Abstract

Flat temperature profiles are achieved in LTX-β via a lithium coated first wall. A 20 kV Neutral Beam Injector, installed in 2019, has recently been observed to heat the plasma. This auxiliary heating, essential for studying the energy confinement scaling in the low-recycling environment and the response of flat temperature profiles to auxiliary heating, was achieved only after a concerted modeling and experimental campaign. Utilizing thermocouple data from the calorimeter, the neutralization fraction was optimized, a misalignment of the source was detected and corrected, and a measure of the beam width as a function of perveance was made, consistent with CHERs data. Modeling suggests that the higher current discharges made available as of 2021 after an upgrade to the ohmic power supply have moved LTX-β into a shoulder regime where good coupling is now possible but challenging. Many factors influence beam coupling, including the beam energy, perveance, and tangency radius, as well as plasma density, current, temperature, and tearing mode activity. Although TRANSP modeling suggests beam heating increases with beam energy up to the max operating voltage of 20 kV, heating was not observed until the beam tangency radius was increased by intentionally misaligning the beam source relative to the neutralizer tank and operating at the mid-range energy of 13 kV. Exploration of the variables controlling beam heating in LTX-β are still underway and the present findings will be presented, alongside future plans to install an NPA and realign the beam during an upcoming vent.

Motivation

- LTX- β provides testbed for study of energetic particles (EPs) in low-recycling boundary plasmas
- Flat T_e profiles observed in LTX and LTX-β remove (or diminish) temp-gradient modes

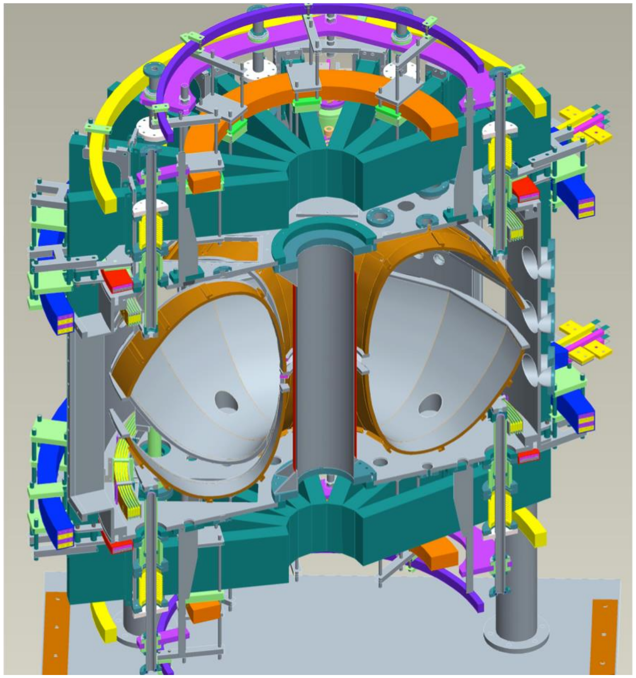
  [D Boyle et al., *PRL* **119**, 015001 (2017)]

- 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 Tokamak Experiment Beta

R=0.4 m; a=0.25 m

I_p ~ 100 – 140 kA

|B| ~ 0.3 T

$T_e(0)$ ~ 200-300 eV

n_e ~ 5×10^{13} cm^{-3}

Pulse length ~ 50 ms

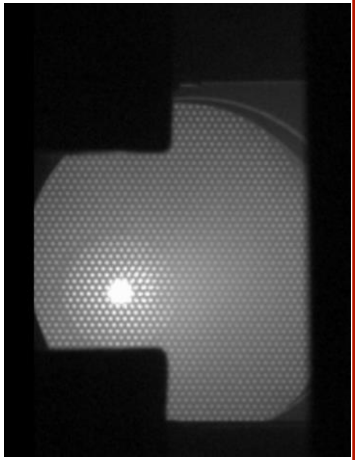
Related LTX-β talks/posters

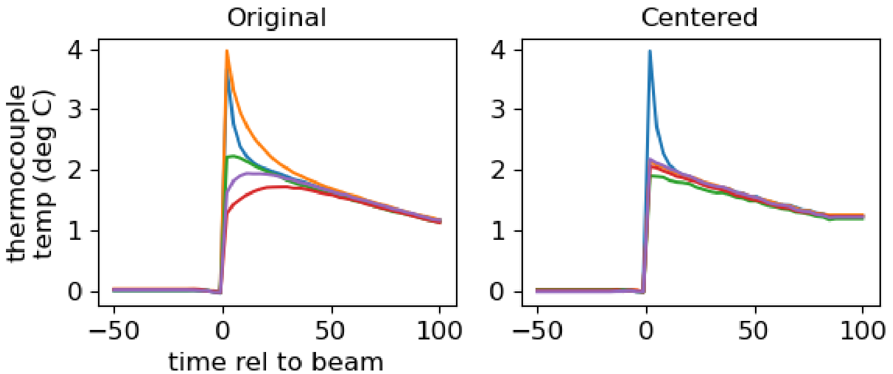
Introduction

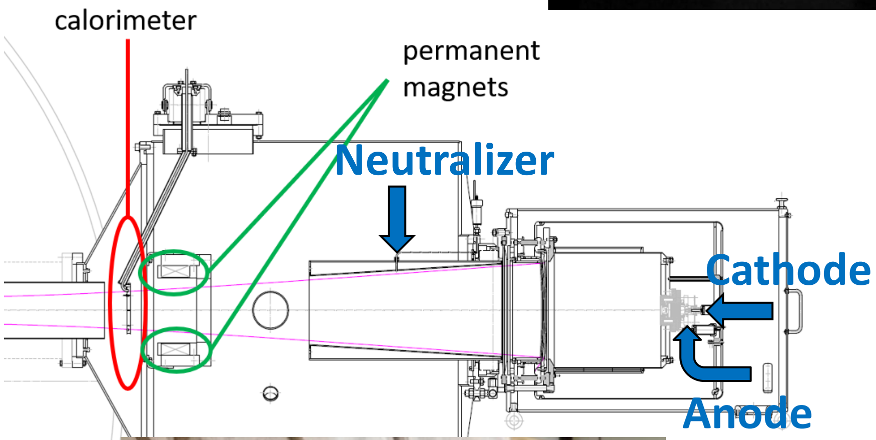
- Initial data after neutral beam installation in 2019 showed no evidence of beam heating
- Good coupling was predicted in higher current and denser plasmas achieved by mid 2021
- Improvements to beam were made with the aid of thermocouple data and modeling
  - Alignment & beam width optimized, then intentionally misaligned to improve coupling
- Experimental observations of heating most robust at modest energy despite TRANSP modeling predicting improved heating (primarily to electrons) over entirety of beam energy range
- Electron heating observed most strongly in dense, peaked temperature plasmas, more moderately in flat temperature profiles See CP11.03
- Neutral Particle Analyzer, essential for fast ion studies going forward, on site and ready for installation during upcoming vent
  - Beam neutral footprint can provide necessary background neutrals for NPA signal
  - Tangential midplane view likely most ideal; sensitive to high pitch core ions
  - Radial port could be valuable, sensitive to low pitch phase space
- Planned upgrades to beam- increased tangency radius, longer pulse, will provide better coupled, larger fast ion population for heating & fast ion studies See CP11.08

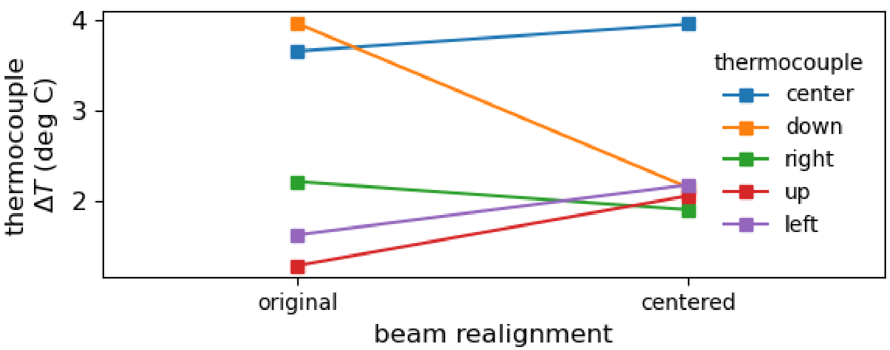
Beam alignment

- Prior repair to calorimeter thermocouples provided critical information leading to beam realignment
- Beam source centered on neutralizer tank axis, minimizes transfer losses
- Vertical asymmetry persists, can't be corrected until upcoming vent
- Source misaligned with neutralizer to increase tangency radius



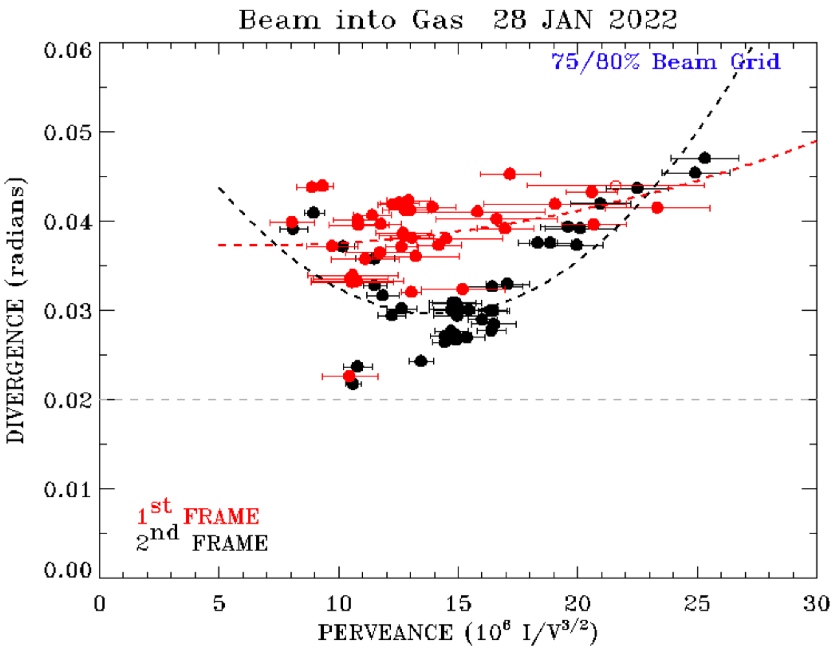


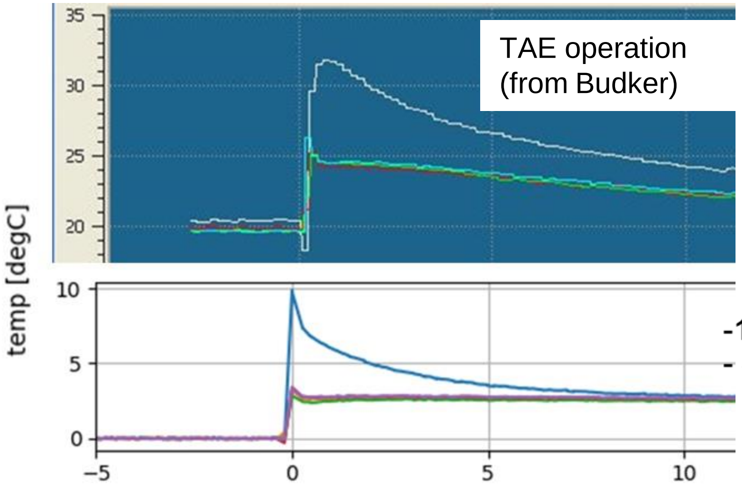




Beam performance optimized

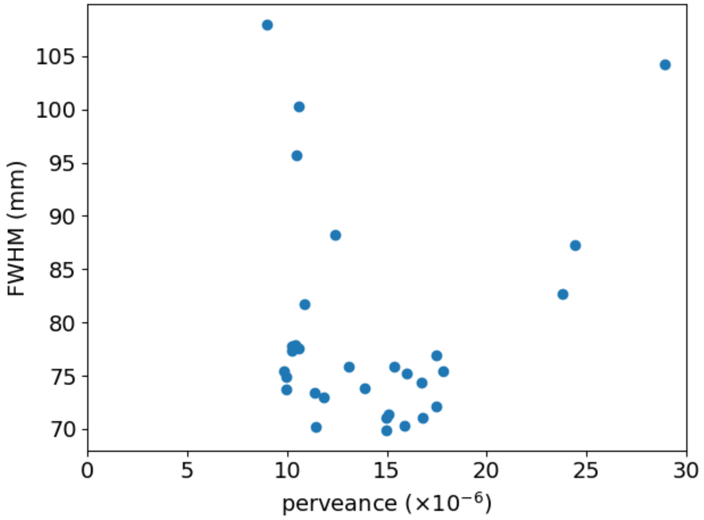
- Optimization of gas pressures with new puff valves/orifices, original beam performance recovered
- Edge/Core ratio gives beam width estimate- ~7.5 cm FWHM at optimal perveance ~ 15e-6, consistent with spectroscopy data





- 20 kV operation at Tri-Alpha
- $\Delta T \approx 12$ °C

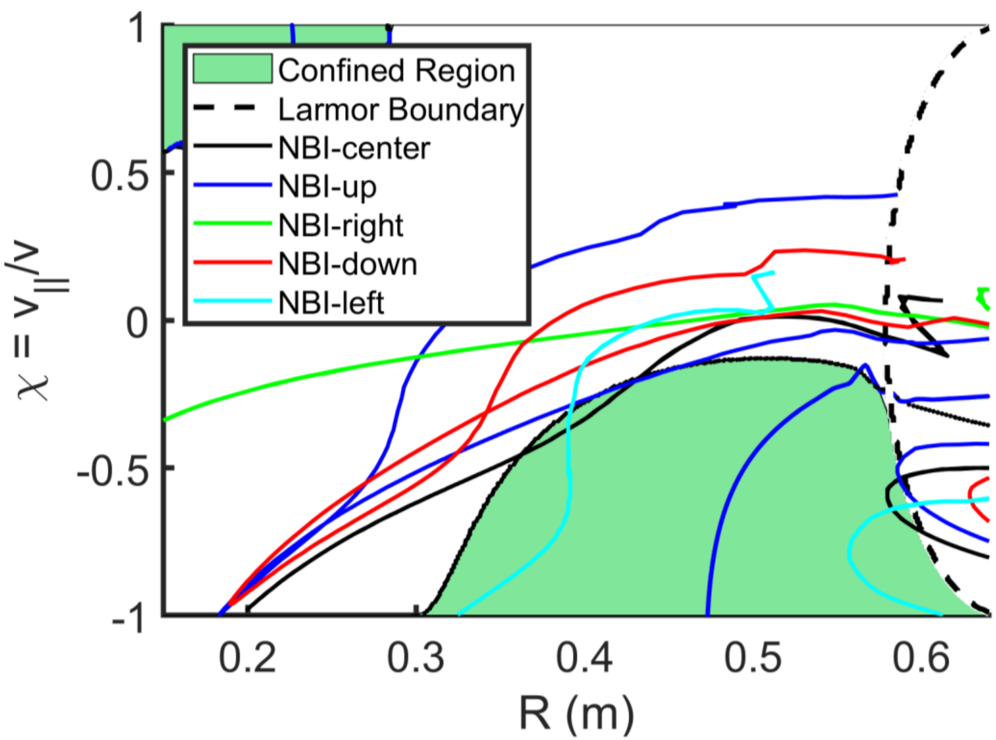
-16 kV LTX operation
- Scales to $\Delta T \approx 12.5$ °C at 20 kV



CONBEAM analysis of beam injection

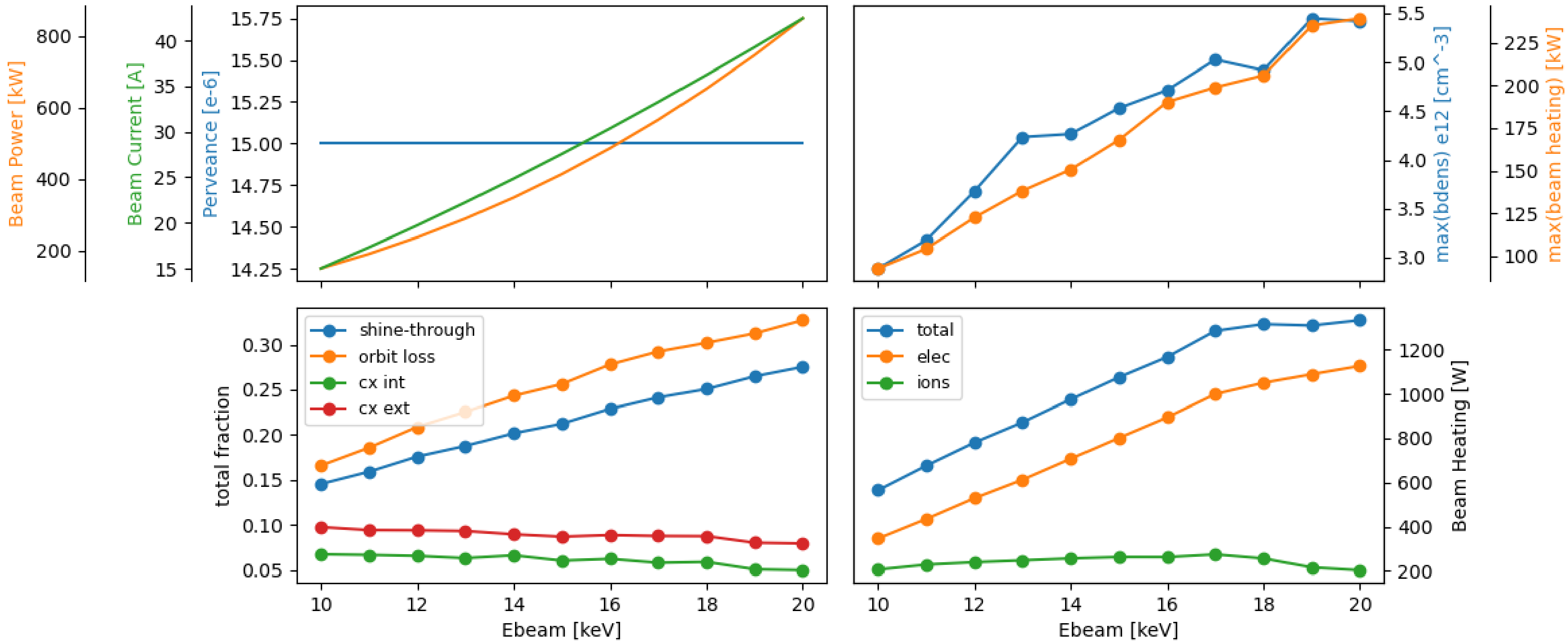
- Post discharge analysis available via CONBEAM fast ion coupling model
  - Equilibrium reconstruction run on available plasma signals, soon to be part of automatic post-discharge analysis
  - Assumption on density profile shape, normalized to interferometer signal determines beam deposition profile (subject to uncorrected fringe shifts)

- 5-chord model estimates beam deposition fractions: coupled, prompt loss, shinethrough
- Note we appear to operate in region where large gains to beam confinement are possible both by increasing Ip (larger confinement region) or increasing beam tangency radius (more intersection with confinement region)



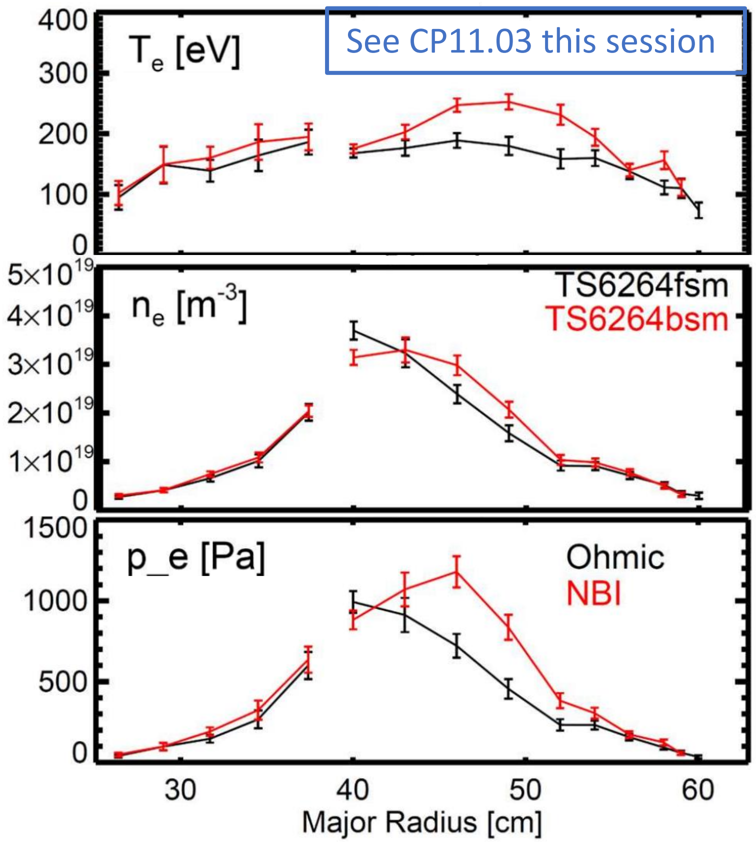
Beam heating should improve up to 20 kV

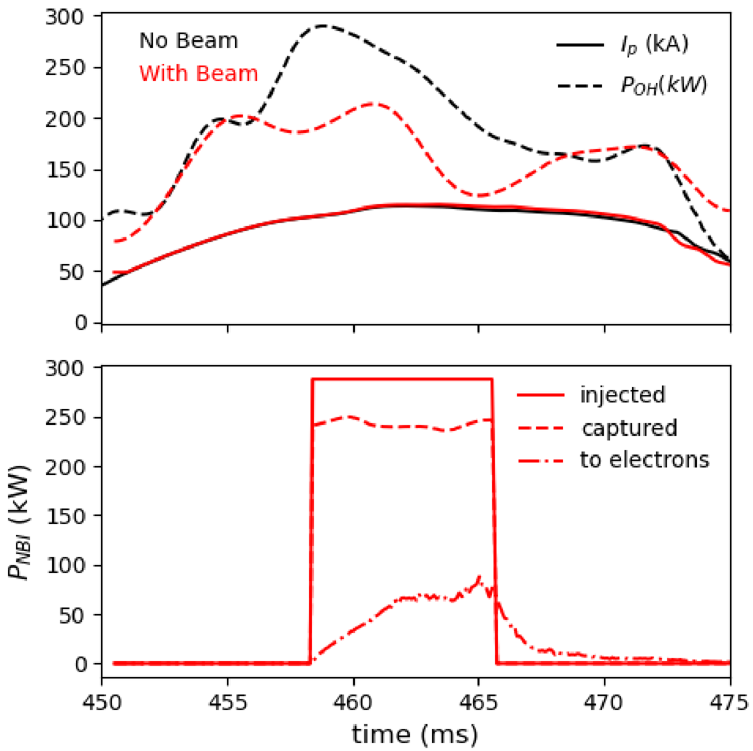
- TRANSP NUBEAM modeling predicts increasing heating over available energy range despite increasing first-orbit and shine-through losses
- Beam tangency ~24 cm gives maximum coupling without need for beam realignment (planned tangency ~33 cm)



Beam heating of electrons

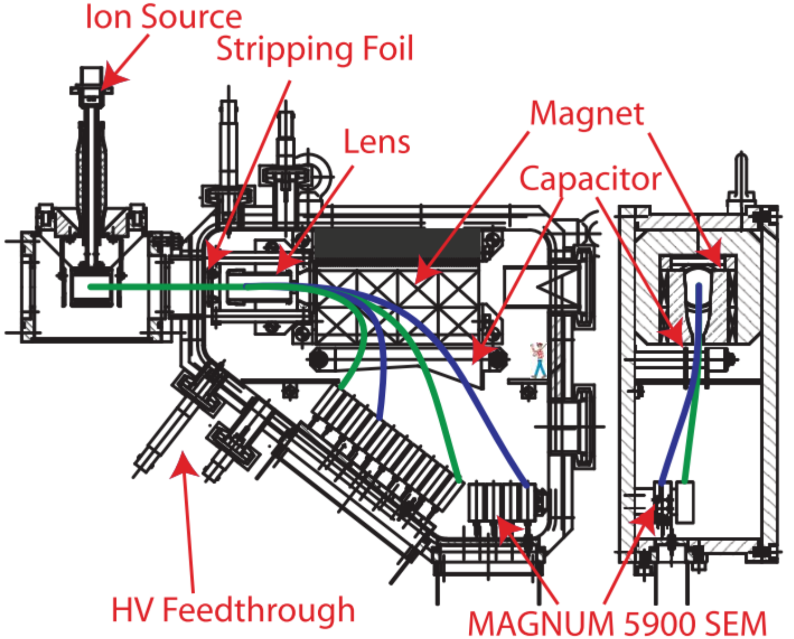
- Large first orbit losses persist at tangency 24 cm
- Beam energy reduced to further limit first orbit losses, strongest beam heating observed ~13 kV
- Good beam heating appears to be very sensitive to plasma and beam parameters. Planned adjustments to beam tangency radius and extended pulse length will improve coupling/heating effects





Neutral Particle Analyzer

- NPA will provide first direct observation of fast ion population in LTX-β
  - Measurement of beam (and potentially bulk) ion energy distribution evolution
- Monitoring fast ion distribution surrounding Alfvenic mode activity is key for measuring fast ion loss, particularly when neutron flux is unavailable (H plasmas only)
- Onsite at PPPL on loan from UW-Madison (prior install on MST)
  - Installation during upcoming vent, operational 2023 plasmas



J. Reusch, Rev. Sci. Instrum. 83, 10D704 (2012)

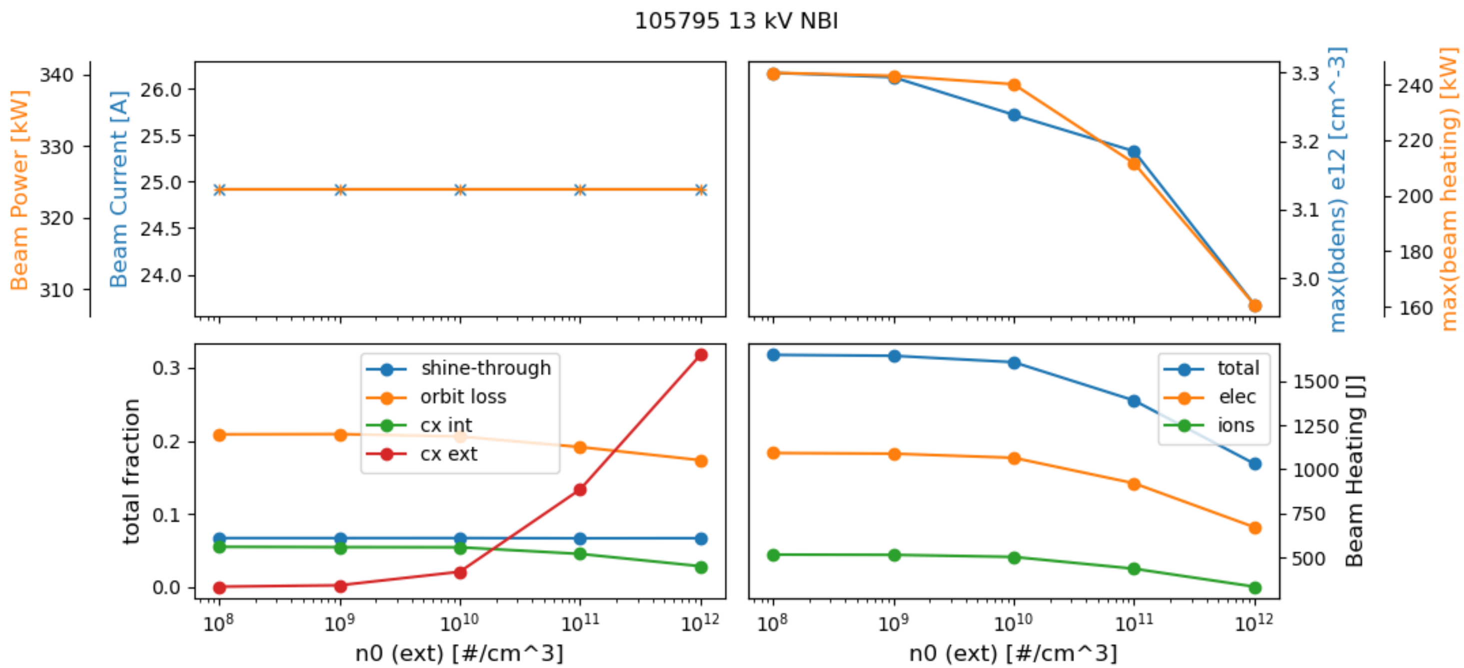
Neutral Particle Analyzer
Energy Range: 35 keV
Variable Offset: 10 keV
Energy Resolution: 2-4 keV
Time Resolution: 10 μs

Neutral Density for NPA

- Background neutral density necessary for NPA signal

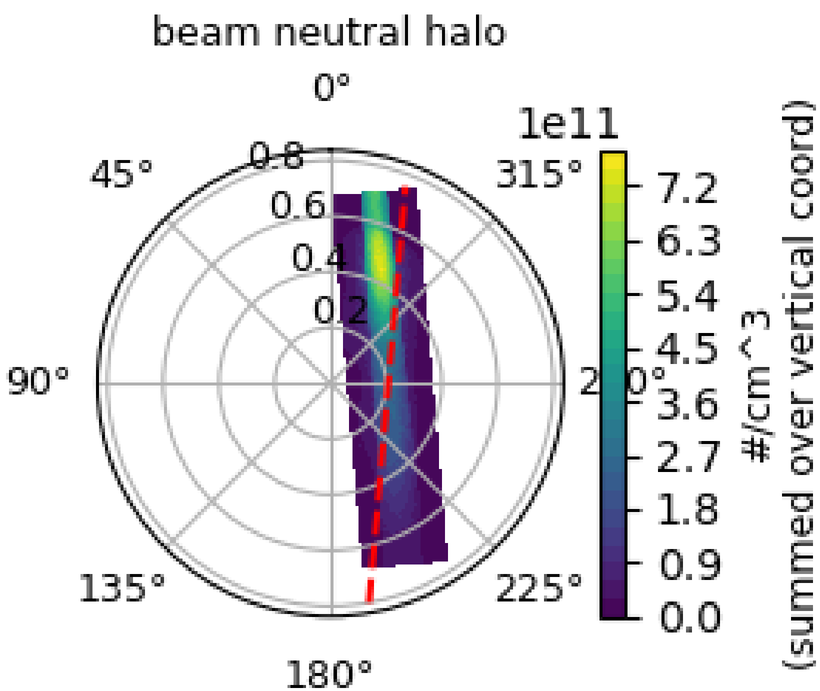
$$\Gamma_{NPA} = \int_L n_0 n_{fi} \langle \sigma v \rangle_{cx} \delta(\gamma - \gamma_c)(1 - f_r) dl$$

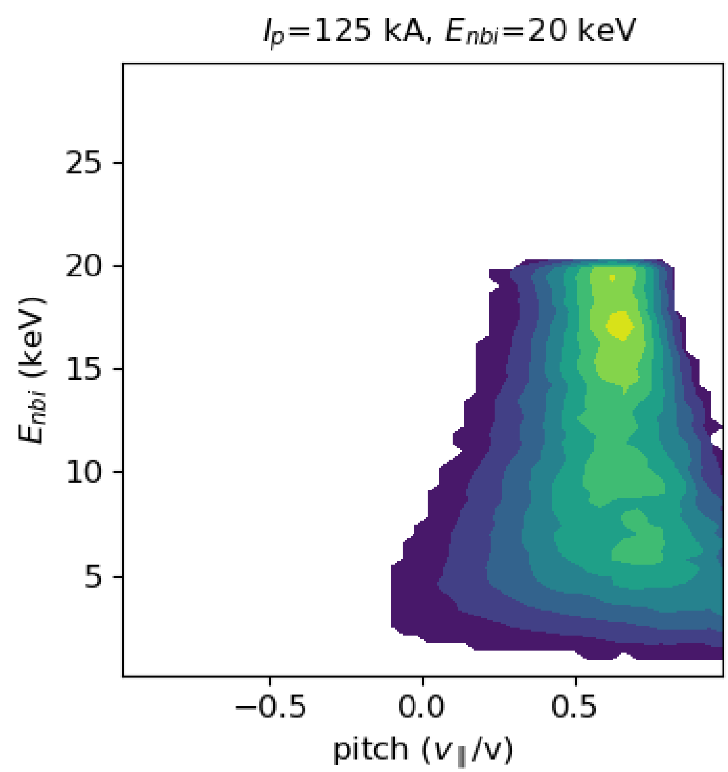
- Edge neutral density in LTX-β expected to be low due to Li wall coating
- Degas2 modeling puts realistic edge value: $10^9 - 10^{10}\ m^{-3}$
- Neutral density scan in TRANSP NUBEAM suggest beam heating fairly insensitive to edge neutral density in this region



Neutral background from beam footprint

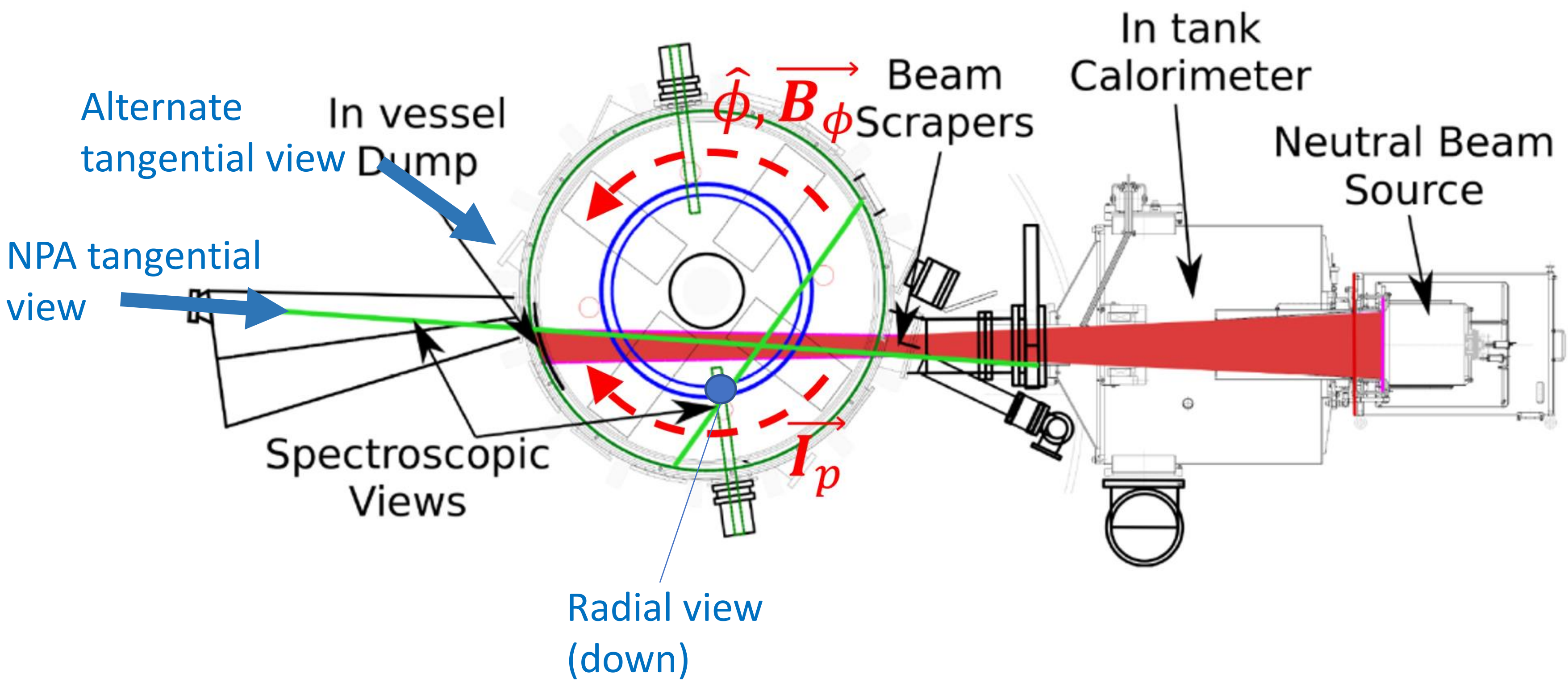
- NUBEAM predicts fast ion population localized near core out to low field side
- Fast ions injected with moderate pitch (0.5-0.6) due to $r_{tan} < r_{mag}$
- Beam neutral footprint is likely essential for adequate signal in low neutral-density core region. TRANSP 3D Halo model shows potentially order of magnitude larger neutral density in beam footprint compared to edge





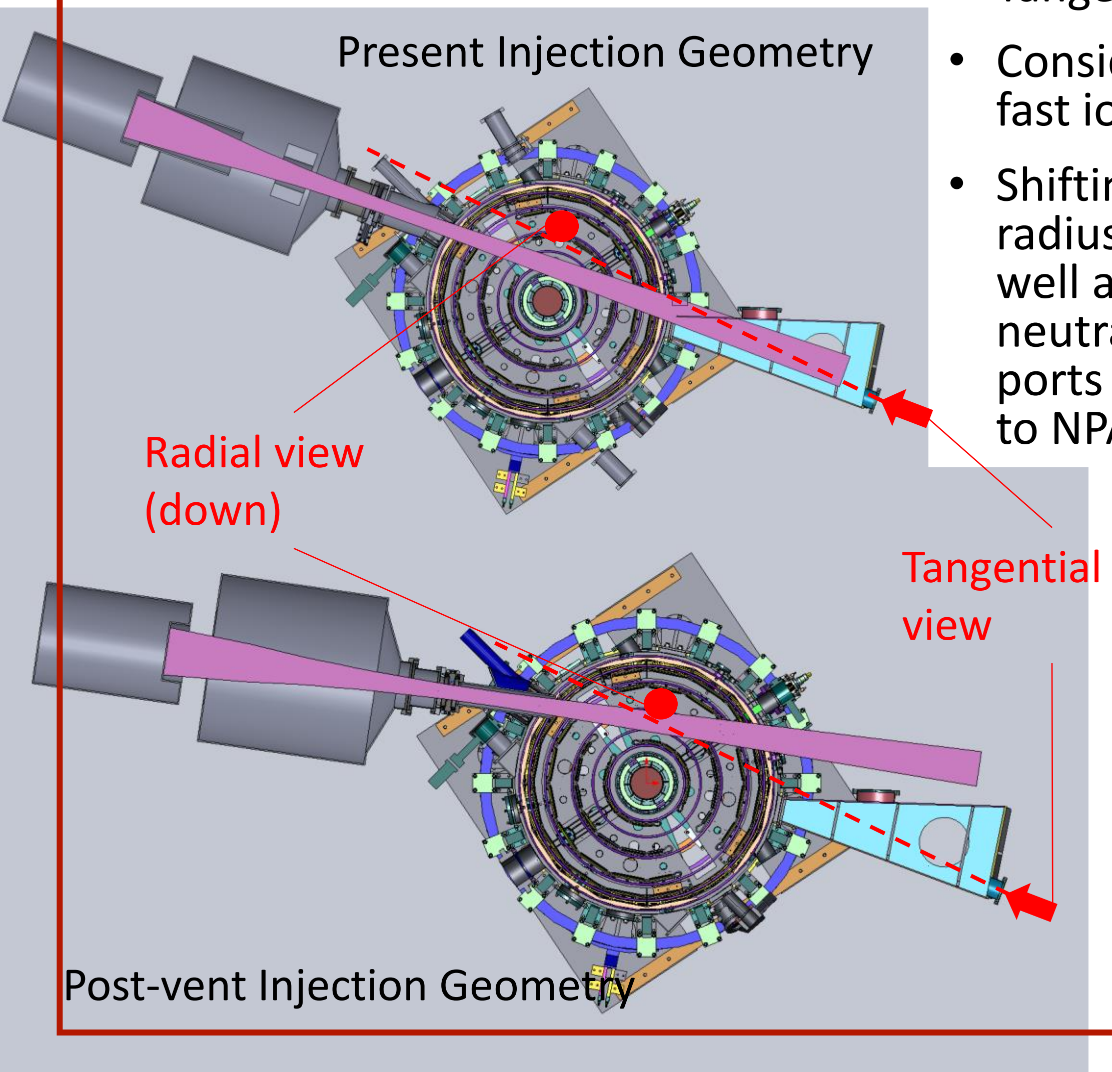
Possible NPA viewing geometries

- Multiple viewing options for NPA on LTX-β ports
- Tangential midplane view (most likely)
- Consider alternate radial view (different fast ion phase space sensitivity)



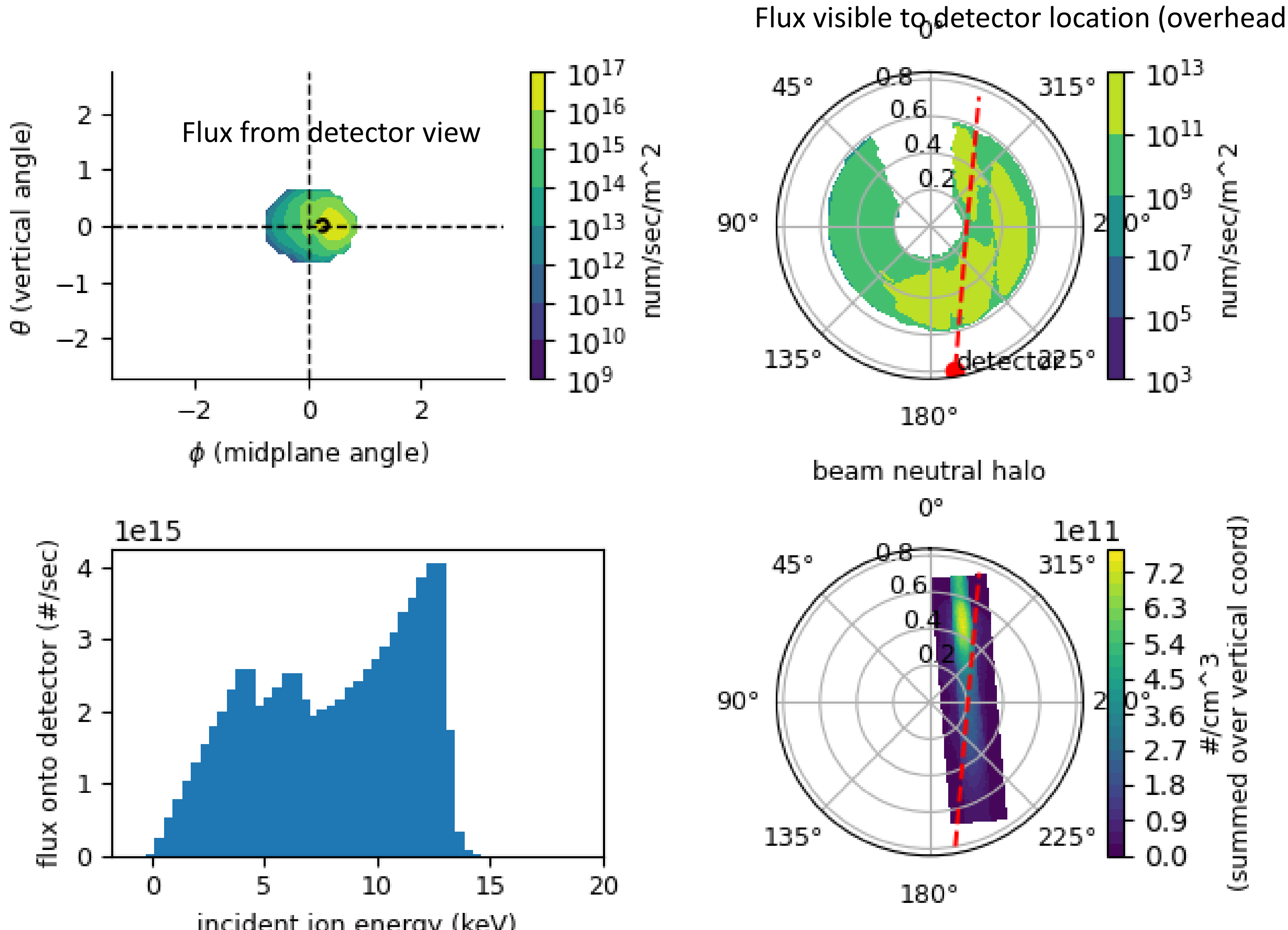
Possible NPA viewing geometries

- Multiple viewing options for NPA on LTX-β ports
- Tangential midplane view (most likely)
- Consider alternate radial view (different fast ion phase space sensitivity)
- Shifting the beam to larger tangency radius will affect NPA viewing angles as well as observation lines through beam neutral footprint. Alternative viewing ports will be considered based on benefit to NPA and availability



NPA modeling of tangential view

- Tangential view: full energy range of fast ions, mid-high pitch



NPA and beam tangency radius

- Larger beam tangency produces higher pitch fast ion population and overall larger population due to better confinement and lower first orbit losses
- Although NPA also has viewing tangency of 33 cm in this case, predicted flux decreases due to tangency occurring outside beam neutral footprint
- Precise location, viewing geometry, and wiggle room for LTX ports will further constrain modeling

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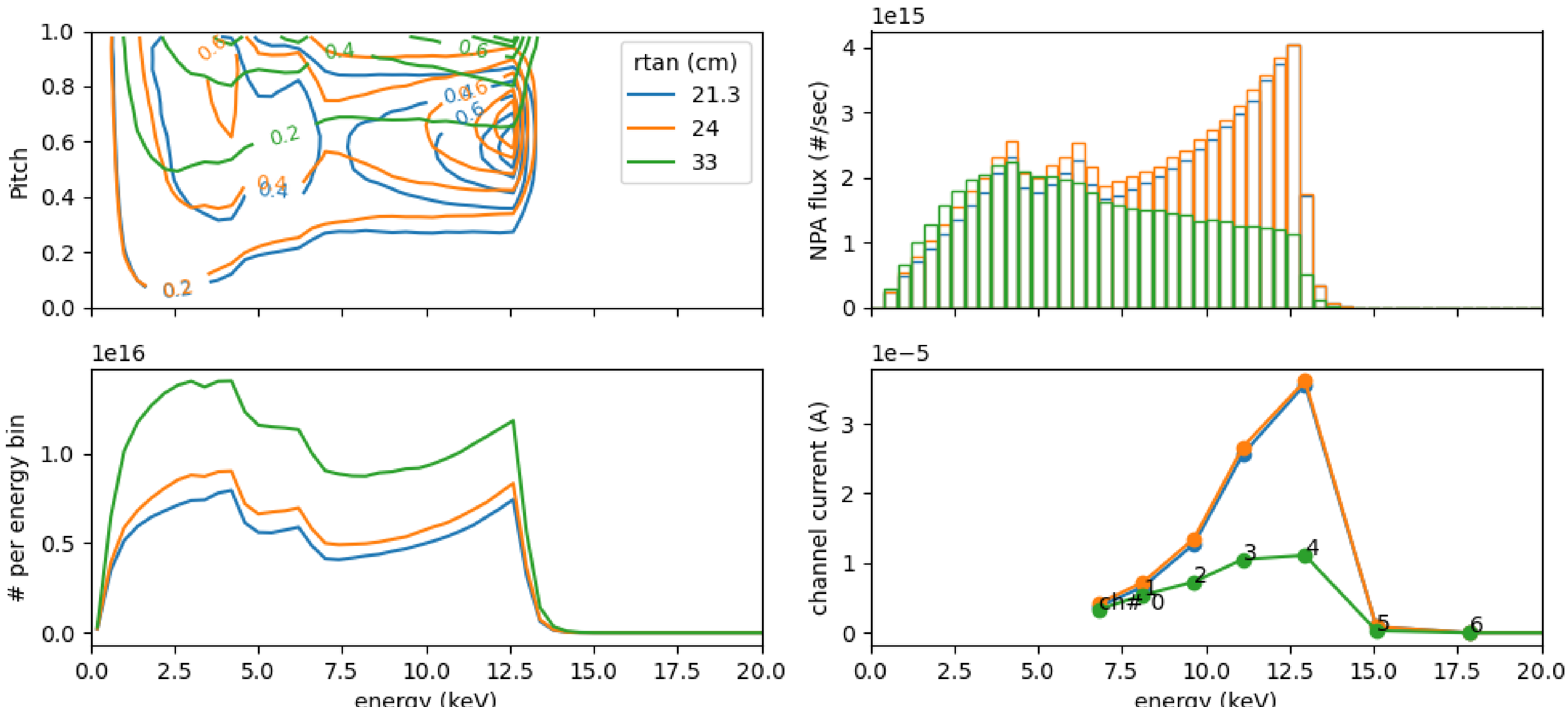
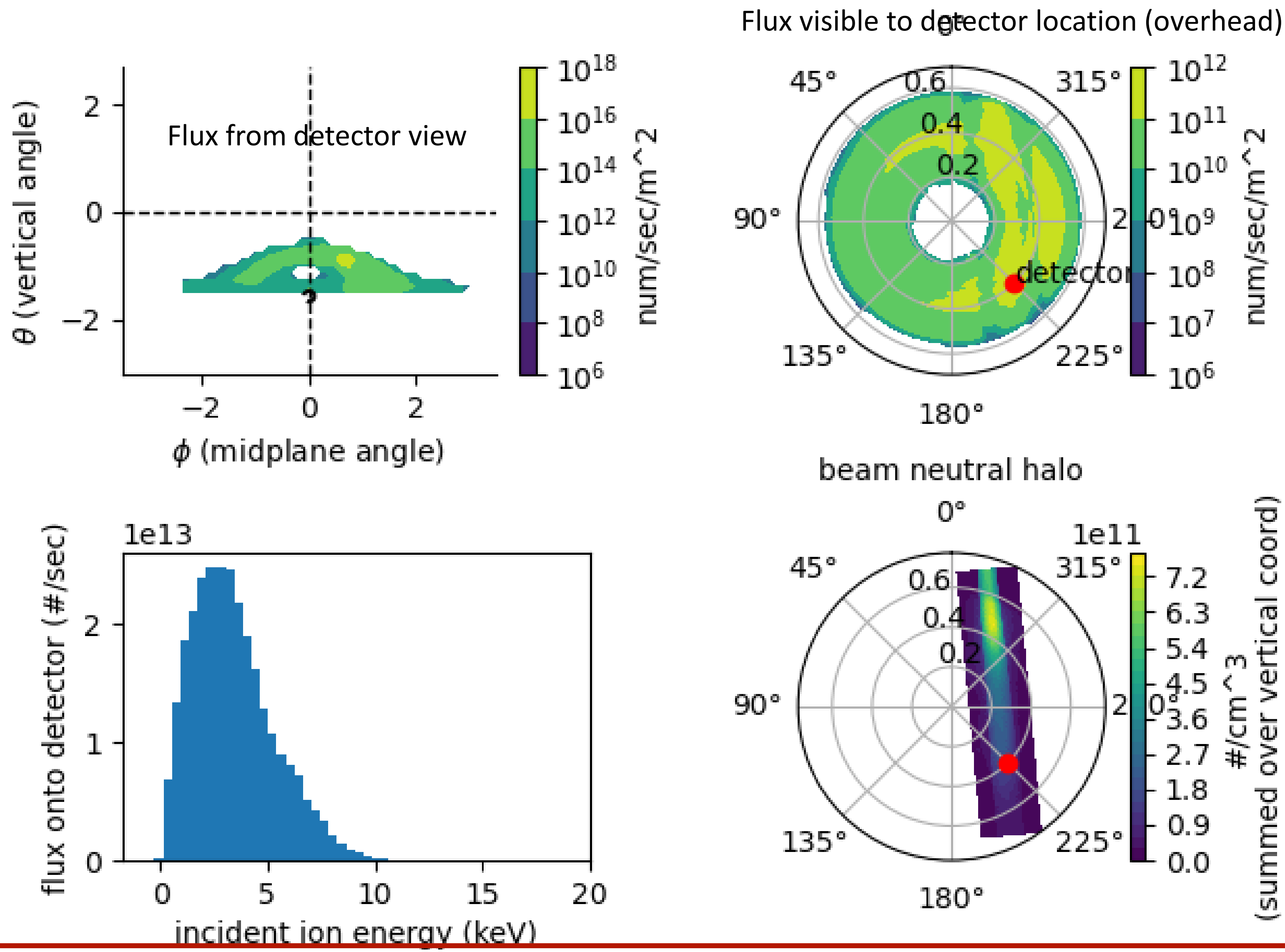


NPA radial view

- Radial view: low energy, low pitch ions



Summary

- Beam performance and alignment has been optimized within machine limitations
- Realignment of the beam to a tangency radius of 24 cm and operating at modest beam energy led to observation of beam heating in low-recycling plasmas in LTX-β
- More robust in peaked temperature profiles, beam heating is sensitive to plasma parameters
- Planned adjustments to beam (larger tangency radius, extended pulse length) will produce higher pitch, better confined, larger fast ion populations, and should provide a more stable regime in which to study beam heating and its effects
- NPA will provide essential information on evolution of fast ion energy distribution during beam injection and in diagnosing fast ion redistribution or loss surrounding magnetic activity

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LTX-β

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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