Liquid metal walls for fusion reactors and the Lithium Tokamak eXperiment (LTX)

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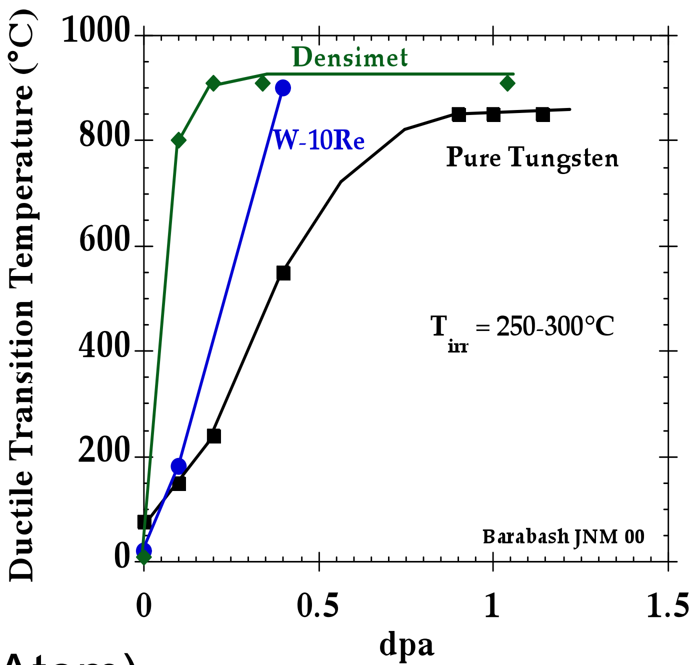
Outline

- Introduction
  - Neutrons
  - Heat removal
  - Liquid metal PFCs
- PFCs and plasma boundary conditions
- Implementation of liquid metal PFCs in near-term devices
- LTX
  - A few recent results
- Summary

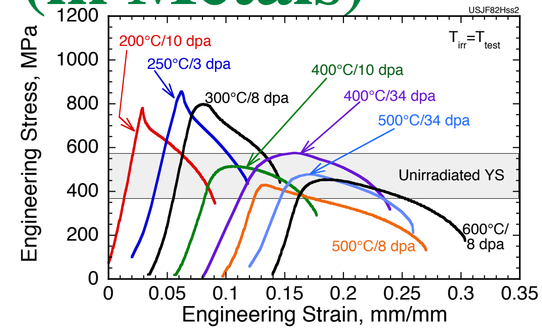
Plasma-facing components (PFCs) for reactors



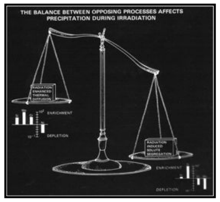
- Only candidate solid material considered viable for reactor PFCs is tungsten
  - Tungsten is high-Z/low sputtering
  - Tungsten has good thermal conductivity
- But:
  - Ductile to brittle transition: 200 – 500 °C
  - Subject to radiation-induced embrittlement above just a few DPA (Displacements Per Atom)
    - » Note: lattice displacement energy for tungsten 80 eV
    - » 1 DPA ~ 10^{25} n/m^2, for neutron energies > 100 keV
    - » Require 10's of DPA lifetime for reactor PFCs
  - Tungsten also subject to surface damage under He fluence
  - Sputtering threshold for D on W limits edge temperature to <200 eV

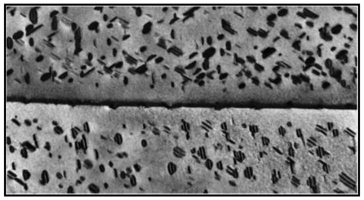
Five Evils of Radiation Damage (in Metals)

- **Radiation hardening & embrittlement**
  (<0.4 T_{Melt}, >0.1 dpa)



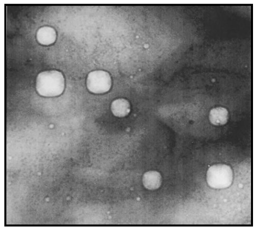
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**





- **High temperature He embrittlement**
  (>0.5 T_M, >10 dpa)

- **Volumetric swelling from void formation**
  (0.3-0.6 T_M, >10 dpa)

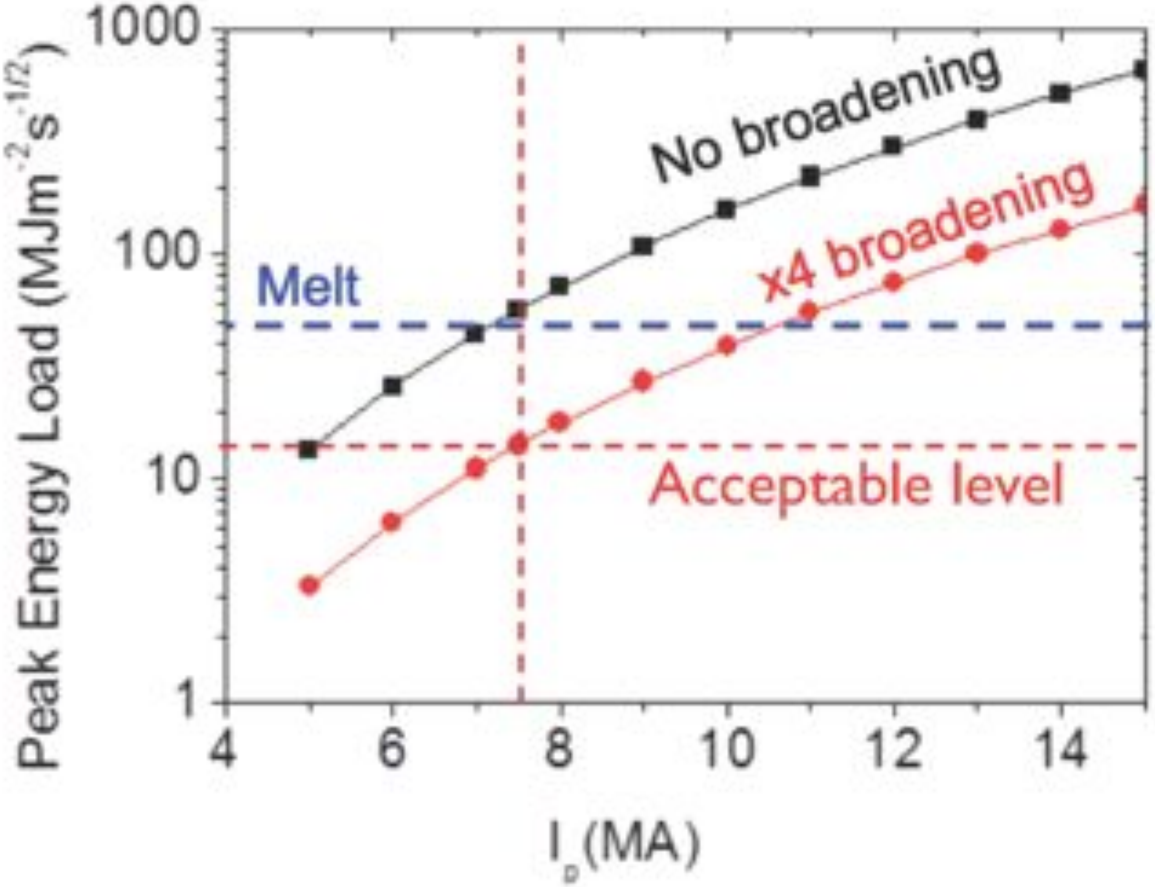


- **Irradiation creep (<0.45 T_M, >10 dpa)**

Lance Snead, ORNL

Cooling solid PFCs is a challenge
Type I ELMs on ITER

Richard Pitts



Unmitigated ELMs in ITER will cause unacceptable heat loads.

Disruptions on ITER

Richard Pitts

W melts at "e" ~ 50

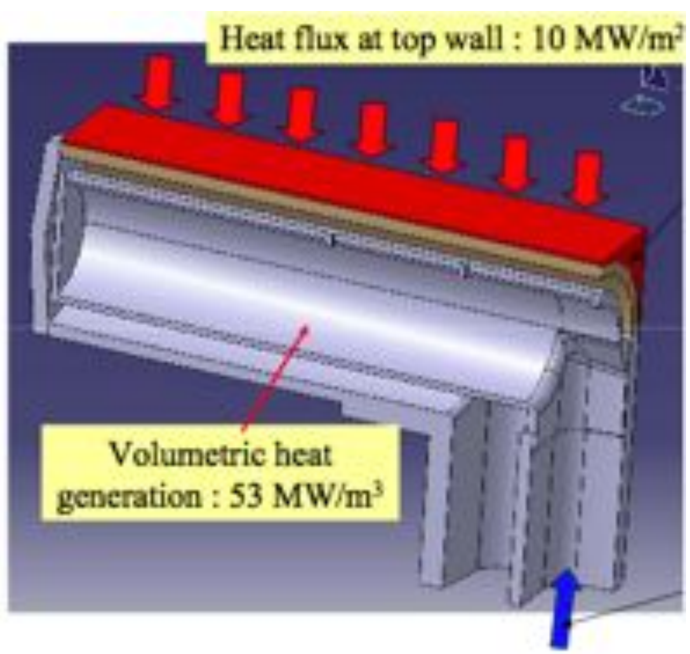
I_p (MA)	Mode	P_{IN} (MW)	Stored energy (MJ)	$E_{transient}$ (MJ)	$l_{q\|\|omp}$ (m)	q_{target} ($MJ\ m^{-2}$)	e ($MJ\ m^{-2}s^{-1/2}$)	
7.5	L	20	26	13 → 26	0.02	0.22 → 2.86	4.1 → 74.3	Non-active phases
7.5	L	30	30	15 → 30	0.02	0.25 → 3.30	4.5 → 84.9	Non-active phases
7.5	H	40	75	25 → 38	0.01	0.83 → 8.3	15.2 → 213	Non-active phases
15	L	8	35	16 → 35	0.01	0.52 → 7.69	9.4 → 199	Non-active phases
15	L	18	52	26 → 52	0.01	0.86 → 3.43	15.7 → 295	Non-active phases
15	L	28	73	37 → 73	0.01	1.21 → 11.4	22.2 → 406	Non-active phases
15	L	40	85	43 → 85	0.01	1.39 → 18.7	25.5 → 483	Non-active phases
15	H	50	350	88 →175	0.005	5.78 → 76.9	105 → 1984	← DT

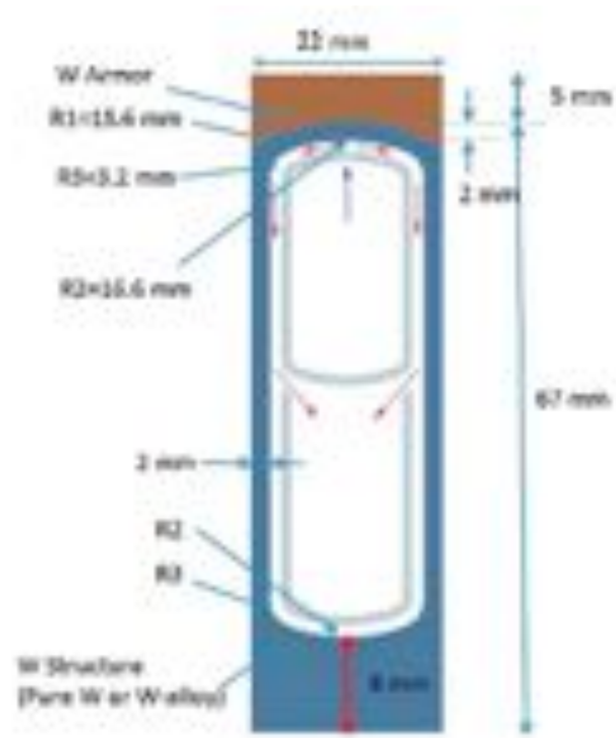
Unmitigated major disruptions in ITER will melt W divertors.

PPPL

Cooling tungsten PFCs in a reactor is demanding

- Lead candidate for divertor, PFC cooling is high pressure helium
- High pressure helium jet cooling suggested for the divertor
  - No water cooling (like ITER)
  - Complex structure, helium pressures ~ 10 MPa, flow rate to remove the alpha power >200-300 m^3/sec (at 10 MPa, for ΔT = 800C)

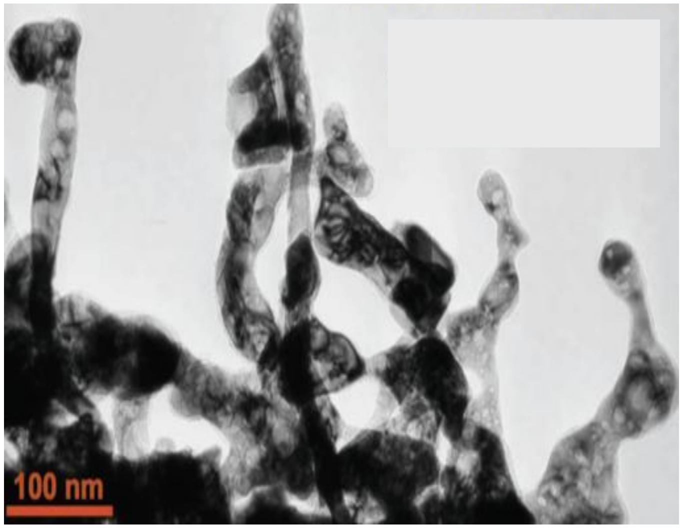




Liquid metal walls offer another PFC solution

- Flowing liquid metal PFC is continuously renewed
  - Eroded material is replaced
- Neutron damage limited to supporting substrate
- Plasma-material interaction (PMI) limited to the liquid metal: sputtering + evaporation
  - No helium blisters
  - No surface modification
- PMI issues and neutron damage issues are *separable* with liquid metal systems
  - Significant simplification for materials development

Tungsten surface after long-term plasma exposure

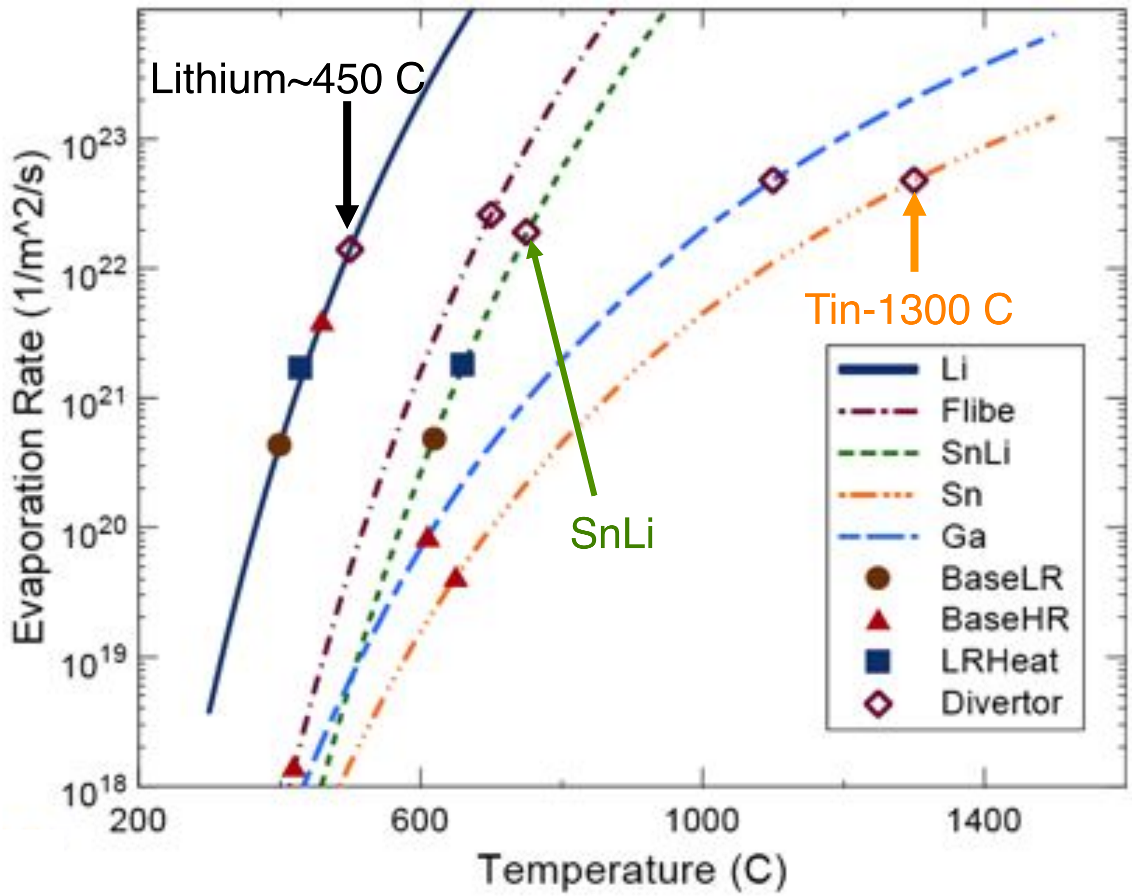


NAGDIS-II: pure He plasma
N. Ohno et al., TEM - Kyushu Univ.

General properties of liquid metals

- Lithium
  - Z=3, atomic weight =6.9
  - Melting point = 180.5 °C, boiling point = 1342 °C
  - Liquid density = 0.5 g/cm^{-3}, sp. heat capacity = 3.58 J/g °C
  - Thermal conductivity: 84.8 W/m°C, electrical res. = 93 nΩ m
  - Vapor pressure = 10^{-7} Torr at 400 °C
- Tin
  - Z=50, atomic weight=118.7 (Mo: Z=42, at. wt. = 96)
  - Melting point = 232 °C, boiling point = 2602 °C
  - Liquid density = 7.0 g/cm^{-3}, sp. heat capacity = 0.23 J/g °C
  - Thermal conductivity: 66.8 W/m°C, electrical res. = 115 nΩ m
  - Vapor pressure = 10^{-7} Torr at 1000 °C
- Gallium
  - Z=31, atomic weight =69.7
  - Melting point = 29.8 °C, boiling point = 2204 °C
  - Liquid density=6.1g/cm^3, sp. heat capacity = 0.37 J/g °C
  - Thermal conductivity: 40.6 W/m°C, electrical res. = 140 nΩ m
  - Vapor pressure = 10^{-7} Torr at 900 °C

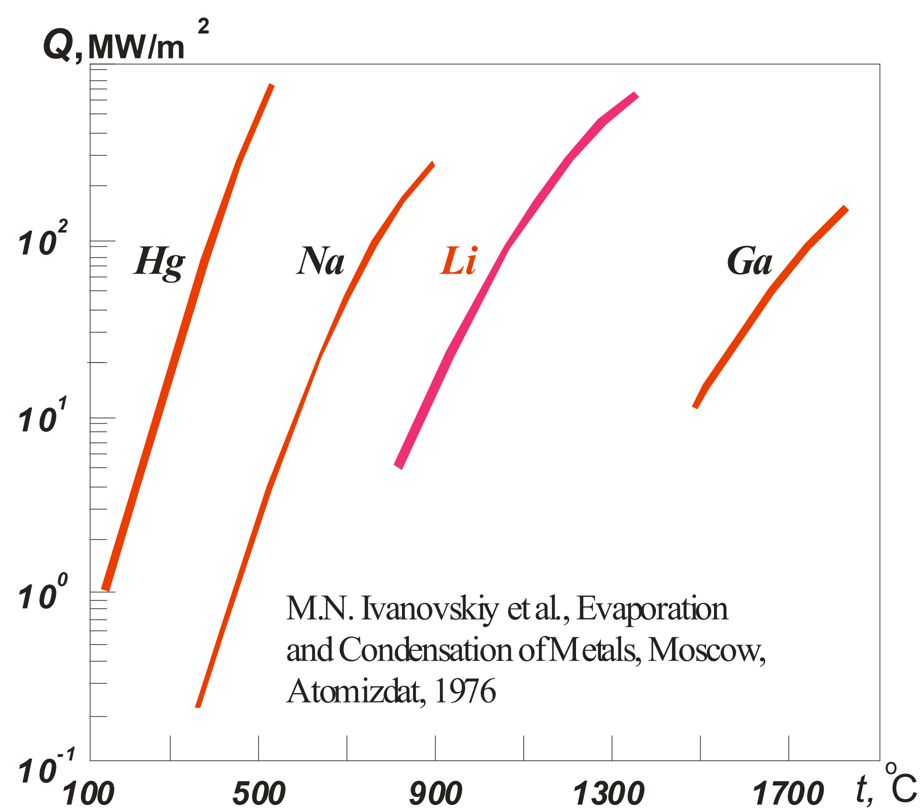
Temperature limits for liquid metal PFCs



- Limit set by evaporation rate, influx to the plasma
- Lithium/tin-lithium/tin system provides a wide range of operating temperature

Heat removal with liquid metals

- Flowing liquid metal systems have high heat removal capabilities
  - Lithium example: alpha power could be removed from a 2 GW (fusion) reactor with a flow rate of 1 m^3/sec, for ΔT = 200C)
    - » Viscosity of lithium is ~half that of water
- Liquid lithium can also disperse highly localized heat loads by evaporation and/or radiation
  - Basis for CPS (Capillary Porous System) used in FTU
  - Radiative divertor or limiter
    - » Disperse heat load to walls
    - » Cool with helium
    - » Alternative: cool with NaK
      - KTM approach



Liquid metals and the plasma boundary

LTX

- Hydrogen is highly soluble in lithium ⇨ *Low recycling wall*
- Low recycling wall ⟺ hot edge in a magnetically confined plasma
  - Power flux is carried by particles at the edge
  - Poor fueling efficiency (~5-10%) for recycled particles *guarantees* high particle density at the wall (for a high recycling wall)
  - For low recycling, *only* edge particles are those lost from the core

  ⇨ High recycling = low power/particle (low edge temperature)

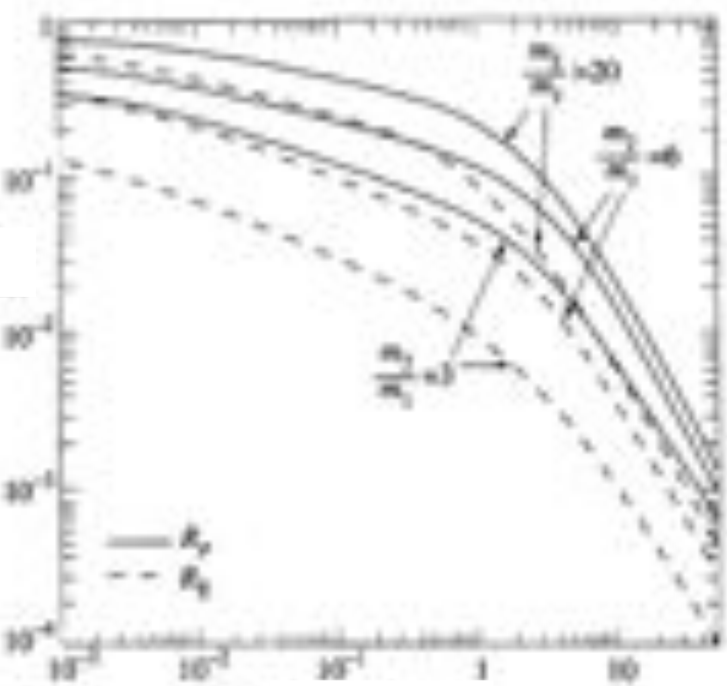
  ⇨ Low recycling = high power/particle (high edge temperature)
- Solubility of hydrogen in liquid tin is appreciable for fusion applications
  - ~2g/100 cm^3 tin at 600 C
  - Clean liquid tin may also modestly reduce recycling
    - » No tests of tin as a PFC as yet

Recycling mechanisms: direct reflection

- Direct reflection: scattering due to hard-sphere collisions between the incident ion and the wall. Irreducible minimum recycling coefficient.
  - Function of the reduced energy ε:

$$\varepsilon \approx \frac{32.5 m_2 E}{(m_1 + m_2) Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{1/2}}$$

  - Where (1) denotes the incident ion and (2) the target, E is the incident ion energy
  - R_p(——) = probability of particle reflection, R_E (– – –) = energy of the reflected particle



Reflection coefficients

Reduced energy (keV)

D⇒Li: ε=4.80 E
D⇒C: ε=2.24 E
D⇒Ti: ε=0.48 E
D⇒Mo: ε=0.21 E
D⇒Sn: ε=0.17 E
D⇒W: ε=0.10 E

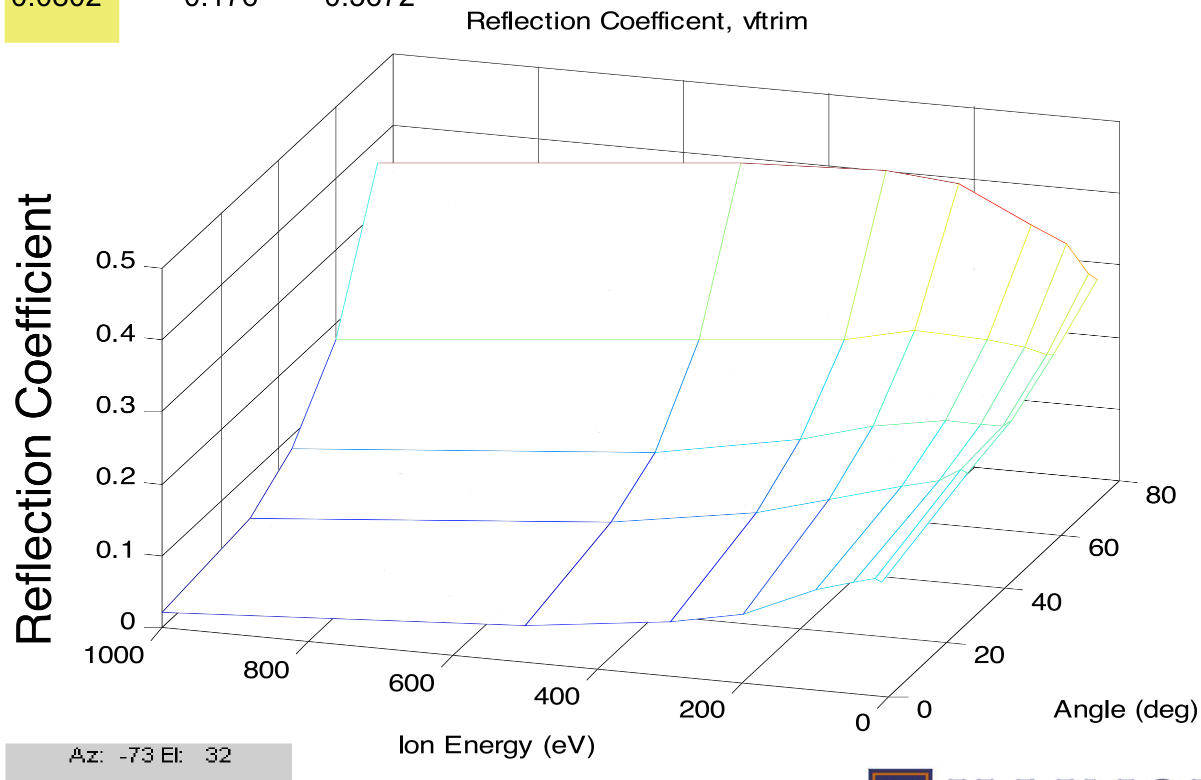
- For edge temperatures of a few tens of eV, only lithium allows low recycling
  - ~20% at 20 eV
- Titanium gettered surfaces have reflection coefficient **~ 80%** at 20 eV

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



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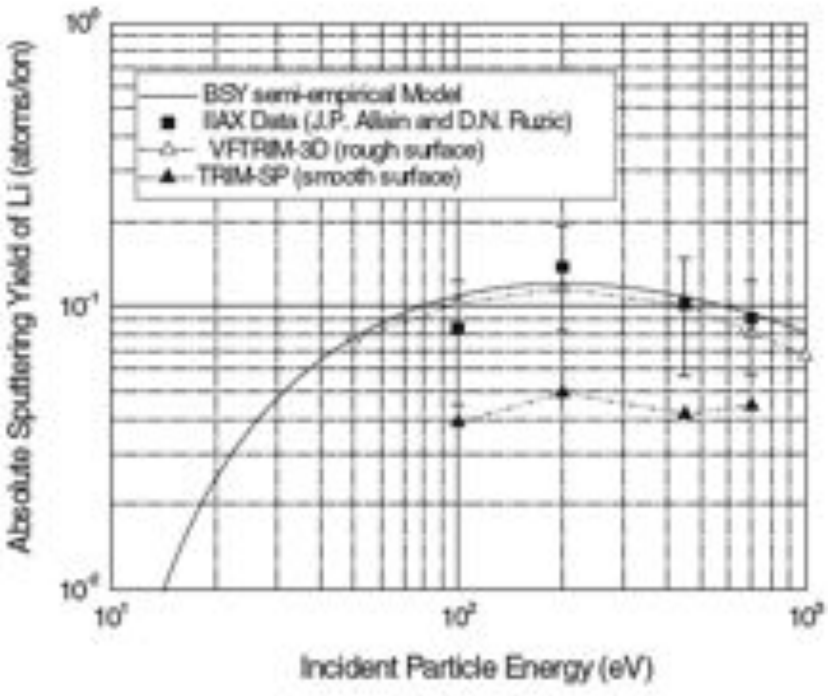
Lithium sputtering and core accumulation



- Li sputtering yield for D on Li at 45° (Allain and Ruzic, Nucl. Fusion 42(2002) 202).
- At 700 eV the yield is 9%
- Most sputtered lithium is redeposited
  - Ionized in the sheath
- 60% lithium sputtered as an ion ~60%, incident ion energy ~0.5 - 1 keV
- Lower-Z impurities are not accumulated in the plasma core

- Resulting core impurity concentration in tokamaks:
  - Low in diverted machines
    - NSTX: Core lithium concentration <0.1% (compared to carbon: 10%)
  - Low in limiter machines with very hot edge plasmas
    - TFTR supershots: T_{edge} > 1 keV
    - Core lithium concentration < 0.5%

Secondary electron effects

- "Recycling" is typically thought of as an ion process
- Electrons are also "recycled" via secondary electron emission
  - Secondaries cool the edge plasma.

$$q_{pe} = (2kT_e + e\varphi_0)\frac{0.6 n_e c_s}{(1-\gamma_e)} - e\varphi_0 \gamma_e \frac{0.6 n_e c_s}{(1-\gamma_e)}$$

- Lithium has the lowest secondary electron emission coefficient of any metal

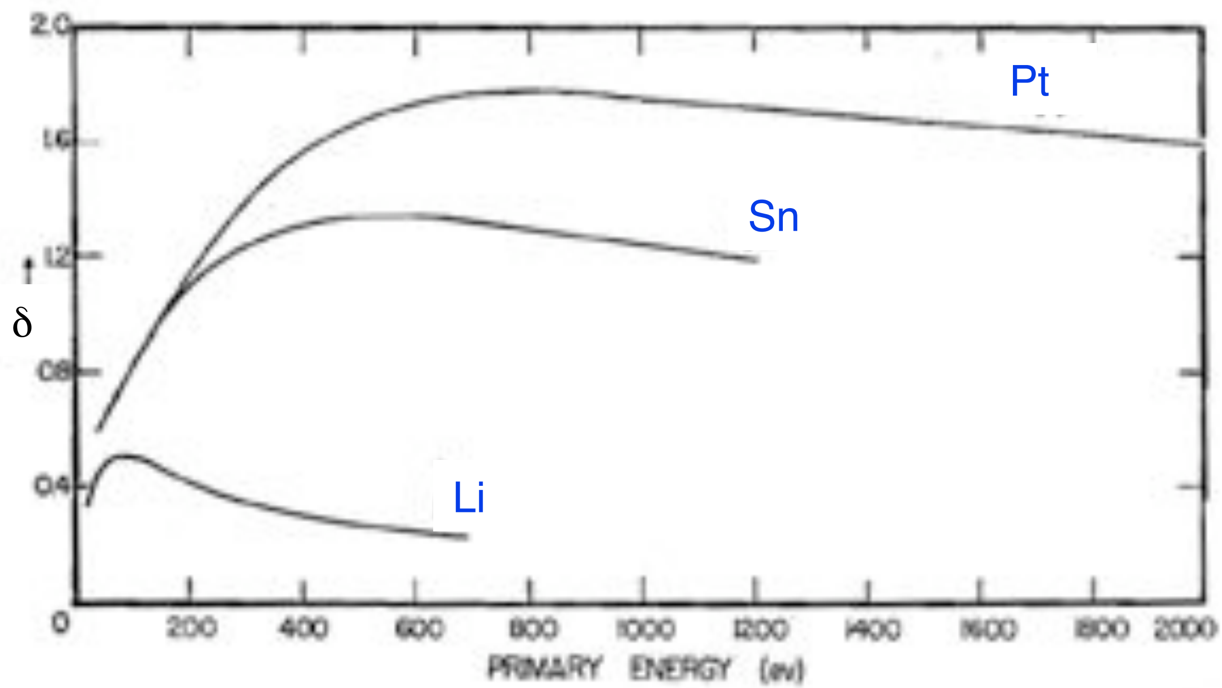


FIG. 2. The total yield as function of primary energy for some metals; for references, see Table I.

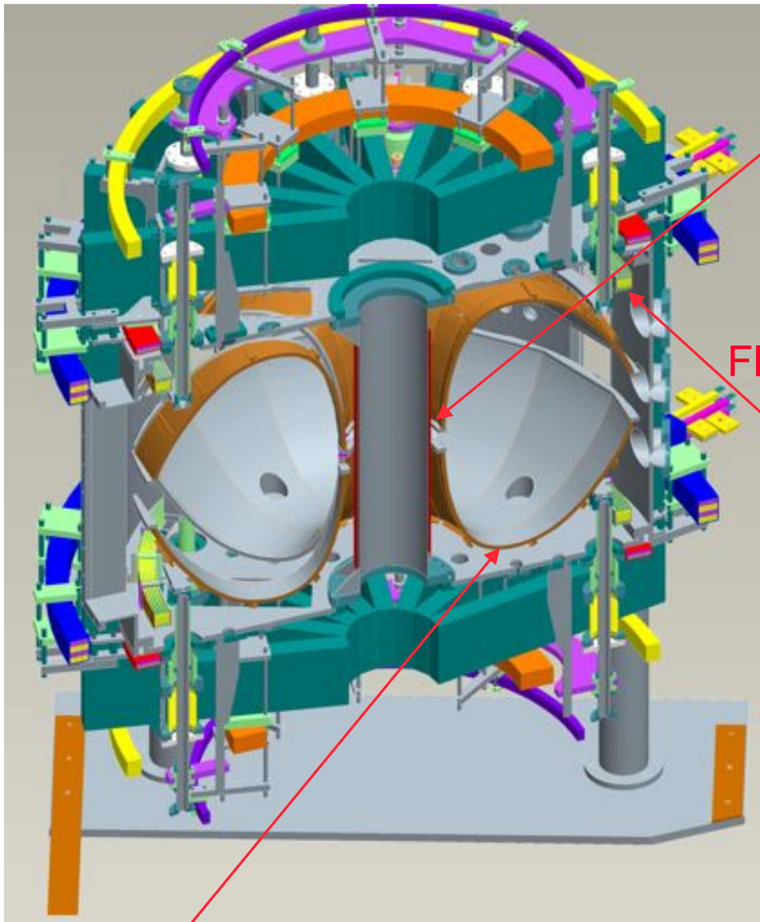
A. J. Dekker, in Solid State Physics, Advances in Research and Applications, Vol. 6 (Academic Press, New York, 1958) pp. 251-311

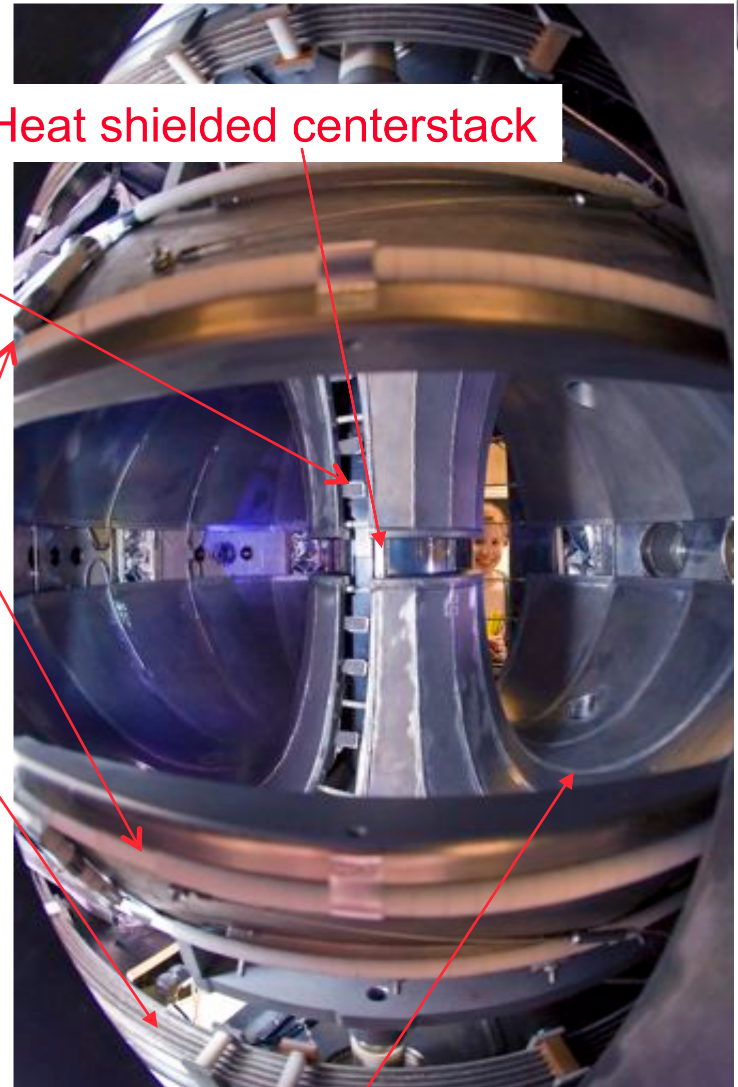
Implementation of LM PFCs

- Reactor implementation requires flow
  - Replace, redistribute eroded liquid metal
  - Remove impurities, hydrogenics (for lithium)
  - Remove heat (for self-cooled designs)
- Flowing systems provide clean LM surface
  - Flowing systems, especially fast flowing LM PFCs require large inventories of liquid metal
  - Fast flow requires axisymmetry to inhibit Hartmann layer formation, reduce MHD drag
- Near term tests do not require flow for erosion replacement
  - Heat removal requirements are relaxed
- But static liquid metals accumulate surface impurities
  - Time scale 10s – 100 seconds in typical fusion experiment
- Near-term challenge is to provide surfaces typical of flowing systems with a simple static or stirred liquid metal system

LTX –full hot metallic wall with solid or liquid lithium coatings

LTX





Inner heated shell (explosively bonded SS on copper)

➡ Bottom of shells form reservoirs for up to 300 cm^3 liquid lithium

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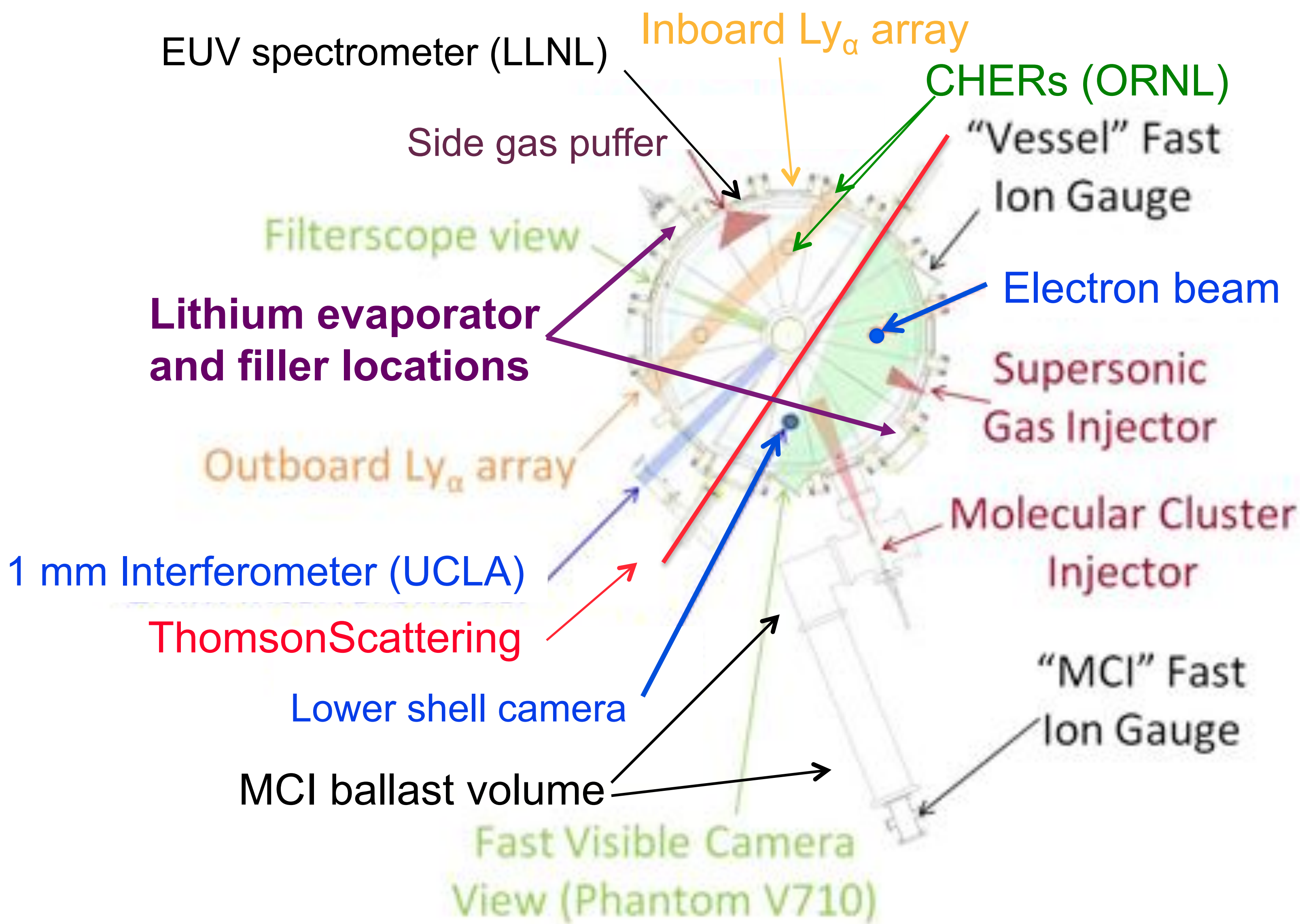
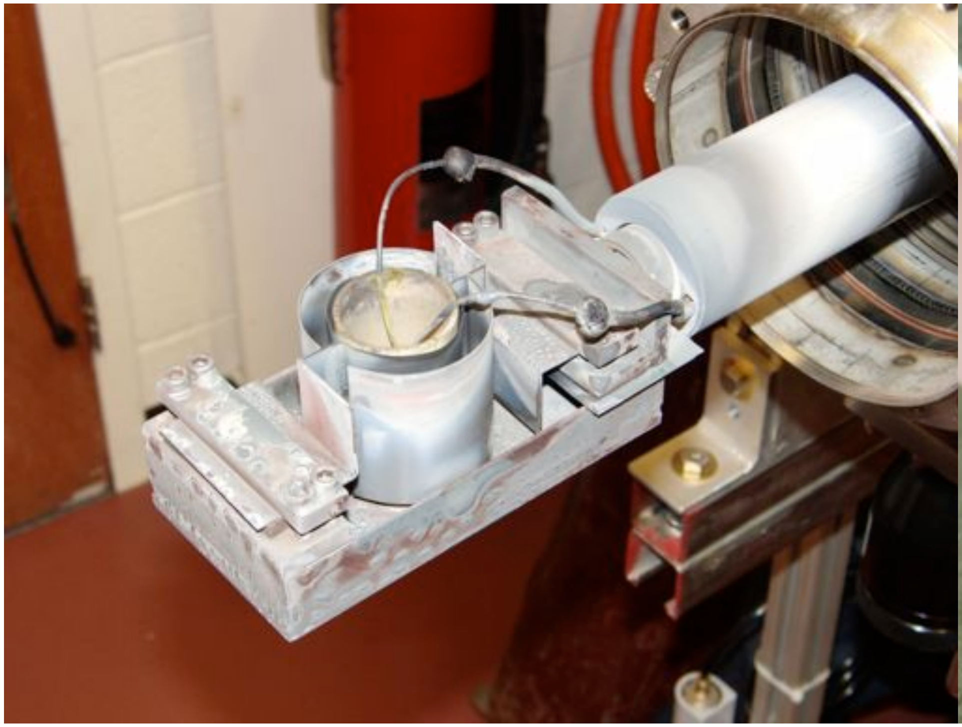
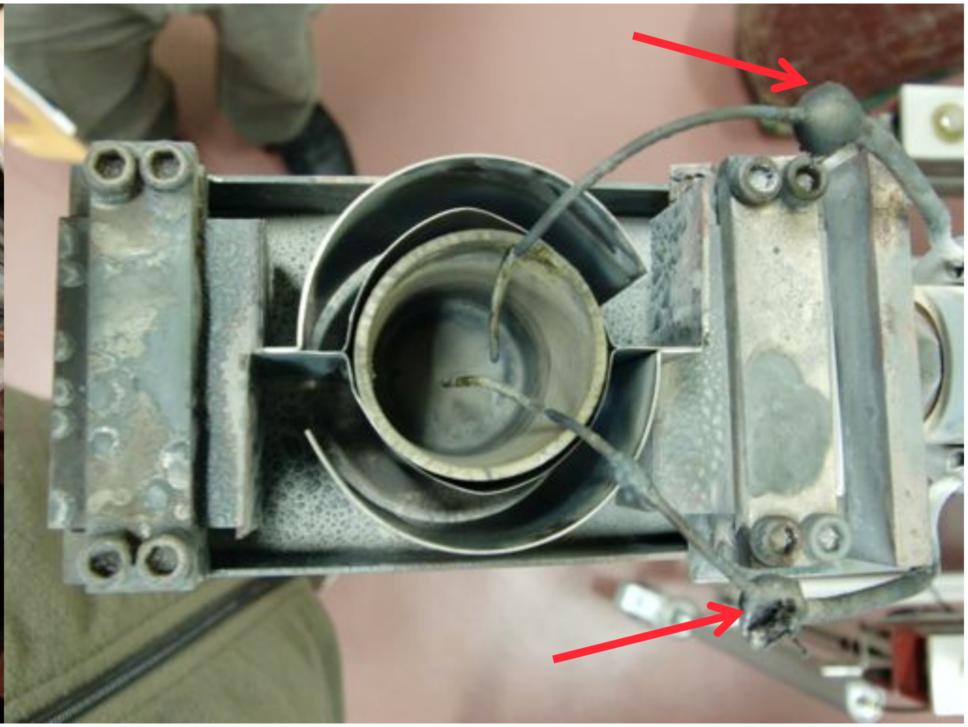
LTX diagnostics and fueling systems



Initial experiments with lithium walls employ evaporated coatings

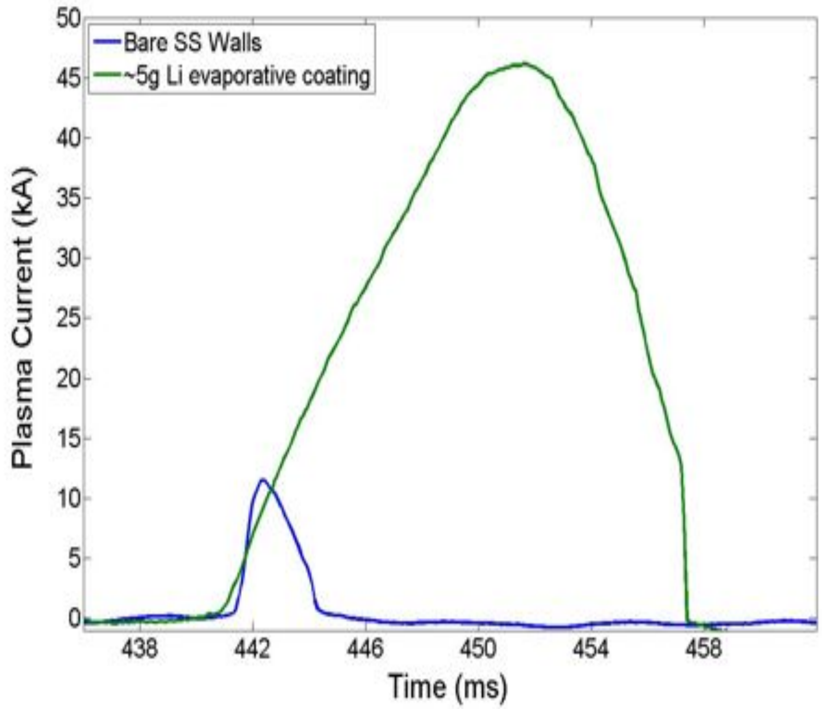
LTX

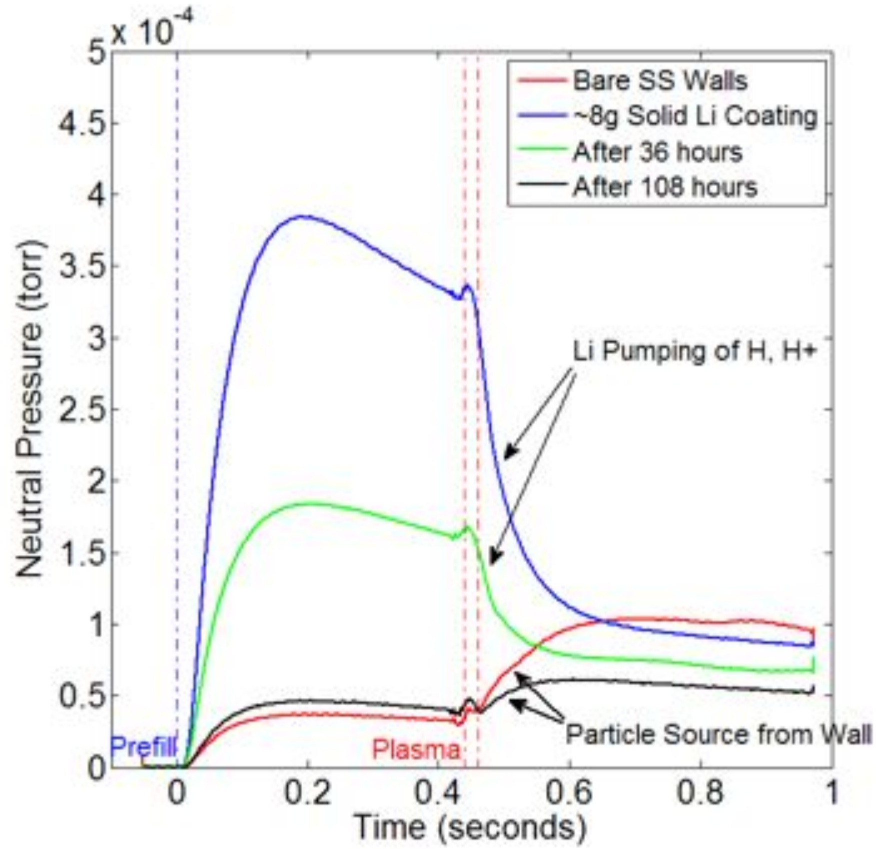




- Yttria crucible and tantalum crucible heater
  - 98 grams lithium evaporated in current campaign (2 evaporators)
- No significant issues with yttria crucibles after 600C operation
- Helium fill pressure of 5 mtorr yielded coatings with good uniformity

Solid lithium coatings have a strong effect on the discharge

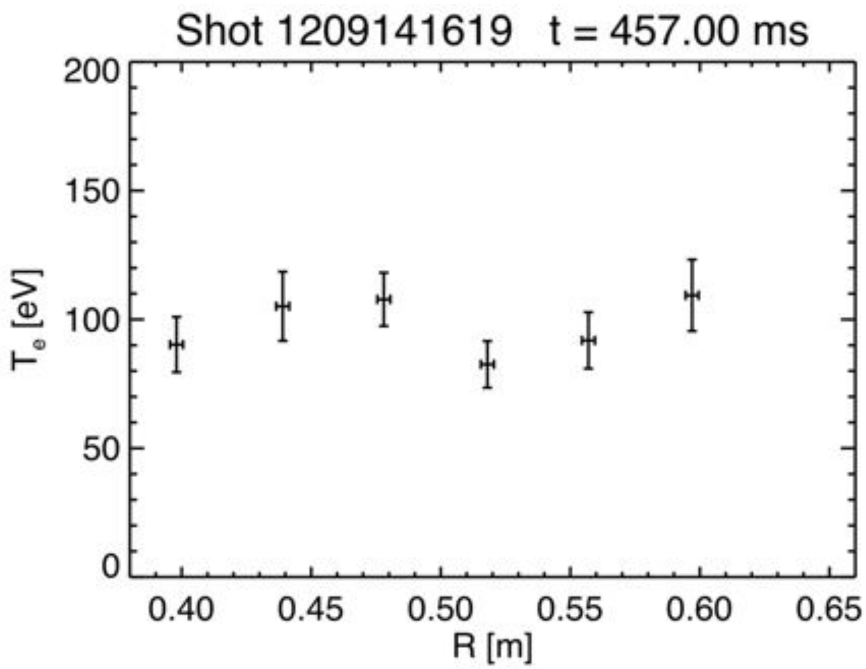




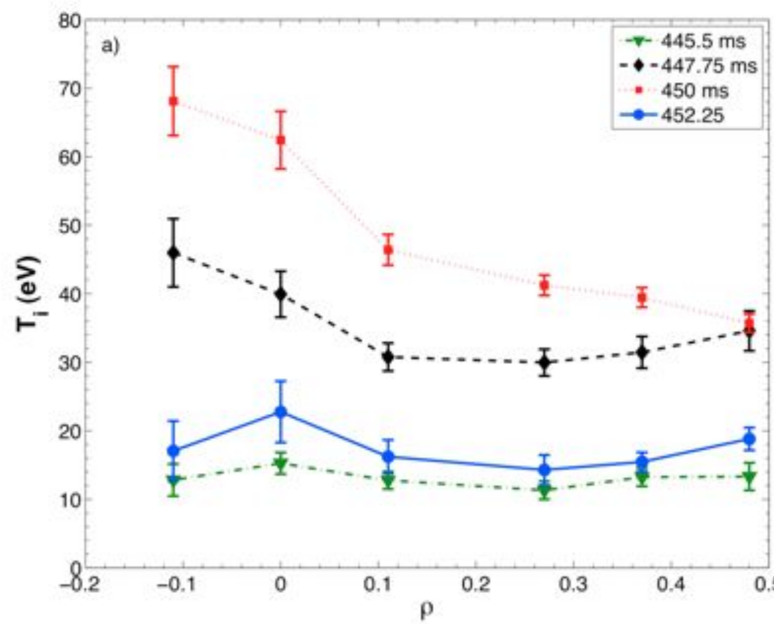
- Matched discharges w/ and w/o lithium coatings
  - Except gas prefill increase required with lithium
- Lithium coated walls are strongly pumping

Initial Thomson scattering profile, CHERs results were obtained for electron, impurity ion (lithium) temperatures

Thomson T_e profile is flat out to last measurement point at r/a ~0.8

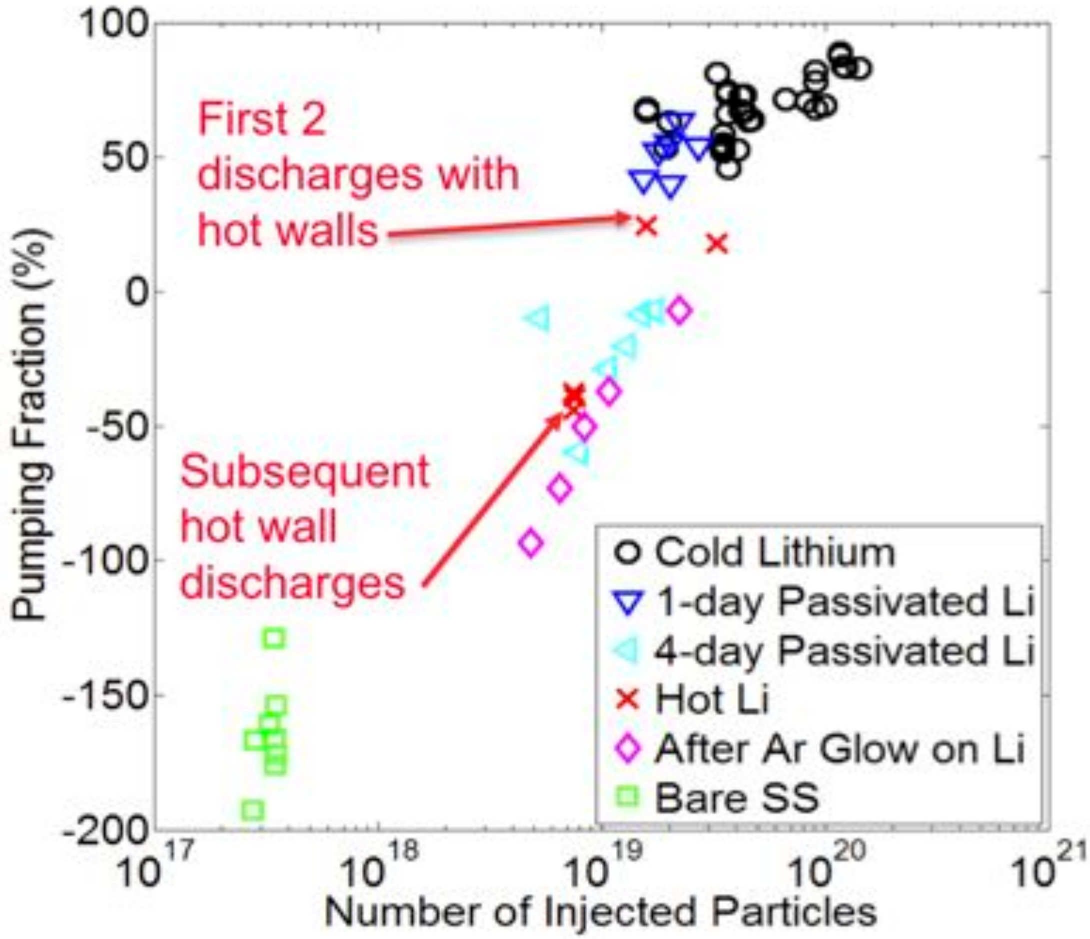


Initial results indicate impurity (lithium) T_i is higher than expected for a low density Ohmic discharge (results from ORNL CHERs system)



- Measurements in low current (~50 kA) increased pulse length discharges
- τ_E ~ 3 - 4 msec (up to ~1.3 × ITER98P)
  – CDX-U confinement 2-3 x ITER ELMy H-mode

Wall pumping effective with cold lithium coatings



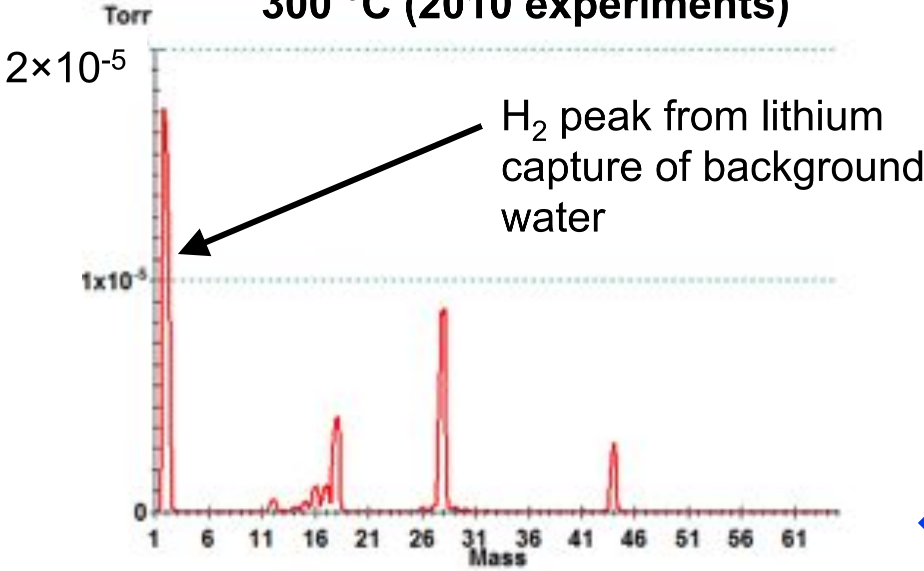
- Initial experiments with lithium coatings on hot (300 °C) walls showed a transient reduction in recycling

➢Cold walls with solid lithium coatings perform as expected in LTX

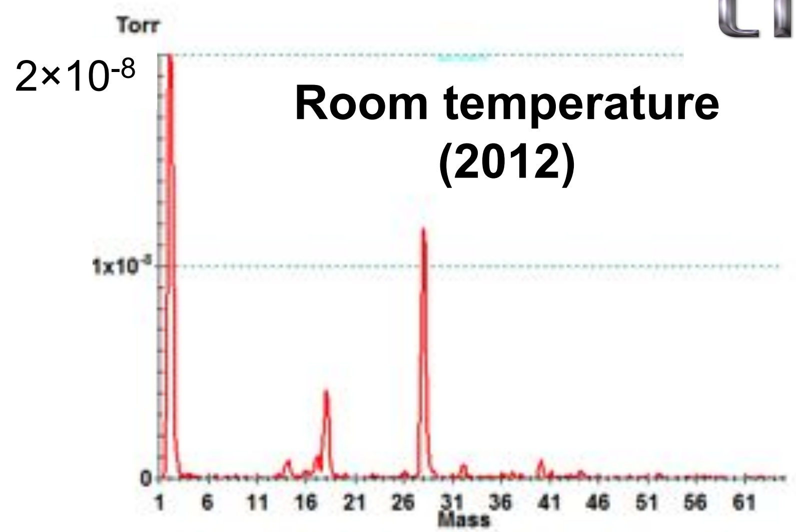
Hot walls: first issue with 5 m^2 heated in-vacuum PFC: maintaining good vacuum conditions

LTX

300 °C (2010 experiments)



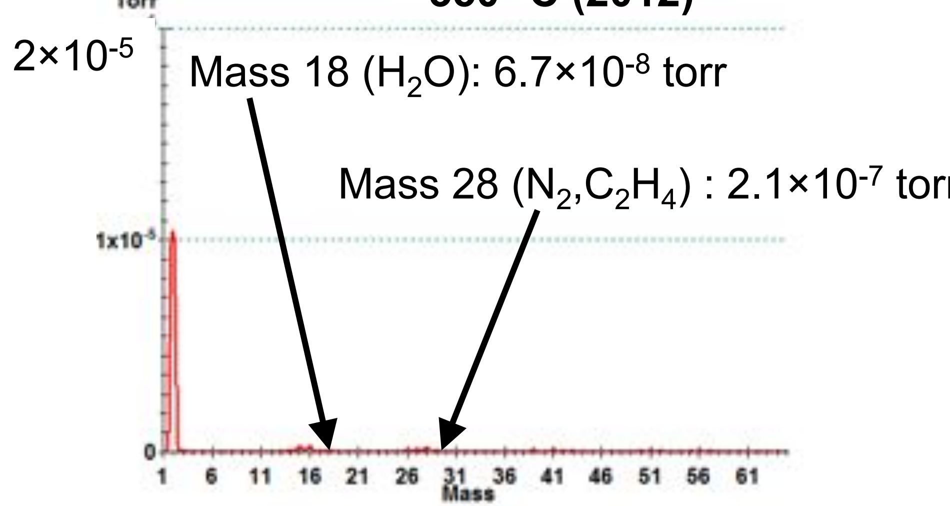
- RGA mass spectrum during initial hot wall (300 °C) experiments
  - Significant water, nitrogen, hydrocarbon lines



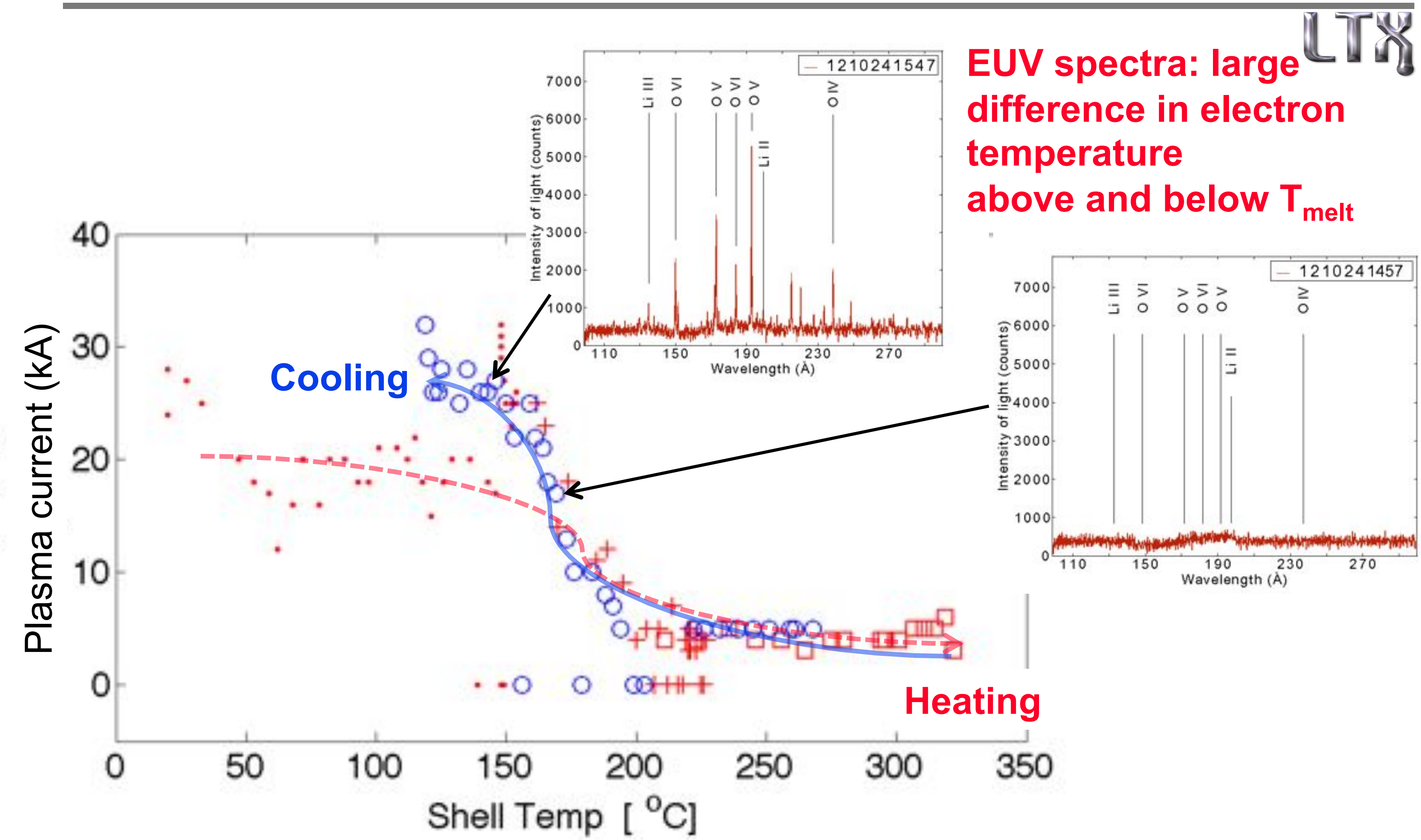
Room temperature (2012)

- Impurity sources now sequestered (presumably in the lithium)

350 °C (2012)

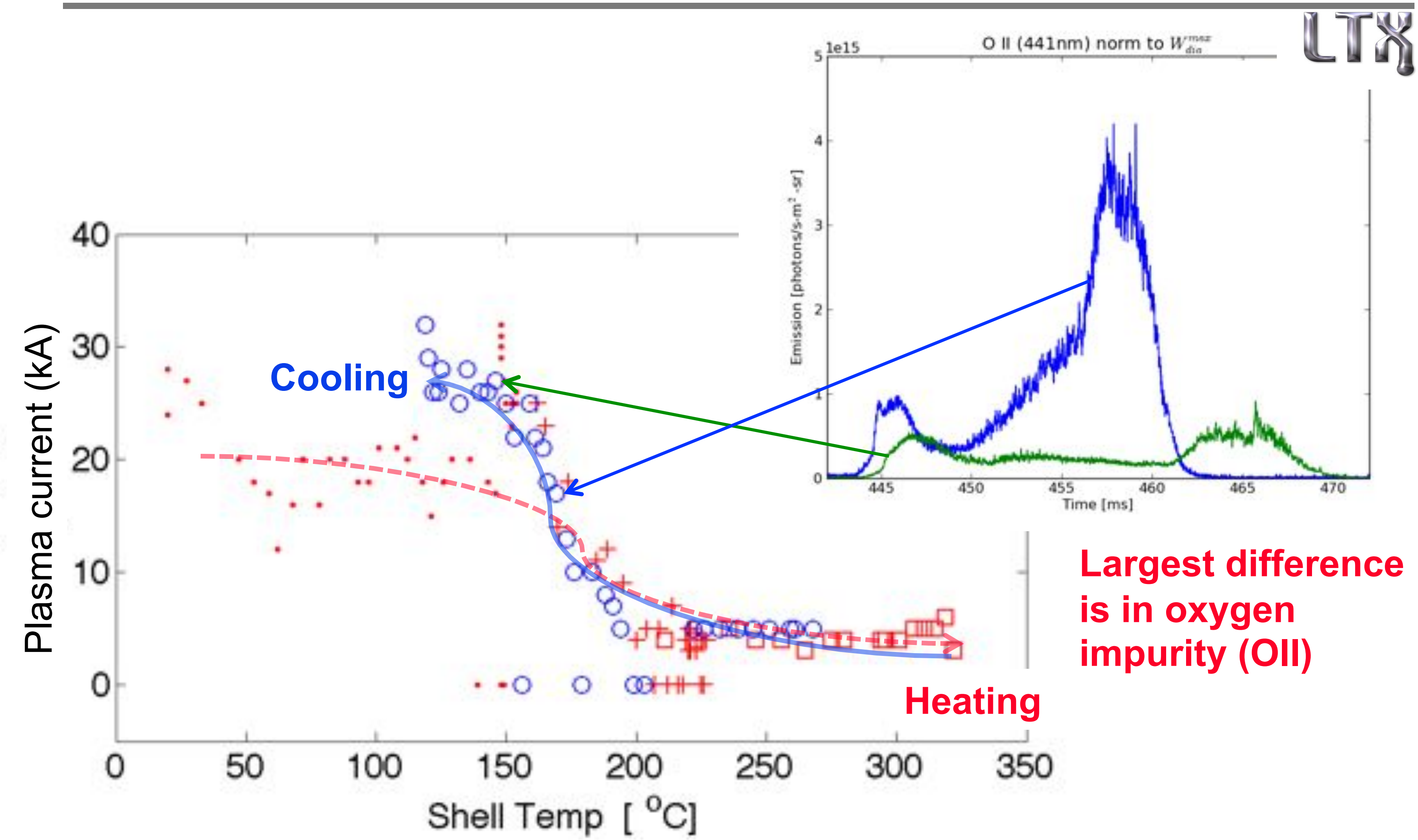


Second issue: surface impurity accumulation, plasma uptake with liquefied thin films



- Thomson scattering comparisons not available

Oxygen, carbon, lithium, hydrogen influxes all increase when lithium coatings liquefied



- Liquefaction of the thin lithium wall coating appears to make pumped impurities available for sputtering for $T \gtrsim T_{melt}$ (180 °C)

Liquid lithium PFCs must be mixed

- Cold lithium coatings improve performance
- Hot walls (>180 °C ~ T_{melt}) produce impurity-dominated discharges
- Surface sequestration of impurities in molten films (few tens of microns at present) dominates
  - Relevant to thin melt layers on solid PFCs as well
- A deeper pool of stirred lithium is necessary, to prevent plasma contamination by surface accumulation of impurities
  - CDX-U: 2-3 mm in tray
  - Capillary porous systems: thin wet layer backed by a reservoir sufficient
- LTX will employ liquid lithium reservoirs a few mm deep in the lower shell quadrants

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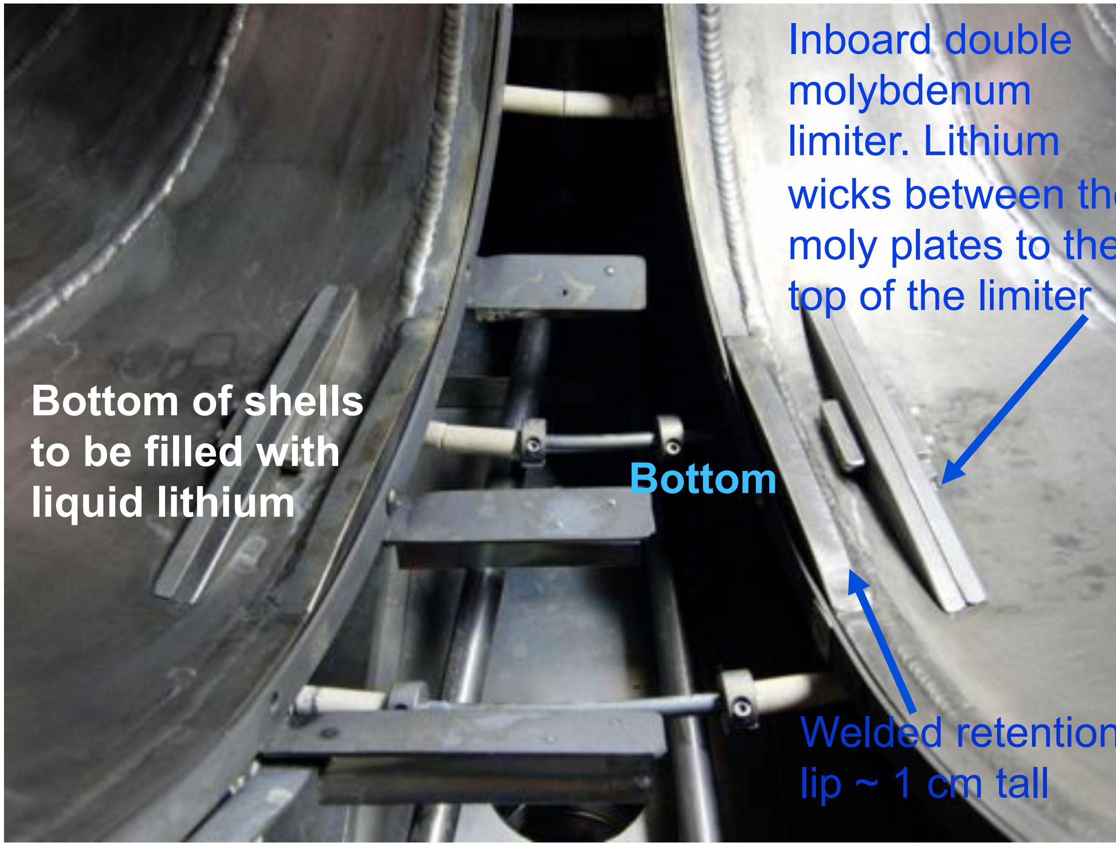
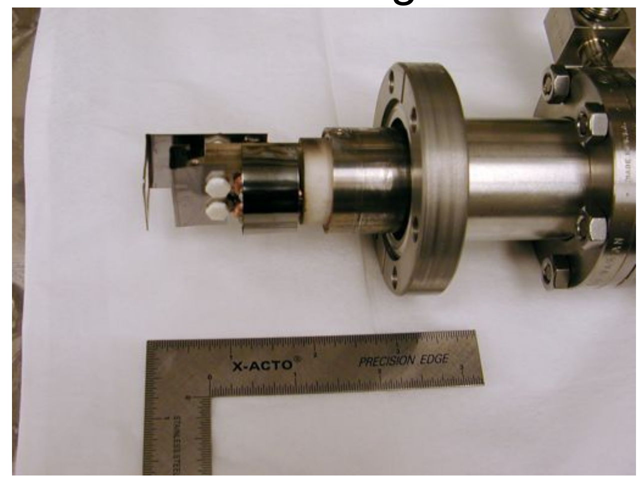
Reservoirs in lower shells will provide a stirred pool of liquid lithium



- Compact 1.6 kW e-beam for stirring LM



- Capacity: 300 cm^3 of liquid lithium

- E-beam stirring of liquid lithium in CDX-U
  - J×B stirring has also been suggested

Summary - liquid metal PFCs

- Tungsten PFCs impose strong constraints on fusion systems
  - Fusion (neutron) power density cannot be too high
  - Eliminates compact reactors (except aneutronic systems)
- Development of LM PFCs is still in early stages
  - Only lithium has been tested at all
  - Very limited testing of liquid lithium PFCs
- Hot wall operation imposes stringent vacuum requirements
- Simplest approach to LM PFCs (molten lithium films) too sensitive to impurities
  - Fully flowing systems require significant development
    - » Initial development requires toroidal test stands, but no plasmas
  - Stirring a liquid lithium system is acceptable for near-term devices
- At present, LTX is the only device testing LM PFCs in the U.S.
  - Chinese program is far more aggressive

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