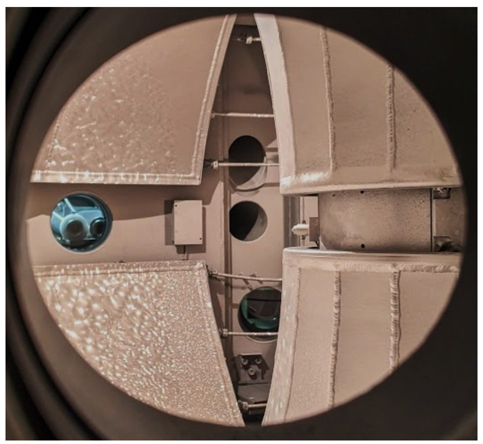
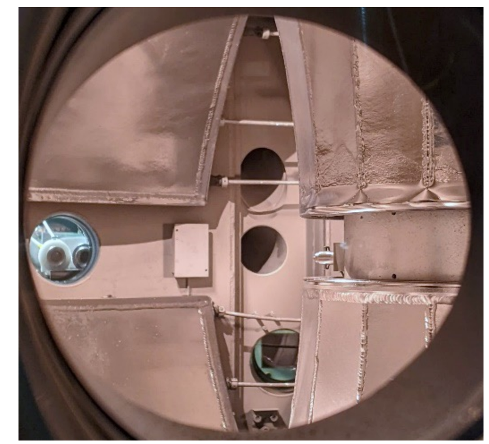
Achievement of key steps toward low-recycling, liquid lithium fusion devices in the Lithium Tokamak Experiment-β





Dennis P Boyle, PPPL

S Abe, S Banerjee, R Bell, W Capecchi, L Delgado-Aparicio, D Elliott, M Francisquez, K Gan, C Hansen, E Jung, B Koel, P Krstic, S Kubota, M Lampert, B LeBlanc, A Maan, R Maingi, R Majeski, A McLean, J Menard, J Morales, E Ostrowski, V Soukhanovskii, K Tritz, G Wilkie, L Zakharov

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LTX-β achieves key prerequisites for low-recycling fusion

LTX-β

- Liquid Li a possible solution to the biggest problems in fusion
  - Power handling + Higher confinement
- Key idea: Low $\boldsymbol{R}$ → Hot edge, $\boldsymbol{T}_{\mathbf{edge}}/\boldsymbol{T}_{\mathbf{core}}$ ~ 0.5-1; ~Flat $\boldsymbol{T}$

New Results:

- High confinement 1.5-2x H98 in ohmic discharges w/o pedestal
- Flat $\boldsymbol{T}_{\mathbf{e}}$ profile sustained with steady density
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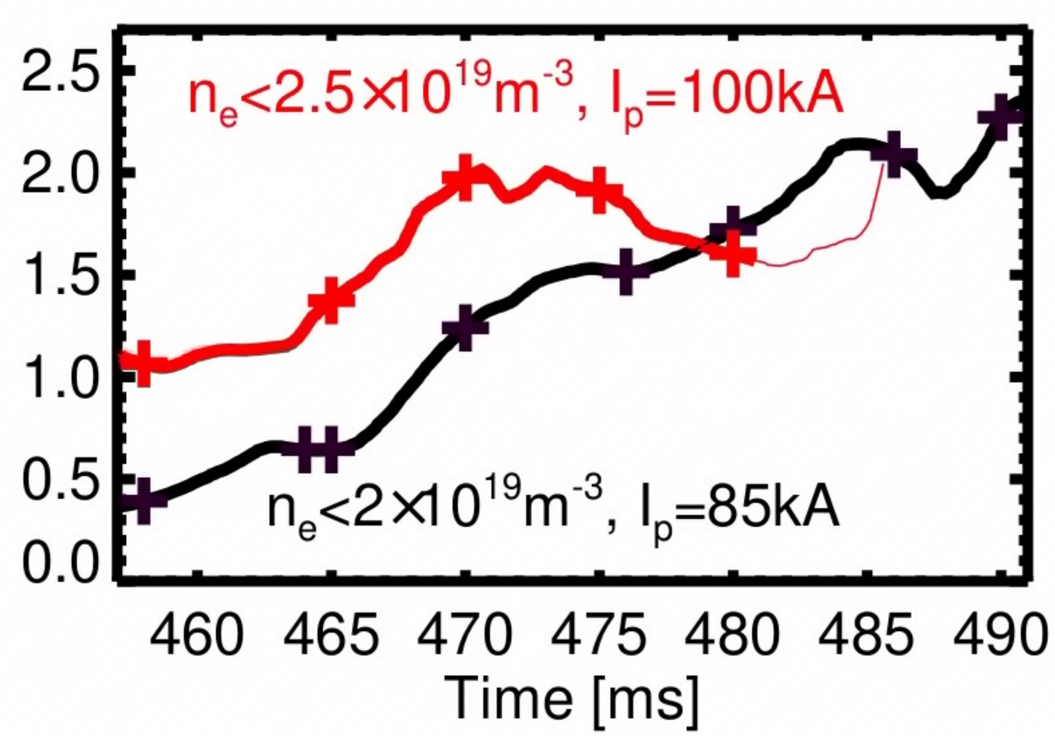
High τ_E exceeds scalings, 2x H98 and 3-4x Linear Ohmic

LTX-β

- Sustained current flattops ~25-35 ms with tailored OH waveform
  - Lower, longer I_p ~ 85 or 100 kA
  - Peaked T_e, not flat, due to higher gas fueling; solid Li
  - Stored energy ∝ density
- 2x H-mode τ_E w/o H-mode pedestal
  - Stored energy from T_e+TRANSP w/ neoclassical ions matches equilibrium reconstructions w/ diamagnetic loop

τ_E / τ_{98y}

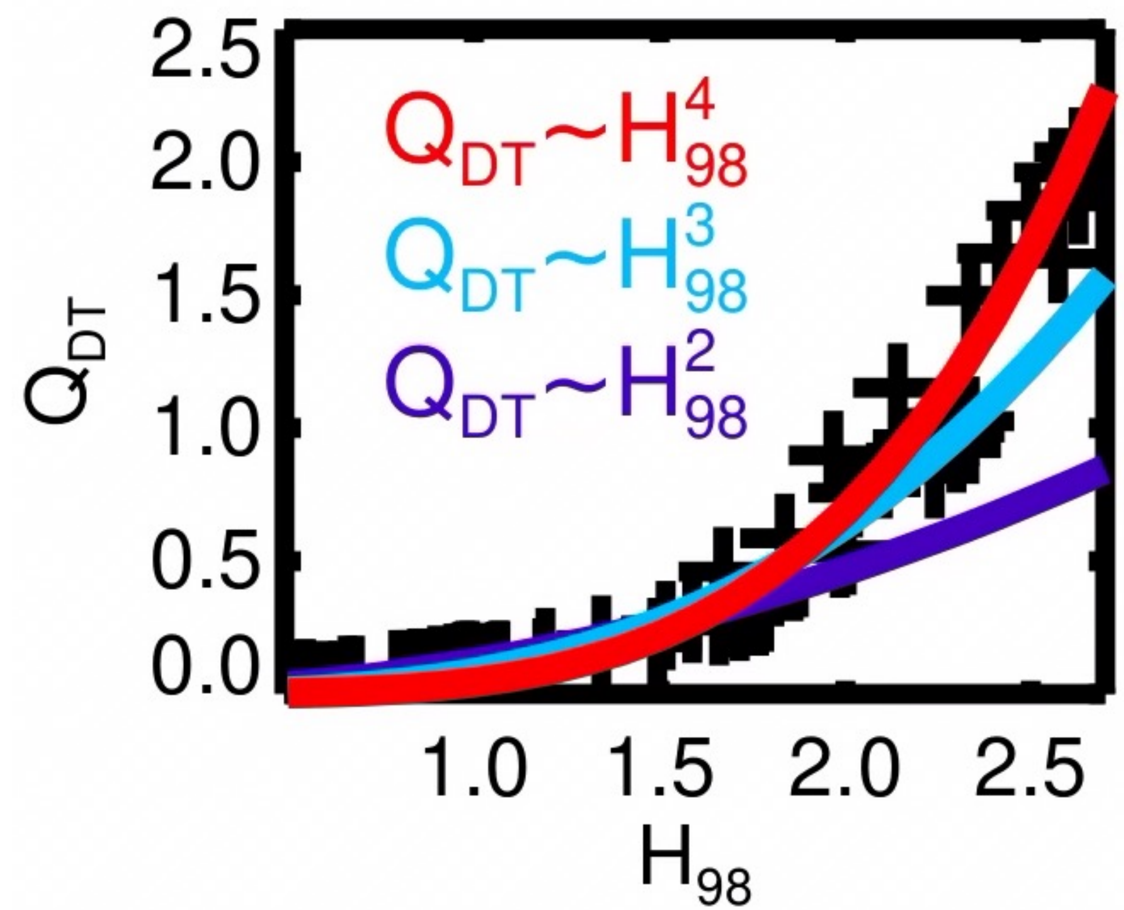


D.P. Boyle NF 2023

Motivation: Strong confinement effect on fusion Q_{DT}~$H^{2\text{-}5}$

- Improving confinement relative to scalings would greatly reduce cost of fusion

- LTX and LTX-β achieved H98 ~ 1.5-2 with ohmic heating using lithium coatings



Data adapted from Menard, NF 2016

See also Menard, Phil. Trans. R. Soc. A 2019

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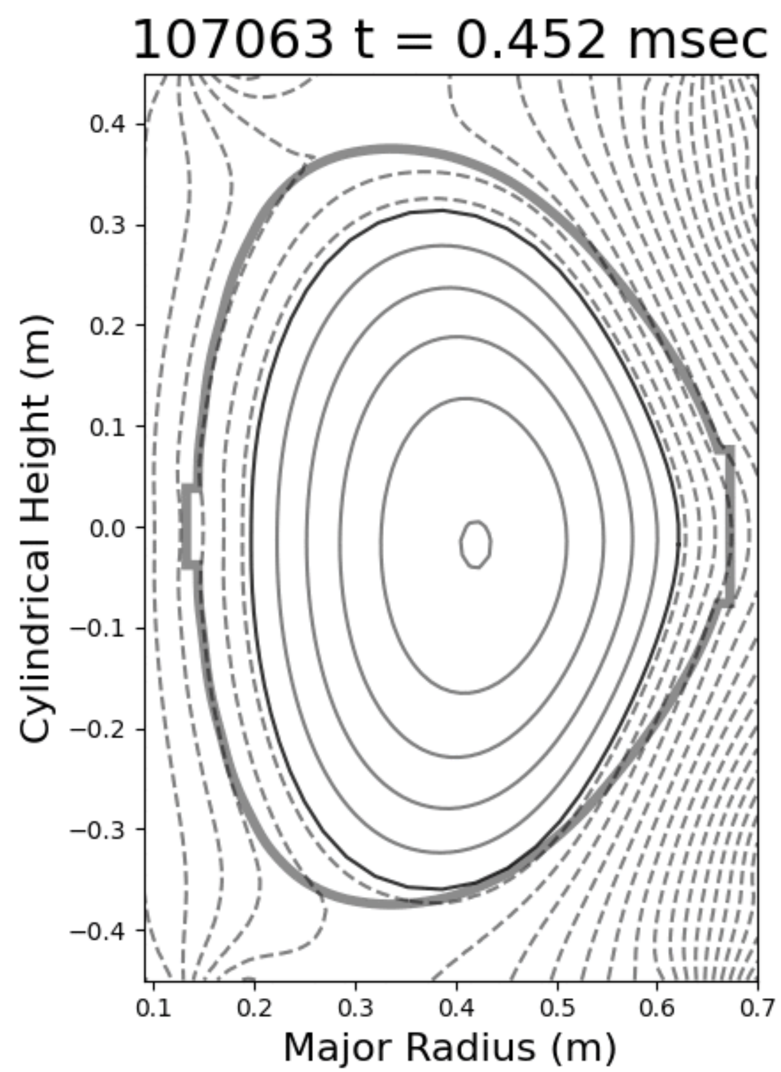
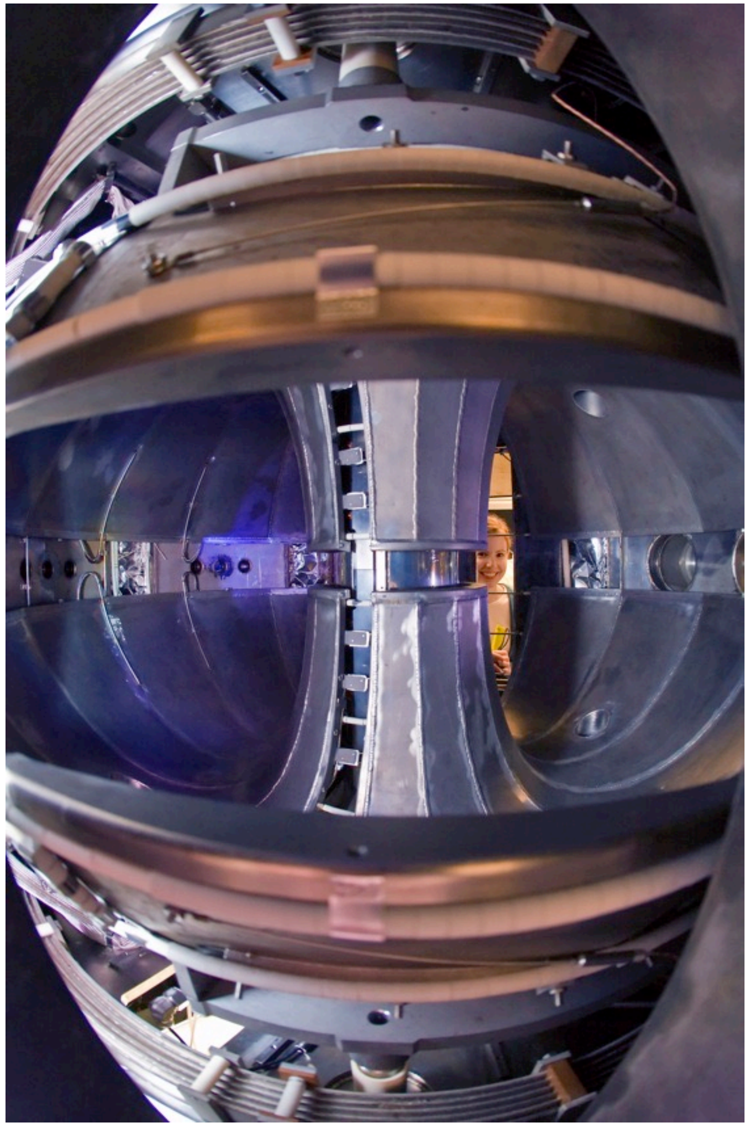
LTX-β is a modest sized spherical tokamak with unique walls

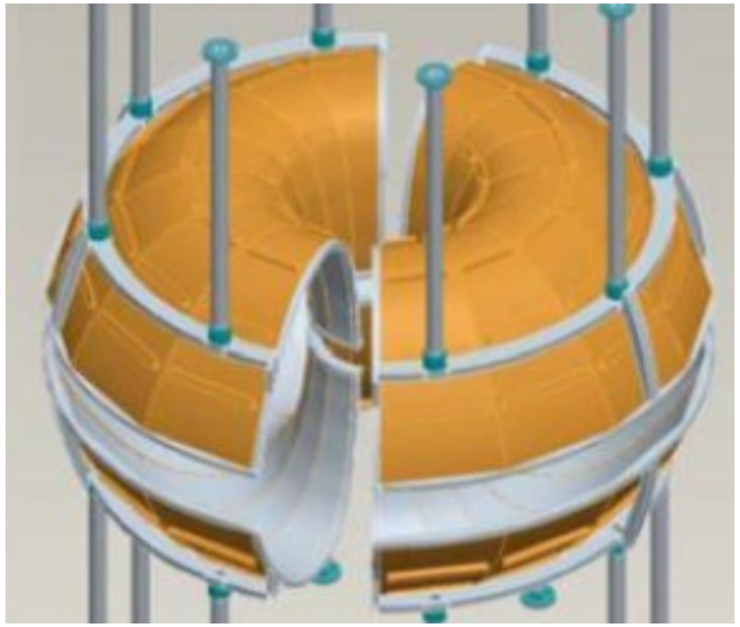
Maximum Parameters		LTX-β
Major Radius	R	40 cm
Minor Radius	a	26 cm
Toroidal Field	B_T	0.3 T
Plasma Current	I_p	135 kA
Flattop Duration	t_{flat}	~35 ms

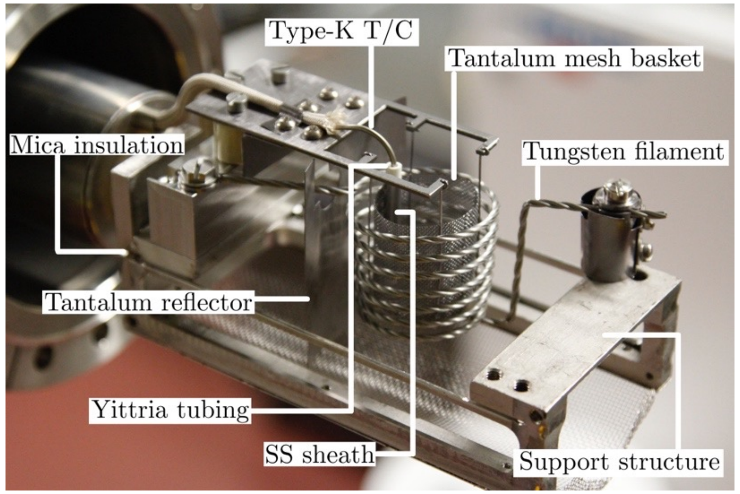


Lithium on stainless steel shell surrounds LTX-β plasma

- Covers ~80% of plasma
- Can be entirely Li coated
- 1.5 mm SS PFC liner
  - 1 cm Cu base, Ni plated
- **Heat to 270 – 350 °C**
  - **Lithium liquefies at ~180 °C**
- Toroidal and poloidal breaks
  - 4 shell quadrants



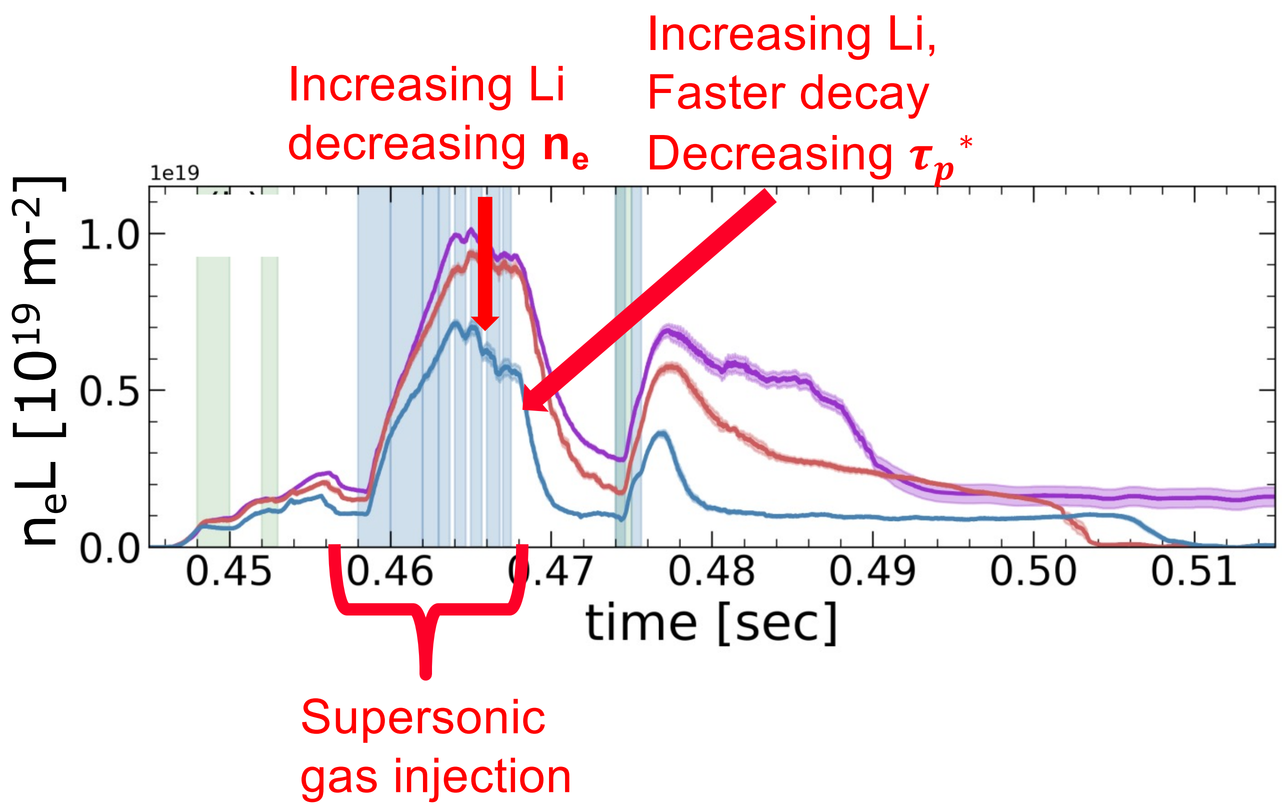




LTX-β Lithium evaporator

Low recycling Li coatings cause rapid density pumpout

- ***R***=flux out of wall / flux into wall
- With constant fueling, more Li → lower n_e
- When external fueling is turned off, density decays ~exponentially
- $\boldsymbol{\tau_p^* \equiv \frac{\tau_p}{1-R} \approx N / \frac{dN}{dt}}$
- ***R*** and $\boldsymbol{\tau_p}^*$ reduced w/ increased Li

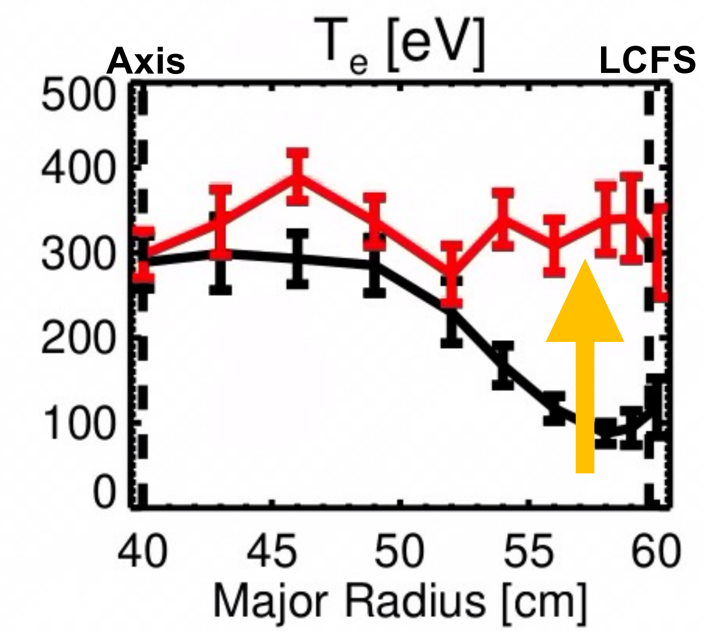


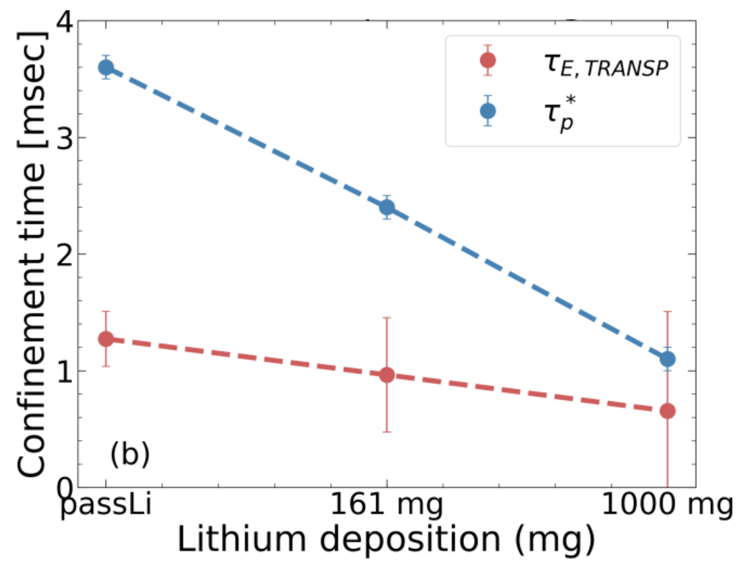
A. Maan APS DPP 2022 Invited, PoP submitted

Friday AM Poster [YP11.047](YP11.047) Anurag Maan

W/o edge neutral cooling, plasma hot all the way to the wall

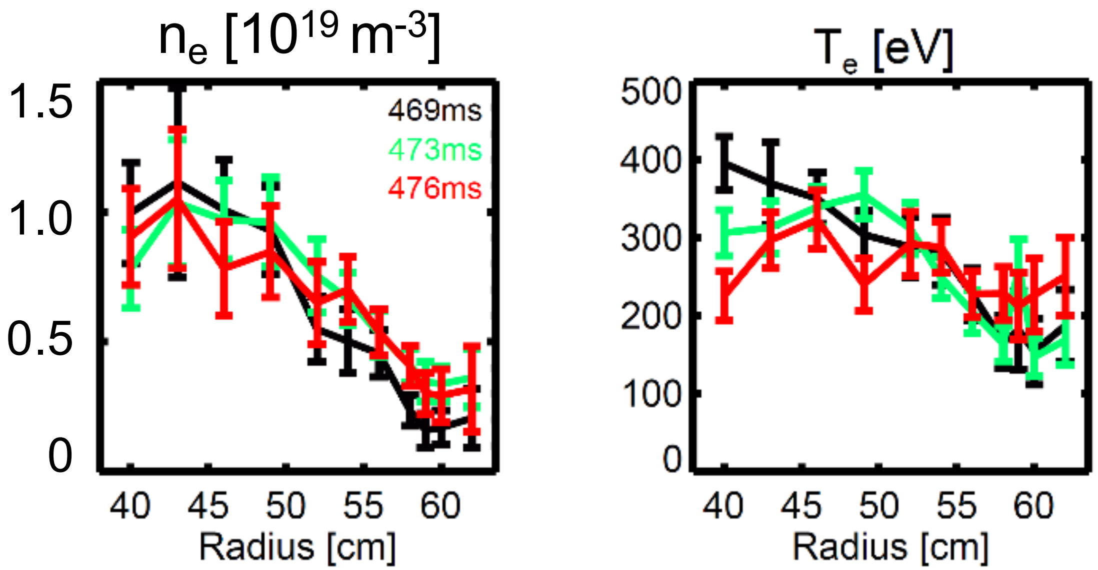
- Suppressing ∇T suppresses drive for ETG/ITG turbulence
  - All losses are from particle convection, not thermal conduction
- LTX saw first flat T_e, hot edge w/ low recycling & high τ_E
  - Long standing prediction
    - » Krashnenikov PoP 2003
    - » Zakharov FED 2004
- LTX-β first measurement of very low R~0.5 coinciding with flat T_e



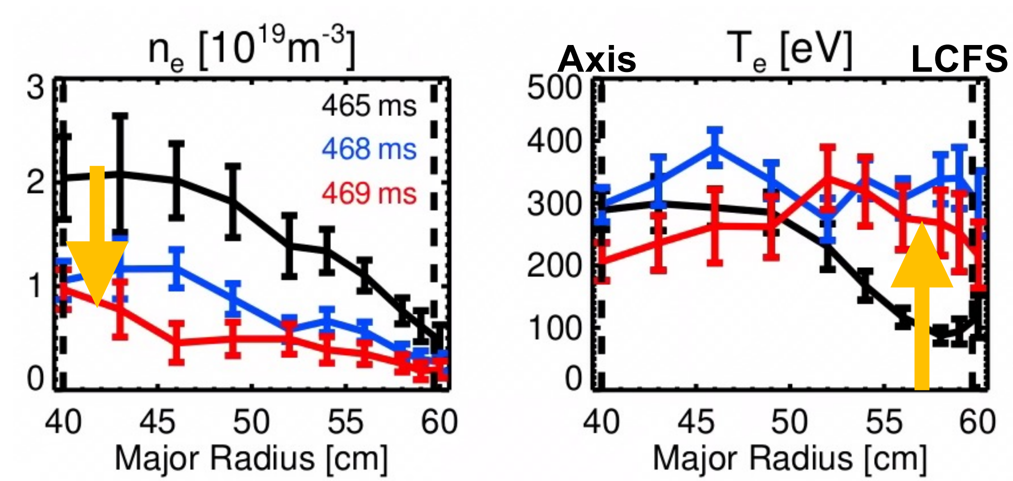


Anurag Maan
PoP submitted,
DPP 2022 Invited
Friday AM
Poster YP11.047

LTX-β: Low-recycling flat T_e profiles sustained for several τ_E



- Flat T_e sustained with steady, moderate fueling, n_e ~10^{19} m^{-3}
  - n_e limit for MHD tearing mode stability & flat T_e coincides



- Previously, flat T_e only with decaying n_e after fueling stopped
  - To further extend low-recycling regime, need to sustain density

D.P. Boyle NF 2023, S. Banerjee NF submitted

Friday AM Poster YP11.043: Santanu Banerjee

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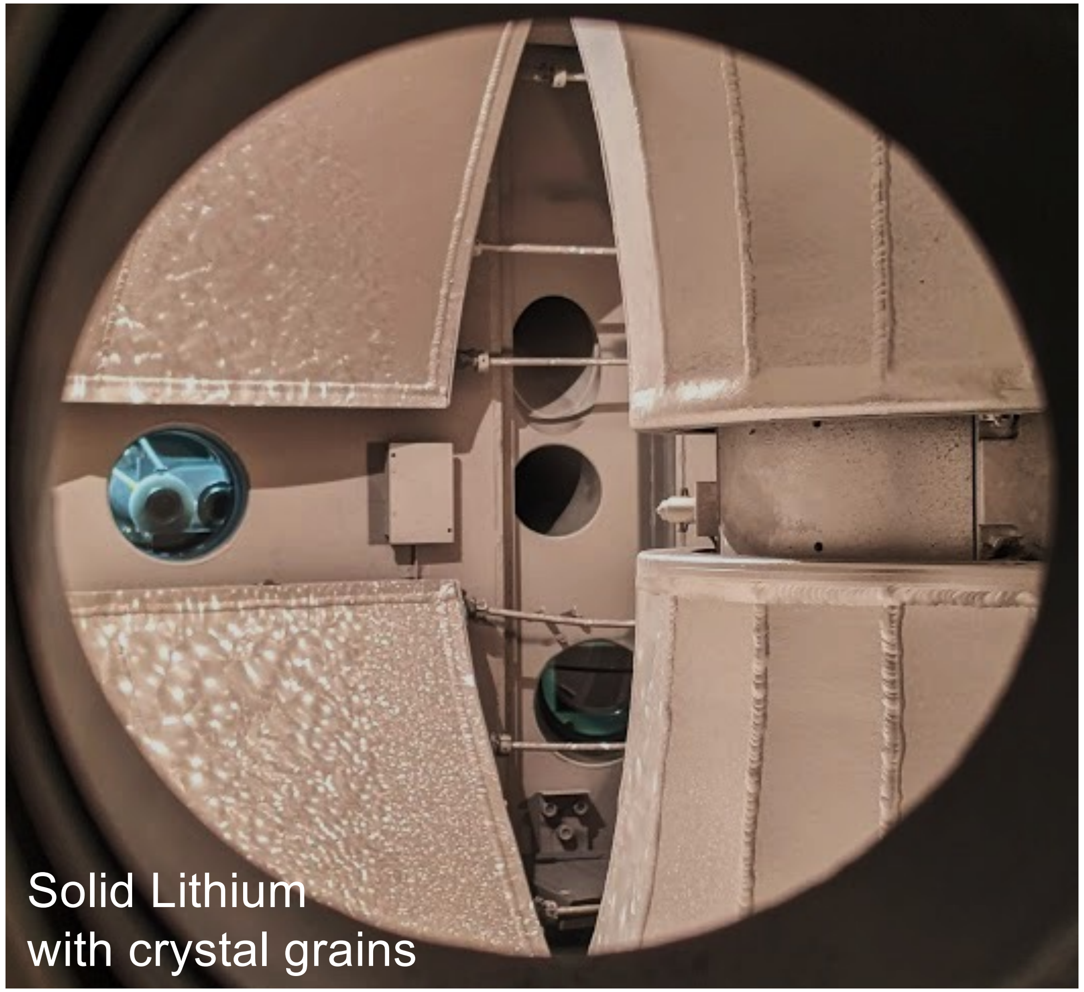
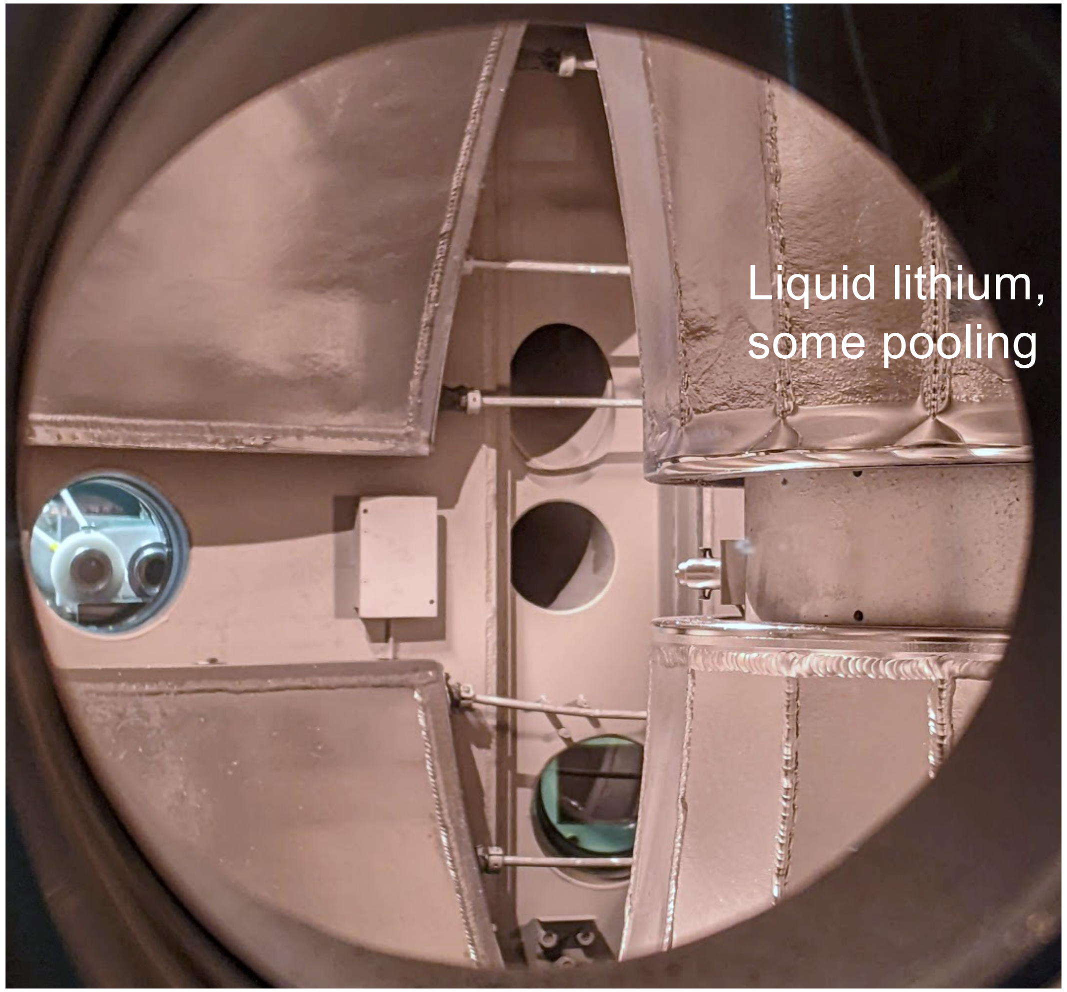
- NBI heating and fueling in very low recycling discharges

LTX/LTX-β first & only tokamak with full **liquid** walls

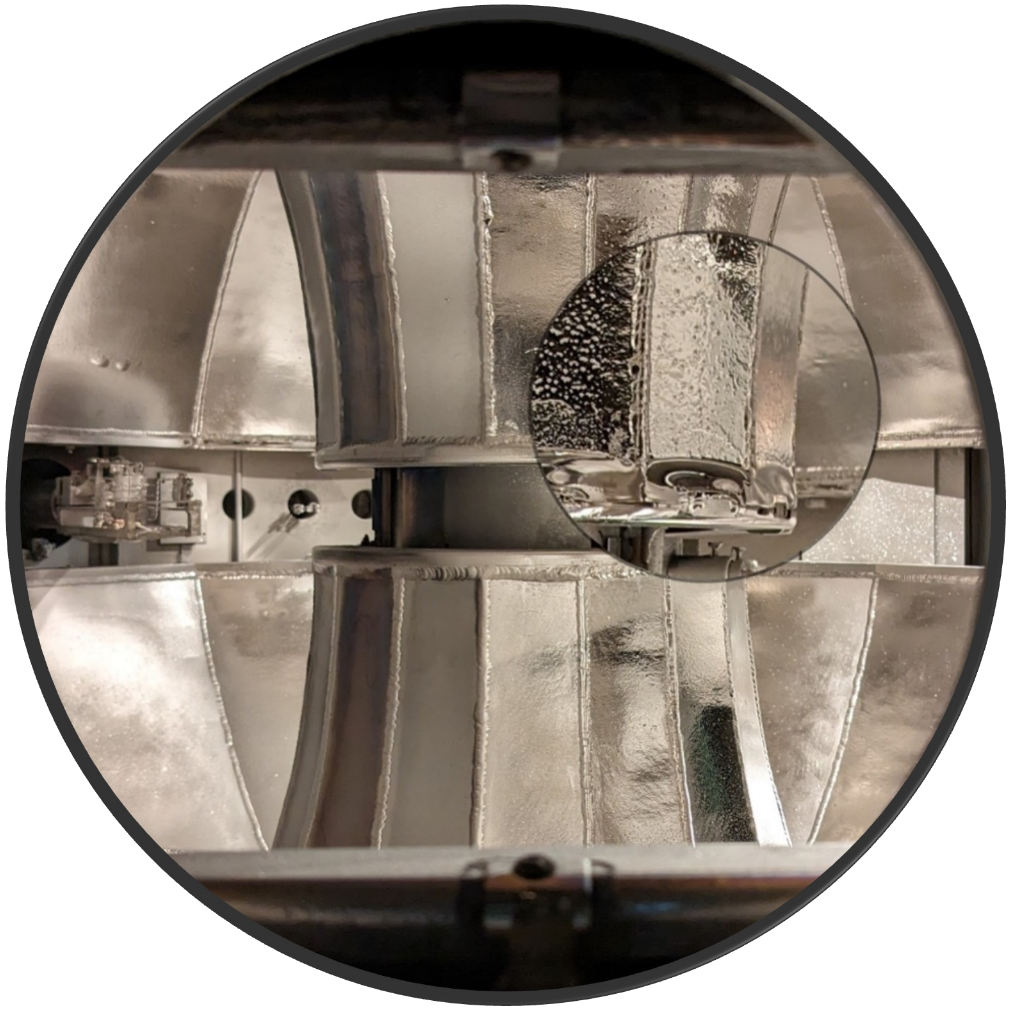
- Motivation: Liquid metals robust and self-healing
  - Survive high heat and particle fluxes in a fusion reactor



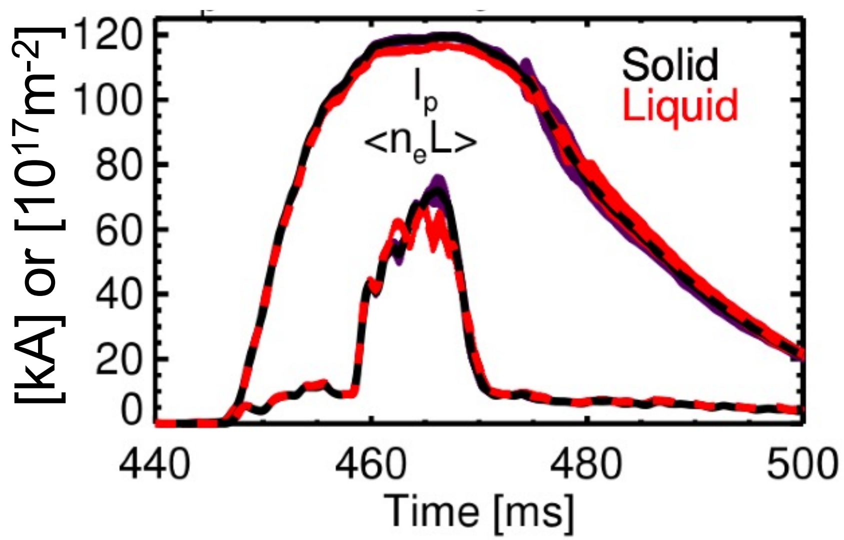


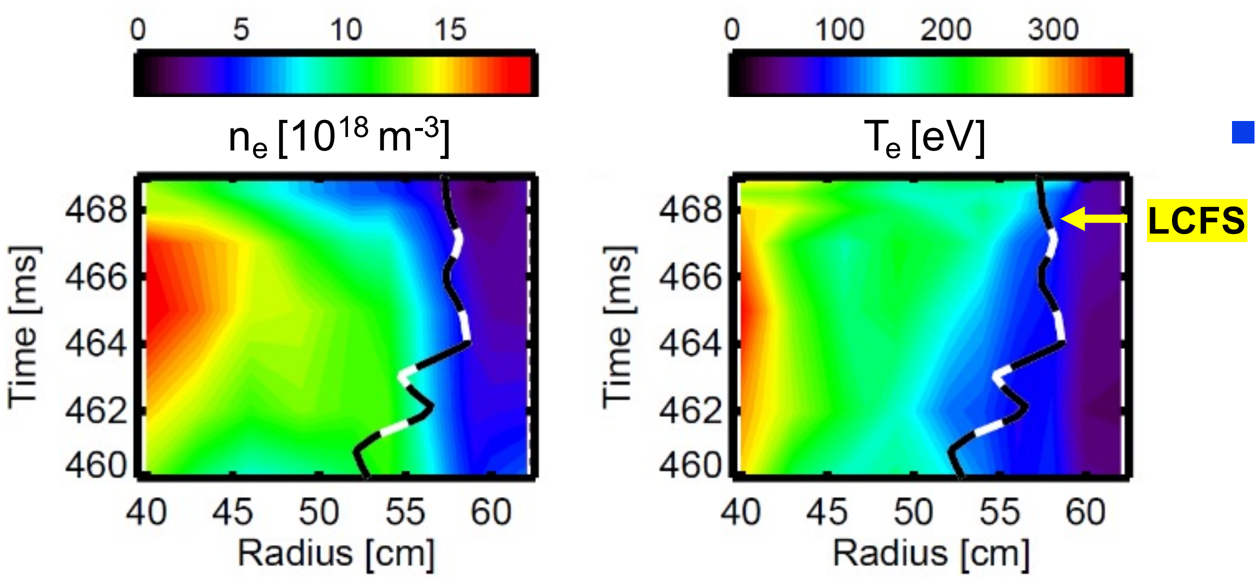
Reliable tokamak operations with a liquid lithium wall

- Liquid wall stable during discharge – no droplet ejection
  - Lots of conditioning + 5 years in vacuum = Visibly clean liquid surface


Low-recycling flat T_e profiles achieved with liquid Li walls

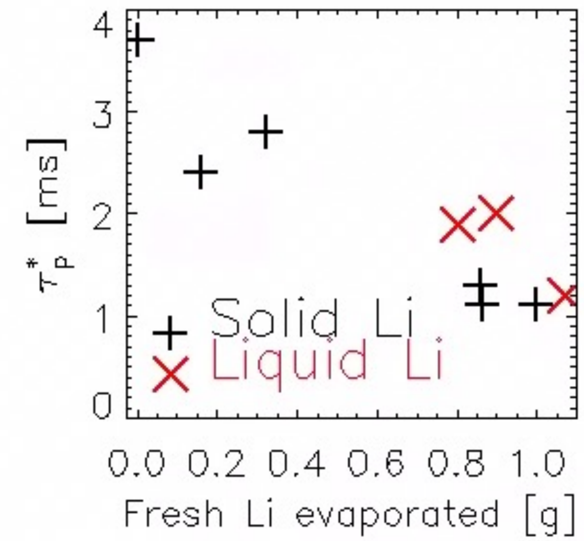


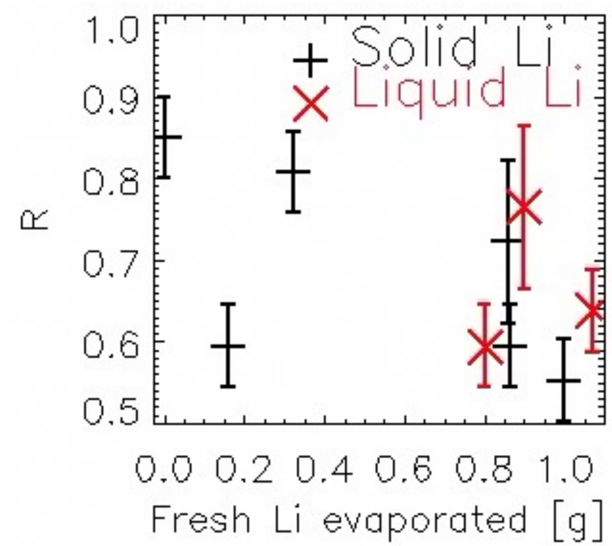


- With clean, shiny liquid Li on ~200 °C shell, performance is similar to solid Li
  - Rapid n_e decay without fueling
- Hot edge, relatively flat T_e profile reproduced with clean liquid Li

Very low *R*~0.6 measured with liquid Li using Ly-α + DEGAS2

- Previously, increasing solid Li shown to reduce ***R*** and $\boldsymbol{\tau_p^*}$
  - Solid ***R*** seen below ~0.6
- Same DEGAS2 and $\boldsymbol{\tau_p^*}$ analysis performed for liquid Li shots
  - Based on Lyman-α profiles, plasma profiles and equilibria
- Similar very low ***R***~0.6 now seen with liquid Li as solid Li

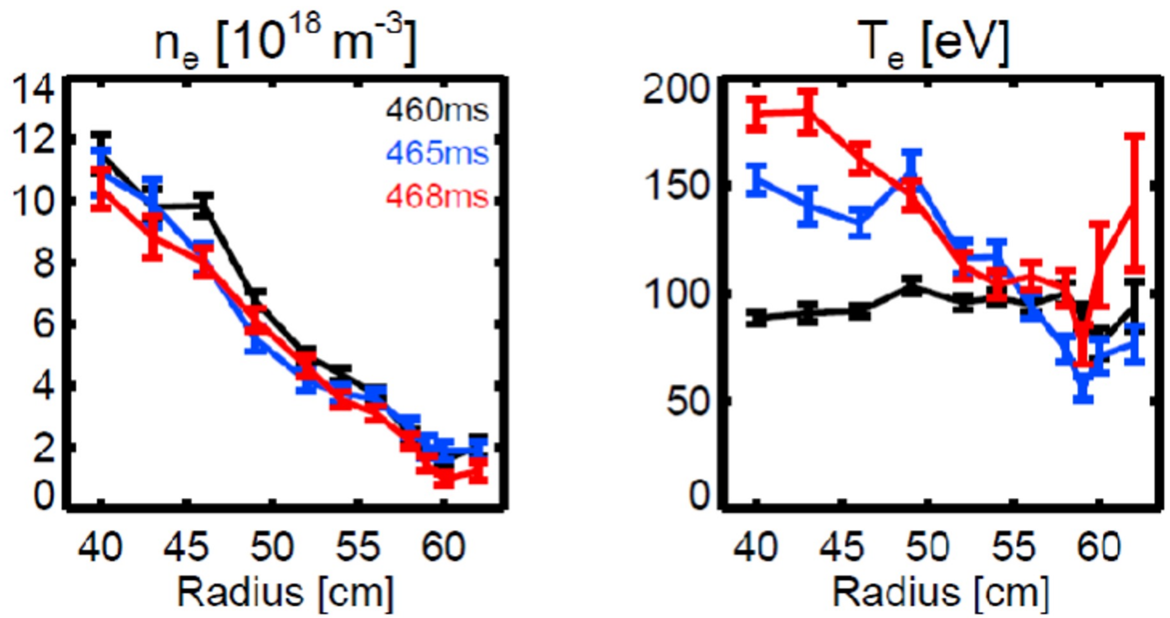




A. Maan APS DPP 2022 Invited, PoP submitted

Friday AM Poster YP11.047 Anurag Maan

Sustained flat T_e profiles also with liquid Li walls



- Liquid Li on ~200 °C shell
- Low $\mathbf{I_p}$ ~ 60 kA LTX-β discharges

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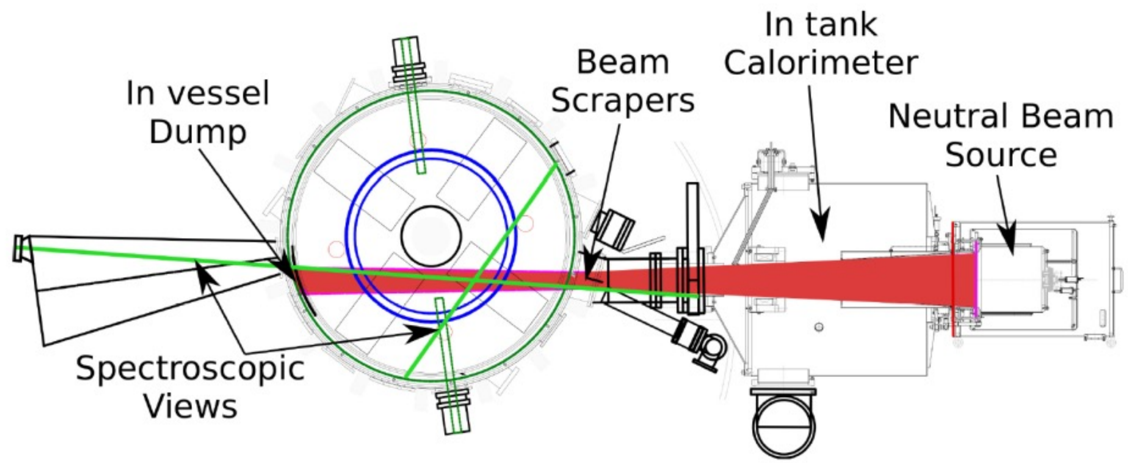
LTX-β explores auxiliary power in low-recycling regime

- Key motivation: W/o ∇T, is power degradation of confinement suppressed?
- Also key: Test NBI core fueling
  - Extend very low recycling regime to higher performance
- Have overcome initial challenges with fast ion losses on close-fitting shell

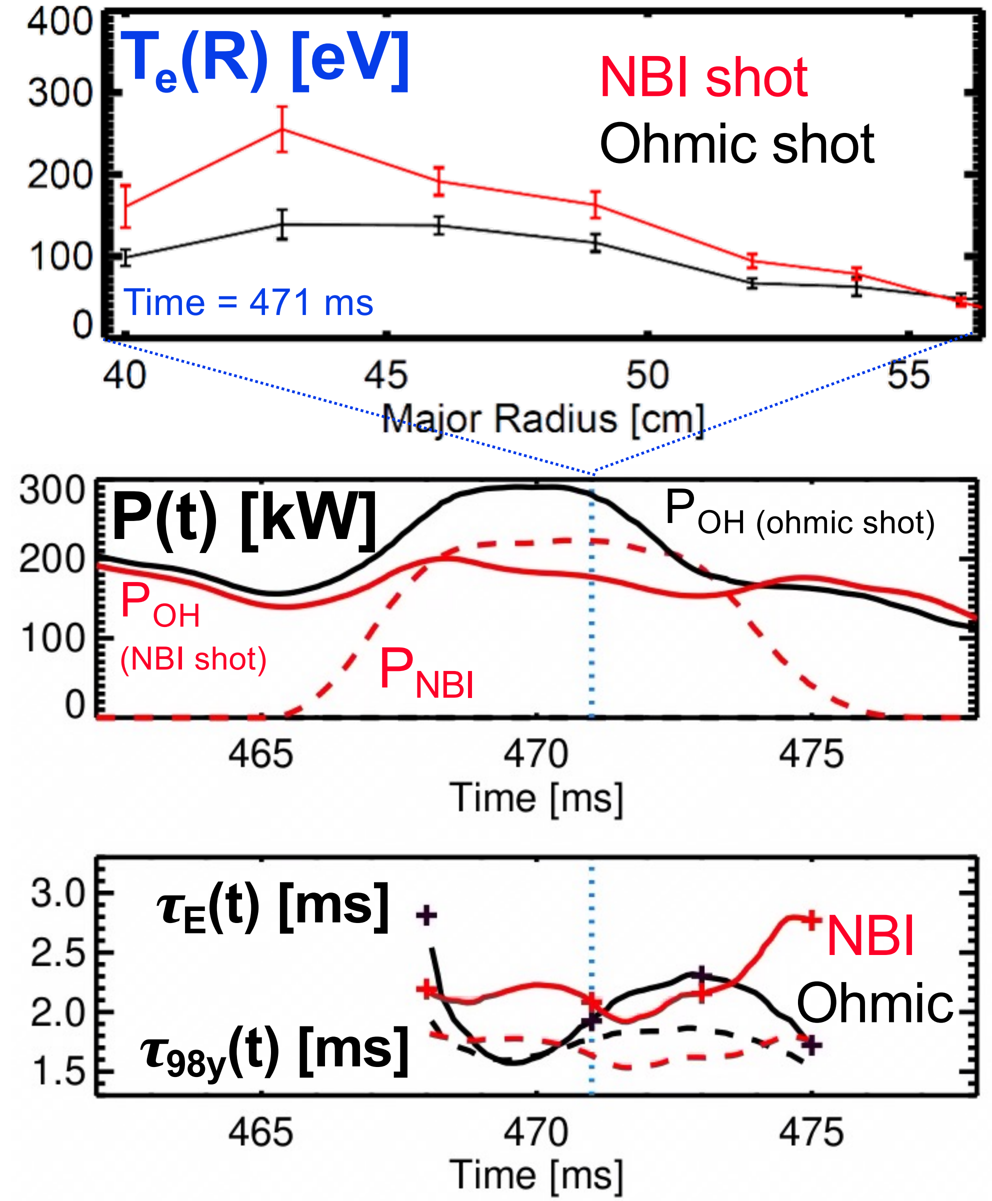


William Capecchi NF 2021
Friday AM Poster YP11.044

Parameters		LTX-β
Neutral Beam Current	I_{nbi}	~35 A
Neutral Beam Energy	E_{nbi}	13-20 keV
Neutral Beam Duration	t_{nbi}	5-10 ms

With peaked T_e, no apparent τ_E degradation with $P_{NBI} \geq P_{OH}$

- Initial challenges with fast ion confinement overcome
  - $I_p > 100$ kA
  - NBI less inboard
  - Plasma axis farther in
  - $E_{NBI} \rightarrow 13$ kV
- Need relatively dense, cool plasma to absorb beam, slow the fast ions
  - Solid lithium used in these results
  - Continuous fueling for high n_e, low T_e
- T_e increases across (peaked) profile



DP Boyle et al Nuclear Fusion 63 (2023) 056020

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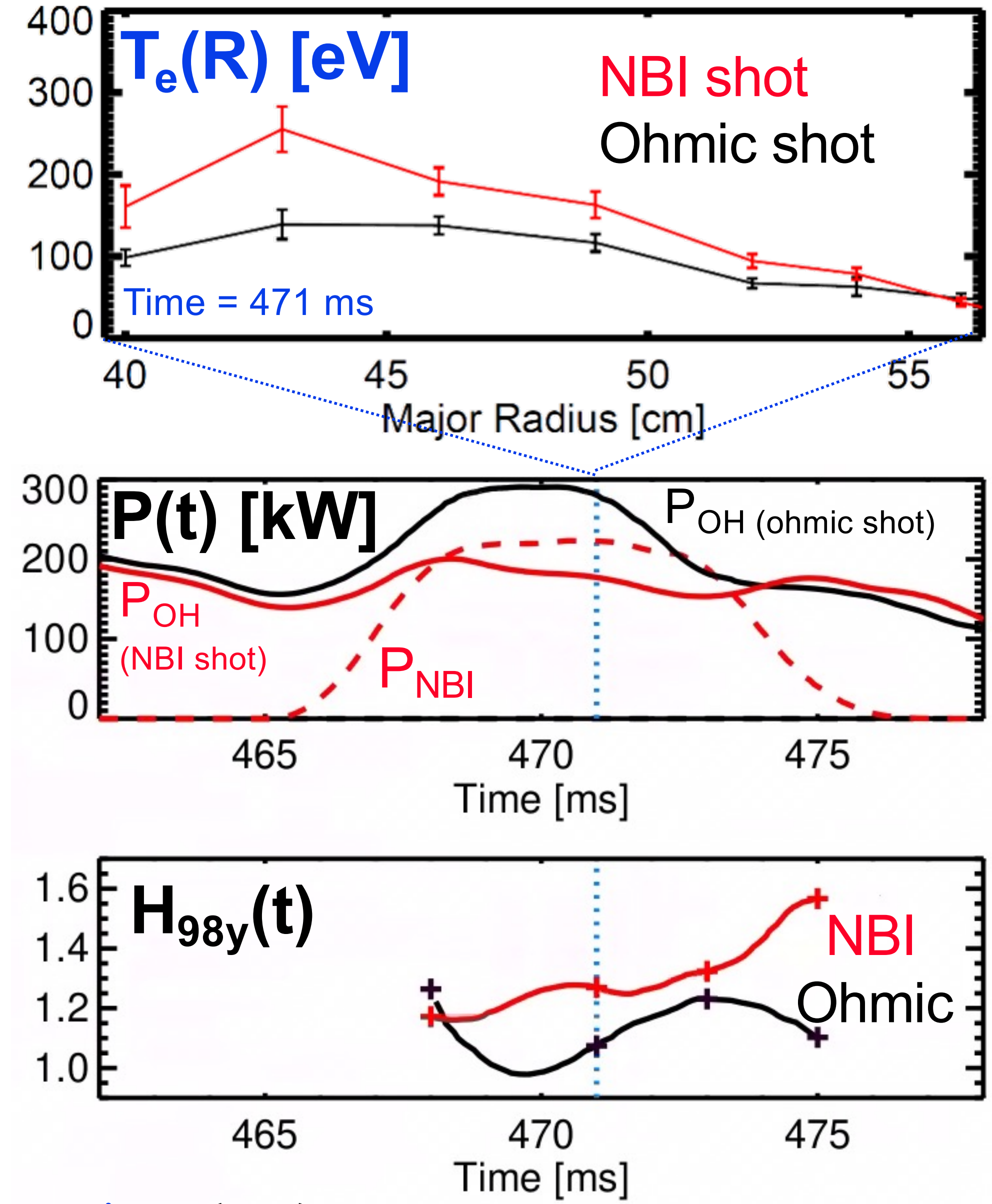
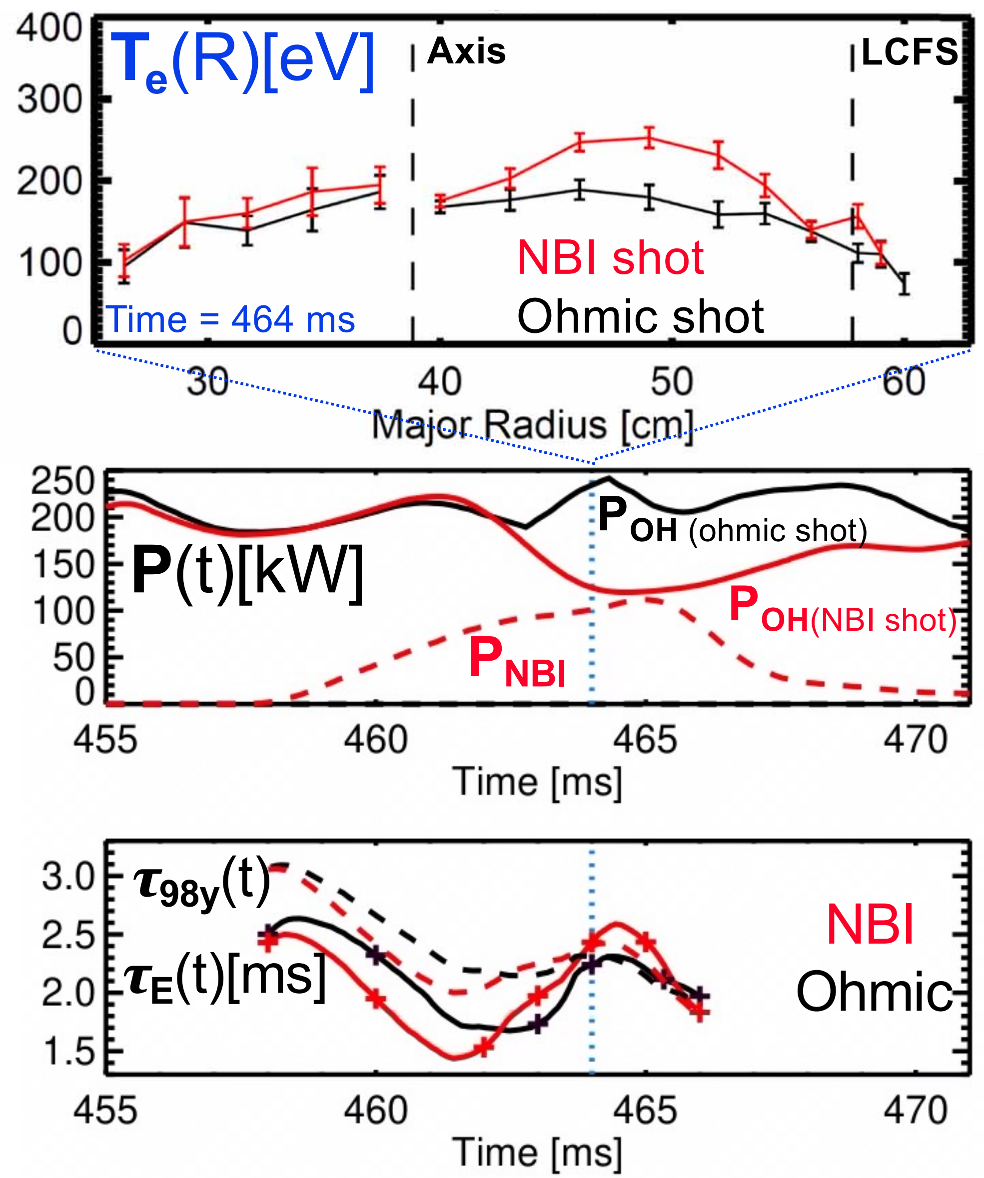


DP Boyle et al **Nuclear Fusion** 63 (2023) 056020

NBI-heating maintains relatively flat, broad T_e profiles

- Generally difficult to get flat T_e + high n_e
  - Extra fueling during I_p ramp allows NBI heating with $T_{edge} \sim T_{core}/2$
  - Solid lithium used in these results
- τ_E similar or better with NBI
  - No apparent degradation with P_{NBI}
  - Overall similar to scalings
- However, $P_{NBI} < P_{OH}$
  - NUBEAM estimates that most NBI power does not couple to plasma
    - » ~170 kW first orbit loss, ~40 kW shinethru, CX



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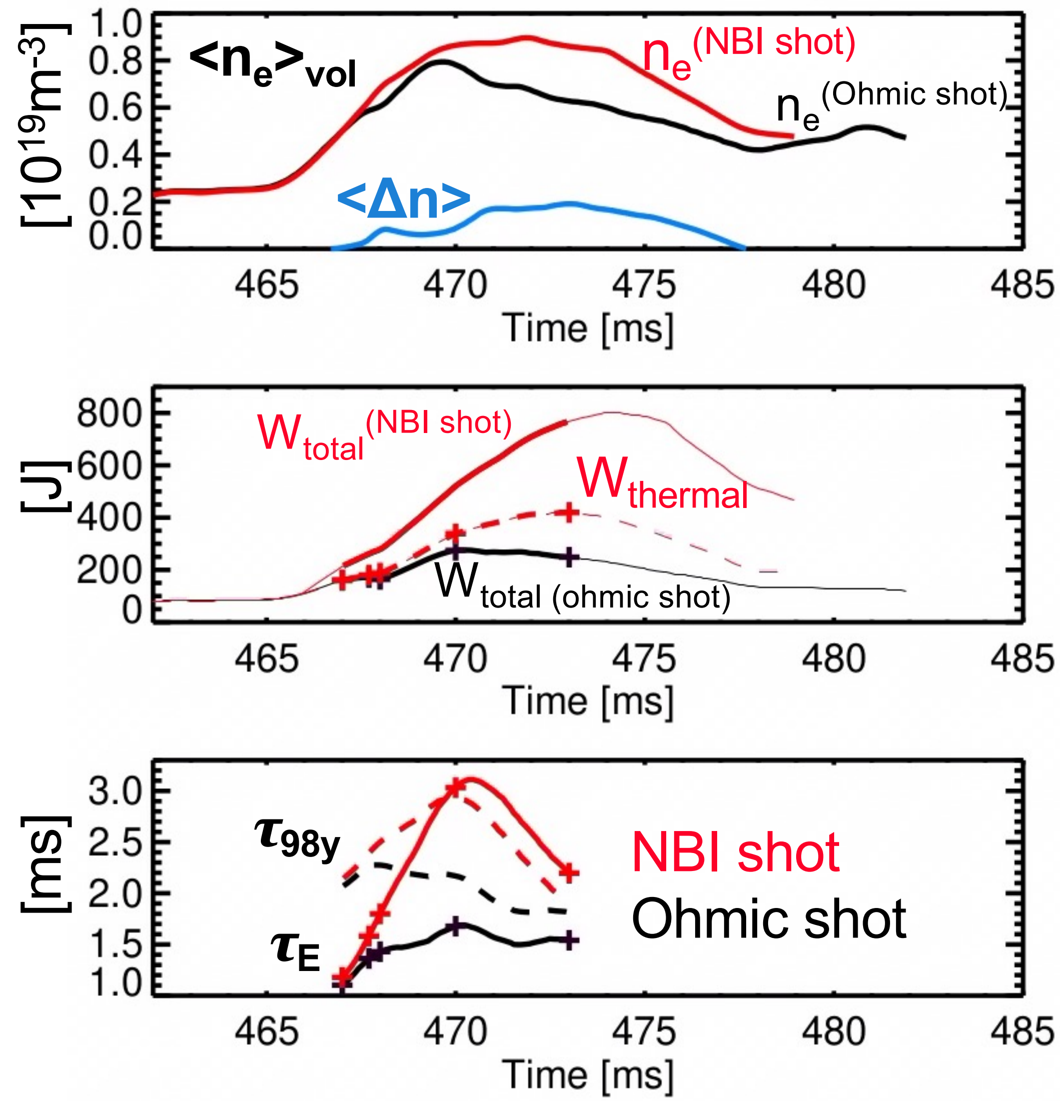
With liquid Li, NBI fueling ~20% density increase

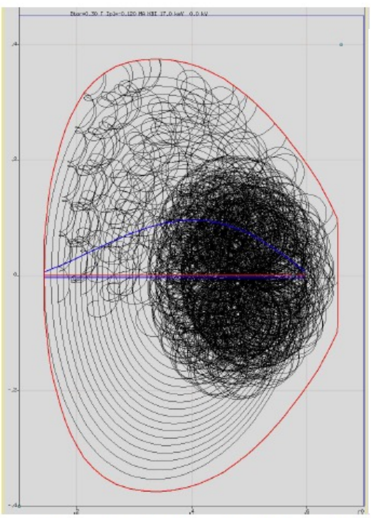
- Core fueling important for low-***R***
  - Consistent but small NBI fueling also demonstrated with solid Li
  - H-H^+ CX → little net fueling
- NBI CX on higher Liquid Li impurity fraction may help fueling
  - ~8-10x Li III emission liquid vs solid
  - Li CX → fueling; cross section>>H
- n_e and T_e increase w/ NBI+liquid
  - TRANSP/NUBEAM: $P_{NBI} < P_{OH}$, P_{total} similar due to lower resistivity
  - High fast ion pressure, high τ_E > H98



Next step: Improved NBI coupling with larger R_{tan}

- Vent for calibrations, clean up, repairs, upgrades after **5 years** in vacuum
- Between shots Li, fueling, ECH breakdown, and plasma control
- Expanded and improved diagnostic set

2021

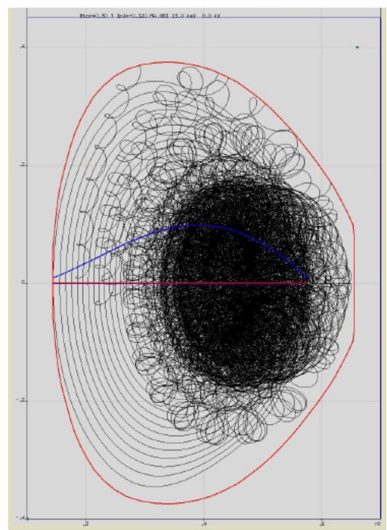


R_{tan}~17 cm
$R_{O\text{-}B}$~60 cm

>50% first orbit losses

E_{NBI}=17-20 kV

2022-23

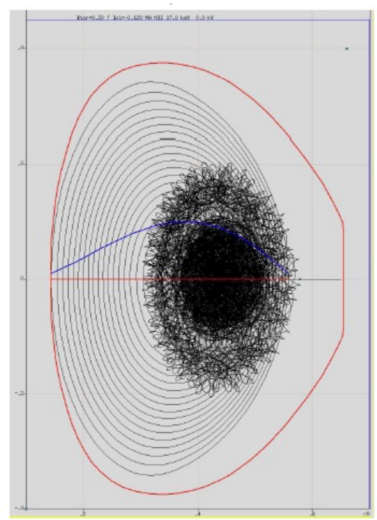


R_{tan}~24 cm
$R_{O\text{-}B}$~58 cm

~25% first orbit losses

E_{NBI}=13 kV
Reduced power

Post-vent



R_{tan}~33 cm
$R_{O\text{-}B}$~58 cm

~*No* first orbit losses

E_{NBI}=17 kV
~Full power

Extended duration

L. Zakharov, 3DOrb modeling, William Capecchi NF 2021, Friday AM Poster YP11.044

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- Flat $\boldsymbol{T}_{\mathbf{e}}$ profile sustained for several $\boldsymbol{\tau}_{\mathbf{E}}$ with steady density
- Hot, low-recycling edge (R~0.6) demonstrated with liquid Li walls
- NBI heating and fueling shown, $\boldsymbol{\tau}_{\mathbf{E}} \geq$ H98, no $\boldsymbol{P}_{\mathbf{NBI}}$ degradation

- Further upgrades to increase beam heating and fueling
  - Improved diagnostics and operations

- **Li provides possible solutions to both confinement and power handling**
  - Novel physics – no temperature gradient, collisionless edge, liquid PMI
  - **Low-recycling liquid lithium walls are a fundamentally different, potentially better, approach to magnetic fusion**

Lithium Tokamak Experiment-β Team, 2019

Thank you!