U.S. NAVAL RESEARCH LABORATORY

PIC-Simulations of an Intense Electron Beam Plasma using EMPIRE

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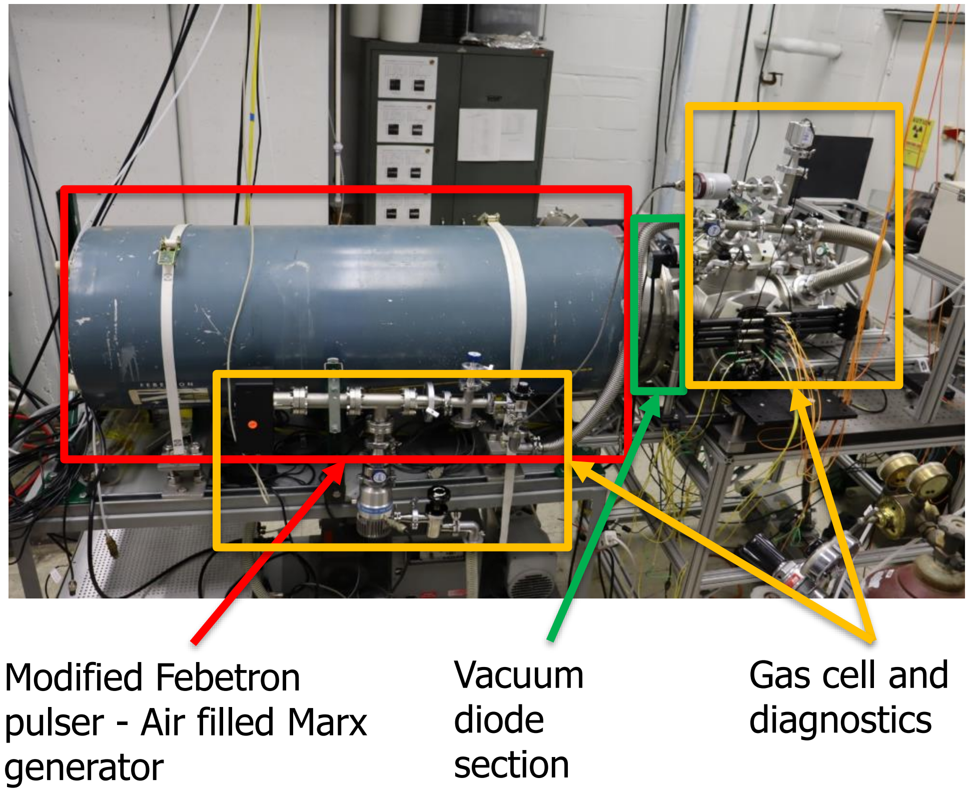
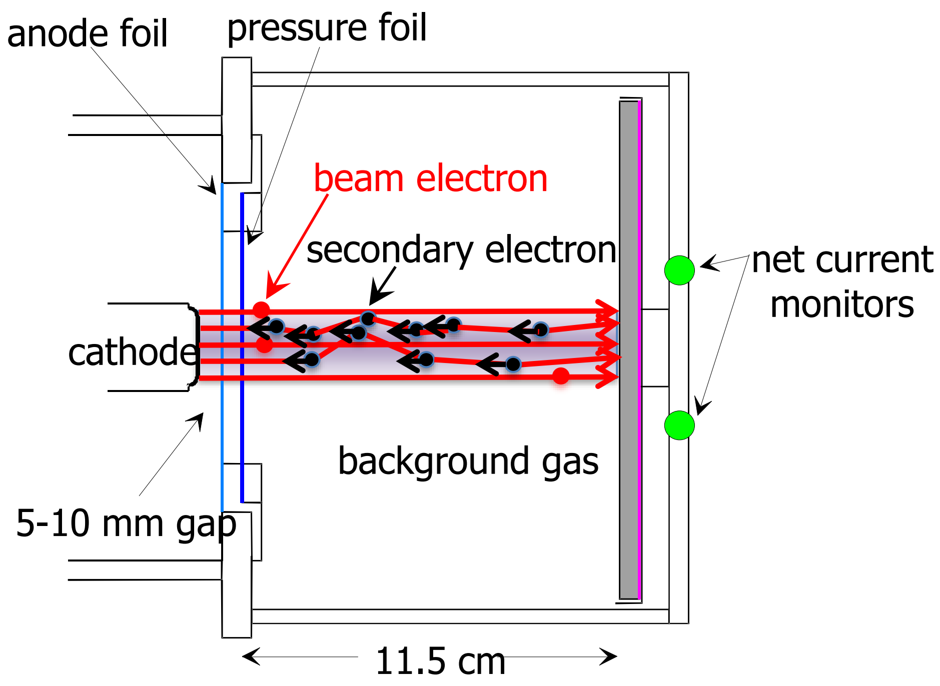
Model of the Febetron experiment and how we generate and intense electron beam

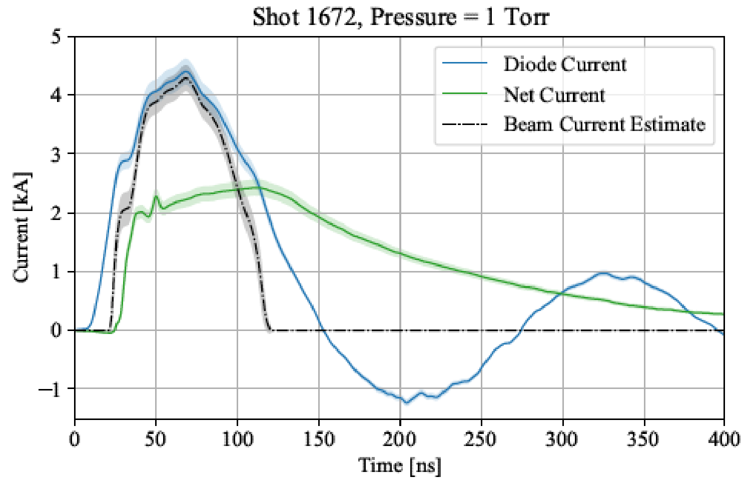
- Pulsed power generator creates an electron beam with conditions at 100 ns, 80 kV, 4 kA
- The electron beam is injected into a low-pressure gas cell
- Beam electrons enter the cell and impact and ionize the gas

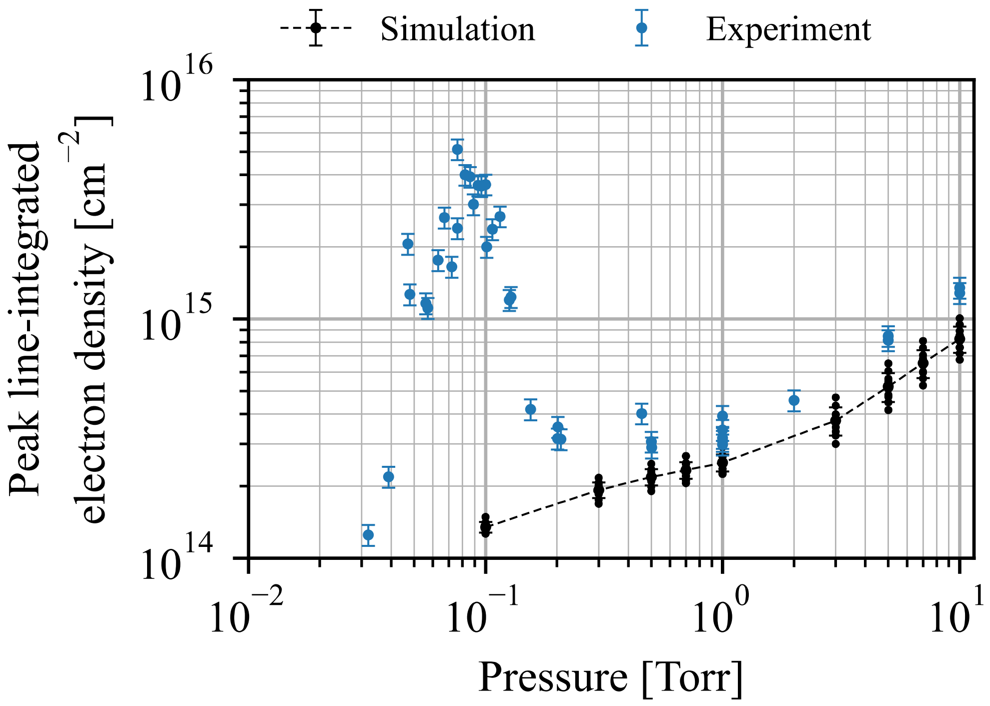


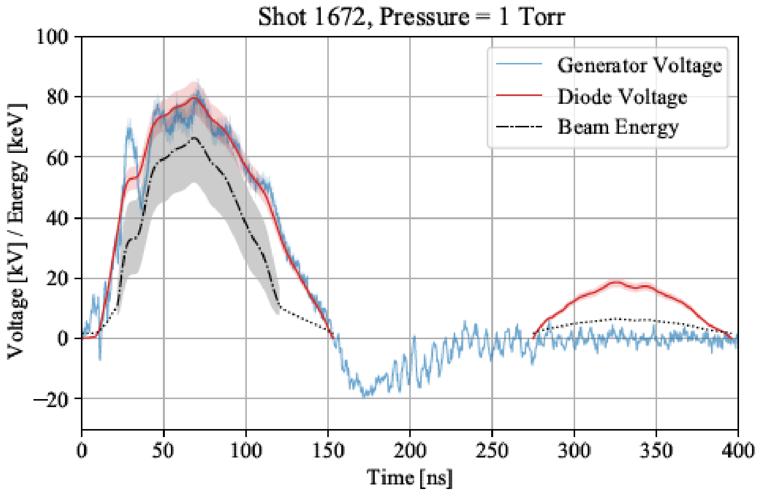


Experimental shots at 1 Torr show the beam current and energy profiles

- Examples of estimated beam current and beam energies from a series of “high current” shots
- The shaded regions are the spread in beam energy from calculated from ITS.
- By varying these shots over pressure we can study the peak electron density

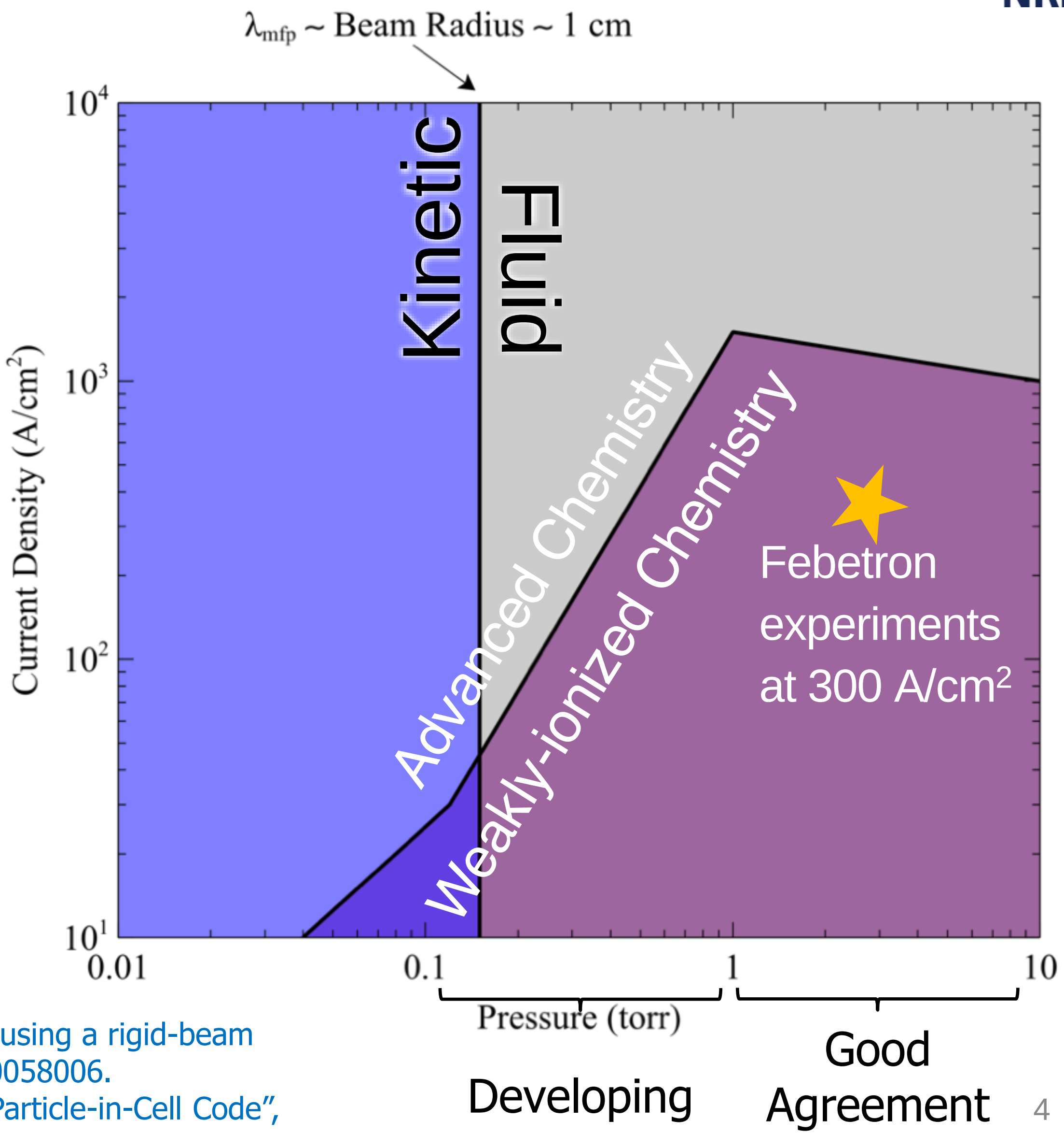






Electron beam modeling dynamics are chosen by what is seen in the physical model

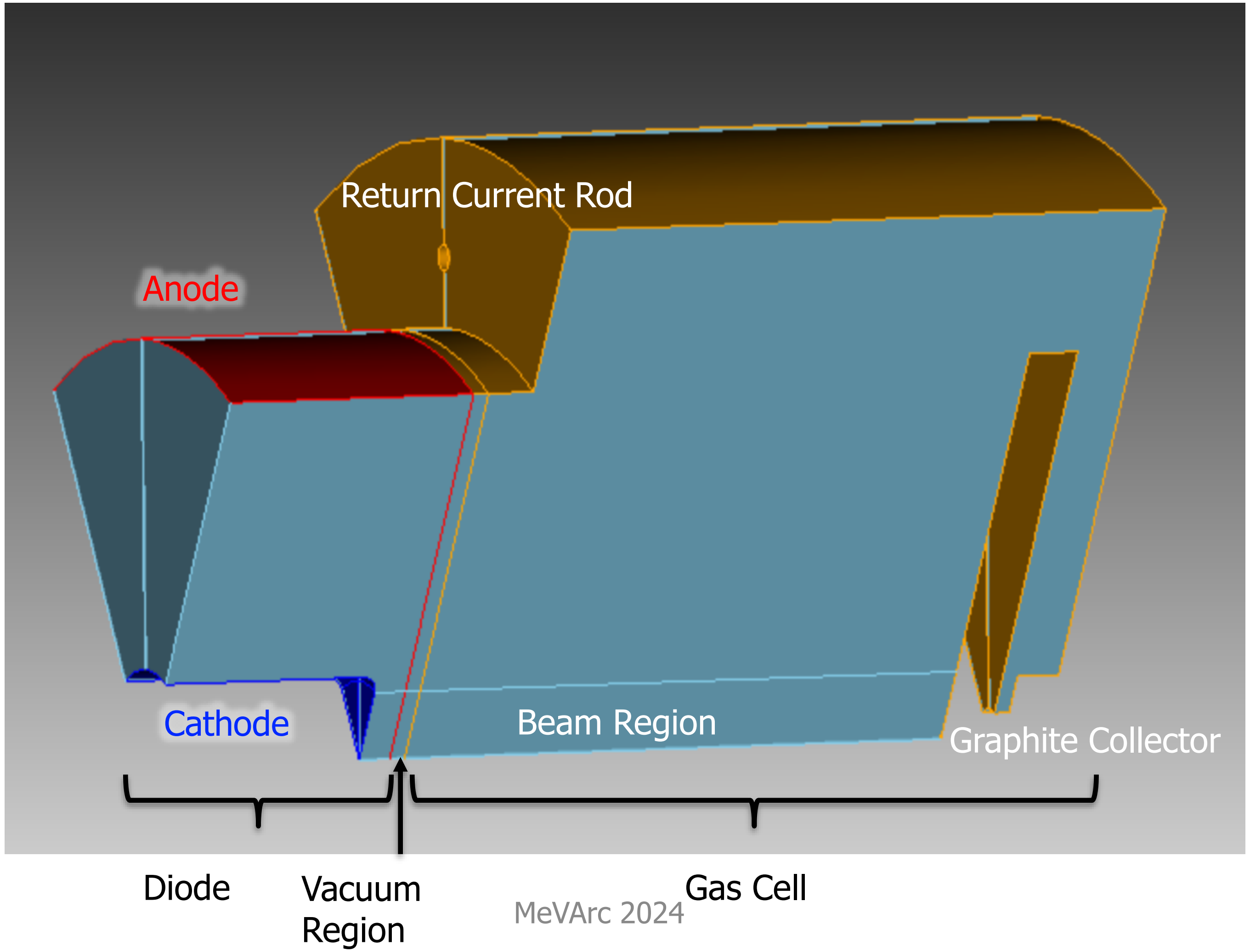
- Choosing a model and the chemistry for a beam-plasma system will depend on the gas pressure and the electron beam current density and one can chose either a
  - Weakly Ionized (molecular interactions) or Advanced Chemistry (excited interactions)
  - Fluid or Kinetic Modeling
- The RBM [1] is fluid treatment of the governing equations and uses the weakly ionized chemistry
- The kinetic description is being developed with EMPIRE [2]



[1] A. S. Richardson et al., "Modeling intense-electron-beam generated plasmas using a rigid-beam approximation," Phys. Plasmas, vol. 28, no. 9, p. 093508, 2021, doi: 10.1063/5.0058006.
[2] M.T. Bettencourt et al., "EMPIRE-PIC: A Performance Portable Unstructured Particle-in-Cell Code", https://www.osti.gov/pages/biblio/1822232

Creating a 3D model in Empire and describing the components

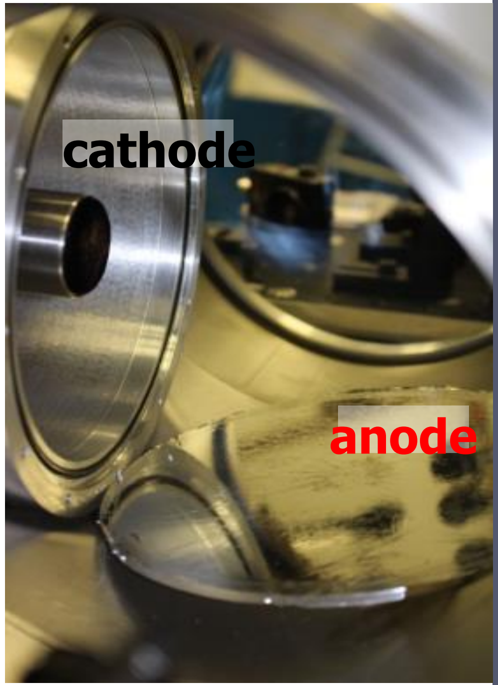
Red is the anode, Blue is the cathode, Orange are the conducting surfaces

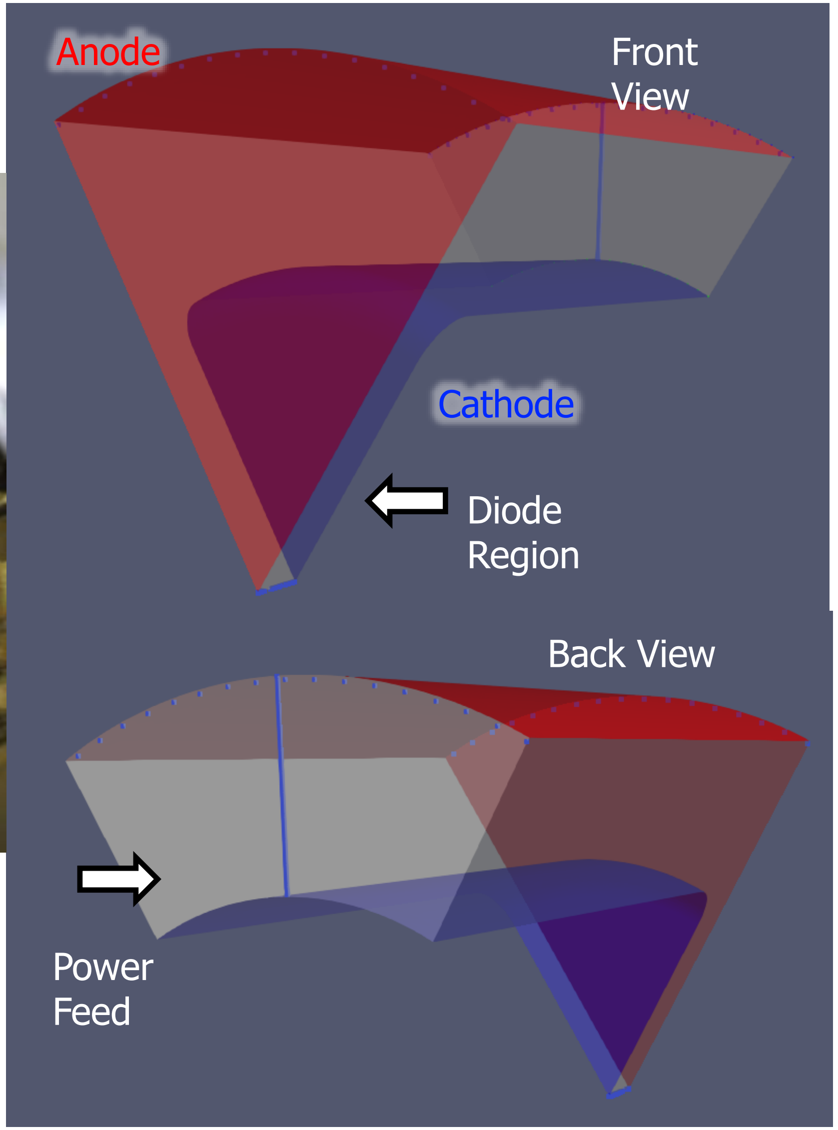


Start by modeling the Vacuum Diode

- Empire simulates the vacuum region of space
- Here our cubit model has the anode in red and the cathode in blue and the grey region is the simulation region.
- The faint blue lines that you can see are where we have place our diagnostics for current and voltage.
- The voltage pulse was with a rise time of τ = 100ns and V_0=100kV

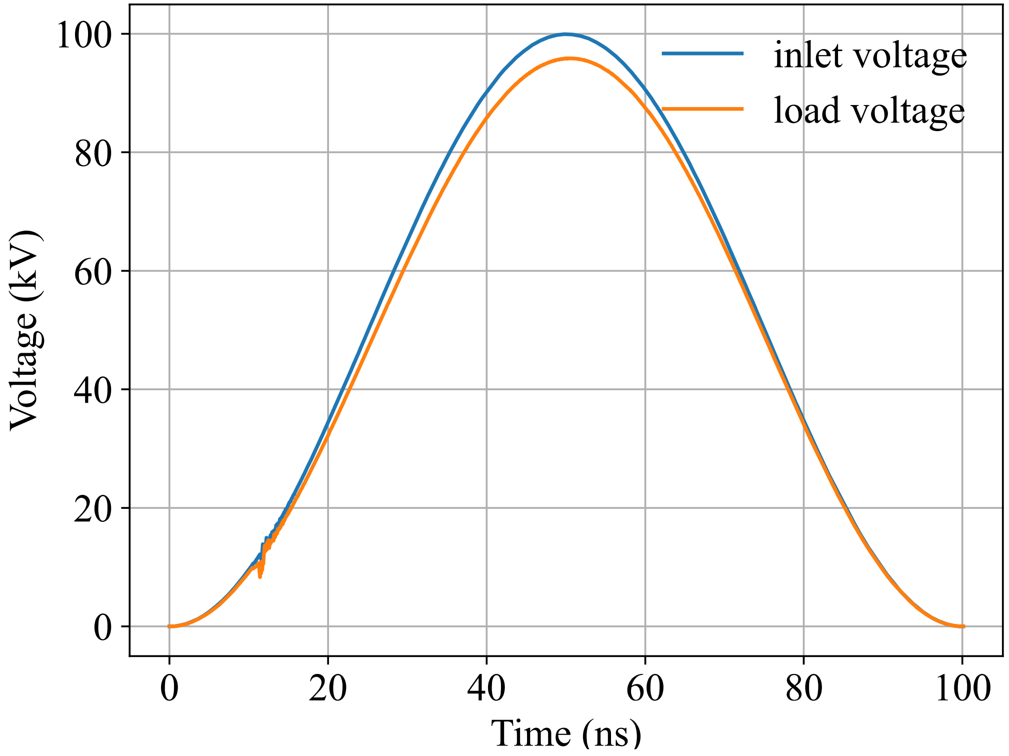
$$-V = V_0 \sin\left(\left(\frac{\pi}{2\tau}\right)t\right)^2$$

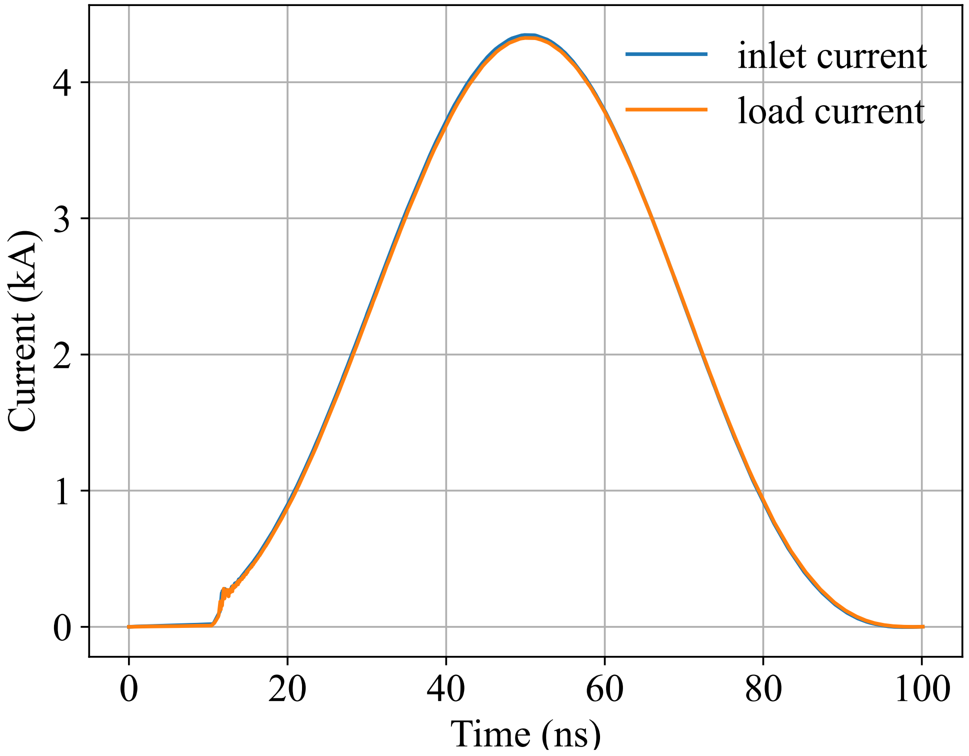




History traces of the voltage, current and electrons of the vacuum diode

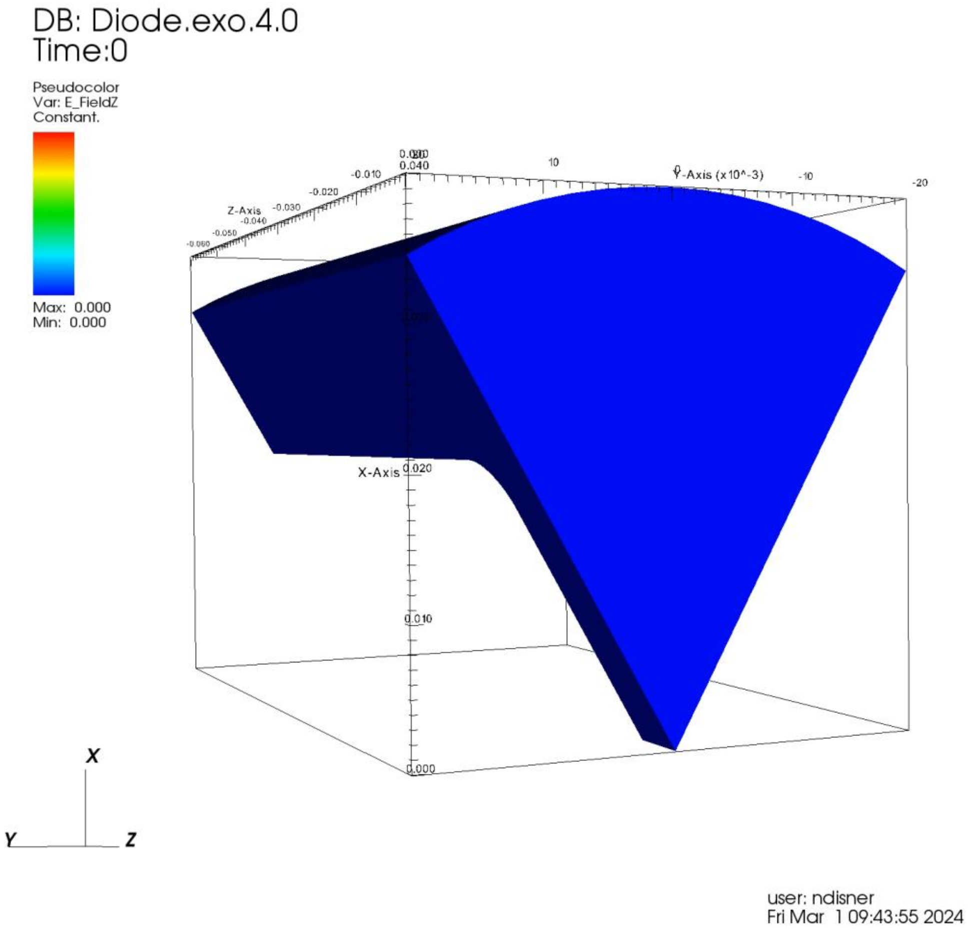
- Here we have the voltage and current traces over time which show the vacuum diode reaching 100 kV and 4 kA.
- At the diode region there is some voltage lost due to inductance



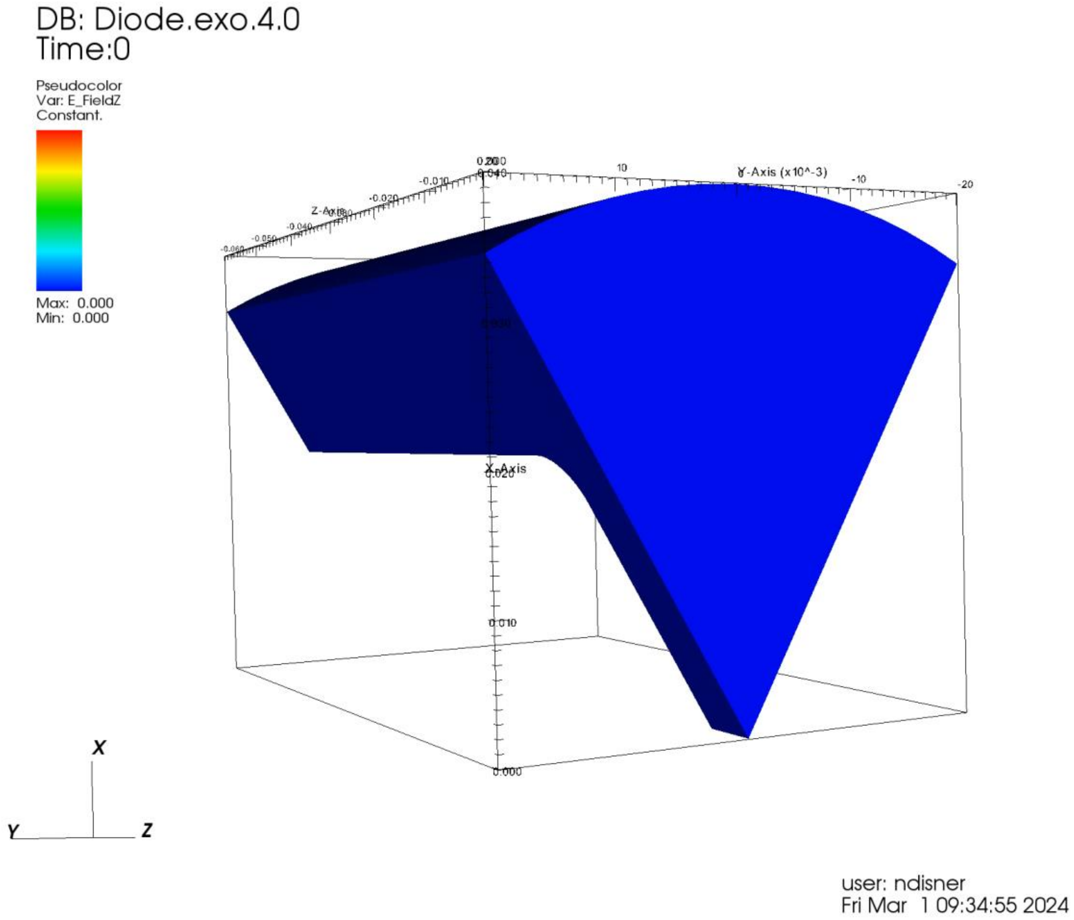


Comparison of time stepping methods for the Electric Field in the Febetron Diode which showed more numerical smoothing was needed

Time Integration: Friedman

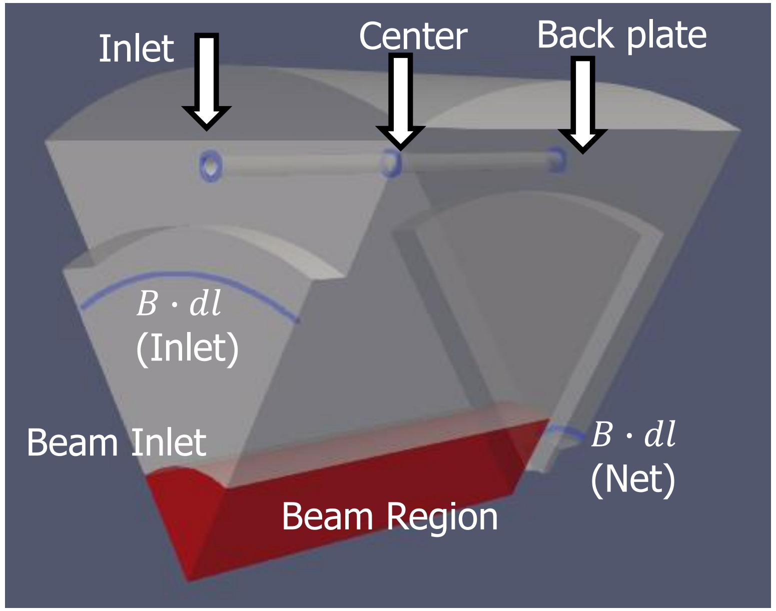


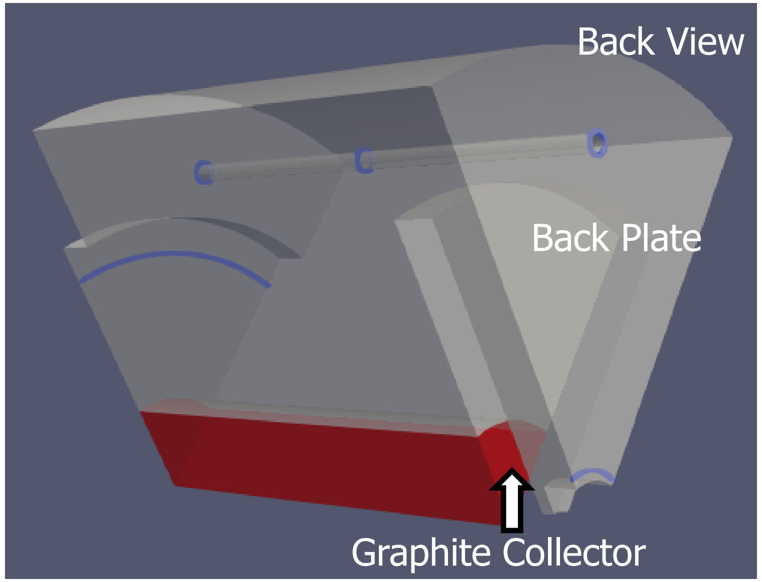
Time Integration: Backward Euler



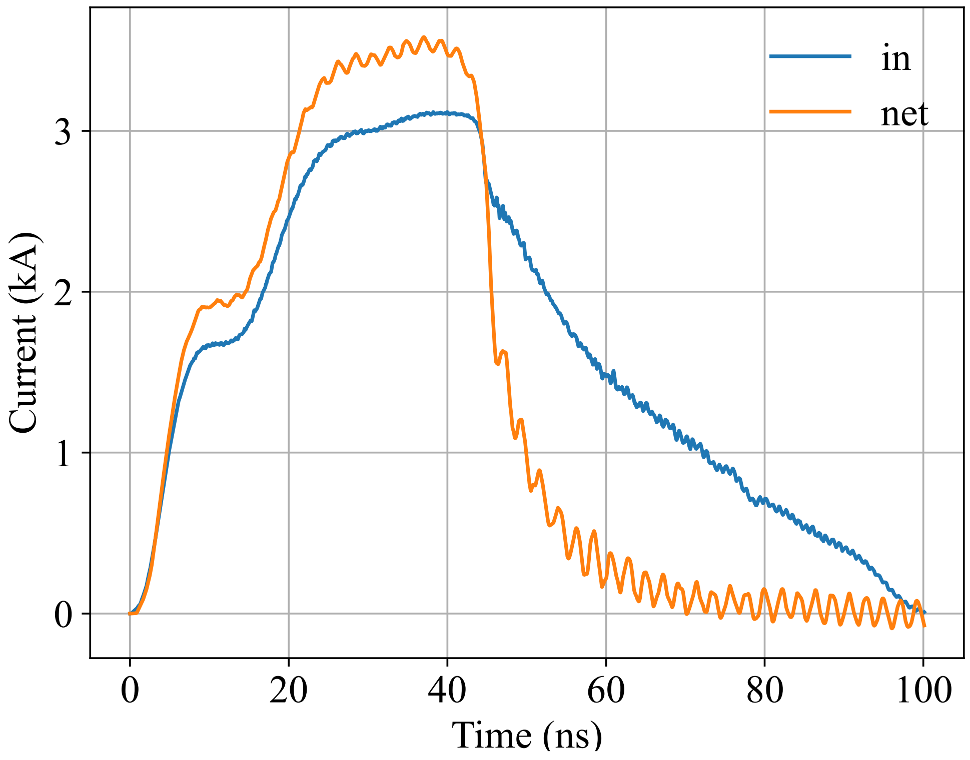
Developed a cubit model of the Febetron gas cell in vacuum

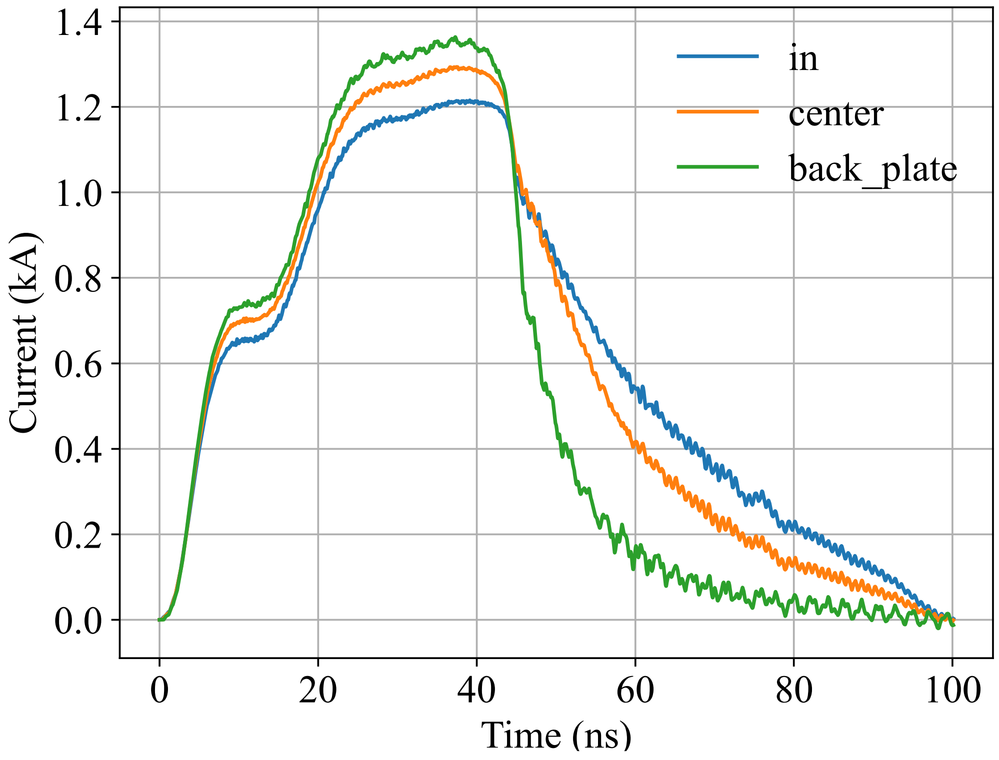
- Grey and red surface is the vacuum region.
- Treating outer grey surfaces as perfectly electrical conductors
- For Empire we use beam type emission and set the region of input to be through the Beam Inlet
- The initial energy is 100 keV and the total current is 4 A, we note that this is different from the experiment but this is because we are testing at vacuum.



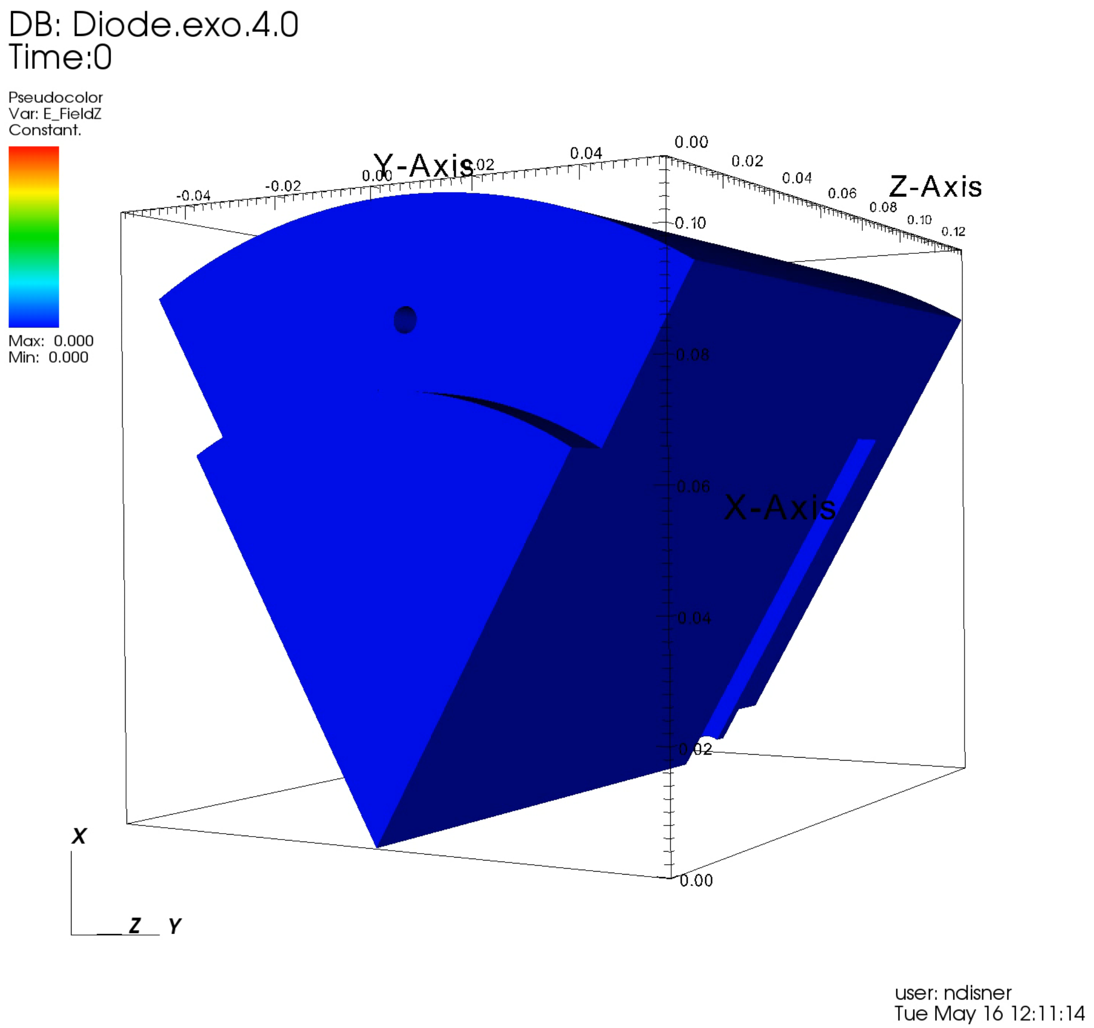


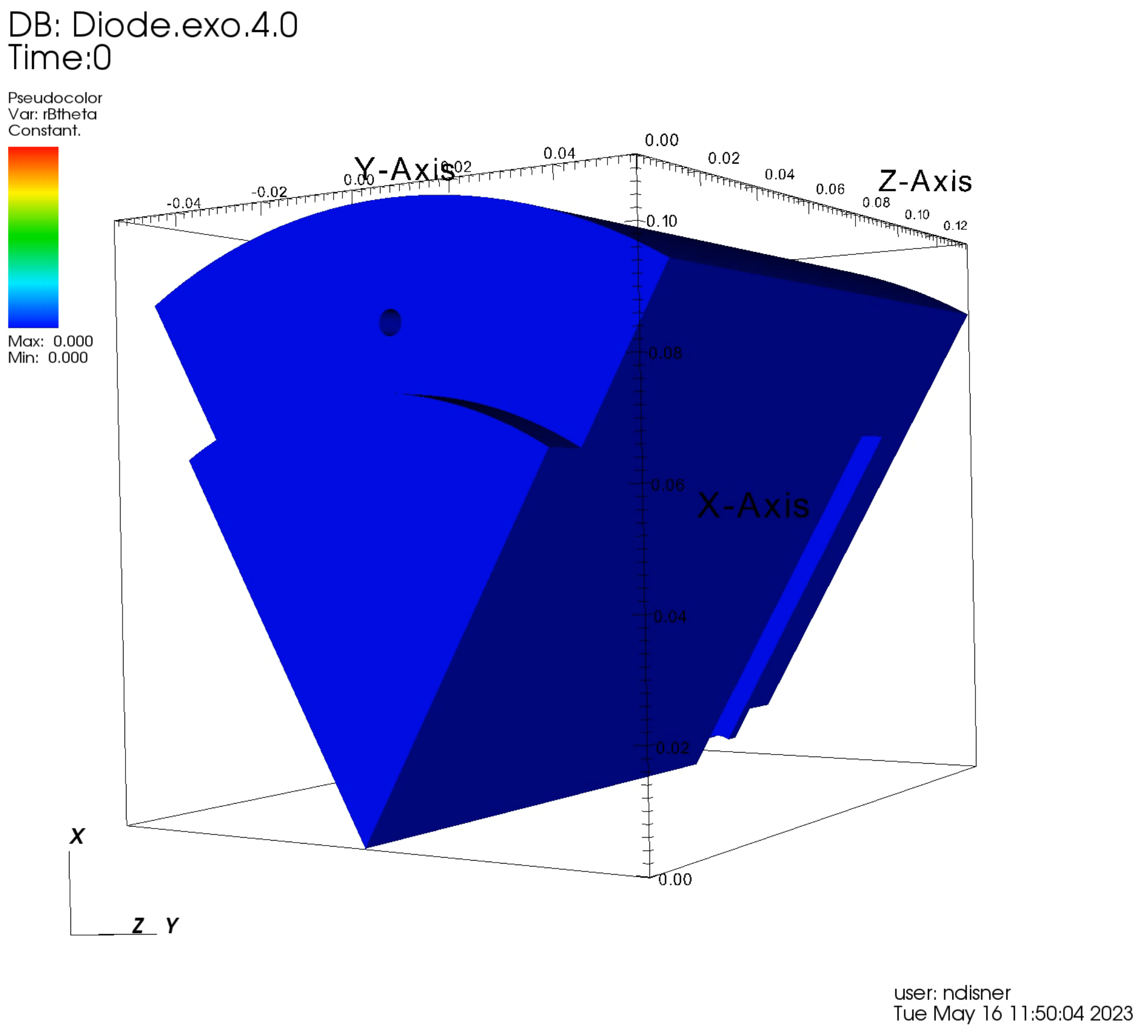
Current traces of the gas cell at vacuum





Result of Electric Field and Current Enclosed for Febetron gas cell at vacuum





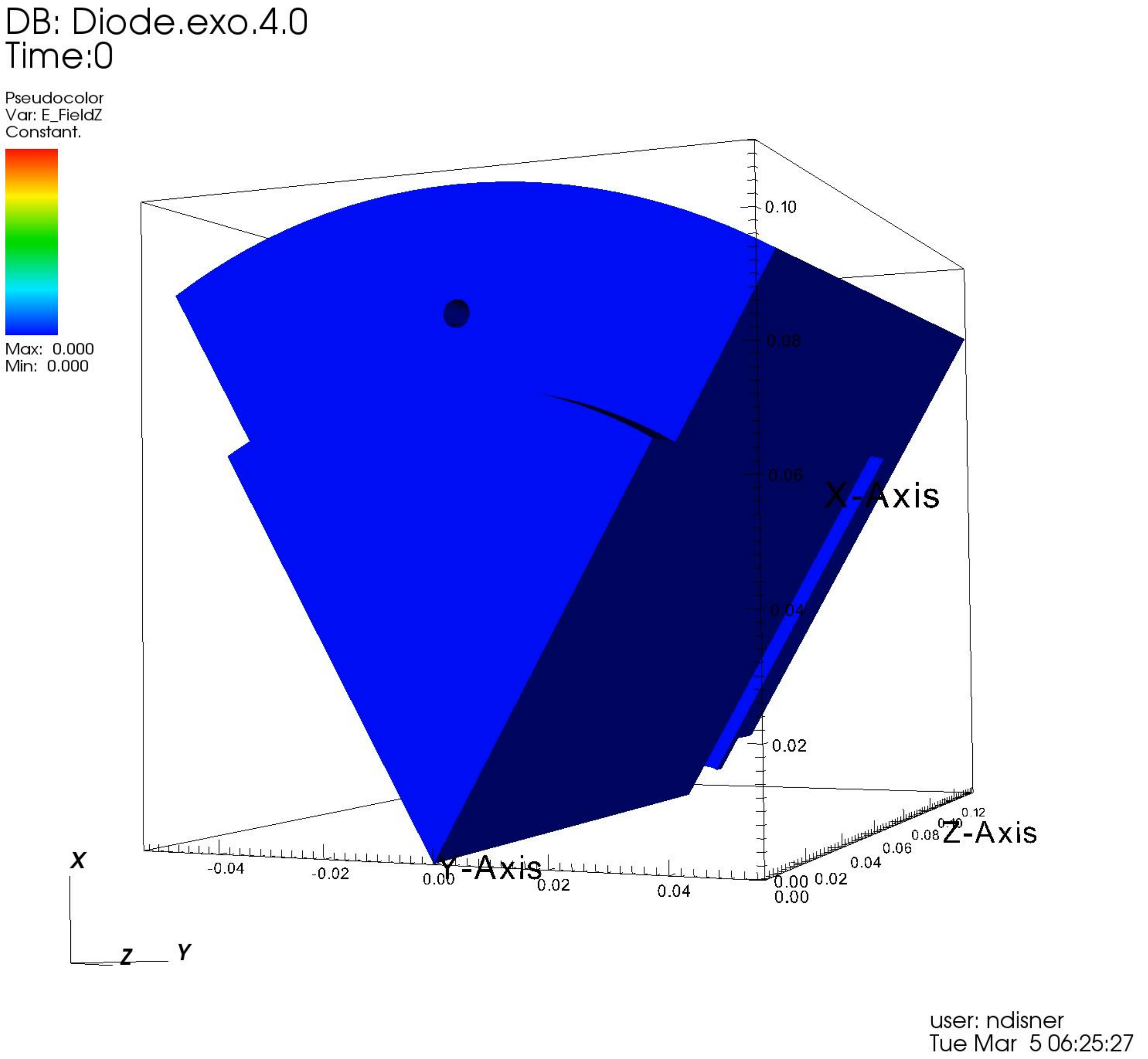
An example of the weakly-ionized plasma chemistry - N_2

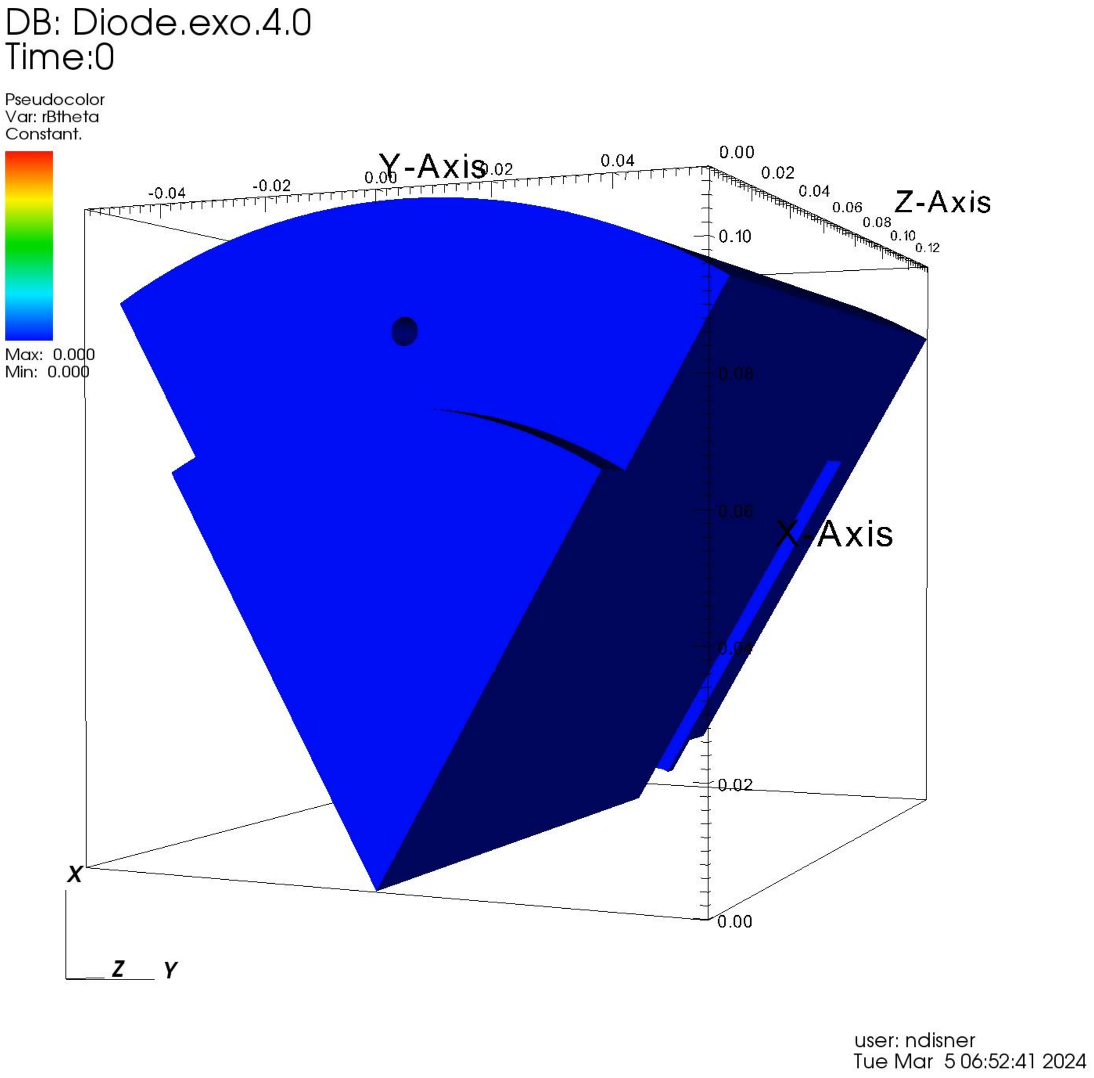
NRL PPD

Added in 24 reactions for a weakly-ionized nitrogen model

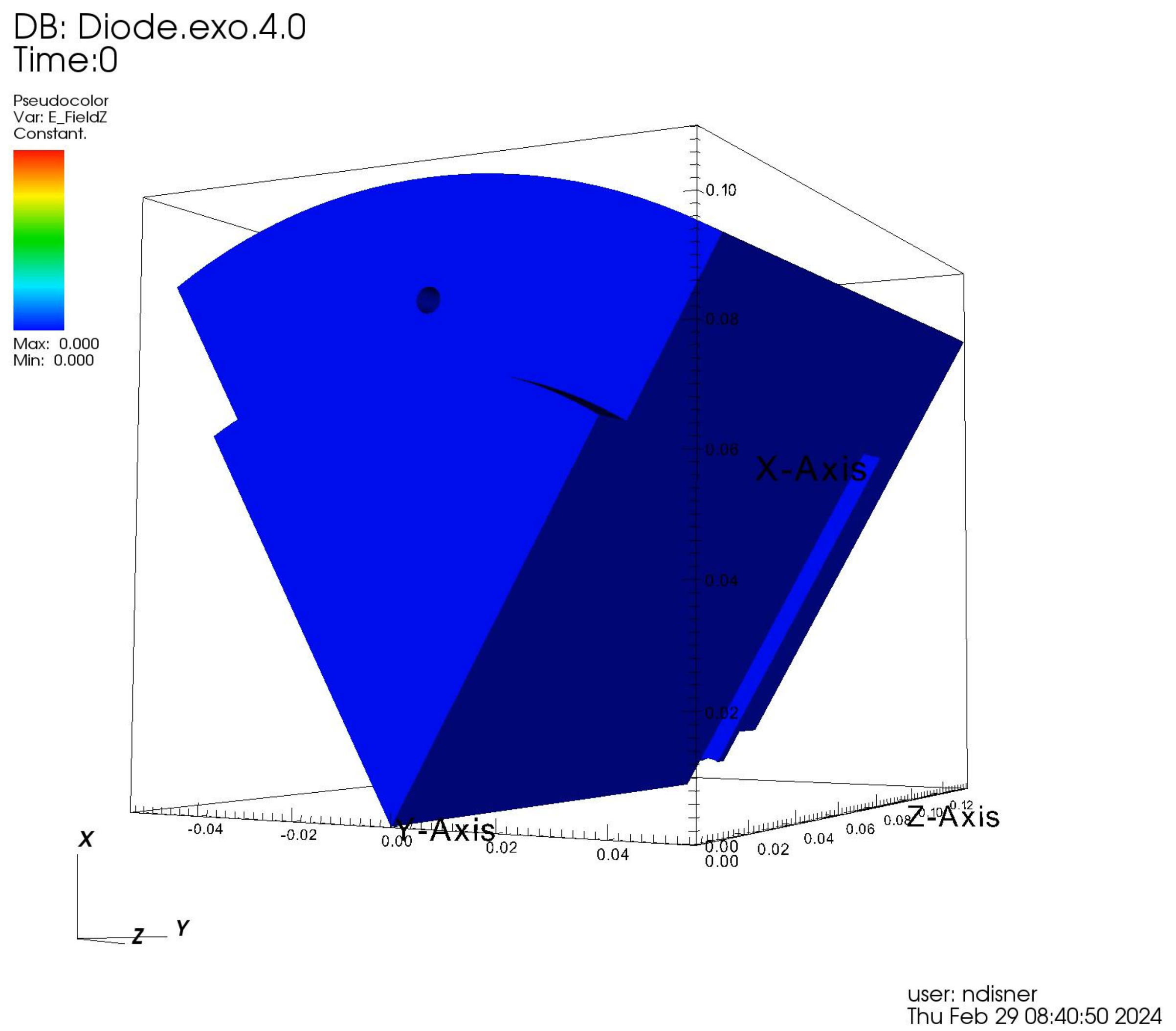
1. $e + N_2(X_1) \rightarrow e + N_2(X_1) + 0.0\ eV\ (momentum\ transfer)$
2. $e + N_2(X_1) \rightarrow e + N_2(rot) + 0.02\ eV\ (rotational)$
3. $e + N_2(X_1) \rightarrow e + N_2(v_1) + 0.29\ eV\ (vibrational)$
4. $e + N_2(X_1) \rightarrow e + N_2(v_2) + 0.59\ eV\ (vibrational)$
5. $e + N_2(X_1) \rightarrow e + N_2(v_3) + 0.88\ eV\ (vibrational)$
6. $e + N_2(X_1) \rightarrow e + N_2(v_4) + 1.17\ eV\ (vibrational)$
7. $e + N_2(X_1) \rightarrow e + N_2(v_5) + 1.47\ eV\ (vibrational)$
8. $e + N_2(X_1) \rightarrow e + N_2(v_6) + 1.76\ eV\ (vibrational)$
9. $e + N_2(X_1) \rightarrow e + N_2(v_7) + 2.06\ eV\ (vibrational)$
10. $e + N_2(X_1) \rightarrow e + N_2(v_8) + 2.35\ eV\ (vibrational)$
11. $e + N_2(X_1) \rightarrow e + N_2(A_3(v_{0-4})) + 6.17\ eV\ (electronic)$
12. $e + N_2(X_1) \rightarrow e + N_2(A_3(v_{5-9})) + 7.0\ eV\ (electronic)$
13. $e + N_2(X_1) \rightarrow e + N_2(B_3) + 7.35\ eV\ (electronic)$
14. $e + N_2(X_1) \rightarrow e + N_2(W_3) + 7.36\ eV\ (electronic)$
15. $e + N_2(X_1) \rightarrow e + N_2\left(A_3(v_{10+})\right) + 7.8\ eV\ (electronic)$
16. $e + N_2(X_1) \rightarrow e + N_2(B_3') + 8.16\ eV\ (electronic)$
17. $e + N_2(X_1) \rightarrow e + N_2(a_1') + 8.4\ eV\ (electronic)$
18. $e + N_2(X_1) \rightarrow e + N_2(a_1) + 8.55\ eV\ (electronic)$
19. $e + N_2(X_1) \rightarrow e + N_2(w_1) + 8.89\ eV\ (electronic)$
20. $e + N_2(X_1) \rightarrow \begin{cases} e + N_2(C_3) + 11.03\ eV\ (electronic) \\ e + 2N + 11.03\ eV\ (dissociation) \end{cases}$
21. $e + N_2(X_1) \rightarrow \begin{cases} e + N_2(E_3) + 11.87\ eV\ (electronic) \\ e + 2N + 11.87\ eV\ (dissociation) \end{cases}$
22. $e + N_2(X_1) \rightarrow \begin{cases} e + N_2(a_1'') + 12.25\ eV\ (electronic) \\ e + 2N + 12.25\ eV\ (dissociation) \end{cases}$
23. $e + N_2(X_1) \rightarrow e + 2N + 13.0\ eV\ (dissociation)$
24. $e + N_2(X_1) \rightarrow 2e + N_2^+ + 15.6\ eV\ (ionization)$

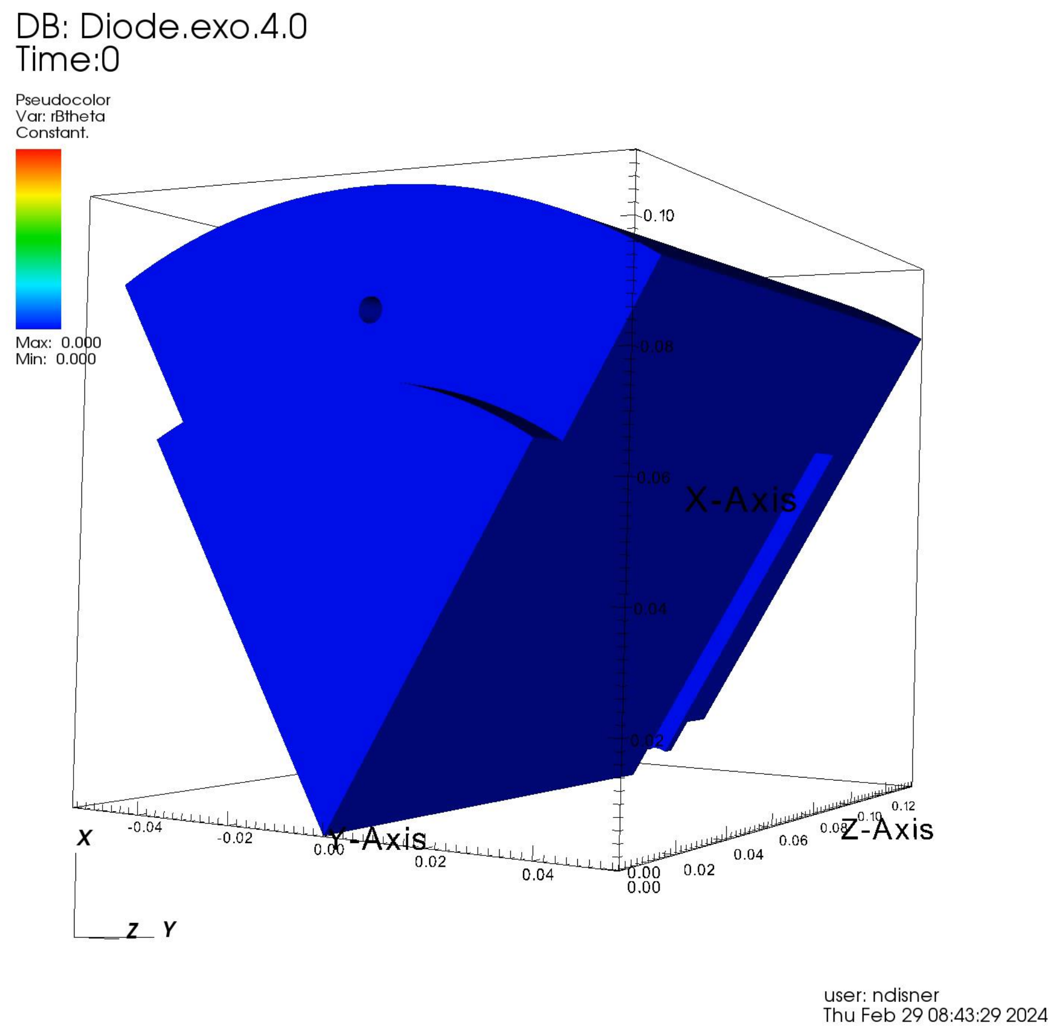
Result of Electric Field and Current Enclosed for Febetron gas cell at 0.1 torr





Result of Electric Field and Current Enclosed for Febetron gas cell at 1 torr





Summary

NRL PPD

- The Rigid Beam model with weakly-ionized chemistry set agreed well in a 1-10 Torr pressure range but a more model is needed for lower pressure cases.
- A kinetic model for the Febetron experiment is being developed using EMPIRE, showing some ongoing results
- The model has proven successful and fast for testing and modeling key parameters in electron beam plasmas.
- Adding in a simple chemistry for molecular nitrogen showed current runoff in a couple pressure cases and we are still working to resolve this numerically

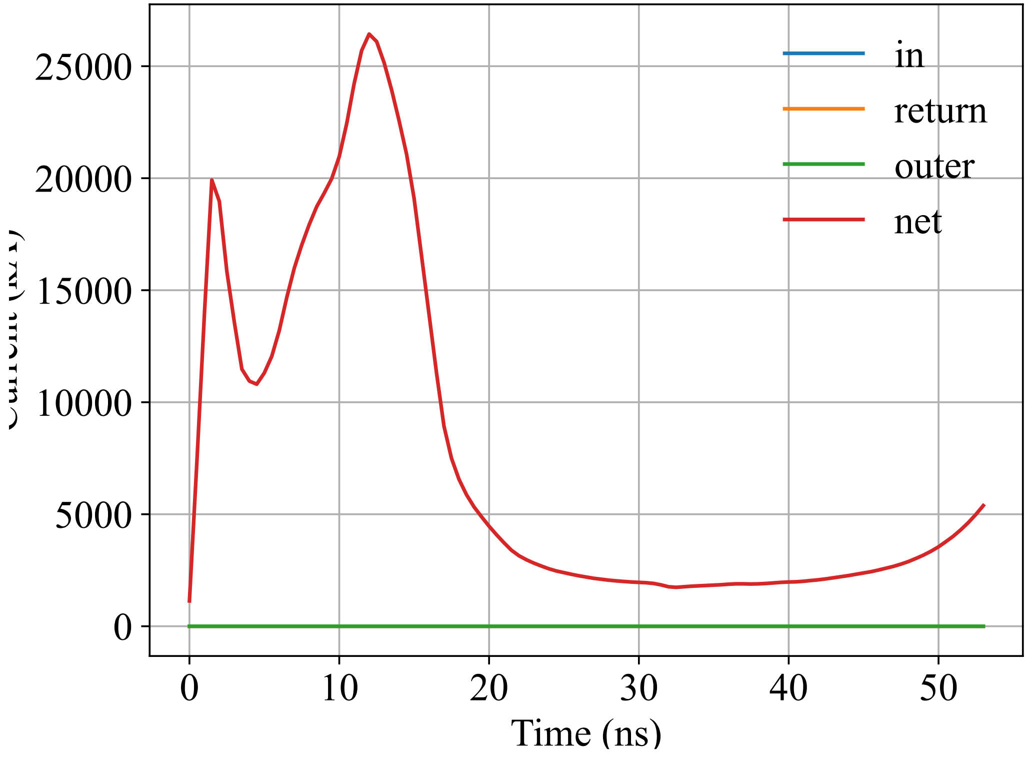
Future Work

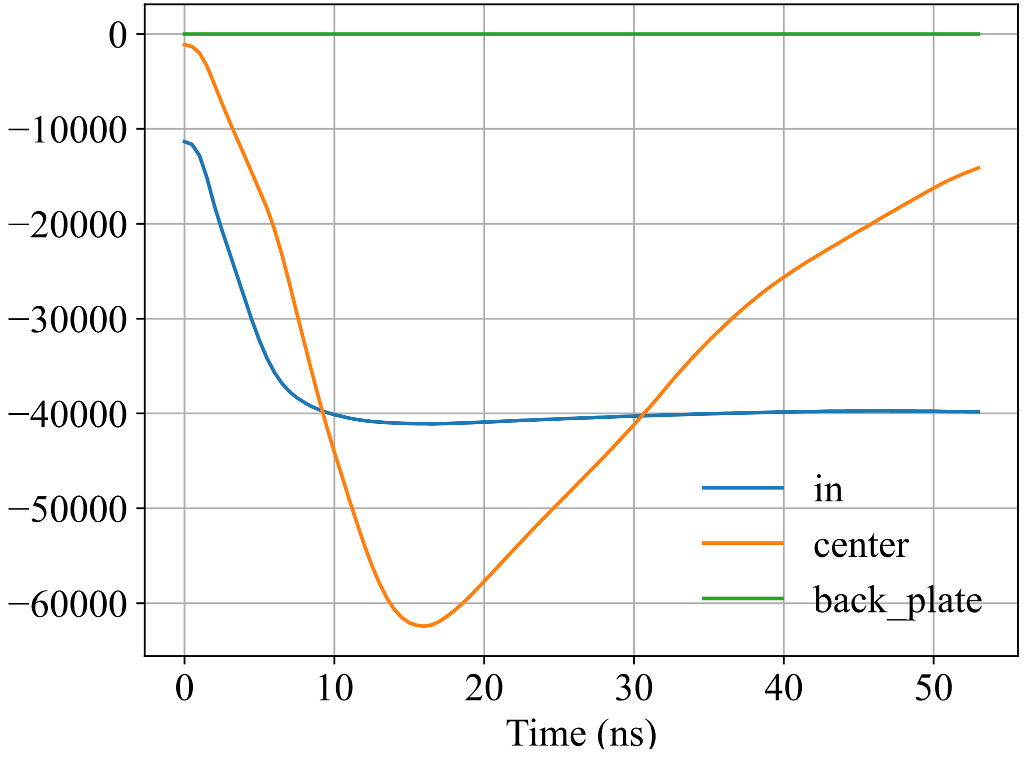
NRL PPD

- Resolve the instabilities of the background gas to see the beam evolve over time and space
- Use the outputs from the vacuum diode as an input to the gas cell
- Add in material dependencies for electron scattering through a thin foil

Thank you, Questions?

Backups 0.1 Torr current traces





Backups 1 Torr current traces