Progress toward LTX-β

Dick Majeski

with:

R. E. Bell, D. P. Boyle, P. E. Hughes, R. Kaita, T. Kozub, E. Merino, J. Schmitt*, X. Zang, *PPPL* (*Presently at Auburn U.)

T. Biewer, J. M. Canik, D. B. Elliott, M. Reinke, *ORNL*

J. Bialek, *Columbia University*

C. Hansen, T. Jarboe, *University of Washington*

S. Kubota, T. Rhodes, *UCLA*

M. A. Dorf, T. Rognlien, F. Scotti, V. Soukhanovskii, *LLNL*

L. Buzi, B. E. Koel, *Princeton U.*

D. Donovan, A. Maan, *U. Tennessee*

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Introduction

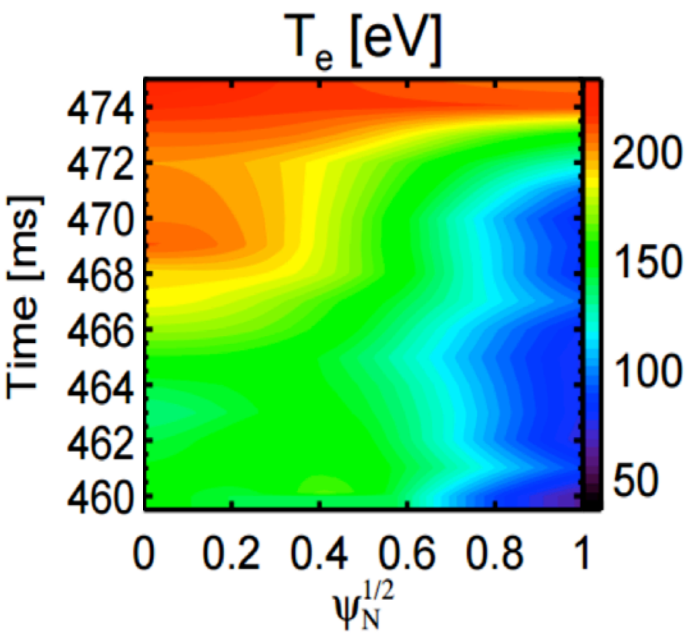
- Experiments on LTX demonstrated benefits of lithium walls for the low aspect ratio tokamak
  - Increased confinement
    - » Especially electron confinement
    - » Without steep edge pressure gradients
  - Low Z_{eff}, even with full liquid lithium walls
  - Broadened scrape-off layer
- But: LTX lacked auxiliary heating (ion or electron channel)
- Results were transitory – required termination of fueling
- Cause of improved confinement could only be inferred

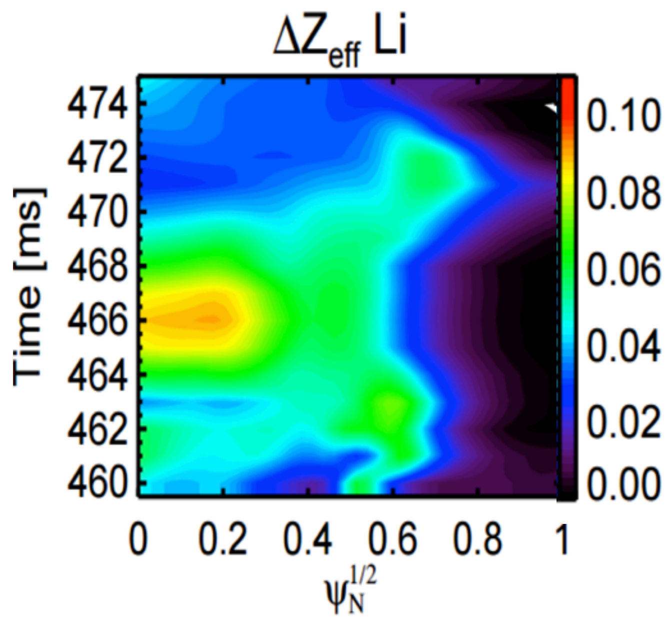
- Upgrade to LTX-β designed to address remaining issues
- Results from LTX-β should provide a basis for lithium wall experiments on NSTX-U

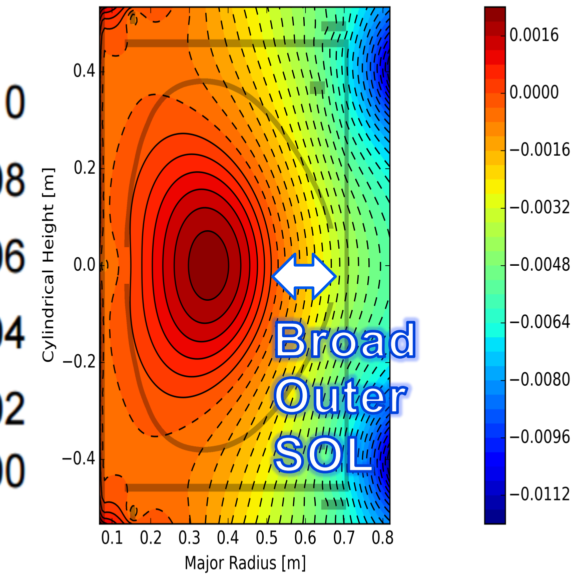
Liquid lithium walls reinvent ST fusion

⇨A lithium ST reduces core plasma volume by 10× or more

- Results from the Lithium Tokamak eXperiment (LTX)





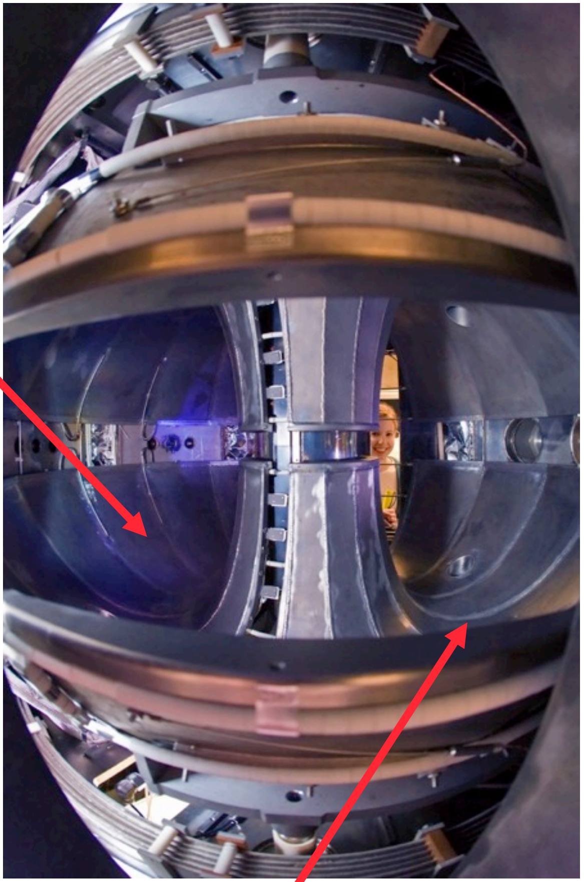


LTX SOL

- *Isothermal* plasmas eliminate ∇T-driven thermal conduction, turbulence
  - Only ∇n remains
- *Reduced* sputtering at high ion energy
  - *Compatible with a very hot edge*
- Hot edge *reduces* peak heat loads
  - *Power is spread*
  - *Higher power density core*

LTX wall: metallic lithium coatings on high-Z

- Low aspect ratio tokamak
  - R_0 = 40 cm, a = 26 cm, κ = 1.6, δ = 0.2
  - B_{tor} < 1.7 kG
  - I_p < 100 kA
- Limited by a conformal wall
  - High-Z wall-limited on the high field side
- Wall is fully coated with lithium
  - One coating applied at the start of a run
  - 100 nm coatings stop ions
- Ohmic only; no auxiliary heating
- Pulse length < 50 msec
- Operated in hydrogen
  - Gas puffing the only fueling source
  - Fueled from the HFS midplane



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

Inner high-Z heated shell (304L SS/Cu) Bottom of shells form reservoir - **up to 300 cm^3** liquid lithium

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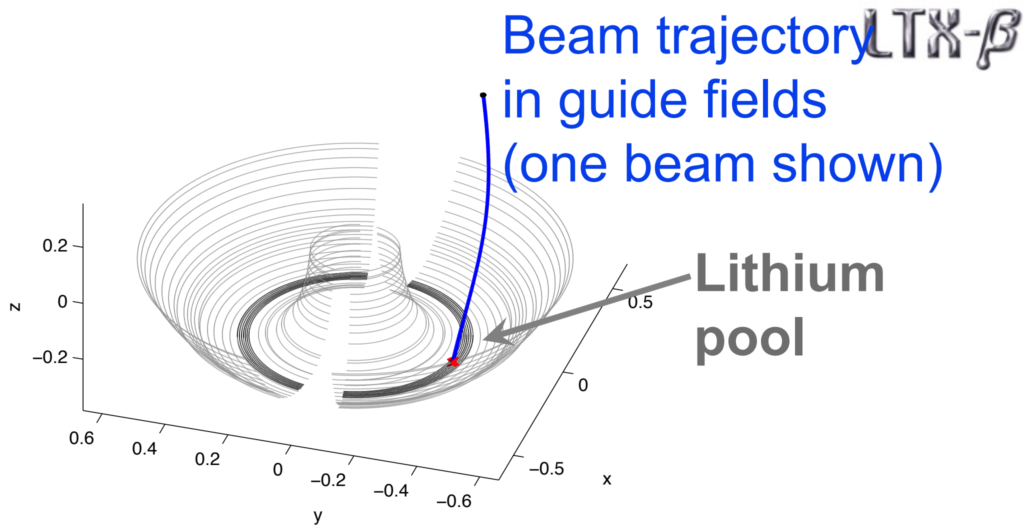
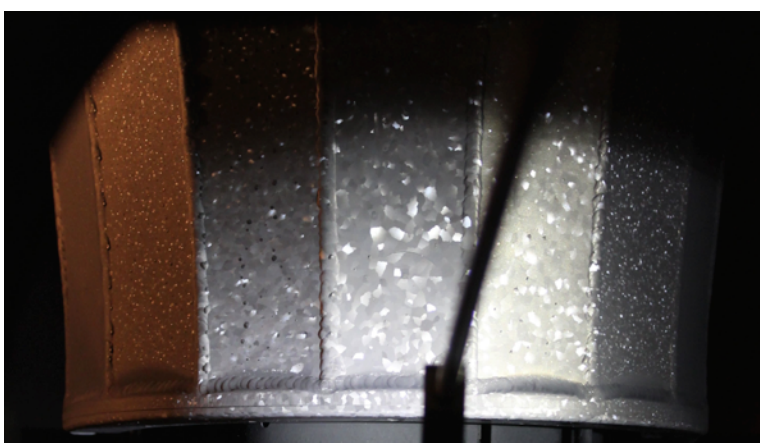
Lithium evaporation system uses shell heaters + two electron guns



- Electron gun – 1-2 kW



- Lithium coating on centerpost

- Difficult to deposit more than one layer of lithium in a day – no between shots coating
- Electron beams magnetically guided by low (~70 G) quasi steady-state magnetic fields
  - 10-20 minute operational cycle
  - Lithium pool must be preheated
    - » Long heating, cooling cycle
- 4 m^2 plasma-facing surface
  - Coating 10's – 100 nm thick

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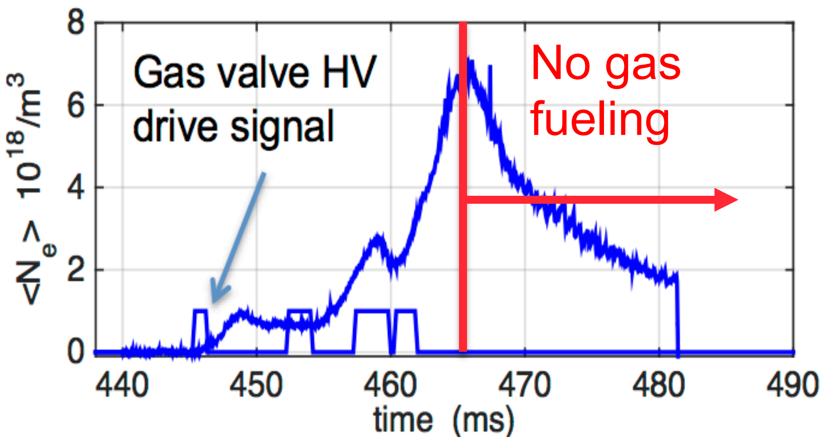
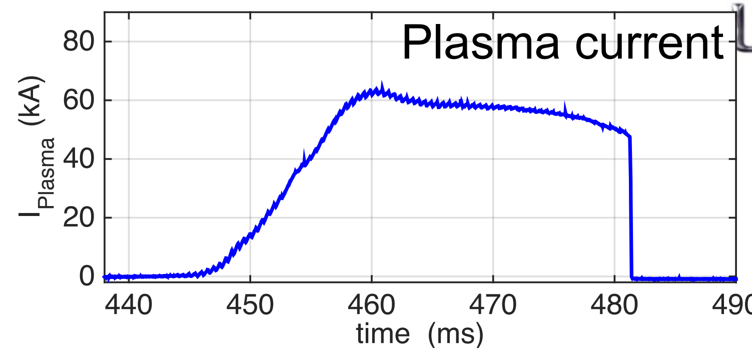
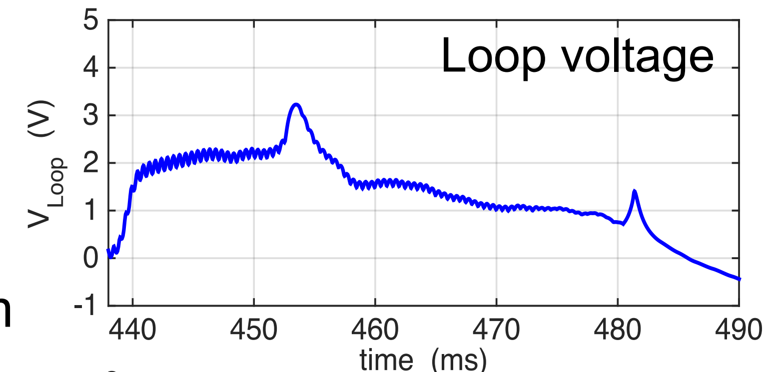
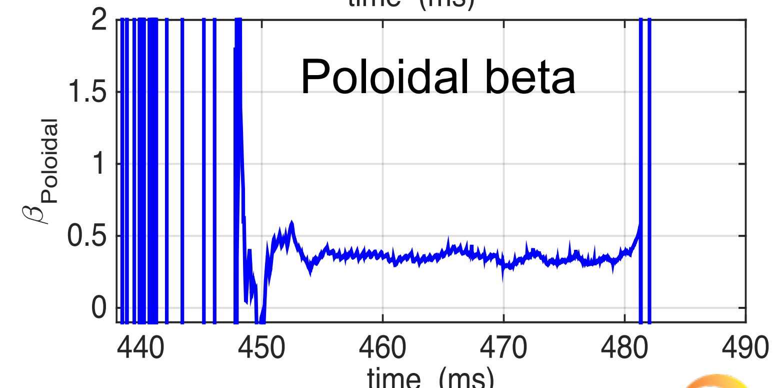
Low recycling with core fueling could only be simulated with transient gas puffing



- Fueling (from centerstack) terminated at 462 msec
  ~3-4 msec required to clear gas from nozzle
- Discharge operated on accumulated particle inventory after that
- Thomson scattering time is stepped through the discharge
  - Dataset of 55 identical discharges
  - Average ~ 5 discharges/time





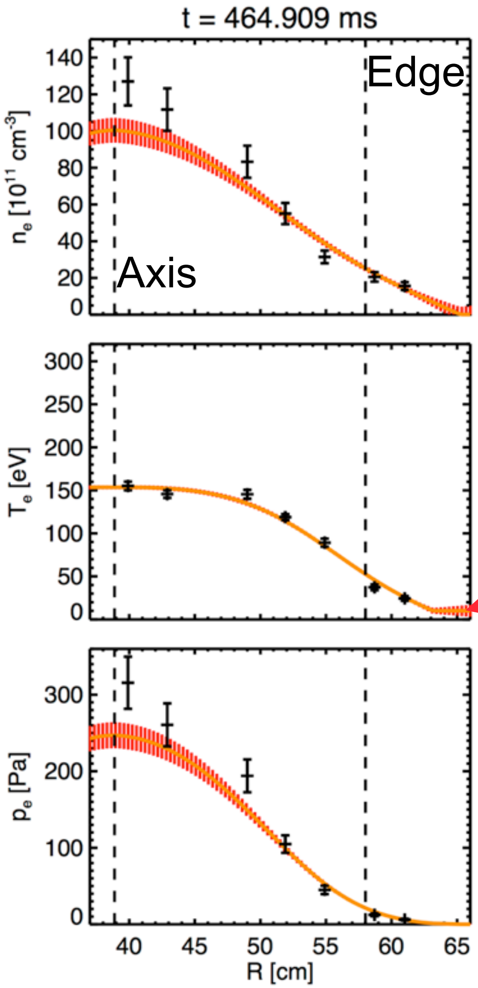


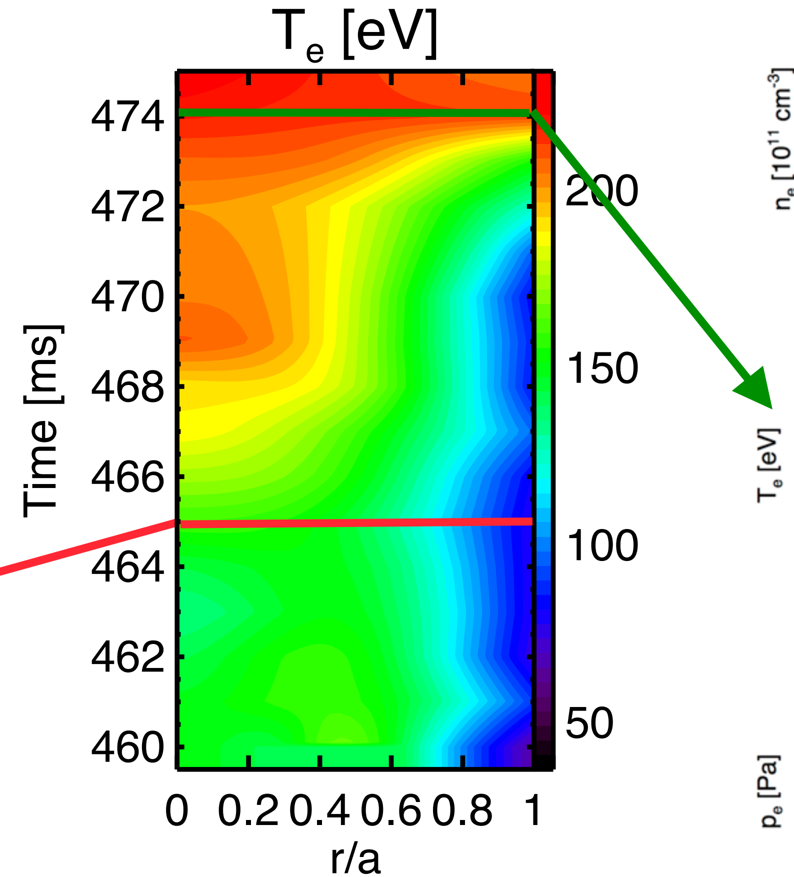
- Energy confinement ~ ITER98P(y,2)

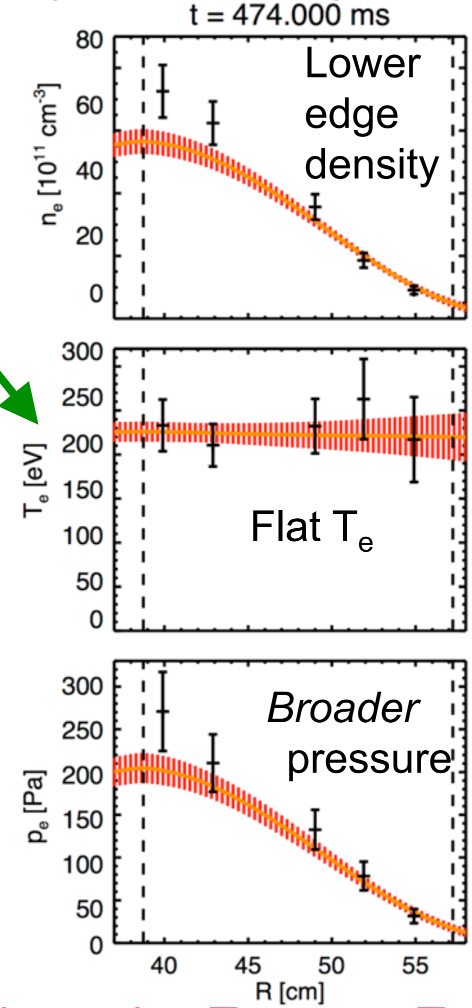
Lithium walls + gas turn-off allowed demonstration of flat electron temperature profiles – not steady-state

- Early in discharge:
  - Lithium suppresses recycling
  - But: gas puffing to raise density

- Late in discharge:
  - Lithium suppresses recycling
  - No gas from puffing



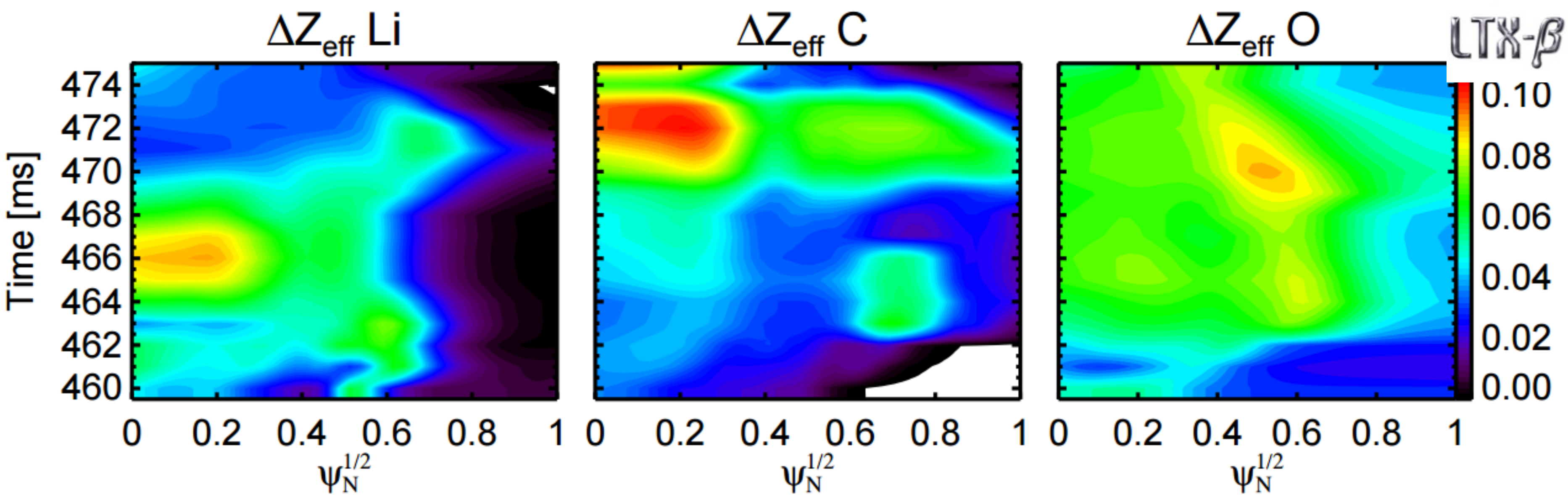




- Ion temperature profile not well known

- Gas puffing cools edge
- No cooling: edge T_e = core T_e

Lithium did not significantly dilute core plasma or radiate power



- Lithium impurity <2-3%
  - Modest radiation losses compared to tungsten walls
  - $Z_{effective}$ remains below 1.2
- Lithium influx will <u>decrease</u> with further energy increases
- But: could not directly measure core lithium concentration
  - Fully ionized in the core
- Radiated power only inferred from line radiation
  - No bolometer array

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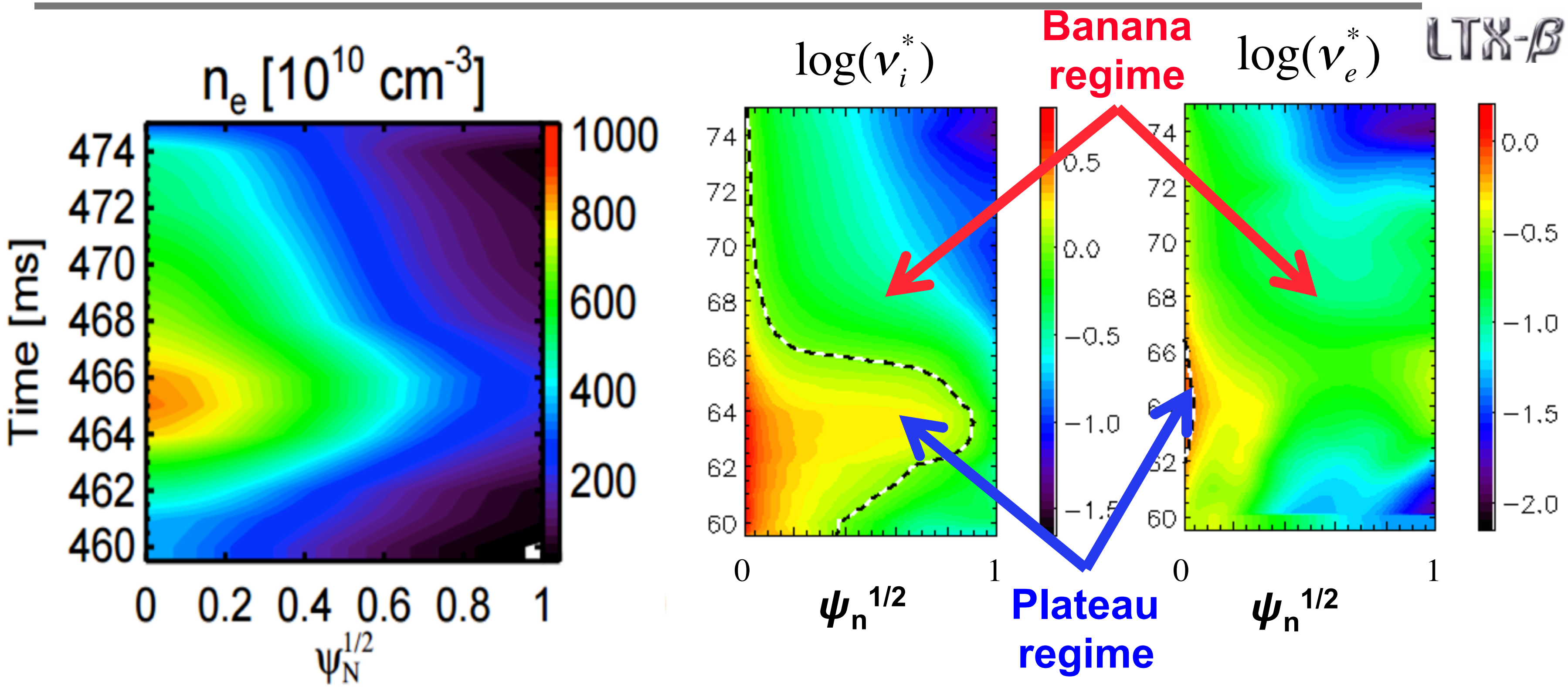
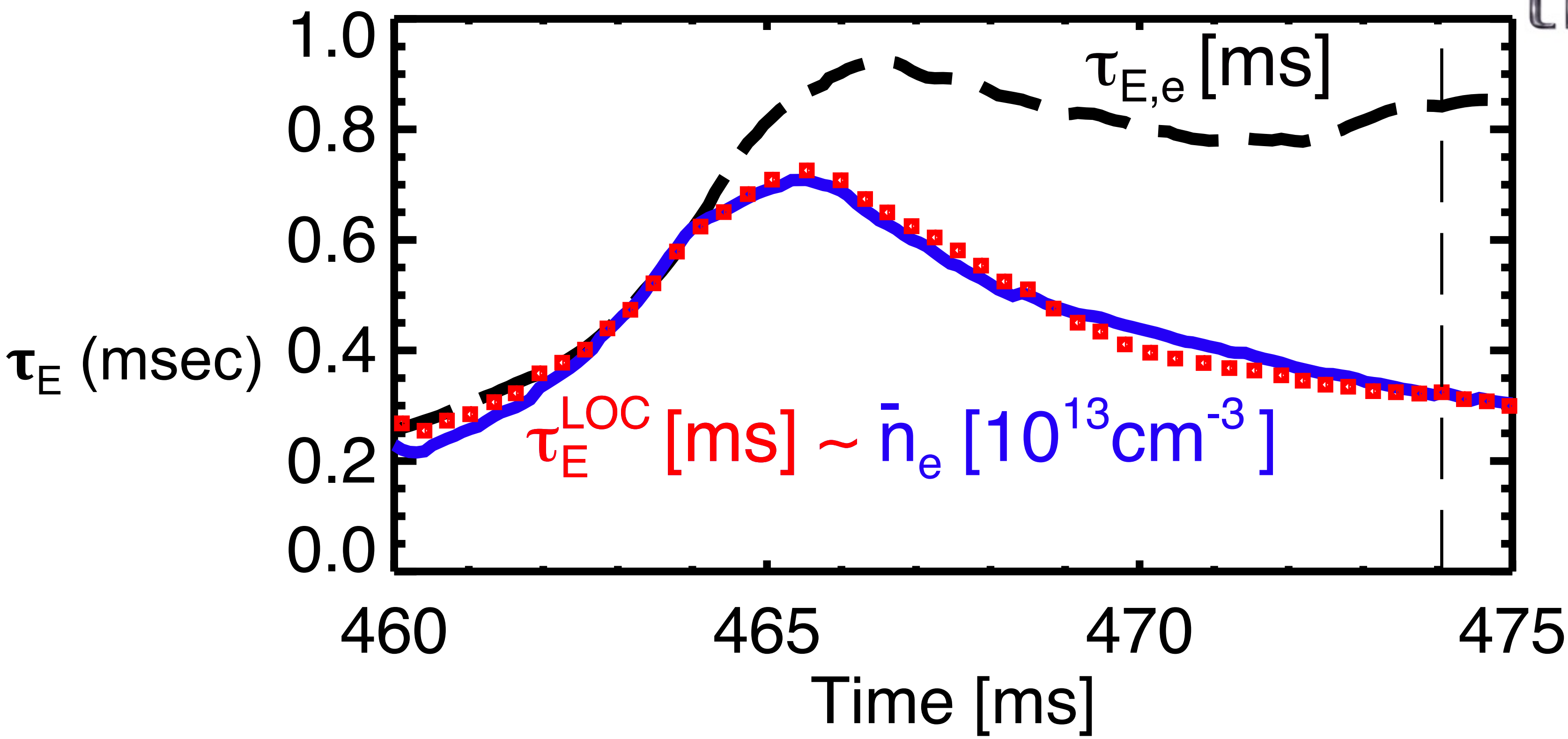
Collisionality is very low in LTX



- High temperature, low collisionality region extends to SOL
- SOL is hot, collisionless, with nonzero pressure
  - Mirror confined. *Radial* transport will dominate.
- Edge diagnostic set in LTX not appropriate for this unanticipated regime

Plasma confinement improves compared to ohmic scaling law

LTX-β



- Comparison is with neo-Alcator Linear Ohmic Confinement scaling
  - Appropriate for small tokamaks without auxiliary heating, like LTX
- Factor of three improvement as electron temperature flattens
  - Estimate neglects ion stored energy
- Core transport and turbulence not diagnosed in LTX

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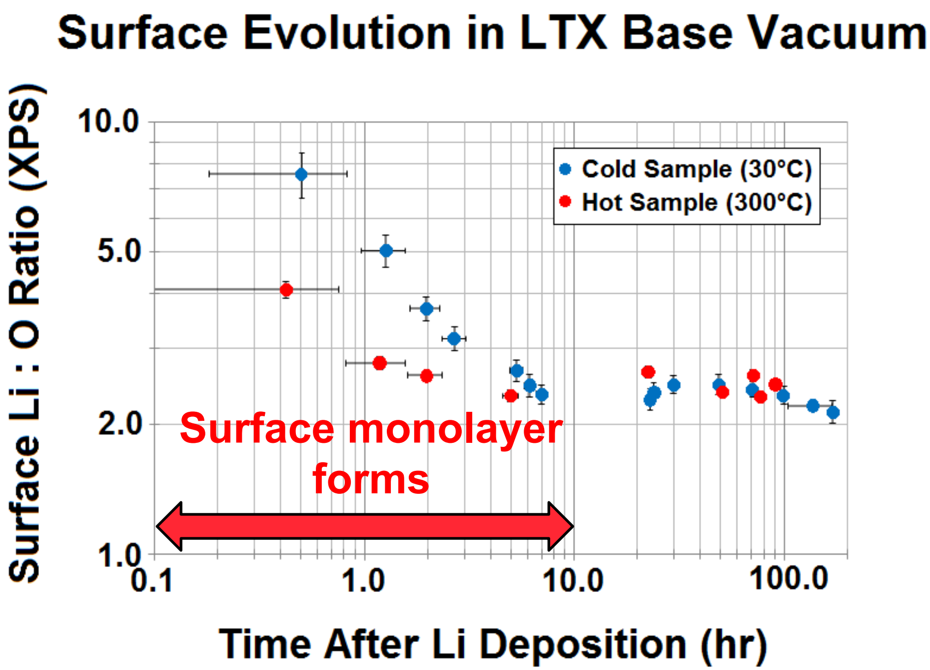
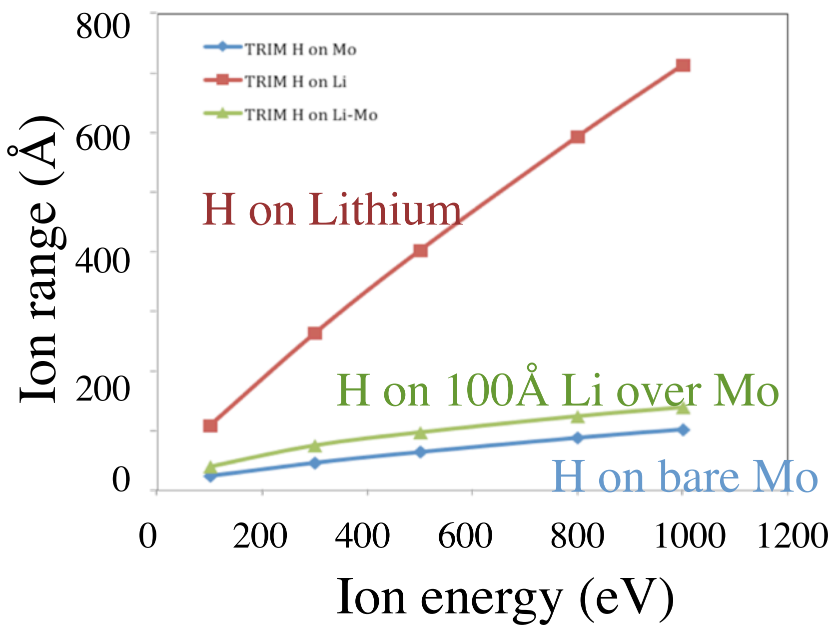
SOL hydrogen is implanted deep in lithium PFC - Capability for materials analysis of lithium coatings modest

LTX-β





TRIM modeling by L. Buzi, Princeton U.

- Range of a proton in lithium can exceed 500 Å
  - LTX operates in hydrogen, with high edge electron temperatures
- Surface analysis limited to XPS – range a few 10s of Å
- Probability of reflection is negligible
- Little energy transferred to surface; low sputtering

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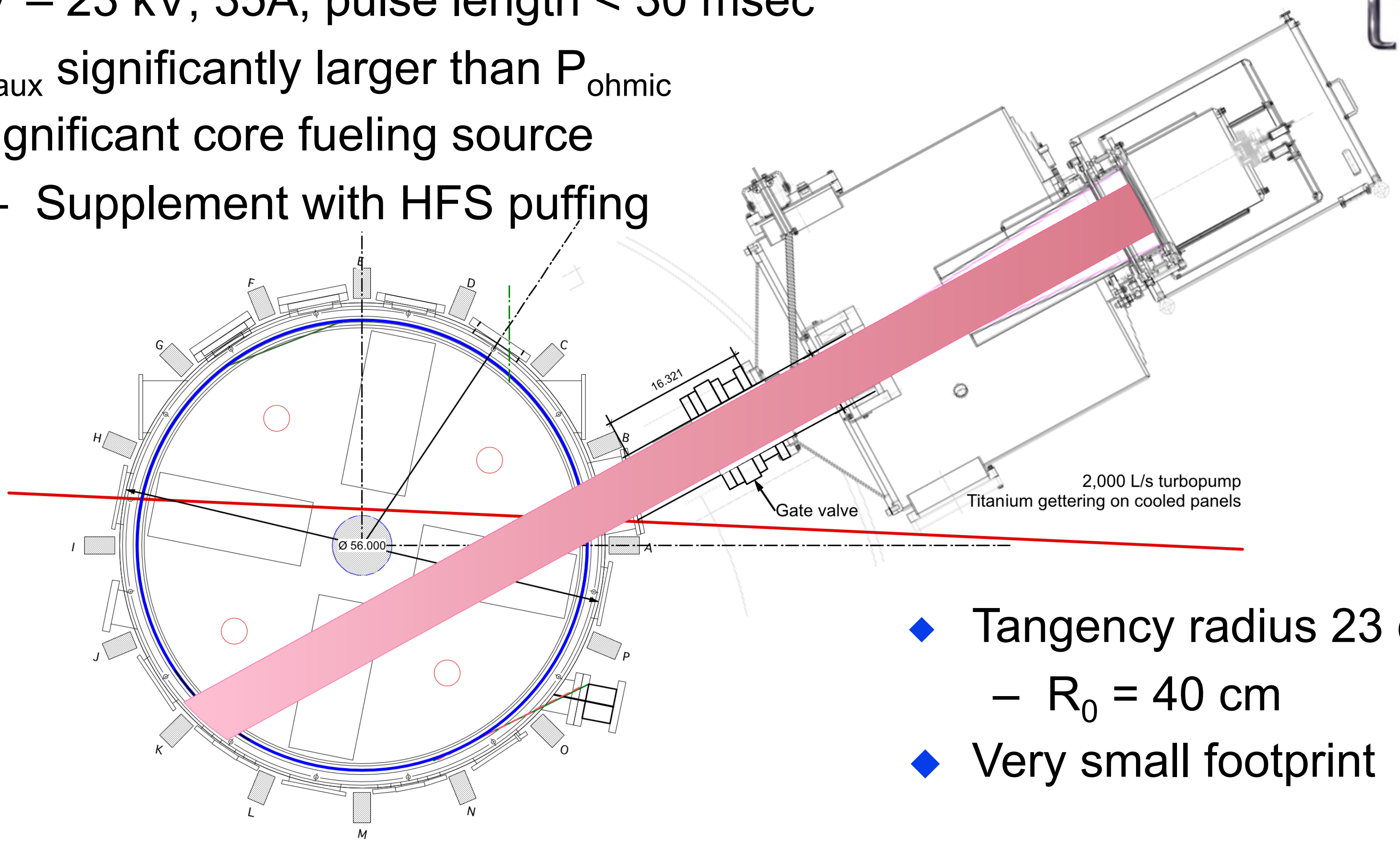
LTX-β extends the capabilities of LTX

- Neutral beam for fueling, auxiliary heating
- Lithium CHERs for ion temperature profiles, rotation profiles
  - Core lithium concentrations
- ECH/EBW for particle-free heating, electron heating
- Transport diagnostics
  - Fluctuation reflectometry for core turbulence
  - Electron heat pulse propagation with EBW
- Higher toroidal field ➪ higher plasma current, to confine beam ions
- New evaporative coating systems
  - More frequent coating cycles
  - Between-shots capability
- Upgraded SOL diagnostics

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

- 17 – 23 kV, 35A, pulse length < 30 msec
- P_{aux} significantly larger than P_{ohmic}
- Significant core fueling source
  - Supplement with HFS puffing



- Tangency radius 23 cm
  - R_0 = 40 cm
- Very small footprint

- 700 kW beam will also provide large toroidal momentum input
  - Beam installation nearly complete

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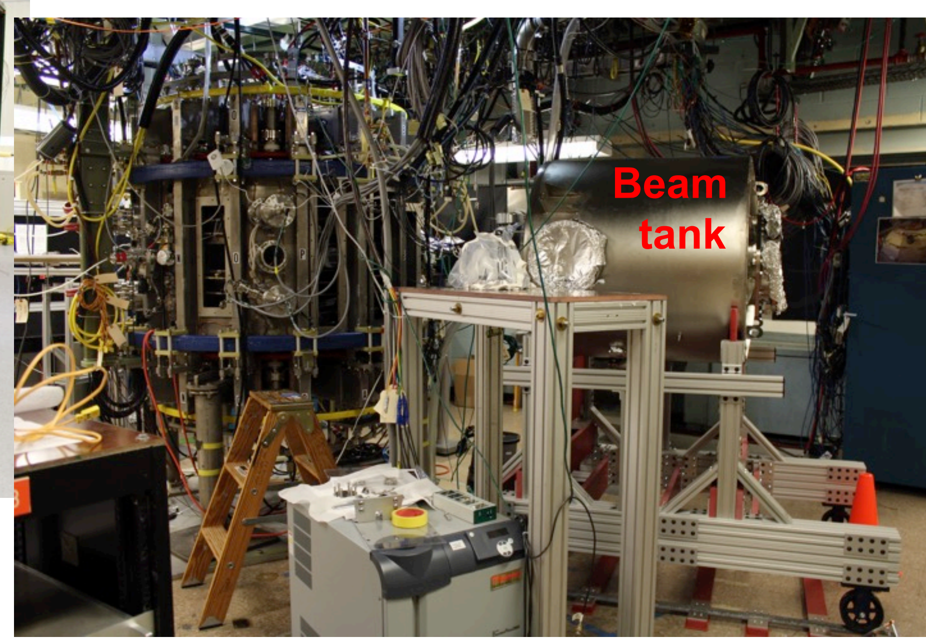
Power supply tested; beam tank in place

LTX-β



- Neutral beam tank in test cell
- NB power supply fully tested into dummy loads.
  - Cabled into test cell.
- Power supply for toroidal field upgrade near dummy load testing
- All vacuum pumping components onsite for installation
- Most vacuum boundary changes complete
- Pumpdown within weeks

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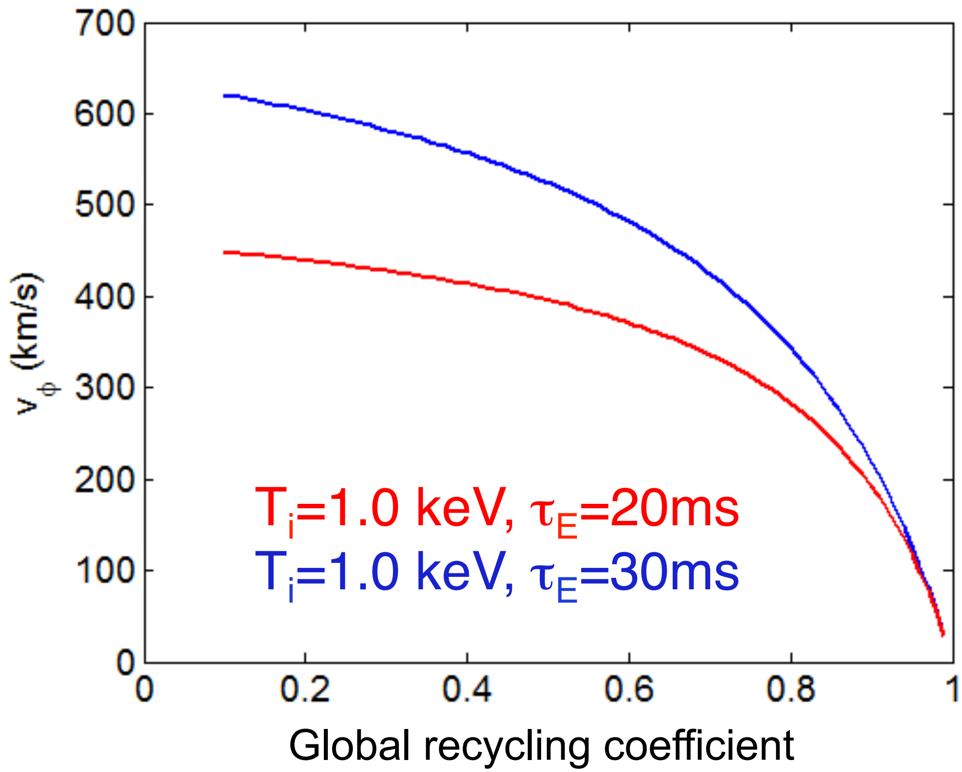
0-D Torque balance indicates that the ion toroidal rotation speed with NBI torque should vary strongly with neutrals in plasma

- **LTX-β** modeling
- T_{NBI} is neutral beam torque

(20 kV, 30 A source, R_{tan}=0.23 m)

- $\langle n_e \rangle = 10^{19}\ m^{-3}$, V_{pl}=0.7 m^{-3}
- Two T_i and τ_E values used from reference projections; $\tau_\phi \sim \tau_E$
- Assume $n_0(R) = 10^{16}\ m^{-3}/(1-R)$
  - R is recycling coefficient
- Minimum R from lithium is ~ 0.1 or less, for high edge T_e



J. Canik, ORNL

- Unknown: magnetic braking from shell eddy current-induced error fields

Modest ECH/EBW source for electron heat pulse propagation to be installed in 2018

LTX-β

Electron Devices

L-6170
1,700 kW X-Band
Coaxial Pulsed Magnetron

- **Linear accelerator applications**
- **9.3 GHz, high frequency stability**
- **Tunable +/- 25 MHz to match accelerator**
- **1,700 kW peak output power**
- **0.0008 duty cycle**
- **Liquid cooled anode**
- **Integral permanent magnets**

- Funded by Small Business Innovative Research grant to Eagle Harbor Technologies
- Eagle Harbor will design, engineer power supply for testing/use at PPPL
- Tube modeled to output 100 kW for >5 msec pulse by design engineer
- Looking at X-B mode conversion
- 2 tubes may be stacked in time for >10 msec pulse, multiple pulses

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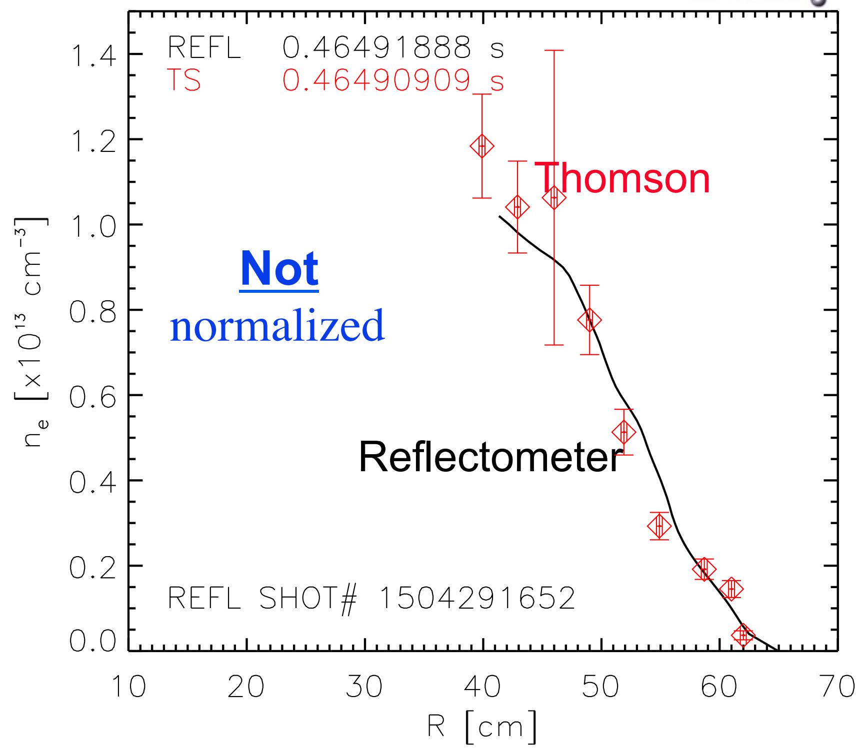
Expanded diagnostic set vital for LTX-β

- Neutral beam-based diagnostics (ORNL)
  - Li-CHERs for ion temperatures
    - » Eliminate uncertainty in core ion temperature from Abel-inverted profiles
  - Rotation profiles
    - » Investigate toroidal momentum transport without edge neutrals
- Install re-entrant bolometer, Lyman alpha arrays
  - Tangential arrays will view full radial chord for accurate DEGAS2 assessment of recycling
  - Additional bolometry (ORNL)
    - » Radiation losses found to be significant in power balance
- Magnetic fluctuation diagnostics
  - Toroidal array of Mirnov coils for MHD studies
- Upgraded equilibrium magnetics for improved reconstructions

Diagnostic set for LTX-β

- Upgrade profile reflectometer for fluctuation measurements (UCLA)
- Investigate 1 mm interferometer upgrade for low-k scattering (UCLA)
- Replace triple Langmuir probes with single-tip probes
  - More robust; suited for high edge temperatures
- Gridded energy analyzers for scrape-off layer
  - Other SOL ion analysis?



- 5 additional Thomson scattering channels for far scrape-off layer
  - Core Thomson adequate for $n_e \sim 2\text{-}3 \times 10^{17}$ m^{-3} with 20J laser
  - New polychromator channels to extend measurement to lower density

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Conclusions

- LTX-β will extend the study of the lithium wall regime to
  - Higher toroidal field and plasma current
  - Auxiliary heated discharges
    - » NBI
    - » Short-pulse EBW
  - Discharges with (partial) core beam fueling
  - More frequent lithium deposition, including between-shots coatings
- Upgraded diagnostics to investigate confinement w/o temperature gradients
  - Effect on core fluctuations
  - SOL diagnostics
  - Surface science
- Validate lithium wall regime for future NSTX-U experiments