AN ICEPIC CONVERGENCE STUDY USING A RELATIVISTIC MAGNETRON

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Technical Memorandum

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14. ABSTRACT

The relativistic magnetron under development at AFRL/DEH is designed and improved by simulation before its actual construction. Construction and testing reveals that the simulation performs very well for many parameters but fails to predict the correct input impedance. Questions are also raised about the cell size in the simulations. Thus, simulations are performed on three different magnetron configurations each at three different grid resolutions to study the numerical convergence of the simulations. It is found that the magnetron must be centered on the computational grid for convergence. Conclusions are drawn regarding the cell size needed to simulate the device.

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1   Introduction

The Improved Concurrent Electromagnetic Particle in Cell (ICEPIC) code is an advanced, parallel simulation tool for high power microwave (HPM) sources [1]–[3]. ICEPIC is an electromagnetic particle in cell (EM-PIC) code that most often employs a regular Cartesian grid of cells to discretize the computational space; cylindrical coordinate grids are also available, but are not discussed herein. The development of the code at the High Power Microwave Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/DEH) is mature to the point that the code is used to design and improve devices before these devices are constructed and tested in the laboratory.

One such device that is simulated before its construction is an A6 relativistic magnetron. Following ICEPIC simulation and design improvement, actual construction and testing of the device shows that most of the ICEPIC predictions are physically accurate. However, ICEPIC under predicts the input impedance of the device. This under prediction runs counter to experience and intuition because laboratory devices generally exhibit parasitic current losses that are not modeled in numerical simulation codes. The parasitic current losses cause the laboratory device to draw more current than the simulated device; hence, the input impedance is usually over predicted in numerical simulation.

Due to the under prediction of the input impedance, questions are raised about the size of the grid cells in the ICEPIC simulations. A numerical convergence study of the device is undertaken to resolve these questions. The results of the study provide guidance for future A6 magnetron simulation and are more broadly applicable to the simulation of similar HPM devices.

2   Simulation background

The ICEPIC simulations leading to the construction of the relativistic magnetron utilize 2mm cubic cells. At the expected L-band frequency of oscillation, this is more than sufficient to resolve the electromagnetics in the problem. However, it allows for only 9 cells across the anode-cathode (AK) gap, and even fewer cells across the expected electron hub height. These features may be under resolved in the simulations.

To gauge the convergence of the simulations, simulations are run using 2mm cells, 1mm cells, and 0.5mm cells. If the 1mm results are significantly different from the 2mm results, the 2mm results are likely unconverged. Similarly, if the 0.5mm results differ significantly from the 1mm results, the 1mm results are likely unconverged. On a COMPAQ ES-45 computer, the observed computational burden of the 2mm simulations is approximately 2.5 hours on 16 processors; the burden of the 1mm simulations is approximately 20.5 hours on 32 processors, and the burden

of the 0.5mm simulations is approximately 86 hours on 128 processors. This places the 0.5mm simulations near the limit of currently available computational resources. Note that cutting the cell size in half increases the number of simulation cells by a factor of 8 and requires the simulation timestep to be cut in half. Thus, the expected increase in computational resources is a factor of 16; the observed increases are close to this expected value.

ICEPIC uses macro particles during a simulation, and each macro particle represents many electrons. At each timestep, a cell on the cathode emits a fixed number of macro particles, and the appropriate charge according to physical field emission laws is assigned to each particle. Increasing the number of macro particles emitted increases the simulation fidelity. To gain more insight into the convergence properties, each simulation is run with 2 emitted particles per cell per timestep and 8 emitted particles per cell per timestep.

During the course of the magnetron development, two major modifications are tested. One modification is to the anode geometry and one is to the power extraction scheme. To gain further insight, three different configurations of the magnetron are studied. The first configuration employs the modified anode geometry and the original extraction scheme. The second employs the original anode geometry but the modified extraction scheme. The third and final configuration employs the modified anode geometry and the modified extraction scheme.

In total, 18 simulations are studied (3 grid resolutions $\times$ 2 emission settings $\times$ 3 magnetron configurations = 18 simulations.) Other simulation parameters such as the input voltage and applied magnetic field are held constant across all of the simulations. Data from all of these simulations is analyzed for convergence trends. There is a large number of predicted quantities that can be examined from these simulations. Three of these, the steady state input impedance, the average output power, and the frequency of oscillation are chosen as representative and are the focus of this report. In examining these quantities, the focus is on how the quantities change as the grid cell size and the number of emitted particles is changed rather than on the absolute magnitude of the quantities.

3 Convergence criteria

Even before performing the 18 simulations discussed above in Sec. 2, an initial convergence scan of the modified anode, original extraction scheme magnetron is performed at 2 emitted particles per cathode cell per timestep. A time-windowed average of the output power from one of the extractors at the three grid resolutions is shown in Fig. 1. Alarmingly, these results appear to be not converging. The change in steady state average power from the 1mm results to the 0.5mm results is approximately the same magnitude as the change from the 2mm results to the 1mm results. Further, the device startup time decreased from the 2mm simulation to the 1mm simulation, then
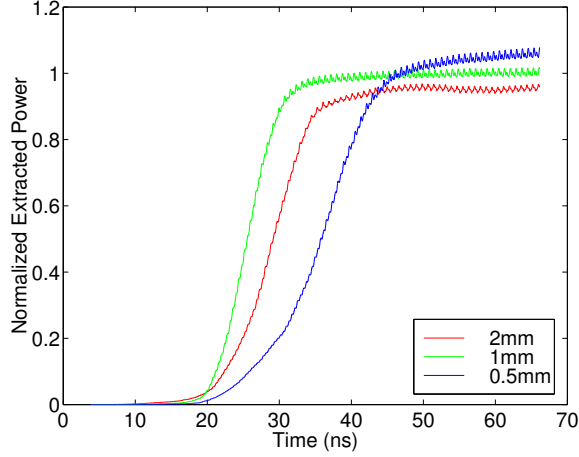
Figure 1: Time-windowed average power from one extractor from the initial convergence scan. The results do not show convergence.

Table 1: Summary of how steady state results change with cell size in the initial convergence scan. The simulation appears not to be converging.

Cell Size	Output Power	Input Impedance	Frequency
2mm to 1mm	4.92%	4.09%	0.00%
1mm to 0.5mm	4.09%	2.56%	0.00%

increased from the 1mm simulation to the 0.5mm simulation. This indicates serious problems with the simulation. Other quantities from this initial convergence scan are summarized in Table 1.

Upon inspection, during this initial scan, the magnetron is found not to be centered on the computation grid, or, in other words, the center axis of the magnetron runs through the grid at an arbitrary location within a grid cell rather than coinciding with a cell corner or the center of a cell. This causes the magnetron to be meshed asymmetrically, as shown in Fig. 2.

Fortunately, when this condition is corrected by centering the magnetron so that its axis coincides with a grid cell corner, the grid exhibits top to bottom and left to right symmetry as shown in Fig. 3. This centering condition is obeyed for all results subsequently discussed herein. These results show that centering the magnetron on the computation grid does lead to numerical convergence. Thus, the simulation geometry should be appropriately centered on the computation grid in general for EM-PIC simulations such as those performed by ICEPIC to be expected to converge.

4   Simulation data

Plots of the normalized output power of the various magnetron configurations as a function of time are shown in Figs. 4–6. As discussed in Sec. 3, the magnetron is centered on the grid for all of

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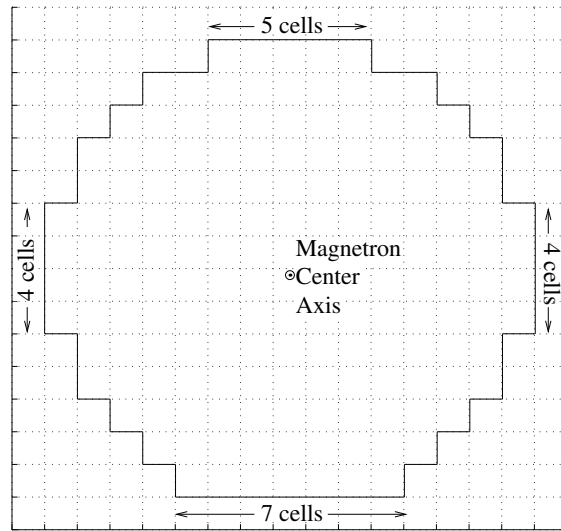
Figure 2: Closeup of the magnetron cathode with the magnetron axis at an arbitrary grid location. Note the top to bottom asymmetry.
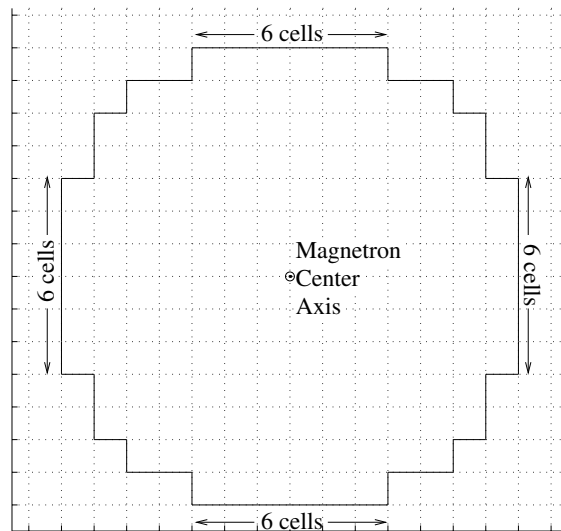
Figure 3: Closeup of the magnetron cathode with the magnetron axis at a grid cell corner. Note the top to bottom symmetry.
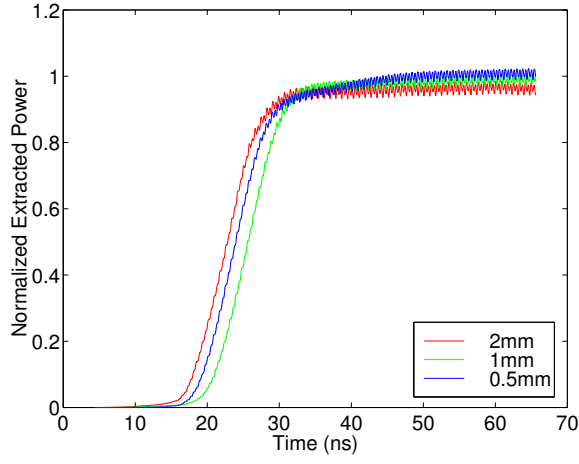
(a) 2 emitted particles per cell per timestep
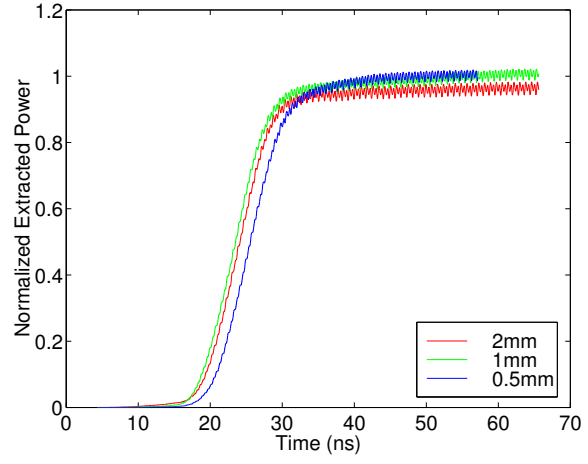
(b) 8 emitted particles per cell per timestep

Figure 4: Time-windowed average power from one extractor from modified anode, original extraction magnetron.
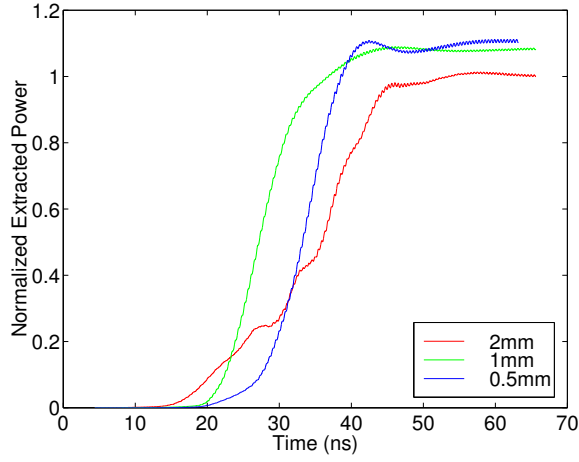
(a) 2 emitted particles per cell per timestep
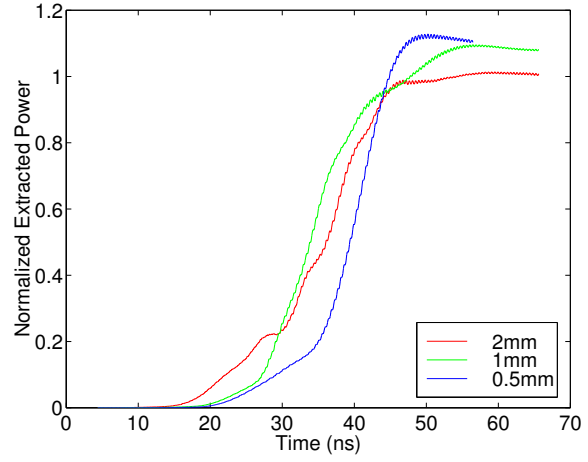
(b) 8 emitted particles per cell per timestep

Figure 5: Time-windowed average power from one extractor from original anode, modified extraction magnetron.

(a) 2 emitted particles per cell per timestep　　　(b) 8 emitted particles per cell per timestep
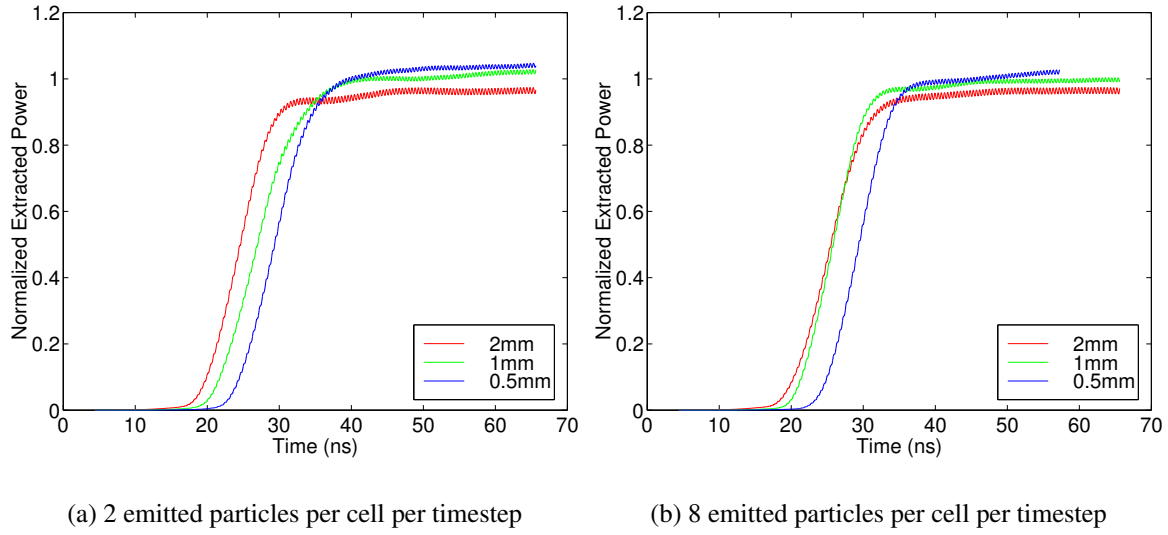
Figure 6: Time-windowed average power from one extractor from modified anode, modified extraction magnetron.

these simulations. Note that a few simulations ended prematurely because the computer platform allowed simulations to run for a maximum of 96 hours. The simulations shown in Figs. 4–6 appear to be converging much better than the simulation shown in Fig. 1, where the magnetron is not centered on the grid. In these latter simulations, the change in steady state output power is smaller when the grid is refined from 1mm cells to 0.5mm cells than it is when the grid is refined from 2mm cells to 1mm cells. Also, with the possible exception of the original anode, modified extraction configuration, which is known to have physical stability problems, the change in the time to reach steady state does not decrease then increase again with grid refinement as it does in Fig. 1. The convergence situation appears to be much improved by centering the magnetron on the computation grid.

The changes in simulation quantities as the grid cell size is changed are summarized in Table 2, and the changes as the number of emitted particles per cell per timestep is varied are summarized in Table 3. In comparing the two tables it is apparent that changing from 2 emitted particles per cell per timestep to 8 particles per cell per timestep has a much smaller effect on the convergence of the simulation than changing the cell size. Therefore, 2 emitted particles per cell per timestep is deemed adequate for these simulations. The output power, input impedance, and frequency of oscillation of the magnetron change by comparatively large amounts as the cell size is varied from 2mm to 1mm, but these quantities change by much smaller amounts as the cell size is varied from 1mm to 0.5mm. Thus, 1mm simulation should be used for most design work. A 0.5mm simulation is advisable to check a design before committing resources to construction of an actual magnetron.

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Table 2: Summary of how steady state results change with cell size for the various simulations.

Configuration	Emission	Cell Size	Power	Input Impedance	Frequency
Mod. anode, orig. ext.	2 parts/cell/step	2mm to 1mm	2.31%	6.88%	2.70%
		1mm to 0.5mm	1.80%	1.31%	0.00%
	8 parts/cell/step	2mm to 1mm	3.63%	6.69%	2.70%
		1mm to 0.5mm	0.92%	1.27%	0.00%
Orig. anode, mod. ext.	2 parts/cell/step	2mm to 1mm	8.45%	5.23%	0.00%
		1mm to 0.5mm	0.93%	3.71%	0.00%
	8 parts/cell/step	2mm to 1mm	7.46%	5.59%	0.00%
		1mm to 0.5mm	4.39%*	3.77%	0.00%
Mod. anode, mod. ext.	2 parts/cell/step	2mm to 1mm	4.41%	7.88%	2.94%
		1mm to 0.5mm	2.76%	1.55%	0.00%
	8 parts/cell/step	2mm to 1mm	3.09%	7.97%	2.94%
		1mm to 0.5mm	2.10%	2.44%	0.00%

* Value may be inaccurate due to truncation of simulation by hard wall clock time limit.

Table 3: Summary of how steady state results change with particle emission for the various simulations.

Configuration	Cell Size	Emission	Power	Input Impedance	Frequency
Mod. anode, orig. ext.	2mm	2 to 8 parts/cell/timestep	-0.38 %	0.19%	0.00%
	1mm	2 to 8 parts/cell/timestep	0.91%	0.01%	0.00%
	0.5mm	2 to 8 parts/cell/timestep	0.03%	-0.03%	0.00%
Orig. anode, mod. ext.	2mm	2 to 8 parts/cell/timestep	-0.05 %	0.08%	0.00%
	1mm	2 to 8 parts/cell/timestep	-0.96%	0.42%	0.00%
	0.5mm	2 to 8 parts/cell/timestep	2.44%*	0.48%	0.00%
Mod. anode, mod. ext.	2mm	2 to 8 parts/cell/timestep	0.10 %	0.03%	0.00%
	1mm	2 to 8 parts/cell/timestep	-1.16%	0.12%	0.00%
	0.5mm	2 to 8 parts/cell/timestep	-1.79%	0.99%	0.00%

* Value may be inaccurate due to truncation of simulation by hard wall clock time limit.

5   Simulation run times

Table 4 summarizes the number of processors and the run times for the various simulations on a COMPAQ ES45 computer. The 0.5mm cell size simulations are close to the limit of computational resources on current super computers. In fact, some of these simulations that employed 8 particle per cell per timestep emission did not run to completion in the 96 hours allowed on the computer. The next generation of super computers may allow for a 0.25mm cell size run. Note that the expected increase in CPU time (wall clock time times number of processors) when halving the cell size is a factor of 16 as the number of cells increases by a factor of 2 in each of 3 dimensions and the maximum stable timestep is cut in half, which doubles the number of required timesteps. The

Table 4: Summary of simulation run times on a COMPAQ ES45 computer. Times are hh:mm:ss. Some simulations did not run to completion due to a 96 hour run time limit.

Configuration	Emission	Cell Size	Processors	Wall Time
Mod. anode, orig. ext.	2 parts/cell/step	2mm	16	2:02:35
		1mm	32	15:38:32
		0.5mm	128	70:56:05
	8 parts/cell/step	2mm	16	2:54:31
		1mm	32	18:15:59
		0.5mm	128	96:00:00+
Orig. anode, mod. ext.	2 parts/cell/step	2mm	16	2:38:22
		1mm	32	20:12:30
		0.5mm	128	96:00:00+
	8 parts/cell/step	2mm	16	3:27:44
		1mm	32	23:20:02
		0.5mm	128	96:00:00+
Mod. anode, mod. ext.	2 parts/cell/step	2mm	16	2:34:48
		1mm	32	20:28:21
		0.5mm	128	86:07:16
	8 parts/cell/step	2mm	16	3:23:32
		1mm	32	25:31:56
		0.5mm	128	96:00:00+

data in Table 4 reflects this expectation. By comparison, the increase in CPU time due to increasing from 2 particles per cell per timestep to 8 particles per cell per timestep is modest, but the data in Sec. 4 shows little or no convergence gain by doing so.

6   Conclusion

The convergence properties of ICEPIC magnetron simulations are examined experimentally. Three different magnetron configurations are examined each at three different grid cell sizes and two different particle emission settings. The simulations reveal that the magnetron must be centered on the computational grid for simulation convergence. Further, the predicted input impedance of the magnetron increases as the computational grid is refined, bringing the value closer to the observed value in the laboratory. The particle emission setting is found to have little effect on the convergence. Simulations employing 2mm cell size are found to be unconverged; 1mm cell size is adequate for most design work, and a 0.5mm cell size check is advisable before finalizing a design.

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