Calabazas Creek Research, Inc.

Multiple Beam IOT Development at Calabaza Creek Research, Inc.

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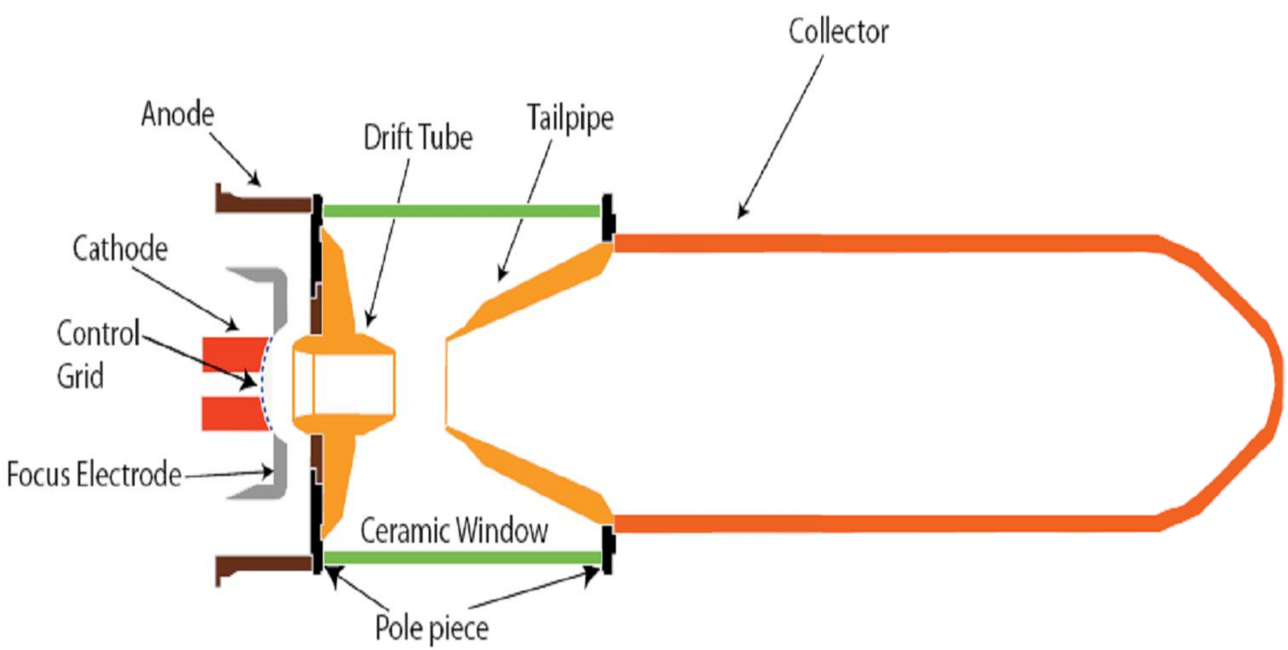
INDUCTIVE OUTPUT TUBES

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



GOAL AND APPROACH

- **GOAL – To develop a high efficiency IOT with a efficiency greater than 80%**

APPROACH

- Add 3rd harmonic drive on the grid in the multi-beam gun*
- Enhance bunching in the gun(s) to improve efficiency
- Use/Modify code NEMESIS to simulate the output cavity
- Use innovative input coupler fordrive signals to the grids
- Use metal grids to reduce cost and improve durability

* U.S. Patent 10734182: *Ultra-high Efficiency Single-Beam and Multi-Beam IOTs* (awarded 4 August 2020)

BACKGROUND/ADVANTAGES

- Multi-Beam IOTs (MBIOTs) previously developed forthe European Spallation Neutron Source
  - 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

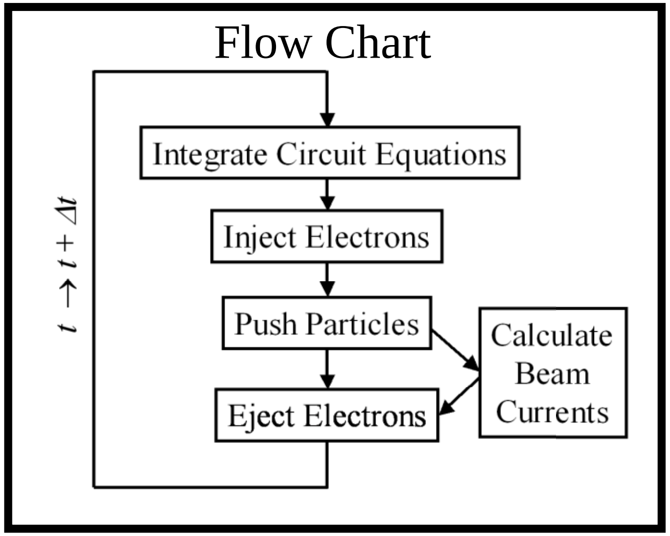
  - lower cost fabrication

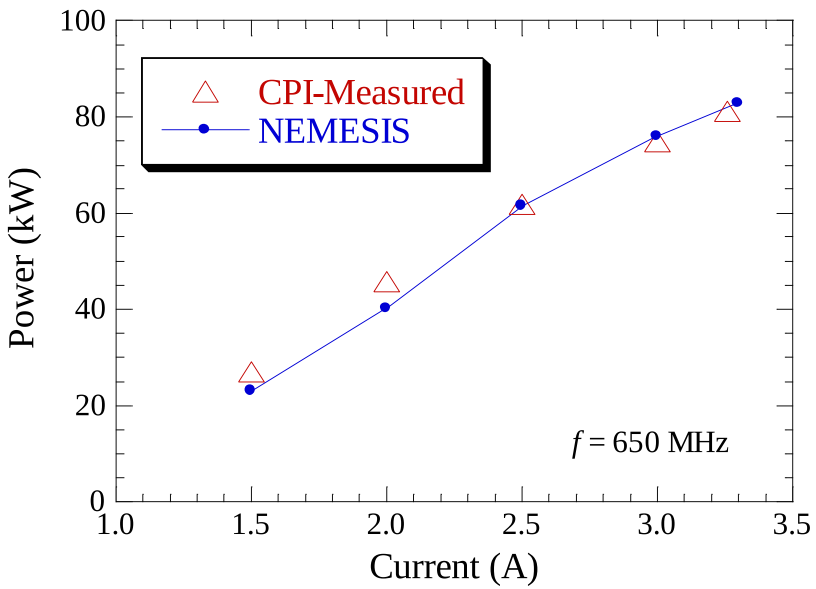
  - lower voltage operation

  - Class C operation

THE NEMESIS CODE*

- Properties of NEMESIS: PIC-like
  - Time-domain integration with leap-frog algorithm
  - RF fields 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
  - Electrons are ejected when they exit the cavity





- 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

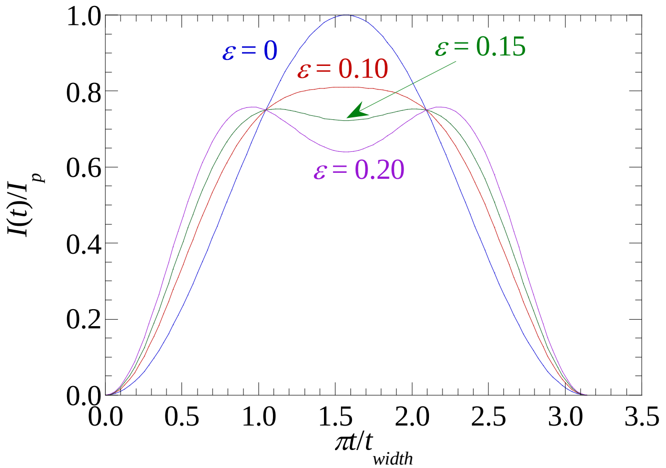
* H.P. Freund *et al*., IEEE Trans. Plasma Sci. **35**, 1081 (2007)

EXTENSIONS TO NEMESIS

- Three extensions to NEMESIS needed
  - Model bunching including the 3rd harmonic

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

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



- Extend injection model to azimuthally symmetric multiple (circular) beams around the symmetry axis

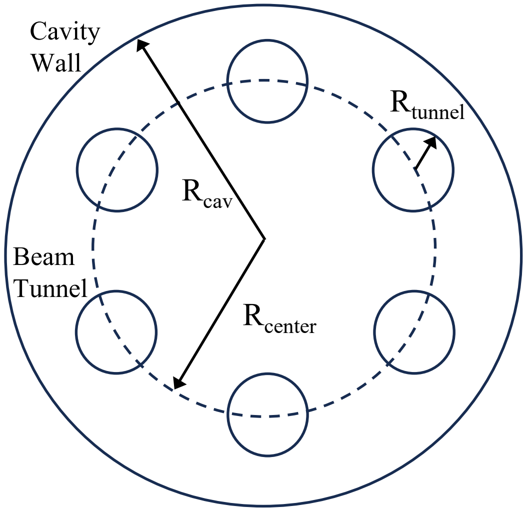
- Both 2-D and 3-D Poisson solvers available
  - 2-dimensional (r,z) Poisson solvers for solid or annular cylindrical beam
  - 3-dimensional (r,θ,z) Poisson solver using the Petsc Package (Argonne Nat'l. Lab.) **and parallelized**

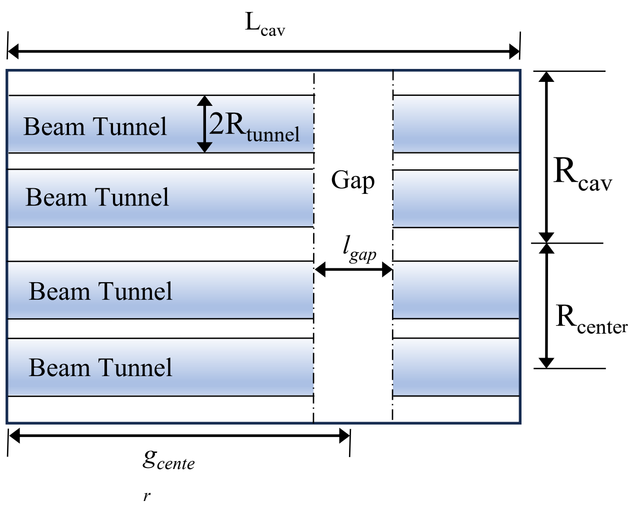
WHOLE-CAVITY SIMULATION

NEMESIS simulates the entire region enclosed by the output cavity wall, ncluding within each beam tunnel

Design Parameters

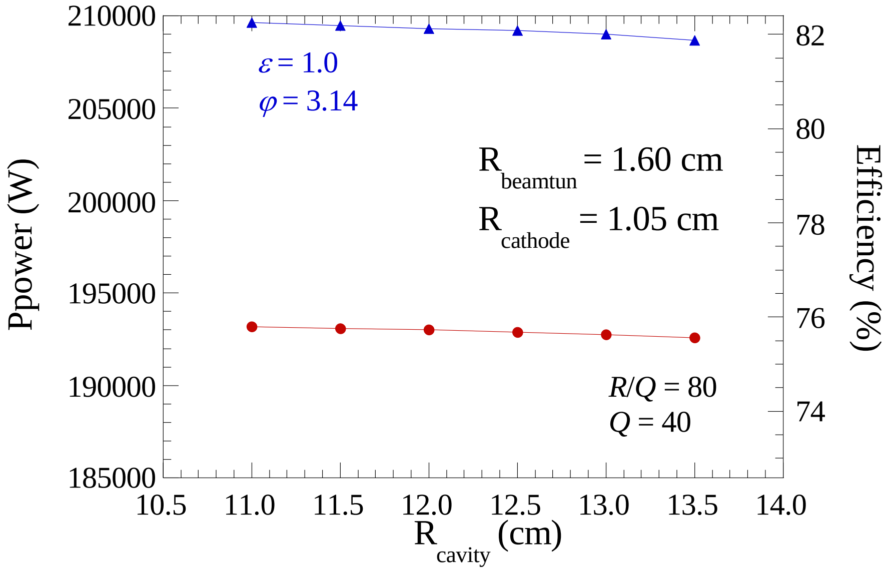
Electron Beam	8 beams
Voltage	35 kV
Average Current	7.25 A
Current Ratio	0.15
Perveance	1.1 mP
Cathode Radius	0.825 cm
Cavity	
Frequency	700 MHz
Cavity Q	40
R/Q	80
Cavity Radius	11 cm
Beam Tunnel Radius	1.6 cm
Cavity Length	9.144 cm
Gap Length	3.9 cm
Performance	
Input Power	4 kW
Output Power	200 kW
Gain	17 dB

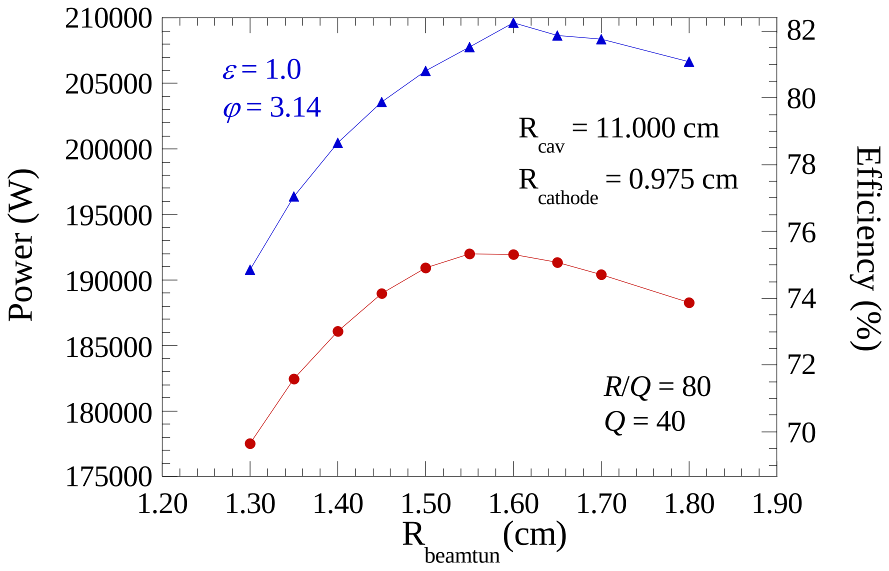


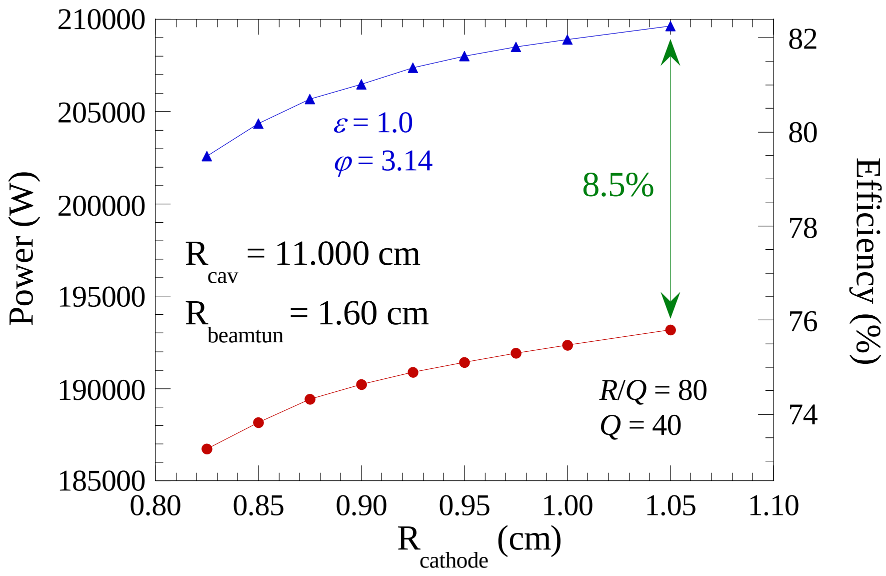


MBIOT PERFORMANCE

- Simulations predict efficiencies exceeding 80% using the 3rd harmonic drive on the grid

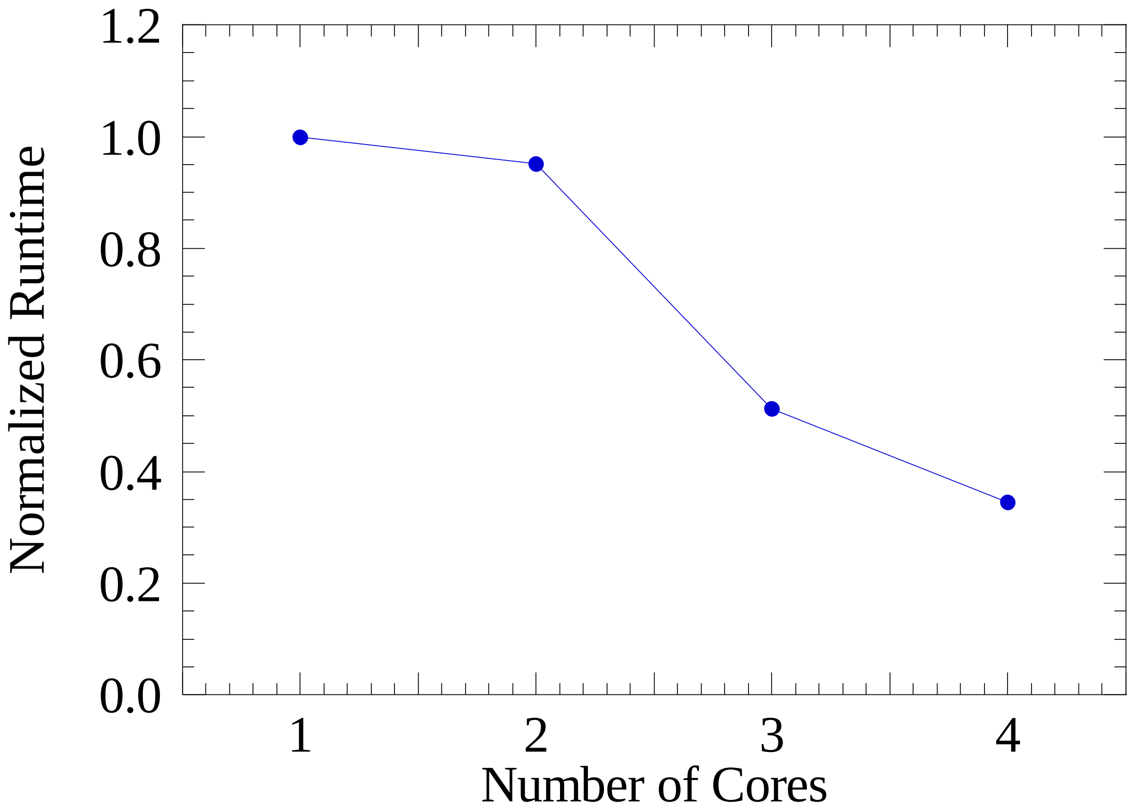






PARALLELIZATION

- NEMISIS parallelized using Microsoft MPI
  - Substantial improvement in run times found on a 4-core laptop

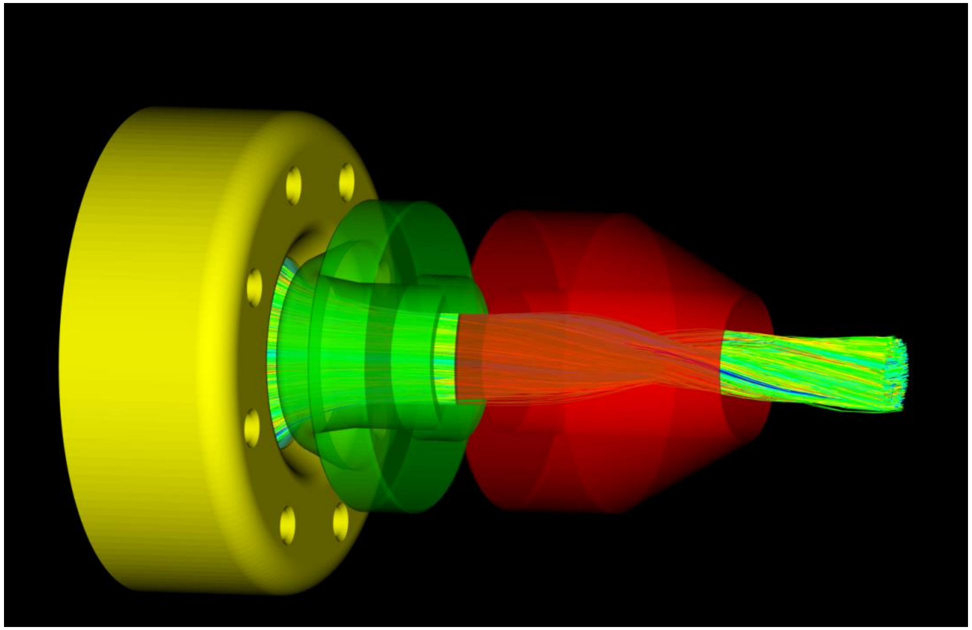


- NEMISIS being extended to single- and multi-beam klystrons

THE GUN

CPI K-2 Gun

BeamOptics Analyzer (BOA)
Gun Simulation



METAL GRID DESIGN

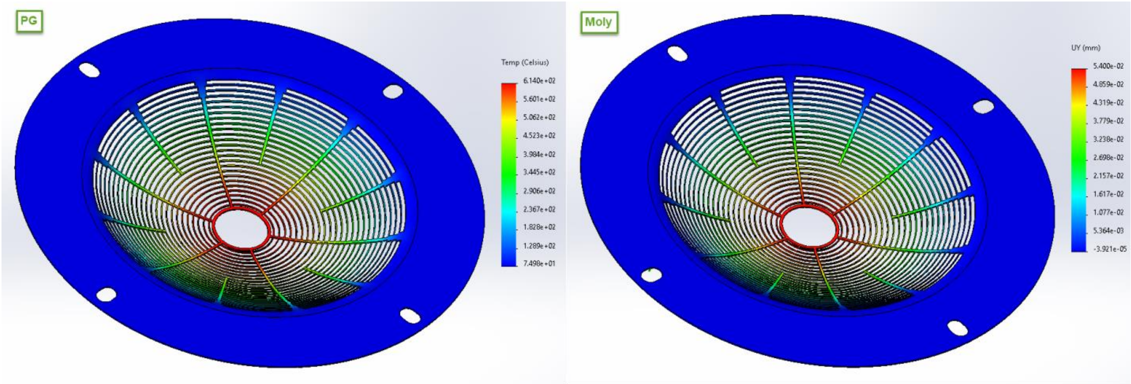
Current IOTs use pyrolytic graphite (PG) grids

- Difficult to fabricate
- Expensive
- Relatively low yield

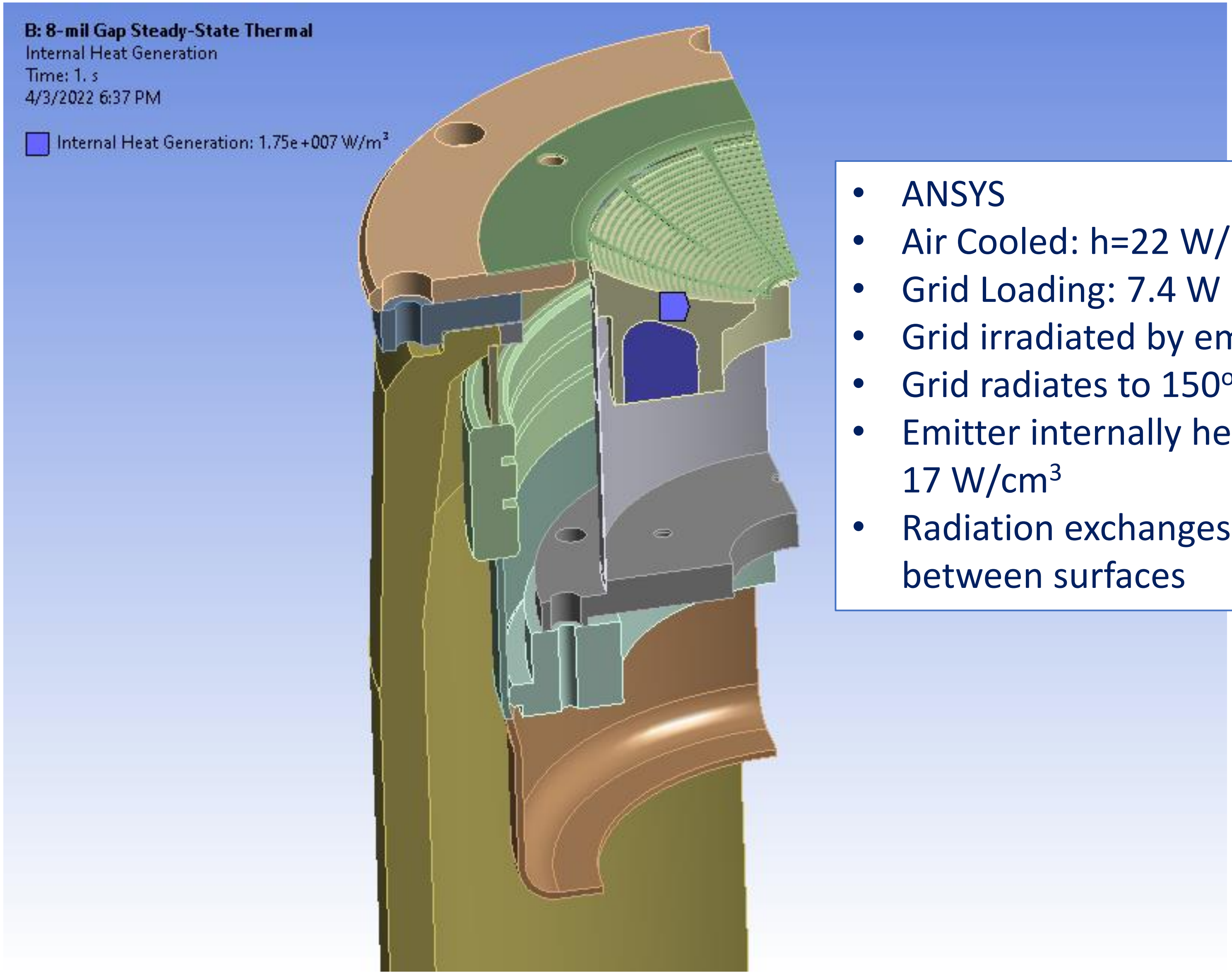
MBIOT beam power distributed over multiple beams

- Reduced power loading
- Thermomechanical analysis predicts good performance
- Potentially cheaper with higher yield

Beam Optics Analyzer (BOA) thermomechanical analysis with beam interception and cathode radiation

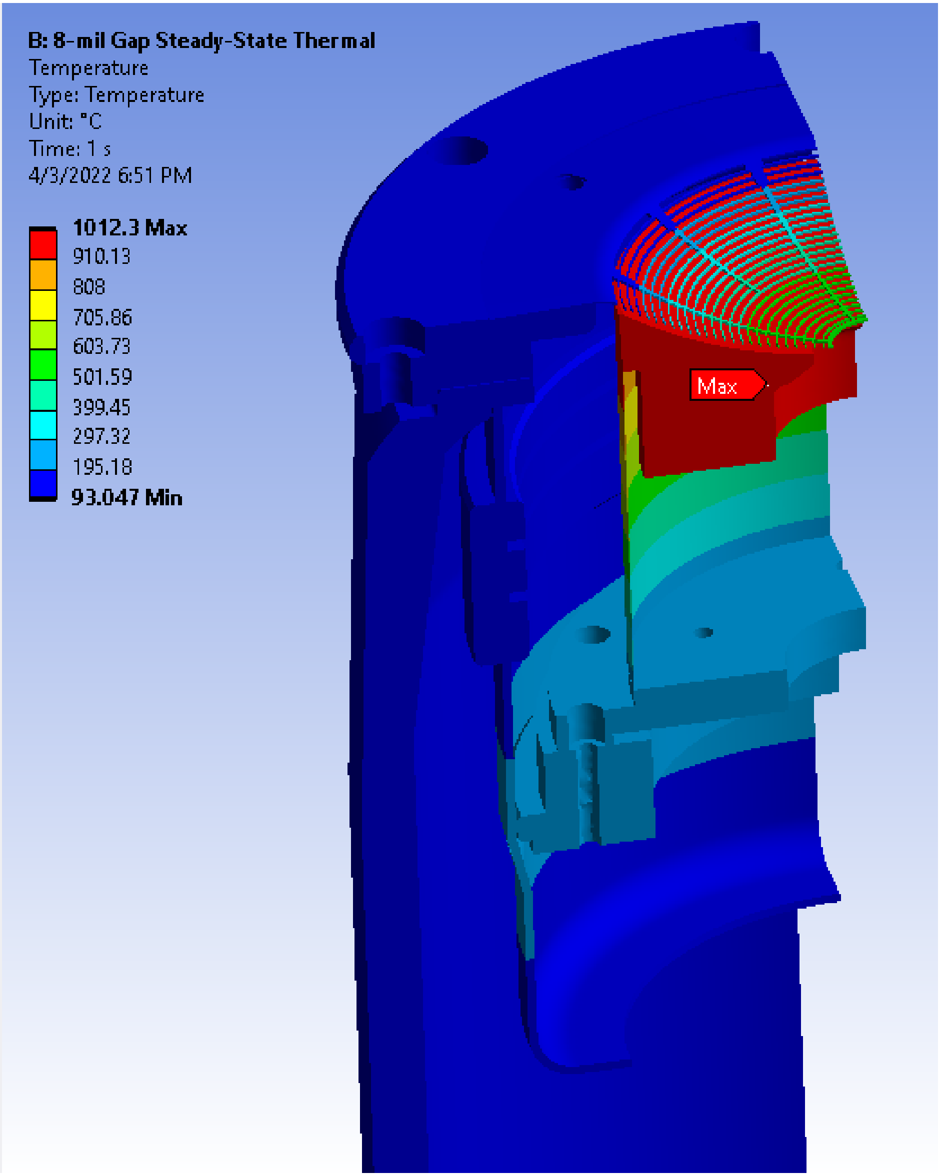


THERMAL & STRESS ANALYSIS MODEL

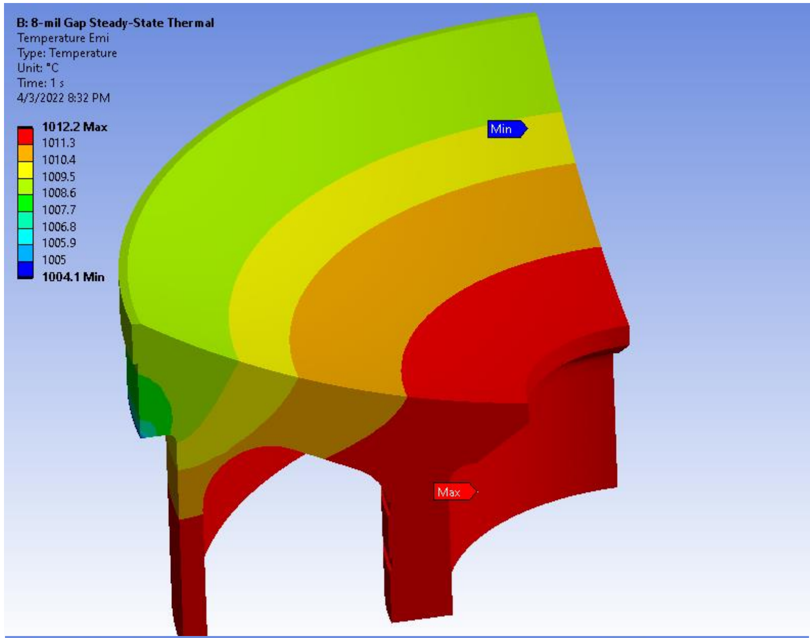


- ANSYS
- Air Cooled: h=22 W/m^2-^{o}C
- Grid Loading: 7.4 W
- Grid irradiated by emitter
- Grid radiates to 150^{o}C sink
- Emitter internally heated, 17 W/cm^3
- Radiation exchanges between surfaces

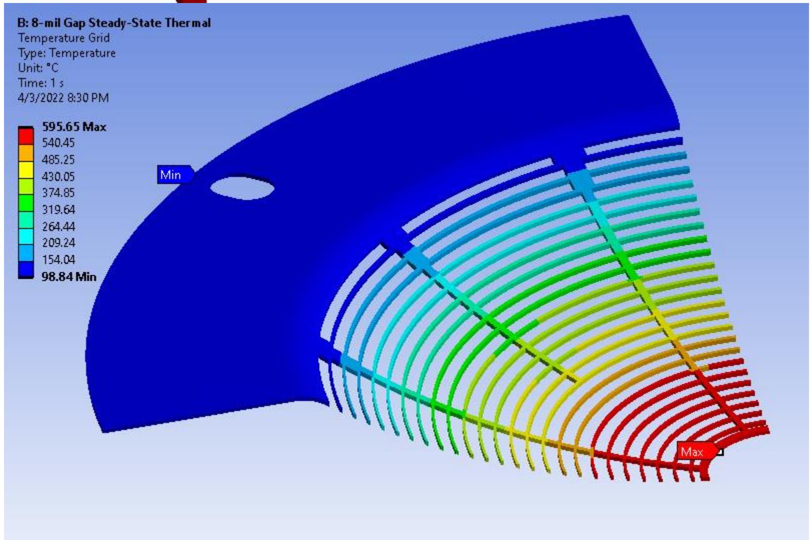
TEMPERATURES



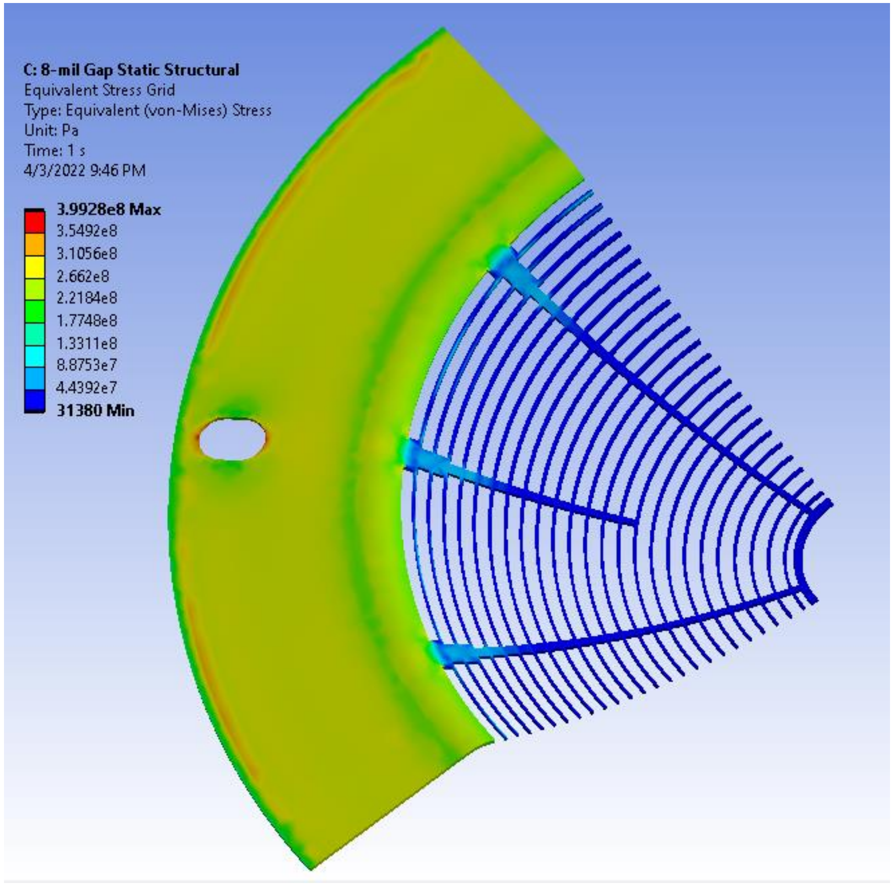
Emitter

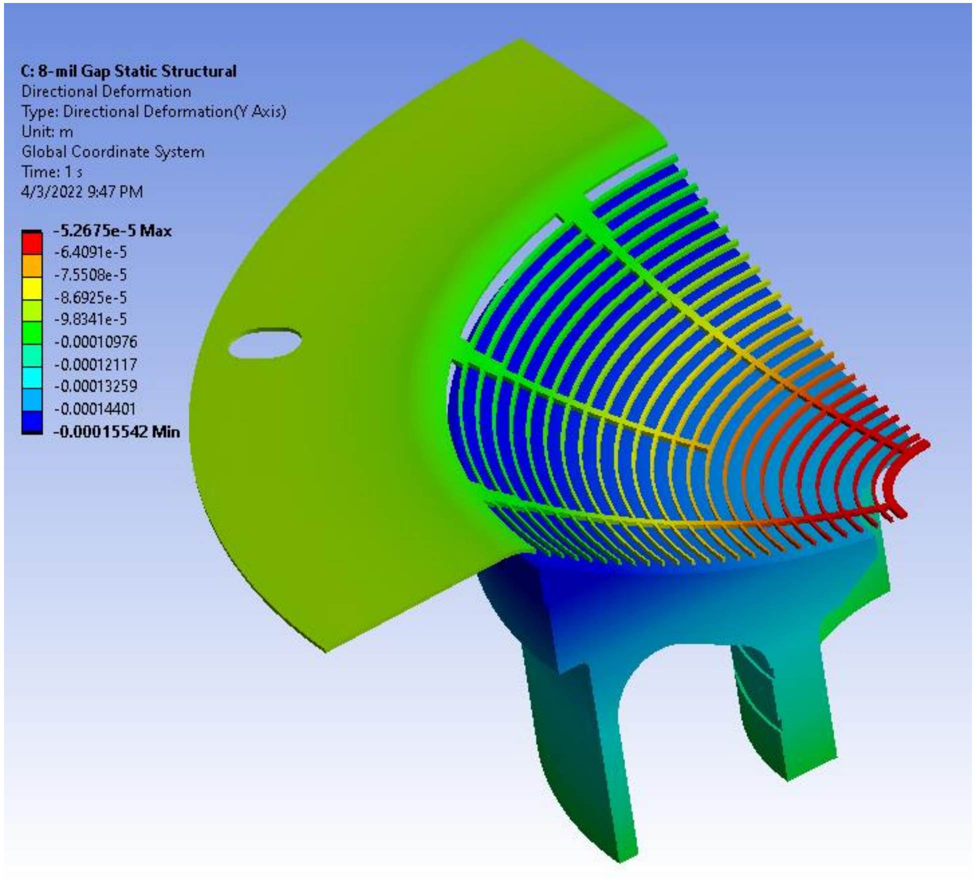


Grid



THERMAL STRESS & AXIAL DISPLACEMENT





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

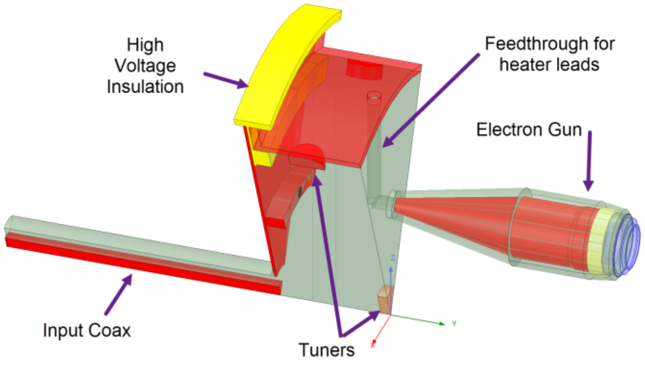
At temperature, grid OD moves closer to the emitter 1.9 mils, ID closer 3.3 mils

Metal IOT Grid Fabrication

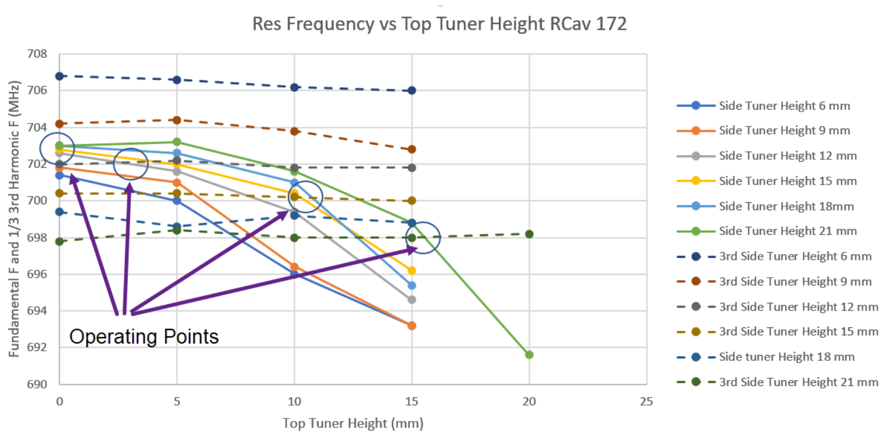
- CCR was unable to identify any grid manufacturers able to make moly grids in the quantities required, except one
- Test grids failed to meet specifications
- There currently does not appear to be a vendor available to make moly IOT grids
- Any guns for the MBIOT will be built using PG grids

INPUT COUPLER

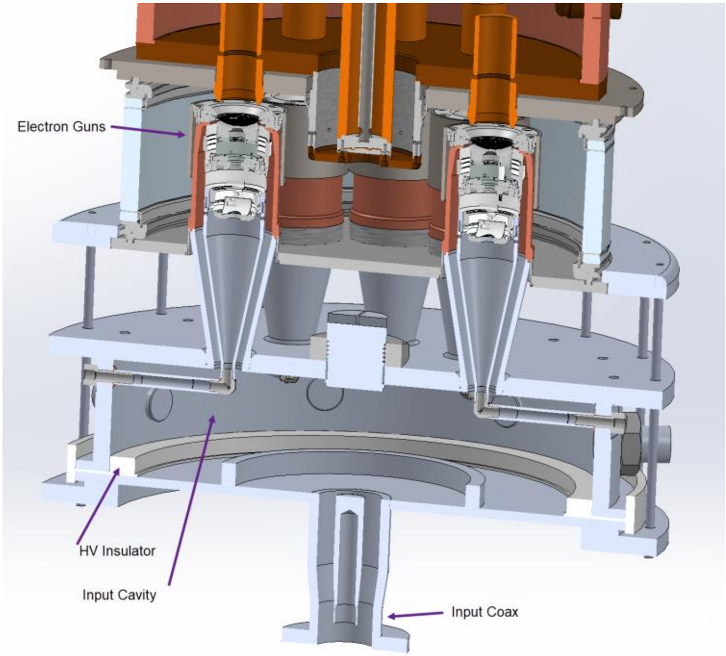
- Must transit both fundamental and 3rd harmonic
- Bessel roots not evenly spaced, perturb fundamental w annulus, side and top tuners to get a range of 3x fundamental = 3rd harmonic
- 60 V grid voltage requires about 2 kW of drive



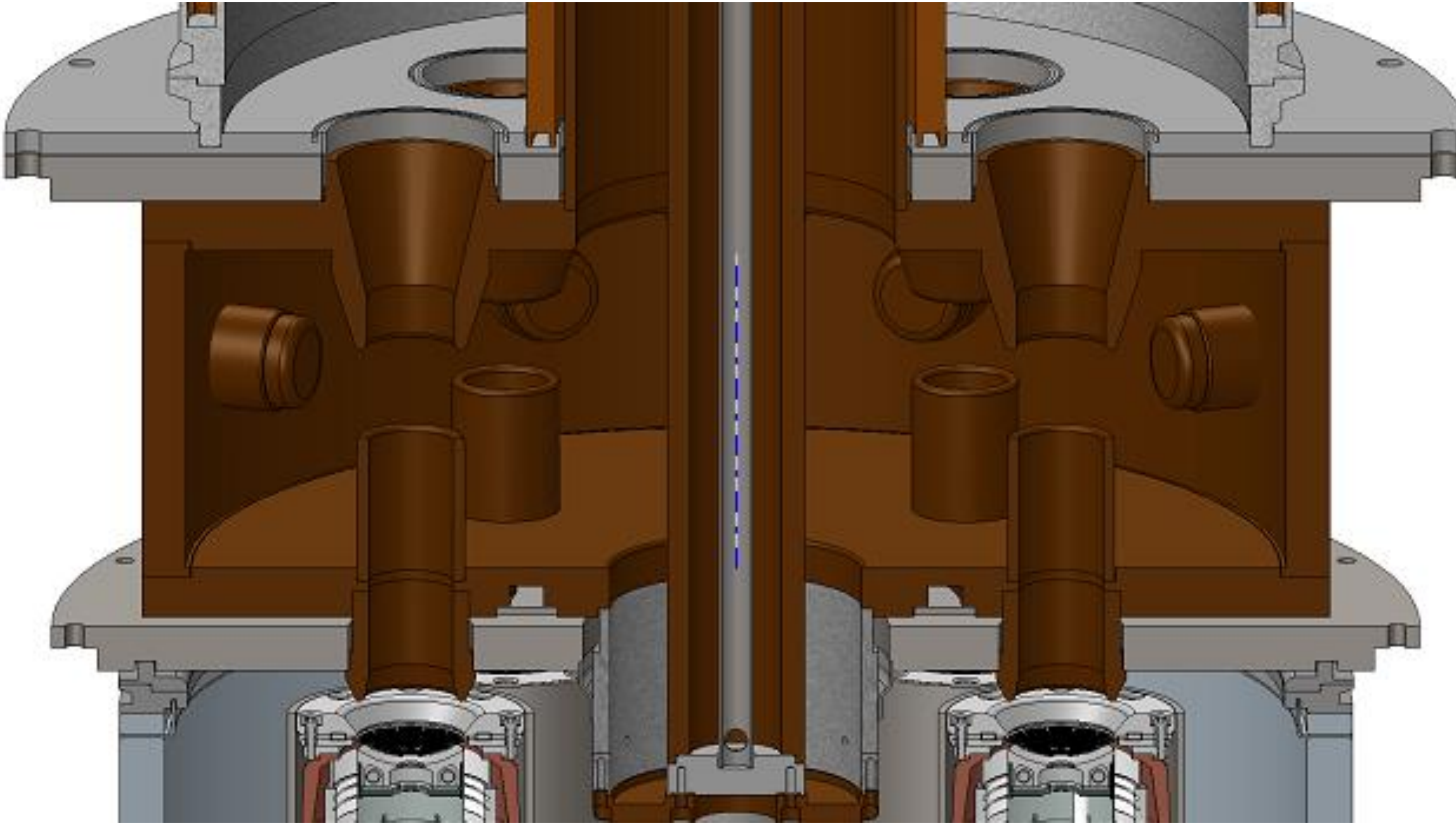
HFSS Model (1/8)



~ 5 MHz tuning range



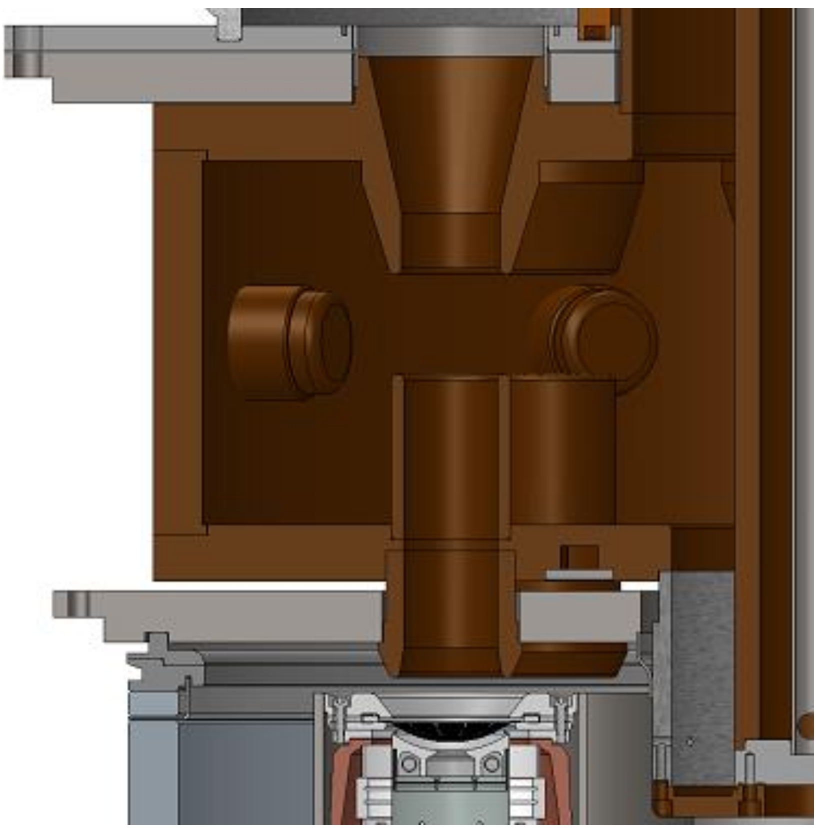
THE OUTPUT CAVITY



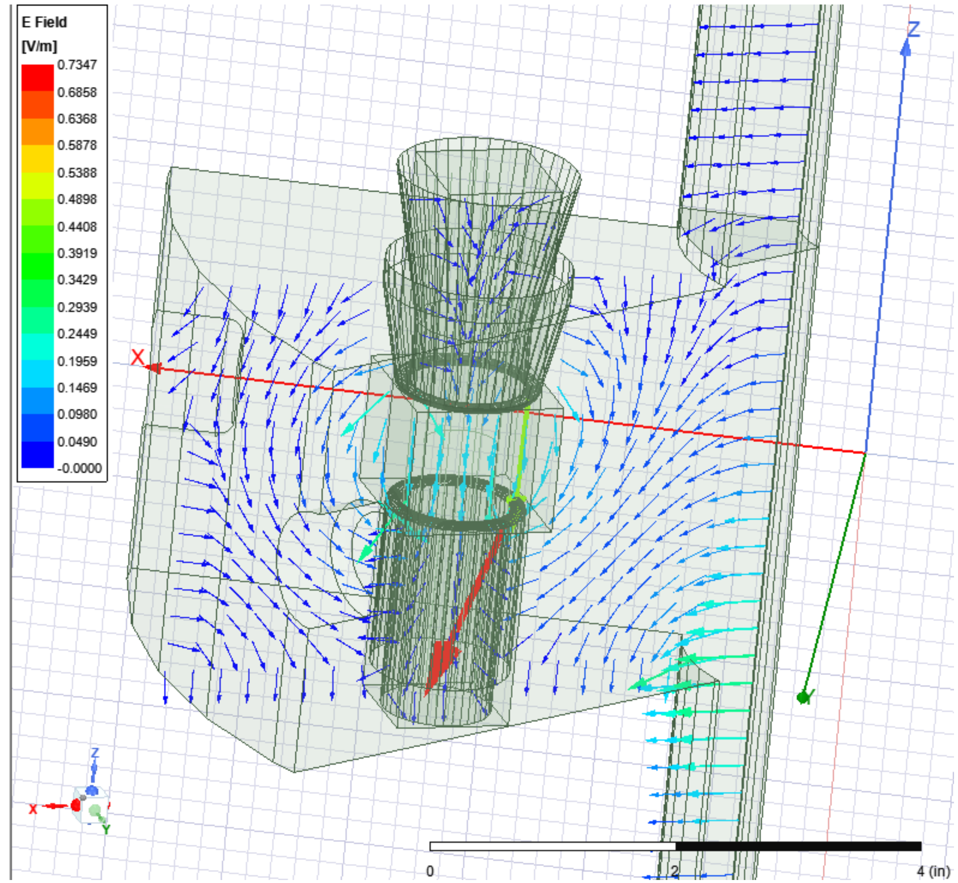
MBIOT OUTPUT CAVITY DESIGN

- HFSS simulations achieved f=699 MHz, R/Q=188Ω, and Qe=140 (to be fine-tuned)
- Coaxial design for better uniformity of RF fields within the beam region

Solidmodel of the output cavity



OP cavity 1/8th slice, HFSS electric field plot on plane through drift tubes



DEVELOPMENT STATUS

Program achieved several goals:

- Improved simulation capability using NEMESIS
  - Includes 3rd harmonic drive
  - 2d and 3d Poisson solvers
  - Parallelized for improved performance
- Demonstrated potential improvement with 3rd harmonic drive
- Developed improved input coupler supporting fundamental and 3rd harmonic drive

- Failed to identify a vendor for metal (moly) grids
- Covid and supply chain issues prevented fabrication and test of prototype tube