Modeling and Design of High-Power Single-Beam and Multiple-Beam Inductive Output Tubes

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*Work supported by the Office of Naval Research
and Naval Sea Systems Command.

Modeling and Design of High-Power Single-Beam and Multiple-Beam Inductive Output Tubes

- The inductive output tube (IOT) is a linear beam amplifier that is ideally suited to high-power operation at UHF and L-band frequencies.

- The IOT RF gridded electron gun directly bunches the beam, resulting in an efficient, compact, linear amplifier.

- The IOT has become the amplifier-of-choice for UHF broadcast applications, typically at peak power levels in the 100's of kW – average power level ~ -6 dB lower. A number of high-power accelerator applications require substantially higher average power than a conventional, single-beam IOT can generate.

- A multiple-beam (MB) IOT has been proposed to overcome the power limitation of the single-beam device while maintaining its extremely attractive features.

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- Although conceptually simple, the design and optimization of an IOT is quite difficult.
- The input cavity is extremely complex due to the intrinsically three-dimensional topology.
- Two factors greatly complicate the modeling and optimization of the RF gridded gun of the input circuit:
  - *Disparate spatial scales (~1000 to 1) of the electrodes and accelerating gap compared to the extremely fine grid and cathode-grid gap.*
  - *Difficulty of accurately modeling beam emission at low voltages, which occur at the beginning and end of each RF extraction cycle (beam head and tail effects).*

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- Our team is developing a suite of modeling and simulation tools that are ideally suited to overcoming these problems and that can be extended and applied sequentially to provide an accurate, computationally efficient end-to-end design tool for the IOT and MB-IOT.

- The primary codes are:
  - *MICHELLE - a 3D steady-state and time-domain electrostatic PIC code.*
  - *Analyst - a 3D electromagnetic simulation code suite.*
  - *TESLA - a 2.5D large signal code for modeling cavity-type linear beam amplifiers.*

- These physics-based design tools have been applied with great success by the vacuum electronics industry to develop an assortment of new and improved devices.
- Initial simulation results for an example IOT follows:

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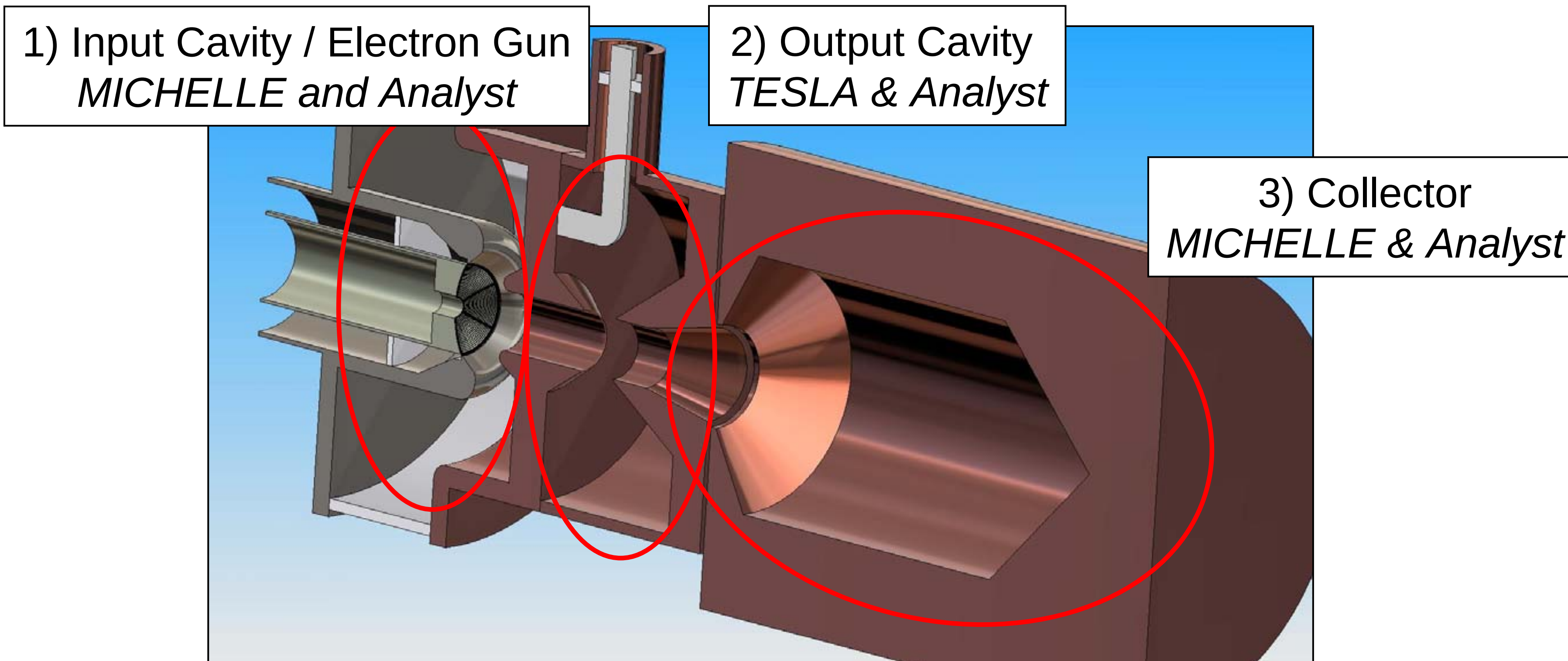
- Code validation is performed on a section of a single-beam IOT model.
  - *Efficient end-to-end modeling achieved by subdividing the problem into three sections.*



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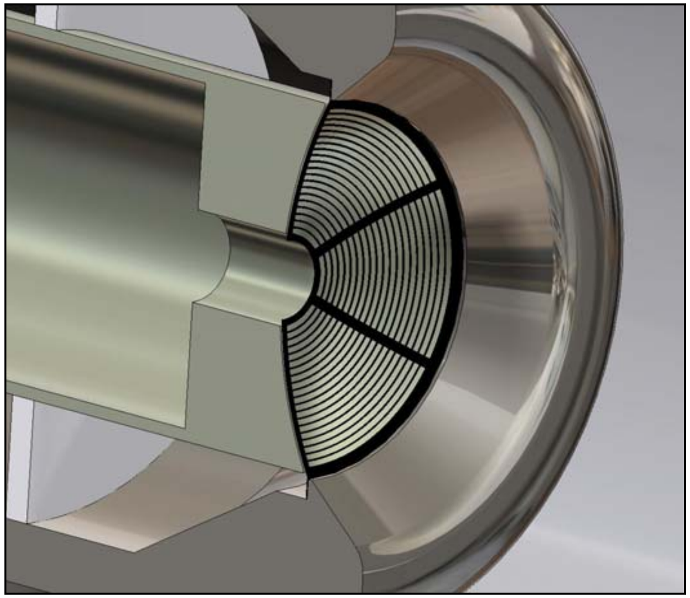
- 1) IOT input cavity / electron gun – modeling is a four-step process
  - *Analyst – Mesh generation.*
  - *Analyst – Cathode to Grid circuit tuned to resonance at 700 MHz.*
  - *MICHELLE – Steady-state with variable cathode to grid bias voltage; determine cutoff.*
  - *MICHELLE – Time-domain PIC with Analyst RF fields modulating the grid.*



- Examples of each step will be shown in the following slides

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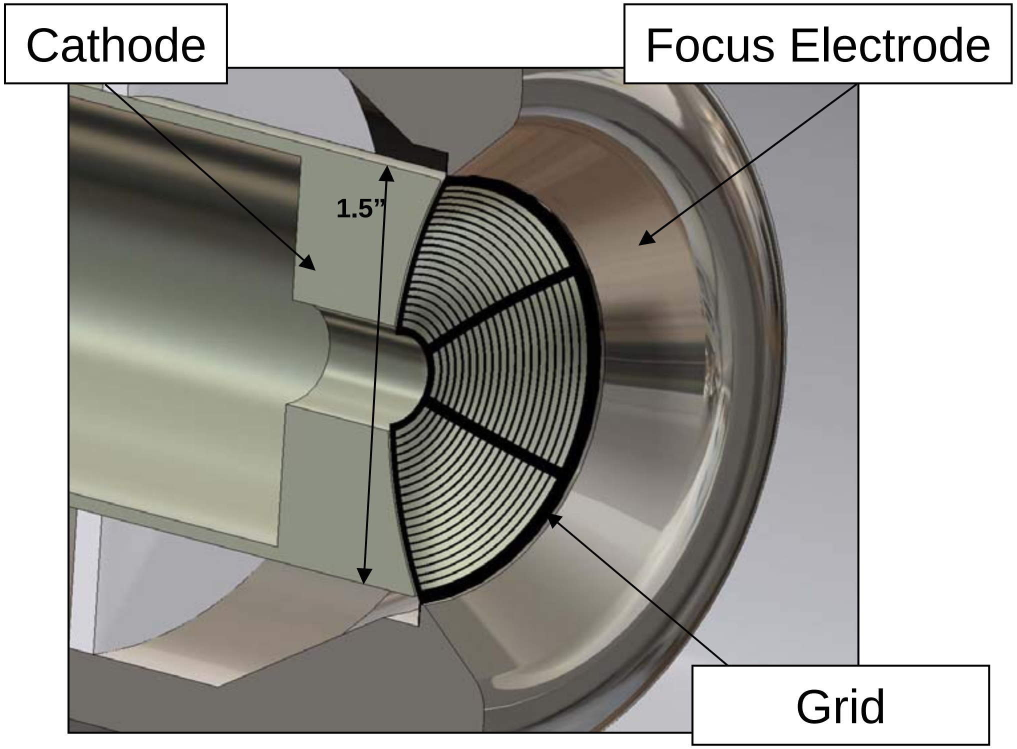
- 1) IOT input cavity / electron gun
  - *Geometry and electrical parameters used in the following example.*

Electrical Parameters

Parameter	***value***	***units***
V_o	40	kV
I_o	var.	A
E_{gk}	$-60<E_{gk}<0$	V
f_o	700	MHz
2a	1	inch



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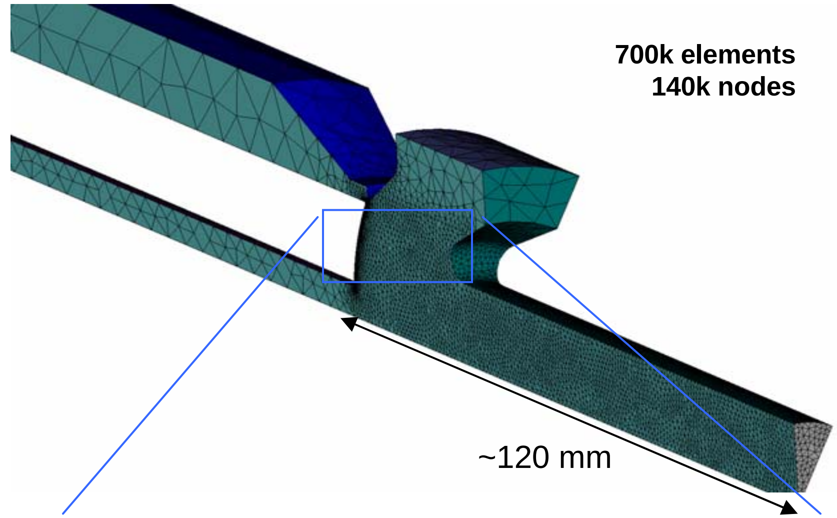
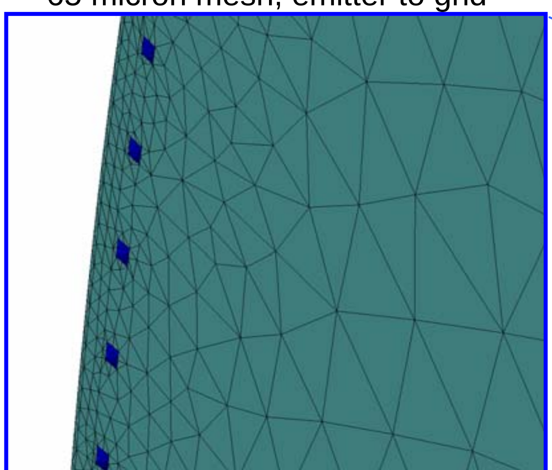
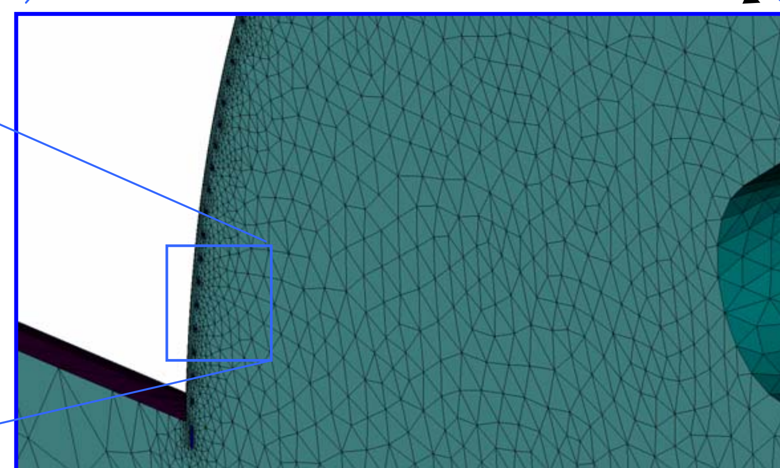
- 1) IOT input cavity / electron gun
  - *Analyst - mesh generation.*
    - Analyst is used to create the model mesh; the same mesh is used for RF and PIC simulation.
    - 30 degree segment modeled.



~65 micron mesh, emitter to grid





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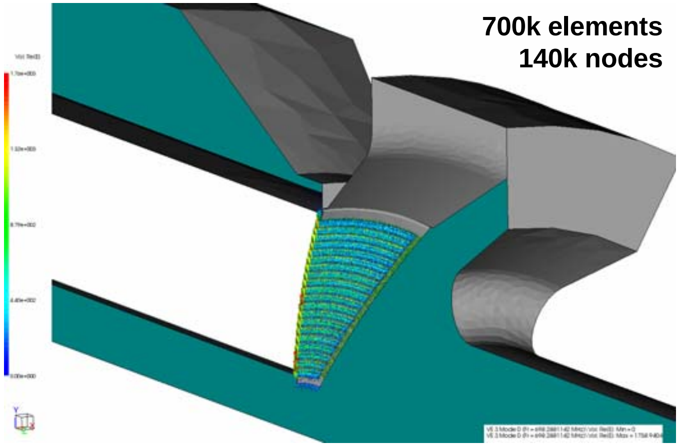
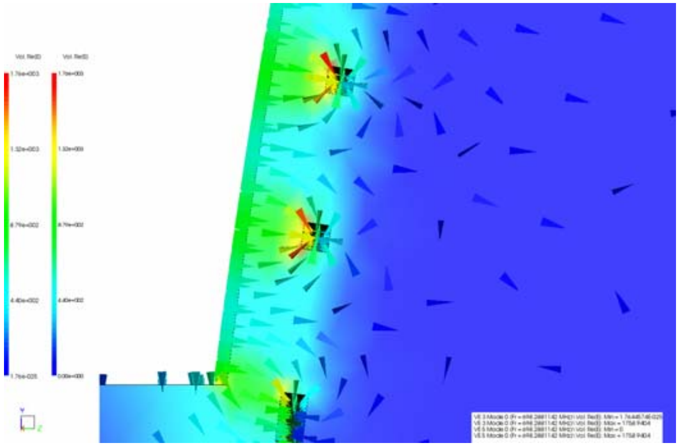
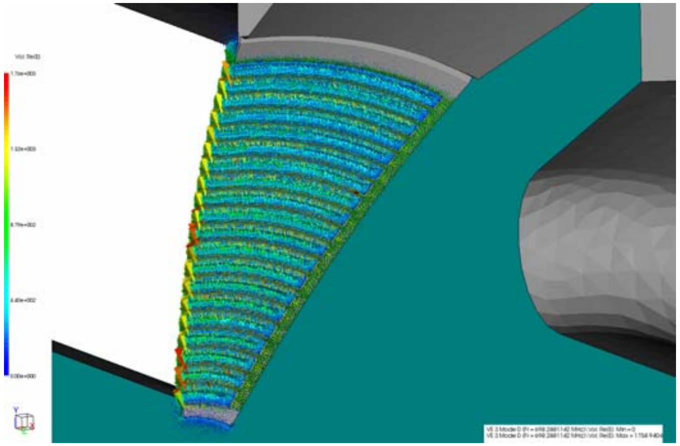
- 1) IOT Input Cavity / Electron gun
  - *Analyst – Cathode to Grid circuit tuned to resonance at 700 MHz*







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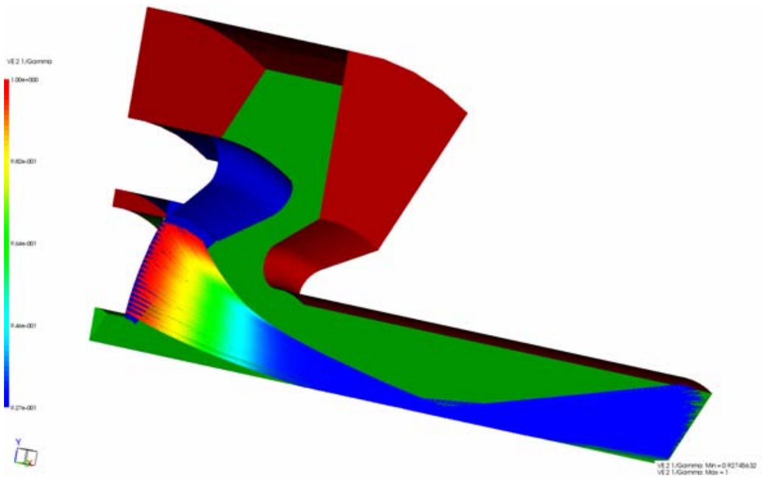
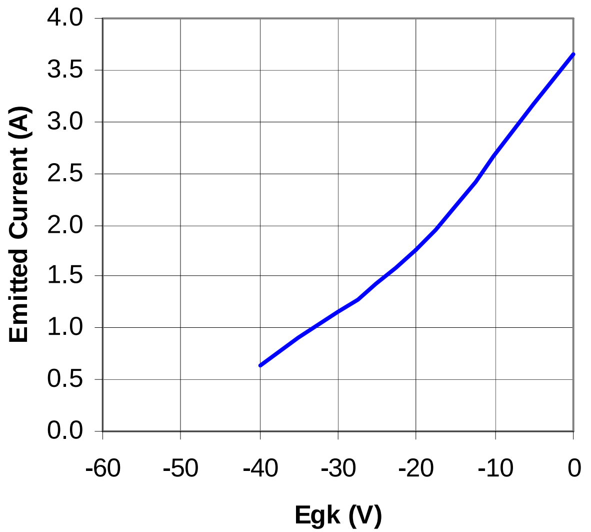
- 1) IOT Input Cavity / Electron gun
  - *MICHELLE – Steady-state electrostatic with variable cathode to grid voltage; determine cutoff.*
    - Grid to anode voltage fixed at -40 kV; grid to cathode variable (Egk).
    - Note: this model is only valid for the electrostatic case. A 60 degree segment will be required when the static magnetic focusing field is included in the model.





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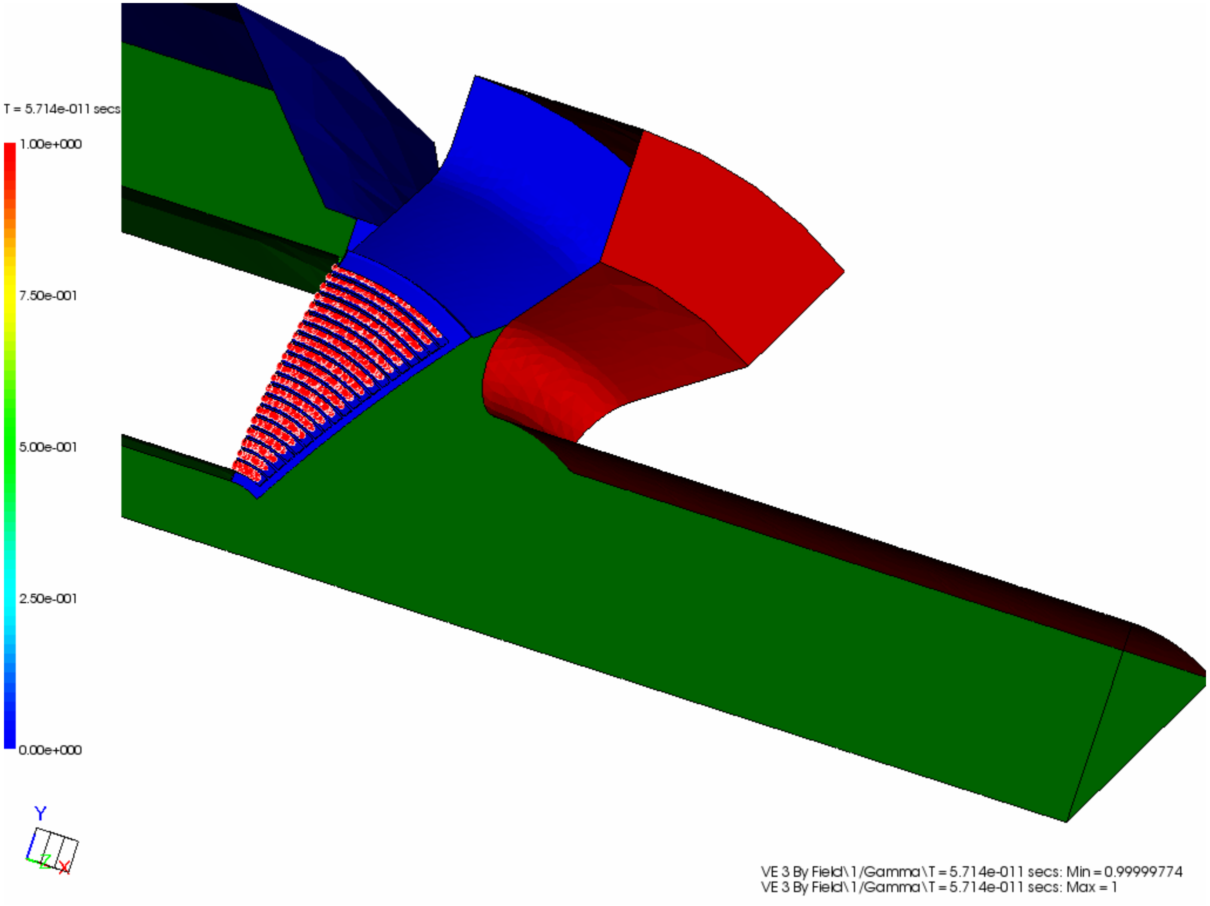
- 1) IOT Input Cavity / Electron gun
  - *MICHELLE – Time domain PIC; 1/100 of total particles shown.*



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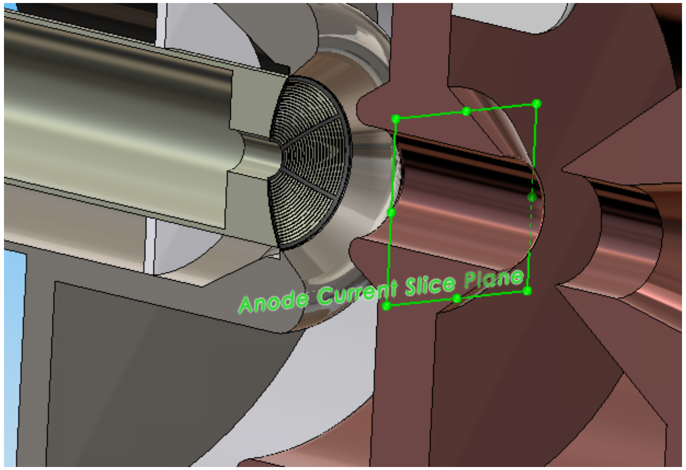
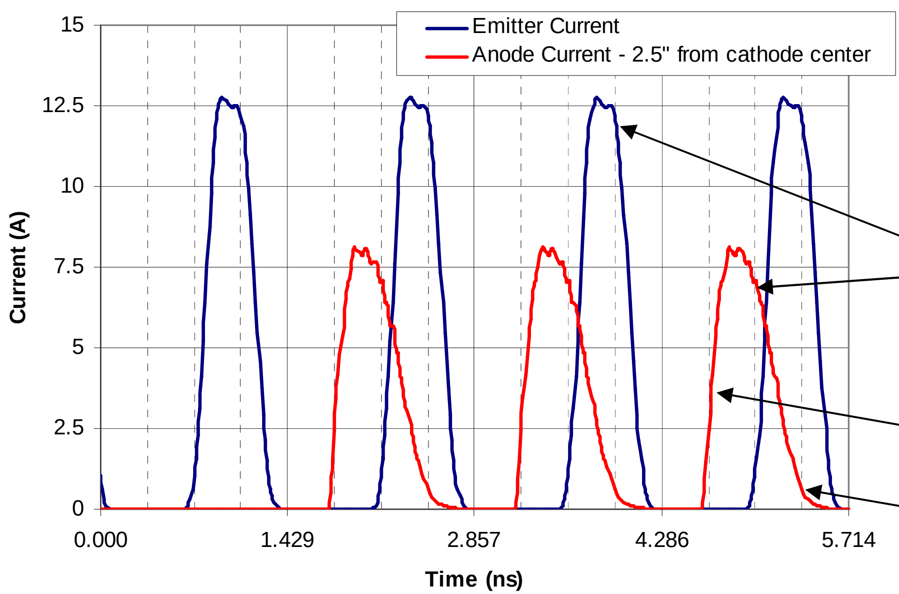
- 1) IOT Input Cavity / Electron gun
  - *MICHELLE – Time domain current from the cathode emitter and through the anode slice plane (63.5 mm from cathode).*





~20% current loss between emitter and anode slice plane – additional diagnostics required.

Leading edge of the bunch well defined

Trailing edge shows the expected tail.

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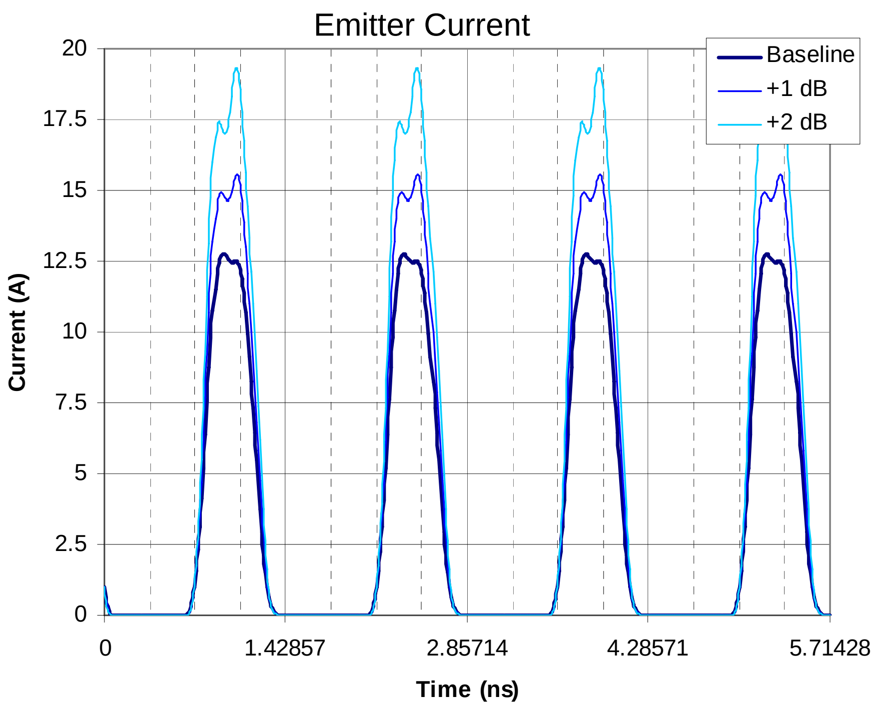
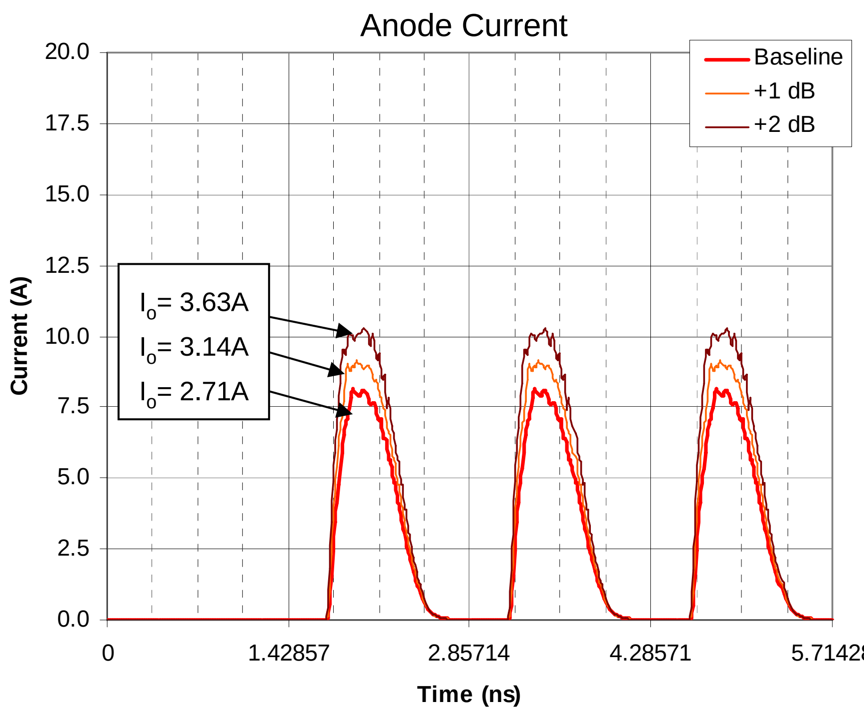
- 1) IOT Input Cavity / Electron gun
  - *MICHELLE – Time domain current for several input drive power levels.*





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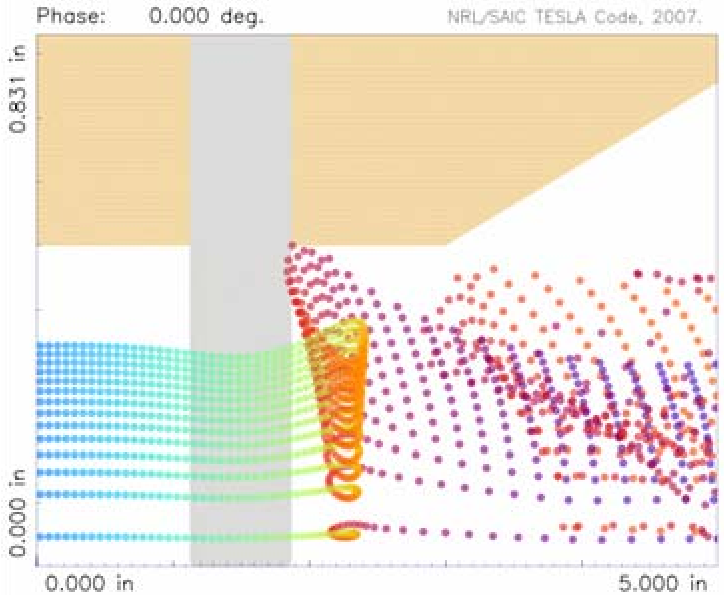
- 2) Output Cavity – Example TESLA simulation
  - *3.14 A current density profile was imported for this example.*
  - *A 12 beam HOM IOT based on the single-single-beam data is a good starting point for future design optimization – but we need to choose a class of MB IOT.*

	single beam	twelve beam	
Parameter	***value***	***value***	***units***
Voltage	40	40	kV
Current	3.14	37.7	A
Power	84.5	1013	kW
Efficiency	67	67	%
B z	0.06	0.06	T



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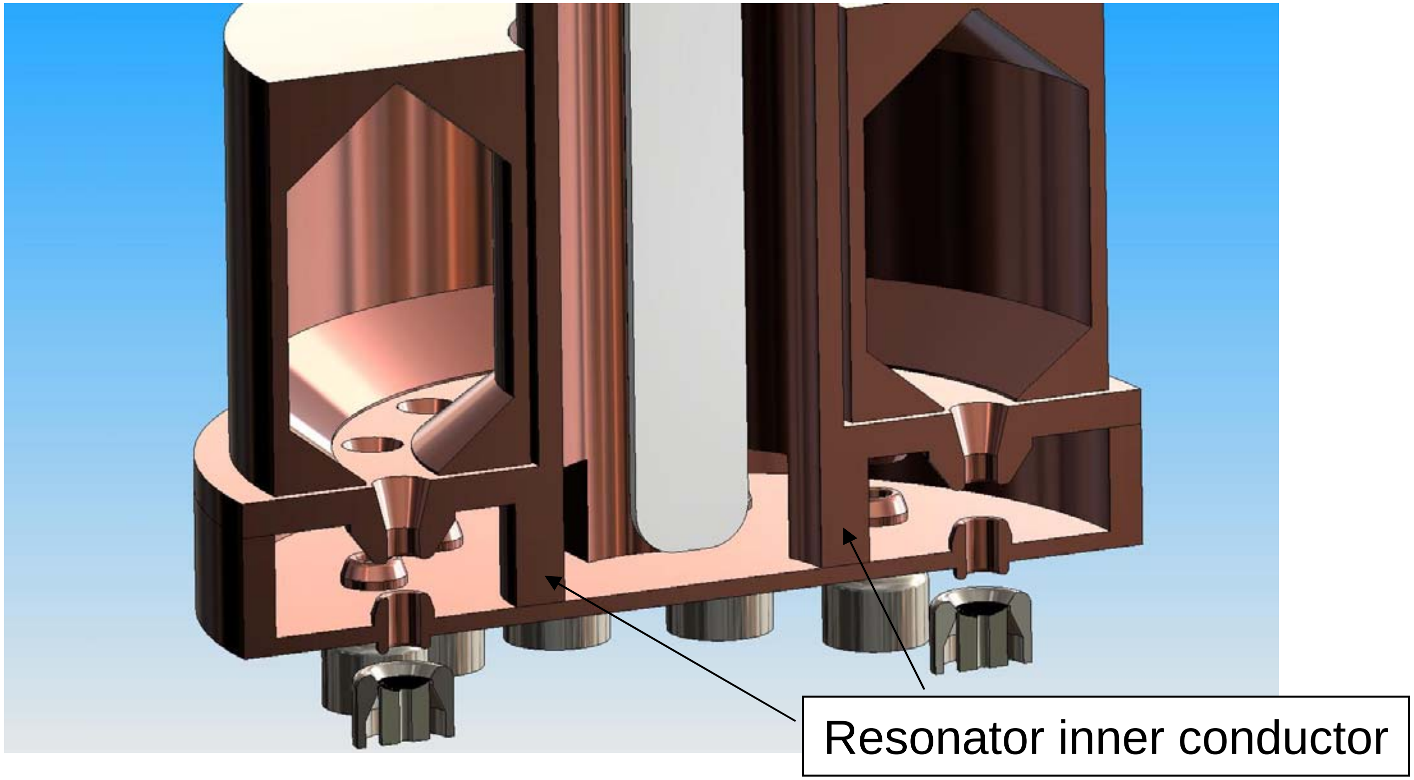
- TM_{010}-coaxial or TM_{020}-cylindrical mode MB IOT.
  - *One possible approach – removal of the resonator inner conductor would provide for the TM_{020}-cylindrical mode.*



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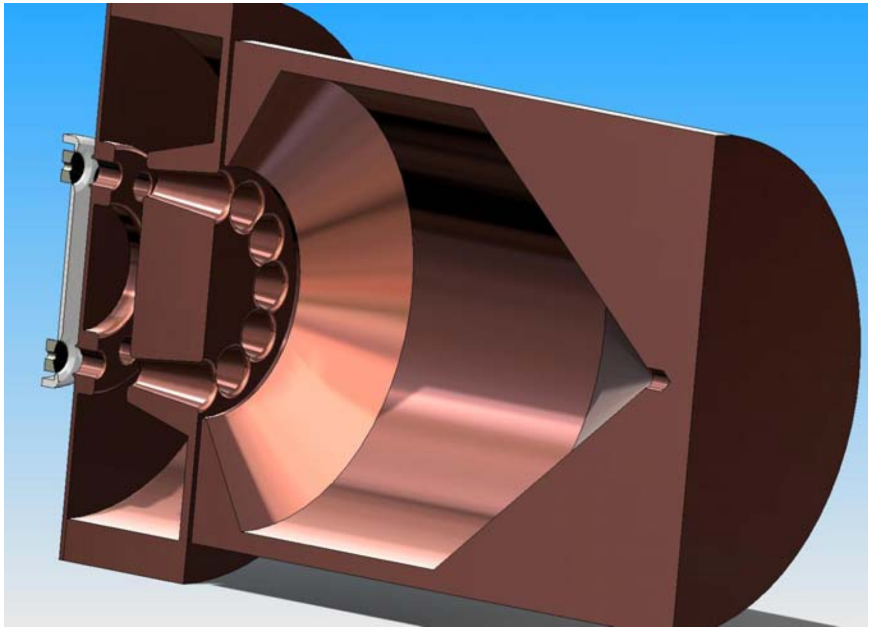
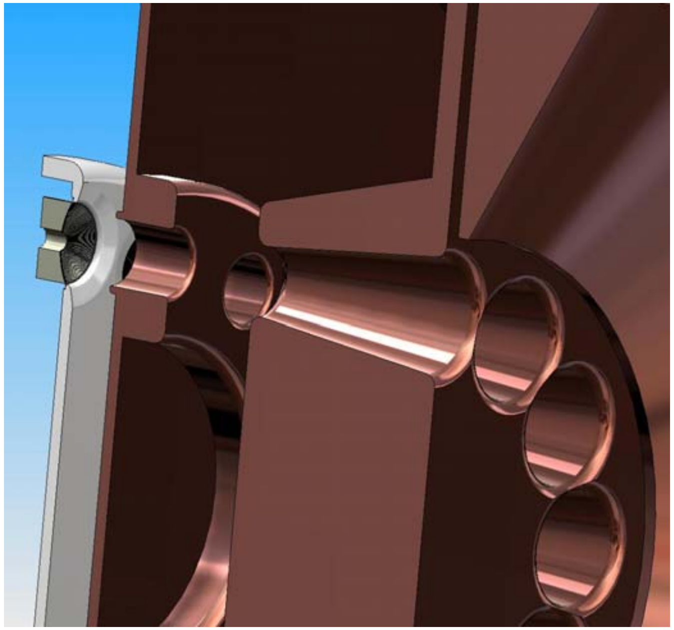
- TM_{010}-cylindrical mode MB IOT
  - *Another approach for high-power applications.*





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- Future code-development and validation effort
  - *Phase II of our program will start in the coming months.*
  - *Code improvements include*
    - Improved meshing capabilities – 64 bit mesher
    - Mesh exclusion and interpolation – RF mapping onto the electrostatic PIC model
    - Improved emission models
    - Implement periodic boundary conditions in Analyst GUI – capability exists within MICHELLE.
    - Implement of a beam loading model.

- Future design effort
  - *MB-IOT design of a megawatt-class MB IOT*

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- Summary
  - *Code development is underway at NRL to develop the tools necessary to optimize high-power IOTs and other density modulated devices.*
  - *Three codes are being modified to provide end-to-end simulation of MB IOTs: MICHELLE, Analyst and TESLA.*
  - *An example of the time-domain simulation of the IOT Gun / Input cavity was shown.*
  - *Time-dependant current profiles, created with MICHELLE, were used to drive TESLA models to predict the IOT large signal performance.*
  - *Several examples of MW-Class IOTs were shown.*

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Acknowledgements

We would like to thank

1) *Office of Naval research and Naval Sea Systems Command for supporting this effort.*

2) *CPI/MPP Palo Alto for providing us with IOT design information – Bob Fickett, Tom Grant and Mike Cusick.*

Thank you