Li-DiMES Exposures on DIII-D: Erosion Yields and Disruptions

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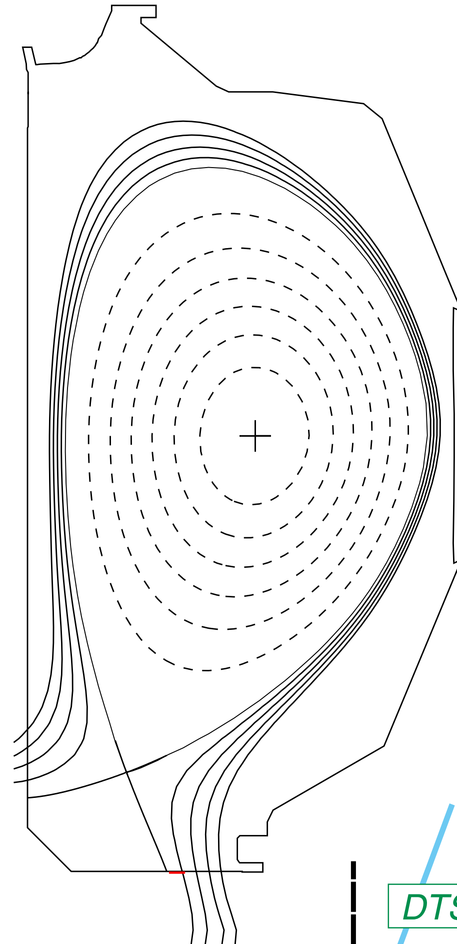
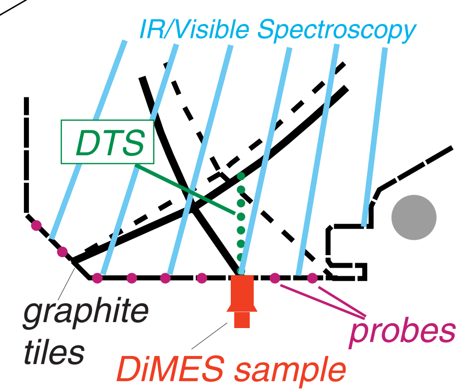
A solid lithium sample was exposed to a very low power DIII-D divertor discharge

- Lower single-null plasma:
  - I_p = 1.1 MA, n_e = 2.5x10^{19} m^{-3}, B_T=2 T.
- L-mode confinement (i.e. no ELMs) maintained with very low heating power:

  P_{NBI} ~ 0.5 MW + P_{ohmic} ~ 0.7 MW = P_{in} ~ 1.2 MW.
- DiMES viewed by one spectrometer, three visible cameras and IR camera.
- Solid lithium sample: O.D. 2.54 cm, thickness 1.3 mm, all-graphite backing.

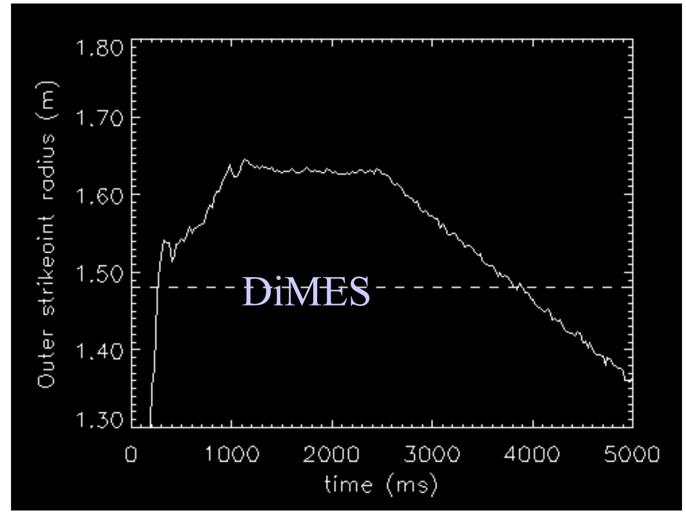


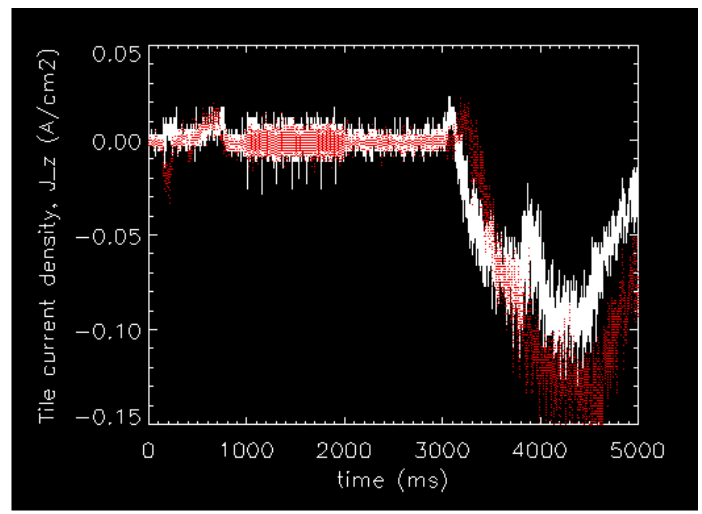


(This is nearly the lowest power discharge available in DIII-D)

The first four exposures swept the OSP past the Li sample

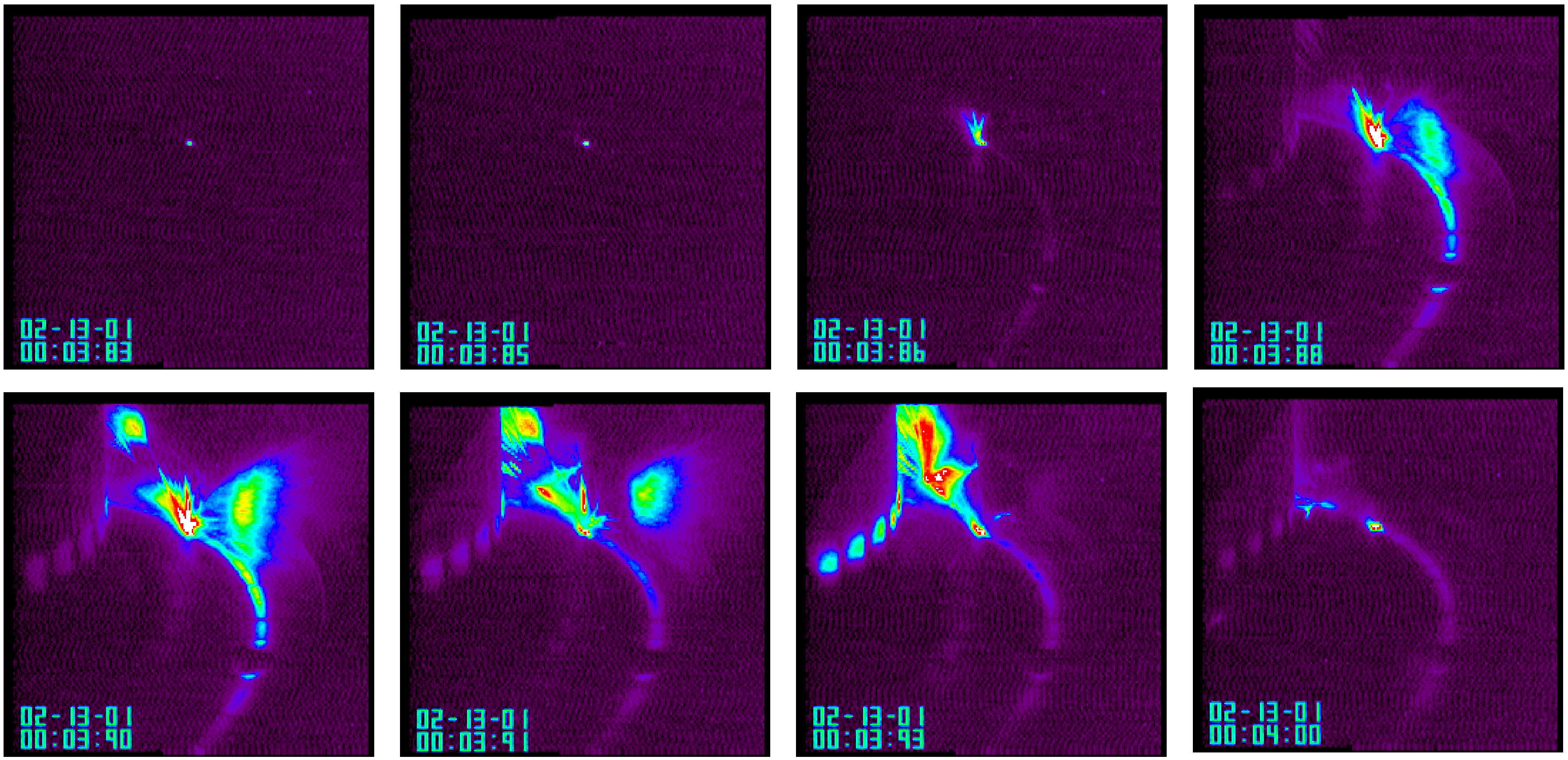
- **First exposure discharge (105506):**
  - Side-viewing camera showed significant "bursts" of lithium removal when the OSP was moved near (see next slide).
  - Subsequent exposure was more quiescent.
  - The lithium bursts had little or no effect on the core plasma.
  - Visual inspection of the sample showed a reflective surface, indicating the lithium had melted.
  - Vertical thermo-electric currents ~ .1 A/cm^2 measured near OSP, going out of plate.
- **Next three exposures (105507-09)**
  - No large influx of lithium.
  - Reproducible shot-to-shot for lithium removal
  - Effective yield near separatrix ~ 10%.

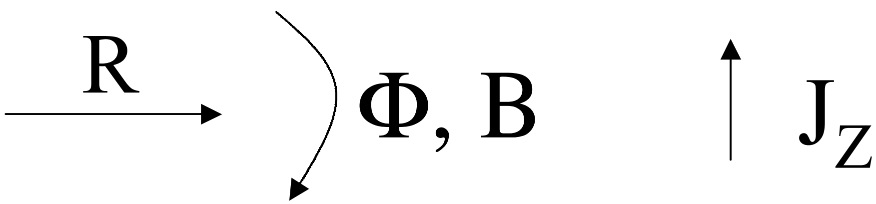




White: f=135°, Red: f=310°
f_{DiMES}=150°

The very first OSP exposure of the lithium resulted in some “bursty” removal of the lithium (105506)

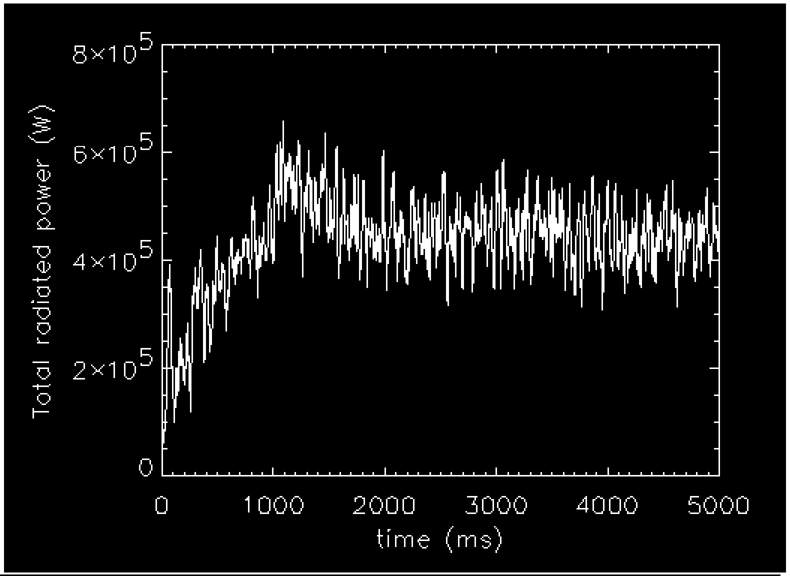




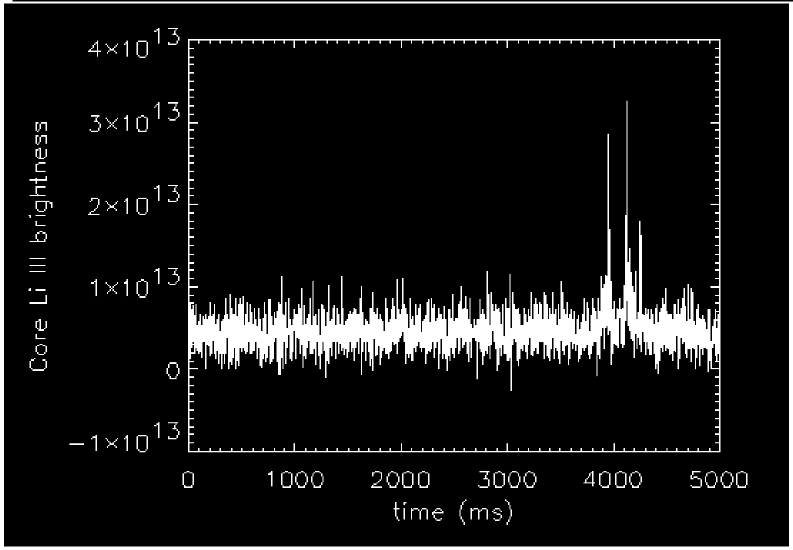
Li I light
(670 nm)

Li bursts in divertor during first exposure shot had little effect on the core plasma

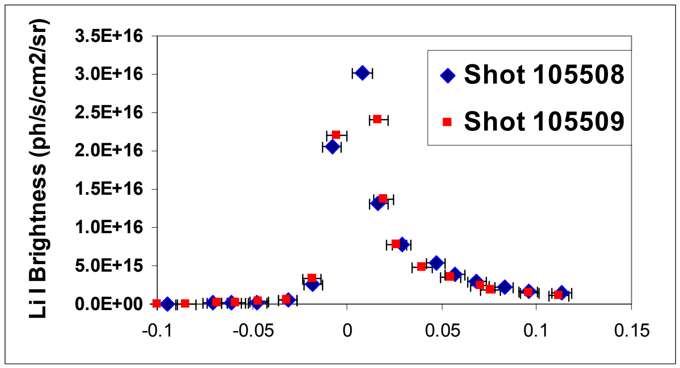
Total radiated power did not change

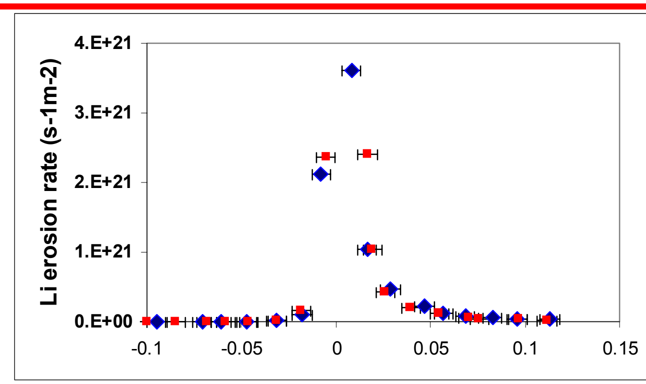


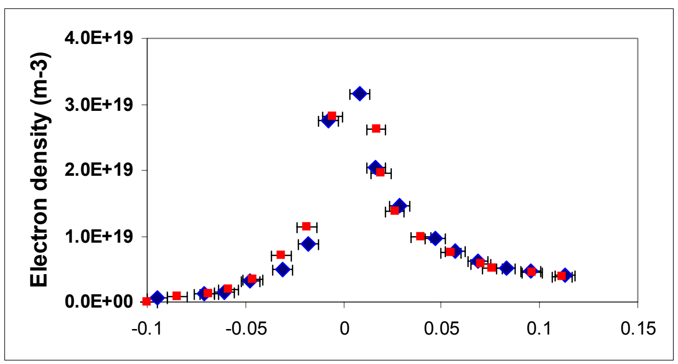
Very weak emissions of Li III in the core plasma

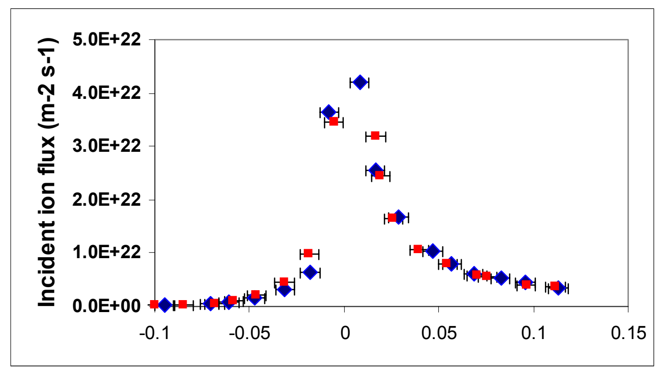


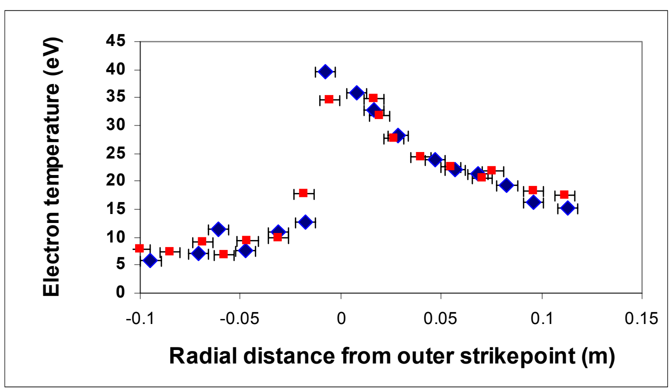
Divertor plasma profiles for Li exposure

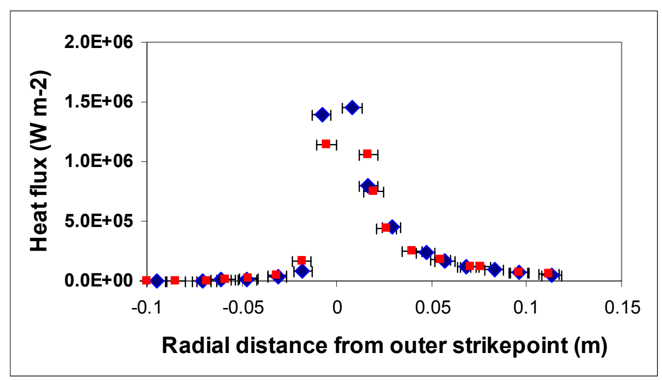




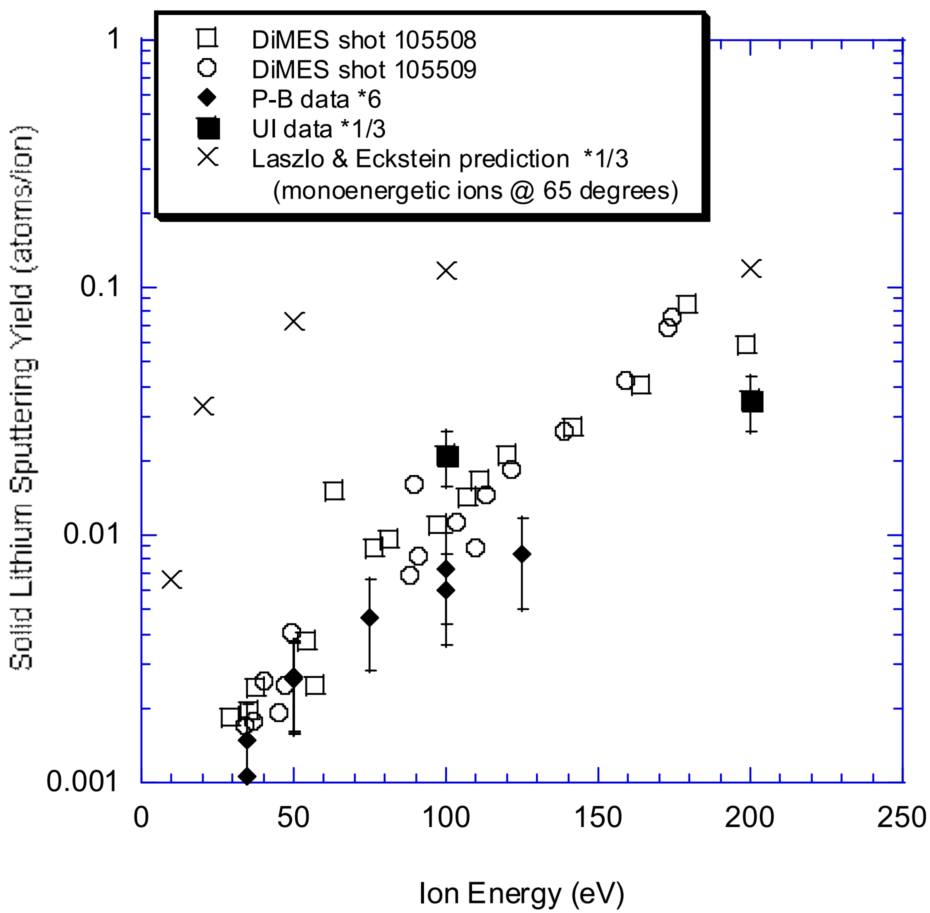








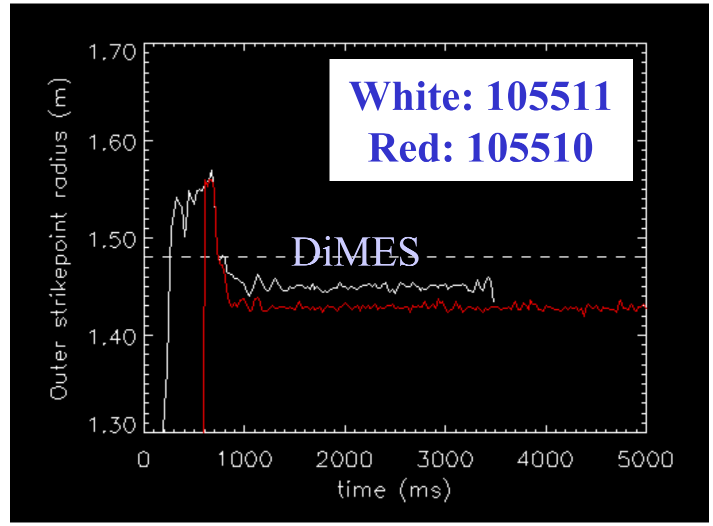
Yield of solid Lithium from reproducible, “well-behaved” swept discharges agrees well with other yield measurements



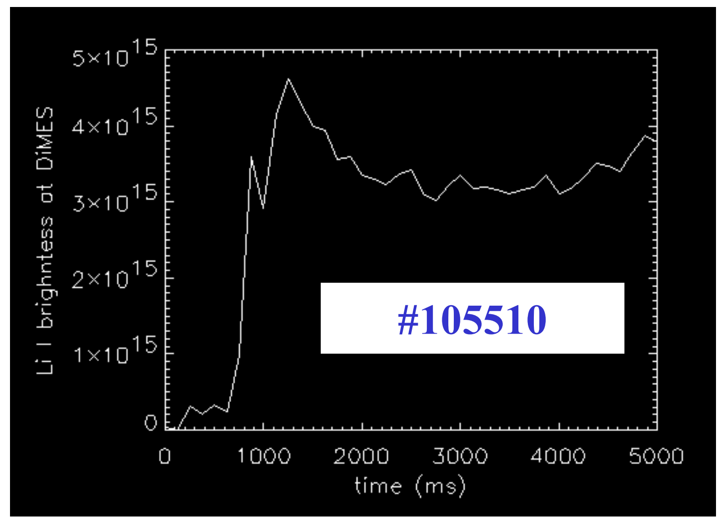
- Yield measurement:
  - Incident flux from Langmuir probe
  - Li efflux from measured Li I brightness x S/XB(n_e,T_e) for transition
- N.B. This is the same technique as developed on PISCES to measured Li erosion yield.

The next two discharges fixed the strikepoint position during the shot

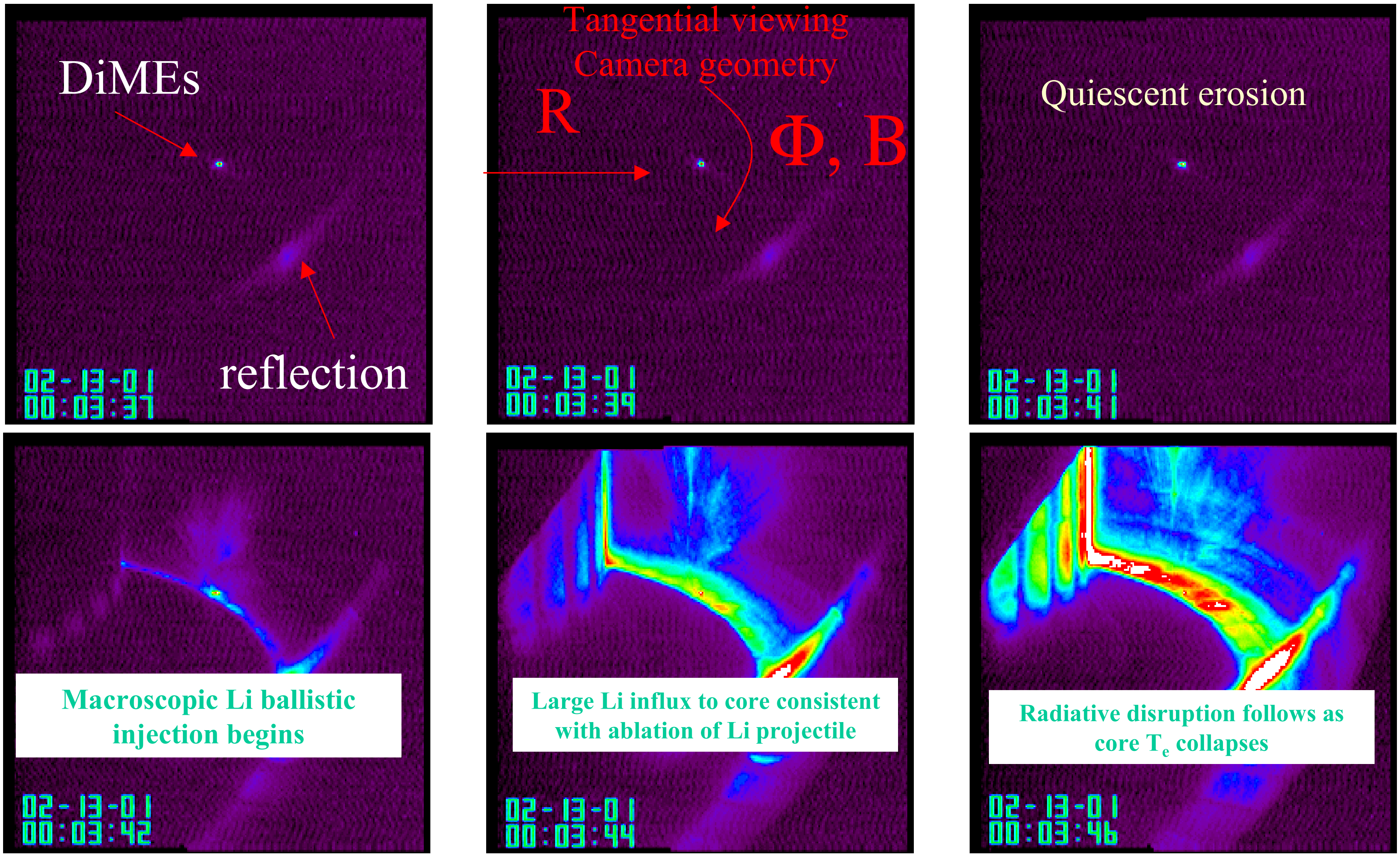
- Shot 105510:
  - OSP ~ 5 cm inboard of DiMES for t >1000 ms.
  - T_e ~ 20 eV, q ~ 0.15 MW/m^2
  - Steady erosion throughout the shot, at a level consistent with the swept discharges.



- Shot 105511
  - OSP ~ 3 cm inboard of DiMES
  - T_e ~ 30 eV, q ~ 0.3 MW/m^2
  - Increasing lithium removal rate t>3000 ms.
  - Radiative disruption occurs at 3478 ms.

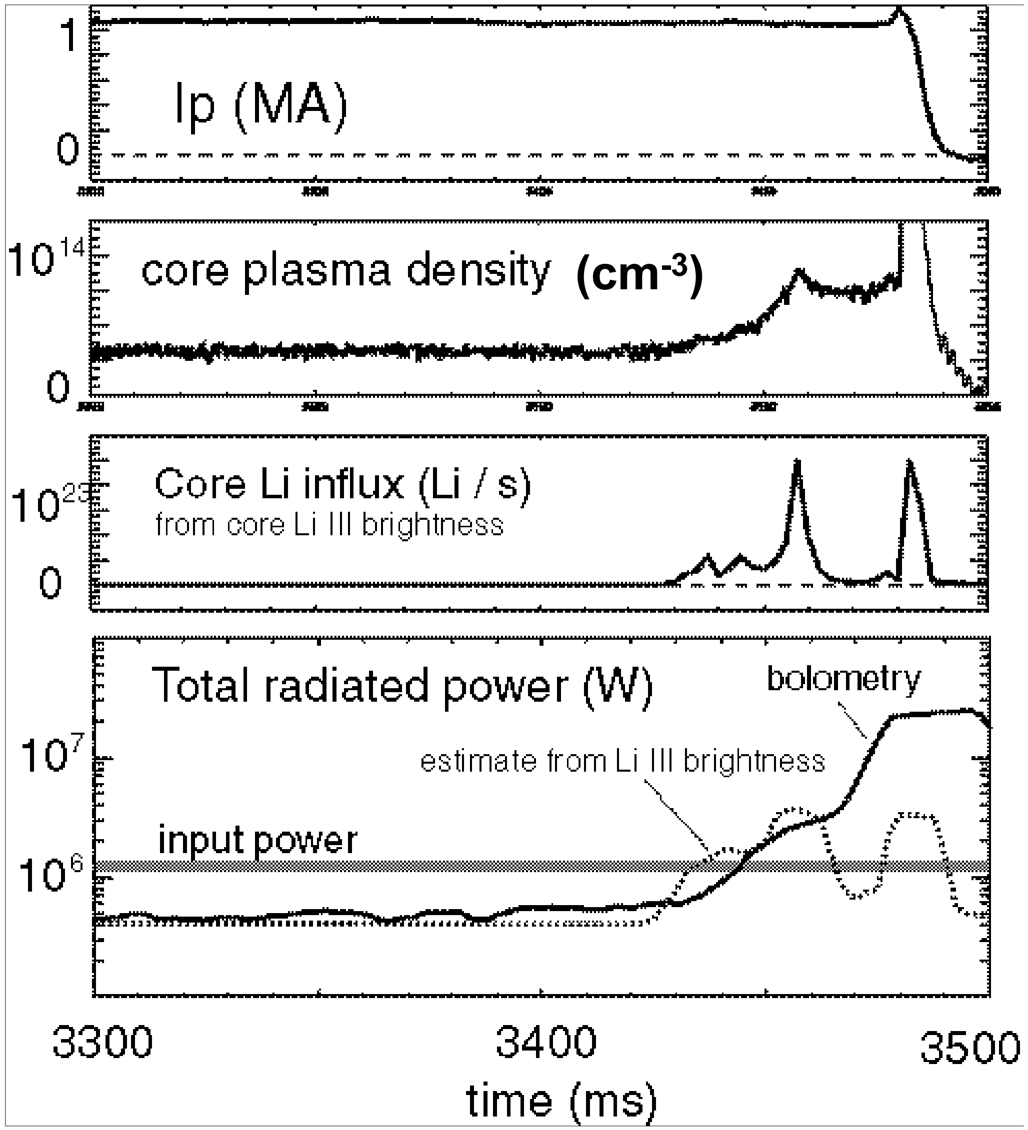


Video sequence of Li I light in divertor , following the large release of Li that causes the disruption (105511)

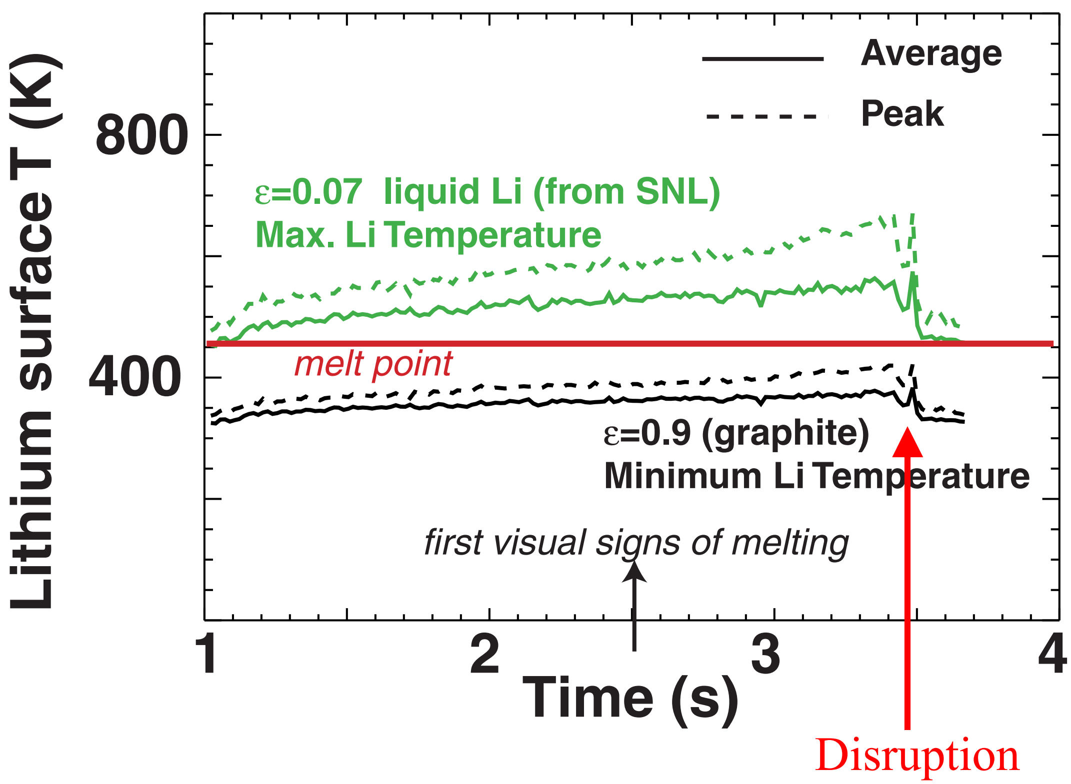


The disruption is caused by a radiative limit due to an enormous influx of Li to the core plasma

- **Lithium completely dominates all other lines on core XUV spectrometer.**
  - **S/XB technique give 0.2-1x10^{23} lithium ionizations / s into core.**
- **Core plasma density doubles in ~ 30 ms coincident with core Li emission**
  - **Implies Li influx / ionization rate ~ 10^{22} s^{-1} in core plasma.**
- **Radiative power becomes much larger than input power leading to a radiative collapse**
  - **Estimate of Li caused radiated power matches well with bolometer.**

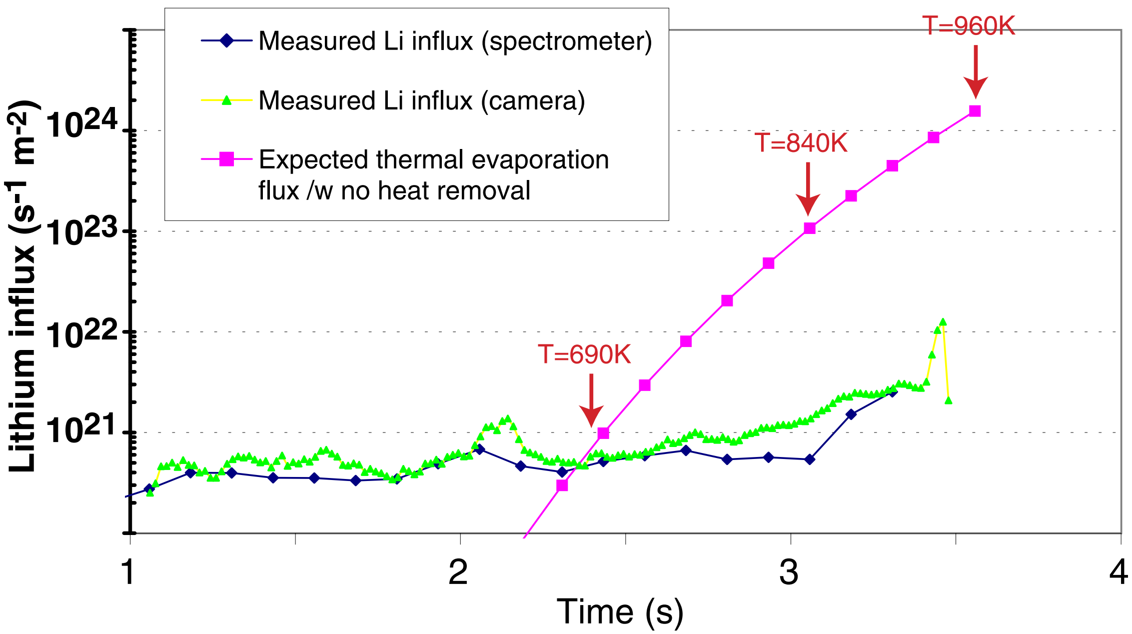


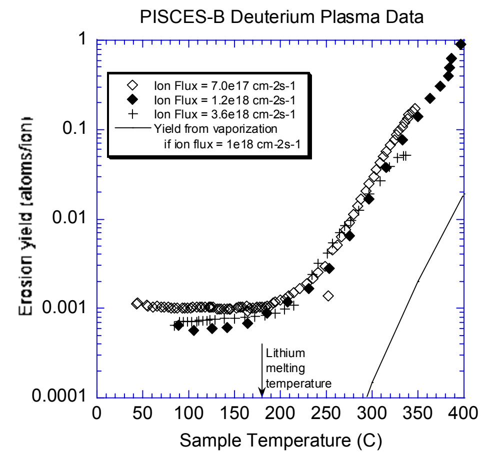
IR Thermography Analysis Indicates that the Lithium Surface Temperature Does Not Go Above 700-800 K. Visual clues from Li imaging suggest that lithium melts somewhere around 2.5-3 seconds into discharge.



- "Corrected temperature" of Li based on:
  - SNL provided ε_{Li}~0.07
  - Solving equality of non-linear Planck's law in IR wavelength region for different emissivity materials.
- Most likely ε and T is in-between these two extremes.
  - Initial temperature should be ~300K.
  - For ultra-pure lithium ε_{Li}~0.04 Ą T_{max}~800K.

Visible atomic Li spectroscopy verifies that the surface temperature could not have greatly exceeded 700K during discharge due to absence of evaporation.



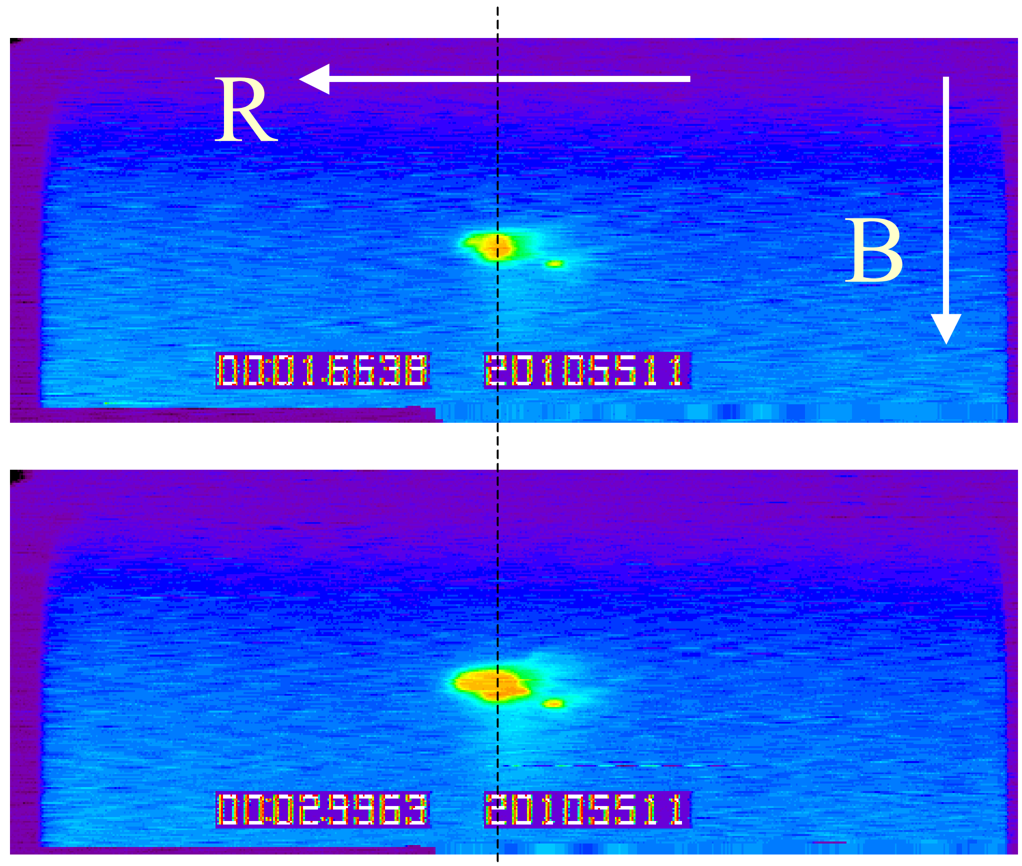


- Above 700K the lithium evaporation itself is the most accurate means of measuring T_{Li}…yet this evaporation is clearly not present up to the point of the "ballistic" injection event.
- The injection event occurred instantly (<20 ms): seems to rule out over-heating as the cause.
- With no thermal contact the sample should heat up to ~1000 K in ~2.5 seconds (SNL result)
  - We should explore reason why our sample seemed to have better thermal contact.

Camera Li I Images Show that the Liquefied Lithium moves on DiMES sample

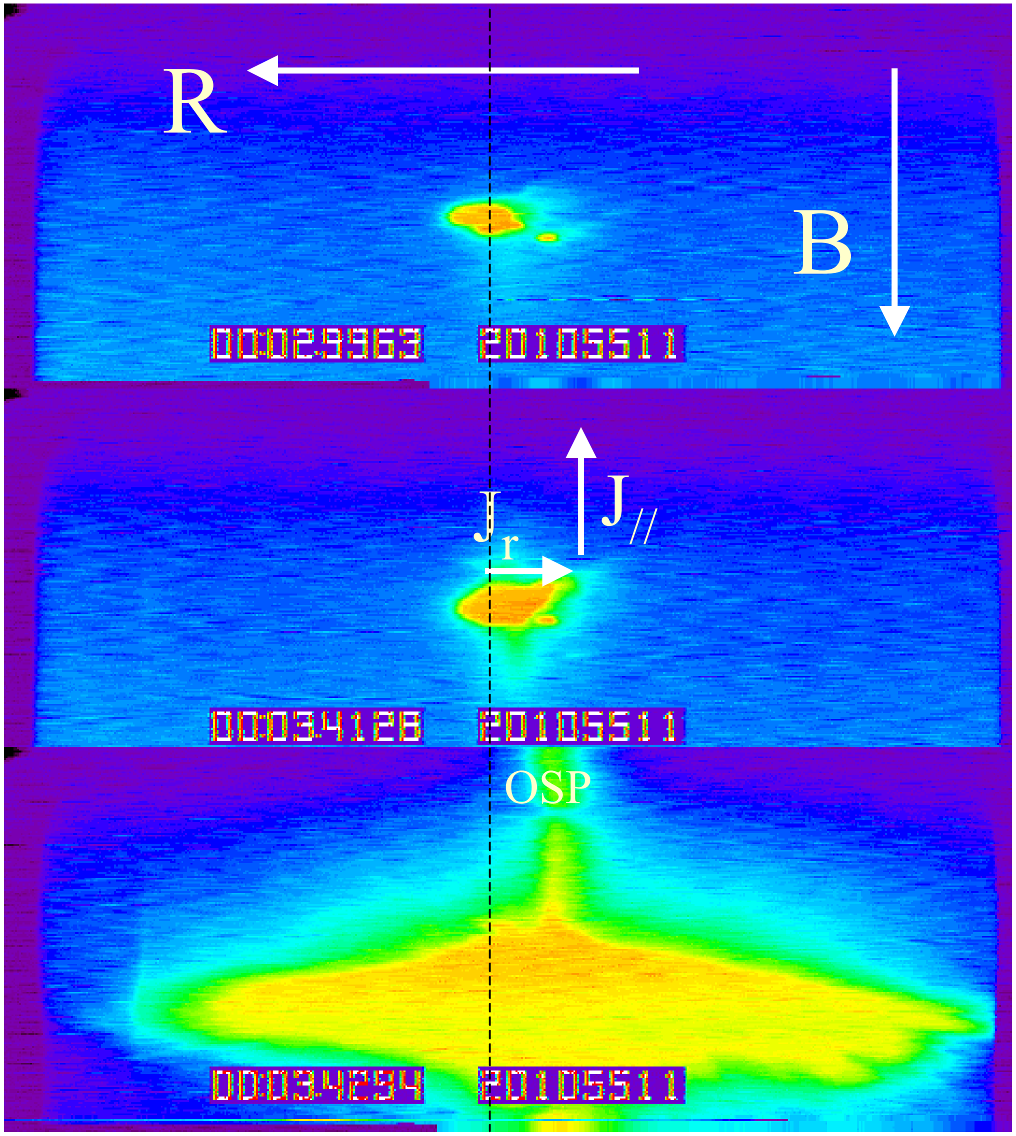
- Exposure for discharge that ends in lithium radiative disruption:
  Ŵεε ~ 0.3 MW m^{-2}
  3 cm outboard of OSP

- Radial outward movement of the lithium seen here is consistent with measured J_z x B direction in steady-state portion of discharge after liquefaction.



Note: mirror image shown

Vertical upward J_rxB force is most likely cause of large lithium removal that caused disruption.

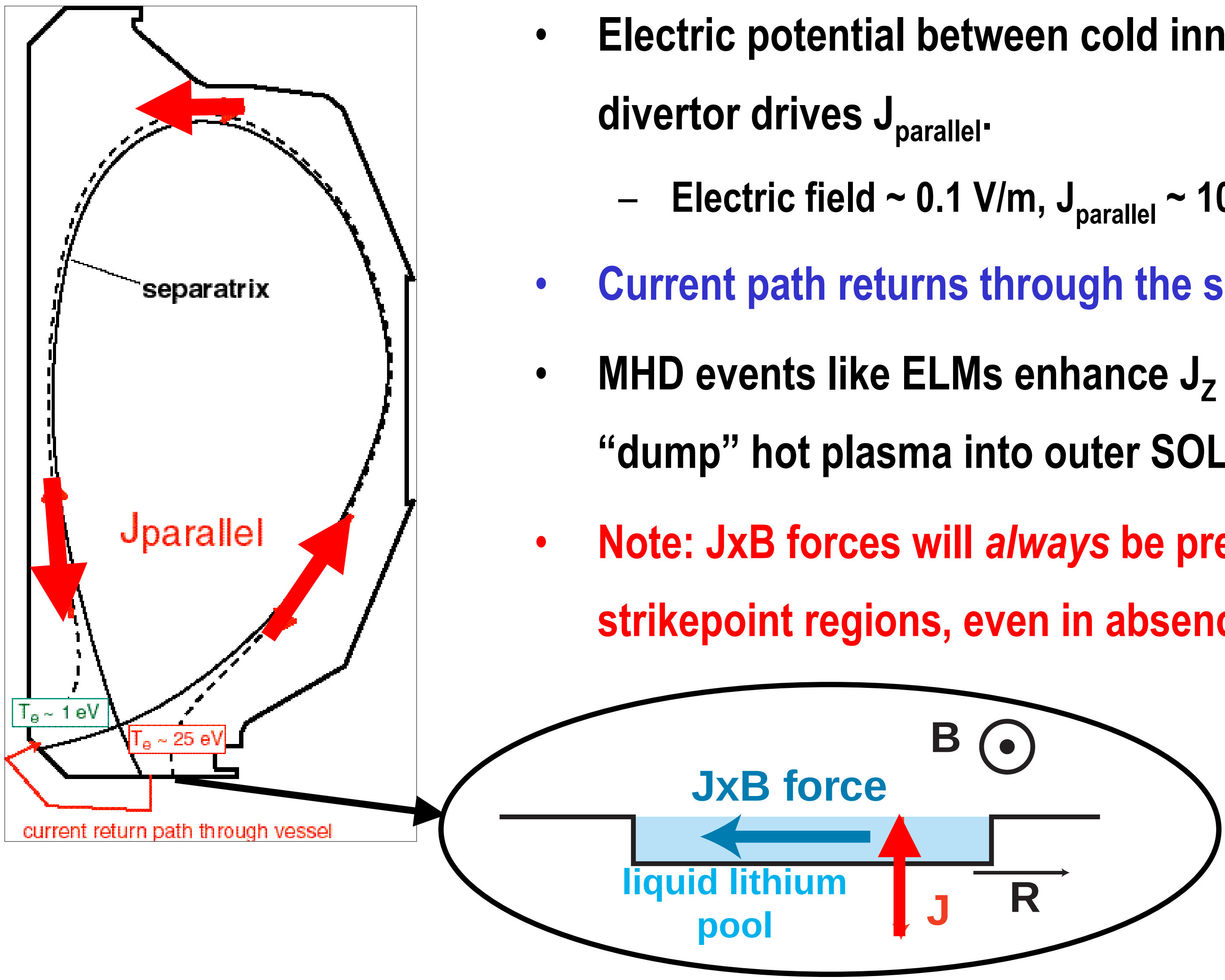


- Close to disruption, the lithium moves radially inward outside of the DiMES cup.
- The large parallel current intercepted by this blob will cause J_r back through DiMES sample.
- Center of lithium release is actually inboard of original DiMES lithium location in cup.
- Estimate of vertical JxB/ρ acceleration seems large enough to cause removal
  - $J_{parallel}$ ~ 35 kA m^{-2}
  - B = 2.1 T
  - a~ $(JxB)\rho^{-1} A_{face}/A_{conduct}$ ~ 150-600 m s^{-2}

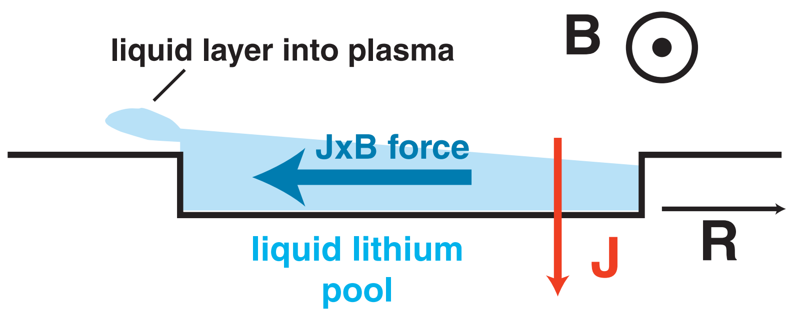
Note: mirror image shown

Large currents are typically driven in the SOL of tokamak plasmas, giving rise to JxB forces at plasma-surface interface

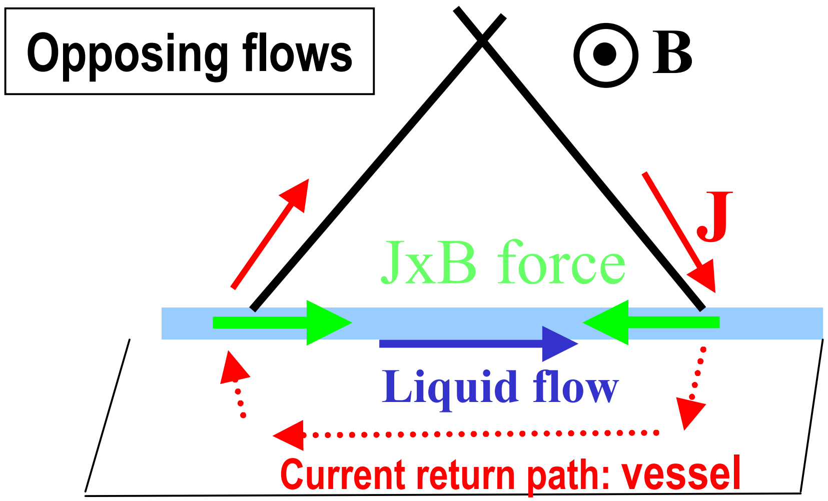
- Electric potential between cold inner and hot outer divertor drives $J_{parallel}$.
  - Electric field ~ 0.1 V/m, $J_{parallel}$ ~ 10^5 A/m^2
- Current path returns through the sheath/vessel, J_Z
- MHD events like ELMs enhance J_Z because they "dump" hot plasma into outer SOL.
- Note: JxB forces will *always* be present near strikepoint regions, even in absence of MHD events.

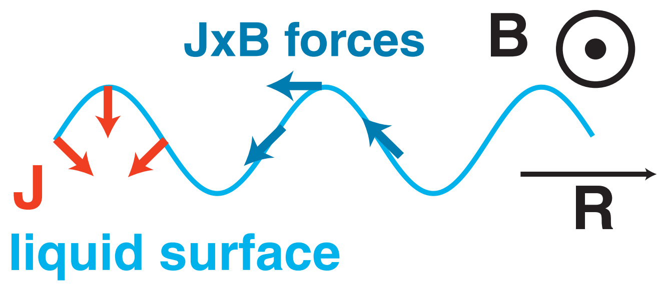


JxB forces can lead to several movement scenarios for the liquid surfaces in the divertor

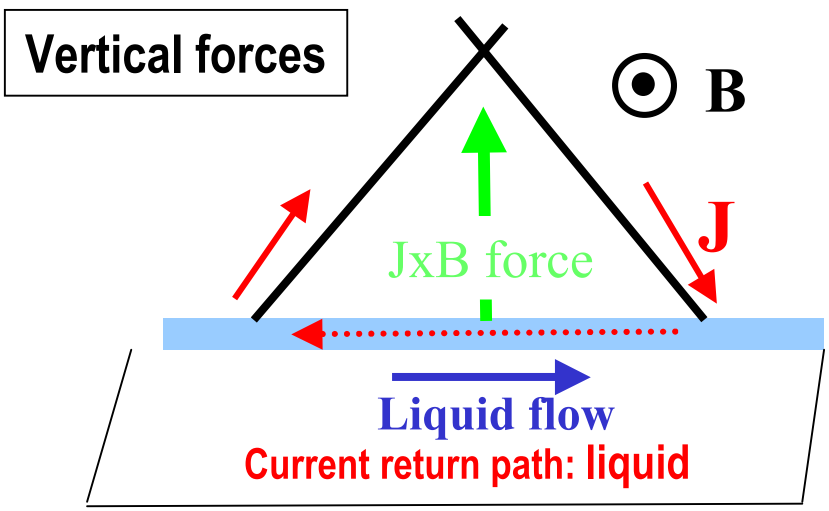


- Splashing out of the static pool.





- JxB acts like a "shearing" force on surface perturbations.



Based on DIII-D/DiMES Experience, MHD Surface Stability is the Main Concern with Liquid-Metal Divertor

- The surface stability or integrity of the liquid is the fundamental issue on the viability to the divertor and plasma.
  - Earlier experiment showed large-scale JxB forces (especially during periodic but non-equilibrium events like ELMs) can readily move the liquid around the divertor (e.g. Three type-I ELMS removed all the lithium from the DiMES cup)
  - More importantly, any surface non-uniformity (i.e. tiny bumps) will likely lead to severe problems:
    - The bump will more quickly evaporate due to parallel heat flux.
    - The bump will also intercept parallel SOL current, which then greatly concentrate J in the interface between the bump and backing layer, probably causing the bump to shear off due to the MHD effect.
  - The core plasma will collapse if the perturbation/loss is macroscopic.
    - Because of low T_e, divertor plasma are essentially transparent to ballistic macroscopic (~mm) projectiles…subsequent ablation/cooling/radiation will take place in high temperature core plasma.

Based on DIII-D/DiMES Experience, MHD Surface Stability is the Main Concern with Liquid-Metal Divertor

- **The DiMES Lithium exposures in the DIII-D tokamak illustrate that tolerance to liquid surface non-uniformity will not be very large.**
  - This naturally arises from the extremely high power / current densities along field lines at grazing incidence to a surface.
  - E.g. a 1 mm steel lip on DiMES near OSP was also able to disrupt plasma.

- **This should not be a surprise..we are placing a free conducting surface into a location of very large MHD forces**
  - Thermoelectric and Pfirsch-Schluter caused SOL currents will *always* be present.
  - E.g. Halo current forces on *solid* objects is always a design concern from disruptions

- **The DiMES experiment indicates a strong need for modeling of the plasma/free-liquid metal surface MHD evolution in a tokamak divertor, with consistent parallel current densities / paths included.**