Results from LTX with solid and liquid lithium walls

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Outline

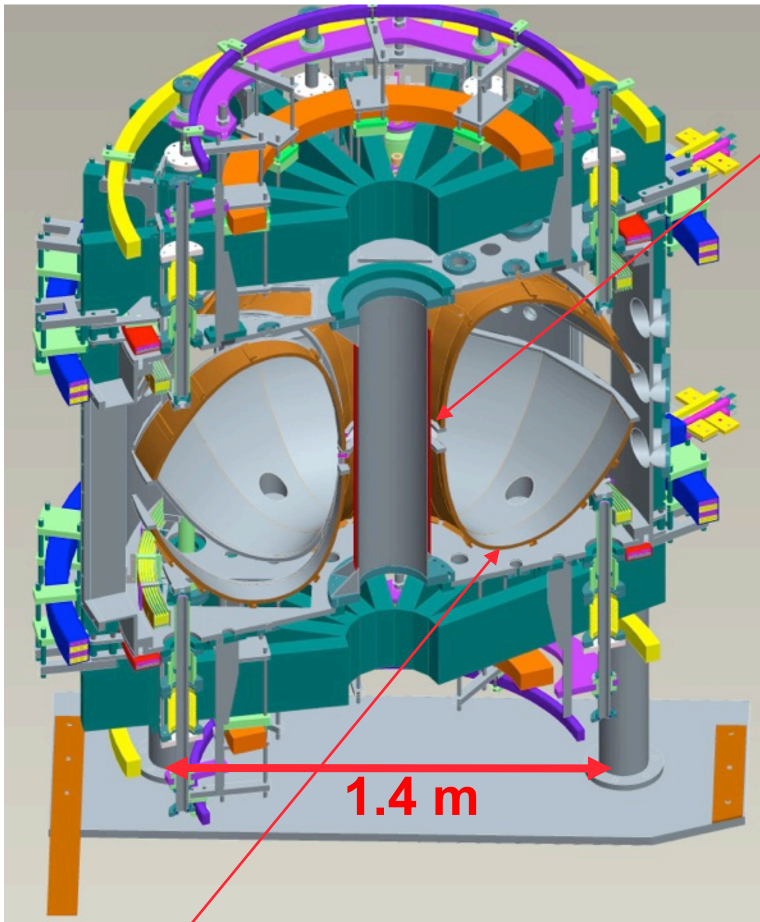
- Research goals and program
- LTX : ohmically heated ST with lithium PFCs
  - R_0=40, a=26, κ=1.6, B_{TF}< 2kg, I_p< 100 kA
  - Hot wall, internal lithium reservoirs for evaporative coating
  - Electron beam-assisted evaporation
- Surface evolution of lithium coatings
- Results with continuous high-field side gas fueling
- Temperature profile evolution when fueling is terminated
  - Development of flat temperature profiles
- Plans for LTX-Upgrade
- Summary

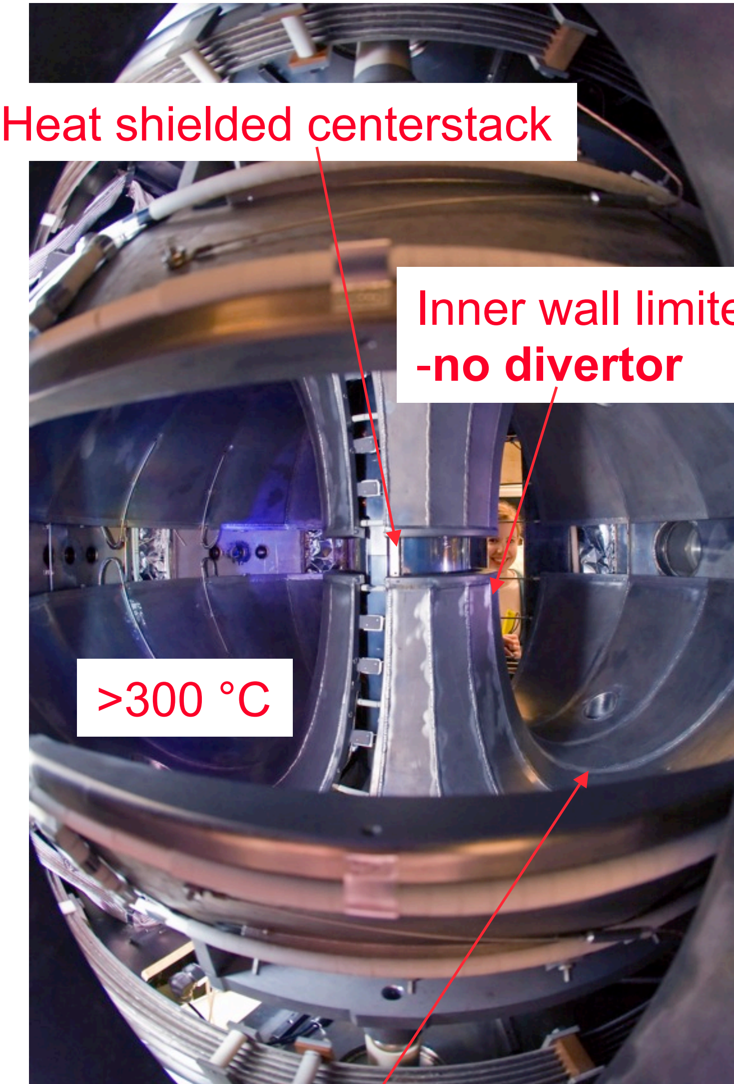
LTX research program goals

- Access very low recycling wall regime
      » A.k.a the lithium walled tokamak
  - Investigate equilibrium, confinement, MHD stability
      » Signature of this regime is flat $T_e(r)$, $T_i(r)$
- Demonstrate compatibility of the tokamak with *liquid* lithium PFCs
  - Modest lithium impurity, even with a full liquid lithium wall
  - Required for extrapolation to a reactor
- Not addressed:
  - Engineering of flowing liquid lithium walls for a tokamak
  - Potential for very high heat removal
  - Neutron tolerance of liquid lithium/ferritic steel construction

Conformal wall in LTX incorporates lithium pools for coating

LTX



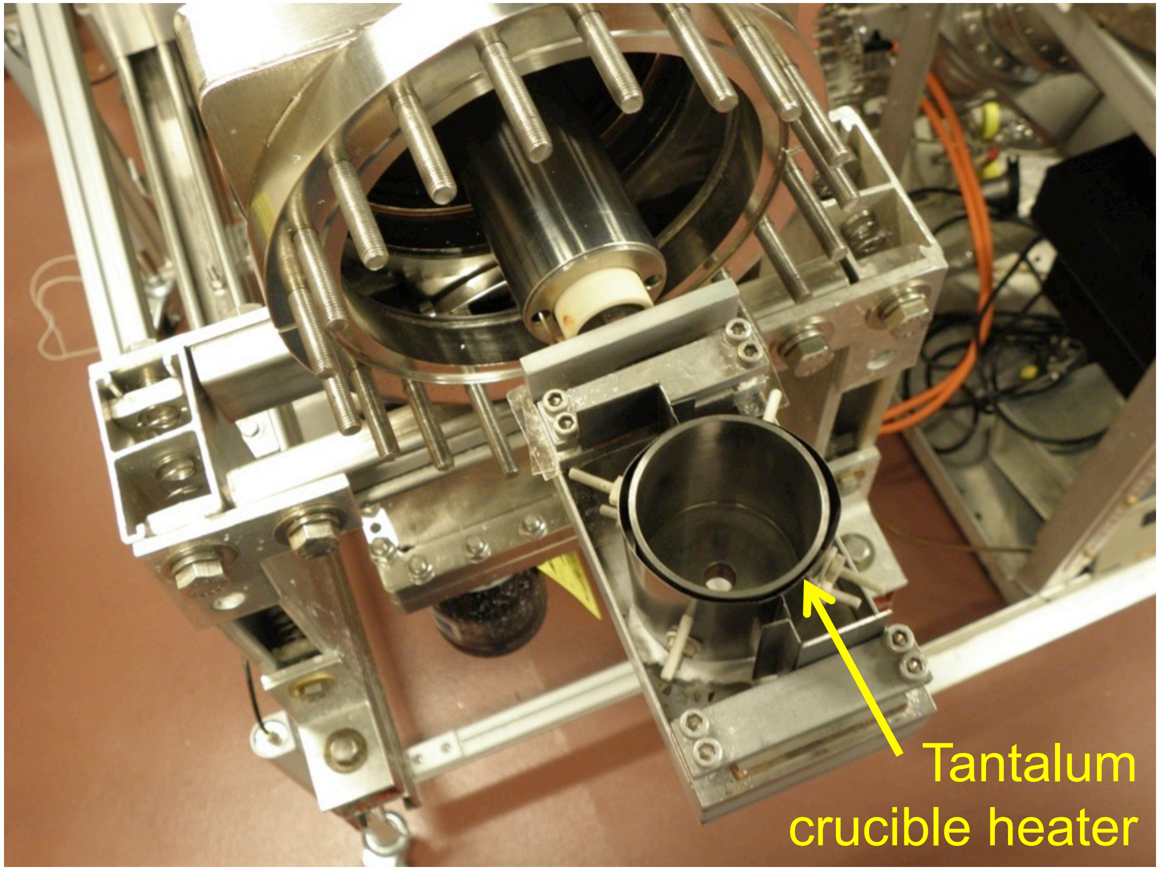


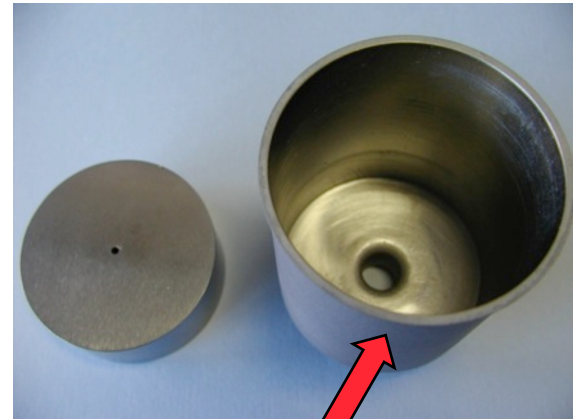
Inner heated shell (explosively bonded SS on copper)

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

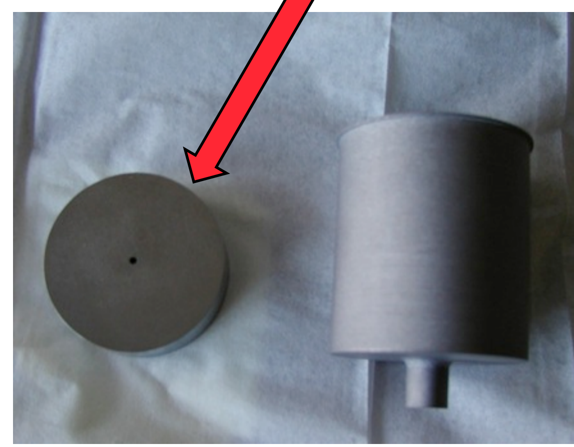
Lithium delivery system uses a simple weighted piston

- Lithium is delivered with a bellows-sealed motion stage
  - Dual gate valves (airlock) to prevent air exposure



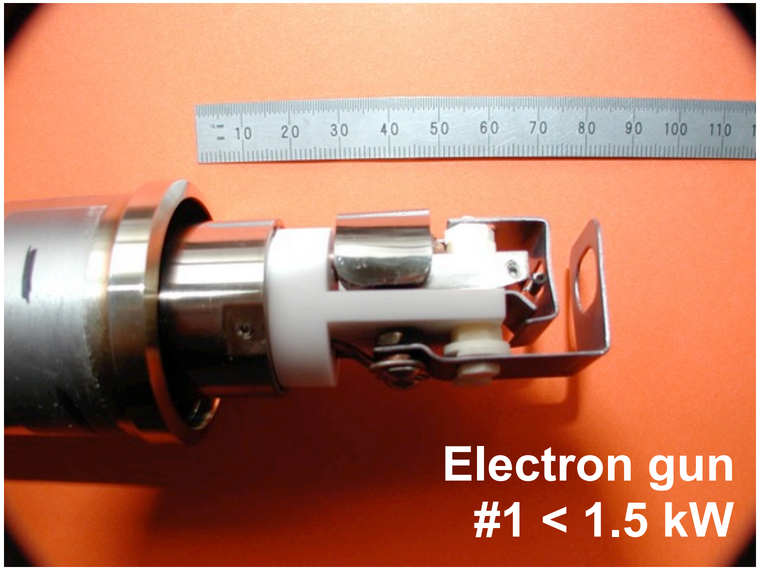


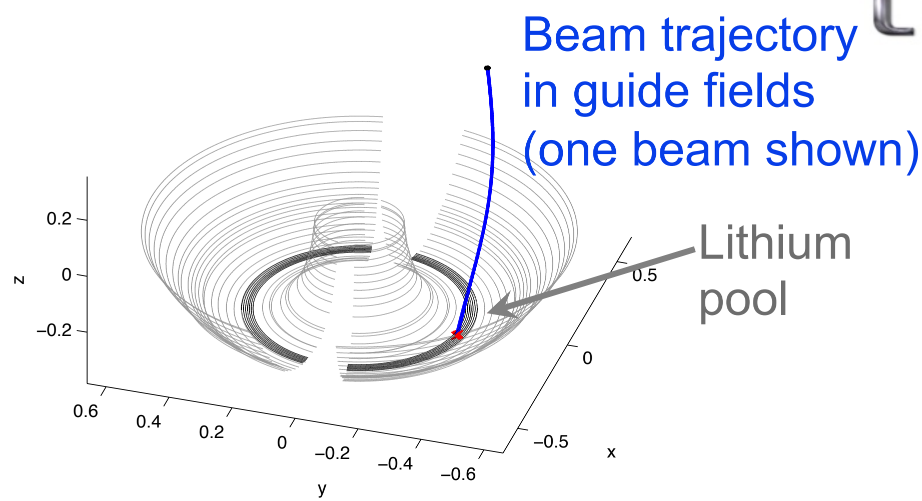
- Electroformed tungsten crucible with outlet
  - Tungsten piston



- Liquefy the lithium and it is ejected through outlet
- Delivers 16 cm^3 of lithium per fill
  - Multiple fills required for lithium pools – 45 g total in 2013-2015 campaign

Electron beam-based lithium evaporation system yields full lithium wall coatings

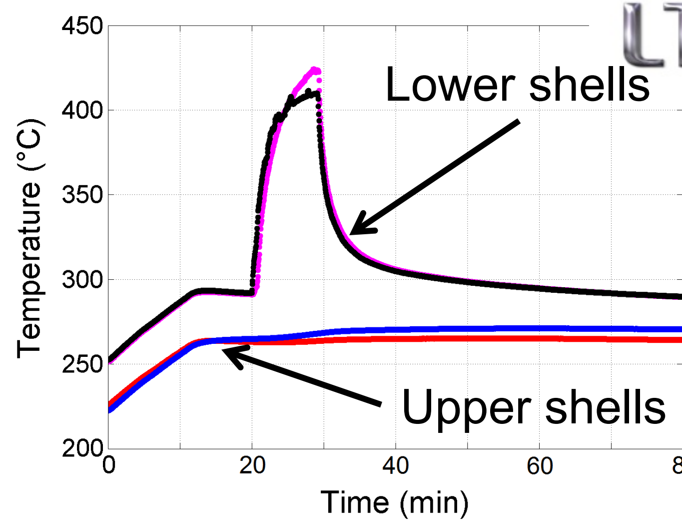




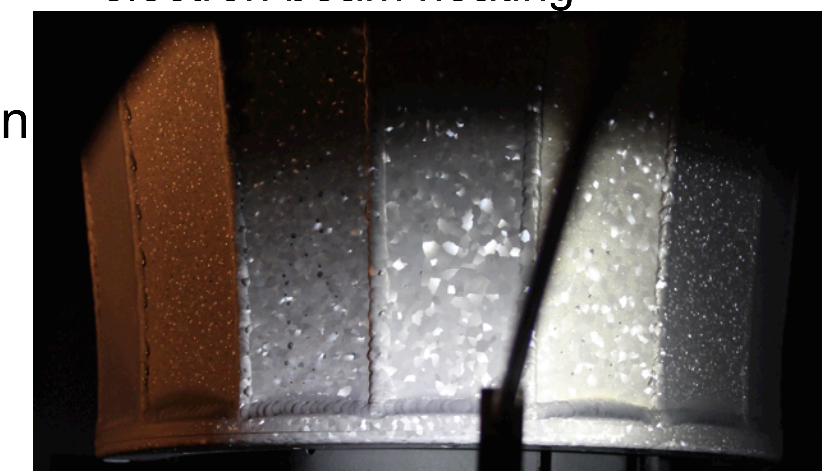
- Electron beams are magnetically guided by low (~70 G) quasi steady-state magnetic fields
- Rapid electron beam-driven evaporation from lithium pools
  - Simultaneous operation of both e-guns coats all four shells at once

Lithium coating sequence

- Preheat shells to ~320 °C
- Establish guide magnetic field
- E-beam heat lithium pools
  - 500 – 1000 Å coating
- Maintain ~300 °C shell temperature
  - Liquid lithium experiments
- Shell heaters off for solid lithium
- <u>No performance degradation</u> seen over a day's run
  - Clean lithium requires near-elimination of residual water from vessel
    - » Water level ~mid 10^{-10} Torr
- Between-shots recoating possible in principle (but not in practice yet)



Shell temperature rise during electron beam heating



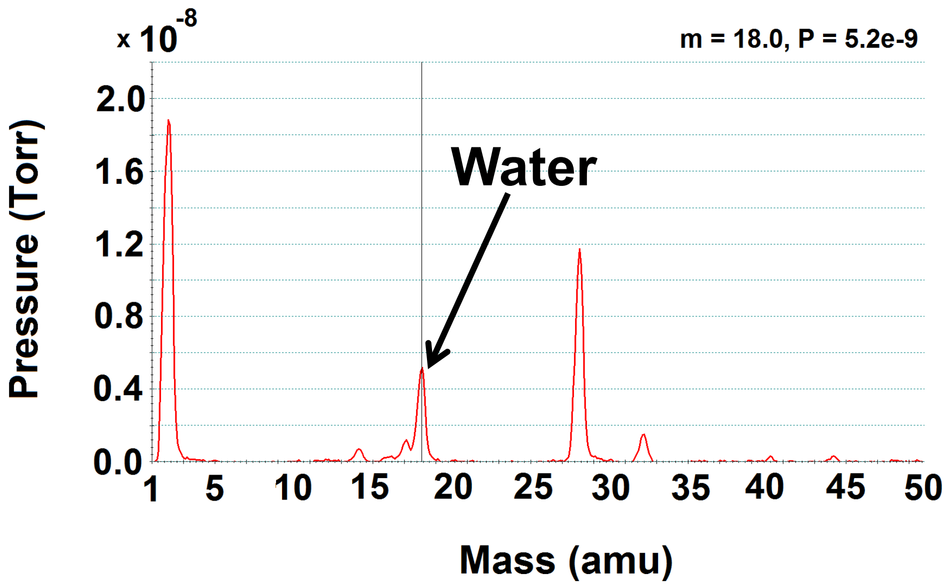
"Spangle" pattern on solidified lithium indicative of clean metallic coating

Successive lithium coating cycles have eliminated most water

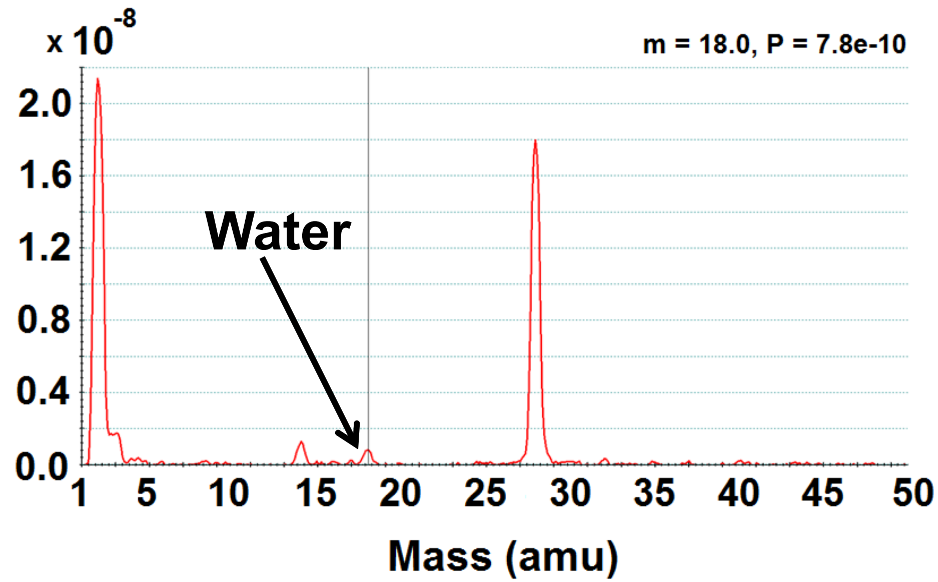
Late 2013 –
After first few e-beam depositions
-single e-beam coating half the shell

Now

Base Pressure RGA Spectrum



Base Pressure RGA Spectrum



- Background water mid × 10^{-9} Torr
- Oxygen 1-2 x 10^{-9} Torr
- Hydrogen dominates RGA spectrum
  - Total pressure 3-5 × 10^{-8} Torr

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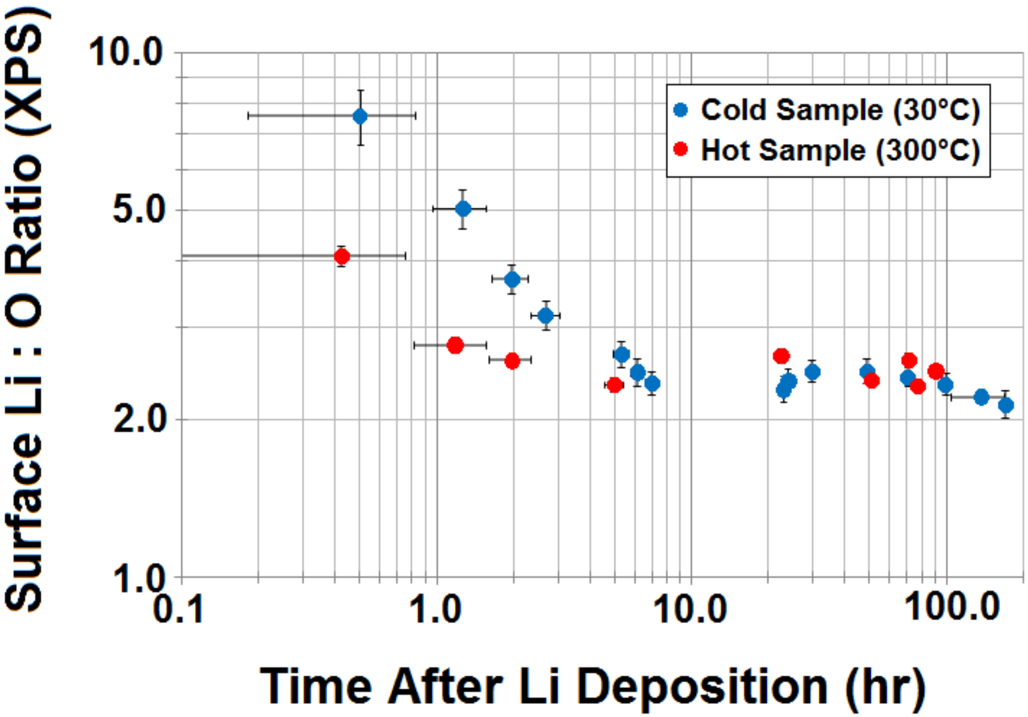
Temporal evolution of lithium coatings

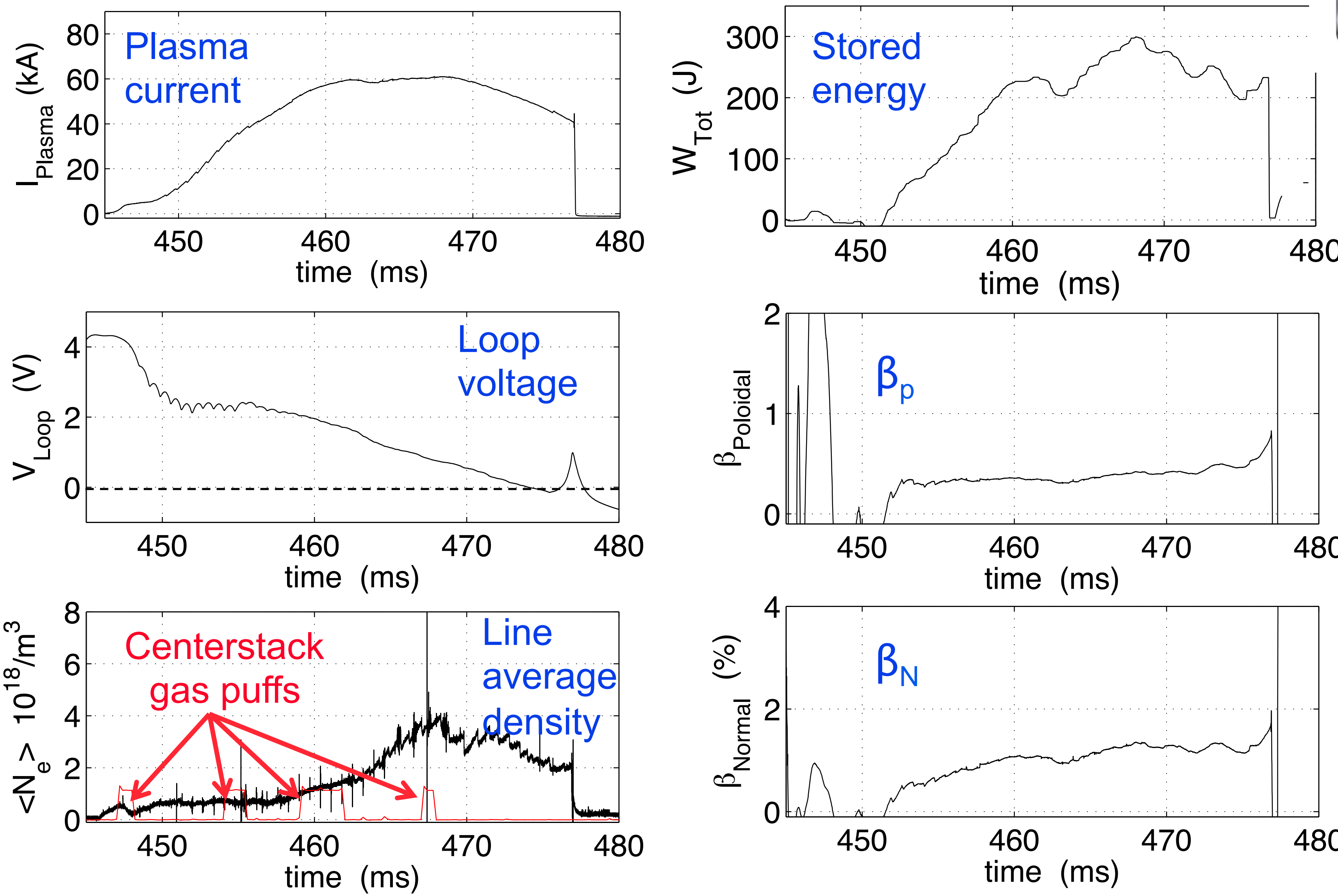
Surface Evolution in LTX Base Vacuum



- Analysis with the UIUC MAPP probe
  - X-ray Photoelectron Spectroscopy (XPS)
  - MAPP has been moved to NSTX-U
  - Surface evolution of lithium-coated graphite, in NSTX-U vacuum, can be compared

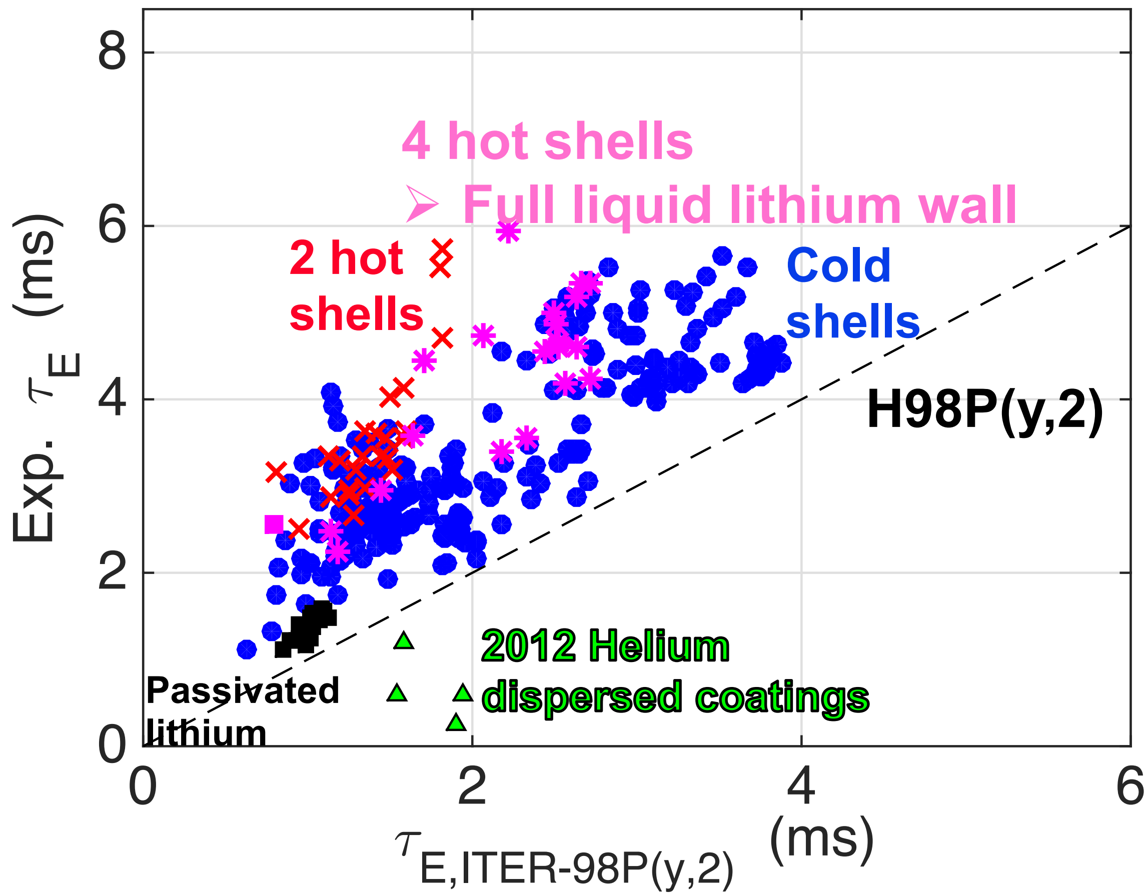
- Li:O ratio initially high
- Ratios asymptotes to 2:1
  - Indicates Li_2O, not LiOH is formed in LTX
- Timescale of surface evolution suggests between-shots coating capability should produce more metallic coatings

Ohmic discharges were used to estimate confinement with e-beam evaporated lithium coatings



- Discharges employ continuous gas fueling with a centerstack gas nozzle

Performance with full liquid lithium PFCs comparable to operation with solid lithium coatings

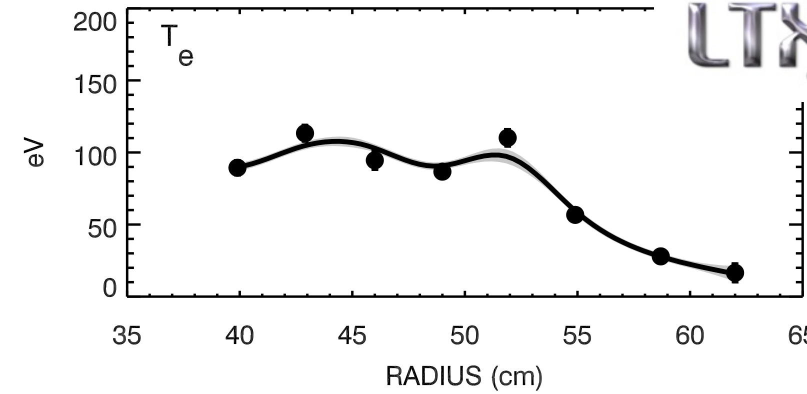


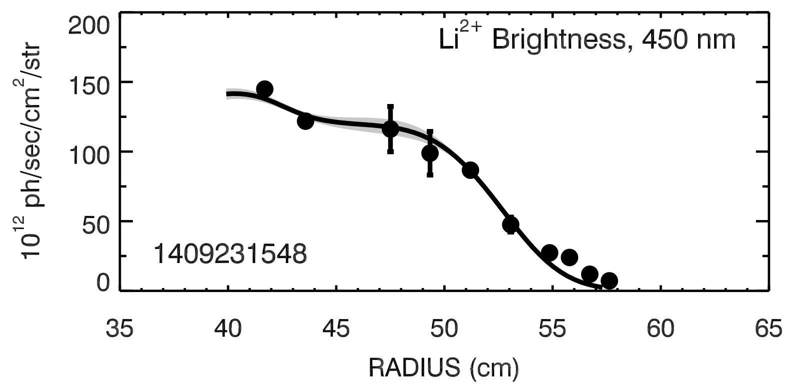
- Only power input is Ohmic heating of electrons
- $\tau_{e\text{-}i}$ ~ 5 msec – ions weakly heated by electrons
- Effects of surface aging (passivation) clear
- Any lithium coating improves performance relative to bare high-Z wall
  - ➢ Improvements in coating quality produce performance improvements

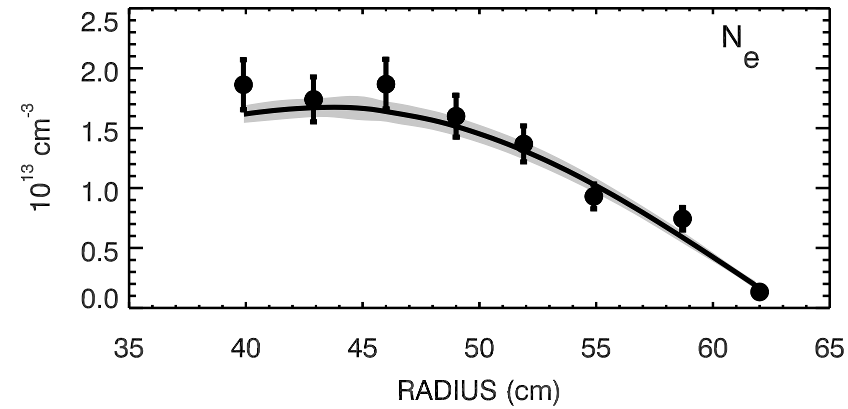
- 4 m^2 liquefied lithium wall
  - ➢ Covers 80% of plasma LCFS

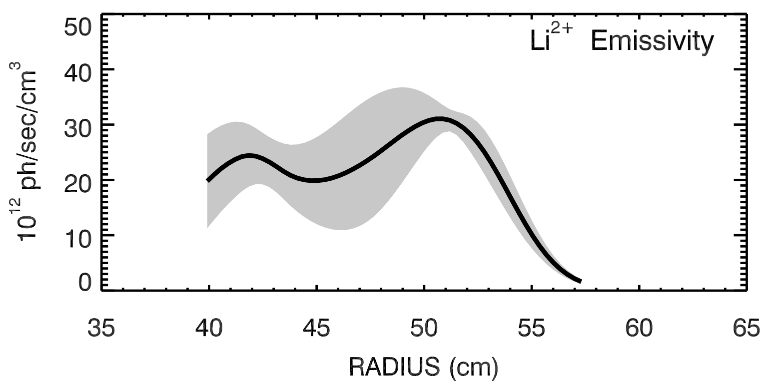
Lithium core concentration modest, even with ***liquid*** lithium walls at 270 °C

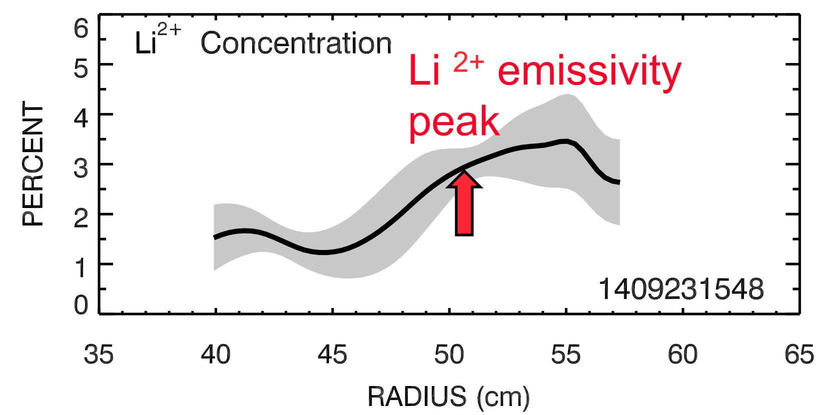
- Lithium core concentration a few %
  - Estimate from concentration at peak in Li^{2+} emissivity
  - Oxygen, carbon lower
  - Total Z_{eff} from O, C, Li ~ 1.5
    - No other ions observed



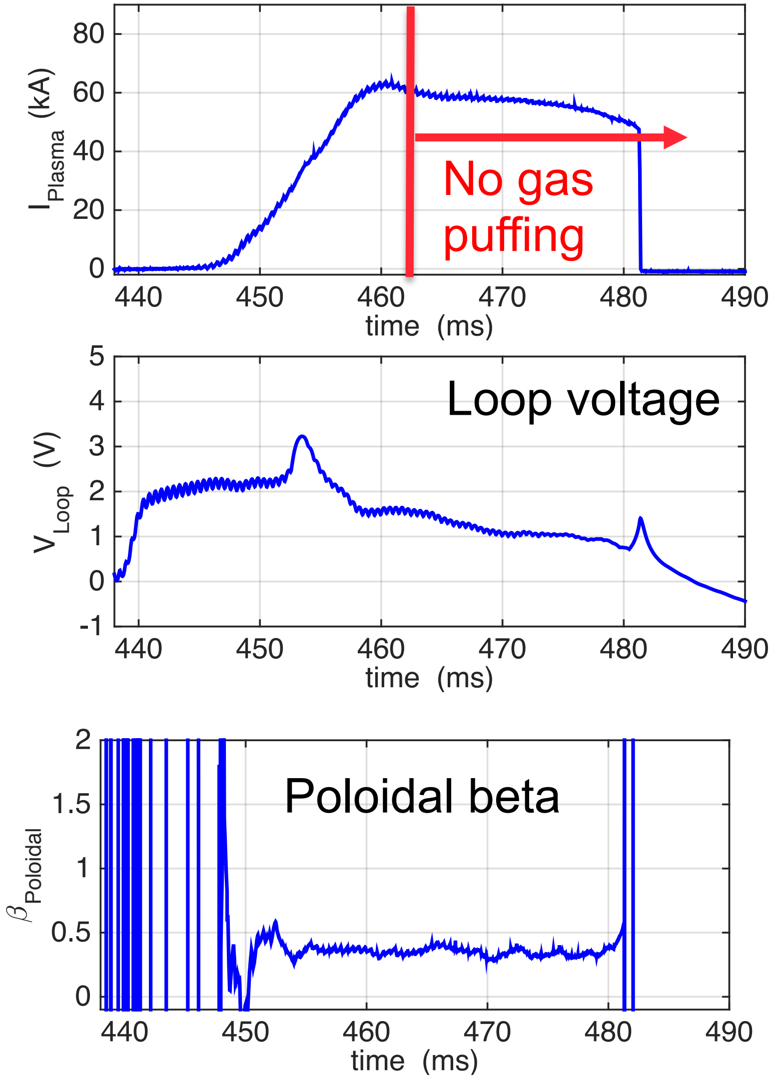


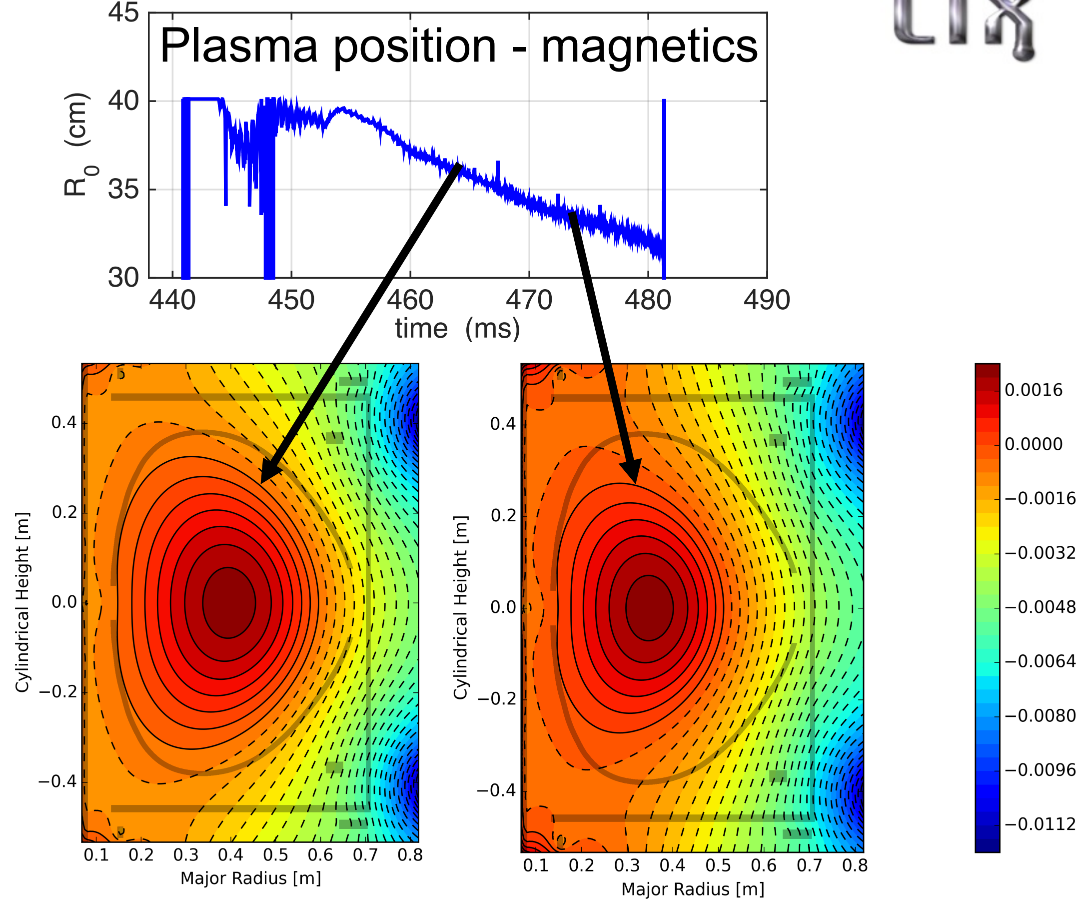






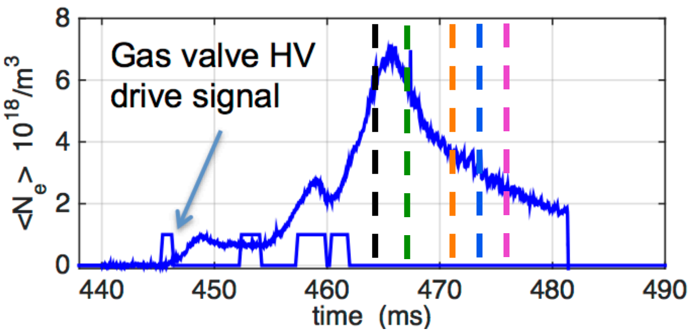
OH modifications allow examination of electron temperature evolution with low edge neutral pressure



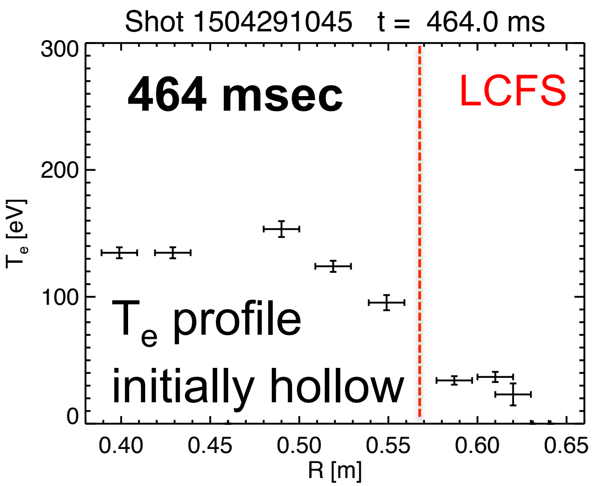


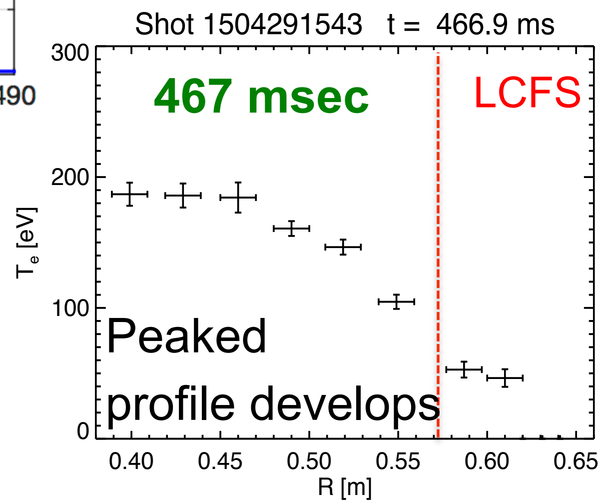
- Plasma axis drifts inward during current flattop
  - Equilibria reconstructed with PSI-TRI code (C. Hansen, Univ. Washington)

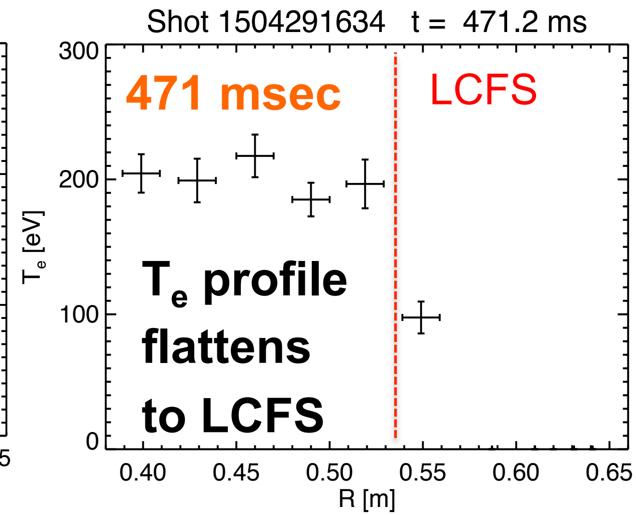
Flat electron temperature profile develops when edge neutrals are eliminated

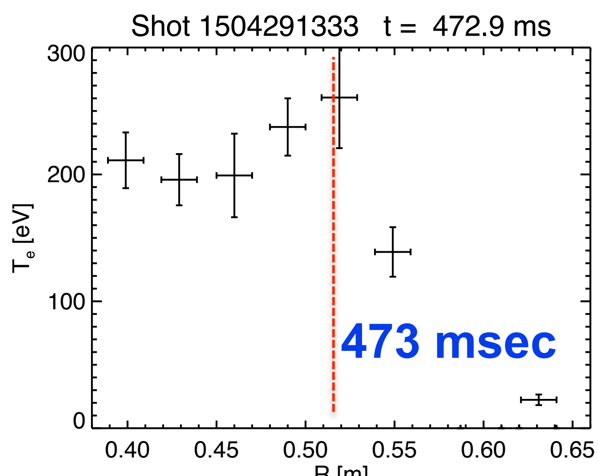


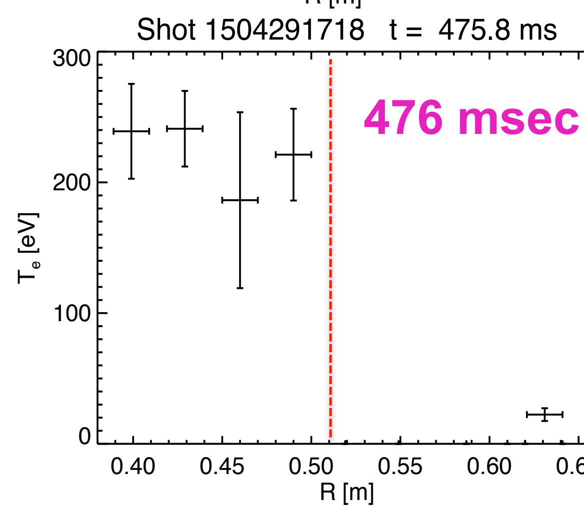
- Longer discharges (new OH programming)
- All fueling (centerstack) terminated at 462 msec
  - ~3-4 msec required to clear gas from duct





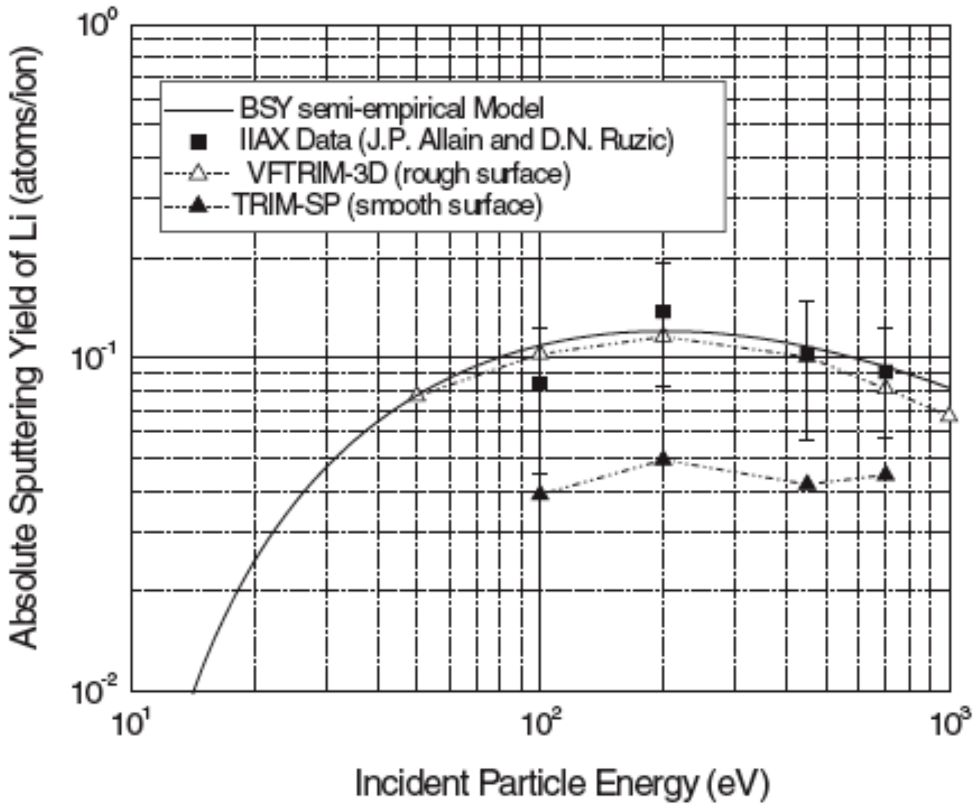






- Electron temperature profile remains flat
  - Thomson data unreliable past 476 msec

Further increases in edge T_e should not increase lithium influx



- Lithium core concentration in LTX still a few % with T_e(edge) ~ 200 eV
  - Wall sheath potential > 600V
- Li sputtering yield for D incident on deuterated Li peaks at ~200 eV

  (Allain and Ruzic, Nucl. Fusion 42(2002)202).
- At 700 eV the yield is 9%
  - Yield rises to slightly above 10%, just above the melting point
  - Yield is similar for D, H
- Additional data at higher impact energies needed

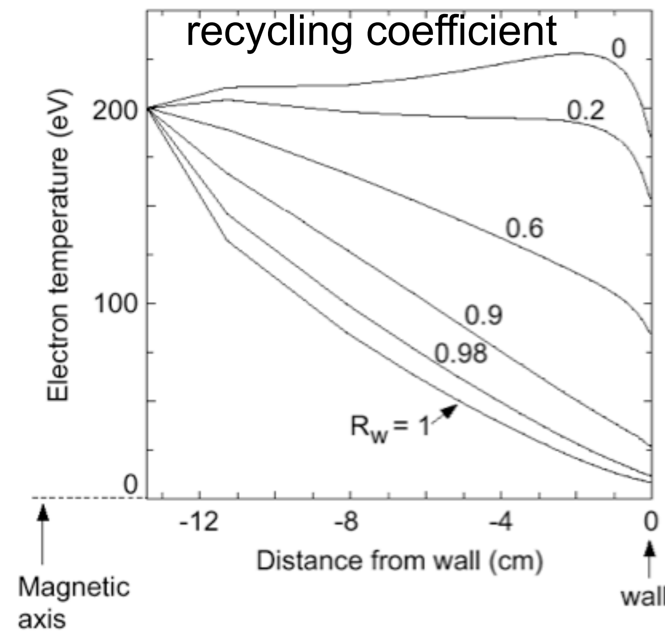
- Self-sputtering of Li on D-treated Li also drops with energy:
  - 24.5% at 700 eV
  - 15.8% at 1 keV
- Probability of direct reflection of incident H from lithium PFC also drops to <10% for incident ion energy >500 eV

Flat temperature profiles predicted for low recycling walls

- High edge T_e, T_i a consequence of nonrecycling boundary conditions (and no injected gas), *not transport*
  - Hot core particles transported without cooling
  - Temperature profile always flat
    - » Independent of particle transport
  - With NBI (Zakharov):

$$\frac{T_i^{edge} + T_e^{edge}}{2} \simeq \frac{1 - R_{e,i}}{1 + (\Gamma^{gasI}/\Gamma^{NBI})} \cdot \frac{\langle E^{NBI} \rangle}{5}$$

- Equilibrium *without* temperature gradient –
  "Isomak" (P. J. Catto and R. D. Hazeltine, Phys. Plasmas **13** (2006) 122508)
  - Weak collisional transport
  - Rigid body ion toroidal rotation
  - Diamagnetic current is finite on axis
  - Density profile depends exponentially on poloidal flux
  - Radial electrostatic potential proportional to the poloidal flux



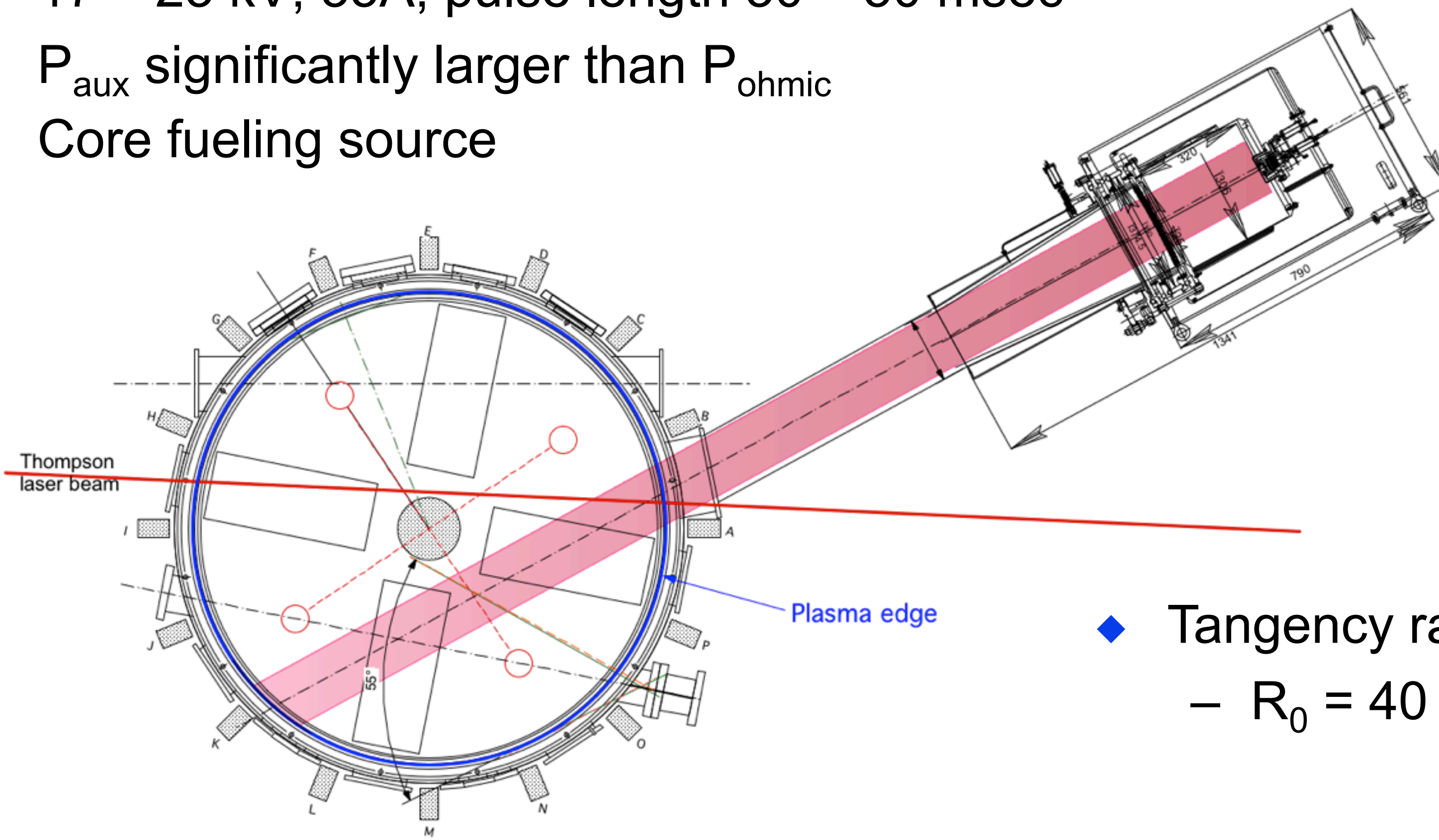
CDX-U modeling
for nonrecycling walls
T. Rognlien, UEDGE

Upgrades are proposed for LTX in 2016

- Double toroidal field (0.17 T to 0.32 T)
- Double energy in ohmic power supply
  - I_p ~ 150 kA
  - Longer flattop
- Improve bakeout
  - Shell systems bakes to >300C, but vacuum chamber to 85 C
  - Improve chamber bakeout to 120 C
- Increase vacuum pumping speed, address minor vacuum leaks
- Add between-shots lithium coating capability
- Expand diagnostic set
  - Reflectometer will provide fluctuation data
- **And add neutral beam injection for heating and fueling**

2016 – Adding neutral beam injection to LTX-U system loaned to LTX by Tri-Alpha Energy

- 17 – 23 kV, 35A, pulse length 30 – 50 msec
- P_{aux} significantly larger than P_{ohmic}
- Core fueling source



- Tangency radius 23 cm
  – R_0 = 40 cm

- 700 kW beam will also provide large toroidal momentum input
  - Beam system is now onsite

Summary

- Experiments on LTX have now demonstrated good tokamak performance with full liquefied lithium walls
- Moderate core lithium concentration
  - Demonstrated with full liquid lithium PFCs
  - Very high edge temperature
- Edge T_e strongly increases with removal of edge neutral gas load
  - Very flat T_e profile develops, out to the LCFS
    - » First access to the "lithium wall regime"
    - » Confirms prediction of Krasheninnikov, Zakharov, Pereverzev (Phys. Plasmas **10**, 1678 (2003))
  - Will permit a test of predictions of Catto and Hazeltine (Isomak)
- Upgrades to LTX will extend operation to higher toroidal field, higher plasma current
- Neutral beam adds auxiliary heating, modest core fueling capability
- Upgrades to be complete in ~ 1 year