Optimized beam fueling in LTX-β

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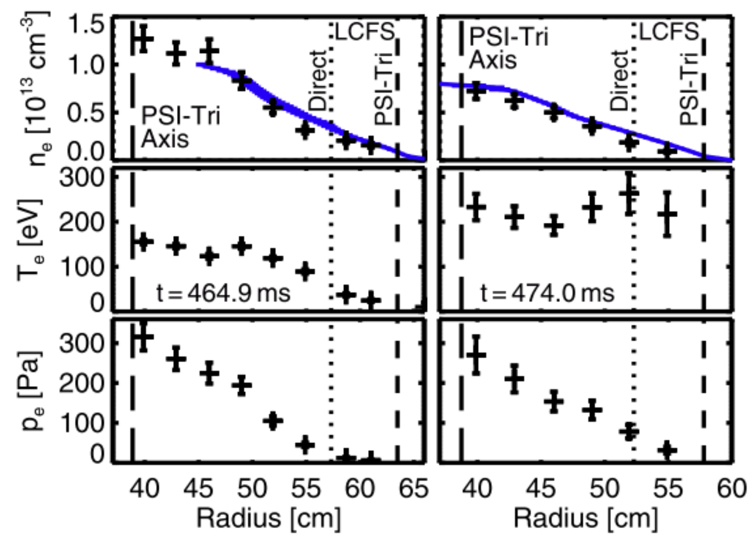
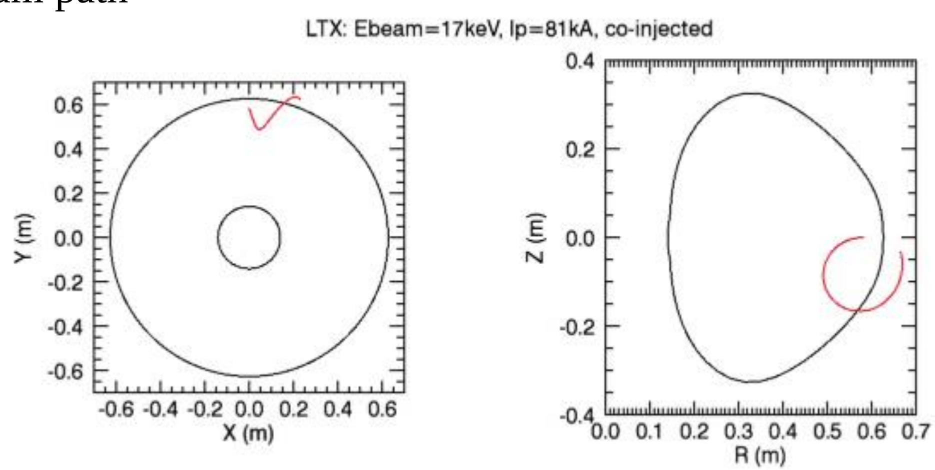
Abstract

The LTX-β upgrade included installation of a new 20kV, 30A neutral beam for heating and fueling, but initial operation of the beam showed high first orbit losses. In the next phase of operation, core fueling though neutral beam injection (NBI) will be essential for studying the low recycling regime where cold edge fueling is undesirable. Doppler spectroscopy is used to analyze beam geometry and maximize throughput into the torus for various beam operational modes. Modeling (TRANSP alongside a full ion orbit code) are employed to predict beam coupling and deposition in various combinations of toroidal field and plasma current orientations to optimize first orbit confinement. Here we report results of the beam performance optimization and map out a path to maximize neutral beam fueling of LTX-β plasmas.

The low recycling regime in LTX-β

- Atypical of most tokamak plasma conditions, LTX has achieved a low recycling boundary resulting in a flat electron temperature profile [D. Boyle 2017]
- Sustainment requires NBI fueling
  - Gas puffing undesirable (cold edge neutral influx)
  - NBI sources particles within plasma
- Initial NBI operation revealed large first orbit losses
  - Full orbit model shows ions born along beam path drift vertically to impact vessel boundary
  - Loss drives counter-NBI torque [P. Hughes ZP06:20]
- Good NBI-plasma coupling is required

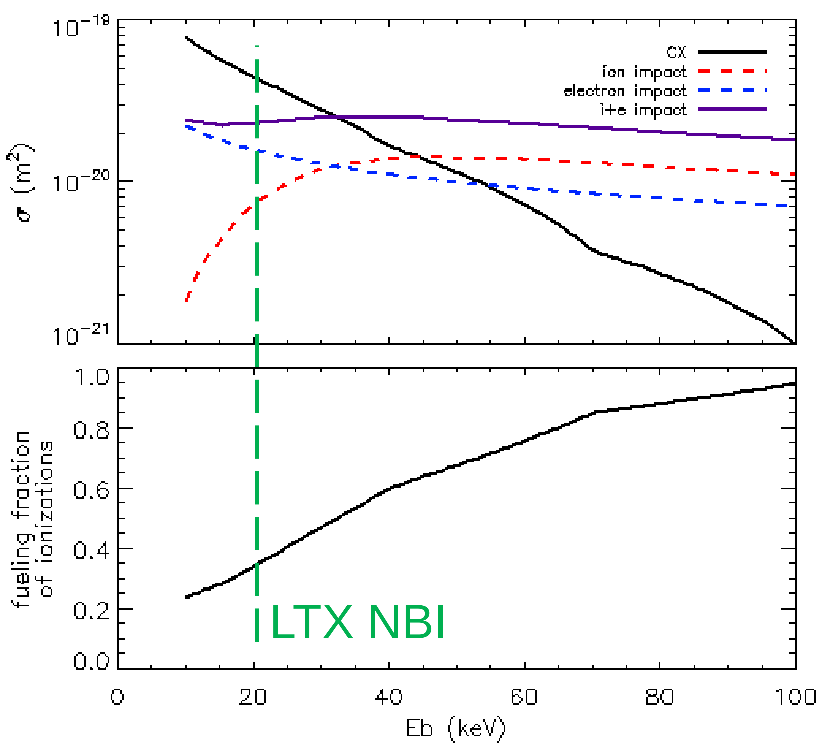


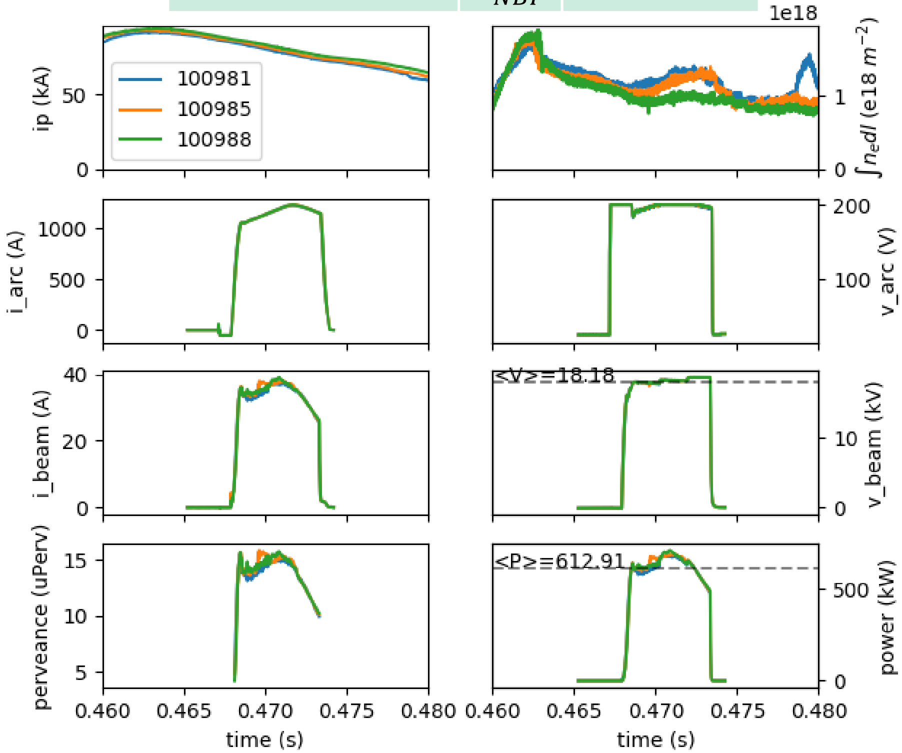


Can NBI sustain plasma?

- LTX's NBI designed to operate at 20keV and 30A
- Beam fueling depends upon amount ionized by i/e impact
- 25-30% of ionized beam neutrals fuel plasma

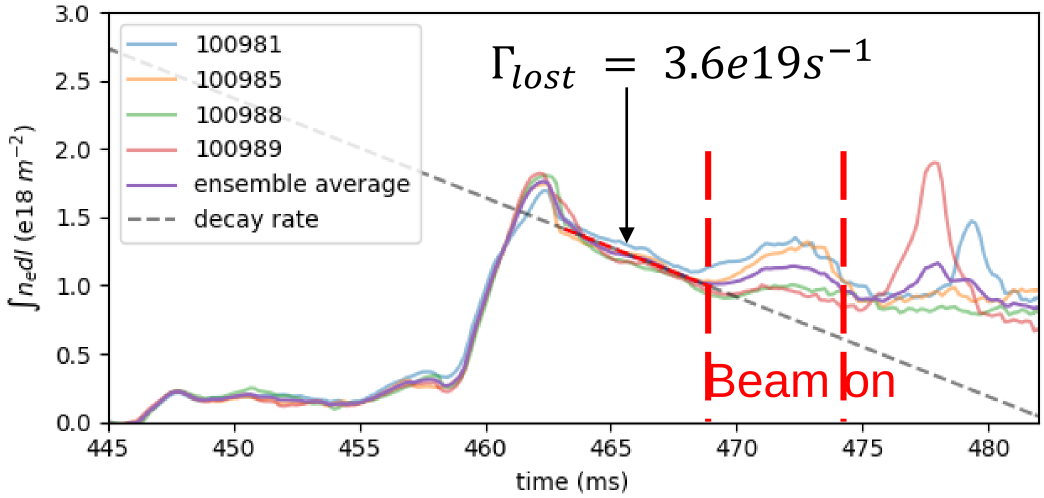
Parameter		LTX-β
Major Radius	R_0	34-40cm
Minor Radius	a	20-26cm
Toroidal Field	B_t	0.3T
Plasma Current	I_p	~100kA
Plasma Duration	t_{shot}	<50ms
Beam Power	P_{NBI}	>500kW
Beam Duration	t_{NBI}	5-6ms





Can NBI sustain plasma?

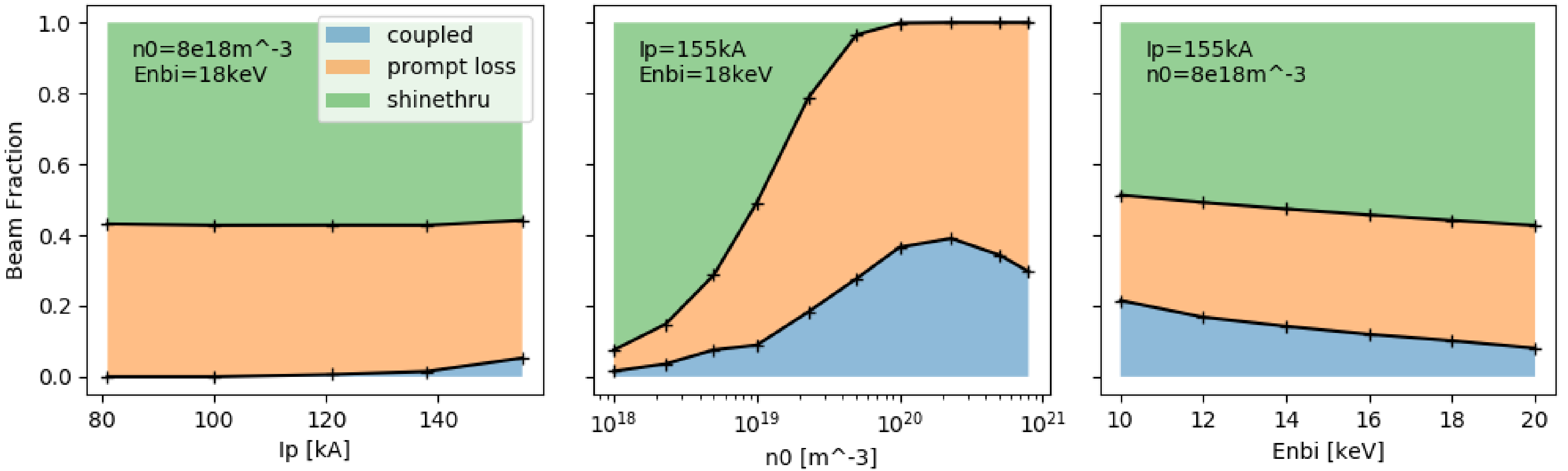
- Simple model applied to assess feasibility of NBI fueling for plasma sustainment
- Fit to decaying density compared to required NBI input



- To compensate loss; $I_{NBI} = \Gamma_{lost} q$ = **$5.8A$ of fueling required**
- Expecting 25% of ionization events to lead to fueling, we need $23.2A$ of NBI current to be ionized
  With operation limited to around $30A$ this would require a shine through fraction of only 26% (a tall order)

Beam coupling depends on beam/plasma parameters

- Injected ions distributed between shine-through, prompt loss, and deposited fractions
- TRANSP modeling predicts larger coupling fraction achieved for higher I_p, larger n_0, or lower E_{NBI}



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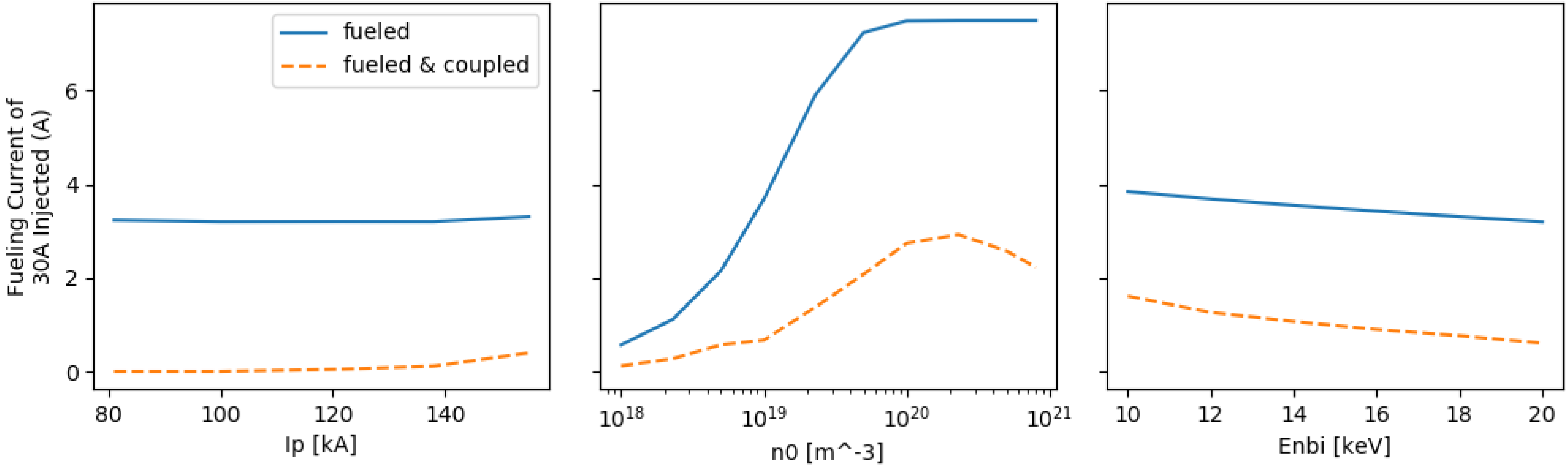
- Accounting for fraction of ionization that fuels plasma it becomes apparent achieving $5.8A$ necessary to sustain is difficult
  - Present operation results in ~3A of fueling, but near total prompt loss of beam ions leads to near immediate loss
  - Must seek to optimize beam and plasma performance to maximize coupled fueling



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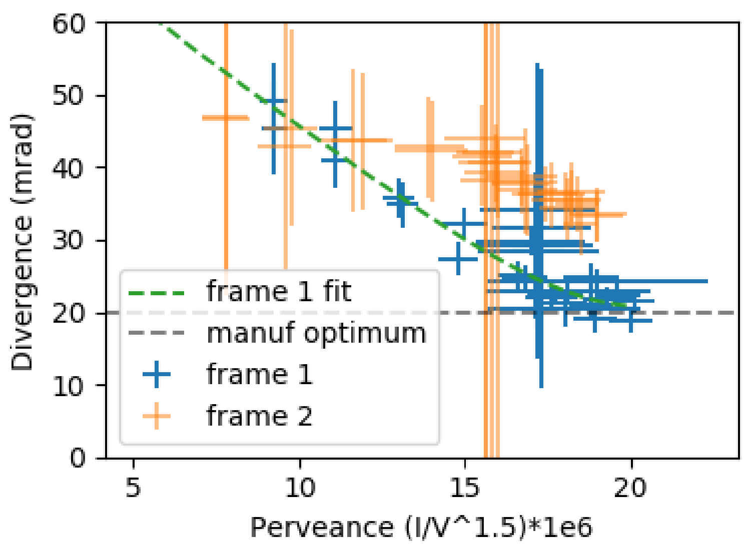
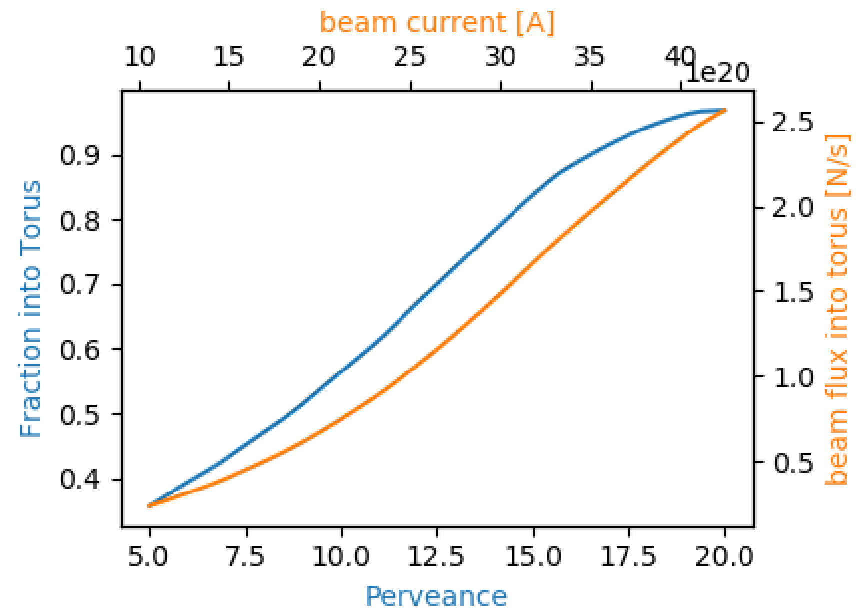
Maximizing confinement of beam fast ions not only improves beam fueling but allows beam to add momentum, current, heat to plasma

Characterizing beam performance

- All inputs to models predicting beam coupling rely on specifications of beam operation
- Spectroscopic data gives beam divergence v. beam parameters allowing optimization of flux into torus
- Also note: More investigation into beam profile is necessary

(Covid effects felt here- very limited experimental data)

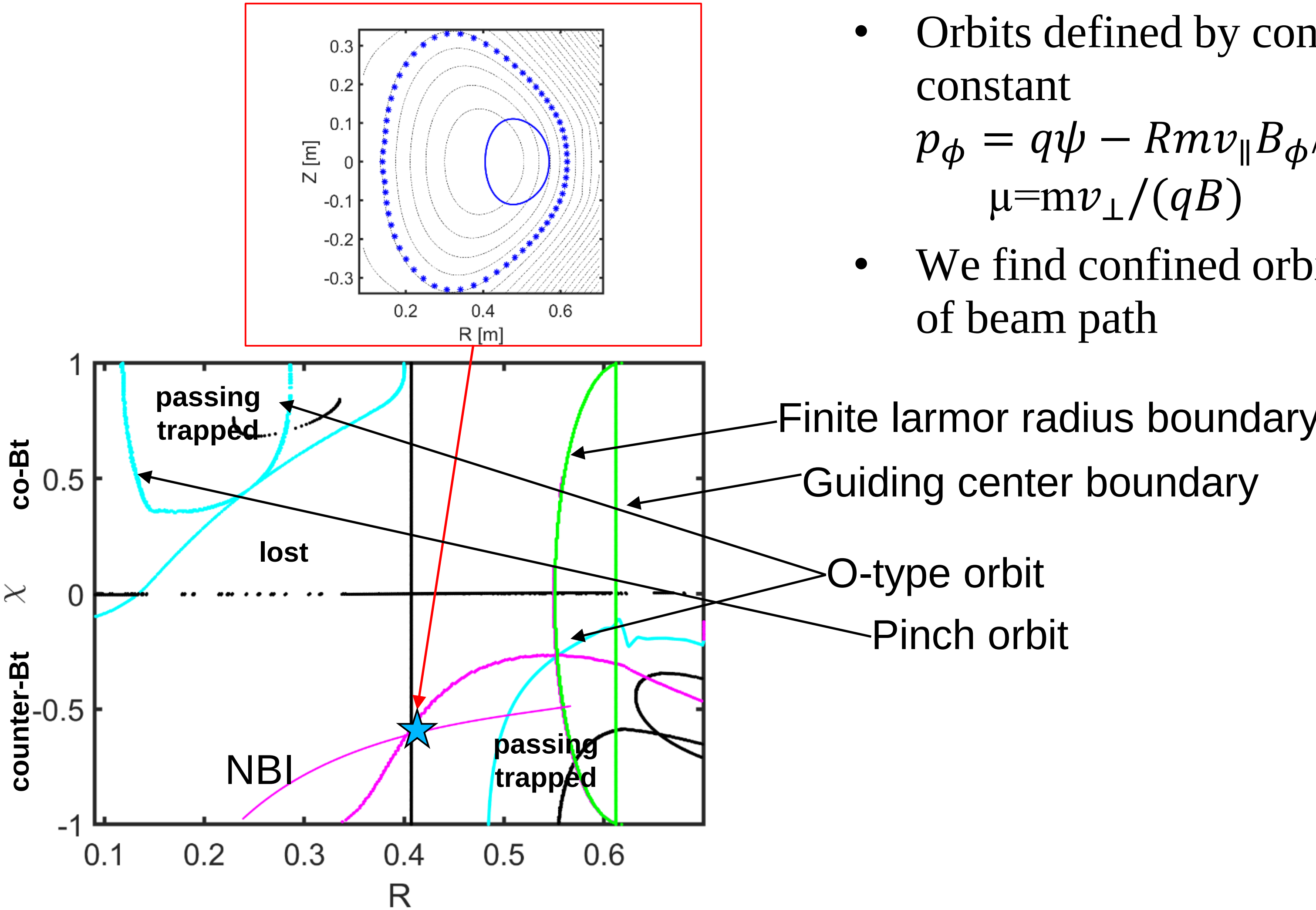




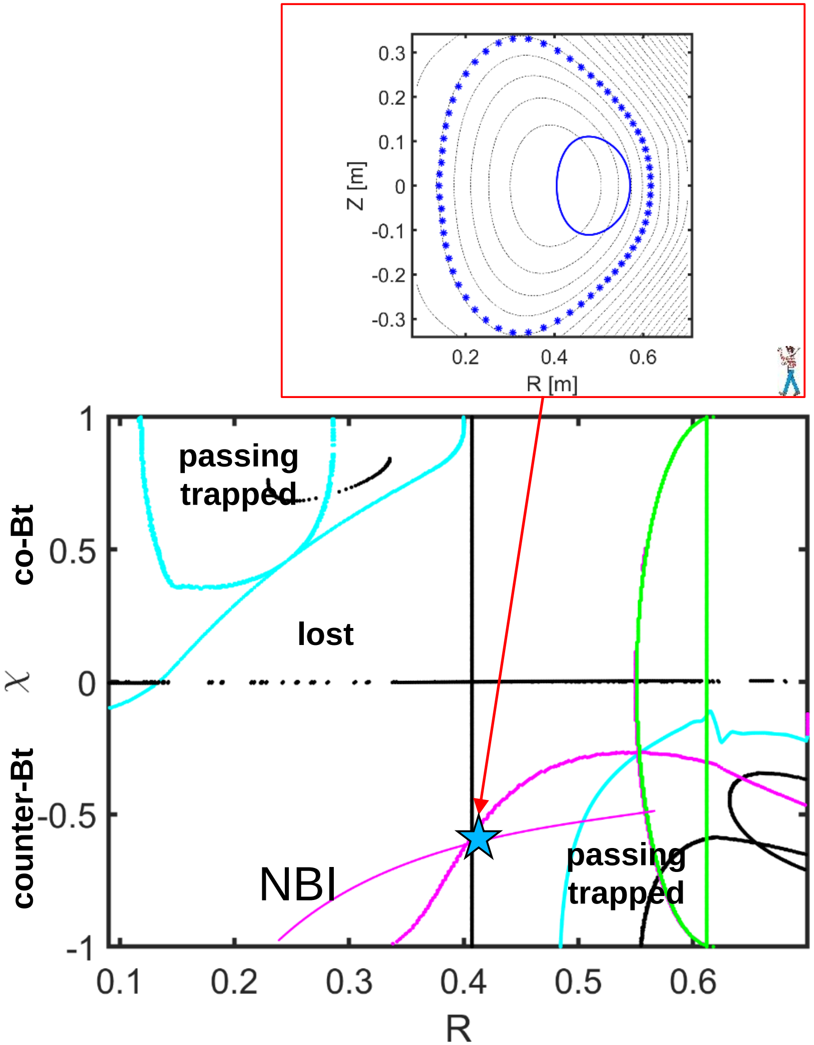
Phase space deposition determines fast ion orbit topology

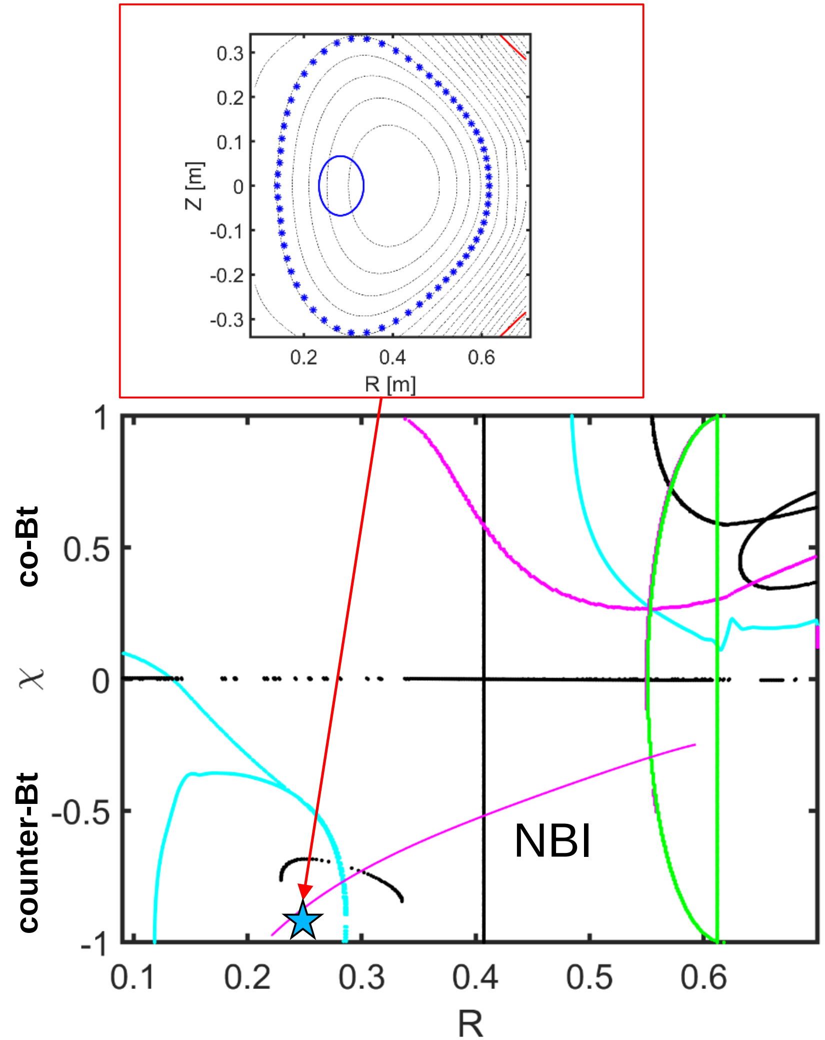
Topology code (guiding center)

- Orbits defined by contours of constant
  $p_\phi = q\psi - Rmv_\parallel B_\phi/\mathrm{B}$
  $\mu = \mathrm{m}v_\perp/(qB)$
- We find confined orbits along LFS of beam path



Reversing Ip direction changes deposition to HFS





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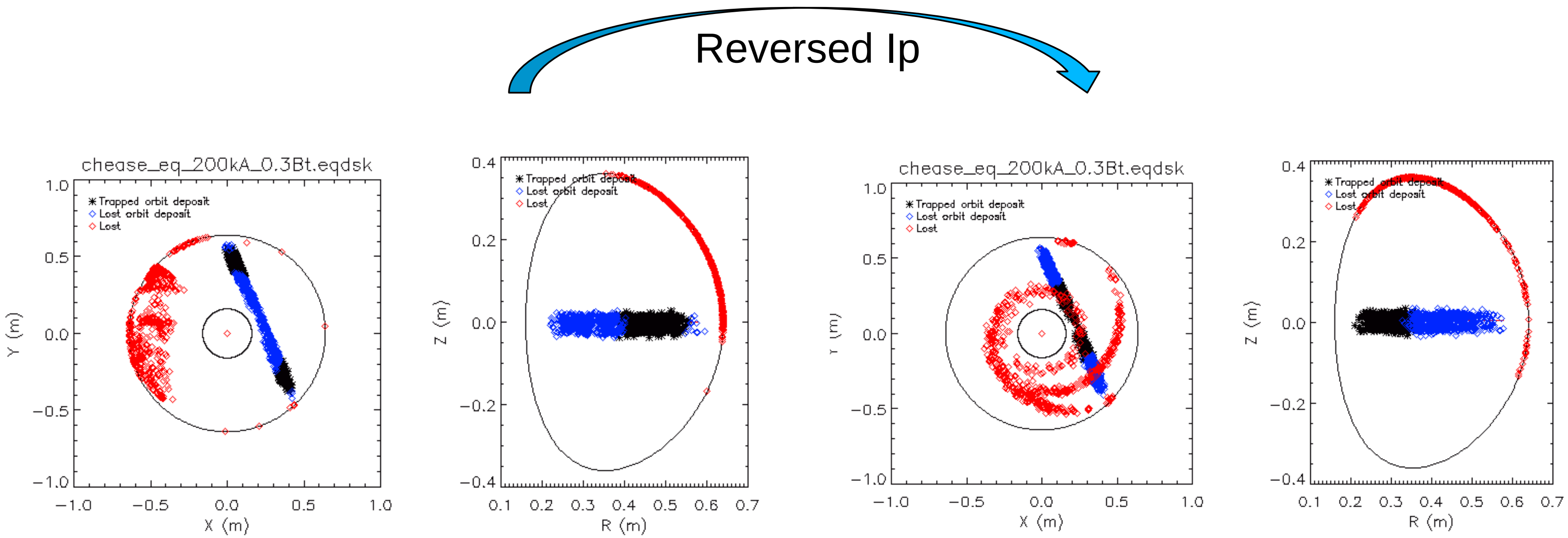
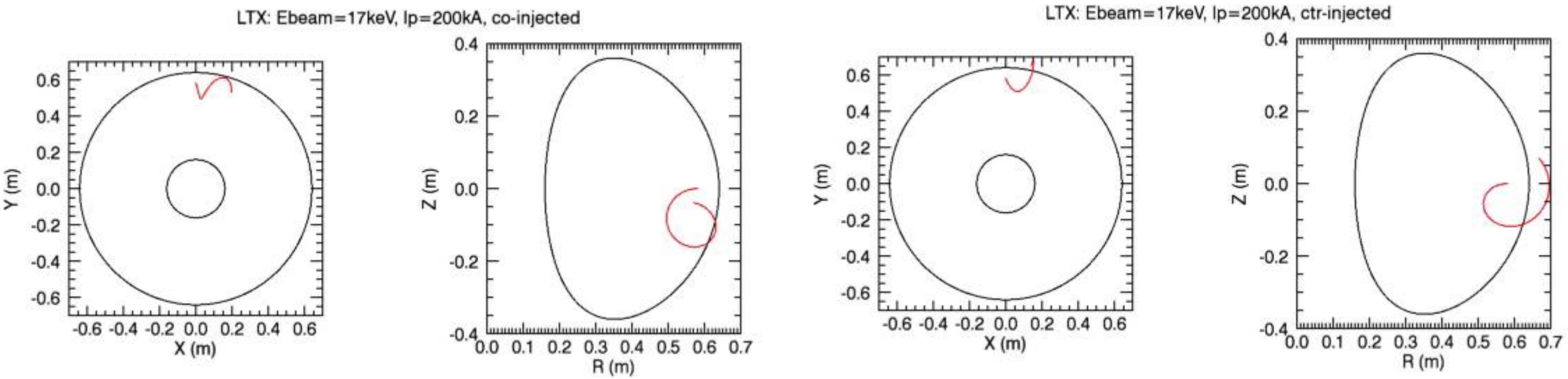
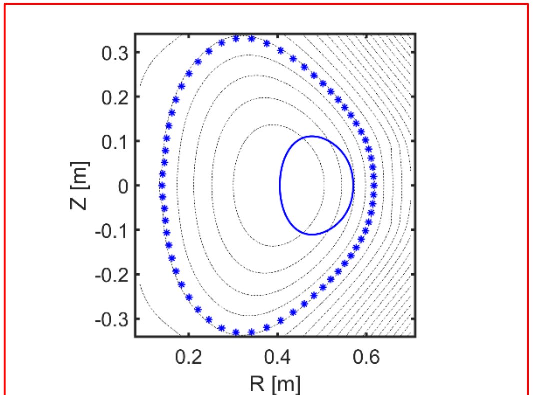


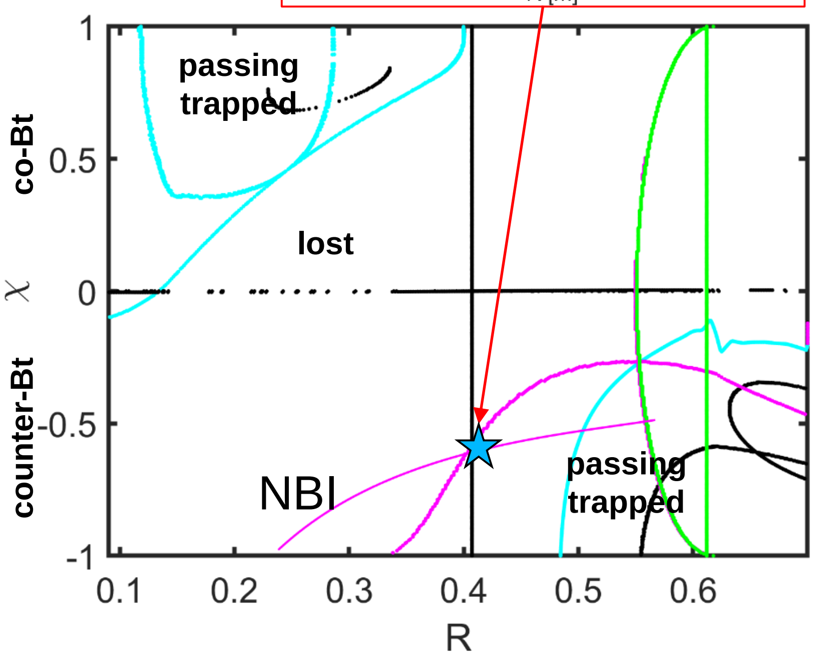


Beam geometry affects phase space deposition

Topology code (guiding center)

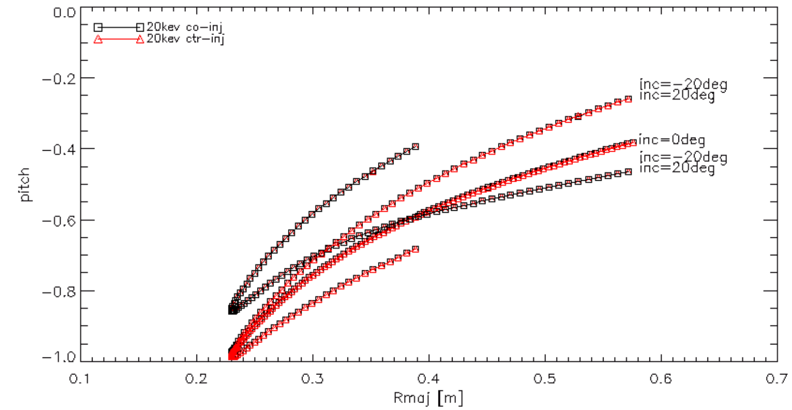
- Confined orbits along LFS of beam path

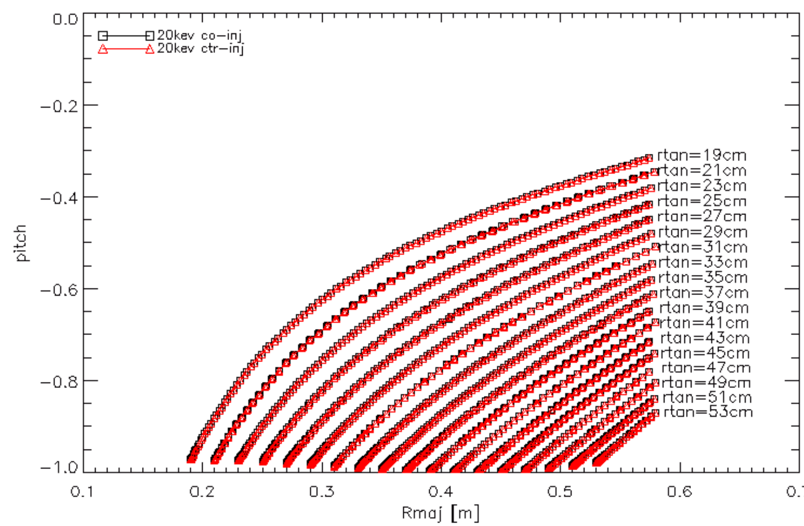




Full orbit code

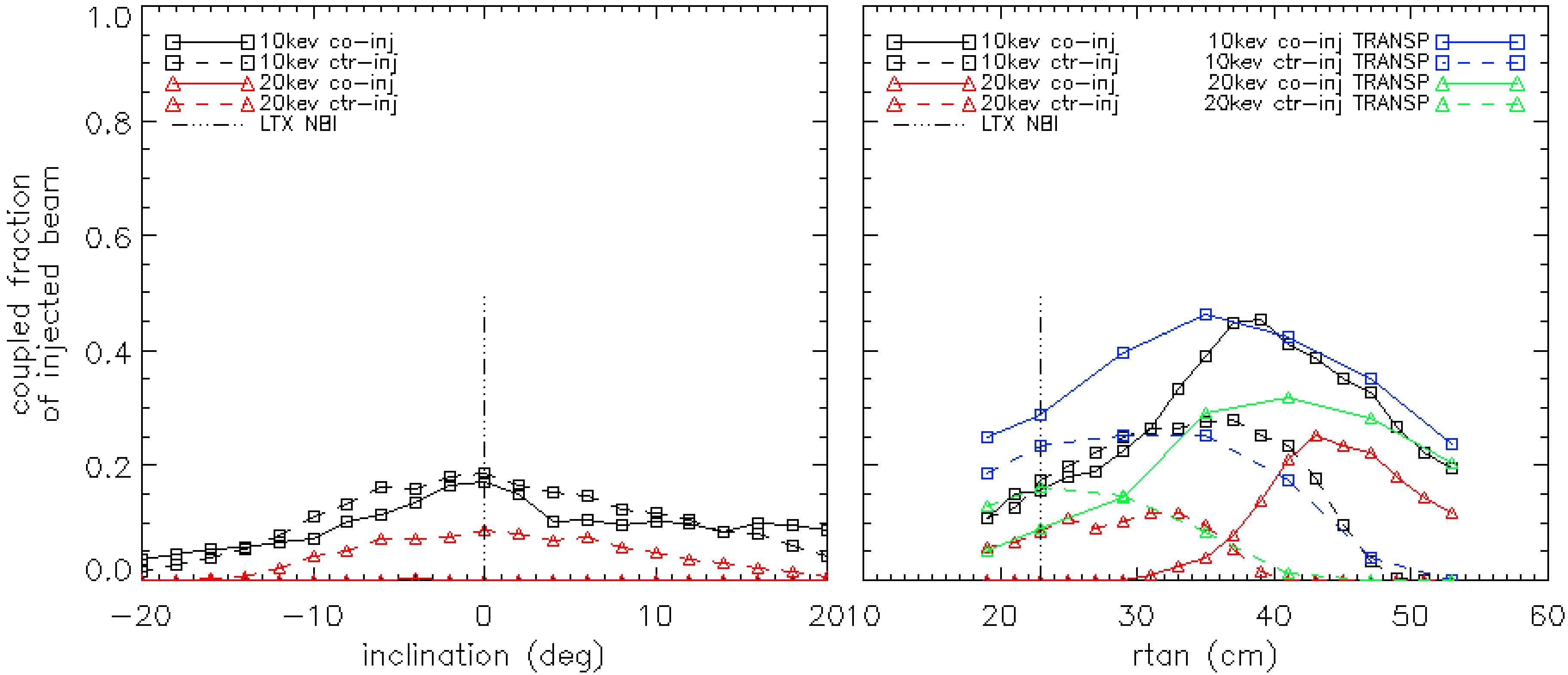
- Beam phase space deposition changes with NBI inclination and tangency radius





Modeling NBI coupling

- Optimal orientation of 0º inclination, rtan near 40cm
- Benefits of a larger tangency radius may be immediately accessible by shifting magnetic axis to smaller radii



Full orbit model of 155kA equilibrium

Summary and future steps

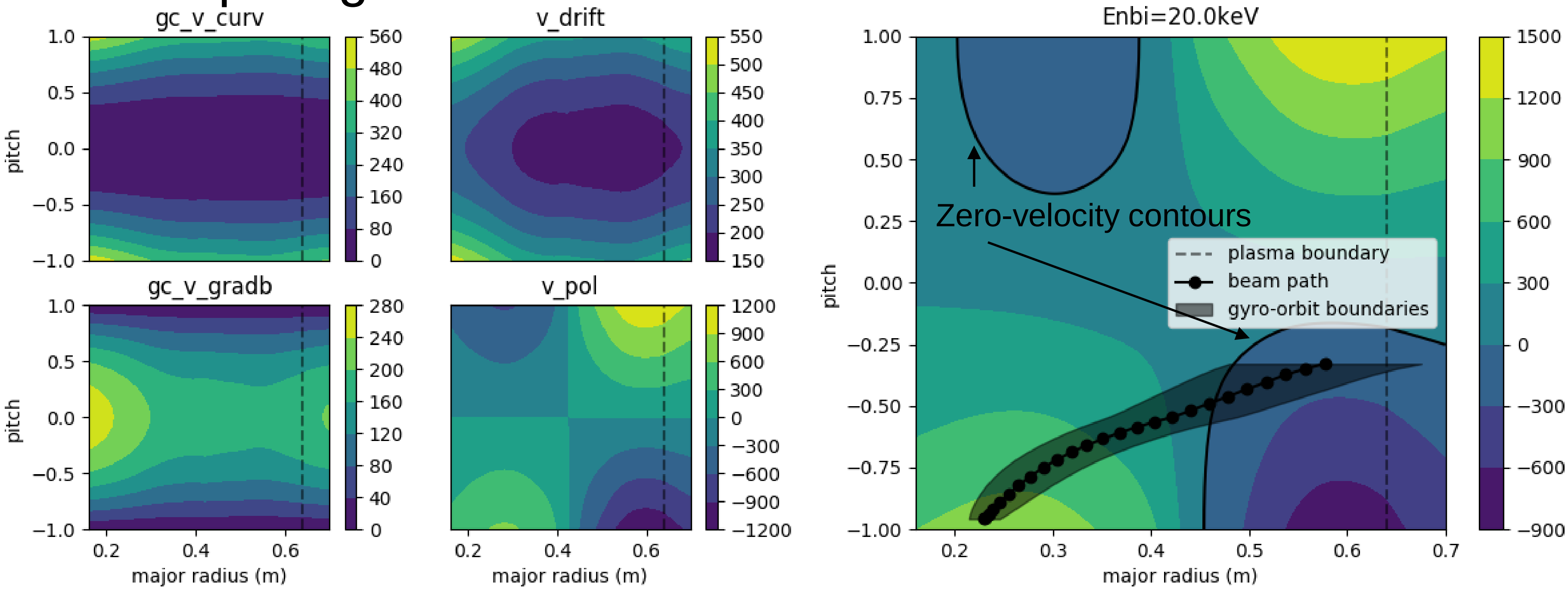
- Extending experimental dataset of beam optics will allow for a model to optimize beam performance and flux into the torus
- Multiple models (TRANSP, full orbit code, and orbit topology) combine to describe beam-plasma coupling
  - Easy to change parameters: ne, Ip, Ebeam
  - Non-trivial parameters: Inclination, tangency radius, direction of Ip
- Orbit topology and full orbit model also serve to inform design process of fast ion diagnostics

- Expand datasets: quantify beam optics and profile
- Validate beam modeling: measure NBI impact on density, current, torque, etc
- Synthesize models into predictive toolkit for optimal beam operation
- Implement NBI diagnostics: do fast ion physics!

extras

Simple explanation of HFS/LFS deposition

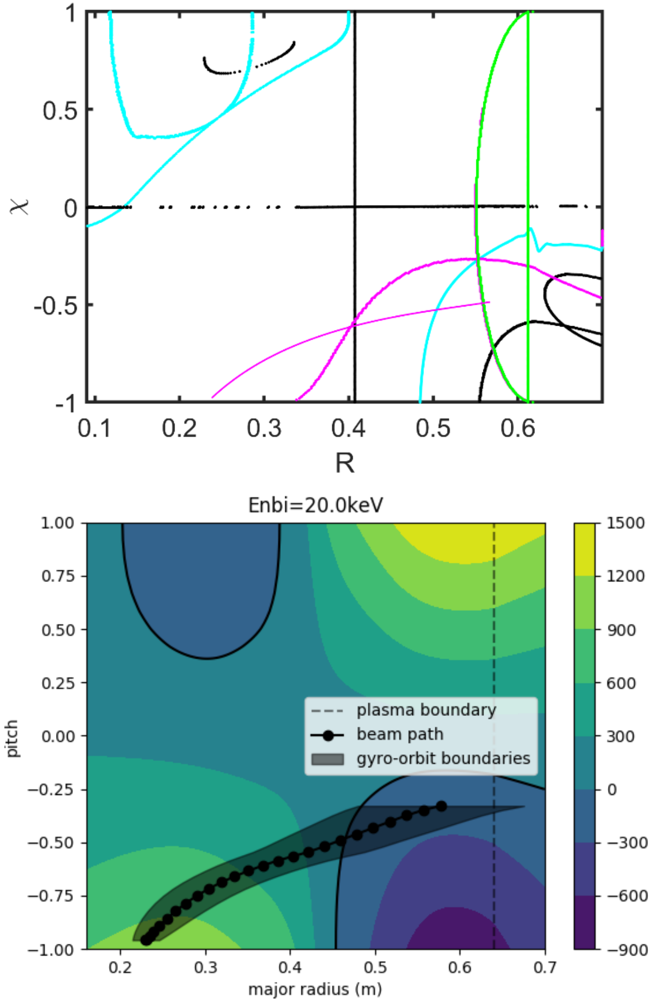
- Deposition depends on balance between ion drift velocity and initial poloidal motion
  - Initial ion parallel velocity vertical component anti-parallel to drift velocity on LFS
  - Reversed Ip flips the initial ion velocity component (but not drift velocity) so anti-parallel velocities switch to HFS
- Expect good confinement near zero contour



Simple explanation of HFS/LFS deposition

- Compare drift velocity model (normal and reversed) to orbit topology code

NBI co-Ip injected



NBI counter-Ip injected