Extending the low-recycling regime to higher performance discharges and liquid lithium walls in LTX-β

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A fundamentally different approach to fusion

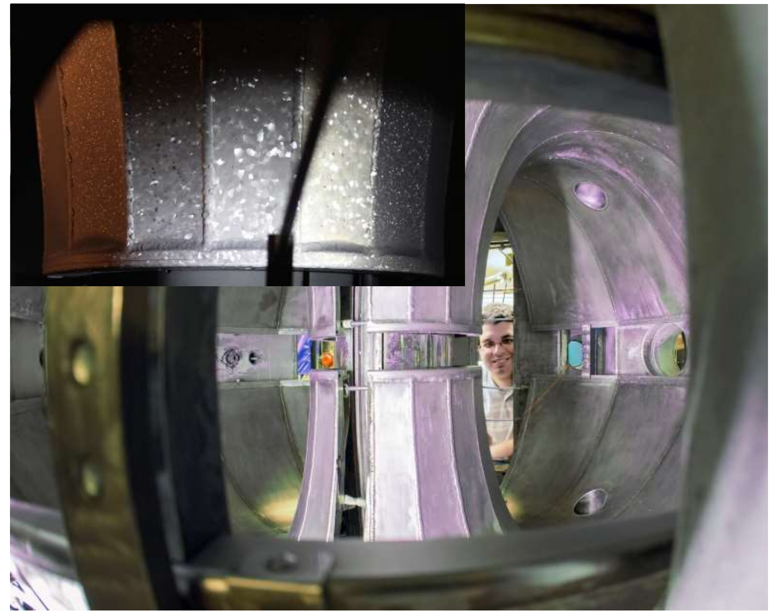
- Li a possible solution to the biggest problems in fusion
- LTX uniquely explored <u>low-recycling</u> and <u>liquid walls</u>
  - With solid lithium, flat $\boldsymbol{T}_{\mathbf{e}}$ profile and hot edge first observed
  - Good performance with full liquid Li wall first demonstrated
- Upgrades enable LTX-β to extend, study new regimes
  - Notables: Achieved main operations goals, initial physics goals
    - » Improved Li, Higher $\boldsymbol{B_T}$ and $\boldsymbol{I_p}$, NBI commissioned
    - » Low-recycling flat $\boldsymbol{T}_{\mathbf{e}}$ for longer duration & with liquid Li
    - » Record $\boldsymbol{I_p}$, $\boldsymbol{T}_{\mathbf{e}}$, $\boldsymbol{p}$, $\boldsymbol{\tau}_{\mathbf{E}}$; $\boldsymbol{\tau}_{\mathbf{E}}$ exceeds Linear Ohmic scaling
  - Now: further improve, explore low-recycling & liquid lithium
    - » Improved diagnostics, modeling: Understand unique physics
    - » High $\boldsymbol{B_T}$, $\boldsymbol{I_p}$, $\boldsymbol{n_e}$ will enable NBI core heating and fueling

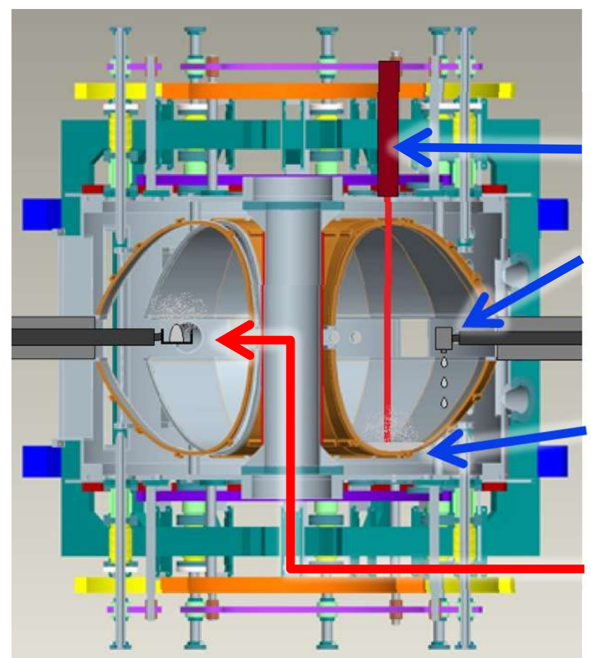
Li predicted, demonstrated to improve fusion

- Low Recycling due to chemical bonding of H/D/T
  - Improves density control
  - Improved energy confinement in TFTR, NSTX, CDX-U, more
  - Reduces edge thermal losses, gradients, turbulence
- Reduce impurities
  - Li relatively benign: Low-Z and low first ionization potential
  - Sputtering decreases for higher edge T_i > 200 eV
  - Getters, buries, dissolves other impurities
- Liquid metals could solve many wall issues
  - Can't break/crack, erosion not an issue, so can be thinner
  - Substrate only has to handle heat & neutrons, not plasma
  - Can flow or evaporate to handle heat, remove tritium
- **All of these explored, demonstrated on LTX(-β)**

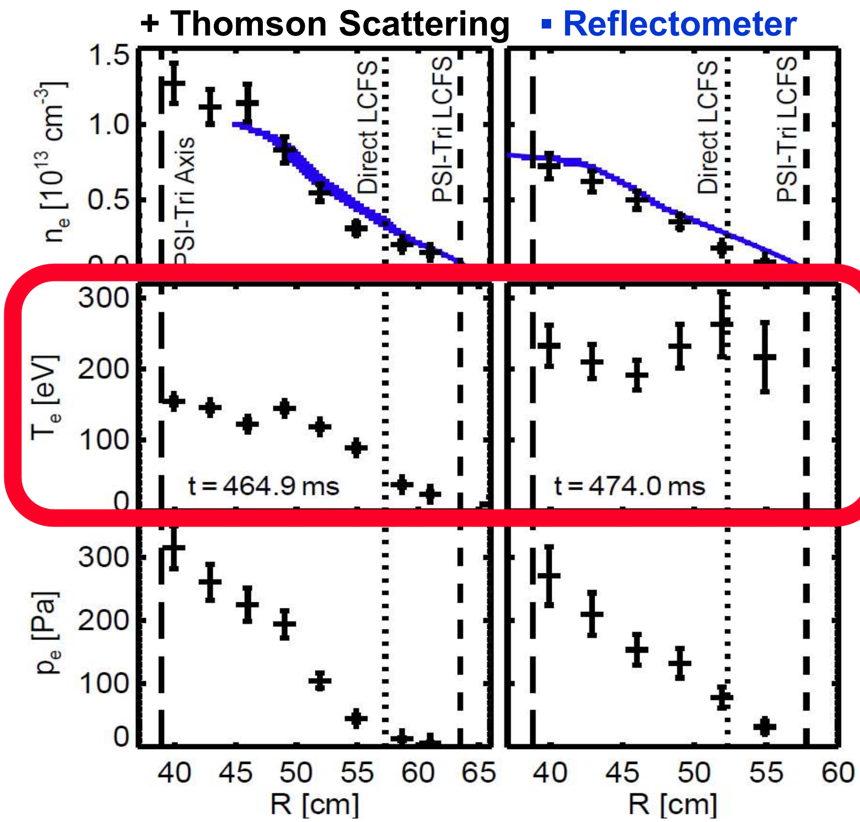
LTX first & only tokamak with full **liquid** walls

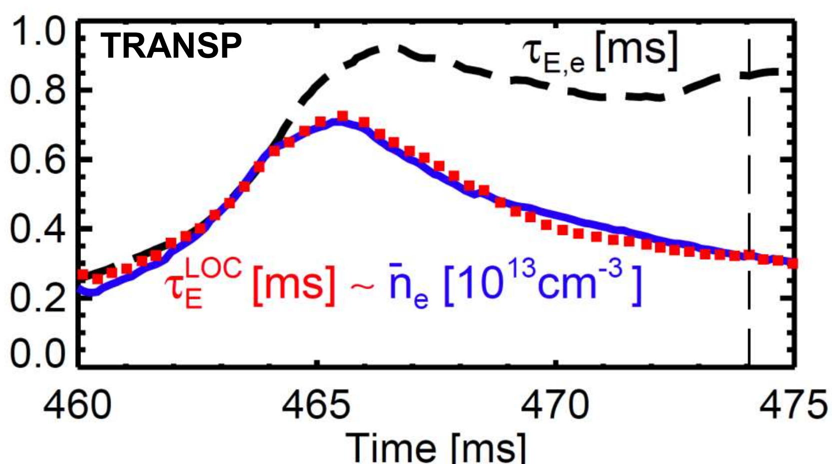
- Lithium on stainless steel shell surrounds plasma
  - Covers ~80% of plasma
  - Can be entirely Li coated
  - 1.5 mm SS liner + 1 cm Cu
  - **Heat to 270 – 350 °C**
    - » **Li liquefies at ~180 °C**
  - 4 quadrants w/ toroidal and poloidal breaks
- Solid coatings sustained good performance for days, weeks, or months
  - Depends on vacuum & Li conditioning technique





Flat T_e, hot edge w/ low recycling & high τ_E





D.P. Boyle PRL 2017

- Even with low recycling, gas puffing cools edge
- T_e profiles flatten w/ hot edge after fueling ends
  - » Long standing prediction
    - Krashnenikov PoP 2003
    - Zakharov FED 2004
- During fueling, follows Linear Ohmic Confinement scaling $\tau_{LOC} \sim n_e \, a \, R^2 \sqrt{q}$
- As edge temperature increases and T_e flattens, $\tau_E \sim$ flat even as n_e drops

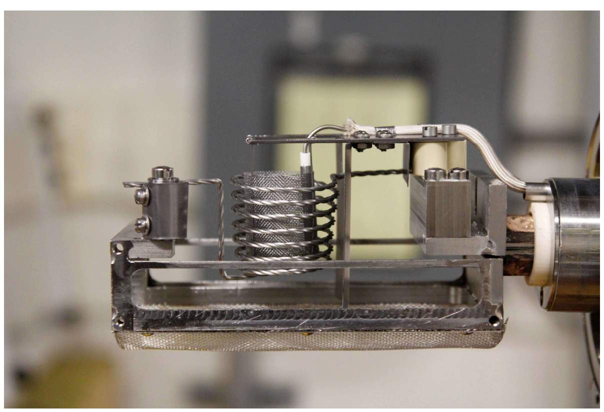
LTX-β upgrades extend, better study new regimes

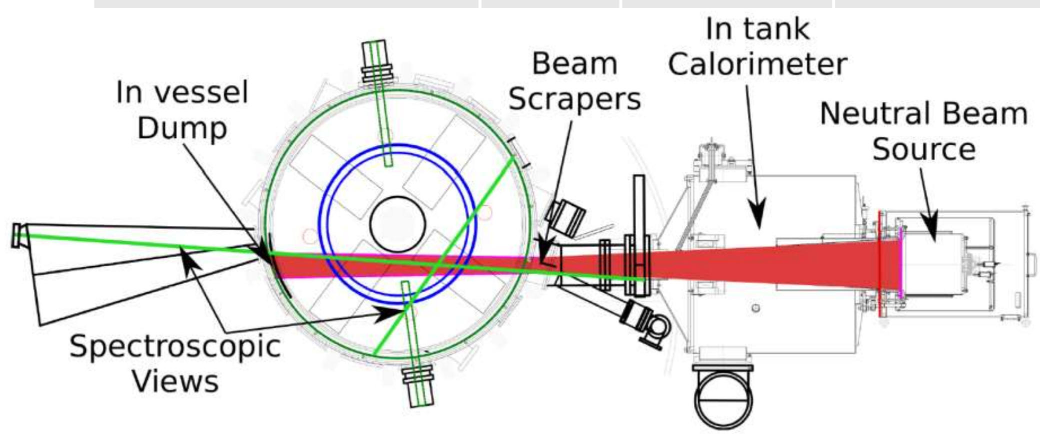
- Improved Lithium and wall conditioning
  - More control over solid/liquid Li and low-recycling
- Higher magnetic fields and plasma current
  - Higher performance, more relevant to large machines
- Neutral Beam Injection
  - Core fueling for steadier density without cold edge gas
  - Auxiliary heating for high performance, relevance
  - Fast ion confinement requires higher field, current
- Enhanced diagnostics → deeper, finer studies
- Broad modeling effort for unique LTX-β physics

Main operations goals achieved, still improving

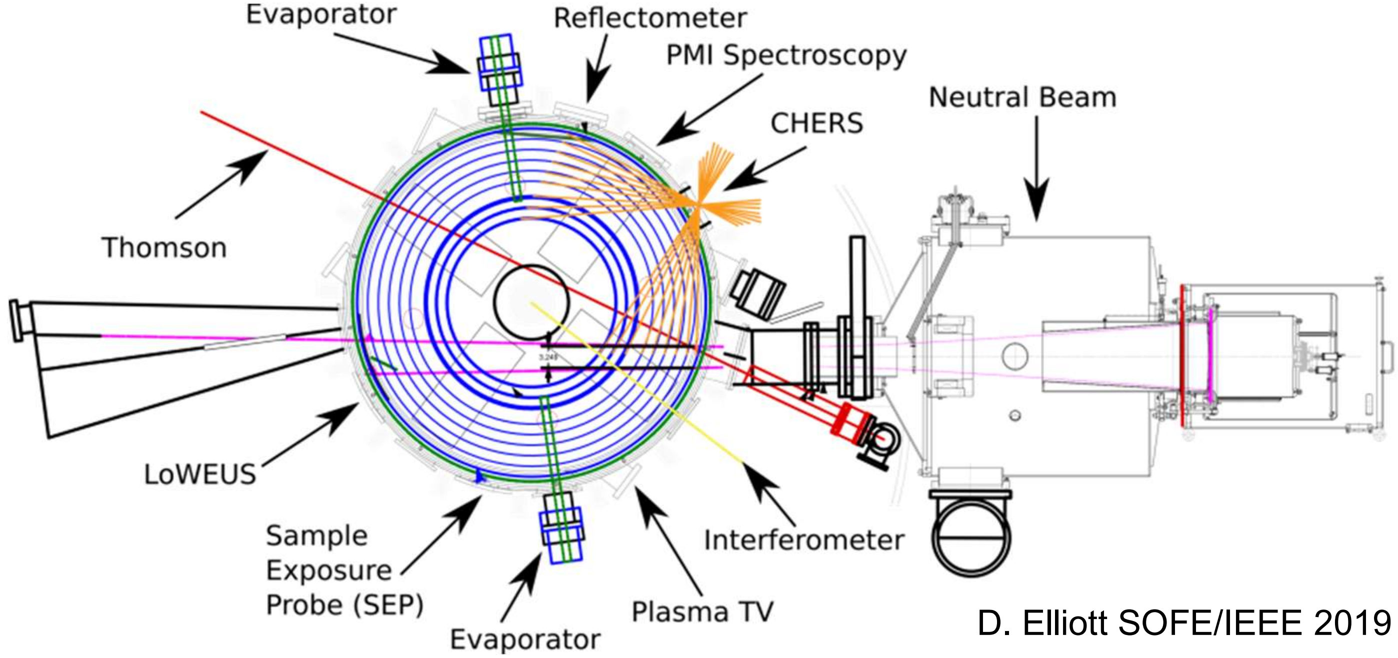
- ☑ Lithium/Wall conditioning
  - ☑ Control solid/liquid Li
- ☑ Higher fields, currents
  - ☑ Performance, relevance
- ☑ Neutral Beam Injection
  - ❑ Core fueling, heating
  - ❑ Fast ions need high current
    - ❑ Initially, poor confinement
    - ❑ Upcoming: High I_p + NBI

Parameters		LTX	LTX-β
Major Radius	R_o	34 – 40 cm	
Minor Radius	a	20 – 26 cm	
Vacuum Pumping		6 m^3/s	12 m^3/s
Heat/Evap/Cool time for Li evap		200/10/ 100 min	10/10/10 min
Toroidal Field	B_T	0.18 T	0.3 T
Ohmic Flux Swing	$\Delta\Phi$	75 mV·s	100 mV·s
Plasma Current	I_p	85 kA	135 kA
Beam Power	P_{NBI}	0	700 kW
Beam Duration	t_{NBI}	0	5-6 ms





Enhanced diagnostics → deeper, finer studies

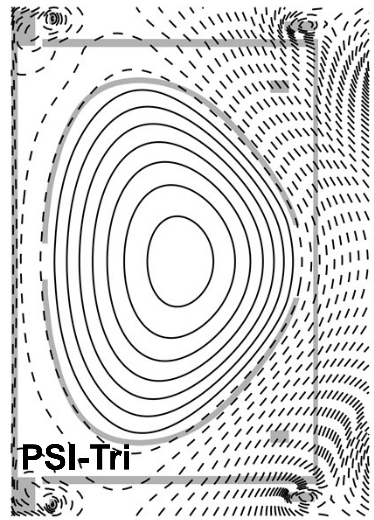


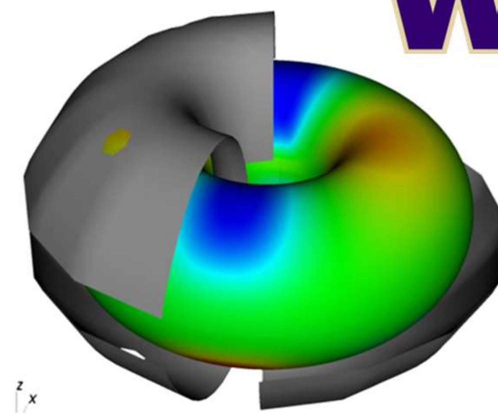
D. Elliott SOFE/IEEE 2019

- Thomson scattering: Reduced background + stray light
  - 11 views, 40-62 cm, Single 6-10J pulse – requires repeated shots
- Magnetics, Langmuir probes, filterscopes, interferometer
- AXUV Lyman-α array for recycling measurements
- ORNL/PPPL: CHERS, multiple visible spectrometers
- LLNL: Filtered fast cameras, XUV/UV spectrometers

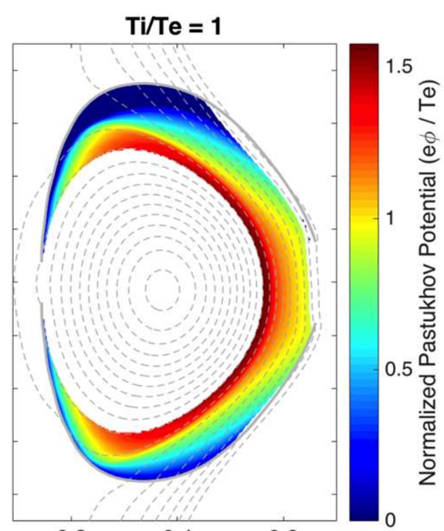
Broad modeling effort for unique LTX-β physics

- PSI-Tri equilibrium reconstructions
  - PSI-Tet eddy currents
- TRANSP integrated analysis
  - NCLASS, NUBEAM
- Fast ions
  - POET, CONBEAM
  - LiWallFusion: 3Dorb
- SOL ion mirror trap
- DEGAS2 neutral recycling

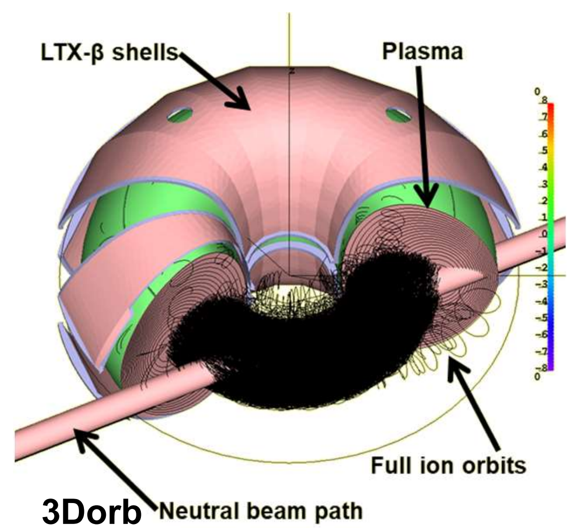




C. Hansen

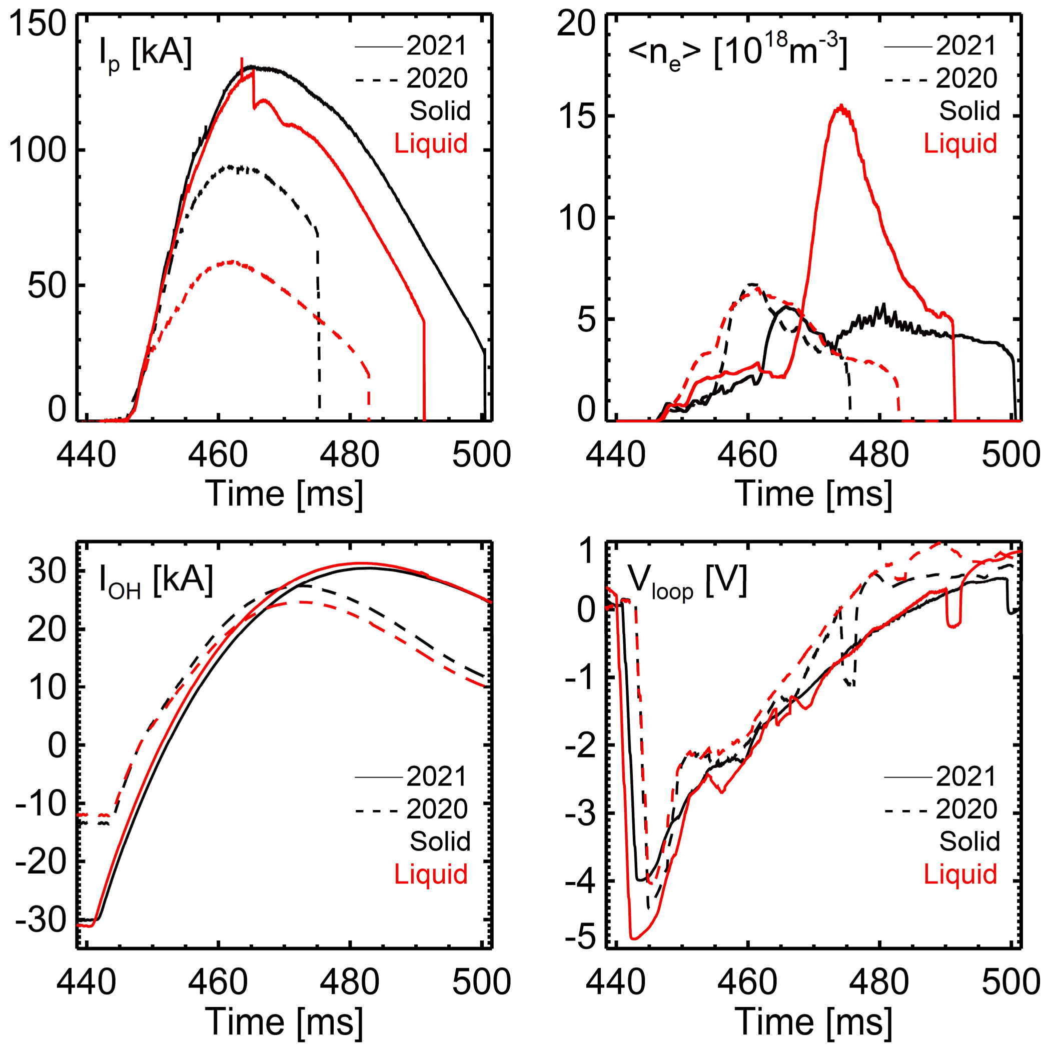


X. Zhang PSI/NME 2019



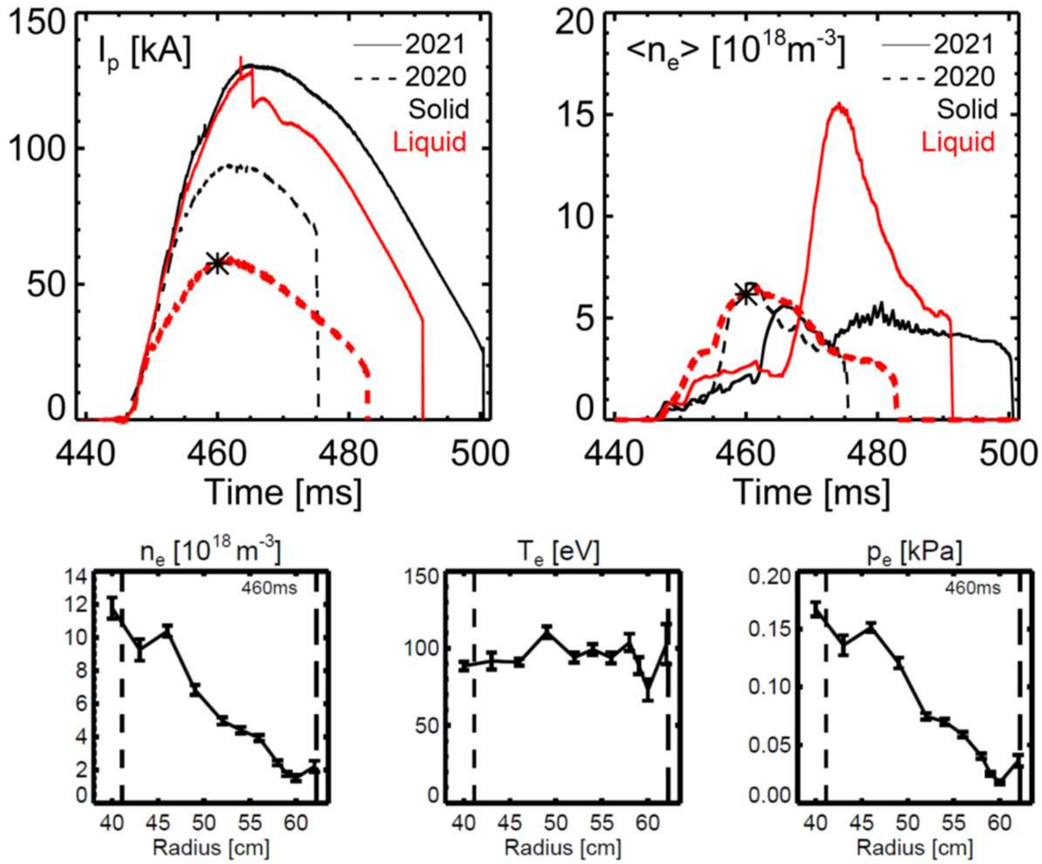
L. Zakharov, LiWallFusion

Record I_p achieved with solid and liquid Li



- Higher I_p enabled by upgraded OH bank
- Breakdown, ramp up greatly improved with ~200 °C shell in 2021
  - Still slightly lower I_p
  - Increased gas puff for high n, p though it further decreased I_p
- Should be enough to confine most fast ions
  - Ohmic plasmas shown
  - NBI experiments, analysis upcoming

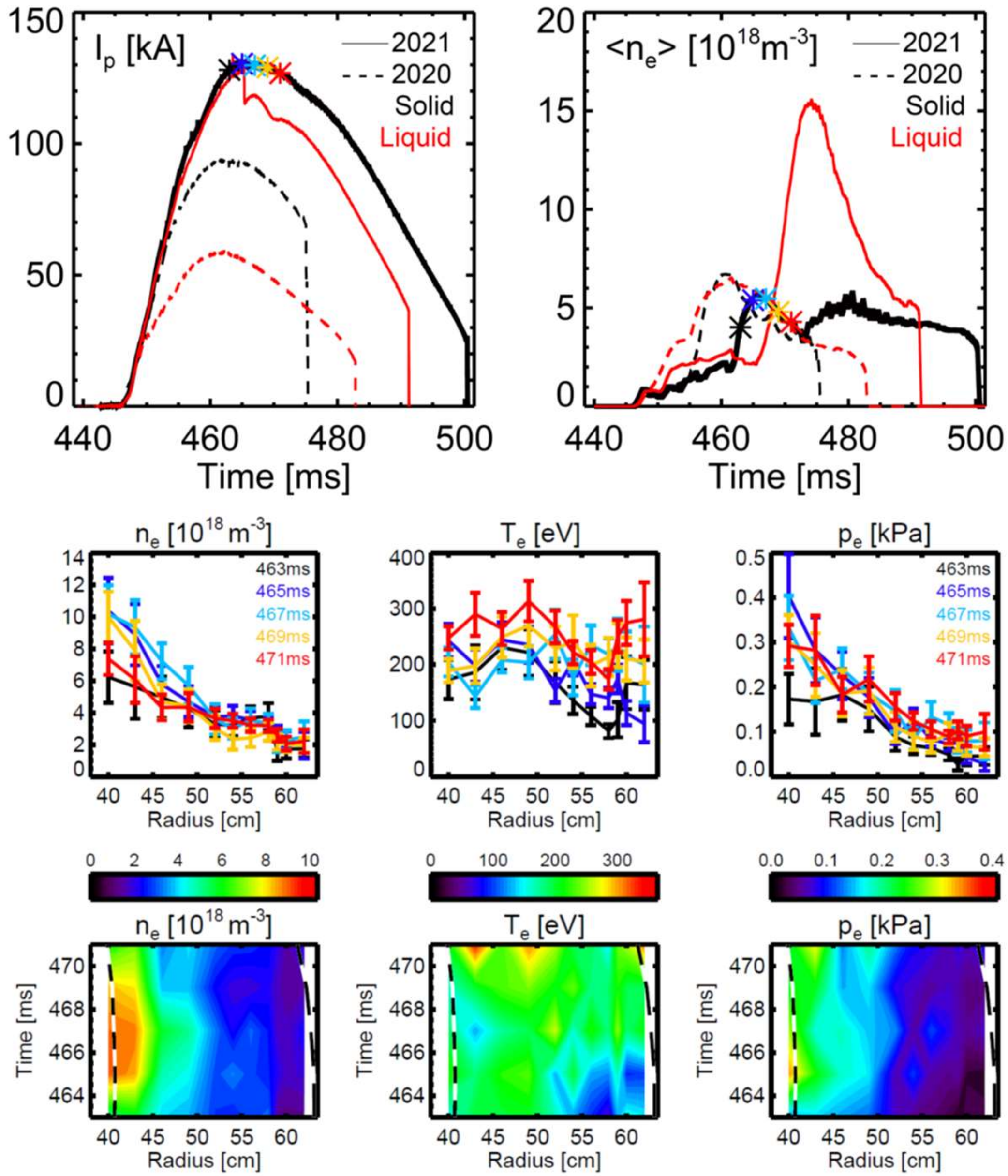
Flat T_e profiles achieved with liquid Li walls



- ~60 kA discharges before OH upgrade
- Li on ~200 °C shell
- Flat T_e profiles with liquid Li walls were not demonstrated previously in LTX

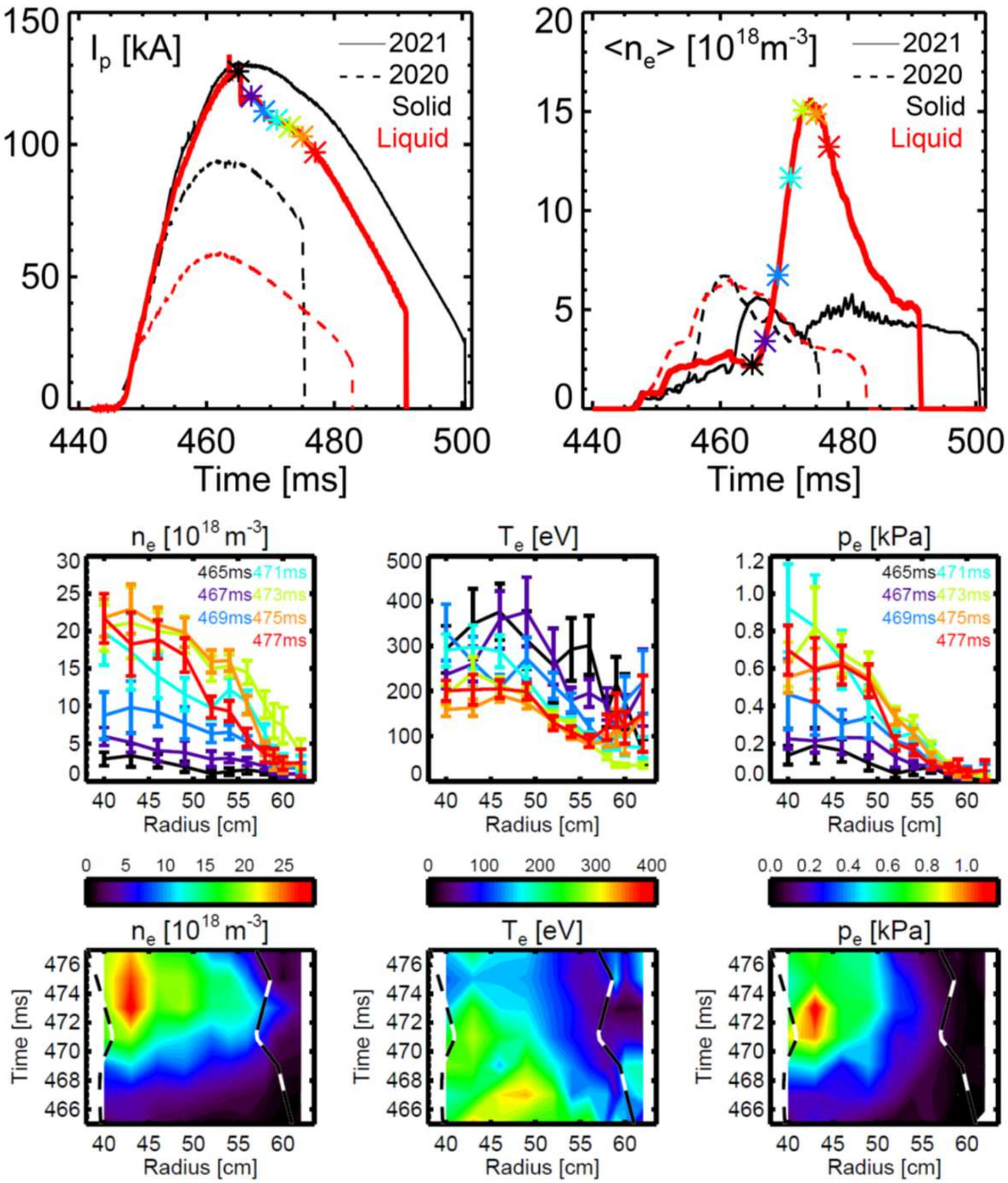
Flat T_e profiles for several τ_E with solid walls

LTX-β



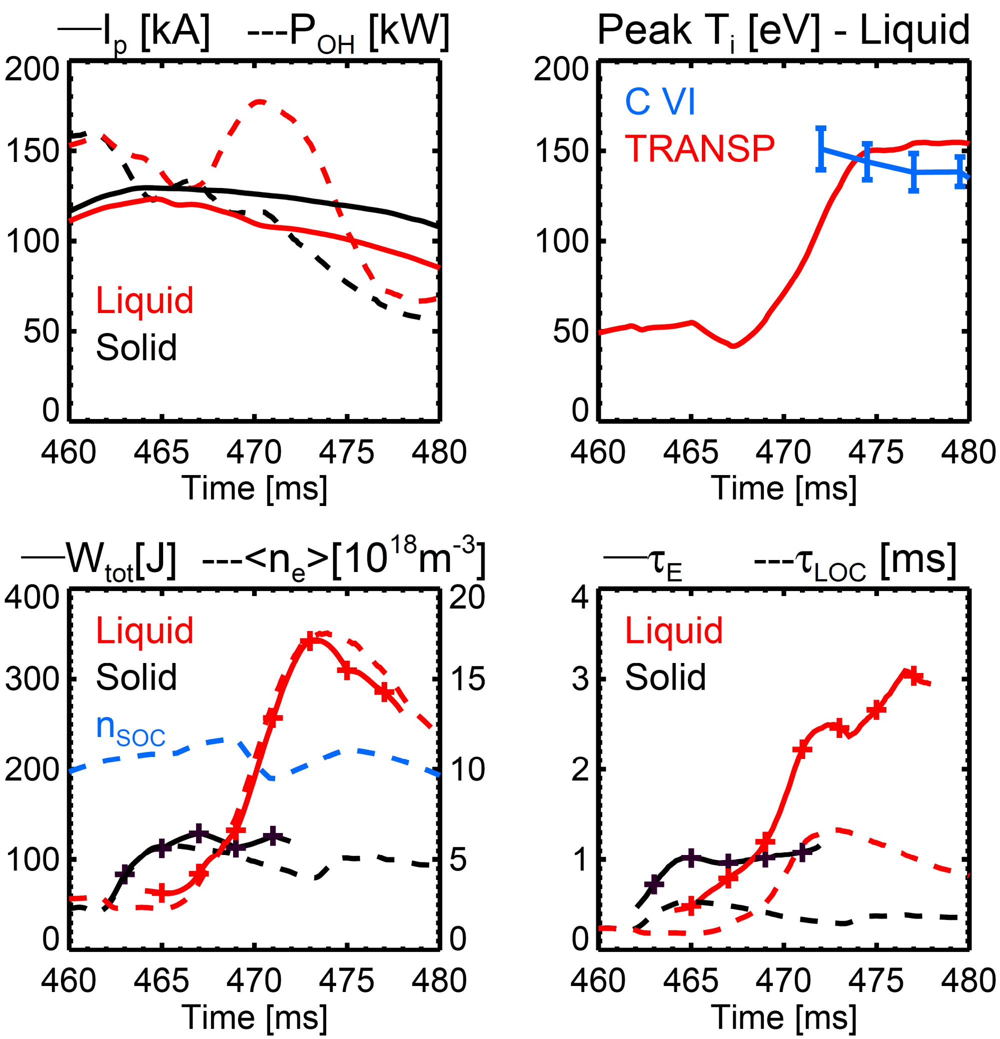
- Edge cools during gas puff, but later recovers
- Low-recycling regime extended to higher I_p, B_T, longer duration
  - Only reported for one time point on LTX

Record T_e~400 eV, p_e~1 kPa values achieved



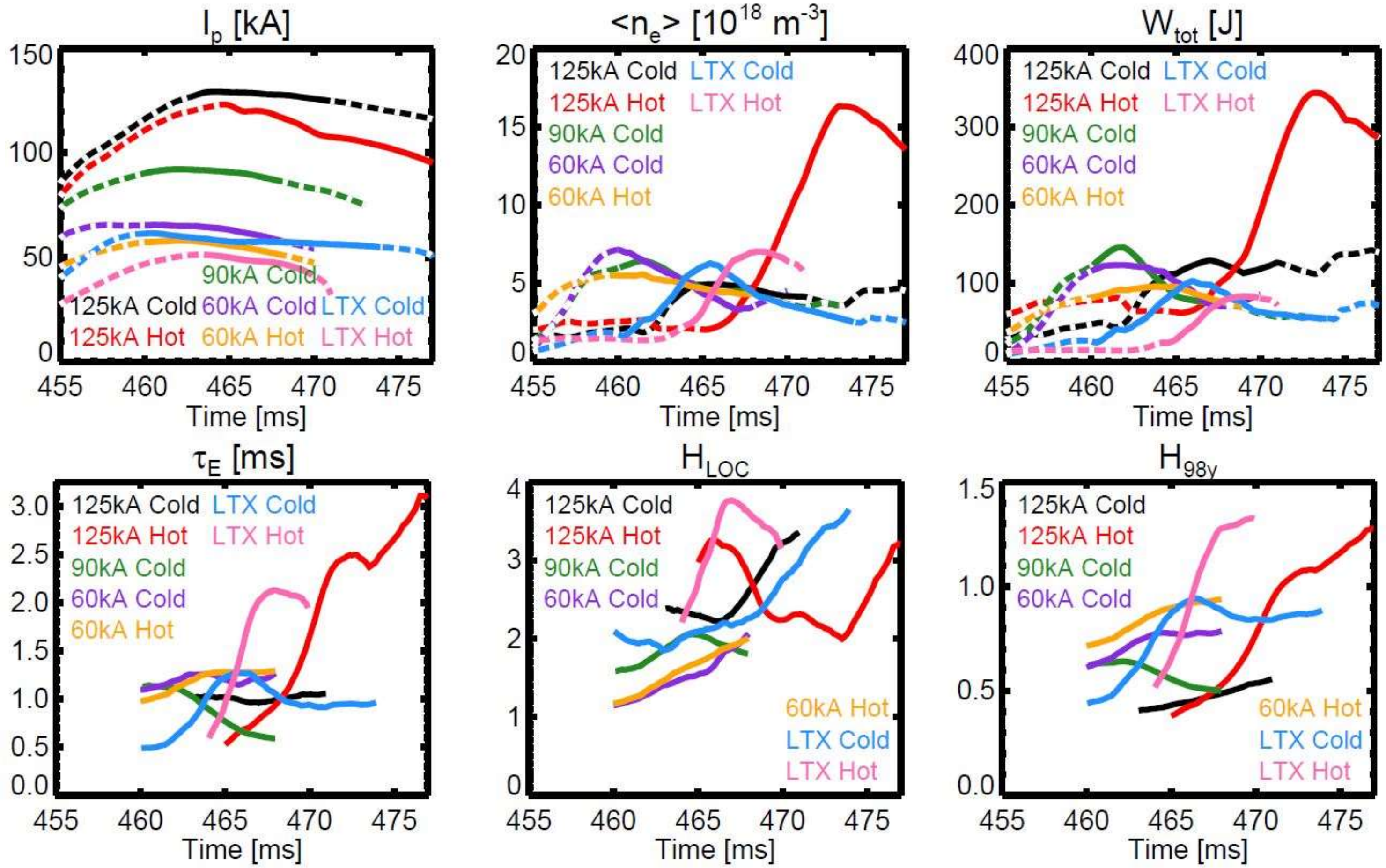
- Still slightly lower I_p
  - More gas early, delay gas puff after peak I_p
  - Increased gas puff for high n, p though it further decreased I_p
- Gas puff too large to recover ~flat T_e by end of TS data

Confinement exceeds Linear Ohmic scaling



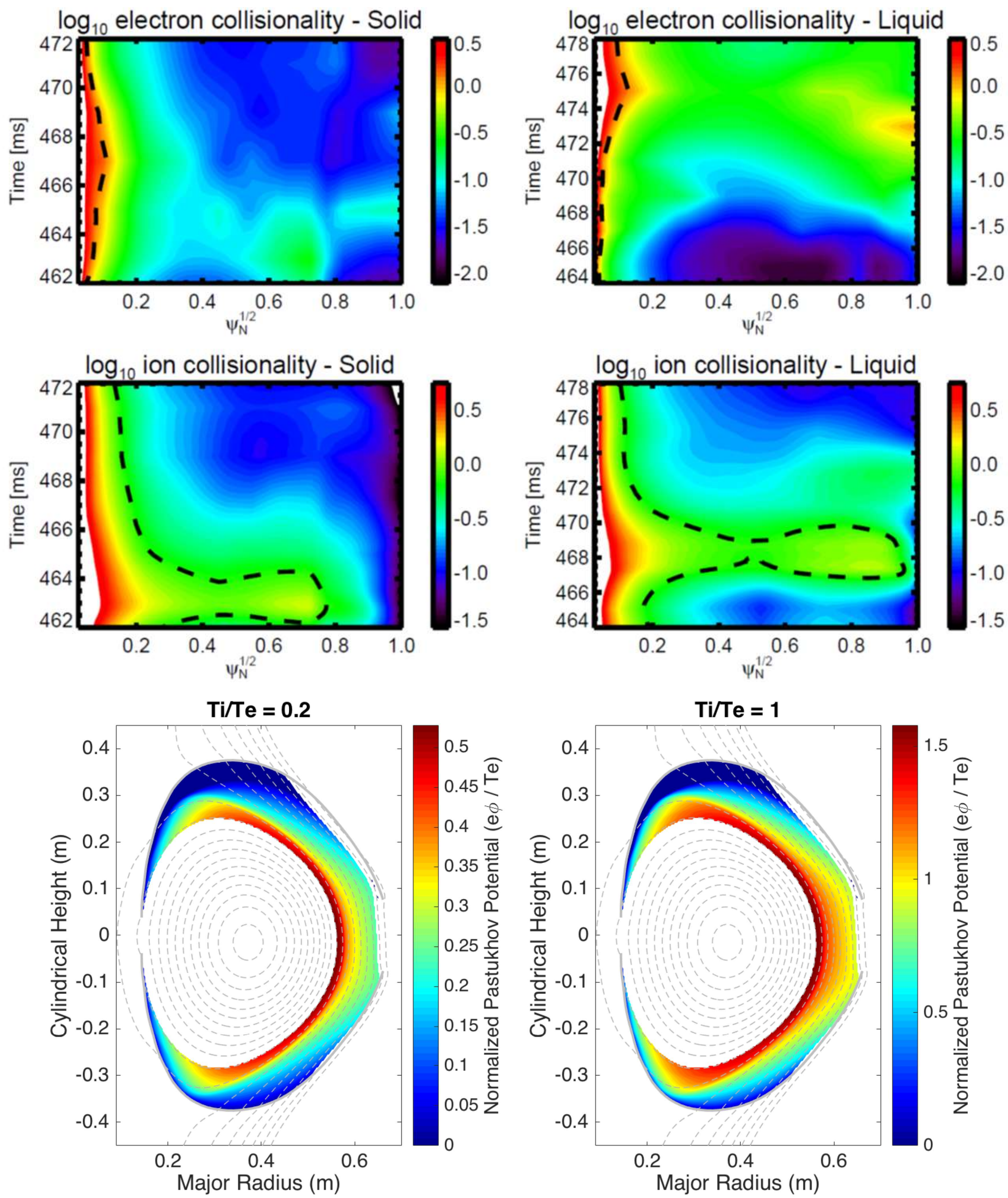
- TRANSP analysis
  - TS, PSI-Tri, $\boldsymbol{I_p}$, $\boldsymbol{V_{loop}}$, $\boldsymbol{n_e L}$
  - Neoclassical $\boldsymbol{T_i}$ matches C VI
- $\boldsymbol{W_{tot}}$, $\boldsymbol{\tau_E}$ increase ~ $\boldsymbol{n_e}$
  - Linear Ohmic Confinement (LOC) or neoAlcator scaling
  - $\boldsymbol{\tau_{LOC} \sim n_e\, a\, R^2 \sqrt{q}}$
- $\boldsymbol{\tau_E}$ does ***not*** decrease w/ $\boldsymbol{n_e}$
  - Similar effect seen in LTX
- $\boldsymbol{n_e}$ above Saturated Ohmic Confinement critical $\boldsymbol{n_{SOC}}$
  - No clear saturation

Starting to compare τ_E to LTX, initial LTX-β



- Higher τ_E with high I_p+n_e Liquid Li, similar H factors
- H factors increasing w/ time, need more late TS data
- Future experiments will also look at NBI heating

Collisionless mirror trapping in edge and SOL

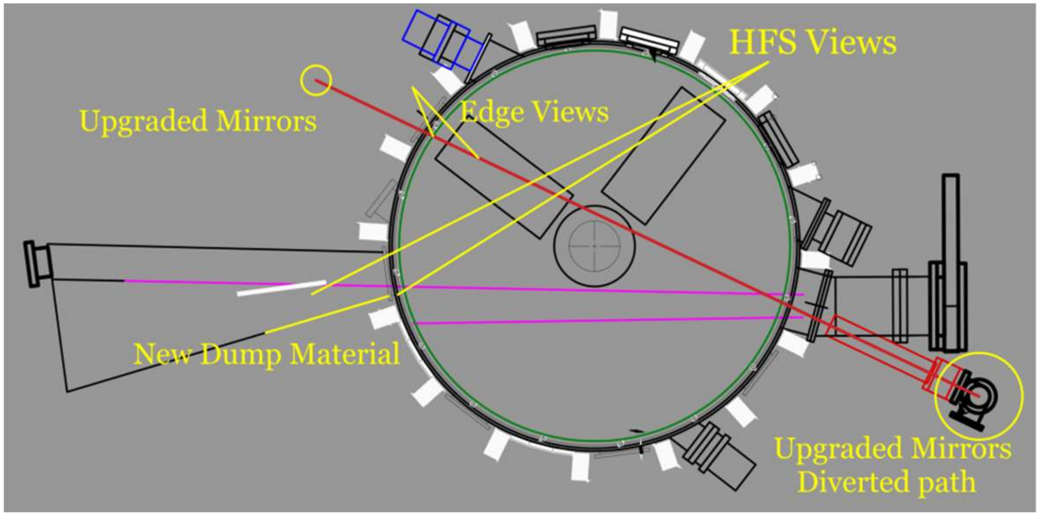


- Large fraction of trapped ions may complicate SOL model for profiles and flux to wall
  - DEGAS2 needs SOL model for recycling estimate
- Simple analytic model suggests ion trapping leads to Pastukhov potential

New capabilities ready to explore new regimes

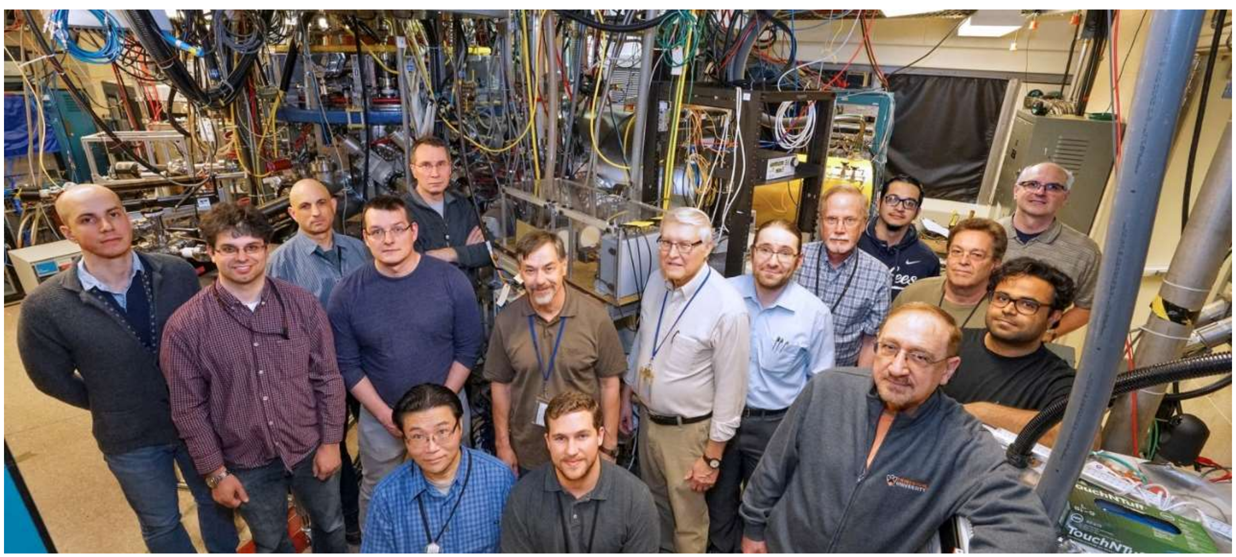
LTX-β

- Optimize discharges for physics studies
  - Further improve breakdown, ramp up, position & shaping
    - » Stronger OH coil leads, clamping for higher I_{OH}
    - » ECRH startup, Improved PSI-Tri tools for coil programming
  - Steadier, longer, higher I_p and n_e
  - Optimize plasma and beam for NBI heating and fueling
  - Recycling studies: “old Li” baseline, SGI/NBI fueling
- Soon: Add polychromators for Thomson Scattering
  - Core views inboard of axis to constrain equilibria
  - Higher etendue, sensitivity for single shot profiles
  - Plans for more views in hot, low density edge/SOL



LTX-β explores low-recycling & liquid walls

- Achieved main operations goals, initial physics goals
  - Improved Li, Higher $\boldsymbol{B_T}$ and $\boldsymbol{I_p}$, NBI commissioned
  - Low-recycling flat $\boldsymbol{T_\mathrm{e}}$ for longer duration & with liquid Li
  - Record $\boldsymbol{I_p}$, $\boldsymbol{T_\mathrm{e}}$, $\boldsymbol{p}$, $\boldsymbol{\tau_\mathrm{E}}$; $\boldsymbol{\tau_\mathrm{E}}$ exceeds Linear Ohmic scaling
- New capabilities ready to extend, explore new regimes
  - Low-recycling liquid lithium walls are a fundamentally different, potentially better, approach to magnetic fusion



Additional improvements envisioned

LTX-β

- Possible operational and diagnostic upgrades
  - Between-shots lithium evaporation
  - PCS – PF coils: position & shaping, OH, fueling, NBI
  - New coils – separatrix? Negative triangularity?
  - Extend NBI pulse from 5 → 10-30 ms
  - ECH/EBW heat pulse
  - AXUV Radiated power / Lyman-α arrays
  - Reflectometer, RFEA, improve Langmuir probes
- Study, understand unique physics
  - Core, edge, and SOL; plasma, impurities, and fast ions
  - Plasma, beam, neutral, and surface interactions
    - » Solid/liquid Li: Recycling, impurities, sputtering
  - Transport, scalings, fluctuations and instabilities