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.
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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.

1) Input Cavity / Electron Gun
   MICHELLE and Analyst

2) Output Cavity
   TESLA & Analyst

3) Collector
   MICHELLE & Analyst
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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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_o$</td>
<td>40</td>
<td>kV</td>
</tr>
<tr>
<td>$I_o$</td>
<td>var.</td>
<td>A</td>
</tr>
<tr>
<td>$E_{gk}$</td>
<td>$-60 &lt; E_{gk} &lt; 0$</td>
<td>V</td>
</tr>
<tr>
<td>$f_o$</td>
<td>700</td>
<td>MHz</td>
</tr>
<tr>
<td>$2a$</td>
<td>1</td>
<td>inch</td>
</tr>
</tbody>
</table>
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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

700k elements
140k nodes

~120 mm
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1) IOT Input Cavity / Electron gun
   Analyst – Cathode to Grid circuit tuned to resonance at 700 MHz
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.*

**Emitter Current**

- Baseline
- +1 dB
- +2 dB

**Anode Current**

- Baseline
- +1 dB
- +2 dB

$I_o = 3.63A$

$I_o = 3.14A$

$I_o = 2.71A$
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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-beam data is a good starting point for future design optimization – but we need to choose a class of MB IOT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>single beam</th>
<th>twelve beam</th>
<th>units</th>
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<tbody>
<tr>
<td>Voltage</td>
<td>40</td>
<td>40</td>
<td>kV</td>
</tr>
<tr>
<td>Current</td>
<td>3.14</td>
<td>37.7</td>
<td>A</td>
</tr>
<tr>
<td>Power</td>
<td>84.5</td>
<td>1013</td>
<td>kW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>67</td>
<td>67</td>
<td>%</td>
</tr>
<tr>
<td>B z</td>
<td>0.06</td>
<td>0.06</td>
<td>T</td>
</tr>
</tbody>
</table>
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- $\text{TM}_{010}$-coaxial or $\text{TM}_{020}$-cylindrical mode MB IOT.

- One possible approach – removal of the resonator inner conductor would provide for the $\text{TM}_{020}$-cylindrical mode.
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- $\text{TM}_{010}$-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-depandanat 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