Journal of Nuclear Materials 415 (2011) S993–S995

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Characterization of a theta-pinch plasma using triple probe diagnostic

S. Jung [a,*], V. Surla [a], T.K. Gray [b,c], D. Andruczyk [a], D.N. Ruzic [a]

[a] Center for Plasma-Material Interactions, Department of Nuclear, Plasma and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[b] Oak Ridge Institute for Science and Education, Oak Ridge, TN, USA
[c] Oak Ridge National Laboratory, Oak Ridge, TN, USA

ARTICLE INFO

Article history:
Available online 1 February 2011

ABSTRACT

Plasma diagnostics were carried out in a theta-pinch device to investigate the applicability for plasma–material interaction under fusion-like conditions. A series of triple probe diagnostics show that the plasma is sustained for approximately 80 μs at each pulse, with 3.0 $(10)^{21}$ m^{-3} plasma density and up to 40 eV electron temperature when a 32 μF main capacitor is discharged at 20 kV. In order to increase plasma density and temperature, an RF antenna is installed near one end of a Pyrex tube and a 50 μF preionization capacitor is connected to an electrode placed at the same end as the antenna. In this configuration, several time delays between the main and preionization capacitors are tested. When the preionization capacitor was triggered 45 μs before the main bank discharge, it resulted in high energetic plasma being obtained with a few density spikes at 10^{22} m^{-3} and electron temperature around 100 eV.

Published by Elsevier B.V.

1. Introduction

Plasma–material interactions are increasingly important in a fusion plasma reactor because as temperatures and densities generally increase, contact with the wall can cause severe degradation. In extreme conditions such as edge-localized modes sudden ejection of high heat flux to the chamber wall severely damages the wall and can be the most significant lifetime constraint. To study how materials respond to such intense plasmas, several devices have been developed and tested [1–3], though this is not an exhaustive list. A similar effort has been undertaken at the University of Illinois at Urbana-Champaign, primarily to look at the effect of vapor shielding, resulting in the design and development of a new laboratory test facility called the Divertor Erosion and Vapor Shielding eXperiment (DEVeX). The goal of this facility is to produce energetic plasmas, similar to ELMs, in order to study the plasma–material interactions in detail [4]. The DEVeX device utilizes a theta-pinch to create and compress the plasma.

Previous experiments in DEVeX have shown that the discharge lasts around 100 μs and the plasma density reaches 10^{21} m^{-3}, which was measured by stark broadening [4]. In addition, an attempt was made to obtain the plasma parameters (number density and electron temperature) using a triple Langmuir probe, but several challenges resulted in significant uncertainity in the electron temperature measurement. It was reported that the coupling between the theta coil and the plasma was not high and the plasma cooled down as it moved to the target chamber, resulting in a very low energy flux to the target. This led to the current ongoing work of modifying DEVeX, and this is the subject of this paper. This paper will present several upgrades added to the device such as an additional capacitor for preionization and guiding magnetic field for efficient delivery of plasma into the target region. Again, a triple Langmuir probe is used to study the effect of these upgrades on plasma density and electron temperature. Moreover, a few different time delays between the preionization and main bank discharges are attempted to optimize and induce an effective pinching effect and its effect is studied as well.

2. Experimental setup

The key components of the experimental setup are the theta-pinch device and the target chamber. The theta-pinch device is used to generate hot and dense plasmas and the target chamber is housed with several diagnostics and diagnostic ports for optical access. Fig. 1 shows the schematic of the experimental setup. A single-turn, four-segmented theta coil is used to generate and compress the plasma and it is conically tapered to ~1° to expel the plasma preferentially into the target region (*z*-direction), although in reality the plasma goes both directions. The theta coil has an inner diameter 0.1 m, an outer diameter of 0.254 m, and a length of 0.36 m. Using the formulae in Ref. [7], the inductance of the theta coil is estimated to be approximately 200 nH. In order to produce high current through the theta coil, 18 capacitors in parallel with total 36 μF are connected to a single turn theta coil through 15 RG-19/U cables. The theta coil surrounds a 10 cm diameter quartz tube, in which plasma is generated and compressed. A main rail-gap switch is used to discharge the main capacitors and is con-

---

* Corresponding and presenting author. Address: 216 Talbot, 104 S., Wright St., Urbana, IL 61801, USA.

E-mail address: jung73@illinois.edu (S. Jung).

0022-3115/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2011.01.046

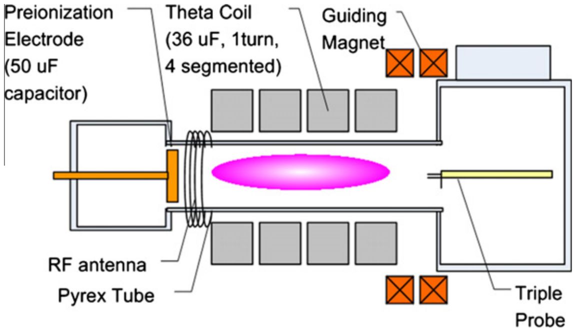

Fig. 1. Schematic of the DEVeX experimental setup which consists of a theta-pinch device and diagnostics housed in the target chamber.

trolled by a high-voltage trigger and handles 300 kA peak current or higher. The capacitors can hold up to 60 kV, however, for all the experiments presented here the charging voltage of the capacitor is fixed at 20 kV, yielding 7.2 kJ. The reason for 20 kV shot is mainly due to self-triggering problem in the rail-gap switch.

A triple Langmuir probe, which is discussed in detail in Ref [5,6], is located in the Pyrex tube to measure electron temperature, and plasma density. Fig. 2 shows a circuit diagram of the triple probe. The size of each tip is approximately 0.5 mm in diameter and 2.5 mm in length. A 1 Ohm resistor is connected in series with the triple probe to measure current. Voltages at the triple probe are measured by 10:1 tektronix probes and 50:1 high voltage differential probes. 65 V external voltage source, composed of 9 V batteries, is applied to the triple Langmuir probe. The triple Langmuir probe is placed approximately 7 cm apart from an end of the theta coil. All the data acquisition is carried out in a Faraday cage to minimize interferences by electromagnetic fields produced during shots.

In order to increase the plasma density and the electron temperature, upgrades have been applied to this device. First, a preionization source is added in an effort to increase plasma density before the main capacitor is fired. A ring-shaped preionization electrode is placed at one end of the Pyrex tube and connected through a spark gap switch to a 50 μF capacitor for preionization. For all experiments presented here, the capacitor for preionization is charged below 9 kV, delivering 1.6 kJ (at most) to the electrode and increasing plasma density before the magnetic field, due to the discharge current in the theta coil, compresses it. At the same end, a 4-turn radio frequency antenna surrounds the Pyrex tube. It is used to produce a low density plasma before the main capacitor or the preionization capacitor is discharged. The power at the antenna is fixed at 120 W for all experimental conditions except for “no-preionization” case.

Second, a magnet is added at the other end of the Pyrex tube to reduce the divergence of magnetic field near the end of the theta coil which is designed to reduce plasma loss to a wall. The guided magnetic field is achieved with two 175-turn magnets, powered by a 25 A DC power supply. Maximum magnetic field produced by these magnets is $(3.8 \pm 0.2)10^2$ Gauss. A pulse signal generator produces multiple trigger signals that control the rail-gap switch at the main capacitor and the spark gap switch at the preionization capacitor independently. Hydrogen gas is used for all the current experiments and pressure is sustained 5 ± 1 mTorr.

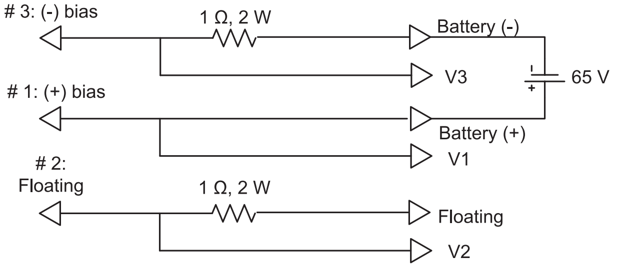

Fig. 2. Electric circuit diagram of a triple probe.

3. Results

Fig. 3 shows the time resolved profiles of plasma density and electron temperature for the baseline case when no preionization source was used. The plasma parameters are measured using the triple probe diagnostic described earlier. As electron temperature gets higher, a triple probe voltage becomes insensitive to electron temperature change. It is quite important to note this since error becomes enormous at high temperature. In this case, the error of the measured voltage at the triple probe is 0.1 V which corresponds in turn to the error bars shown in the figure. In density, for every case error range is assumed 30%, which is moderate in triple Langmuir probe diagnostic. [8],

The main capacitor is fired at 0 μs. Density starts to increase and is sustained $3(10)^{21}$ m^{-3} which lasts 80 ± 10 μs. Electron temperature varies between 5 and 40 eV, although it shows a few points around 100 eV between 80 and 100 μs. This graph implies that much of the energy in the main capacitor is consumed in producing plasma rather than compressing it.

In order to observe the effect of preionization, a preionization capacitor is discharged at 8.8 kV. Two different time delays between preionization and main capacitor discharges are tested. Fig. 4 shows the data when preionization capacitor and the main capacitor are discharged at the same time. An RF plasma produces a low density plasma before two capacitors are discharged to facilitate preionization. For the first 50 μs, voltage ringing at the preionization electrode results in a huge effect on plasma and therefore negative current is picked up at the triple probe from 25 μs to 50 μs. The plasma becomes more stable approximately after 50 μs, when the electron temperature and density increases take place synchronously by magnetic pinching effect. Fig. 4 shows that the plasma density and electron temperature change periodically. The phenomenon is due to current ringing in the theta-pinch coil. Its shape is similar to an underdamped sine curve so that magnetic field induced by the current ringing compresses and decompresses the plasma repetitively. Although the density shows increases up to 10^{22} m^{-3} and peaks of electron temperature reach higher than 100 eV, a large amount of energy in the capacitor bank is dissipated at first few tens of μs when the plasma is considerably affected by preionization voltage. Since preionization plasma takes a few tens of μs to stabilize, initial loss of energy in main capacitor

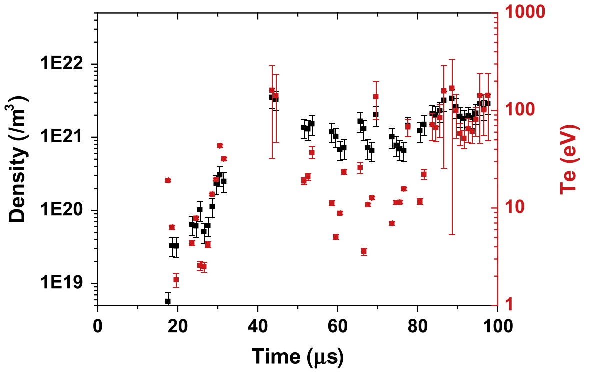

Fig. 3. Temporal behaviors of density and electron temperature in the case of charging the capacitor bank to 20 kV and no preionization.

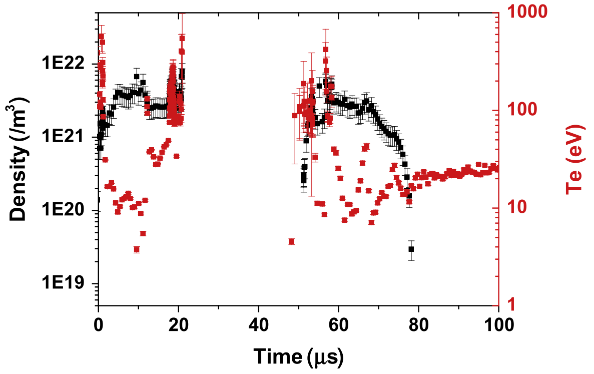

Fig. 4. Temporal behavior of density and electron temperature when the preionization capacitor and the main capacitor are discharged simultaneously. The data between ~22 and ~43 μs was consistently too noisy to plot due to the preionization source.

bank resulted in a rapid decrease in density after the main capacitor discharge is finished and the pinched plasma lasts only 25 μs. Although adding preionization source improves the number density and electron temperature of the plasma reaching the target, a better triggering control is necessary for more effective and longer compression.

Fig. 5 shows the time behavior of density and electron temperature when the preionization capacitor is discharged 45 μs before the main capacitor is discharged. The preionization capacitor is charged up to 8.8 kV and discharged at 0 μs. The figure starts when the main bank is fired. Since the flux loop signal measures average magnetic field in the plasma volume, the plasma is compressed during the period when absolute value of flux loop signal is increasing. Grey areas in Fig. 5 indicate plasma compression periods by this increasing magnetic field. It can be seen from Fig. 5 that the temperature and density increases synchronously with increasing magnetic field. In this case, the density reaches up to 10^{22} m^{-3} and electron temperature peaks at 100 eV and these conditions are sustained for approximately 40 μs. These plasma parameters yield a plasma pressure around 3 atm, which is the consistent with a magnetic pressure of 0.88 T induced by 210 kA theta coil current.

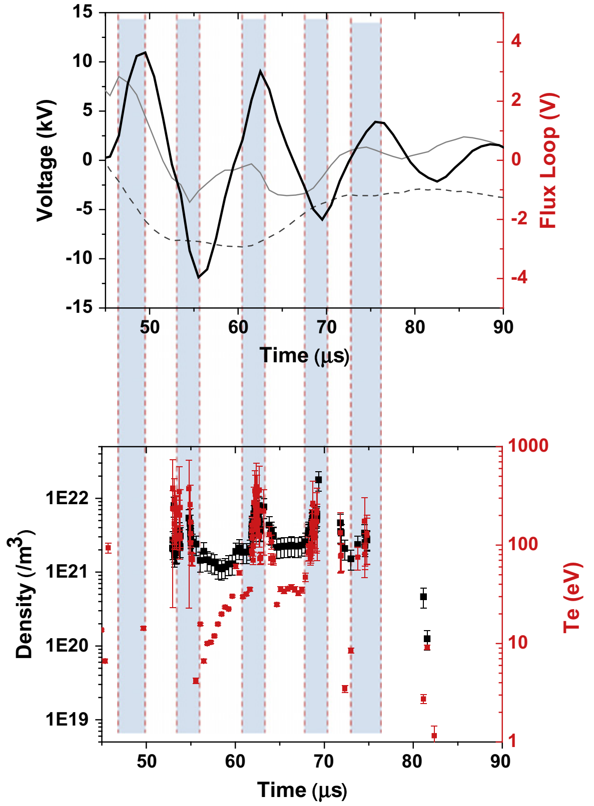

Fig. 5. Temporal behavior of density and electron temperature when the preionization capacitor is discharged 45 μs before the main bank is triggered. Black solid line indicates flux loop voltage, grey solid line theta coil voltage, and the grey dash line the preionization capacitor voltage. These plots start when the main bank is fired. Grey areas indicate regions where magnetic field increases. These correspond to peaks in the electron density and temperature.

Since the magnetic field expands out from the theta coil, it is important to keep the plasma flow in the axial direction of the cylinder without loss to the wall. However, since the magnetic field by the guiding magnets is so small compared to the field from the theta coil, the guiding magnetic field contributes little to plasma loss reduction and no significant change in plasma density and temperature by using the external guide magnetic field are achieved. Since the distance from the end of the theta coil to the target chamber is 22 cm, a stronger magnet would need to be installed to keep the magnetic field from reversing. These results show the importance of keeping the magnetic field in one direction without current ringing at the theta coil. We will attempt to do this with a crowbar circuit in future work.

4. Conclusions

The time resolved profiles of number density and electron temperature are measured in a theta-pinch device using a triple Langmuir probe in various operational scenarios. Based on the measurements of the incident plasma parameters, it is shown that the device produces 10^{21} m^{-3} and 20–40 eV plasma parameters without preionization source. When the main capacitor is discharged 45 μs after the preionization capacitor is discharged, it results in increases in density up to 10^{22} m^{-3} and electron temperature up to 100 eV which are sustained for 40 μs. Plasma pressure calculated values are in good agreement with the magnetic pressure produced by the theta coil. No significant effect of the guiding magnetic field is observed because the magnitude of the field is very small compared to that of the theta coil. At least a few thousands gauss magnetic field or a crowbar circuit are required to transport the pinched plasma to the target region without serious divergence of magnetic field and attendant plasma loss to the walls.

Acknowledgements

This work is supported by DOE contract DE-FG02-04ER54765. The author would like to thank an undergraduate researcher Hyunho Yun for his time and commitment in the laboratory.

References

[1] V.R. Barabash, A.G. Baranov, J. Gahl, V.L. Litunovsky, J. McDonald, I.B. Ovchinnikov, J. Nucl. Mater. 187 (1992) 298–302.
[2] P.D. Rockett, J.A. Hunter, J.M. Gahl, J.T. Bradley III, R.R. Peterson, J. Nucl. Mater. 212–215 (1994) 1278–1282.
[3] J.M. Gahl, J.M. McDonald, A. Zakharov, S. Tserevitinov, V. Barabash, M. Guseva, J. Nucl. Mater. 191–194 (1992) 454–459.
[4] T. Gray, Ph.D dissertation, University of Illinois at Urbana Chamapaign, 2009.
[5] N. Gatsonis, L. Byrne, J. Zwahlen, E. Pencil, H. Kamhawi, IEEE Trans. Plasma. Sci. 32 (2004) 2118–2129.
[6] B. Johnson, D. Murphree, Am. Inst. Aeronaut. Astronaut. J. 7 (1969) 2028–2030.
[7] F.W. Grover, Inductance Calculations: Working Formulas and Tables, Dover, New York, 1962. p. 94.
[8] M. Kamitsuma, S.L. Chen, J.S. Chang, J. Phys. D: Appl. Phys. 10 (1977) 1065–1077.