 mm
Disk Inner Diameter	2.239 mm
Matching Cell Iris Aperture Diameter	18.4 mm
Matching Cell Aperture Diameter	22.86 mm
Disk Thickness	1.45 mm
Dielectric Cell Length	8.541 mm
Number of Ceramics	7

Results of Simulations

Parameter	Value
Accelerating Gradient at 400 MW	108 MV/m
Field Enhancement Factor	~1.5
Group Velocity*	0.24 c
Quality Factor	18,900
r	172 MΩ/m
r/Q	9.10 kΩ/m
S11 10 dB Bandwidth	> 800 MHz
S21 3 dB Bandwidth	> 800 MHz

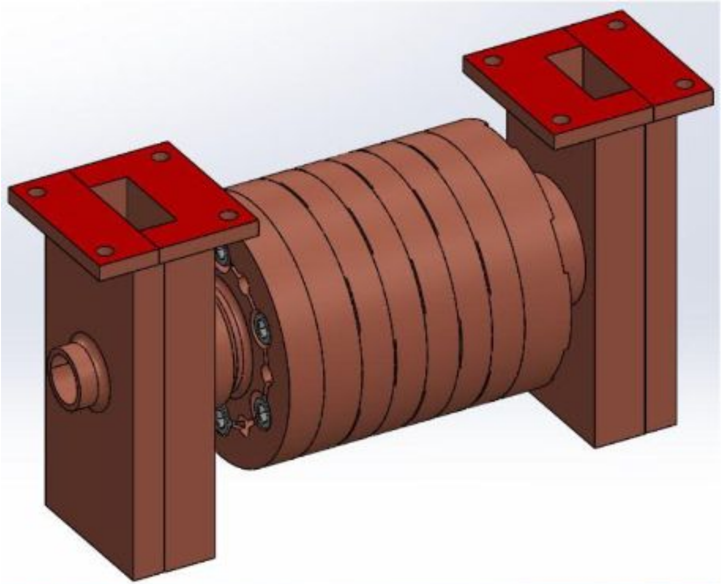


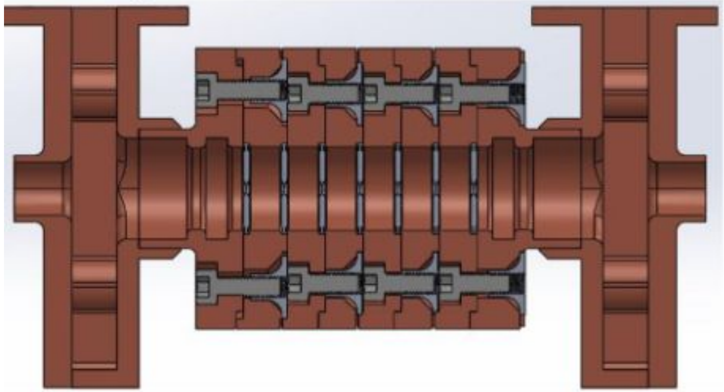


Maximum electric field over one RF period.

Engineering Design

- **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.**



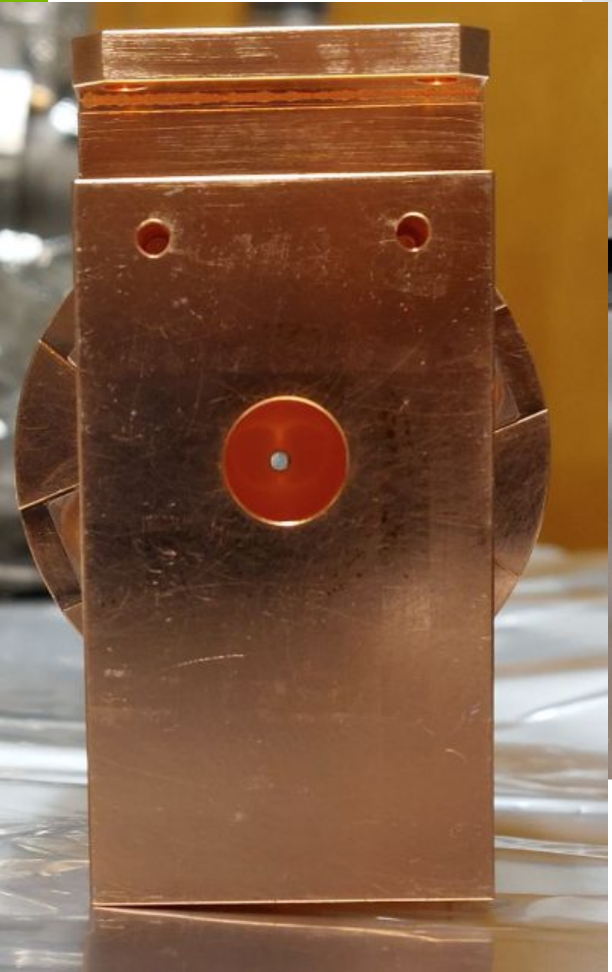


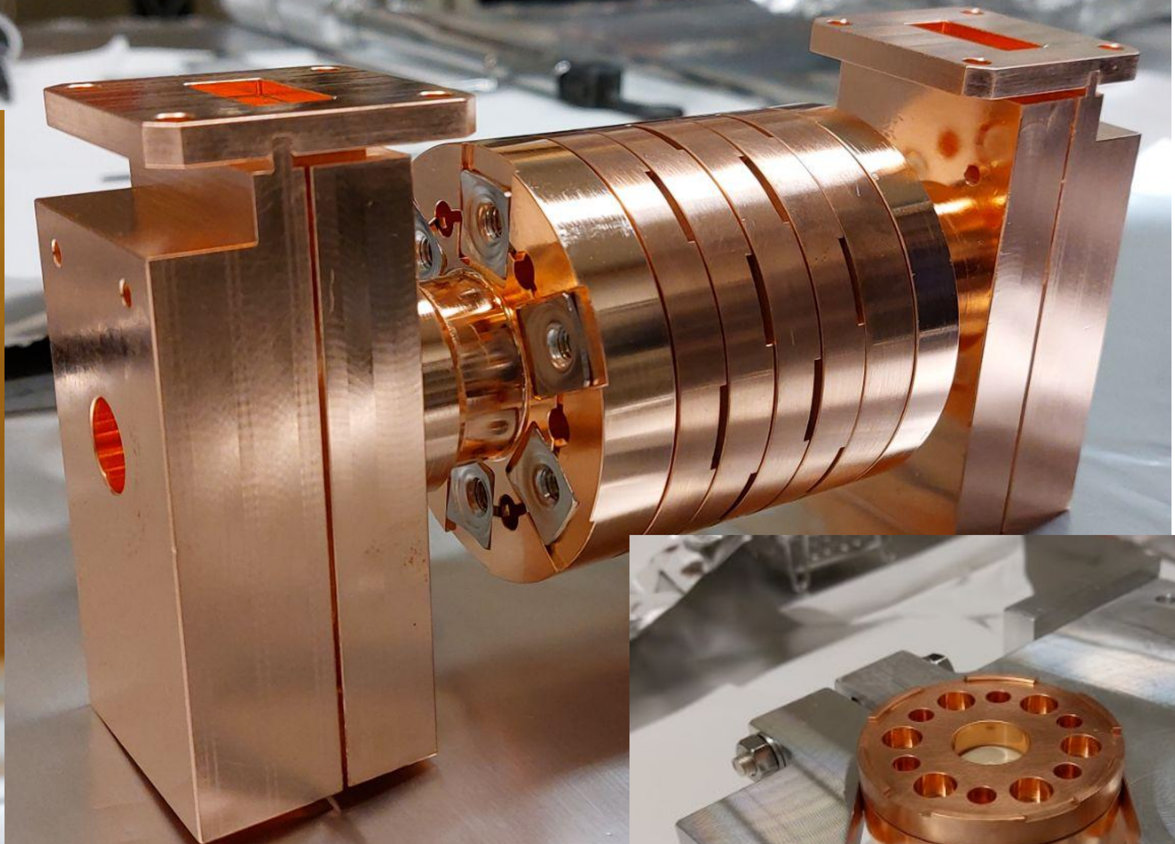
Issues with Fabrication

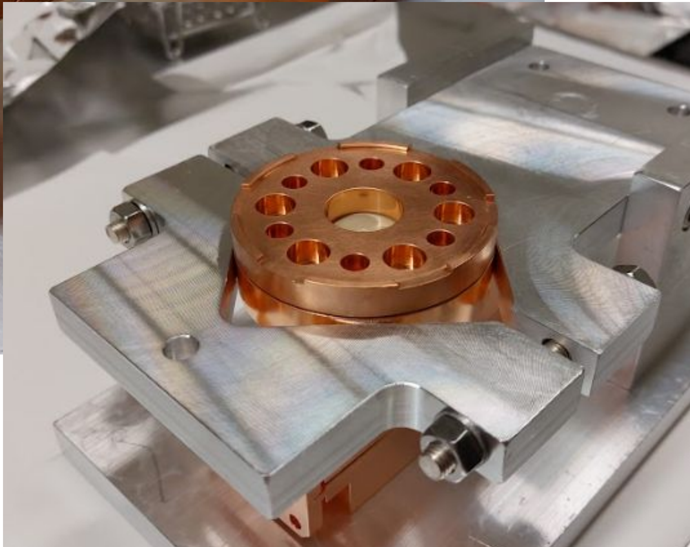
- Due to the small features of the ceramic disks, only 6 of the 15 fabricated disks were useable for the experiment

- Simulations results were done for the five cell structure that had results comparable to the full scaled structure so the experiment may continue.

Assembly





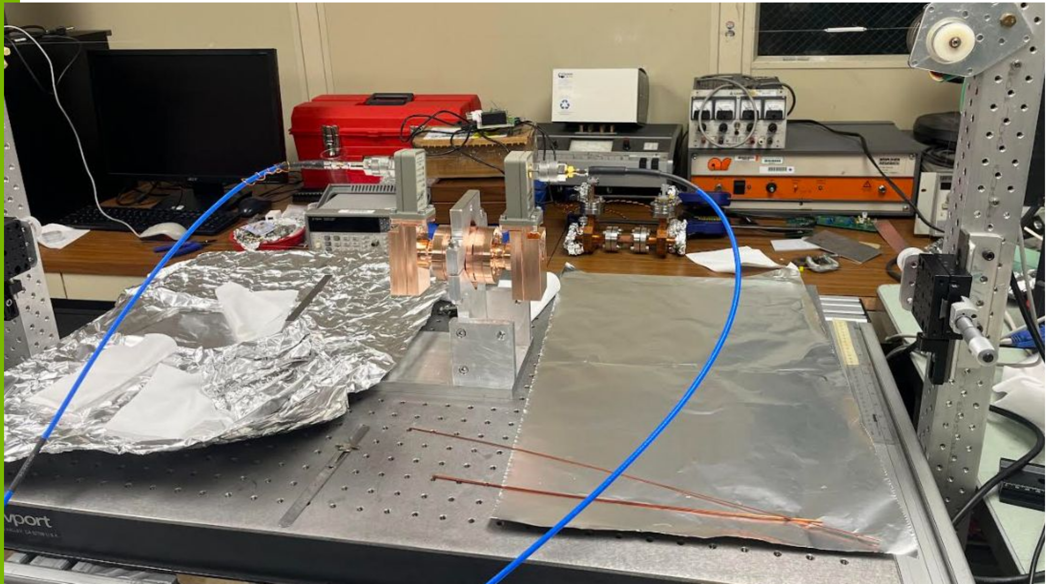


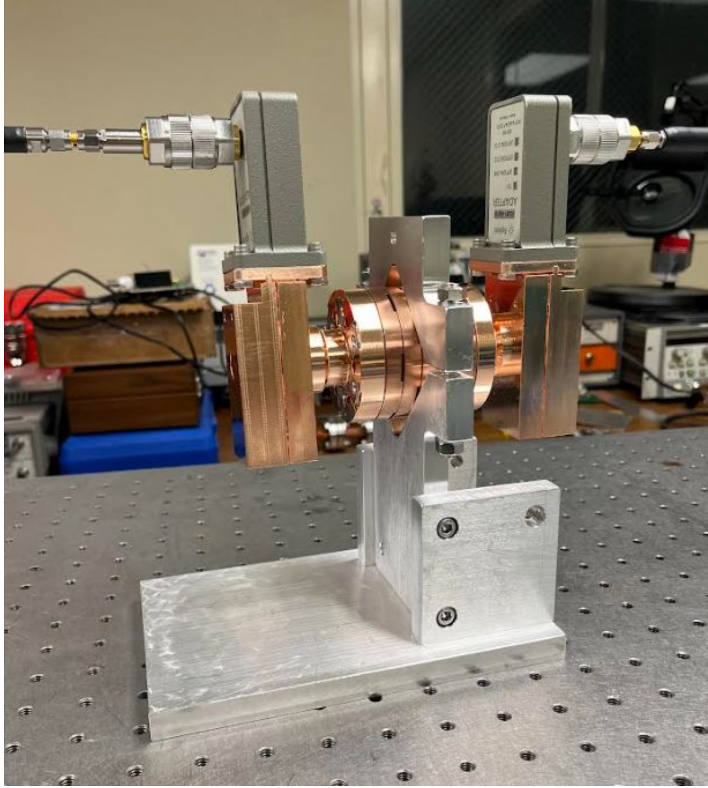
- Assembly occurred at AWA March 2023

Low Power Tests

- Low power tests were conducted to investigate the transmission and reflection of power through the structure as well as what form the electric field took on the structure axis.

- This step helped to determine which port would be the input and output.





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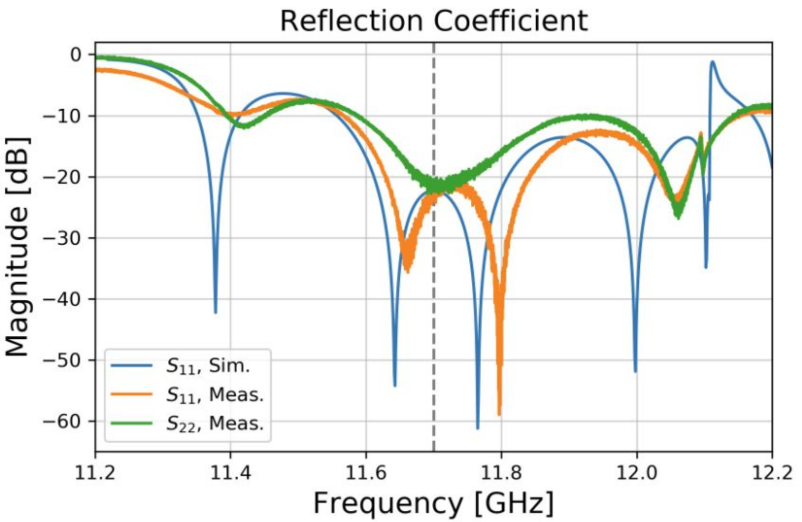
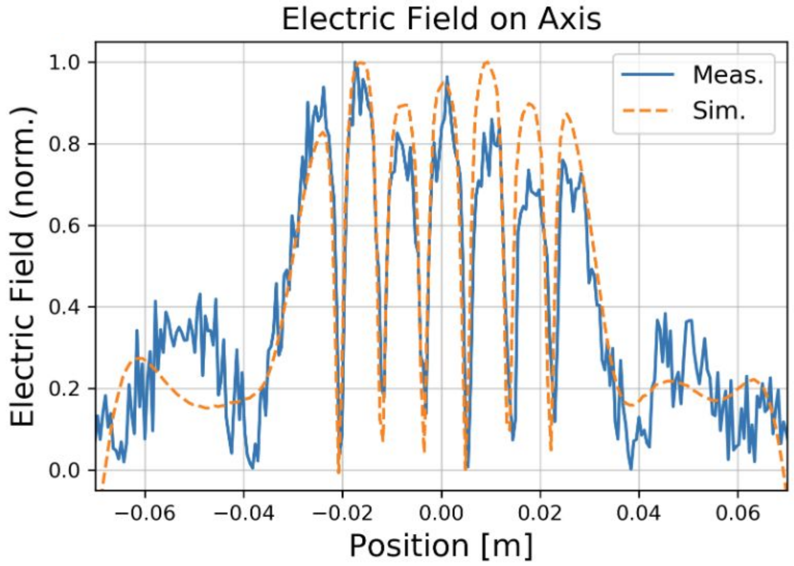
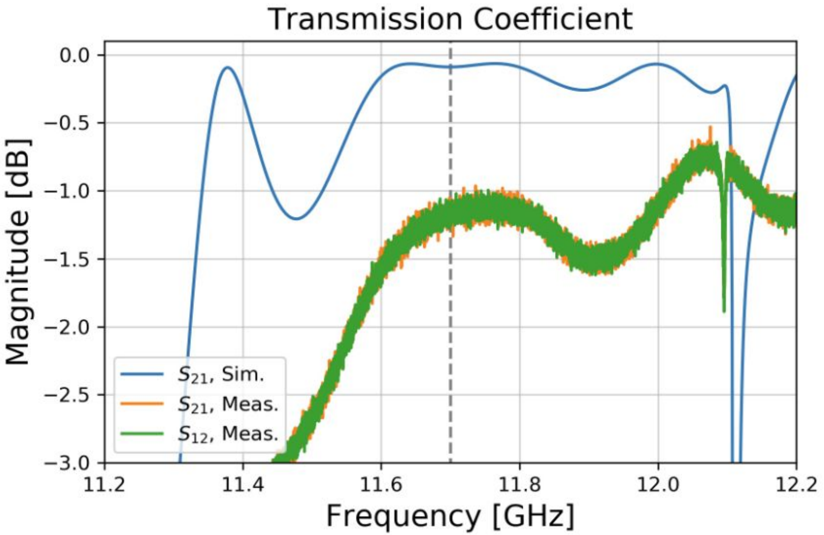
Low Power Tests Results

Parameter	Simulated Value	Measured Value
S11 at 11.7 GHz	-22.25 dB	-21.25 dB
S21 at 11.7 GHz	-0.090 dB (97.9%)	-1.18 dB (76.2%)
S11 10 dB Bandwidth	> 600 MHz	~ 600 MHz
S21 3 dB Bandwidth	> 700 MHz	> 650 MHz







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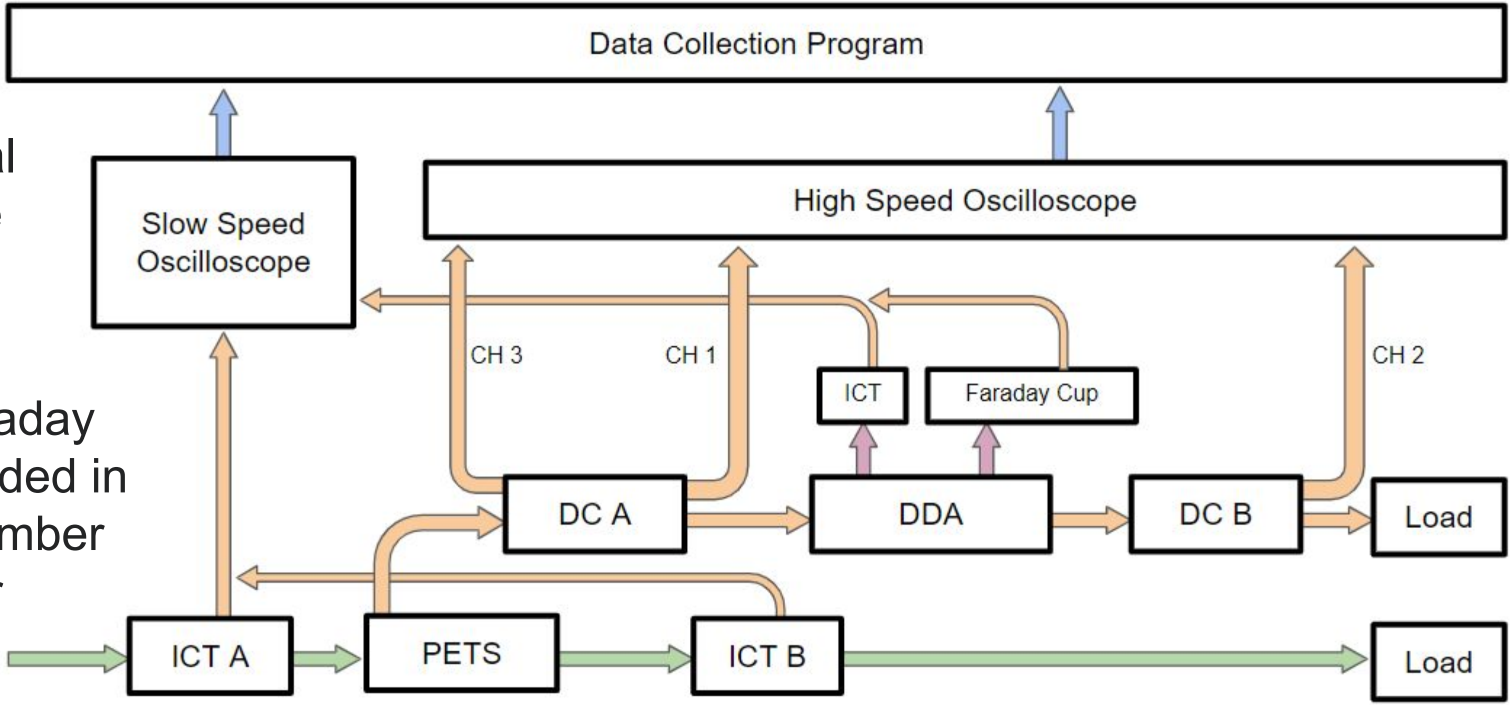
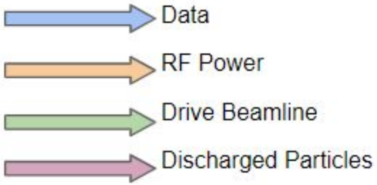
Multicell High Power Test

Testing

- Experimental setup for the experiment.
- ICT and Faraday cup were added in vacuum chamber with DDA for breakdown information.





CH 1	Output Power from PETS
CH 2	Output Power from DDA
CH 3	Reflected Power from DDA

DC- Directional Coupler

ICT- Integrated Current Transformer

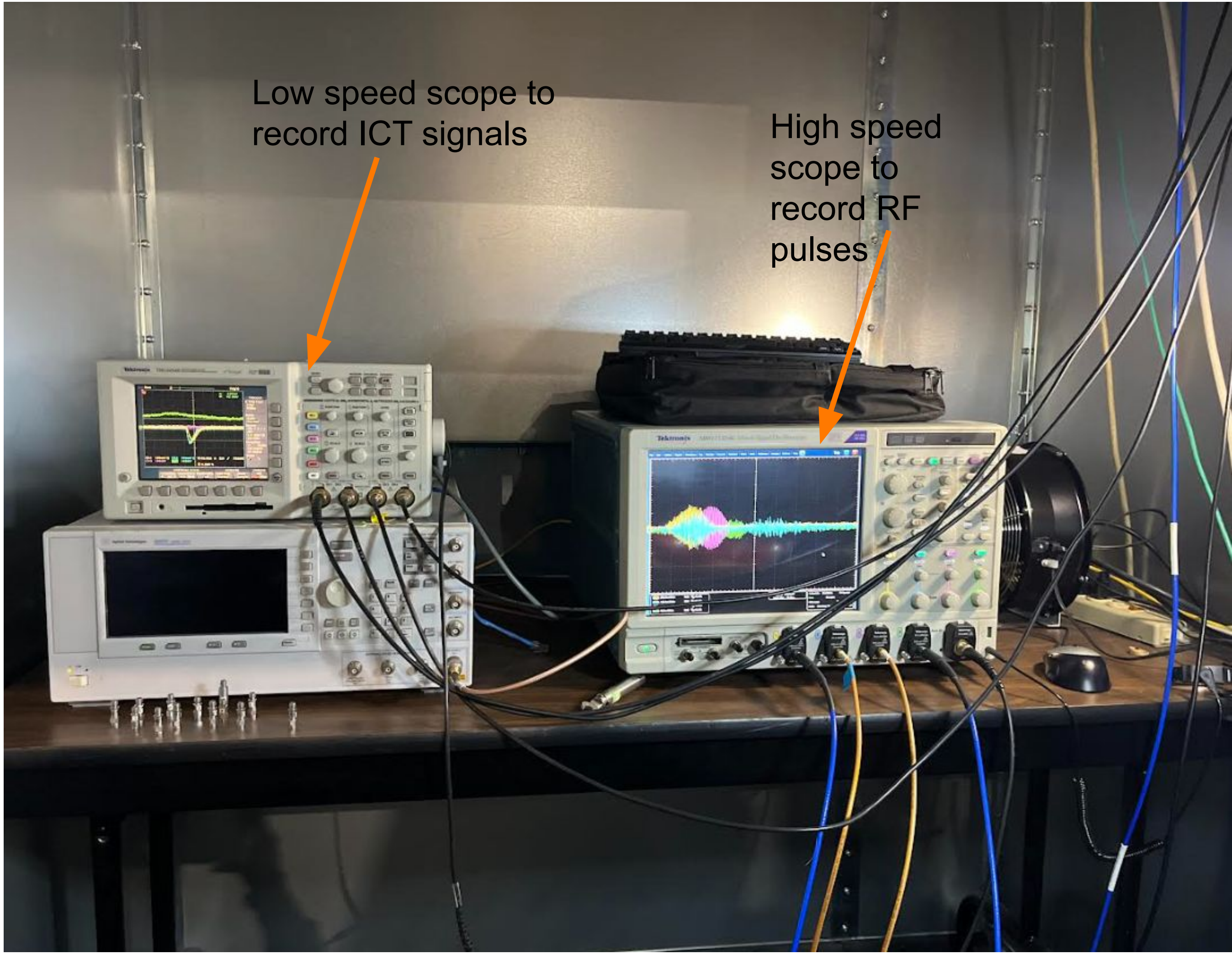
DDA- Dielectric Disk Accelerator

PETS- Power Extractor and Transfer System

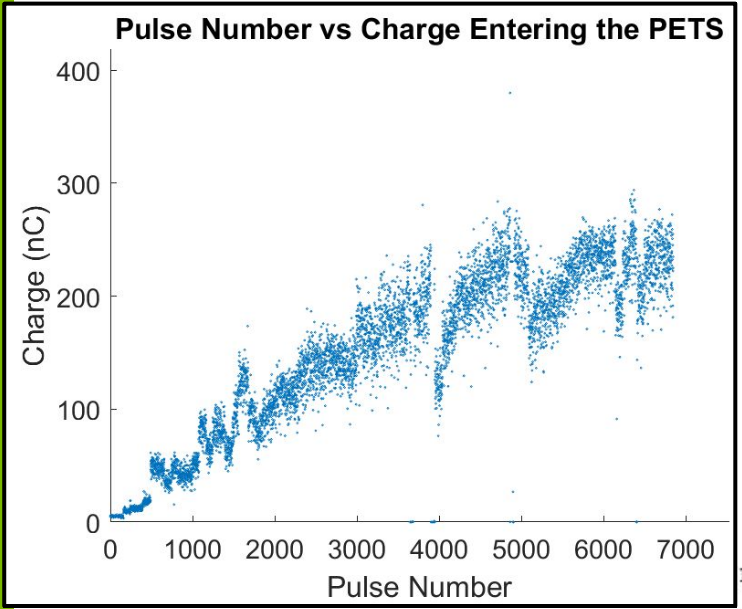
Data Collection

All data was recorded in a shielded room using:

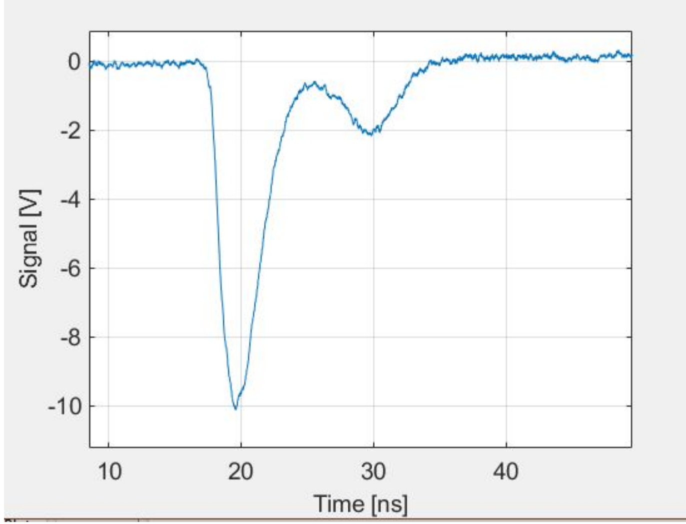
- A low power scope (for ICT and Faraday cup signals)
- A high speed scope (for RF signals from direction couplers)

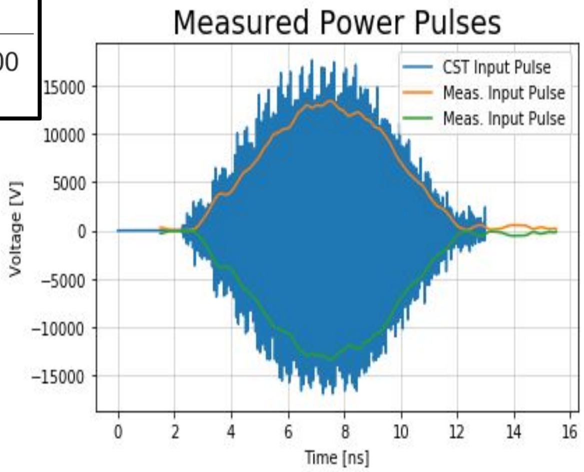


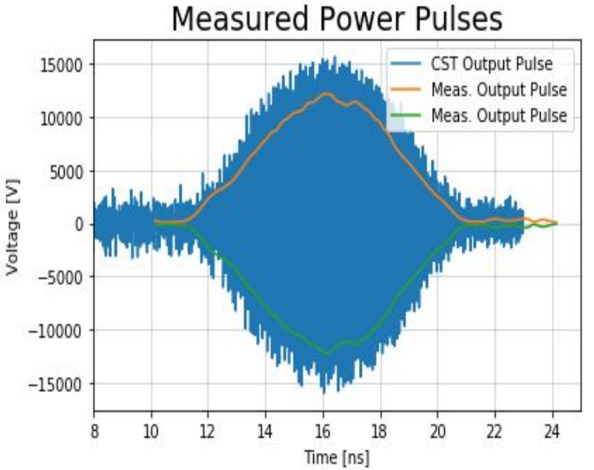
Data during Experiment



Example ICT signals and RF pulses.

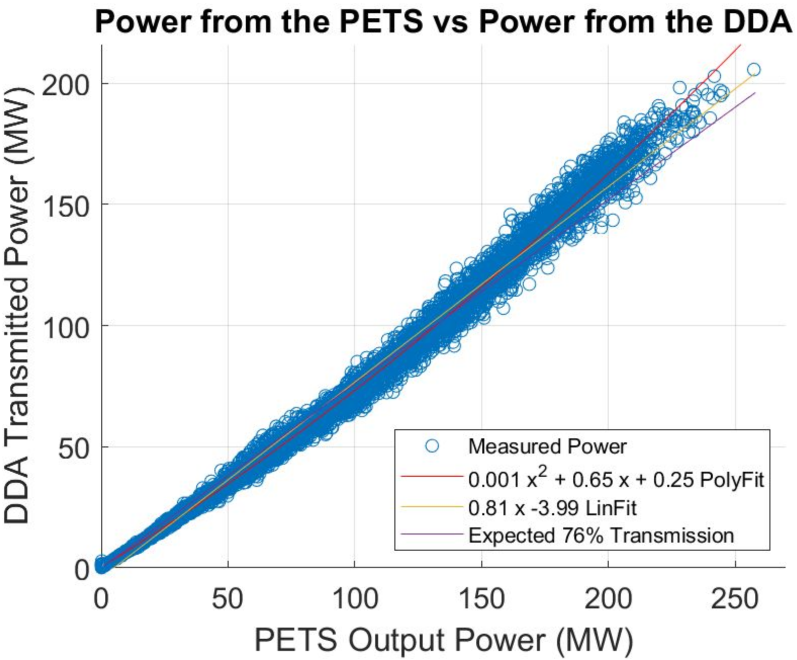




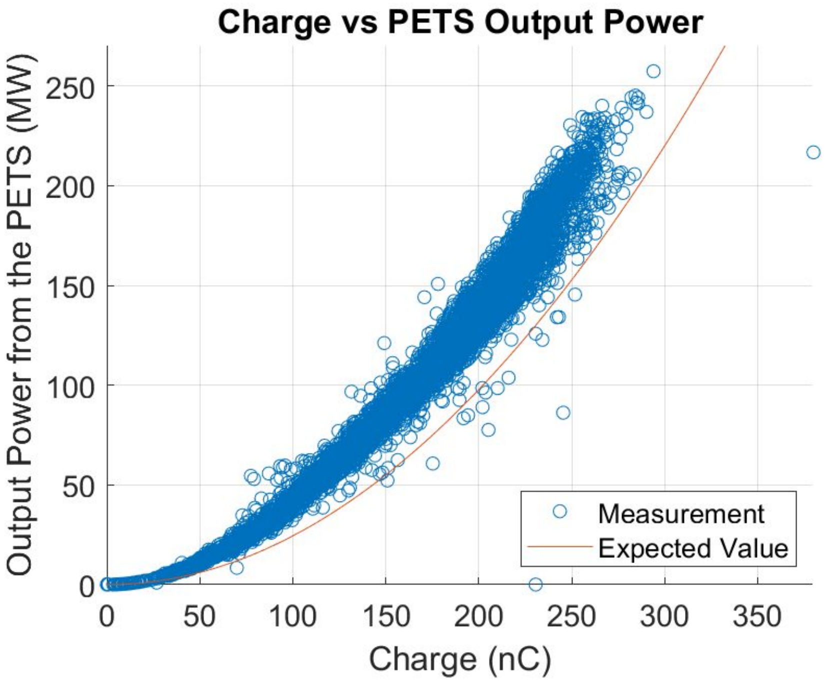


- Max charge reached was 380 nC (caused by arcing in gun).
- Second highest was 293 nC (correlates to 222 MW of input power)

Results



Power from the PETS vs Power from the DDA
DDA Transmitted Power (MW)
PETS Output Power (MW)
0
50
100
150
200
250
Measured Power
0.001 x2 + 0.65 x + 0.25 PolyFit
0.81 x -3.99 LinFit
Expected 76% Transmission



Charge vs PETS Output Power
Output Power from the PETS (MW)
Charge (nC)
0
50
100
150
200
250
300
350
Measurement
Expected Value

Future Plans

Short Term Plans

- Recent improvements in the laser and gun means a higher charge, more consistent drive beam can be produced.

- High power tests for multicell clamped structure will continue this fall.

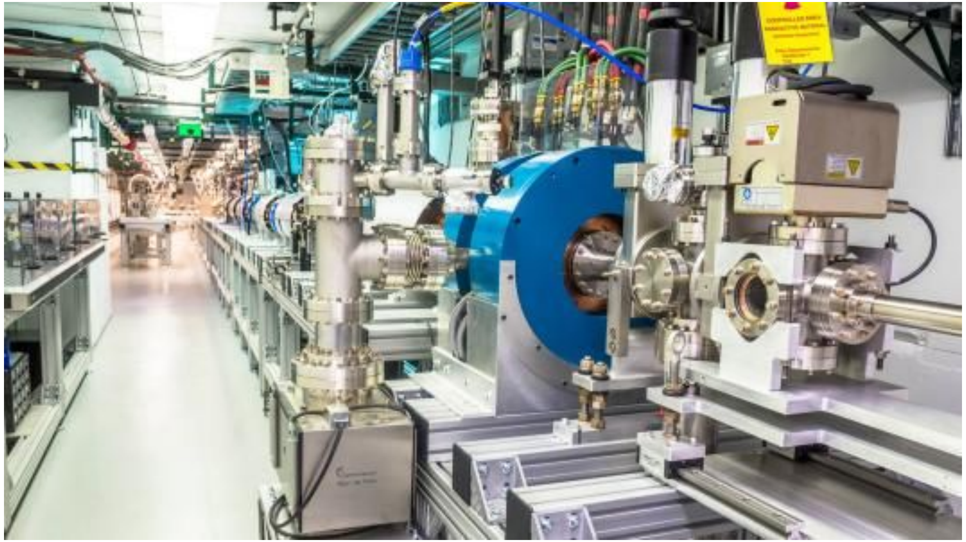


Image courtesy of ANL

Future Plans for DDA

- Current results indicate DDA structures are viable candidates for short pulse, high gradient beam acceleration.

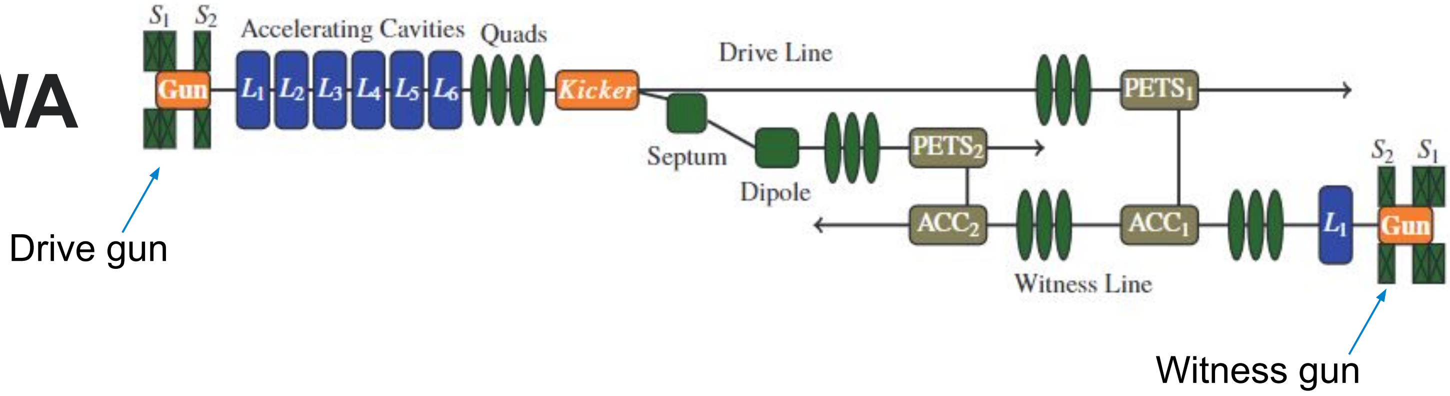
- After high power testing, beam acceleration tests will be conducted.
  - Optimized multicell DDA structure will be designed, fabricated, and used to accelerate electron beam.

- AWA has previously demonstrated capabilities for TBA scheme.

STAGED TWO BEAM ACCELERATION BEAM LINE DESIGN FOR THE AWA FACILITY

N. Neveu*[1], L. Spentzouris, Illinois Institute of Technology, Chicago, IL, USA
J. G. Power, W. Gai, [1]Argonne National Laboratory, Lemont, IL, USA
C. Jing, Euclid Techlabs LLC, Solon, OH, USA

TBA at AWA



- TBA requires the drive beam and the witness beamline to be used at the same time.
- A DDA is a attractive candidate to be used in a TBA scheme for a high energy, small footprint accelerator like the 500 MeV demonstrator.

N. Neveu, L. Spentzouris, J. G. Power, W. Gai, and C. Jing, "Staged Two Beam Acceleration Beam Line Design for the AWA Facility," in Proceedings of IPAC2018, Vancouver, BC, Canada, Summer 2018.

Thank you for listening!

Questions?

Extra Slides

Components Testing

- One goal of research is to test thresholds of materials used, such as the dielectrics.

- The ceramic selected to be used brazed single cell and clamped multicell is barium titanate ($BaTiO3$). Clamped single cell (previous talk) used is Calcium Titanium Lanthanum Aluminum Oxide.

- Ceramic was chosen for high dielectric constant and low loss tangent