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ELM Simulating Plasma Gun Development and Experiments

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Introduction

The ELM Simulating Plasma Gun (ESP-gun) has been constructed with the goal to show it would be possible to simulate the conditions of a Type I Edge Localized Mode (ELM) event in a scaled-up version of this prototype machine. ELMs represent the limiting heat flux on divertor surface. Additionally, ELMs represent the largest cause of divertor erosion and impurity production in a fusion reactor. These facts combine represent a significant hurdle to the success of any large scale, fusion experiment and in particular ITER. Domestically, there is a need for an experiment to serve as a test bed for candidate Plasma Facing Components (PFCs) materials. This needs to be done in a controlled setting, where the target is easily accessible and in an experiment dedicated to PFC studies. The study of candidate materials under a simulated heat load as well as plasma flux could yield information on material survivability, surface effects and viability of vapor shielding.

Apparatus

The basic components of the experiment consist of a conical, theta-pinch coil used to compress and eject hot, dense plasma[1]. A pre-ionization plasma source is used that consists of a Helicon antenna typically operating with 100 W of forward RF power at 13.56 MHz. Typical gas flows used consist of Hydrogen kept at 50 mTorr. An external DC magnetic field, shown in Figure 1, is used to guide the expanding plasma from the theta-pinch downstream to the target region of the experiment and to replicate the magnetic field conditions found in the divertor region of a fusion experiment such as ITER or NSTX.

A high voltage, low inductance pulse forming network (PFN) is used to discharge a short, ringing high current pulse through the theta-pinch coil. The PFN can be seen in Figure 2; it consists of a 55 μF, 500 nH capacitor with a total energy storage of 6 kJ.

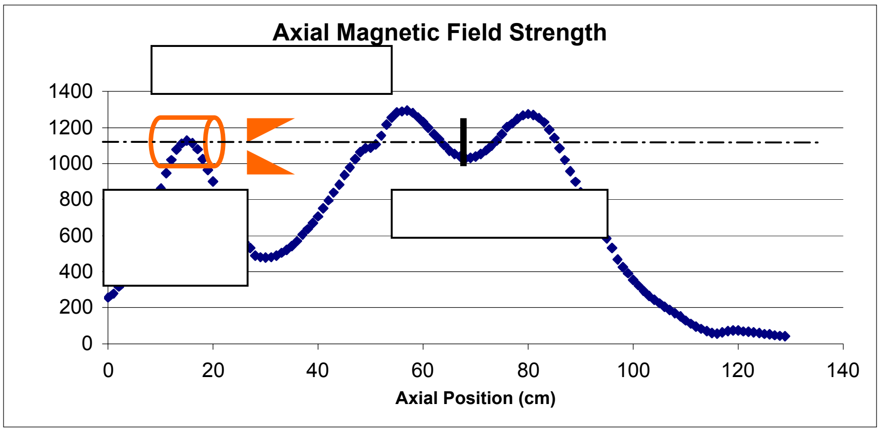


Figure 1: External, steady-state magnetic field measured on axis.

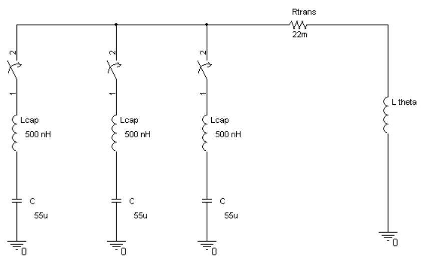


Figure 2: Schematic of the total pulse forming network (PFN)

Each PFN is discharged through a spark gap switch, which is independently triggered from a set of Maxwell delay generator. The delay between the discharge of each spark gap is limited by the lack of a crowbar switch to dump residual current in the previous pulse forming network.

Electrical Characteristics

The current in the theta-pinch coil and the voltage on each of the three capacitors are shown in Figure 3. A peak current of 50 kA is reached with a rise time $\lambda/4 \sim$ of 13 μs. However, $\lambda/4$ is on the order of the magnetic diffusion time for the pre-ionization plasma used. Therefore, the pinch may not be effective due to the magnetic field diffusing into the plasma before a significant compression can take place.

While a theta-pinch can provide plasma densities and temperatures comparable to (or greater than) ELM events in proposed reactor designs, the length of the plasma pulse is far too short to accurately simulate the duration of an ELM event. The length of a theta pinch plasma pulse can be effectively extended by using multiple pinches. This has the added benefit of simulating the pulse-burst nature of ELMs, while providing the requisite overall length. One way to create multiple pinches is to use multiple independent pulse forming networks, each providing one theta pinch pulse. This approach requires many (~50-100) pulse forming networks to reach the desired plasma stream duration of 0.5-1 ms. Therefore, each PFN is allowed to ring for a short time. This creates several pinches per capacitor discharge, and greatly reduces the number of PFNs required to reach 1 ms as shown in Figure 3.

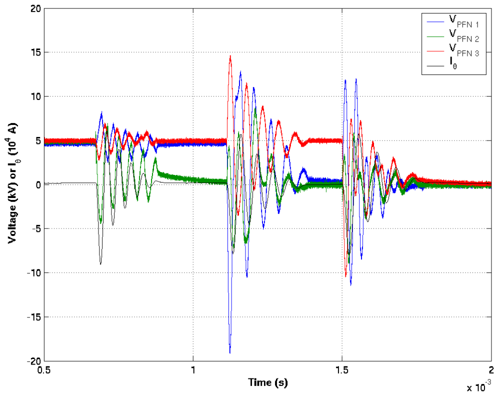


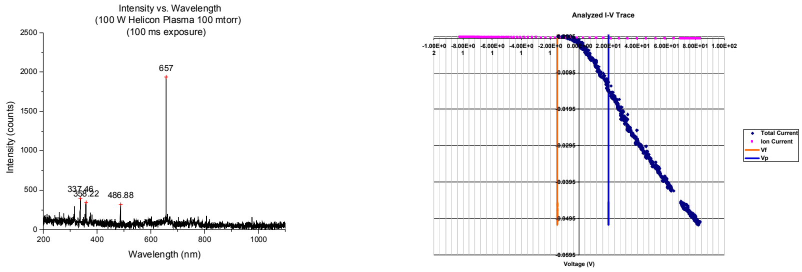
Figure 3: Consecutive PFN discharges

Plasma Parameters

The pre-ionization source utilities a Helicon antenna as part of a "pi" matching network. Typically, at lower powers such as 100-250 W, matching was accomplished with zero reflected power. Through optical emission spectroscopy, the electron temperature, Te was found to be 3.6 eV based upon the relative line ratios of the H_α and H_β lines. Additionally, the electron density and temperature were measured at the target region using a single Langmuir Probe. The electron density, n_e was found to be $2x10^{16}$ /m^3, and the electron temperature was found to be 3 eV. The graphs of both the optical spectroscopy and the I-V characteristic of the pre-ionization plasma can be seen in Figure 4.

Due to the relatively low density of the RF plasma source, the conductivity of the plasma, if a Spitzer resistivity is assumed, is only 1.93 m**Ω.** This yields the characteristic magnetic diffusion time, $\tau \sim \mu_0$ R/ η = 16.5 μs, where R is the radius of the helical antenna and η is the plasma resistivity.

The pulsed plasma hat travels to the target during the theta pinch is lower in density than expected, with a peak electron density, n_e of $2x10^{18}$ /m^3 and a peak electron temperature, T_e of 25 eV. The plasma blobs ejected during the pinch, as seen in Figure 5, have a frequency of 10 kHz, which is similar to the NSTX ELM frequency of 10 - 100 kHz. As seen, the density blobs are higher when the capacitor voltage is increasing (negative polarity to positive). This is when the magnetic field produced by the conical, theta-pinch coil is aligned in the direction opposite to the external, steady-state magnetic field. This could indicate a field-reversed configuration is formed during the pinch; however, detailed, internal magnetic field measurements are needed to verify this.



(a) (b)

Figure 4: (a) Optical emission spectroscopy of a 100 W RF plasma. (b) I-V trace of the 100 W RF plasma measured in the target region.

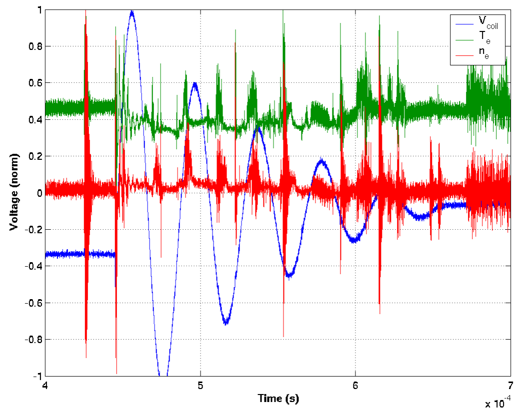


Figure 5: Triple Langmuir probe trace of the electron temperature and density overlaid on the capacitor voltage for a 7.5 kV (0.6875 kJ) discharge.

Conclusions

The ESP-gun is only a prototype machine. It is believed higher density target plasma will be produced by reducing the rise time of the PFN discharge and by increasing the power, and therefore the density, of the RF pre-ionization plasma. Currently, the PFN's have been upgraded to 2 μF capacitors with less than 50 nH inductance. In preliminary low voltage testing, a λ/4 of 3 μs was achieved. Additionally, a higher power RF plasma source has been constructed and performs reliably at powers of 200 W. These modifications to the ESP-gun experiment should allow for higher density target plasmas and direct scaling to ITER relevant conditions for phase II of the project where a 250 kJ capacitor bank is available.

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[1] J.M. Taccetti, et. al., "FRX-L: A Field-reversed configuration plasma injector for magnetized target fusion." **(74)** 10. pp. 4314-4323.