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Plasma production and heating in VASIMR – A Plasma Engine for Space Exploration

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Research on the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine began in the late 1970's, as a spin-off from investigations on magnetic divertors[1] for fusion technology. A simplified schematic of the engine is shown in Figure 1. There are three stages: (1) the injection of propellant gas and its ionization; (2) the "RF booster" that acts as an amplifier to further energize the plasma; and 3) a magnetic nozzle, which converts the energy of the fluid into directed flow.

VASIMR is a radio frequency (RF) driven device where the ionization of the propellant is done by a helicon type discharge[2]. Plasma ions are further accelerated by ion cyclotron resonance heating (ICRH), used extensively in magnetic confinement fusion research.

Due to magnetic field limitations on existing superconducting technology, the system presently favors the light propellants; however, the helicon, as a stand-alone plasma generator can efficiently ionize heavier gases such as Ar and Xe, as well as mixtures of various gases.

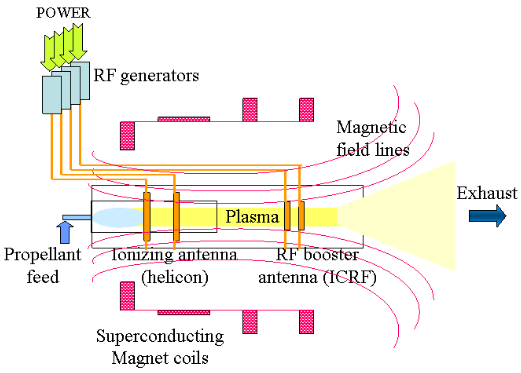

Figure 1: Simplified system schematic of the VASIMR engine.

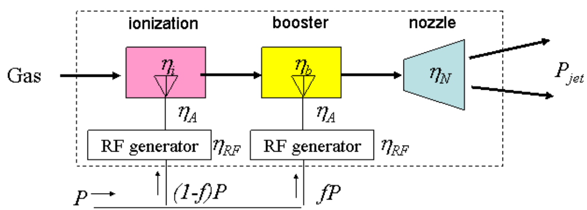

Figure 2: VASIMR power flow diagram

The performance of this concept can be examined by considering that of the various subsystems and their interrelationships. In Figure 2, electric power P is partitioned into two legs by the power partition fraction f. RF generators convert electrical into RF power with efficiency η_{RF}. The transmission lines and antennas also have their efficiencies η_A; for simplicity we assume they are equal. Power transfer efficiencies for the ionization and booster stages, η_i and η_b respectively, are not equal, however, and many of current experimental investigations are focused on understanding these quantities. Finally, plasma output at the RF booster is further scaled by the magnetic nozzle efficiency η_N.

A nominal set of component efficiencies for various propellants has been developed and used to predict realistic performance for a hypothetical 1MW engine[3,4,5]. Figure 3 shows expected performance curves for a 1 MW engine as functions of the specific impulse. The efficiency curves are relatively flat at high I_{sp}. We have included Lithium in Figure 3 since it is the heaviest propellant in which ICRH can operate with current technology.

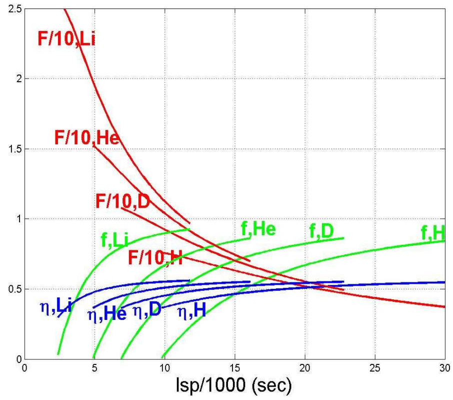

Figure 3: Performance parameters as functions of I_{sp} for various propellants. The system efficiency η, the RF booster power partition f are dimensionless, the thrust F has units of Newtons.

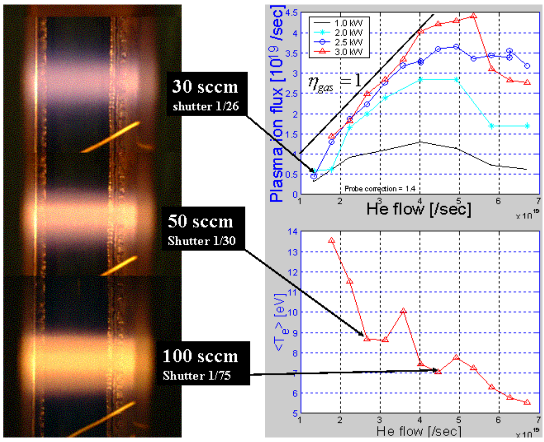

Figure 4: Plasma production and electron temperature as functions of the neutral gas injection rate for helium. Discharge brightness at various flow rates is shown at left. Visible color change, and elevated electron temperature confirm neutral gas depletion.

The physics of the VASIMR engine are being investigated primarily in the experimental VX-10 device at the NASA Johnson Space Center (JSC.) However, supporting investigations are being carried out at the Oak Ridge and Los Alamos National Laboratories, the University of Texas at Austin and the NASA Marshall Space Flight Center in Huntsville Alabama.

The helicon first stage is critically important inasmuch as its performance sets the tone for that of the second stage or RF booster. The present helicon source has now been well characterized theoretically and experimentally, with hydrogen, helium, deuterium and other propellants[6,7,8]. Stable plasmas are routinely produced at densities of 10^{18} to 10^{19} m^{-3}.

While the helicon is mainly a plasma production stage, its operation also produces thrust and direct measurements of flow momentum have been carried out[9]. The standard 3kW helicon discharge produces 6-7 mN on a target a few centimeters away from the magnetic throat. The neutral propellant input rate (~3×10^{-7} kg/sec) leads to an I_{sp} estimate of about 2000 sec. However, present pumping limitations increase the neutral background pressure downstream of the helicon throat, leading to collisions, which tend to reduce measurement quality.

These helicon I_{sp} estimates are considered reasonable, as nearly complete gas burn-up in the helicon tube has now been measured. Quantities related to propellant utilization efficiency are shown in Figure 4, where measured ion output and neutral particle input fluxes are seen to have an essentially 1-to-1 correlation between $2x10^{19}$ and $4x10^{19}$ ions per second.

Present activities now focus on the physics of the RF booster, or ion cyclotron stage, where it is important to understand how rapidly ion cyclotron waves are absorbed by the high-speed plasma flow. This process differs from that in a tokamak as the particles in VASIMR pass under the antenna only once. Sufficient ion cyclotron wave (ICW) absorption has nevertheless been predicted by recent theoretical studies[10,11,12]. Recent experiments have confirmed these theoretical predictions with a number of independent measurements. What follows are brief highlights of some of these results.

The VASIMR plasma acts as a resistive load on the RF circuit and measurement of plasma loading on the ICRF antenna thus gives power absorption, which is then compared with theoretical prediction. Figure 5 shows loading as a function of RF frequency normalized to the ion cyclotron resonance frequency at the axial mid point of the antenna.

Several conclusions can be drawn from Figure 5. First, loading values of the order of 200 mΩ are considered acceptable for achieving a preliminary demonstration of the ICRH process (our goal in 2003.) These values are mainly a result of the high plasma density produced by the helicon source and the ICRH antenna design. Second, as a significant check, it was verified that loading with Argon is virtually zero as expected, as cyclotron resonance does not exist for heavy gases in our configuration. Third, in comparing theory and experiments, two models are considered: one, neglecting electron collisions and two, including collisions. It is seen that the collisional model fits experimental data best. Fourth, a 5 % shift in the measured vis-à-vis predicted resonance, may be due to a number of things, including a possible Doppler effect caused by the plasma flow, which was not accounted for in the theoretical simulation.

Other measurements provide evidence of significant RF absorption in the booster stage. Data from two retarding potential energy analyzers (RPAs) show a strong shift in ion distribution to higher energy when 1.5KW of ICRH is applied[3]. Figure 6 shows the data from one of these RPAs, confirming that ions are heated when the ICRH antenna is turned on – this is the 'VASIMR RF booster', as we clearly see that a high-energy population appears when ICRH power is applied.

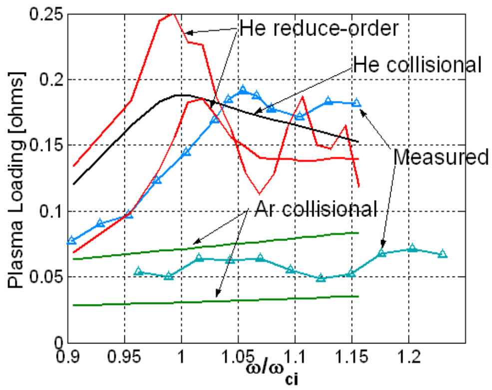

Figure 5. Measured (blue and green traces) and predicted (red, black and olive traces) plasma loading as a function of applied RF frequency, near the ion cyclotron resonance.

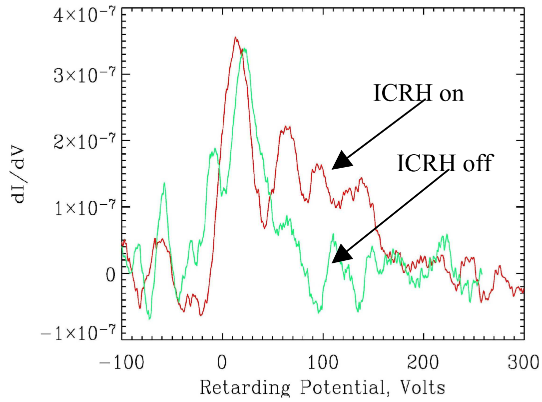

Figure 6. The un-collimated RPA measures the kinetic energy distribution of downstream moving ions with pitch angles within a 10^{o} cone about the beam axis.

In summary, the production of plasma in the VASIMR engine is effected through the use of a helicon antenna placed just downstream of the neutral gas injection port. As gas enters into the helicon, it is ionized and then passes towards the ICRH antenna, underneath which it is further energized. The plasma then exits the engine and the mostly transverse energy that existed in the high magnetic field region is transformed into mostly axial energy. This provides the possibility of high specific impulse, which we fully expect to occur in this class of electric rockets, and a demonstration of high I_{sp} in VASIMR is one of our primary goals.

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