High Efficiency RF Source Development

Lawrence Ives,
Calabazas Creek Research, San Mateo, CA. USA

- 100 kW, 1.3 GHz Magnetron w/ Phase and amplitude control
- Magnetron frequency/phase control with varactors
- 100 kW, High efficiency, L-Band 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

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[2] Fermi National Accelerator Laboratory Batavia IL 60510-5011

[3] Communications and Power Industries LLC, Beverly, MA, USA 01915

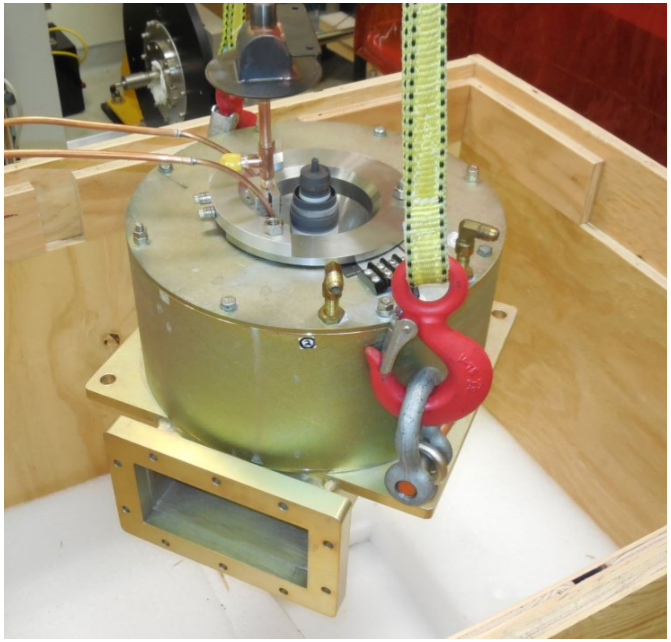
Funded by the US Department of Energy under SBIR grant DE-SC0011229

Fermilab Approach

- Externally phase lock the magnetron,
- Achieve amplitude control by phase modulating the locking signal to transfer power to side bands
  - Side bands are rejected by high Q accelerator cavity
  - Power into the cavity = Magnetron power less the side band power

CPI Magnetron

- 1.30 GHz
- 100 kW peak
- 10 kW average
- 1.5 ms pulsewidth



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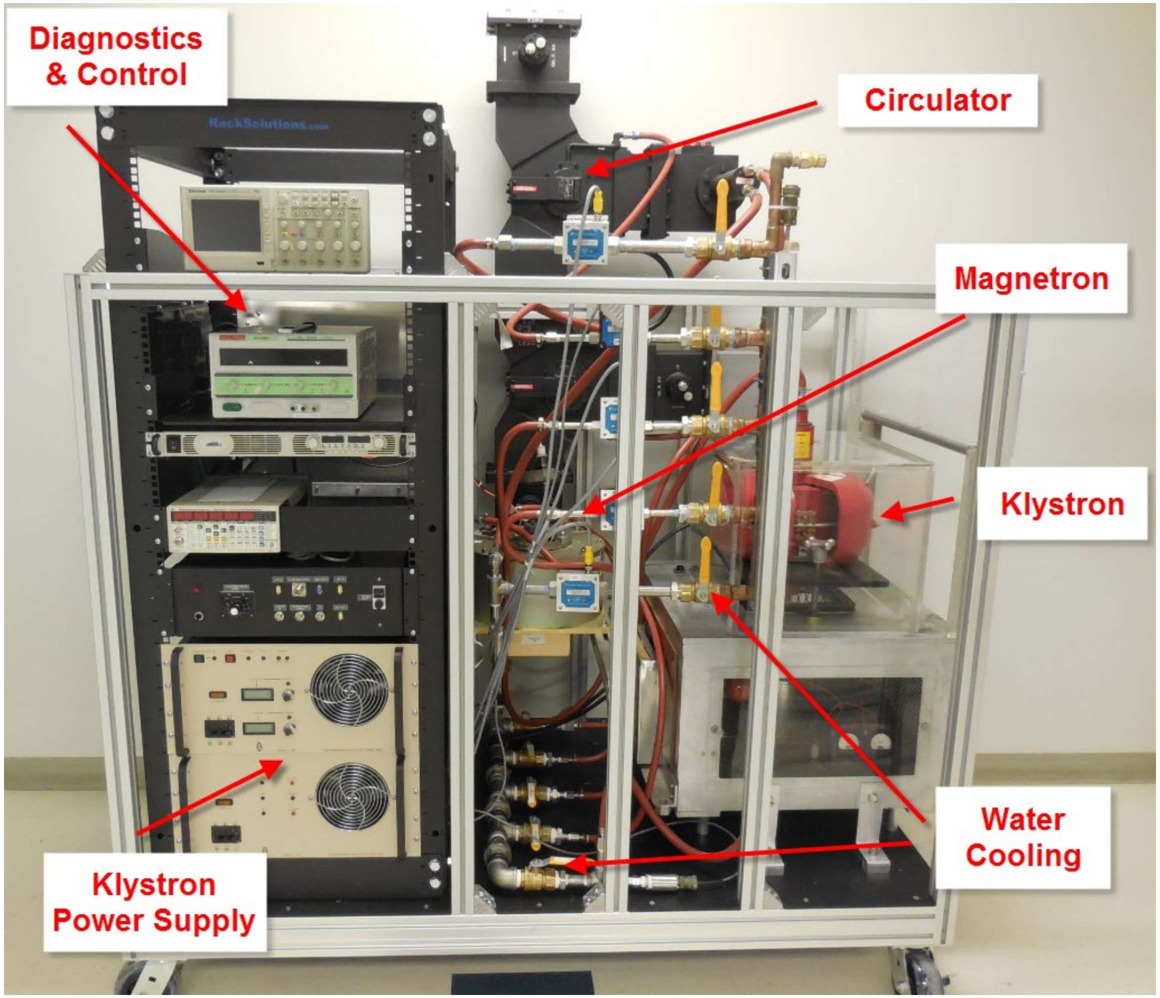
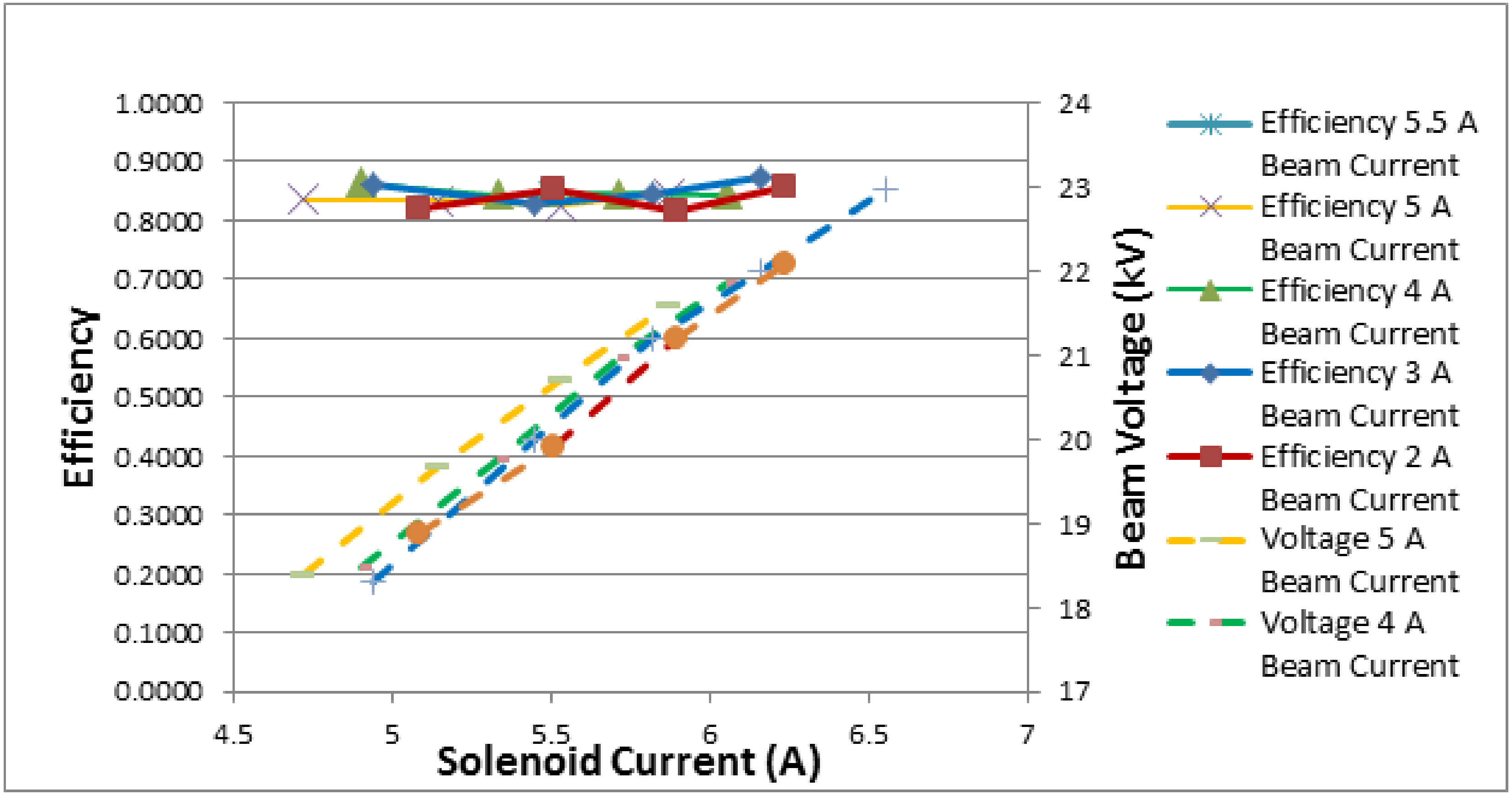
Packaged Magnetron System



Efficiency

Efficiency varied between 81% and 87%, depending on parameters



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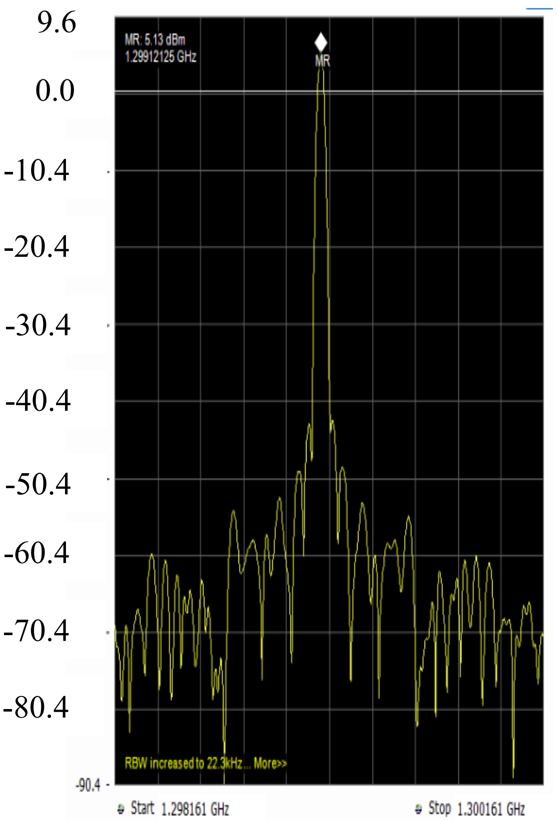
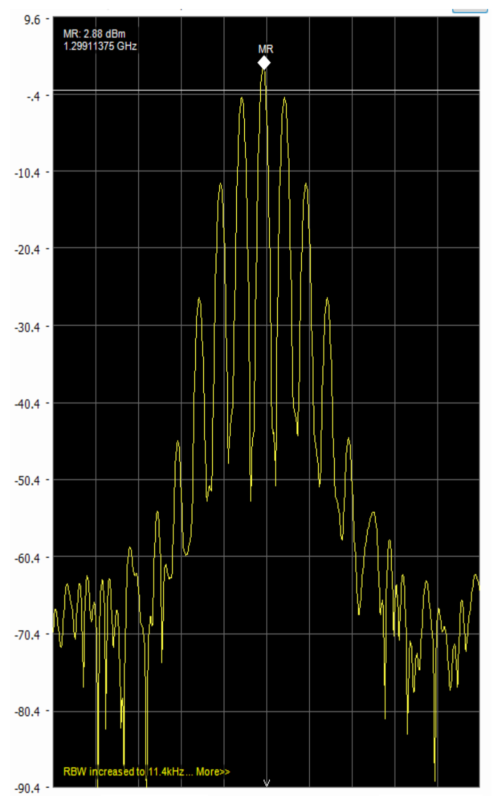
Phase Modulation

50 kHz Phase Modulation



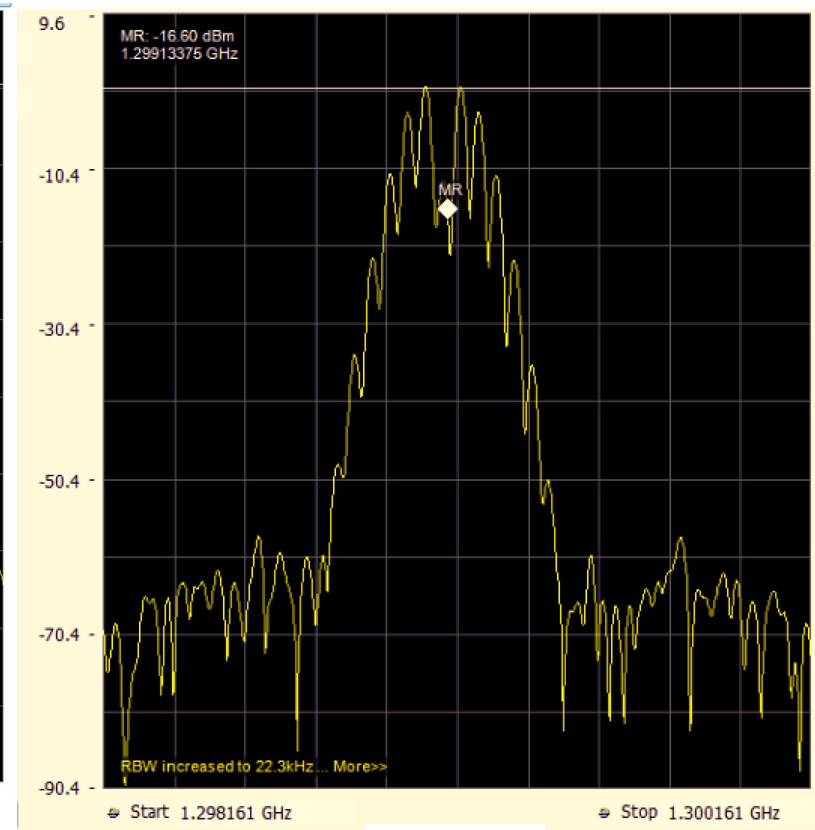
← 2 MHz →

No Modulation



← 1 MHz →

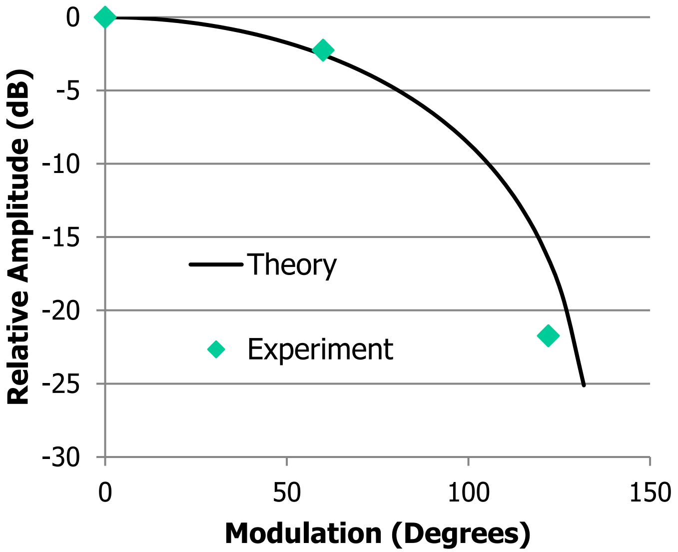
60° Modulation



← 2 MHz →

122° Modulation

Magnetron Amplitude vs Phase Modulation



Theory:

$$Sii(f,M) := \left[J0(M)\,\delta(f,f_c) + \sum_{k=1}^{20} \left[Jn(k,M)\cdot\delta\left[f,\left(f_c + k\cdot F_m\right)\right] + (-1)^k\cdot Jn(k,M)\cdot\delta\left[f,\left(f_c - k\cdot F_m\right)\right]\right]\right]$$

Cost for 100 kW System

(Exclusive of high voltage supply)

Magnetron	$40,000
500 W SS amplifier	$17,000
Circulator w waveguide	$20,000
Controls	$10,000
Packaging	$10,000
Total	**$97,000**

Magnetron System Cost ~ $1/Watt

(Klystron cost ~ $4/Watt)

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Poster: 2.09 Wednesday 5:00 PM

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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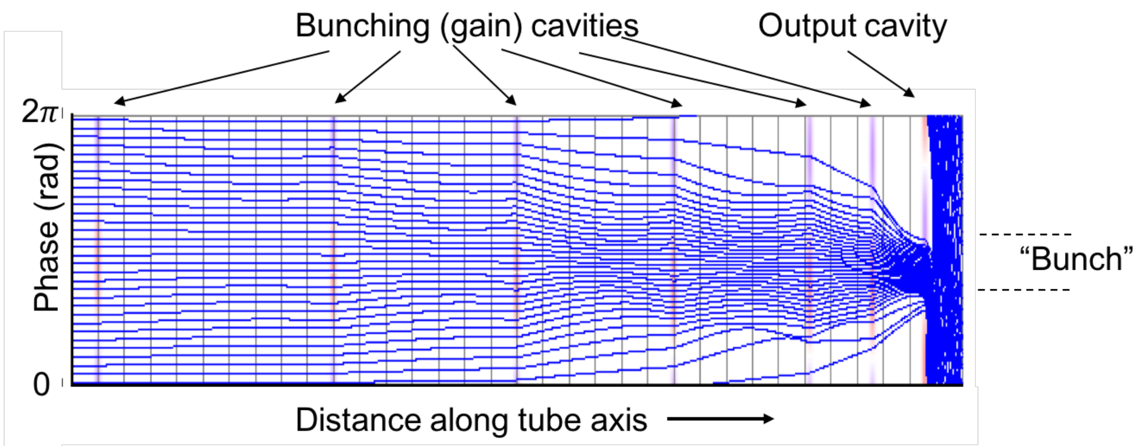
[2] Leidos, Center for EM Manager DEOST, Billerica, MA 01821

Communications & Power Industries, LLC, Palo Alto, CA 95304

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

Core Oscillation Method (COM)*

- Cavity spacing set wider than the normal bunch oscillation length
- Antibunch particles monotonically approach the central bunch



- Circuits are long

* A. Yu.Bajkov, D.M.Petrov "Problems of creation powerful and super- power klystrons with efficiency up to 90%", International University Conference "Electronics and Radio physics of Ultra-high Frequencies", St. Petersburg, May 24–28, 1999, pp. 5–8.

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

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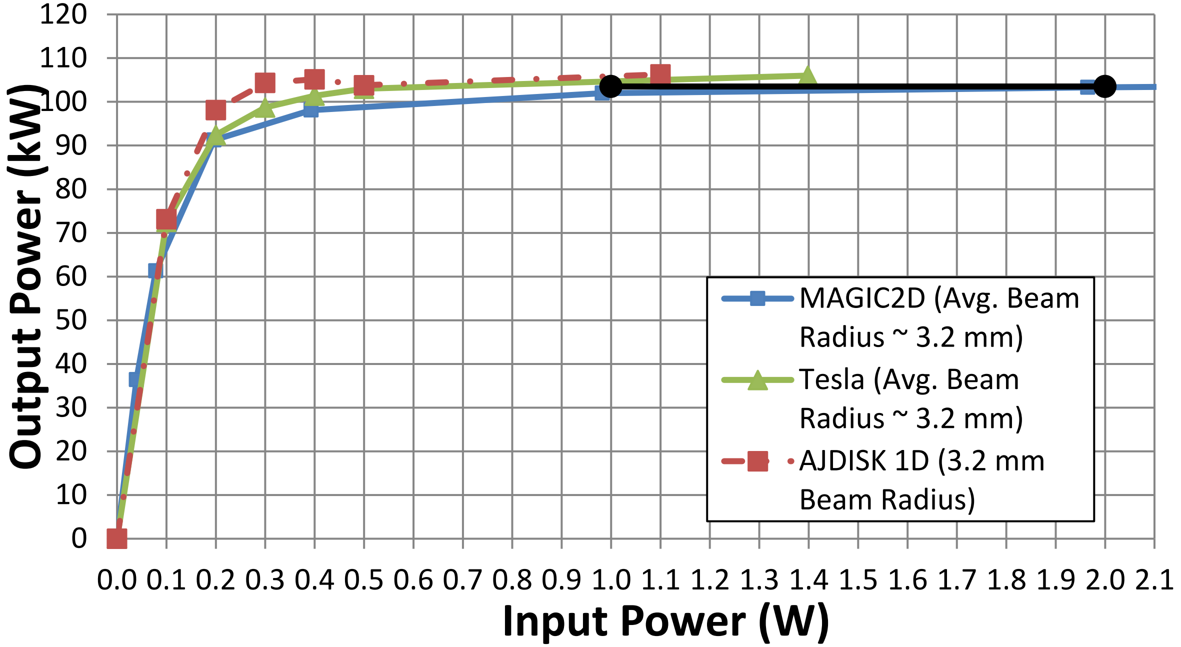
Simulation Summary



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

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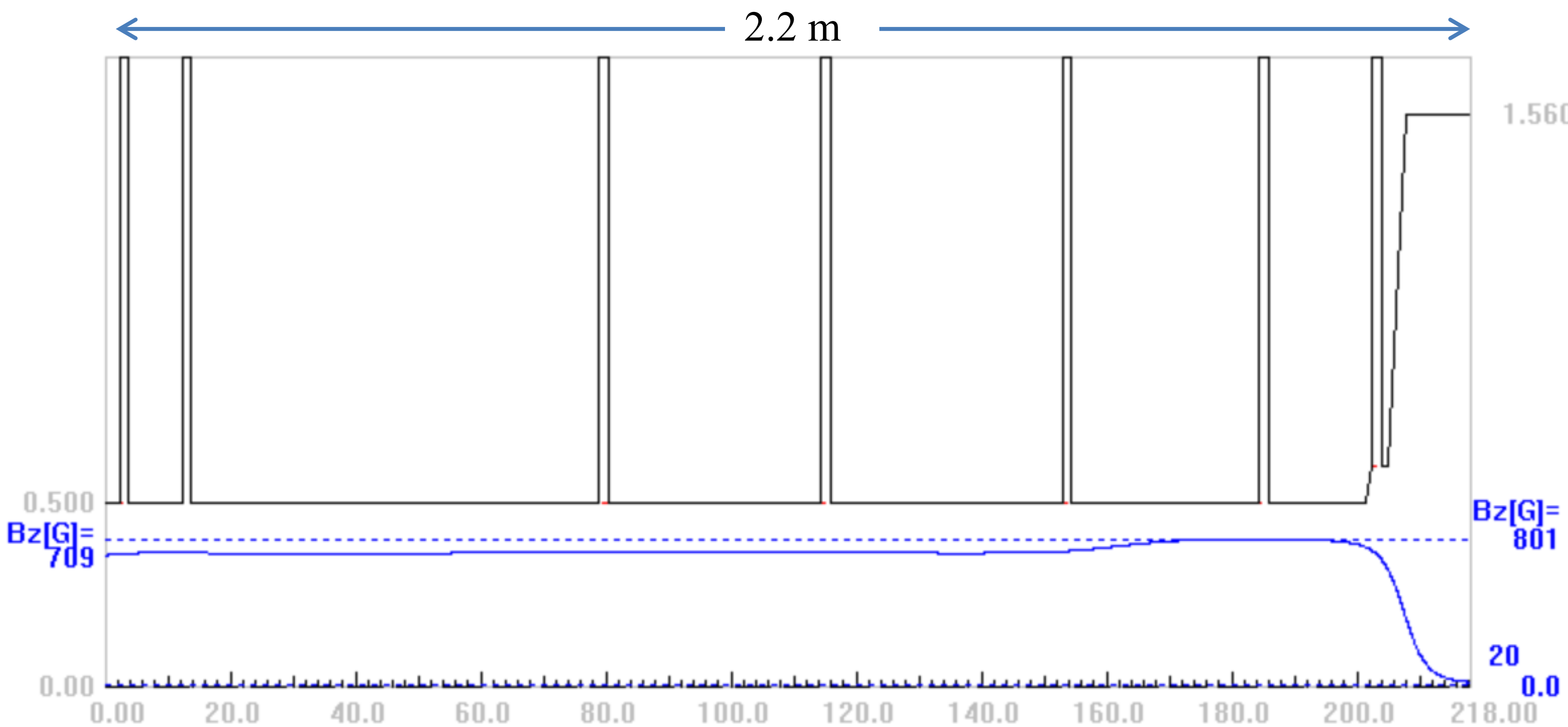
Cavity Locations and B-Field Profile

P = 104.5 kW

η = 79.5%



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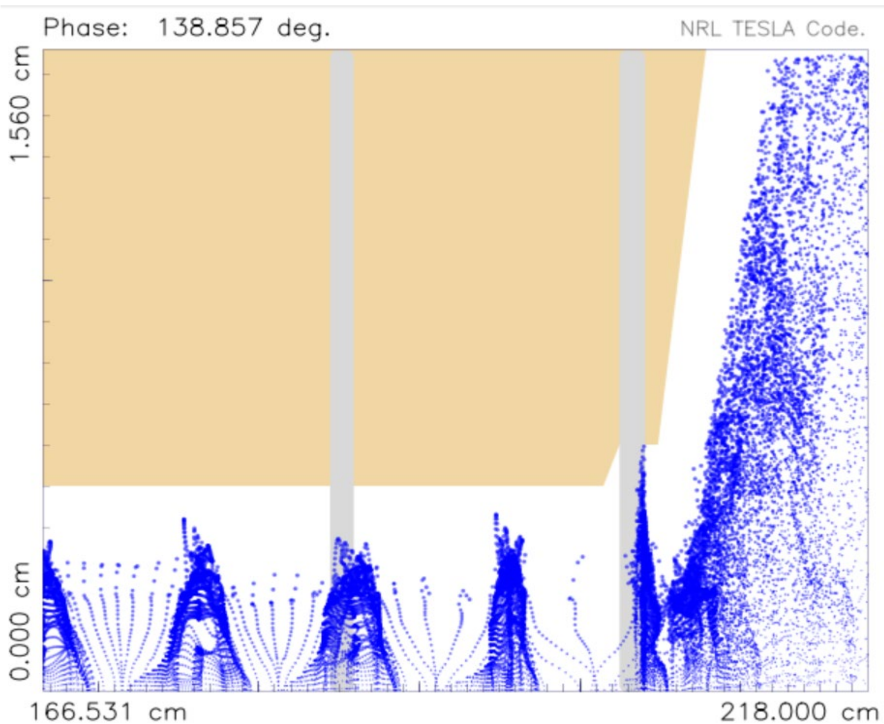
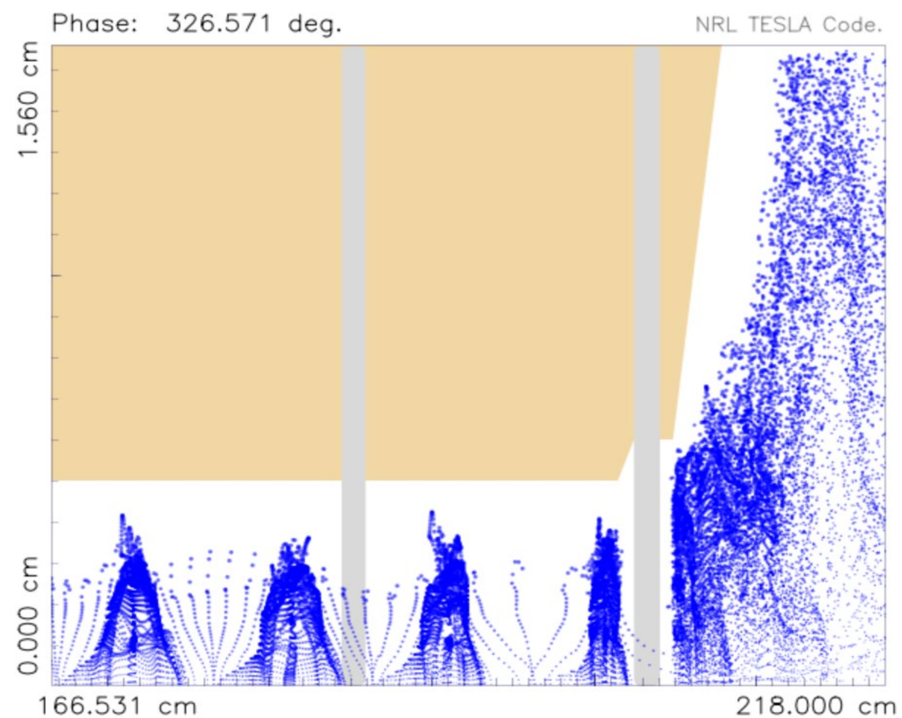
Beam Trajectories Near Output



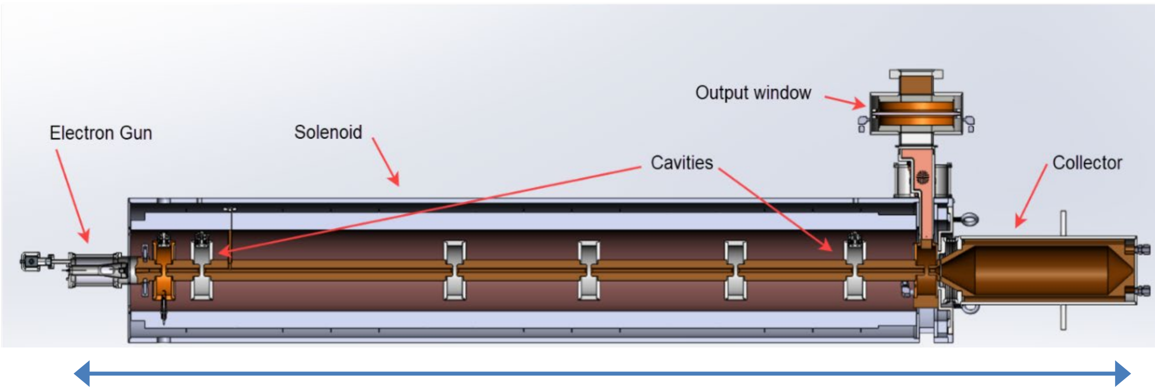
Phase with most interception



Phase with least interception

~ 200 W/cm^2 over ~ 5 mm

Solid Models of Klystron



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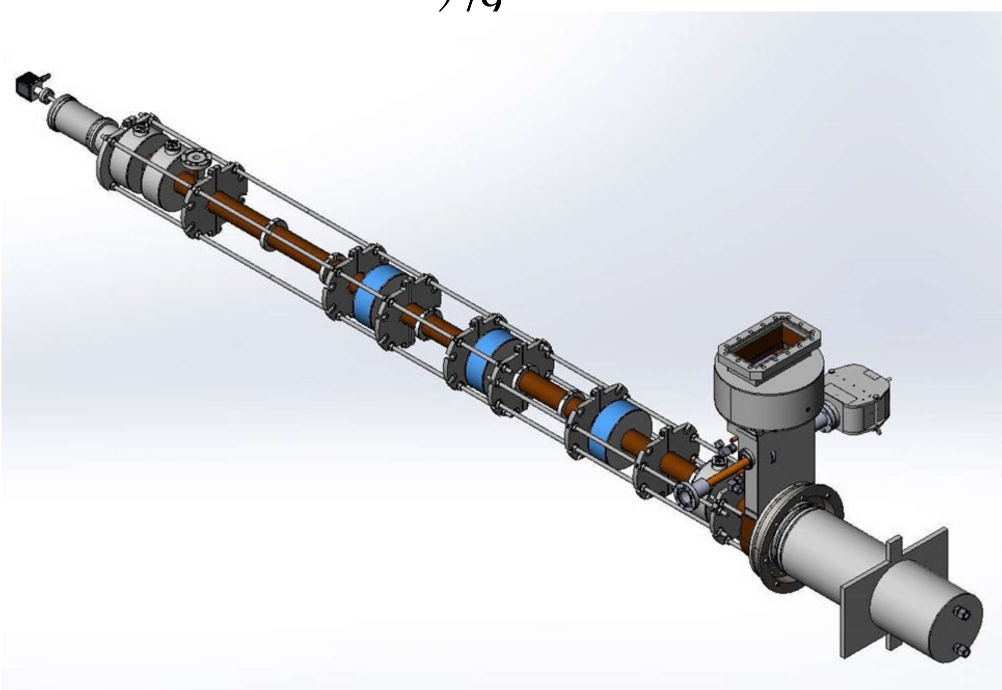

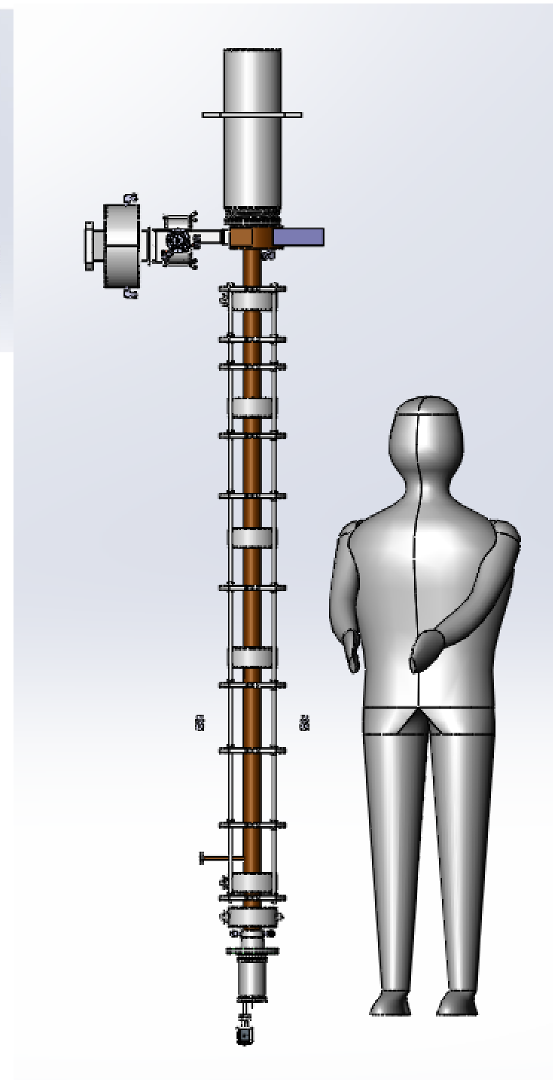

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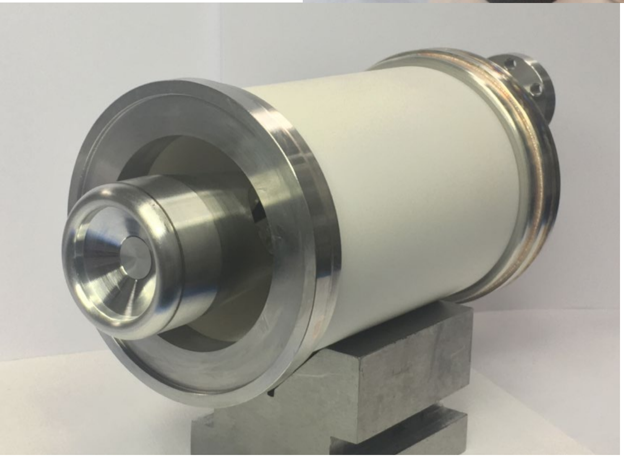
Partial Seal-in



High Efficiency Klystron Summary

- Seven Cavity COM design
- Simulation of ‘as built’ klystron predicts 78.2% efficiency
- Final seal in next two weeks
- Testing to start January 2023

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Multiple Beam Power Grid Tubes for High Frequency and High-Power Operation

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This research funded by DOE SBIR Grant DE-SC0018838

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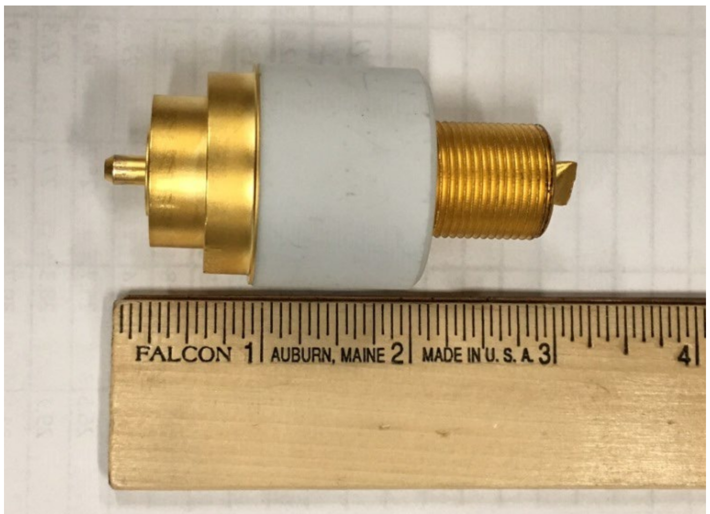
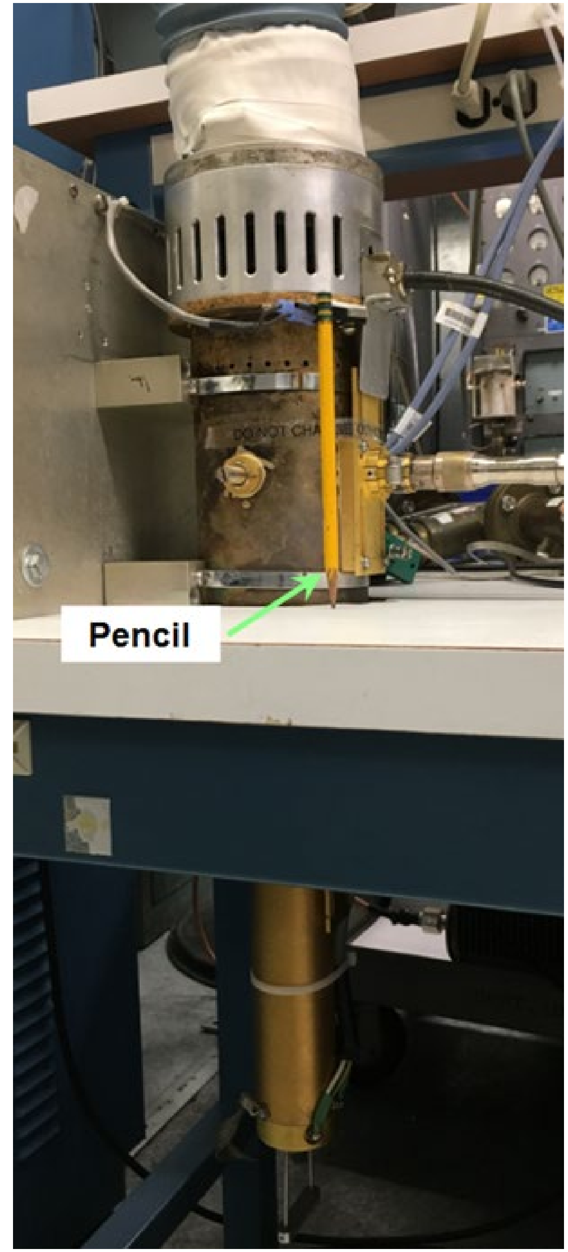
25 kW 425 MHz
Triode-based RF Source



YU-176 Triode

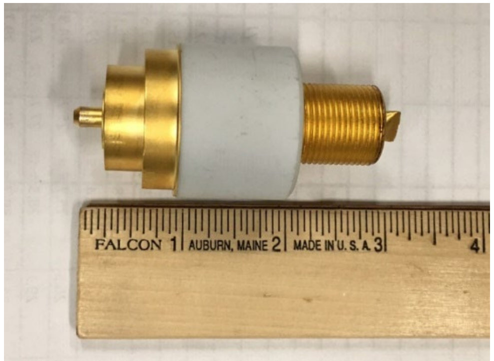
Efficiency 90% (Class C)



YU-176 Grid Cathode Assembly

Features

- Oxide cathode
  - $916 factory cost
- Grid
  - cut from commercial tungsten screen
  - brazed to tungsten supports
- Integral ceramics and vacuum seals
- Beam power – 28 kW
- Total cost - $1,500



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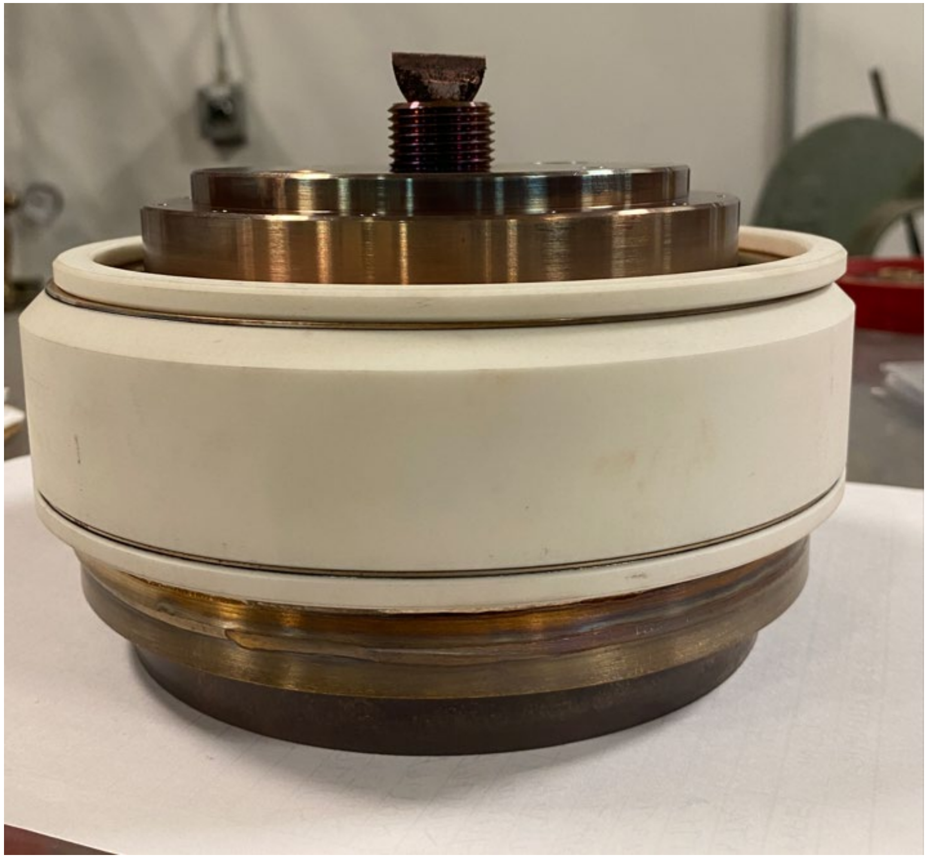
Beam Power for 200 kW RF Source

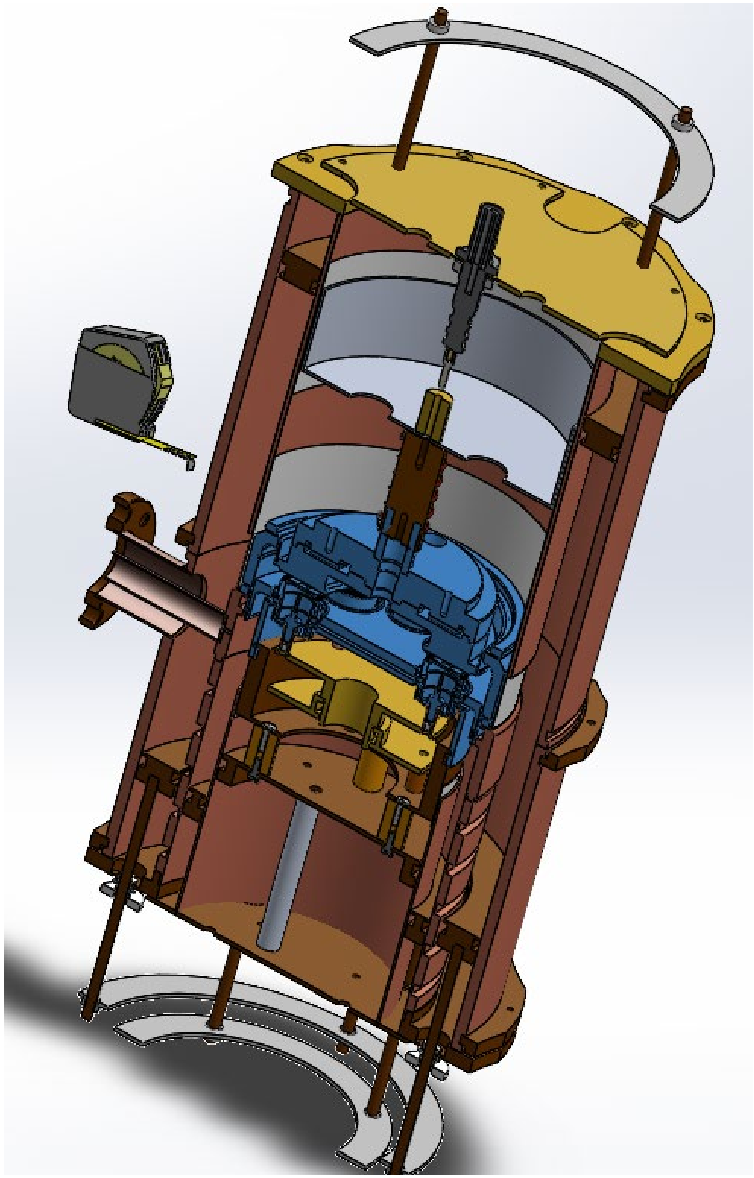
Eight YU-176 grid cathode assemblies

230 kW of beam power



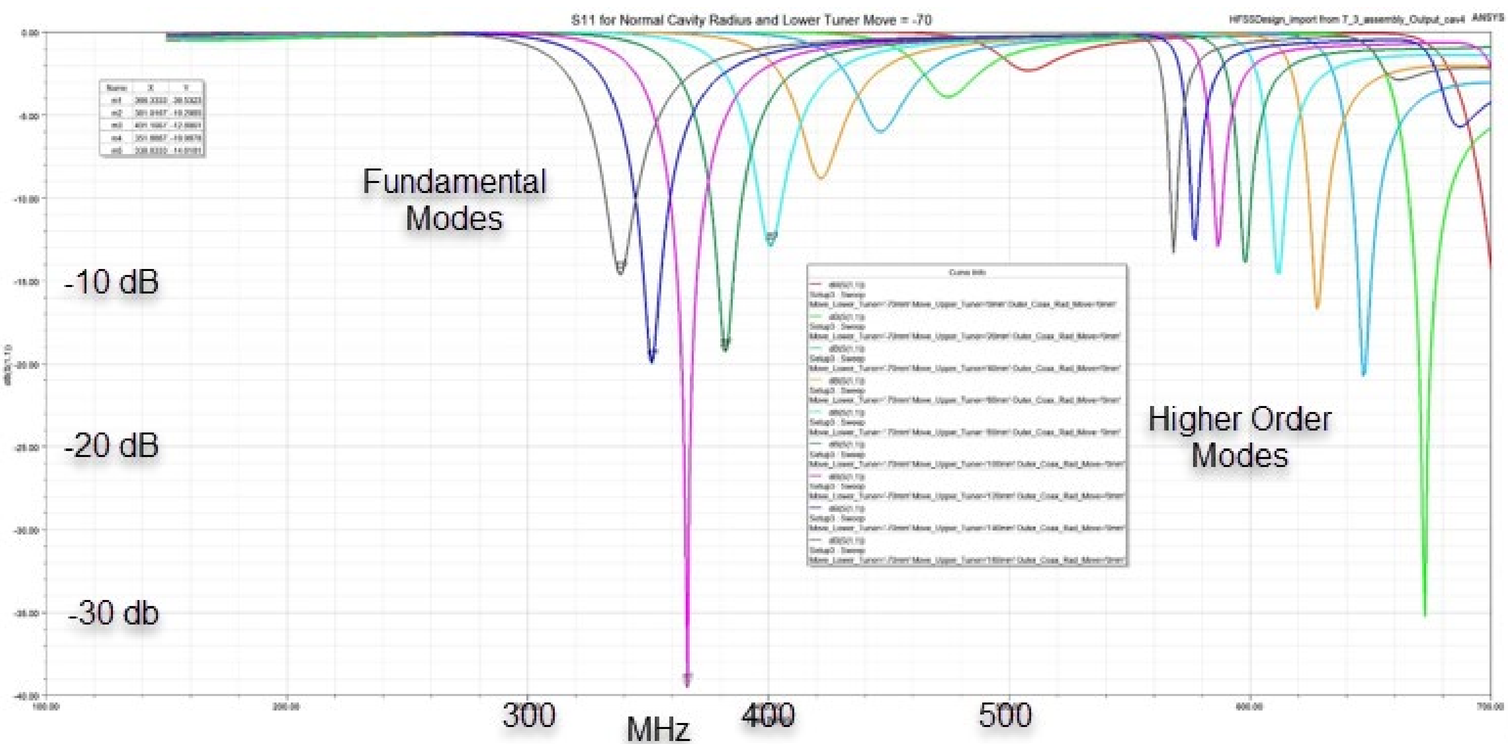
350 MHz Cavities

- MB triode tube installs from top (blue)
- Single input cavity below tube
- Upper and lower output cavities with coax output between
- Upper cavity is frequency tuning element
- Lower cavity is variable output coupling element



Output Cavity Simulation

Tuning range for output cavity
(325 – 500 MHz)

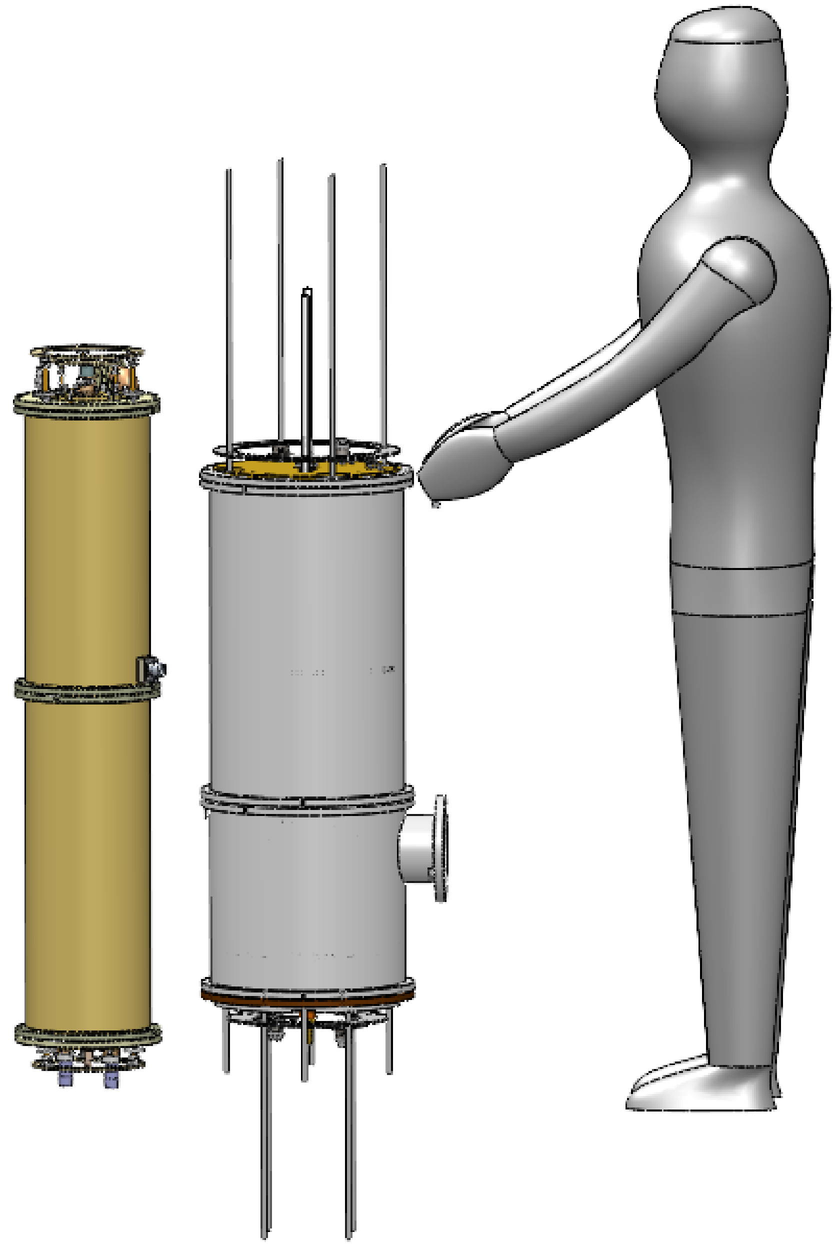


Gain Issue

- Gain ~14 dB for triode based sources
- 200kW RF source requires 6.5 kW driver
- Driver: Single-beam triode driver - Same length as multi-beam source with smaller diameter

200 kW, 350 MHz RF System

Net Gain	28 dB
Net Efficiency	~80?%



200 kW CW RF Source Cost
350 – 700 MHz

Estimated cost: $100K for 200 kW source and driver

Triode-based system	$0.50/Watt	~72%
Klystron:	($4/W)	50-65%
MBIOT:	($2-$4/W)	65-75%
Solid State:	($4/W)	~60%

MB Triode Assembly Status and Scheduled

- MB Triode assembly completed and testing in progress (grid to cathode resistance, peak emission, current division, cutoff voltage)
- Once tube is successfully verified, will assemble the multiple beam cavities for testing in early 2023

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HIGH-EFFICENCY, HIGH AVERAGE POWER INDUCTIVE OUTPUT TUBES

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Paul Krzeminski[2], Takuji Kamura[2]
[1]Calabazas Creek Research, San Mateo, CA
[2]Communications & Power Industries, LLC, Palo Alto, CA

Work supported by the US Department of Energy Grant No. DE-SC0019800

Goals and Approach

Goals:

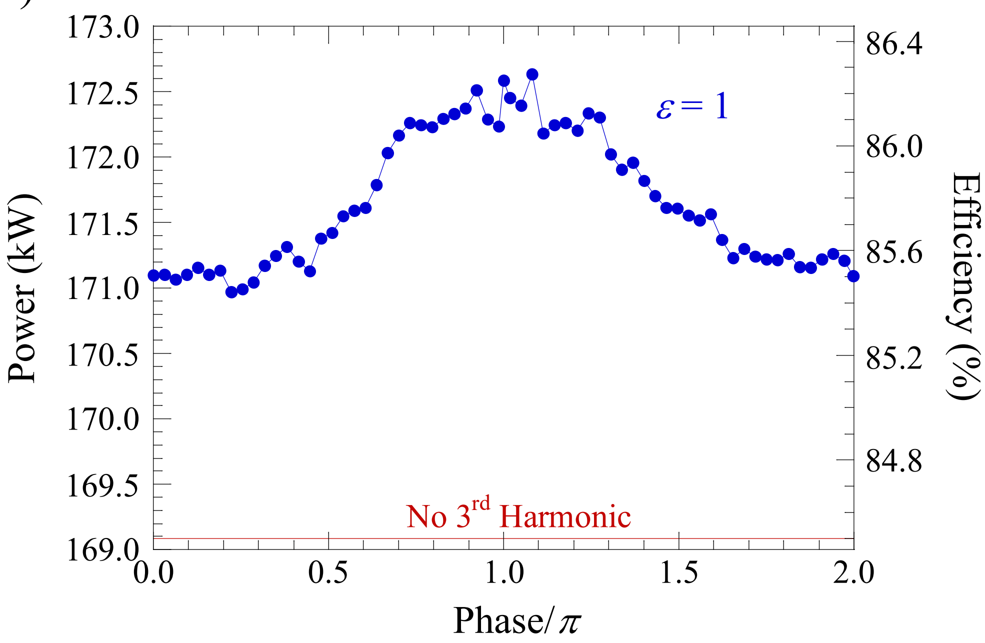
• Output power	200 kW CW
• Frequency	700 MHz
• Number of beams	eight
• Efficiency	80+%
• Reduce size and cost	

Approach

- Include 3rd harmonic drive power to increase efficiency
- Implement compact input coupler to reduce size and cost
- Use molybdenum grids to reduce cost and risk

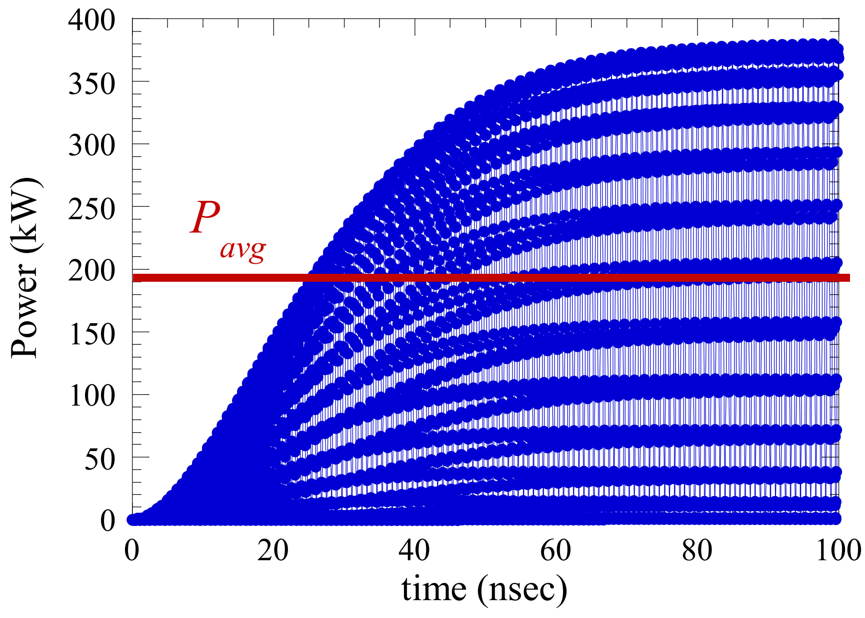
3rd HARMONIC TEST CASE

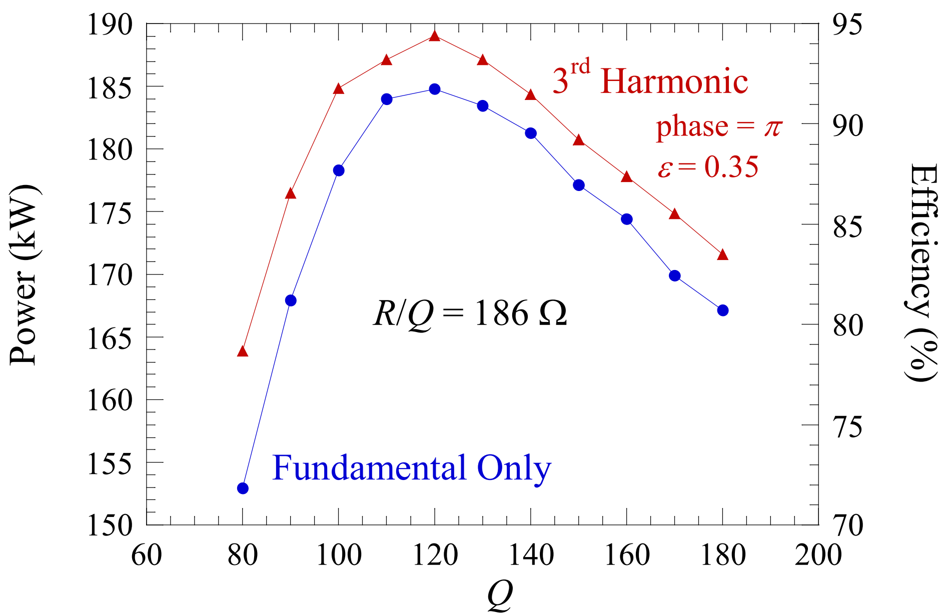
- Simulated annular beam at 700 MHz with:
  - 37 kV/6.67 A
  - Annular Beam with inner/outer radii = 5.128 cm/8.079 cm
  - $I_{avg}/I_p = 0.15 \rightarrow \tau_{width}/\tau_{pulse} = 0.3$
  - $R/Q = 100\ \Omega$
  - $Q = 84.6$ (loaded)
  - Cavity Radius = 9.009 cm
  - Cavity Length = 9.144 cm
  - Gap Length = 3.1 cm (centered in the Cavity)
  - Solenoid Field = 126 G (Brillouin Field)
- Simulation results indicate:
  - Optimal performance when the phase of the 3rd harmonic relative to the fundamental is π
  - Efficiency is enhanced from 84.4% to 86.3%



NEMISIS MBIOT SIMULATON

- Eight beam configuration circulating the cavity at the midpoint
  - f =700 MHz
  - 30 kV/6.67 A
  - R/Q = 186 Ω, Q = 120
  - L_{cavity} = 9.144 cm, L_{gap} = 3.9 cm (centered)





- Perveance ≈ 1.3 µP
- Peak efficiency with the 3rd harmonic
  - Peaks for phase shift of π radians
  - **Peak efficiency ≈ 94%**
  - Expect to reach wallplug efficiency above 80%

METAL GRID DESIGN

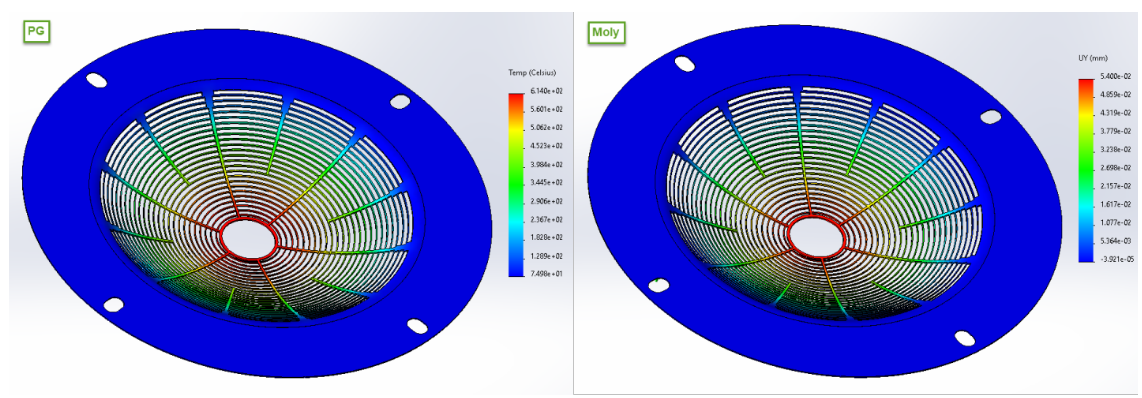
Current IOTs use pyrolytic graphite (PG) grids

- Difficult to fabricate
- Expensive
- Relatively low yield

MBIOT beam power distributed over multiple beams

- Reduced power loading
- Thermomechanical analysis predicts good performance
- Significantly cheaper and higher yield

Beam Optics Analyzer thermomechanical analysis with beam interception and cathode radiation



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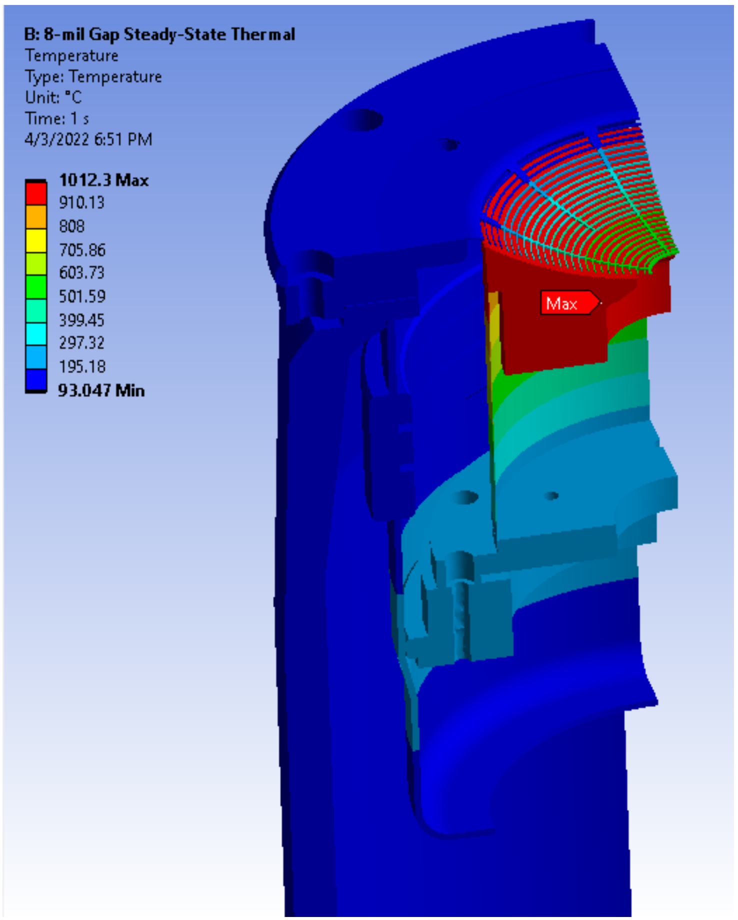
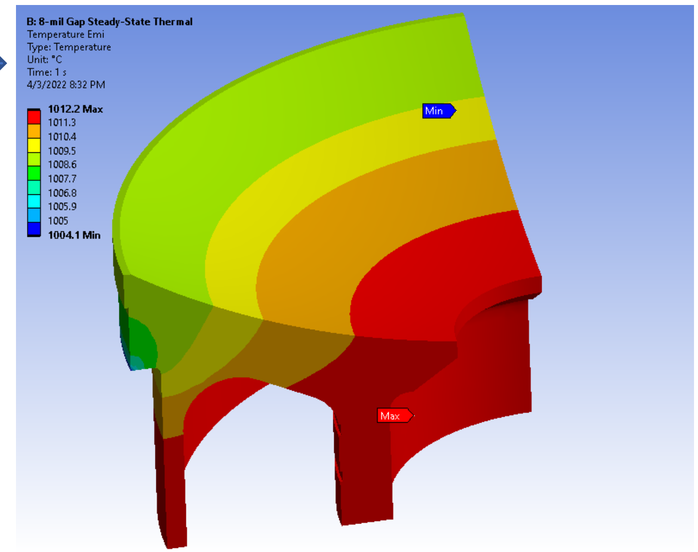
TEMPERATURES

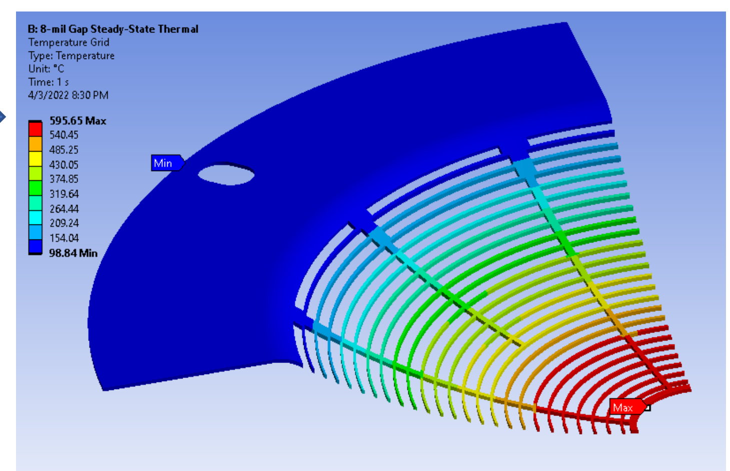
Moly grids considerably cooler than PG grids



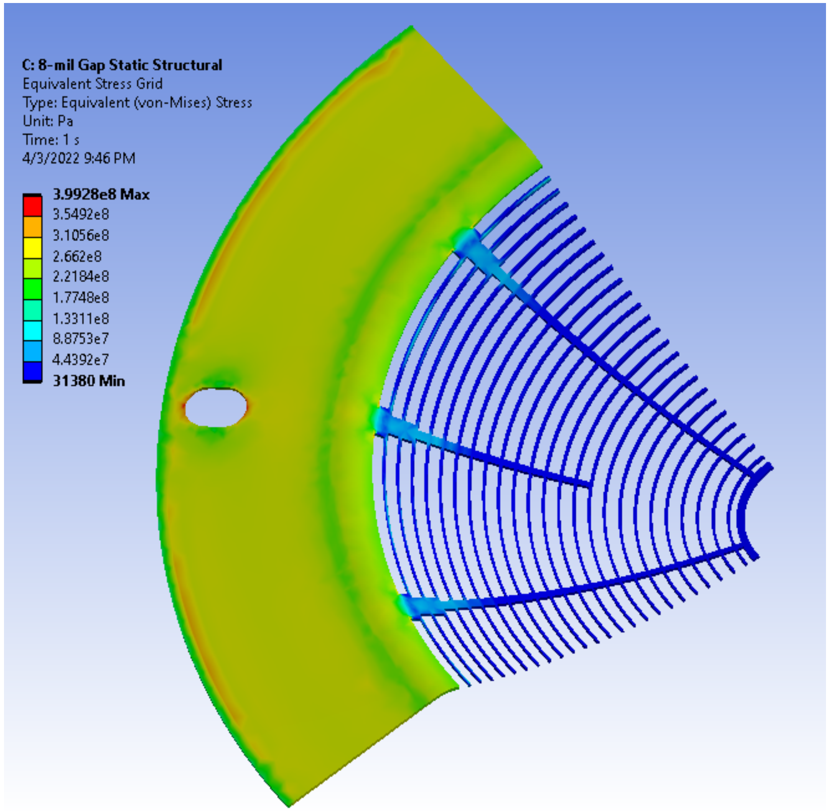
Emitter

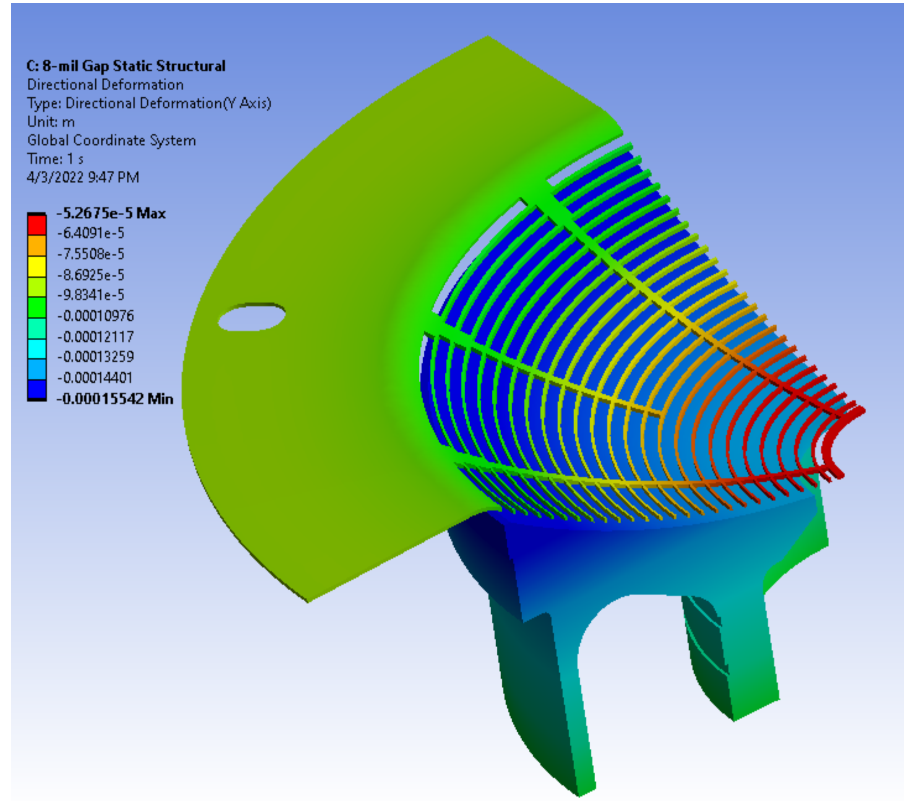


Grid



THERMAL STRESS & AXIAL DISPLACEMENT





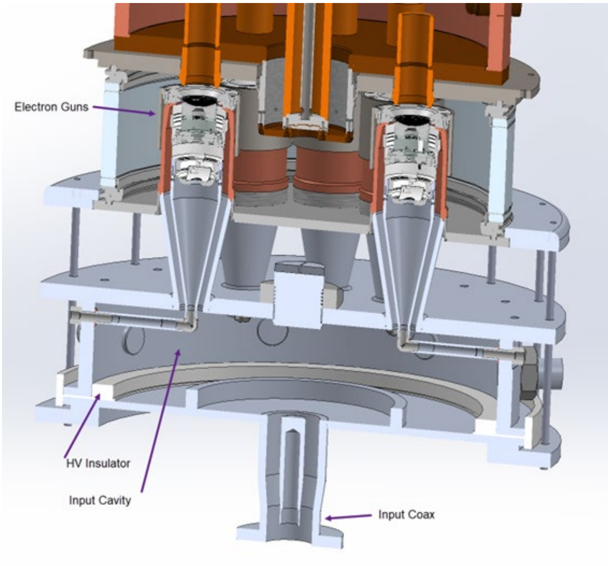
Highest stress is on the grid rim, but still below Moly tensile strength

At temperature, grid OD moves closer to the emitter 1.9 mils, ID closer 3.3 mils

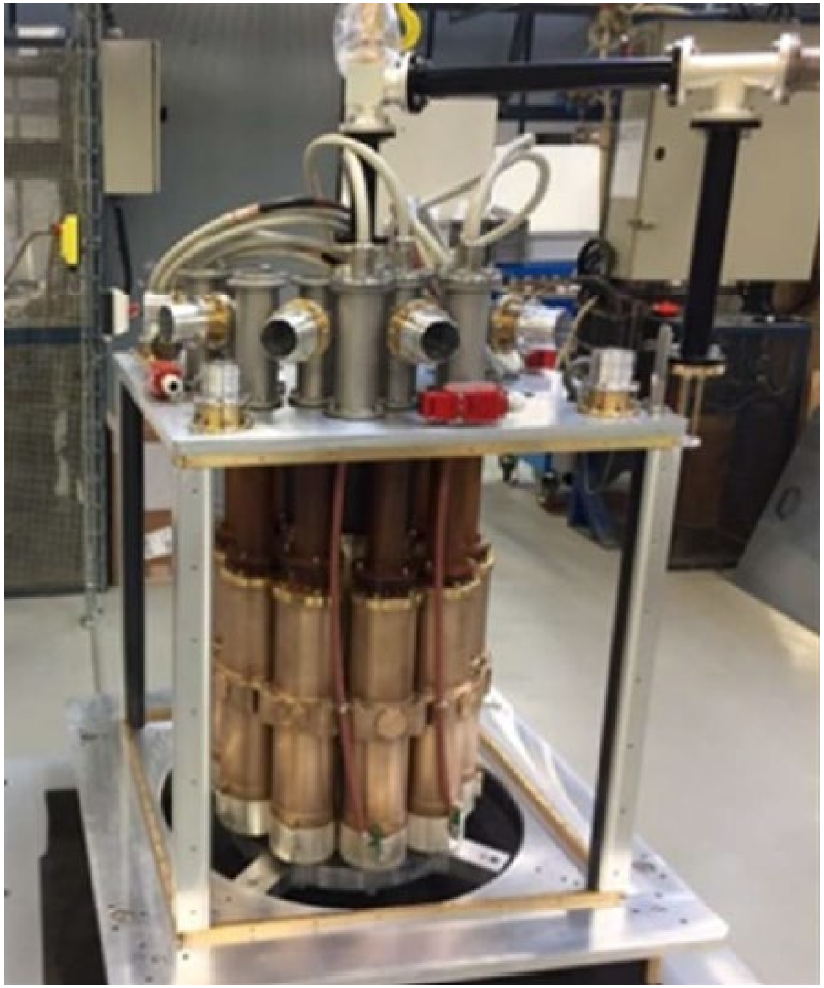
Compensation required for increased thermal expansion

Input Coupler

- Input Coupler for CPI/Thales and L3 MBIOTS large and complex
- CCR input coupler design much simpler



Input coupler for CCR MBIOT



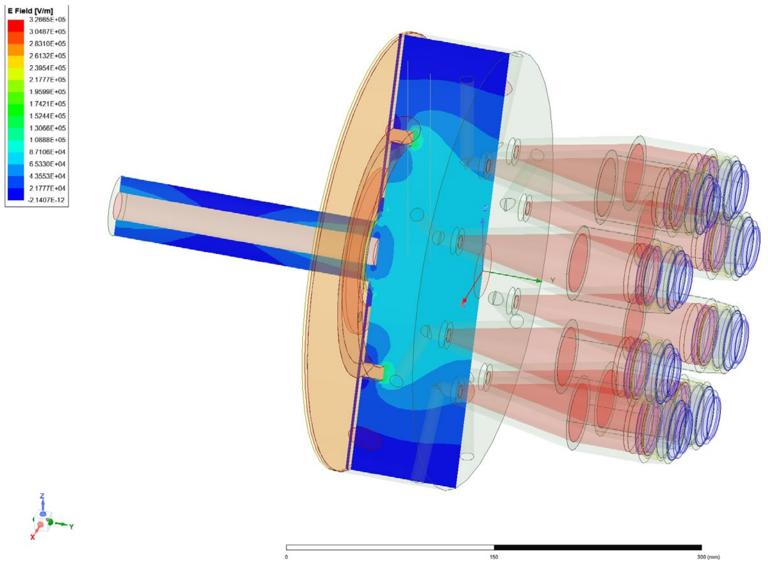
Input coupler for CPI/Thales MBIOT

Input Coupler

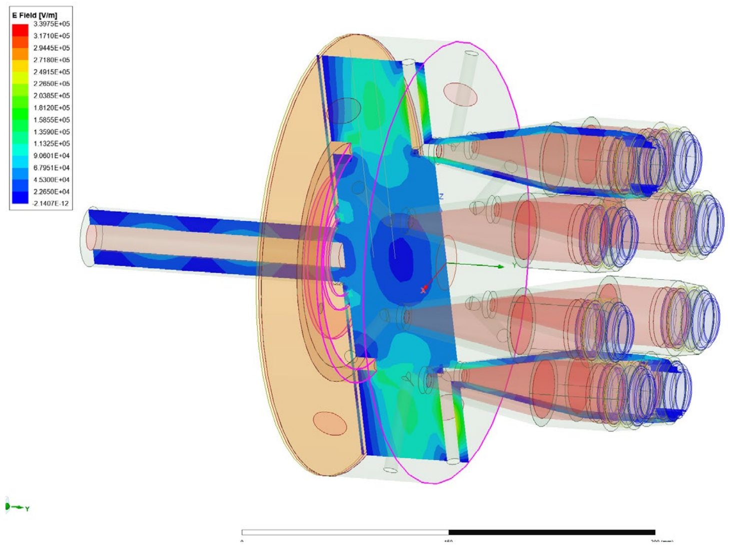
Challenge – develop coupler transmitting fundamental and 3rd harmonic

Incorporated structures/tuners specific to each frequency

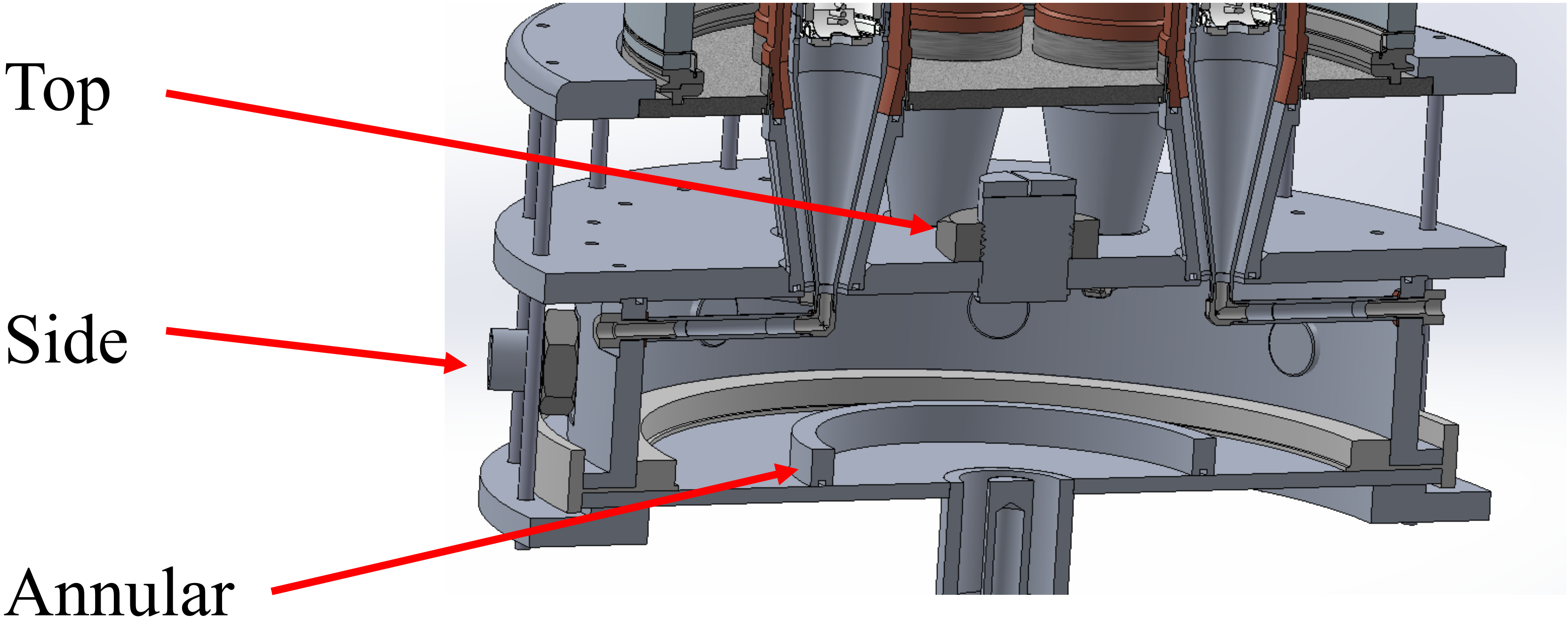
700 MHz



2100 MHz



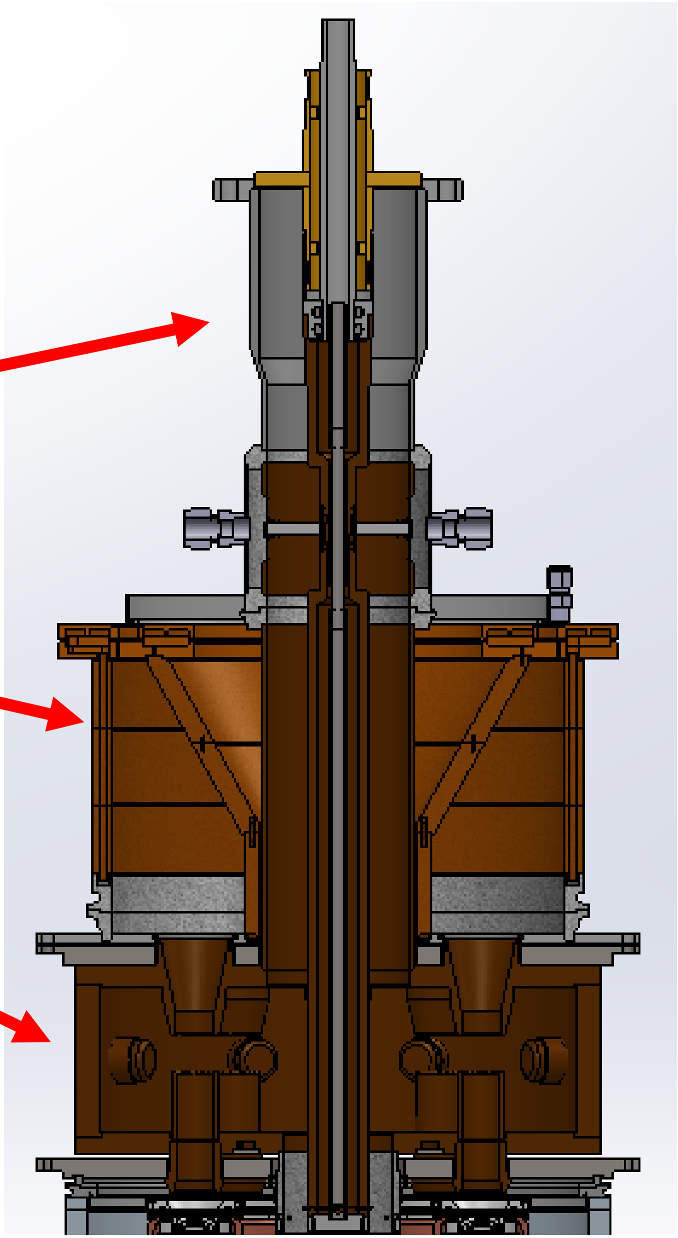
Input Cavity Tuning



Note – Input cavity is at atmospheric pressure

MBIOT Design

- Coaxial output window
- Single collector for all beams
- Simple output cavity



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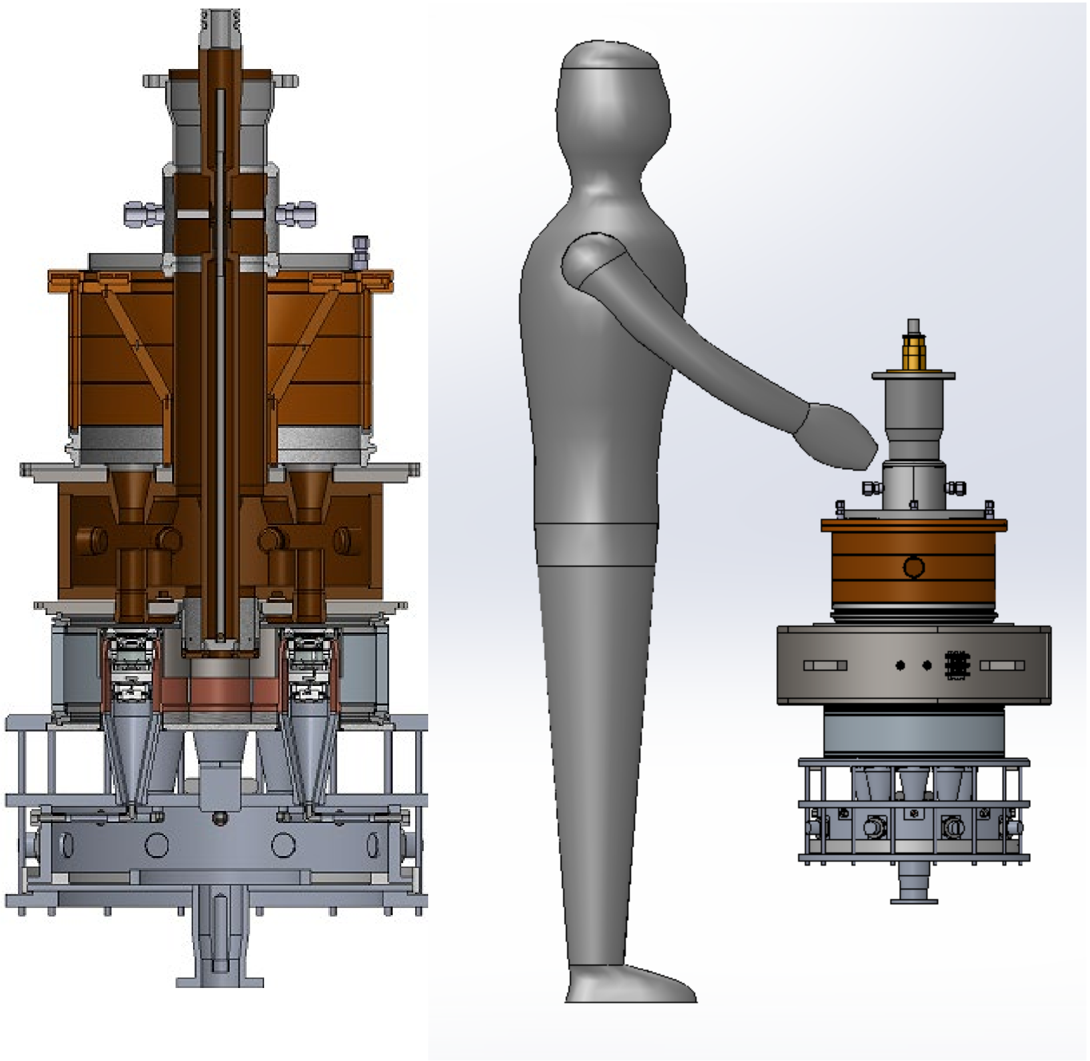
200 kW, 700 MHz MBIOT

- Computational design complete
- Drawings and parts procurement in progress
- Tests scheduled for spring 2023



MBIOT Status and Summary

Investigating three improvements

- Adding 3rd harmonic drive to improve efficiency
  - is efficiency gain achieved
  - does improvement justify the cost
- Replacing PG grids with molybdenum grids
- Simplifying the input coupler

Status

- Most drawings completed
- Long lead time parts are on order
- Expect to start assembly in January 2023
- Testing scheduled for spring 2023

Summary

RF Sources and Key Features

- Magnetron System 100 kW 1.3 GHz Amp/Phase Control 80+% efficiency $1/Watt Completed

- High Efficiency Klystron 100 kW CW 1.3 GHz 78% Freq/Pwr Scalable Test in January 2023

- Triode-base RF sources 200 kW CW 350–700 MHz $0.5/Watt compact MB Triode in test

- Multiple Beam IOT 700 MHz 200 CW kW 80% Drawings and fabrication in progress Test in spring 2023

New RF Source Development

RF Sources and Key Features

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- High Efficiency Klystron 100 kW CW 1.3 GHz 78% Freq/Pwr Scalable Test in January 2023
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