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

.

Calabazas Creek Research, Inc.

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]

[1] Calabazas Creek Research Inc., San Mateo, CA 94404
[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

Phase Locked Magnetrons

- Application is for driving superconducting accelerators
- Magnetrons are very inexpensive
  - ~ $0.50/W for magnetrons to 100 kW CW at 915 MHz
  - ~$2.5/W for accelerator relevant magnetron system versus ~$5/W for klystron
- Phase locking to control phase and combine multiple magnetrons demonstrated
- Fermilab demonstrated method for amplitude control as well[1]

[1] B. Chase, R. Pasquinelli, E. Cullerton and P. Varghese, "Precision Vector Control of a Superconducting RF Cavity driven by an Injection Locked Magnetron," Journal of Instrumentation, Volume 10 March 2015.

Fermilab Approach

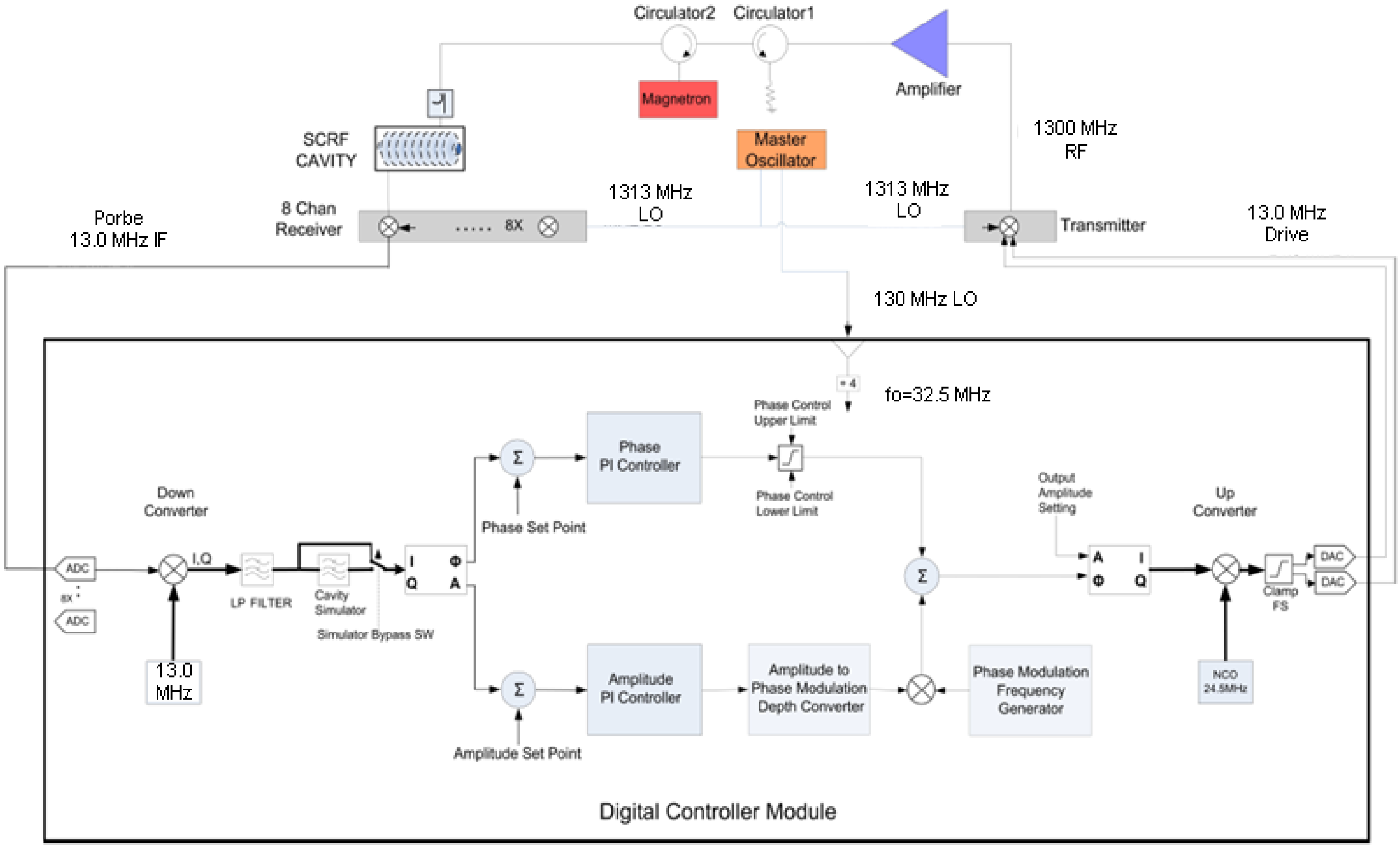
- Externally phase lock the magnetron,
- Achieve amplitude control by phase modulating the locking signal to transfer power to side bands
  - Side bands are rejected by high Q accelerator cavity
  - Power into the cavity = Magnetron power less the side band power

Program Goals

Demonstrate a phase locked, 100 kW, 1300 MHz magnetron with fast amplitude and phase control

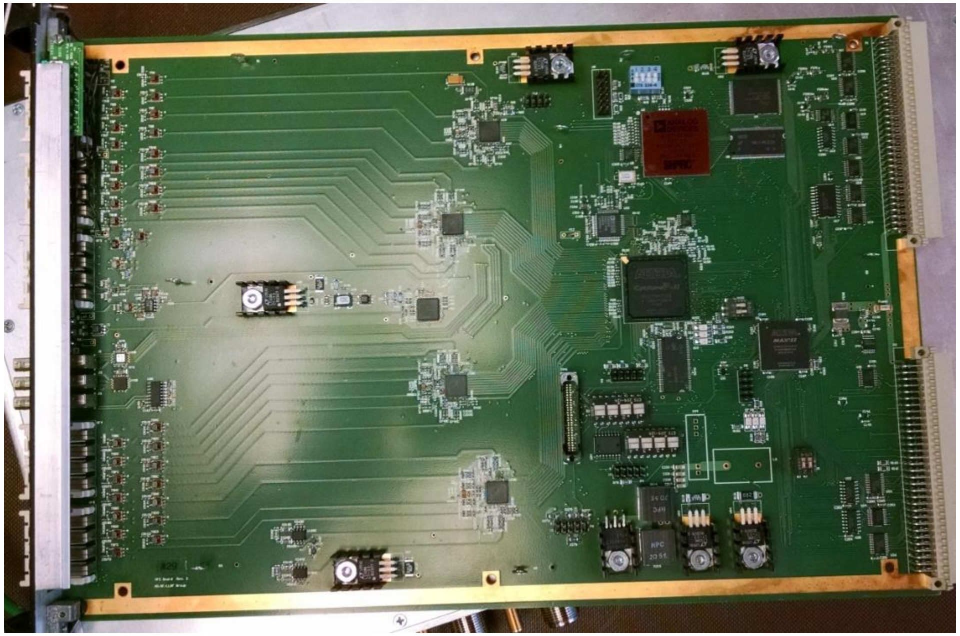
1. Develop a 100 kW 1300 MHz magnetron with 10% duty
2. Assemble hardware to test Fermilab approach
3. Test system at high power

Fermilab System Layout



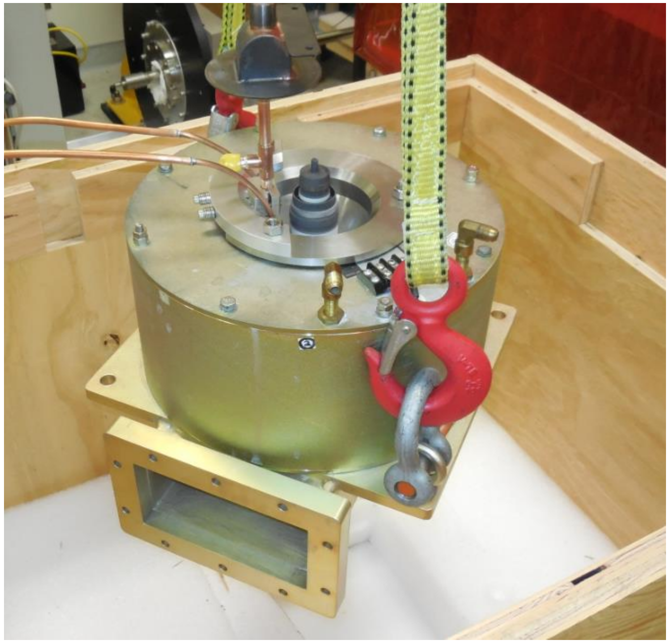
Electronics Development

Electronics, including the Field Programmable Gate Array (FPGA), will be next generation of board developed at Fermilab

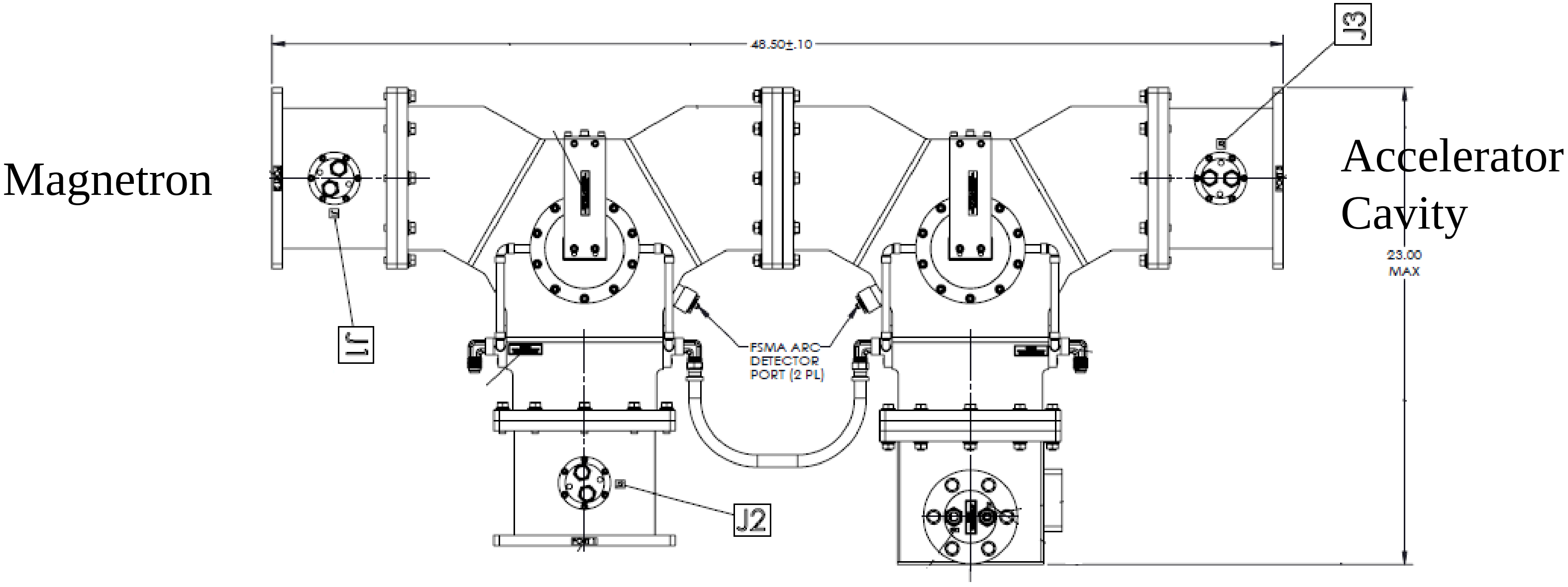


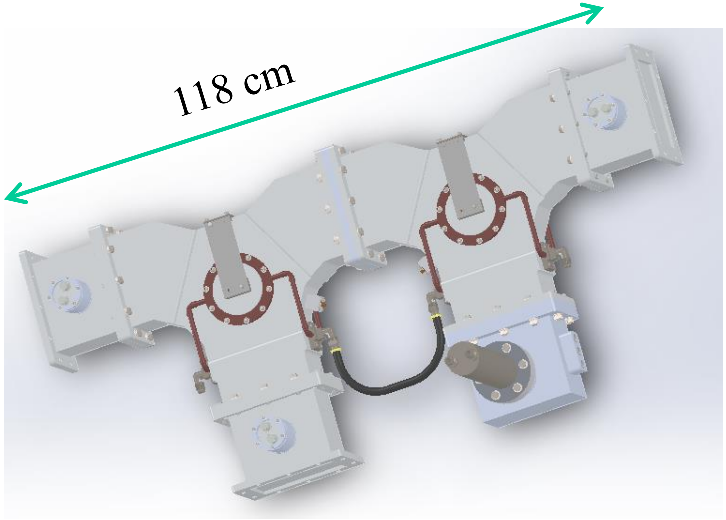
CPI Magnetron

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



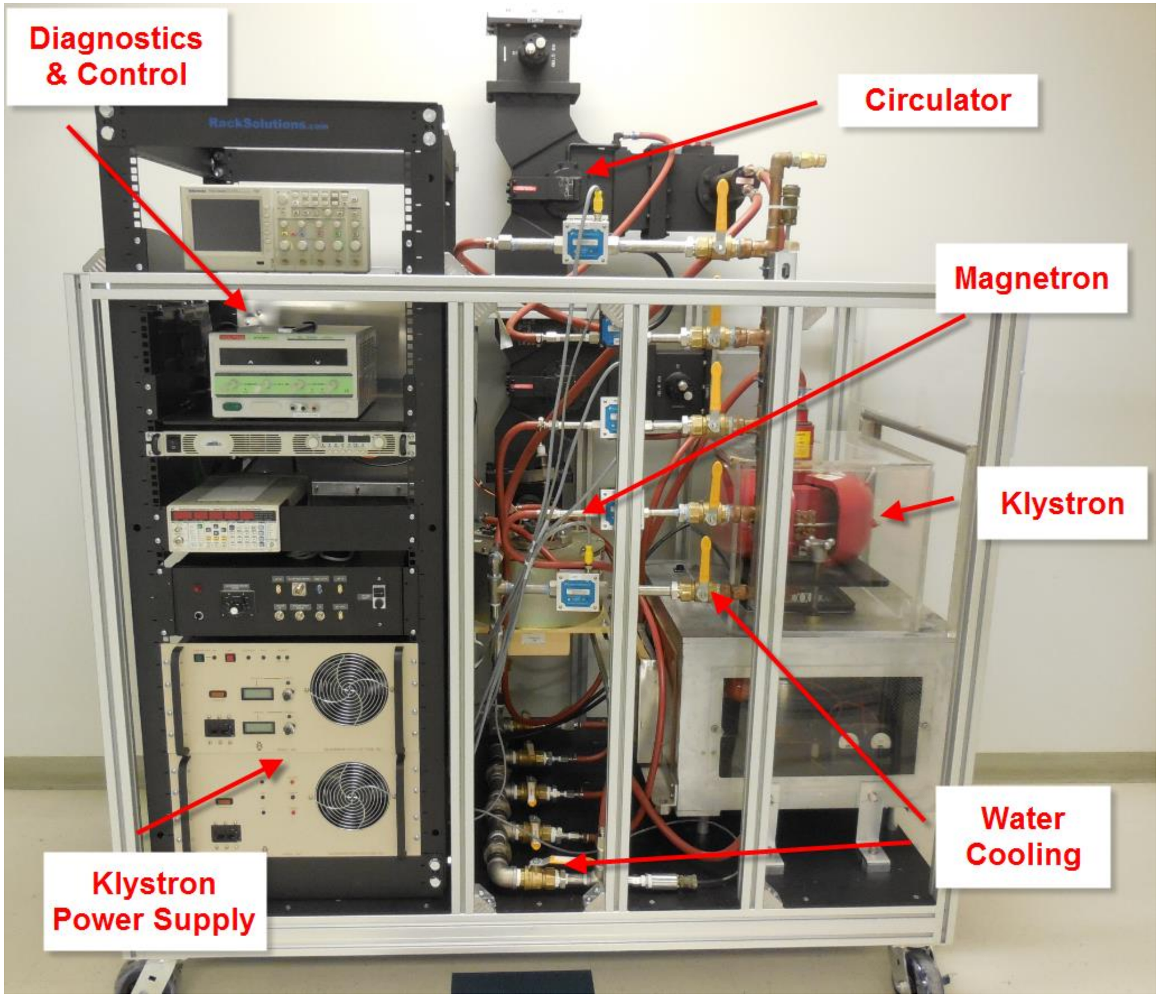
Circulator





Manufacturer:
Ferrite Inc.

Packaged Magnetron System

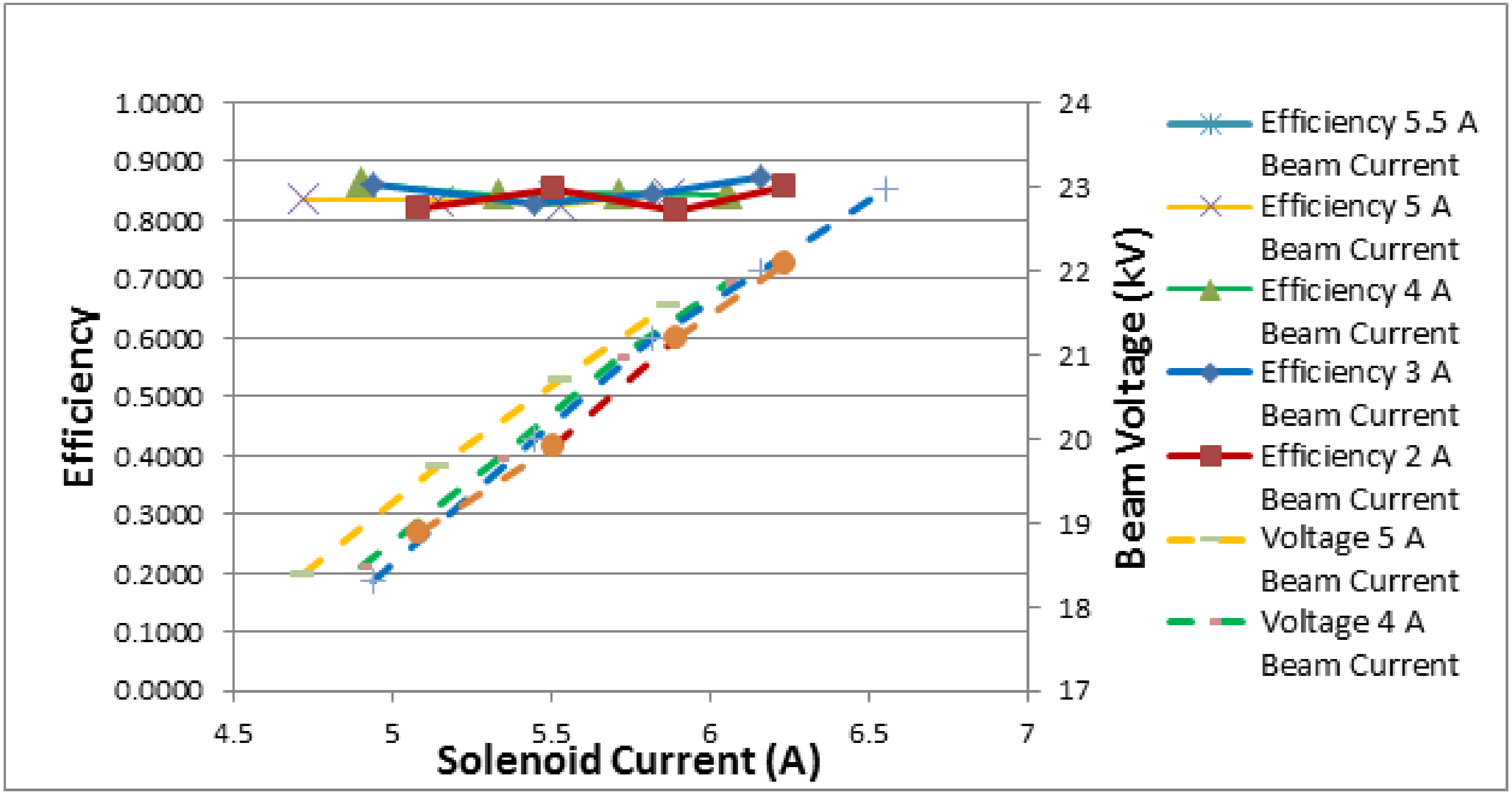


Test Results

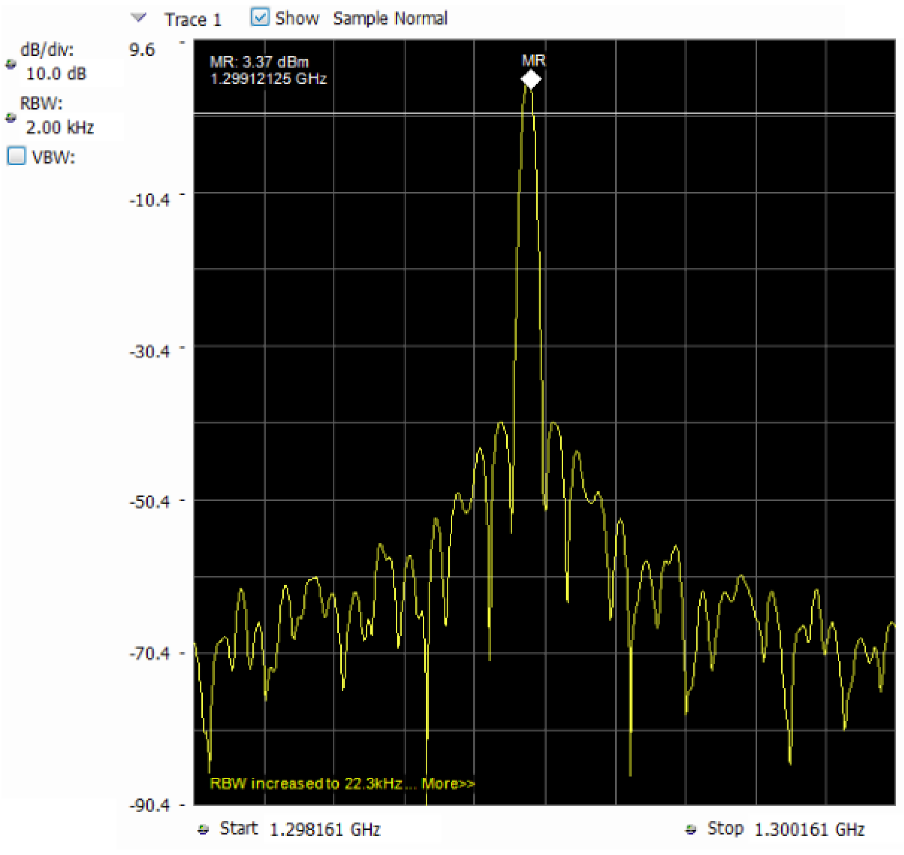
- Magnetron operated to full 1.5 ms pulse width and 100 kW peak power
- Average power of 300 W limited by test time
  - Scaling from 915 MHz by $f^{-2.5}$ gives a power capability of 42 kW at 1300 MHz
- Locking demonstrated at
  - 2.6 MHz with -15 dB drive
  - 0.9 MHz with -25 dB drive
- Phase modulation demonstrated

Efficiency

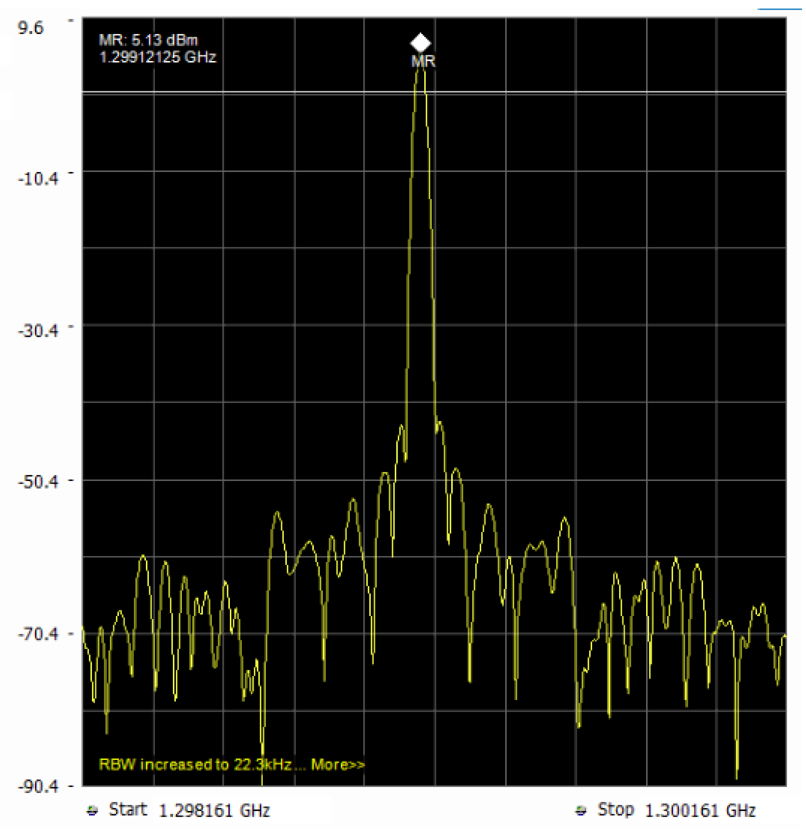
Efficiency varied between 81% and 87%, depending on parameters



Magnetron Spectra

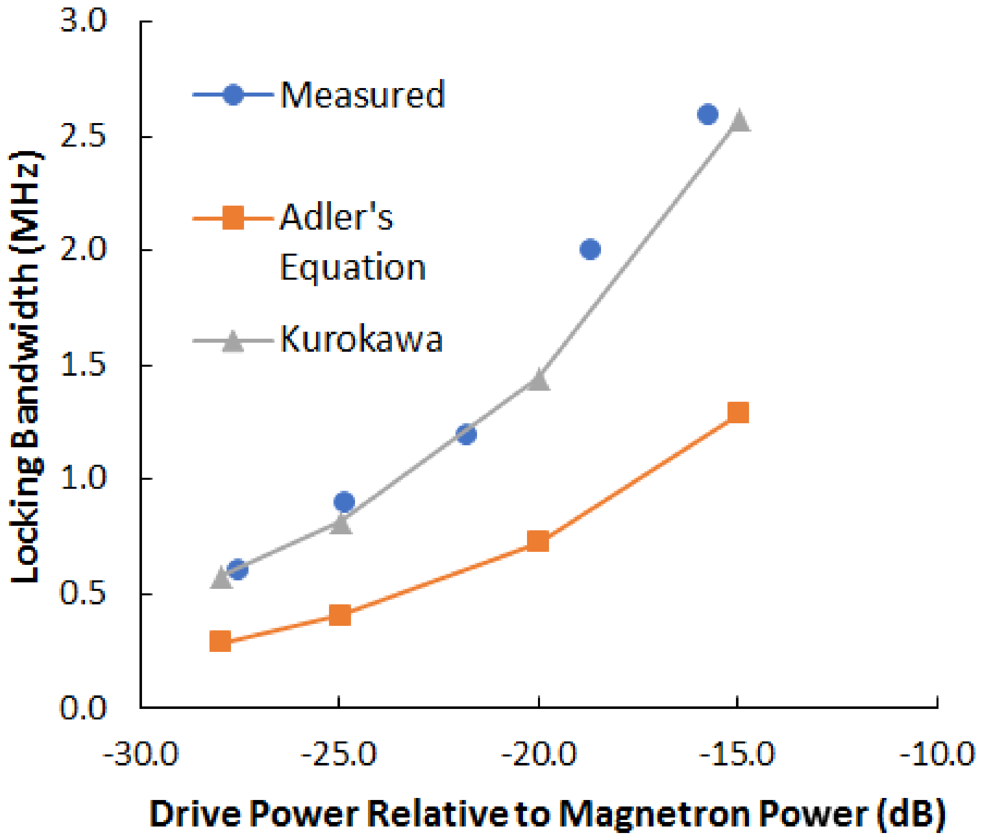


Free Running Magnetron



Driven magnetron with drive power -15 dB at the natural frequency of the magnetron.

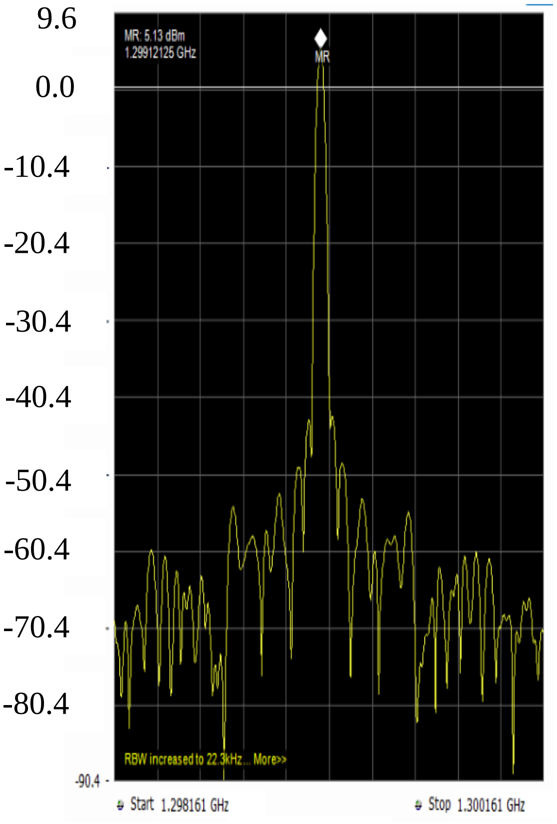
Locking Bandwidth



Kurokawa’s formulation includes the presence of a circulator. It is the same as Adler’s equation, but with a factor of 2 in the numerator. It clearly gives a best fit to the data.

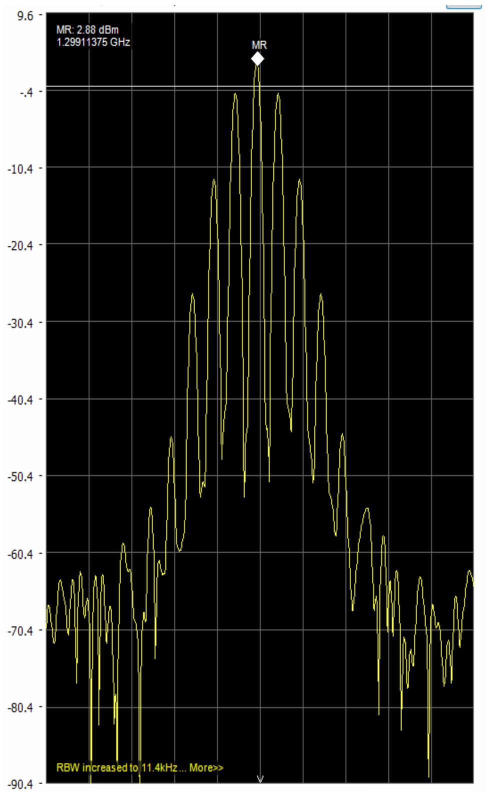
Phase Modulation

50 kHz Phase Modulation



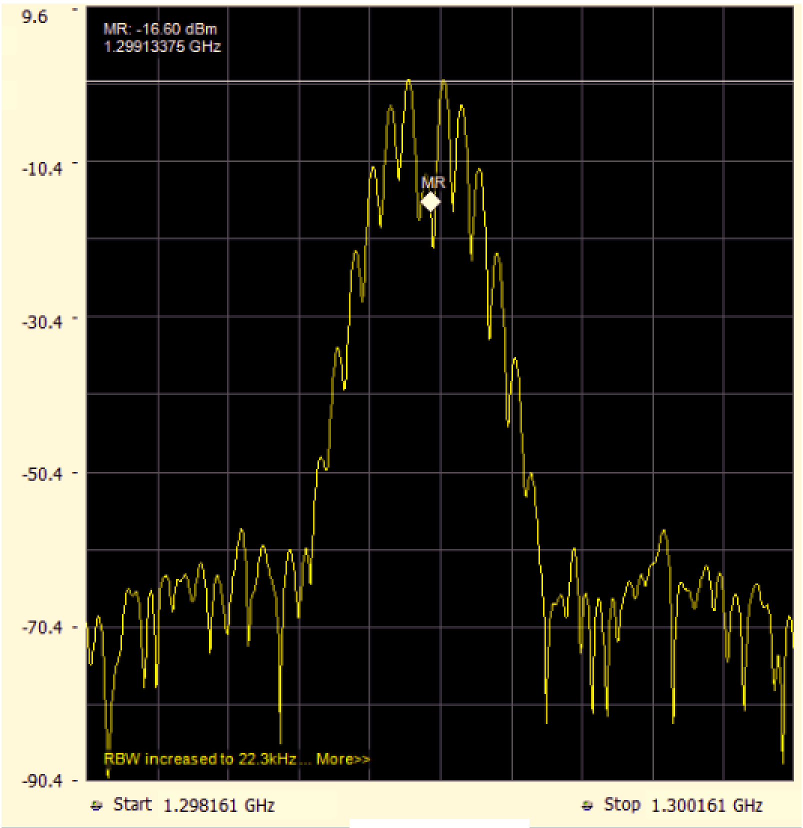
← 2 MHz →

No Modulation



← 1 MHz →

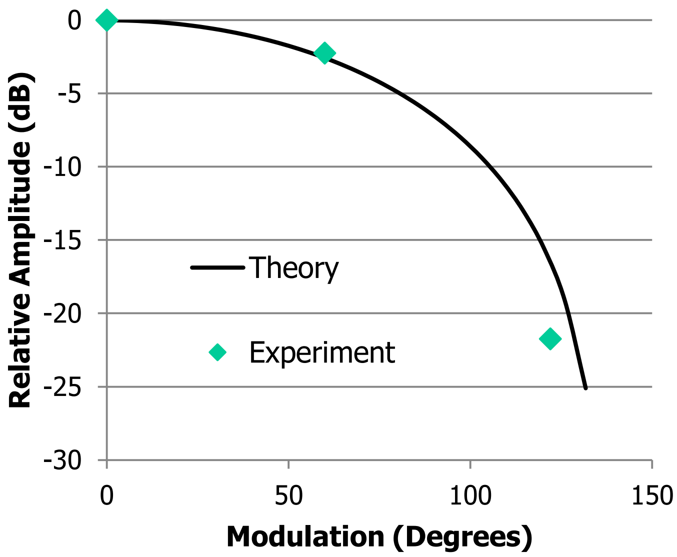
60° Modulation



← 2 MHz →

122° Modulation

Magnetron Amplitude vs Phase Modulation



Theory:

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

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)

Compact and Efficient Magnetron Source with Fast Phase and Frequency Control

Michael Read
Calabazas Creek Research, Inc.

Lili Ma, Joseph Frisch
SLAC National Accelerator Laboratory

Chris Walker
Communications & Power Industries – Beverley

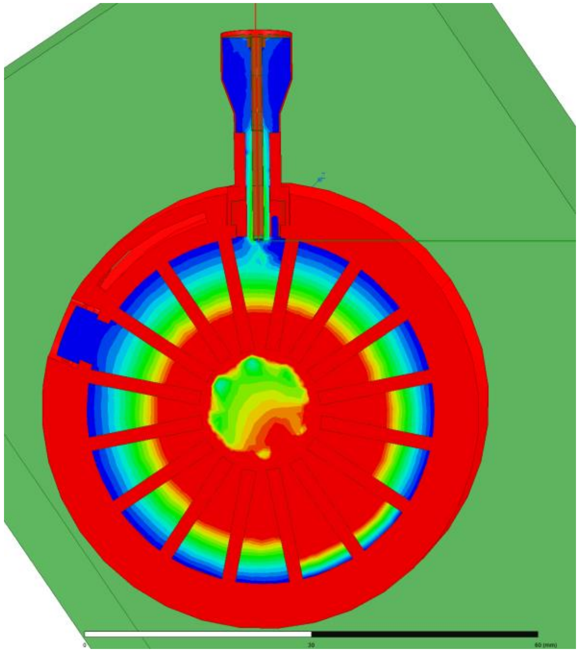
Funded by US Navy Contract N6833520C0822

Goals

- Develop S-Band, 5 kW magnetron with frequency and phase control
- Minimize weight and power
- Eliminate requirement for circulator

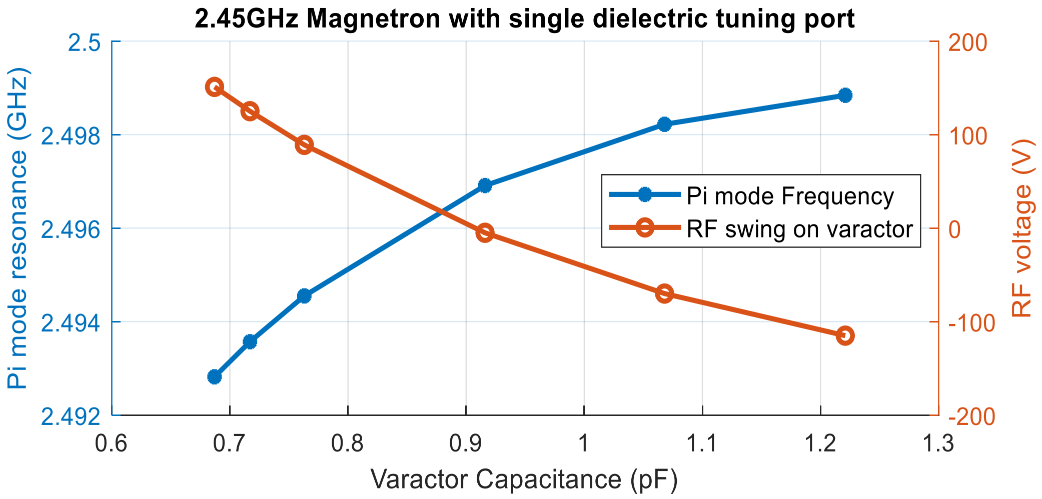
Approach

Varactor tuning of magnetron by changing capacitance



0.5 pF swing   5 MHz shift

Simulated Performance



Summary of Magnetron Program

- Magnetron produced 100 kW peak as designed
- Pulse width of 1.5 ms
- Average power achieved limited by processing time
- Locking achieved with < 00 W
- Demonstrated fast amplitude control using phase modulation

Calabazas Creek Research, Inc.

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]

[1] Calabazas Creek Research Inc., 490 Port Drive San Mateo, CA 94404

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

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

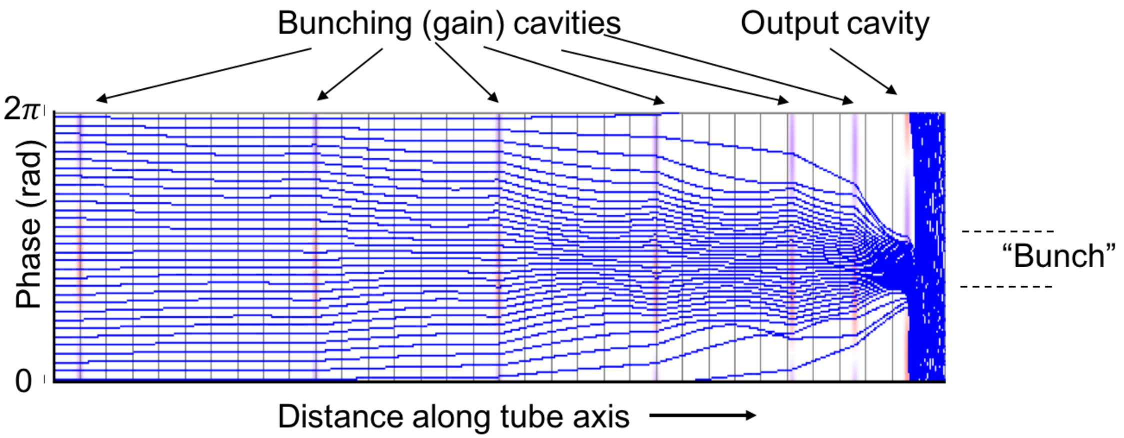
Funded by the US Department of Energy under SBIR grant DE-SC0017789.

Design Methods

- Advanced methods developed by Baikov and Guzilov shown to be paths to klystrons with efficiencies to ~90%
  - Use RF circuits to more effectively collect unbunched electrons
  - Bunch, Align and Collect (BAC)
  - Core Oscillation Method (COM)
- CCR investigated both methods for design of 100 kW, 1300 MHz klystron

Core Oscillation Method (COM)*

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

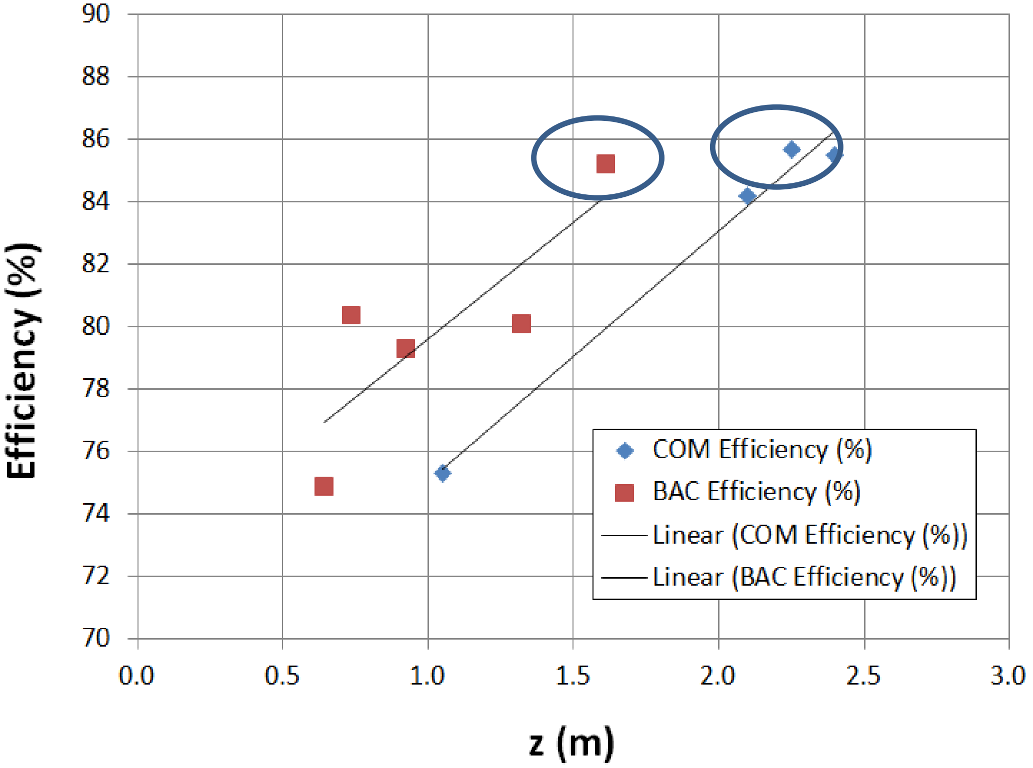


- Circuits are long

* 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.

Efficiency for BAC and COM Designs

- Scan of efficiency vs length for both BAC and COM designs for 100 kW 1.3 GHz using 1D Code AJDISK
- COM designs have similar efficiencies, are longer but have fewer cavities (eg, 7 vs 13 for BAC)
- COM chosen because of lower cost



Design Parameters

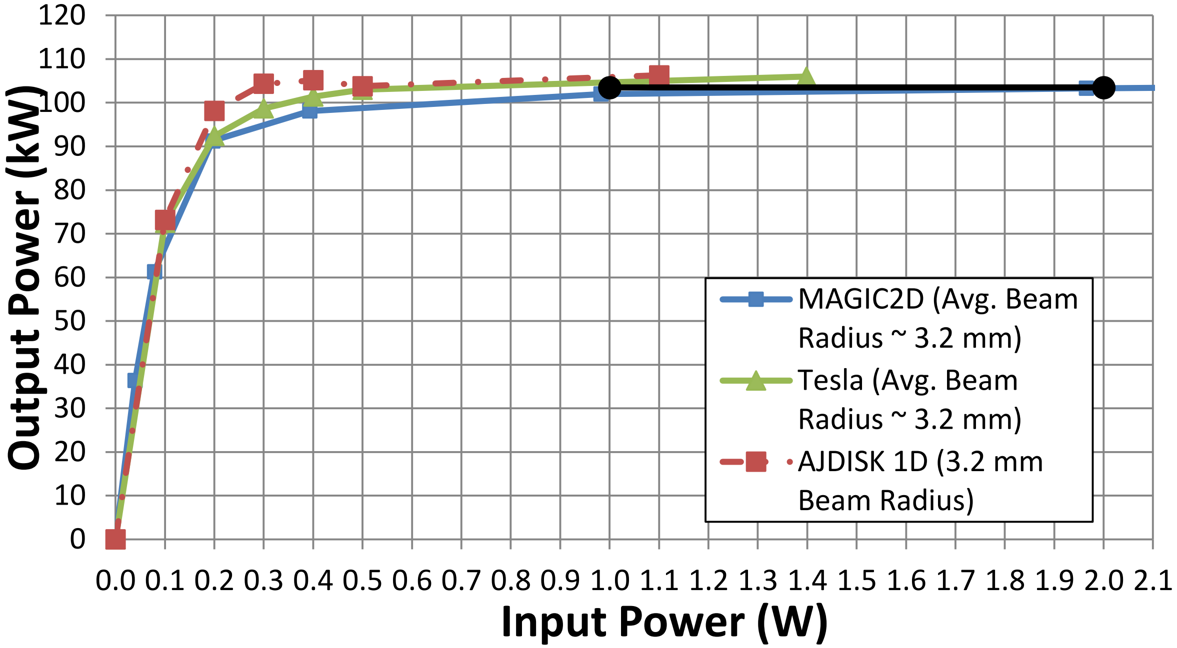
- COM design with 7 cavities
- Parameters

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

Simulations

- AJDISK
  - 1D Code by Aaron Jensen (SLAC / Leidos)
  - Effectively assumes infinite magnetic field
  - Typically gives results within about 5% of more complex codes; has been used for many klystrons
  - Runs very quickly and is very useful for optimization
- TESLA
  - 2 ½ D Code from Naval Research Laboratory
  - Can include trajectory code-generated beams and magnetic field profiles
- KlyC
  - Developed at CERN
  - Includes 2D fields, but 1D beam dynamics
- MAGIC 2D
  - Particle-in-Cell (PIC) code that includes all relevant physics

Simulation Summary

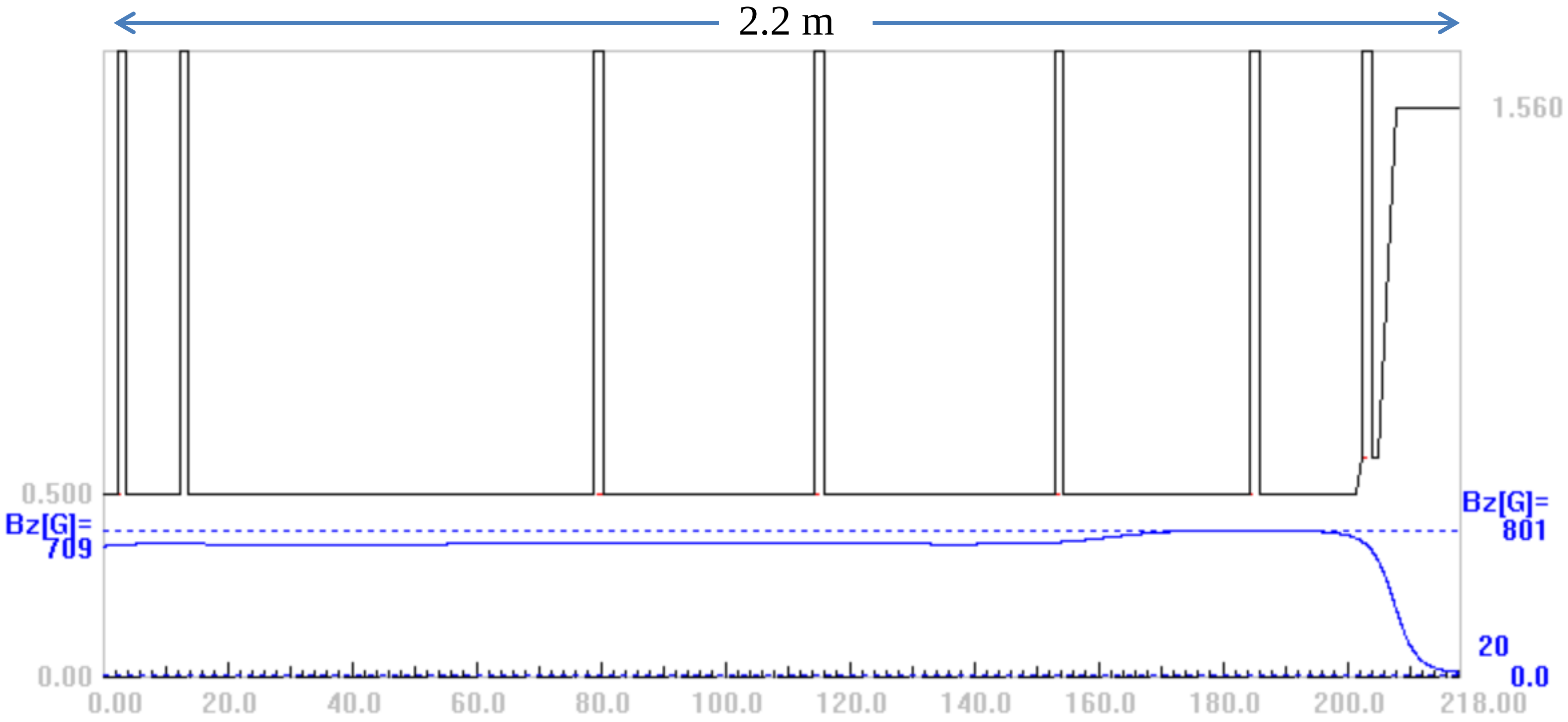


Code	Power	Efficiency
TESLA	104.5 kW	79.5%
AJDISK	106 kW	81%
KLYC	103.5 kW	79%
MAGIC	102 kW	78%

Cavity Locations and B-Field Profile

$P = 104.5$ kW

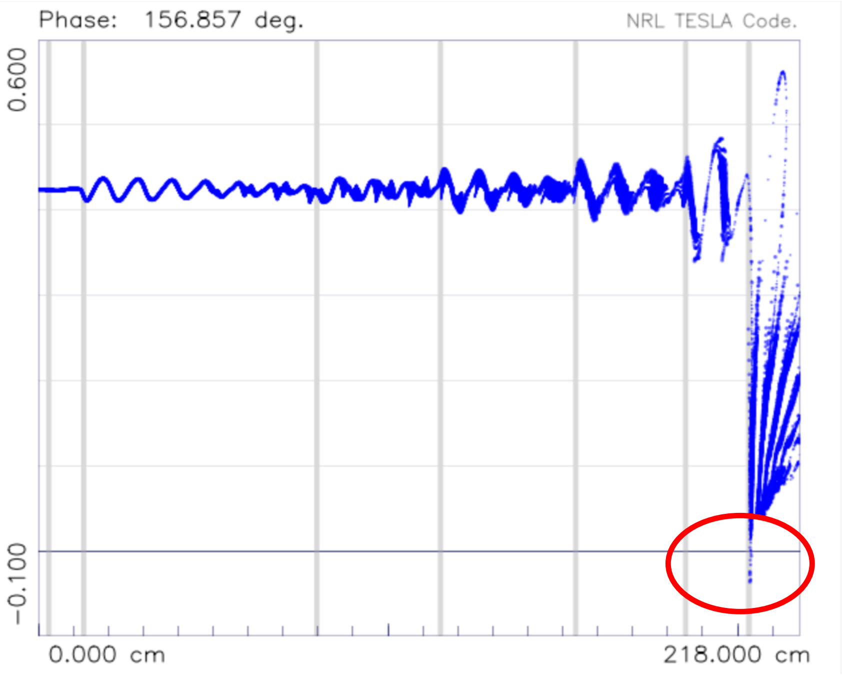
$\eta = 79.5\%$

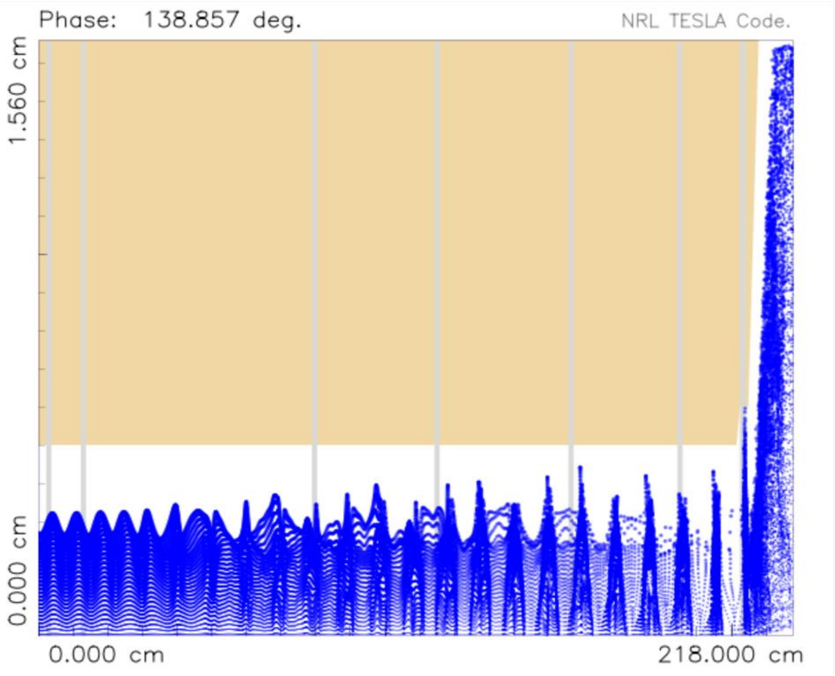


Beam Dynamics

Beta (v/c)

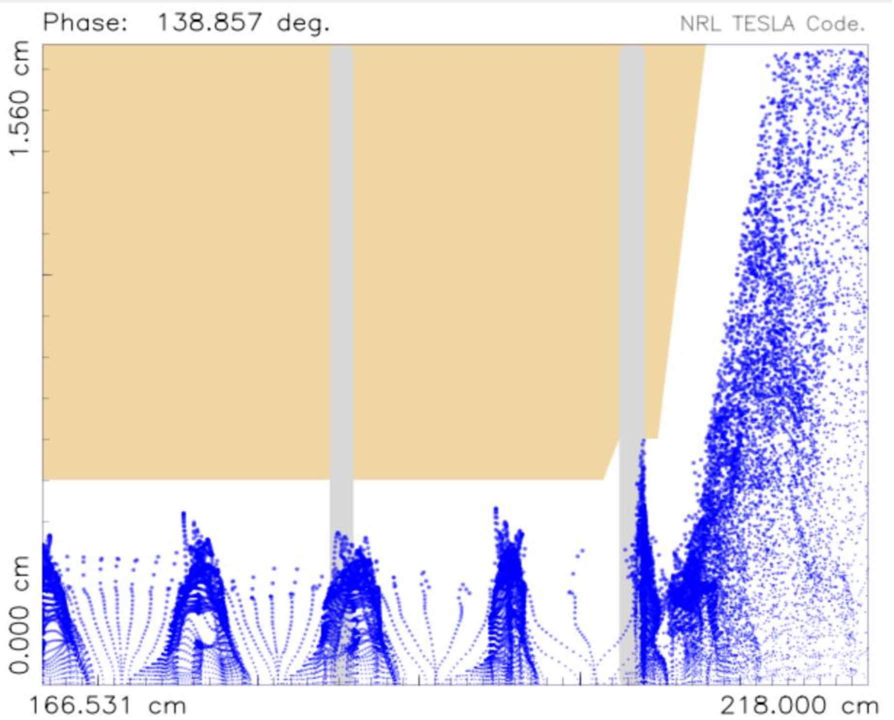
Beam Trajectories



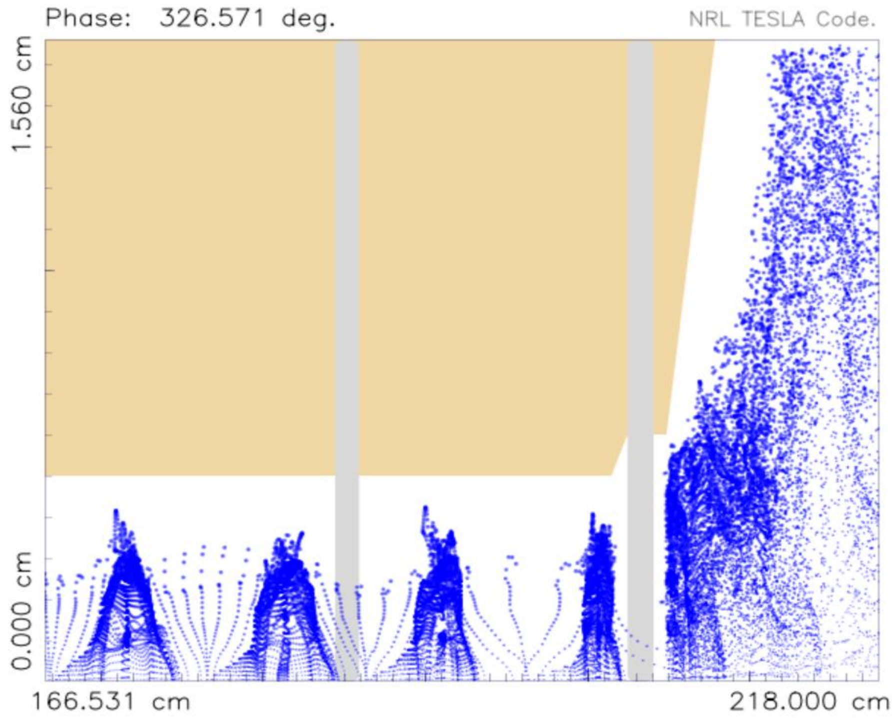


No reflected particles

Beam Trajectories Near Output



Phase with most interception

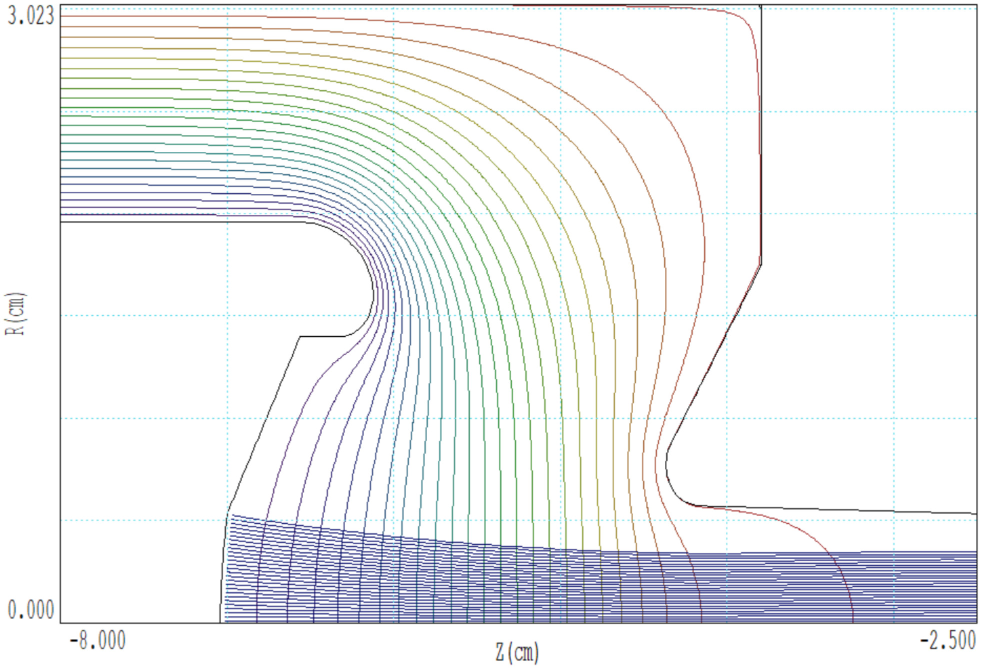


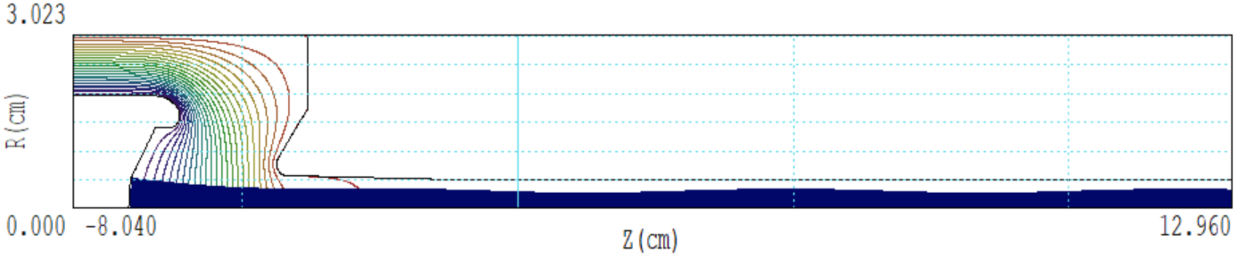
Phase with least interception

~ 200 W/cm^2
over ~ 5 mm

Electron Gun

Simulation
with TRAK

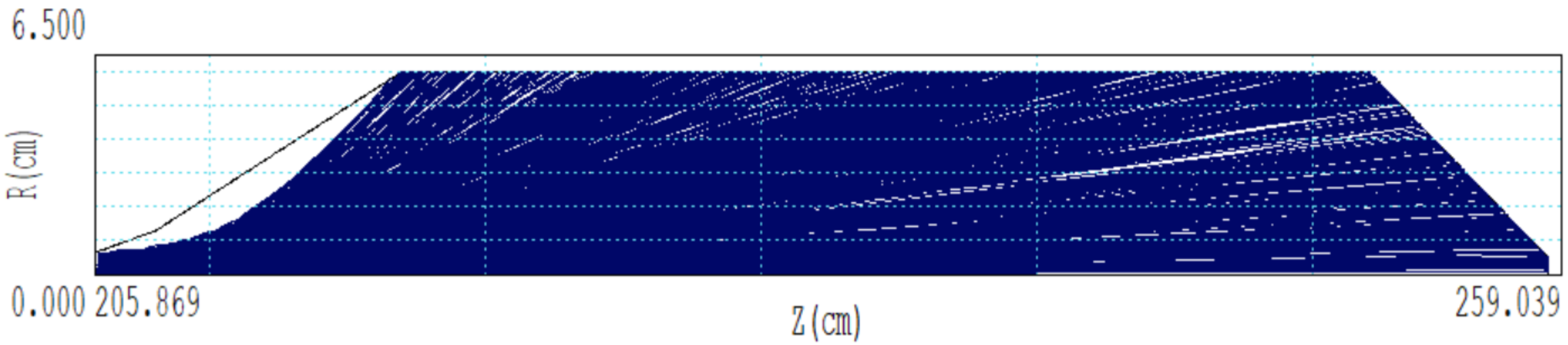


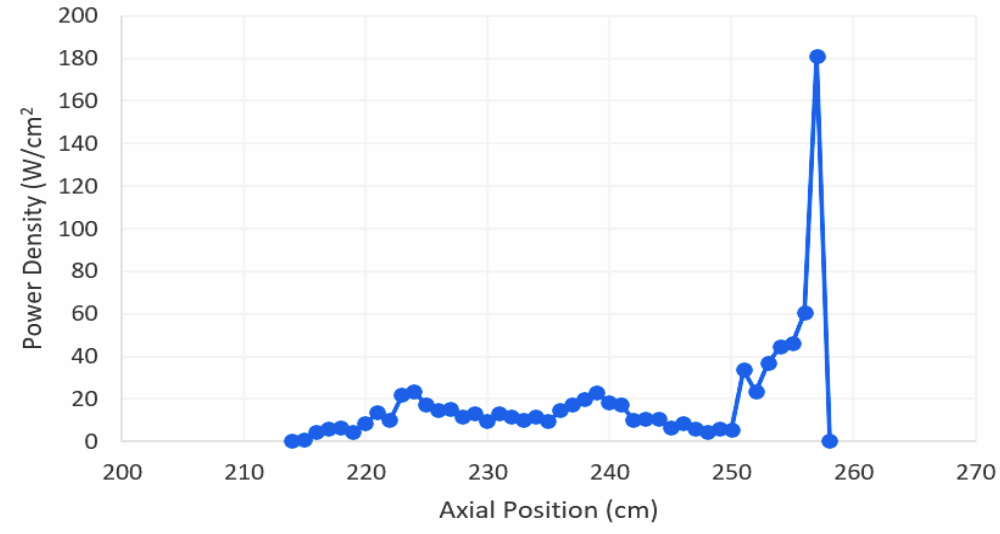


Ripple
+/- 10%

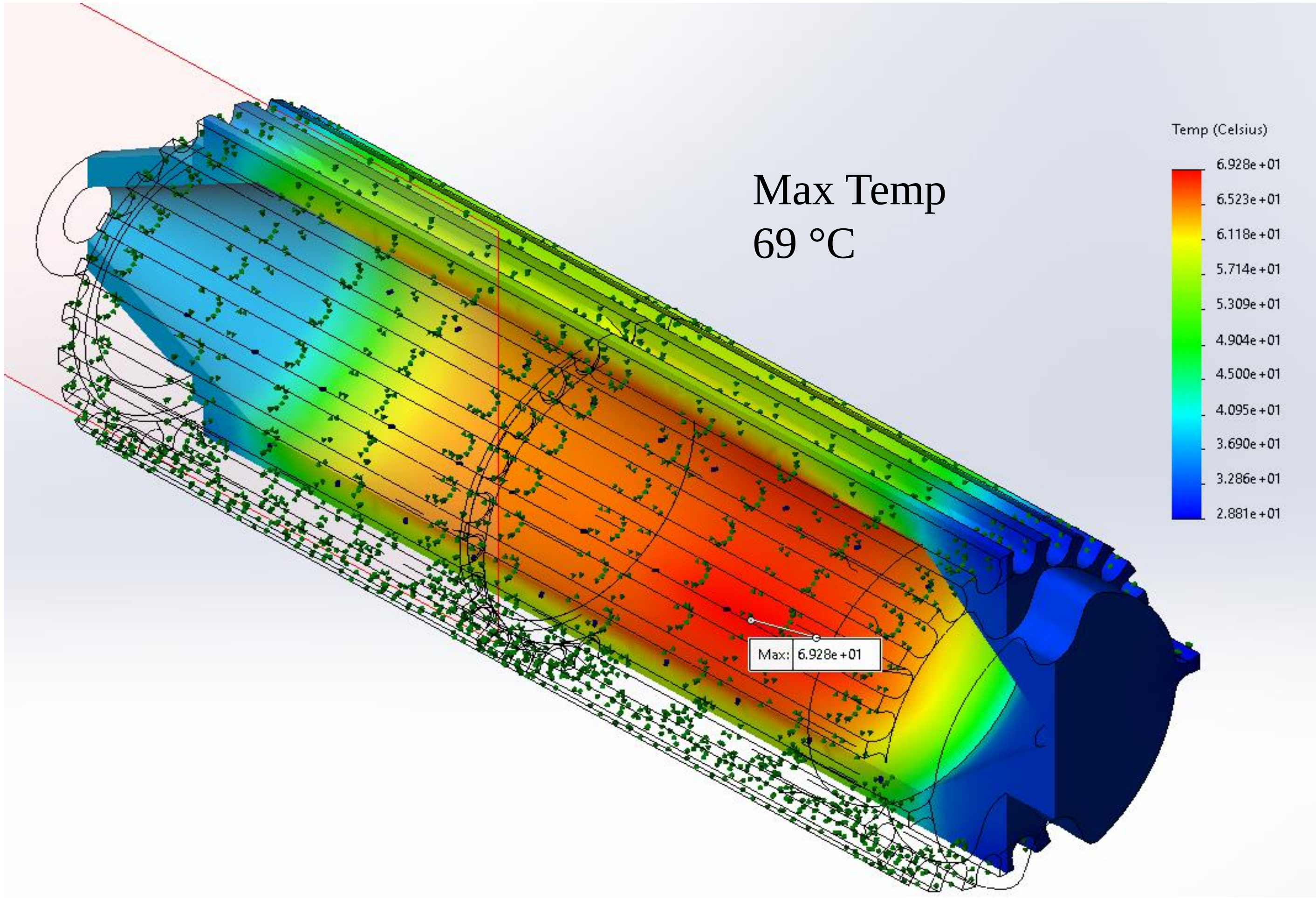
Collector

2D simulation with TRAK with spent beam from TESLA



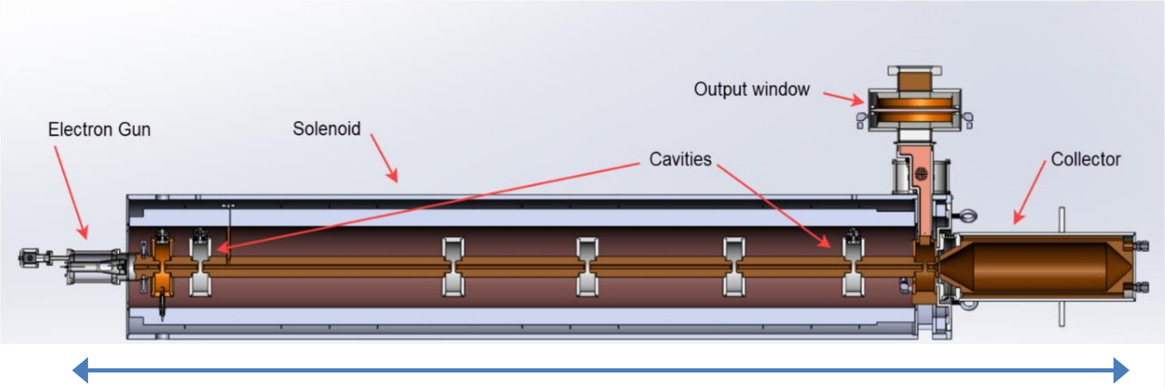


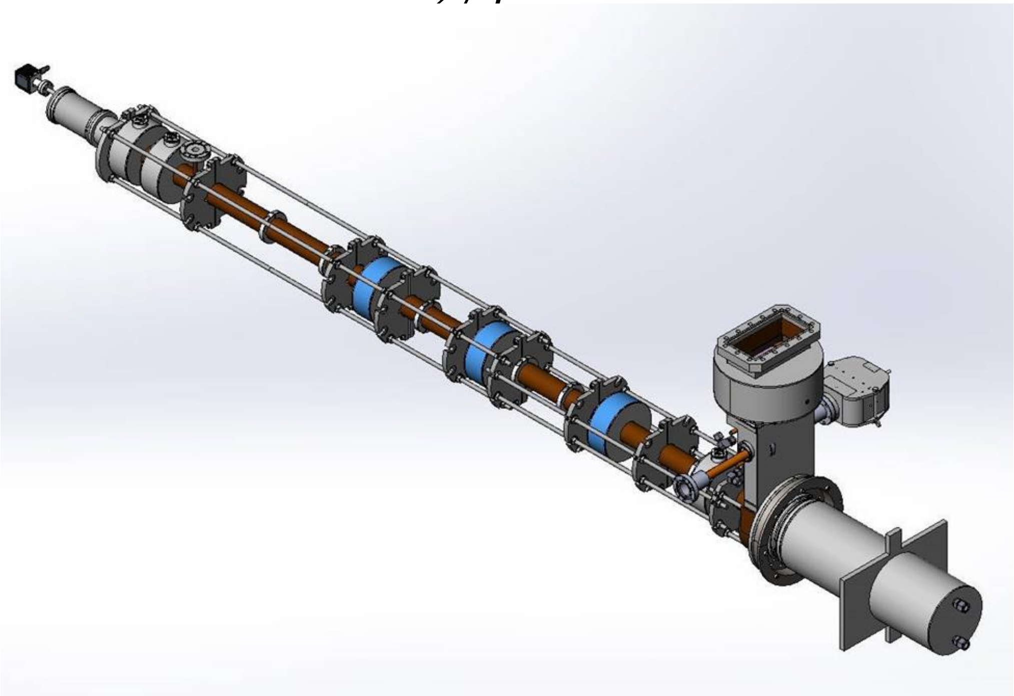
Collector Thermal Analysis

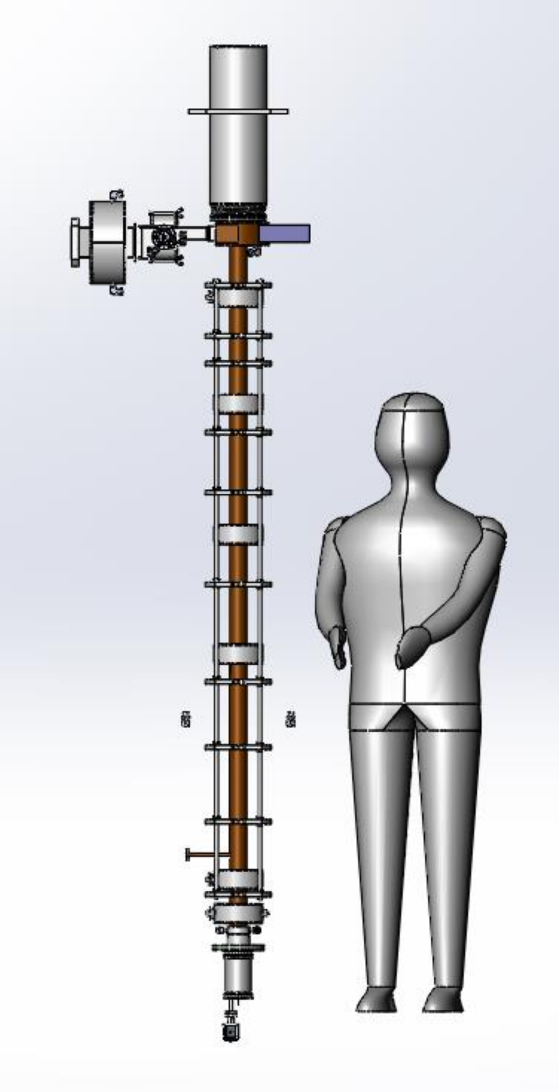


Max Temp
69 °C

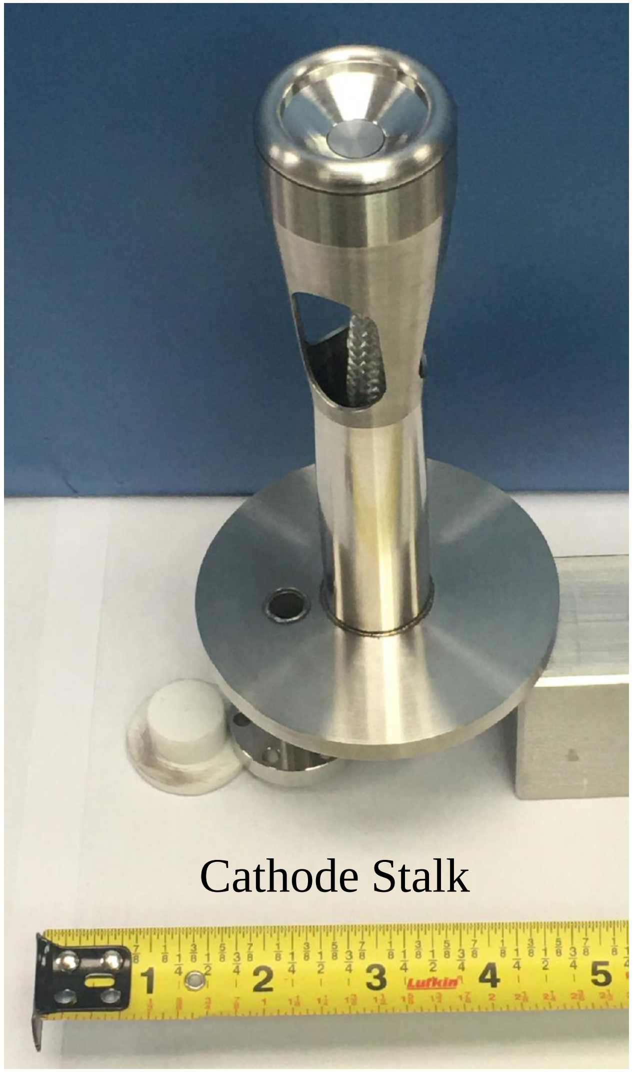
Solid Models of Klystron







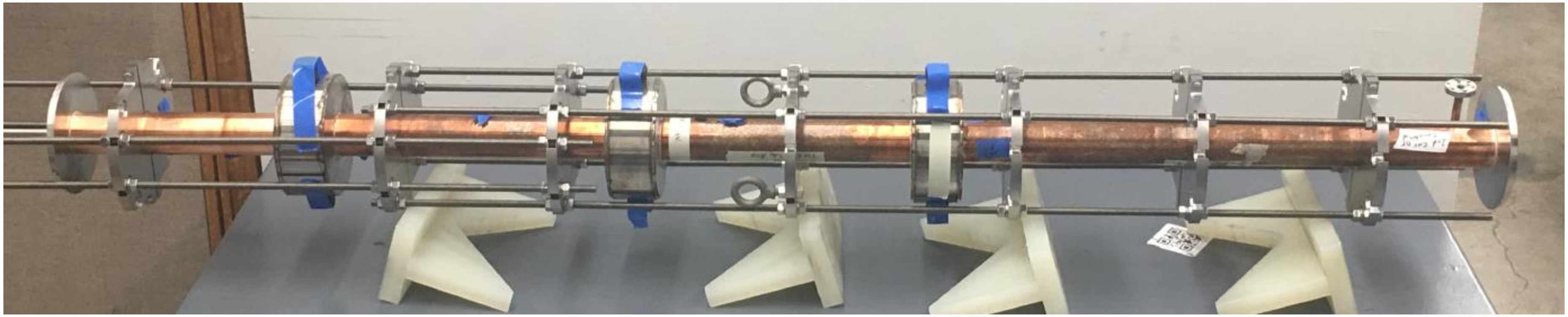
Electron Gun



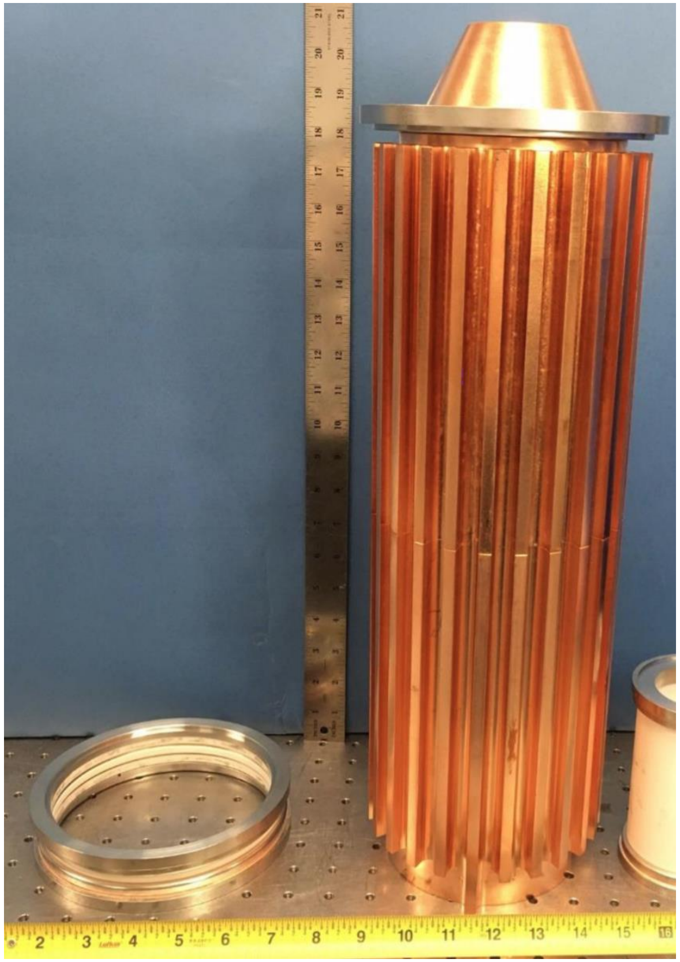
Cathode Stalk

High Voltage Insulator and Cathode Stalk

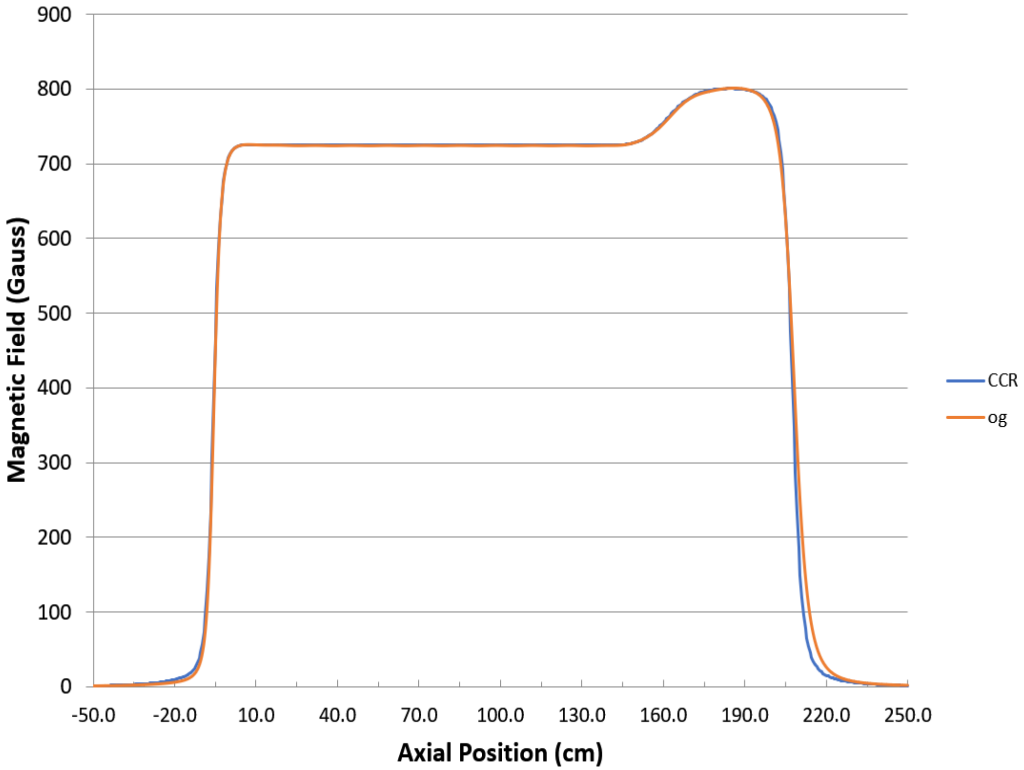
Partial RF Circuit



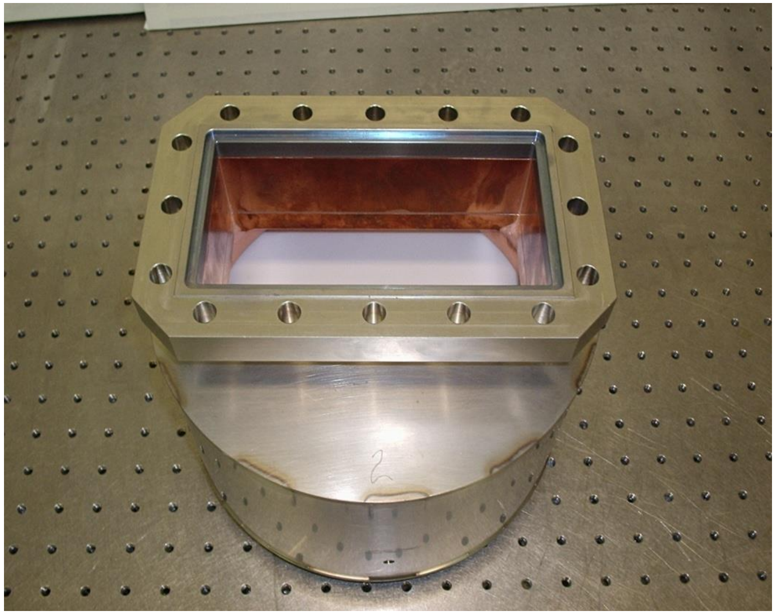
Collector Components

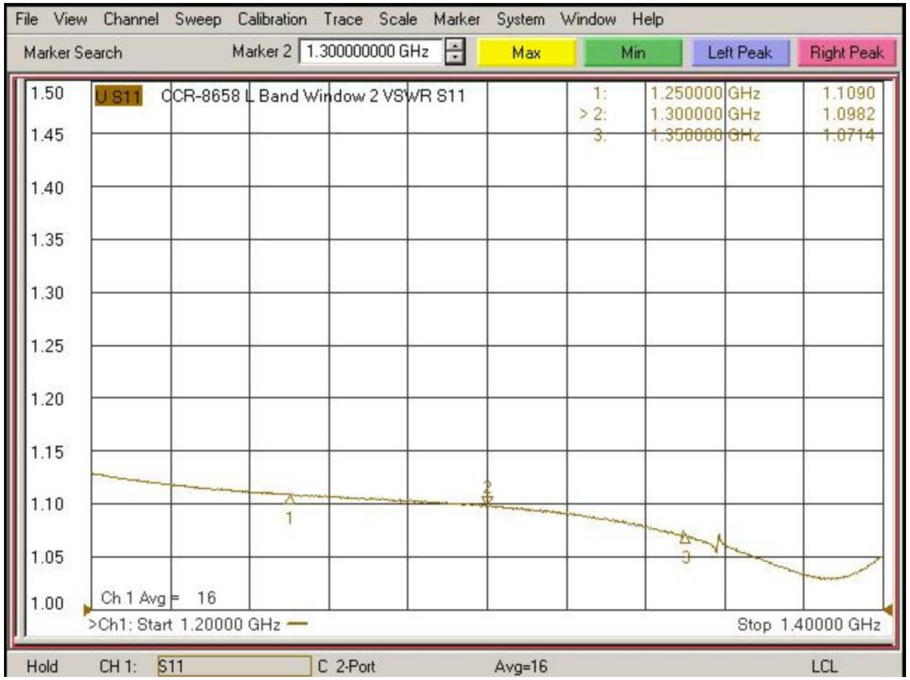


Solenoid


Magnetic Field (Gauss)
900
800
700
600
500
400
300
200
100
0
-50.0
-20.0
10.0
40.0
70.0
100.0
130.0
160.0
190.0
220.0
250.0
Axial Position (cm)
CCR
og

Output Window





Marker 2 1.300000000 GHz

CCR-8658 L Band Window 2 VSWR S11

1: 1.250000 GHz 1.1090
> 2: 1.300000 GHz 1.0982
3: 1.350000 GHz 1.0714

Ch 1 Avg = 16

>Ch1: Start 1.20000 GHz

Stop 1.40000 GHz

CH 1: S11

C 2-Port

Avg=16

Max temp at center of window: 74°C
Max Stress: 99.6 MPa

High Efficiency Klystron Summary

- 7 Cavity COM design
- 4 Simulation codes predict output powers over 100 kW with efficiencies from 78% - 81%
- Tube is in final assembly
- Testing to start summer, 2022

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

Lawrence Ives, Michael Read,
David Marsden, Thuc Bui
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Ricky Ho, Nileshwar Chaudar,
Christopher McVey, Tom Cox
Communications & Power Industries, LLC
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James M. Potter
JP Accelerator Works
Los Alamos, NM USA

This research funded by DOE SBIR Grant DE-SC0018838

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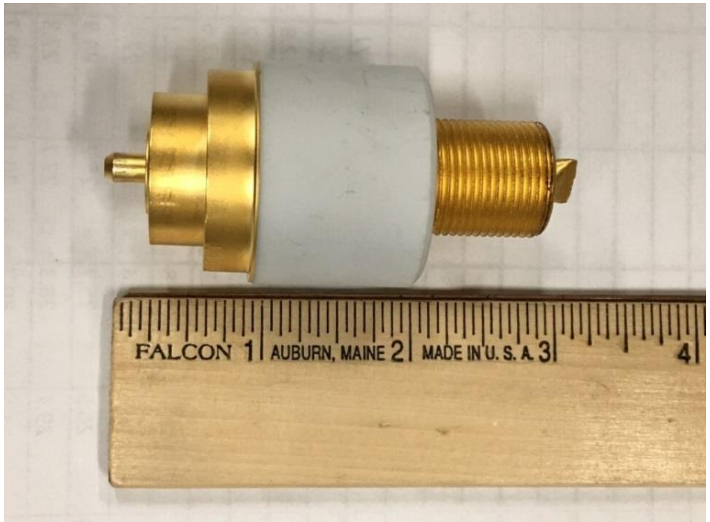
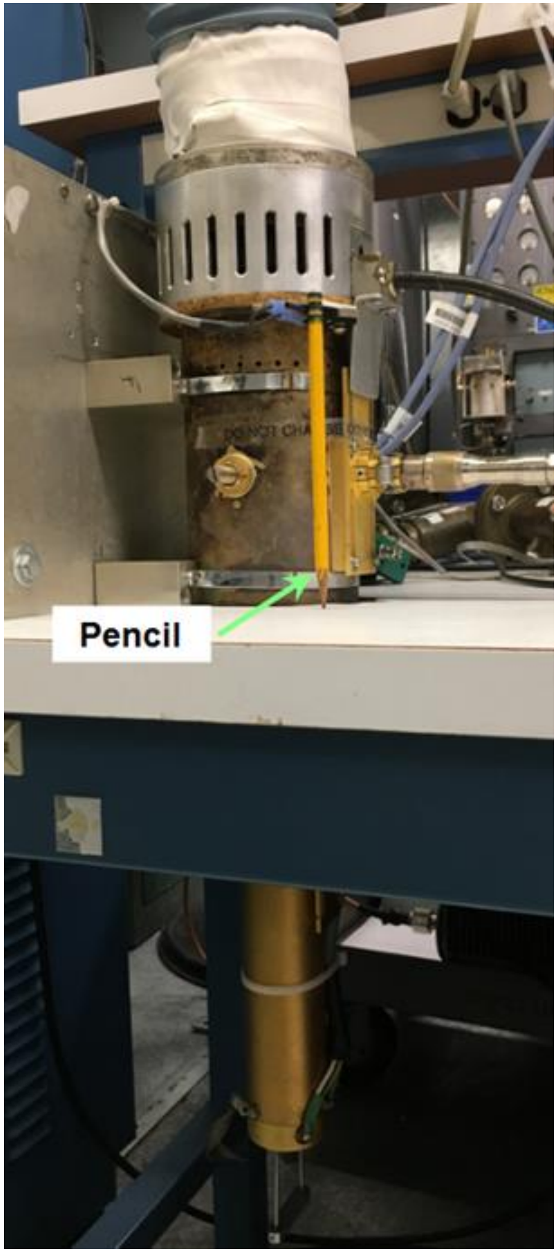
25 kW 425 MHz Triode-based RF Source



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

GI-39B Russian Triode Tube

- 20 kV DC
- 140 kW peak power at 10 microseconds
- Rate to 1200 MHz

GI-39B GI39B Russian pulse Power TRIOD

Condition: New

Quantity: 1 3 available / 2 sold

Price: **US $64.90**

60-day returns

7 watchers

Shipping: $28.00 Standard Shipping from ou

International shipment of items may be subje

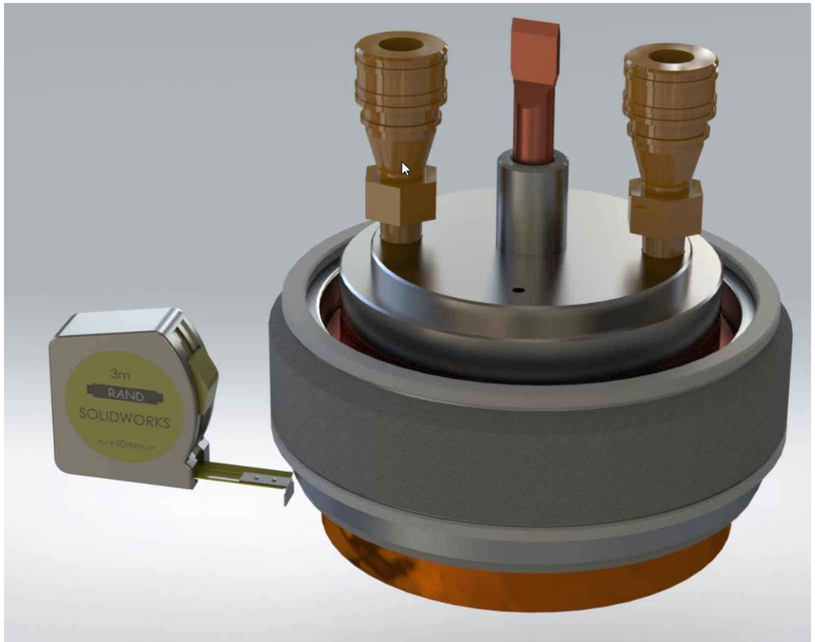
Item location: UA, Ukraine

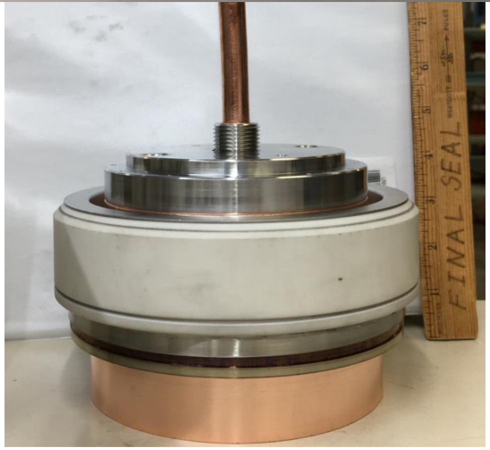
Ships to: Worldwide

Beam Power for 200 kW RF Source

Eight YU-176 grid cathode assemblies

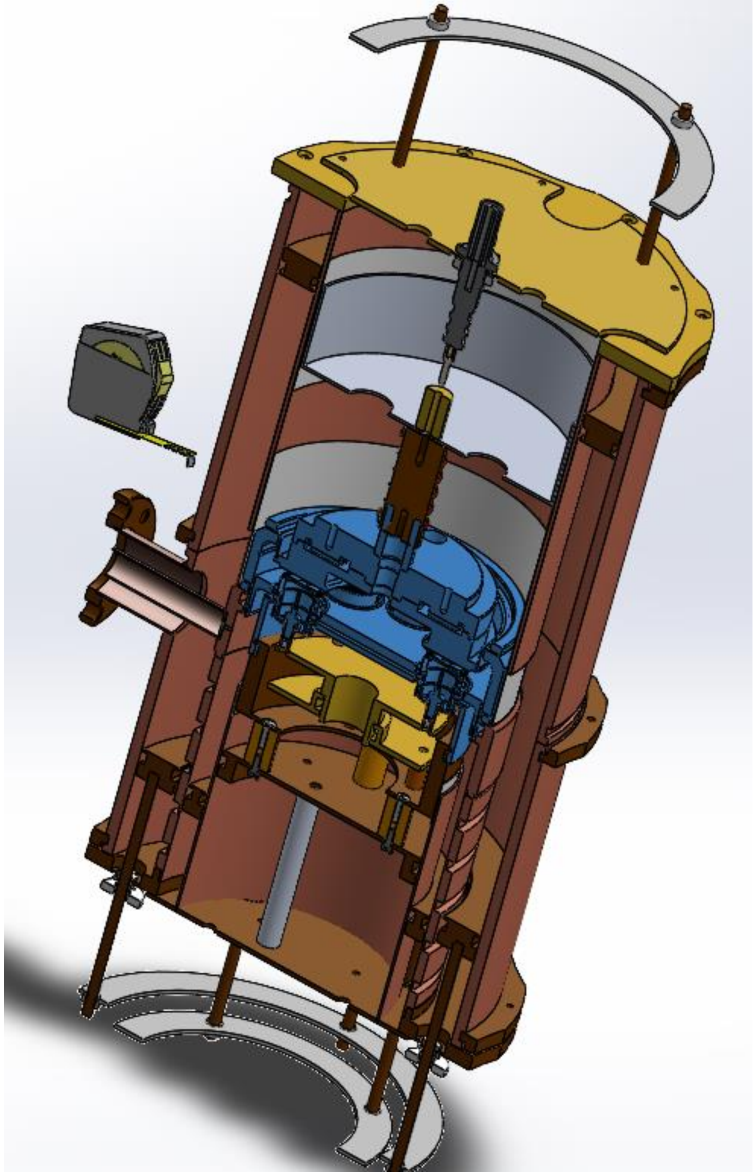
230 kW of beam power





350 MHz Cavities

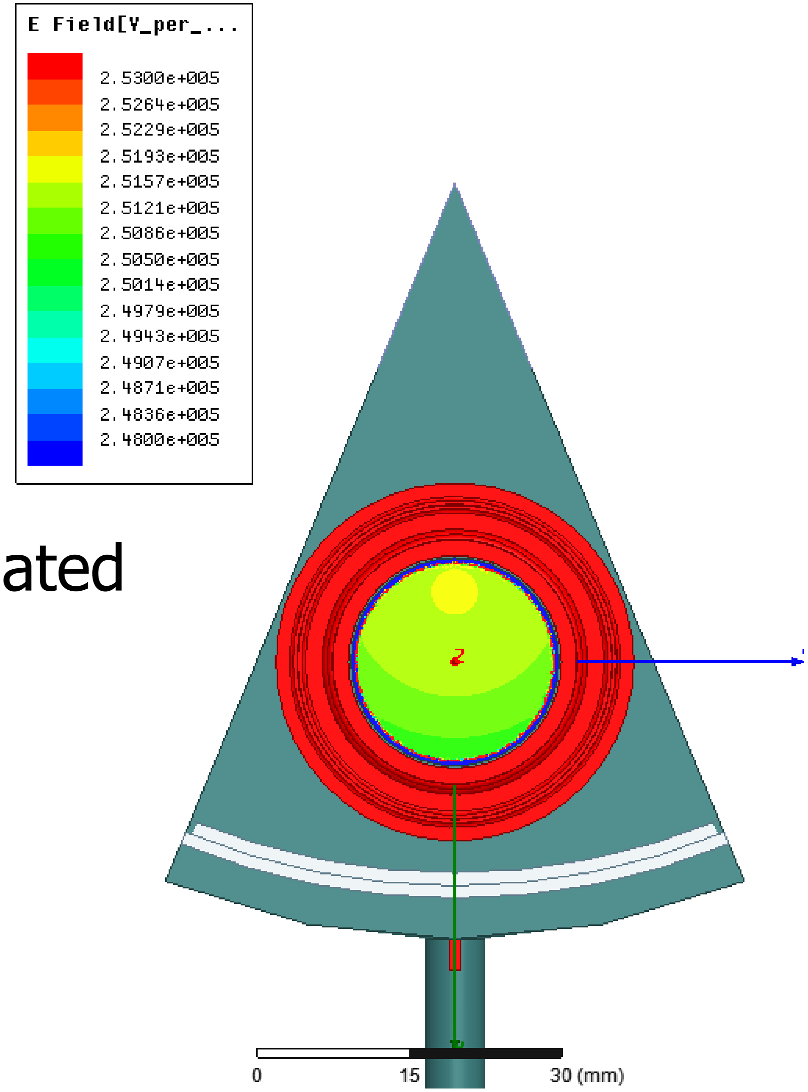
- MB triode tube installs from top (blue)
- Single input cavity below tube
- Upper and lower output cavities with coax output between
- Upper cavity is frequency tuning element
- Lower cavity is variable output coupling element



Electric Field Uniformity on Grids

Field variation across grid - 0.6%

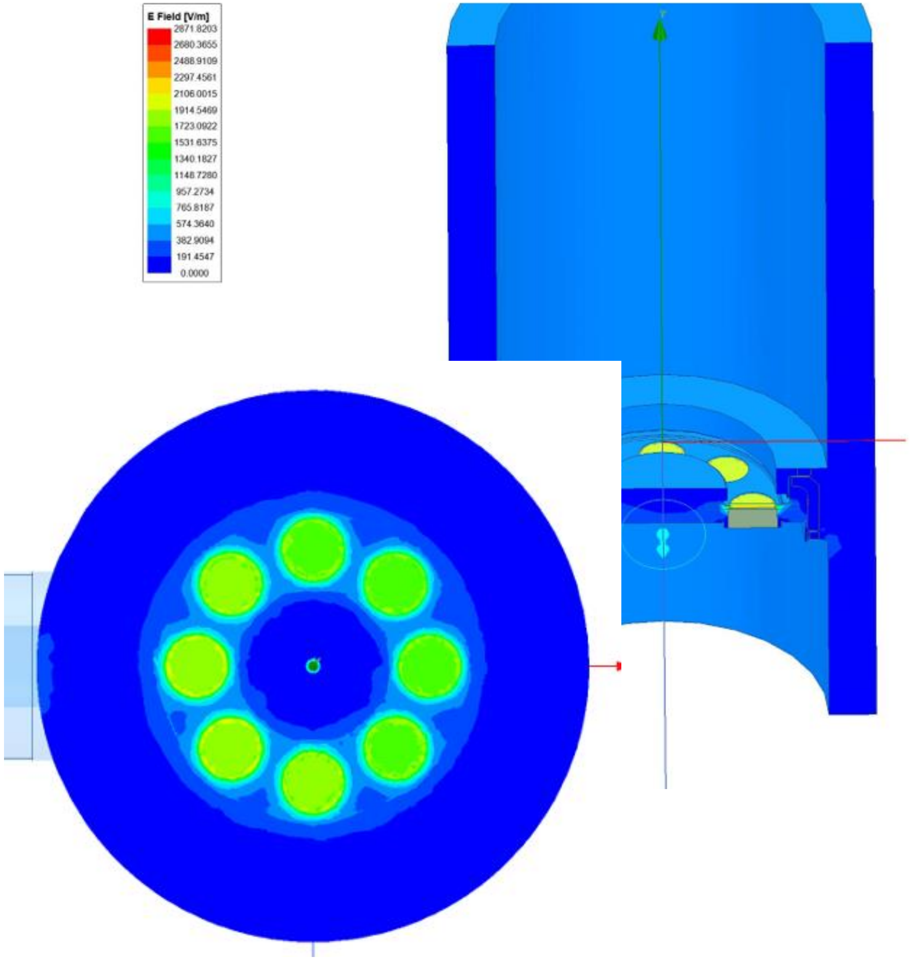
No impact on performance anticipated



Output Cavity Analysis

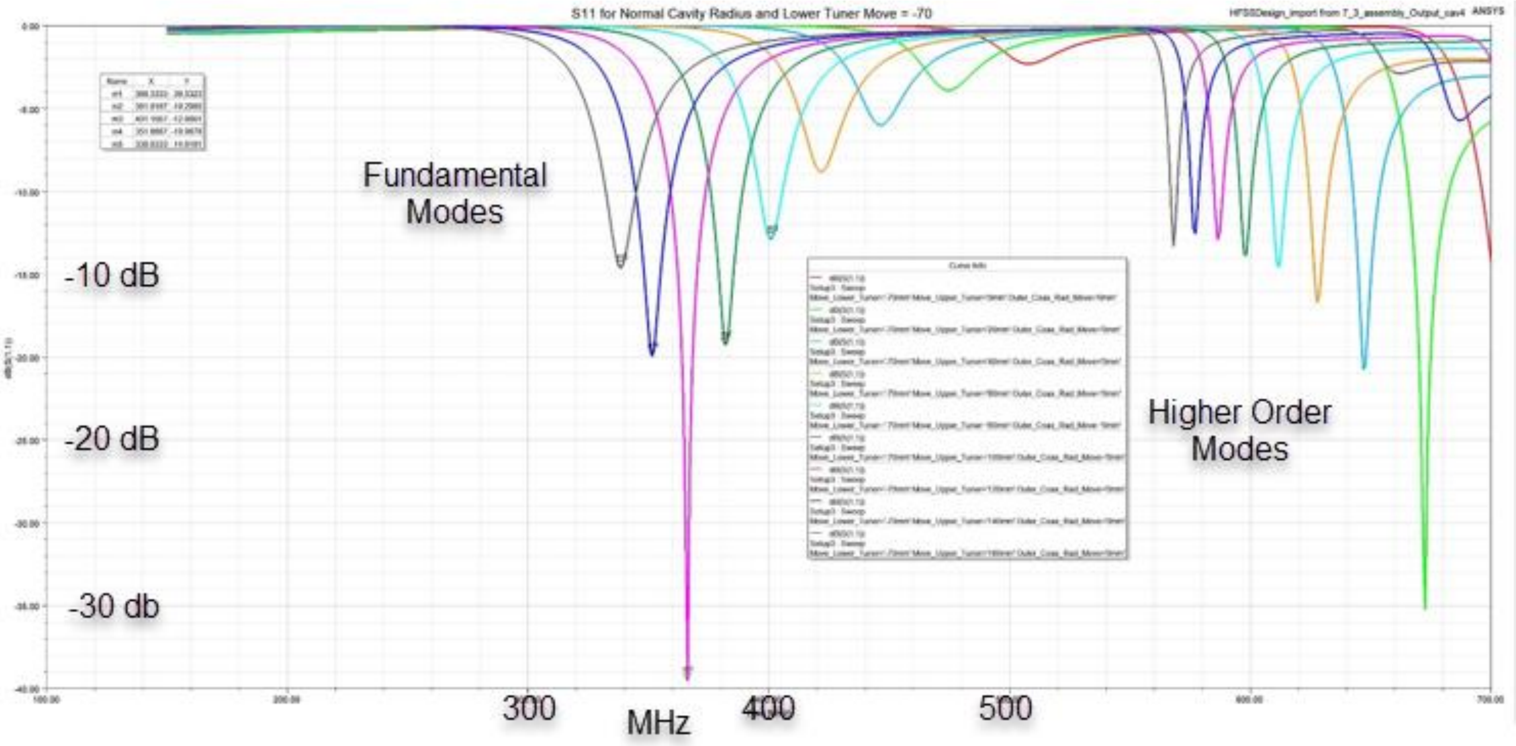
Simulation of output cavity fields

- Confirm single mode operation
- Confirm uniform fields in grid-anode gap



Output Cavity Simulation

Tuning range for output cavity
(325 – 500 MHz)



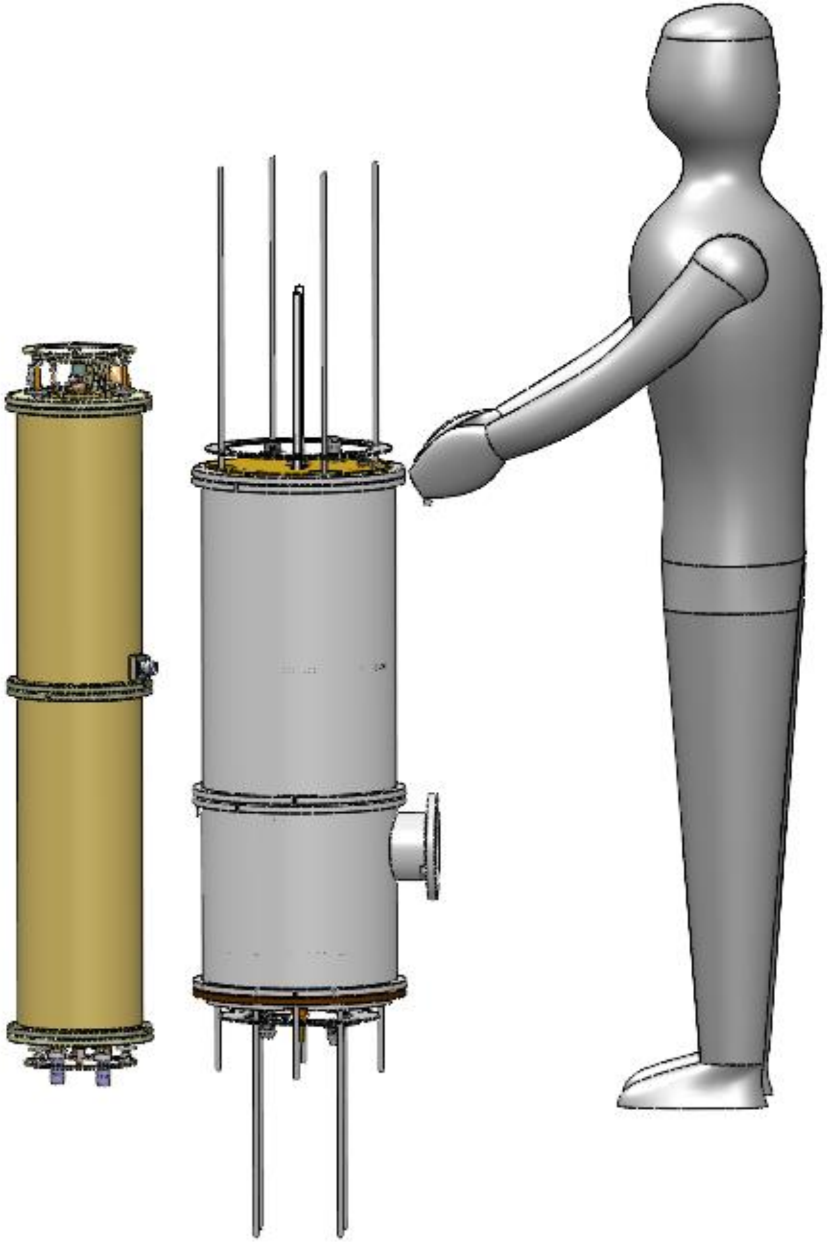
Gain Issue

- Gain ~14 dB for triode based sources
- 200kW RF source requires 6.5 kW driver
- Driver options:
  - Solid State – expensive, may be difficult to find

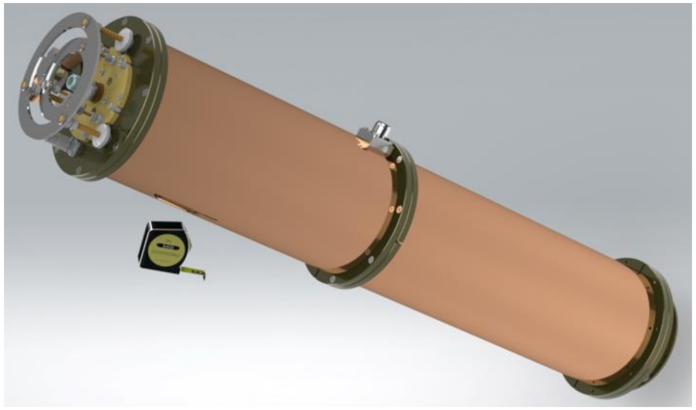
  Single-beam triode driver - Same length as multi-beam source with smaller diameter

200 kW, 350 MHz RF System

Net Gain	28 dB
Net Efficiency	~~~80~~?%



200 kW CW, 350 MHz RF System



10 kW single beam driver

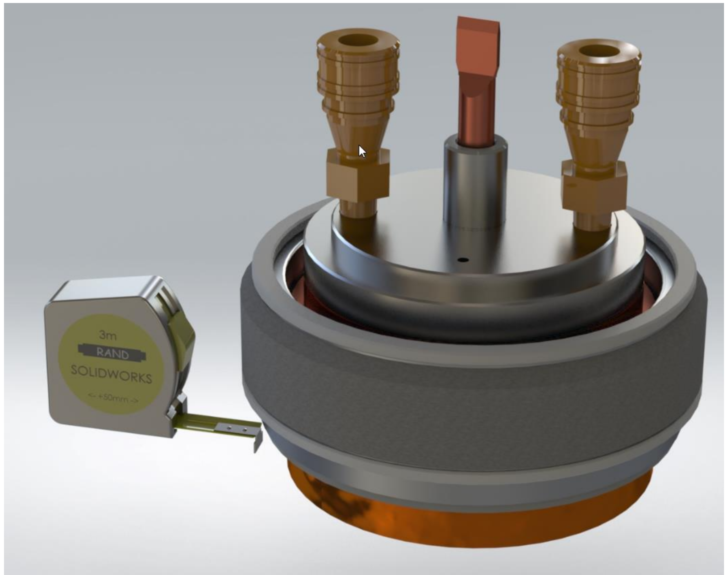
200 kW multiple beam RF source

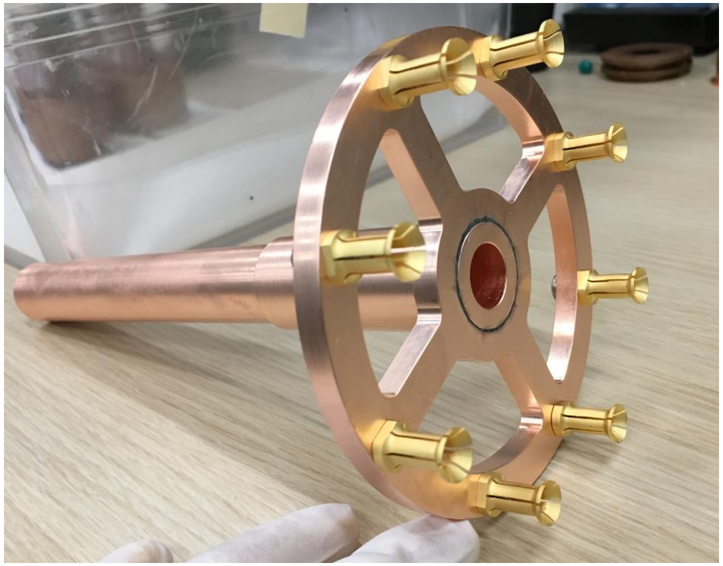
Net Gain	28 dB
Net Efficiency	~72%

High power tests scheduled for Fall 2022

Multiple Beam Triode

- Triode is vacuum tube providing the electron beams for RF generation
- Final assembly in progress





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

- Brazing of grid assemblies into copper support plate in progress
- Expect triode sealed in and baked by end of July
- Will begin testing of the tube in August without the cavities (grid to cathode resistance, peak emission, current division, cutoff voltage)
- Once tube is successfully verified, will assemble the multiple beam cavities for testing in fall

HIGH-EFFICENCY, HIGH AVERAGE POWER INDUCTIVE OUTPUT TUBES

H.P. Freund,[1] R.L. Ives,[1] M. Read,
T. Bui[1], T. Habermann[1], David Marsden[1],
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:

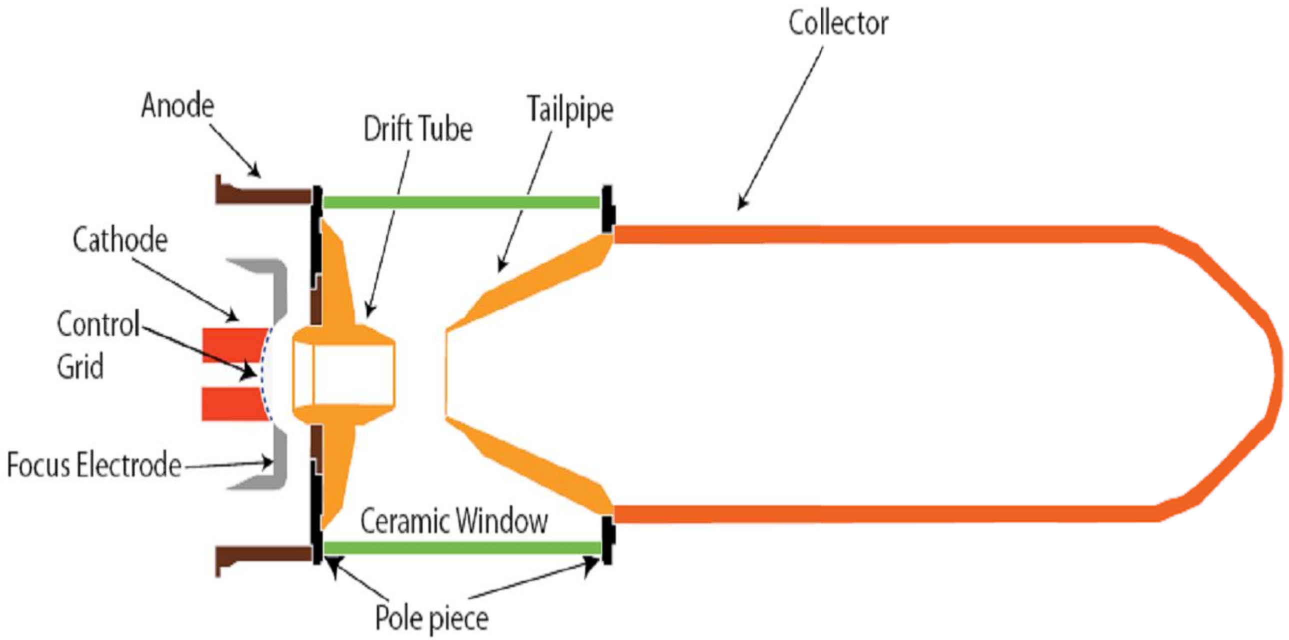
• Output power	200 kW CW
• Frequency	700 MHz
• Number of beams	eight
• Efficiency	80+%
• Reduce size and cost	

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

INDUCTIVE OUTPUT TUBES

- Used as drivers for radio frequency accelerators and (formerly) TV transmitters
- A prebunched beam generated in a gridded gun is accelerated to higher energies by a DC potential and then injected into the output cavity
- The modulated beam excites the resonant mode of the output cavity



BACKGROUND/ADVANTAGES

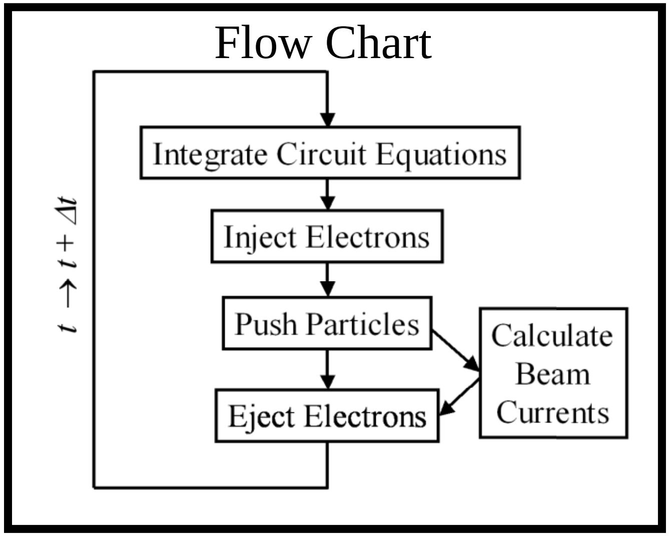
- Multi-Beam IOTs (MBIOTs) have been developed to drive the European Spallation Neutron Source
  - CPI/Thales* with the characteristics
    - Operating Frequency = 705 MHz
    - Peak Power = 1.2 MW
    - Efficiency = 65%

- IOTs inherently high efficiency RF sources
- Significantly more compact than klystrons
- Opportunities for significant system cost reduction
  - improved operating efficiency
  - lower cost fabrication
  - lower voltage operation

*A. Beunas *et al*., paper presented at the18th IVEC, London, UK, 24 – 28 April 2017

THE NEMESIS CODE*

- Properties of NEMESIS: PIC-like
  - Time-domain integration with leap-frog algorithm
  - RF fields found by integrating the circuit equations for the voltage followed by a Kosmahl & Branch algorithm to obtain the fields
    - Poisson solver used for space-charge fields
  - Electrons injected using a model of the bunch current and tracked with the 3D Lorentz force equations



Flow Chart

$t \rightarrow t + \Delta t$

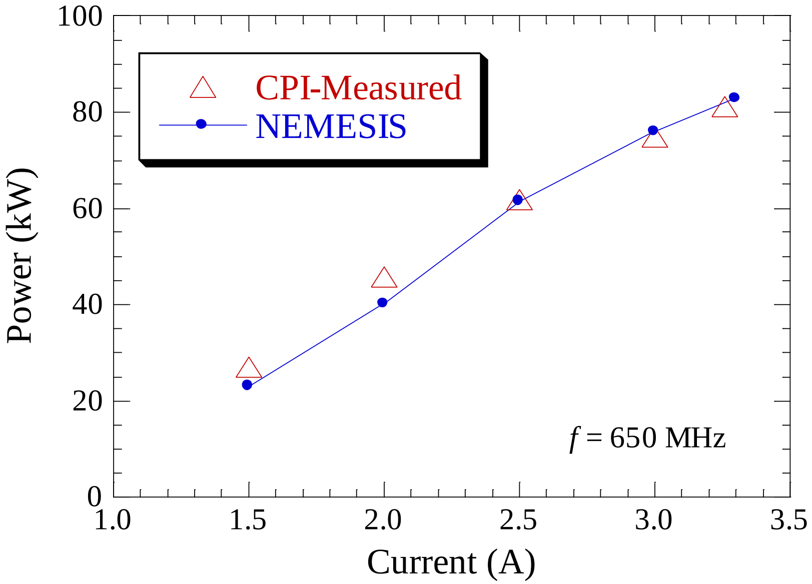
Integrate Circuit Equations

Inject Electrons

Push Particles

Eject Electrons

Calculate Beam Currents



- NEMESIS Validation
  - Comparison with performance of the CPI K5H90W-2 IOT
  - 37 KV/1 – 4 A, tunable 650 – 805 MHz
  - Comparison of output power over a range of currents yields good agreement

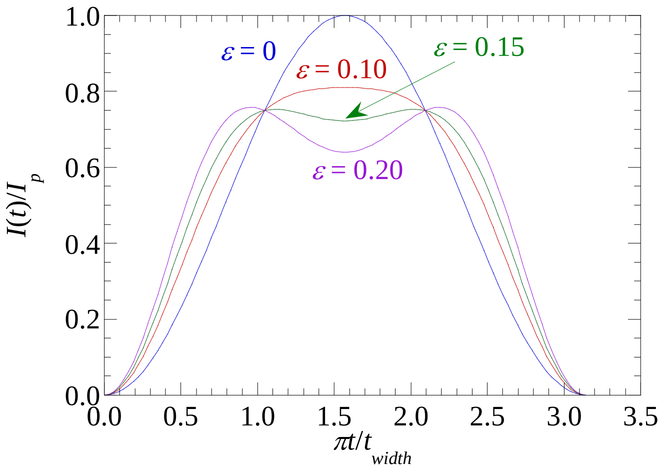
* H.P. Freund *et al.*, IEEE Trans. Plasma Sci. **35**, 1081 (2007)

EXTENSIONS TO NEMESIS

- Three extensions to NEMESIS needed
  - Model the bunching from the gun that includes the 3rd harmonic

$$\boxed{I(t)=I_p\begin{cases}\left[\sin\left(\pi\frac{t}{t_{width}}\right)+\varepsilon\sin\left(3\pi\frac{t}{t_{width}}+\varphi\right)\right]^2 & ;0\le t\le t_{width}\\ 0 & ;t_{width}<t\le\tau_{period}\end{cases}}$$

$$\longrightarrow \boxed{\frac{I_{avg}}{I_p}=\frac{1+\varepsilon^2}{2}\frac{\tau_{width}}{\tau_{period}}}$$

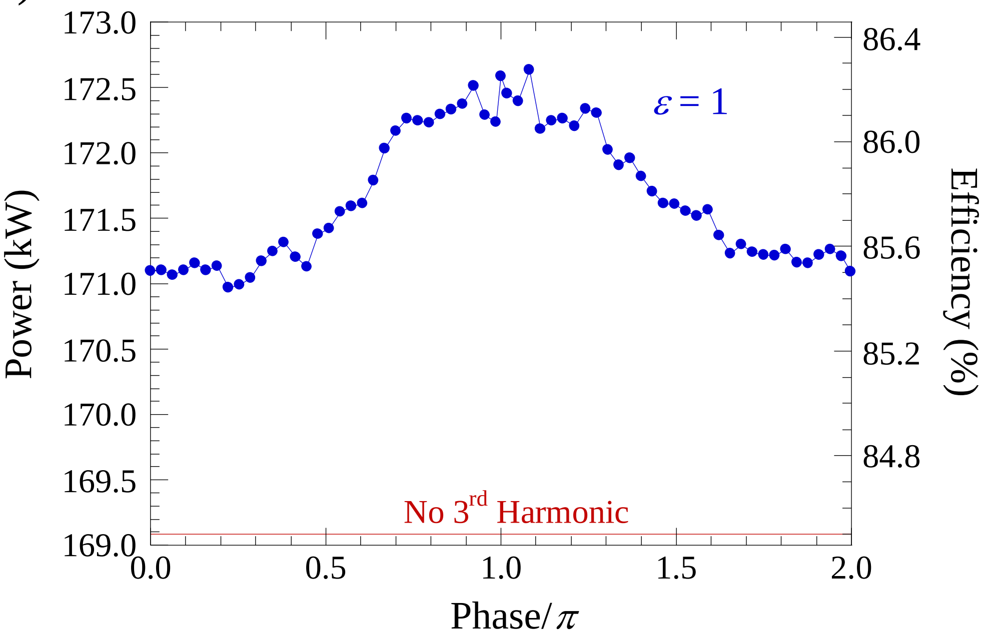


  - Modify the injection algorithm to include multiple (circular) beams
  - The original Poisson solver is 2-dimensional (*r*,*z*) corresponding to a solid or annular cylindrical beam
    - A 3-dimensional (*r*,*θ*,*z*) Poisson solver is under development

3^{rd} HARMONIC TEST CASE

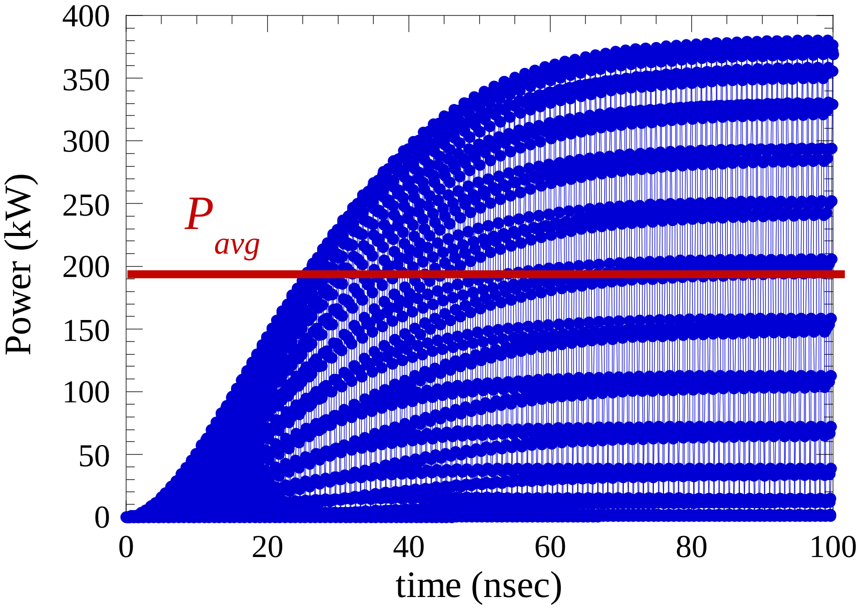
- Simulated annular beam at 700 MHz with:
  - 37 kV/6.67 A
  - Annular Beam with inner/outer radii = 5.128 cm/8.079 cm
  - $I_{avg}/I_p = 0.15 \rightarrow \tau_{width}/\tau_{pulse} = 0.3$
  - $R/Q = 100\ \Omega$
  - $Q = 84.6$ (loaded)
  - Cavity Radius = 9.009 cm
  - Cavity Length = 9.144 cm
  - Gap Length = 3.1 cm (centered in the Cavity)
  - Solenoid Field = 126 G (Brillouin Field)

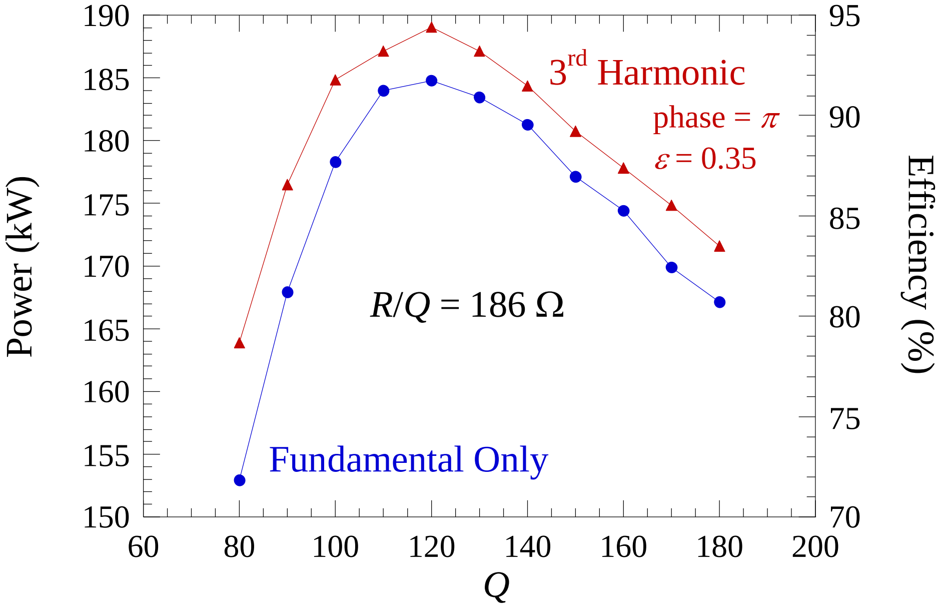
- Simulation results indicate:
  - Optimal performance when the phase of the 3^{rd} harmonic relative to the fundamental is π
  - Efficiency is enhanced from 84.4% to 86.3%



MBIOT SIMULATON

- Eight beam configuration circulating the cavity at the midpoint
    - *f* =700 MHz
    - 30 kV/6.67 A
    - $R/Q = 186\ \Omega$, $Q = 120$
    - $L_{cavity} = 9.144$ 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%

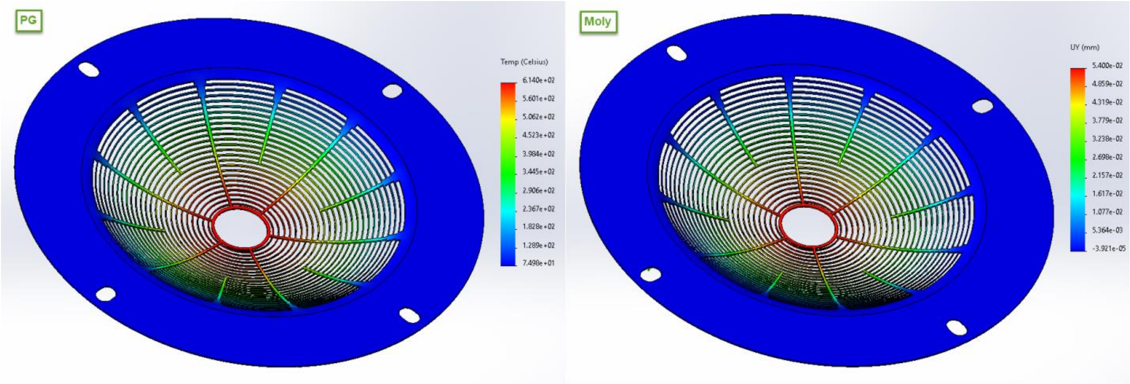
METAL GRID DESIGN

Current IOTs use pyrolytic graphite (PG) grids

- Difficult to fabricate
- Expensive
- Relatively low yield

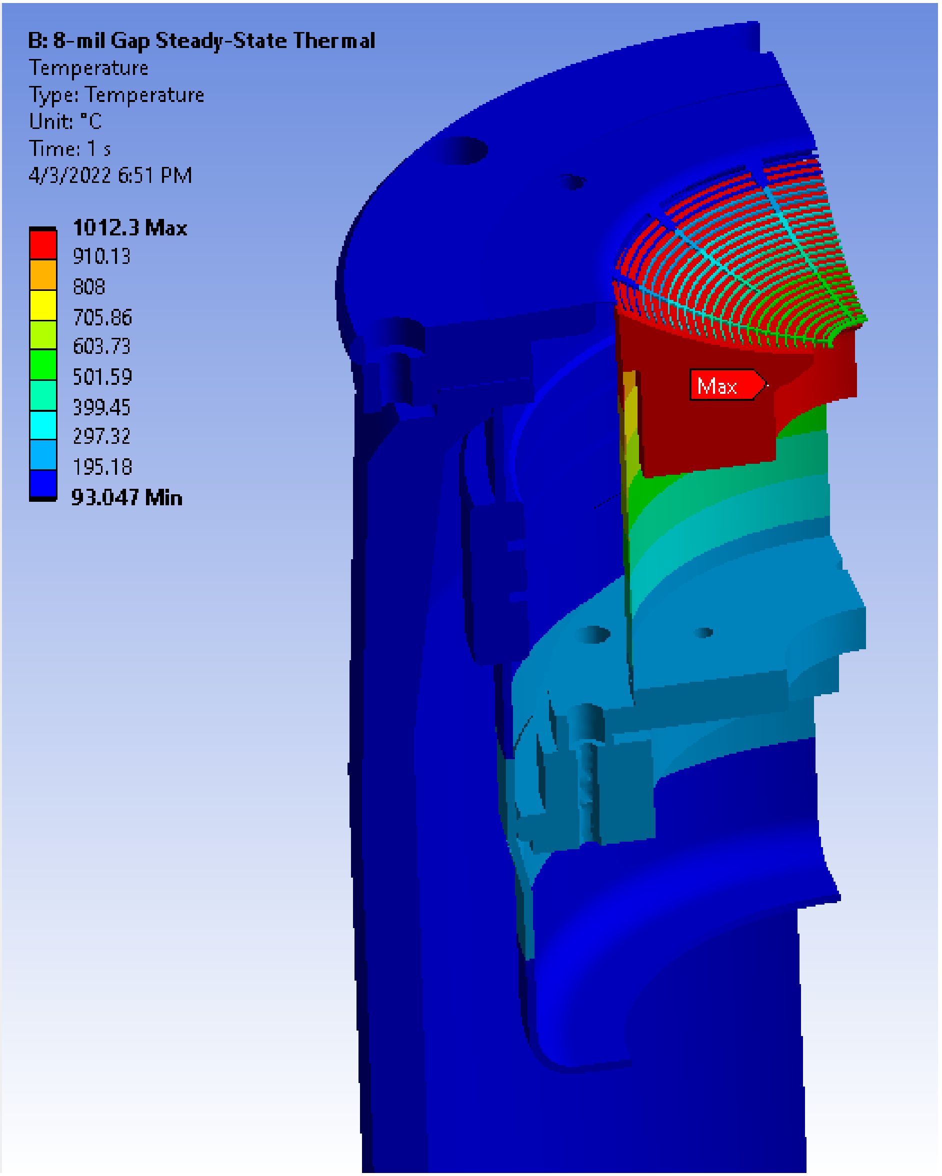
MBIOT beam power distributed over multiple beams

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



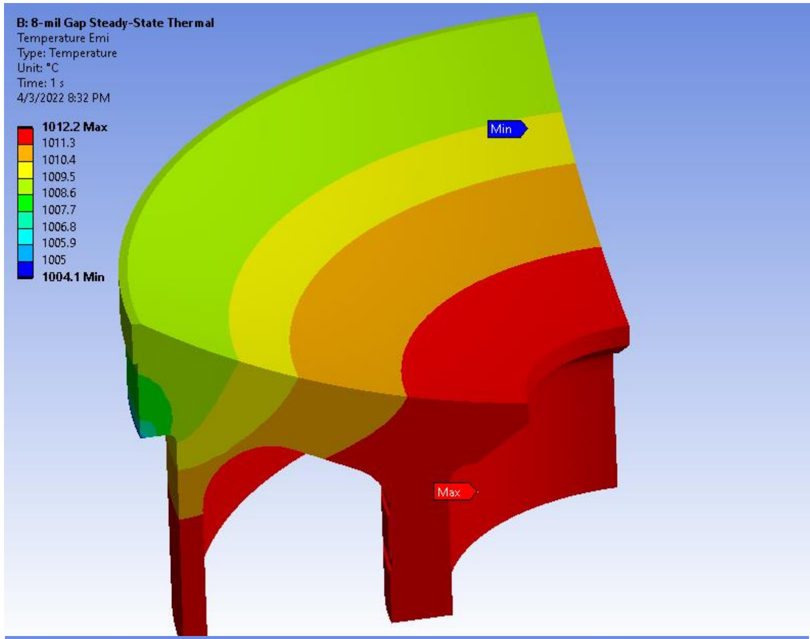
Beam Optics Analyzer thermomechanical analysis with beam interception and cathode radiation

TEMPERATURES



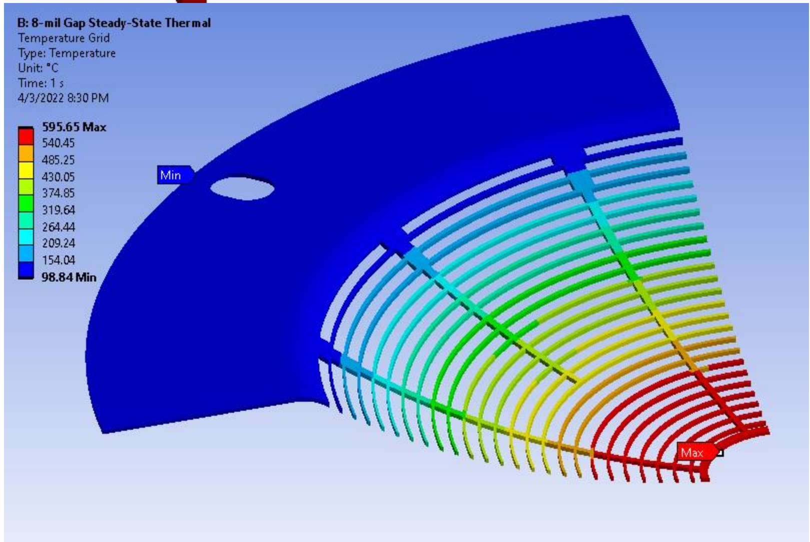
B: 8-mil Gap Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1 s
4/3/2022 6:51 PM

Emitter



B: 8-mil Gap Steady-State Thermal
Temperature Emi
Type: Temperature
Unit: °C
Time: 1 s
4/3/2022 8:32 PM

Grid



B: 8-mil Gap Steady-State Thermal
Temperature Grid
Type: Temperature
Unit: °C
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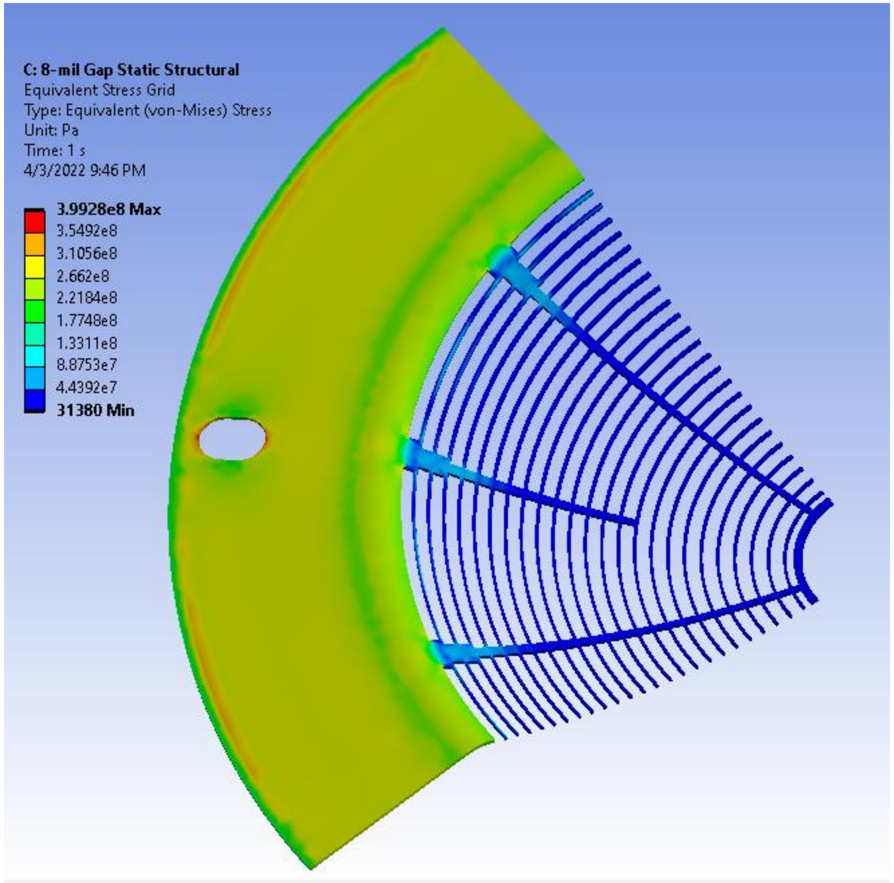
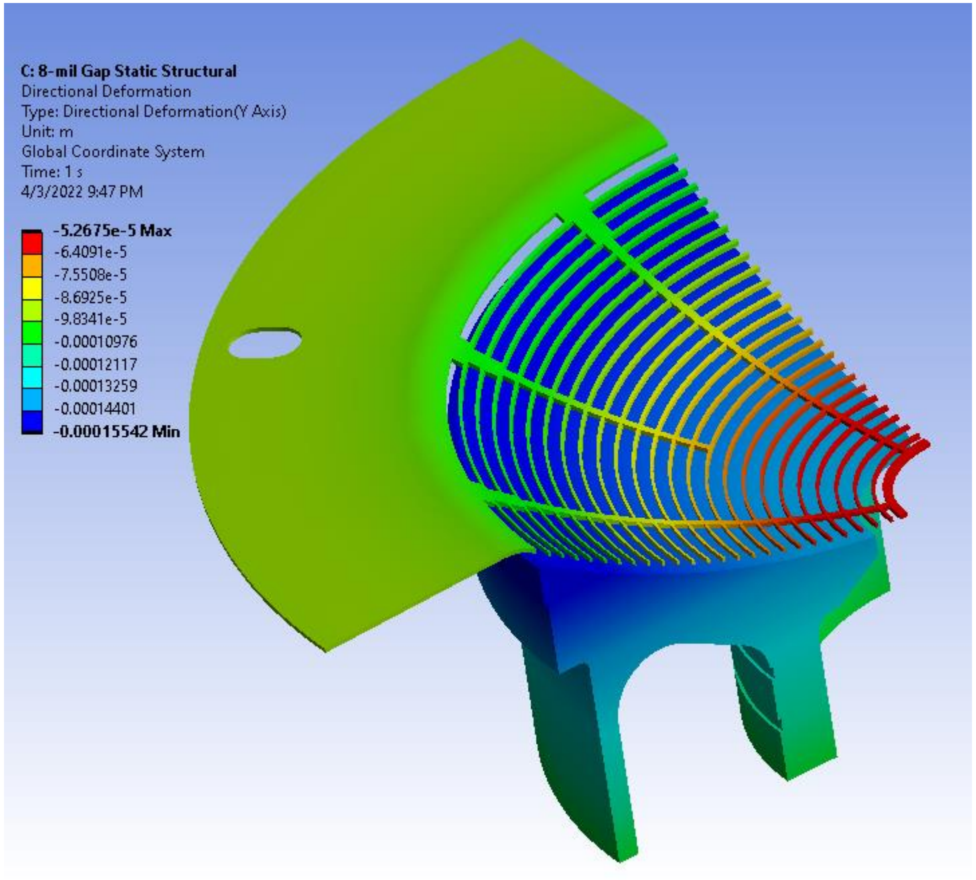
THERMAL STRESS & AXIAL DISPLACEMENT



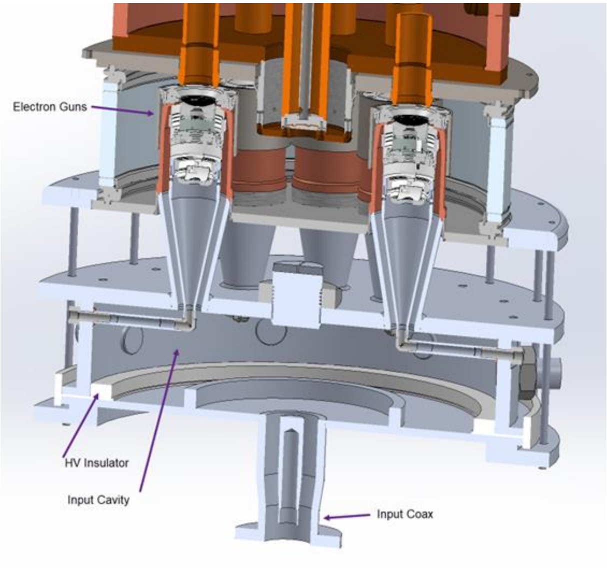
Highest stress is on the grid rim, but still below Moly tensile strength



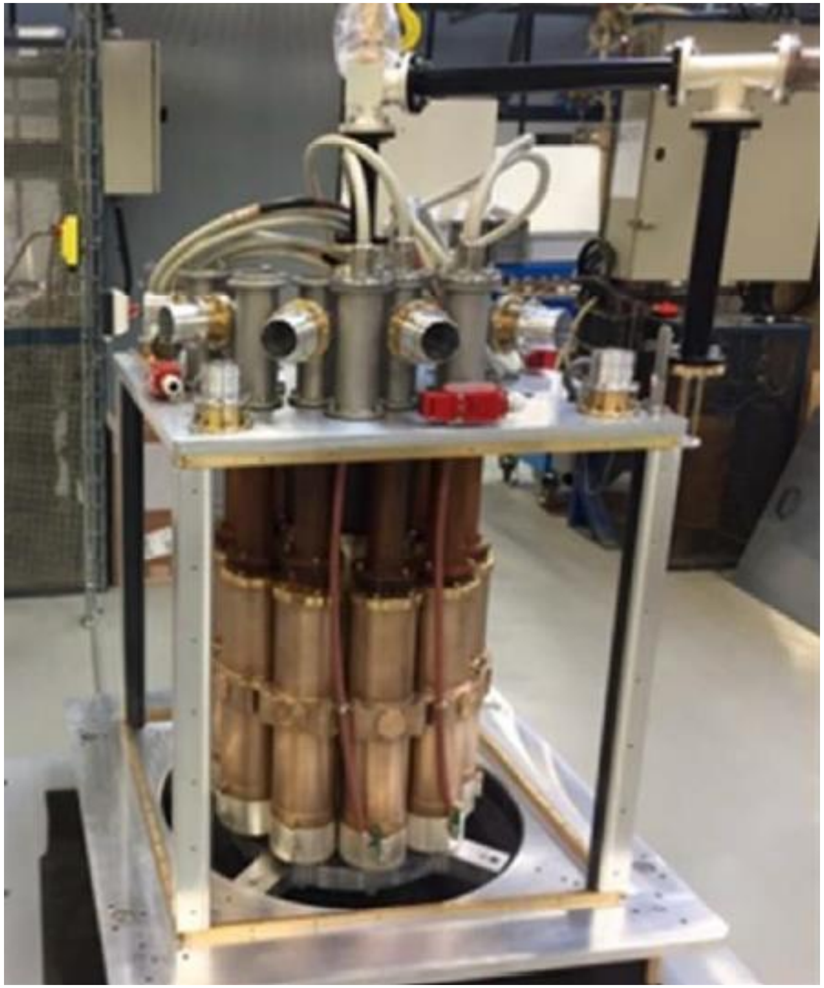
At temperature, grid OD moves closer to the emitter 1.9 mils, ID closer 3.3 mils

Input Coupler

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



Input coupler for CCR MBIOT



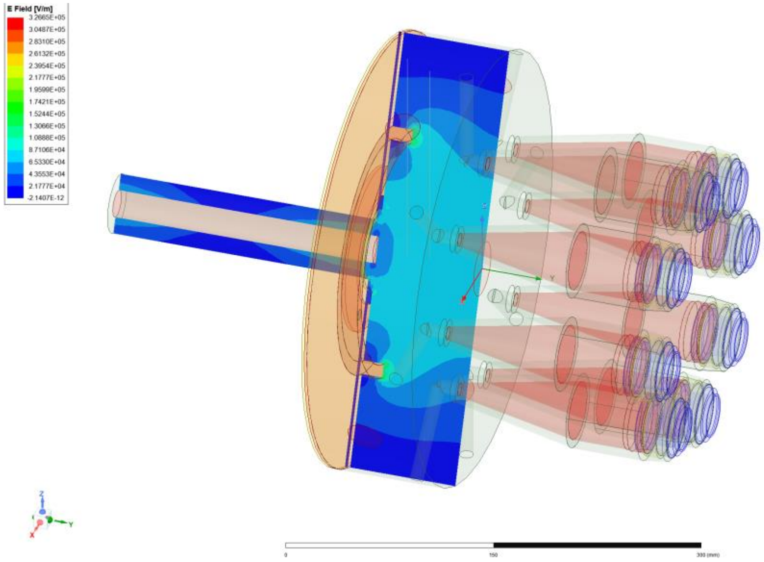
Input coupler for CPI/Thales MBIOT

Input Coupler

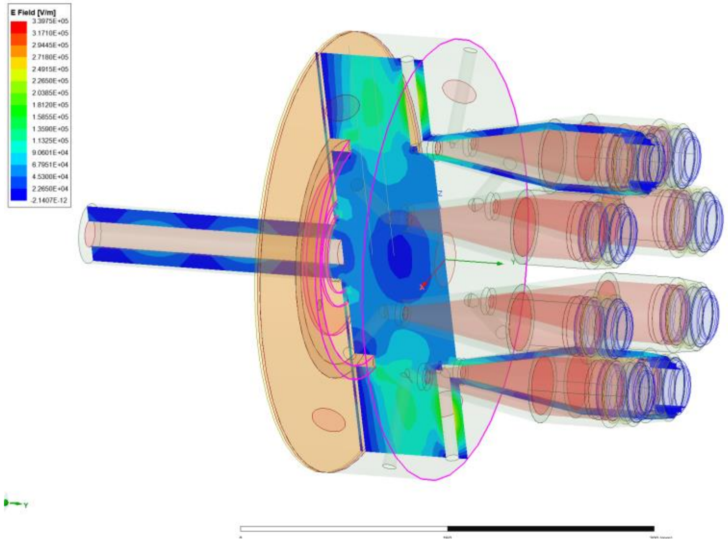
Challenge – develop coupler transmitting fundamental and 3rd harmonic

Incorporated structures/tuners specific to each frequency

700 MHz



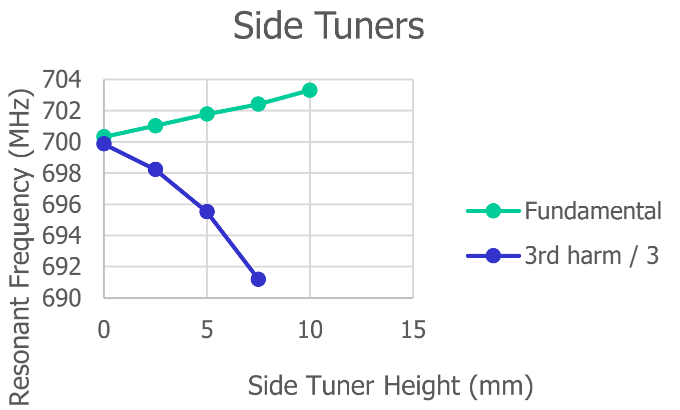
2100 MHz

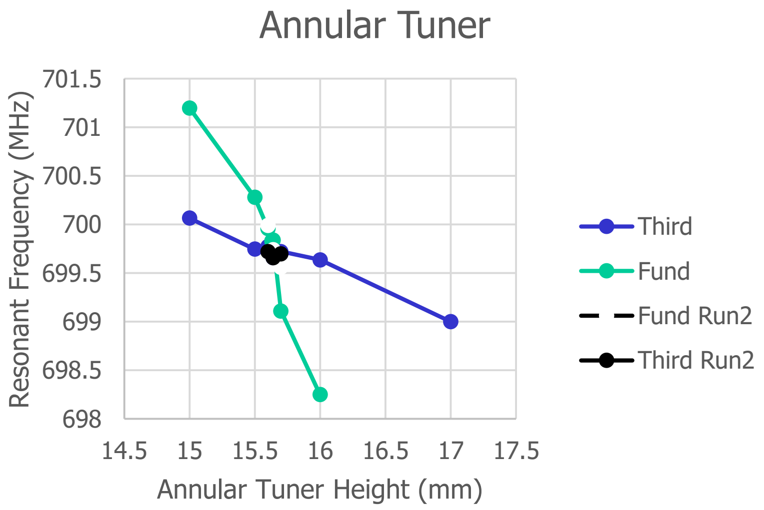


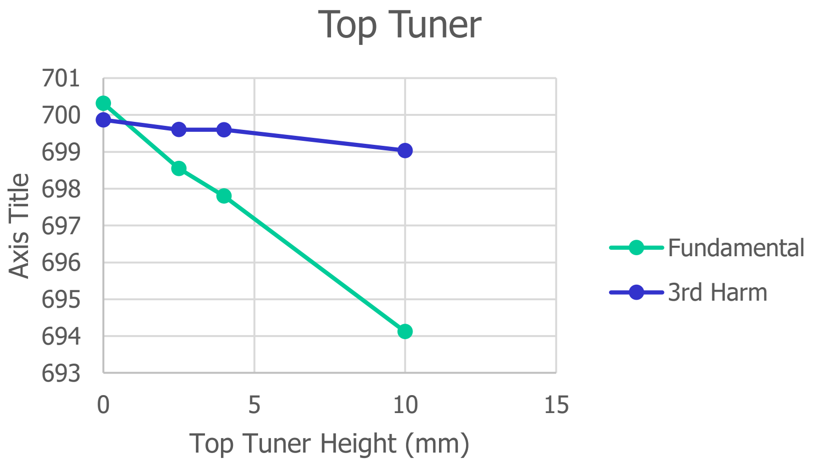
Input Cavity Tuning

Three sets of tuners for adjusting fundamental and 3rd harmonic

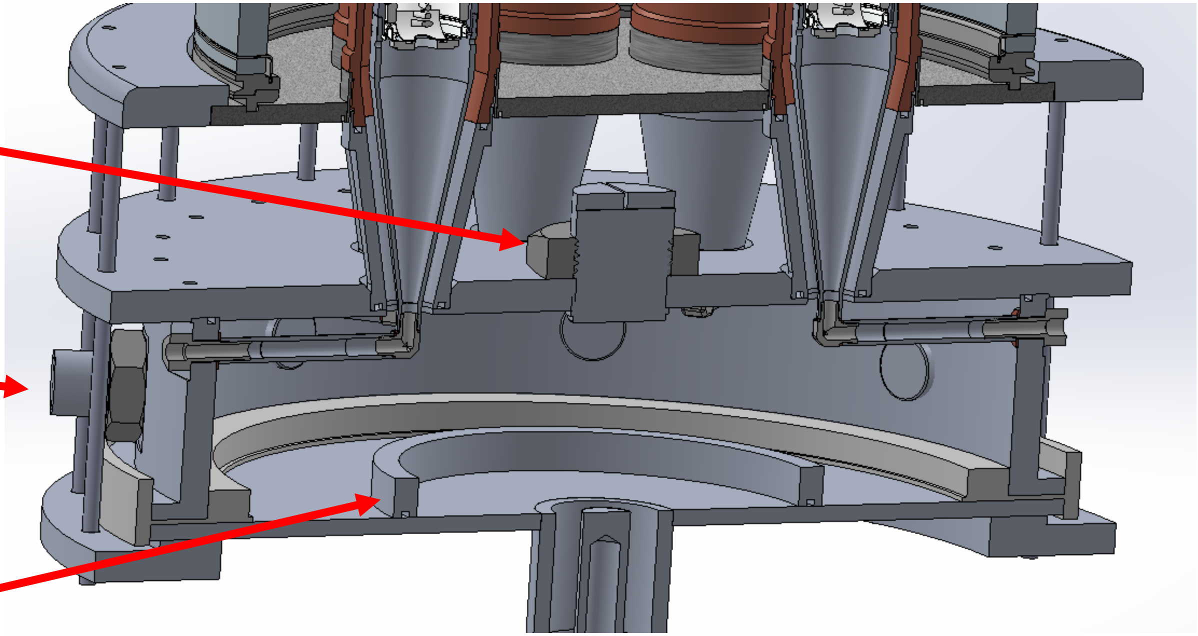
- Annular tuner
- Side tuners
- Top Tuner







Input Cavity Tuning



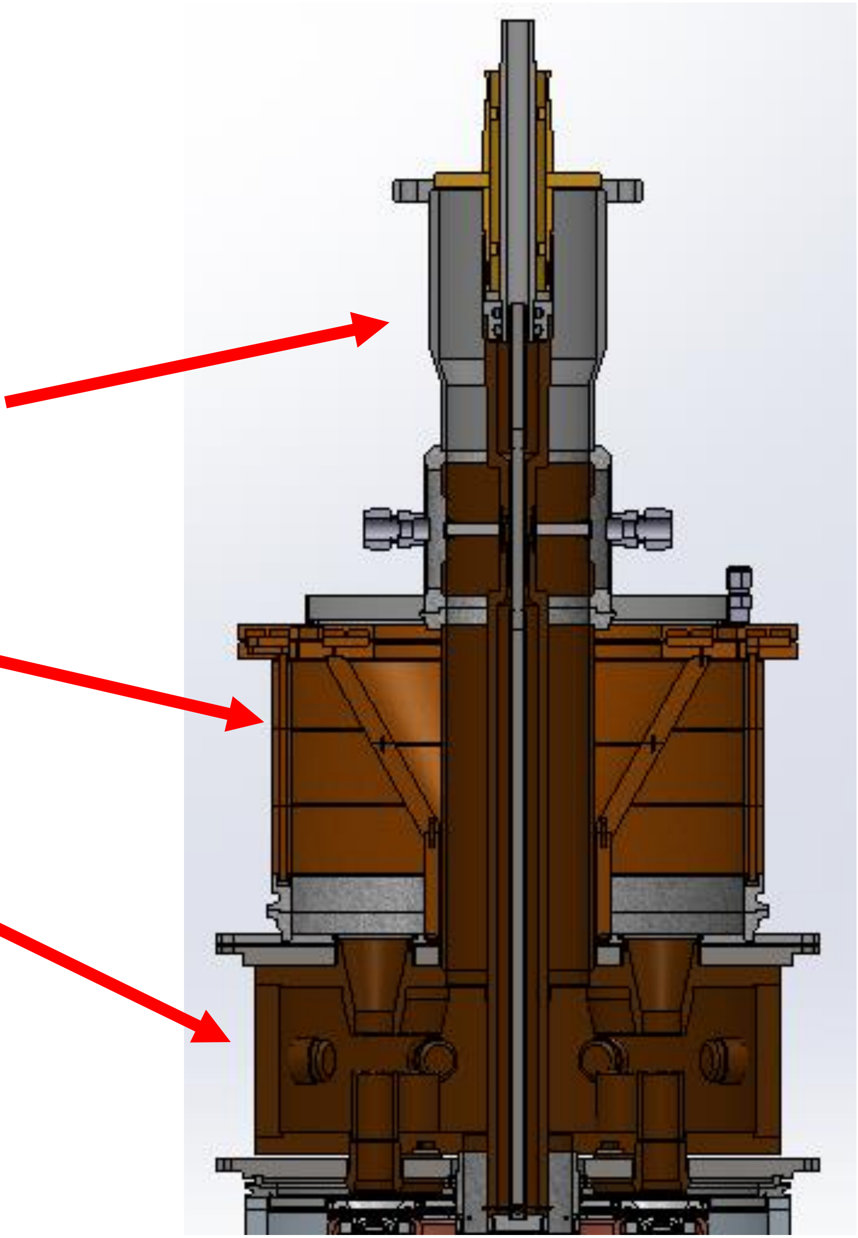
Top

Side

Annular

Note – Input cavity is at atmospheric pressure

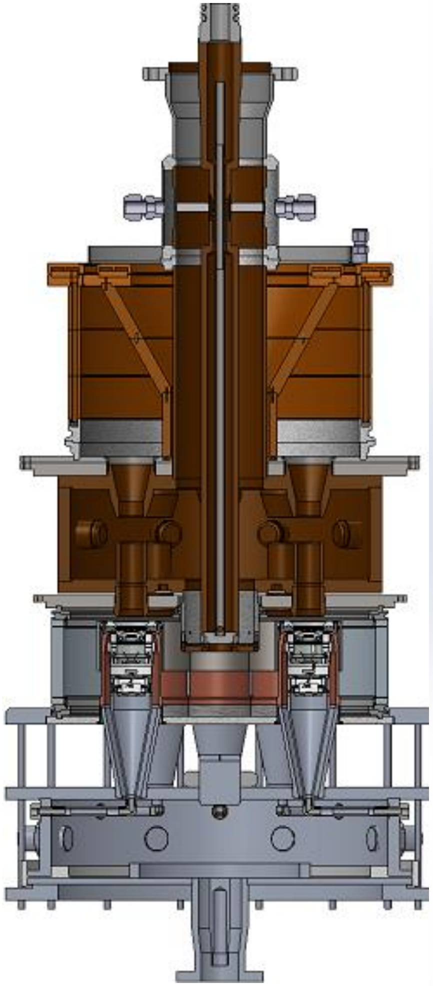
MBIOT Design

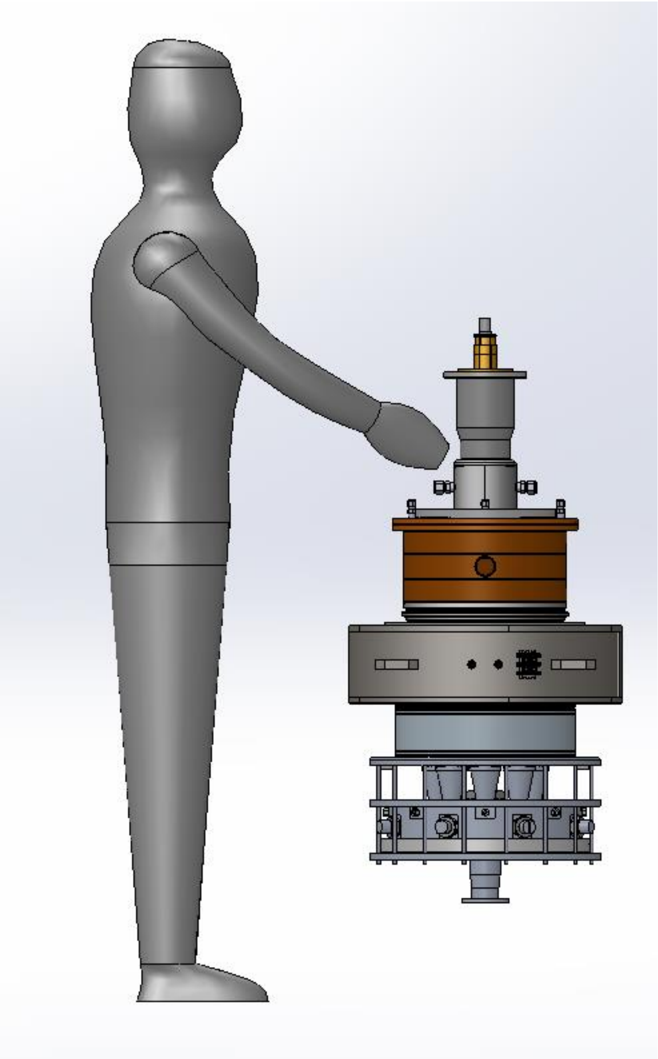


- Coaxial output window
- Single collector for all beams
- Simple output cavity

200 kW, 700 MHz MBIOT

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





MBIOT 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

Goals

- Improve efficiency
- Reduce cost and complexity
- Generate 200 kW CW at efficiency exceeding 80%

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 80% Freq/Pwr Scalable
- Triode-base RF sources 200 kW CW 350–700 MHz $0.5/Watt compact Assembly in progress
- Multiple Beam IOT 700 MHz 200 CW kW 80% Drawings and fabrication in progress