Effects of Lithium Wall-coatings on Impurity Ions in the Lithium Tokamak Experiment (LTX)

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Abstract

By reducing neutral recycling and providing a low-Z plasma-facing surface, lithium wall coatings have led to major performance improvements in TFTR[1], CDX-U[2], and NSTX[3]. The effects of lithium coatings on plasma performance are being studied in the Lithium Tokamak Experiment (LTX), a modest size (R=0.4 m, a=0.26 m) spherical tokamak. In LTX, lithium coatings can be applied to close-fitting stainless steel surfaces surrounding ~80% of the plasma. The surfaces can be heated to ~300°C, allowing plasma operations with partly or fully liquid lithium surfaces.

A potential issue for lithium in fusion devices is the possibility of core impurity contamination due to lithium's relatively high sputtering and evaporation rates. On the other hand, lithium coatings can also getter and bury more harmful, higher-Z impurities. Experiments on NSTX have shown very low levels of lithium contamination in the core plasma[4]. However, these experiments used partial lithium coatings on carbon surfaces and had high levels of carbon contamination, which caused a large friction force that pushed out lithium[5]. Here, we will present measurements of lithium and other impurities in a tokamak with all-metal walls fully coated in solid and/or liquid lithium.

We present results of Doppler spectroscopy of intrinsic line emission in LTX, which measures the emissivity, velocity, and temperature profiles of the various impurity species. 15 toroidal views cover the plasma core with $r/a < 0.7$, while 6 pairs of poloidal views cover $0.2 < r/a < 0.9$. A novel high-throughput, high-resolution variable wavelength spectrometer has been installed[6]. It has similar capabilities to the existing Kaiser Holospec spectrometer (which measures Li III and C II emission), but can be adjusted between shots to measure any impurity lines in the visible range with high accuracy.

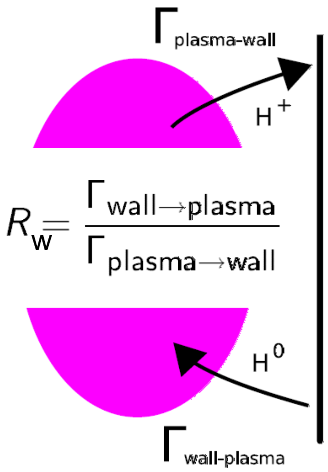
1. D.K. Mansfield, et al., Phys. Plasmas. 3 (1996) 1892.
2. R. Majeski, et al., Phys. Rev. Lett. 97 (2006) 075002.
3. H.W. Kugel, et al., Phys. Plasmas. 15 (2008) 056118.
4. M. Podesta, et al., Nucl. Fusion. 52 (2012) 033008.
5. F. Scotti, et al., Nucl. Fusion. 53 (2013) 083001
6. R.E. Bell, F. Scotti, Rev. Sci. Instrum. 81 (2010) 10D731.

Why lithium plasma-facing components?

- Liquid walls eliminate downtime for first-wall replacement
  - Naturally spread intense localized heat loads with convection
  - With flow, self-replenishing under steady erosion & transient events
  - Even major disruption will at worst cause evaporation
  - Substrate only subject to damage by neutrons, not plasma
  - Retained tritium can be removed by pumping liquid out of the vessel
- Reduced impurity levels and less radiative losses
  - Low first ionization potential: more likely to be ionized on open field lines and redeposit rather than penetrate into core
  - Low-Z so less electrons & fully stripped at low temperature ~100eV
- Lithium reactive with hydrogen atoms and ions, prevents them from returning into plasma as cold neutrals
  - Liquid Li continues pumping up to 1:1 Li:D ratio
  - **Li suppresses plasma recycling**

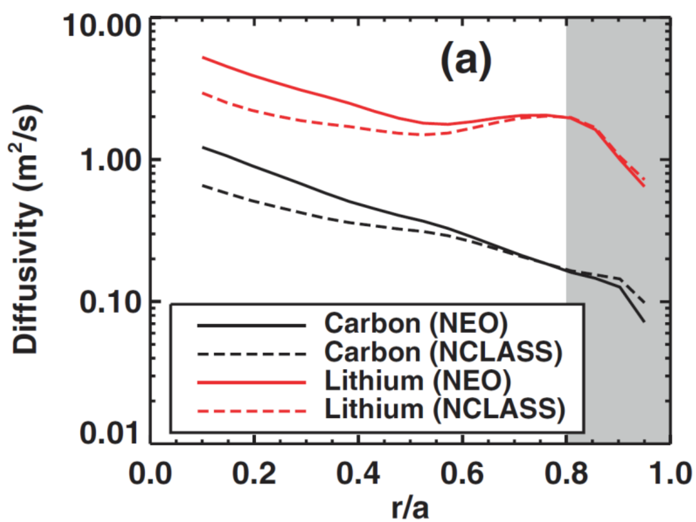
Recycling has large impact on transport

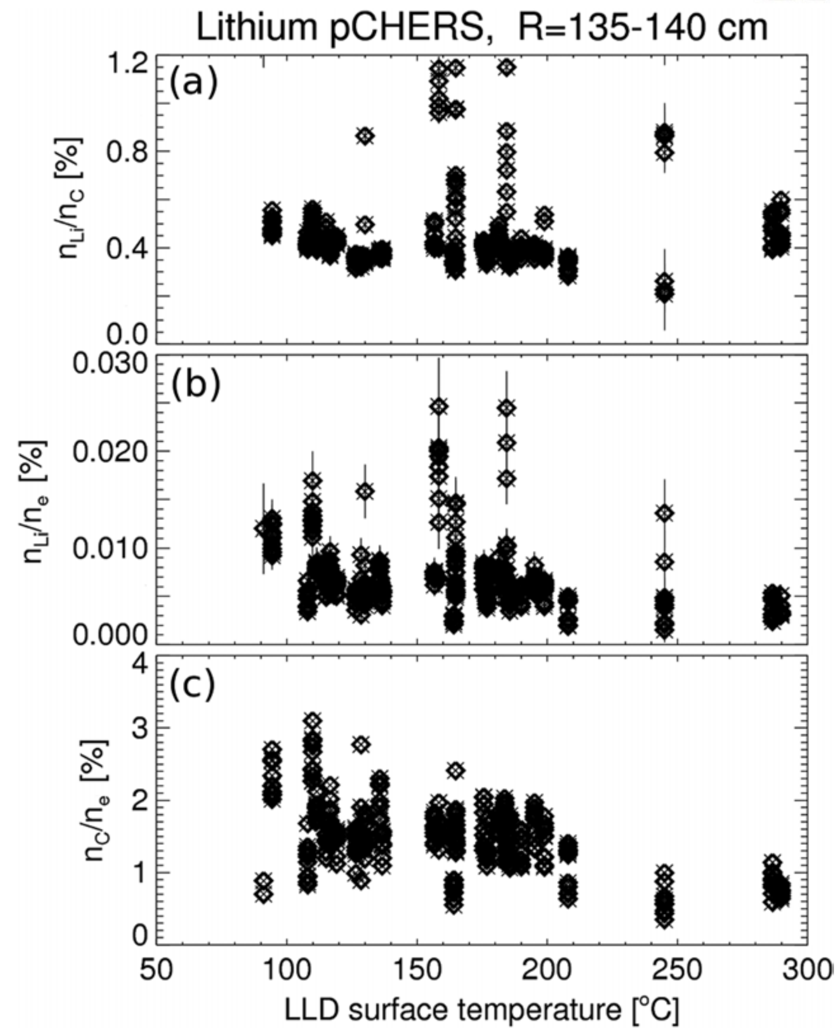
- Recycled neutrals are usually dominant particle/fueling source
  - Can be hard to control density profile or even total density
- Neutrals cool electrons and ions at plasma edge
  - Edge temperature gradient drives turbulent instabilities & further increases transport
- Previous experiments showed large improvements w/ lithium
  - TFTR: "Super shots"
    - » Large increases in τ_E, fusion gain Q, triple product $nT\tau_E$
  - CDX-U: Liquid Li tray limiter
    - » Up to 6x increase in τ_E
    - » 2-3x improvement over ITER98P(y,1)
    - » Loop voltage reduced 4-6x
  - NSTX: LITER evaporations in lower divertor
    - » 50% increase in H97L factor
    - » Suppression of ELMs



NSTX has very little core Li contamination

- Up to 1.3 kg of Li in vessel
- C impurity accumulates and pushes out Li
- C accumulation gets worse as more Li suppresses ELMs, improves confinement





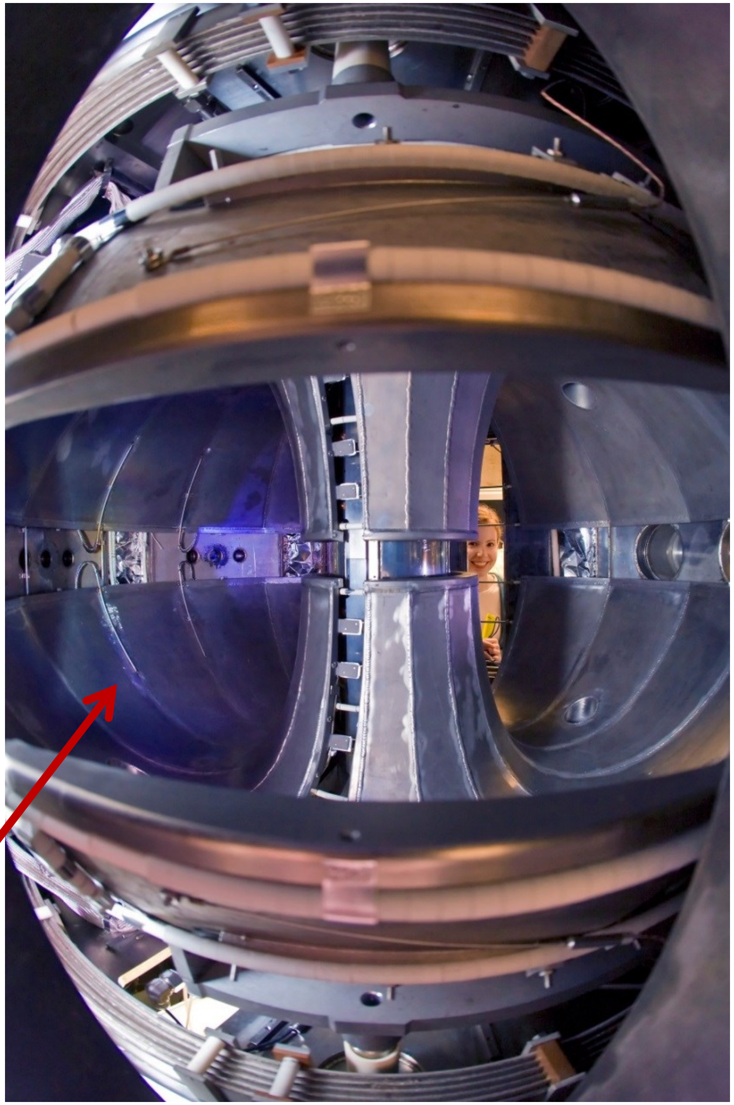
Ref: F. Scotti, Nucl. Fusion. **53** (2013) 083001

Ref: M. Podesta, Nucl. Fusion. **52** (2012) 033008

Lithium Tokamak Experiment (LTX) built to explore lithium technology & low-recycling physics

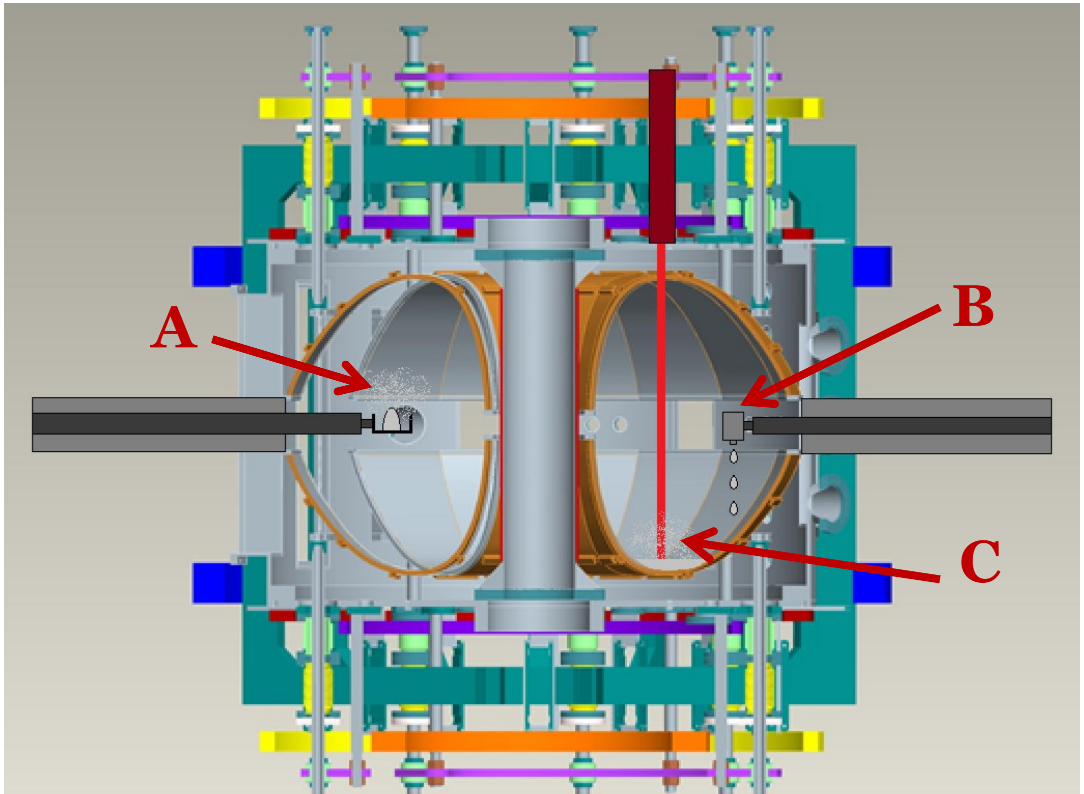
- All metal PFCs (no bulk C)
  - Can be entirely coated w/ Li
- 4 shells cover ~80% of surface
  - Heatable to ~350 °C for liquid Li

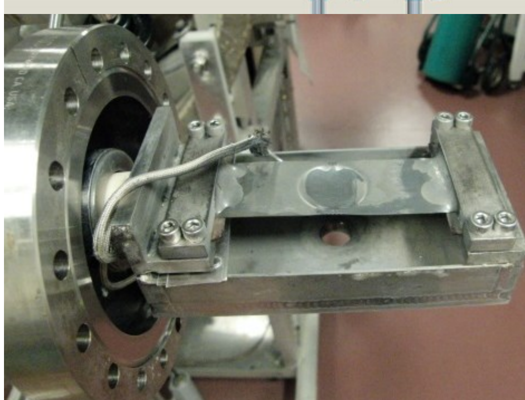
Operational Parameters	
Major Radius	R_0=0.40 m
Minor Radius	a=0.26 m
Toroidal Field	B_T=0.18 T
Plasma Current	I_p< 75 kA
Plasma Duration	t< 50 ms

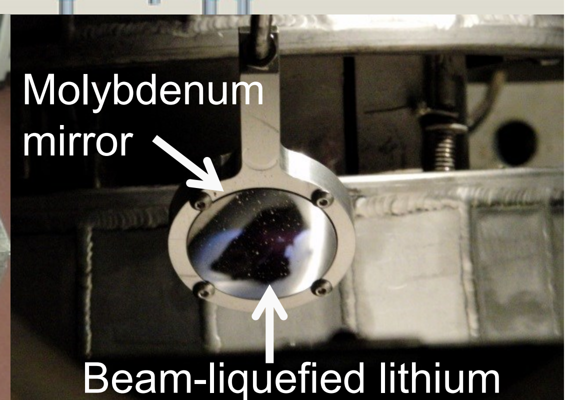


Shells are 3/8" OFHC copper explosively bonded to 1/16" 304 stainless steel liner, for good thermal conductivity and lithium resistance.

Lithium introduced with evaporators and fillers





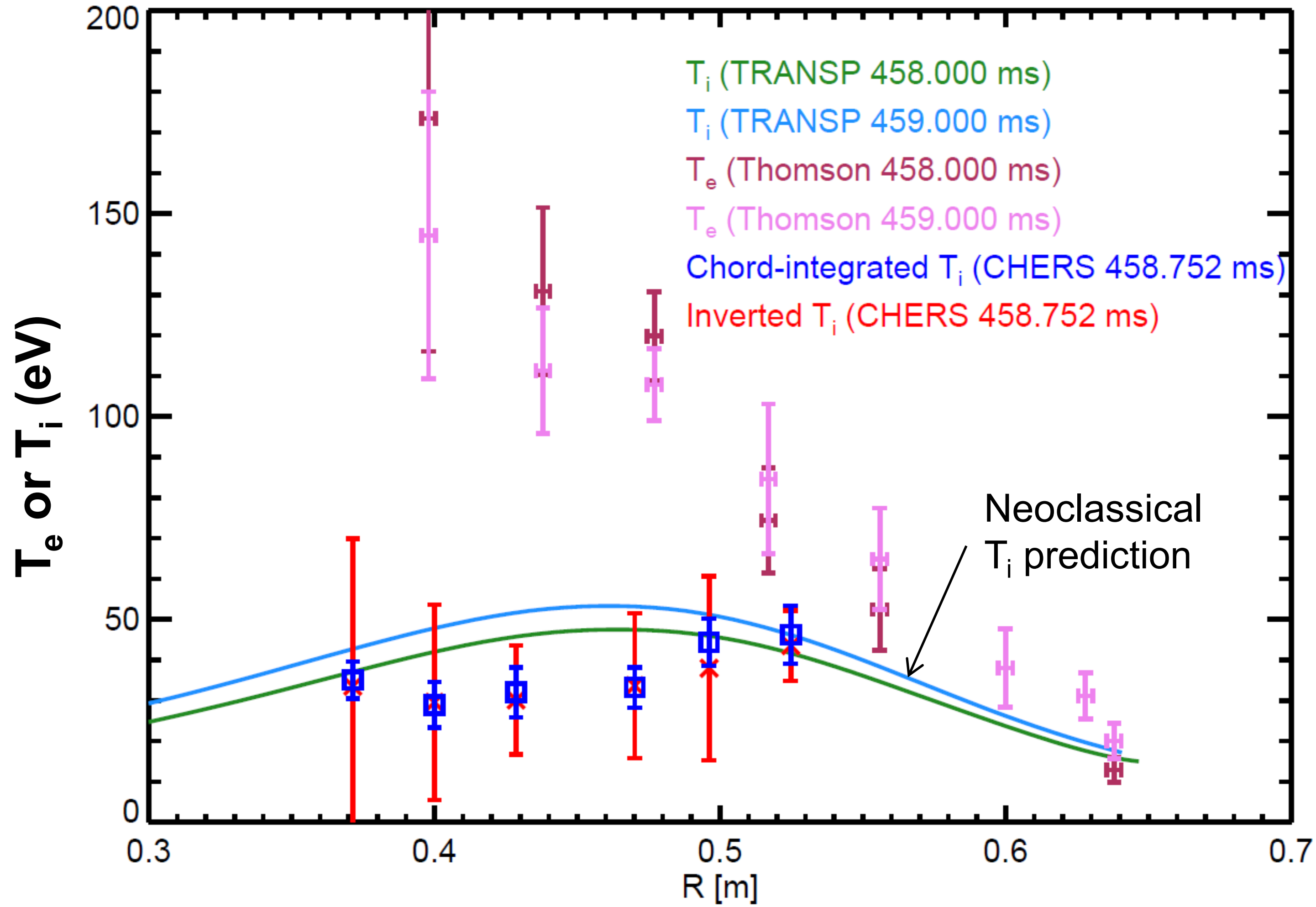


A – Resistive heating of Li above 500°C, evaporating onto upper shell (or both shells with He backfill)

B – Resistive heating of Li above 180°C, dripping onto lower shell and forming Li reservoir

C – Electron beam heating of Li reservoir above 400-500°C, evaporating onto both shells (requires shell pre-heating to ~300°C)

Initial LTX T_i measurements consistent with neoclassical ion confinement from TRANSP



- Core χ_e ~ 5 m²/sec from TRANSP analysis

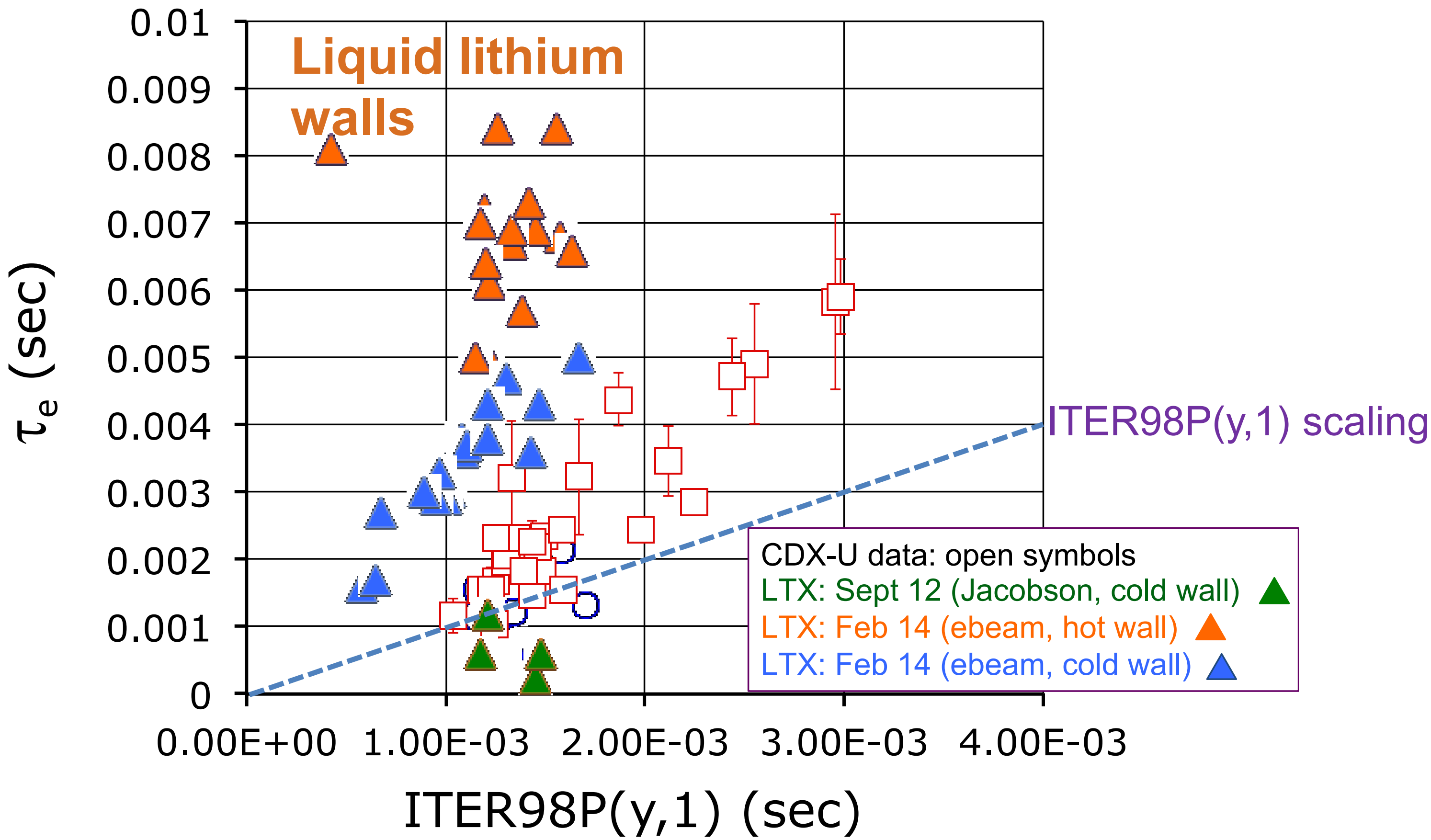
C. Jacobson, Thesis, Feb 2014

Data with helium-dispersed solid lithium coatings – Sept. 2012

Initially, hot walls degraded performance

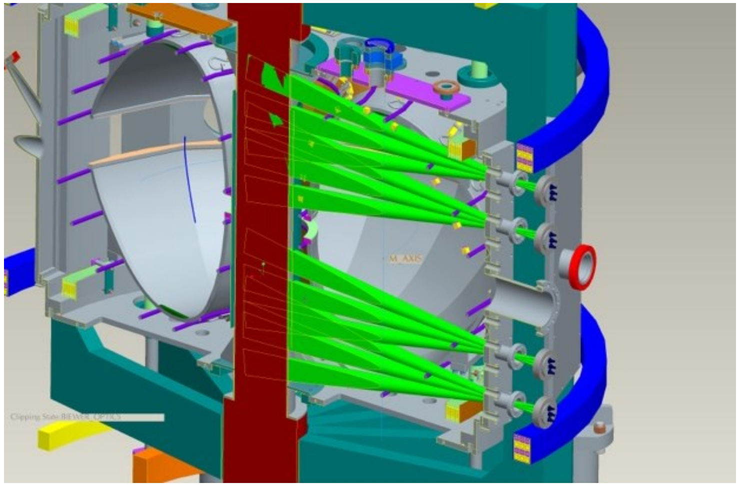
- Cold lithium coatings improved performance
  - Impurity + recycling reductions
- Heating produced impurity-dominated discharges
  - Long time interval between the application of lithium coatings and hot wall experiments
- A thick layer of liquid lithium will sequester impurities
  - CDX-U, test stand results (VEHICLE-1)
- Decided to pursue faster deposition rates and capability for thicker lithium films in 2014
  - Also improved vacuum conditions & discharge development
- This approach now appears to be successful
  - LTX has now operated successfully with 2 of 4 shell quadrants coated with liquid lithium (~ 2 m^2)
  - First operation of a tokamak with large area liquid Li PFCs

Recent (preliminary) results indicate liquid lithium walls can greatly increase Ohmic confinement



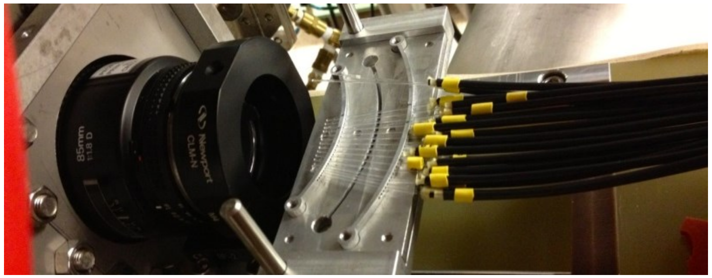
- Measurements from global magnetic diagnostics
  - Rogowski coil, toroidal flux loop, diamagnetic loop
  - Thomson scattering repairs needed for confirmation

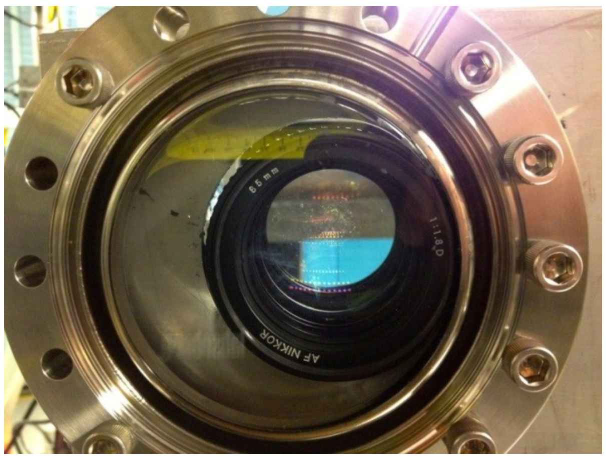
Passive Doppler spectroscopy upgraded to better measure impurity n_i, v_i, T_i profiles and transport

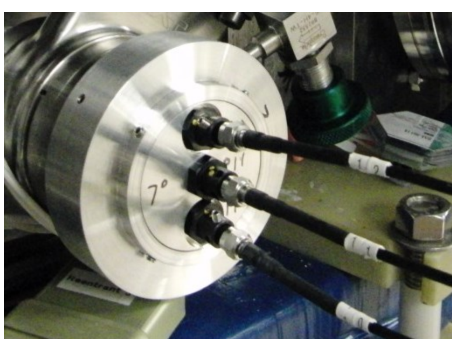


- New views improve spatial resolution & coverage
- 15 Toroidal views
  - -0.24 < r/a < 0.68
  - Resolution ~ 2 cm in core,
    ~ 1 cm nearest edge
  - Spot size ~ 0.6 cm
- 6 radial Poloidal view pairs
  - 0.2<r/a<0.95 (nominal)
  - Above and below midplane
  - Matched pairs allow cancelation of atomic physics effects
  - Assumes up-down symmetry, but also measures it

Toroidal array uses single f/1.8 85mm lens





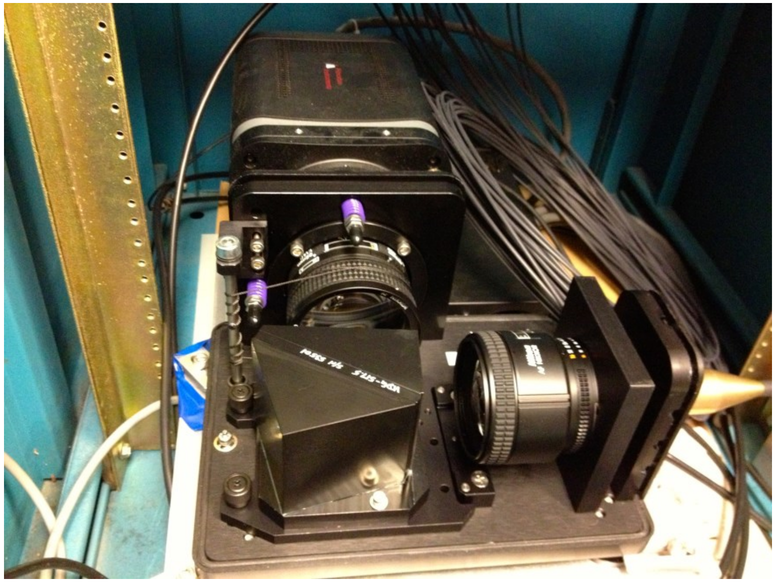


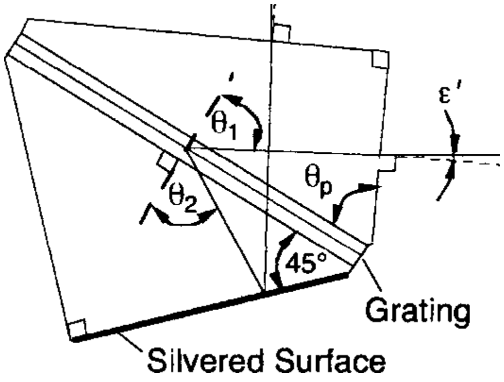
- Uses optics from NSTX Edge Rotation Diagnostic
  - Fiber holder has room for 40 fibers
  - Spatial resolution could be doubled with more fibers
  - Inboard coverage to r/a ~-0.3 possible
- 600 µm, 0.37 NA plastic clad silica fibers
- Poloidal arrays use small modular lenses for each view
  - f/2 10 mm, collimating fused silica Ocean Optics 74-ACR lenses
  - Screw into "pucks" mounted on windows, SMA connection to fibers

Kaiser Holospec f/1.8 Spectrometer

LTX

- Short focal length
  - Gives curved image
- Slit curved to give plane image
  - 75 μm width gives instrument function ~0.9 Å / 35 eV for Li
- Commercial camera lenses
  - 85 mm entrance & exit
  - Could de-magnify exit to get more vertical fibers
    - » 58 mm/15 fibers; 50 mm/17
- High dispersion holographic transmission grating + prism
  - Central wavelength 5175 Å
  - Could use bandpass filter to allow 2 or 3 slits & fiber bundles





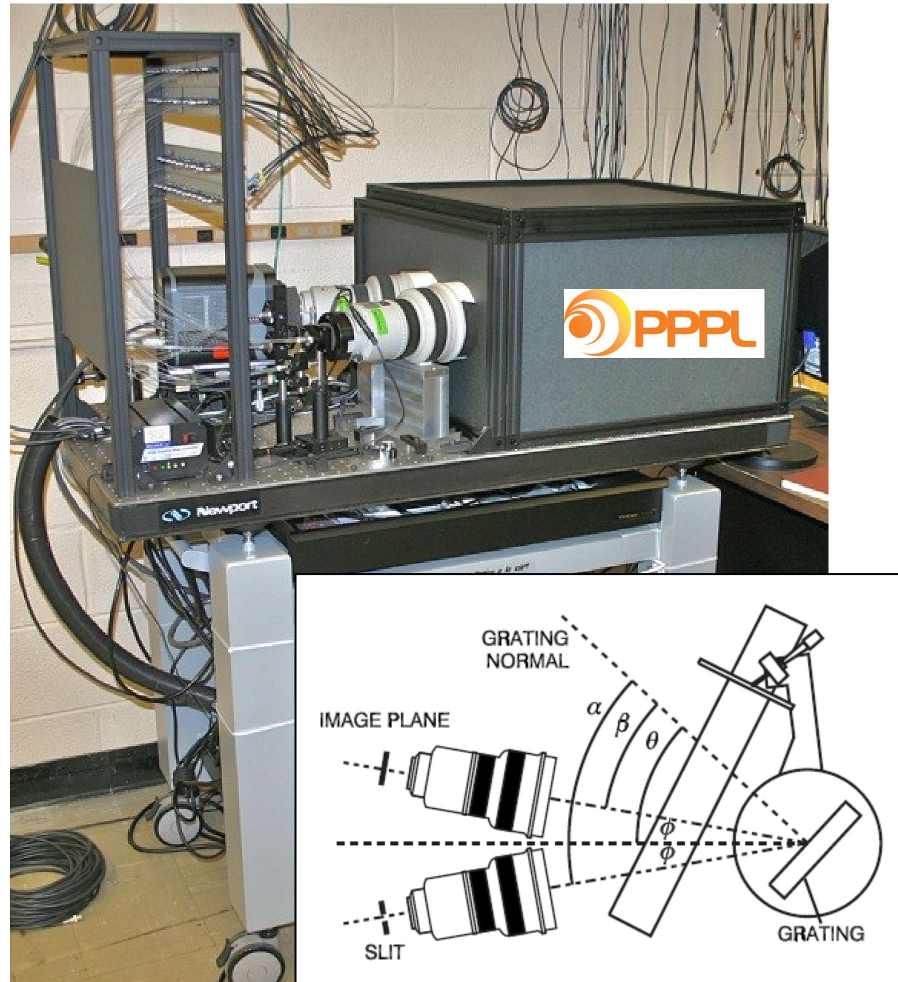
Ref: R.E. Bell, Rev. Sci. Inst. **75**(10): 4 (2004)

Oak Ridge National Laboratory

High-throughput Accurate-wavelength Lens-based Spectrometer (HAL)

LTX

- Wavelength variable over entire visible range ~4000-8000 Å
- Similar performance to Holospec
  - Canon 200 mm f /1.8 EF lenses
  - Large plane reflection grating
  - Throughput ~40% of Holospec for same instrumental width
  - Min. Error <0.005 Å (~0.3 km/s)
- GUI written in Visual Basic to control spectrometer, function generator, and camera, and upload to MDSplus
  - Can automatically self-calibrate wavelength
- Precision fiber holders & patch panel



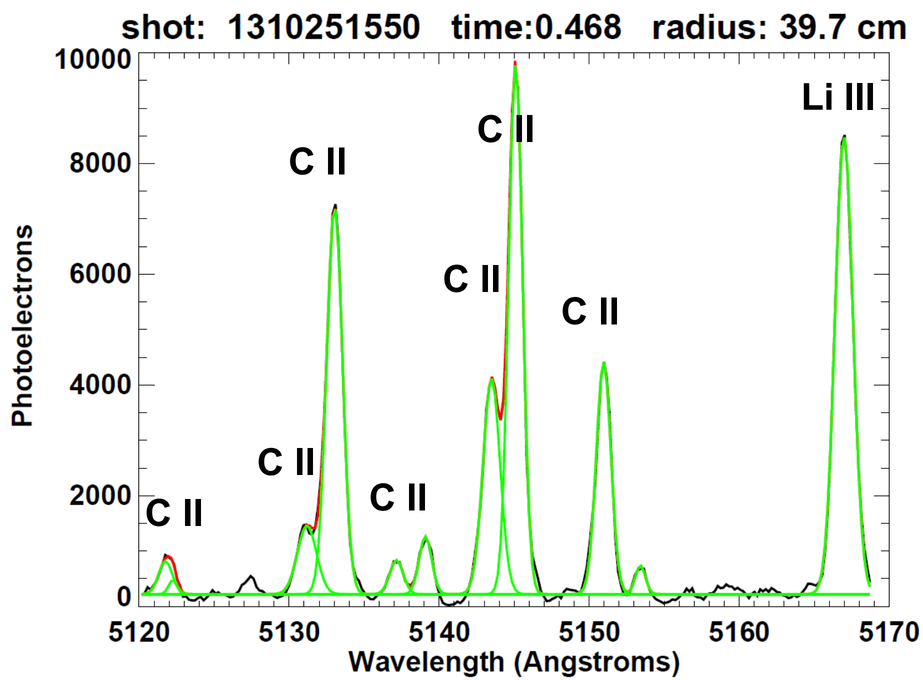
Ref: R.E. Bell, Rev. Sci. Inst. **81**, 10D731 (2010)

Princeton Instruments ProEM 512 Camera

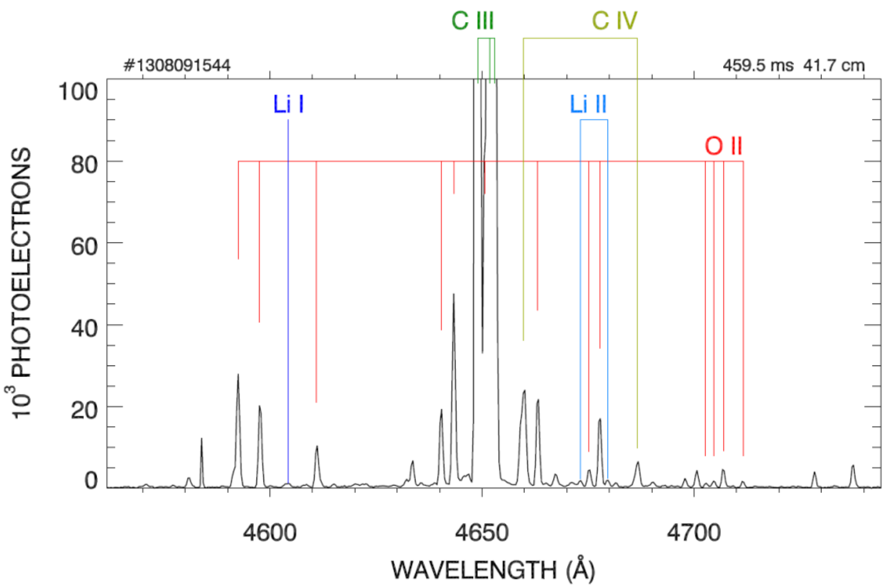
- Used in Holospec and HAL
- 512 x 512 pixel CCD
  - 16 x 16 μm ~ 0.2 Å
  - Holospec range ~5090-5190 Å
  - HAL bandwidth ~120-180 Å
  - 11 600 μm fibers (Holospec)
  - 13 400 μm fibers (HAL)
- High sensitivity & efficiency
- Image shifted behind mask for concurrent read out & exposure
  - On chip binning reduces read time
- 1.5 ms minimum frame time
  - 2.25 ms w/ low-noise readout
  - 2.5 ms on HAL
  - Well below $t_{discharge}$ ~30-40 ms

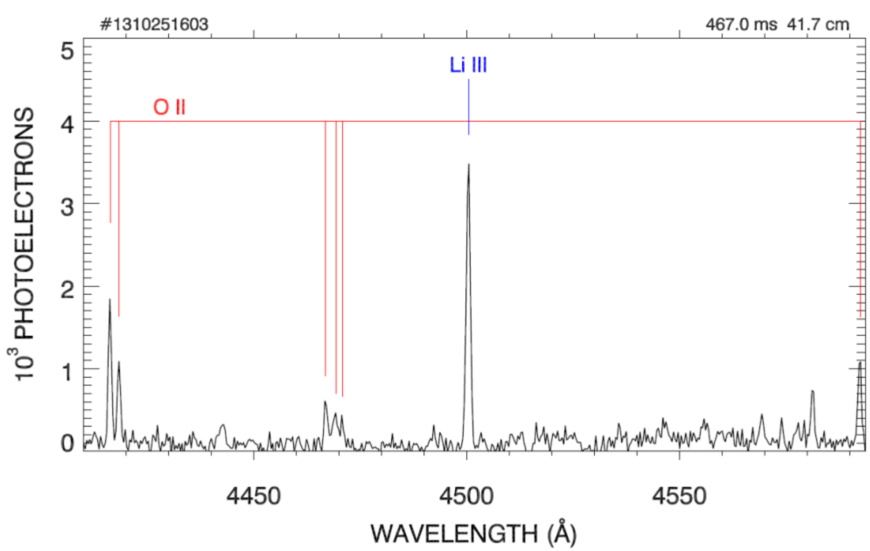
Holospec measures CII and Li III emission

- No Li III seen in ~30 kA discharges following Li fill and Ar glow
- Li III appears in higher current discharges after Li e-beam evaporation
- Preliminary analysis indicates peak line integrated T_i ~ 50 eV in highest current discharges



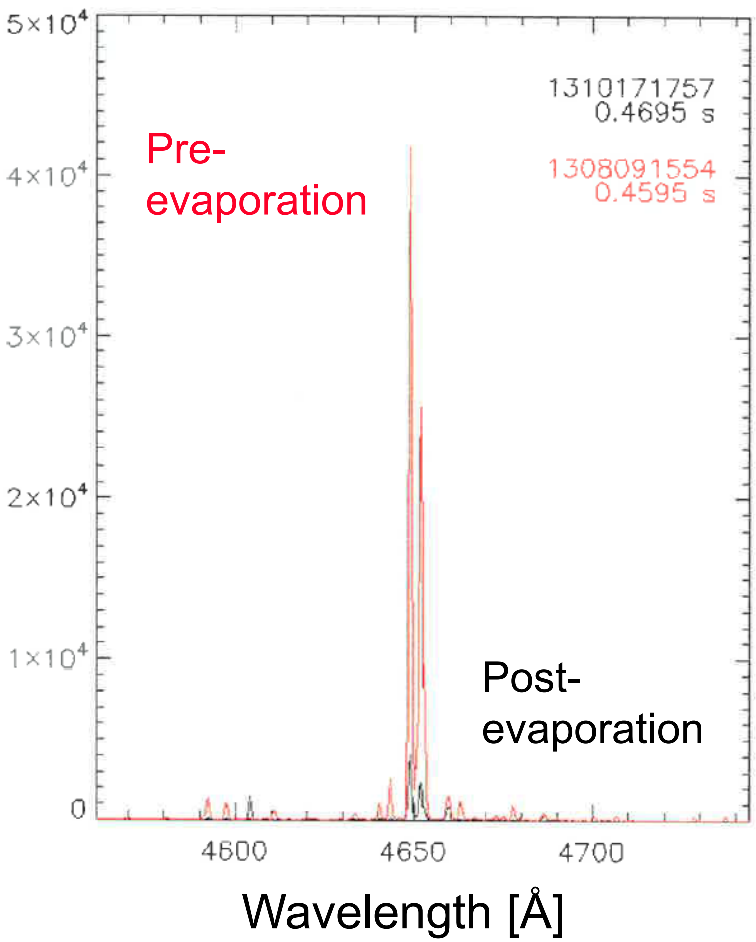
HAL measures spectra at multiple wavelengths

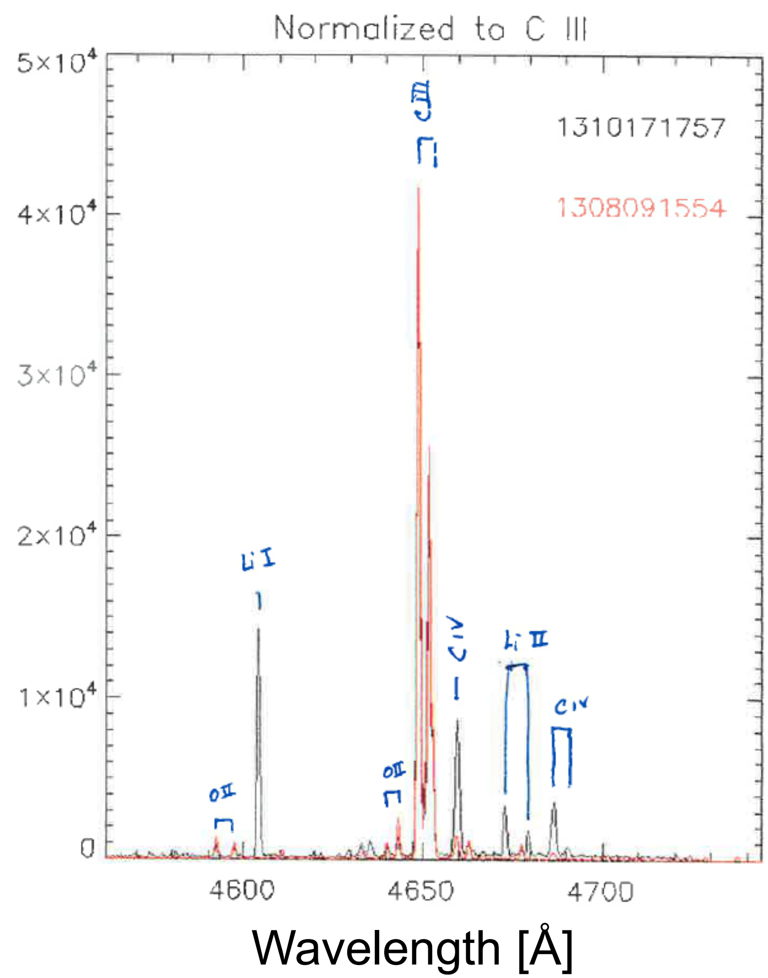




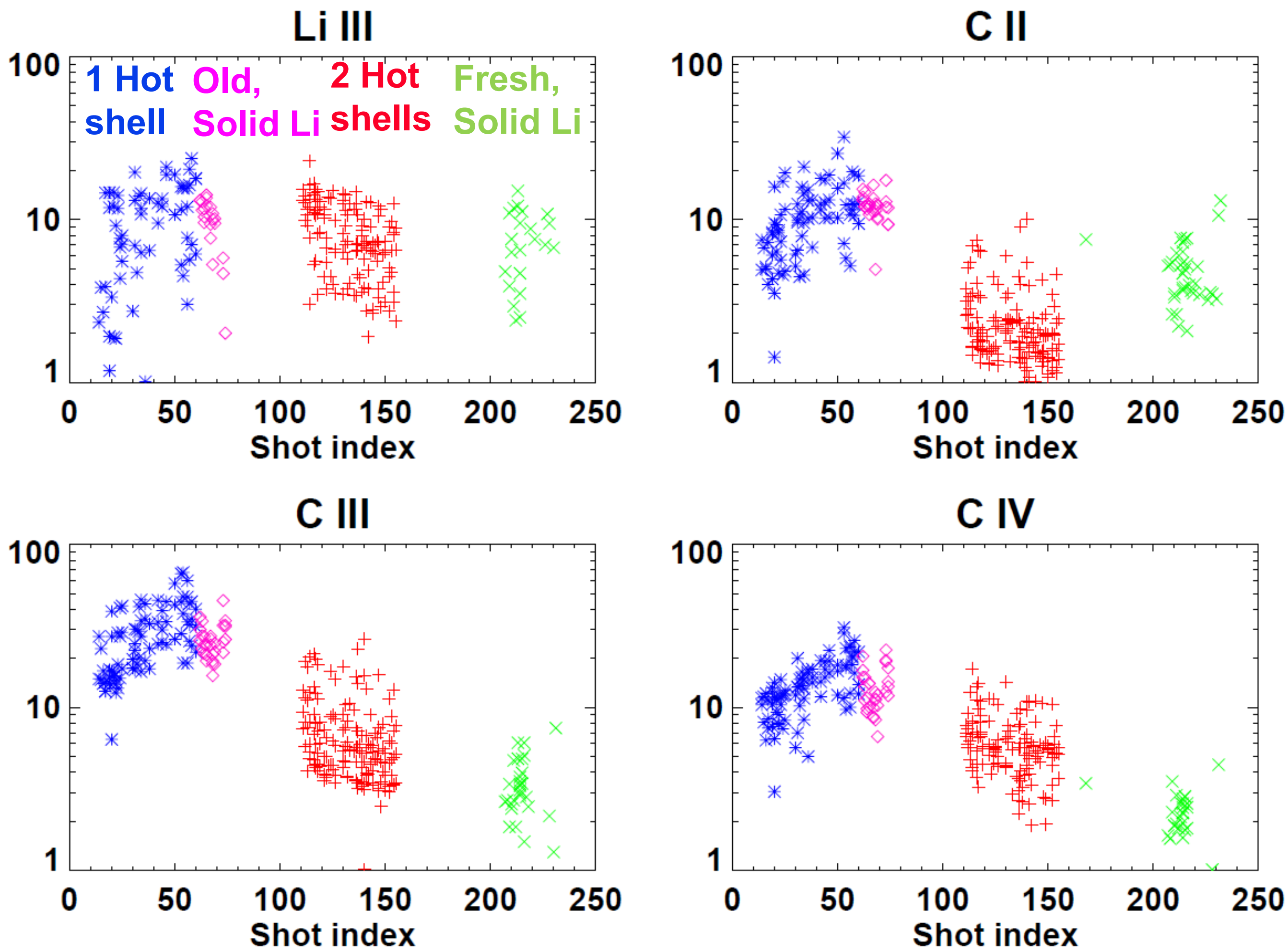
- Usually kept at 4650 Å to monitor C III, C IV, Li I, Li II, and O II
- Has also looked at
  - Li III 4499 Å
  - Li III 5167 Å (Holospec)
  - Li II 5484 Å
  - O III 5592 Å
  - Li I 6708 Å
  - C IV 5801 Å

Carbon reduced, Li increased after evaporation

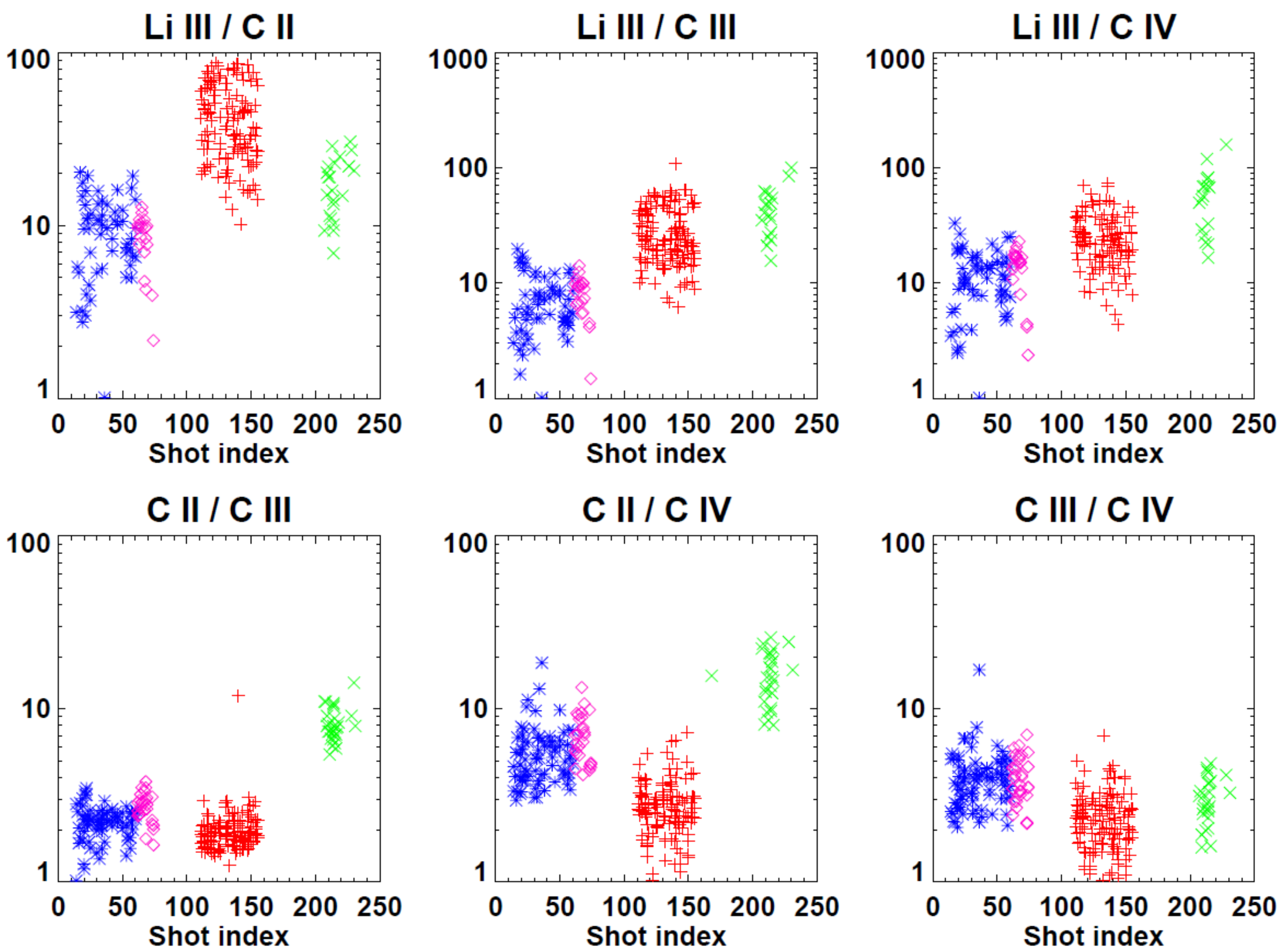




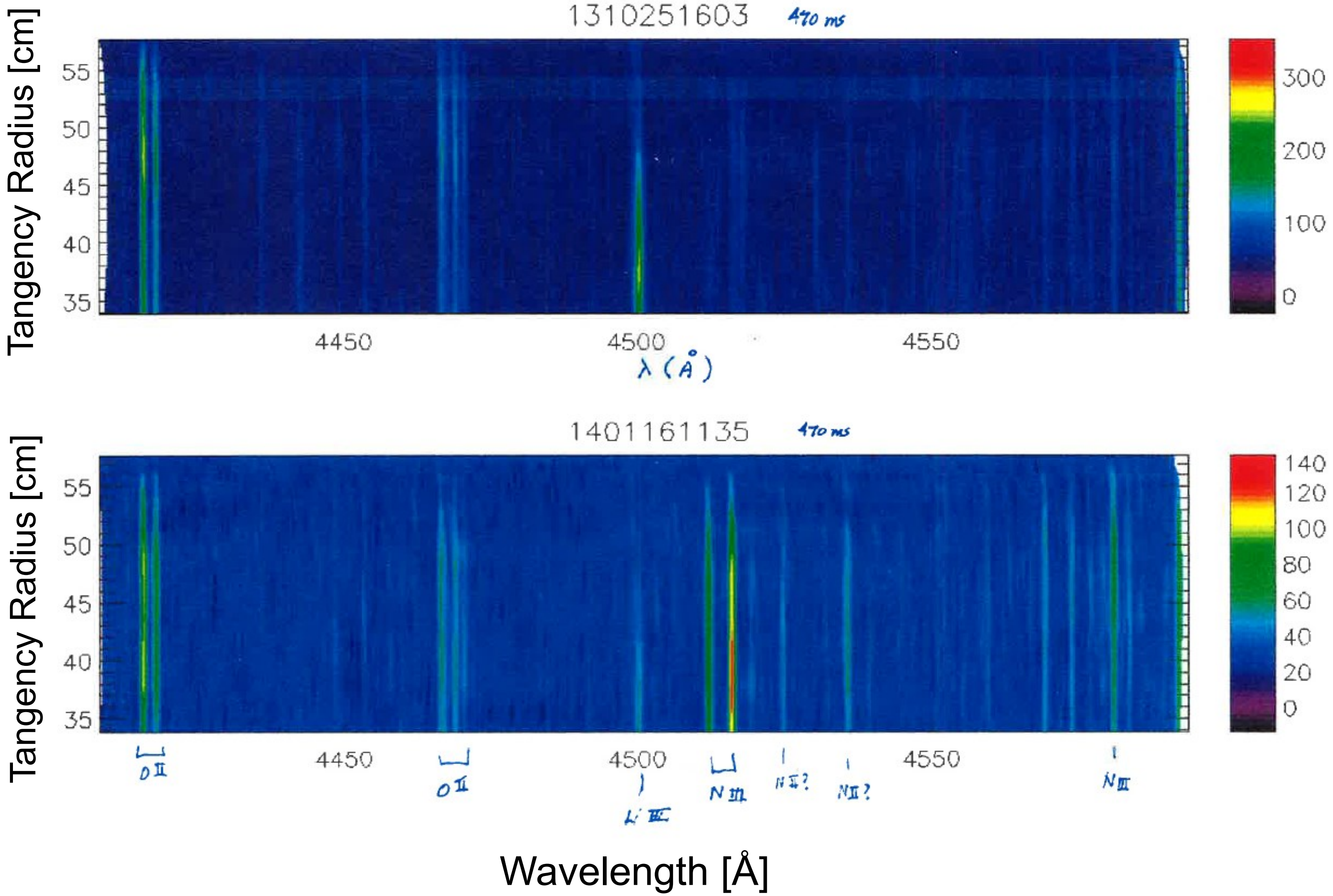
Wall conditions have significant effect on impurity emission levels



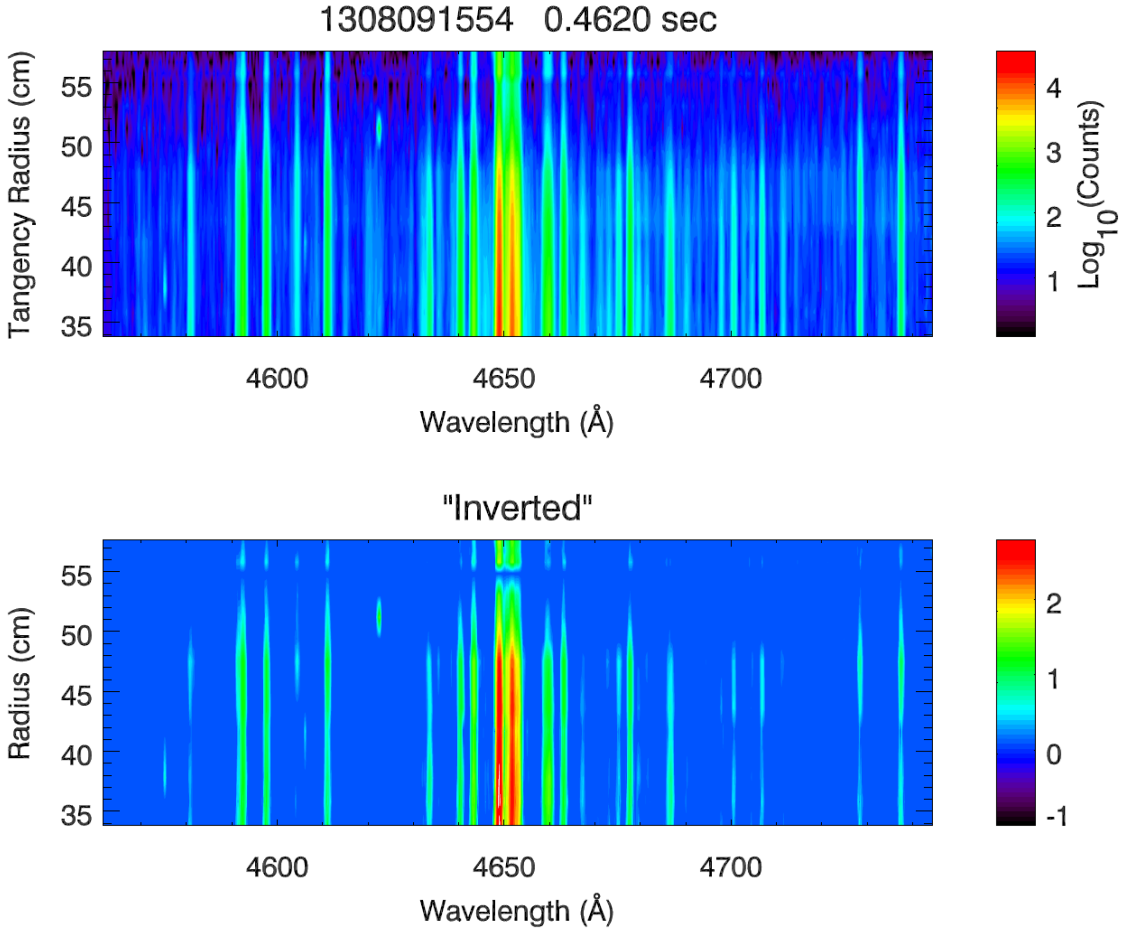
Line ratios helpful in absence of n_e, T_e profiles



HAL detects air leak in fueling lines

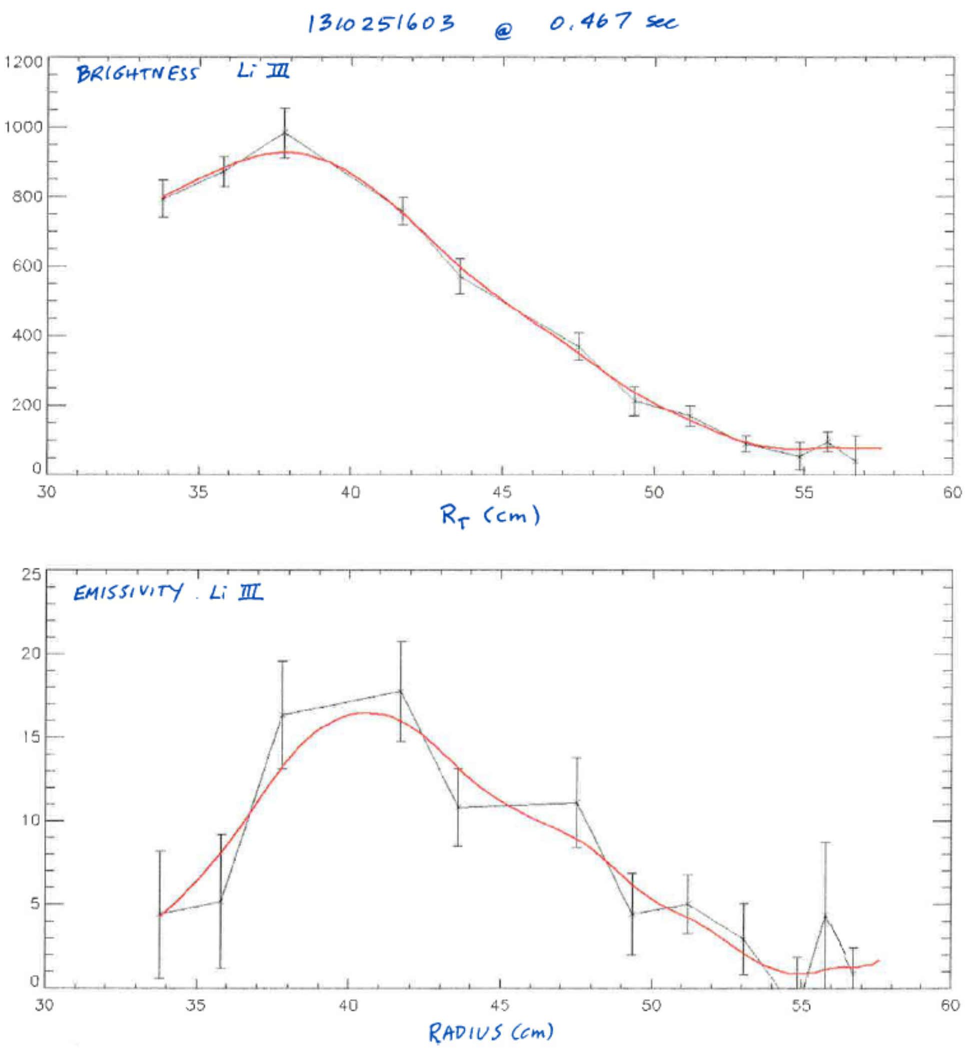


Toroidal array shows higher charge states exist mostly in core



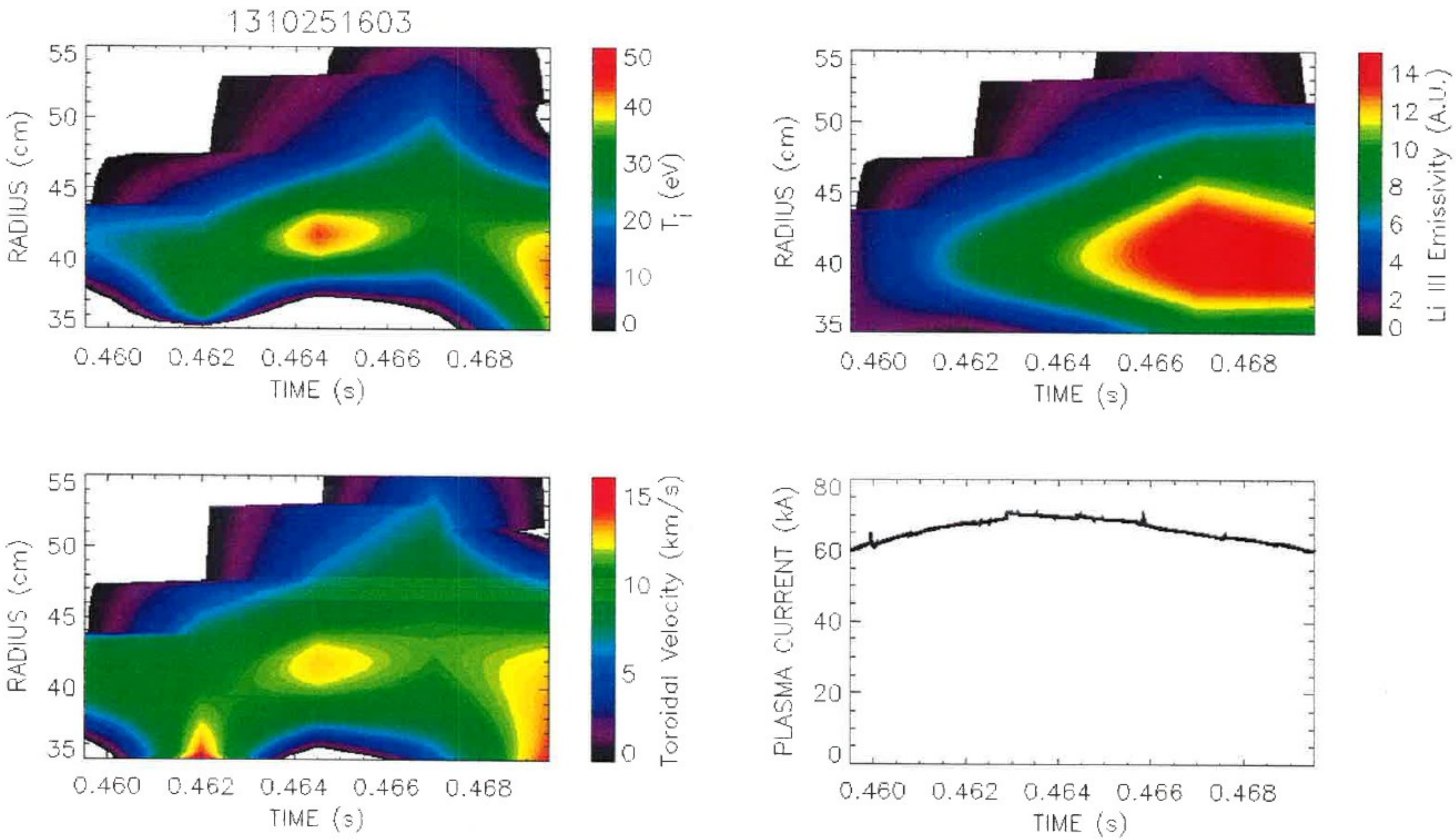
- Psuedo-inversion of spectra aids in line identification
  - As long as velocity shear is small

Smoothing splines used to invert line-integrated profiles



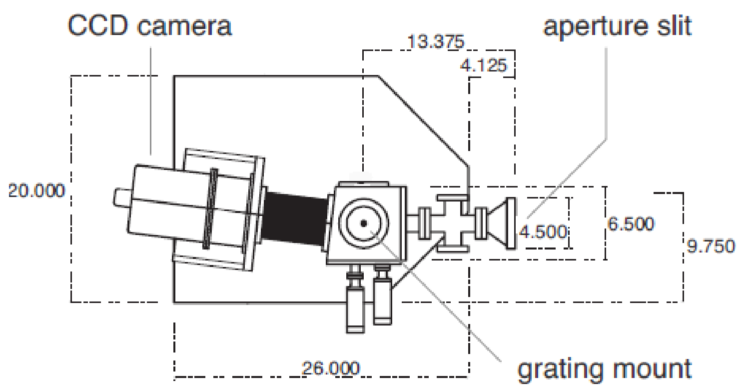
- Still improving quality of fitting to reduce errors
- Optimizing camera settings will improve signal to noise
- Errors compound in inversion

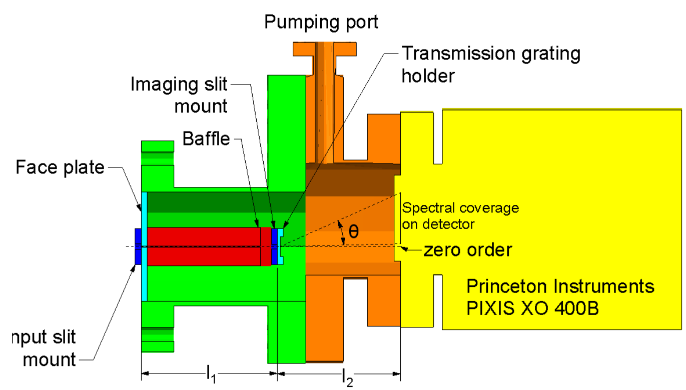
Inversions show peaking of toroidal profiles

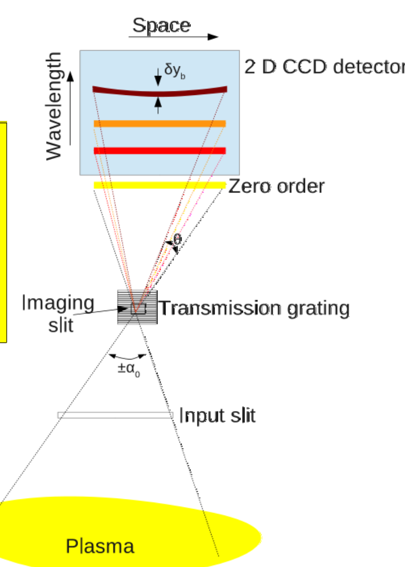


Extreme Ultraviolet Spectroscopy

- Long-Wavelength Extreme Ultraviolet Spectrometer
  - Range ~ 20-450 Å, Bandwidth ~ 180 Å, Resolution ~ 0.3 Å
  - Single frame integrated over time & radial midplane
- Transmission Grating Imaging Radiometer
  - Range ~100-700 Å, instrumental width >> LoWEUS
  - Tangential view, capable of temporal and spatial resolution





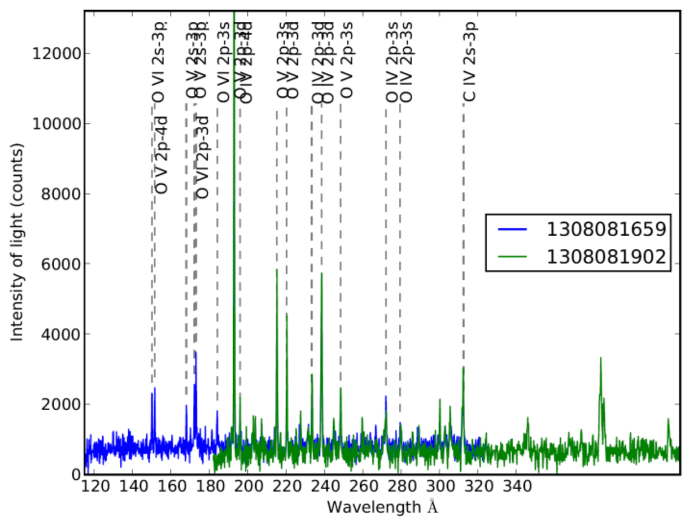


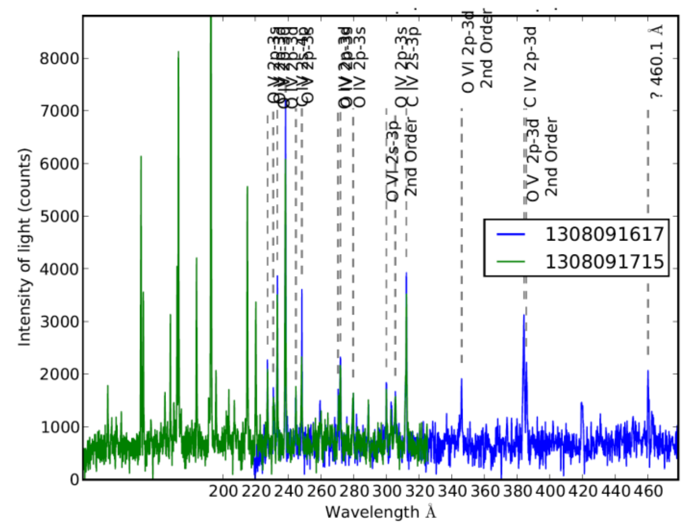
Lawrence Livermore National Laboratory

Johns Hopkins University

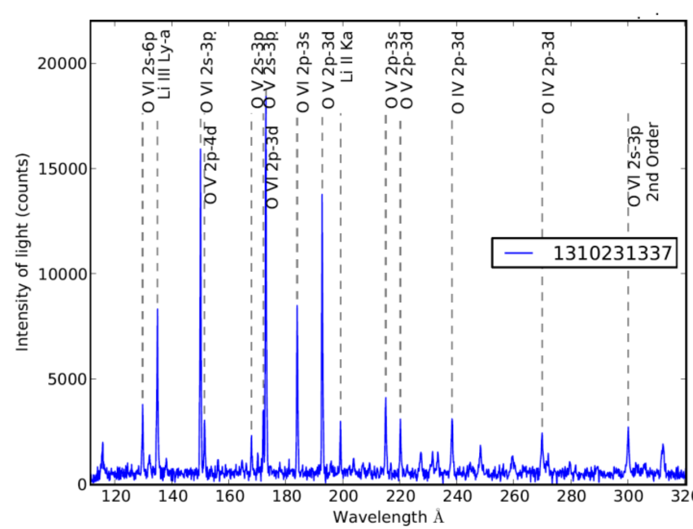
Ref: Clementson, et al., Rev. Sci. Inst. **79**, 10F538 (2008)

Past EUV spectra dominated by oxygen



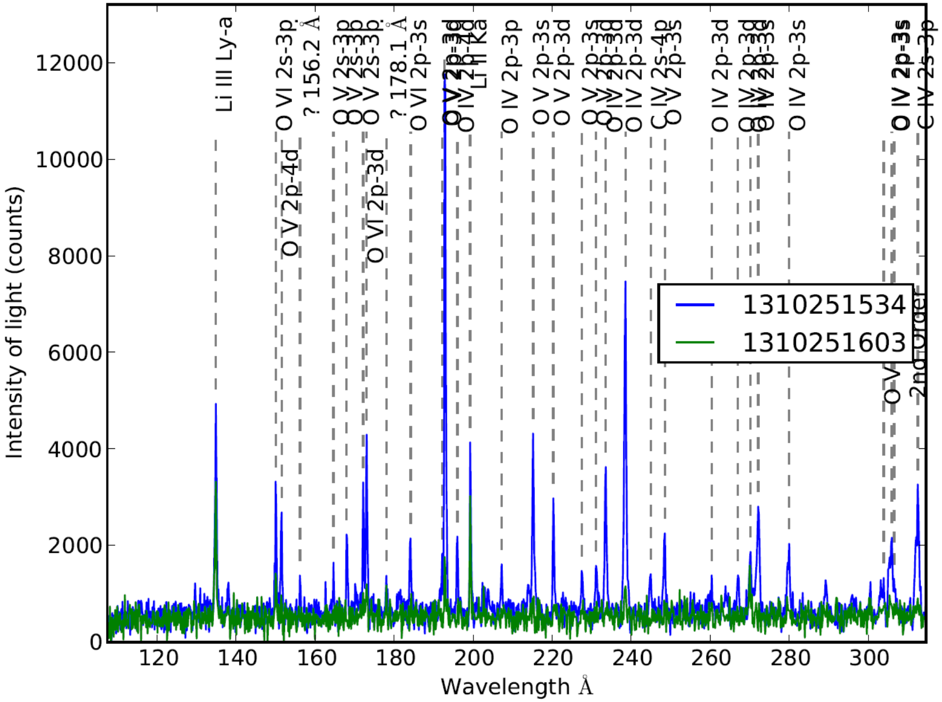


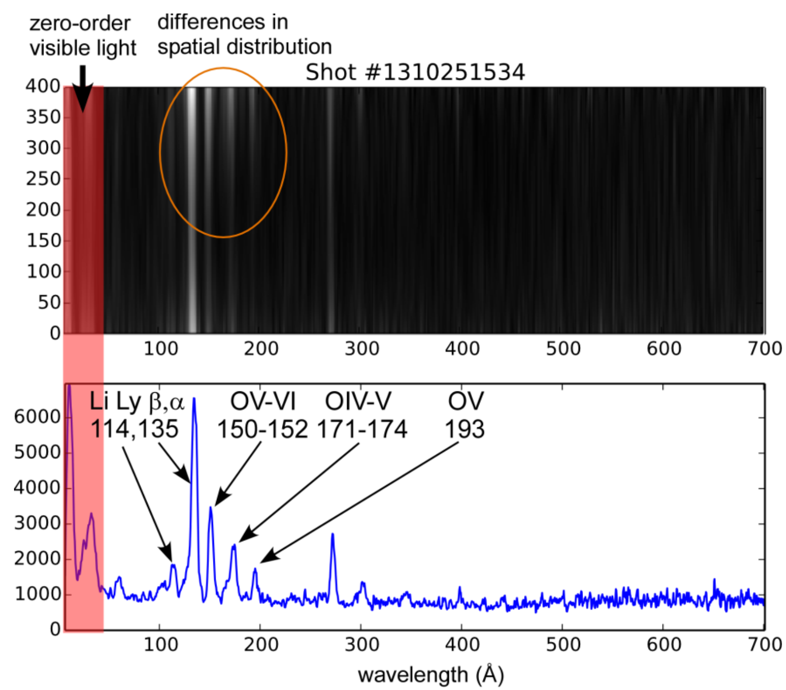
- O IV, V, VI, also C IV
- Li II & III appear after e-beam evaporation
- Line ratios complicated by integration over entire radius and discharge time



Li remains bright even when O & C get dim

- On tangential view, TGIR sees Li as brighter even when LoWEUS sees O brighter
  - TGIR also resolves spatial variations in brightness





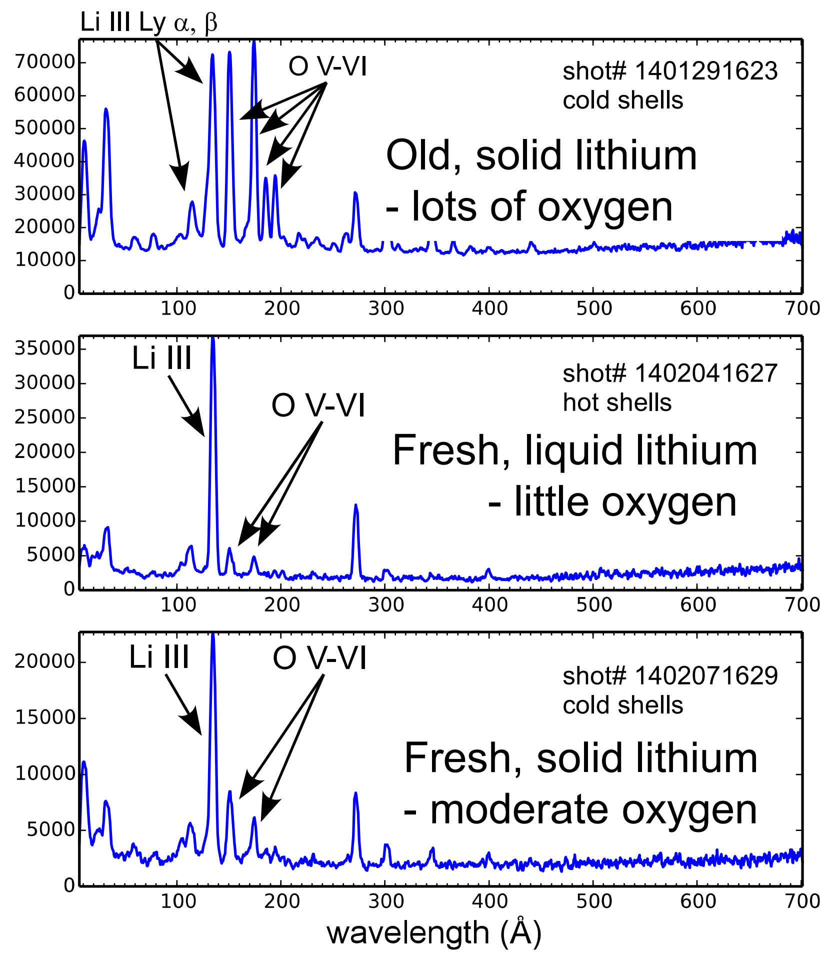
TGIR space-resolved spectrum for LTX discharge

K. Tritz, JHU

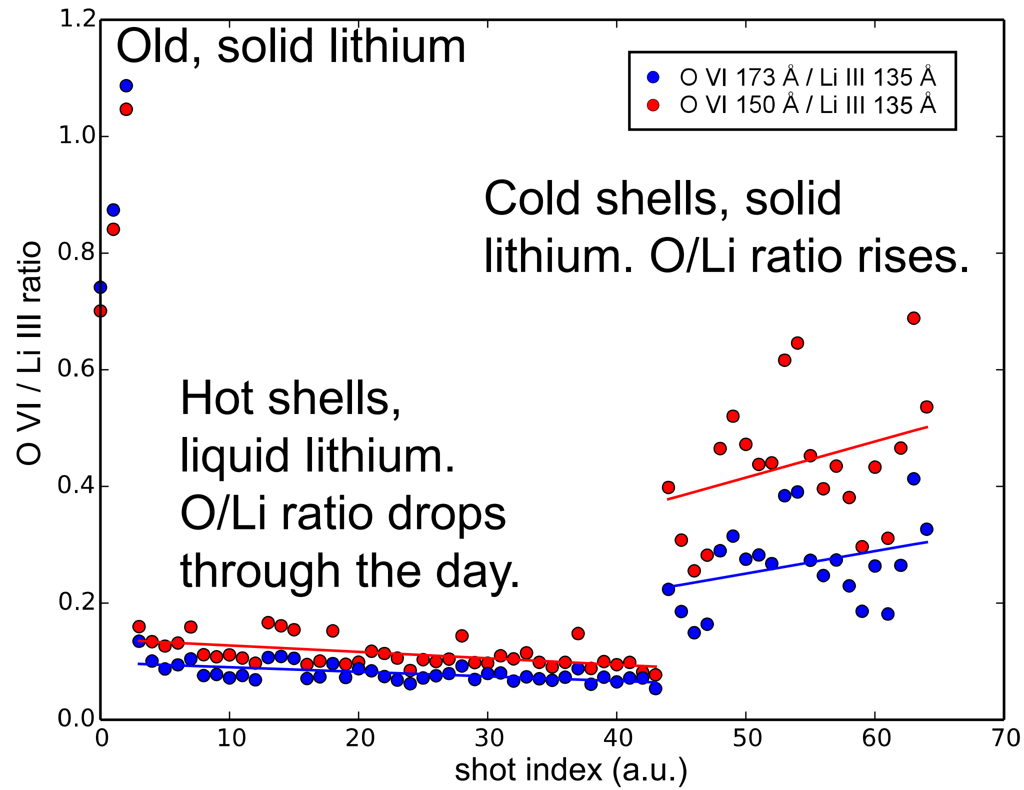
Oxygen impurities in discharge are now suppressed with liquid lithium PFCs

LTX

Spectra from TGIR



Oxygen/Lithium line ratio – shot history



JOHNS HOPKINS
UNIVERSITY

Conclusions

- LTX has demonstrated large confinement improvement with liquid lithium walls
- Doppler spectroscopy optics upgraded
  - Measures profiles, toroidal inversions performed
- New HAL spectrometer monitors many impurity lines
  - XUV spectroscopy monitors higher charge states
- Impurity levels & ratios vary with wall conditions
  - Solid Li coatings reduce C emission
  - Li emission does not increase too much when heated
  - C emission reduced with fresh liquid and solid Li
  - O emission most reduced by fresh liquid Li

Future Work

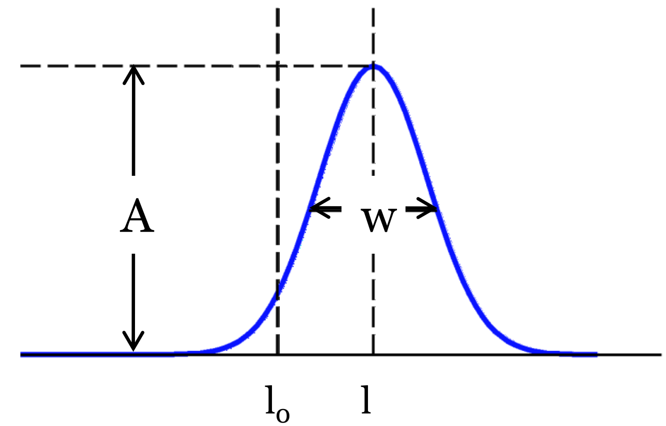
- More surveying with HAL and LoWEUS
- Improve fitting software
  - Routine fits to more lines, better fits, routine inversions
- Integrate other diagnostics for full impurity picture
  - Filterscopes
  - Fix Thomson alignment – n_e,T_e for impurity densities
  - Upgrade bolometer – P_{rad}, Z_{eff}
- Interpretive modeling for transport analysis
- Additional Li improvements
  - Second e-beam for full evaporation coverage
  - All 4 shells heated
  - Spread liquid Li pool to entire lower shell?

Thank you

Local values are extracted from line-integrated measurements with a matrix inversion approach

Line integrated measurements

- Spectral Brightness, B^{λ}
- Total Brightness, $B = \int B^{\lambda} d\lambda$



Fitted Parameters

- Amplitude, A $\quad A = \frac{B}{w}\sqrt{\frac{4\ln 2}{\pi}}$
- Line width, w
- Line shift, $(\delta\lambda)$

$$B^{\lambda} = \frac{B}{w}\sqrt{\frac{4\ln 2}{\pi}}\exp\left(-\frac{4\ln 2(\lambda - \lambda_0 - \delta\lambda)^2}{w^2}\right)$$

(Form for a Gaussian line shape)

Emissivity from Brightness

- Subscript i refers to a particular sightline (line-integrated measurement)
- Subscript j refers to a particular zone in the plasma (local value)
- L_{ij} is a matrix of path lengths
- Line-integrated brightness (ph/s/cm²/sr) can be related to local emissivity (ph/s/cm³) by length matrix
- Local emissivity is obtained using inverted length matrix

$$4\pi B_i = \sum_j L_{ij} E_j$$

$$E_j = 4\pi \sum_i L_{ij}^{-1} B_i$$

Inversions of passive emission for local velocity and temperature

Velocity inversion

$\hat{s}_i$ is unit vector along sightline

$\vec{v}_j$ is local velocity vector

$$\hat{s}_i \cdot \vec{v}_j = v_j \cos\theta_{ij}$$

$$(\delta\lambda)_i = \frac{\int B_i^\lambda(\lambda-\lambda_0)d\lambda}{\int B_i^\lambda d\lambda} = \frac{\lambda_0}{c} u_i$$

$$M_{ij} = L_{ij}\cos\theta_{ij}$$

$$v_j = \frac{\sum_i M_{ij}^{-1} B_i u_i}{\sum_i L_{ij}^{-1} B_i}$$

Temperature inversion

$$q_i = \frac{\int B_i^\lambda(\lambda-\lambda_0)^2 d\lambda}{\int B_i^\lambda d\lambda} = \frac{w_i^2}{8\ln 2} + (\delta\lambda)_i^2$$ *(See note below)*

$$Q_i = 8\ln 2\left(B_i q_i - \sum_j L_{ij} E_j \left(\frac{\lambda_0}{c} v_j \cos\theta_{ij}\right)^2\right) = \sum_j L_{ij} E_j w_j^2$$

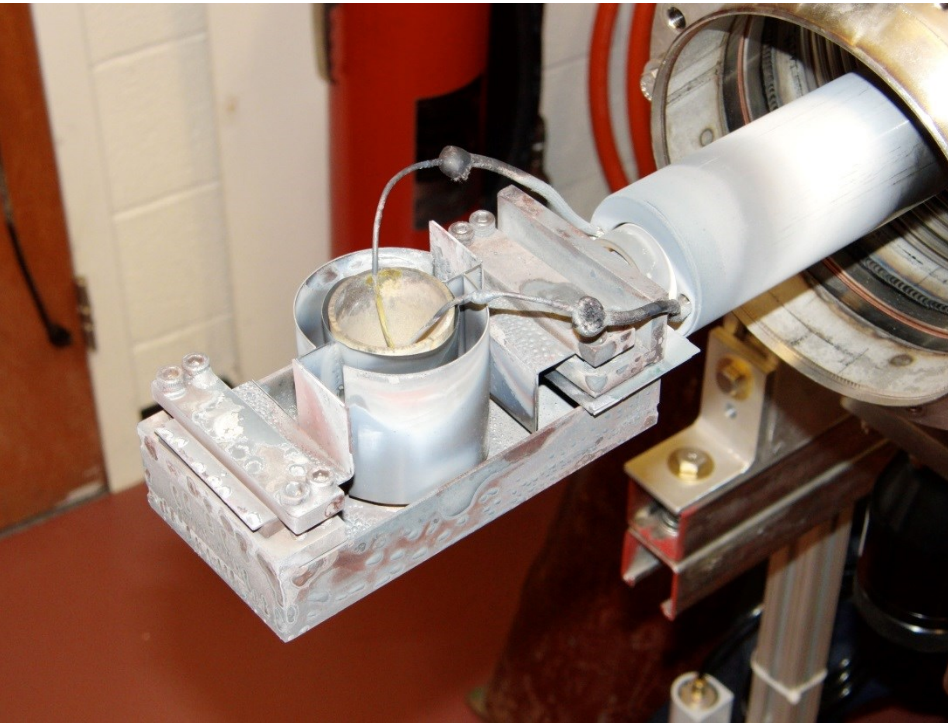
$$w_j^2 = \frac{\sum_i L_{ij}^{-1} Q_i}{\sum_i L_{ij}^{-1} B_i}$$

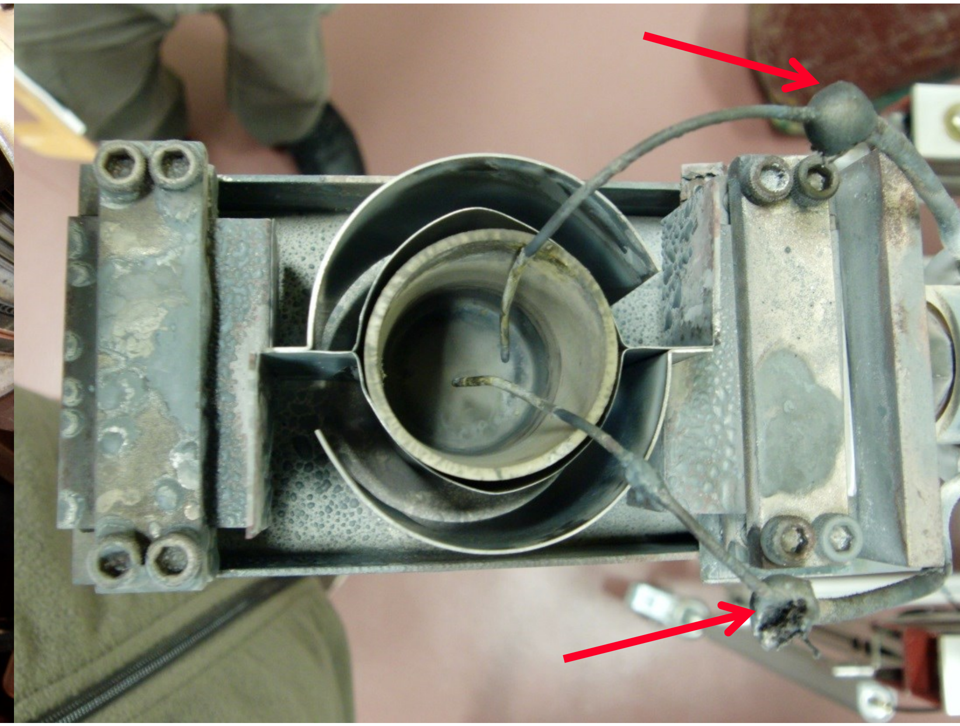
$$T_i(keV) = 1.68\times 10^5 M(amu)\frac{w^2}{\lambda_0^2}$$

Note: this form assumes a Gaussian line shape.
A multi-gaussian fit is necessary for high velocity shear.

Initial experiments with lithium walls employ evaporated coatings – shells at room temperature

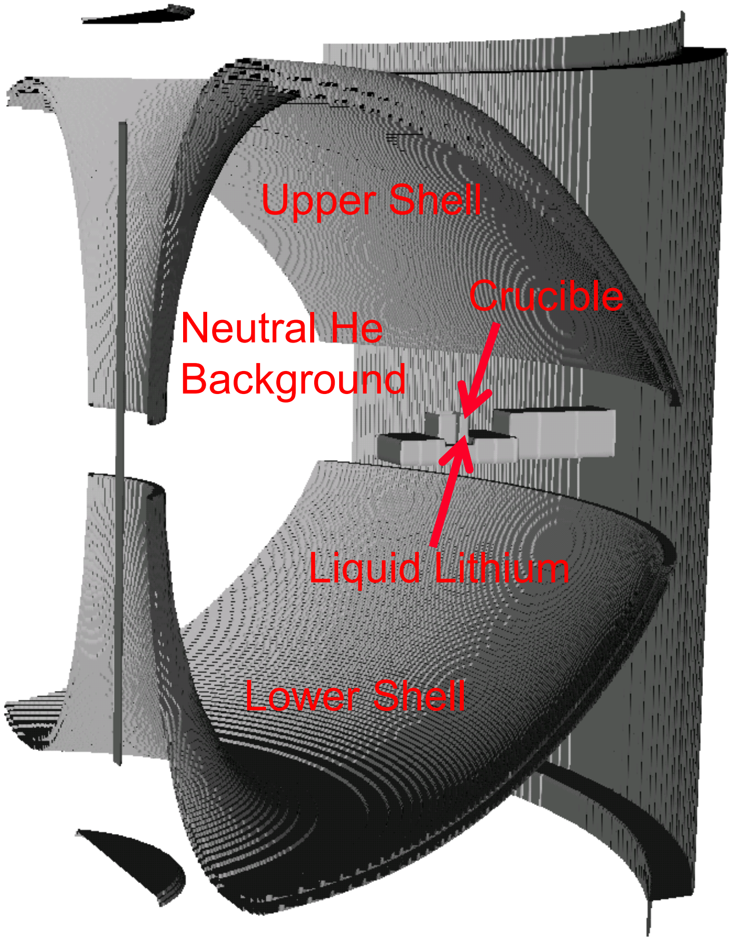
LTX



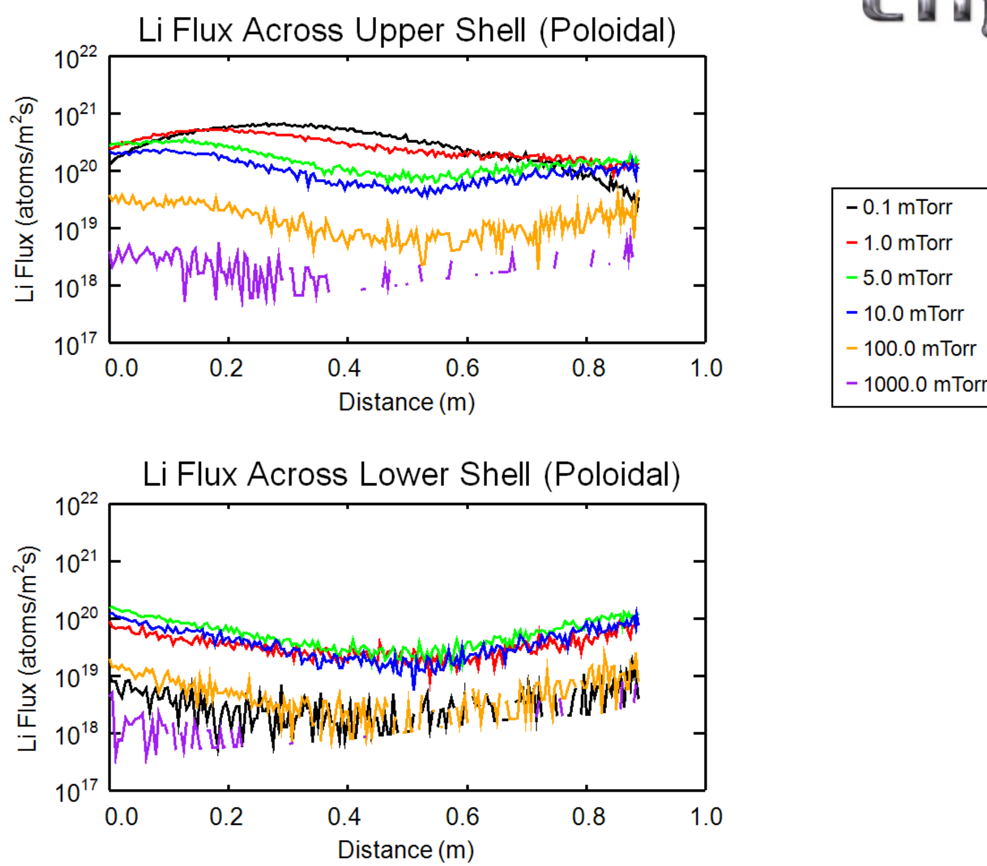


- Yttria crucible and tantalum crucible heater
  - 98 grams lithium evaporated in current campaign (2 evaporators)
- No significant issues with yttria crucibles after 600C operation
- Helium fill pressure of 5 mtorr yielded coatings with good uniformity

DEGAS2 calculations of the poloidal distribution of lithium coatings in LTX

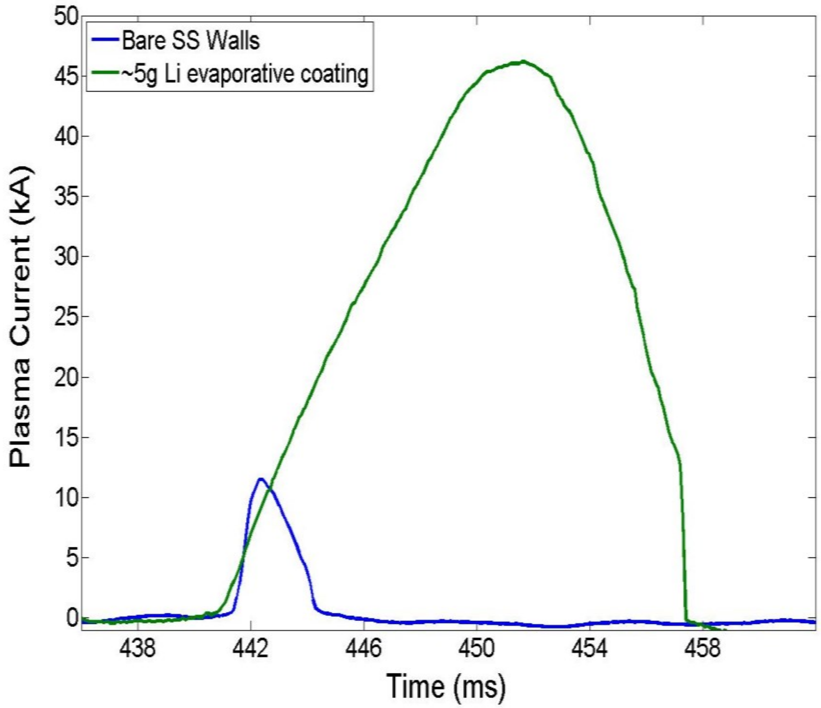


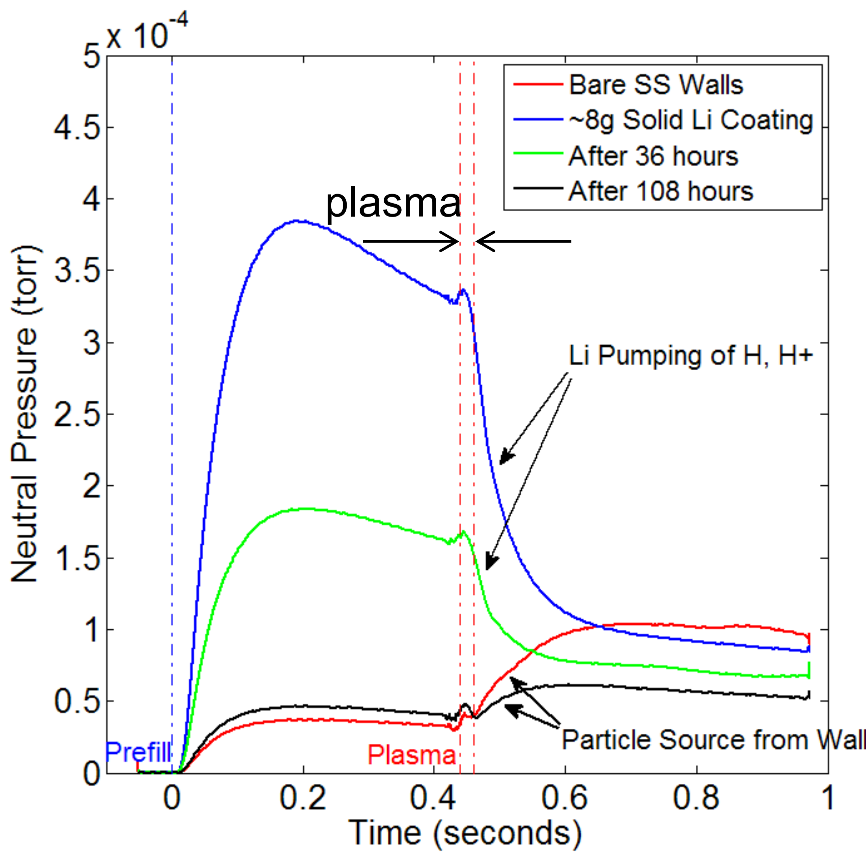
3-D shell model for deposition calculation



~5 mTorr helium backfill used in LTX experiments to distribute lithium

Solid lithium coatings had a strong effect on the discharge



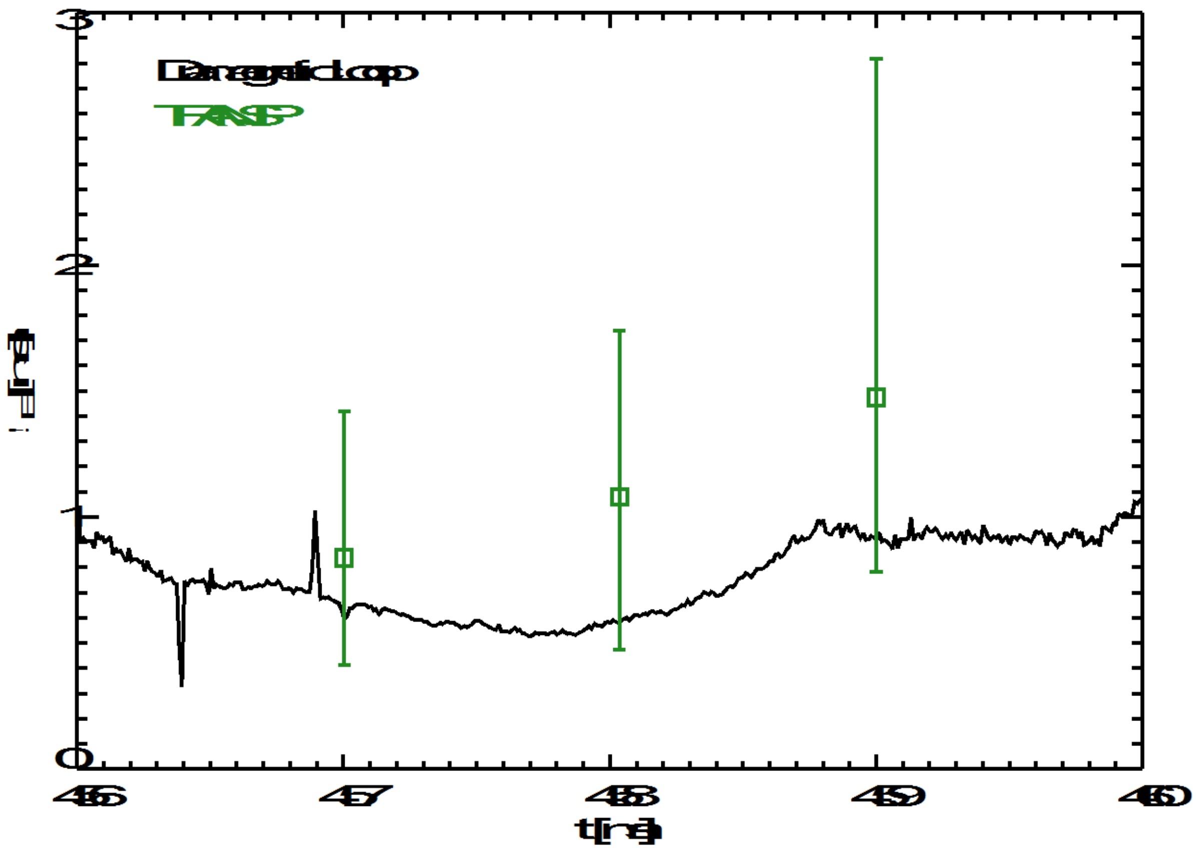


- Matched discharges w/ and w/o lithium coatings
  - Except gas prefill increase required with lithium

- Lithium coated walls are strongly pumping

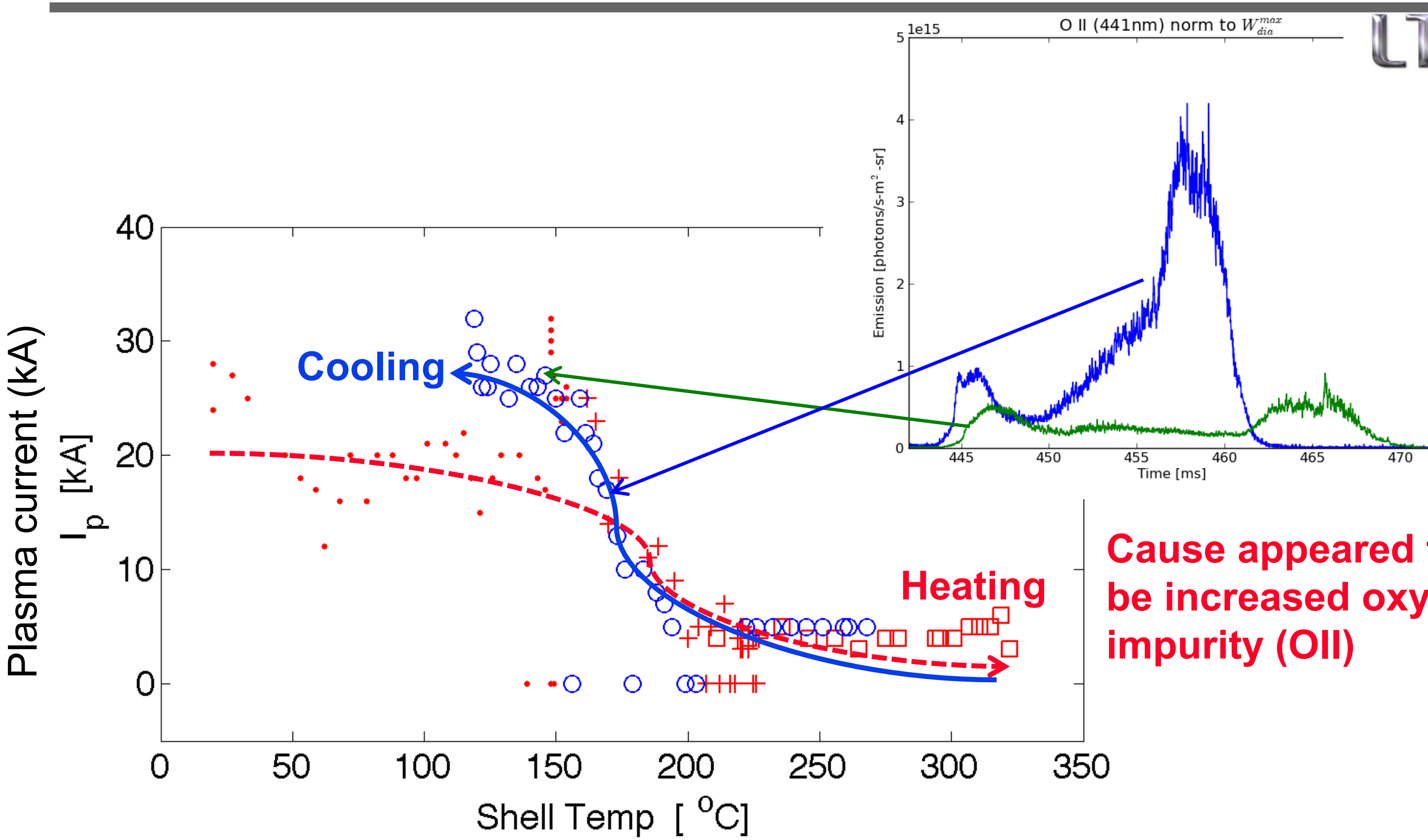
DEGAS2 modeling indicated a wall recycling coefficient of ~0.8 for helium-dispersed lithium coatings

Comparisons of kinetic (T_e from Thomson, T_i) and magnetic diagnostics of the plasma stored energy have been made



- Note that diamagnetic measurements underpredict the plasma stored energy in this case
  - Data from September 2012

But: in 2012, LTX discharges were found to deteriorate when the wall coatings were liquefied

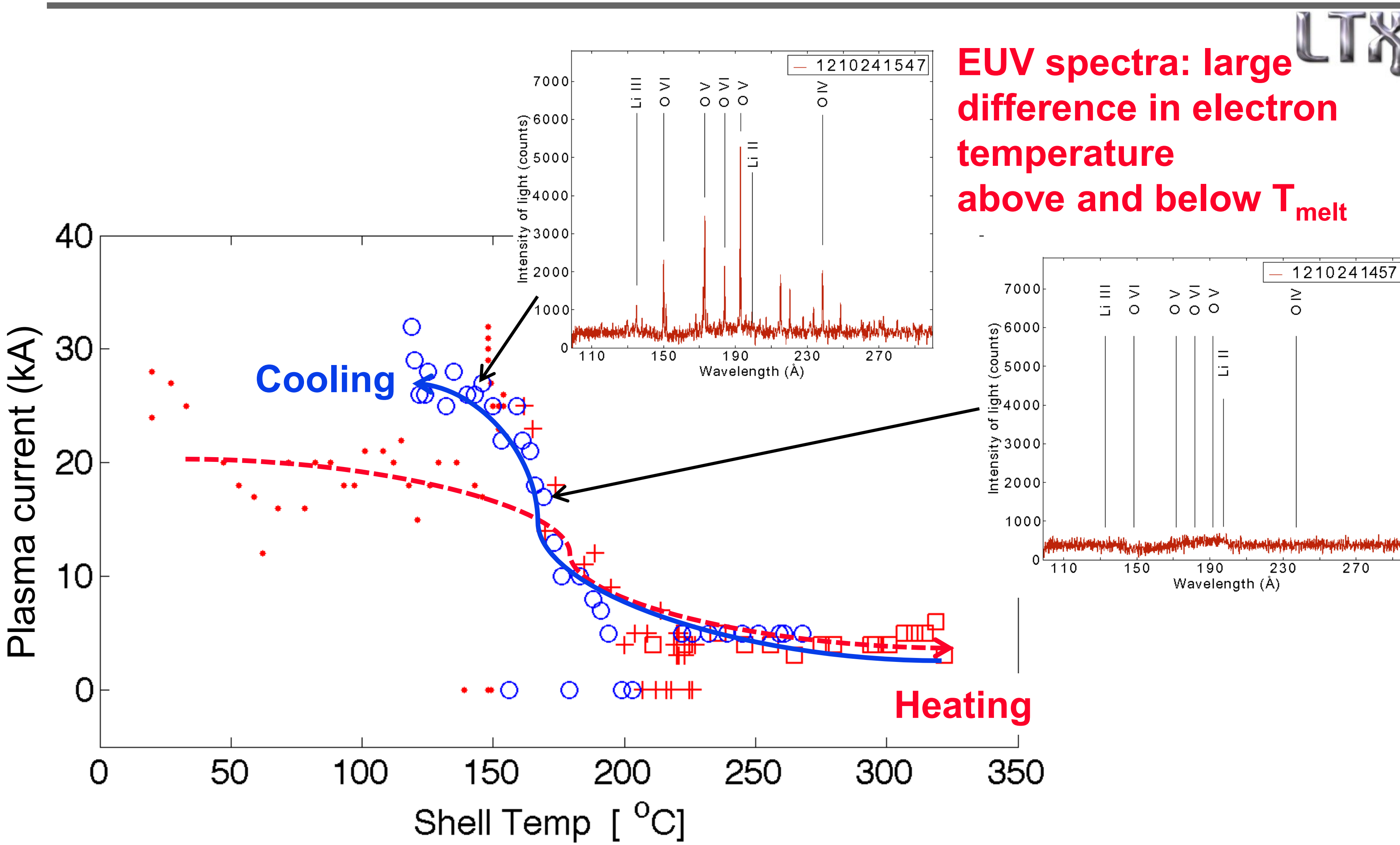


Cause appeared to be increased oxygen impurity (OII)

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

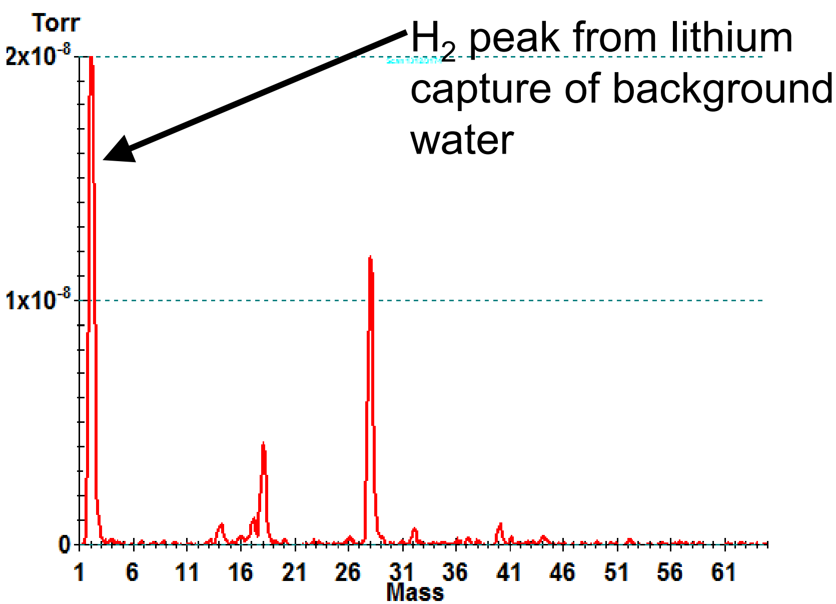
Discharges are strongly degraded when the lithium film liquefies (2012 result)

EUV spectra: large difference in electron temperature above and below T_{melt}

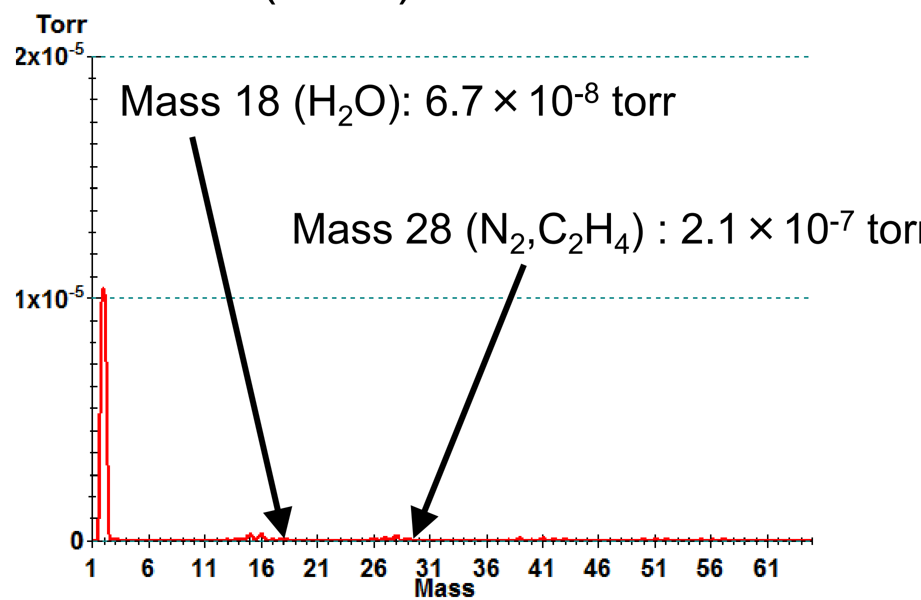


Liquefied lithium films: good vacuum conditions are now maintained even with 4 m^2 of 300 °C shell

Room temperature
(2012)

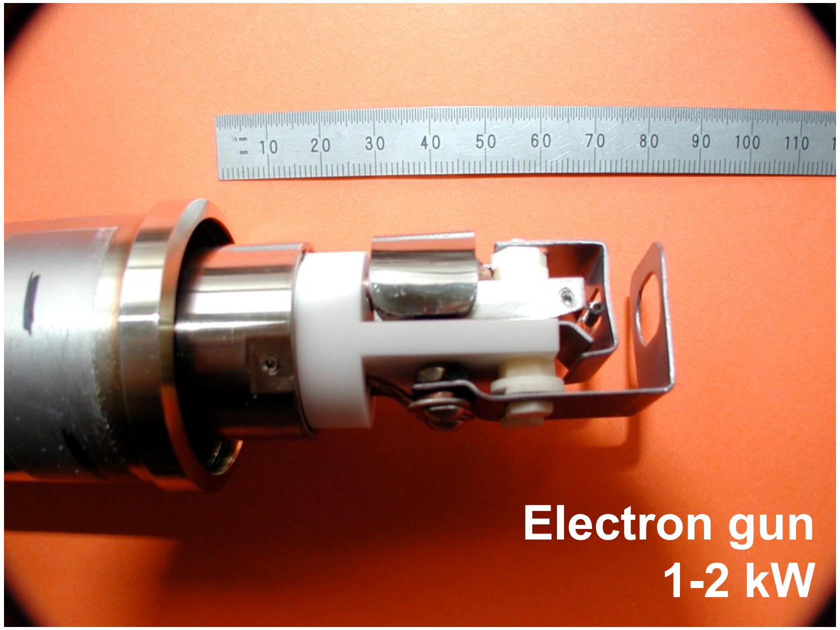


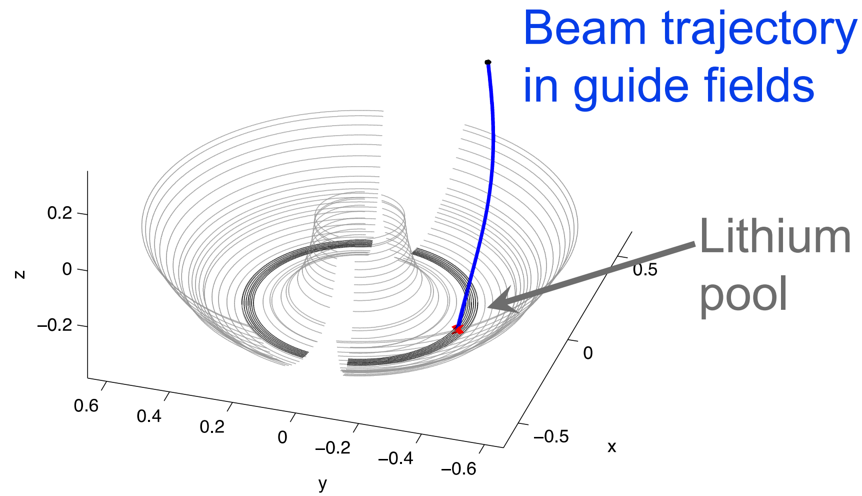
330 ° C
(2012)



- Impurity sources were sequestered (presumably in the lithium)
- Note that 2013 base pressure remains in the 10^{-8} Torr range

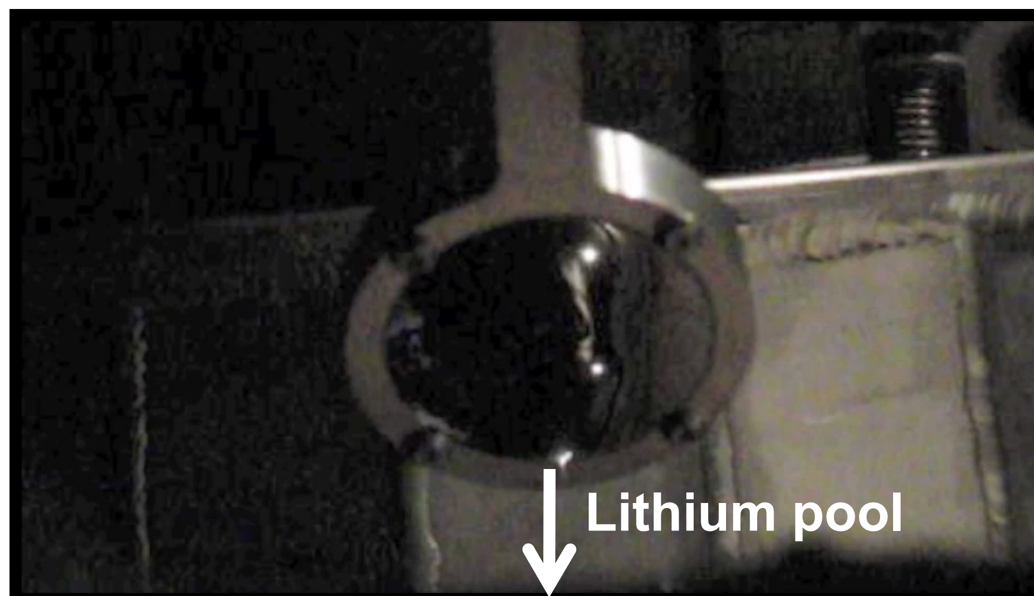
New approaches to lithium coatings developed





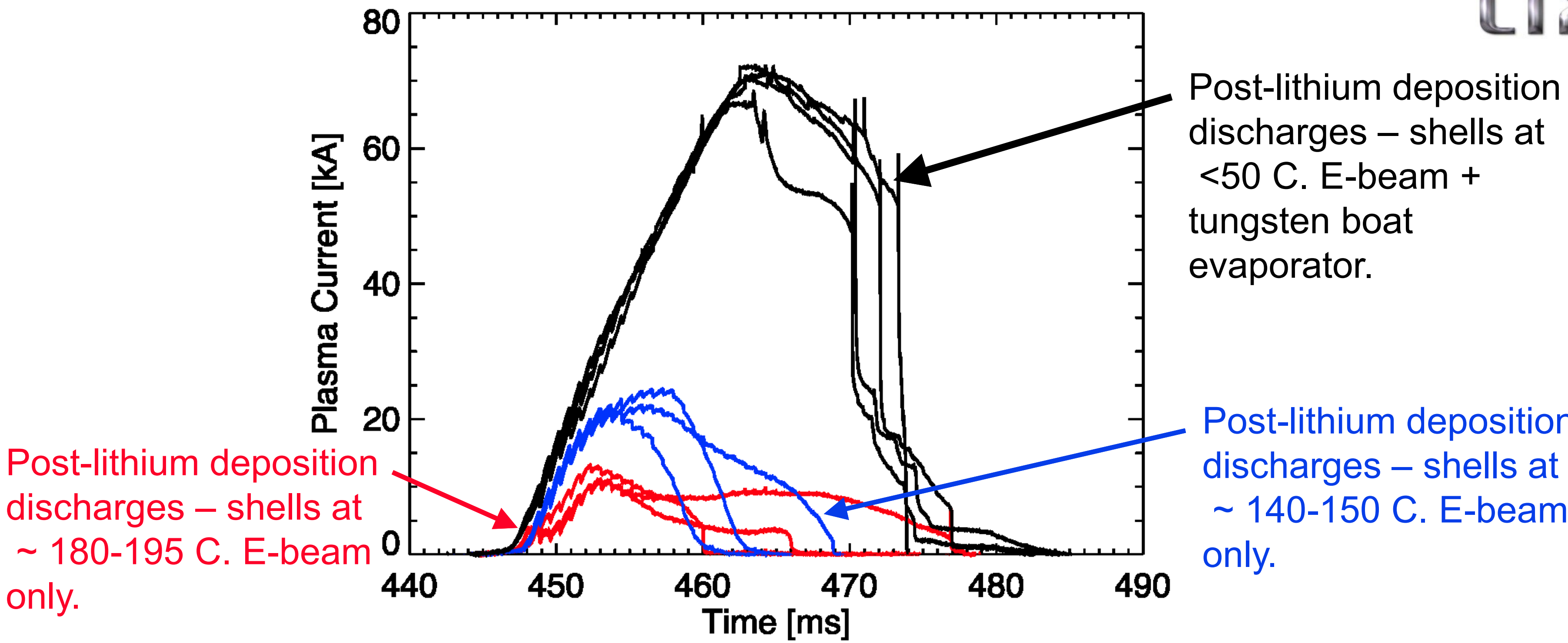
- Rapid electron beam evaporation from lithium pools
  - 5 minute cycle

Lithium pool viewed with a retractable molybdenum mirror



Disc m coverage

2(d discharges



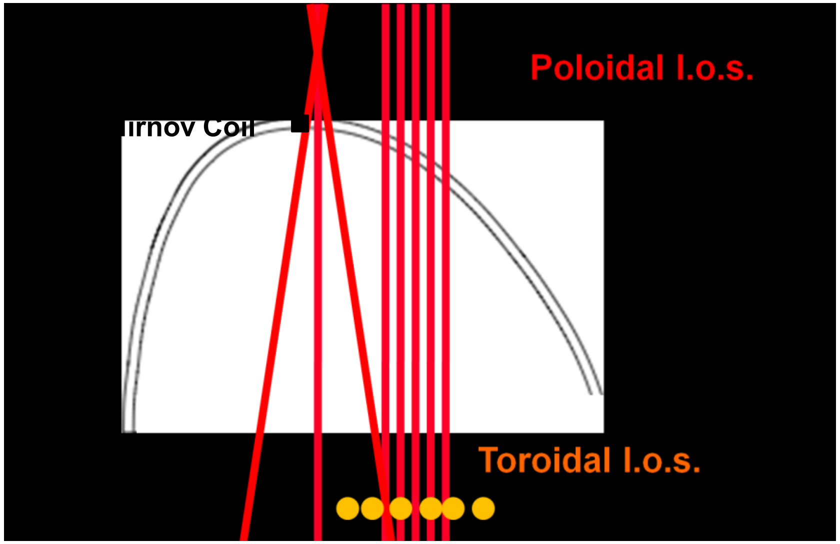
- Comparison is complicated by operator “learning curve”
  - Deposition procedure requires that hot walls come first
- Next experiment:
  - Establish tokamak discharges with hot walls
  - Interrupt operations and deposit fresh lithium
  - Resume tokamak discharges (walls still hot)
    - » Cessation of deposition ➔ tokamak operations requires only a few minutes

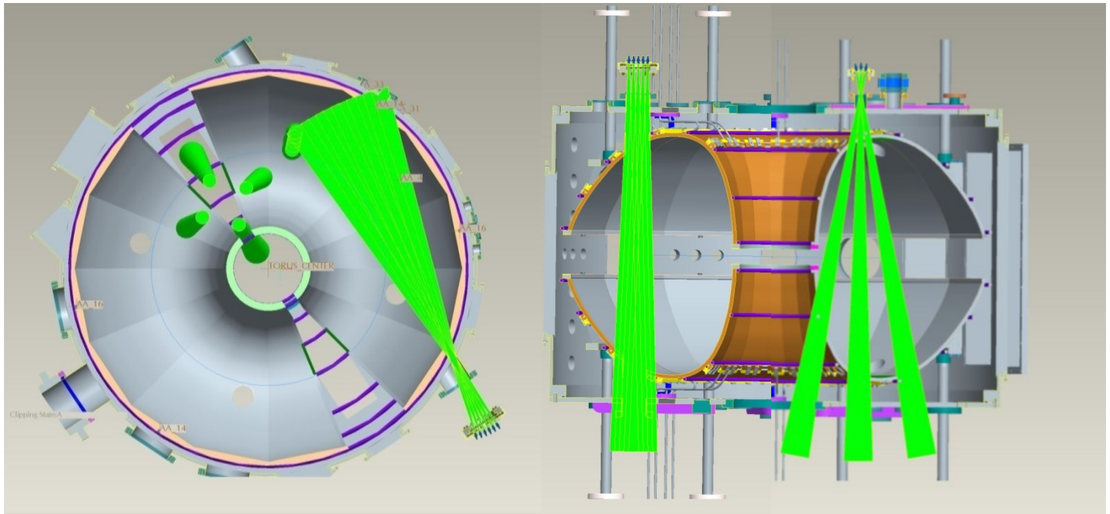
Future work

- Improve fitting to reliably extract profiles
- Invert line-integrated profiles to local measurements
- Survey entire spectrum on HAL
  - Look for O IV-VI, other impurities
- Time resolution on VUV spectroscopy
  - Use higher readout rate on TGIR
  - Trigger LoWEUS after current ramp-up
- Look for higher ionization states (O VII, O VIII, C V) at shorter wavelength on LoWEUS and TGIR
- Measure changes in impurities and ion profiles as wall conditions are varied and recycling reduced

Initial passive spectroscopy used in 2011-2012

- 6” midplane tangential port
  - 6 toroidal sightlines
  - r/a: -0.11, 0.0, 0.11, 0.27, 0.37, 0.48
- 4-5/8” port pair:
  - 5 poloidal sightline pairs
  - r/a: 0.06, 0.12, 0.17, 0.23, 0.29
- 2-3/4” port pair:
  - 3 poloidal sightline pairs
  - Tilted: ~0, -0.22, ~-0.46
  - Mirnov coils obscure innermost views
- Toroidal and Poloidal coverage 0<|r/a|<0.5

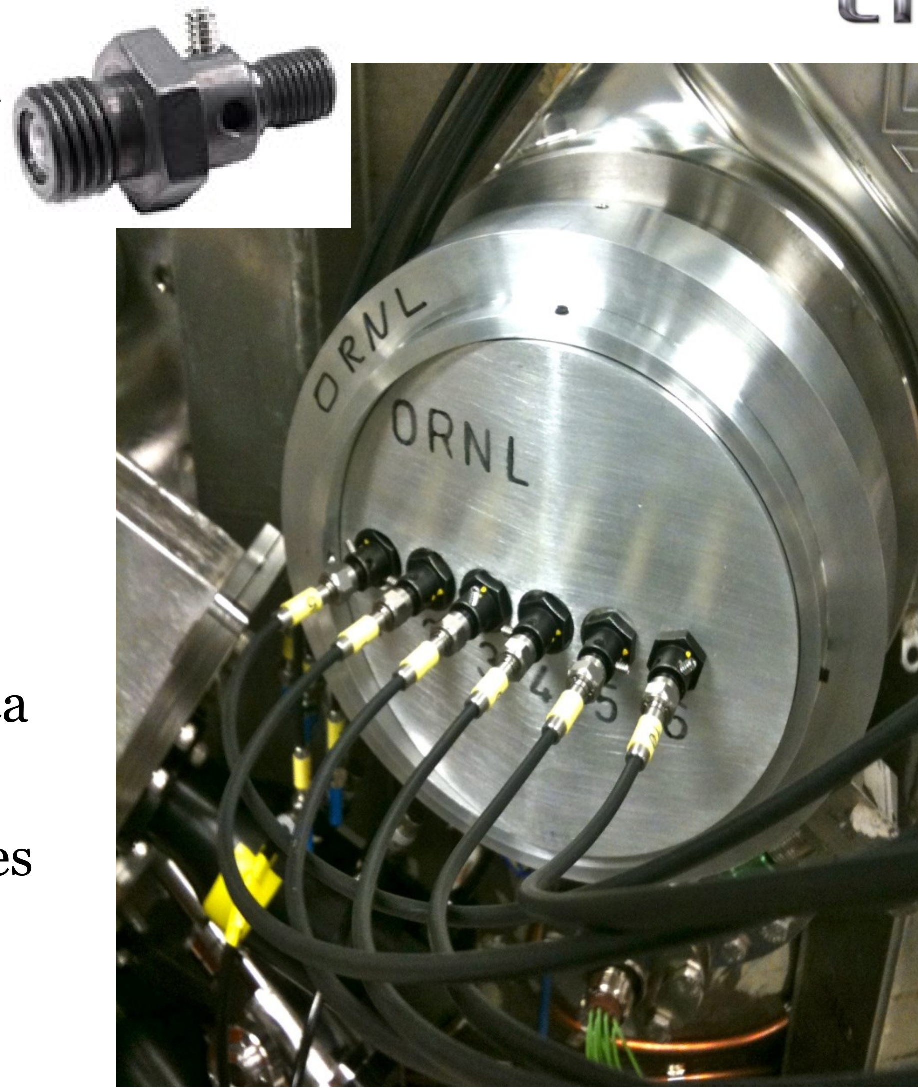




Initial system used small modular lenses

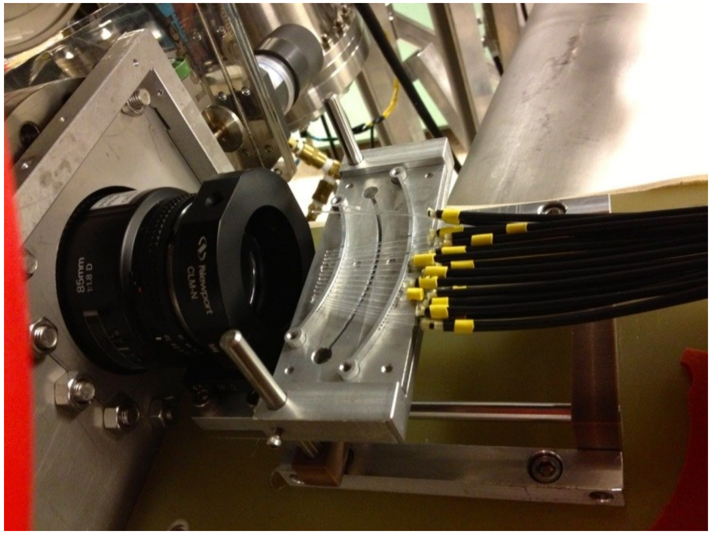
LTX

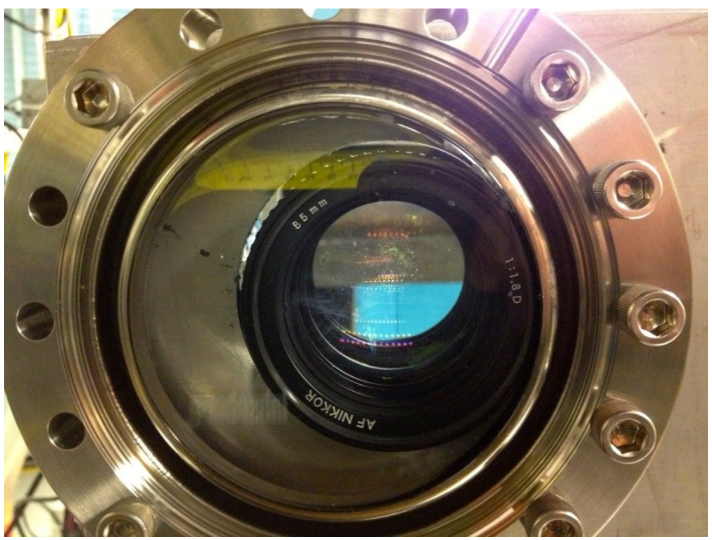
- Collimating fused silica Ocean Optics 74-ACR lenses
  - f/2 10 mm
  - Screw into “pucks” mounted on windows
- 17 channel fiberbundle (11 used)
  - 600 μm plastic-clad silica
  - 7 m length
  - SMA connection to lenses



Oak Ridge National Laboratory

Toroidal array uses single f/1.8 85mm lens

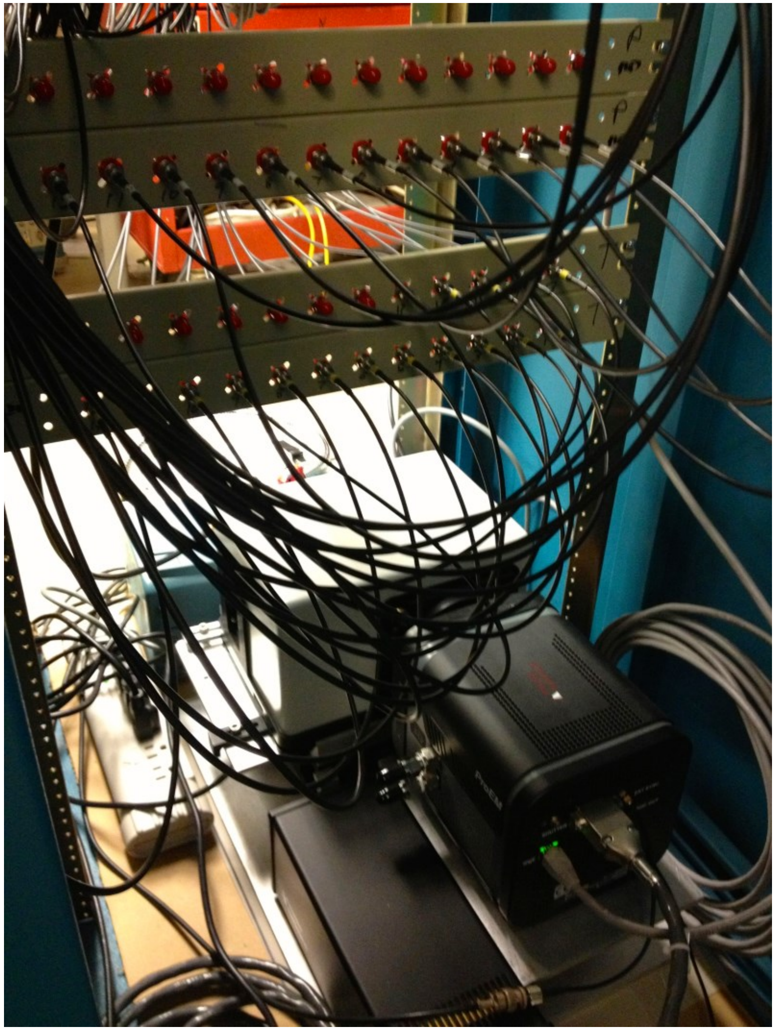




- Uses optics from NSTX Edge Rotation Diagnostic
- Fiber holder has room for 40 fibers
  - 3 outer & 6 inner views are obstructed
  - Spatial resolution could be doubled with more fibers
  - Inboard coverage could extend to r/a ~0.3
- 600 μm 0.37 NA plastic clad silica fibers
- New poloidal arrays use similar modular lens/puck design

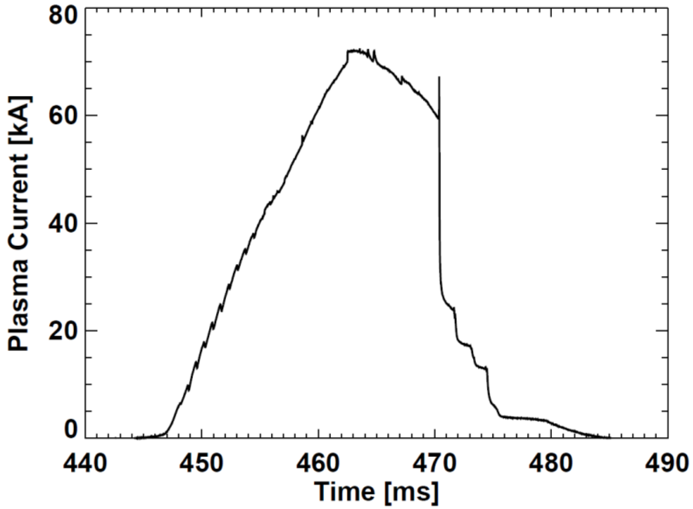
Patch panels improve flexibility

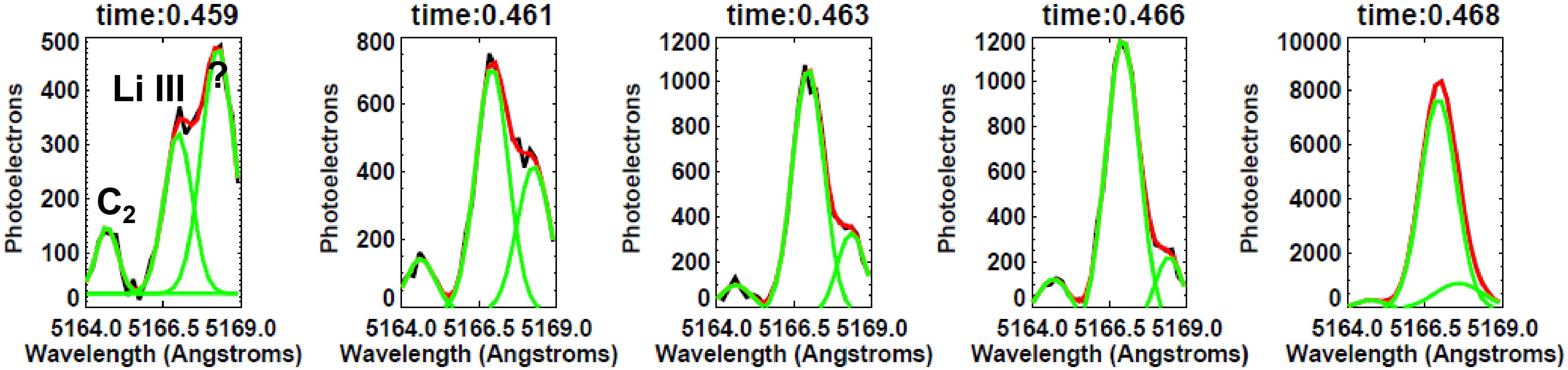
- Spectrometer/CCD moved from LTX test cell to diagnostic room
  - Reduced noise/pickup
  - Improved light environment
- "Transfer" fiber bundles bridge from diagnostic room to LTX collection optics
- Fiber-optic patch panel allows for view-swapping without machine access
  - Easily switch between toroidal/poloidal arrays, core/edge views, HAL and Holospec



Li III signal strongest when $I_p > 60$ kA

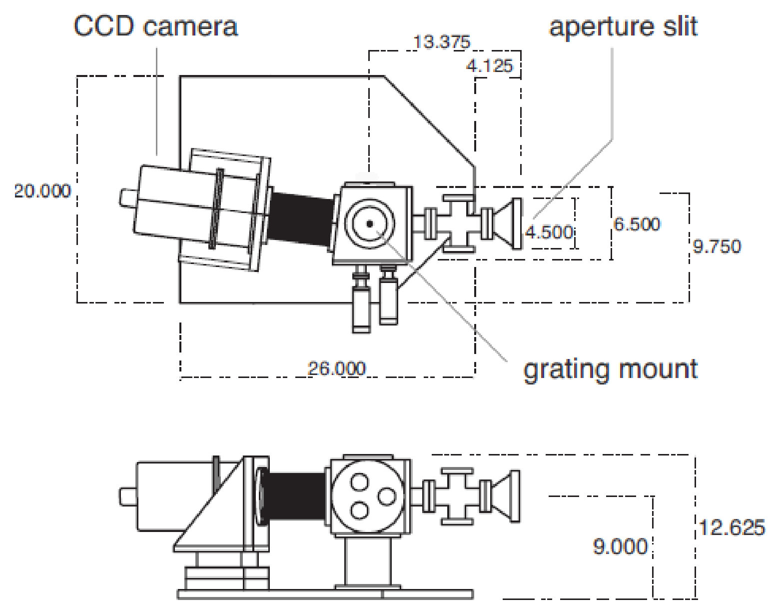
- Molecular carbon Swan band at ~5165 Å and unknown (Fe?) line at ~5168.3 Å overlap Li III
- Li III signal strongest in core toroidal views





Long-Wavelength Extreme Ultraviolet Spectrometer

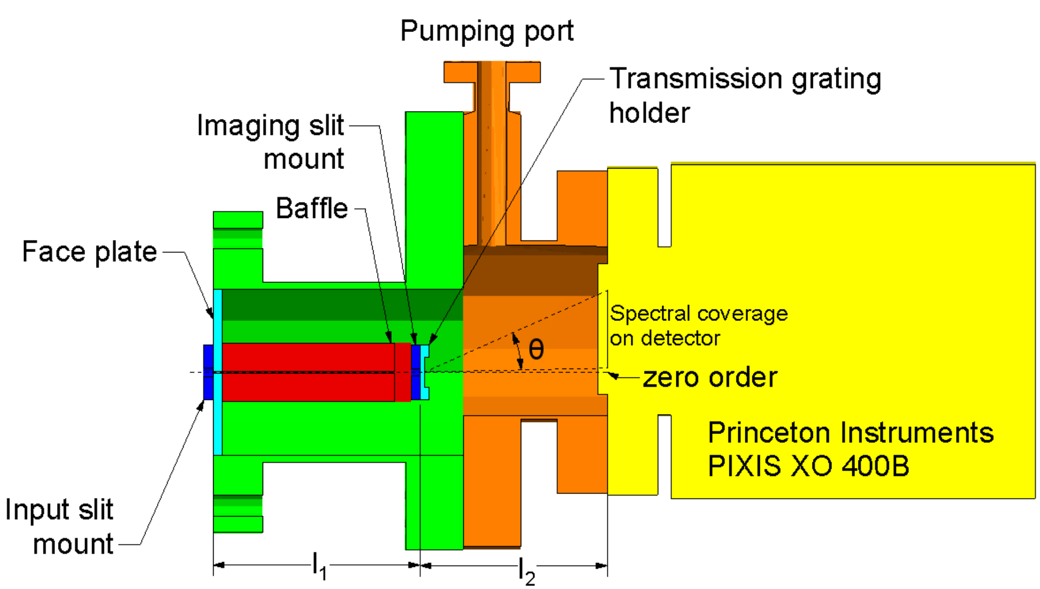
- LoWEUS
  - Survey spectrometer w/ range: ~ 20 - 450 Å
  - Resolution: ~ 0.3 Å
  - Bandwidth: ~ 180 Å
  - 1340 x 1300 pixel LN2 cooled PI-SX camera
    - » Single frame per shot integrated over time and radial midplane
    - » Vertical binning improves signal

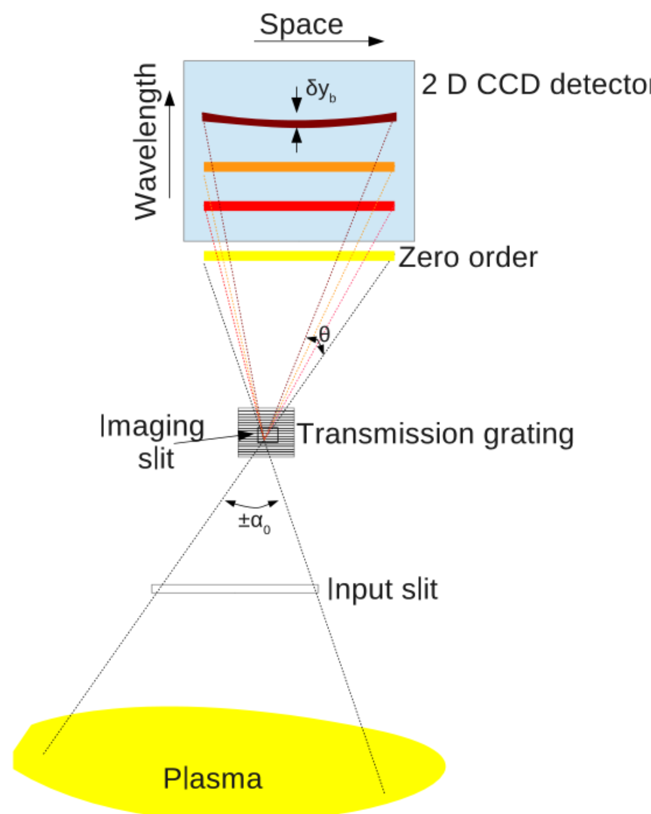


Ref: Clementson, et al., Rev. Sci. Inst. **79**, 10F538 (2008)

Transmission Grating Imaging Radiometer

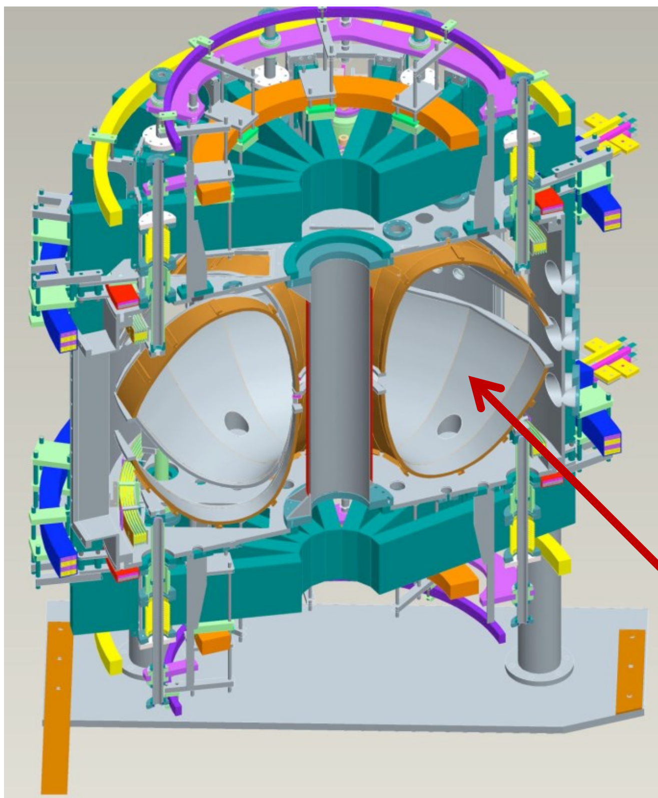
- TGIR
  - Tangential view
  - Much broader instrument function than LoWEUS, but adds temporal and spatial resolution





Lithium Tokamak Experiment (LTX) built to explore lithium technology & low-recycling physics

LTX is a low aspect ratio tokamak designed to provide ~80% coverage of lithium (solid or liquid) PFC. The shells holding the lithium were designed to be conformal to the last closed flux surface, providing a conducting wall at the plasma edge.



Operational Parameters	
Major Radius	R=0.40 m
Minor Radius	a=0.26 m
Toroidal Field	B_T=0.18 T
Plasma Current	I_p< 75 kA
Plasma Duration	t< 50 ms
Shell Temperature	< 350 °C

Shells are 3/8" OFHC copper explosively bonded to 1/16" 304 stainless steel liner, for good thermal conductivity and lithium resistance.

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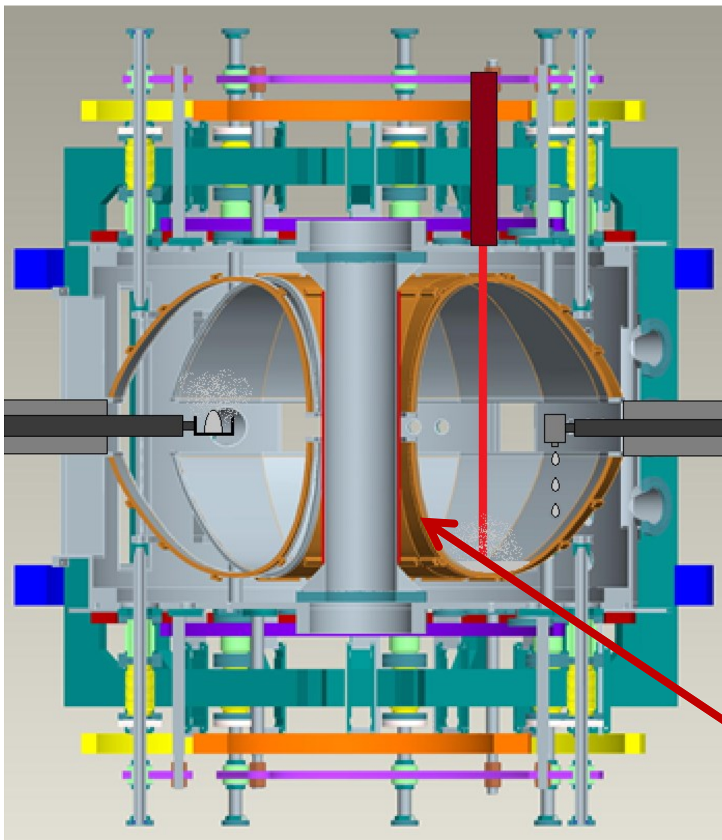

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LTX

LTX is a low aspect ratio tokamak with all-metal (no bulk C) plasma facing components that can be fully coated with lithium. 4 shells surround ~80% of the plasma surface and can be independently heated for studies w/ liquid and/or solid lithium.

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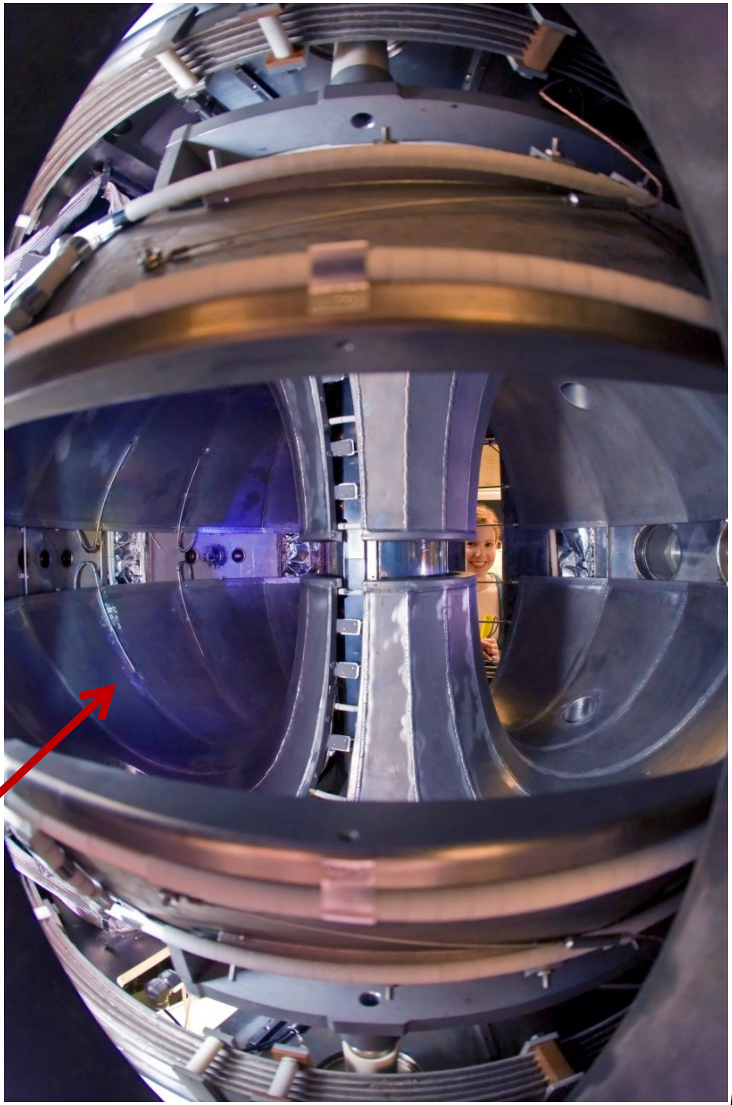

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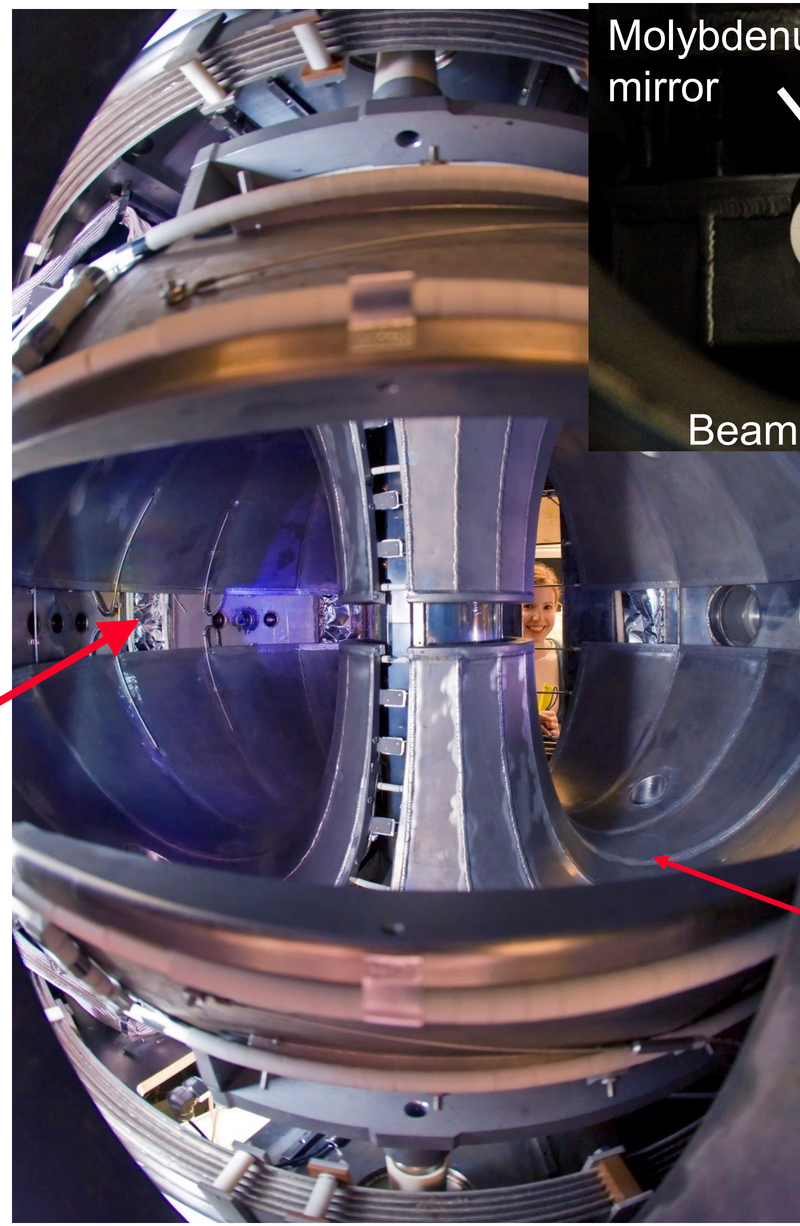
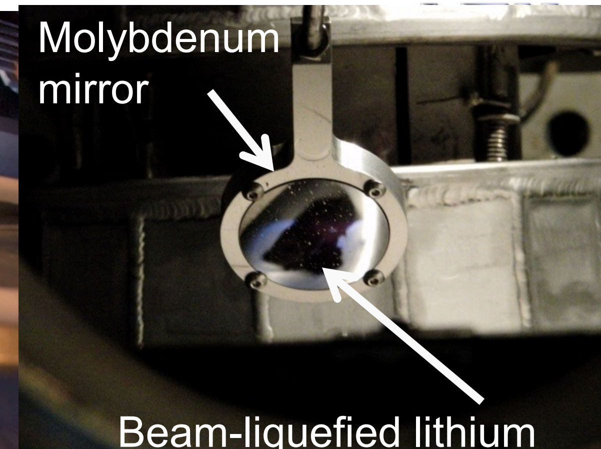
Lithium introduced with evaporators and fillers

- New lithium coating systems developed
  - Electron beam evaporation of lithium inventory in lower shell
  - Direct evaporation from a tungsten “boat”
  - Systems are cooled and discharges initiated in less than an hour

Insertable lithium-filled tungsten boat at midplane





Lithium pool is imaged in a molybdenum mirror during beam heating.

e-beam evaporation of lithium pool