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High Efficiency RF Source Developments

Lawrence Ives,
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- 100 kW, 1.3 GHz Magnetron w/ Phase & amplitude control
- 100 kW, High efficiency, L-Band klystron
- 200 kW L/C-Band Multiple Beam High Efficiency Klystron
- 10 MW L-Band Annular Beam Klystron
- 350 – 700 MHz, 200 kW Power Grid Tube RF sources
- 700 MHz Multiple Beam IOT

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A 100 kW, 1.3 GHz Amplitude and Phase Controlled Magnetron for Accelerators

Michael Read[1], R. Lawrence Ives[1], Brian Chase[2], John Reid[2], Chris Walker[3] and Jeff Conant[3]

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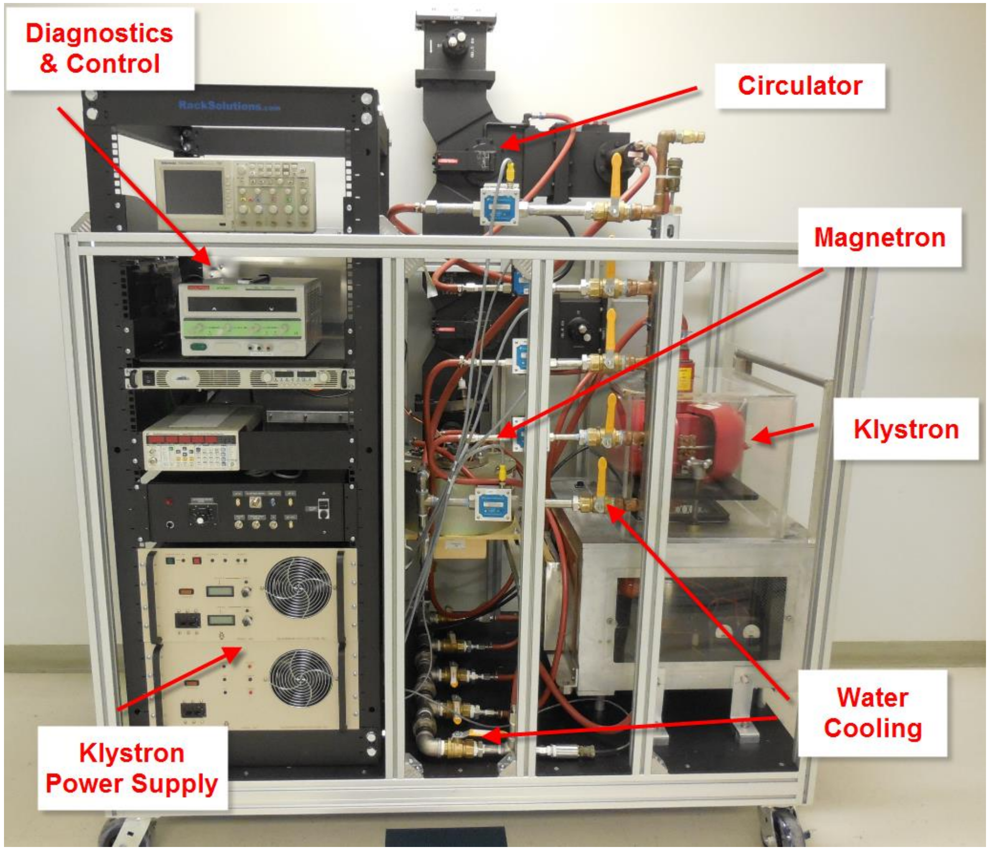
Fermilab
Communications and Power Industries LLC,



Funded by the US Department of Energy under SBIR grant DE-SC0011229

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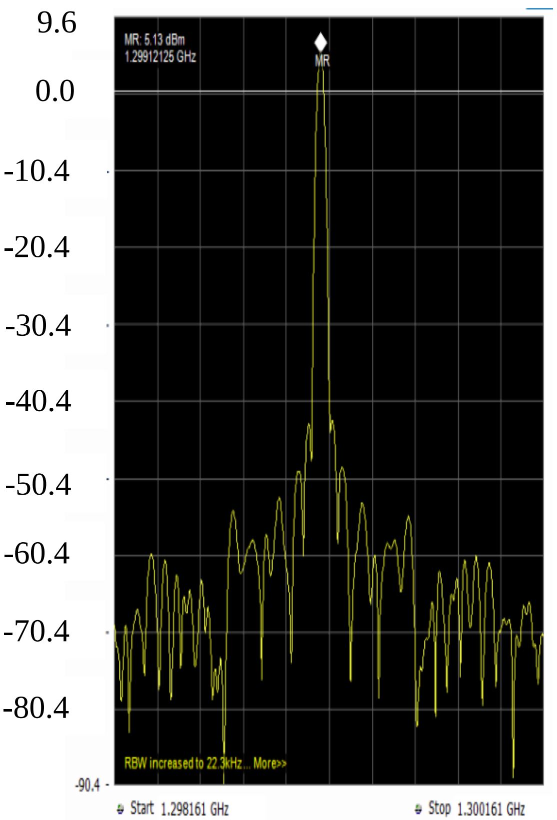
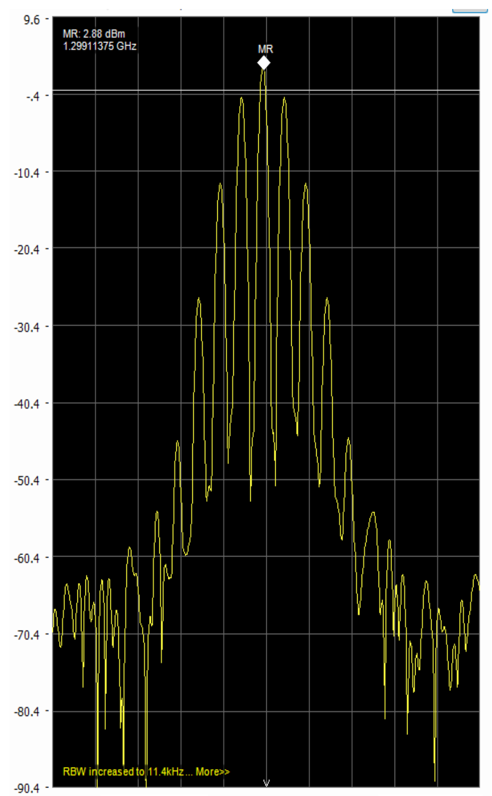
Phase Modulation

50 kHz Phase Modulation



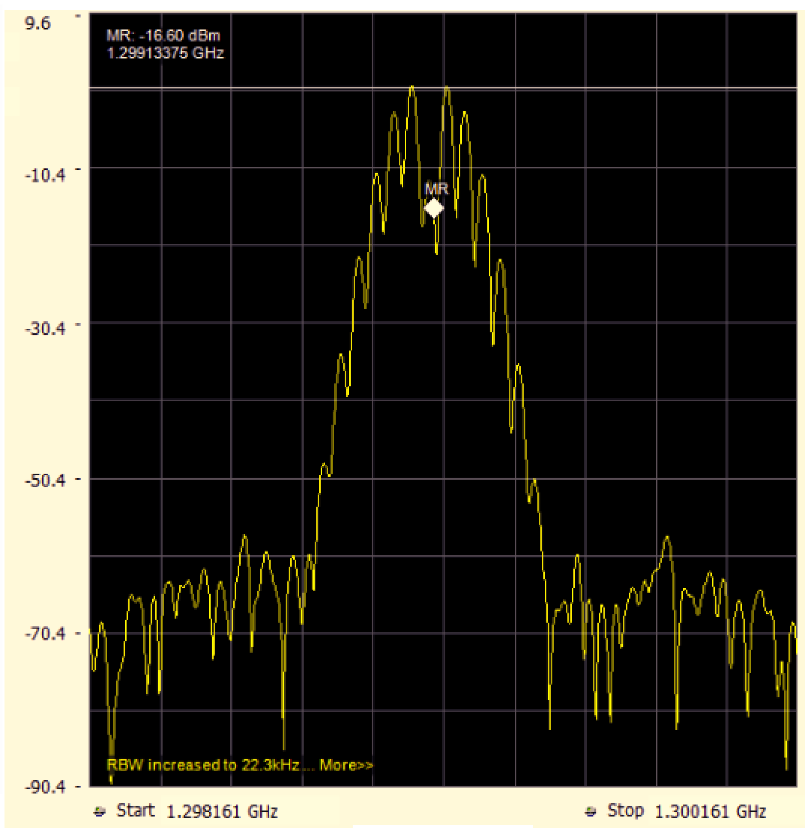
2 MHz

No Modulation



1 MHz

60° Modulation



2 MHz

122° Modulation

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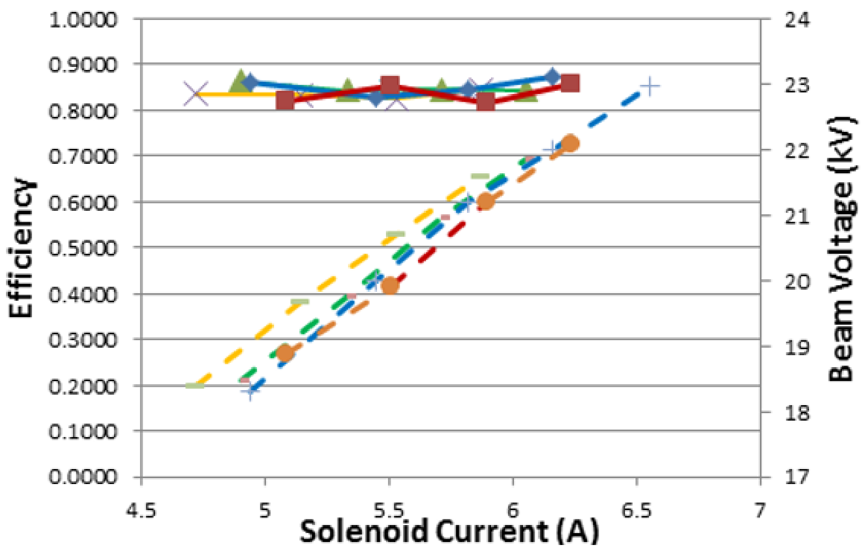
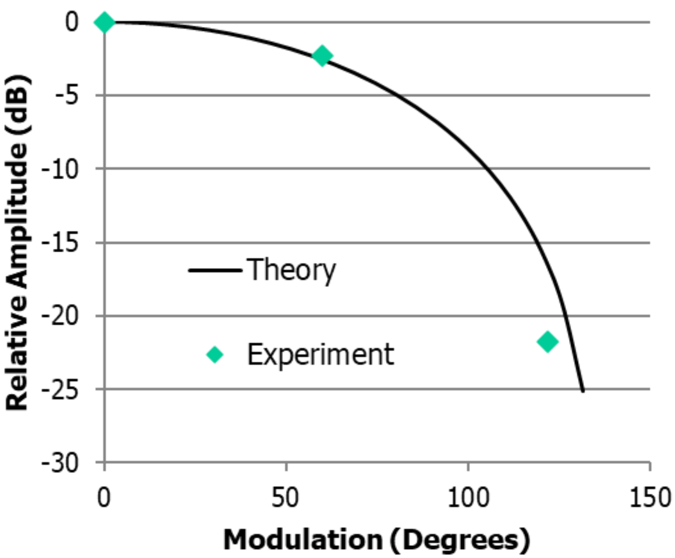
Fast Amplitude and Phase Control with Modulation of Locking Signal

Efficiency exceeded 80% in all operating modes.
Amplitude smoothly varied over 25 dB range





Cost approximately $1/Watt

Proposed Development

- Revise previous design for commercial deployment
  - implement solid state driver
  - redesign cooling, electrical circuits, diagnostics, and interlocks
  - update PLC control system
- Increase average power to 20 kW
- Develop Feedback-based control electronics
  - Operation requires amplitude/phase control based on accelerator operation
  - develop electronic control based on feedback
  - implementation on Field Programmable Gate Array (FPGA)
- System tests on superconducting cavity at Fermilab

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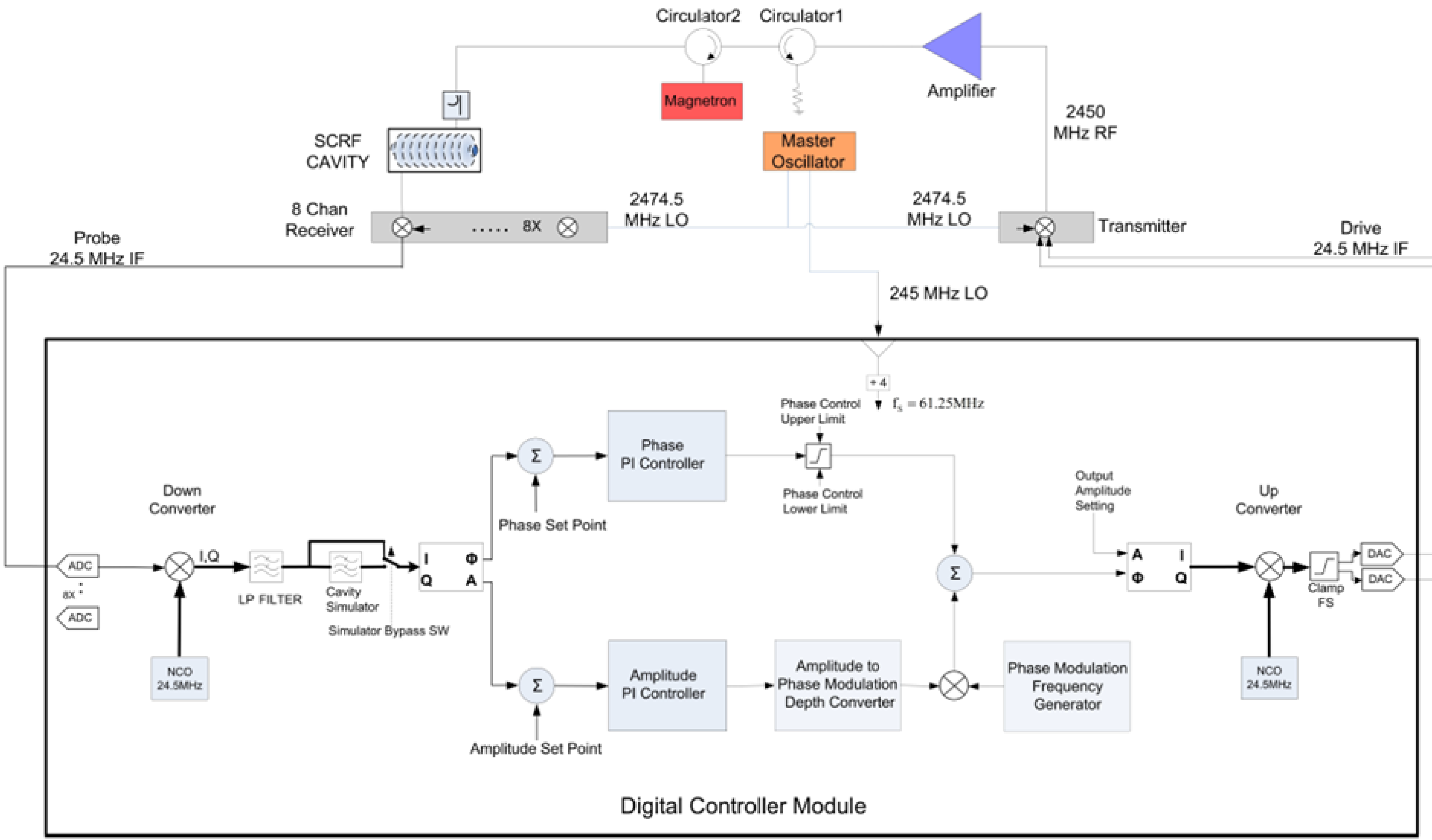
Feedback Control Circuit



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A 1.3 GHz 100 kW Ultra-high Efficiency Klystron

Michael Read[1], Aaron Jensen[2], R. Lawrence Ives[1], Thomas Haberman[1], David Marsden[1], and George Collins[1]

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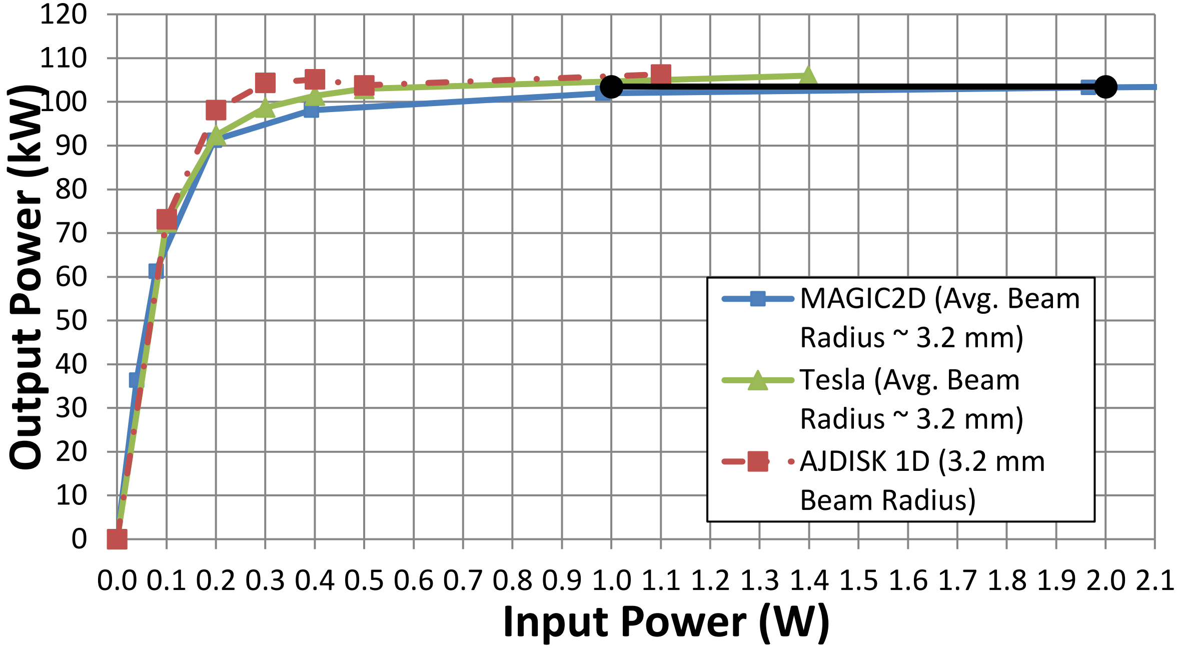
Leidos
Communications & Power Industries, LLC

Funded by the US Department of Energy under SBIR grant DE-SC0017789.

Design Parameters

- COM design with 7 cavities
- Parameters
  - Voltage 53.5 kV
  - Current 2.46 A (0.2 micropervs)
  - Beam diam 0.6 cm
  - Drift tube diam 1.0 cm
  - RF structure length 205 cm

Simulation Summary



Code	Power	Efficiency
TESLA	104.5 kW	79.5%
AJDISK	106 kW	81%
KLYC	103.5 kW	79%
MAGIC	102 kW	78%

High Efficiency Klystron Status

- Initial testing in CW test set
- Processed to ~18 kV
- 95+% beam transmission
- Encountered test set issue, terminating testing
- Seeking funding test set to resume testing

Estimated cost ~ $4/Watt

This tube needs a home!

Multiple Beam High Efficiency Klystron

- Phase II SBIR program awarded September 2024
- Phase I Power/Frequency goal of 200kW @ 5.8 GHz
- Efficiency goal is 80+%
- Six beams
- Input power: 45 kV, 0.995 A
- Considered BAC, COM, and CSM approaches – selected COM

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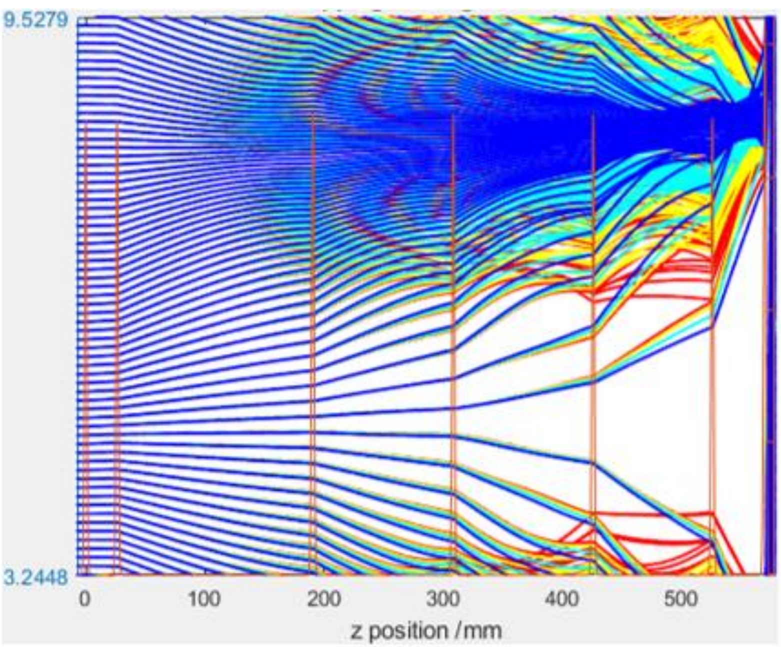
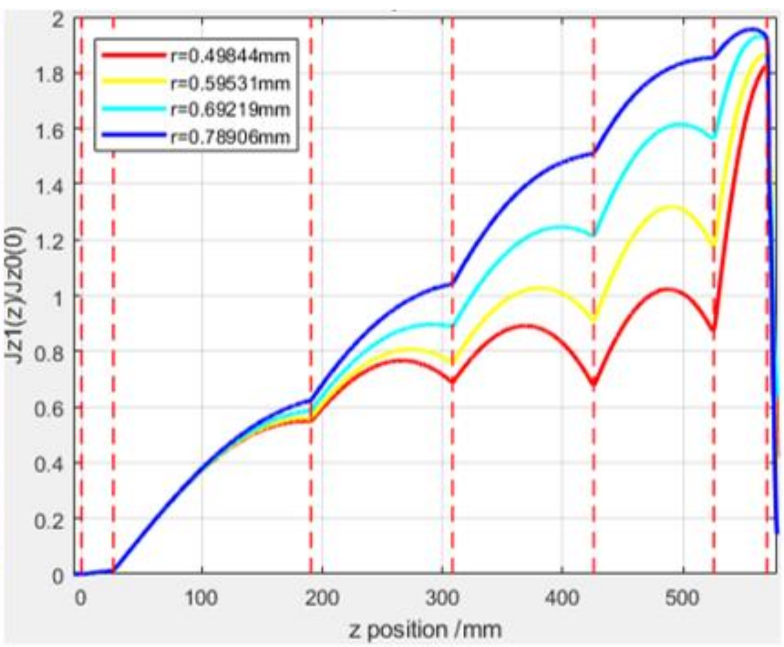
RF Circuit Design

- Seven cavities
- Analyzed using HFSS, KlyC, and Tesla
- Considered solid and hollow beams
  - Solid – 81% efficiency
  - Hollow – 84.1% efficiency





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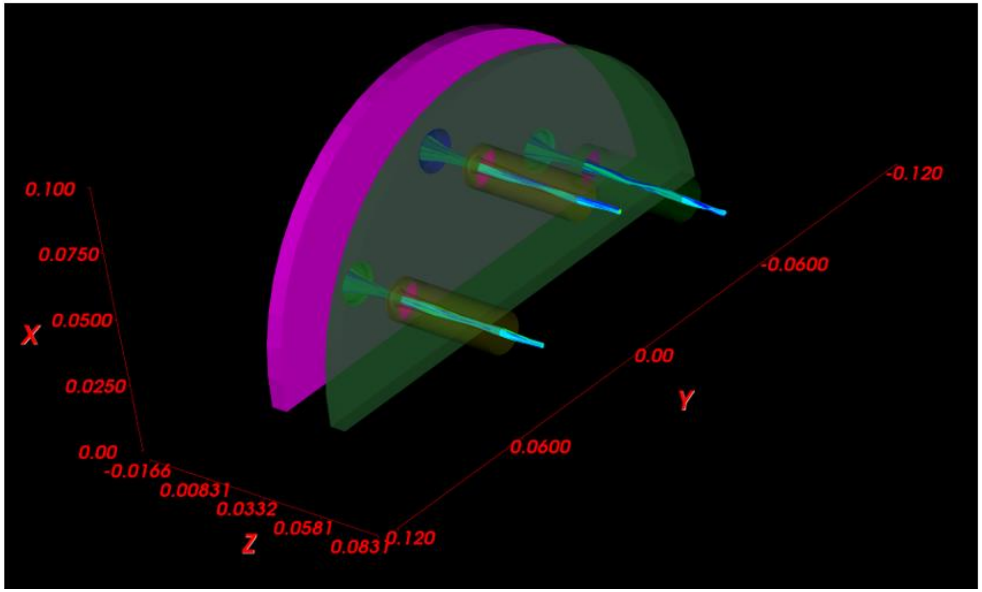
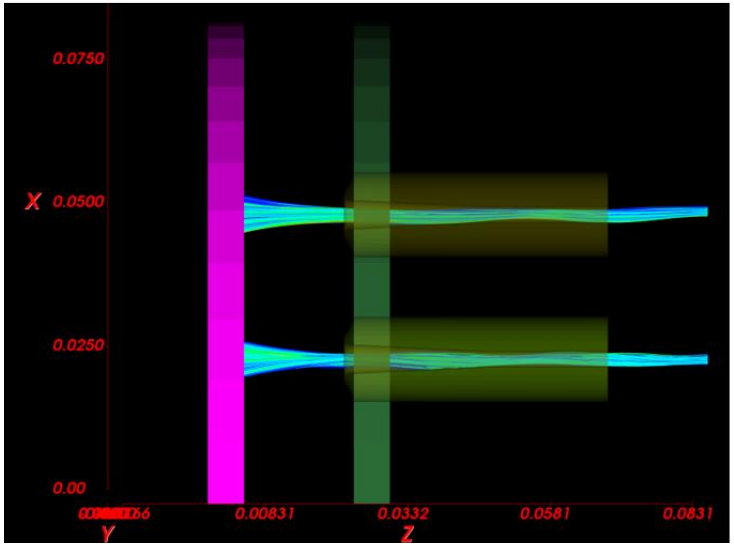
Electron Gun Design

- Initial design in 2D with Trak, final design in 3D with Beam Optics Analyzer
- Hollow beam most challenging
- Simulations predict no interception





Phase II Multiple Beam – High Efficiency Klystron Program

- Plan to switch to 2.856 GHz, 200 kW CW
- Initial simulations with KlyC predicting 79% (one week of simulation)
- Scheduled to build and test to full power during two year program

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Multiple Beam Power Grid Tubes

Lawrence Ives, Michael Read, James M. Potter, David Marsden,
Thuc Bui, Ricky Ho, Tom Cox,
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Communications & Power Industries, LLC
JP Accelerator Works

This research funded by DOE SBIR Grant DE-SC0018838

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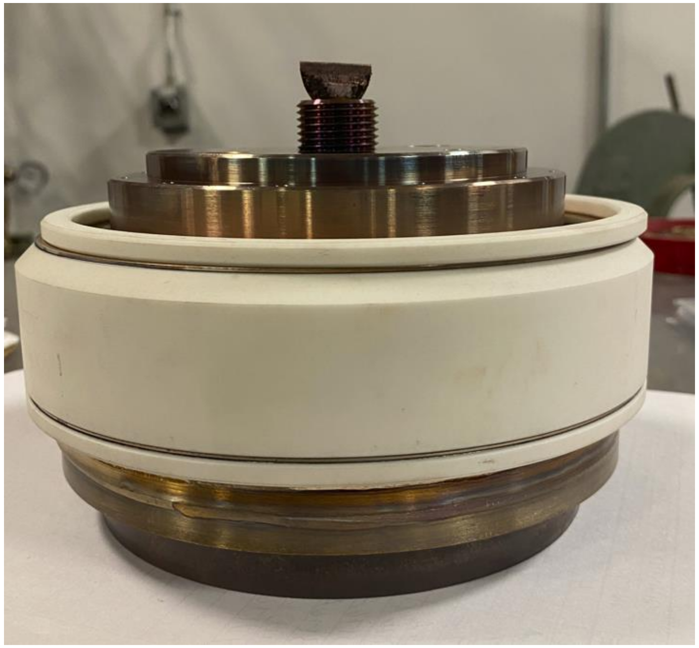
Multiple Beam Triode for 200 KW RF Source

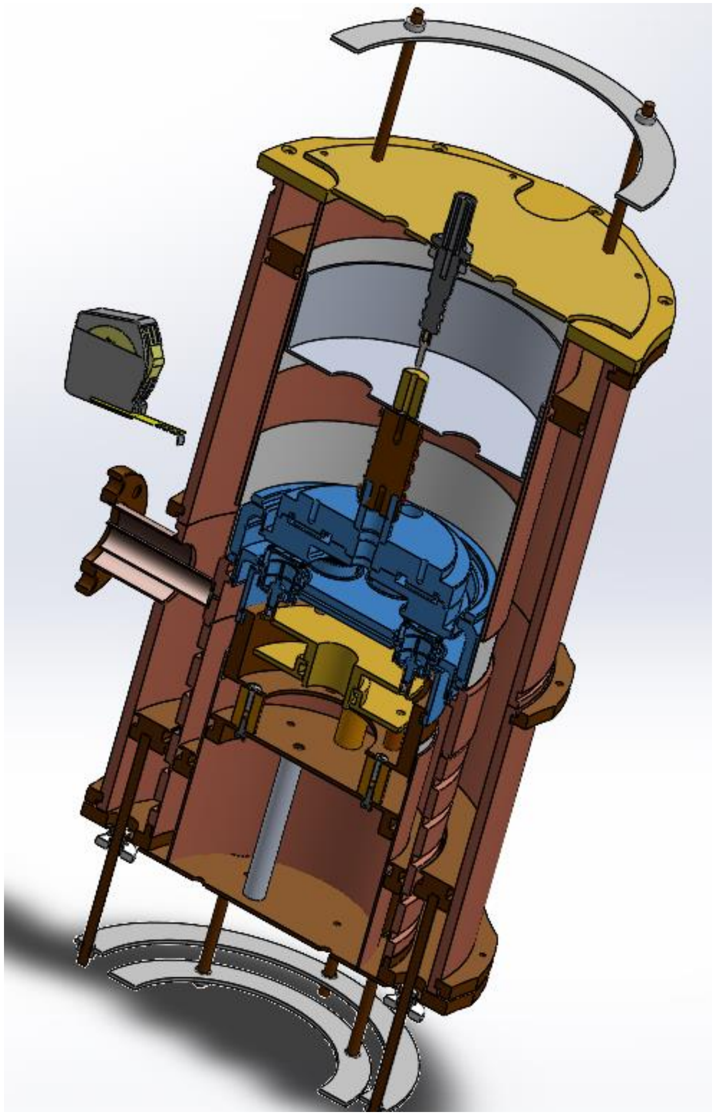
Multiple beam triode provides beam for external cavities converting beam power to 200 kW of RF power .

Frequency range : 300 MHz to 1 GHz



RF Cavities

- MB triode tube installs from top (blue)
- Single input cavity
- Upper and lower output cavities with coax output between
- Upper cavity tunes frequency
- Lower cavity varies output coupling
- RF cavities are NOT under vacuum and built primarily from aluminum with mechanical fasteners



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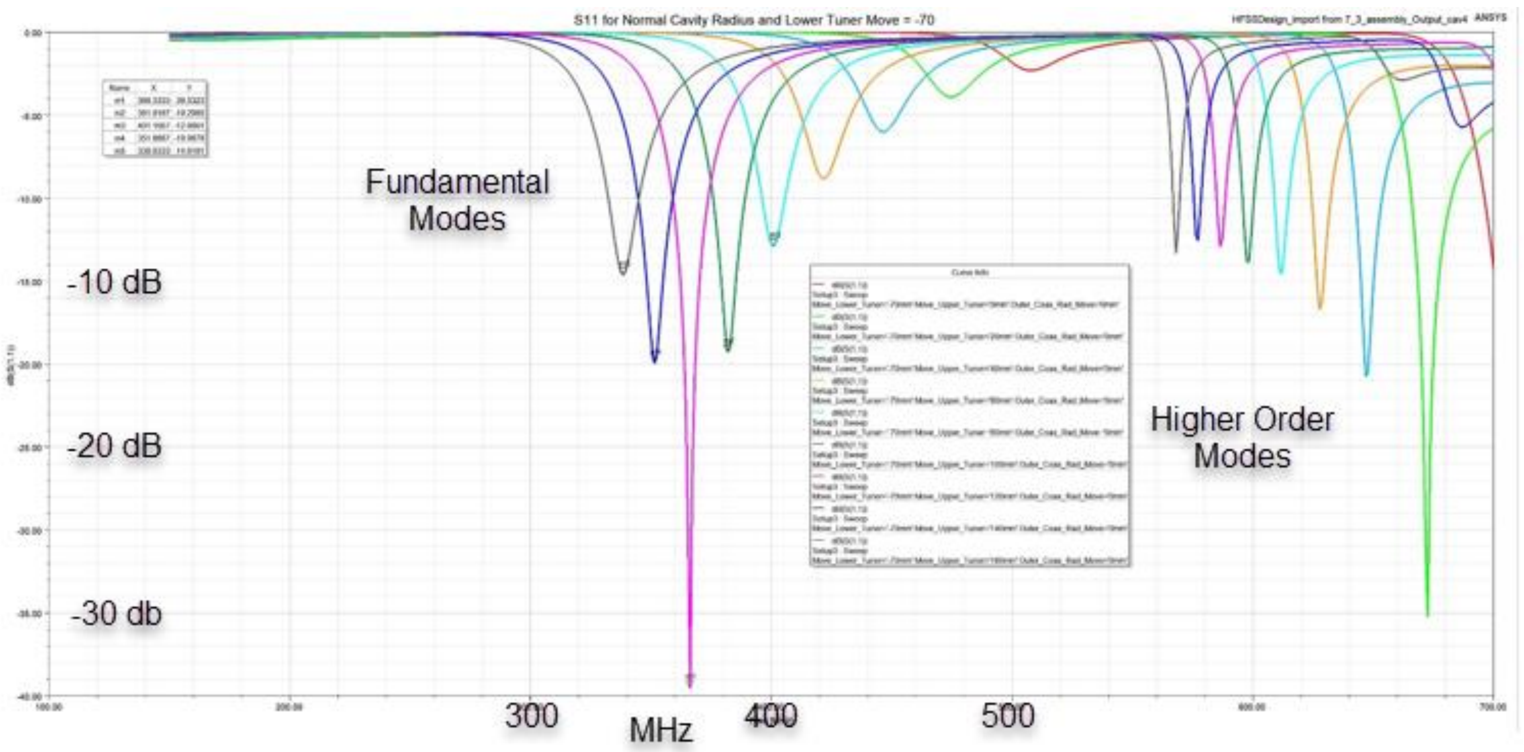
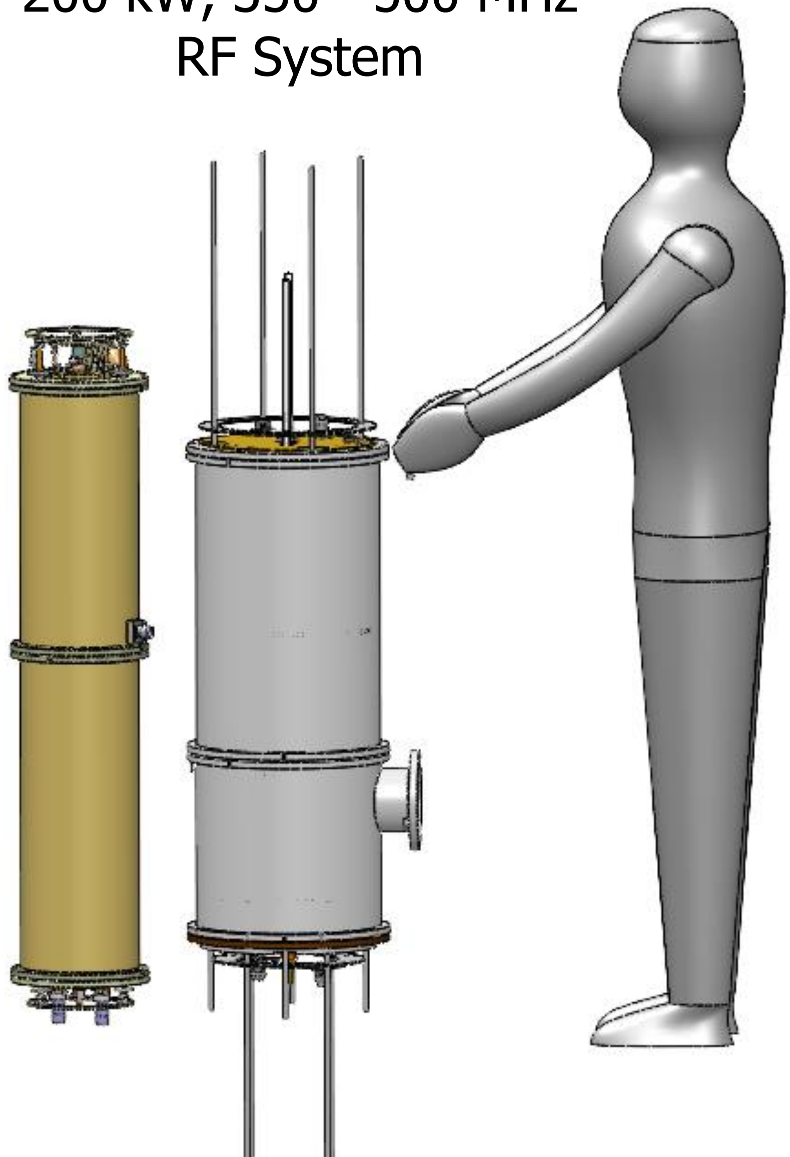
Output Cavity Simulation

Tuning range for output cavity (325 – 500 MHz)



Gain Issue

200 kW, 350 - 500 MHz
RF System



Triode RF source limited to 14 dB gain

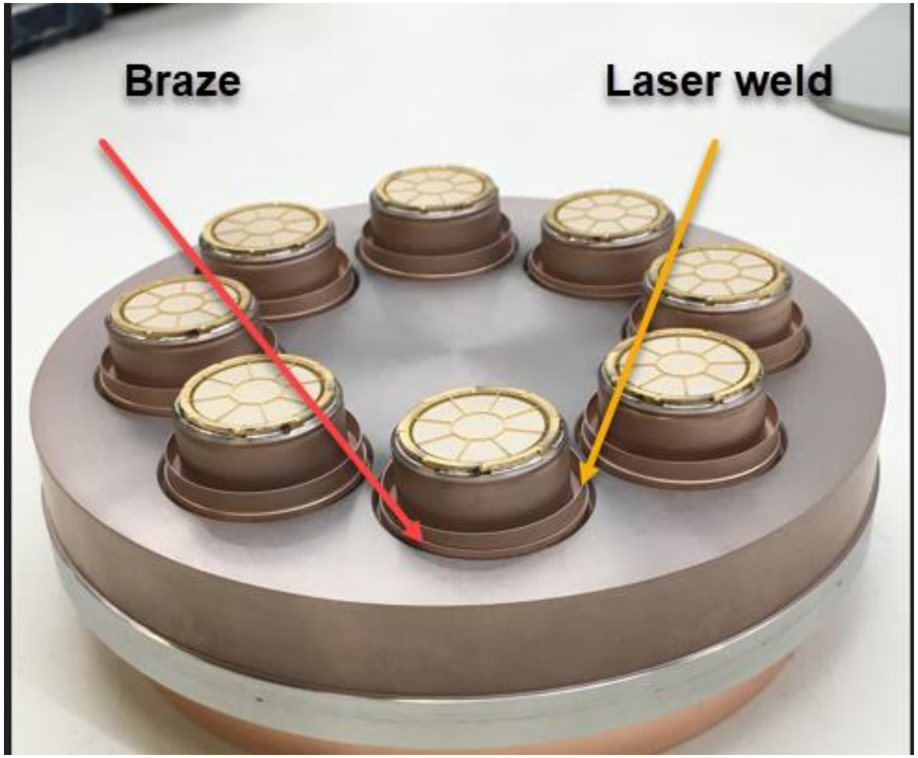
High power system requires single beam triode driver

Net Gain	28 dB
Net Efficiency	>75%

Estimated cost – 50 cents/Watt

Previous Test Results

- Oxide cathode version of MB triode built and tested in 2023
- Encountered issues with assembly
  - required to braze/weld eight grid-cathode assemblies into vacuum-tight structure
  - attempted to maintain original grid-cathode assembly design – with marginal results



Previous Test Results

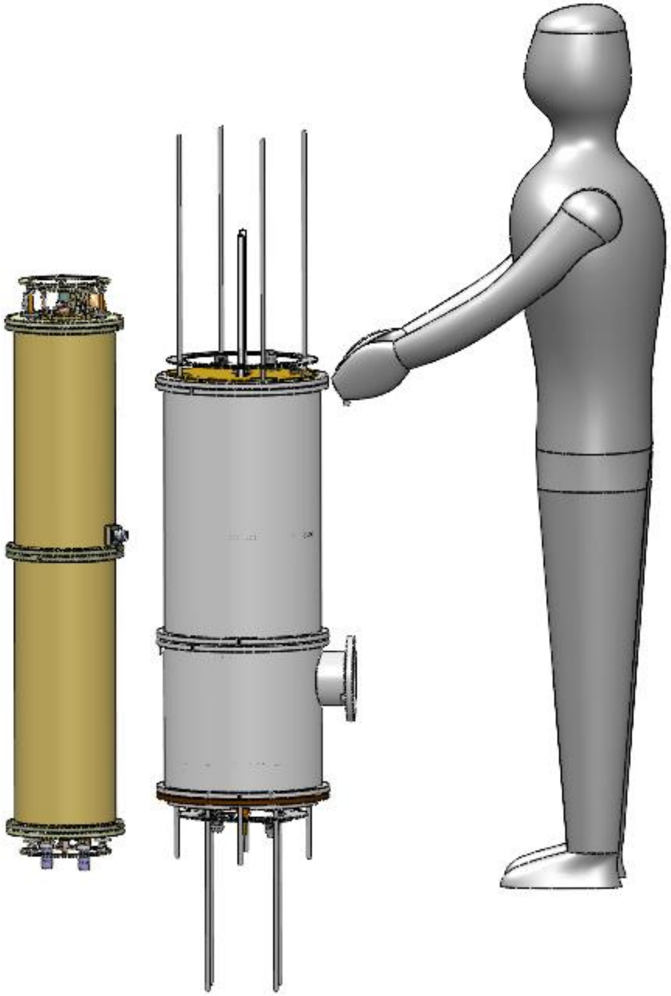
- Triode successfully built and baked
- During processing to full power, encountered intermittent arcing form grid to anode
- Attempted to clear arcing – resulting in fatal grid to cathode short
- Subsequent inspection indicated significant damage (arc marks) on all eight oxide cathodes

Current Development Program

- Phase I program initiated February 2024
- Replacing oxide cathodes with dispenser cathodes
- New grid structure built and tested in single beam triode
  - lower cathode heater power than expected
  - higher screening factor reducing anode current
  - grid more robust – facilitating higher power/duty operation
  - Projecting 8-beam device will produce 160 kW (previous design predicted 200 kW)

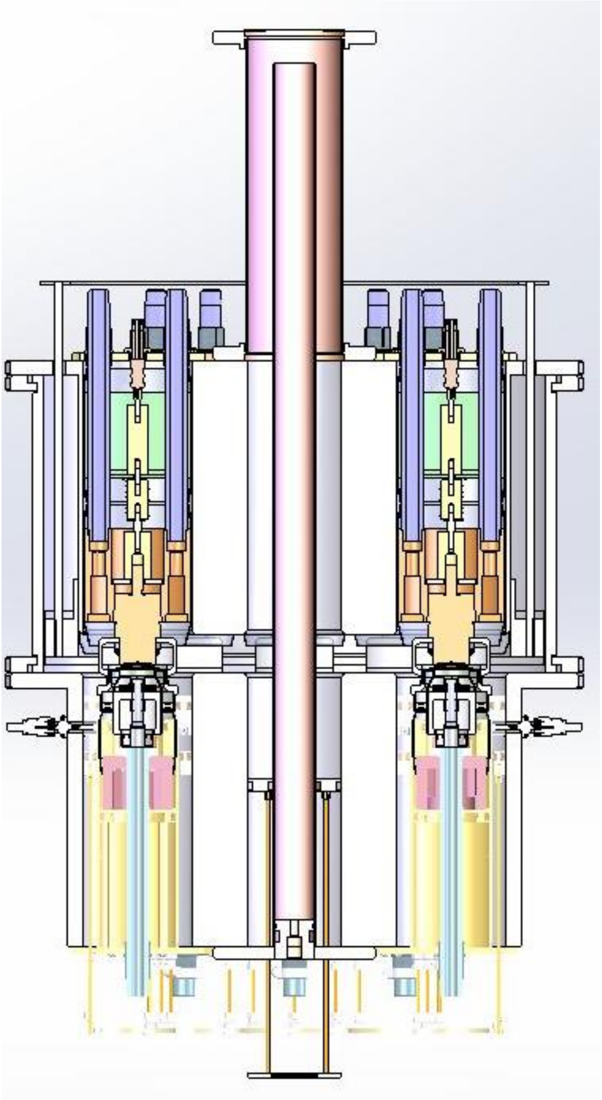
Current Development Program

- Building 8-beam triode for scheduled tests in October
- Assembling cavity structure for scheduled tests in November
  - One braze of copper input cavity
  - One weld of aluminum output cavity
  - Remainder assembled with fasteners (screws, bolts, nuts)



Proposed Phase II Development

- Redesign MB triode for higher power
  - Larger grid-cathode assemblies and/or more beams
  - Optimize grid structure of high efficiency (requires high grid current loading)
- Redesign cavities for more uniform beam loading
- If funded, program would start in February 2025



Summary – RF Source Options

- 100 kW, 1.3 GHz Magnetron w/ Phase & amplitude control
  - technology successfully demonstrated
  - proposing to develop electronics for deliverable system
- 100 kW, High efficiency, L-Band klystron
  - built but not yet tested
- 200 kW S/C-Band Multiple Beam High Efficiency Klystron
  - starting 2-year program to build and test prototype
- 350 – 700 MHz, 200 kW Power Grid Tube RF sources
  - addressing issues encountered in previous program
  - scheduled to test prototype device by end of November
  - planning further development to increase power and efficiency