Flat temperature profiles and the implications of very high edge temperatures in LTX

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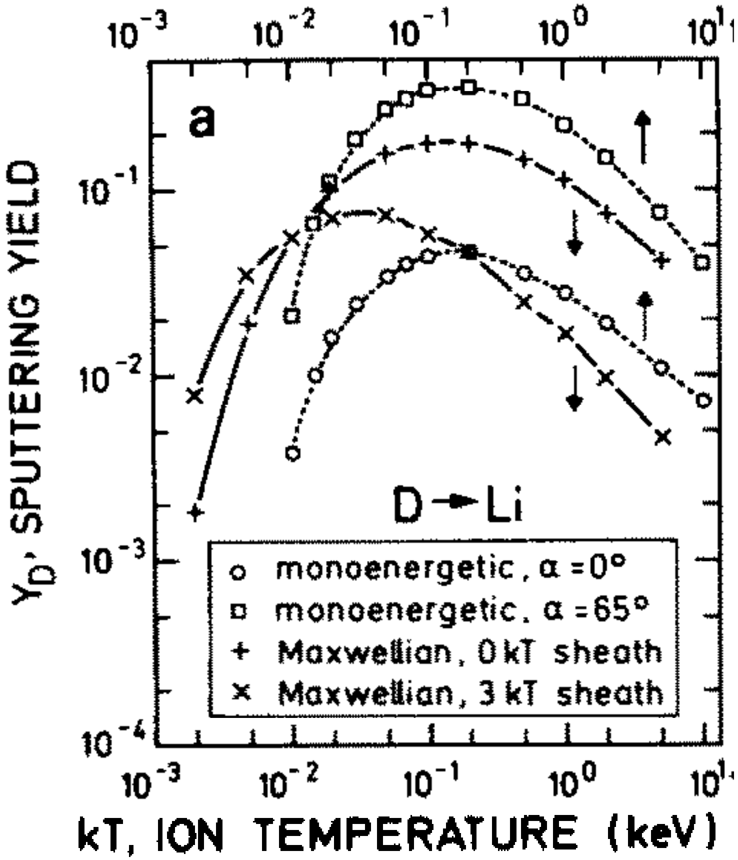
Outline

- Hot edge plasmas for enhanced tokamak performance
  - Alternative to high recycling edge, with tungsten PFCs
  - Compatibility of lithium PFCs with hot, low density edge plasmas
  - Innovative edge rather than magnetic configuration
- Recent progress on LTX toward an evaluation of lithium walls for fusion
  - Achievement of flat electron temperature profiles
  - Extends to the LCFS, and into the near SOL
- Upgrade plans for LTX
- Summary

Hot edge plasmas for enhanced tokamak performance

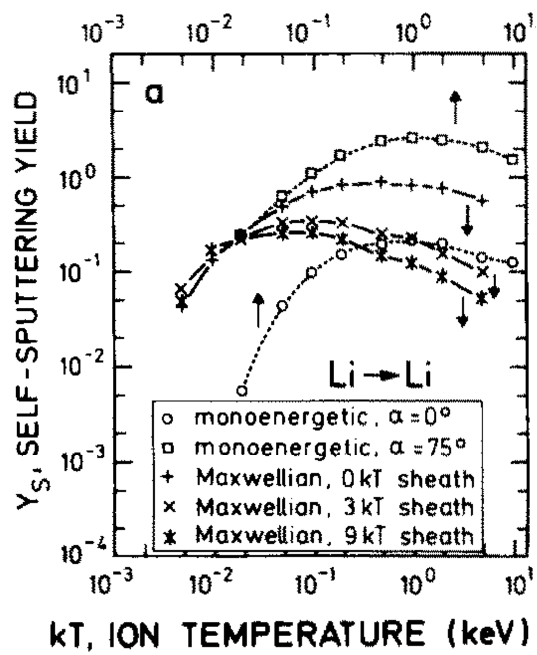
- Current approach to plasma-material interactions (PMI) is to strongly cool the plasma edge by recycling, gas injection, and radiation
  - Ensure edge particle energies are *below* the sputtering threshold
  - Compatible with high recycling edge, high Z materials
  - But: performance impacted (JET, ASDEX, C-mod w/o boronization)
- Low recycling walls result in a very hot, low density edge
  - Inconsistent with gas puffing to cool edge
- Low Z liquid lithium PFCs provide alternative PMI approach
  - Hot, low density edge - particle energies *above* the sputtering peak
    - » No damage to the liquid PFC
  - Compatible with low recycling operation
- Hot edge enables enhanced fusion performance
  - Access to new regimes

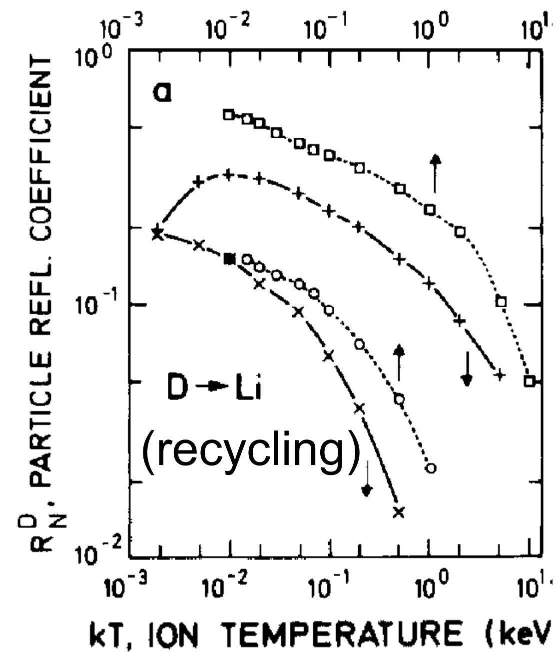
Sputtering characteristics of lithium PFCs compatible with a hot, low density edge



- At T_i ~ 10 keV ion sputtering yield for D on lithium is less than 1%
  - Comparable to yield for a ***1 eV*** plasma

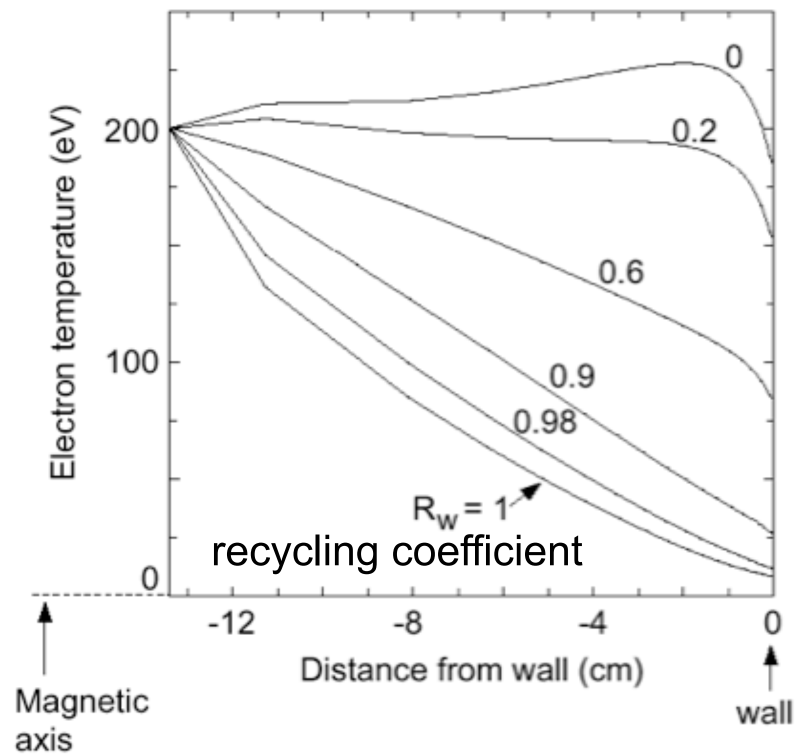
- Sputtering for D incident on Li peaks at 100-200 eV (J. Laszlo and W. Eckstein, J. Nuc. Mater. 184(1991)22)
- At 700 eV the yield is 9%. Yield similar for D, H
- Fraction of lithium sputtered as an ion increases with energy
- Self-sputtering of Li on Li also drops with energy
- Reflection of D from Li drops





Expect T(a) ~ T(0) with low recycling wall

- Edge temperatures predicted to be comparable to core with low recycling lithium walls
  - » Krasheninnikov, Zakharov, Pereverzev (Phys. Plasmas **10**, 1678 (2003)
- High edge T_e, T_i a consequence of low recycling boundary conditions, *not transpo*
  - – Hot core particles transported to wall without mixing with a cold population
  - – Temperature profile *always* flat
    - » Independent of particle transport
  - – NB fueling of the core should produce hot particle distributions (Zakharov):



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

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

- 1-2 keV edge temperatures expected for LTX with NBI, partial gas fueling

Confinement *without* temperature gradients is fundamentally a new plasma regime

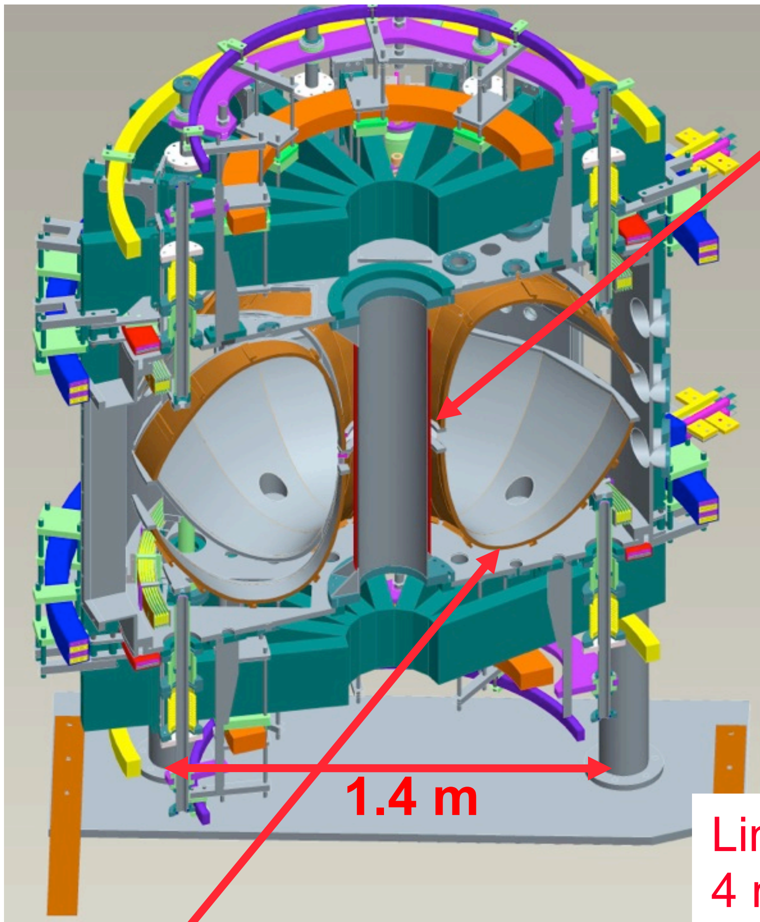
- Innovative confinement concepts have focused on magnetic configurations
- A nonrecycling wall produces a change in the *boundary* conditions
  - Reflecting (conventional) vs. absorbing (low recycling, lithium) wall
- Tokamak example:
  - For high aspect ratio (conventional) ohmic tokamaks
    - » Peaked T profile produces a current profile which peaks on-axis.
    - » *Flat* T profile, peaked n profile produces a <u>hollow</u> current profile.
- Example of tokamak equilibrium *without* temperature gradient –

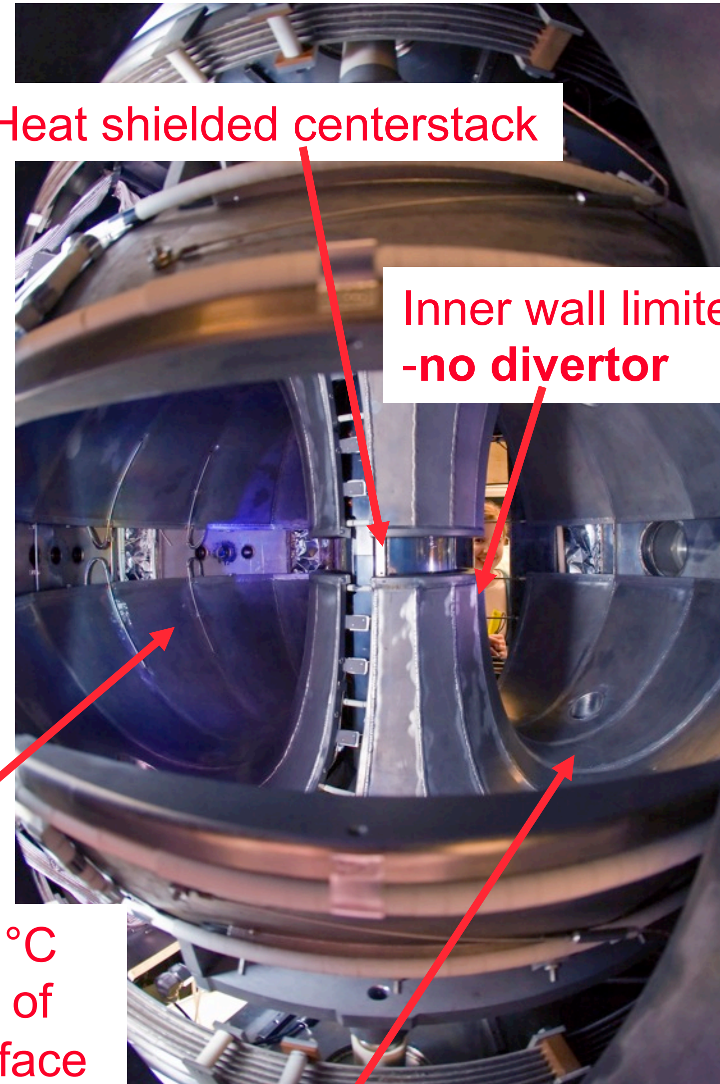
"Isomak" (P. J. Catto and R. D. Hazeltine, Phys. Plasmas **13** (2006) 122508)
  - Very weak transport
    - » No perpendicular ion heat flux
    - » Off-diagonal electron heat flux remains
  - Rigid body ion toroidal rotation
  - Diamagnetic current is finite on axis
  - Density profile exponential in poloidal flux
    - » Thermodynamic equilibrium
  - Radial electrostatic potential proportional to the poloidal flux

LTX

- Small, low aspect ratio tokamak
  - R_0 = 40 cm, a = 26 cm, κ = 1.55, δ = 0.2
  - B_{tor} < 1.7 kG
  - I_p < 100 kA
- Limited, not diverted
  - Conformal wall
  - Typically wall-limited on the high field side
- Ohmic only; no auxiliary heating at present
- Pulse length typically ~50 msec
- Operated in hydrogen
  - Fueled from the high field side midplane

All plasma-facing surfaces are lithium coated





Heat shielded centerstack

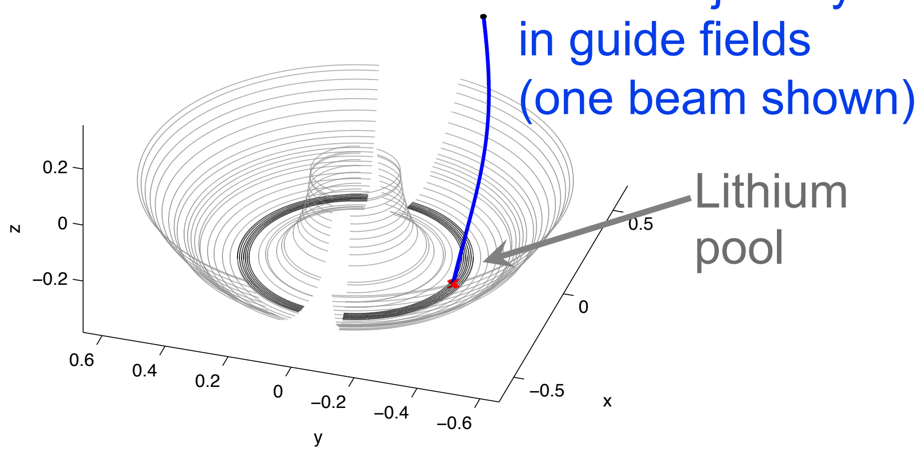
Inner wall limited
-no divertor

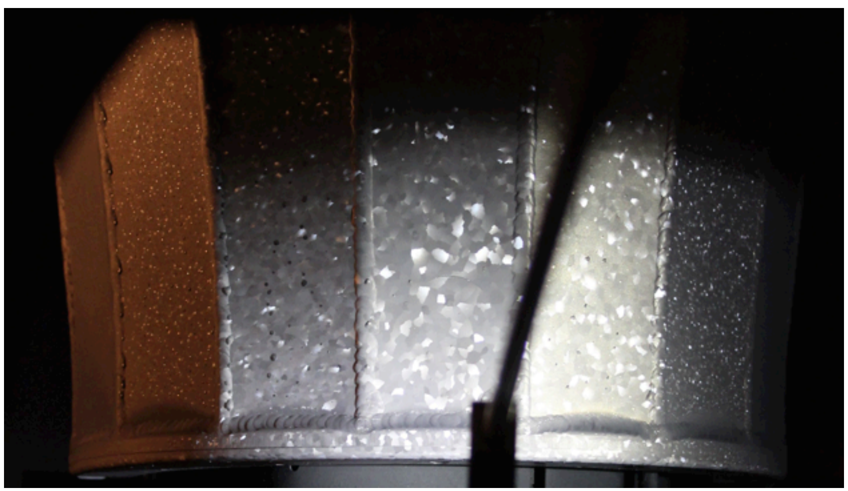
Liner >300 °C
4 m^2 - 80% of
plasma surface

Inner heated shell (304L stainless steel on copper)

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

Electron beam-based lithium evaporation system yields clean, metallic lithium wall coatings



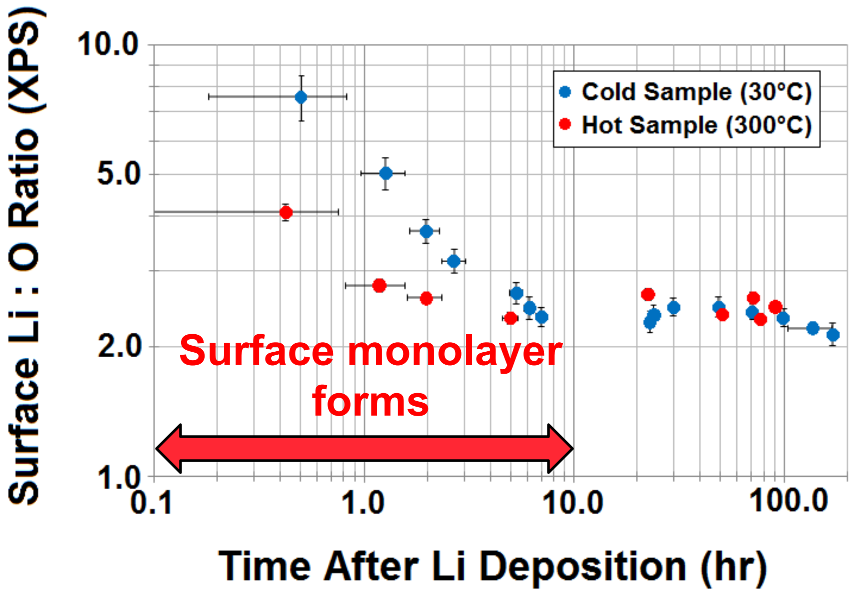


“Spangle” pattern on solidified lithium indicative of clean metallic coating

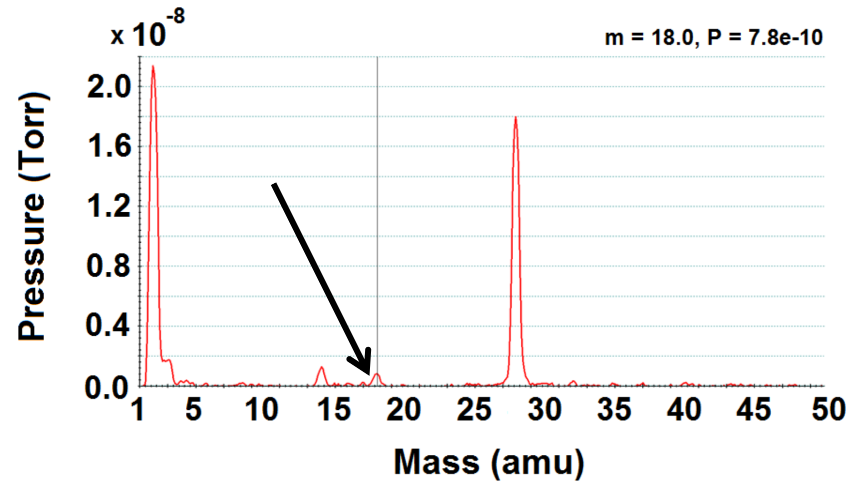
- Preheat shells to ~320 °C
- Establish ~70 G guide magnetic field
- E-beam heat lithium pools to >450 °C
  - 500 – 1000 Å coating
- Maintain ~300 °C shell temperature
  - Liquid lithium experiments
- Shell heaters off for solid lithium

Surface condition of lithium PFCs largely determined by base vacuum

Surface Evolution in LTX Base Vacuum



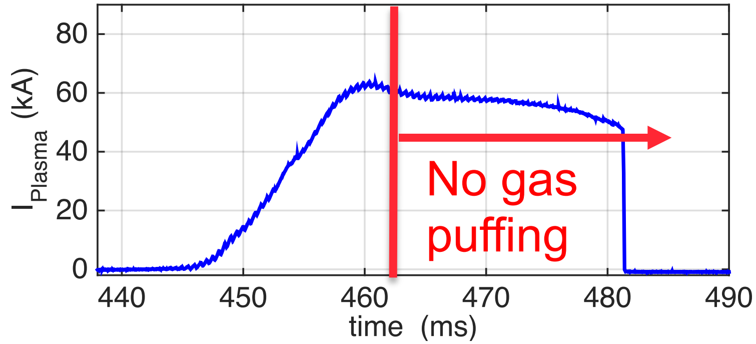
Base Pressure RGA Spectrum

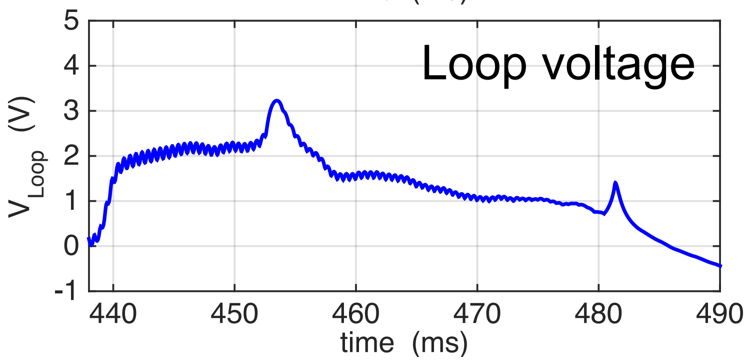


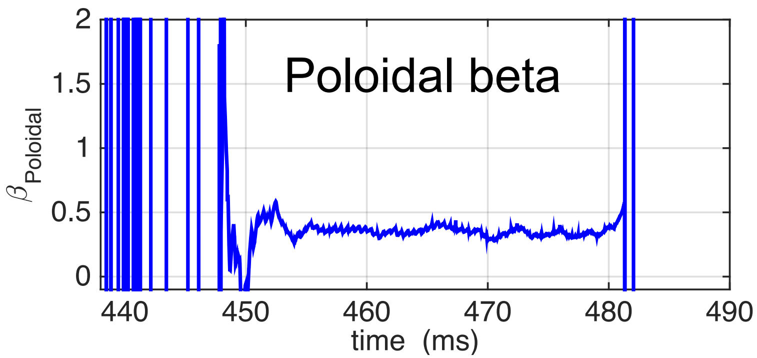
- Analysis with the UIUC MAPP probe
  - X-ray Photoelectron Spectroscopy (XPS)
- Li:O ratio initially high
- Ratios asymptotes to 2:1
  - Indicates Li_2O, not LiOH is formed in LTX
- Timescale of surface evolution suggests between-shots coating capability should produce more metallic coatings

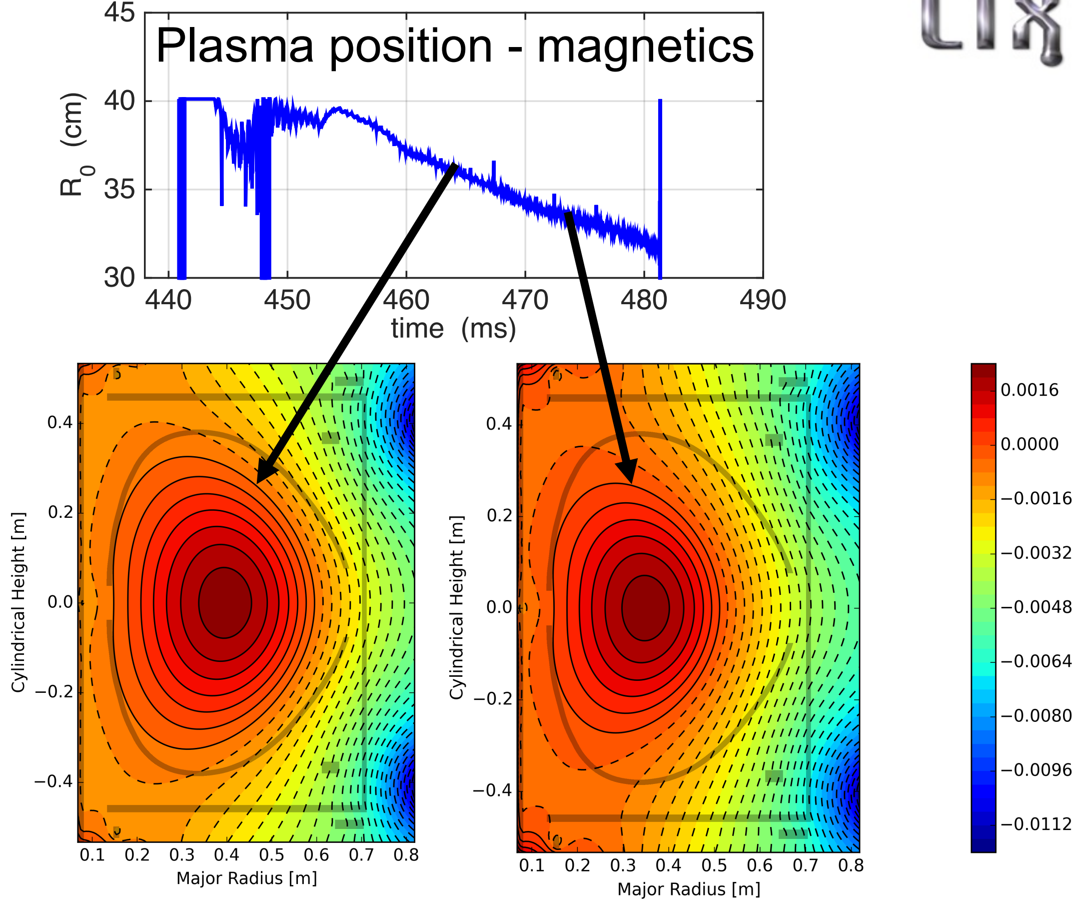
- Background water 5-9 × 10^{-10} Torr
- Oxygen 1-2 x 10^{-10} Torr
- Hydrogen dominates RGA spectrum
  - Total pressure <2×10^{-8} Torr
- Clear benefit from further reduction in base pressure

Recent experiments greatly reduce edge neutrals in LTX by termination of gas puffing



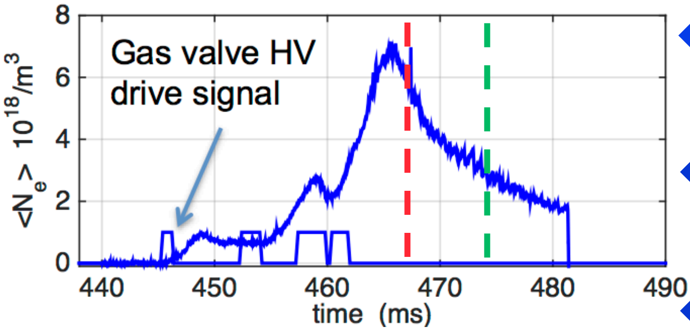




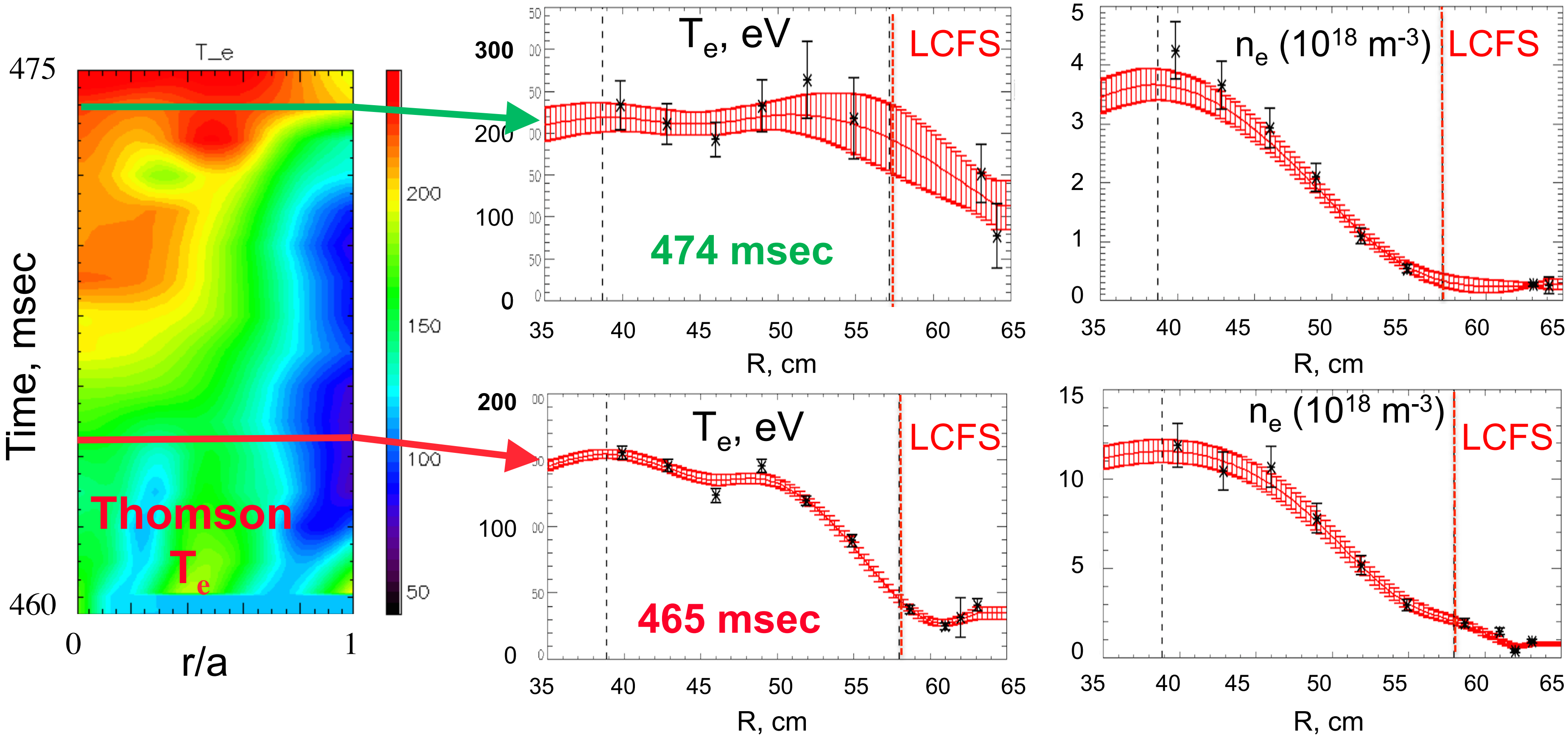


- Plasma axis drifts inward during current flattop
- Energy confinement: 1-2×ITER98P(y,2)
  - Equilibria reconstructed with PSI-TRI code (C. Hansen, U. Wash., & J. Schmitt, P2.019)

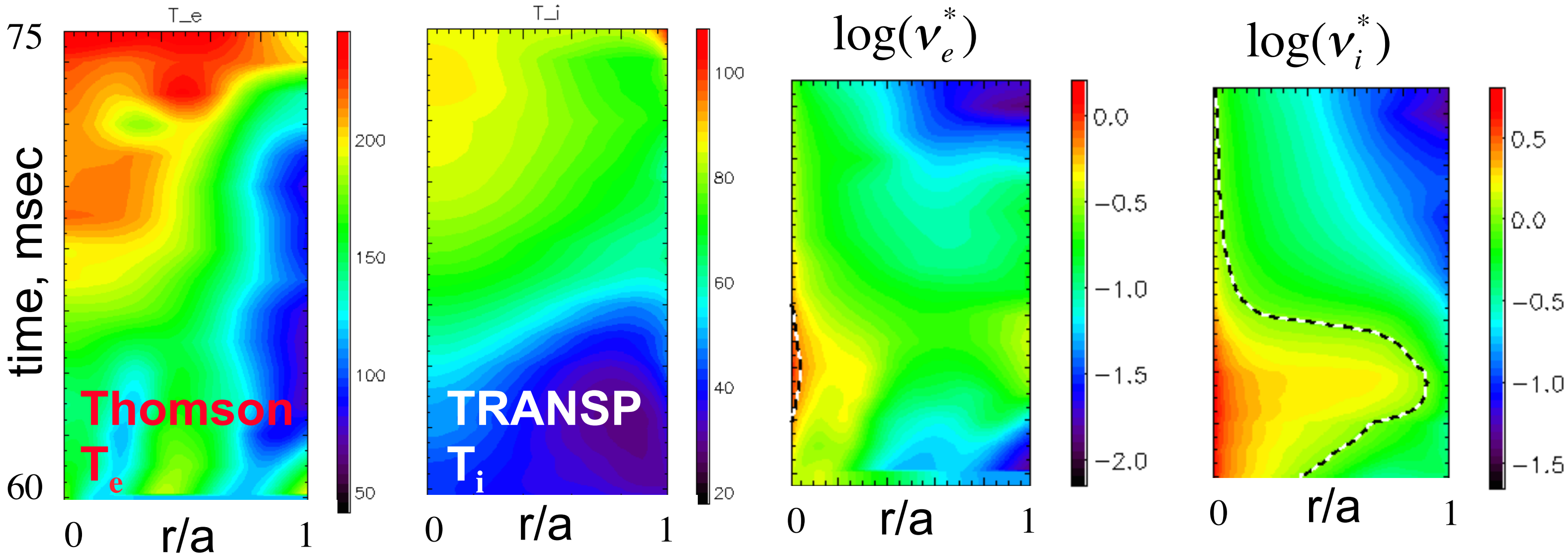
Flat electron temperature profile develops in LTX when edge neutral pressure drops

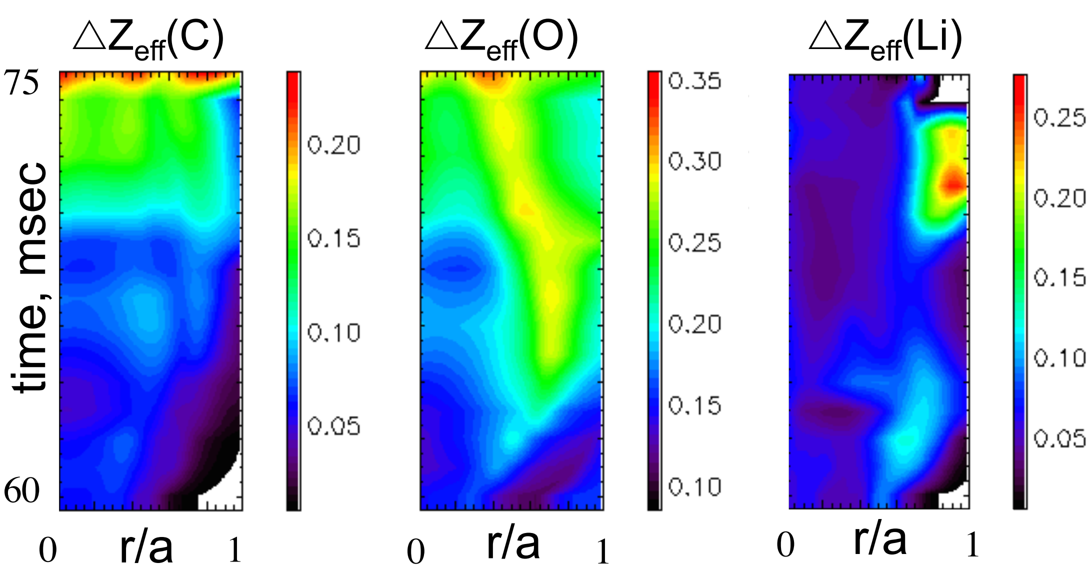


- Fueling (centerstack) terminated at 462 msec
  - ~3-4 msec required to clear gas from duct
- Thomson scattering time stepped through discharge
  - Series of 60 identical discharges
- Note: LCFS maps to HFS wall



Low impurity levels persist without fueling, with a hot edge, in low density, low collisionality plasmas

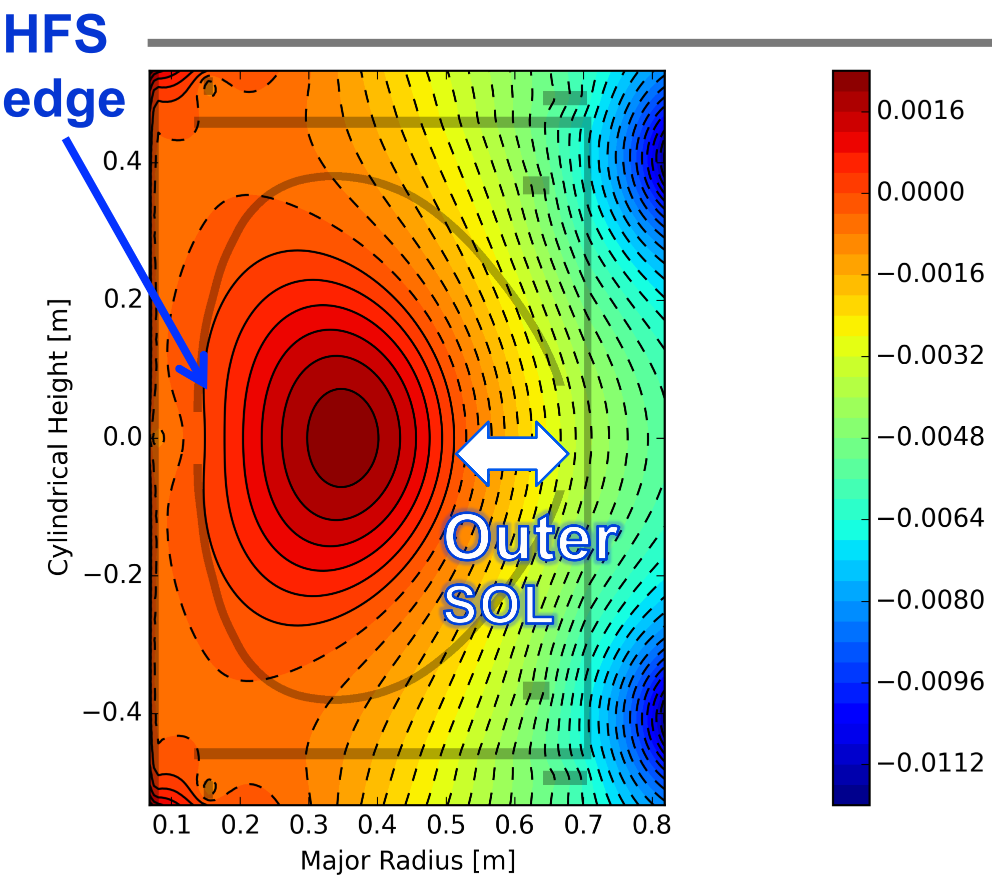




- Very low collisionality
- Low impurities
  - Z_{eff} ~ 1.2 - 1.5
  - Sputtering yield should not increase for further increases in edge energy

- Neutral pressure < 10^{-5} Torr ⇨ mean free path for ion-neutral CX ~ 1 km

LTX SOL dominated by kinetic effects



PSI-TRI reconstruction

- Plasma is limited in HFS equatorial plane
- Significant mirror ratio (4-5) from LFS to HFS
- Large banana orbits ensure broad outer SOL
- Trapped ions within the LCFS are also trapped in the SOL
  - LTX is an ST ~ 85% of the ions in the edge trapped
- CX losses negligible
- Low $n_e(a) \sim 2\text{-}3 \times 10^{17}\ m^{-3}$

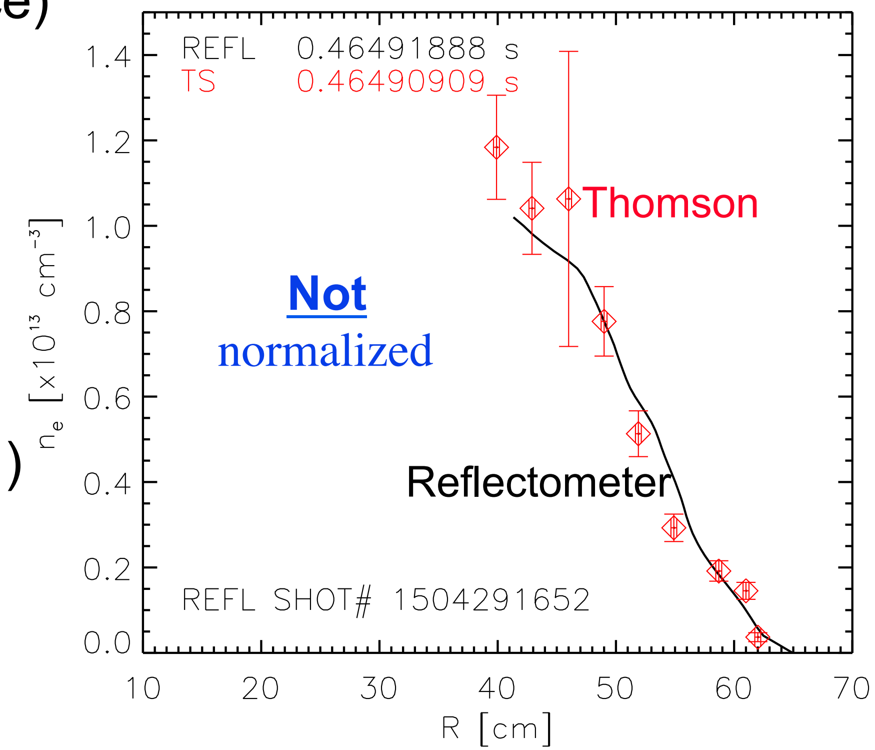
- Ions lost along field lines in the SOL by pitch angle scattering
  - τ_{ii} > 1 msec. >> L_{conn}/C_s – flow at the sound speed (<100 μsec)
- **Power losses in the near SOL are very modest, despite very hot edge**
  - Very high potential in the SOL may help eject impurity ions (e.g. lithium)

LTX-Upgrade

- Installation of neutral beam injection system. Components:
  - Higher toroidal field
  - Higher plasma current, longer flattop
  - Neutral beam and power supplies (ORNL help)
- Lithium plasma-facing surface improvements:
  - Better pumping and baking
  - Elimination of residual vacuum leaks
  - Remote electron beam operation for between-shots coating capability
- Expanded diagnostics
  - See J. Schmitt, P2.019

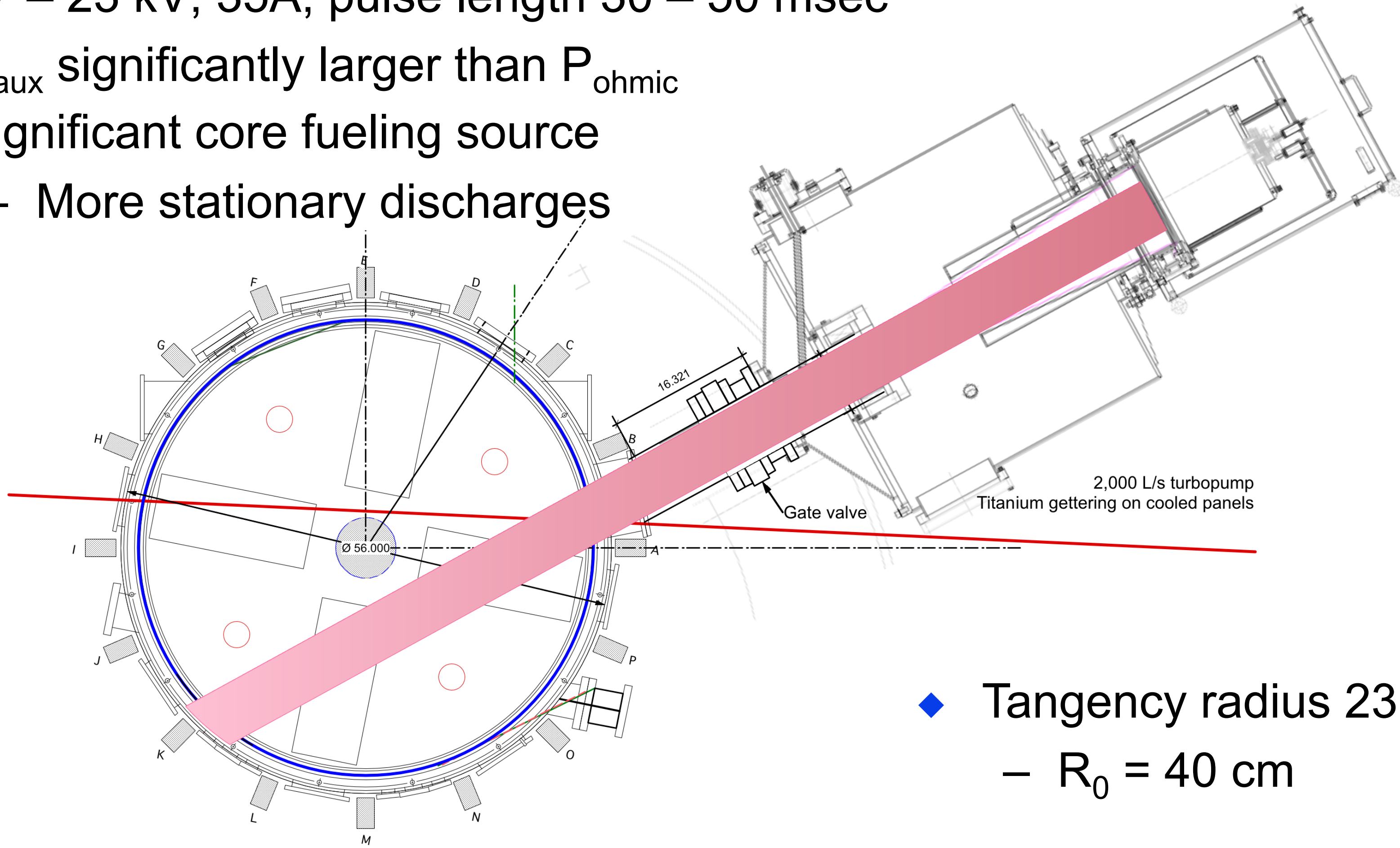
LTX-U will be a collaborative effort

- ORNL is the major collaborator (T. Biewer, M. Reinke, J. Canik)
  - All beam-based diagnostics: Lithium CHERs for ion temperature measurements, plasma rotation
  - Modeling (beam torque balance)
- UCLA (S. Kubota, T. Peebles)
  - 1 mm interferometer
  - Profile reflectometry
  - Electrostatic fluctuations
- Magnetic reconstructions:
  - C. Hansen, U. Wash. (PSI-TRI)
  - J. Bialek, Columbia U.
- Surface science:
  - D. Donovan, U. Tenn.
  - B. Koel, Princeton U.
- Spectroscopy:
  - P. Beiersdorfer, LLNL (VUV)



Neutral beam will extend lithium wall studies in LTX
2 NBI systems on loan from Tri-Alpha Energy

- 17 – 23 kV, 35A, pulse length 30 – 50 msec
- P_{aux} significantly larger than P_{ohmic}
- Significant core fueling source
  - More stationary discharges



- Tangency radius 23 cm
  - R_0 = 40 cm

- 700 kW beam will also provide large toroidal momentum input
  - Beams are onsite, assembly has begun

Summary

- Low recycling liquid lithium PFCs *produce* a hot edge
- Low-Z liquid lithium PFCs will *tolerate* a hot, low density edge
- Isothermal plasmas are a new confinement concept
  - Not a variant in the magnetic field configuration
  - Distinct thermodynamic state
    - No ion conduction losses
- Accessible in a relatively small device like LTX