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Target heat loading due to fast, transient heat pulses produced from a conical θ-pinch as a prototype for benchmarking simulations of transient heat loads

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Abstract

The ELM simulating plasma gun (ESP-gun) has been developed to study the effects of transient, blob-like plasmas on the plasma facing components of TOKAMAKs. ESP-gun utilizes a RF helicon plasma to pre-ionize a plasma column underneath a conical, θ-pinch coil, which is used to compress and eject plasmas. Measurements have been made of the existing RF plasma and the subsequent compressed plasma. A copper target was placed downstream of the θ-pinch, and its temperature rise was measured with respect to time. For modest argon plasmas, $n_e \sim 10^{18}\ \mathrm{m}^{-3}$ and $T_e \leqslant 100$ eV, the target temperature was observed to have an equivalent heat loading of up to 90 kJ/m^2. Given that the plasma density and temperature are low, it is believed that the target heat loading will scale linearly with plasma density such that plasmas of 10^{20}–$10^{21}\ \mathrm{m}^{-3}$ would reach target heat loading in excess of 1 MJ/m^2. A zero dimensional thermal model will be presented to estimate the expected target heat loading.

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Keywords: Divertor; Divertor materials; Plasma facing components; Power loading

1. Introduction

Edge localized modes (ELMs) have been characterized over the years during H-mode operation of devices such as DIII-D, JET, NSTX, Alcator C-MOD and are predicted to occur in ITER on a scale not seen on the current generation of fusion experiments [1]. Of the several different types of ELMs observed on these large devices, it is believed that large, type-I ELMs represent the largest concern to the first wall and divertor. Each type-I ELM could carry as much as 1–10 MJ/m^2 of heat loading onto the plasma facing components (PFCs). Such large, repetitive heat fluxes could cause significant erosion resulting in contamination from the edge materials into the core plasma thus degrading performance of the reactor.

However, it is difficult to study the effects ELMs will have on the PFCs used in a fusion reactor since access to PFCs in large TOKAMAKs is limited to large torus openings or the material itself is subject

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to a wide range of experiments such that no definitive causality can be determined for the damage to the PFCs. Therefore, a smaller scale experiment is required that could produce a plasma similar to that of an ELM event to study how candidate PFC materials behave under plasma and heat loads of an ELM. To accomplish this, its believed that the simulated ELM must closely match the plasma parameters of an ELM namely density, electron and ion temperatures as well as flow speed. Additionally, the simulated ELM must also have the same, discrete plasma blob structure [2] found in ELMs as well as the same characteristic time duration as shown in Table 1. However, given the parameters shown for NSTX and ITER in Table 1, the current design of ESP-gun is several orders of magnitude away from accomplishing its end result. At present, ESP-gun operates with up to 500 J of discharge energy; an increase in the discharge energy should provide an increase in the plasma on target, which would corresponding increase the energy flux incident on the target.

Table 1
ELM parameters of ITER and NSTX compared to the parameters of ESP-gun

ELM parameter	ITER	NSTX	ESP-gun
Power loading	$\sim$10 MJ/m^2	<1 MJ/m^2	$\sim$10 kJ/m^2
ELM event frequency	1–10 Hz	10–20 Hz	Single shot
Total ELM duration (ms)	$\sim$0.1–1	$\sim$1	0.1–1
Blob subfrequency (kHz)	$\sim$10–100	$\sim$10	10
T_e during ELM	1–2.5 keV	100 eV	30–40 eV
ELM density, n_e (m^{-3})	$\sim$10^{21}	10^{19}–10^{20}	10^{18}
Divertor field, B_t (T)	1–5	$\sim$0.5	0.1

2. Experimental apparatus

The ELM simulating plasma gun (ESP-gun), shown in Fig. 1, has been developed to produce plasmas similar to those measured during disruptions on larger machines such as DIII-D, NSTX and the expected parameters of ITER. ESP-gun consists of a conical θ-pinch connected to a capacitor bank (2, 2 μF capacitors in parallel) discharged through a spark gap switch. Current rise times, $\lambda/4$ of 2 μs have been measured with pulse lengths on the order of 50 μs for each individual pulse. Charging voltages ranging from 10 to 15 kV have been used in the course of experimental campaigns for discharge energies ranging from $200 \leqslant E_0 \leqslant 500$ J on the capacitor bank. Because the capacitor bank is allowed to ring to achieve maximum discharge current with the shortest rise time, the discharge of the bank is only 44% efficient. Up to 3, 4 μF capacitor banks have been sequentially discharged using three spark gap switches and a Maxwell delay generator capable of 10 μs increments. An example of a current waveform from this configuration is shown in Fig. 2. Spacing between the individual discharges was set to 1 ms to prevent one spark gap from having a conduction path while

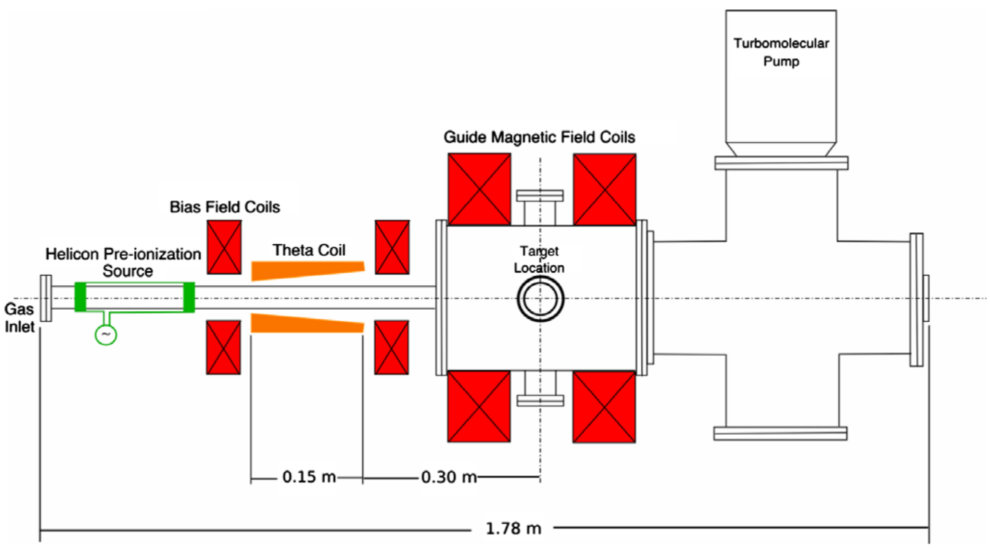

Fig. 1. Schematic drawing of the top view of the ELM simulating plasma gun (ESP-gun) at the University of Illinois, Urbana-Champaign.

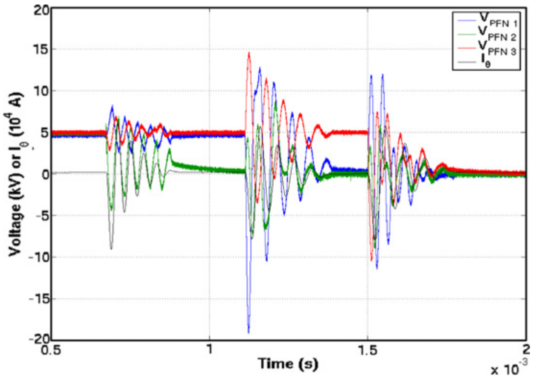

Fig. 2. Voltage and current waveforms for three consecutive pulses for a total pulse length of 1 ms.

another bank discharged. In the future, this could be remedied by adding a crowbar switch that would close at the peak current of each bank discharge. This was done to show the efficacy of firing multiple capacitor banks sequentially to produce the 'bursty' nature of ELMs.

A copper target is placed 0.3 m downstream of the conical, θ-pinch measuring 0.01 m × 0.02 m × 0.0019 m cemented onto the end of an alumina tube for structural support. Behind the graphite target, a K-type thermocouple is cemented in place. Target surface temperature is measured using a P-179-13 Hammamatsu IR photo-resistor. The photo-resistor was calibrated using a resistive, button heater located behind the graphite target. The voltage response of the IR photodiode was measured as a function of the surface temperature of the graphite target using a thermocouple mounted to the front of the target. The photo-resistor response was found to be 4 ± 1 mV/°C.

2.1. Pre-ionization source

Conical θ-pinches and field reversed configurations (FRCs) require some form of pre-ionized plasma to pinch. DC plasmas, inductively coupled RF plasmas [3] as well as ringing the θ-coil prior to the pinch [4] have all been used in the past. ESP-gun utilizes a helicon antenna to create pre-ionized plasma. This was done due to the comparatively low discharge energies being used on ESP-gun to date since helicon plasmas have been shown to have relatively high electron densities and temperatures when compared to other similar discharges [5]. It is believed that higher quality pre-ionized plasma will lead to more effective compression by the θ-pinch discharge. A static fill pressure of argon is maintained of 0.2 mTorr (2.5 sccm) using an MKS 100 sccm flow controller with constant pumping from a Seiko Seiki 300-STP turbo-molecular pump backed by a belt driven, roughing pump. For the experiments presented, the forward RF power to the helicon antenna and matching network was set at 500 W. RF powers up to 1000 W are possible but lead to significant heating of the matching network and antenna.

An external magnetic field is required both for the successful operation of the helicon discharge as well as providing a bias magnetic field for the θ-pinch. Typically, the field coil between the helicon source and the θ-pinch coil is the only one used at full strength; however, there are two bias field coils available as well as two guide field each capable of producing an on-axis peak field strength of 0.1 T. Each field coil can be independently controlled so that the external magnetic field can be tailored for each experiment if necessary.

3. Results and discussion

3.1. Plasma parameters

The plasma has been measured in the 'target' region of ESP-gun approximately 0.3 m from the exit of the conical, θ-pinch using a triple Langmuir probe. An example of the waveforms measured can be seen in Fig. 3, for a 450 J argon discharge. From the traces, the plasma blob ejected from the conical θ-pinch is rather gaussian with some sinusoidal

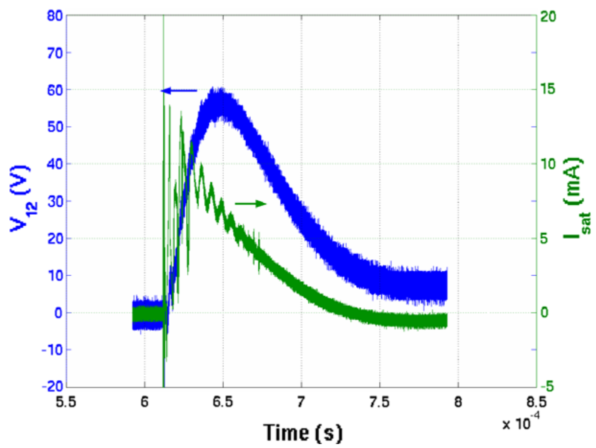

Fig. 3. Triple Langmuir probe waveforms (V_{12} and i_{sat}) acquired during a 450 J discharge. V_{12} is proportional to T_e, and i_{sat} is proportional to n_e.

variation coinciding with the ringing of the capacitor bank. From these raw data the electron temperature, T_e and density, n_e can be determined [6]. The peak values of this analysis can be seen in Fig. 4. The data were taken for discharge energies, $E_0 \leqslant 500$ J for both argon and deuterium discharges. While there is an increasing trend for the argon electron density data, the data has a significant amount of scatter. However, the deuterium data are more consistently grouped showing a linearly increasing trend. Fig. 4(a) also shows that the deuterium densities are lower than the argon densities. It is believed that this is because the helicon, RF plasma source used for creating the pre-ionized plasma has a dependence on the ion mass [5] such that denser discharges are produced when using heavier gases. So that, the deuterium plasma created as a pre-ionization source would be initially less

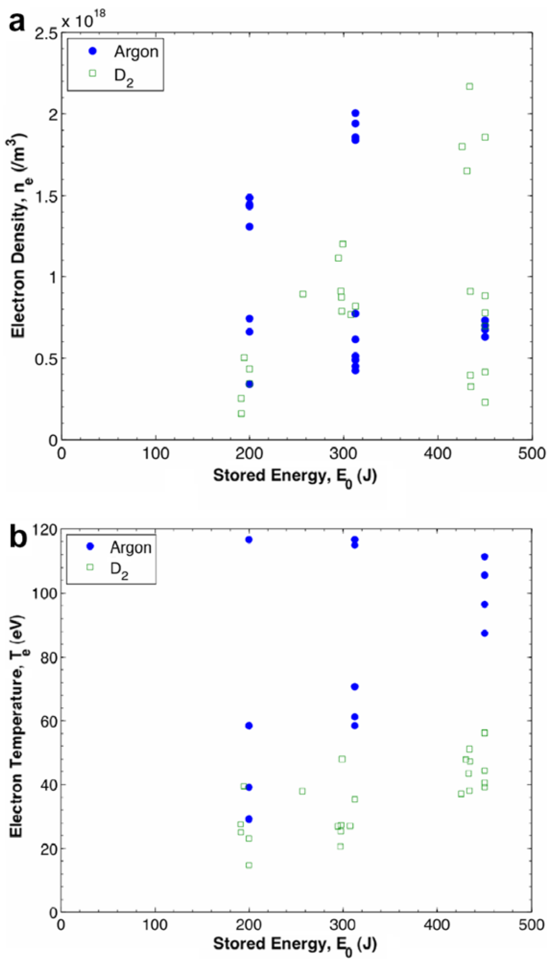

Fig. 4. Peak electron density measurements (a) and temperature (b) as a function of discharge energy.

dense than the argon plasma produced under the same conditions. Likewise, the electron temperatures measured in Fig. 4(b) shows the same scatter in the argon T_e measurements with a linearly increasing trend for deuterium discharges with peak electron temperatures up to 50 eV.

3.2. Expected target heating

For a grounded copper target, the total plasma flux to the target can be estimated using the measurements of the plasma obtained from the triple Langmuir probe and sheath theory. If s is defined as the sheath thickness with $r = 0$ referring to bulk plasma parameters, the ion flux can be found using flux conservation across the sheath such that

$$\Gamma_i = n_i(r = s)v_i(r = s) = n_0 u_B, \tag{1}$$

where n_0 is the bulk plasma density at $r = 0$ and u_B is the Bohm speed required for an ion to enter the sheath. The electron flux will be assumed to follow

$$\Gamma_e = n_e(r = s)v_e(r = s) = \frac{1}{4} n_0 v_{th_e}, \tag{2}$$

where

$$v_{th_e} = \sqrt{\frac{8kT_e}{\pi m_e}}. \tag{3}$$

Such that the total energy flux, ε to the target can be found by summing the contributions from both the ion and electron fluxes such that

$$\varepsilon = \Gamma_i E_i + \Gamma_e E_e = n_0\sqrt{\frac{kT_e}{m_i}}E_i + \frac{1}{4}n_0\sqrt{\frac{8kT_e}{\pi m_e}}E_e, \tag{4}$$

where the energy/particle can be estimated to be a linear combination of the particles thermal energy and the kinetic energy imparted by the particles flow speed.

$$E_n = \frac{3}{2}kT_n + \frac{1}{2}m_n u_n^2, \tag{5}$$

where $n = $ i, e for either ions or electrons. For the purpose of this analysis, it is assumed that the ion and electron temperatures have thermalized, and that they move with the same flow speed. The results of this model are presented in Fig. 5 with the measured response of the IR photo-resistor. As shown, the model can be in reasonable agreement with the energy flux measured from the photo-resistor. However, while n_0 and T_e can be measured by the triple Langmuir probe, the plasma flow speed

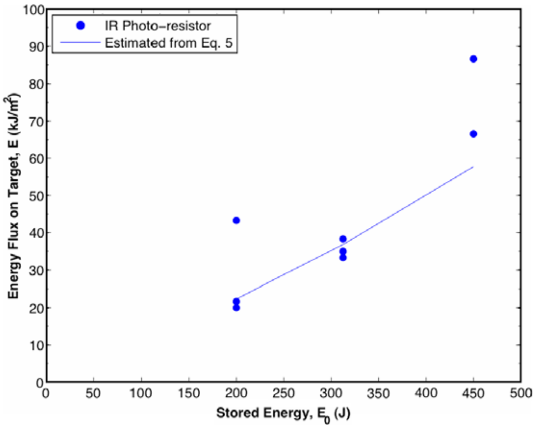

Fig. 5. Energy flux measured from the IR photo-resistor measurements (●) and estimated from the triple Langmuir probe (TLP) measurements (—).

was not directly measured. In this analysis, reasonable agreement between the plasma flux model described here and the measured incident energy flux was achieved only when the plasma flow speed was assumed to be 1×10^6 m/s. This flow speed is quite high, but not totally unreasonable for θ-pinch plasma sources depending upon the mirror ratio. Although, current estimates of the flow speed in ESP-gun place are on the order of $3–5 \times 10^5$ m/s, this suggestions either the flow speed in ESP-gun is much greater than has been observed to date, or, more likely, the current model needs to be refined to better agree with measured energy fluxes.

4. Conclusions

Based on the initial measurements of incident energy flux on a grounded copper target, the plasma density and temperature produced in ESP-gun ($\sim 1 \times 10^{18}$ m^{-3} and 50–100 eV) are not adequate to simulate the conditions required for an ELM event. However, even with such relatively low plasma parameters, incident energies of up to 90 kJ/m^2 have been observed for argon discharges. Therefore, a continued increase in discharge energy should increase the plasma density and therefore the energy flux on target. In light of this result, work progresses on ESP-gun to increase the stored energy in the capacitor bank beyond the 500 J limit currently in place. Further improvements could come by increasing the density in the pre-ionization plasma, which is directly proportional to the compressed density of the θ-pinch [3]. This could either be accomplished by increasing the RF power and/or the magnetic field for the helicon system, or a high current annular z-discharge as described elsewhere [3] could be implemented. The increase in plasma density will allow the study of plasma surface interactions at the material interface such as measuring the effect of vapor shielding on absorbing the incident plasma energy.

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