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Necessary conditions for pumping with liquid lithium

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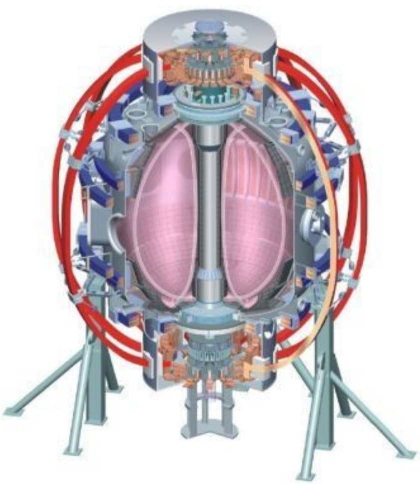

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Conservation of mass must be observed

- Three necessary conditions are described here
  - 1) The number of lithium atoms must exceed the number of implanted deuterium ions
  - 2) The maximum possible rate at which deuterium leaves the surface into the bulk must exceed the incident ion flux
  - 3) Incident deuterium must interact with chemically available lithium
- Possible reasons why some of these conditions may not be met previously in NSTX will be discussed
  - 1) Plasma interacts with the surface layer of the LLD only, not the bulk
  - 2) Diffusivity of hydrogen isotopes in liquid lithium dubious in the literature
  - 3) Unknown quantities of impurities

1:1 trapping ratio is the maximum available

- Laboratory experiment PISCES-B at USCD
  - Linear plasma device
  - 1e22 ions/m2s fluxes
  - 3mm thick X12mm DIA lithium sample
- Retained = incident
  - Indicates Li+D→ LiD is the relevant reaction
  - States, "When saturated, the sample abruptly changes from a low recycling medium to a high recycling medium." p.1321
  - CDX-U – macroscopic pool and reduced density

$$N_{Li} \geq N_D$$

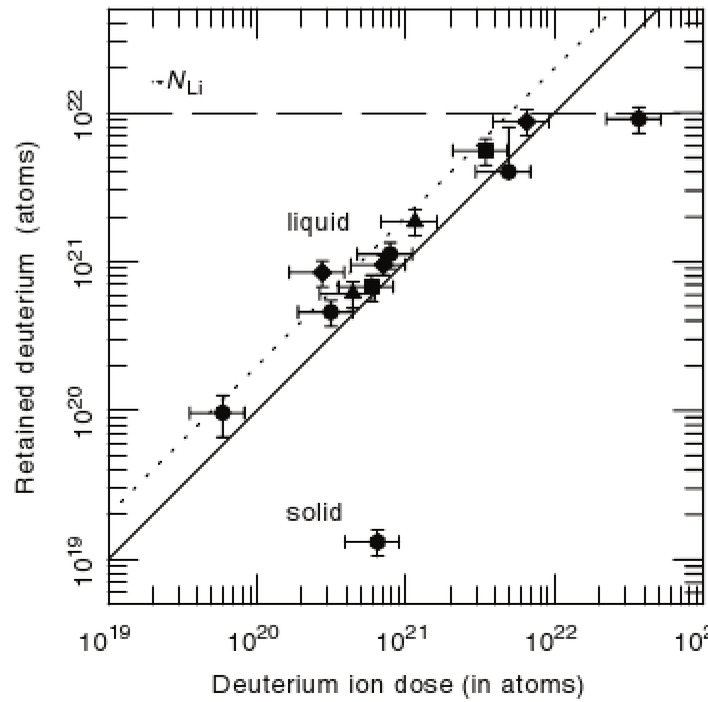


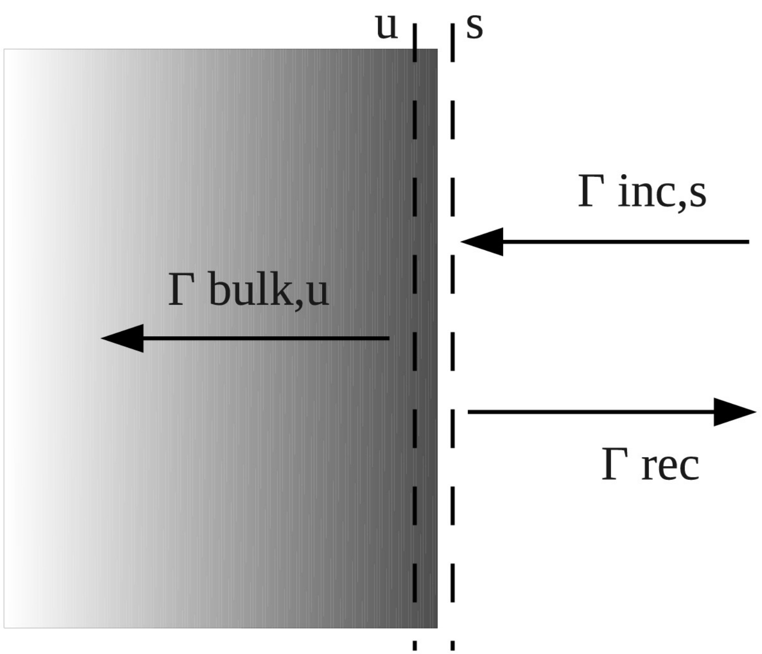
Figure 5. Plot of deuterium atom retention against plasma ion fluence. Data points are TDS measurements for lithium samples (liquid and solid) exposed to deuterium plasma. The sample exposure temperatures were: (solid) 323 K, (liquid) ● 523 K, ■ 573 K, ♦ 623 K, ▲ 673 K. The solid line indicates full retention of ions. The upper dashed line is the number of lithium atoms in samples. The dotted line is an estimate of the total atom fluence received by samples: the sum of the measured ion fluence and calculated neutral atom fluence [34].

Baldwin, et al., Nucl. Fusion, **42** (2002) 1318.

Possible deuterium transport into the bulk must exceed incident flux

- Particle fluxes at the surface must balance in steady-state
  - Incident on surface *s* less recycling from surface *s* is flux into the bulk
  - Flux into the bulk includes physical transport and chemical reaction sinks
- The maximum possible flux of deuterium into the bulk must at least equal the incident ion flux
  - The bulk lithium must be able to remove the incident deuterium from the surface or it will saturate (see condition 1)

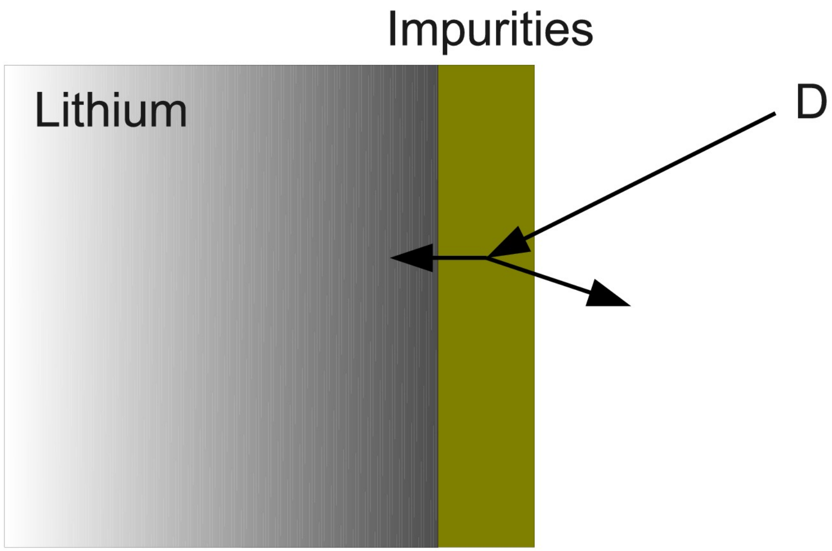
$$\Gamma_{\mathrm{bulk,u}} = \Gamma_{\mathrm{inc,s}} - \Gamma_{\mathrm{rec}}$$



$$\Gamma_{\mathrm{bulk,u,max}} \geq (1 - R)\Gamma_{\mathrm{inc,s}}$$

Deuterium must be able to interact with chemically available lithium

- Impurity layer subject to the same conditions as in (2)
  - Solid diffusivities << liquid diffusivities
  - It is not thermodynamically favorable for LiD to form in the presence of Li-O compounds nor Li_2C_2 or other impurities (C.C. Addison, "The Chemistry of the Liquid Alkali Metals" John Wiley & Sons, 1984)
- Lithium atoms already bound to impurities reduce available atoms for pumping (see 1)



$$N_{Li} = N_{Li,0} - \sum N_{impurities}$$

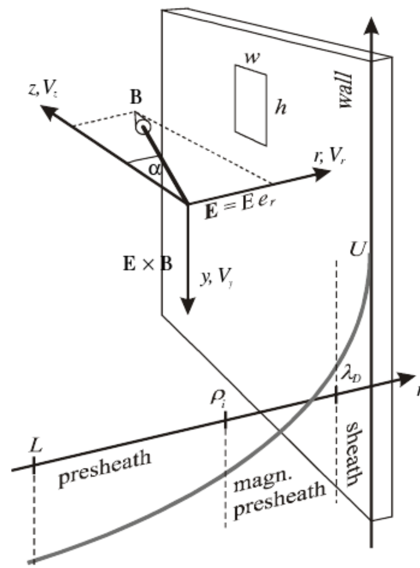
Reasons why LLD may not satisfy necessary conditions

- Available lithium atoms
  - Porous material front face, geometric area matters
  - Debye sheath small
  - Magnetic pre-sheath large – determines the ion flux entering Debye sheath
  - Size scale of MPS removes information about surface roughness as ions stream in - geometric surface area receives ion flux, not porous surface area
- Number of lithium atoms in the surface layer determined by liquid number density and thickness

Measured ↓

$$J_{probe} = \frac{I_{probe}}{eA_{probe}} \approx 2e23 \quad \mathrm{ions/m^2s}$$

$$\begin{array}{cccc} \lambda_{Debye} < & r_{pore} & < L_{porous} < \lambda_{MS} \\ 2.9[\mu m] < & 20[\mu m] & < 150[\mu m] < 430[\mu m] \end{array}$$

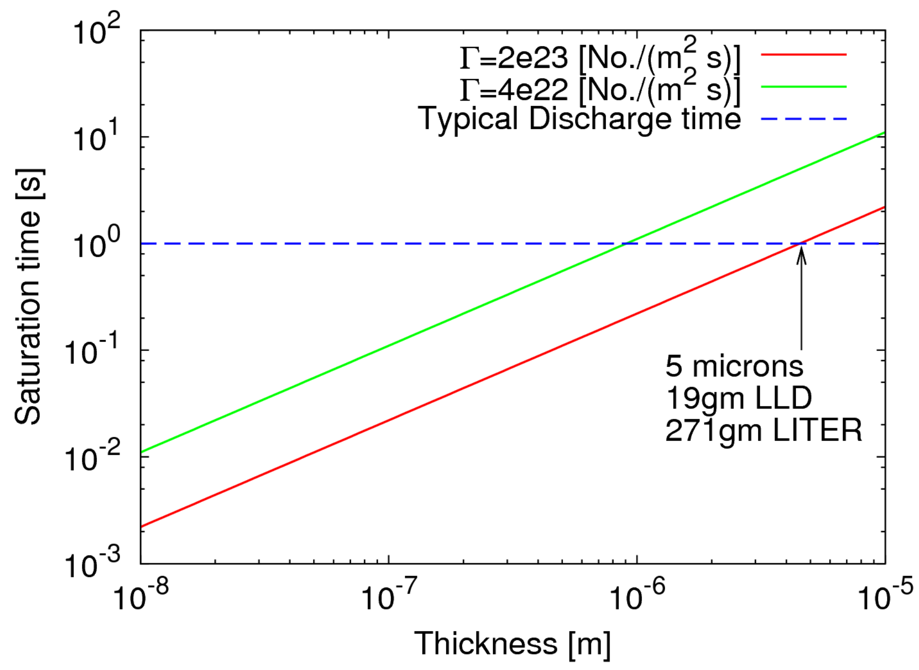


Wolters, PPCF, 1999

$$N_{Li} = 508\frac{\mathrm{kg}}{\mathrm{m}^3} \times \frac{1\mathrm{mol}}{6.941\mathrm{gm}} \times 6.022e23\frac{\mathrm{atoms}}{\mathrm{mol}} \times 1000\frac{\mathrm{gm}}{\mathrm{kg}} \times 250\mathrm{nm} = 1.1e22\frac{\mathrm{atoms}}{\mathrm{m}^2}$$

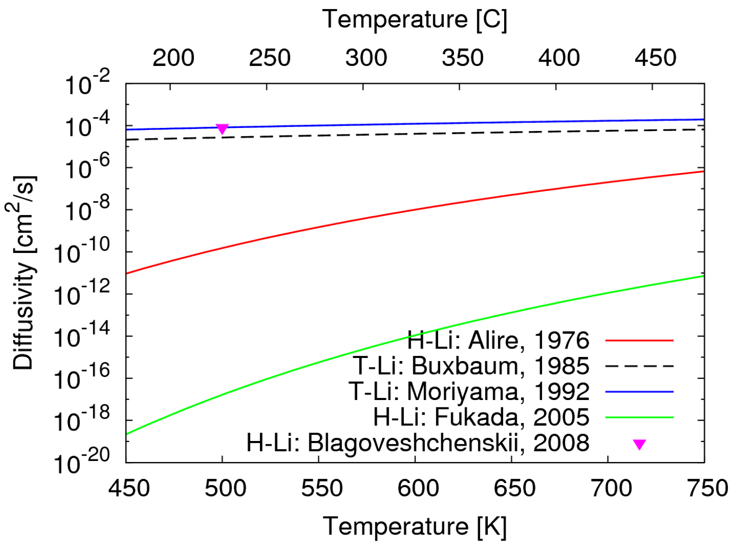
Saturation time of the front layer
Condition 1

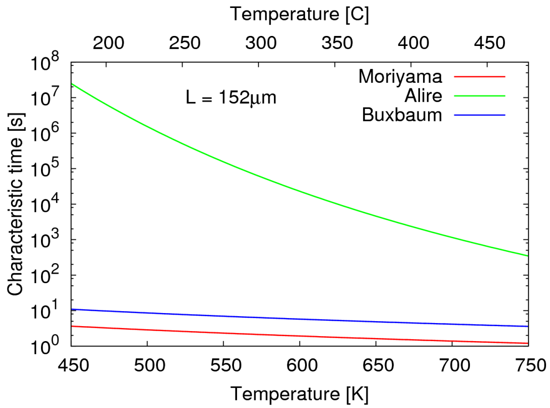
- Saturation time depends on incident flux and availability
  - 4e23 may indicate probe ion flux during high recycling
  - Low recycling, sheath limited conditions should result in lower incident flux
- 5 micron surface layer contains enough atoms to handle the “worst case” high recycling flux
  - Surface tension coats LLD surface area uniformly
  - Results in uniform loading, larger loading than might be expected

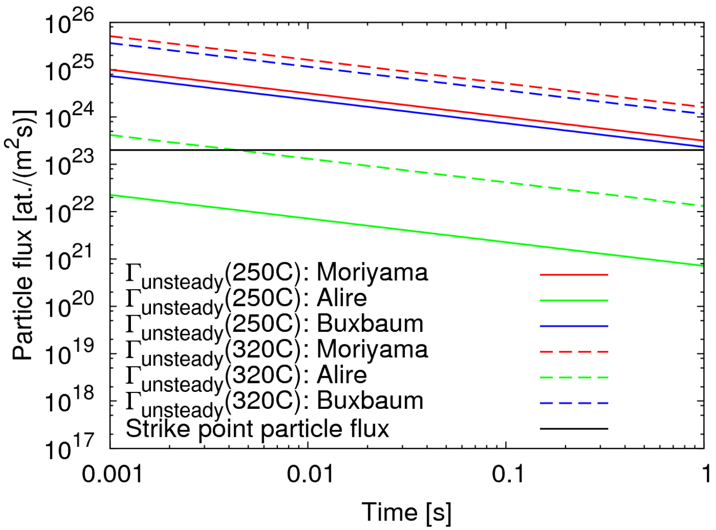


Diffusion from the surface can access more Li Condition 2

- Available lithium atoms for bonding more than surface layer due to diffusion
  - True, but depends on diffusivity and impurity transport
  - Serious discrepancies in literature about actual value of diffusivity
  - Flux condition either not a problem, or a big problem
- Shot cycle allows surface layer to diffuse in – depends on diffusivity







The issue of impurities
Condition 3

- Every shot erodes C, O, and other and redeposits everywhere
  - The amount landing on LLD is unknown (general transport and impurities problem)
  - Cannot be removed by degas processes
  - Preferentially segregate to the surface at modest temperature
- Long glow processes and high temperatures are both known to remove from surface
  - PISCES-B cleaning by discharge (Baldwin, 2002, NF)
  - PISCES-B cleaning by heating (Baldwin, 2002, JNM)
  - CDX-U experience, SLiDE experience
  - L245 experiments on proto-LLD sample
- Previous glow examples are done with biased samples
  - NSTX has biased electrode, grounded LLD
  - Carbon+other redeposition an issue during glow
- Strike point may provide sufficient cleaning

Implications for XP1000

- Deposit more lithium than before
  - Remove possibility of early saturation due to thinness
  - Reduce impurity to Li ratio, remove possibility of early saturation
  - Be prepared to operate at 320C, remove possibility of early saturation due to flux limit and diffusion into bulk as well as impurity sinking
- Run XP immediately following deposition
  - Minimize discharges which introduce impurities
  - Minimize deuterium loading prior to experiment
  - Minimize background gas reactions
- Do everything to actually test pumping by liquid lithium
  - As in, not pumping by LLD+Li+C+O+D loading
  - Begin replicating the CDX-U test on something more macroscopic than 250nm
  - Persistence tests with LITER off once definite effect on plasma can be observed (may indicate alternative fill system required to test LLD specifically)

Summary and caveats

- Three necessary conditions for pumping described
  - Fluence limitation
  - Flux limitation
  - Impurities (feeding into 1 and 2)
- May not be exhaustive list
  - Surface physics between incident plasma and bulk diffusion not considered here
  - Something like PMI probe / MAPP or other could help address these issues intershot
- Serious deficiency in literature regarding diffusivity
  - If CDX-U and PISCES are indications, probably not an issue