Energy Conversion and Loss Processes in Heavy-Gas Field Reversed Configuration Electric Thruster Plasma

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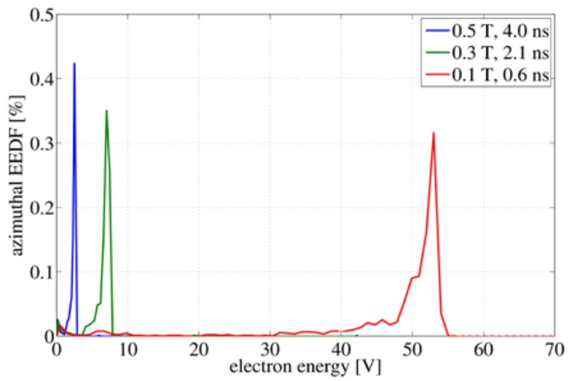
The United States Air Force requires a new type of high-power AND higher specific power (kW/kg) electric propulsion system. Pulsed inductive accelerators have the potential to meet this need and AFRL has an active research program in this area. These devices create plasma (plasmoids, compact toroids, field reversed configurations) through magnetic induction and accelerate the plasmoid electromagnetically via the Lorentz force. Realization of high-thrust, high-specific impulse electric propulsion requires heavy gas propellant (e.g., xenon). However, most previous plasmoid investigations have focused on hydrogen plasma. Results with heavy gases have only recently been pursued and have focused mainly on specific plasmoid attributes, such as plasma properties and plasma exhaust speed. The project is designed to develop a complete picture of the energy processes that comprise plasmoid formation, determine the efficiency of the formation process, and elucidate the main loss mechanisms.

Recent efforts have used numerical modeling to explain long-standing anomalous pre-ionized plasma formation in plasmoid devices, while also developing an experimental plasmoid test article and associated diagnostics for characterizing electric, magnetic, and internal plasma properties. A description of recent results, current efforts, and upcoming activities follows.

Recent Results:

Recent results have used plasma modeling to explain the delayed gas breakdown in pulsed inductive devices. This phenomenon, referred to as “zero-crossing”, has been observed in many previous pulsed inductive plasma research efforts, most notably the FRX series and more recently FRCHX at Kirtland AFB, and has been deemed partially responsible for reducing trapped bias flux in FRCs and subsequently reducing FRC lifetime and device efficiency. These previous research efforts show that gas breakdown (plasma formation) in a biased theta-pinch device is delayed until just after the net magnetic field passes through zero. Our modeling work has recently shown that electrons are unable to gain sufficient energy to ionize the gas because of their inherent gyro-motion. This is despite the presence of large (typically peak) electric fields. Figure 1a illustrates this with a simple constant field test-case that was performed using a PIC solver (OOPIC). Three magnetic field magnitudes are individually applied to a common electric field magnitude and the EEDF is tracked. The super-thermal peak in each case swings to a maximum (at times shown) and is plotted demonstrating that magnetic field has to be reduced significantly before ionization level energies are observed.

When the estimated field profiles from FRCHX were input into both a single electron and PIC solver the electron energy does not surpass ionization levels until just after the zero-crossing. Results of this study are shown in Figure 1b and correlate well with reported findings in the FRCHX device. Furthermore, using this model data we show a novel parametric study approach which provides selection criteria for bias and primary discharge magnetic field magnitudes. In this approach we find that: 1) having approximately the same magnitude of bias and primary fields will most likely yield erratic (i.e., unreliable) ionization levels, and 2) that having a primary field magnitude of at least double that of the bias offset maintains an electric field above nearly 90% of peak at the time of zero-crossing. Thus maximizing the amount of energy gained during this critical time. References regarding this work can be found in Ref. 1-3.

a) 

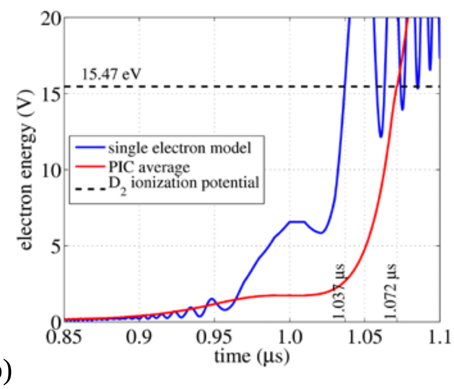
b) 

Figure 1: a) Electron energy distribution results from PIC simulations for a fixed electric field (500 kV/m) and varied magnetic field magnitudes and b) Two model approach each showing the delay in ionization-level electron energy for field conditions reproduced from FRCHX.

Recent results have also been obtained experimentally on a plasmoid test article called the Missouri Plasmoid Experiment (MPX). This device is a cylindrical theta-pinch that uses a 0.7 μF capacitor charged to 15-25 kV and connected to a cylindrical copper coil through a spark-gap switch. A photograph is shown in Figure 2. Closing the switch results in a 500 kHz, 30-50 kA peak current waveform that auto-ionizes the low pressure gas contained within the coil. This device has been operated with background pressure between 1-100 mTorr on argon and air. Details on this device and results can be found in Refs. 4-5. Most recently, experimental measurements of magnetic field and flux both spatially and temporally have led to estimations of plasma energy deposition versus time and background pressure. These results are presented in Figure 3 and show the magnetic energy difference between results with and without plasma, i.e., zero pressure discharge (no plasma) versus pressure case (with plasma). Results indicate that there is an optimum pressure for each gas species at which there is the greatest change in magnetic energy. Additionally, results indicate that there is an optimum pressure for each gas species at which the difference in magnetic energy is altered at earlier times. The difference in magnetic energy (shown in Figure 3) is related to the energy deposited into the plasma, in which case only ~20-25% of the energy initially stored in the capacitor is being deposited to the plasma.

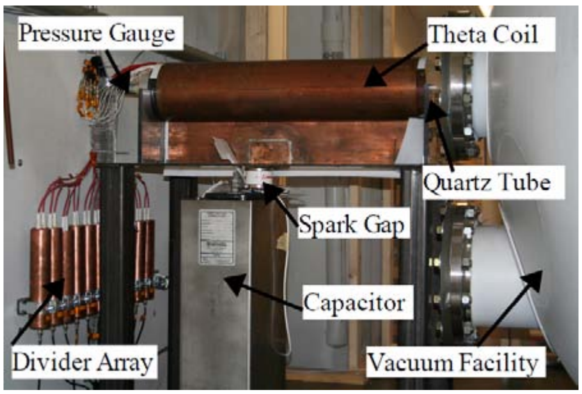


Figure 2: Photograph of Missouri Plasmoid Experiment, a test article for fundamental study of pulsed inductive plasma.

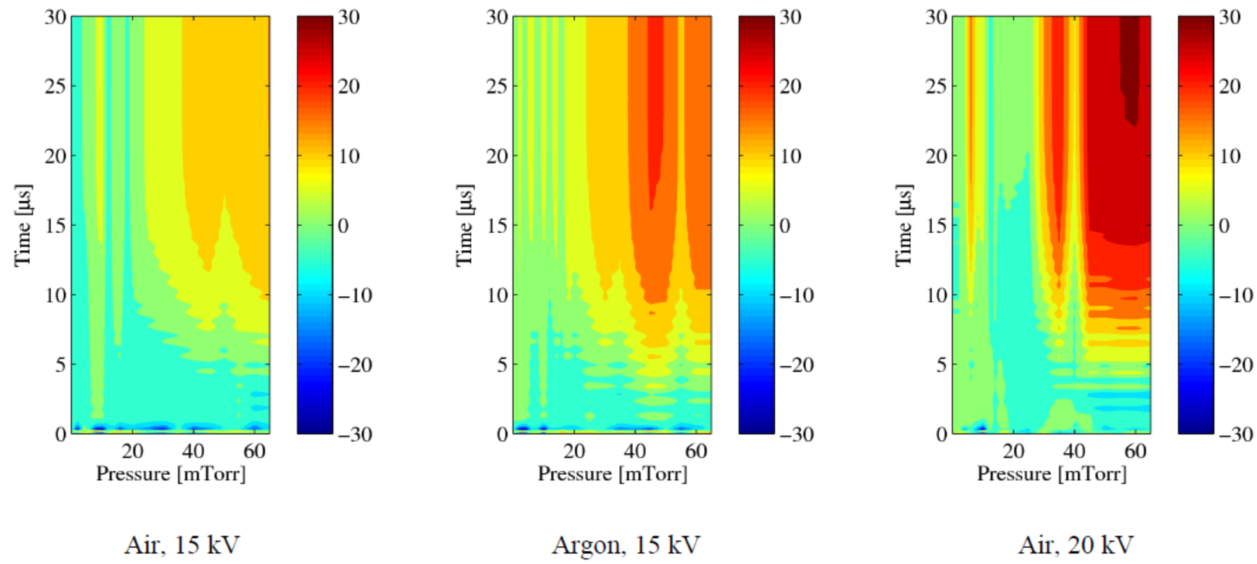


Figure 3: Results showing the difference in magnetic energy versus pressure and time between the no plasma and plasma cases. No plasma results are obtained with ~zero background pressure, while plasma results are obtained with the pressure indicated. Units are in Joules.

Current Efforts:

Current efforts are focused on studying the electric, magnetic, and internal plasma properties of the plasmoid test article. New magnetic probes with capacitive pick-up rejection have been designed and tested on the FRCHX device at Kirtland AFB and are being implemented on the MPX machine. Additionally, a shunted electrostatic probe has been developed and used to characterize the internal plasma of the MPX discharge.

We have recently developed a new magnetic (B-dot) probe designed to mitigate capacitive coupling to plasma and electrostatic pickup during testing. The probe has a differential design by using two identical loops constructed on a printed circuit board (PCB) in series. The advantage to using a PCB layout is that it minimizes probe-to-probe variations and simplifies construction. This layout produces two identically sized loops with the same turn-area and thus identical calibration factors. The key advantage to this design is that both loops generate the same magnitude signal for a given time-varying magnetic field, but with opposite polarity. This is referred to as the differential mode signal which results in the differential mode signals (magnetic field) becoming additive while the common mode signals (capacitive and electrostatic pickup) are canceled out. This ensures that the signal being measured by the probe is exclusively the magnetic field generated by the experiment.

The first iteration of magnetic field probes have been designed and fielded. Preliminary work was done using facilities at AFRL Kirtland on FRCHX. Calibration of the probes was accomplished with a pulsed-power Helmholtz coil test stand operated at 2 and 3 kV. Results from 2 kV testing are shown in Figure 4 for the new MPX probe and the Prodyn design B-dot probes used by AFRL Kirtland on FRCHX. The measured calibration values based on testing in the Helmholtz coil yielded a calibration value for the MPX probe of 1.60×10^5 T/V-s and 1.53×10^5 T/V-s at two and three kilovolts, respectfully. The calibration factors for the Prodyn probe are 3.14×10^4 T/V-s and 2.98×10^4 T/V-s at two and three kilovolts, respectfully. The variation in linearity of the MPX probe pair is 4.5% compared to 5.2% for the Prodyn probe. This indicates that the MPX probe is less sensitive to errors in signal pickup due to non-linear effects. Additionally, the manufacturer specified calibration value for the Prodyn probe is 2.44×10^4 T/V-s. This corresponds to a variation of 28.6% and 21.9% from the measured calibration factor for this probe at 2 and 3 kV, respectively. This error results from the non-linear calibration value as a function of discharge frequency and highlights the importance of calibrating these types of probes using waveforms with magnitude and frequency representative of the devices they will be used on.

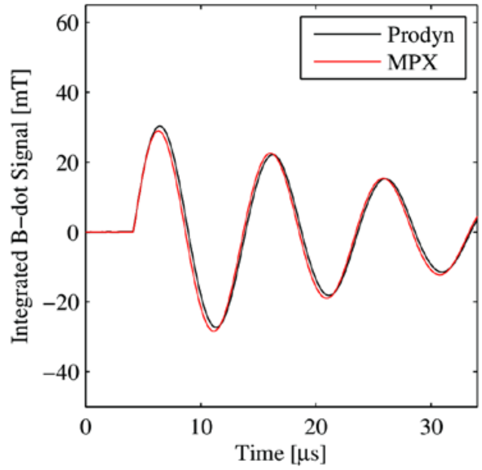


Figure 4: Magnetic field measured for a two kV discharge in the Helmholtz coil platform.

One important capability with magnetic field probes is to determine the size and position of the resulting plasmoid. This is done by incorporating flux data from additional flux loop probes. Together, these probes provide information that can be used to calculate the excluded flux of the plasmoid corresponding to the separatrix radius. The MPX magnetic probes were demonstrated on the FRCHX machine at Kirtland with results shown in Figure 5. The bias, PI, and main bank discharges are all clearly discerned by the MPX probe. However, the vertical resolution on the digitizer is insufficient to capture the entire waveform. This causes the peak integrated signal to occur at a different time than the raw signal. The clipping due to the main bank discharge causes the time between the peaks of the two signals to vary by approximately ten μs.

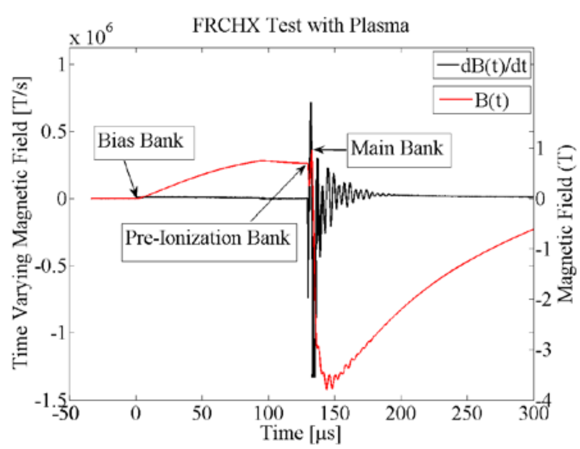


Figure 5: FRCHX discharge measured by MPX probe. All three primary banks are visible and indicated on the figure.

A shunted electrostatic probe has been used to interrogate internal plasma of the MPX device, shown in Figure 6. Currently this consists of a 50 Ω dual shunted probe configuration on a 2-D translation table. The dual probe concept allows the user to isolate RF and other non-plasma noise effects from measured signals. This is done through the use of two electrically identical probes (to ensure a common frequency response both between the probes and with their environment) placed at very close proximity to one another to provide nearly identical noise pick-up. The key to this approach is that one of the probes is shielded via a dielectric barrier while the other is left to plasma exposure. Once both data sets are obtained, subtraction of one from the other ideally removes all non-plasma effects. The difficulty inherent in this concept is in creating two electrically identical probes, which includes all transmission lines, connections, biasing circuitry, etc.

Figure 6: Photograph of dual probes, one probe is shielded from plasma to isolate non-plasma effects.

The dual shunted probes are spatially translated along a radial half chord (at the desired number of radial steps) and probe voltage as a function of discharge time is recorded using a Tektronix 8-bit 1GS/s oscilloscope. An example data waveform is shown in Figure 7. Both the shielded and exposed probes initially record the noise of the spark-gap switch, however, then the two signals drastically diverge. The exposed probe signal oscillates at the frequency of the coil with a net positive voltage offset. Figure 8 shows a comparison between a previously taken time-lapsed photo of MPX during discharge and probe voltages recorded during a peak time in activity at 34 radial locations. This shows a spatial correlation between large levels of light emission in the plasma and the typical regions of large voltage levels on the probe. The voltage is measured across a 50 Ω resistance so a time-resolved probe current can be directly obtained. Further study and testing are required to better elucidate the implications of these results.

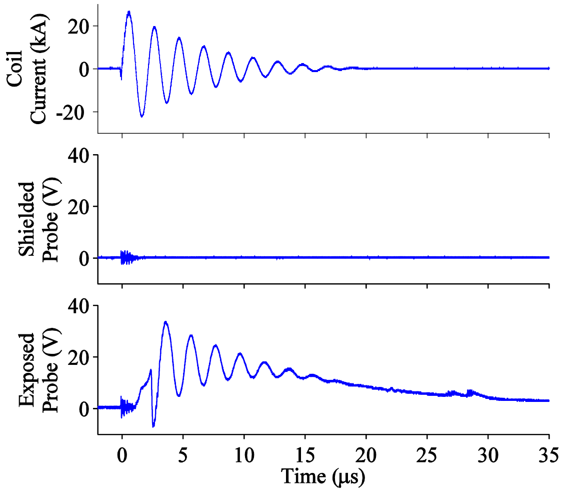


Figure 7: Data from dual internal probes showing the shielded probe and exposed probe signals in relation to the discharge coil current. Data for 14 mTorr Argon.

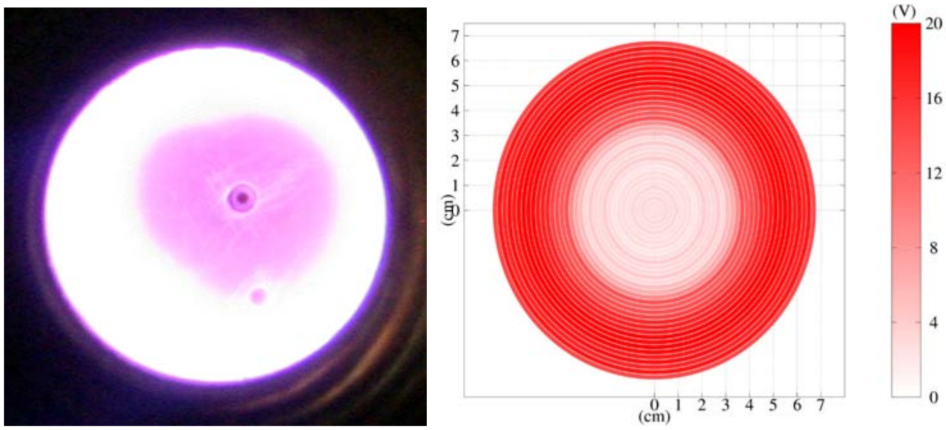


Figure 8: Time-lapsed exposure of MPX operation at 30 mTorr along side shunted probe voltage data taken at 14 mTorr.

Upcoming Activities:

All upcoming activities focus on better characterizing the temporal and spatial plasma within the MPX test article at different discharge energy, gas species, and pressure levels. Specifically, studies focused on obtaining information relating to ion density, electron temperature, and instabilities are planned. We plan to implement ion saturation biased electrostatic probe, fast spectroscopy, and a fast framing camera for these studies. Building off the shunted probe previously described, we plan to use the dual-probe technique with a biased electrode. The exposed electrode will be constantly biased negative with respect to plasma to constantly operate in ion saturation regime. Measurements from this diagnostic will provide probe current as a function of spatial position and time, and be related to plasma density. We also plan to implement fast spectroscopy setup to do emission spectroscopy of MPX plasma. A Princeton Instruments PI-MAX ICCD camera with UV intensifier will be used with an Acton spectrometer to quickly capture line emissions from the plasma. Specifically, gating speeds as fast as 2 ns are possible and we anticipate capturing wavelengths relevant for comparison with collisional radiative models for argon, xenon, and air. Finally, a fast framing camera with frame speeds of 100 MHz will be used to capture the spatial and temporal evolution of light emission from the plasma to visualize instabilities and asymmetries within the plasma structure.

References:

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[2]Meeks, W. C., Rovey, J. L., "On the delayed gas breakdown in a ringing theta-pinch with bias magnetic field," *Physics of Plasmas*, Vol. 19, pp. 052505, May 2012.

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