Nuclear Scattering Models for D-55 TAL Hall Thruster Plasma

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Introduction

The D-55 TAL Hall Thruster is an electric propulsion system used to direct and maneuver a satellite's trajectory. It does so by ionizing the propellant using the Hall Effect stemming from a radial magnetic field, hosting a floating ionization region, administered by a system of electromagnets. The thrust is generated due to the conservation of momentum from deflecting the ionized propellant to exhaust velocities as high as 17 km/s using large discharge potentials.

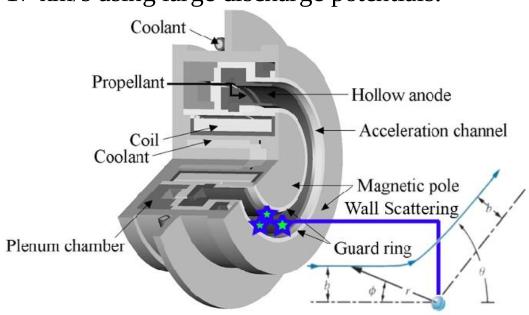

Fig 1: TAL Hall Thruster Cross Section

Scattering Adaptation

Research on plasma characteristics in the discharge chamber can improve a Hall Thruster's lifetime, efficiency and thrust. Assumptions in Plasma Physics in general, use Maxwell Boltzmann statistics for characterization. However, using scattering models like the Born Approximation to incorporate quantum effects to plasma behavior could elevate inferences in contrast to the classical collisional theory. Hence, we investigate quantum effects (for the plasma species using wxMaxima) over the current classical approximation. Scattering models that account quantum effects proves promising in devising a coherent vocabulary to address plasma behavior in Hall Thruster. A shift from the classical approximation could help better predict engineering solutions for Hall Thruster optimization.

Rutherford Scattering

Rutherford scattering is used to estimate the scattering cross section. The famous alpha particle experiment generalizes the behavior of a positive charge with kinetic energy moving towards a target nucleus using:

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4\pi\epsilon_0}\right)^2 \frac{1}{E^2 sin^2\left(\frac{\Theta}{2}\right)} \quad \dots (1)$$

$$d = \frac{2kqQ}{mv^2} \dots (2) \qquad b = \frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 K} cot\left(\frac{\theta}{2}\right) \dots (3)$$

Substituting the scattering interaction between a single charge Xenon propellant and the D-55 TAL Thruster's Tungsten wall, we obtain the following graph to represent the scattering cross sections for scattering angles ranging from 0-90 degrees

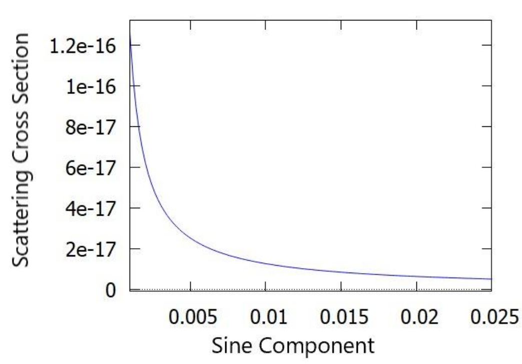

Fig 1: D-55 Propellant-Wall Scattering

A propellant study can help compare the scattering cross sections of popular propellants adopted in Hall Thruster Technology, namely – Xenon, Argon, Krypton, Iodine and Bismuth. During the gas discharge, the single and doubly ionized species often contribute to the thrust. Assuming a scattering angle of 45 degrees, parameters like distance of closest approach, impact parameter and scattering cross section are computed and tabulated in Table 1.

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Species	*KE* *10^-17*	*d Closest Approach* *10^-30*	*Impact Parameter* *10^-30*	*Cross Section* *10^-18*
Xe	4.806	4.39676	4.28723	5.88079
Kr	4.806	4.39680	4.28728	5.88092
Ar	4.806	4.39685	4.28732	5.88104
I	4.806	4.39676	4.28723	5.88079
Bi	4.805	4.39716	4.28763	5.88189

Table 1: Scattering of Propellant species

Wall studies can help shed light on phenomenon of sputtering. The scattering considerations for different metals like Tungsten, Molybdenum, Nickel, Rhenium and Copper-have be computed. The radiation lengths R_L (affinity to particle penetration) is obtained from:

$$X_0 = \frac{716.4\ g/cm^2}{\rho} \frac{A}{Z(Z+1)ln\left(\frac{287}{\sqrt{Z}}\right)}$$

Symbol	*W*	*Mo*	*Ni*	*Re*	*Cu*
R_L (cm)	0.351	0.977	1.462	0.318	1.796

Table 2: Radiation Lengths of TAL Wall metals

The following study generalizes the scattering interactions between the TAL wall metals and electric propulsion propellants. The scattering cross sections obtained for a 45 degree scattering angle is tabulated below:

Symbol	*Xe* *(10^-19)*	*Kr* *(10^-19)*	*Ar* *(10^-19)*	*I* *(10^-19)*	*Bi* *(10^-19)*
W	58.808	58.809	58.810	5.881	5.882
Mo	18.944	18.944	18.945	1.894	1.895
Ni	8.4195	8.4197	8.4199	8.419	8.421
Re	60.408	60.409	6.0411	6.041	6.042
Cu	7.2597	7.2599	7.2600	7.259	7.261

Table 3: Propellant-wall scattering cross section

In addition, the TAL thruster walls are maintained at cathode potential to reduce sputtering by reducing electron-wall collision through electrostatic repulsion.

Born Approximation

The electron scattering on the D-55 TAL thruster wall is computed using Soft sphere Born Approximation. A low energy electron is assumed to scatter off a grain of Tungsten atoms, whose radius is 1 nm. We substitute the net charge due to the induced discharge voltage into the Coulombic potential for the following equations.

$$f(\Theta,\phi) = \frac{-m}{2\pi\hbar}\int V(r)d^3r \xrightarrow{yields} \frac{2mV_0a^3}{3\hbar^2}$$

$$|f(\Theta,\phi)|^2 = \left(\frac{2mV_0a^3}{3\hbar^2}\right)^2 \qquad \sigma_T = 4\pi|f(\Theta,\phi)|^2$$

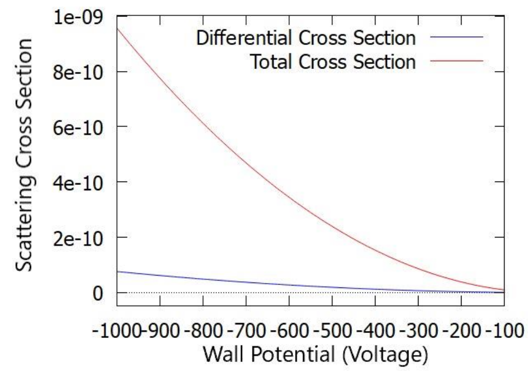

Fig 2: Scattering Cross Section at TAL Walls

Therefore we obtain the above scattering amplitude, differential and total scattering cross sections across varying wall potentials.

Conclusion

Computations of Rutherford Scattering indicate wall materials possessing a greater impact on cross section over propellants type. The Born Approximation indicates a strong dependence on the wall potential for electron scattering. Scattering characteristics can help determine the kinetic energy of an incident particle imparted to the thruster wall. Hence it can address the phenomenon of sputtering, a contributing cause to wall erosion, whose data can aid in improving the lifetime and performance of the thruster.

References

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