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**MAGNETIZED TARGET FUSION PROPULSION: PLASMA INJECTORS FOR MTF  
GUNS**

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## **Introduction - MTF: Plasma Injector**

To achieve increased payload size and decreased trip time for interplanetary travel, a low mass, high specific impulse, high thrust propulsion system is required. This suggests the need for research into fusion as a source of power and high temperature plasma. The plasma would be deflected by magnetic fields to provide thrust. Magnetized Target Fusion (MTF) research consists of several related investigations into these topics. These include the orientation and timing of the plasma guns and the convergence and interface development of the "pusher" plasma. Computer simulations of the gun as it relates to plasma initiation and repeatability are under investigation. One of the items under development is the plasma injector. This is a surface breakdown driven plasma generator designed to function at very low pressures. The performance, operating conditions and limitations of these injectors need to be determined.

## **Plasma Injector and Plasma Gun Initiation**

The basic plasma gun is a cylindrically symmetric coaxial line. An inner conductor is charged positive by several kilovolts with respect to the outer conductor. The injection of plasma initiates a vacuum arc breakdown between the anode and cathode. The resulting high current flow through a low inductance circuit produces a strong magnetic field circulating around the central anode. The Lorentz Force on the arc produces acceleration down the tube towards the gun muzzle. Rapid heating of the ion and neutral population ahead of the plasma produces a hypersonic shock wave out the gun. This wave collects and pushes the background gas out the muzzle. The basic gun configuration has been tested and verified.

A significant factor in the performance of the proposed multi-gun configuration is the consistency and reliability of the arc initiation in the breech of the plasma gun. Variable delays in plasma formation in the gun breech could result in timing problems in the multi-gun configurations. In particular the firing jitter of a plasma gun needs, at a minimum, to be known and repeatable. In turn, the plasma formation time in the gun breech needs to be controlled and is heavily dependent on the behavior of the plasma injection system during the surface breakdown.

In a normal field initiated surface breakdown, the process is started by field electron emission at the triple point between dielectric, cathode metal and vacuum. The electrons are accelerated by the anode-to-cathode applied field and attracted back to the surface by imbedded charge. Secondary electron emission produces additional electrons and embedded positive charges causing an avalanche to the anode. Devolved or decomposition gas from the surface is impacted producing mobile ions that migrate towards the cathode. The redistribution of space charge reinforces the triple point electron emission [3]. In low impedance systems, large currents may flow. This constricts the conduction path in the gas and along the dielectric. The result is "tracking" - the creation of a depressed trace where dielectric material has been preferentially removed to provide gas for the constricted discharge / arc. Frequently these tracks exhibit deposits of the non-volatile components of the dielectric after the surface breakdown has been externally interrupted.

In this system Vacuum UltraViolet (VUV) and charge generated in and near the surface of the dielectric initiates the process. This process is not as well characterized, developed or documented [4]. As a result research is required for the MTF guns.

To further the gun development, an experiment was planned to characterize the behavior of the plasma injectors. Of particular interest was the plasma temperature and density as a function of plasma injector parameters. Consistent performance of the plasma guns depends in part on the characteristics of the plasma injected into the breach from the plasma injectors. It also depends on the time delay and stability of the plasma injectors. Though a total investigation of this is beyond the scope of a ten-week program, instrument design and construction was completed and preliminary data was obtained. A description of the apparatus, a sample of the results and implications are detailed below. Further detail will be published under separate cover.

### **Experimental Apparatus**

The experimental apparatus is shown in figure one. An existing vacuum system based on a turbomolecular pump was tested and demonstrated a base pressure of  $0.7 \times 10^{-6}$  Torr. A platform was introduced to the system. The initial version of the plasma injector was mounted to the platform. The injector contains a 50 nF capacitor in a coaxial configuration. One terminal of the capacitor is connected to the inner pin of the plasma injector. The other end of the capacitor is connected to a coaxial outer sheath. This sheath encloses the capacitor providing the return current path. The plasma-generating portion of the injector consists of a brass inner pin and outer shield held in a coaxial configuration by an insulator. The injector resembles a cut coaxial cable except the inner pin stops short of the outer jacket by about 0.25 inches. The insulator is cut in a conical shape - gradually slopping from the inner pin to outer sheath. The resulting structure is a negatively sloped cone whose surface breakdown characteristics have been described previously [4]. The unique aspect of this implementation is that the cone has been reversed so that the vacuum is inside rather than outside as shown in Latham [4]. This was an expediency of design and should not significantly impact its surface breakdown behavior under vacuum. [5,6] Teflon and polyethylene were the dielectric materials chosen to insulate the injectors and two injectors were built.

A RF shielded charge-dump system was built. This allowed the charging of the 50 nF capacitor through an electrically insulated wire. The charge-dump system used four HV relays, a 40kV Bertan High Voltage (HV) supply, assorted control relays and fiber optics communication components. In addition a test system was constructed from a HV choke and power supply. The temporary test system was used to prove the basic plasma injector design. A fiber optics based control system was developed for use in a pre-existing RF shielded control room.

Under normal operation the plasma injector capacitor is charged to 5-8 kV and the charging supply disconnected HV relays. In the temporary design test configuration a 660 nH high voltage inductor is used to isolate the HV supply during discharge. Either way, the capacitor is charged to its operating voltage and a surface break down initiated by a HV spark. The carbon spark is generated from two closely spaced wires impregnated with graphite. This assembly is positioned even with the top of the outer brass shell and approximately  $\frac{3}{4}$  of a cm. from the end

of the injector. An inductively generated HV pulse produces a spark. This initiates a surface breakdown along the dielectric.

As shown in figure one an experimental apparatus was built around this core device. A 0.75 meter spectrograph with three gratings ( 600, 1200, 2400 l/mm) on a rotating turret was joined to a 512 x 512 Charge Coupled Device (CCD) array. The CCD array and spectrograph are both computer controlled. The CCD array can be gated or operated as a fixed array. The light collection optics for the spectrograph is mounted on a Newport Research Corporation (NRC) rail. A pair of mirrors was mounted with four degrees of freedom. This allows the spectrograph field-of-view to be directed to any location with respect to the plasma injector nozzle. A f<sup>#</sup> 9.7 condensing lens focuses the light from a collimated field-of-view onto the slits of the f<sup>#</sup> 9.7 spectrograph. A 10x beam expander reduces the diameter of the spectrograph field-of-view to 1/10 of the setting of an aperture stop iris. Thus the location, orientation and diameter of the field-of-view of the spectrograph can be controlled. Location can be varied over the entire observation window and is repeatable to  $\pm 0.1$  mm. Orientation is repeatable to  $\pm 100$  micro-radians. Diameter is variable from 2.54 mm to 100 microns. Removal of a couple of optical posts converts the optics to an imaging type collection system.

In addition an optical fiber with a numerical aperture of 0.5 was used to collect spatially and temporally integrated spectra over the visible band. The fiber is routed to the Radio Frequency (RF) shielded control room into a separate spectrograph with CCD array. This second system is also under computer control and is used for wavelength survey and species identification. It was extensively calibrated and verified last year. Though it has a specified  $3 \Delta$  resolution, sub-pixel resolution has been previously demonstrated. Wavelength accuracy was previously demonstrated to be less than  $1 \Delta$ .

All instrumentation and vacuum system components are isolated from building power by battery powered Un-interruptible Power Supply (UPS). RF and HV protection was provided to all instruments via mylar sheets and Kapton tape insulation, grounded metal RF shields and air gaps. Insulation tests were conducted in the vacuum chamber to verify HV integrity. Optical alignments were verified and triggering and control circuits tested. Wavelength calibration of the 0.75 meter spectrograph was accomplished using a set of hollow cathode spectroscopic standards.

### **Results, Post Processing and Discussion**

Data sets were taken with the apparatus. These results will be reported under other cover. As an example of a raw data set, consider figure two below. It originated from a calibration run. The curve in figure two was signal processed and converted through MathCAD and Roper Scientific software but has not been digital signal processed to extract the desired parameters. In this figure there are ten discernable spectral lines attributable to neon. Several exhibit asymmetrical inhomogeneous broadening, possibly due to the relatively high percentage of isotopic contamination in natural neon. The large line at the right appears to be associated with neon at 3520.47 Å. To obtain the desired plasma information a set of eight MathCAD programs were written to redistribute any error in the ten identified lines, compensate for baseline, extract this line [3520] from the spectra, convert from wavelength to frequency, remove system resolution

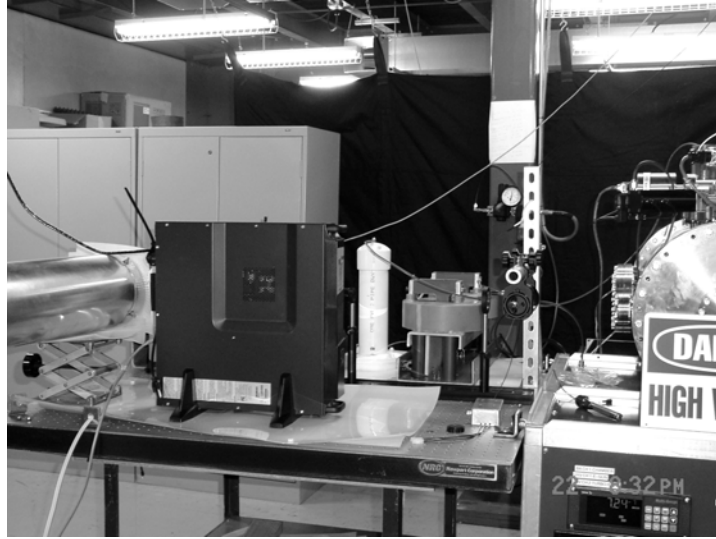


Fig. 1: Experimental apparatus

(partially), identify and de-convolve the Voigt profile into the Lorentzian and Gaussian forms, and identify the widths associated with these. Most programs were fairly straightforward. The system resolution removal used standard techniques, based on a detailed optical analysis of the system, to generate a theoretical description of the optical transfer function (OTF) [1]. It was then removed from the data. The last two programs used an algorithm based on the transform of the magnitude of the spectral line. It was shown by closed form analytical development that the Lorentzian and Gaussian forms were separably related to the slope and curvature of the result. Actual implementation developed some problems caused by the limited sampling capability of the CCD array available in conjunction with the dispersion capabilities of the spectrograph. These were overcome by a DSP scheme though they could also be addressed by the use of 2k, 4k or larger linear CCD arrays. The resulting software was verified by processing the output below which originated from a previously characterized and documented lamp and by multiple test runs on software generated lines.

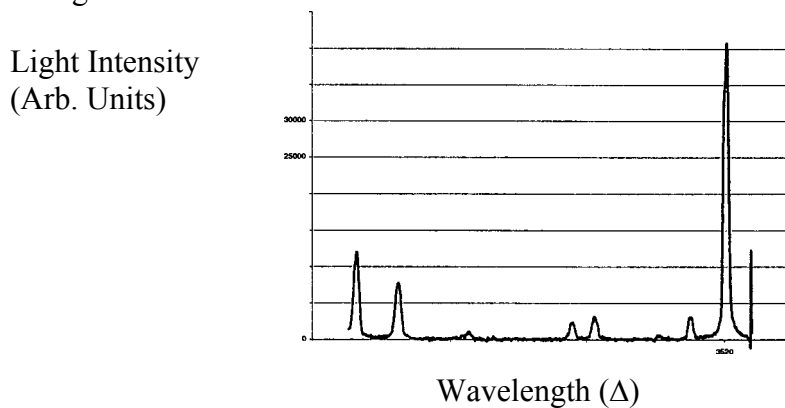


Fig. 2: Intensity versus Wavelength

In addition, initial firings of the Teflon plasma injector provided several important results. Several different states were observed for the injectors. These included a glow discharge like diffuse emission, an intermediate constricted, but still diffuse emission and a highly intense, low volumetric, arc like emission. Which occurred depended on charging voltage, background pressure, igniter placement, etc. With each optical emission, chamber ion gauge pressure was observed to jump from half of an order of magnitude to significantly more than an order of magnitude. Pressure jumps to a little below  $10^{-5}$  Torr were observed in some cases. The time constant associated with its subsequent decay was consistent with gas evolution rather than electrical phenomena. Given a background pressure in the low to medium  $10^{-7}$  Torr, it seems likely that the dielectric decomposition products dominate the plasma during the injection. The injector is currently producing an intense and pronounced optical plume. The initial test is considered a success and no further igniter modifications will be implemented at this time.

Some limitations were noted in the charging voltage. An initial charge voltage ceiling around 7500 volts was observed due to field initiated surface breakdown. After several shots, this voltage ceiling gradually lowered and filaments were observed in the dielectric. Some observers indicated the presence of carbon on the traces. After a few conditioning shots the ceiling was restored. The formation of the traces and/or carbon appears related to the type and intensity of the breakdown. These in turn appear related to the breakdown conditions.

### **Conclusions and Subsequent Work**

Several conclusions can be drawn from the results to date.

- (1) The injector demonstrates glow, abnormal glow and arc like behavior depending on a number of parameters.
- (2) There is a maximum voltage to which the injector can be charged before field initiated self breakdown occurs. This breakdown depends on injector history.
- (3) The current igniter placement appears a good choice for initial work.
- (4) The surface breakdown in the current injector design provides significant plasma injection. It is likely that no additional gas source will be required.
- (5) Spectroscopic analysis using old techniques and modern computers is able to provide density and temperature information for this application [2].

It is recommended that subsequent work emphasize the characterization of the plasma injector. The intention is to develop a set of parameters to guarantee consistent injection performance. For example, depending whether the injector generates a glow, abnormal glow or arc, the plasma injected may be very different in its composition and produce a different initiation sequence in the main gun. With six injectors per gun and multiple guns, it is advantageous to establish a stable parametric space and develop experience diagnosing behavior for a single injector.

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