Model Based Extrapolation of Hall Thruster Electrical Impedance between Test Facilities

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Understanding the discrepancy between ground test (in vacuum chambers) and in-space operation is critical to the development and deployment of the electric propulsion systems. The key potential physical mechanisms of the facility effects include background pressure, electrical circuit effects, and contamination due to carbon back-sputtering. All of these phenomena may affect the thruster operation by modifying some plasma properties. Recent measurements are conducted on the walls of the vacuum chamber. We present a work-in progress framework to assess the electric impedance between test facilities.

I. Introduction

Facility effects of electric propulsion play an important role in extrapolating the vacuum chamber data to space-like conditions. First, the background pressure effects have been considered the key mechanism in the community. The particles that exist in the plume inside the vacuum chamber may come back to the thruster and get ingested, leading to enhanced ionization, thrust, and specific impulse. Understanding the thruster performance at near-vacuum condition requires some physical understanding of the effects of the neutral particles on the discharge plasma. Second, the electric facility effects may occur due to the far field plume being exposed to a vacuum chamber wall, which is electrically conducting and grounded. In space, the thruster body together with the cathode are connected to the spacecraft, which is electrically floating with respect to the ambient plasma environment due to the lack of ground. While there are strategies to mimic a thruster body that is floating with respect to the vacuum chamber walls in ground testing, understanding the electrical properties and the beam neutralization could be important for predictive modeling of plasma thruster testing. Finally, the ions that bombard the beam dump can produce carbon species that may transport back to the thruster. There is evidence that the thruster operating in a vacuum chamber results in black coating (typically due to carbon deposition). Understand the carbon deposition rate may play an important role in estimating the erosion rate of local components of the thruster and assigning the correct boundary conditions for the plasma discharge. While the primary interest of the community with regard to the facility effects has been the background pressure effects, investigation of the electrical facility effects is

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an interesting yet challenging physics problem due to the following reasons. (a) The spatial scale separation is large, i.e., the plasma density is large near the channel exit and hollow cathode plume, while the plasma density is a few orders of magnitude smaller in the plume. (b) Solving plasma dynamics in such a large scale requires simplification to the models, such as using quasineutral drift-diffusion or Boltzmann potential relation, which may not be able to investigate the electron current path with high fidelity. (c) If the plasma discharge experiences various plasma oscillations from high (∼100 MHz) to low (∼10 kHz) frequencies, modeling such plasma oscillations in the entire vacuum chamber requires computational cost.

II. 0D plasma circuit model

Recent experimental data from Georgia Institute of Technology show detailed information of the current paths in the far field plume. 47 witness plates and 8 Langmuir probes are placed inside the vacuum chamber. In particular, when biasing a plate in the plume, it was observed that the thruster performance is unchanged, while the cathode-to-ground voltage is affected and there is an indication that the electrical impedance of the thruster also got affected. An outstanding question and hypothesis is whether such electrical impedance changes occur specific to a certain vacuum chamber facility or occur in other facilities as well.

A. Jovel's model

The HET discharge circuit can be decomposed into the discharge channel processes and the plume-facility processes as indicated in Figure 1, which is taken from David Jovel's PhD thesis.[1] The vacuum camber is grounded.

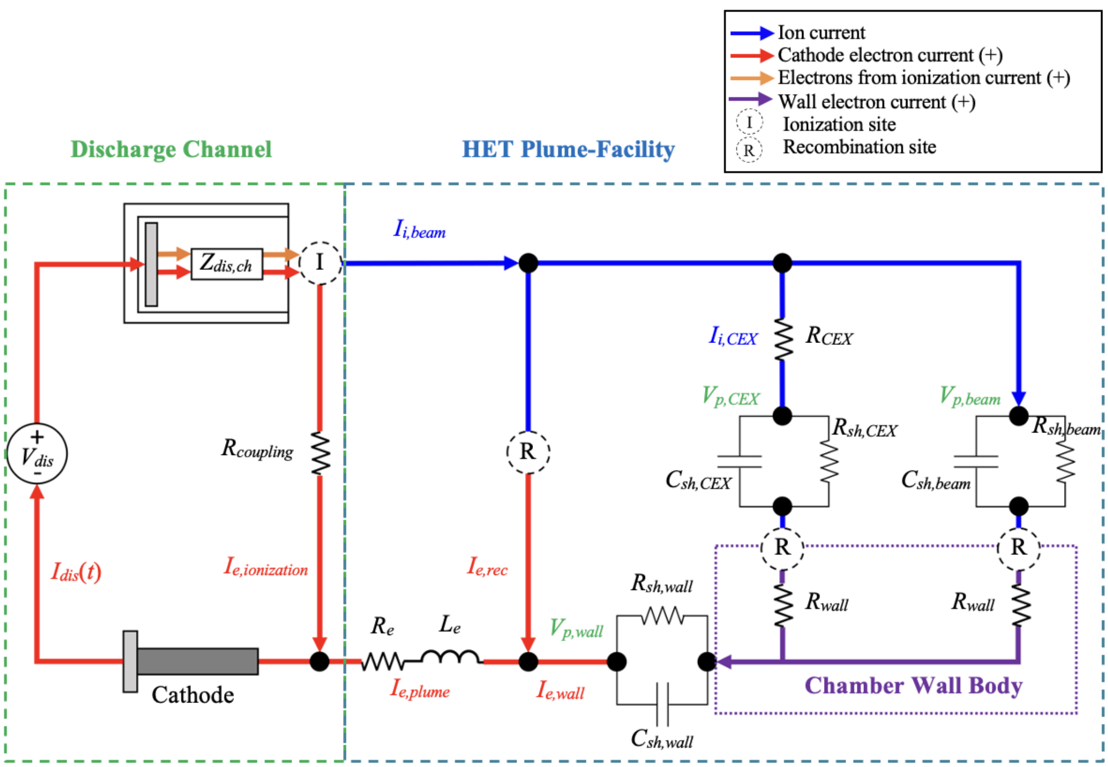

Figure 1. Current pathways in HET ground test. Reproduced from Ref. 1.

The DC power supply is connected to the anode and cathode electrodes, which feeds energy into the entire circuitry, including the discharge channel, near-field plume, cathode, as well as the vacuum chamber body. Within the discharge channel, the discharge current, $I_{dis}(t)$, can vary with at the fixed discharge voltage, V_{dis}. The current I_{dis} can be regarded as an AC current with a mean DC value. The electron-impact ionization inside the thruster discharge channel is denoted with 'I' and represents a charge source.

The discharge is connected with the cathode through the coupling, $R_{coupling}$ in this model. The key idea is that the discharge current inside the channel is split into two paths: (i) the ion beam to the near-field plume and (ii) the electron current from the cathode.

The plume-facility segment includes the ion and electron current pathways required to satisfy plume neutralization. First, if ion-electron recombination events occur within the volume, this can considered to be a current path, as the ions and electrons that come from the anode and cathode, respectively, recombine. The dashed circles with 'R' indicates such volumetric ion-electron recombination throughout the circuit. Second, the ion beam can experience charge exchange (CEX) collisions and transport to the vacuum chamber walls. Finally, the ion beam in the downstream (without any collisions with other species) can also reach the vacuum chamber wall (e.g., beam dump). Both the CEX and ballistic ions will feel the presence of a plasma sheath near the chamber walls, due to the existence of electrons. These plasma sheaths can be considered to be either a capacitor (e.g., at the steady state) and a resistor (e.g., during the transient because the net current may not be zero). During the plume plasma and chamber wall interaction, a plasma sheath will be established, which can generate a sheath potential to accelerate ions and decelerate ions.

B. Zivre's model

One of the confusions about a circuit model in a plasma is the separation between ion and electron paths. It is always important to note that net current is the important information for the circuit. With this in mind, Zivre proposed a simplified circuit diagram shown in Fig. 2.

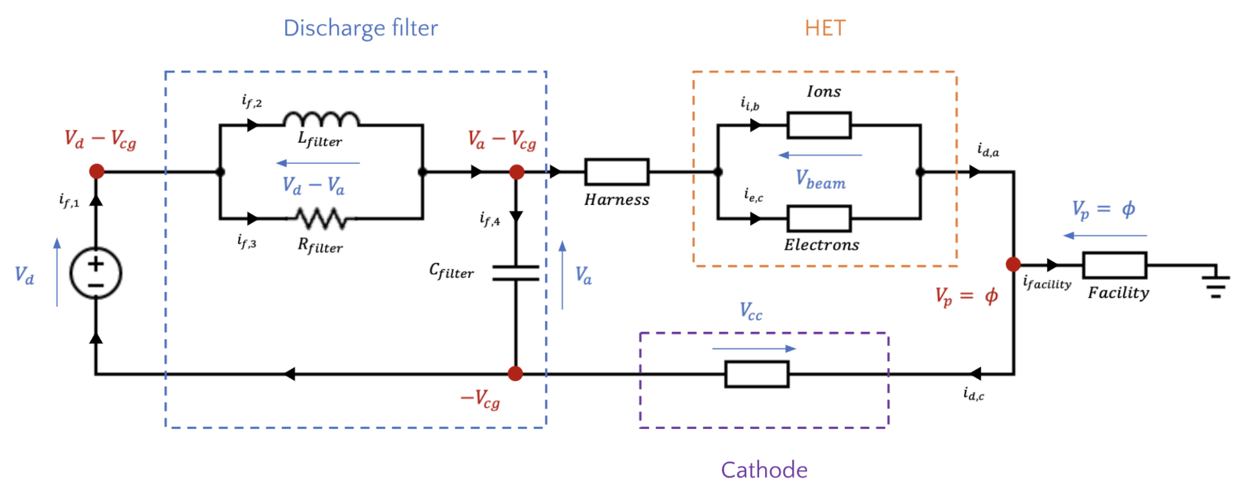

Figure 2. Another plasma circuit model.

The discharge filter consists of an inductor, resistor, and capacitor, which is standard. The anode current is provided via the ion current and electron current in the HET discharge channel. The reason why we separate this is because ions are ballistic while electrons follow a more fluidic transport (e.g., Ohm's law). The cathode provides the electron current (here we neglect the contribution of ion current for the net current at the cathode, although the presence of ions is not negligible to understand the cathode physics). Here, from this schematic, it can be seen that both the net current pathways from the HET (anode) and from the cathode will merge in the near- or far-field plume.

From the thruster-cathode system, both ions and electrons are emitted and can reach the vacuum chamber walls. Consider if at initial condition, all electrical components are grounded and if the thruster and cathode are turned on, the charged species start to collide with the vacuum chamber walls, generating a current. This current to the chamber wall, results in *charging* of the vacuum chamber walls, forming a sheath all around the plasma-immersed chamber wall surfaces. At steady-state, both ion and electron currents must be equal so that there is no charge buildup. Thus, the walls experience essentially zero net current. Under this condition, a plasma sheath will form and the impedance acts more like a capacitor because the sheath potential is set up so that the current is zero. Hence, the facility impedance shall be considered to capture such transient effects as well as the steady-state operation.

Additionally, another important consideration is that the plasma sheath around the chamber walls must be net zero current from a *global* perspective. If one considers the ion and electron current densities toward an object, i.e., $j_i(x,y)$ and $j_e(x,y)$, where x and y are the spatial coordinate that represent the surface. Then, net current condition means that

$$I_{net} = \int_A (j_i + j_e) dx dy = 0. \tag{1}$$

This does not mean that the local net current densities are zero: $j_i + j_e \neq 0$. To study this global feature of the chamber wall sheaths, we are currently developing a particle-based kinetic simulation of the near and far field plume.

III. Analysis

John Williams's group kindly shared some current data with us. The data include: anode current, cathode-to-ground voltage, cathode-coupling voltage, and AC component of the anode voltage.

We have performed a state estimation using extended Kalman filter with a 0D plasma global model. Using the current and voltage oscillations, Figure 3 shows an example of the anode plasma oscillation, estimated using the EKF model.

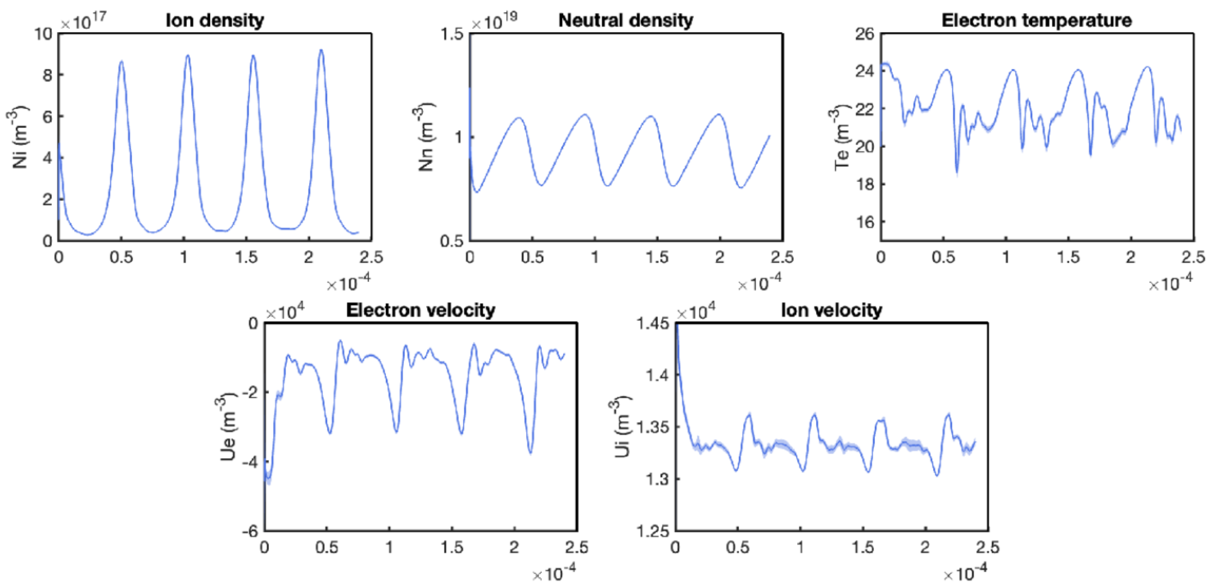

Figure 3. Anode plasma state estimation using extended Kalman filter.

The 0D anode plasma global model can now incorporate the circuit effects, as shown in Fig. 2.

IV. Summary

We propose utilizing a state estimation technique to infer the plasma states and variables from a multimodel experimental data stream. The dynamical model is a combination of the HET discharge plasma, simplified cathode plasma, and circuit effects (e.g., discharge filter and plume). The experimental data will be fed into the data assimilation technique to study the electrical impedance effects. This technique would be highly useful when experimental data are available.

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References

[1]D. Jovel, *Impedance characterization of a Hall effect thruster discharge in a ground-based vacuum test facility.* PhD thesis, 2024.