# LTX : Exploring the advantages of liquid lithium walls


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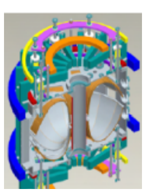
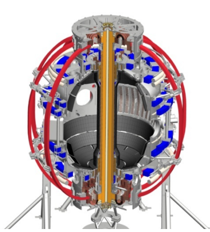
# US STs aim to accelerate fusion development

- **Advance ST as Fusion Nuclear Science Facility**
  - NSTX-U: physics + scenario basis for FNSF-ST (also ST DEMO)
  - Pegasus, NSTX-U: plasma start-up via helicity injection
- **Develop solutions for plasma-material interface**
  - NSTX-U, **LTX-U: liquid Li walls for very high confinement, liquid metal PFCs**
  - NSTX-U: novel divertors: snowflake/X, detachment , vapor shielding
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - Pegasus, NSTX-U: high $\beta$, toroidicity, rotation - for MHD & transport
  - NSTX-U: non-linear Alfvénic modes, electromagnetic turbulence


LTX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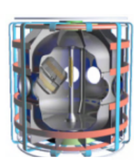
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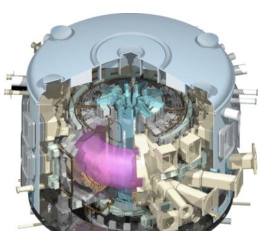
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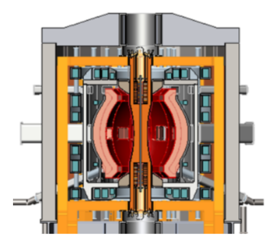
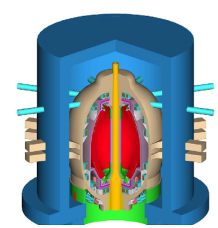

FNSF-ST


ST DEMO

# LTX program elements

- Demonstrate compatibility of a tokamak plasma with liquid lithium walls
- Investigate changes in tokamak confinement and equilibrium with low recycling (lithium) walls
- LTX-U - extend studies to high auxiliary heating power and core neutral beam fueling

# Knowledge gaps in edge, plasma material interactions prominent in Greenwald, ReNeW

LTX

- Solid (tungsten) walls tightly constrain reactor design
  - Power loading, erosion, neutron damage constraints mandate large reactor scale size ($R_0$ possibly 9 m)
  - Unclear that a reactor with tungsten PFCs will be economically feasible
- Advances in confinement which enable smaller fusion core not compatible with limits of tungsten walls, divertor
- Liquid metal walls offer significant improvements in power handling, erosion, and neutron tolerance
  - Divertor, wall solution for AT reactor designs
  - *Lithium* offers advanced confinement + advanced wall for a more compact fusion reactor
- Integrated solution for an ST-based FNSF, pilot plant, ST-based power reactor

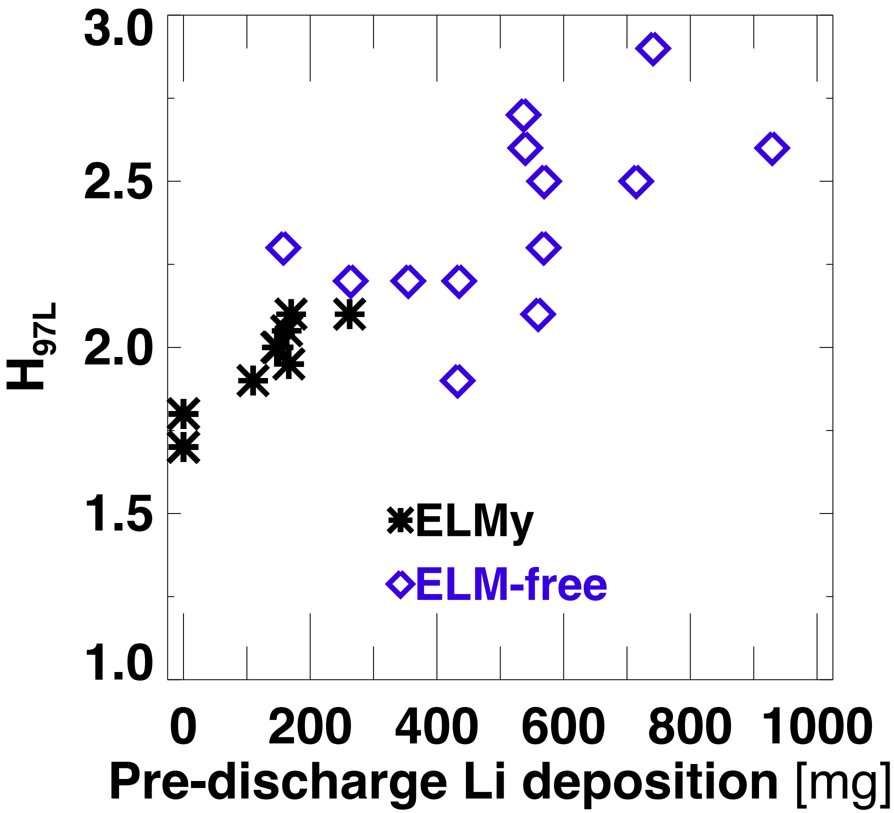
# *Lithium* plasma-facing components improve confinement

- Recycling small (~10 – 20%) for clean lithium surface
- Low recycling wall ⇔ hot edge in a magnetically confined plasma
  - –Core power flux is carried to the wall by particles
  - ⇨ High recycling = lots of edge particles = low energy/ particle
  - ⇨ Low recycling = only core particles in edge = *high* energy/particle
    - High edge temperature
    - Reduced core temperature gradient, instability drive
    - Reduction in anomalous transport
- Enable compact reactor designs with higher confinement

# *Solid* lithium coatings in NSTX improve confinement

NSTX-U

Plasma confinement increases ~continuously with increasing Li evaporation



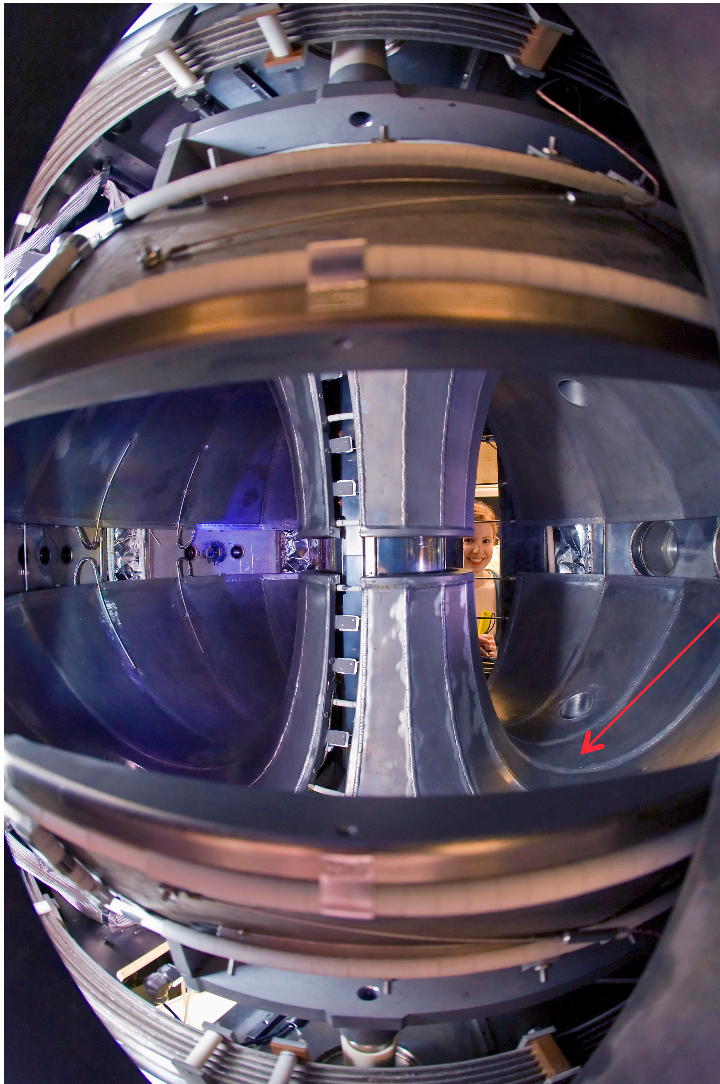

- Global confinement improves
- Core lithium accumulation < 0.1%
- ELM frequency declines to zero
- Edge transport declines
- High $\tau_E$ critical for FNSF, next-steps

- Best estimate: Recycling reduced from ~0.99 ⇒ 0.9 ± 0.05

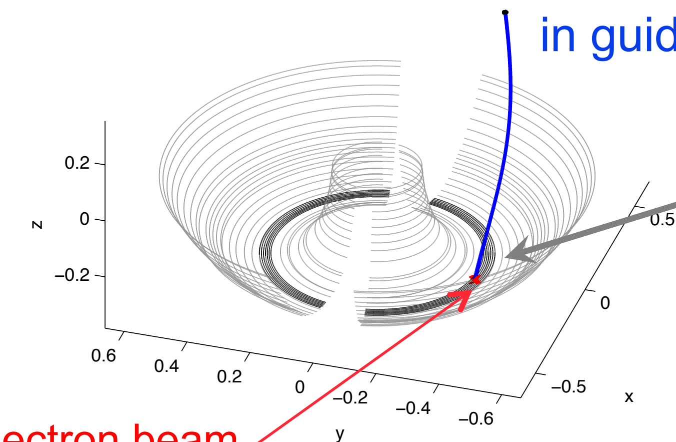
D. P. Boyle et al., J. Nucl. Mater. 438, S979 (2013)

What is $\tau_E$ upper bound?

# LTX – full, conformal liquid lithium-coated liner ⇒up to 80% of plasma surface area surrounded by liquid lithium



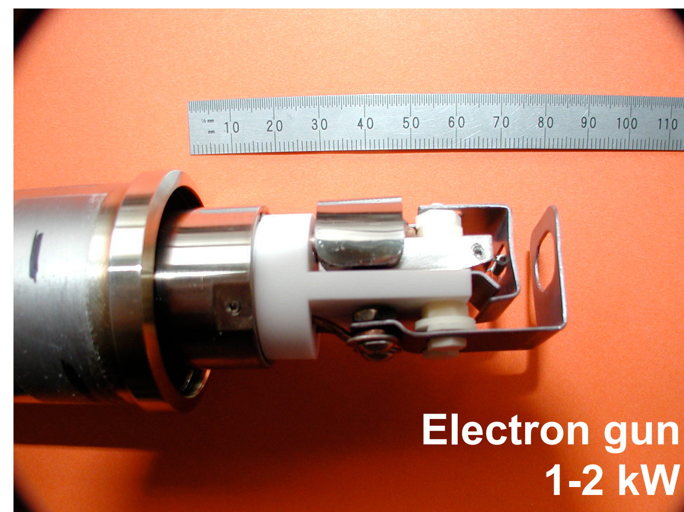
Beam trajectory in guide fields




Lithium pool

Electron beam magnetically guided to lower shell lithium Reservoir

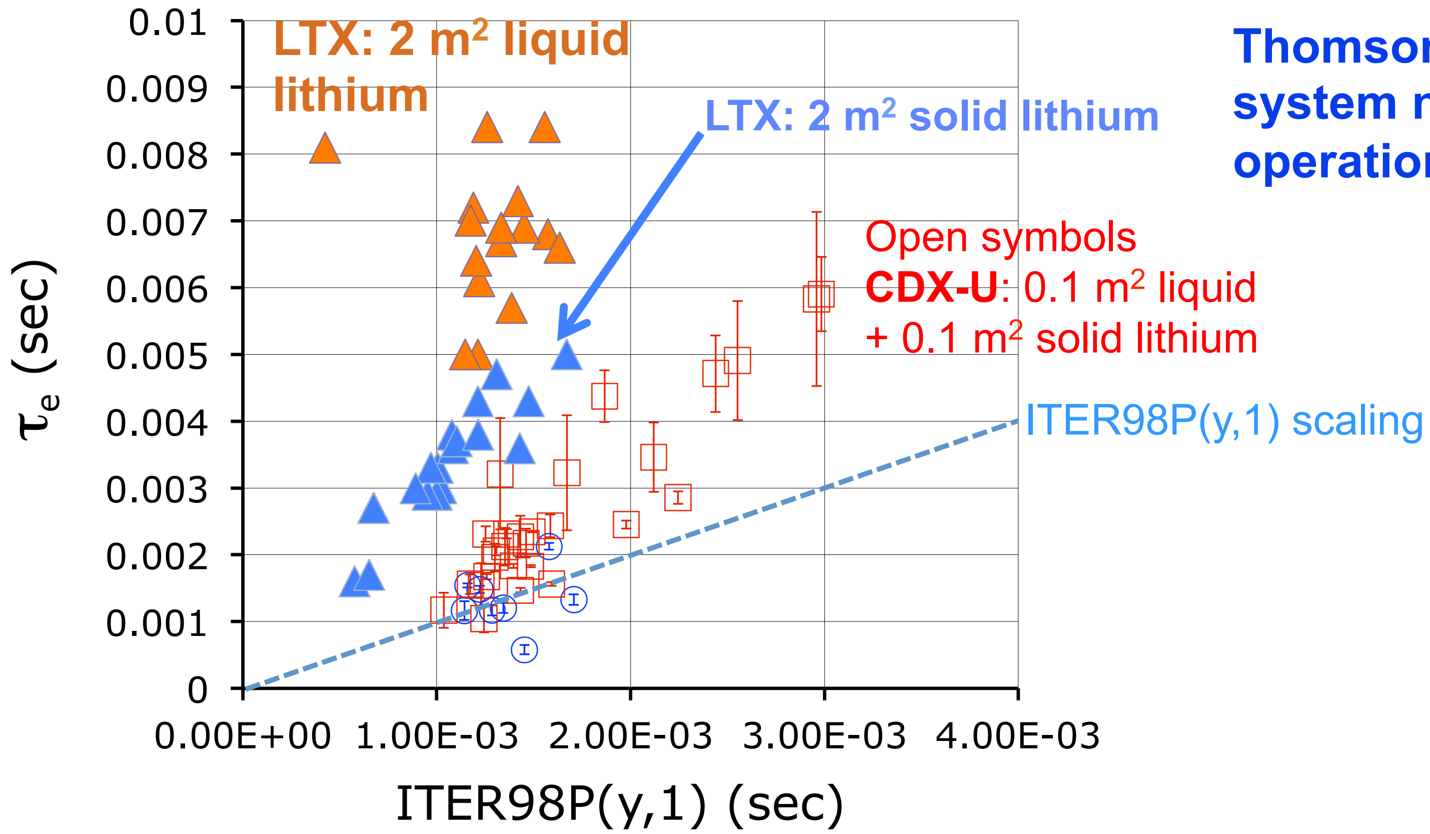
*Half* ($2m^2$) of liner coated with liquid lithium at present




Inner heated high-Z shell (explosively bonded SS on copper)

➡ 2014: Fast (5 minutes for ~1000 Å) Li coating via electron beam evaporation

# Confinement increases with lithium coverage
## ⇒*Liquid* lithium more effective




**Thomson scattering system now aligned, operational**

- First operation of any tokamak with large area liquid lithium walls
- 2 $m^2$ of liquid lithium coated wall; 40% of plasma-facing surface
- **Ready for experiments with full (4 $m^2$) liquid lithium coverage**

# LTX-U, NSTX-U, liquid lithium program

- **Proposed initiative** is to add NBI to LTX **(☞LTX-U)**
  - 700kW, 20 keV, 100 msec system (no cost) from Tri-Alpha Energy
- Confinement with $P_{aux}$ ~ 10x $P_{ohmic}$, low recycling wall, higher beta
  - ➢ Core fueling
- **Establish the physics basis for large area, liquid lithium walls in NSTX-U**
  - NSTX-U: Increased heating power, pulse length, diagnostic capabilities
- Technology program needed to develop circulating liquid lithium walls
  - Test stands to develop liquid lithium walls, divertor for ST
  - Companion talks on development of liquid metal PFCs Wednesday and Thursday (R. Goldston, R. Maingi, M. Jaworski, J.P. Allain)

# Budget, University/lab participation

- Base program (LTX-U with NBI) requires ~ 2.5 M$/year
- Continued ORNL funding (0.5M$/yr) required for diagnostic support
  - Spectroscopy and Li-CHERs
    - » Active CHERs with neutral beam
      - Toroidal momentum transport studies
  - Provide core $T_i$, lithium impurity concentrations
- Additional participation (~0.4-0.5 M$/yr increment):
  - UCLA: 300 GHz interferometer and profile reflectometer
  - UIUC: Materials Analysis Probe (existing probe to return to NSTX)
  - Johns Hopkins: Survey EUV spectrometer
  - LLNL: High resolution EUV spectrometer (impurity $T_i$)
  - Princeton University: Surface science of liquid lithium
  - More University participation needed
- Research strongly dependent on Princeton University grad students

# Conclusions

- Large increase in energy confinement *demonstrated* with liquid lithium walls in LTX
  - Results will be further extended in the near term
- Liquid lithium walls also offer:
  - Tolerance to high heat loads
  - Long lifetime
  - Reduced reactor scale
- LTX program goal is to provide a sound physics basis for a next-step in liquid lithium walls ⇒ NSTX-U
- Initiative to install a neutral beam on LTX – **LTX-U** - will enable this goal

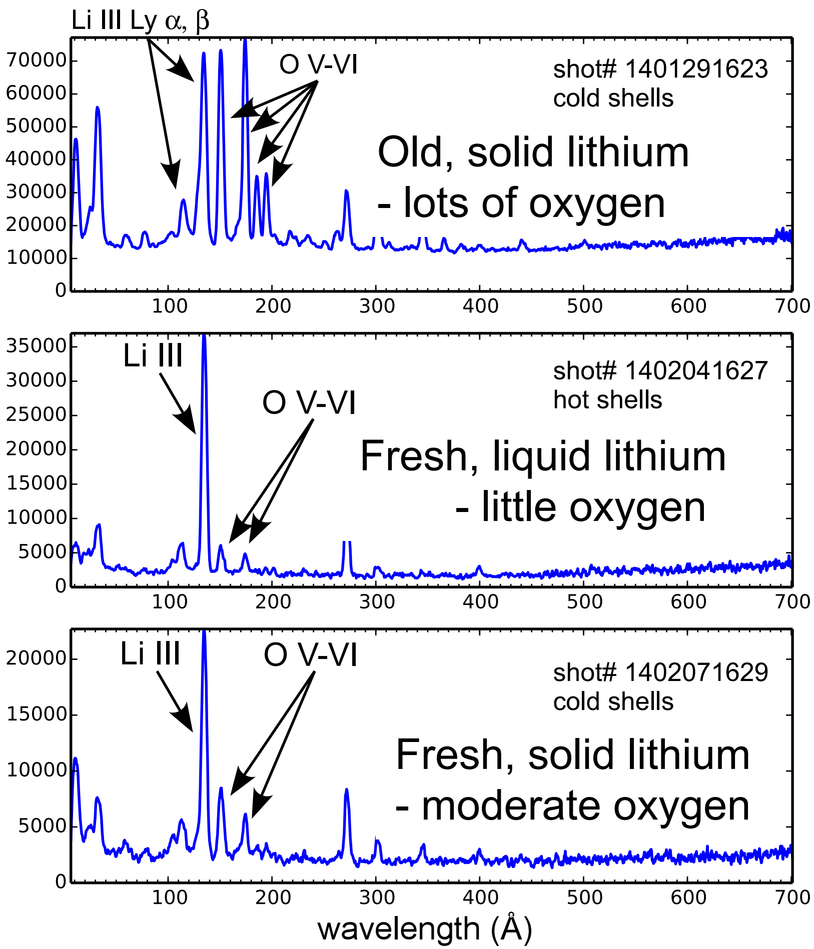
# Backup

# Lithium safety

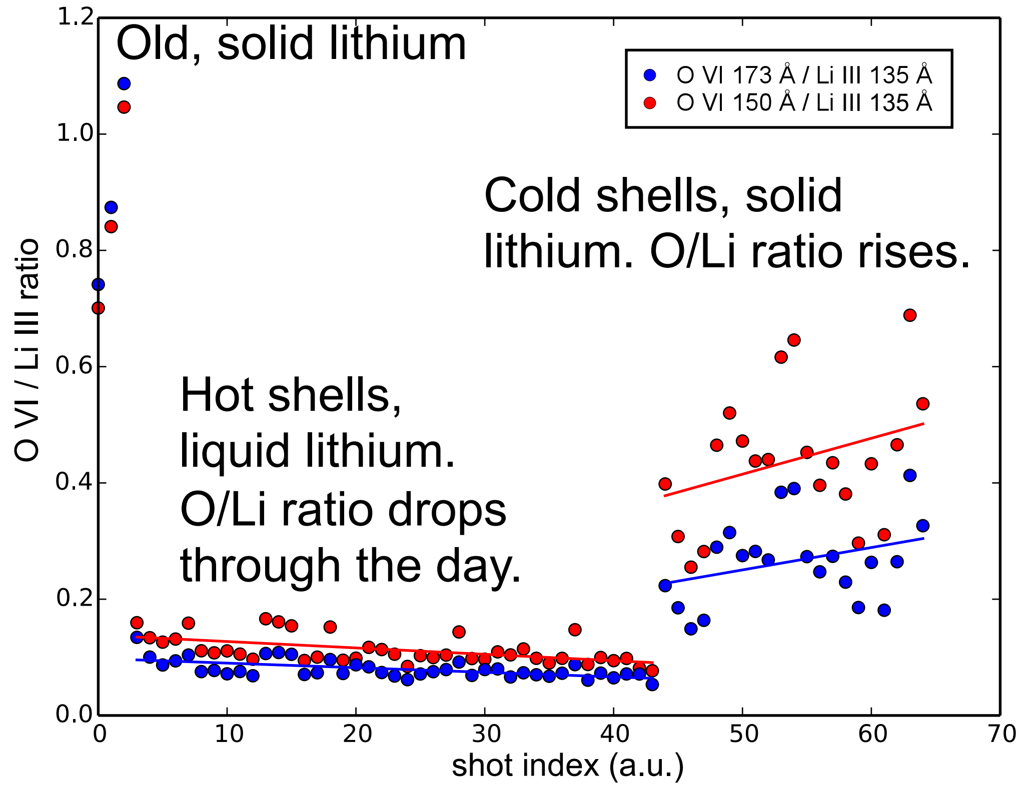
- CDX/LTX experiments have run 14 years without incident
- Extensive engineering controls for lithium systems
  - Secondary stand-by vacuum system (Roots blower) maintains reduced pressure in LTX, even if a vacuum window cracks
  - Tertiary turbopump system on 15 min. uninterruptible power
  - Heaters are interlocked to pressure sensors
  - **ALL** windows are mounted on gate valves
- **No** direct water cooling of the vacuum boundary or internal sturctures
- **No** argon gas pressurization to transfer liquid lithium
- **No** use of demountable joints for lithium containment
  - Difficult/impossible to effectively leak check once in service
  - Liquid lithium containment employs welded or formed stainless steel or tungsten structures
- Vacuum boundary is NOT heated above the melting point of lithium
  - Lithium will freeze out on the wall. No possibility of egress into air

# Oxygen impurities in discharge are now suppressed with liquid lithium PFCs

Spectra from JHU transmission grating instrument




Lithium/oxygen line ratio – shot history from JHU TG EUV spectrometer

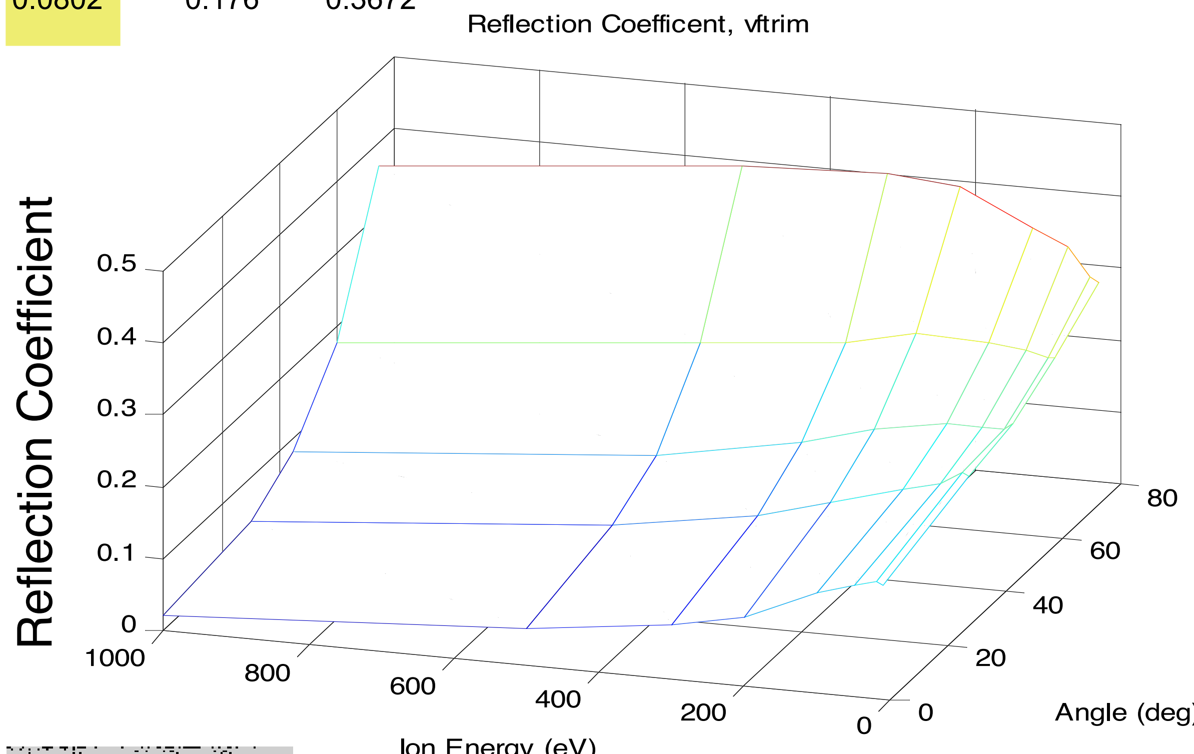


# Recycling via direct reflection from lithium

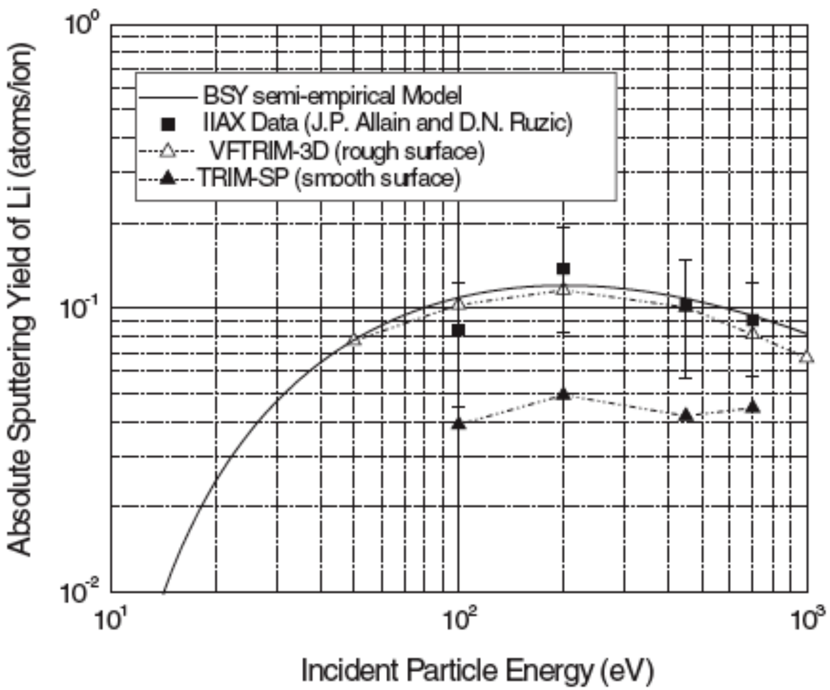
D on 100nm of Li

| Energy,Angle | 0 | 30 | 45 | 60 | 75 |
|---|---|---|---|---|---|
| 10 | 0.1568 | 0.1966 | 0.2125 | 0.2492 | 0.2979 |
| 20 | 0.1613 | 0.2019 | 0.2046 | 0.2491 | 0.3045 |
| 50 | 0.153 | 0.1826 | 0.2054 | 0.2564 | 0.3425 |
| 100 | 0.1387 | 0.17 | 0.2042 | 0.2616 | 0.3639 |
| 200 | 0.0939 | 0.1411 | 0.1889 | 0.2647 | 0.4137 |
| 300 | 0.0746 | 0.114 | 0.1596 | 0.2435 | 0.4225 |
| 500 | 0.0509 | 0.0817 | 0.1237 | 0.224 | 0.4139 |
| 1000 | 0.0221 | 0.0401 | 0.0802 | 0.176 | 0.3672 |

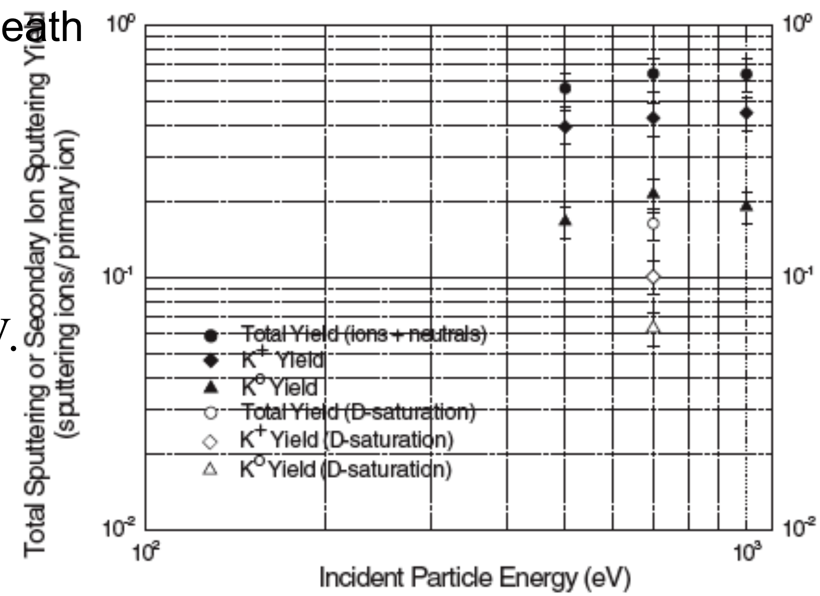
- Lithium has the lowest probability of direct reflection of any candidate PFC material
- For an average incident angle of 45º, the reflection coefficient at low energy is ~20% (edge $T_e$~30 eV)
- Drops to <10% for edge $T_e$ ~ 300 eV



# Lithium sputtering




- Li sputtering yield for D incident on deuterated Li, calculations and IIAX measurements (Allain and Ruzic, Nucl. Fusion 42(2002)202). Angle of incidence 45°
- At 700 eV the yield is 9%
- Fraction of sputtered lithium = redeposited is high
  - Low ionization energy - ionized in the sheath

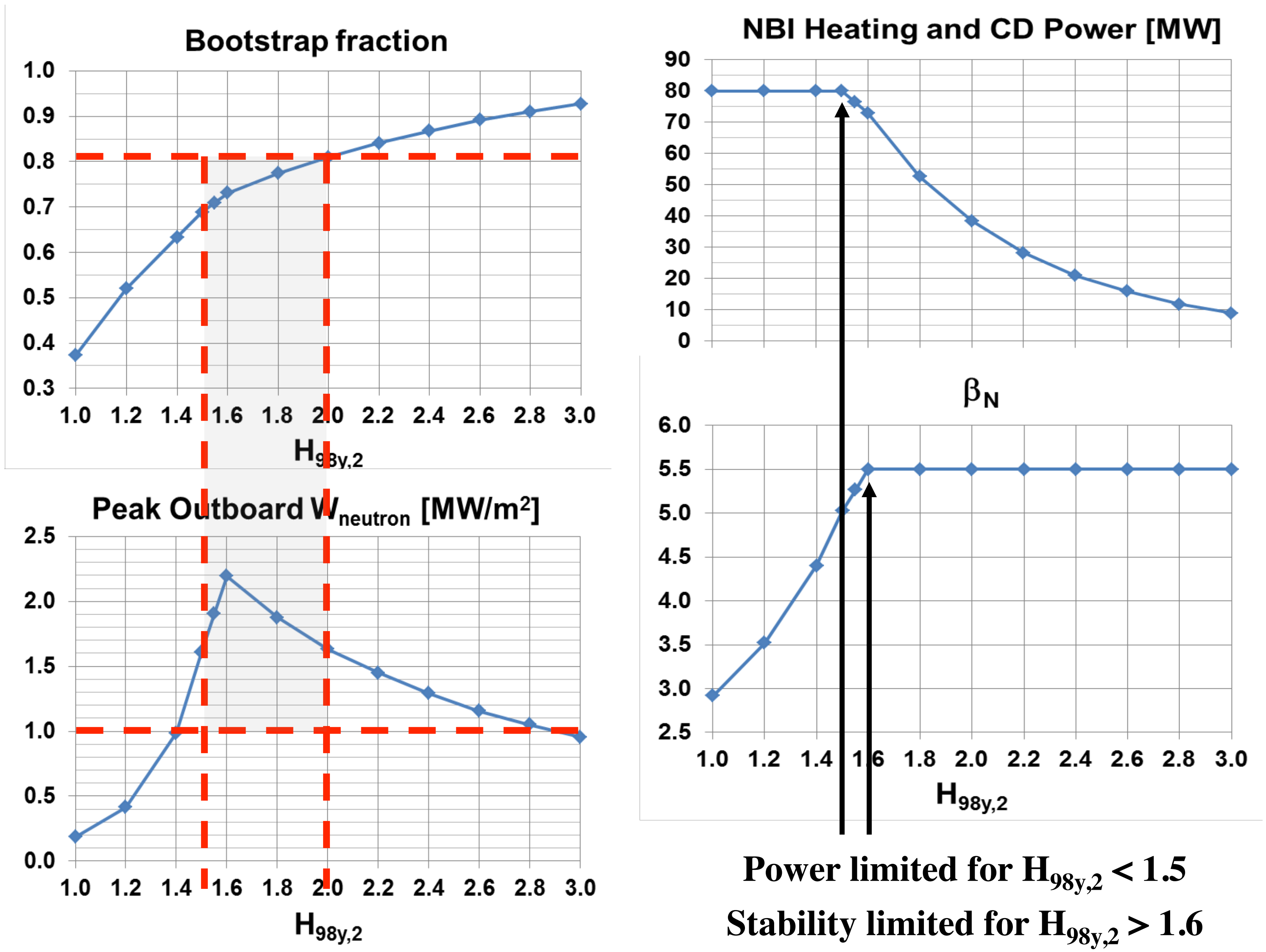



- Fraction of lithium which is sputtered as an ion ~60% for incident ion energy ~0.5 - 1 keV. $He^+$ incident at 45°
- Self-sputtering of Li on D-treated Li:
  - 24.5% at 700 eV
  - 15.8% at 1 keV

# $H_{98y,2}$ range of 1.5-2 favorable for high neutron wall loading ≥ 1.5MW/m² (peak outboard), $f_{BS}$ < 80% for external control

**ST-FNSF**

- A = 1.75
- $R_0$ = 1.7m
- $B_T$ = 2.9T
- κ, δ = 2.8, 0.55
- $f_{Greenwald}$ = 0.8
- $f_{NICD}$ = 100%
- $E_{NNBI}$ = 0.5MeV
- $P_{NNBI}$ ≤ 80MW




**Power limited for $H_{98y,2}$ < 1.5**

**Stability limited for $H_{98y,2}$ > 1.6**