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Study of Gas Burn-out Regime in the VASIMR Helicon Plasma Source*

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Introduction

The complete VASIMR plasma propulsion concept [1,2], which has originated from the double magnetic mirror fusion research, consists of two consequent RF-driven sections – helicon plasma source, and ICRH booster as shown in Fig. 1. Recent MIT simulations [6,7] and ASPL experimental results [3] indicate that there is a promising regime of the VASIMR helicon operation, when almost 100% of the gaseous propellant is ionized. Following the so-called gas burn out stage, the electron temperature rises to relatively high values on the order of 10-20eV. High electron temperature prompts high ambipolar potential, which effectively accelerates ions axially. Experiments show ion exhaust velocities on the order of 40km/sec and up, suggesting that the first stage of VASIMR may serve as a plasma thruster on its own. The requirements [4] for the VASIMR engine missions imply certain levels of RF-to-beam power conversion and propellant utilization efficiencies for the plasma source. Presently, there are certain physical issues that have to be answered to guarantee optimal operation of the VASIMR helicon source, especially at higher, 10-50KW, input powers. Moreover, plasma source performance at much higher than now power densities, which will be typical for the MW-class VASIMR thrusters, has to be studied as well. We report theoretical study of the helicon plasma source operating with various light ions [5], and identify optimum operational parameters for a broad range of input powers. Our analysis is based on a set of different level models for the VX-3 and VX-10 helicon sources, drawn in Fig. 2.

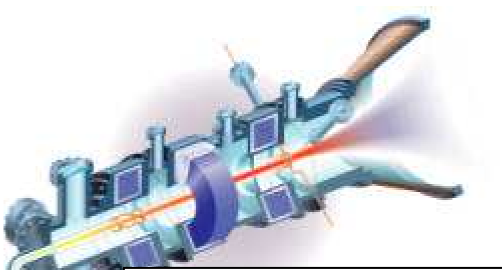

Fig.1. Cutaway view of VX-10

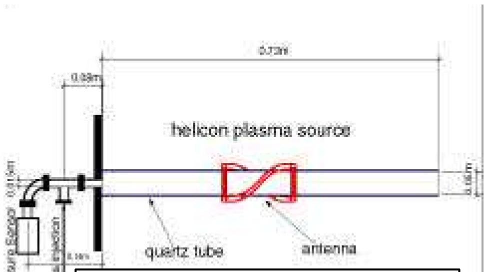

Fig.2. Gas-feed – helicon source section of the VX-10

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Hybrid model for mixed-collisional flow of gas propellant

As the heavy gas (Ar, Xe) helicon discharge plasma has low degree of ionization (~1%) [8] one can try match existing experimental data for the pressure drop (~100-200 mtorr) in the VX-10 gas feed system assuming that gas and plasma flows are decoupled. Helicon consists of a set of connecter circular pipes of variable radius $R \approx 0.5 - 10cm$. Estimate shows for typical mass flow rate $\mu \approx .2 - 2\times 10^2\ sccm$ typical Knudsen number $Kn = \lambda(\rho, T)/2R$ varies in the 0.1-10 range. Mass throughput is constant, therefore, that the asymptotic Poisseuille, $\mu = a(T)R^4 dP/dz$, and Knudsen, $\mu = b(T)R^3 dP/dz$, results should be valid in the limits of small, $Kn = \lambda(\rho, T) \to 0$, and large, $Kn \to \infty$, Knudsen numbers, respectively, we may find the following "hybrid" expression:

$$\mu = \int_0^R \pi r^2 \rho V_Z dr = const = \mu_P + (\mu_K - \mu_P)\left\{1 - \exp^{-Kn}\right\} = C(T,P,z)\frac{dP}{dz} \qquad (1)$$

where C(T,P,z) is a new composite function. By inverting Eq. (1) we obtain a finite-difference expression for gas pressure drop, which can be integrated numerically the gas injector down to the end of the quartz tube. From the bottom chart in Fig.3 experimental data for the pressure drop along the system are within 1% of accuracy for constant helium flow rate μ=200sccm. Experimental points are actual pressure gauge data. Axial temperature profile fits quartz tube temperature from thermocouples. Our original assumption about mixed viscous-free molecular flow is verified a posteriori. The most important for our immediate goal is that mean gas flow is very subsonic with average Mach number <M> ≈0.03-0.06. This result was crosschecked using purely kinetic model for collisional gas given in [9,10]:

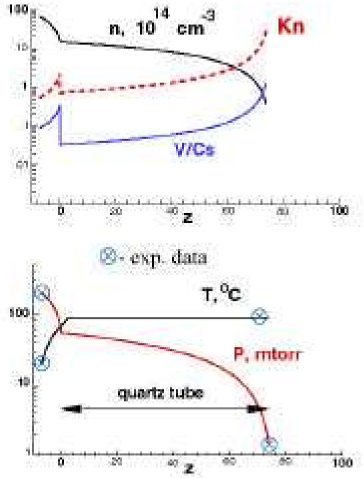


Fig.3. Calculated gas profiles

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} = \mathrm{St}_{N-N} + \mathrm{St}_{Wall} + \mathrm{S}$$

where rhs includes neutral-neutral, wall collisions and gas puff. Though non-Maxwellian neutral distribution and eddy formation are possible, these two-dimensional and kinetic features are not crucial for the 0-D balance model of the helicon to be discussed next.

0-D power and mass balance model of helicon discharge

Let's accept the following physical model of a hydrogenic helicon plasma source. Plasma is magnetized by a relatively strong magnetic field $B \approx 0.05 - 0.5T$. Correspondingly electron gyroradius $r_e \approx 10^{-2}\,cm$, ion – $r_e \approx 0.2cm$, which is still much smaller than tube's diameter. Cross-field transport is classical, week to affect the flow. Thus, the plasma flux onto outer wall is negligible. Electrons strictly follow field lines, which are parallel to the cylinder axis. We expect that the continuous puffing of H_2 through the inlet will keep the plasma density low near the end plate. We assume that the ion's exhaust velocity is sub-sonic with a fraction of the ion sound speed, $C_{Si}=(2T_e/M_i)^{0.5}$. The plasma in the volume is quasineutral and the plasma flow is ambipolar. The electron density is equal to the combined density of all ion species (H^+, H_2^+, H_3^+ here). The electron exhaust velocity is such to automatically maintain the ambipolarity of plasma $V_e=(n_{H+}C_{SH+}+n_{H2+}C_{SH2+}+n_{H3+}C_{SH3+})/\,(n_{H+}+n_{H2+}+n_{H3+})$. The plasma chemistry reaction rates used in our model are presented in Fig. 4. In addition to that gas puff, species exhaust, wall collisions, and geometrical characteristics – tube dimensions, gas choke – are included into model. More details could be found [8-10], where full set of 14 non-linear balance equations is presented and discussed.

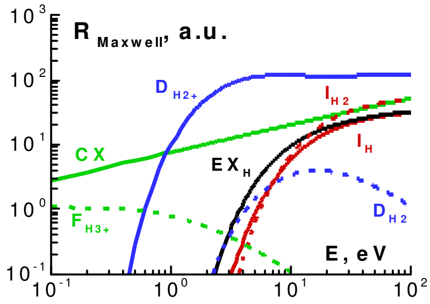


Fig.4 – H-species rates used by model

Scaling to high power

At higher power densities we no longer can neglect the rising radial loses to the walls.

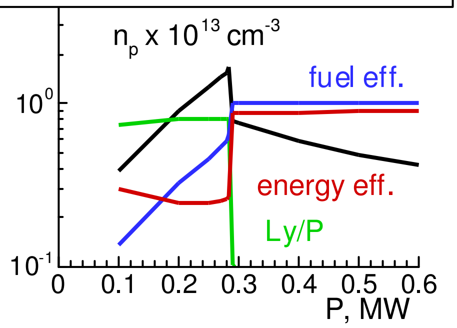
There are two major acceptable models for the cross-field transport – classical collisional

$$K_\perp / K_{II} \approx \frac{1.5}{\omega_{ce}^2 \tau_e^2} \approx 4\times10^{-26}\left(\frac{n_p \Lambda}{T_e^{1.5} B}\right)^2 \approx 1.5\times10^{-8}, \quad \text{where} \quad K_\perp \approx 4.7\frac{n_p k T_e}{m_e \omega_{ce}^2 \tau_e} \approx \frac{1.5}{\omega_{ce}^2 \tau_e^2} K_{II},$$

and anomalous Bohm-like transport,

$$D_B \approx 0.06\frac{ckT_e}{eB} \approx 3.2\times10^4\,cm^2/\sec.$$

Fig.5 – Discharge parameters vs input RF power, showing transition to gas burnout



The corresponding heat fluxes re given by expressions

$$q_W \approx S\,K_\perp \nabla_R (kT_e) \approx S\,K_\perp \frac{kT_e}{R},$$

$$q_D \approx S\,k\,T_e D_B \nabla_R n_p \approx S\,k\,T_e D_B \frac{n_p}{R}, \quad \text{respectively.}$$

Estimates show that for 20x100cm tube, $4\mathrm{x}10^3\mathrm{cm}^{-3}$ plasma density, 100eV temperature, and 1000G-field strength, the classical flux is negligible, while anomalous can't be ignored. $q_D \approx 10^{-12}\frac{ST_e^2 n_p}{RB} \approx 250{,}000W$. Simulations show interesting transition to gas burnout regime, as shown in Fig. 5. Simulations also indicate low, on the order of 60eV ionization cost for burnout regime.

Experimental verification of gas burn-out

Gas burn-out regime was achieved in the ASPL experiments with higher than previously power density using gas choke. Gas flow rate was reduced to ~10-60 and 20-100sccm for H and He gases, respectively. The results are presented in Figs. 6a and 6b below

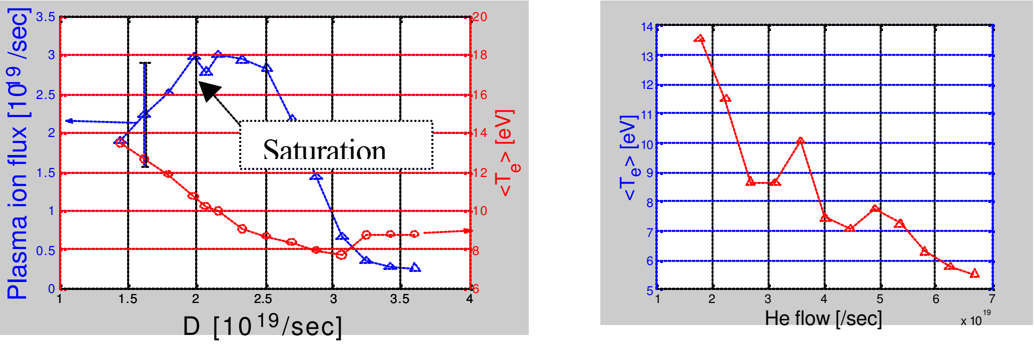


Fig.6 – Mass flow scans for fixed 3KW RF power a) H (ion flux and T_e) and b) He (T_e)

The gas burn-out regime is indeed characterized with $T_e > 10eV$, which is very unusual for the heavy gas helicon discharge. Plasma outflow accounts for 100% of gas influx.

Conclusions

Several models to study light gas flow and plasma conditions in the helicon source of VASIMR have been developed. These models were benchmarked against experimental data of the VX-10 setup. Numerical results demonstrate good agreement with the lab data. Our modeling has predicted an extremely promising gas burnout regime at higher energy densities, which was confirmed by the ASPL experiments.

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