Calabazas Creek Research, Inc.

Final Report

Development of A 402.5 MHz 140 kW Inductive Output Tube

Contract DE-SC0004566

Calabazas Creek Research Inc.

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Introduction

This report contains the results of Phase I of an SBIR to develop a Pulsed Inductive Output Tube (IOT) with 140 kW at 400 MHz for powering H-proton beams. A number of sources, including single beam and multiple beam klystrons, can provide this power, but the IOT or Klystrode has higher efficiency. Efficiencies exceeding 70% are routinely achieved. The gain is typically limited to approximately 24 dB; however, the availability of highly efficient, solid state drivers reduces the significance of this limitation, particularly at lower frequencies.

While klystrons use cavities to velocity modulate the electron beam, the IOT produces bunched electrons from the electron gun. An input RF signal is applied between the cathode and a grid that is biased so that electrons are emitted only during the positive half cycle of the RF wave. The electron bunches are accelerated toward the anode, and the RF power is extracted by a single output cavity.

Figure 1 shows the layout of a typical IOT. An input coupler drives an input cavity, where the RF electric fields are excited between the cathode and grid. Electrons are extracted from the cathode on the positive half cycle of the RF wave and accelerated by the applied voltage through a beam tunnel into the output cavity. Energy from the bunched electron beam is converted to RF energy with the RF power extracted through a coaxial output waveguide. The remaining electron beam energy is dissipated in the collector.

IOTs were developed originally for UHF television applications, where transmitters operate continuously. The increased efficiency of the IOT over klystrons represented major cost savings.

Researchers are now extending IOT capabilities to higher and lower frequencies and higher power levels. Operation of the grid places an upper limit on the frequency at around 1.3 GHz. Lower frequencies appear to be achievable, and Calabazas Creek Research, Inc. (CCR) is currently fabricating a multiple beam IOT at 350 MHz. This device is designed to produce 200 kW CW and is targeted for muon colliders. The multiple beam approach was required to meet the CW power requirement. A challenge in the current program was achieving the required frequency and power level with a single electron beam. This required development of a new, electron gun operational at a higher power level than previous IOTs. The single beam approach will be much less expensive than a multiple beam device, both for development and production.

A critical issue addressed by this program is the lack of large signal simulation codes for design of IOT's. Accurate calculation of the output requires simulation of the beam formation as well as the interaction of the bunched beam in the output cavity. In 2009, The Department of Energy awarded CCR a grant to develop a large signal analysis code for IOT cavities based on the Science Applications International Corporation (SAIC) code NEMISIS [1]. NEMESIS is a time-domain formulation that relies on integration of equivalent circuit equations coupled with the Lorentz force equations for particle trajectories. The code currently employs a 2D model for the circuit fields and a 2D Poisson solver. This new program will extend the formulation for fully 3D operation specifically for IOT design. This will allow simulation over a wider parameter range and more complex geometries. CCR is working with SAIC on this development.

Also of interest is TESLA [2], a code developed by the Naval Research Laboratory for the analysis of klystrons and other cavity-based devices. Features were added recently to allow the simulation with pre-bunched electron beams. This should make it well suited to the analysis of IOT's. This Phase I compares the use of the two codes for the 402.5 MHz IOT.

After the award of the contract, CCR learned that Oak Ridge National Laboratory (ORNL), the potential DOE user for this technology, no longer required the tube. They have opted for solid state amplifiers. Given the lack of market, CCR did not submit a Phase II proposal. For the Phase I, rather than perform a detailed design of the specific IOT, CCR focused its effort on design methods that could be applied to future requirements. The objective was to assemble a suite of codes that could be used to simulate bunch formation by the electron gun, and the transfer of power to RF of that bunched beam in the output cavity. Those elements of the tube, such as the input cavity, that were conventional and would be designed using commercial software were not addressed in detail.

The industrial partner on this program is Communications & Power Industries, Ltd. (CPI). CPI is the major U.S. developer of IOTs for the TV industry and is assisting CCR on the 350 MHz MBIOT development. This provides a direct path to production with access to years of experience and technical expertise.

Technical Objectives

The program objectives were:

- Design an efficient output circuit
- Design a high power, gridded electron gun and input cavity
- Design the RF windows, input and output couplers, spent beam collector, and magnet
- Generate a mechanical model of the complete RF source
- Determine anticipated operating parameters, including power supply and RF driver specifications

Phase I Results

Design of an Efficient Output circuit

CCR examined the use of two codes, NEMESIS and TESLA, for the design of the output circuit. Both codes model a beam in a drift region, with fields in that region calculated based on user-provided values for the gap position, length and cavity resonant frequency, Q and R/Q. The last value indicates the relative strength of the fields at the gap relative to the energy stored in the cavity. These values are obtained from cavity codes such as SUPERFISH or HFSS. CCR uses both codes.

For an IOT, the beam entering the cavity region is bunched by the gridded electron gun. While the ideal code would include the beam formation, only the relatively (very) slow PIC codes do so, and we have separated the beam formation and interaction of the bunched beam in the cavity.

Both TESLA and NEMESIS allow for input of an analytical specification of the bunching. TESLA will also take trajectory information.

Selection of the code to be used for cavity simulations

Introduction

Since both of these codes were relatively new, the first step was to compare their performance against an established standard. The code used for that purpose was MAGIC, a particle-in-cell code that includes all of the relevant physics and has been used by researchers to model a wide range of beam-wave interactions.

The geometry used for the comparison is shown in Figure 1. It was a modification of an existing klystron cavity previously modeled with MAGIC. While certainly not an optimum IOT output cavity, it gave an efficiency close to 60% and avoided the time-consuming effort required to create a model for MAGIC from scratch. The output cavity Q and R/Q were equal to 116 and 83.7, respectively. The resonant frequency for the cavity as constructed in MAGIC was 432.2 MHz. Adjusting the resonant frequency in MAGIC can be tedious, so 432.5 MHz was used for TESLA and NEMESIS, as well. The other parameters are summarized in Table 1.

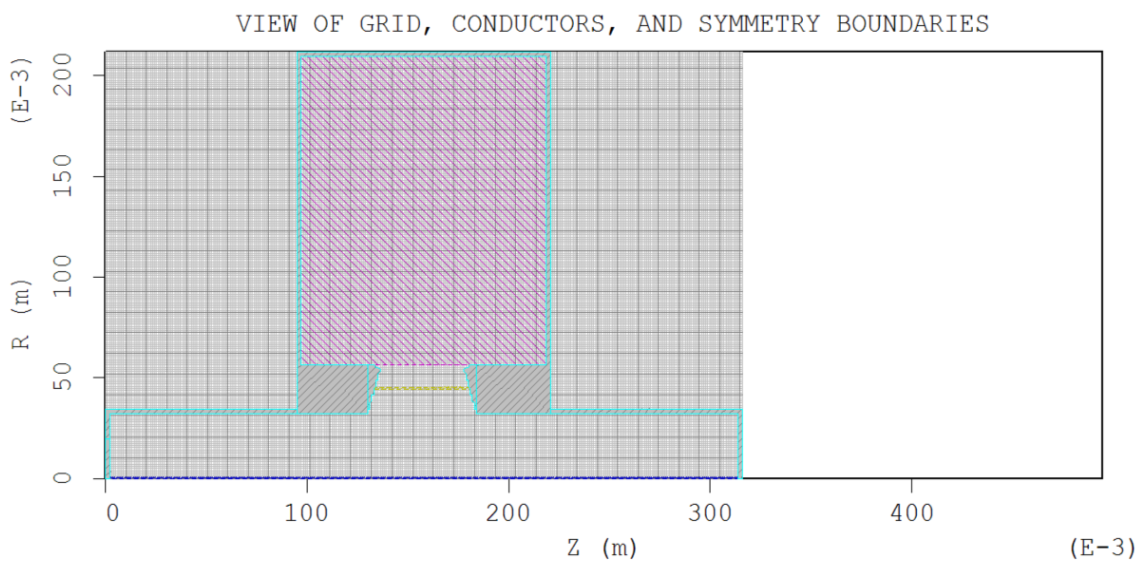


Figure 1. Geometry used for the simulations. This is the actual geometry for MAGIC. For TESLA and NEMESIS, the cavity gap was specified to be in the same location, but the cavity is represented by fields at the gap, and Q and R/Q were specified to be the same as those calculated by MAGIC.

Table 1. Common parameters of the simulations.

Beam voltage	40 kV
Average current	6.95
Drift tube radius	3.22 cm
Beam radius	1.94 cm
Frequency	432.5 MHz
Cavity Q (nominal)	116

R/Q	83.7
Magnetic Field	288 G
Gap	5 cm

Two temporal profiles were used for the bunching. For MAGIC and TESLA, one-half period of sine(ωt) was used. (This profile was used for convenience in the first MAGIC run. While not really representative of a realistic profile, nevertheless, it was valid for comparison with TELSA.) One half period of a $\text{sine}^2(\omega t)$ was used for other runs of MAGIC and TESLA, and NEMESIS, as well. This is more representative of IOT operation.

For the sine bunching, the results are shown in Table 2. TESLA and MAGIC are in very good agreement.

Table 2. . Summary of results for the sine bunching.

	Power (kW)	Efficiency
TESLA	182	51.5%
MAGIC	180	50.9%

The power and efficiency predicted by the three codes for $\sin^2(\omega t)$ pre-bunching, for the nominal Q of 116, are shown in Table 3.

Table 3. Summary of results for the sine^2 bunching.

	Power (kW)	Efficiency
TESLA	160	57.6%
NEMESIS	188	67.6%
MAGIC	161.6	58.2%

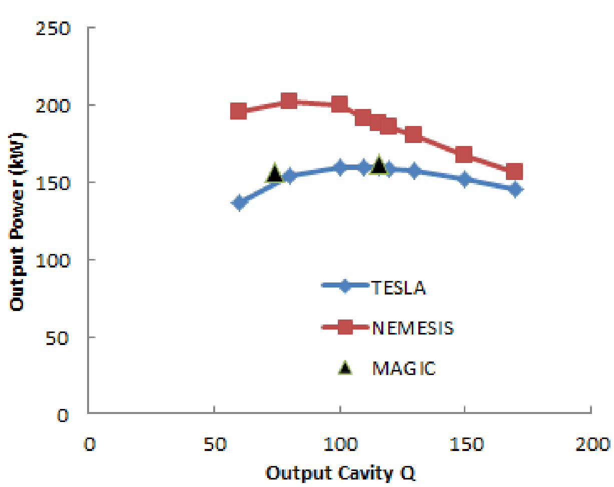


Figure 2. Output power as a function of the output cavity Q for TESLA and NEMESIS. R/Q = 83.7.

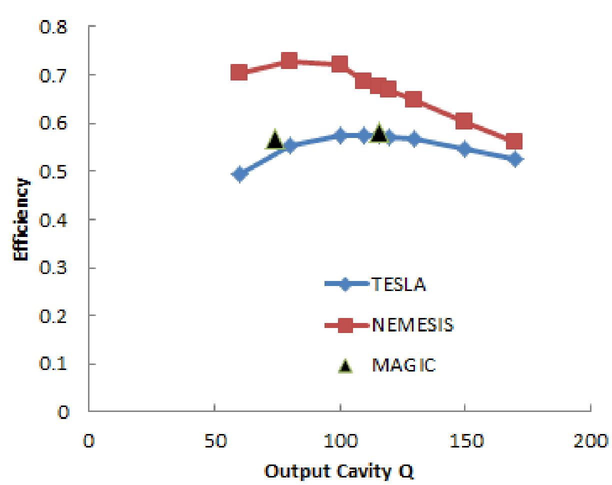


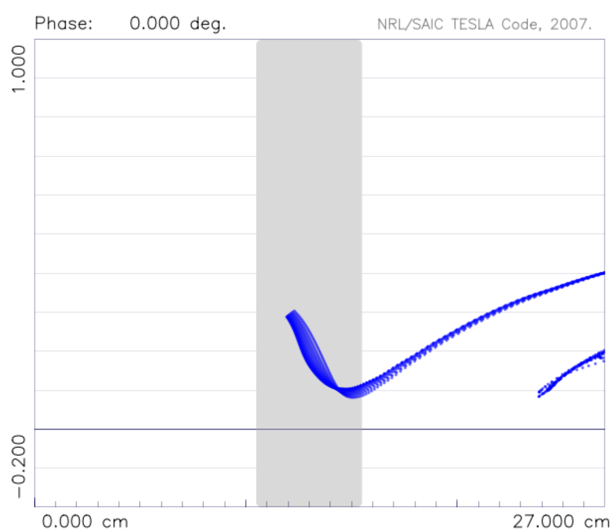
Figure 3. Efficiency as a function of the output cavity Q for TESLA and NEMESIS. R/Q = 83.7.

Plots of the power and efficiency predicted by the codes with $\sin^2(\omega t)$ pre-bunching, as a function of output cavity Q, are shown in Figure 2 and Figure 3. TESLA and MAGIC are in good agreement for the two Q values used in MAGIC, while NEMESIS predicts not only a substantially higher efficiency, but also a lower optimum Q.

Details of the Predicted Performance for Q=116

Beam velocity (beta)

Plots of the beam velocity, normalized to the speed of light, are shown in Figures 4 through 6. The plots from TESLA (Figure 4) and MAGIC (Figure 6) are very similar. No reflected electrons are predicted by these codes. As shown in Figure 5, the plot for NEMESIS is quite different. Consistent with the higher efficiency, this code predicts reflected electrons.



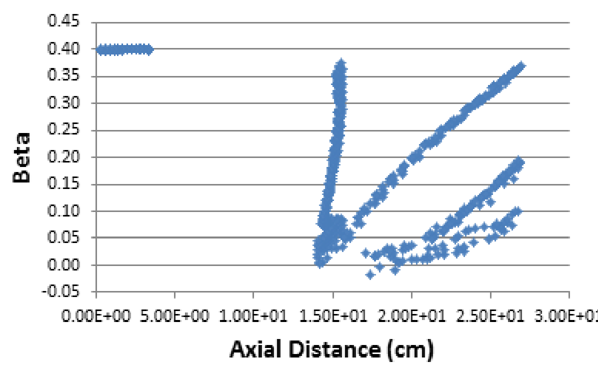


Figure 5. Beta vs z, from NEMESIS.

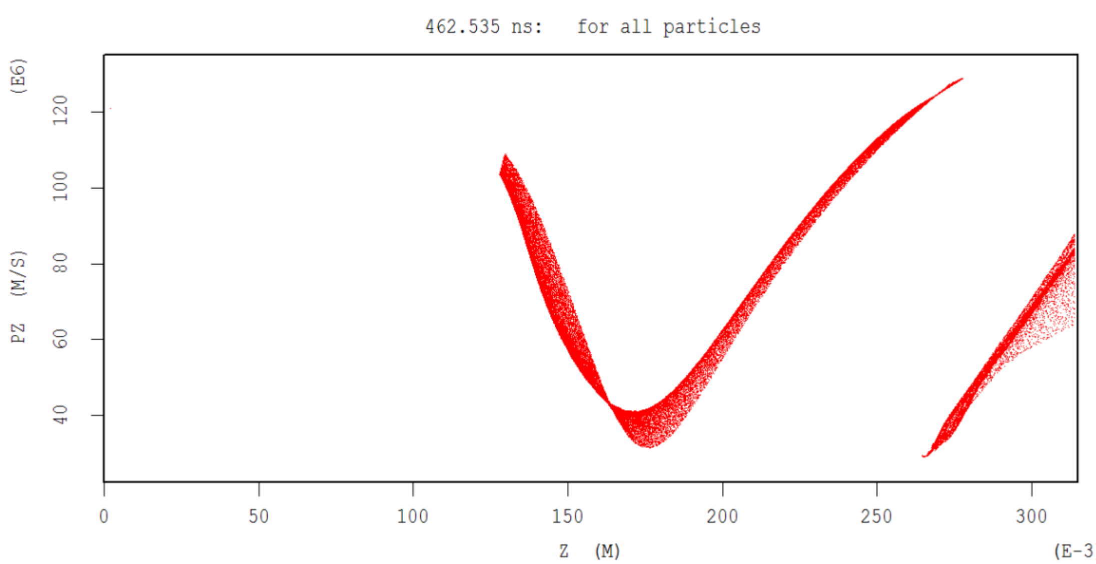


Figure 6. Beta vs z, from MAGIC. 120 10^6 m/s is a beta of about 0.4.

Beam Trajectories

The beam trajectories predicted by the codes are shown in Figures 7 through 11. They are all snapshots at a given time during an RF cycle, or phase. The phase for the plots of the trajectories can be chosen in the post-processor of TESLA, and thus that parameter was varied to match the BUNCH positions given by the other codes. As can be seen from the figures, the bunch shapes predicted by MAGIC and NEMESIS match reasonably well with TESLA's.

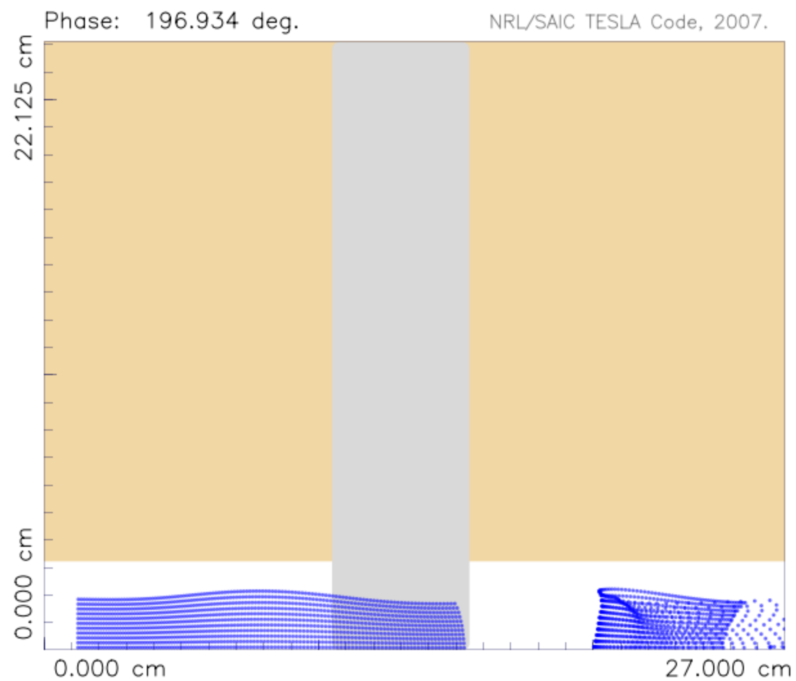


Figure 7. TESLA beam snapshot at a phase of 197°, to place the bunch locations similar to those from MAGIC.

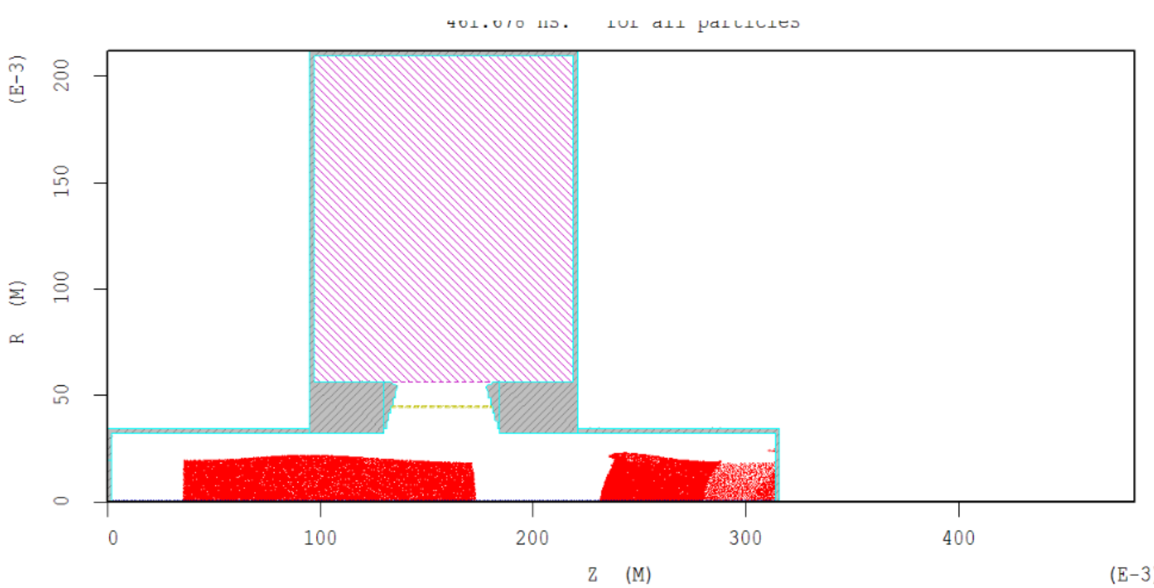


Figure 8. MAGIC beam snapshot.

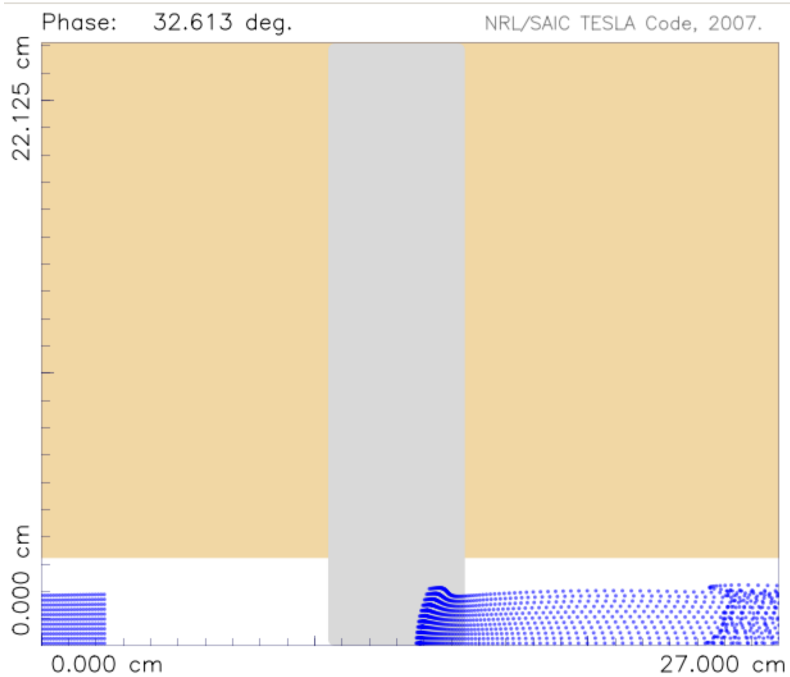


Figure 9. TESLA beam snapshot, at a phase of 32.6°, to place the bunches at the same location as those in the NEMESIS output.

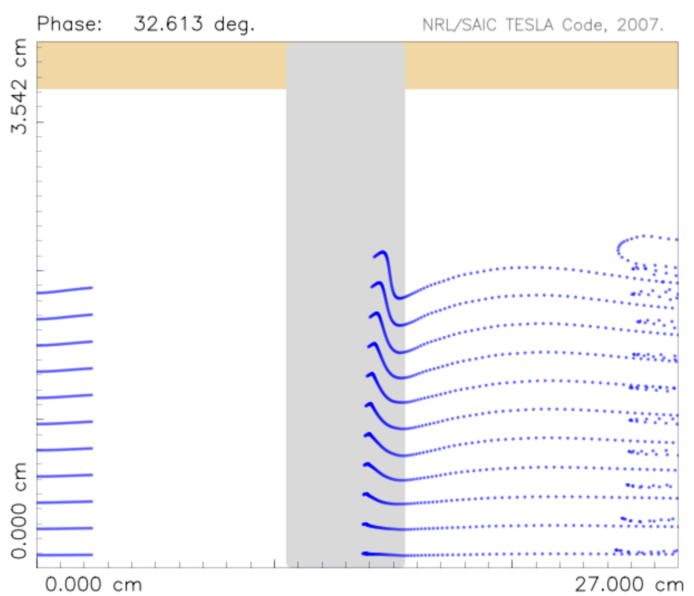


Figure 10. Same as Figure 9, with expanded radial scale.

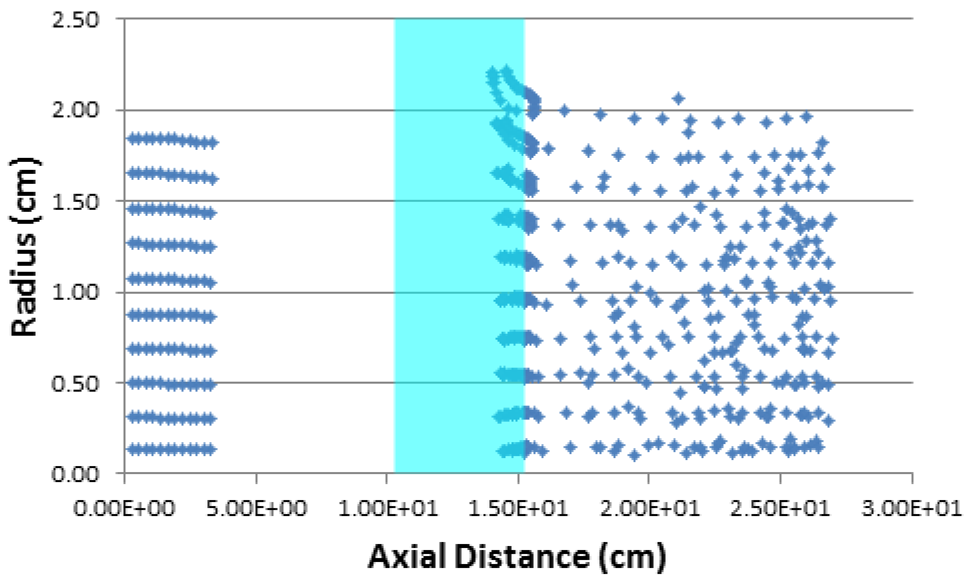


Figure 11. NEMESIS beam snapshot, as plotted in Excel. (The other codes produced the plots directly.)

Comparisons to Experiment

Freund [1] and Chernyavskiy [3] have both presented comparisons of measured results for a 650 MHz IOT with calculations of NEMESIS and TESLA, respectively. Excellent agreement was reported for both codes. Chernyavskiy's unpublished results are shown in Figure 12. We used his input parameters to run TESLA and NEMESIS with a variation of Q. The results are shown in Figures 13 and 14.

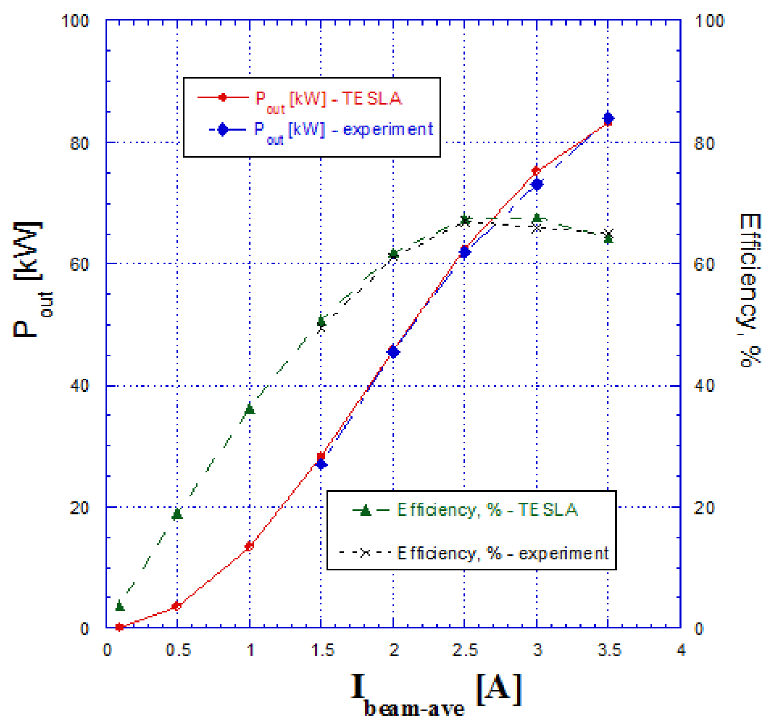


Figure 12. Comparison of TESLA calculations for output power with measured results from a CPI 650 MHz IOT. From reference 3.

NEMESIS and TESLA predict an output power of 82.5 kW and 87 kW, respectively, for the design Q of 176. This is consistent with the plot in Figure 12 and in good agreement with measurements. NEMESIS predicts a power of 87 kW, 5% higher than observed. But, unlike TESLA, the power increases with decreasing Q to a peak of 94 kW at Q of 78.

Conclusions of the code comparisons

TESLA agrees quite well with MAGIC, as well as experimental data. There is disagreement between NEMESIS and the other two codes which persists for a wide range of cavity Q, and for two different IOT designs. Freund [1] has shown good agreement of NEMESIS with an experiment, but there is evidence from our studies that this may have been due to a fortunate choice of output cavity Q. Thus, TESLA appears to be the more accurate code. In addition, TESLA allows for the input of a bunched beam from a trajectory code. We therefor used TESLA for all of the modeling in this program.

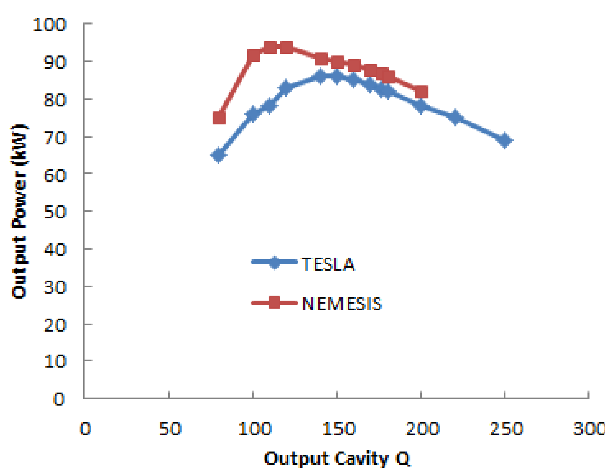


Figure 13. Output power versus Q for Chernyavskiy's data.

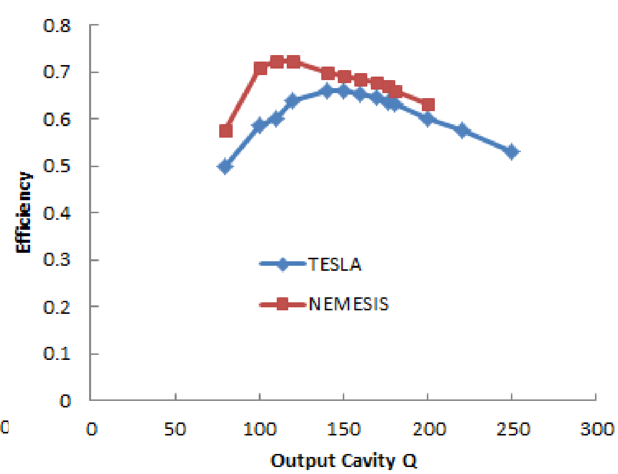


Figure 14. Efficiency versus Q for Chernyavskiy's data

Design of the output cavity

The form of the output cavity was conventional, and is shown in Figure 15. The cavity was modeled using HFSS. The TESLA model is shown in Figure 16. As discussed above, it models the cavity as gap in the drift tube, with the resonant frequency, Q and R/Q specified in the input file.

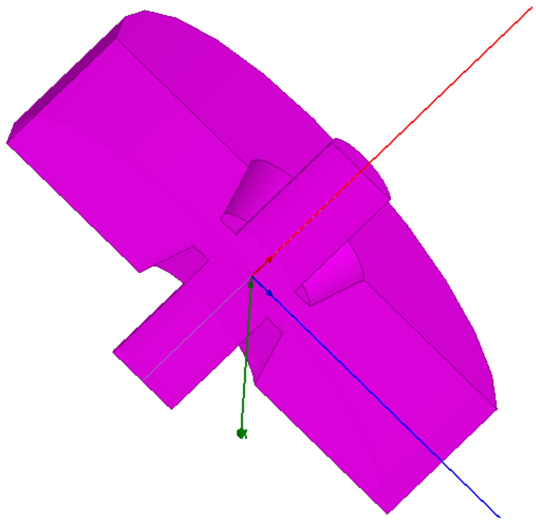


Figure 15. Output cavity, as modeled using HFSS.

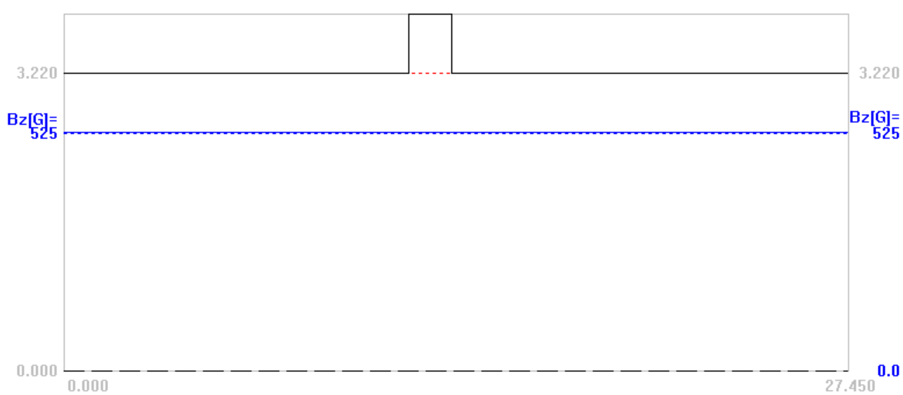


Figure 16. TESLA model of the IOT.

A rough parameter scan was made to determine a potentially optimum operating space. A low beam density was desired to minimize grid heating. The filling factor was set at a maximum of 0.67 to avoid beam interception. Two beam radii were used in the study. The first was 1.93 cm. After some initial studies, a value of 1.45 was chosen. This gave higher efficiency, but allows the use of the same grid albeit inverted) as an existing gun. Even if the exact design would not be used, the resulting grid is not expected to have more difficulties associated with fabrication. The maximum perveance was limited by spreading of the beam bunches due to space charge. The spreading could be observed by running TESLA with the RF suppressed.

The results for varying the beam voltage with a constant beam power sufficient to produce 140 kW RF with 70% efficiency are shown in Figure 17 and Figure 18. Figure 17 shows the shape of a bunch at the beginning of the drift region, while Figure 18 shows the bunch at the end of the drift tube for 30 kV, 35 kV and 40 kV. In all cases the bunch was specified by I ∝ $\sin^2(\omega t)$ for a half cycle, with a bias to adjust the fraction of the half-cycle that the current is non-zero (i.e., that the beam is on.) The ratio of average to peak current was 0.15. As can be seen from Figure 18, spreading of the pulse is small for 40 kV, but is quite significant for 30 kV. A plot of efficiency, shown in Figure 19, confirms the deleterious effect of the bunch spreading. The beam voltage was chosen to be 40 kV.

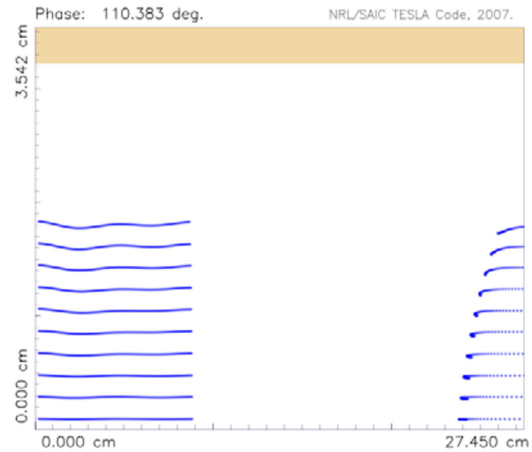


Figure 17. Beam bunch shape at the beginning of the drift region, for a voltage of 40 kV.

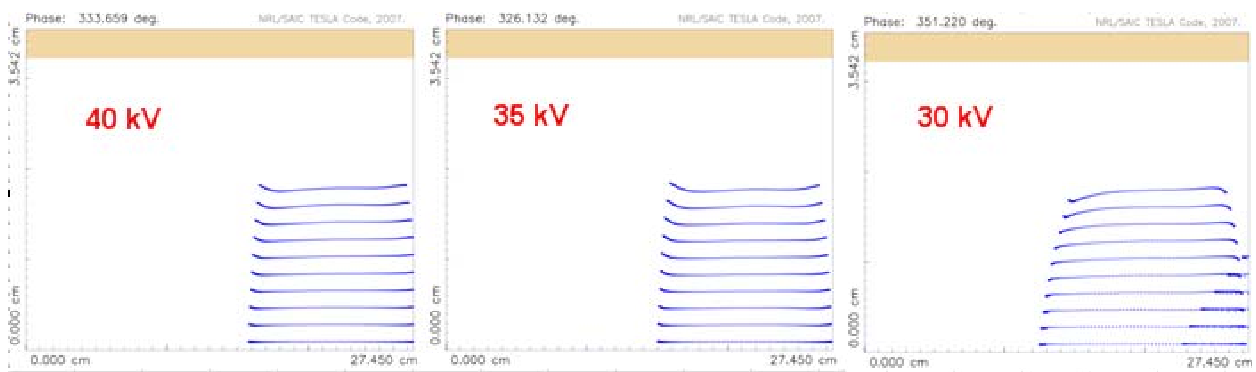


Figure 18. Beam bunch shapes at the end of the IOT, with no RF, showing the effects of space charge-induced spreading. The beam power was fixed at 206 kW.

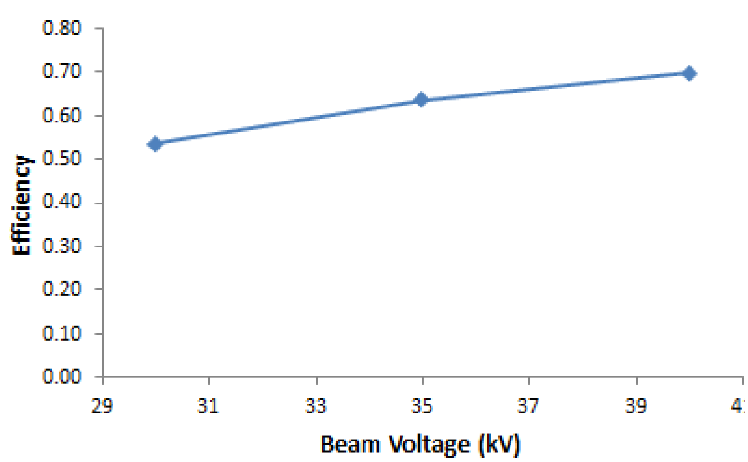


Figure 19. Efficiency versus beam voltage, for constant beam power

Parameter variations were made to determine the optimum gap and Q. (The value for R/Q was determined by the geometry, and, hence, the gap.) Again, the input bunch was a modified $\sin^2(\omega t)$ with a ratio of average to peak current of 0.15. The results are shown in Figure 20. The efficiency was almost independent of the gap length, but there is a shallow peak at a gap of about 1.5 cm. Choosing that gap fully defines the cavity. The parameters are summarized in Table 4. The efficiency was 70%.

Table 4. Summary of the parameters of the optimized IOT.

Voltage	40 kV
Average Current	5.15 A
Drift tube radius	2.5 cm
Beam radius	1.5 cm
Cavity Q	70
R/Q	101.7
Gap	2.0 cm

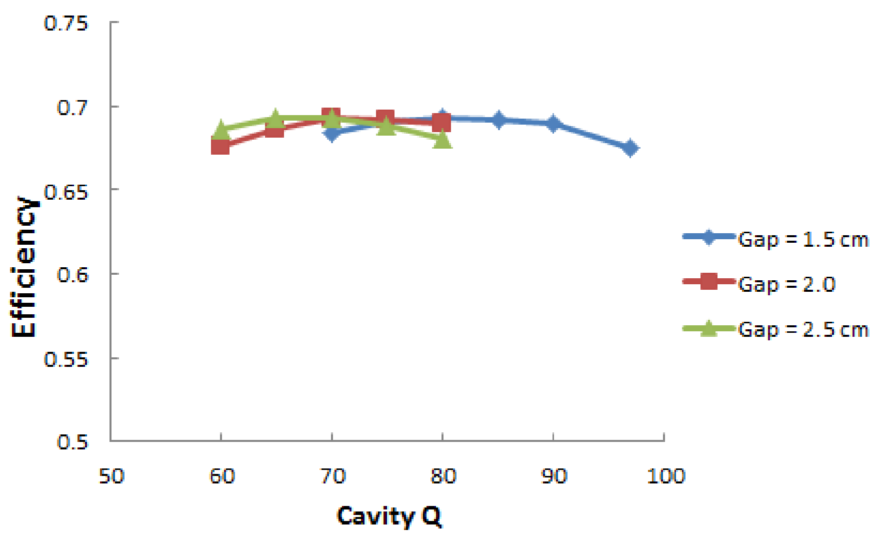


Figure 20. Efficiency as a function of cavity Q for varying gap lengths.

Other results from the TESLA run are shown in Figure 21 through Figure 24.

Figure 21. Beam beta (normalized axial velocity) versus distance.

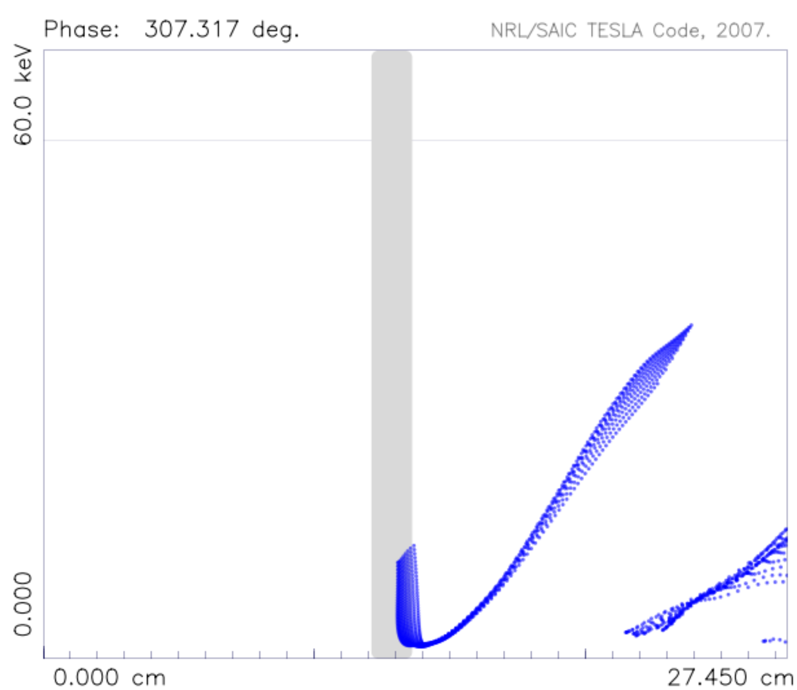


Figure 22. Plot of beam energy versus distance.

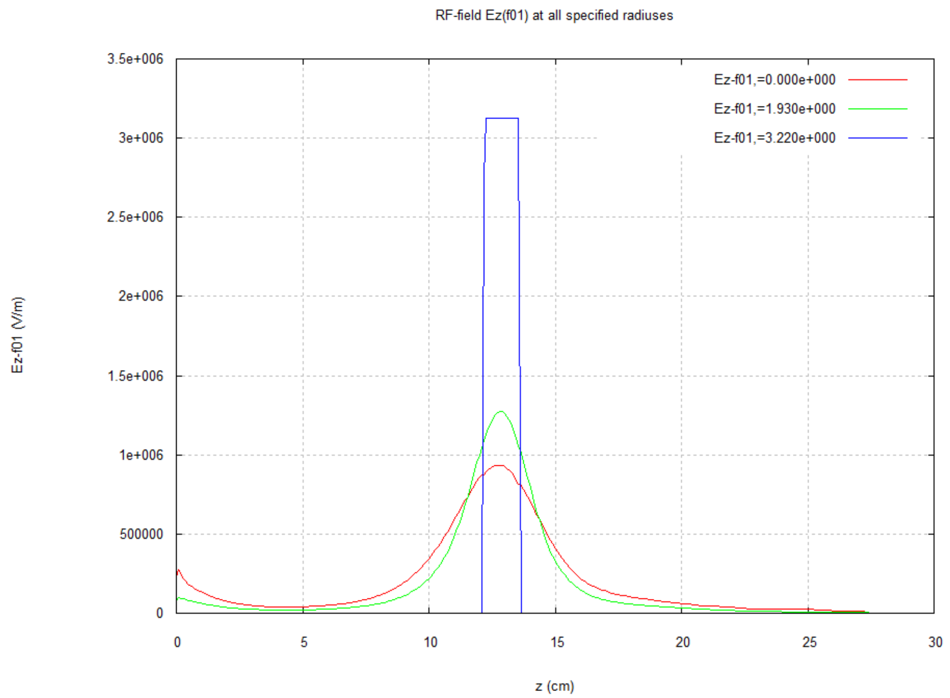


Figure 23. Ez at three different radii.

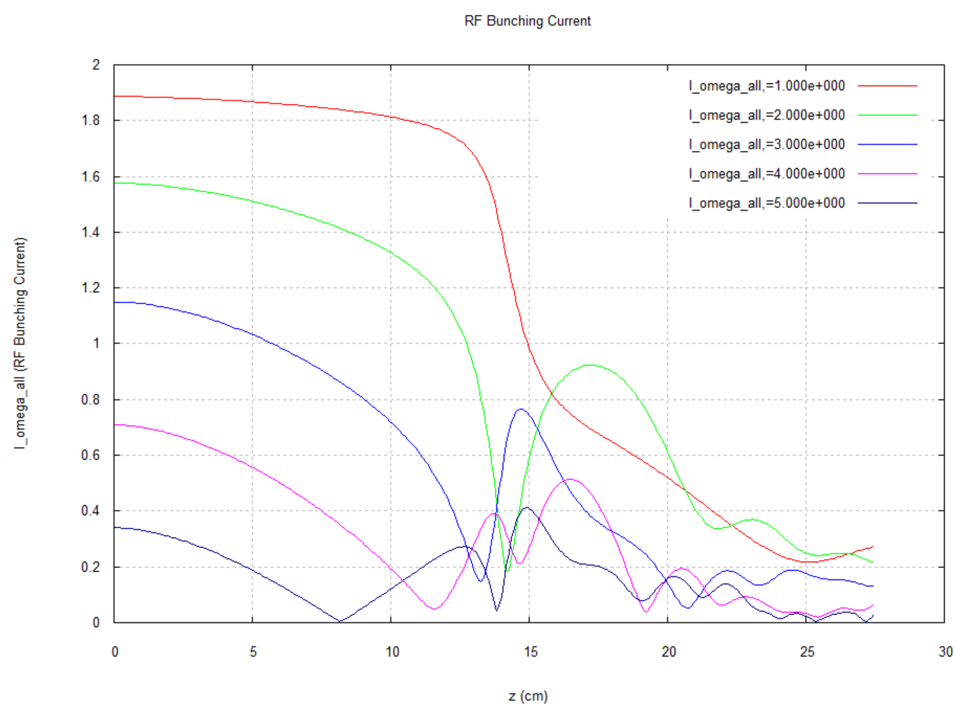


Figure 24. RF current at different harmonics.

Electron Gun

The electron gun is the most difficult component of an IOT to design and fabricate. The grid required for modulation of the beam is fine scaled, making for a complex 3-D modeling problem. CCR examined 2 gun geometries, shown in Figure 25 and Figure 26 . The first was essentially that used in CPI IOT's, and was essentially a conventional Pierce gun with a grid. The second was based on the CCR "dome cathode" approach. Here the cathode is convex. It has several advantages. It operates with a uniform magnetic field, thereby simplifying the magnetics design. The lack of beam compression is not a drawback for low frequency IOT's where the beam current densities in the drift region can be very low. For the IOT, the most important advantage is due to the grid being more stable. In a conventional (concave) gun, as the grid heats up due to electron bombardment, it expands toward the cathode. This increases the current, and causes more heating. Thus, the geometry is inherently unstable. The dome cathode is inherently stable because the beam heating will cause the grid to expand away from the cathode, decreasing the current and the heating.

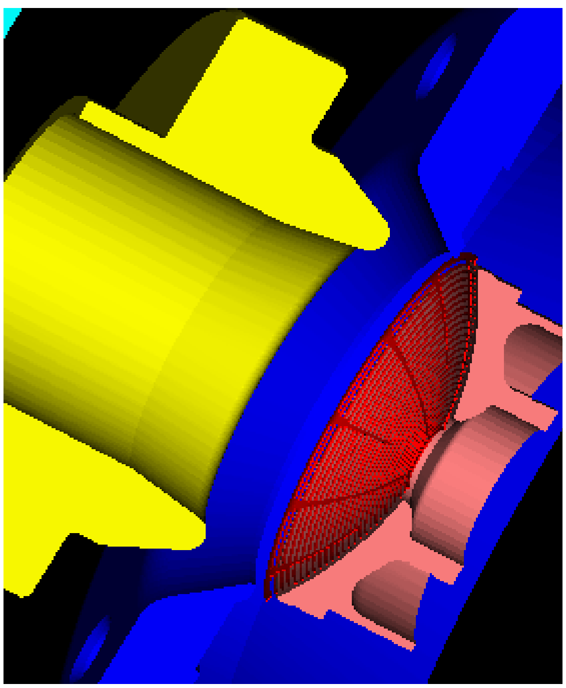


Figure 25. Conventional gridded gun for an IOT.

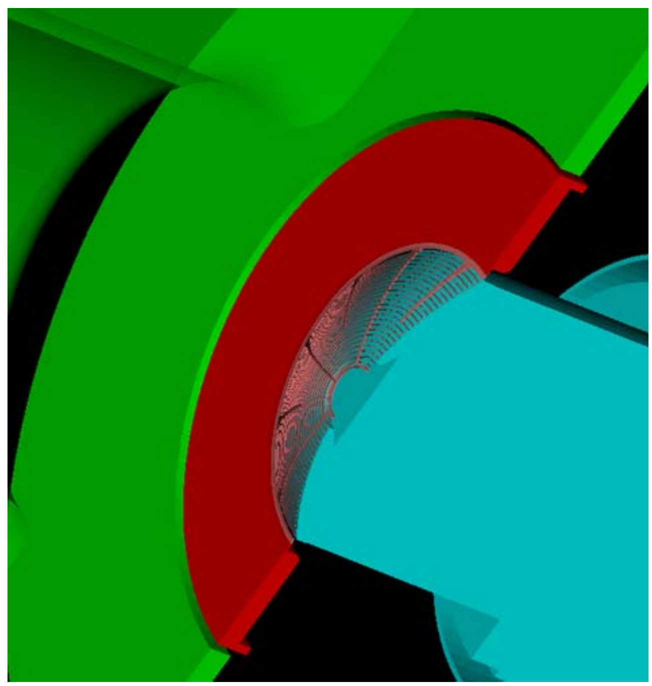


Figure 26. Dome cathode.

The method and problems of simulating the two guns are the same. Because of the lack of axial symmetry of the mesh, the problem is 3D. The internal mesh dimensions are quite small, and require that a simulation code have the ability to mesh preferentially around the grid elements. In addition, while the beams from the guns can be roughly simulated by a steady-state (equilibrium) trajectory code, the essentially 100% modulation of the beam by the input signal demands a time dependent simulation. CCR's Beam Optics Analysis (BOA) has the meshing capability, and can be run in both equilibrium and time dependent modes. In the latter, it functions as electrostatic particle in cell (PIC) code.

An equilibrium simulation of the conventional gun is shown in Figure 27 and Figure 28. The ability to model the trajectories around the grid is shown in Figure 28.

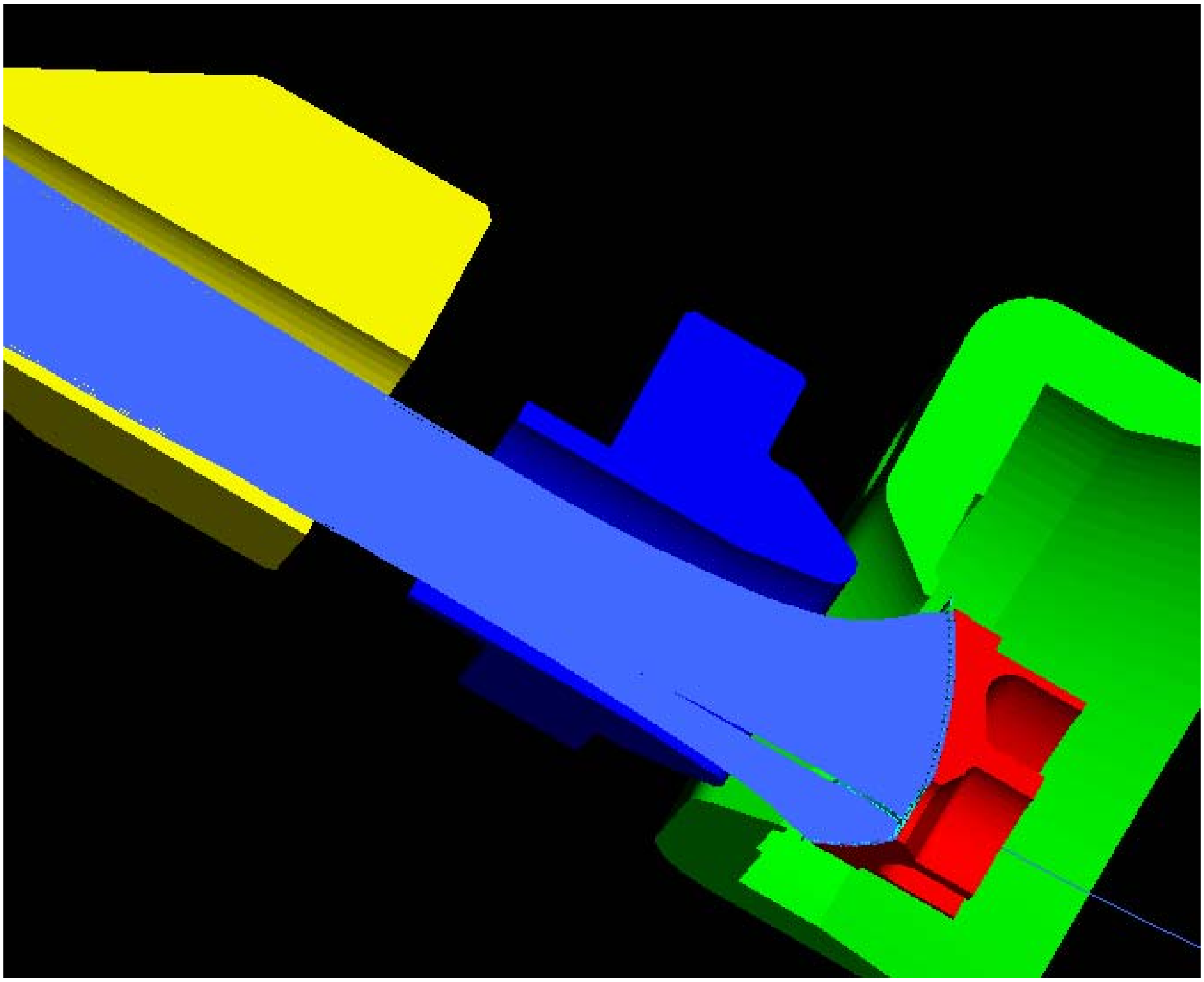


Figure 27. BOA simulation of the conventional gun. Anode voltage equal to 30 kV, grid voltage equal to 0, the cathode voltage. The current was 2 A.

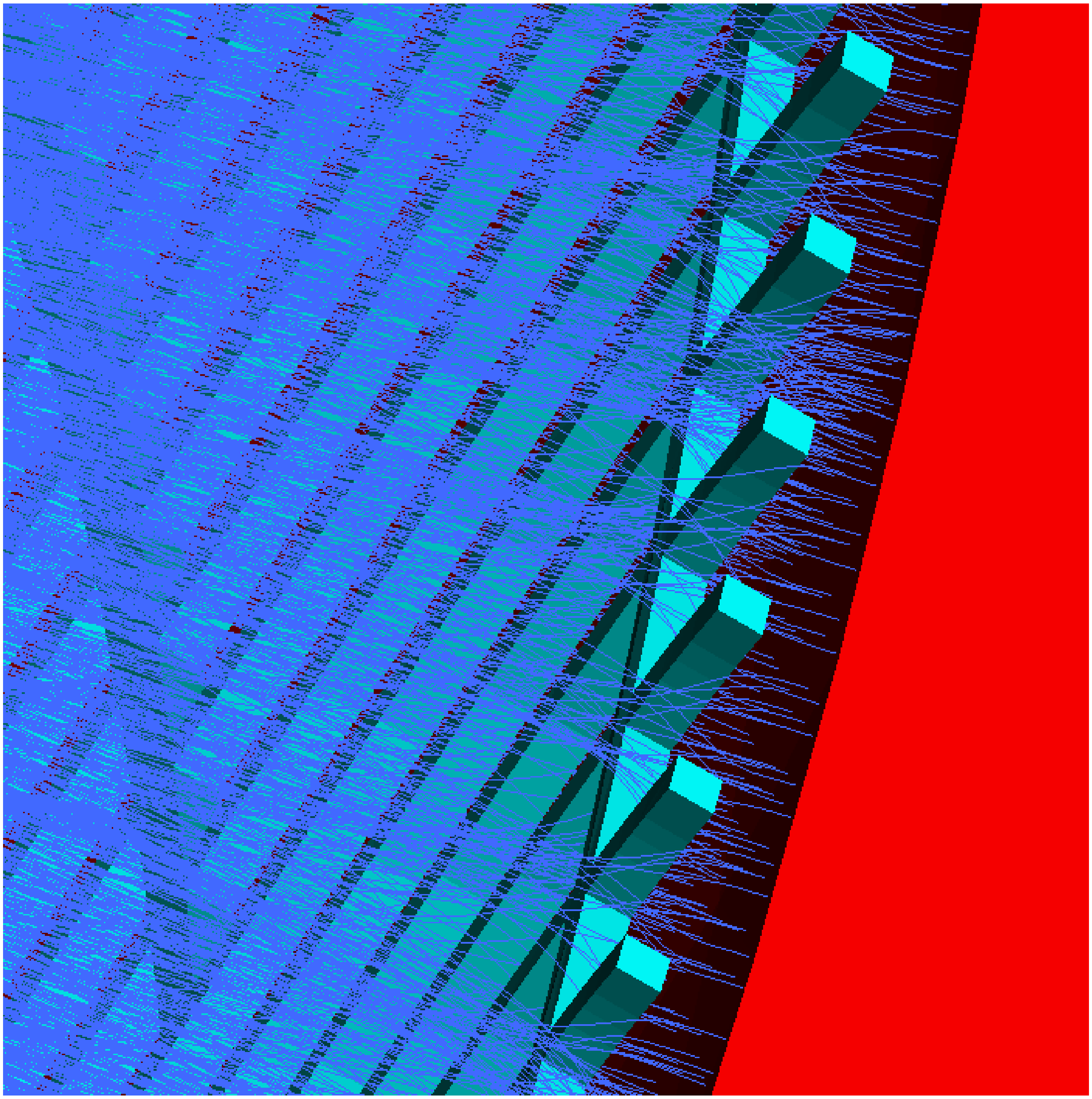


Figure 28. Grid region of the simulation shown in Figure 27.

BOA can work as an electrostatic Particle-in-Cell (PIC), and can thus simulate bunching. The results of simulations of the conventional and dome cathodes in the PIC mode are shown in Figure 29 and Figure 30, and Figure 31and Figure 32, respectively.

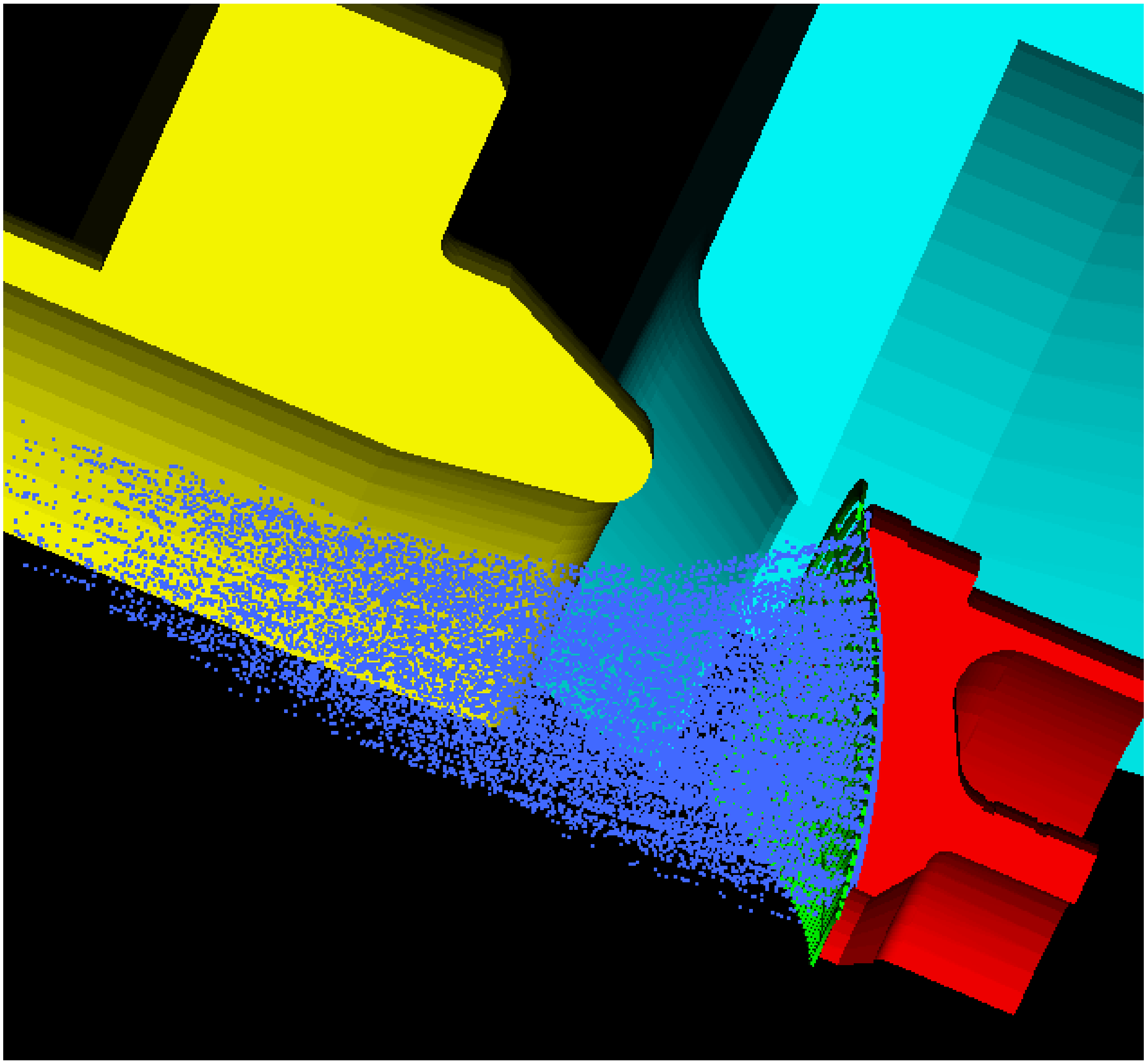


Figure 29. Start of bunch formation in a conventional IOT gun, from a BOA simulation in the PIC mode. The anode voltage was equal to 30 kV, and the grid voltage equal to (100 sin(ωt) – 100) V. The cathode voltage was zero.

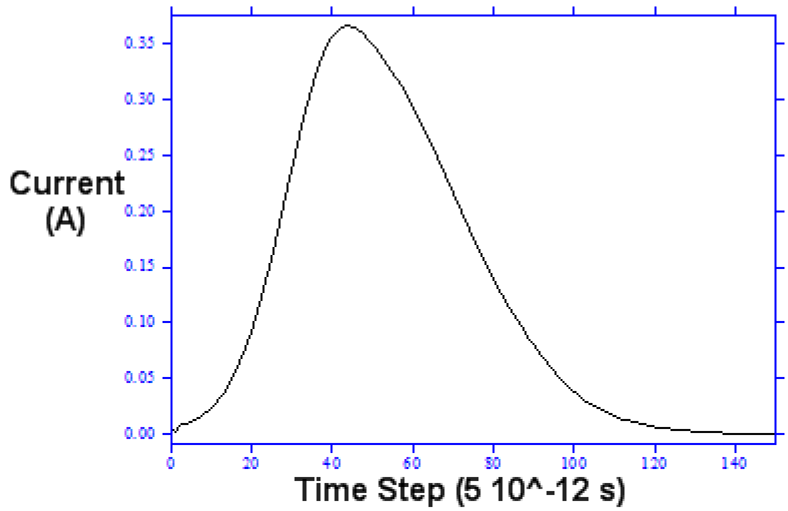
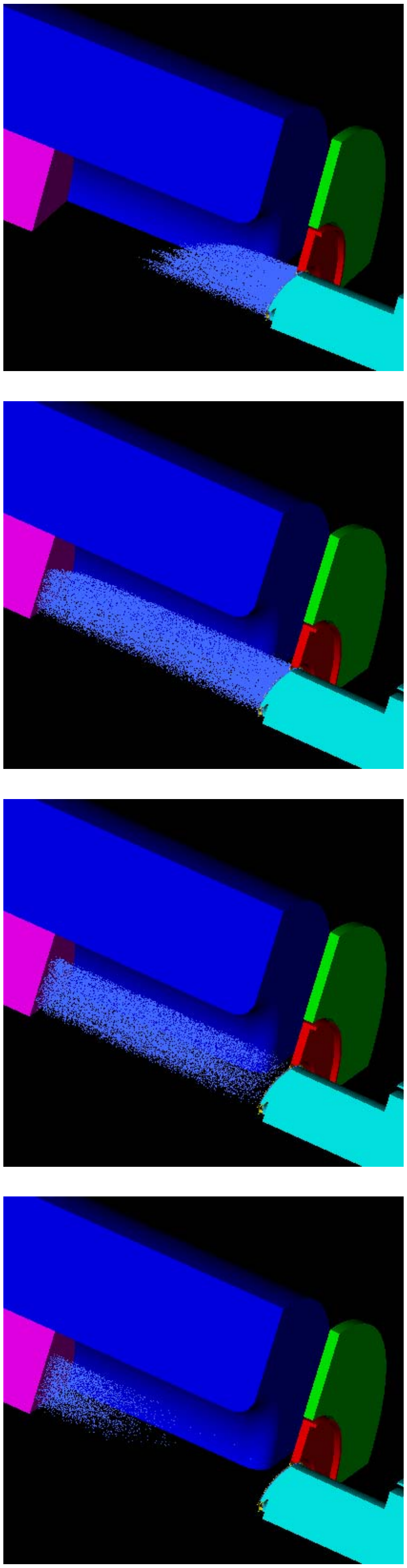


Figure 30. Current versus time for the simulation shown in Figure 29. The current is for the ¼ problem modeled, and thus the peak current for the whole gun was 1.5 A.



0.69 ns

1.04 ns

1.38 ns

1.72 ns

Figure 31. Snapshots from a BOA PIC simulation of the dome cathode gun.

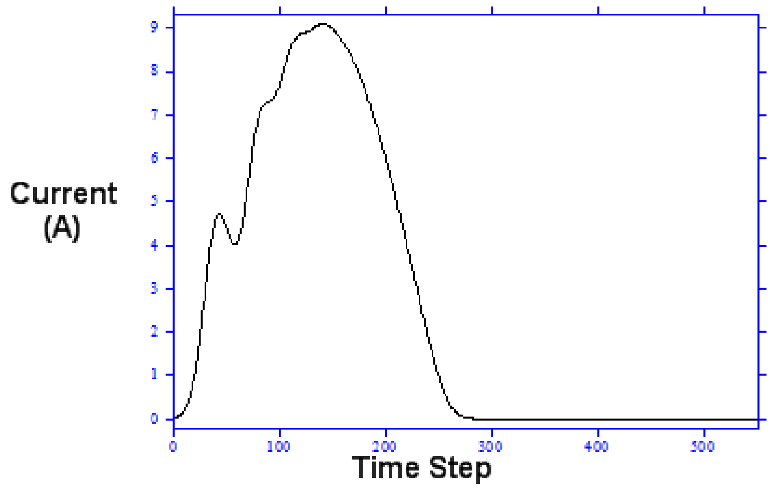


Figure 32. Time history of the current for the beam of Figure 31.

Output cavity modeled with TESLA with Modulated Beam from BOA

The modulated beam simulated with BOA was used as the input to TESLA. The results are shown in Figures 33 - 37. Figure 33 shows the geometry. Figure 34 shows the beam at a single point in time. (The variation in current is not indicated.) The beam axial velocity is shown in Figure 35. The phase is 334 degrees, rather than 248 degrees as was chosen for Figure 34. Accordingly, the bunch as drifted farther.

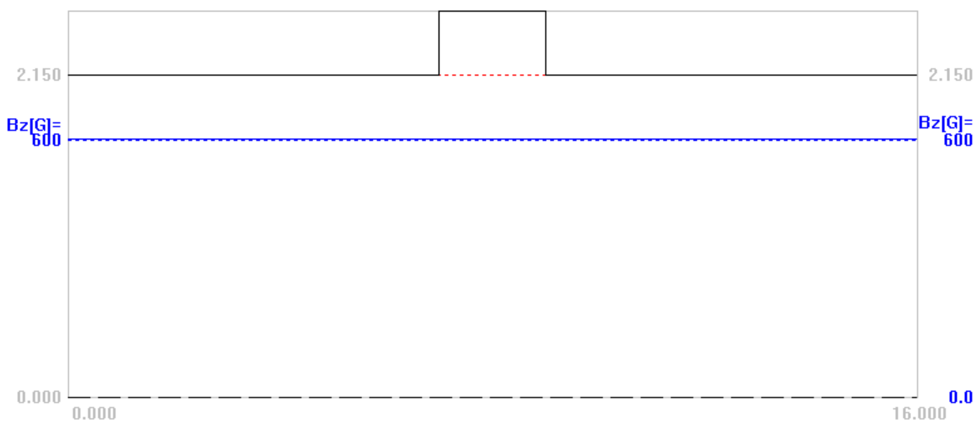


Figure 33. Geometry used in TESLA.

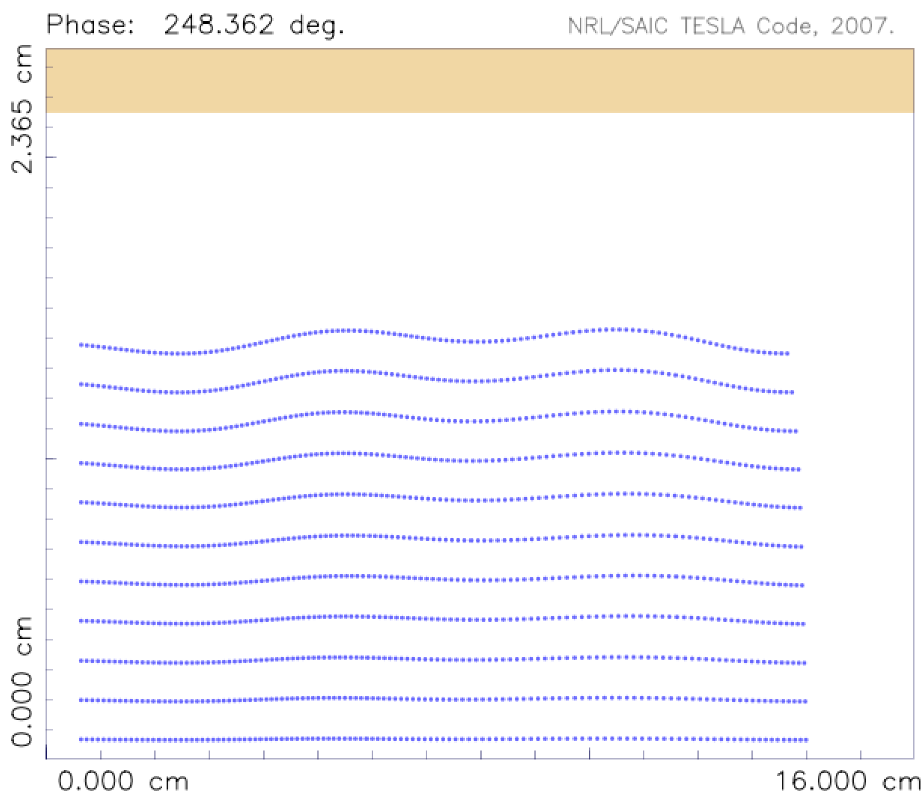


Figure 34. Beam used in TESLA.

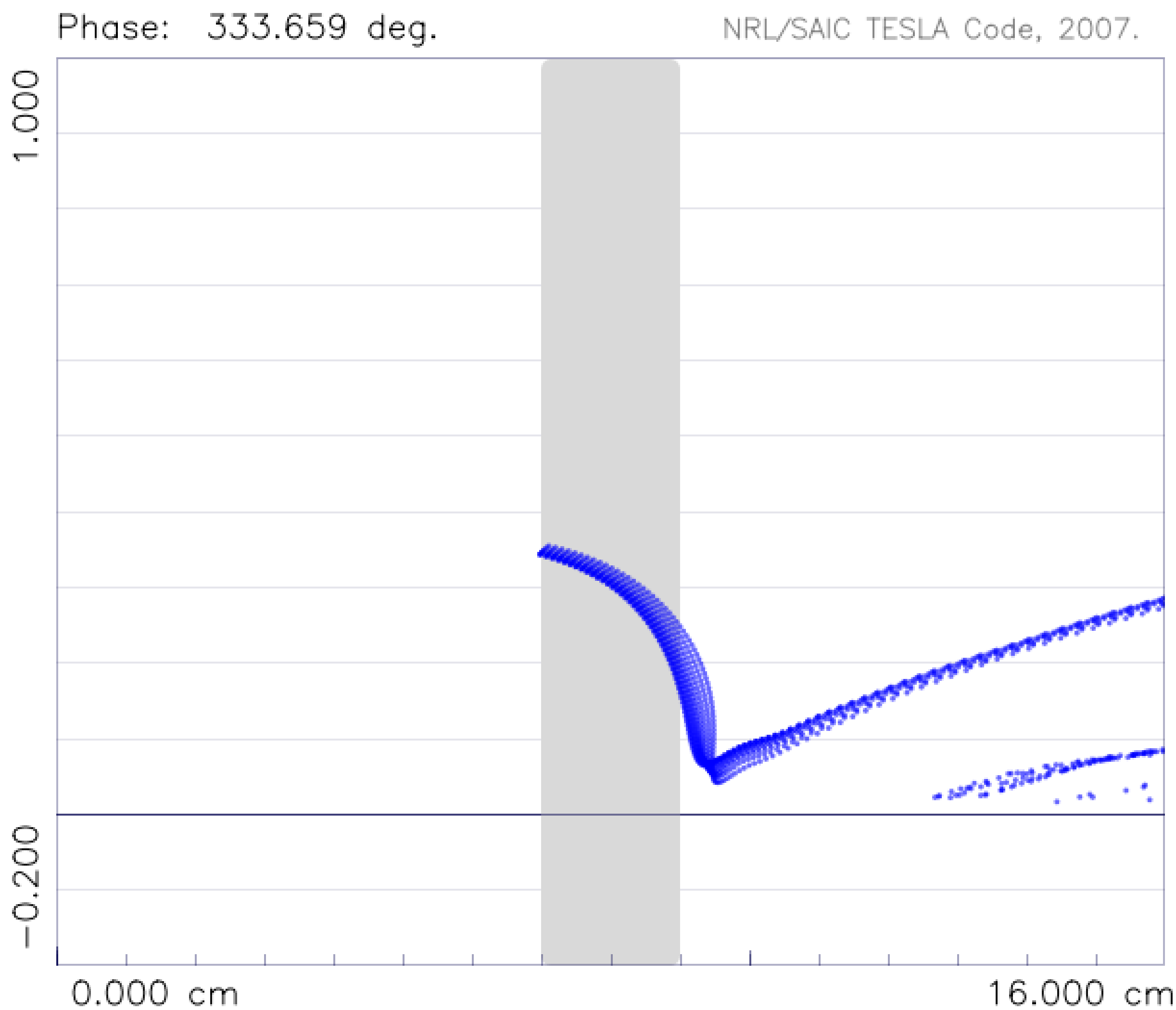


Figure 35. Beam beta (normalized axial velocity) as a function of axial distance. The output cavity gap is indicated by the greyed area. 334 degrees was the phase at which the beta was minimum.

Figure 36 shows the output power as a function of time. Figure 37 shows the same plot for a beam with a modified sine-squared modulation. The ratio of the average to peak current was chosen so that the equilibrium power was the same as that for the IOT with the pre-modulated beam from BOA. That ratio was 0.28. A plot of the power for various current ratios is shown in Figure 38.

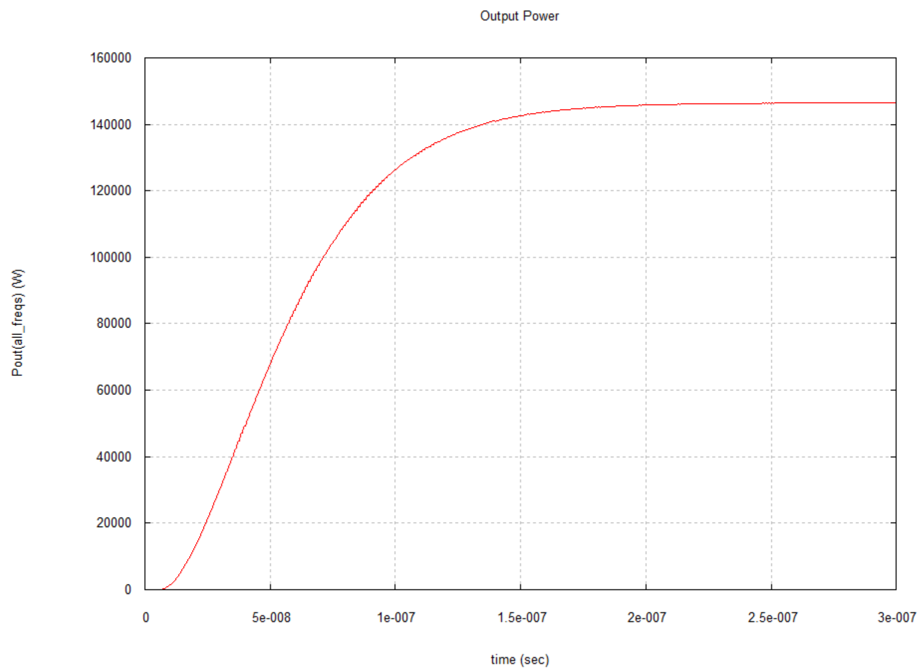


Figure 36. Power versus time from TESLA for the IOT with the pre-modulated beam simulated by BOA. The voltage and average current were 40 kV and 4.84 A, respectively. The output power was 145 kW.

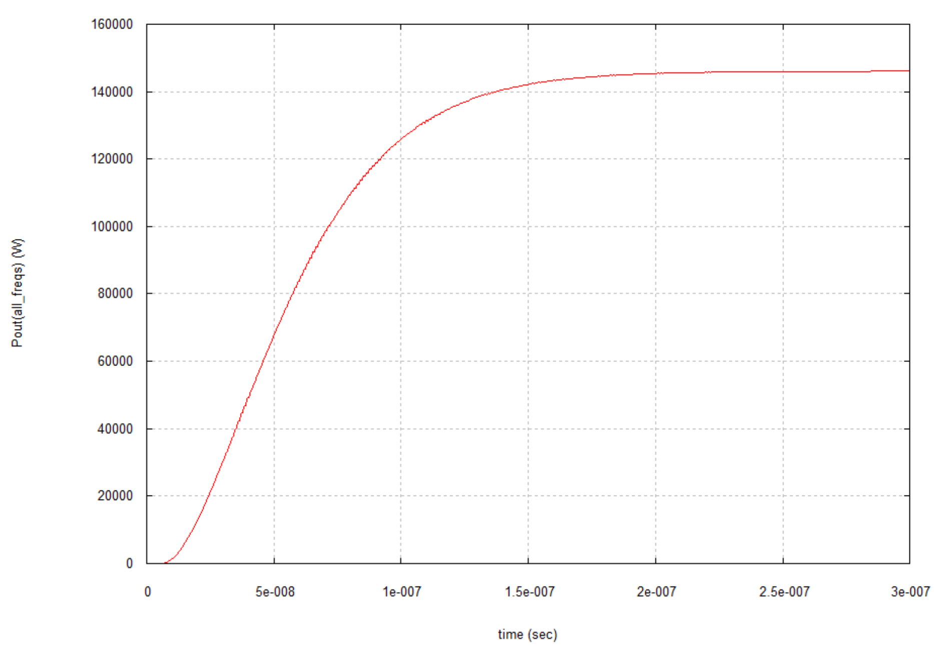


Figure 37. Output power versus time for modified sine^2 modulation, with Iave/Ipeak = 0.218, and an average current of 4.84, the same as used in the calculations with the BOA-generated beam.

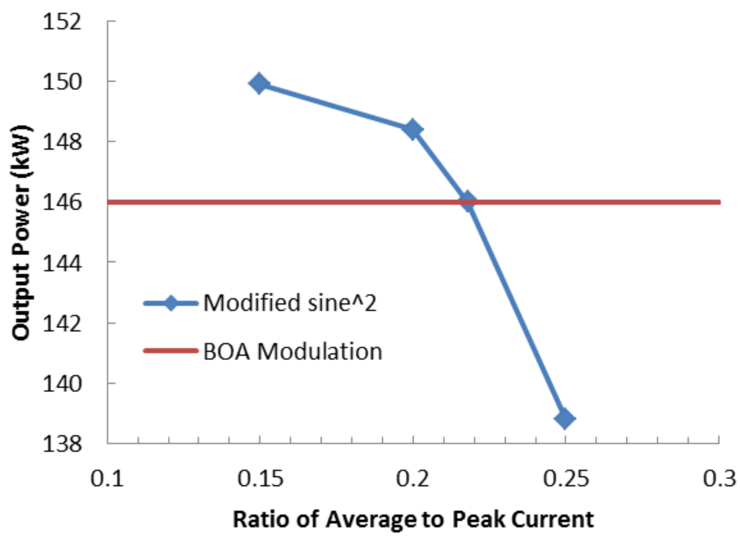


Figure 38. Output power vs ratio of average to peak current for a modified sine^2 modulation, compared with the power produced by the modulated beam as predicted by BOA. The average current was held constant at 4.84 A. The simulations with the modified sin^e modulation give the same power as with the BOA-simulated beam when the ratio of average to peak current equals 0.218.

Summary

Methods for simulating the gun and output cavity have been demonstrated. Results from NEMESIS and TESLA, codes for calculating the interaction of a pre-bunched beam in the output cavity, were compared. TESLA was found to be in better agreement with results from MAGIC, a PIC code, and available experimental data.

BOA, was demonstrated for one of the first times in the electrostatic PIC mode, and was used to produce a bunched beam that was then used in TESLA to simulate operation of the gun and output cavity of a 403.5 MHz IOT. An output power of 145 kW was obtained.

References

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2. See, for example, I.A. Chernyavskiy, A.N. Vlasov, T.M. Antonsen, Jr., S.J. Cooke, B.Levush and K.T.Nguyen, “Simulation of Klystrons with Slow and Reflected Electrons Using Large-Signal Code TESLA”, IEEE TED, Vol.54, No.6, June 2007.

3. I. Chernyavskiy, personal communication (2011).