Fast gas injection as a diagnostic technique for particle confinement time measurements

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The determination of the effective particle confinement time (τ_p^*), i.e., the particle confinement time normalized to recycling coefficient, is difficult when its value is long compared to the discharge duration in magnetically confined plasmas. Recent experiments on the current drive experiment upgrade (CDX-U) spherical torus have successfully achieved a significant reduction in recycling with large-area liquid lithium plasma-facing surfaces. The low recycling walls result in an increase in particle pumping and make it possible to measure τ_p^* in short duration plasmas. Measurements of τ_p^* are made using a supersonic gas injector which is closely coupled to plasma. A fast gas pulse is emitted from the supersonic gas injector, after which the density decay is measured using a microwave interferometer. The design of the supersonic gas injector and its configuration on CDX-U will be presented. The results of this technique will be shown as applied to the study of the effects of a liquid lithium toroidal limiter and evaporative lithium coatings on overall plasma density and τ_p^*. *© 2006 American Institute of Physics.* [DOI: 10.1063/1.2219379]

INTRODUCTION

Finding a first wall suitable for fusion reactors is a significant challenge. Liquid metals are an attractive option since they provide high heat handling as well as resistance to erosion, neutron activation, and radiation damage due to their constantly renewed natures. Lithium is particularly suited for this since it is low Z and is required for the tritium cycle. Lithium has also been shown to pump and retain deuterium up to a 1:1 ratio in Li:D.[1] This ability to pump deuterium provides for low recycling of hydrogen and deuterium, which opens up a new operational regime for fusion devices.

The current drive experiment-upgrade (CDX-U) has been investigating the effects of liquid lithium limiters and plasma-facing components (PFC) on discharge performance. Significant improvements have been achieved, including a substantial reduction in wall recycling.

DESCRIPTION OF CDX-U AND LITHIUM SOURCES

CDX-U is a small spherical tokamak with a major radius of 34 cm and a minor radius of 22 cm. The toroidal field on the magnetic axis is 2.1 kG and the plasma current is $\leqslant$80 kA. Central electron temperatures are $\sim$100 eV and central electron densities are $\sim 6\times 10^{19}$ m^{-3}. Discharges last on the order of 25 ms. In the past few years, research on CDX-U has been focused on liquid lithium limiters and PFC coatings and their affects on a plasma performance.

Prior experiments on CDX-U utilized a fully toroidal tray limiter filled with lithium located at the bottom of the vacuum vessel (see Fig. 1). The tray consisted of two 10 cm wide, 0.64 cm deep stainless steel halves that were centered at a radius of 34 cm. The two halves were electrically separated. Heaters attached to the underside of the tray provided temperature control up to 500 °C. The lithium was liquefied and provided for a plasma-facing surface area of up to 2000 cm^2. Plasma discharges with the liquid lithium limiter showed a reduction in D_α and a significant increase in the amount of external deuterium gas required to maintain plasma density.[2,3]

Recent experiments focused on lithium evaporation to form lithium plasma facing surfaces. The first technique used a modified commercial 4 kV electron beam mounted on the top of the vacuum vessel (see Fig. 1). The vertical and toroidal field coils were used to guide the electron beam to several positions on the lithium-filled toroidal tray. This system was used to both liquefy and evaporate the lithium in the tray. The temperature of the lithium was monitored by thermocouples installed in the tray. It varied from between $\sim$360 to $\sim$440 °C. The electron beam was capable of generating a coating of $\sim$1000 Å at 85 cm between plasma discharges (every 5–6 min).

An additional source of evaporative lithium coatings was added at the end of the CDX-U run. A resistively heated oven evaporator was installed on the opposite side of the vessel from the e-beam (see Fig. 1). This oven evaporator provided center stack coatings during the final run of CDX-U. The oven evaporator was run continuously and was capable of deposition rates of $\sim$120 Å min at 85 cm.

Evaporative coatings were monitored with Inficon quartz crystal deposition monitors. Two monitors were placed at different toroidal locations to monitor the thickness of the evaporative lithium coatings.

Besides recycling from the wall, CDX-U has two forms of external fueling. The first is a standard gas puffer, based

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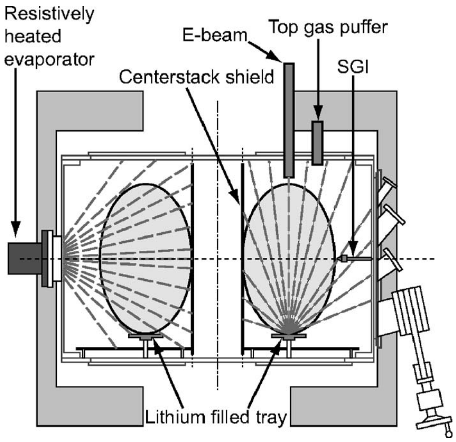

FIG. 1. Cutaway of CDX-U machine. A resistive oven lithium evaporator is located on one side of the vessel. An electron beam is mounted on the top of the other side. The e-beam is guided towards lithium in the toroidal tray limiter, where it either liquefies or evaporates the lithium. The conventional puffer is located on the top of the vessel near the e-beam, while the supersonic gas injector (SGI) is mounted radially at the midplane and is positioned near the last closed flux surface.

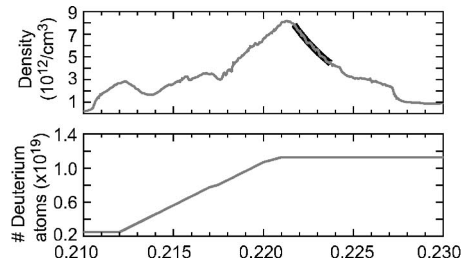

FIG. 3. The top graph shows the line integrated density as measured by the microwave interferometer in gray and a fit of Eq. (1) to the density in black. The fitted value for τ_p^* for this particular shot is 3.54 ms. The bottom graph shows the integrated particle input from the external gas puffers. At $t = 222$ ms, the external gas feed was shut off and the density trace starts to drop.

on a Veeco PV-10 piezoelectric valve. The conventional puffer is located on the top of the vessel at the wall. It has a throughput of 4.4×10^{21} D at./s, or 63 Torr l s.

The second external fuel source is a supersonic gas injector (SGI). The SGI is also based on a PV-10 piezoelectric valve and is fitted with a Laval nozzle which enables the gas flow to reach supersonic speeds (see Fig. 2). The Laval nozzle of the SGI is a Mach 8 design for a large wind tunnel[4] scaled down to 0.01 in. diameter throat. Offline characterization of the nozzle in conditions similar to operation show a Mach number of ~ 4 at the nozzle exit.[5]

The SGI has a throughput of 2.2×10^{21} D at. s, or 31.5 Torr l s. It is mounted on a movable vacuum bellows that allows the SGI to move radially. It is normally positioned within 1 cm of the last closed flux surface as defined by the limiter on the rf antenna. The SGI has a fast gas dynamic time and is responsive down to ~ 1 ms. Experimental measurements made during plasma operations point to a fueling efficiency of $\sim 25\%$. This is compared to $\sim 10\%$ of the conventional puffer.

MEASURING τ_p^*

In earlier experiments with liquid lithium on CDX-U it was found that the external gas puffers had to be run throughout the discharge to maintain the electron density (n_e) at levels comparable to discharges without lithium.[2] The liquid lithium surfaces were very effective at pumping the atomic deuterium working gas. The SGI was developed in response to this need as a means of more efficient external fueling. It also became apparent that it would be possible to obtain measurements of the effective particle confinement time τ_p^*.

If all external fueling is turned off, the average density $\bar{n}_e$ will decay according to a simple exponential decay. The observed density decay can then be fit to the following form:

$$N_e = N_e(0)\exp\left(-\frac{t}{\tau_p^*}\right). \quad (1)$$

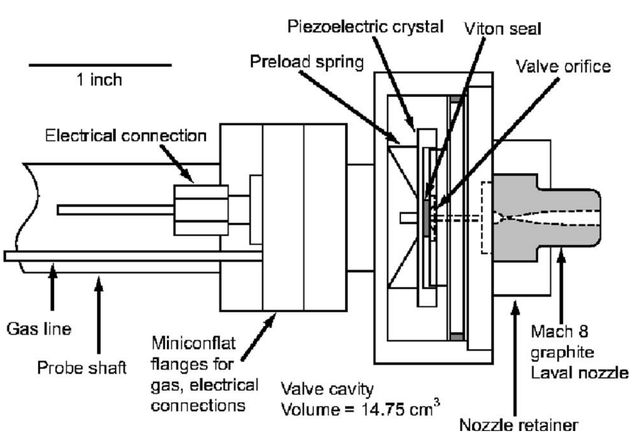

FIG. 2. Supersonic gas injector (SGI). The SGI is built around a Veeco PV-10 piezoelectric valve. It is mounted on the end of vacuum bellows which enables the nozzle to be positioned radially with respect to the plasma. The nozzle itself is based on a Mach 8 design and is constructed out of graphite, which allows it to be positioned in close proximity to the plasma.

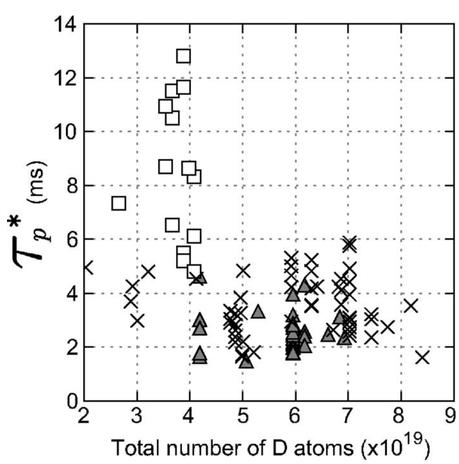

FIG. 4. τ_p^* vs external fueling. The number of D atoms injected is the amount added by the two external gas feeds. The shots represented by squares have relatively fresh cold clean lithium in the toroidal tray limiter. The x's represent discharges in which the lithium in the tray was liquified by means of the electron beam. The triangles represent discharges where the liquid lithium in the tray was heated by heaters mounted on the tray.

τ_p^* is the density decay time of this exponential fit. It is intimately related to the recycling coefficient R and can also be expressed as

$$\tau_p^* = \frac{\tau_p}{1-R}. \tag{2}$$

As $R \to 1, \tau_p^* \to \infty$ and as $R \to 0, \tau_p^* \to \tau_p$.

τ_p^* is usually much larger than τ_p since most tokamaks operate in a high recycling regime with $R \sim 1$. On CDX-U this is certainly the case; on shots with no lithium, it is impossible to measure τ_p^* since it is longer than the discharge time. However, when there is liquid lithium in the toroidal tray or there are fresh lithium PFC coatings, the particle pumping effect is large enough that τ_p^* can be measured.

The SGI was used to determine τ_p^* by injecting short pulses of deuterium gas fuel into the plasma. The fast gas dynamic time of the SGI enables it to have a rapid shutoff with relatively little "dribble," making it ideal for the task. Before the peak in the plasma current, the gas feed was shut off. The decay of the line integrated density following the termination of gas was fitted to Eq. (1). An example of this can be seen in Fig. 3.

RESULTS FOR CDX-U PLASMAS

Following this method, values of τ_p^* were obtained for a variety of shots. As can be seen in Fig. 4, shots with liquid lithium had dramatically reduced values of τ_p^*. Consequently, they were also capable of utilizing large amounts of external fueling. Larger values of τ_p^* were obtained when the lithium was solid and the time elapsed since the last heating and evaporation cycle was less than two days. It was not possible to measure τ_p^* for discharges in which the solid lithium had not been liquified in the previous two days or when there was no lithium in the vessel at all.

On short duration discharges such as those found on CDX-U, the effective particle confinement time τ_p^* can be difficult to measure since its value is long compared to the discharge duration. It can be reduced significantly by application of large amounts of liquid lithium to the PFC's. This reduction due to the low recycling lithium surfaces enables one to perform this measurement. A particle source that is closely coupled to the plasma, such as the SGI, is also necessary in making this measurement on a short duration plasma.

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