SAND2015-9708C

Plasma Modeling of Ion Beam Scattering by Helium Background

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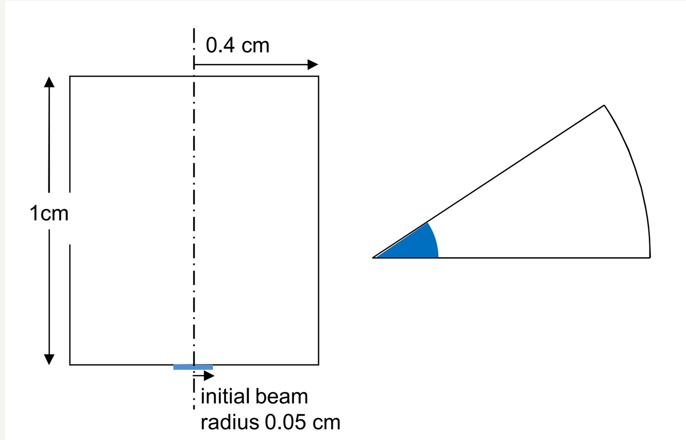
Abstract:

Plasma modeling calculations have been performed for deuterium ion beam transport including coherence and energy deposited on a target. The presence of background neutral gases such as helium can cause the deuterium ion beam to spread, which may reduce current on a target, cause a portion of the beam to miss the target, or reduce the energy of incoming ions. Initial studies were performed on a deuterium ion beam without any background gas. Spreading of the beam due to thermal diffusion is compared to the analytical theory of Lee & Cooper [1].

$$R^2 = R_0^2 + V_0^2(t-t_0)^2 + \left(\frac{\epsilon'}{3\gamma m}\right)(t-t_0)^3.$$

Geometry:

The Aleph plasma modeling code was used to calculate the transport and evolution of the charged particle beam including the self-consistent electric field. Deuterium ion beam is injected in the center of a cylindrical domain containing various helium pressures.



Geometry for ion beam calculations.

Boundary Conditions:

Inlet: D+ beam radius 0.05cm
$v_z=10^6$ m/s, T=0-10eV
atoms can exit

Side: reflect specularly, V=0

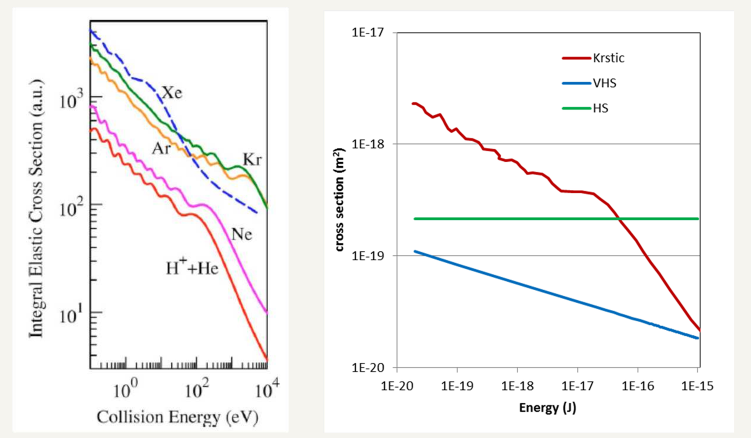
Outlet: atoms can exit freely

Helium: specified pressure, T=273K

Ion – Neutral Collisions:

Collision probabilities are calculated from quantum mechanical integral elastic cross sections by Krstić & Shultz [2] for collisions of protons and helium. Cross sections for deuterium are calculated using:

$$\sigma^{D^+ + He} = \sigma^{H^+ + He}\left(\frac{\mu_{D^+ + He}}{\mu_{H^+ + He}}\right)$$

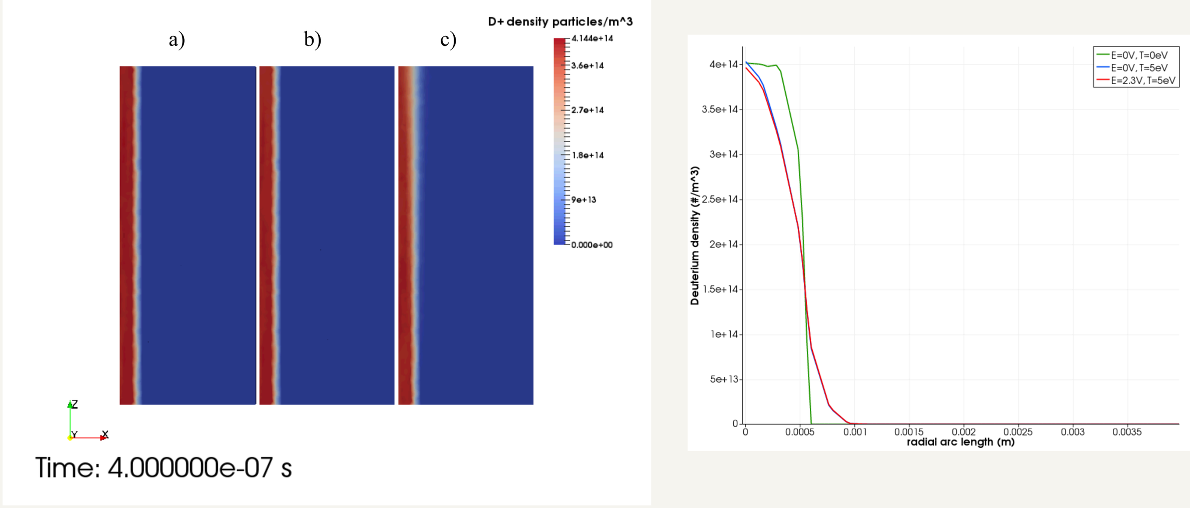


Integral elastic cross sections a) Quantum mechanical calculations by Krstic & Shultz (2006) for H^+ and He; b) Derived values for D^+ and He compared to hard sphere (HS) and variable hard sphere (VHS) models

Collision cross-sections for these charged species at high collision energy are not well represented by classical DSMC hard sphere and variable hard sphere models (Bird [3]).

Comparison of Ion Beam Spreading in Vacuum:

Calculations of deuterium ion beam spreading in a vacuum were compared with the analytical envelope equation derived by Lee & Cooper [1] for a range of ion temperatures and densities. Their theory for thermal diffusion does not account for space charge of the charged ion beam which also causes the beam to spread. Space charge effects were much smaller than thermal diffusion for 5 eV ions at the low particle densities used for these calculations. If space charge is removed from the calculations (E=0V), Aleph results agree to within three significant figures with the Lee & Cooper predicted beam diameters.



Deutrium beam in vacuum: a: T=0 eV, E=0 V, b) T=0 eV, E=2.3 V, c) T=5 eV, E=2.3 V

Temp\Voltage	0V	Lee & Cooper prediction	2.3V ($n\sim4\times10^{14}$ p/m^3)	23V ($n\sim4\times10^{15}$ p/m^3)
0 eV (0K)	R^2=0.124e-6 m^2	R^2=0.124 e-6 m^2 V_0=0	R^2=0.126e-6 m^2	R^2= 0.145e-6 m^2
5eV (58000K)	R^2=0.172e-6 m^2	R^2=0.172 e-6 m^2 V_0=2.19 e4 m/s	R^2=0.174e-6 m^2	
10eV (116000K)	R^2=0.220e-6 m^2	R^2=0.220 e-6 m^2 V_0=3.10 e4 m/s		

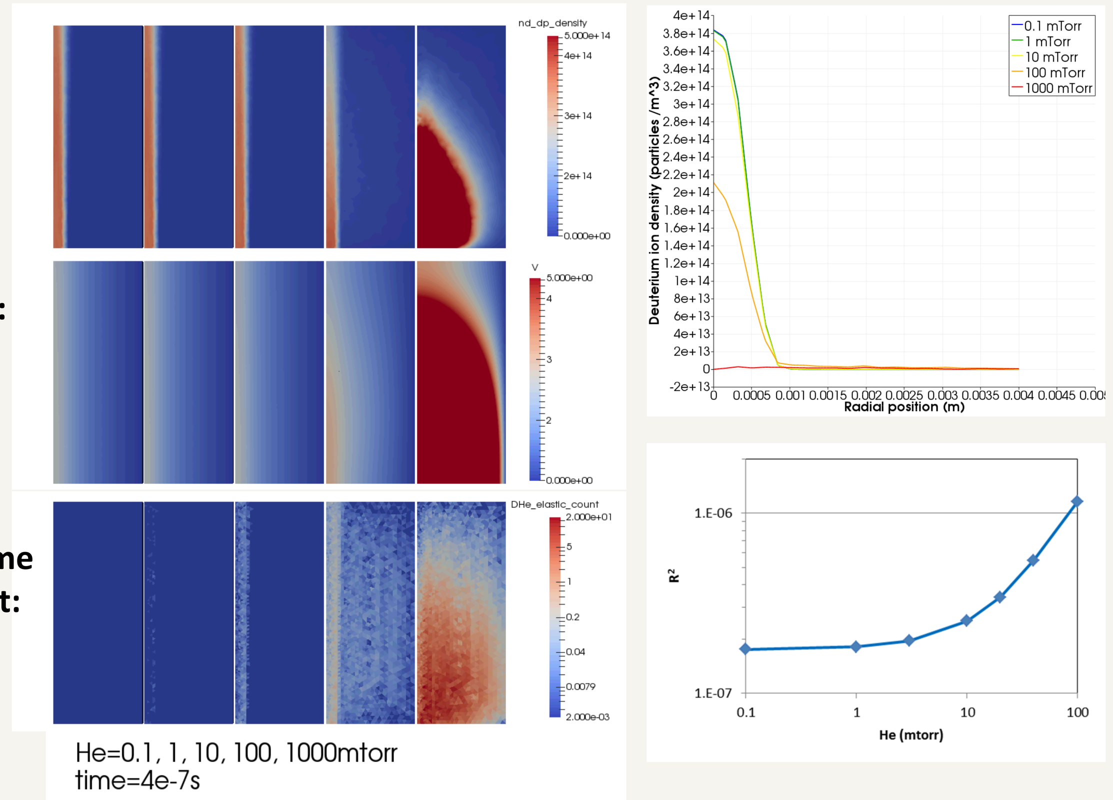
Ion Beam Transport Through Helium Background Gas

The presence of a neutral background gas will cause the deuterium ion beam to scatter and the beam to become more diffuse. The figure below shows a brief survey of the impact of the helium gas over a range of pressures using isotropic elastic collisions. For low helium pressures (≤1 mTorr), the beam diameter increased less than 5% and beam current decreased by less than 1%. At larger pressures, scattering of the beam becomes apparent until the beam is essentially thermalized and unable to cross the domain. It should be noted that the calculation at the highest pressure of 1000 mTorr, the particle densities become so large that the time step and mesh are no longer sufficiently resolved.

Ion density:

Electric Field:

Collisions/time step/element:

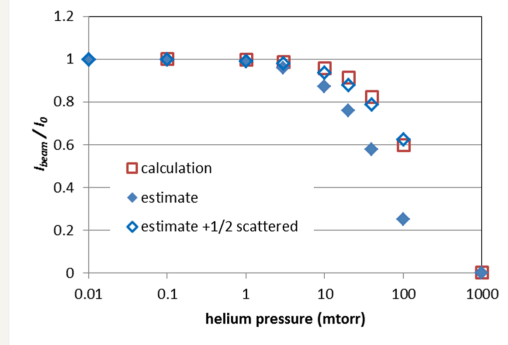


He (mTorr)	0	0.1	1	10	100	1000
R^2 (m^2)	0.174 e-6	0.175 e-6	0.181e-6	0.251 e-6	1.16 e-5	4.19 e-5
% change	-	0.6%	4%	44.8%	566.7%	2309.8%

The absorbance *A* and transmission *I* of the particle beam are calculated from the number density of the helium *n*, the collision cross section σ based on the ion velocity of 10^6 m/s and the length of the domain *l*=0.01m.

The beam current is scaled relative to the beam current in a vacuum I_0.

$$A = n\sigma l \qquad I = 10^{-A} \qquad I^* = 1 - 0.5*(1-I)$$

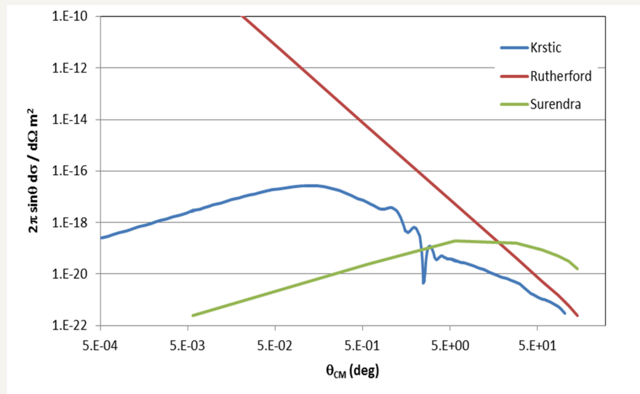


Conclusions:

Aleph has been used to calculate the transport of a charged particle beam through a neutral background gas. Calculations in vacuum were verified against the general envelope theory by Lee and Cooper [1]. Calculations of beam transport through a background neutral gas were also performed using quantum mechanical calculations for integral elastic cross sections between deuterium ions and helium. Beam dispersion increased rapidly with increasing helium pressures. The beam intensity was well captured by a simple estimate based on the mean free path after acknowledging that half of the scattered ions will still exit by the same domain boundary as the particle beam.

Future work:

In this work we assumed collisions were isotropic, but they are actually anisotropic with a large number of small angle scattering events.



We are currently working to implement relevant anisotropic scattering models into Aleph to more accurately predict ion beam dispersion.

Figure : Anisotropic elastic scattering of deuterium and helium at 100 eV: quantum mechanical calculations (Krstic & Schultz (1999)) compared to Surendra model and Rutherford scattering theory.

References:

1. E. P. Lee and R. K. Cooper, General Envelop Equation for Cylindrically Symmetric Charged-Particle Beams, in *Particle Accelerators*, vol.7, pp.83-95, 1976.
2. P. S. Krstić and D. R. Schultz, Elastic and related transport cross sections for protons scattering from the noble gases He, Ne, Ar, Kr, and Xe, in *Physics of Plasmas*, vol.13 pp.053501, 2006.
3. G. A. Bird, *The DSMC Method*. CreateSpace Independent Publishing Platform, Kentucky, 2013.

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SAND No. 2011-XXXXP

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