Upward-facing Lithium Flash Evaporator for NSTX-U*

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Abstract−NSTX plasma performance has been significantly enhanced by lithium conditioning [1]. To date, the lower divertor and passive plates have been conditioned by downward facing lithium evaporators (LITER) as appropriate for lower null plasmas. The higher power operation expected from NSTX-U requires double null plasma operation in order to distribute the heat flux between the upper and lower divertors making it desirable to coat the upper divertor region with Li as well. An upward aiming LITER (U-LITER) is presently under development and will be inserted into NSTX-U using a horizontal probe drive located in a 6" upper midplane port. In the retracted position the evaporator will be loaded with up to 300 mg of Li granules utilizing one of the calibrated NSTX Li powder droppers[2]. The evaporator will then be inserted into the vessel in a location within the shadow of the RF limiters and will remain in the vessel during the discharge. About 10 seconds before a discharge, it will be rapidly heated and the lithium completely evaporated onto the upper divertor, thus avoiding the complication of a shutter that prevents evaporation during the shot when the diagnostic shutters are open. The minimal time interval between the evaporation and the start of the discharge will avoid the passivation of the lithium by residual gases and enable the study of the conditioning effects of un-passivated Li surfaces [3].

Two methods are being investigated to accomplish the rapid (few second) heating of the lithium. A resistive method relies on passing a large current through a Li filled crucible. A second method requires using a 3 kW e-beam gun to heat the Li. In this paper the evaporator systems will be described and the pros and cons of each heating method will be discussed.

Keywords_- Lithium evaporator; e-beam heating; spherical tokamak

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I. Introduction:

Lithium evaporators have been utilized on NSTX since the 2008 run campaign. Li has shown to be beneficial in reducing recycling, and mitigating the deleterious effects of ELMS. The present evaporators have a Li reservoir capable of holding up to 80 gms of molten Li. The reservoir is heated to ~ 400°C in the morning and usually remain at temperature all day, evaporating continuously. This method was adopted since the time it takes between discharges to reheat the evaporator to ~400°C, where evaporation occurs, and then to cool it to below 250°C where evaporation is virtually eliminated, would result in far fewer discharges in a given run day. Between discharges, the evaporator is inserted into NSTX where it deposits up to 200 mg of Li onto the Plasma Facing Components. However, if the evaporator is "on" when the diagnostic shutters are opened, it will coat any diagnostic window in its line of sight so, when the evaporator is not being used to coat the PFC's, it is retracted from the vessel interior and parked behind a rotating shutter. Approximately 1/3 of the Li inventory is deposited onto the closed shutter and the majority then runs down to a drip pan below.

An upward aiming LITER of the same design would encounter the problem of handling the excess Li discharged onto the closed shutter now located above the evaporator. The excess Li would drip back onto the evaporator and run inside the torus interface valve and probe drive. It is therefore, desirable to redesign the upward-facing system to eliminate this problem. As a basic concept, a system with a limited reservoir capacity of around 200 mg could quickly evaporate its entire contents eliminating the need for a shutter. This would require developing a method to refill the evaporator between shots. Two different methods have been investigated to heat the Li to temperatures where evaporation occurs. The first method requires passing a high current through a crucible made of refractory metal. Boat-style crucibles are industries standards in the thin film industry. A second method utilizes a kV-range electron beam (e-beam) to heat the Li to evaporation temperatures. Each of the methods will be discussed below.

II. Operation of the evaporator

The upward facing evaporator will be mounted on a probe drive. The probe will have an extended stroke of 80cm in order to reach from the loading station, some 40 cm behind the vessel wall, to 30 cm into the interior of the vessel. One of the uppermost ports on a main midplane flange will be utilized in order to reduce the risk that vapor will reach any of the midplane diagnostic ports. The crucible will be loaded using a calibrated Li powder dropper[2]. The crucible will be then be inserted through a 10cm clear aperture flight tube into the vessel to await evaporation.

After evaporation, the standard operating procedure would be to retract the evaporator behind the plane of the vessel before the discharge commences. This will take less than 1 minute to achieve. However, it is possible to park the evaporator in a safe location in the vessel during a discharge to eliminate the retraction time. This will be used to test the hypothesis that the fresher the Li coating, the better the plasma performance. The location inside the vessel is crucial, if designed properly, the evaporation can occur in a location set ~5cm behind the nominal inboard edge of the boron nitride limiters. At this location, it is conceivable to evaporate a few seconds before initiation of a discharge, leaving an off-time of just long enough to open the diagnostic shutters. In this way, the plasma will interact with a truly fresh coating of Li.

After a discharge, retracting and reloading the crucible will require less than approximately 2 minutes with another minute required to insert the evaporator inside the vessel. Even if the crucible had to be reloaded after every discharge, reloading time is far less than the 15-45 minutes period between discharges. A schematic of the system is shown in Fig. 1.

A. Characteristics of a flash evaporator

The evaporator primarily needs to be capable of rapid or “flash” evaporation as opposed to the 10-minute evaporation time presently required for the downward facing LITER’s. The present LITER’s remain hot continuously throughout the day and thus require a shutter to block the vapor during discharges to prevent vapor from coating the diagnostic windows after their shutters are opened. A flash evaporator would either evaporate its entire inventory of Li, or be capable of quickly terminating the evaporation process, by for instance, turning of the electron beam in an e-beam system. Either way, the need for a shutter is eliminated.

Some form of aiming is desired so that the thickest application of Li vapor coats primarily the upper divertor region of NSTX-U and not the surrounding walls. If enough collimation can be provided, it may be possible to separate the importance of Li interaction in the divertor region only, as opposed to the more global interaction with the walls.

Finally the evaporator must be compact enough to fit through a 10cm clear aperture to be accommodated by one of the upper midplane ports on NSTX-U.

There are two competing methods discussed below for the Li flash evaporator, each is an industry standard and each can be adapted to fulfill the requirements needed for the evaporator needs for NSTX-U.

B. Resistive evaporation

The resistive method uses a crucible made from one of the refractory metals. Typically, large current of approximately 500 amperes at 3 volts, passes through the crucible shell quickly raising the crucible temperature to 1800°C, which is well above the 1340°C boiling point of Li. Heat is conducted to the Li from the hot shell causing rapid evaporation. This method is very rugged and can evaporate a gram of Li in less than 3 seconds. The open crucible would naturally be facing upward, and would be easy to fill. However there are a few draw backs with this kind of evaporator. The large currents of ~500 Amperes requires special high-current feed throughs and presents significant risks inside a vacuum vessel, especially on a probe drive that is frequently cycled. Since the entire Li inventory is heated to it boiling point, all of the Li in the crucible will be evaporated, requiring a refill after each discharge. The crucible with be heated to red-hot temperatures and would require a cool-down period so as not to interfere with diagnostic interpretations. Also there is little or no aiming capability, with evaporation occurring upward in 2π steradians though it may be possible to develop an independently heated collimator above the crucible. The lack of aiming implies that the probe would have to be inserted further into the vessel to sufficiently coat the upper divertor requiring a probe with a fairly long stroke.

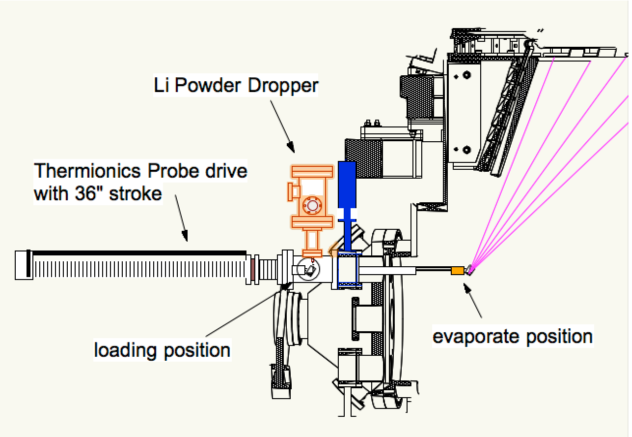

Fig 1. Operation of U-LITER. Loading is done by the Li powder dropper and the evaporator is inserted into NSTX-U by an 80 cm long probe drive.

C. Electron beam evaporation

Electron beam heating has been used to evaporate Li inside of tokamaks previously [4]. The most favorable aspect of the electron beam heating is that the beam strikes the surface of the Li in the reservoir and causes evaporation to occur directly from the surface without significantly elevating the temperature of the bulk of the Li. As soon as the beam is turned off evaporation ceases and the crucible remains cool unless the beam is allowed to directly impact the crucible.

A magnetic field is required to bend the e-beam into the crucible. Typically, a set of permanent magnets are used to bend the beam but these would not survive in the high magnetic fields of NSTX-U. In order to generate the

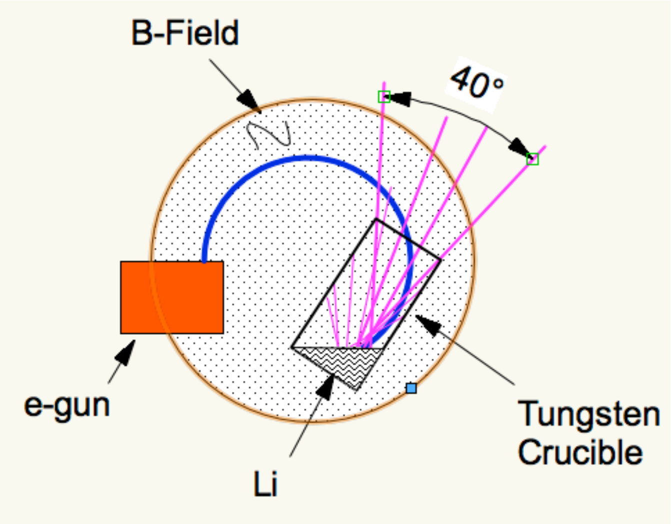

Fig. 2 The crucible depth to opening ratio combined with tilt to crucible will provide modest aiming capability.

required fields, a set of Helmholtz coils need to be installed that move with the e-gun and also easily fit through the 10cm diameter flight tube. Requirements for this coil pair are modest and are discussed below.

Another important advantage of the e-beam system is that rough aiming can be accomplished by proper crucible design and orientation. A ratio of crucible depth to opening of 2:1 and for a beam spot size that fills ~1/3 of the opening, a solid angle of 40 degrees will be obtained. The crucible can be tilted as shown in Fig 2, to aim the 40 degree pattern on the geometric center of the upper divertor.

By concentrating the Li on the upper divertor as opposed to the more global application of the present LITER's it will be possible to separate divertor-only effects from the divertor plus wall interactions.

By controlling either the beam current or beam voltage it is possible to control the power density of the beam impacting the Li. Some control is required to be able to prevent tunneling of the beam through the Li and to maintain control over the evaporation rate. If the evaporation rate can be controlled sufficiently, it may well be possible to fill the crucible with enough Li for up to 4 discharges without refilling.

Comparing the pros and cons of the resistive heating versus e-beam heating it was decided to concentrate on the e-beam system as the more versatile application. A 3-kW e-beam system has recently been ordered.

D. Magnetic Field Requirements of e-beam guns.

A modest magnetic field is required to bend the e-beam into a circular arc. For a beam of between 3-5 kV and 2-3cm bending radius, the required field strength will vary between 60 to 120 Gauss. The more stringent requirement is that the e-beam system and associated Helmholtz coils can be comfortably moved through a 10 cm diameter vacuum system.

Fig. 3 shows the proposed system inside a 10 cm aperture.

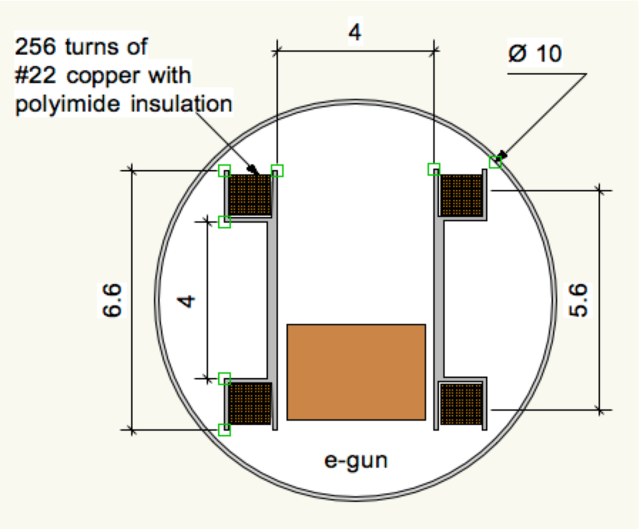

Fig 3. Helmholtz coil parameters required to fit inside of a 10 cm clear aperture

This system allows for a pair of coils with each coil mandrel 6.6 cm in height and can be wound with 216 turns of #22 magnet wire capable of carrying a continuous current of 3 amps. The outside diameter of the coils is ~6 cm. These parameters will produce a field of up to 160 gauss. Because the coil operates in a vacuum, heat buildup in the coil is a concern for the magnet wire insulation. A calculation was made to determine the heat build up during a full day of operation assuming 40 Li applications per day at 140 gauss field and an average on-time of 10 second per application. The heat build up would amount to ~100°C, a temperature well within the working temperature of the polyimide insulation on the magnet wire. In reality, some heat will be radiated away through out the day and the field–on time should in practice be somewhat less that 10 second.

III Considerations for e-beam evaporation of Li

There are some important considerations to account for when applying an e-beam to evaporate Li, which are mostly associated with controlling the power density of the beam. For instance a 3 kW beam focused onto a 1 mm spot size will have a power density of 3000 MW/m^2 whereas the same beam spread over 1 cm area will have 30 MW/m^2. The 1 mm spot size is to be avoided as it can cause tunneling through the Li bulk and begin to evaporate the tungsten crucible and may require beam sweeping to spread the energy to acceptable levels. Assuming the spot size is known, it is useful to know the evaporation rate of the Li. Fig 4 displays the results of calculations that were done at PPPL [5] to determine the evaporation rate for various beam power densities in atoms/cm^2 vaporized versus beam-on time. Note in particular that even at the lowest power density of 10MW/m^2, it takes only ~0.5 seconds for a beam size of 1 cm^2 to evaporate an equal number of Li atoms as

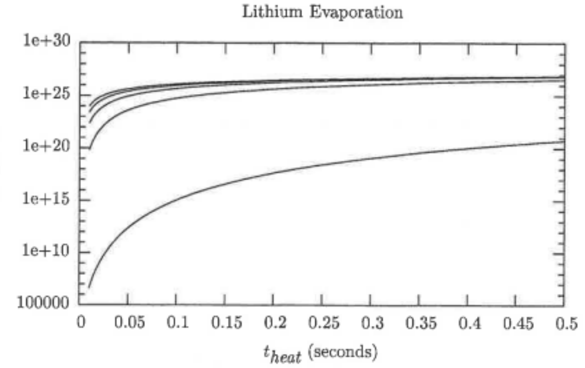

Fig 4 Number atoms vaporized by an e-beam per cm^2 beam foot print as a function of applied power for 10, 82, 155,227 and 300 MW/m^2.

the number of deuterium atoms present in an NSTX discharge (~ $4X10^{20}$ atoms).

Present LITERs typically put down a layer of 200 mg of Li per discharge or about $1.7X10^{22}$ Li atoms. Fig. 5 shows how the evaporation changes as a function of beam voltage for a fixed current of 0.75 amps. It is clear that for a voltage of 2kV and 0.75Amps current, 200 mg could be evaporated in ~ 1 sec making the more risky higher beam energies unnecessary while also reducing the requirements on the magnet current. Of course, for the predicted 5-sec long discharges on NSTX-U, even thicker coatings will almost definitely be applied and the higher beam energies may become necessary.

As mentioned above, knowing the spot size of the beam is important to determine the beam power density. Fig 6 shows how spot size can vary for a fixed beam energy and fixed Helmholtz ratio of radius/gap=1 but increasing the physical size of the coils. For this application, the larger spot sizes are preferred to spread the energy over ~$1cm^2$. This size should be large enough to eliminate the need to sweep the beam across the surface of the Li though additional enlargement of the spot size may be accomplished by varying the gap between the coils. Only experimental time in the laboratory will determine the need for beam-sweeping but it is one more complication that is desirable to eliminate.

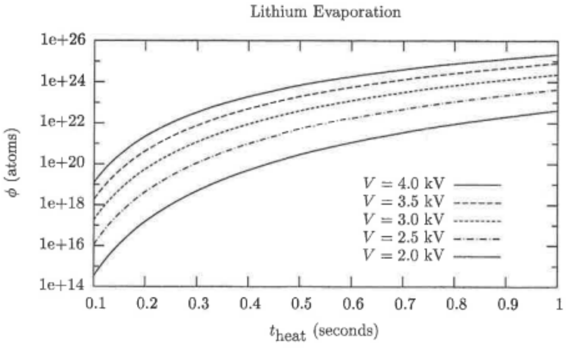

Fig. 5 Number of atoms evaporated as a function of applied voltage. Note that using a 2 kV beam, approximately 200 mg of Li ($1.7 X10^{22}$ atoms) will be evaporated in 1 second.

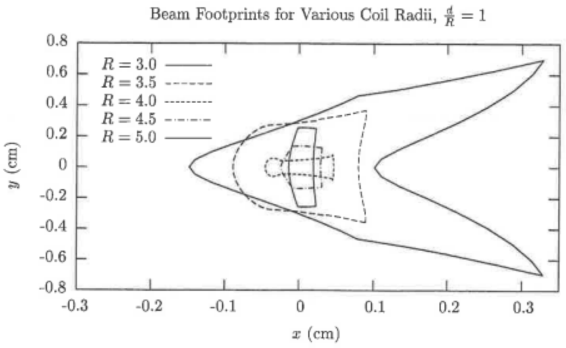

Fig 6. Beam foot print for various size Helmholtz coils each with Helmholtz coil ratio of gap/radius =1. The same beam parameters are used in each calculation.

IV Comparison between e-beam evaporator and present LITER evaporator

Present evaporator technology as used in the LITER evaporators can be improved upon using the e-beam system. Table 1 compares the two technologies. In particular the high surface tension of Li when touching a wetted surface will allow the e-beam system to evaporate downward as well as upward. Also the need for a shutter is completely eliminated and the time scales for evaporation are much shorter. Reloading the powder dropper is significantly easier than reloading the LITER canister, and the e-beam system is more efficient with its use of Li.

	LITER	U-LITER
Probe Required	Yes	Yes
Shutter Required	Yes	Yes
Evaporation time	600 sec	<1 sec
Aiming direction	down only	Up/down
Cool-down time	120 minutes	0 sec (Surface heating only)
Efficiency (Li use)	60%	100 %
# shots/fill	250 with 80 grams	250 with 50 grams
Reload time	48 hours	4 hours
Evaporation end-time before onset of discharge	2 minutes (time to retract probe and close shutter)	5 seconds (time to open diagnostic shutters)

Table 1 Comparison of LITER versus U-LITER parameters

VI Conclusions

An upward facing evaporator has been proposed for NSTX-U. This method utilizes a probe drive to insert the evaporator into the vessel between shots and a calibrated Li powder dropper to refill the evaporator crucible. Two methods of making a flash evaporator were investigated and it was decided on the basis of versatility, to pursue the application of an e-beam evaporator. A target tank is being prepared for testing complete with quartz micro balances to determine the evaporation rate. This system is planned to be installed on NSTX-U after the first run campaign is completed.

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