AFRL-AFOSR-VA-TR-2021-0088

Experiment, Modeling, and Simulation of Advanced Materials - Plasma Interactions in the Space Environment

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08/04/2021
Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04-08-2021

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
01 Apr 2019 - 31 Mar 2021

4. TITLE AND SUBTITLE
Experiment, Modeling, and Simulation of Advanced Materials - Plasma Interactions in the Space Environment

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-19-1-0164

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Josh Rovey

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF ILLINOIS
364 HENRY ADMINISTRATION BLDG
URBANA, IL 61801
USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTA1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2021-0088

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Profs. Rovey and Levin have been working on a two-year joint experiment and modeling approach to study the fundamental kinetic behavior of plasma sheaths found in electric propulsion devices with an extension to high-altitude air reentry plasmas. Understanding and accurately predicting the behavior of low-density plasmas with multi-species is fundamental and paramount to these applications, and this is the focus of our project. The goal of our research is to compare and assess different modeling approaches in capturing true system dynamics, by techniques such as time-lag phase portrait, within the context of plasma and space propulsion systems. Experiments focused on measuring the true system dynamics in a canonical plasma system relevant to pulsed plasma propulsion and air-breathing electric propulsion applications. High-fidelity fully-kinetic modeling was used to predict the plasma system dynamics and is compared with experiments. We compare the measured plasma system properties with the modeling results to assess the level of fidelity in predicting true dynamics of the system.

The objective was to compare the experimentally measured and numerically predicted temporal response of a low-density plasma when it is perturbed by a fast electric potential pulse. We measured the temporal response of the plasma within the sheath of a nanosecond pulsed electrode, and capture the response of the plasma on the timescale of the plasma frequency. Instead of only using probe theory (and the inherent assumptions) to calculate plasma parameters from probe data and comparing those with model predictions (e.g., plasma frequency), we also directly compared the raw temporal probe measurement with numerical predictions. Our approach here allowed us to evaluate and study the adequacy of probe theory-based evaluation of experimental data and its adequacy in describing the dynamics and characteristics of the system. Specific objectives included: (1) creating a low-density, “low” plasma frequency, quasi-steady multipole argon plasma; (2) applying a known controlled perturbation with a nanosecond pulsed electrode; (3) measuring the temporal evolution of floating potential and current to a probe within the sheath of the pulsed electrode; (4) testing the ability of simulations to accurately resolve electron velocity distribution functions (EVDF) in steady state and time varying plasmas; and (5) comparing existing probe theory predictions with numerical simulations, and where necessary exploring modified theory that may better capture system dynamics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** MITAT BIRKAN
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)* 426-7234
U	U	U	UU	14	

Experiment, Modeling, and Simulation of Advanced Materials - Plasma Interactions in the Space Environment

FA9550-19-1-016
April 1, 2019 – March 30, 2021

FINAL REPORT
May 26, 2021

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I. Review of Goal and Objectives of the Project

Profs. Rovey and Levin have been working on a two-year joint experiment and modeling approach to study the fundamental kinetic behavior of plasma sheaths found in electric propulsion devices with an extension to high-altitude air reentry plasmas. Understanding and accurately predicting the behavior of low-density plasmas with multi-species is fundamental and paramount to these applications, and this is the focus of our project. The **goal** of our research is to compare and assess different modeling approaches in capturing true system dynamics, by techniques such as time-lag phase portrait, within the context of plasma and space propulsion systems. Experiments focused on measuring the true system dynamics in a canonical plasma system relevant to pulsed plasma propulsion and air-breathing electric propulsion applications. High-fidelity fully-kinetic modeling was used to predict the plasma system dynamics and is compared with experiments. We compare the measured plasma system properties with the modeling results to assess the level of fidelity in predicting true dynamics of the system.

The **objective** was to compare the experimentally measured and numerically predicted temporal response of a low-density plasma when it is perturbed by a fast electric potential pulse. We measured the temporal response of the plasma within the sheath of a nanosecond pulsed electrode, and capture the response of the plasma on the timescale of the plasma frequency. Instead of only using probe theory (and the inherent assumptions) to calculate plasma parameters from probe data and comparing those with model predictions (e.g., plasma frequency), we also directly compared the raw temporal probe measurement with numerical predictions. Our approach here allowed us to evaluate and study the adequacy of probe theory-based evaluation of experimental data and its adequacy in describing the dynamics and characteristics of the system. **Specific objectives** included: (1) creating a low-density, “low” plasma frequency, quasi-steady multipole argon plasma; (2) applying a known controlled perturbation with a nanosecond pulsed electrode; (3) measuring the temporal evolution of floating potential and current to a probe within the sheath of the pulsed electrode; (4) testing the ability of simulations to accurately resolve electron velocity distribution functions (EVDF) in steady state and time varying plasmas; and (5) comparing existing probe theory predictions with numerical simulations, and where necessary exploring modified theory that may better capture system dynamics.

II. Motivation and Background

The motivation for this project is twofold. First, reduced order models for plasma and propulsion systems are necessary for engineering and design activities. However, plasma and propulsion systems are inherently dynamic systems and reduced order models generally fail to capture these dynamics. What is needed are tools and methodologies for assessing and quantifying the real system dynamics, and thereby determining when and where higher fidelity simulations are necessary, and when and where lower fidelity/reduced order models will suffice. Second, low-orbital-altitude spacecraft may be able to use the ambient atmosphere as propellant. However, the dynamics of low pressure multi-species chemically-reactive plasma must be better understood and characterized to enable these envisioned type of propulsion systems. Specifically, the effects of multi-species on the temporal sheath physics and corresponding wave propagation when subjected to fast transient pulse can be informative and foundational for development, prediction, and application to more complex systems.

The Air Force has been and continues developing and advancing models to predict and understand the behavior of plasma electric propulsion systems, such as Hall thrusters (HET) and field-reversed configurations (FRCs). The fundamental work proposed here supports operational systems, such as HETs, and FRCs for next generational plasma propulsion capabilities. These plasma electric propulsion systems are dynamic systems with temporal changes and oscillations in the plasma conditions (e.g., breathing mode (10's kHz), pulsed inductive fields (100's kHz)), and these dynamic plasma changes give rise to dynamic system operation (fluctuations in performance). Previous models have been developed to predict the quasi-steady plasma conditions and performance of these systems (e.g., quasi-steady density, temperature, ion energy in HET channel/plume, quasi-steady thrust/specific impulse). These codes also use approximate models for some of the thruster and plasma physics (e.g., electron transport).

These previous models are benchmarked and validated with quasi-steady experimental measurements. Further, the model validation data are rarely the raw experimental measurements. Instead, the raw experimental data are analyzed using probe theory,[1] which inherently has assumptions such as Maxwellian particle distribution. Because of these approximate models and experimental data analyses, the major problem is that these previous models and experiments do not capture the true system state. They approximate, ignore, or assume important dynamics and characteristics of the system. New models are now being developed with shorter timescales that can better capture the dynamics of these systems (i.e., the fast temporal fluctuations/changes inherent to these systems), and eliminate the need for approximate models and assumed system characteristics. Models being developed at AFRL and in academia (e.g.,our own CHAOS code) can predict the temporal evolution of the plasma and performance of these systems, eliminating the need for approximate models by directly simulating the physics on very short timescales (i.e. electron timescale). But an important question still exists: Can we use these new models to aid our understanding of the true dynamics and characteristics of the plasma system? Hence, our project here focuses on high temporal resolution physics-based models validated with raw experimental data, and thereby demonstrates a new approach to model validation that promises to provide a deeper understanding of plasma propulsion system dynamics.

III. Progress and Results on Specific Objectives

Recently we have fabricated a low-density multipole plasma cell as a canonical system for steady-state and transient plasma sheath measurements. We have also simulated this plasma system using fully-kinetic CHAOS model. Our experiments and modeling show good agreement for single species Argon plasma. Specifically, in pulsed transient sheath experiments and modeling, we identify Langmuir waves on the electron timescale and measure the effect of density and pulse duration (time scale) on the amplitude and frequency.

A. Objective 1: Creating a low-density, “low” plasma frequency, quasi-steady multipole argon plasma

Experiments have focused on measuring the temporal sheath dynamics in a low-density Argon plasma. The low-density of the plasma increases the Debye length and reduces the plasma frequency enabling electric probe measurements of fluctuations on the order of 10’s MHz that are characteristic of Langmuir waves.

All experiments are conducted at the University of Illinois at Urbana-Champaign in the Electric Propulsion Laboratory vacuum chamber, which is 1.2 m diameter and 2.1 m long. High vacuum is achieved with 1.2 m diameter TM1200 cryopump and the chamber base pressure is typically 5×10^{-8} Torr. A combination of an Alicat MCV (MCV-500SCCM-D-DB15-PCV10) mass flow controller and a HAM-LET needle valve (H300USSLR1/4M) is used to control the flow of Argon gas into the chamber. The pressure is measured by KJLC Cold Cathode Pirani Gauge (KJLC CCPG-H2-6).

Plasma is generated in a multipole plasma cell (MPC). MPCs have been extensively used for plasma sheath studies and ion acoustic wave studies by other researchers. The MOC used in the experiments here is shown in Figure 1. The MPC is cylindrical with 20 inch diameter and 32 inch long and made of 24 aluminum u-channels holding nine CM-0127 ceramic disk magnets in line. The magnets are oriented with the same polarity on each u-channel with adjacent u-channels assigned opposing poralities to configure a broken line cusp magnetic field. The magnets are eqully spaced 2 inch apart on center along the u-channels. A schematic of the electrical setup is shown in Figure 1. The MPC is electrically isolated from the vacuum chamber (which is grounded). In order to control the plasma potential of the plasma, the MPC is positively biased by Kepco MSK 125-1M DC power supply. The nominal biasing voltage to hold the plasma potential at 0V is 40 V. Electrons are emitted thermionicaly into the MPC from an array of five 0.005 inch diameter tungsten filaments heated by electrical current supplied by a TDK-Lambda GENH30V-25A DC power supply. The plasma discharge is formed by negatively biasing the filaments with respect to the MPC by a Kepco BOP 1000M power supply. The nominal filament heating current is 9 A for a 38 mA discharge current. The probe assembly is mounted on the Velmex XSlide motion stages allowing the x-z plane travel. The steady-state plasma measurement by the probes is conducted at the center of the computational domain. The probe assembly is out of the computational domain during the pulse experiment.

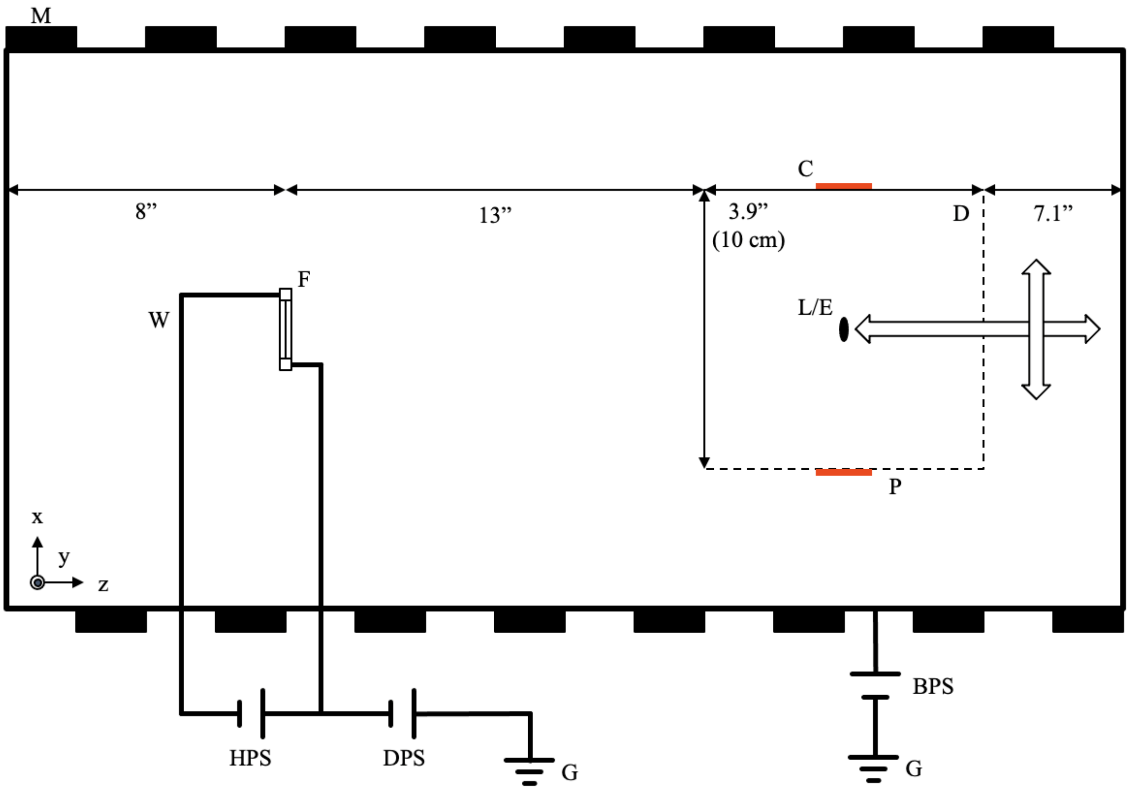

Figure 1: Experimental Setup; M = magnet, F = Filament, W = wire, C = collector electrode, D = computational domain, L/E = Langmuir/emissive probe, P = pulser electrode, HPS = heating power supply, DPS = discharge power supply, BPS = biasing power supply, G = ground

Three plasma conditions at three different pressures were tested in the experiments. Several initial experiments found that the variation of the electron density from different discharge currents (which is limited to be 40 mA maximum by the power supply) is too small when it is measured by the electron frequency. A large enough variation of electron densities are obtained by changing the experimental pressures while holding the discharge voltage and current. Three experimental pressures used in this experiments are $(7.50 \pm 0.50) \times 10^{-5}$, $(1.50 \pm 0.50) \times 10^{-4}$, and $(3.00 \pm 0.50) \times 10^{-4}$ Torr. The ion-neutral mean-free-path corresponding to the experimental pressures are 0.81 ± 0.058, 0.407 ± 0.203, and 0.203 ± 0.041 m. They are large enough compared to Langmuir probe (LP) and the collisionless plasma is safely assumed.

The plasma potential is meausured by an emissive probe (EP). The EP is a “hair-pin” shape that is made of a tungsten wire tip of 0.005 inch diameter and its body is enclosed by a ceramic tubing of 0.188 inch diameter. The EP is heated by Sorensen DLM 20V-30A DC power supply and biasd by Keithley 2410 Sourcemeter. Keithley 2410 Sourcemeter also measures the current thought the emissive probe. Nominal heating power is 2.5 V and 2.3 A.

Other plasma parameters (density and temperature) is determined by the LP. It is common to use the cylindrical probe with the Orbital Motion Limited (OML) theory for a low-density ($n_e < 1 \times 10^{14}\ m^{-3}$). However, the previous research [1] pointed out that the small collection area of cylindrical probe leads to a large signal-to-noise ratio and could result in inaccurate measurement. As the aforementioned research did, the planar disk probe with 7.7 mm diameter and 0.5 mm thickness is used. Table 1 summarizes the obtained plasma parameters at three different pressures.

Table 1: Steady-state plasma parameters from probe diagnostics

Pressure [Torr]	7.26×10^{-5}	1.42×10^{-4}	4.48×10^{-4}
Temperature [eV]	0.441	0.512	0.950
Density [m^{-3}]	1.57×10^{12}	2.26×10^{12}	4.39×10^{12}
Electron frequency [MHz]	11.24	13.49	18.80

B. Objective 2: applying a known controlled perturbation with a nanosecond pulsed electrode;

Inside the MPC, there are two square electrodes having a side of 20 mm made of a stainless steel, separated by 100 mm and parallel to each other. One electrode is a "pulser" that is connected to Stanford Reseach System Model PS350 Signa generator to perturb the plasma. Another electrode is a "collector" that is connected to Tektronix DPO 2024 Oscilloscope to measure the change in current due to the perturbation. The current is measured by reading the voltage drop across 1 kOhm resistor using Tektronix P2221 Voltage probe. The pulse from the signal generator is negative-exponential from 0 to -10V. The pulse duration ($\Delta pulse$) is approximately the time taking from 0 to -10 V. The pulse is repeated every 1 ms. The Oscilloscope averages the last 128 data into one to reduce the noise. The sampling speed is 1 GS/s, and its bandwidth is 200 MHz. Figure 2 shows the data collected in the pulse experiment.

C. Objective 3 - measuring the temporal evolution of floating potential and current to a probe within the sheath of the pulsed electrode;

We measure the temporal response of the collector plate when a pulse of known magnitude and duration is appliepd to the pulser plate. This effectively electrostatically perturbs the sheath, giving rise to Langmuir wave propagation, and we detect the Langmuir waves with the collector electrode. The raw temporal variation in the pulser and collector plate volteages is shown in Figure 2a while the Fourier transform of the data is shown in Figure 2b.

Several observations are made from Figure 2:

1. The collector electrode reads the current in the case without plasma. This is the displacement current due to the propagation of the electromagnetic wave from the pulser electrode.
2. The existence of plasma significantly alters the collected current. After the Fast Fourie Transform is applied (below), the new frequency mode (A in Figure 2) appears at 18.75 MHz accompanying its 1st harmonic mode (B in Figure 2) at 36 MHz.
3. The high frequency mode (C in Figure 2) at around 42.5 MHz are observed in both plasma and no-plasma cases. This is due to the impedance mismatch in the collector circuit.

These observations indicate that the Langmuir wave is excited when the pulse is applied on the pulser electode.

Figure 3 compares the electron frequency calculated from the electron density obtained by the probe diagnostic and the electron frequency otbtained from the pulse experiment (the 1st peak in each data). The horizontal error bar size depends on the electron density uncertainty in the probe diagnotics. While the error in the electron density depends only on the deviation from the ion current linear fit and its percentage error is within 5%, the error size is not small when the density is converted to the frequency ($f \propto \sqrt{n_e}$). The vertical error bar size correspoinds to the FFT resolution. Due to the pulse shape generated from the signal generator, there are more data points used for the FFT when the pulse duration is longer. For all three pulse duations, the electron frequencies from different experiments well agree, and it confirms that the Lagmuir wave excitation when the pulse is applied.

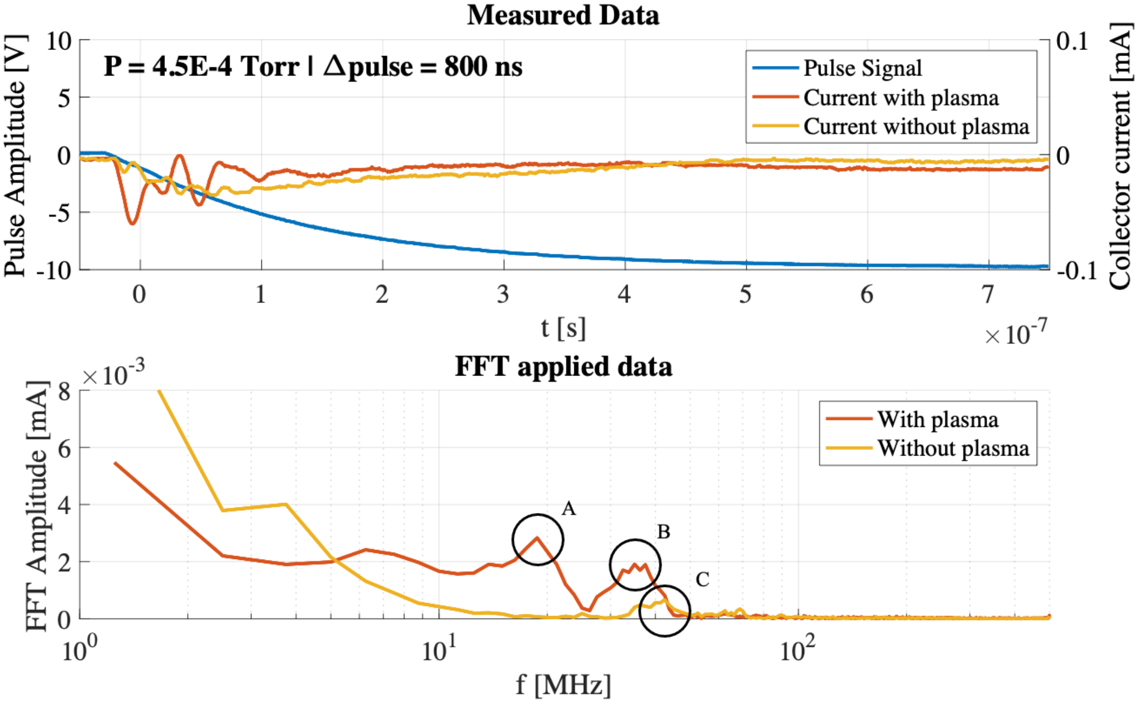

Figure 2: The data collected in pulse experiment (P = 4.5E-4 Torr, Δpulse = 800 ns). Top: the applied pulse shape (blue) and the current through the collector circuit (orange: with plasma yellow: without plasma), Bottom: The data after the FFT is applied; A = the peak at 18.75 MHz, B = the 1st harmonic of the peak at 36 MHz, C = the high frequency mode at 42.5 MHz

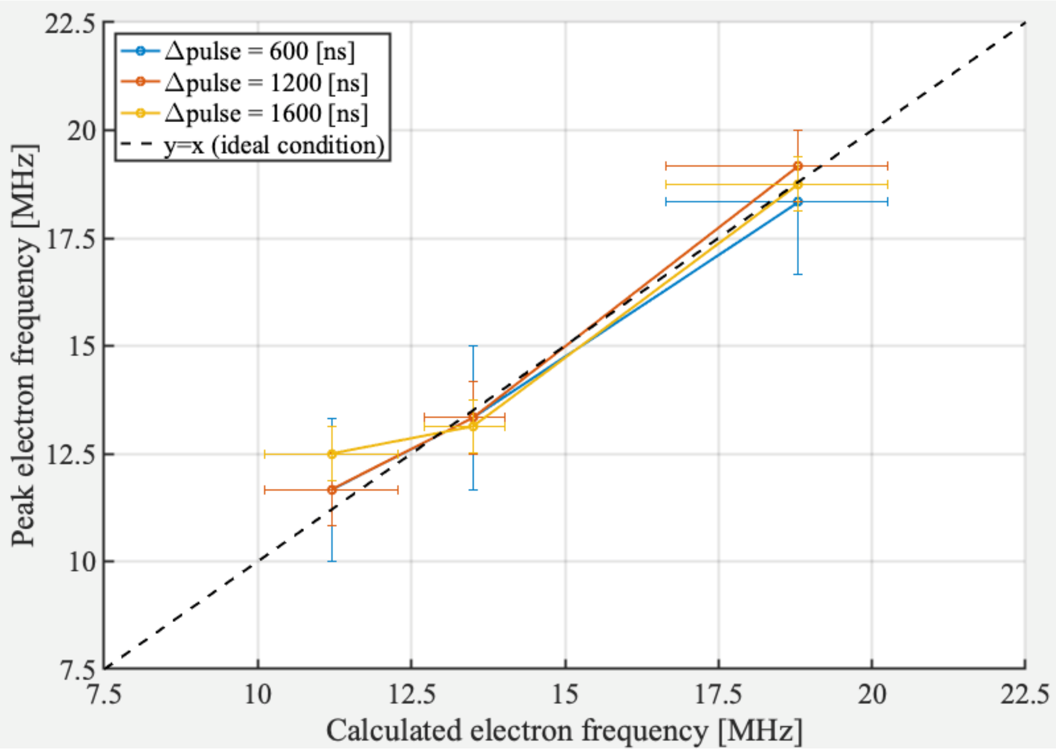

Figure 3: Comparison of the electron frequency for three different pulse duration. x-axis: from probe diagnostic, y-axis: from pulse experiment

Figure 4 shows the amplitude of the peak frequency in the FFT-applied data vs the pulse duration for three different pressures. The amplitude of the 1st peak (i.e., Langmuir wave) is inversely proportional to the pulse duration. In other words, the amplitude of the Langmuir wave is proportional to the slope of the pulse. When the pulse duration is short and the slope is steep, the electrons in the vicinity of the pulser electrode "see" a higher potential change in the same time interval (i.e., the electron timescale). The electron timescale, which is inverse of the electron frequency, are about 50-100 ns for this experiment and it supports the idea that the initial slope of the pulse shape is an important factor to determine the Langmuir wave characteristics.

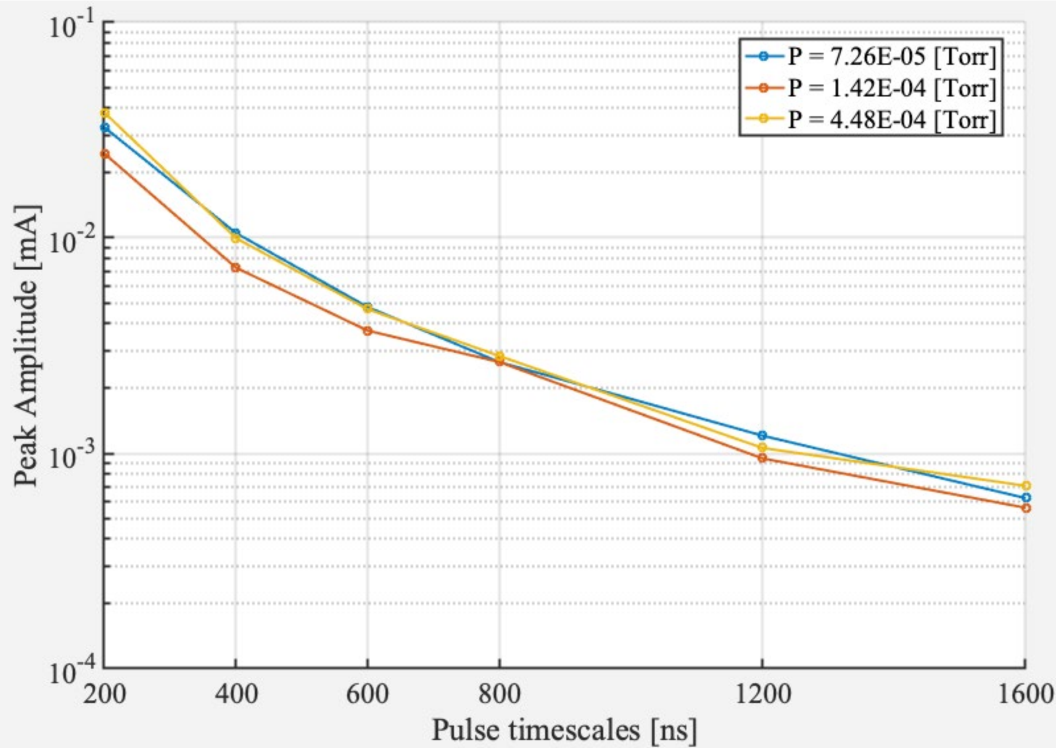

Figure 4: The peak amplitude vs pulse duration

These are several highlights from the experimental activities:

1. The experimental setup (i.e., MPC) to test a low-density plasma was built and several low-denstiy plasma experiments were carried out.

2. The I-V curve interpolation method for the low-density plasma with a planar Langmuir probe was established and steady-state plasma properties were determined.

3. The capability of capturing the Langmuir wave was demonstrated and the excitation of the Langmuir wave as well as its properties as function of the pulse shape were confirmed.

D. Objecitve 4: testing the ability of simulations to accurately resolve electron velocity distribution functions (EVDF) in steady state and time varying plasmas – predicting single-species Langmuir waves

To model the pulsed-plasma in the plasma chamber, the numerical domain is filled with a plasma of density $n_e = n_i = 1 \times 10^{13}$ m^{-3} and charged particles can leave the domain from the conducting plates at z = 0 and 100 mm, and domain boundaries in the y direction. Since in our experiments, the source of the plasma lies outside the numerical domain, we replenish the charged particles initializing new particles in 5 mm thick regions near y = 0 mm and y = 100 mm boundaries shown by dashed lines in Figure 5. The charged particles are specularly reflected from non-conductive regions of z = 0 and 100 mm boundaries to represent the symmetry of the plasma on either sides of z direction domain edges. These boundary conditions were found to correctly result in a Maxwellian particle z-velocity distribution at steady state.

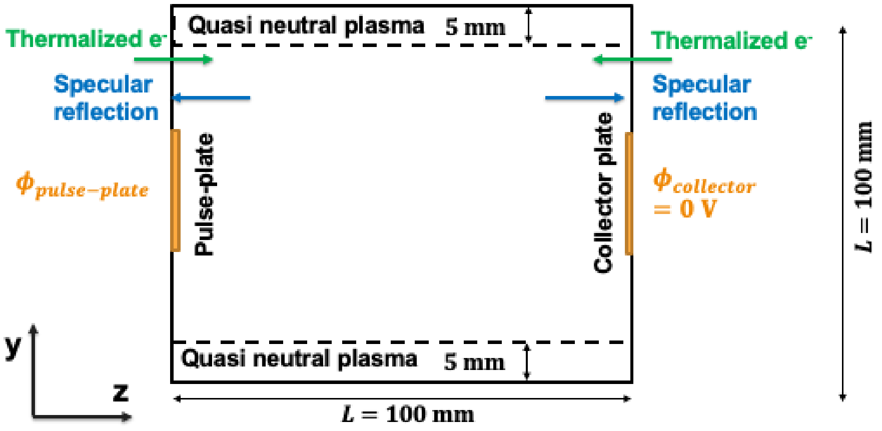

Figure 5: Set up of CHAOS PIC simulations of pusled plasma measurements.

The simulation results in Figure 6 suggest the presence of Langmuir waves. Based on the steady state calculations, the sheath edge for a -100 V biased pulser plate lies near z = 20 mm along the center-line of the domain at y = 50 mm. As the pulse eolves in time, the electric potential at (y,z) = (50,20) mm drops and oscillates with a timescale $\tau = 0.035$ µs, as shown in Figure 6 LHS. The electric potential at the other probe locations also oscillates but for probes at z > 20 mm, as shown in Figure 6 (a), it does not trend towards a more negative value. The oscillatory behavior of electrons is also seen in the collected current at the collector as shown in Figure 6 (b). Based on the time-scale of these oscillations, $\omega/\omega_{pe} = 0.93$, the oscillations are caused by the Langmuir (LM) waves traveling through the plasma.

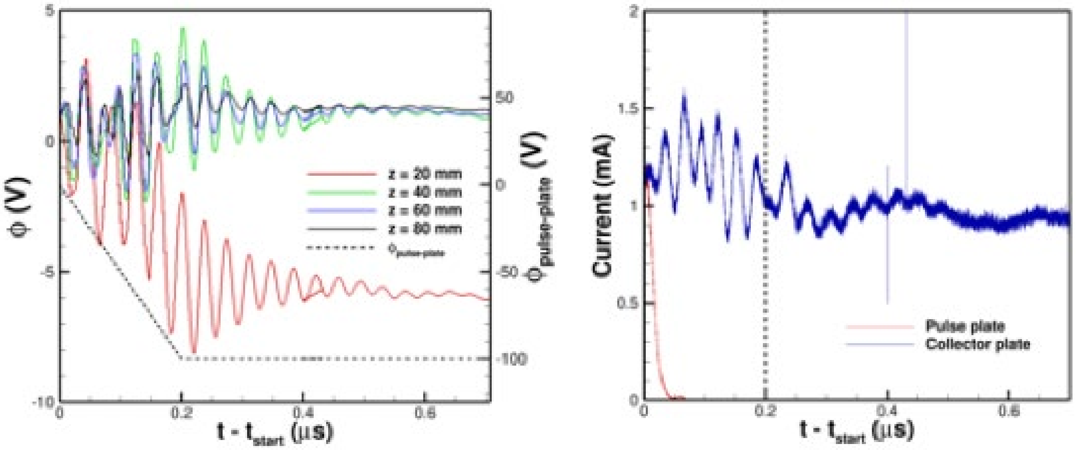

Figure 6: Simulated temporal variation of plasma potential for a pulse of 0.2 µs. LHS shows electric potential with time at different probe locations along the centerline of the domain (y=50mm, of fig. 1)- (b) RHS shows predicted electron current at the pulser and collector plates. The vertical dashed line indicates the end of the linear pulse.

Figure 7 shows the sensitivity of the plasma potential to distance from the pulse plate as well as to pulse width. The absence of plasma oscillations in the Laplace solution (Figure 7 LHS) confirms that they are due to space charge effects induced by the applied pulse. Additional examination of oscillations in the local electron velocity distribution functions (EVDF) along the z-direction closest to the pulser plate showed that they are of a time scale ~0.05-0.1 μs. This confirms that the electron response is consistent with the predicted electric potential. Such comparisons are only possible because CHAOS fully models electron kinetic dynamics. In Figure 7 RHS we can see a comparison in the change of the plasma dynamics when we change the pulse width from 0.2 to 1μs. The average trend in the potential is similar for both pulse lengths, however, the lack of oscillations in the 1 μs pulse case is because electrons do not have enough time to reach their equilibrium position and hence do not oscillate with the changing pulse plate voltage. Also, after $t/t_{\text{pulse}} > 1$, the probe potential for the 1 μs pulse decreases because the ions close to the pulse plate start leaving the domain. In the 0.2 μs pulse case, the potential asymptotes, although still oscillating, because $t{\sim}t_{\text{pulse}} = 1$ is too early for ions to respond to the electric field .

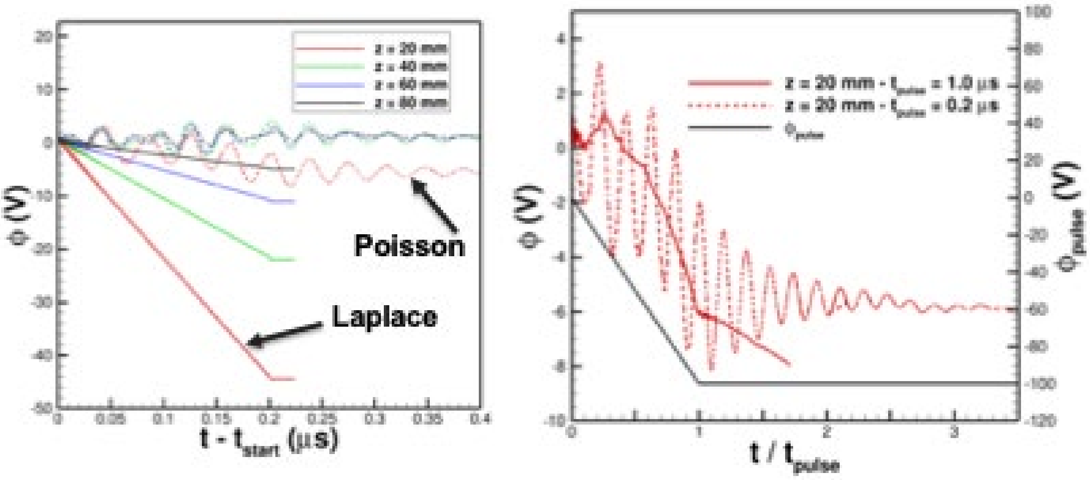

Figure 7: Comparison of simulated plasma dynamics for different locations and pulse widths in the monopole device. LHS shows a comparison of Poisson vs. Laplace solutions and RHS shows the dependence of dynamics on pulse width. For the LHS figure note that the abscissa is normalized by the two pulse time values.

We have begun to explore analyzing the CHAOS code time-accurate plasma modeling through the use of predictive techniques such as Time-Lag Phase Portrait (TLPP). Figure 8 shows our very first attempts to do this where we have taken the spatially varying 0.2μs data at (y,z) = (50,20) mm. The spirling behavior observed indicates the presence of Landau damping with the damping radius becoming smaller as the plasma decays. This prediction is for a electron/Xe$^+$ species.

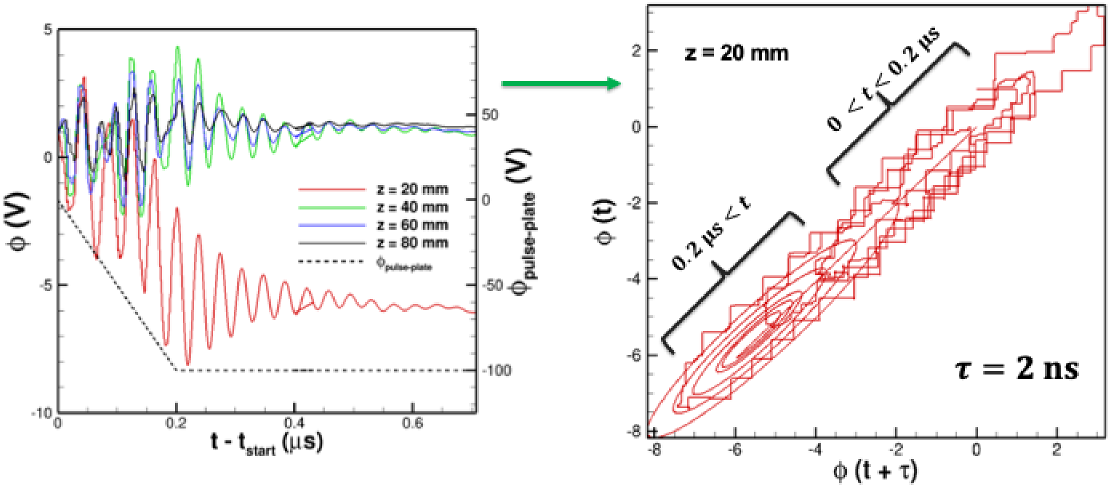

Figure 8: Time-Lagged Phase Portrait (TLPP) shown on the RHS applied to pulsed plasma PIC simulation of time varying potential (LHS).

E. Objective 5: comparing existing probe theory predictions with numerical simulations, and where necessary exploring modified theory that may better capture system dynamics.

Figure 9 shows a comparison of PIC results with theory and experiments. The FFT analysis of the collector current data from experiments showed that the measured frequency if the current oscillations is nearly equal to the electron plasma frequency calculated from the measured plasma density, shown by the close proximity of data points to the dashed $\omega_{\text{LM}} = \omega_{pe}$ line in Figure 9 (LHS). Similarly, the sheath edge oscillations for $t_{\text{pulse}} = 0.2, 0.4, 0.7, \text{and} 1.0\ \mu s$ cases in PIC are shown to be close to the $\omega_{\text{LM}} = \omega_{pe}$ line in Figure 9 (LHS). From this, we can conclude that the waves observed in both the experiments and the PIC simulations are Langmuir oscillations (LM waves). The amplitude of LM waves in Figure 9 (RHS) is taken from the probe data shown in Fig. 9 (LHS) for PIC simulations and it is normalized such that the peak amplitude for the LM wave found in $t_{\text{pulse}} = 0.2\ \mu s$ case, i.e. $\omega_{pe} t_{\text{pulse}}$= 35.6, matches the normalized value of 0.44 found in experiments. For the experiments, the peak amplitude of LM wave is obtained from the total current results at the collector plate and is then normalized by the amplitude value for $t_{\text{pulse}} = 0.4\ \mu s$ case, i.e. $\omega_{pe} t_{\text{pulse}}$= 35.6.

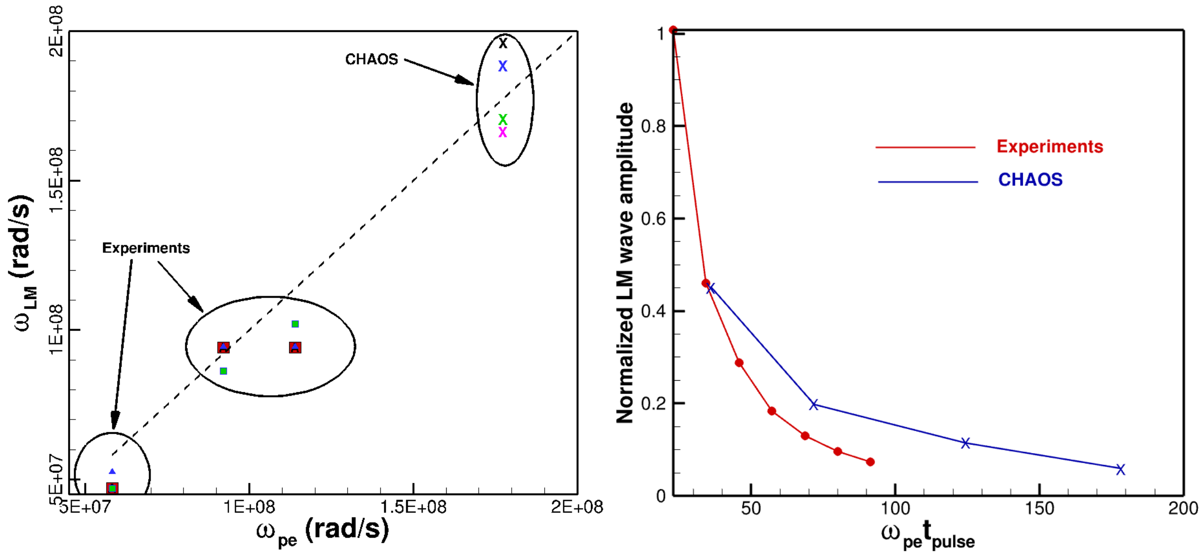

Figure 9: Comparison of Langmuir (LM) wave frequency with the plasma frequency from experiments and PIC simulations (LHS). Also, in RHS, a comparison of LM wave amplitude with the pulse width is shown.

IV. Future Work

Experiments should be used to continue to use the multipole plasma cell to create low-density plasmas with large Debye length and relatively slow plasma frequency. Pulse transient sheath dynamics should next be investigated for gas mixtures containing disparate mass species, such as Helium and Xenon. Plans should include measuring the resulting sheath oscillations, specificallyLangmuir waves, and then also investigate timescale intermediate to the heavy and light plasma species. Experiments could then transition to reactive gases such as nitrogen-oxygen air plasma.

Modeling should focus on combinations of ions such as including both heavy and light species which we suspect will produce different plasma dynamics from those of a single ion species based on the different sheath behaviors that we mentioned above. As different concentrations of charged species are studied, the sheath type should be characterized (e.g. ion, inverse, SLC etc). Eventually, experiments and PIC simulations should transition to low-orbit-altitude airbreathing or ambient atmosphere propulsion. This will require modeling new ionic species such as N2+, N+, O+, O2+ in the PIC module of CHAOS as well as their collisions with neutrals (in the DSMC portion). Adding the appropriate CEX reactions too will be required, but, this cannot be completed in a one year but can serve as the basis for future modeling.

V. Publications and AFRL Engagement

Yamauchi, T., Nuwal, N., Sharma, A., Levin, D.A., Rovey, J.L., “High Resolution Modeling and Experiments for Deeper Understanding of Plasma Dynamics,” AIAA-2021-0522, *AIAA SciTech Forum and Exposition*, virtual event, Jan. 11-15, 2021.

Nuwal, N., Yamauchi, T., Sharma, A., Levin, D.A., Rovey, J. L., "Kinetic modeling and experiments of pulsed plasma in a multipole plasma cell", in preparation.

We have recently (April 12, 2021) had conversations with AFRL researchers (Drs. Koo, Martin, Eckhart, and Bilyeu) to make sure we are not duplicating work. In general there was much interest in using the canonical plasma system we have developed (multipole plasma cell) to explore fundamental multi-species plasma physics (sheath physics) in a joint experiment-modeling project wherein experimental measurements of temporal sheath dynamics are predicted and compared with high-fidelity fully-kinetic CHAOS code results. Our initial progress along this path is described in this report. Additionally, in conversations with AFRL we discussed our common interests in providing fundamental validation simulations using the CHAOS code with multi-species plasmas. We explored the possible use beyond the third year of using CHAOS to generate reduced order models for use in AFRL plume codes that model internal Hall thruster instabilities, 2-channel flows, and SEE for external plume - spacecraft materials interactions.

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