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Computational Modeling of Hall Thrusters

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Overview



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- Motivation
- Hall Thruster Background
- Computational Modeling
- Results
- Acknowledgements



Rocket Equation



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- Force balance on a spacecraft
- Neglect gravity and drag forces and integrate

$$M \frac{dv}{dt} + U_{Exit} \frac{dm}{dt} = F_{gravity} + F_{drag}$$

$$M_{final} = M_{initial} \exp\left(\frac{-\Delta V}{U_{Exit}}\right)$$

Mission	ΔV Requirement
Earth to LEO	7600 m/s
LEO to GEO	4200 m/s
LEO Escape	3200 m/s
LEO to Moon	3900 m/s
LEO to Mars	5700 m/s

Table from Mechanics and Thermodynamics of Propulsion, 2nd Edition, Peterson and Hill, 1992



Specific Impulse



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- Thrust per unit mass propellant (measured in s)

$$I_{sp} = \frac{\int T dt}{\dot{m}_{propellant} g_e} = \frac{U_{exit}}{g_e}$$

- Put this into the rocket equation

$$M_{final} = M_{initial} \exp\left(\frac{-\Delta V}{I_{sp} g_e}\right)$$



Chemical vs EP



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- Chemical Propulsion
 - Limits on propellant exit velocity are based on thermodynamic properties of propellant and material properties of combustion systems
 - Typical I_{sp} between 150 s and 450 s
 - High thrust applications (especially Earth to LEO)
- Electric Propulsion (EP)
 - Limits on propellant exit velocity are based on power supply mass and lifetime issues
 - For Hall thrusters typically between 1500 s and 2500 s
 - Low thrust applications (LEO to GEO and beyond)
 - Tradeoff between thrust and I_{sp}



LEO to Mars



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- Suppose $\Delta v = 5700$ m/s is required
- With typical bipropellant chemical propulsion
 - $I_{sp} = 250$ s
 - Ideal Payload Fraction = 9.8%
- With EP (Hall Thruster)
 - $I_{sp} = 1600$ s
 - Ideal Payload Fraction = 69.5%
- Primary present application is to satellite stationkeeping which requires small ΔV corrections over a number of years with savings of hundreds of pounds on satellites that weigh thousands of pounds



Hall Thruster Performance



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- **UM/AFRL P5**: 3 kW, 300 V, 10 A operating condition with a thrust of 180 mN, I_{sp} of 1650 s, and efficiency of 51%
- **NASA-457 M**: >50 kW operating condition with thrust of nearly 3 N, I_{sp} of 1750s - 3250 s, and efficiencies of 46% - 65%



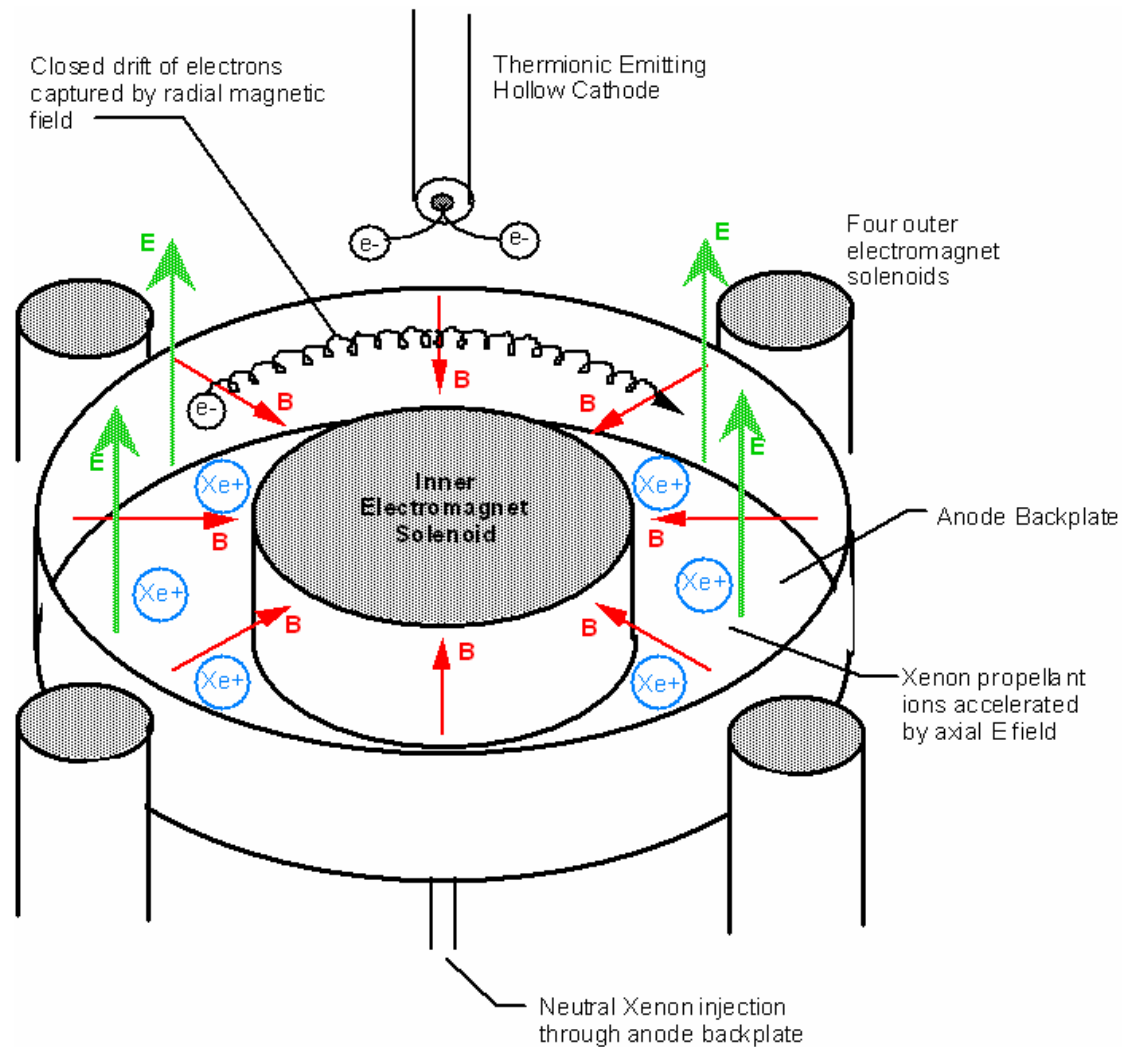
UM/AFRL P5 Photo courtesy of PEPL



Hall Thruster Schematic



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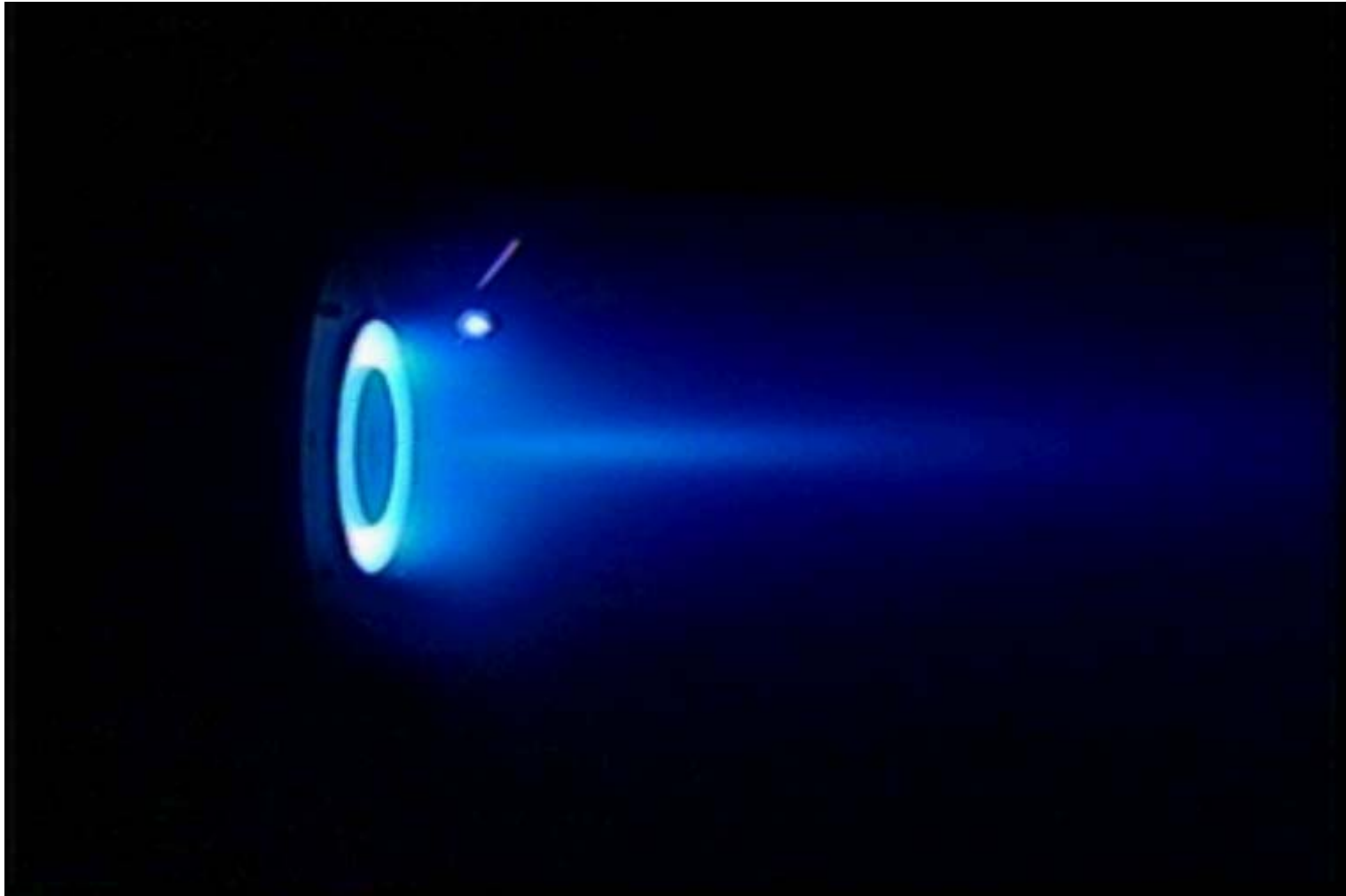
Schematic courtesy of PEPL



UM/AFRL P5



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UM/AFRL P5 Video courtesy of PEPL



Modeling Benefits



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- Many good reasons to develop computational Hall thruster models
 - Spacecraft Integration
 - Existing plume models need better boundary conditions at the device exit
 - Contamination of solar panels and sensitive instruments
 - Quantify chamber effects
 - Vacuum chamber performance of Hall thrusters is affected by finite neutral background density
 - Virtual life tests
 - Thruster lifetimes (>8,000 hours) require erosion modeling to determine lifetime limiting design characteristics
 - Understand physics relevant to thruster operation
 - Experimental measurements inside device are limited by probe dimensions, probe lifetime and other (optical, RF) access issues



Computational Model



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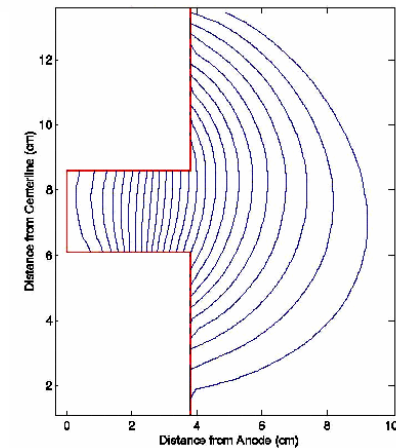
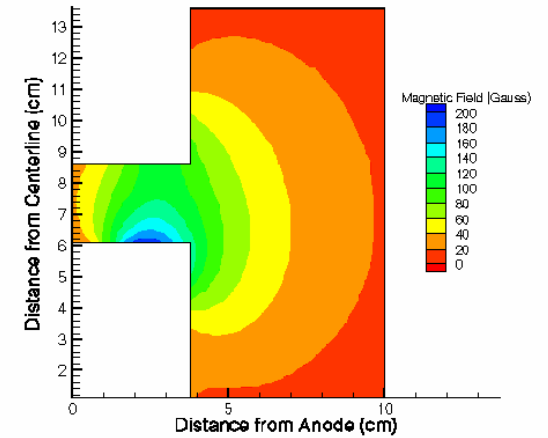
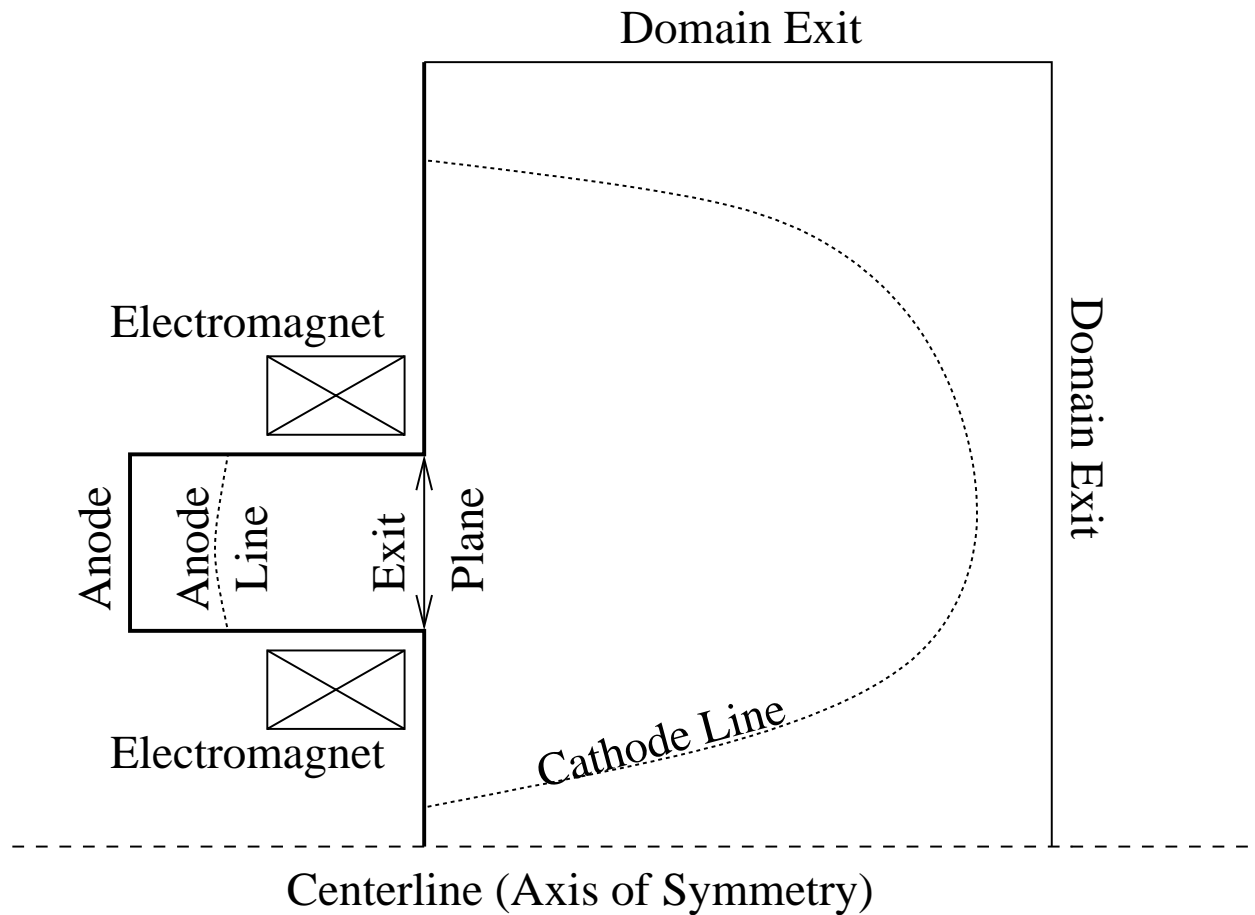
- 2-D axisymmetric hybrid PIC-MCC
- Domain includes acceleration channel and near-field of dielectric wall-type Hall thruster
- Based on a quasi-neutral plasma description
- Heavy particles (Xe , Xe^+ , Xe^{++}) are treated with a PIC-MCC model
- 1-D energy model assumes isothermal Maxwellian electron distribution along magnetic field lines
- Plasma potential based on Ohm's Law formulation
- Anode region potential model based on generalized analytic Bohm criterion



Computational Schematic



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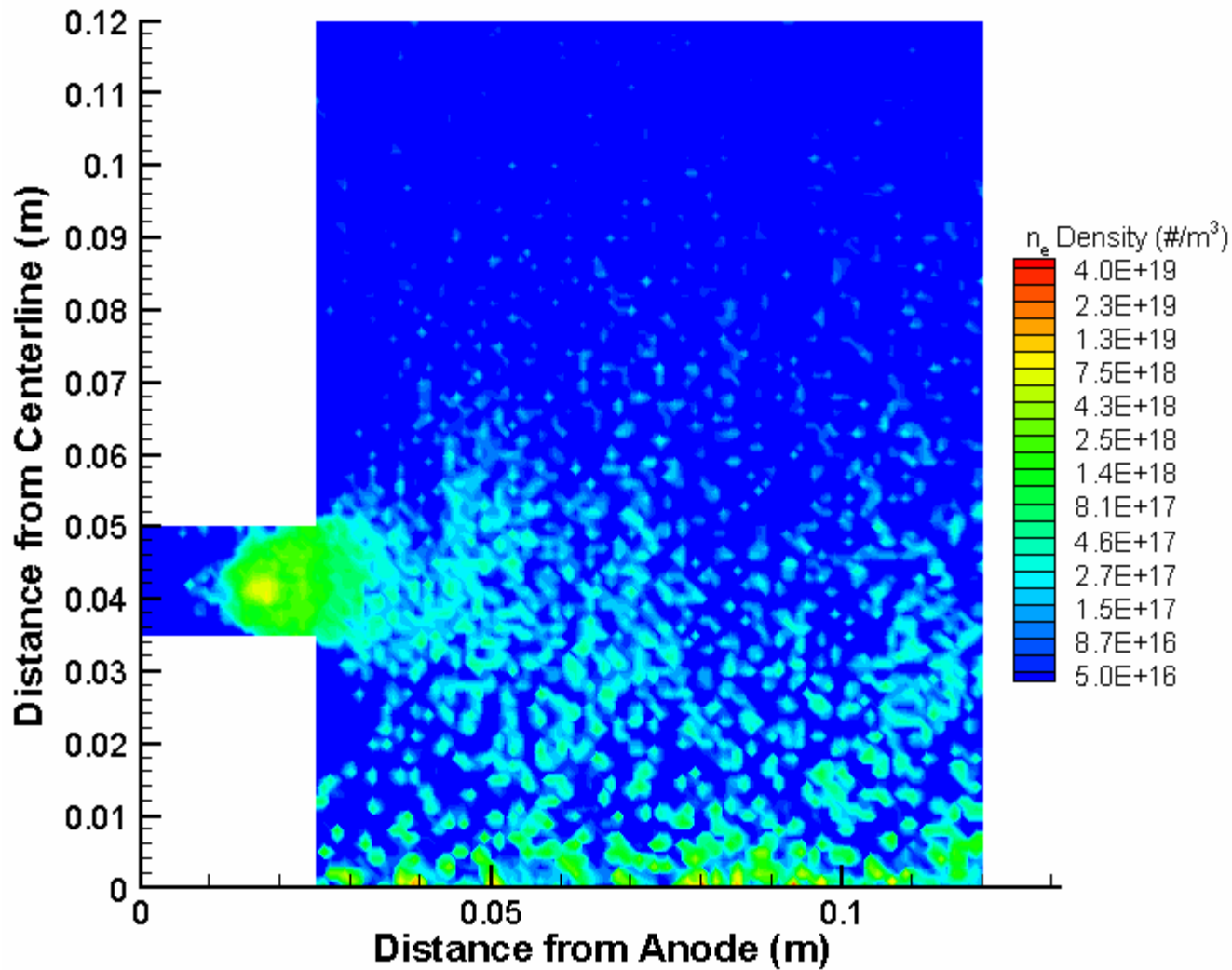




SPT-100 Plasma Density



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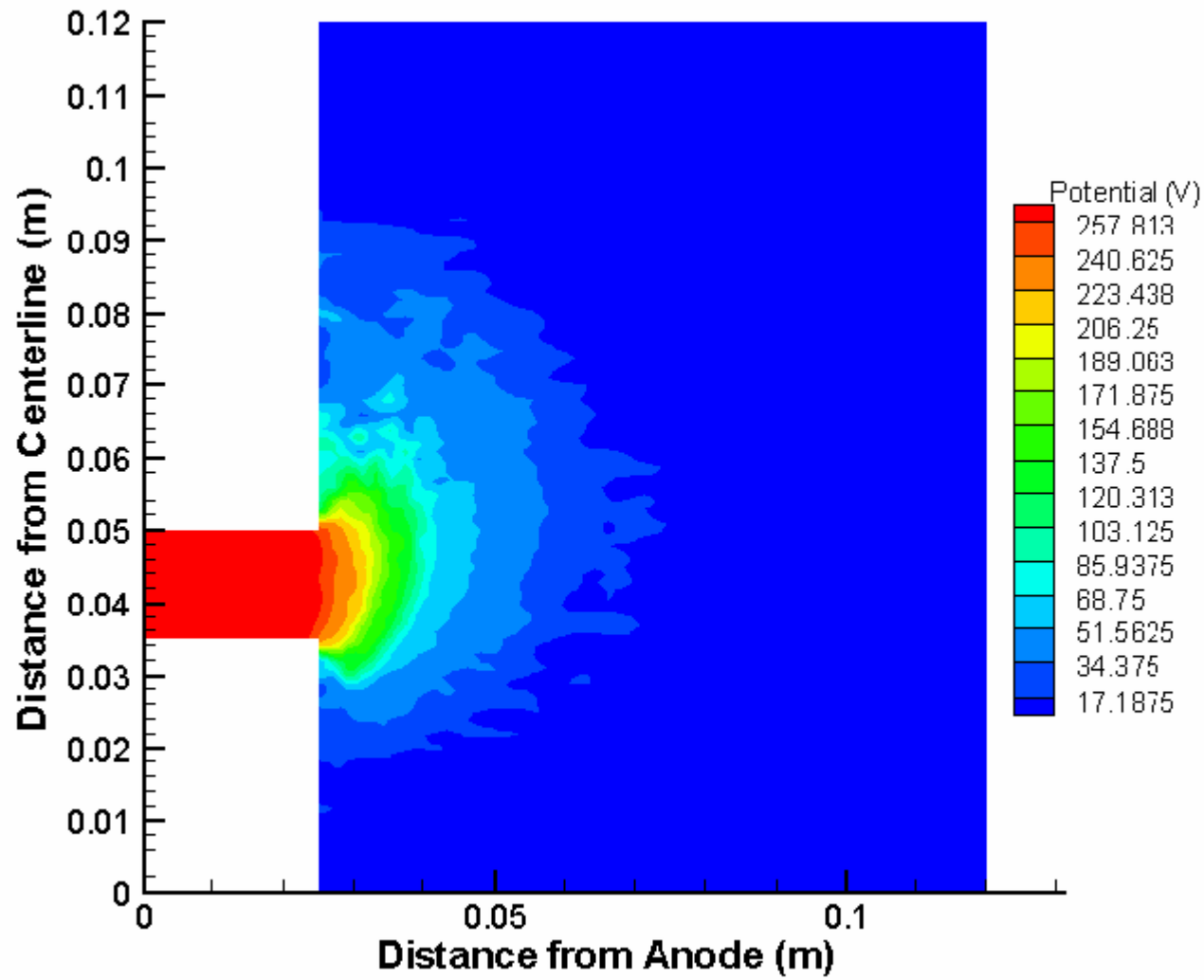




SPT-100 Potential



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Mobility Modeling



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- Calculated from classical transverse electron mobility form:

$$\mu_e = \frac{e}{m\nu_{mom}} \frac{1}{1 + \left(\frac{\omega_{B,e}}{\nu_{mom}} \right)^2}$$

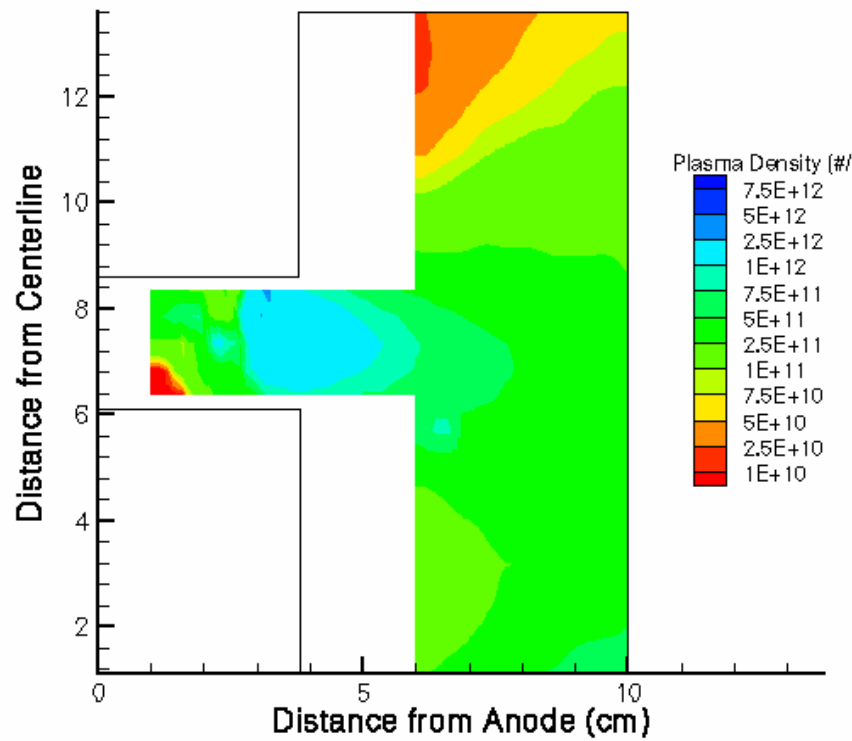
- Electron momentum transfer frequency is supplemented by a modeled bohm mobility term or wall-collision term



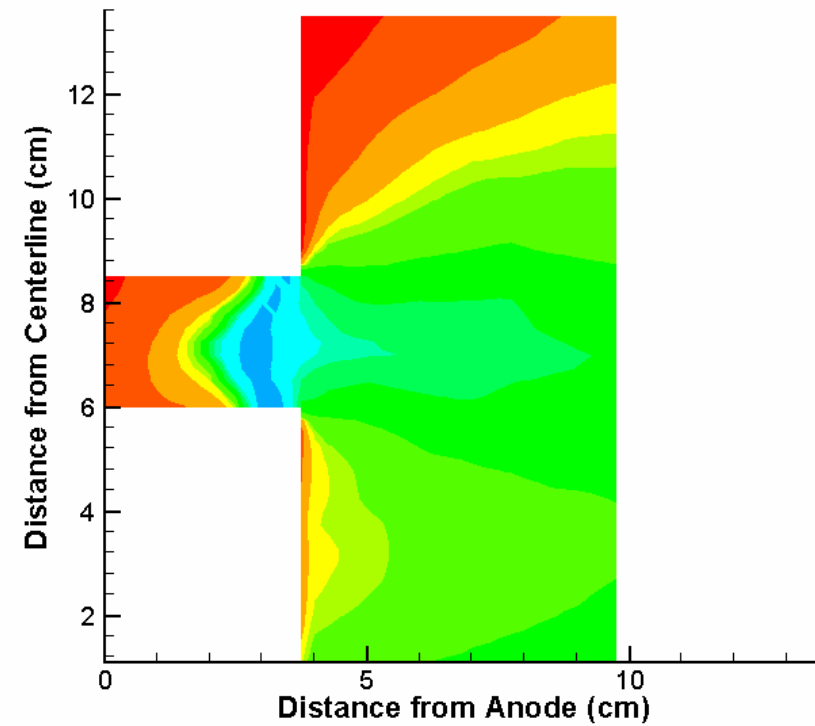
P5 Mean Plasma Density



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Experimental



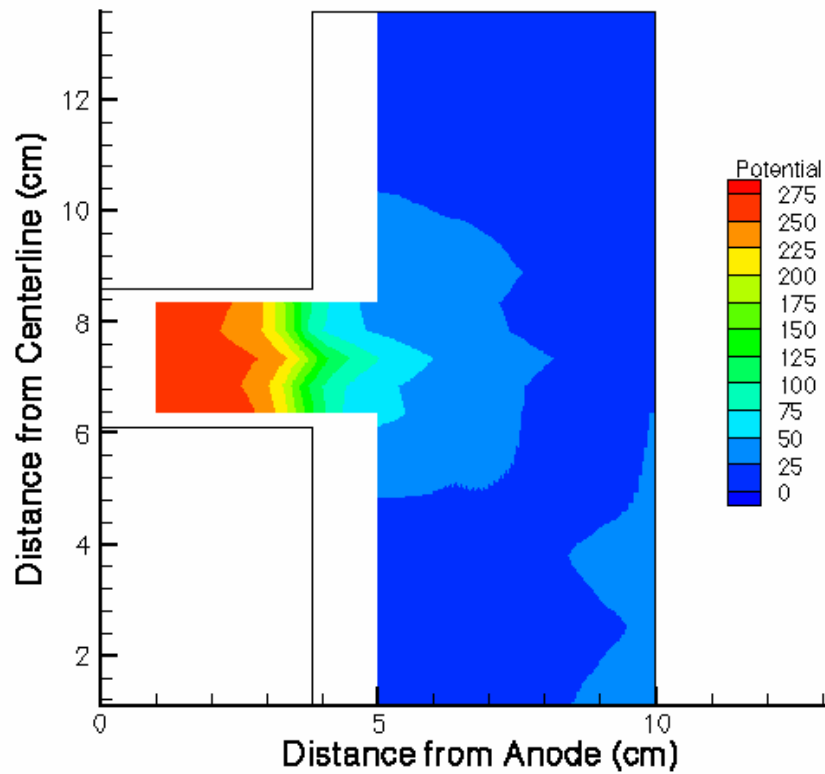
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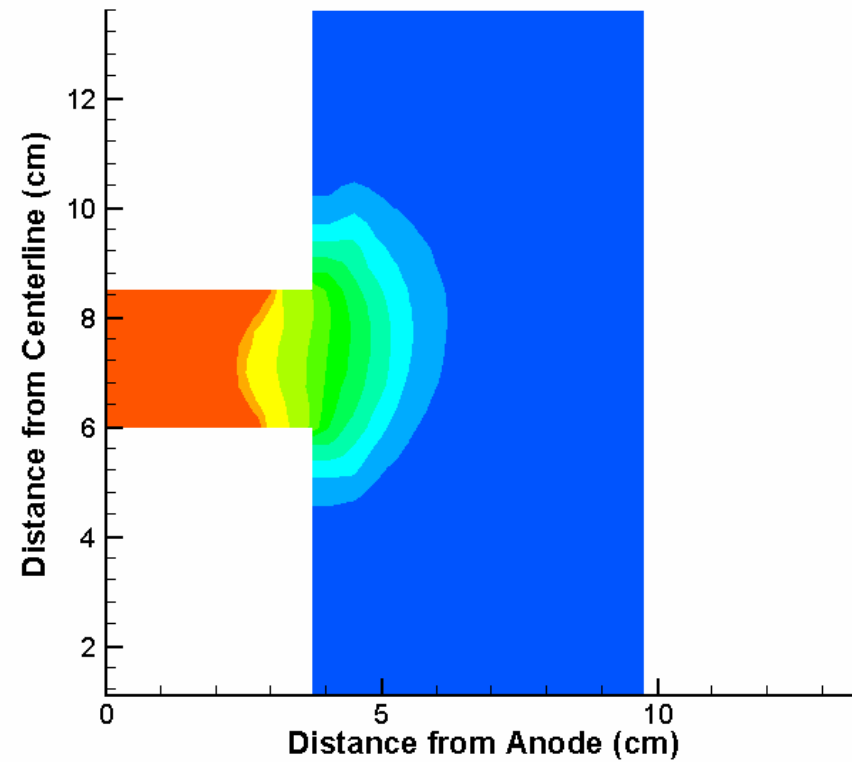
P5 Mean Potential



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Experimental



Computational



Acknowledgements



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- Department of Energy Computational Science Graduate Fellowship

