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Development of a high energy pulsed plasma simulator for the study of liquid lithium trenches

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HIGHLIGHTS

- A pulse device for a liquid lithium trench study is developed.
- It consists of a coaxial plasma gun, a theta pinch, and guiding magnets.
- A large energy enhancement is observed with the use of the plasma gun.
- A further increase in energy and velocity is observed with the theta pinch.

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ABSTRACT

To simulate detrimental events in a tokamak and provide a test-stand for a liquid-lithium infused trench (LiMIT) device [1], a pulsed plasma source utilizing a theta pinch in conjunction with a coaxial plasma accelerator has been developed. The plasma is characterized using a triple Langmuir probe, optical methods, and a calorimeter. Clear advantages have been observed with the application of a coaxial plasma accelerator as a pre-ionization source. The experimental results of the plasma gun in conjunction with the existing theta pinch show a significant improvement from the previous energy deposition by a factor of 14 or higher, resulting in a maximum energy and heat flux of 0.065 ± 0.002 MJ/m^2 and 0.43 ± 0.01 GW/m^2. A few ways to further increase the plasma heat flux for LiMIT experiments are discussed.

1. Introduction

Plasma–wall interactions in a tokamak have become significant issues as energy in tokamak plasmas has increased and detrimental events, such as edge-localized modes, were discovered. These violent events occur on a very short timescale, typically over a few hundred microseconds to milliseconds, resulting in a huge amount of power bombarding the target. For example, typical energies of ELMs (edge-localized modes) are about 0.01–0.05 MJ/m^2 for ASDEX-upgrade, 0.1–0.5 MJ/m^2 for JET and is expected to be 1–5 MJ/m^2 for ITER [2]. A recent report says that ITER will not be able to tolerate damage to its plasma facing components unless ELMs can be eliminated or reduced in magnitude by 95% [3] and the peak energy density must be smaller than 0.5 MJ/m^2 to have a lifetime of 10^7 thermal pulses of 500 μs duration [4]. Therefore, a major part of the tokamak research effort is aiming toward the development of physics and technologies to cope with these extreme events including (1) mitigation of ELM events such as resonance magnetic perturbation [5] and (2) studies of plasma–wall interactions at high levels of heat flux [28–30].

A recent study at the University of Illinois [1] shows that a heat gradient between the front and back surfaces of a liquid metal can be coupled with an external magnetic field to generate a thermo-electric magneto-hydromagnetic (TEMHD) force. This configuration, with a slit-shaped electron beam source implemented to create a heat gradient within the trench, removes a peak heat flux of 3 MW/m^2, and has the potential of removing up to 20 MW/m^2 [1]. This concept is a good candidate as a plasma facing component, not only because lithium displays several beneficial effects such as less radiation losses than carbon and tungsten, a better gettering of carbon and oxygen, and a lower recycling coefficients [6,7], but also because the liquid lithium can be replenished by the TEMHD force.

An unexplored part of the work related with the LiMIT device is how the trenches will behave with a larger amount of heat flux

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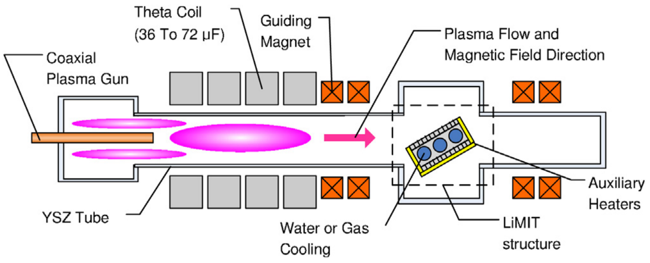

Fig. 1. A diagram of the TELS device. While the LiMIT stucture is not tested in this paper, the structure is added to the figure for readers to understand the final experimental setup.

on a shorter time scale (∼100 μs). In order to further investigate in detail the feasibility of the lithium-trench as a plasma facing component, a new project entitled thermoelectric-driven liquid metal plasma facing structures (TELS) has started. For this project, we are mainly focusing on two subtasks: (1) develop and refine the geometry of new thermo-electric driven structures to handle higher heat flux and (2) develop a laboratory-scale experiment to simulate off-normal events in tokamak devices and to test the trenches in those environments. This paper presents mainly the development of a small-size (≤2 m in length) pulsed-plasma heat load simulator to investigate the short-pulse effect on the liquid lithium infused trenches.

In this paper, development of a pulsed plasma source using a theta pinch in conjunction with a coaxial plasma gun for LiMIT device testing is presented. In Section 2, the principal elements of the device and experiment, including a description of the physical components as well as the electrical circuit and diagnostics, will be described. In Section 3, initial experimental results such as plasma density, electron temperature, plasma heat flux, and plasma velocity are presented. In Section 4, the results are summarized and concluded with future directions for further improvement.

2. TELS description

There are numerous works that aim toward the development of laboratory-scale energetic plasma generators to simulate and study the interaction between plasma and plasma-facing components [8–16]. A distinctive feature of the new device described in this paper is the use of the existing theta pinch at the University of Illinois [17–19] to allow for an additional control of ion temperature [20]. New additions to the existing pinch device include a coaxial plasma gun and guiding magnets for plasma creation, acceleration, and transport to the target region. A diagram of the initial experimental setup is shown in Fig. 1. The device is planned to be further modified to implement a liquid lithium-infused trench device and other equipments, including an electron beam for initial heating of LiMIT and electron beam focusing magnets. In summary, the device aims at achieving $n_e \geq 10^{21}\,\mathrm{m}^{-3}$, $T_{i+e} \sim 100$ eV, $v \sim 50$ km/s, and a plasma heat flux ∼0.1 MJ/m^2 in 100–200 μs.

2.1. Plasma gun

The coaxial plasma gun is used to create a high density plasma and provide it with an axial momentum through a Lorentz force. Oxygen-free copper has been chosen as an electrode material for initial testing. The cathode is an oxygen-free copper cylindrical rod with a 1 in. outer diameter and 12 in. length. An existing 8 in. stainless CF nipple serves as an anode, since it minimizes modification of the device. The inner diameter of the chamber is 6 in. and the length is 15 in. This setup gives an inductance of approximately 0.1 μH. A 500 μF capacitor with a maximum voltage of 10 kV is charged up to 6 kV (= 9 kJ) and discharged through a T-508 spark gap switch and 10 RG-217 cables. Hydrogen gas is fed by a Parker series 9 pulse valve from the end of the chamber. In most experimental cases, the plenum pressure is between 35 and 100 psi, which gives approximately 130–300 mTorr of gas pressure in the chamber. The base pressure in the chamber is 10^{-7} Torr.

2.2. Theta pinch and guiding magnets

Conventional resonance-type wave heating is not an effective way to heat the plasma from the gun since the plasma lasts for a very s hort time (≤150 μs) and the temporally changing plasma parameters result in difficulties in coupling and matching. Therefore, the theta pinch is a good alternative to heat the plasma given the current experimental setup. For example, 10 kJ of capacitor energy discharged in 100 μs with an energy transfer efficiency of 10 % results in 10 MW of electric power. Therefore, the theta pinch provides a simple way to heat the plasma. A pyrex tube is surrounded by a conical theta coil (#12μ13#) which is connected by 15 LDF5-50A Heliax cables to a 72 μF capacitor bank. The capacitor bank has been upgraded from 36 μF bank to increase the stored energy in the bank and to facilitate a crowbar operation. While the capacitor bank can be ideally charged up to a maximum of 60 kV, experiments are carried out under 20 kV (=14.4 kJ) due to limitations on the railgap switch and high voltage insulation issues.

We have two magnets at the target chamber. Guiding magnets initially serve to simulate an external toroidal magnetic field for LiMIT the trench. At the same time, the magnets also suppress expansion of the plasma after the plasma is ejected from the theta coil. While the magnets are supposed to ideally generate a long pulse to drive the liquid lithium flow, the magnets are powered by separate capacitor banks through 50RIA60 SCR switches for the purpose of this paper. Peak magnetic fields of 0.30 T from the the magnet between the theta coil and the chamber and 0.15 T from the magnet at the end of the target chamber are generated. A 316 stainless steel magnetic flux excluder is inserted between the theta coil and the guiding magnetic field to decouple magnetic fields from each other. It turns out that the voltage of the capacitor for the magnet next to the theta coil is perturbed only by the maximum of 2 V during the main bank discharge.

2.3. Diagnostics

Since the plasma lasts for approximately 150–200 μs and the density and temperature changes relatively fast, this experimental condition allows for very limited choices in diagnostics. Here, we use a triple Langmuir probe [21] to measure the plasma density and electron temperature. The triple Langmuir probe data is sensitive to noise and small changes in the signal at high electron temperature. This is more severe when the probe is not saturated; therefore, error propagation is taken into account for the analysis. Many different types of circuits for biasing the probe have been tested. The triple probe current is measured by a 4100 Pearson coil and the voltages at the tips are measured by two P5200 Tektronix high voltage differential probes. The probe is oriented parallel to the tube to reduce the plasma velocity effect.

We have also manufactured a calorimeter to estimate the incoming plasma energy. A button-type calorimeter, similar to those in [22,23], made of copper with a 6.4 mm. diameter and with a 5 mm length is used. The copper is insulated with Macor ceramics on all sides except the front surface. A K-type thermocouple is attached to the back surface of the copper and the thermocouple is connected to a computer through a U-3 Labjack interface to record the rise in temperature. The calorimeter is located at the target region, approximately 30 in. away from the plasma gun.