First operation of the Lithium Tokamak Experiment - β

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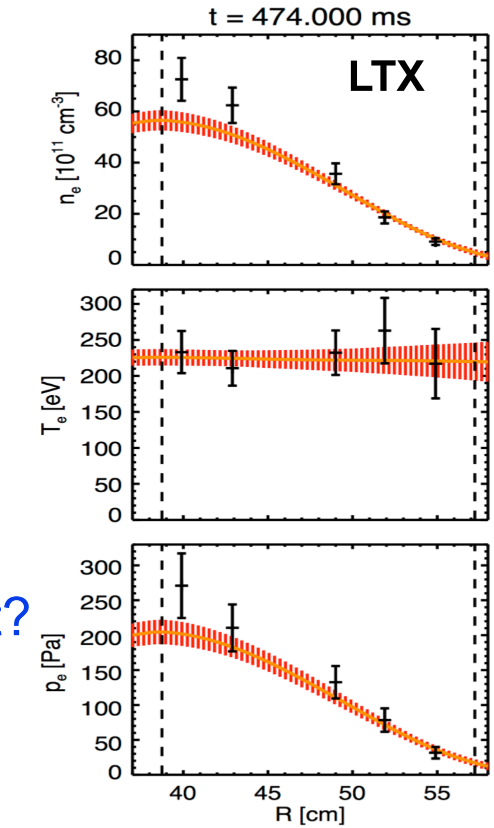
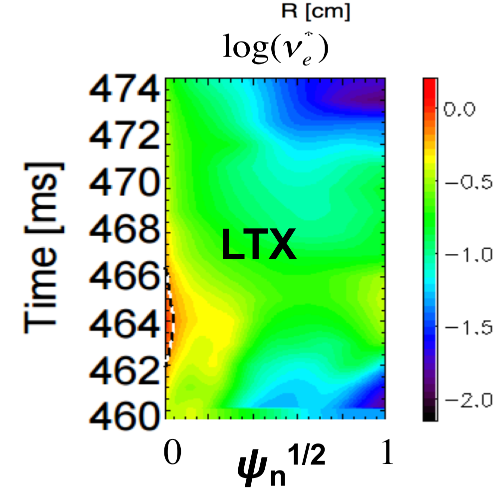
Outline

- **Core plasma studies in LTX-β**
  - NBI for plasma fueling
    - » Supplemental high efficiency gas puffing
  - Effect of NB ion heating, hot ions on T_i, T_e profiles
  - Detailed confinement studies
    - » Equilibrium reconstructions constrained with Thomson scattering and CHERs
- How does confinement vary with global recycling?
- How would lithium walls impact a compact power plant?
- **Edge/scrape-off layer studies**
  - *Collisionless* SOL
  - What is the effect on λ_q?
  - What fraction of the SOL ions are trapped, and do not pass to the limiter (➪divertor)?
  - What is the resultant split in wall vs. limiter (➪divertor) power loading?
- What are the implications of a low recycling SOL for divertor design?

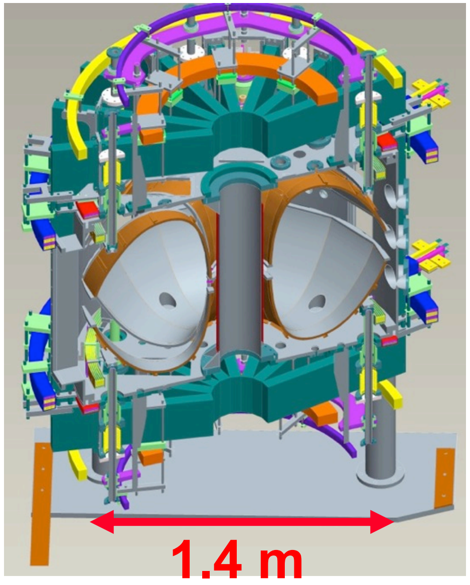




LTX and LTX-β

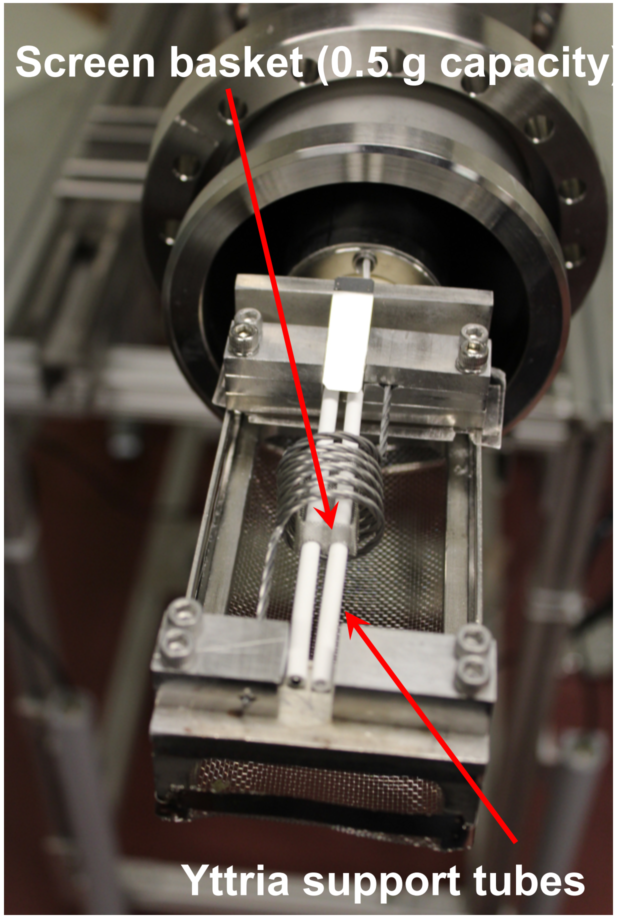
Parameters		LTX	LTX-β achieved	Planned
Major Radius	R_0	34 – 40 cm		
Minor Radius	a	20 – 26 cm		
Vacuum Pumping		6,000 L/s	12,000 L/s	13,000 L/s + Ti
Li Heat/Evap/Cool time		200/10/100 mins	10/10/10 mins	5/5/5 mins
Toroidal Field	B_T	0.17 – 0.2 T	0.3 T	0.34 T
Plasma Current	I_p	< 85 kA	~ 100 kA	>125 kA
Plasma Duration	t_{shot}	< 50 ms	< 50 ms	> 100 ms
Beam Power	P_{NBI}	0	> 500 kW	700 kW
Beam Duration	t_{NBI}	0	5-6 ms	10-30 ms

- High field-side limited by a conformal, high-Z wall
- Lithium coatings on all plasma-facing surfaces
  - LTX: Lithium evaporation from pool in lower shells
  - LTX-β: Midplane evaporators
  - Shell pre-heating not required for evaporation
- Operated in hydrogen (gas puffing)
  - LTX: Fueled from the high field side midplane
  - LTX-β: 35A neutral beam fueling
  - improved HFS puffing, topside SGI



New LTX-β midplane lithium evaporators

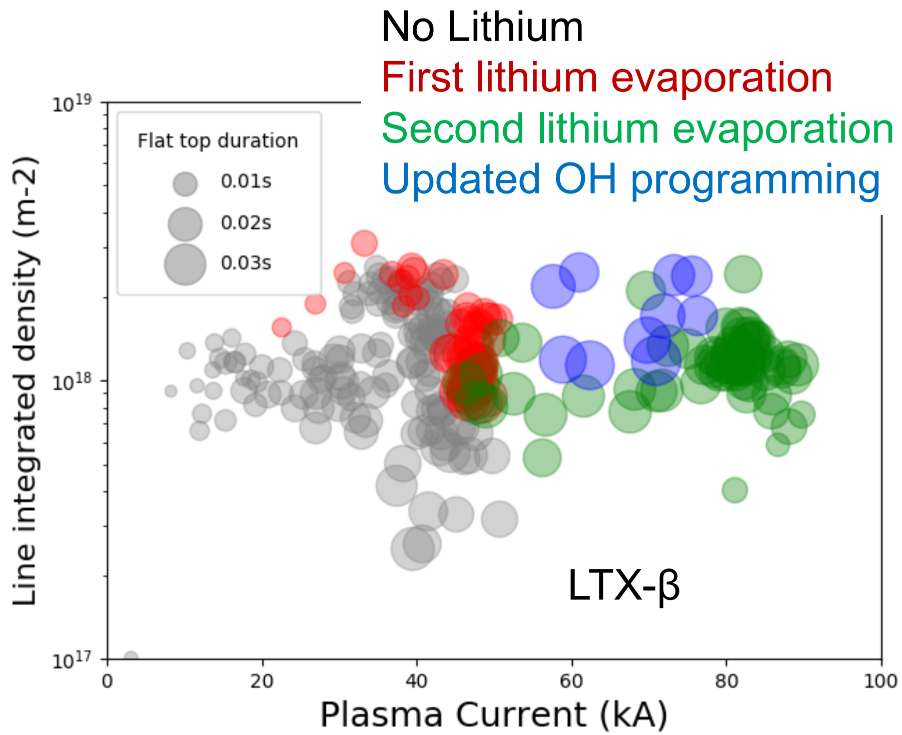
- Fast evaporation cycles without need for shell pre-heating
  - Full evaporation (0.5 g lithium) now < a minute
- Quartz Crystal Deposition Monitors measure Li film thickness
- XPS scans show elemental Li remains after 1.5 hrs
- More upgrades planned
  - Larger lithium inventory (6 g)
  - Easier loading
  - Preferential evaporation on high-field side PFCs
    - » Where the plasma limits
  - Faster coating, between shots operation
- Only solid lithium coatings to date



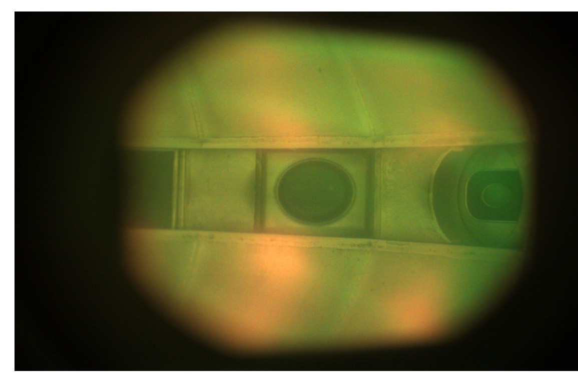
First generation LTX-β evaporators. Modified version installed last week

LTX-β is operating with fully lithium coated walls

- Tokamak operated at > 3 kG
  - Requires second TF power supply. Maximum field ~3.5 kG
- 100 kA plasma current
  - Further OH power supply expansion this year
- Short-pulse neutral beam injection
- Fully lithium coated plasma-facing surfaces
- Continuing with periodic lithium evaporation
  - Further evaporator upgrades later this year



Fast camera image showing Li I (yellow-orange) and Li II (green) light

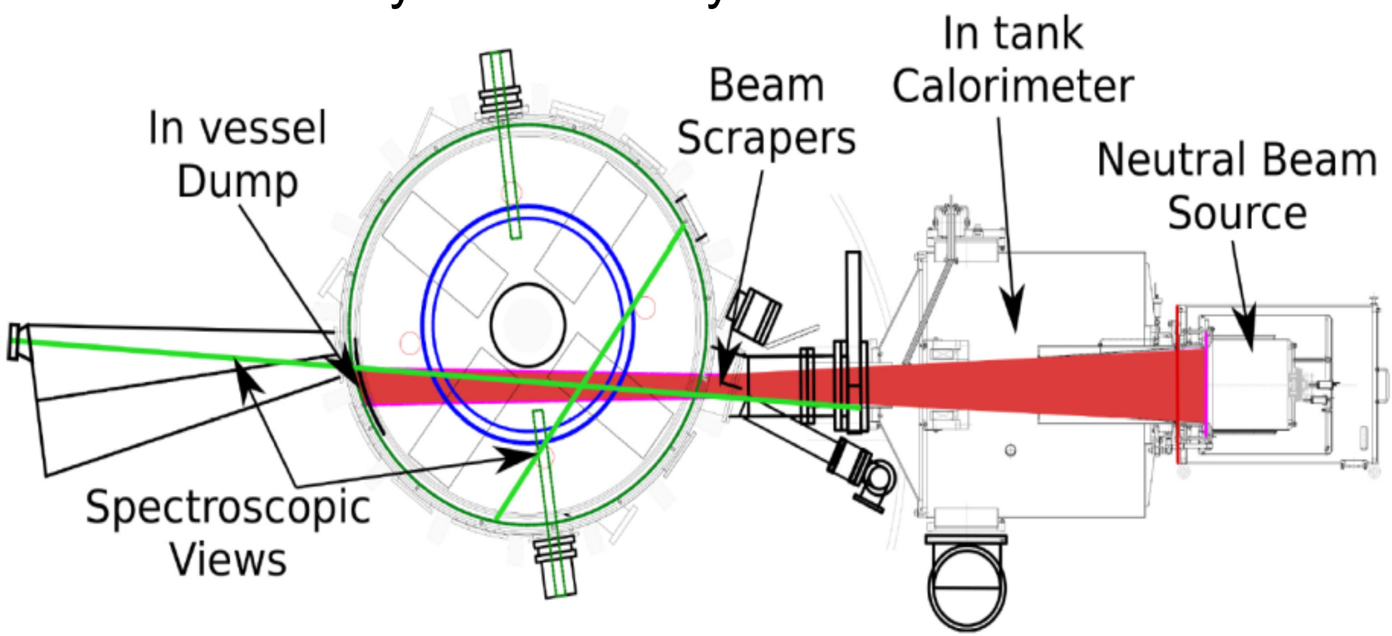


LTX-β neutral beam is operating close to specifications

LTX-β

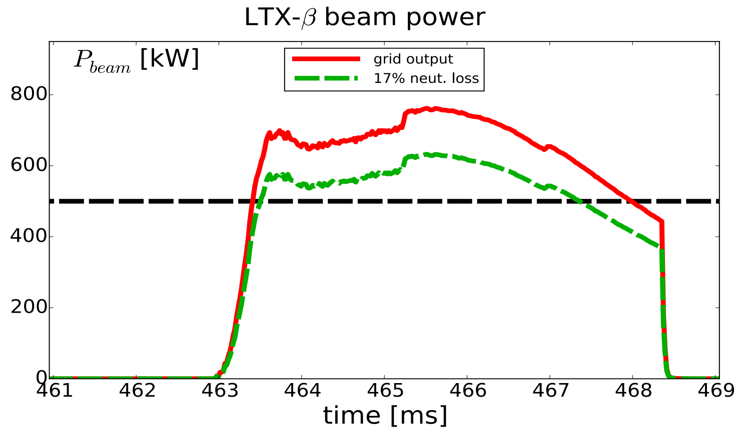
- ~600 kW injected so far, presently 5 msec pulse duration
  - 700 kW maximum
  - Plan to increase pulse length to 15 - 30 msec
    - » Maintain steady-state density

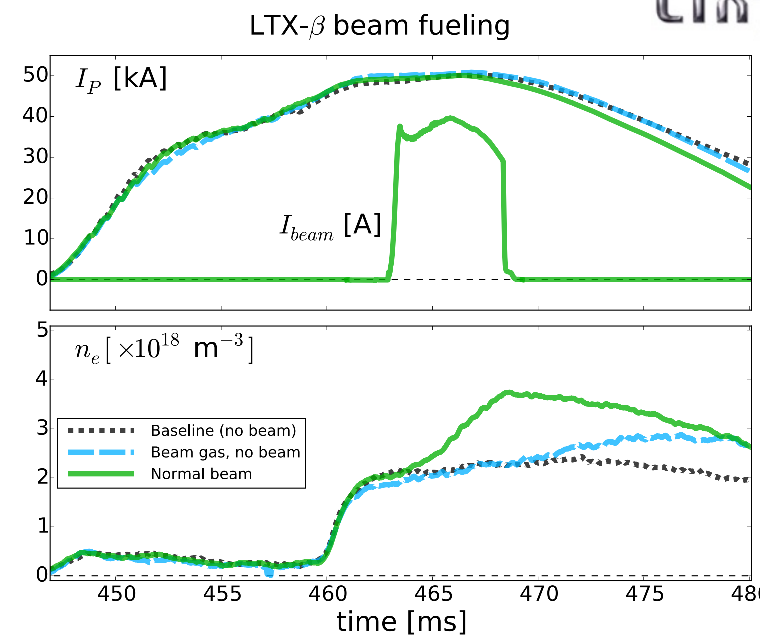
Beam provided by TAE



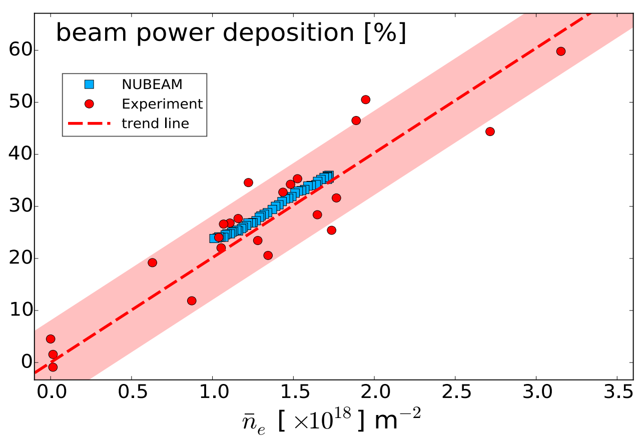
- Beam provides fueling, ion heating (P_{NBI} nearly 10× P_{ohmic})
- CHERs diagnostic for T_i (ORNL)
- U. Wisconsin supporting beam operations

Significant beam fueling observed



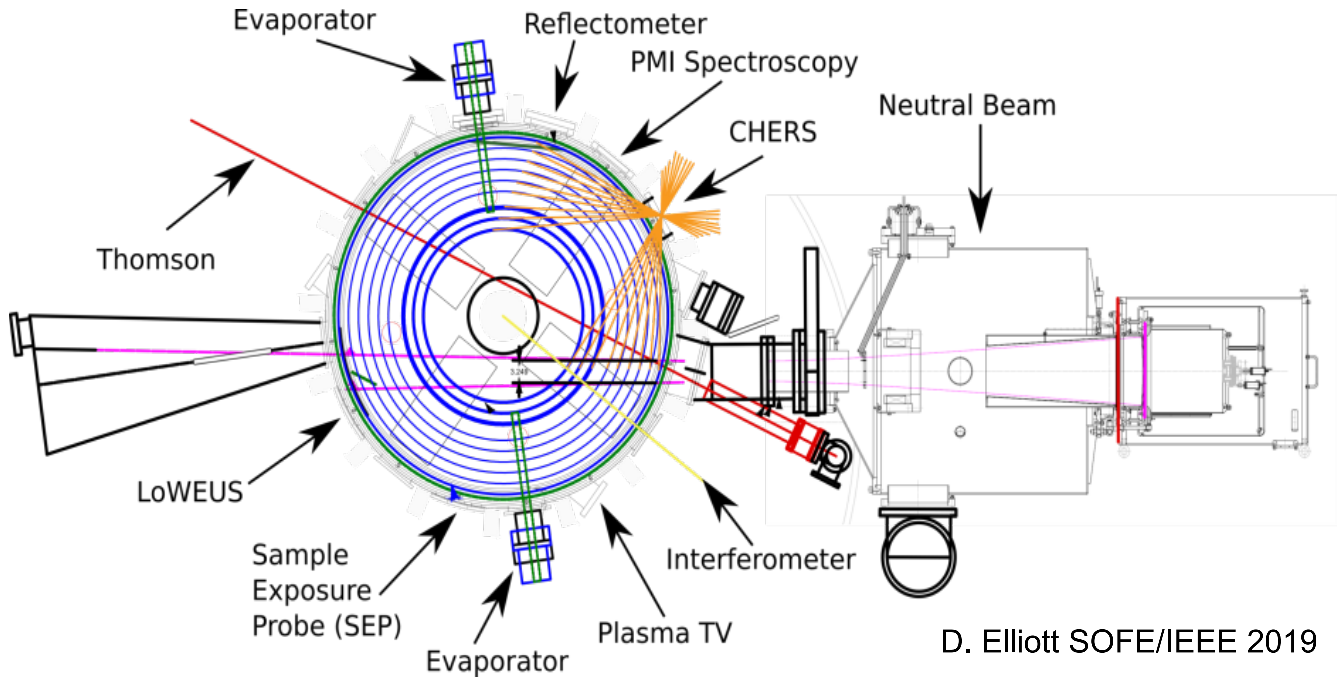


- 700 kW expected NB power



- Initial indications are that beam fueling of the discharge is effective
- Discharge development needed
- Modifications to the TAE beam underway
- Up to 60% beam power deposited
  - Typically 30 – 40%
- Higher target density discharges under development

New or improved diagnostics in LTX-β

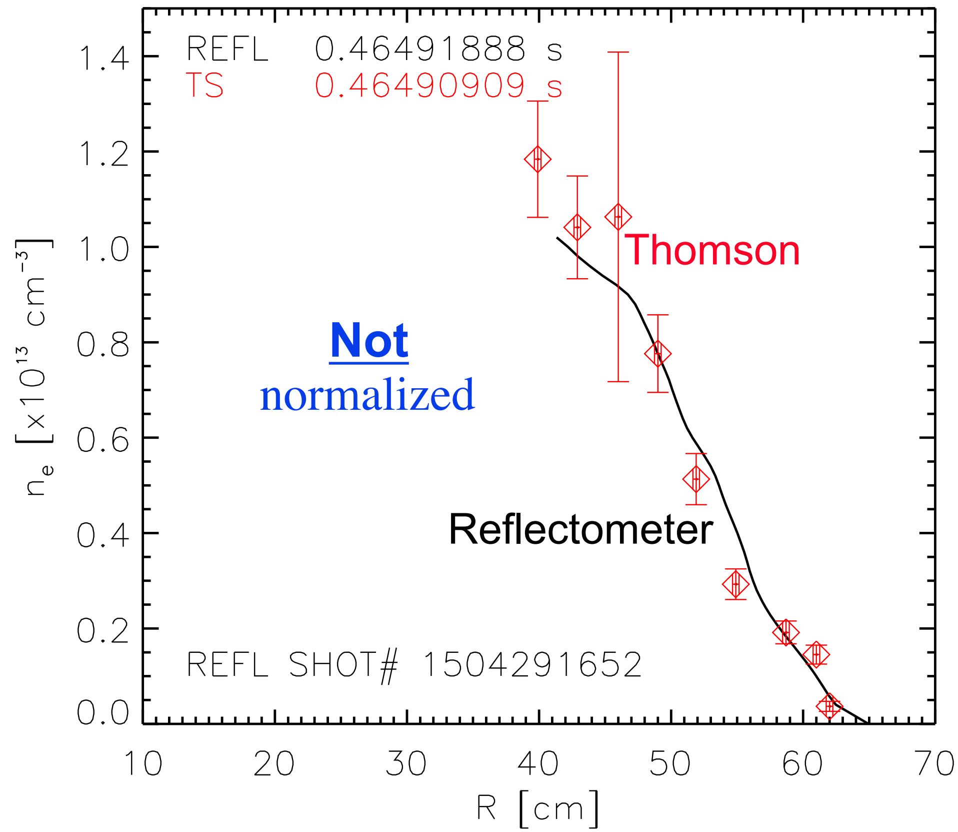


D. Elliott SOFE/IEEE 2019

- Thomson scattering: Improved camera, fibers, dump
- Two new lyman-α detector arrays for recycling
- Expanded magnetic diagnostics to increase fidelity of reconstructions
- ORNL/PPPL: CHERS, multiple visible spectrometers
- LOWEUS soft x-ray spectrometer (LLNL)
- UCLA: Microwave interferometer & reflectometer

Improved core diagnostics for LTX-β

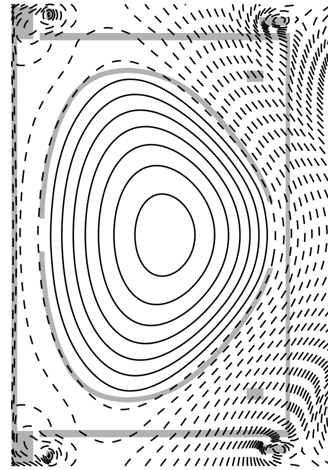
- UCLA profile reflectometer has been upgraded
  - Provides core measurements of $\tilde{n}_e$
- Investigate 1 mm interferometer upgrade for low-k scattering (UCLA)
- Additional core high-field side Thomson scattering sightlines added to improve equilibrium modeling
  - New laser sightline



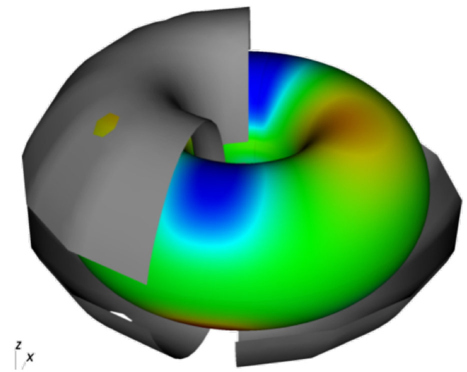
- Additional new edge Thomson scattering channels for SOL
  - Core Thomson shown to be adequate down to $n_e \sim 2\text{-}3 \times 10^{17}$ m^{-3} with 20 J laser
  - New channels employ APD detectors, polychromators to extend measurement to lower density

Broad modeling effort for unique LTX-β physics

- PSI-Tri equilibrium reconstructions
  - Psi-Tet eddy currents
- TRANSP integrated analysis
  - NUBEAM, NCLASS
- LiWall Fusion – new codes
  - ASTRA-ESC (Cbesc) for equilibrium, SOL
  - Cbshl eddy currents
  - HPE Hot Particles
  - Cbped for NB ion orbits
    - » Full ion orbit code

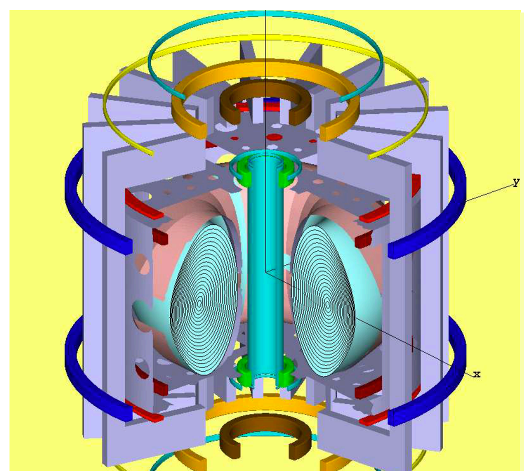


PSI-Tri

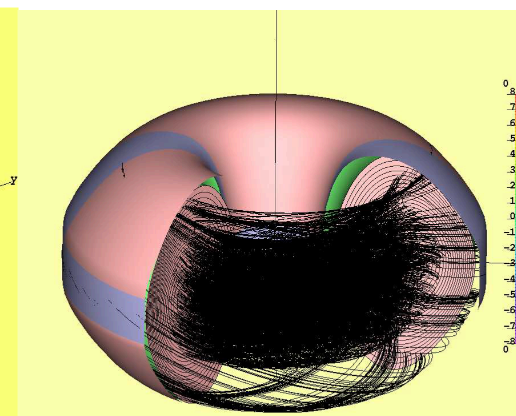


Psi-Tet

C. Hansen, U. Washington



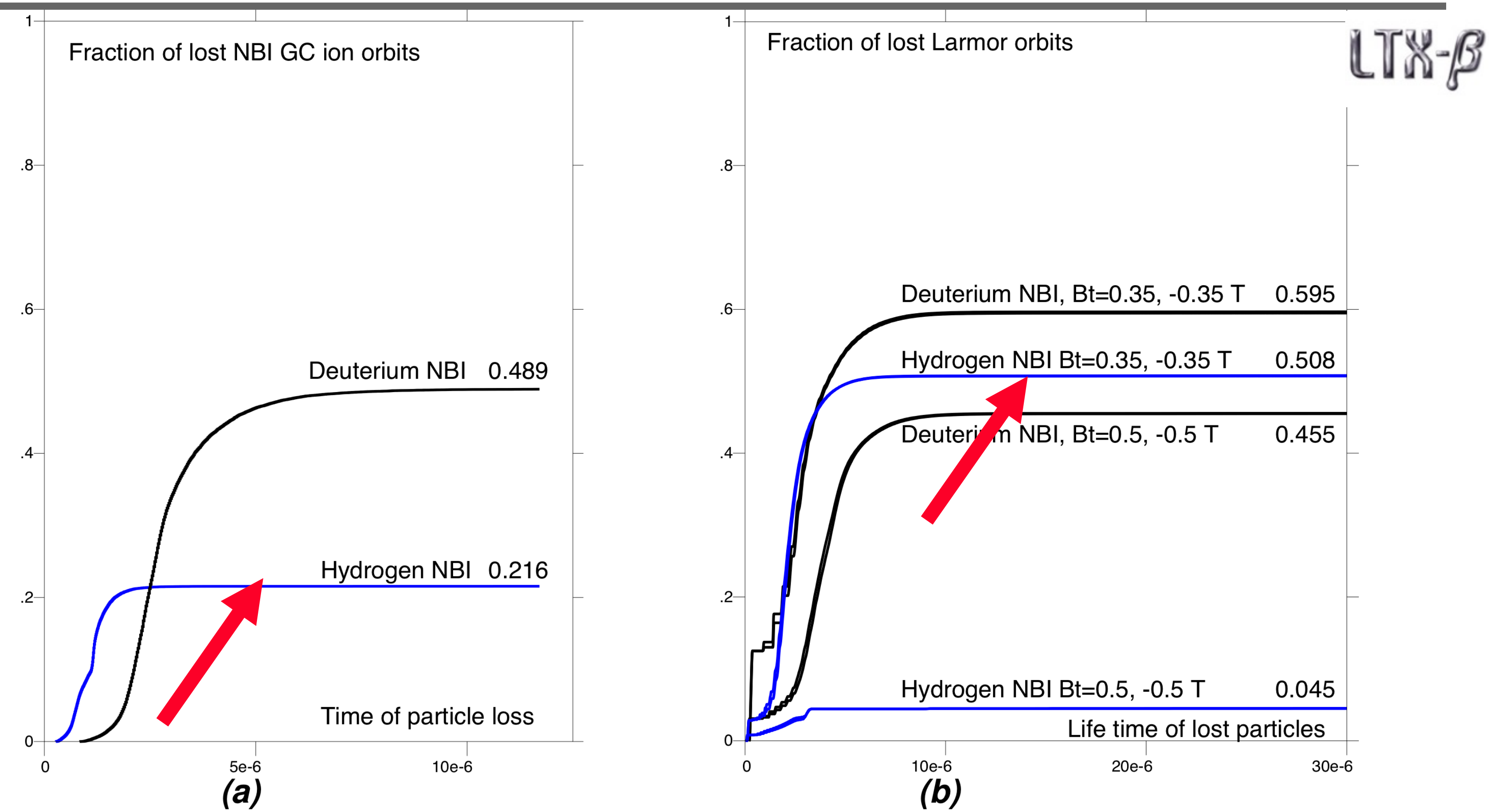
Cbesc modeling – full LTX



Cbped – fast ion orbits

L. Zakharov, LiWallFusion

Accurate estimate of NB ion losses requires full ion orbits

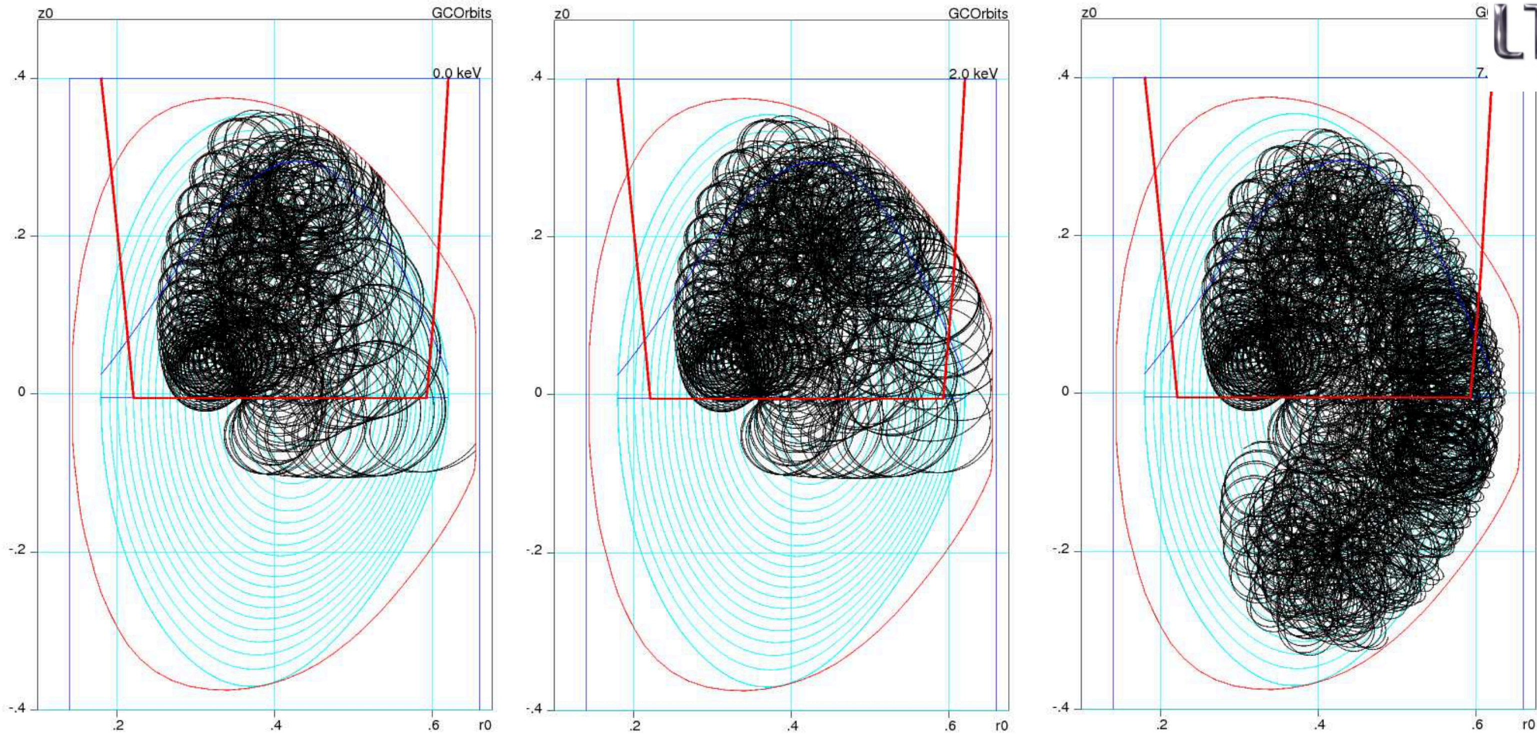


Integral losses of CX ions generated by 17 keV NBI.

(a) Guiding Center calculations for H (blue) and D (black) loss fraction for the case with $B_{tor} = 0.35$ T.

(b) Larmor orbits calculations of fraction of particle losses for 4 H and D cases with $B_{tor} = 0.35, \; -0.35 \; 0.5, \; -0.5$ T.

Radial electric field development will affect equilibrium



(a) ***(b)*** ***(c)***

A sample of 32 lost H^+ 17 keV NBI particle orbits.

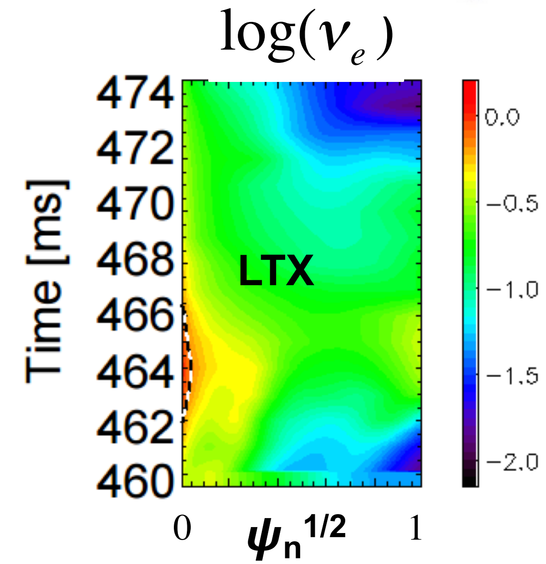
(a) $\phi^E = 0$ keV, all 32 trajectories are lost

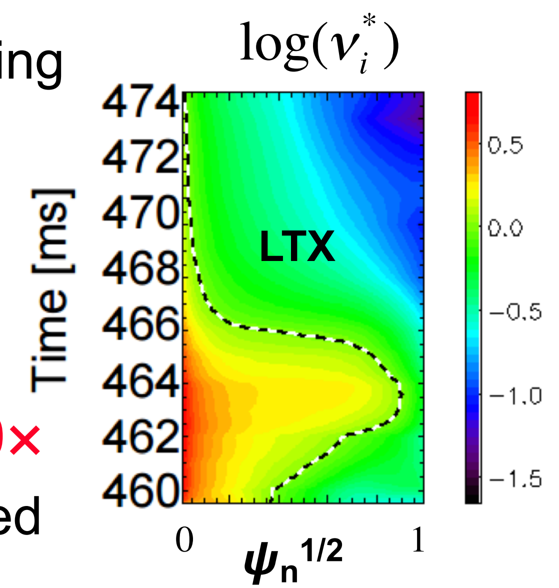
(b) $\phi^E = 2$ keV, also all 32 trajectories are lost;

(d) $\phi^E = 7$ keV, all 32 trajectories are confined;

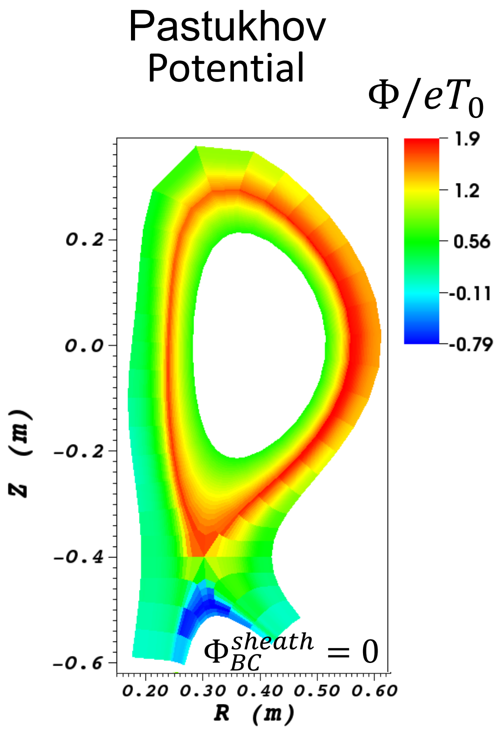
Low recycling SOL will be studied in LTX-β

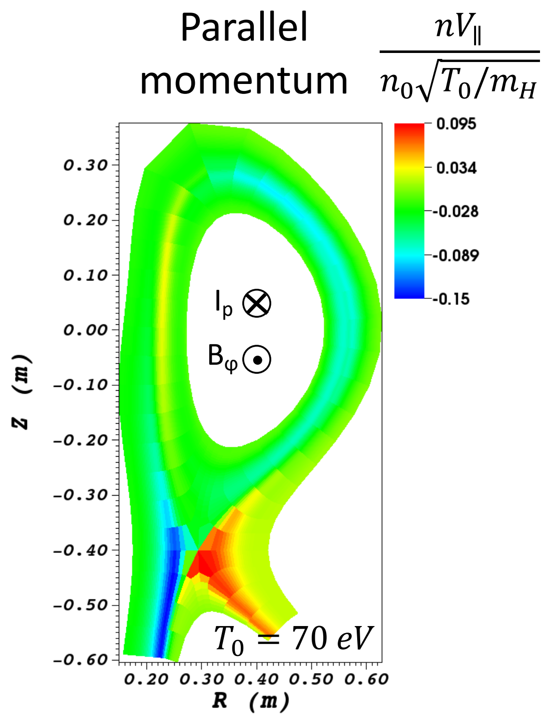
- SOL collisionality very low
  - SOL ν^* already <0.1 in LTX, <0.01 in a reactor
- Ion population trapped (confined in the SOL) or "passing" (within loss cone, transiting to the divertor)
  - $\Theta_{LC}=\sin^{-1}(1/R_{mirror})^{1/2}$
  - R_{mirror} here = B_{div}/B_{LFS}
- ⇨60 - 80% of an initially isotropic ion distribution trapped in the SOL
  - Can't access divertor without pitch-angle scattering
- Very hot SOL (~10 keV) in a reactor
  - λ_q (passing) ~ poloidal ion gyroradius: 10× increase
  - 10× reduction in peak heat load
- **Total drop in peak divertor heat flux: 25 – 50×**
  - Reduces requirements for Li inventory, flow speed

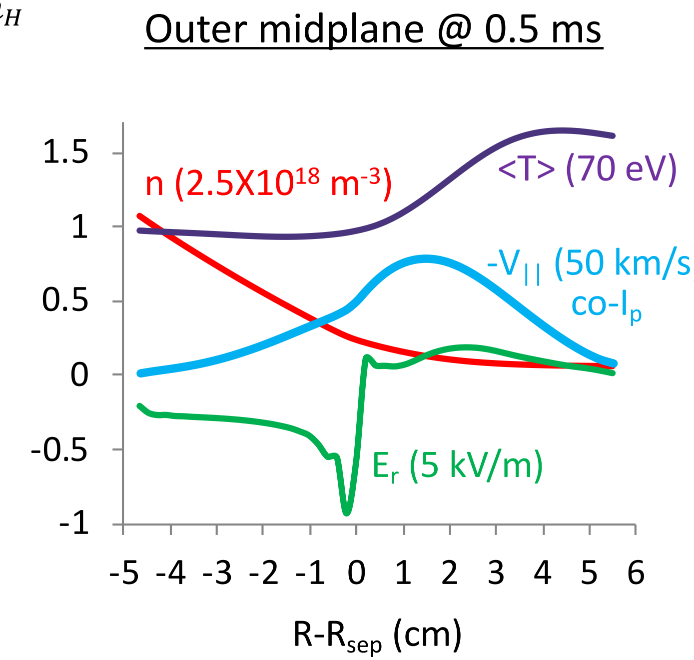




Illustrative edge modeling of an LTX-like discharge: no neutrals / strong magnetic bottle effect







- Full ion-ion Fokker-Planck collisions, $R_0/(V_{Ti}\tau_i) \sim 0.01$
- Absorbing divertor plates; zero-Neumann BCs on outer (SOL and PF) boundaries; Dirichlet BC on inner (core) boundary
- Grid resolution (core: $N_\psi = 24, N_\theta = 32, N_{v_\parallel} = 96, N_\mu = 96$)
- $B_\phi R = 0.08\ \mathrm{T\cdot m},\ B_\phi/B_\theta \sim 3$ (at the outer midplane), $m_i = m_H$

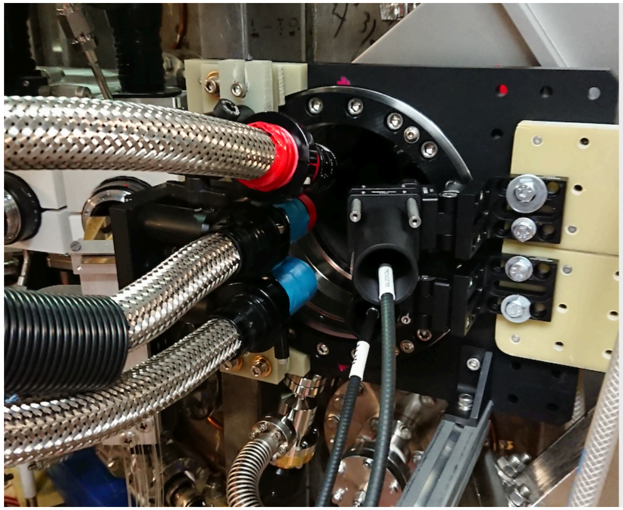
- Simple anomalous diffusion

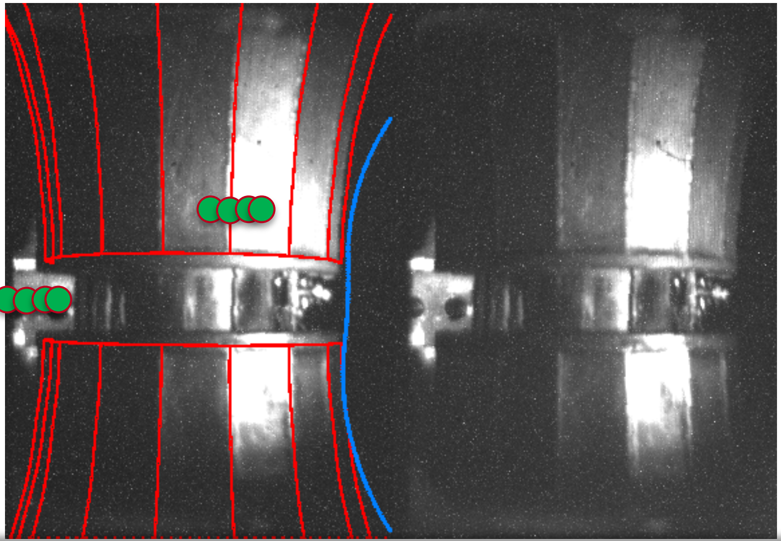
$$D_{AN}[f_i] = \nabla_\psi D(\psi)\nabla_\psi f_i$$
$$D_{AN} = 4\ m^2/s$$

M. Dorf (LLNL), COGENT modeling. PPPL XGC1 modeling in progress.

Spatially, spectrally resolved UV-VIS diagnostics enable analysis of plasma-limiter interaction

- Suite of spectroscopic diagnostics installed to support PMI studies:
  - Two fast cameras with 2-color adapters [Scotti RSI 2015] for imaging at 4 wavelengths (Li, O)
  - One fast camera for H-α imaging
  - High spectral resolution UV spectrometer (for T_i measurements) [Soukhanovskii RSI 2010]
  - High-throughput visible spectrometer for molecular spectroscopy [Bell, RSI 2010]
- Radial views aimed at HFS limiter
  - Shells consist of welded toroidal segments, limiters located at welds between segments



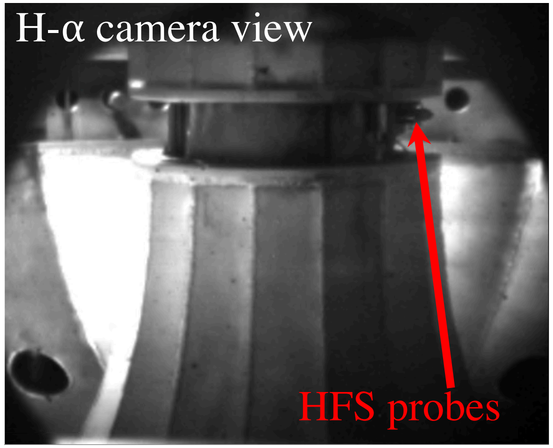


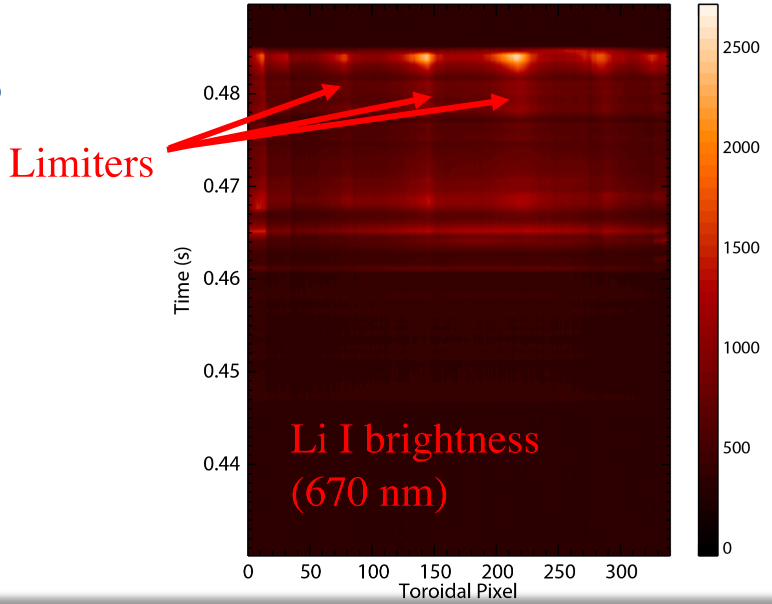
Radial camera views
Spectrometer views
Limiting shell edges

LLNL-PRES-791713
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Fuel recycling, lithium erosion studies planned as a function of lithium passivation and T_{surf}

- Recycling inferred from H-α camera and Ly-α diode on radial views + probes
- Lithium influx and sputtering yield Y_{Li}:
  - Changes in Y_{Li} with surface chemical state of lithium coatings (changes in SBE) -> LiH, Li_2O
  - Role of thermal sputtering vs evaporation for lithium influxes in LTX-β
- Oxygen influx and sputtering yield:
  - Measure oxygen sputtering/influx with oxidation of lithium coatings
  - Study impact of oxygen segregation within lithium coatings on oxygen influx and LTX-β high temperature operation





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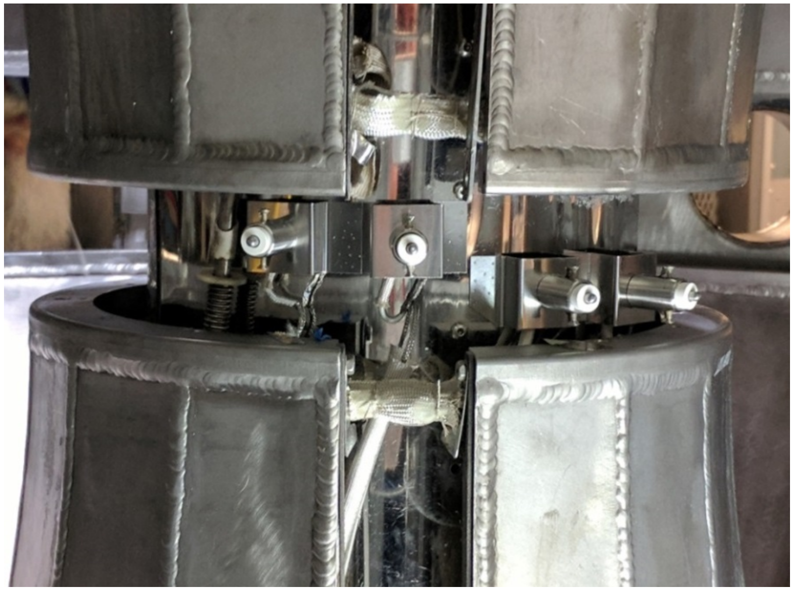
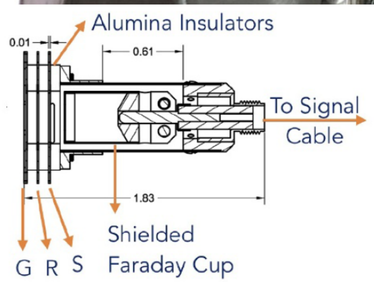
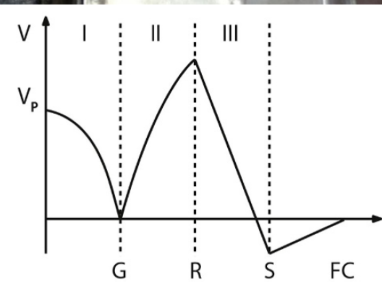
SOL diagnostics: Langmuir probes and RFEA





(a)



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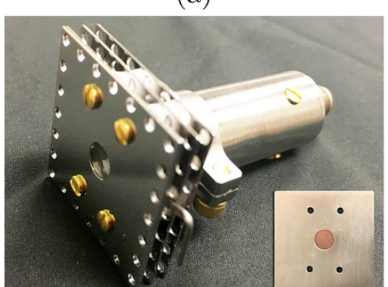
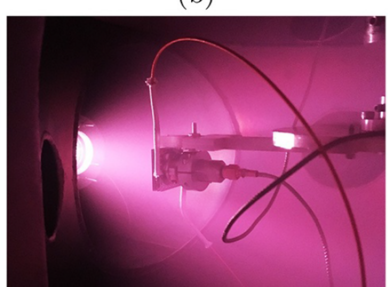
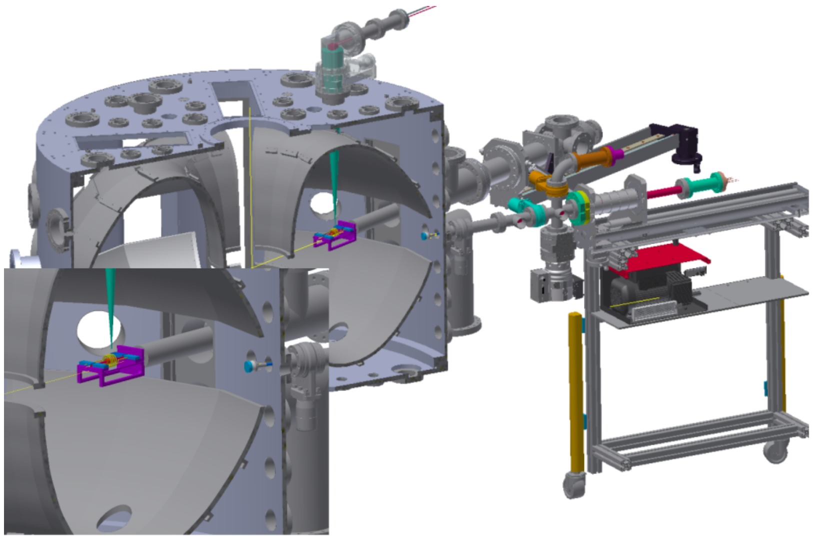


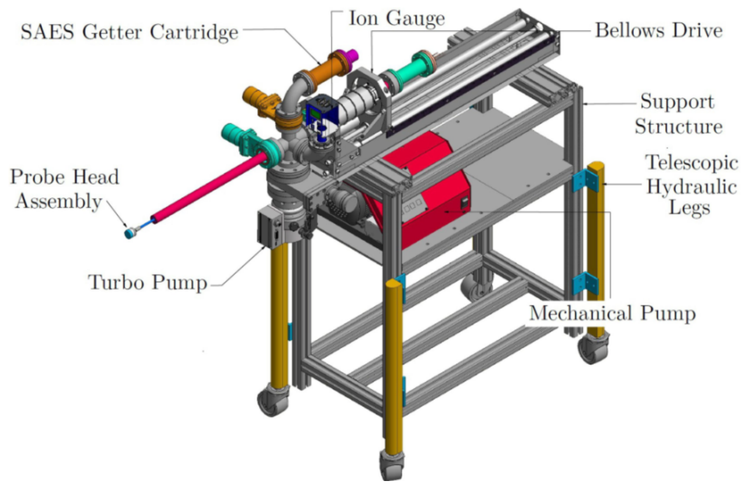


- SOL mirror confined
  - Electric fields not confined to sheaths
  - Loss rate determined by ion pitch angle scattering
  - Pastukhov potential $\varphi_p \sim 0.7\ T_e$ for LTX
  - SOL electric field should eject sputtered impurities
- High field side single Langmuir probes
- Low field side probe
- Retarding Field Energy Analyzer

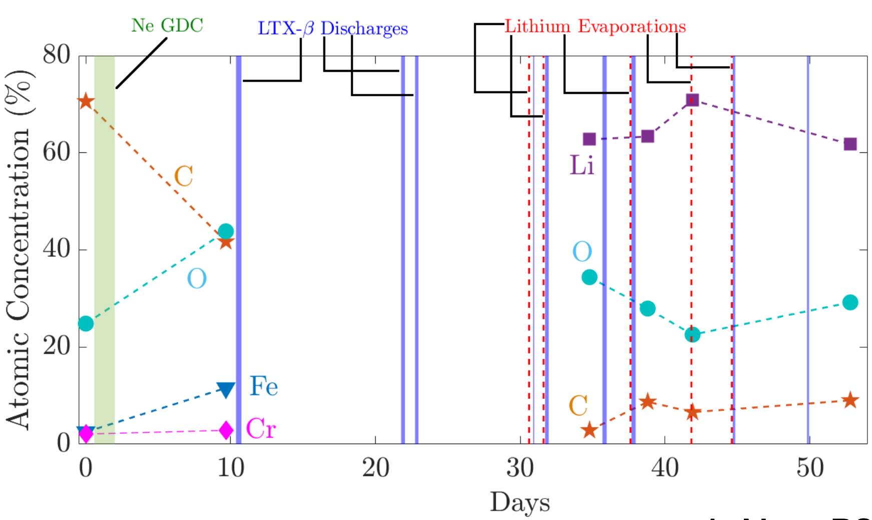
X. Zhang PSI/NME 2019

UT-K: Sample Exposure Probe for PMI study

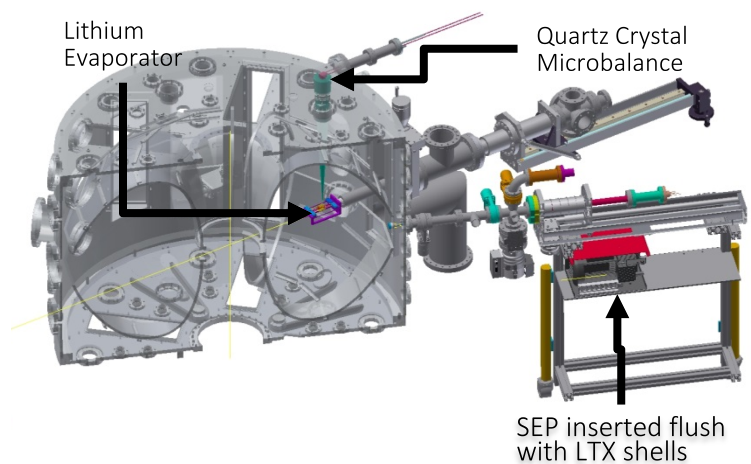




Exposed sample analyzed in adjacent Princeton University surface science lab



Mechanism for hydrogen retention in lithium PFCs explored on LTX-β with Sample Exposure Probe (SEP)



A. Maan RSI 2019; SOFE/IEEE 2019

Summary

- LTX-β, the upgrade to LTX, is now fully operational
  - Modest additional upgrades in progress
- Major component of upgrade – NBI – operating well
  - Modest beam fueling observed
  - Discharge development in progress
    - » No beam-injected flat T discharges yet
- New approach to lithium coatings implemented
  - Revamped large-capacity system to be installed in a few months
- Thomson scattering and CHERs both operational
- Research goal for this FY: characterize confinement with NBI as a function of recycling
- Focus on SOL studies to follow
  - Modeling effort is now underway