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Extremely low recycling and high power density handling in CDX-U lithium experiments

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Abstract

The mission of the Current Drive eXperiment-Upgrade (CDX-U) spherical tokamak is to investigate lithium as a plasma-facing component (PFC). The latest CDX-U experiments used a combination of a toroidal liquid lithium limiter and lithium wall coatings applied between plasma shots. Recycling coefficients for these plasmas were deduced to be 30% or below, and are the lowest ever observed in magnetically-confined plasmas. The corresponding energy confinement times showed nearly a factor of six improvement over discharges without lithium PFC's. An electron beam (e-beam) for evaporating lithium from the toroidal limiter was one of the techniques used to create lithium wall coatings in CDX-U. The evaporation was not localized to the e-beam spot, but occurred only after the entire volume of lithium in toroidal limiter was liquefied. This demonstration of the ability of lithium to handle high heat loads can have significant consequences for PFC's in future burning plasma devices.
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1. Introduction

The primary mission of the Current Drive eXperiment-Upgrade (CDX-U) spherical tokamak has been to investigate lithium as a large area plasma-facing component (PFC). This research has been motivated by the need to develop materials that would be suitable for a first wall in a fusion reactor. Liquid metals as a first wall material introduce complexities related to their fluid nature. Their advantages, however, make them attractive compared to solid material alternatives.

For example, liquid metals can be made to flow through the reactor chamber, and this characteristic

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enables high heat handling while significantly minimizing activated waste [1]. Liquid lithium in particular can reduce recycling at the plasma boundary [2]. Theoretical predictions have shown that the flat temperature profiles achievable under such conditions can lead to stable confinement regimes, and result in significant performance improvements for ITER-scale plasmas [3]. Using a combination of a toroidal liquid lithium limiter and lithium wall coatings, the latest CDX-U experiments have made significant progress in demonstrating the benefits of lithium PFC's for tokamak discharges.

2. Extremely low recycling with lithium plasma-facing components

Since CDX-U is a spherical tokamak, its plasmas have low aspect ratios, with a typical major radius of 34 cm and a minor radius of 22 cm (Fig. 1). The toroidal field on axis is 2.1 kG, and the maximum plasma current is about 80 kA. Central electron temperatures are in the 100 eV range, and line-averaged densities are between 0.5 and 1×10^{19} m^{-3}.

Most of the lithium PFC experiments on CDX-U were performed with a fully-toroidal liquid lithium limiter [4]. The lithium was contained in a stainless steel tray in two semicircular halves at the bottom of the vacuum vessel (Fig. 1). The tray was 10 cm wide and 0.64 cm deep, and centered at the plasma major radius of 34 cm. Resistive heaters beneath the tray were used to control the lithium temperature. When the tray was filled, its 2000 cm^2 area provided the largest free surface lithium surface PFC to date for a tokamak plasma.

Substantial changes in plasma behavior were observed in these experiments. In discharges without a liquid lithium limiter, only a 'prefill' of gas had to be injected prior to forming the plasma. Wall recycling then provided sufficient fueling for the duration of the discharge. For this reason, a recycling coefficient of 1 was assigned to these plasmas. Up to 8 times the prefill gas puff, however, was required during discharges with a liquid lithium limiter to achieve a comparable density, and this is consistent with a much lower recycling coefficient [5,6].

In the last series of CDX-U experiments, techniques for applying lithium coatings to the vacuum vessel walls were tested, and their effects on plasma performance were explored. The lithium wall coatings for the creation of active lithium PFC's were obtained with a resistively-heated lithium oven and an electron beam (e-beam) for evaporating the lithium in the toroidal limiter. Under these circumstances, a particle pumping rate of $1–2 \times 10^{21}$ particles/second was achieved from an active wall area of only 0.4 m^2.

Active lithium PFC's result from lithium being evaporated continuously during the discharge when the resistively-heated lithium oven was operated, or if the lithium evaporation ended within 30 s prior to plasma initiation in the e-beam evaporator case. Lithium PFC's were considered inactive if their coatings were left overnight or longer without new lithium being evaporated onto them. This was based on the fact that the CDX-U vacuum was typically in the 10^{-8} Torr range, with the primary contribution coming from the partial pressure of water.

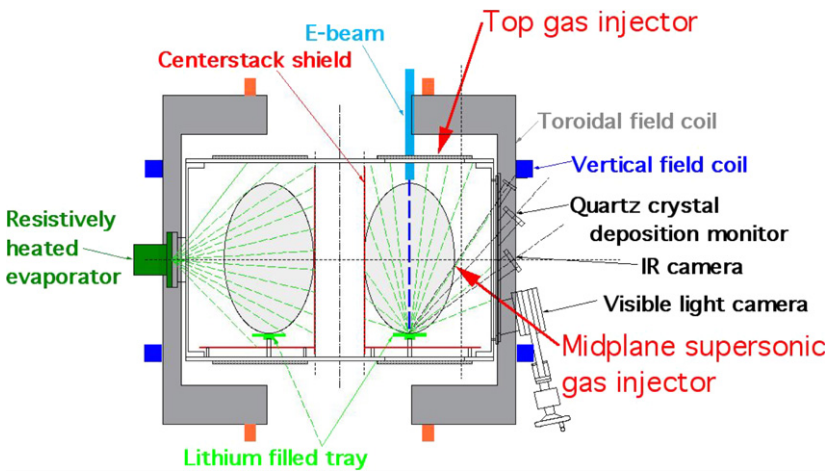

Fig. 1. Schematic of CDX-U showing components related to lithium PFC's, plasma fueling, and diagnostics.

The deuterium alpha light in the vicinity of the centerstack, which is the primary contact point for CDX-U discharges, was measured with a filterscope [7]. The emission levels in plasmas without liquid lithium in the limiter tray were about a factor of three to four higher than discharges with a liquid lithium limiter [5,6]. Since the recycling coefficient (R) for plasmas that are limited on an empty tray is assumed to be 1, the ratio of the filterscope signals provides an estimate of R for the liquid lithium limiter case. The deuterium alpha light levels have to be corrected, however, for any difference in the edge parameters, which were measured with a triple Langmuir probe.

For discharges with and without a liquid lithium limiter, the edge density was $1 \times 10^{12}\,\mathrm{cm}^{-3}$, but there was a difference in the edge electron temperature. Without a lithium limiter, the edge electron temperature was 20 eV, while in the liquid lithium case, its value was 30 eV. The deuterium alpha emission increases with electron temperature, and when modeling of the relevant atomic physics is used to compensate for this effect [8–10], a value of 0.3 for R is deduced for plasmas with a liquid lithium limiter.

The energy confinement time τ_E is defined as follows:

$$\tau_E = \frac{W_{\mathrm{kinetic}}}{\left(-\frac{d\psi_{\mathrm{edge}}}{dt} I_p - P_{\mathrm{mag}} - P_{\mathrm{kinetic}}\right)}, \quad (1)$$

where W_{kinetic} is the stored plasma kinetic energy, and V_{edge} is the surface voltage

$$V_{\mathrm{edge}} = \frac{d\psi_{\mathrm{edge}}}{dt}. \quad (2)$$

Because the Ohmic heating power is delivered to CDX-U plasmas by discharging capacitor banks, both the time derivative of the magnetic stored energy (P_{mag}) and the time derivative of the stored kinetic energy (P_{kin}) must be evaluated in calculating the energy confinement time.

The Equilibrium and Stability Code (ESC) [11] was used to reconstruct the plasma equilibria that permitted the contributions to τ_E to be deduced for CDX-U discharges [12]. The ESC was used to determine when the time derivative of the magnetic stored energy was zero. This was close to the peak in the plasma current, as measured with a Rogowski coil. The ESC also provided the poloidal flux at this time, and thus the surface voltage.

Energy confinement times deduced from this approach were obtained for plasmas with active and inactive lithium PFC's. In plasmas with inactive lithium coatings, energy confinement times were in the 1–2 ms range. With active lithium coatings, these values rose to between 5 and 6 ms. The improvement in energy confinement is most strongly correlated with the time rate of change of the plasma density, or 'pumpout rate' (Fig. 2). Fueling during the discharge was provided with a supersonic gas injector (SGI) [13].

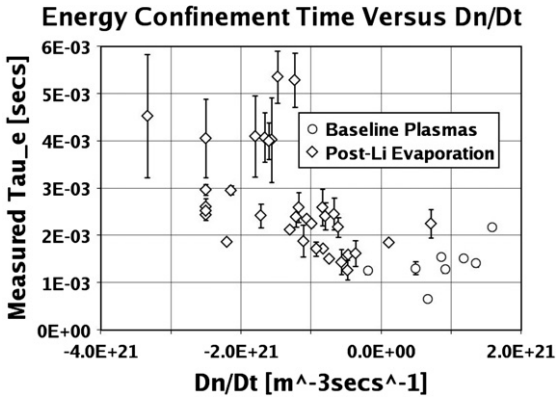

Fig. 2. Energy confinement time as a function of rate of change of density.

The pumpout rate was obtained by terminating the SGI fueling just before the peak in the plasma current, and measuring the decay rate of the line-averaged density with a microwave interferometer. The largest energy confinement times occur when the highest pumpout rates are observed. These rates are expected with low recycling walls, and they are correlated with discharges having active lithium PFC's. Plasmas with inactive lithium PFC's have low or even positive time rates of change in the plasma density after the SGI fueling ended, and they had the lowest energy confinement times.

3. High power handling with liquid lithium

One of the techniques for the production of lithium evaporative coatings also demonstrated the effectiveness of liquid lithium in redistributing extremely high heat loads. The e-beam was used to deposit about 1.5 kW of power on a 6 mm spot on the toroidal lithium limiter. If conduction was the only mechanism for heat dissipation, such power densities would mean that within tens of milliseconds, the lithium reaches the 400–500 °C temperature range where significant evaporation occurs. Instead, the entire volume of lithium in the tray first

liquefied before any evaporation was observed. The power deposited by the e-beam was effectively dissipated, even though the lithium had a depth of only 3 mm.

Support for convection as the power dissipation mechanism was provided by infrared camera images (Fig. 3). The camera views a section of the tray at an oblique angle (Fig. 1), so that its curved inner and outer edges are visible in the images. Regions of comparable brightness correspond to broad temperature isotherms. While the entire tray was above the 180.5 °C melting point of the lithium, the darkest, coolest isotherm in the image actually includes the e-beam spot. The regions of intermediate brightness and the brightest regions correspond to isotherms that include temperatures up to 55 °C and 100 °C, respectively, above the coolest isotherm. The swirling pattern in the image reflects the convection that dissipates the heat from a small region with a power density of about ~50 MW/m^2 for the 240 s duration of the e-beam pulse. The exact drive mechanism for the convection is still uncertain, but the Marangoni effect [14], which is related to surface tension differences caused by temperature gradients, offers a possible explanation.

The Marangoni effect arises as the surface tension of a fluid decreases with temperature. The MHD equation of motion for liquid lithium can be written as follows:

$$\rho \frac{\mathrm{D}\vec{V}}{\mathrm{D}t} = -\nabla P + \vec{j} \times \vec{B} + \nu \Delta \vec{V}. \tag{3}$$

The product of the density and the time derivative of the lithium velocity depends on the pressure gradient, the $j \times B$ force, and the viscosity.

The following viscosity boundary condition has to be satisfied:

$$\nu \frac{\partial \vec{V}_s}{\partial n}\bigg|_{\text{surface}} = \frac{\mathrm{d}\sigma(T)}{\mathrm{d}T} \nabla_s T_s. \tag{4}$$

The vector n is normal to the lithium in the tray, and s is parallel to its surface. The drive term for the Maragoni flow arises from the product of the temperature derivative of the surface tension, $\sigma(T)$, and the temperature gradient across the lithium surface.

Eq. (4) can be solved for the fluid velocity in terms of the temperature gradient resulting from the e-beam

$$\frac{\partial \vec{V}}{\partial n} = \frac{1}{\nu} \frac{\mathrm{d}\sigma(T)}{\mathrm{d}T} \nabla_s T_s, \tag{5}$$

$$\vec{V} = \frac{1}{\nu} \frac{\mathrm{d}\sigma(T)}{\mathrm{d}T} \nabla_s T_s d. \tag{6}$$

The relationship between the flow thickness d and the skin depth specifies the time scale for setting up the convective motion. When lithium parameters are used, a temperature gradient of 10^5 K/m would

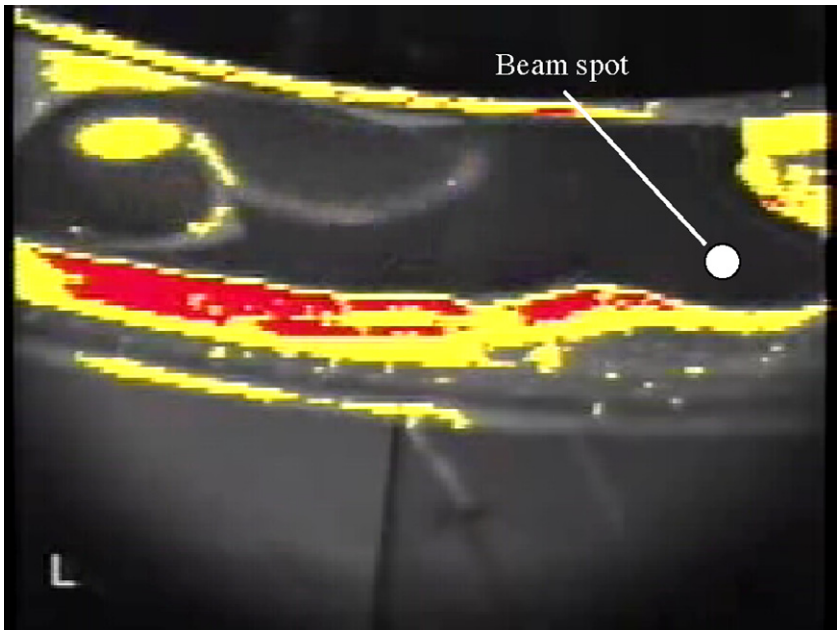

Fig. 3. Infrared image of liquid lithium in limiter tray during e-beam heating.

establish a velocity of 10 m/s within a fraction of a second. Fast flows could then be possible in CDX-U, where temperature gradients of hundreds of degrees over several millimeters are rapidly created by the e-beam heating of the lithium. While detailed analysis has yet to be performed, the model provides a qualitative explanation for the rapid lithium motion that enables the efficient heat dissipation observed experimentally.

4. Conclusions and future plans

Dramatic improvements in plasma performance were observed in CDX-U with partial PFC coverage with lithium. How these results extend to plasmas almost completely enclosed within a lithium PFC conformal shell will be investigated in the Lithium Tokamak experiment (LTX), which is under construction.

The conformal copper shell of LTX will fit inside the existing CDX-U vacuum vessel, with a lithium coating evaporated onto its inner stainless steel liner. By heating the shell above the melting point of lithium, the PFC's will be liquid lithium. The resulting low recycling wall is expected to cause major changes in the temperature, density, and current profiles and transport that go well beyond those observed in CDX-U.

The CDX-U results also have potentially significant consequences for PFC's in future burning plasma devices. The demonstration of efficient convective heat dissipation when heated with an intense e-beam suggests that lithium may have important applications in the handling of extremely high power densities.

Acknowledgement

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