White Paper for *Frontiers of Plasma Science Panel*

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Title:	**Problem of Cooling Plasma in Vacuum Chamber**
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Problem of Cooling Plasma in Vacuum Chamber

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New NASA 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 [1]. Plasma thruster generates comparatively dense plasma that interacts with solar array, and these interactions may cause some detrimental consequences. Besides these factors the performance of a high-voltage (over 300 V) solar array in natural and generated environments was never studied before. 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 of this problem: 1) performing extensive computer simulations; 2) measuring plasma parameters in ground chambers. It turns out that the electron temperatures measured in chamber and computed are essentially different, and understanding the causes of this difference is the main **challenge** for further work.

Plume plasma parameters in chamber and space are different: backpressure of neutral gas and a vessel walls influence on plasma density, plasma potential, and electron temperature. The quantitative characteristics of these differences for any thruster depend on chamber dimensions and pumping speed.

The experimental study of all these factors was performed in [2]. Background pressure (Xenon) varied from 3.5 μTorr to 73 μTorr. The electron temperature variations at the distance of 1 m from thruster exit plane (at the angle of 50 deg from axis) were determined within the range of 1-2 eV for floating thruster and 0.9-1.3 eV for thruster grounded. The electron temperature increased with pressure decreasing, and measurements error was estimated at 20%. In order to establish adequate test conditions the influence of a test arrangement on plume plasma parameters was analyzed and some criteria for appropriate ground test conditions were presented. The effect of backpressure was studied for P5 Hall thruster in a quite large chamber with a diameter of 6 m and length of 9 m [3]. Two sets of measurements were performed at xenon background pressures of 3.6 μTorr and 11 μTorr. Probes were positioned at the distance of 1 m from exit plane, which was equal to seven thruster diameters approximately (D_0=148 mm). Certainly, ion current density was decreased about two times with increased pressure, and electron number density demonstrated dependence on pressure with factors of 2-4. Electron temperature varied within the range of T_e=1.2-1.6 eV, and no correlations were established between electron temperature and neutral gas pressure.

Plasma properties of Electron Cyclotron Resonance (ECR) thruster in the near field (2 cm from exit plane) were investigated in Ref.4. Measurements were performed by probes moving in radial direction (-50 cm<y<50 cm), and there was revealed practical independence of electron temperature on input power (P=0.9-1.6 kW). However, electron temperature was decreasing with increasing flow rate: T_e=2.5-3 eV at $\dot{m} = 20\,sccm$, and T_e=1.3-2.3 eV at $\dot{m} = 36\,sccm.$ These results were obtained in fairly large chamber (D=2.2 m, L=7.9 m), and they confirmed that low electron temperatures were caused by processes inside thruster but not the influence of background gas pressure. Many other tests resulted in electron temperatures of 3-5 eV at about 0.5 m distance from thruster and 0.9-2 eV at 1-2 m distances [5-8]. Theoretical calculations and computer simulations pointed to electron temperatures of 3-5 eV in far field [9-12]. We performed extensive measurements of electron temperatures in different plasma chambers for a variety of thrusters [13-18]. In all cases, the electron temperatures in far field were determined within the range of 0.3-0.9 eV. Plume plasma consists of three main components: electrons, ions, and neutral atoms. In order to obtain a detailed picture of spatial distribution of plasma parameters the set of equations for each component and electric field is supposed to be solved. Due to low ratio of bulk speed of electrons to the thermal speed the dynamic equation for electrons can be written as really static. All measurements performed to date demonstrated the dependence of electron temperature on spatial coordinates: sharp drop from 20-30 eV to 4-8 eV near exit plane and slow decrease to 1-3 eV over a scale of 1-2 m. This long scale

temperature gradient might be caused by interactions of electrons with background gas in plasma chamber, and/or by high thermal conductivity of electron plasma.

For stationary plasma ($\frac{\partial}{\partial t} = 0$) the equation for electron temperature can be written in the following form:

$$\vec{V}_e\left(\frac{3}{2}n_e\frac{\partial T_e}{\partial \vec{r}} - T_e\frac{\partial n_e}{\partial \vec{r}}\right) = -\frac{\partial \vec{q}_e}{\partial \vec{r}} + \sum_{i,j}(\pi_e)_{ij}\frac{\partial \vec{V}_{ei}}{\partial r_j} + Q_e \qquad (1)$$

Thermal flux is proportional to the temperature gradient:

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

The thermal conductivity tensor χ_{eij} has different diagonal components and non-vanishing other components if magnetic field is strong enough to be taken into account. Magnetic field strength was measured along the plane distanced at 1.2 m from thruster exit, and it was demonstrated that magnetic field strength was equal to Earth's one; thus, magnetic field effects were disregarded in the analysis. Contribution to the energy balance due to collisions with other species (ions and neutrals) Q_e is determined by the corresponding cross-sections. It was shown that in far field $r,z>8D_0$ the electron temperature dropped to constant value of 2 eV with electron number density in the range of n_e=(1-3)*10^{10} cm^{-3}. It should be stressed that Eq.1 is valid in the area where electron free path is much shorter than the scale of density and temperature variations. Electron free path depends on temperature and number density

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

and it exceeded chamber dimensions for all experiments conducted to date.
An essential difference between orbital reality and ground simulation is the spatial distribution of neutral atoms. When thruster works in orbit, the neutral gas density decreases with distance from exit according to the formula:

$$N_{Xe}(r) = N_0\Omega\frac{D_0^2}{4r^2}$$

For example, solid angle for SPT-50 was equal to Ω=0.4. Due to very high ratio of masses $\frac{M_{Xe}}{m_e} = 2.4\cdot 10^5$ elastic collisions of electrons with neutral atoms cannot change their energy or, in other words, to cause cooling of electron component. Excitation and ionization cross-sections are below 5*10^{-16} cm^2 for electron energy in the range of 9-100 eV, which means that energy losses for electrons caused by inelastic collision with xenon atoms are negligibly low. Energy losses for the electron gas caused by excitation of rotational levels of water molecules were insignificant in most experiments conducted in chambers with cryogenic pumps. The only exclusion might be test in Tank 6 that was equipped with diffusion pumps. If water vapor partial pressure were about 4 μTorr then mean free path would be comparable with chamber dimensions.

Plume plasma electron temperature is very important parameter for evaluating the **interactions between** spacecraft elements and **thruster plume**. The understanding of electron cooling mechanism in chamber is the necessary element for **providing reliable tests** for spacecraft power elements. This is very important issue because of developing and implementing more powerful **plasma thrusters for future missions**.

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a) b)

Fig.1. Spatial distributions of plume plasma parameters in vertical plane distanced at 120 cm from SPT-50: a) electron number density; b) electron temperature.

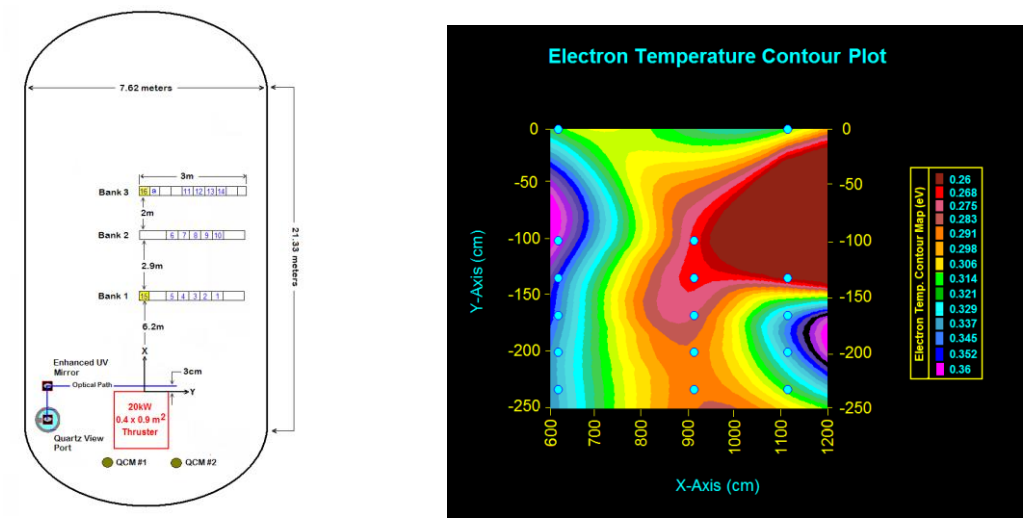

Fig.2. Electron temperature spatial distribution for HiPEP plume plasma in Tank 6.

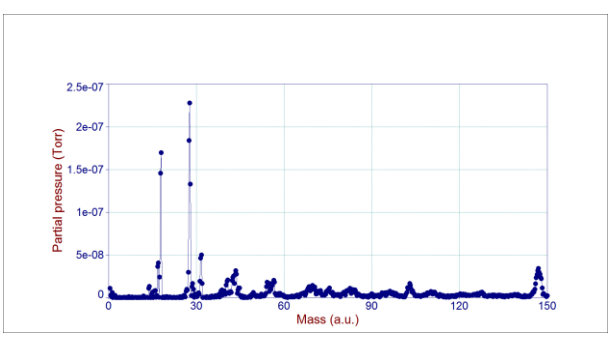

Fig.3. One example of RGA scan in SPT 50 experiment.