Neutral Beam Injection in LTX-β

Optimizing coupling, improving performance

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APS-DPP 2021, Pittsburgh PA

Supported by US DOE awards DE-SC0019006

Abstract

Prompt loss of beam injected fast ions approaches 100% in LTX-β discharges, though significantly improved confinement is expected for the higher current plasmas made available by a recent upgrade to the Ohmic Heating Power Supply. Modeling of fast ions using TRANSP/NUBEAM finds a maximum coupled beam fraction of 76% at the near-term limits of the LTX-β operating space. The full ion orbit code POET is employed to validate NUBEAM results against possible non-adiabatic effects on fast ion orbits, but corrections to the prompt loss fraction due to collisionless transport are found to be small. The graphical method code CONBEAM is used to investigate the topology of fast ion phase space as it relates to neutral beam deposition, and counter-injected NBI is considered as a way to access a region of high field side beam deposition. A metric is developed within the CONBEAM using a beam filament model to estimate the prompt loss fraction and shown to agree well with both POET and NUBEAM, enabling near real-time analysis and potential feedback to operators between plasma discharges.

Motivation

- LTX- β provides testbed for study of energetic particles (EPs) in low-recycling boundary plasmas
- Fueling essential for plasma sustainment during low-recycling phase (no gas puffing)

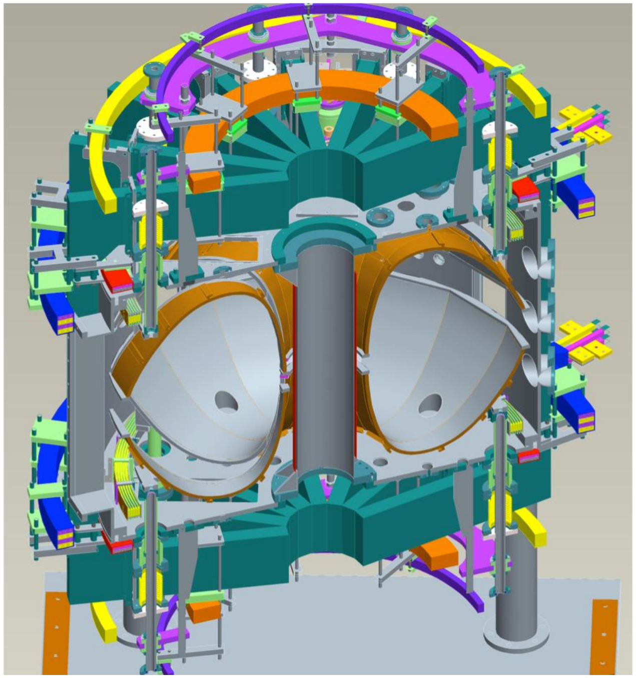
[Elliott D. et al 2020 IEEE Trans. Plasma Sci. 48 1382–7]

- Auxiliary heating probes energy scaling in low-recycling plasmas previously observed to exceed ITER98P(y, 1) ELMy H-mode scaling by factor of 3

[Kaita R. et al 2007 Phys. Plasmas 14 056111]

- Lithium coated first wall via evaporation led to observation of flat T_e profiles

[D Boyle et al., *PRL* **119**, 015001 (2017)]



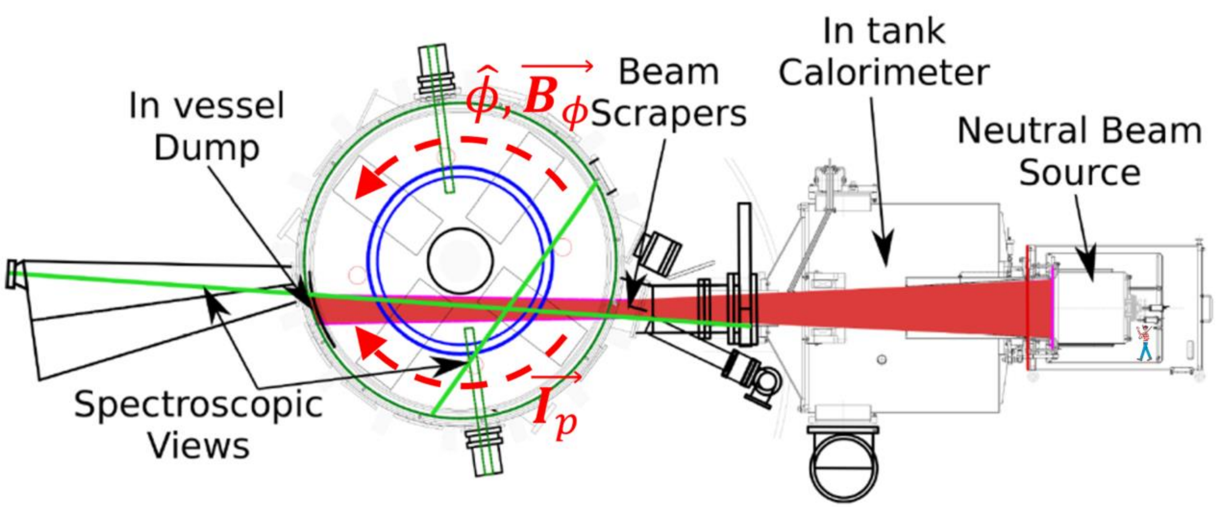
Lithium Tokamak Experiment Beta
R=0.4 m; a=0.25 m
I_p ~ 100 – 150(?) kA
|B| ~ 0.3 T
$T_e(0)$ ~ 200-300 eV
n_e ~ 5×10^{13} cm^{-3}
Pulse length ~ 50 ms

Outline

- Modeling of NBI on LTX (<100 kA) plasmas shows near total prompt loss of beam ions due to large drift and insufficient poloidal field
- Upgrades enabling >100 kA plasmas result in modeling predictions of good confinement and beam heating
- Experimentally, no evidence of beam heating led to investigation of NBI performance which revealed only ~20% of NBI power entered vessel
- Improvements to beam operation has improved power into vessel up to 45% with work in progress to increase this further
- Low throughput to vessel may account for lack of experimental evidence of beam heating
- Other sources of reduced beam heating (3d field effects, instabilities, etc.) are being investigated

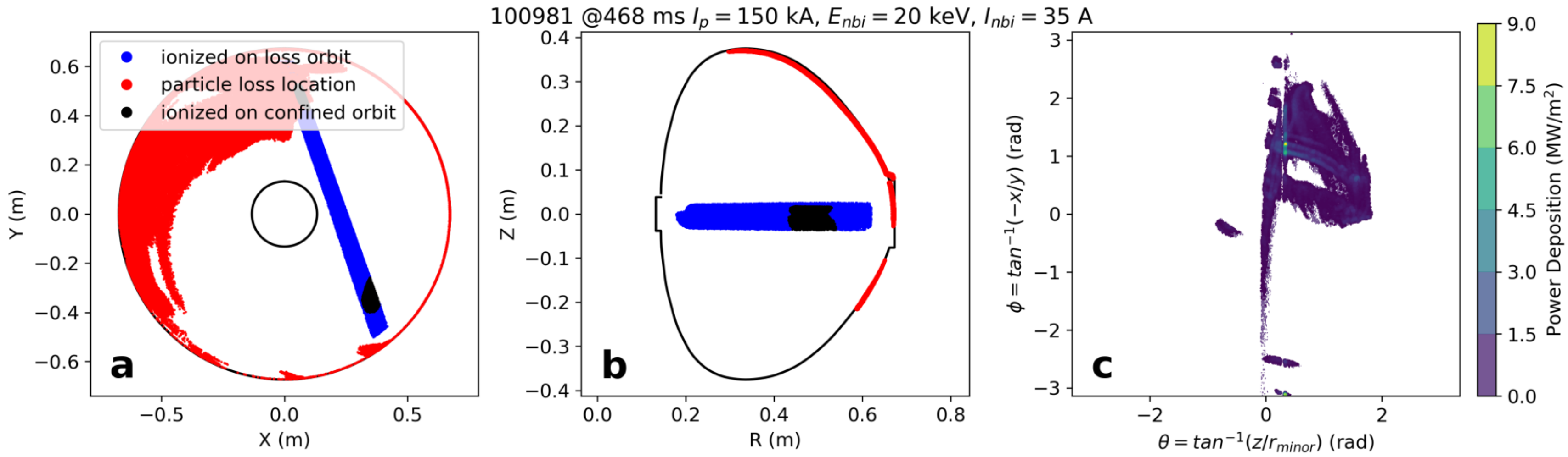
(near) Total prompt loss in < 100 kA plasmas

- Nominally co-injected with plasma current (I_p can be reversed), counter-injected to B_ϕ
- With typical $R_{mag} = 40$ cm, beam tangency radius of 21 cm, beam path half low-field half high-field side of magnetic axis
- Typical pitch near $p = {}^{v_\parallel}/_{v} = -0.5$, range $p \in (-1,0)$
- Modeling shows shine-through and prompt loss account for nearly 100% of injected beam



NBI Parameter	Specification
Beam energy	20 keV
Beam power	700 kW
Pulse length	5-7 ms
Composition	100% H

- Poloidal field insufficient to confine particles against large ∇B and curvature drift
- Anisotropic "spray" pattern leads to highly localized heat flux up to 8 MW/m^2

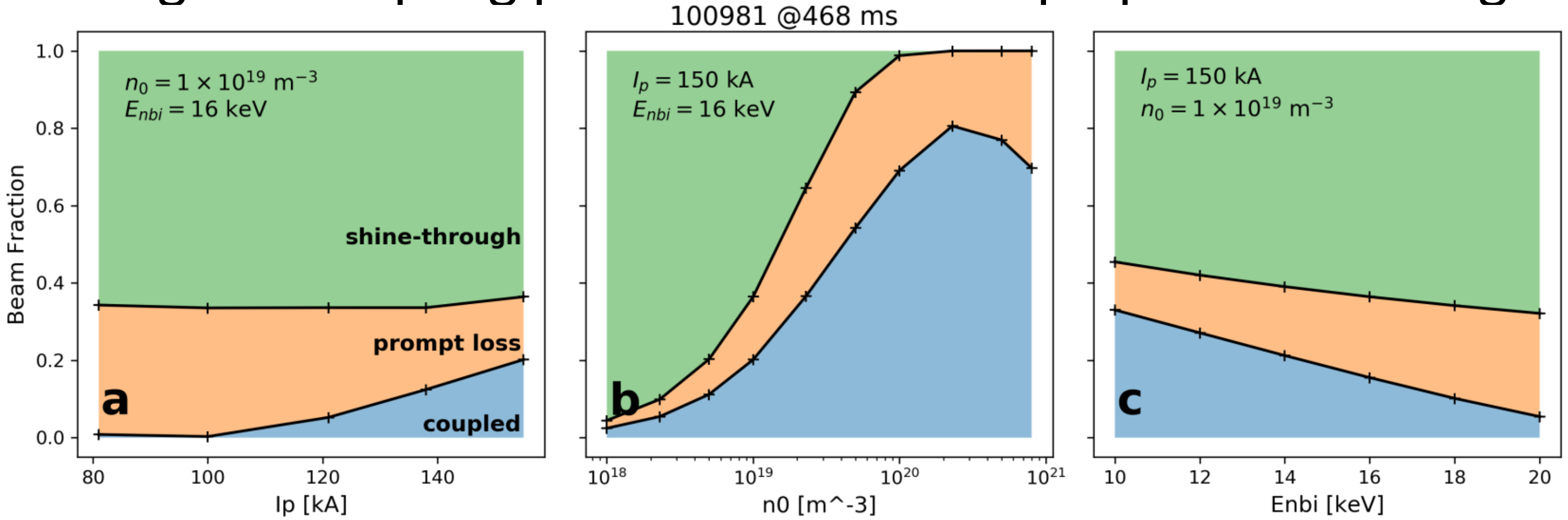


- Shell deposition sensitive to equilibria geometry
- Counter-NBI torque observed due to prompt loss

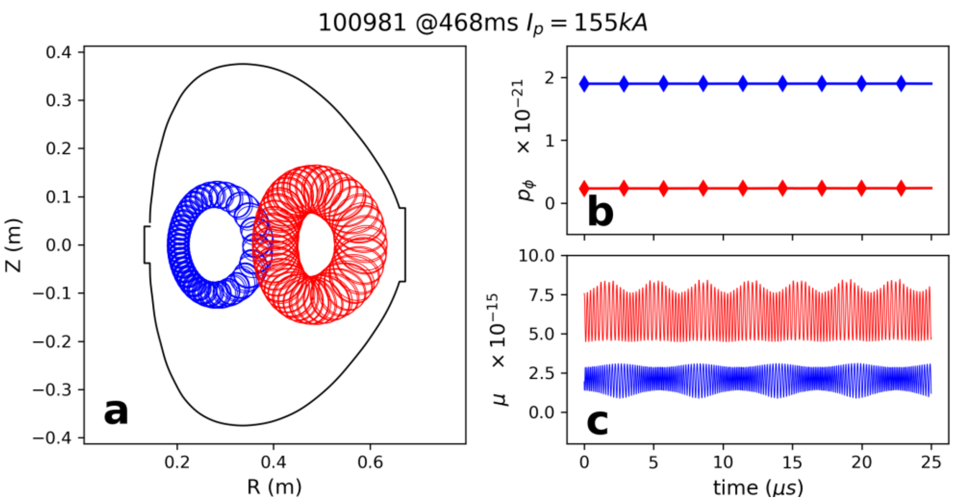
[P E Hughes et al 2021 Plasma Phys. Control. Fusion 63 085020]

Modeling tools for beam coupling improvement

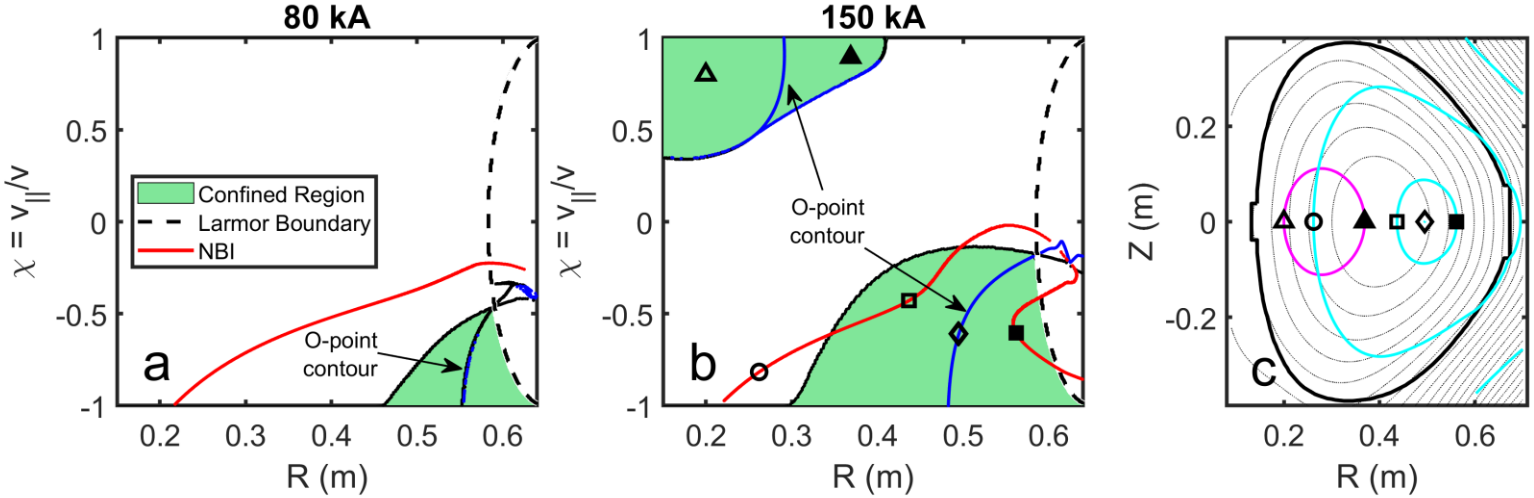
- **TRANSP**: sensitivity to plasma current, density, beam energy shows good coupling possible within LTX-β operational range



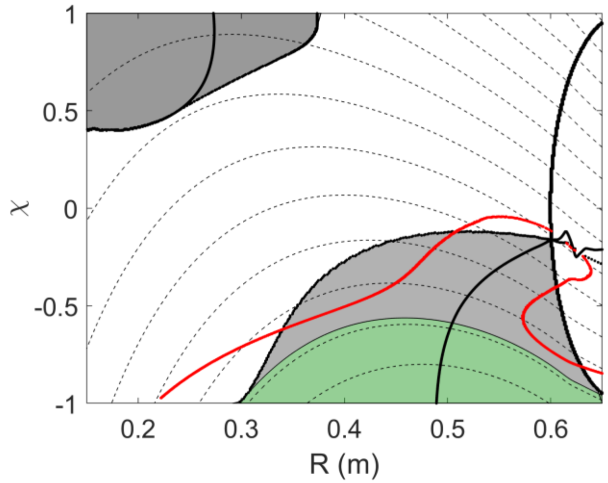
- **POET**: full ion orbits predict first wall load, no significant loss enhancement due to non-adiabaticity

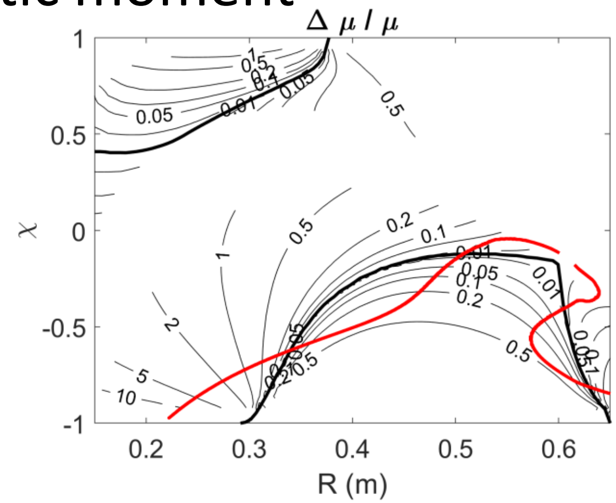


- **CONBEAM**: graphical guiding center analysis
  - Confinement map and particle orbits generated by computing contours of constant canonical angular momentum ($p_\phi = q\Psi - Rmv_{\|}B_\phi/B$) and magnetic moment ($\mu = mv_\perp/(qB)$)

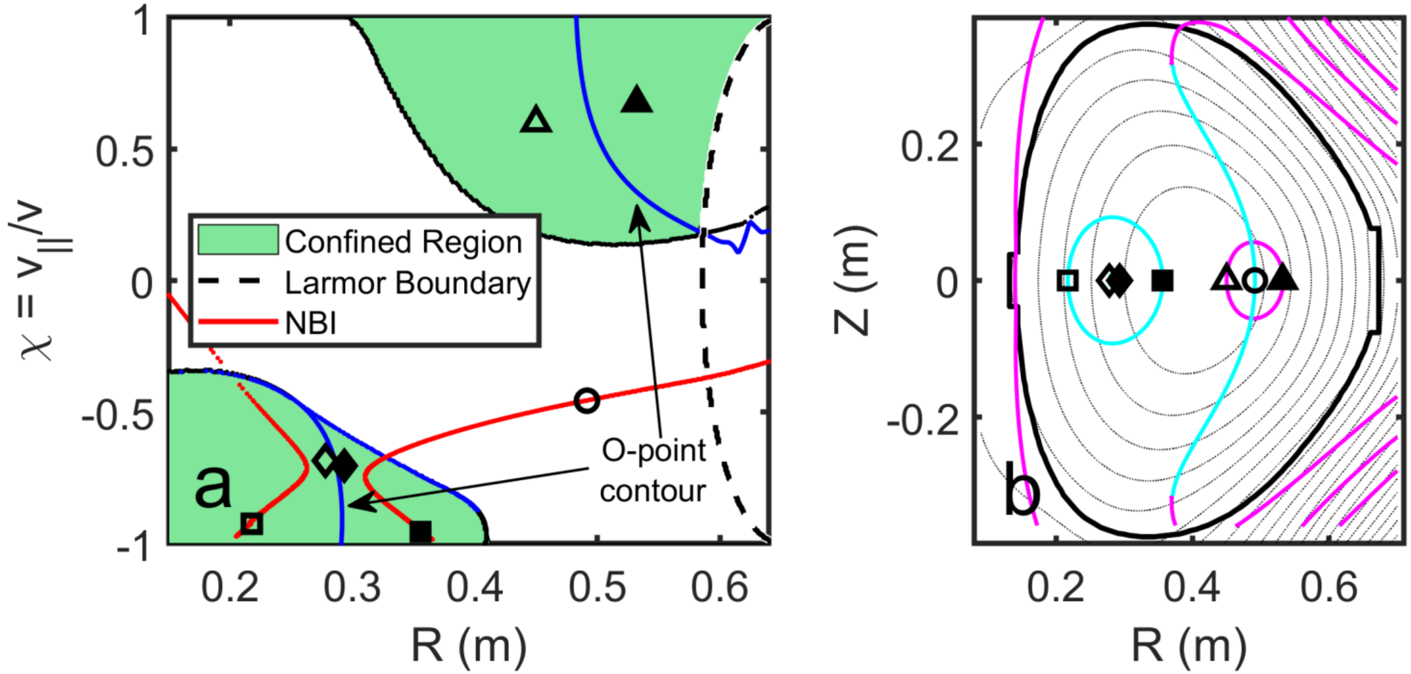


- Large portions of confinement region susceptible to loss but would require large “kick” to magnetic moment



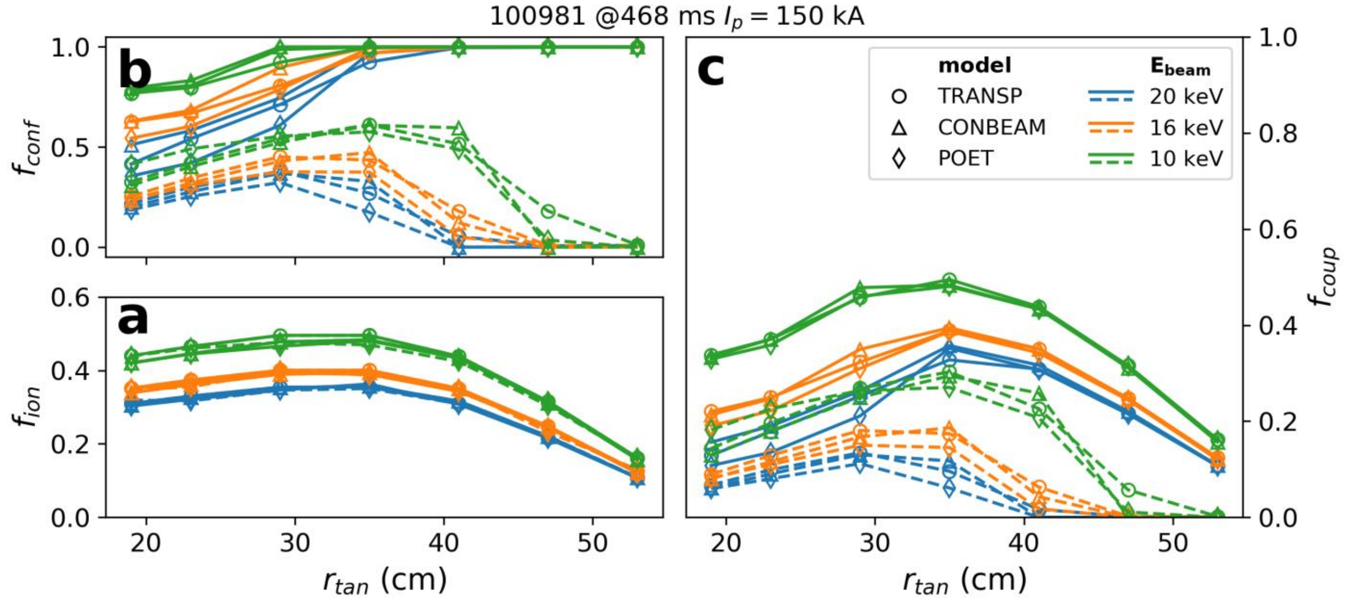


- Confinement region on high-field side of magnetic axis accessible by NBI with reversed-I_p operation

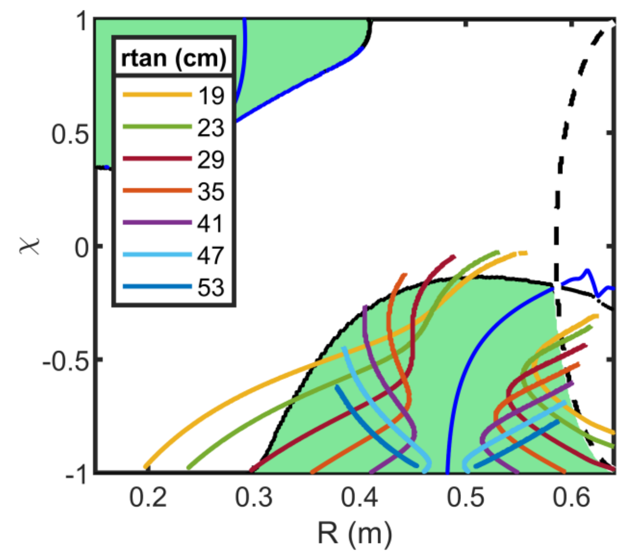


- Two distinct confinement zones give two (as yet) disjoint operating regimes with good confinement on the low (high) field side when operating NBI co- (counter-) injected with plasma current
    - NBI tangency scan could potentially be optimized for either case

- NBI tangency radius scan for both co-injected (solid) and counter-injected (dashed) scenarios. Good agreement between three models showing optimal ~35 cm



- Confinement of ionized fraction goes to unity at large r_{tan} for co-inj ions as pitch deposition shifts further into confined region

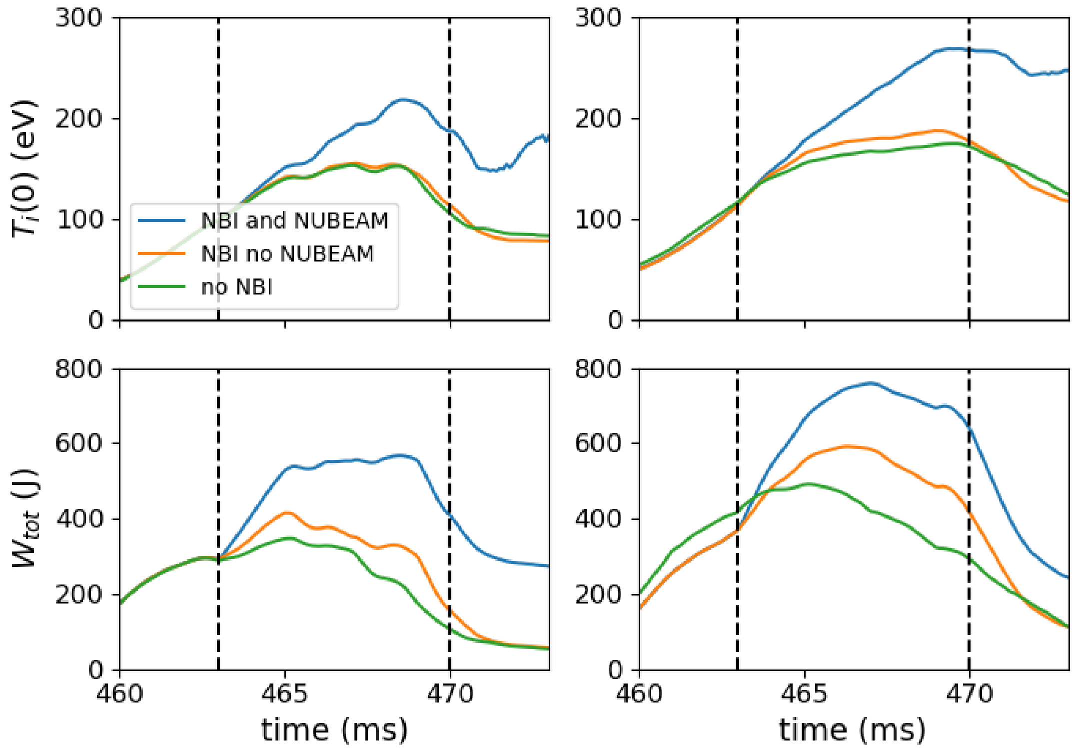


Modeling wrap-up

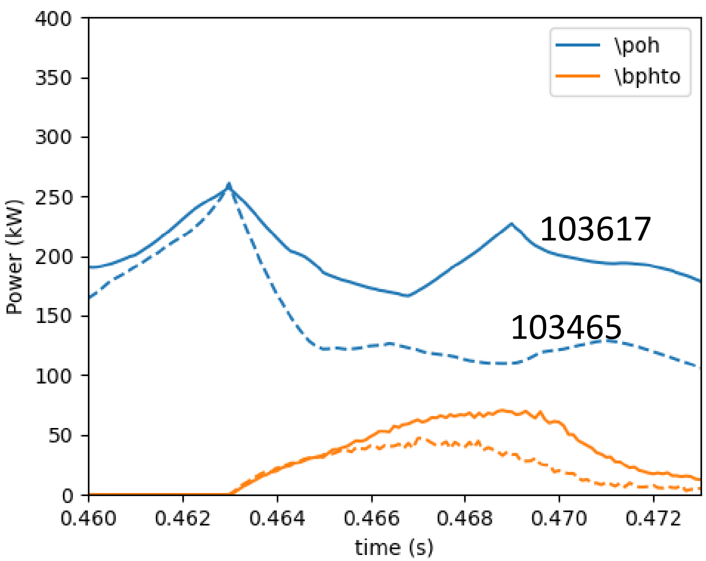
- Good confinement is predicted for > 100 kA plasmas
- Optimization possible within plasma density, current, and beam energy space
- Coupling dependencies are essential in understanding NBI-plasma interaction, but ultimate heating efficiency will also depend on achievable extracted beam current
  - Child's Law suggests $I \propto V^{\frac{3}{2}}$, so although coupling decreases with beam energy, optimal heating likely increases with energy until prompt loss overcomes gains in extracted current
- Metric developed within CONBEAM model utilizing beam-filament model to estimate coupling fractions
  - Non-MC code, suitable for inter-shot diagnostic tool for operators
  - Large database being created to analyze coupling dependencies on equilibrium parameters

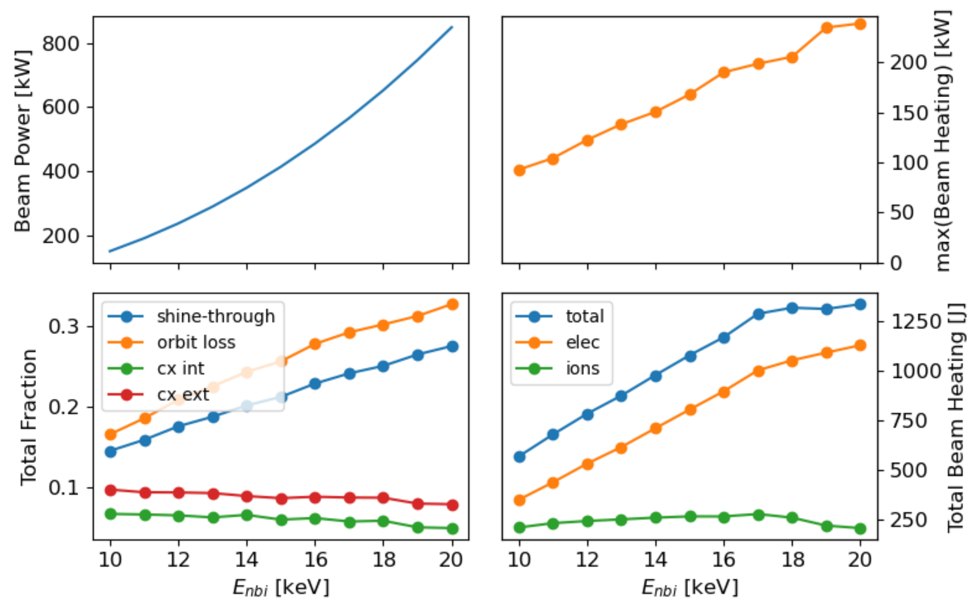
Predicted beam heating not observed

- Recent upgrades and shot development led to 130 kA plasmas
- TRANSP analysis shows increase to core T_i, W_{tot}
  - Not observed on experimental diagnostics
- Constrained by TS data, W_{tot} increases w/o NUBEAM modeling



- Beam heating improves with E_{nbi} despite reduced coupling efficiency
- Large fractional power to electrons should be obvious experimentally, contributing significant fraction of ohmic power

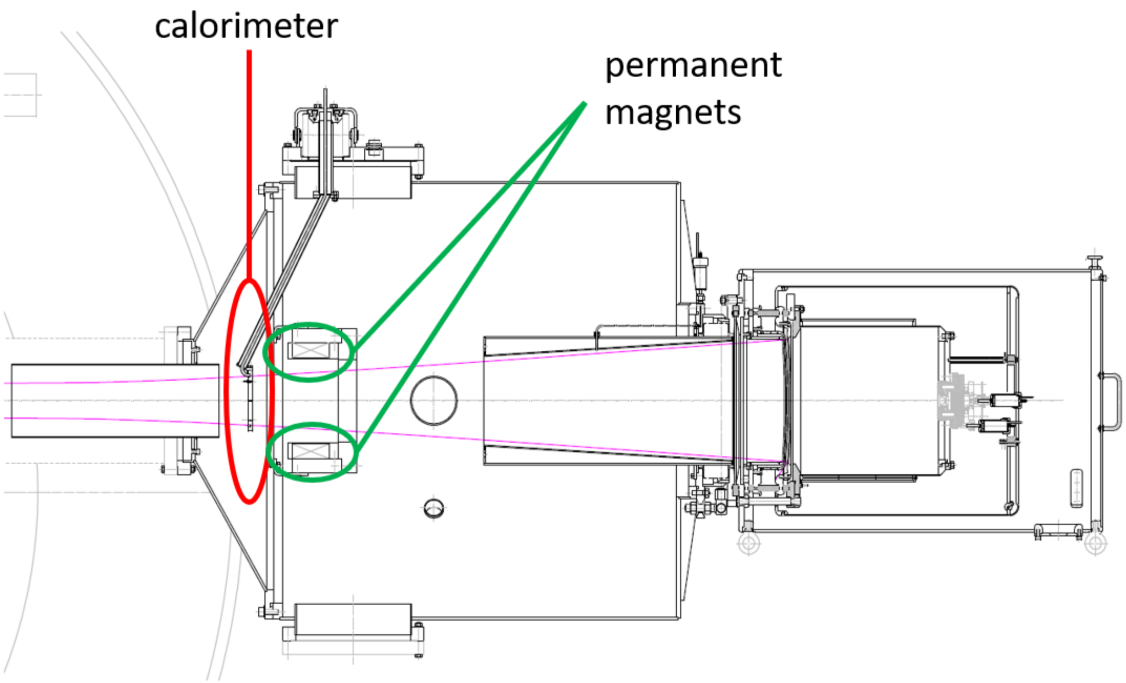




- Following these results, investigating beam for underperformance leading to lower than expected beam heating

NBI performance optimization

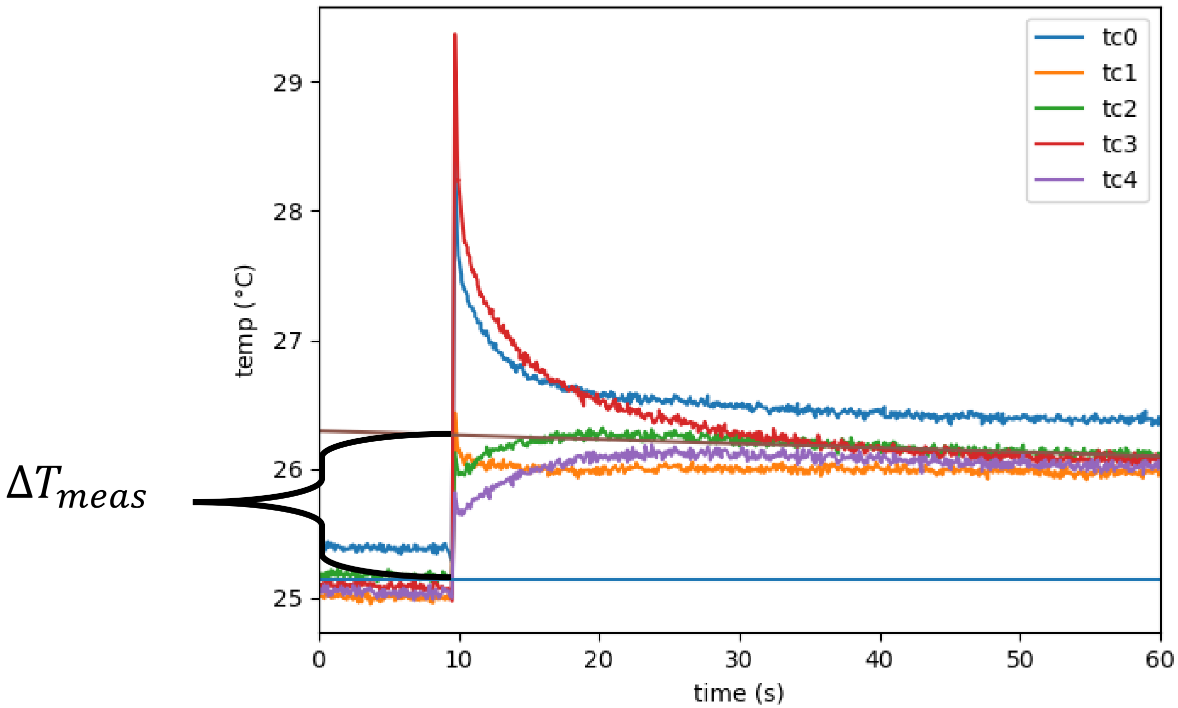
- Calorimeter in beam neutralizer tank features 5 E-type thermocouples measuring deposited beam energy
- Strong permanent magnet likely eliminates residual ionized fraction before calorimeter



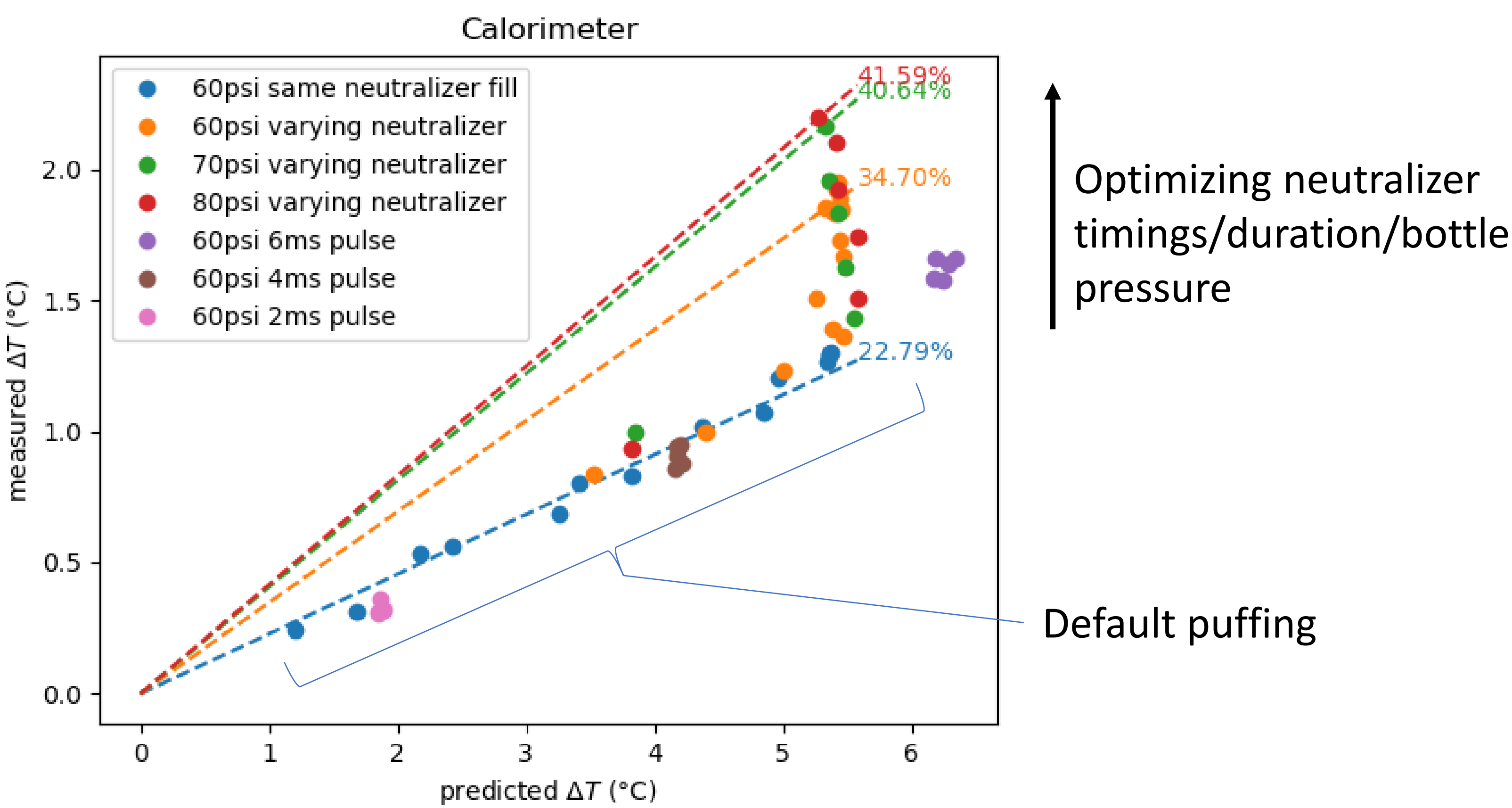
- Predicted temperature rise computed: $\Delta T_{pred} = \frac{\int I_{nbi} E_{nbi} dt}{c_{ps} m_c}$

  Specific heat of copper (c_{ps}) and mass of calorimeter copper (m_c)

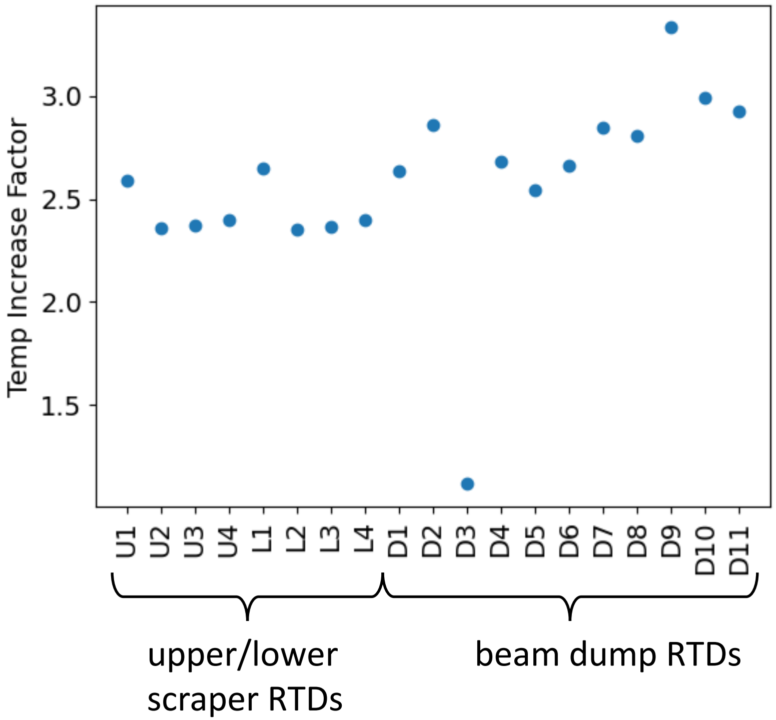
- Effective instantaneous measured temperature rise on calorimeter extracted from thermocouple signals
  - Long timescale cooling fit extrapolated back to time of beam discharge



- Neutralizer tank calorimeter measuring only 20% of beam power, consistent with fast IR camera data
- Able to double beam power to calorimeter by optimizing anode, cathode, neutralizer puff timings, durations, bottle pressures, but improvements beyond 45% elusive



- Diminishing returns with increased bottle pressure in neutralizer scanning suggests equilibration is being reached
- Expect 80% neutralization at 20 keV. Measured ΔT limited to 45% of predicted, thus ~35% unaccounted for
- RTD analysis shows factor of 2-3 increase in deposited energy with optimal puffing over nominal settings, consistent with calorimeter increase from 20 to ~45%
- Further enhancement of beam performance will proceed with data from calorimeter, beam scraper/dump RTDs, fast IR thermography, and beam spectroscopy



Conclusion

- Good neutral beam coupling is expected for present LTX-β plasmas, but no experimental evidence of beam heating
- Enhancement to prompt loss due to non-adiabatic effects is expected to be small, other sources of enhanced loss (3d fields, instabilities) being investigated
- Good coupling sensitive to beam/plasma/equilibrium parameters and optimization will progress as database of >100 kA plasma equilibria grows
- Throughput to vessel observed to be limited to 20% during nominal beam operation, increased to 45% with optimal puffing
- With 80-85% neutralization expected (dependent upon beam energy and energy fractions), remaining 35-40% of beam energy still unaccounted for
- Investigation ongoing to improve NBI performance to enhance heating of LTX-β plasmas

Extras

- Optimization data for neutralizer, anode, and cathode puff valves
- Timing, duration, and bottle pressure varied to increase measured fraction of predicted temperature rise