COOLING ELECTRONS IN FAR FIELD OF PLUME PLASMA

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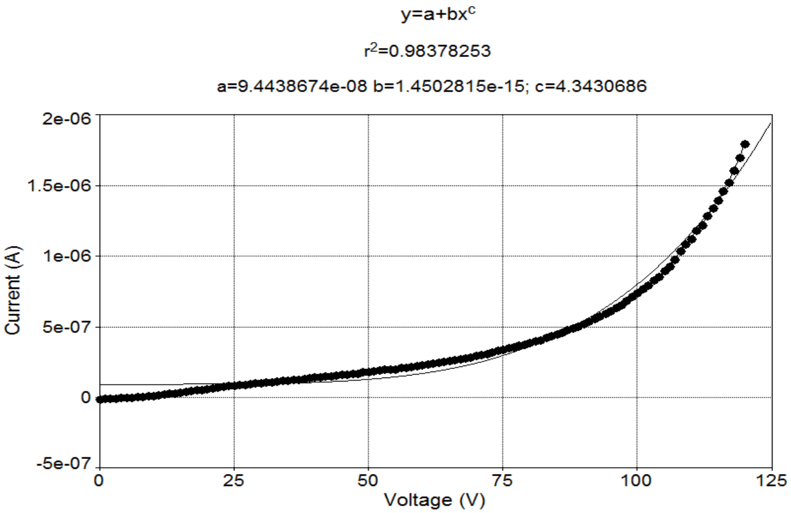
Electric propulsion systems have been used for space exploration for a long time. Recently, the deployment of Solar Electric Propulsion come up to consideration for a manned mission to astronomical bodies [1]. This project includes powerful plasma thruster (300 kW) and high-voltage solar array providing approximately 350 kW of electric power at distances about 1 AU from the Sun. Taking into account the highest solar cell efficiencies achieved to date one can estimate the area of prospective array as of 800-900 m^2.

Parasitic current collection is one of the very important characteristics of interaction between solar array and surrounding plasma. Collected current depends on electron density, electron temperature, and array potential:

$$I(U) = A \cdot n_e \cdot T_e^{1/2} \cdot \left(1 + \frac{U}{T_e}\right)^{\alpha} \qquad (1)$$

Where A, α=Const.

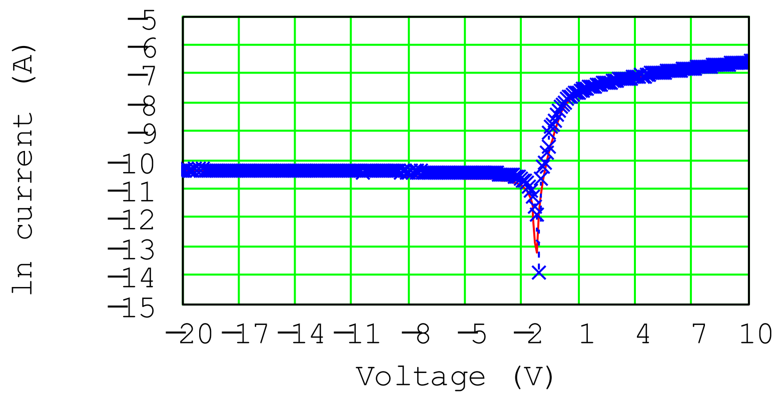


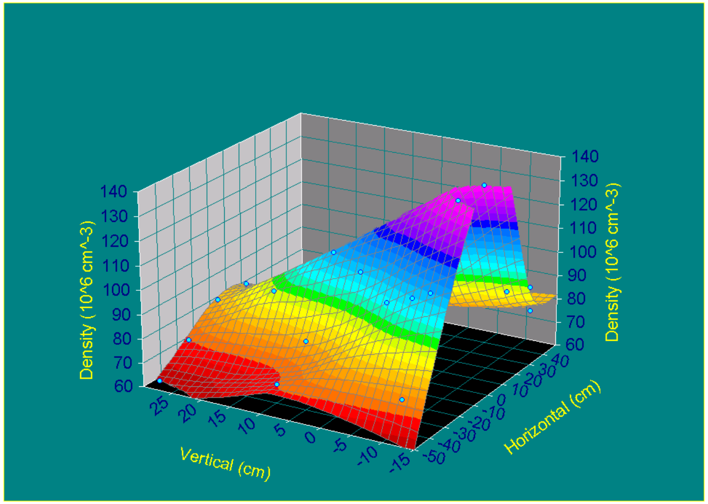
[1] Brophy, J.R., Gershman, R., Strange, N., Landau, D., Merrill, R.G., and Kerslake, T. "300-kW Solar Electric Propulsion System Configuration for Human Exploration of Near-Earth Asteroids", AIAA Paper 2011-5514, July 2011.

In order to perform respective tests in vacuum vessels one needs to know the parameters of plume plasma in very far field. There are two complimentary approaches to the search for solution : 1) performing extensive computer simulations; 2) measuring plasma parameters in ground chambers. Plume plasma parameters in chamber and space are different – and this is the problem!

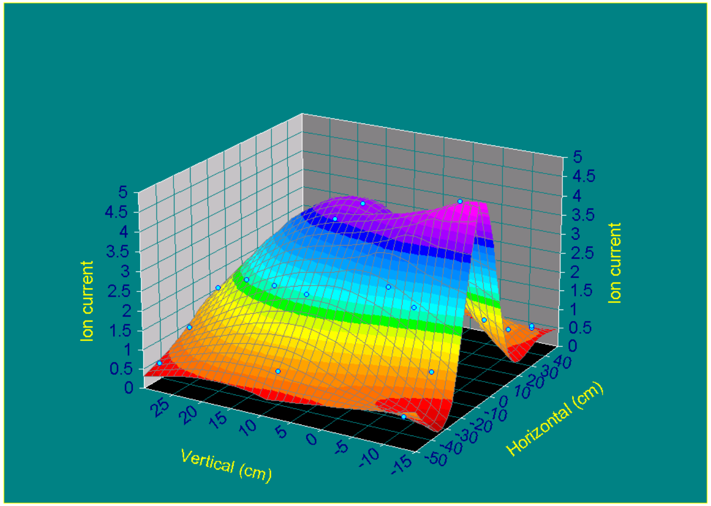
All measurements performed in vacuum chambers indicated rather low electron temperatures (0.5-2 eV) in far field while computer simulations and measurements in space (one only) pointed to significantly higher temperatures (3-6 eV). The physical mechanisms of electron cooling in far field were not understood because of seemly collisionless electron gas in a vessel.

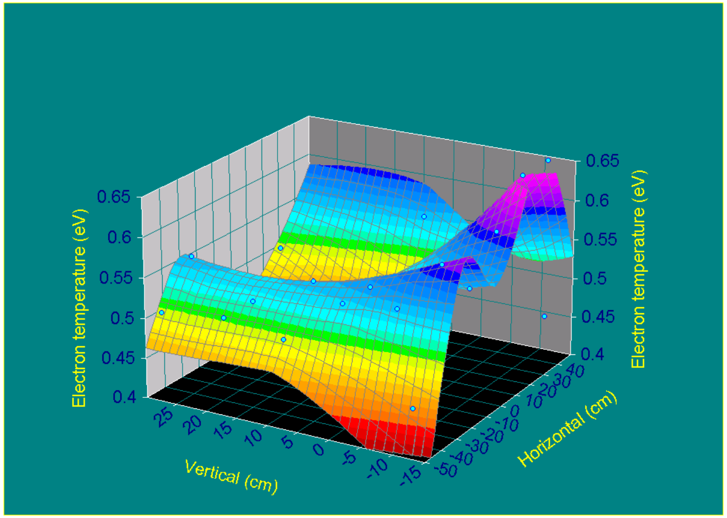
Example- SPT 50



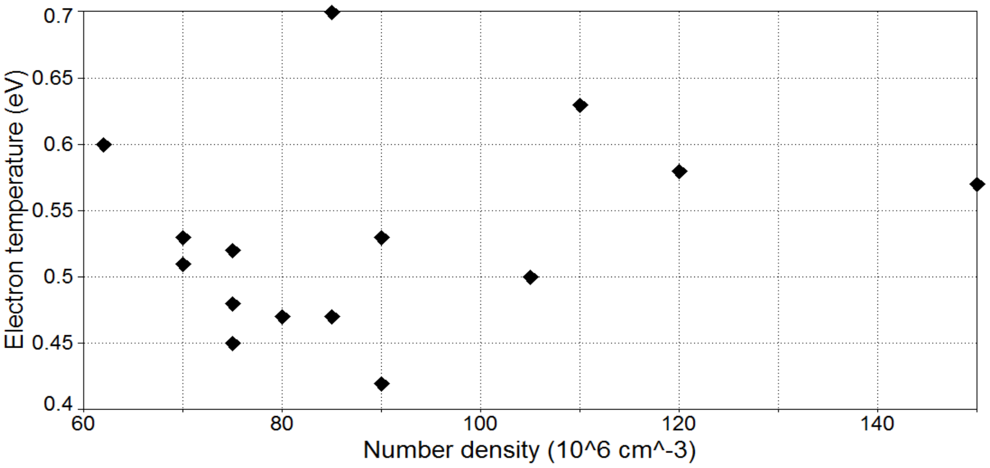


Flat LP sweep indicates density n_e=150, and plasma potential U_{pl}=1 V





Power *P*=200 W, and flow rate 4.5 sccm. Operational neutral gas pressure was 6 μTorr (initial 0.3 μTorr), and temperature changed from 17-21 C to 25 C for 7 hour operational time.

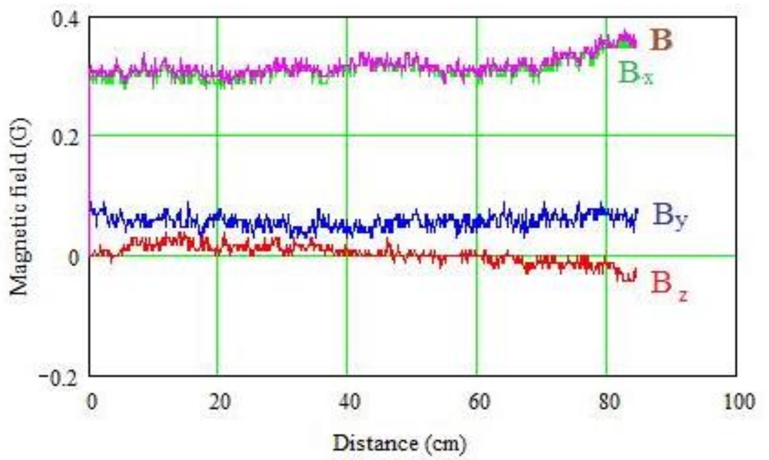


Electron temperature vs. number density for all measurements.

$$\vec{V}_e\left(\frac{3}{2}n_e\frac{\partial T_e}{\partial \vec{r}} - T_e\frac{\partial n_e}{\partial \vec{r}}\right) = -\frac{\partial \vec{q}_e}{\partial \vec{r}} + \sum_{i,j}(\pi_e)_{ij}\frac{\partial \vec{V}_{ei}}{\partial r_j} + Q_e$$

Ashkenazy, J., and Fruchtman, A. , 2001

$$q_{ei} = \sum_j \chi_{eij}\frac{\partial T_e}{\partial r_j}$$

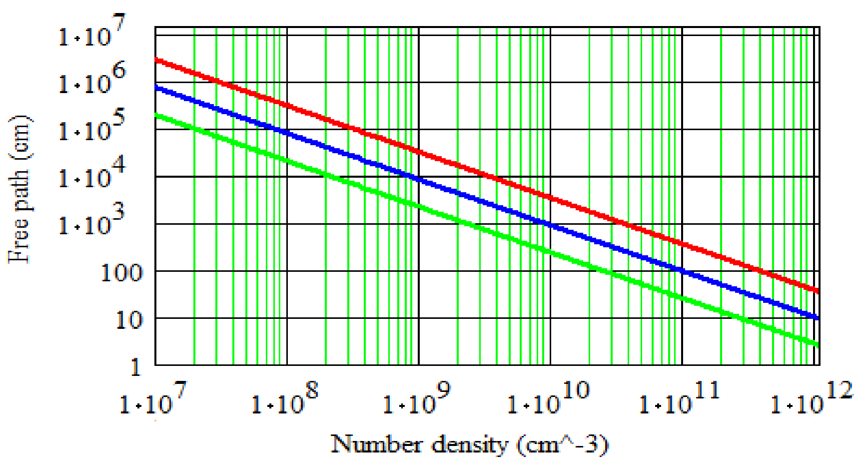


$$Pe = \frac{V_e n_e k L_t}{\chi_e}$$

$$\chi_e = 4\cdot 10^4 T_e^{5/2}(\ln\Lambda)^{-1}\, erg/s\cdot cm\cdot K$$

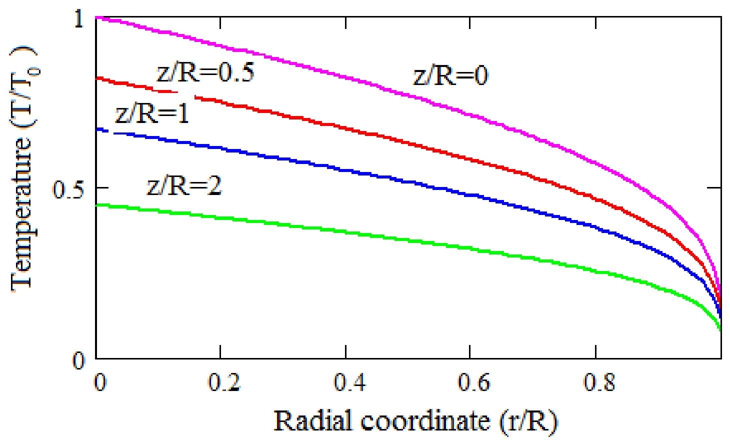
$$Pe = 10^{-3}T_e^{-5/2} << 1$$

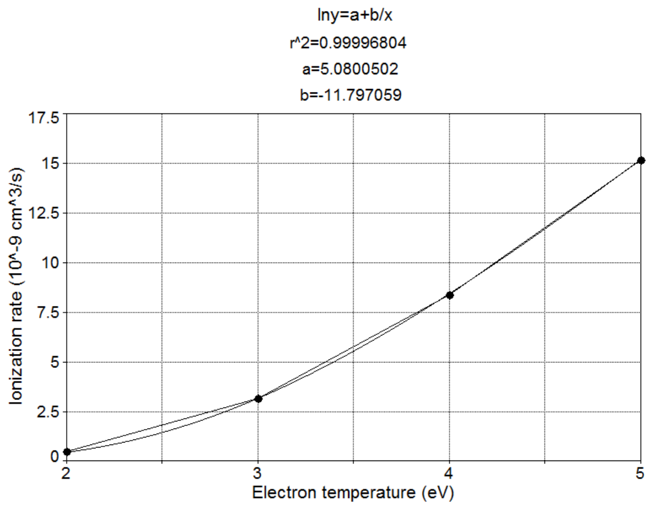
$$l_{ee} = \frac{2\cdot 10^{13}}{n_e \ln\Lambda}T_e^2\, cm$$



T_e=4, 2, and 1 eV

$$T_e(r,z) = T_{e0}\cdot\exp\left(-0.4\frac{z}{R}\right)\cdot J_0^{2/7}\left(2.4\sqrt{\frac{r}{R}}\right)$$



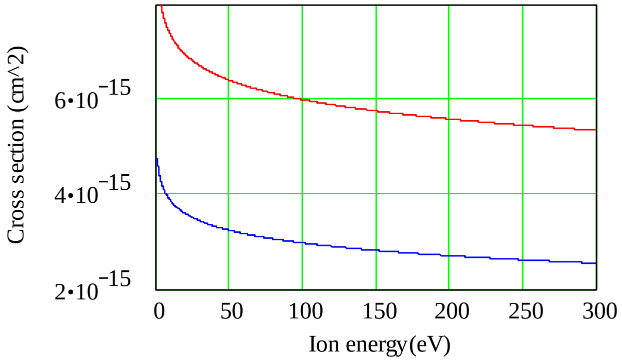


The rate of ionization/excitation for *e+Xe* collisions

$$l_{eXe} = 10^6\ cm \quad at\ T_e = 2\,eV, \quad and \quad l_{eXe} = 5\cdot 10^4\ cm \quad at\ T_e = 5\,eV.$$

$$\langle \sigma v_e \rangle = \frac{\int_{8.3}^{\infty} \sigma(\varepsilon)\cdot\left(\frac{2}{m_e}\right)^{1/2} \varepsilon\cdot\exp\left(-\frac{\varepsilon}{T_e}\right)d\varepsilon}{\int_0^{\infty}\varepsilon^{1/2}\cdot\exp\left(-\frac{\varepsilon}{T_e}\right)d\varepsilon}$$

$$l_{CEX} = \frac{1}{\sigma_{CEX} N_{Xe}} = 0.9\cdot 10^4 \cdot p_{Xe}^{-1} \qquad cm$$



$$\oint j_{ew}(r)dS = \oint j_{iw}(r)dS$$

Ira Katz, 2015

Equations for ion and electron “liquids” and electrostatic potential in 1-D model can be written as following:

$$\frac{d}{dy} n_{e,i} v_{e,i} = 0 \qquad \frac{d}{dy}\left(m_{e,i} n_{e,i} v_{e,i}^2\right) = -\frac{d}{dy} n_{e,i} T_e \pm e n_{e,i} \frac{d\Phi}{dy} \qquad \frac{d^2\Phi}{dy^2} = 4\pi e\left(n_e - n_i\right)$$

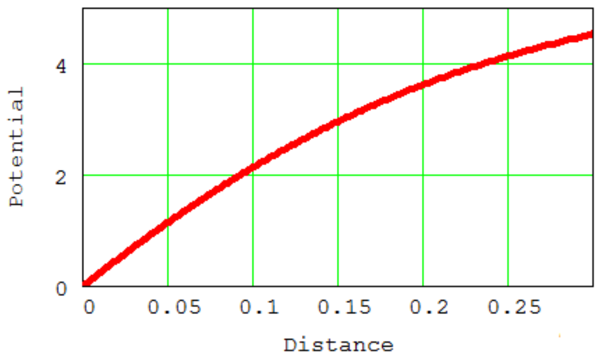
Average ion charge is set to
Z=1 for simplicity, and $T_e >> T_i$.

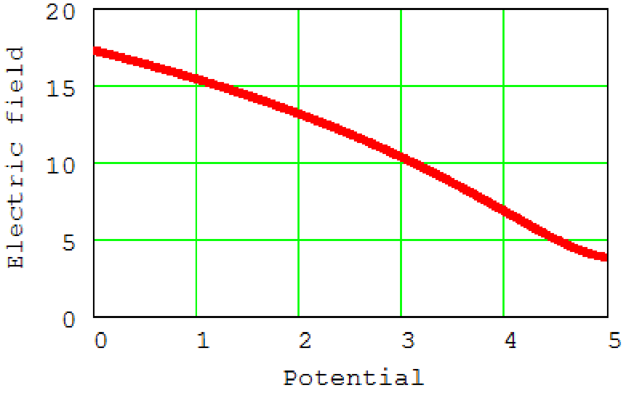
$$n_e(x) = n_{ew} \exp(\Psi) \qquad n_i(x) = n_{iw}\left(1 - \beta\Psi\right)^{-1/2} \qquad \frac{d^2\Psi}{dx^2} = \exp(\Psi) - \frac{\alpha}{\left(1-\beta\Psi\right)^{1/2}}$$

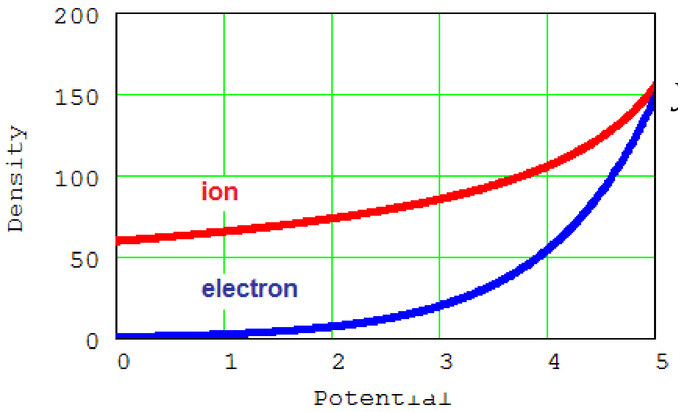
the following dimensionless variables and parameters are introduced:

$$\Psi = \frac{\Phi}{T_e} \geq 0; \qquad x = y \cdot \left(\frac{4\pi n_{ew} e^2}{kT_e}\right)^{1/2}; \qquad \alpha = \frac{n_{iw}}{n_{ew}}; \qquad \beta = \frac{2T_e}{m_i v_{iw}^2}$$

Border conditions are obvious: at $x_. = 0 \qquad \Psi = 0$







Dimensional distance from the wall to the bulk plasma is:

$$y_b = 0.3 \cdot \alpha^{1/2} \left(\frac{kT_e}{4\pi n_e e^2} \right)^{1/2} \approx 2\,mm \quad for\, T_e = 1eV \quad and \quad n_e = 10^7\, cm^{-3}.$$

Thus, very thin layer of separated charges can provide necessary balance of ion and electron currents.

Ion life time in chamber can be estimated as

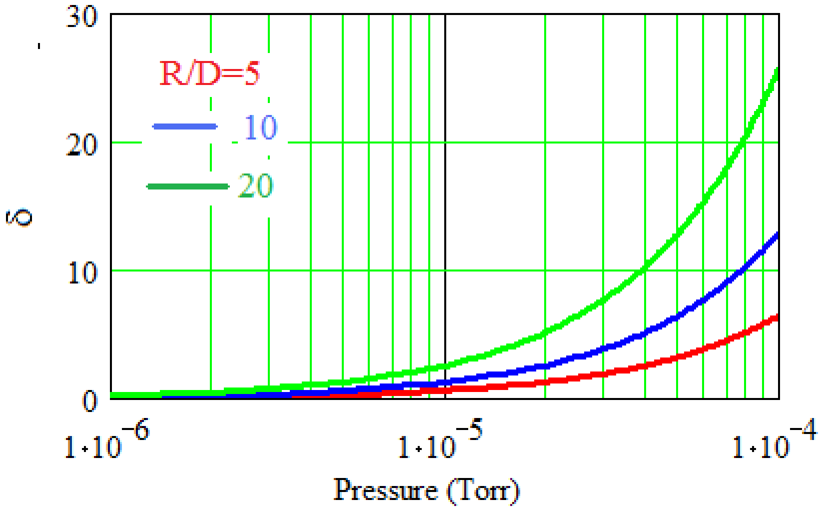
$$\tau_i = \left(\frac{m_i}{2e\Phi_b} \right)^{1/2} L \approx \left(\frac{m_i}{10T_e} \right)^{1/2} \cdot L$$

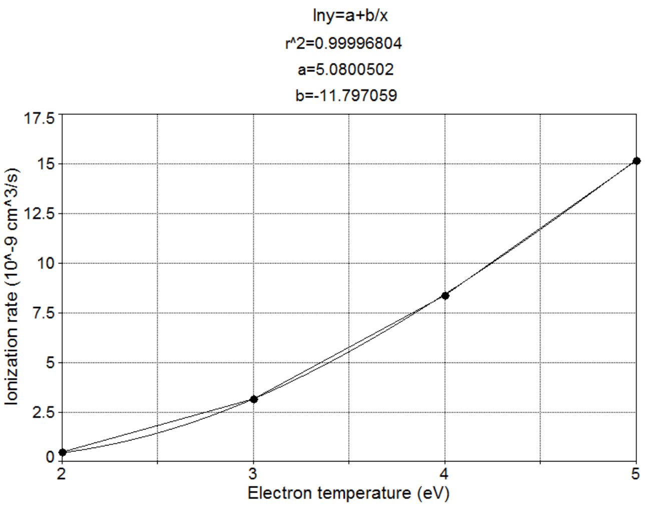
In order to support current balance the life time of an electron should be the same.

The length of electron trajectory in chamber is

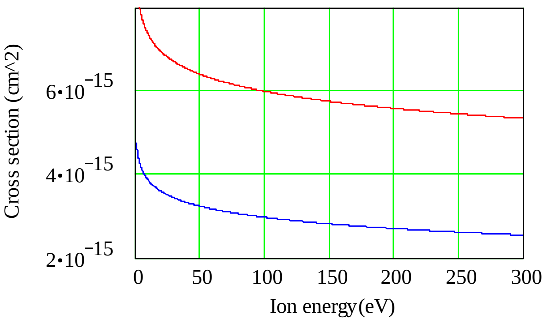
$$l_e = \left(\frac{2T_e}{m_e} \right)^{1/2} \cdot \tau_i = \left(\frac{m_i}{5m_e} \right)^{1/2} \cdot L \approx 220L$$

Elementary Processes





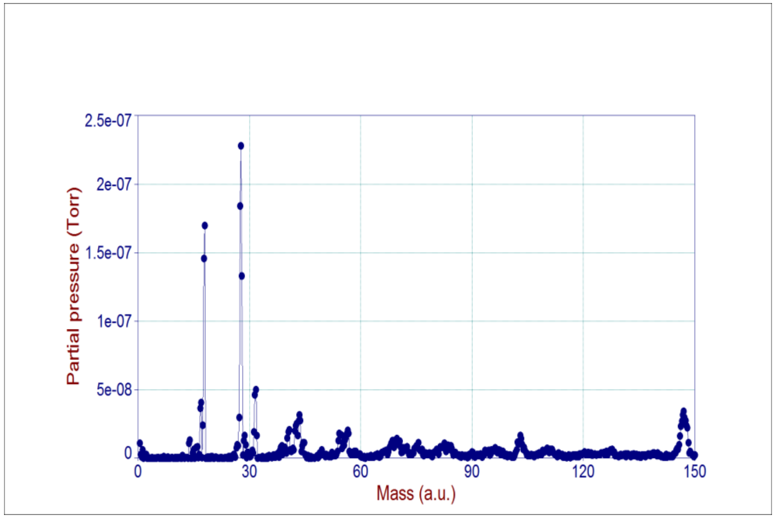
Ratio of number of collisions vs. pressure for R/D_0=5, 10, and 20. N_0=3*10^{12} cm^{-3}, T_{Xe}=500 K. (Space/chamber, e+Xe)



$$l_{eXe} = 10^6\, cm \quad at\, T_e = 2\, eV, \quad and \quad l_{eXe} = 5 \cdot 10^4\, cm \quad at\, T_e = 5\, eV.$$

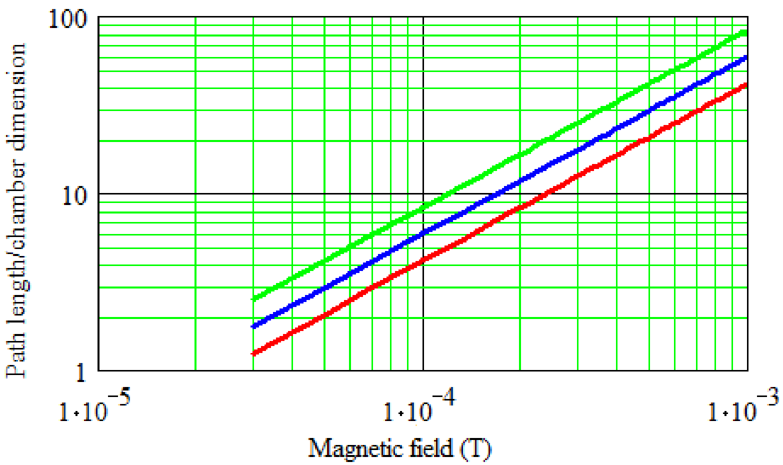
$$l_{CEX} = \frac{1}{\sigma_{CEX} N_{Xe}} = 0.9 \cdot 10^4 \cdot p_{Xe}^{-1} \qquad cm$$

CEX processes cross sections for singly (top) and doubly (bottom) ionized xenon atoms



$$l_{eW} = \left(\sigma_{eW} \cdot \frac{p(H_2O)}{kT_W} \right)^{-1} = \frac{3 \cdot 10^3}{p(H_2O)} cm$$

$$R_{eff} = \frac{eBR^2}{(32\pi m_e k T_e)^{1/2}}$$



***R*=2 m, T_e=1, 2, and 4 eV.**

$T_e(r,z>4\ m)$=??

Thruster with *P*=20-40 kW

Adequate ground experiment-?

CONCLUSIONS

Of course, one cannot expect a quantitative agreement between simple 1-D model and experimental data obtained for different thrusters in vacuum chambers of widely varied dimensions, but these calculations support conclusion regarding unavoidable influence of chamber walls on spatial distributions of plasma parameters even for experiments with very low neutral gas pressures.

Plume plasma electron temperature is very important parameter for evaluating the interactions between spacecraft elements and thruster plume. All measurements performed in vacuum chambers indicated rather low electron temperatures (0.5-2 eV) in far field while computer simulations and measurements in space (one only) pointed to significantly higher temperatures (2-6 eV). There are a few mechanisms for cooling electrons in plasma chambers, and they should be taking into account while designing ground tests revealing interactions between plume plasma and spacecraft elements.

References are in paper