NSTX

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Impact of the X-point Radius and Divertor Recycling on the L-H Transition Dynamics and P_{LH} on NSTX

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and the NSTX Research Team

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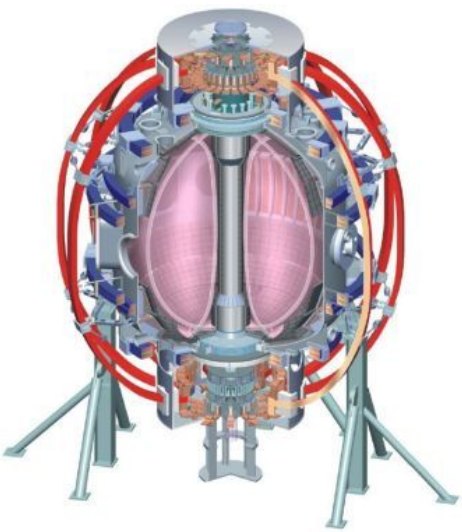

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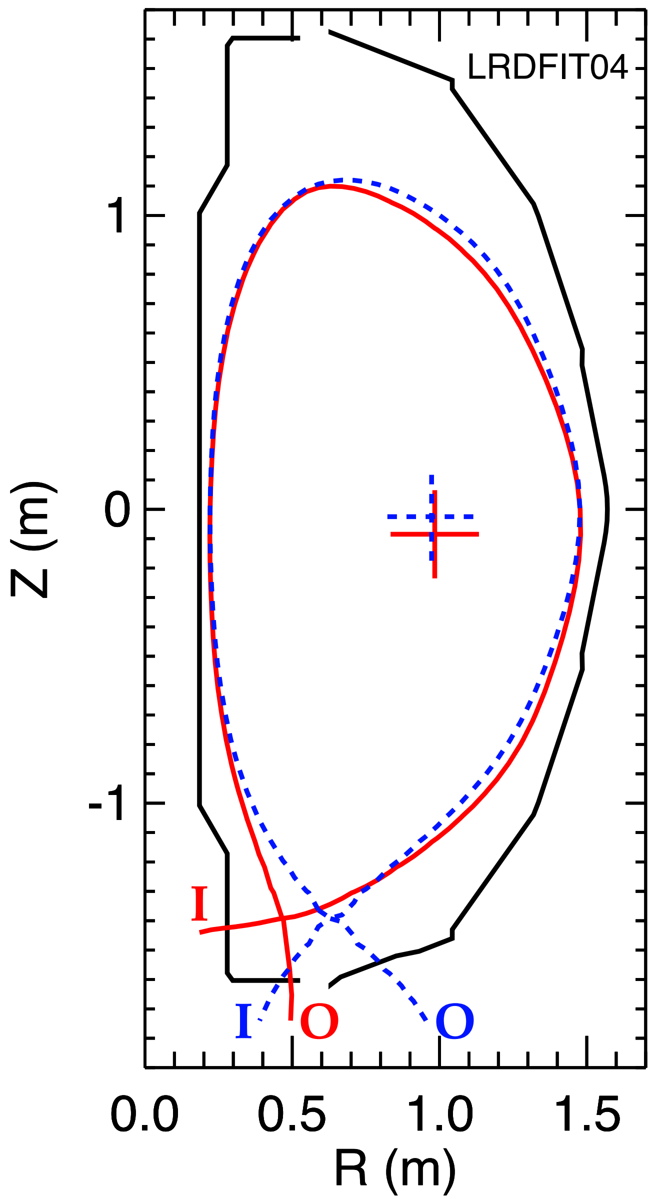
Outline and Motivation

- Properties of X-point and divertor are "hidden variables" of P_{LH}
  - ITER and beyond: predict and control conditions for L-H and H-L
  - NSTX: Investigate P_{LH} vs R_X over large range of recycling/fueling
    - Enabled by unique open divertor and lithium pumping scheme

- P_{LH} increases with larger triangularity (δ), and neutral density
  - T_e and n_e profiles at L-H transition are similar despite a large range in heating and neutral fueling
  - Large increase in divertor currents observed prior to transition

- Results are interpreted using XGC0
  - Self-consistent pedestal-SOL kinetic model
  - Preliminary understanding: single-ion orbit loss hole and ion-neutral physics influence $E_r \times B$ flow shear available for turbulence suppression

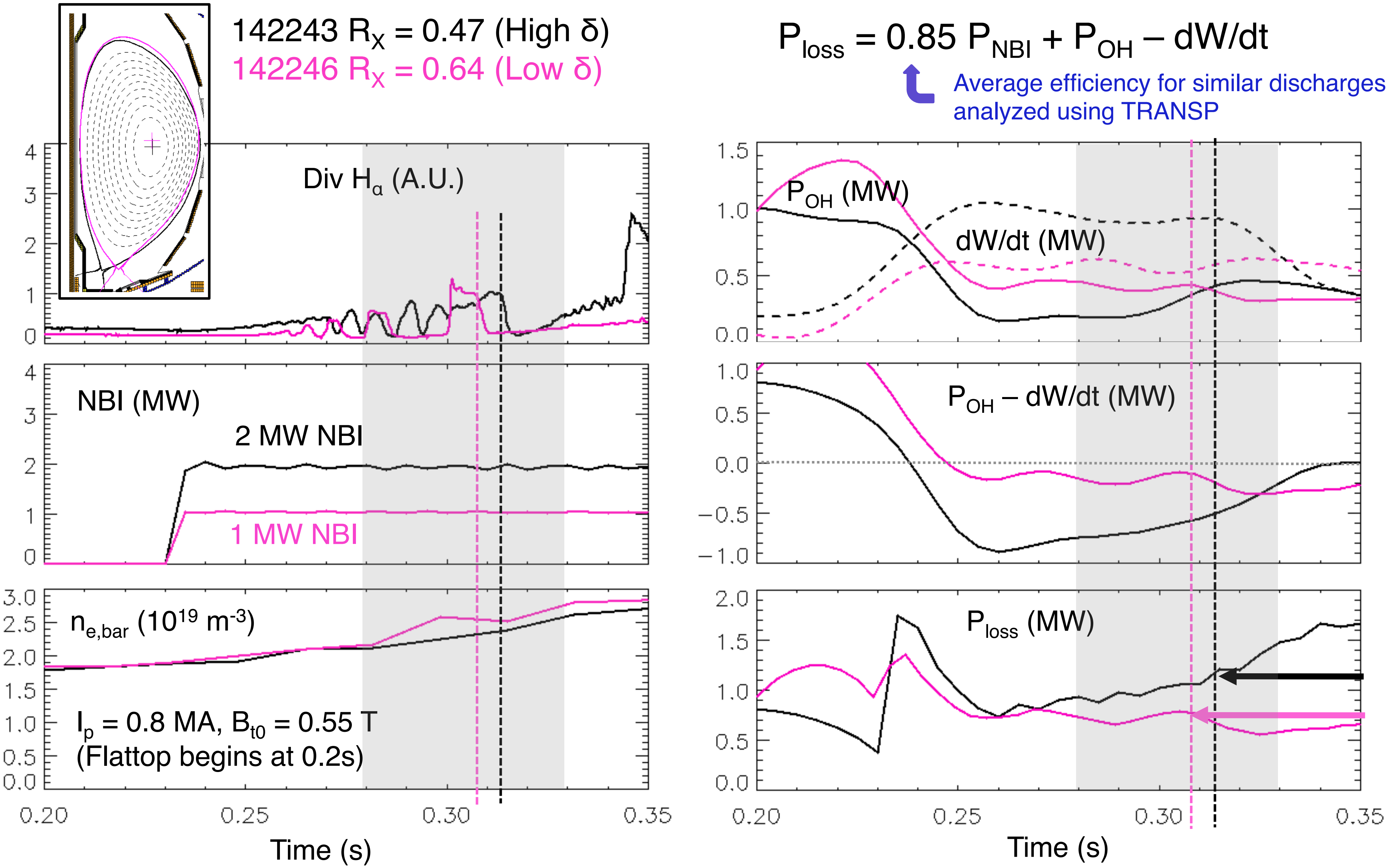
NSTX provides unique capability to examine impact of divertor recycling and X-point conditions



- Ubiquitous tokamak observation:
  - Change P_{LH} via R_X, Z_X, divertor leg length, divertor pumping, wall conditioning, shot number…
- Goal: Quantify P_{LH} and edge profiles over a large range of triangularity and divertor pumping
  - Match R_{IN}, R_{OUT}
  - Nearly match X-point height, surface area, B_{T0}, B_{OUT}, density
  - Reproduce shapes under different pumping & fueling conditions
  - Require LH > 50 ms after NBI step

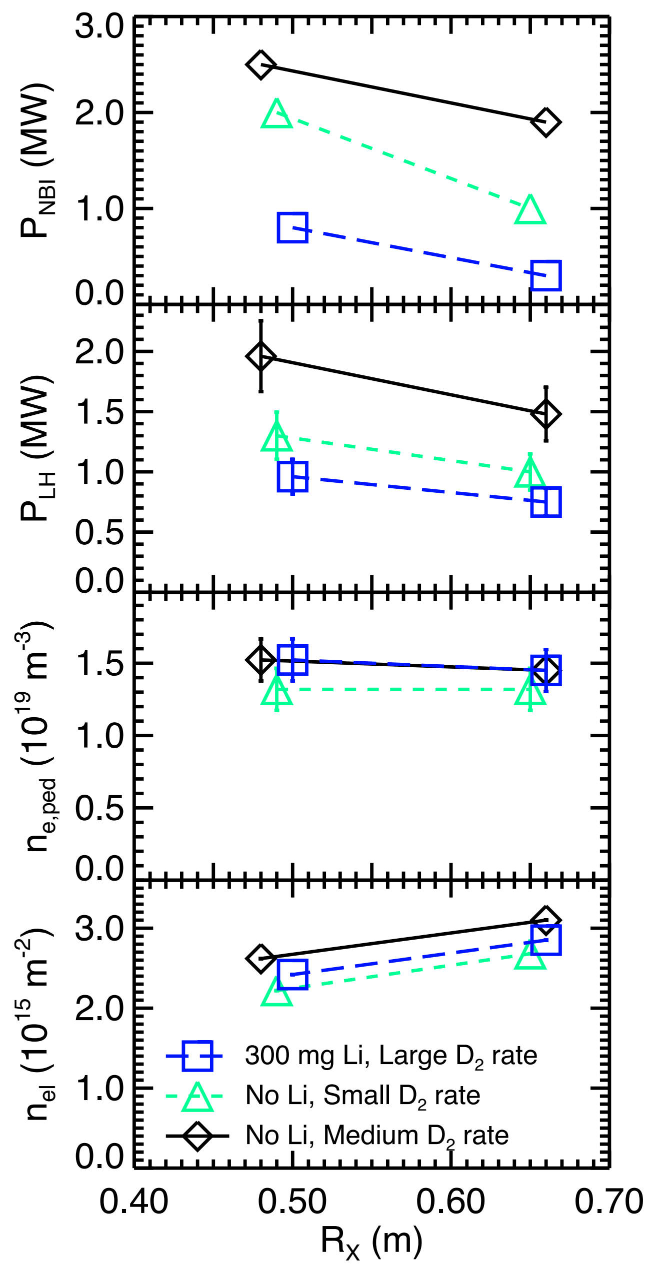
First results reported in: R. Maingi, et. al. *Nucl. Fusion* **50** (2010)

200 – 300 kW shot-to-shot variation in NBI power to get L-H when (P_{OH} – dW/dt) is slowly varying and free of MHD

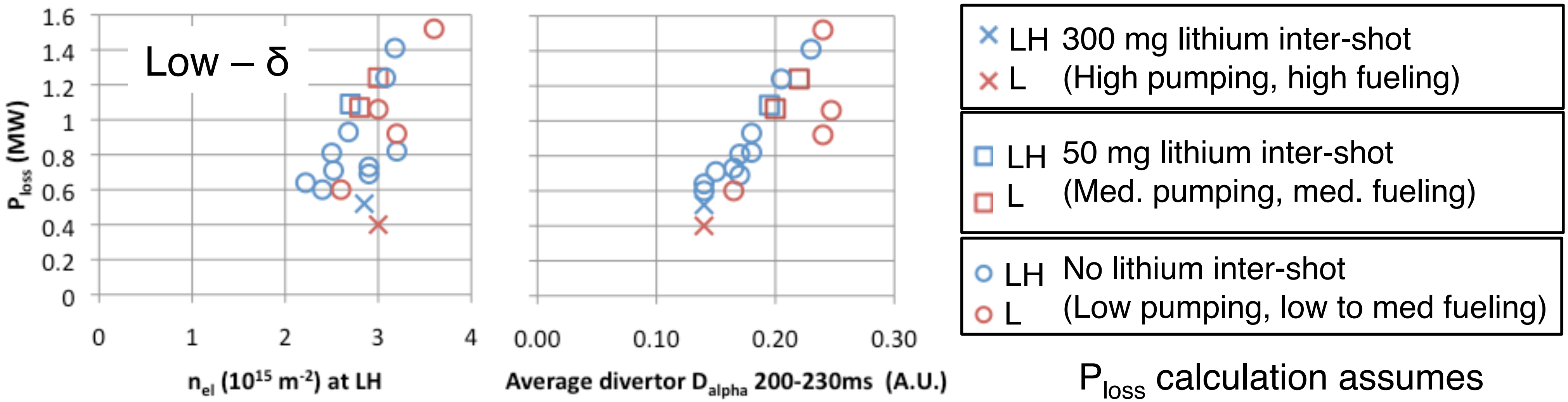


P_{LH} varies with the neutral fueling/pumping scenario and R_X

- Three pumping & fueling conditions
  - Divertor pumping on NSTX varied using inter-shot Lithium deposition rates
  - Density "locked-in" by operational constraints
- P_{LH} increases …
  - Factor of 2 over pumping/fueling range
  - About 30% from large to small R_X
- L-mode density pedestal
  - Nearly matched for all cases
  - Line-averaged showed larger change in opposite direction of P_{LH}



P_{LH} scales strongly with the inferred divertor recycling



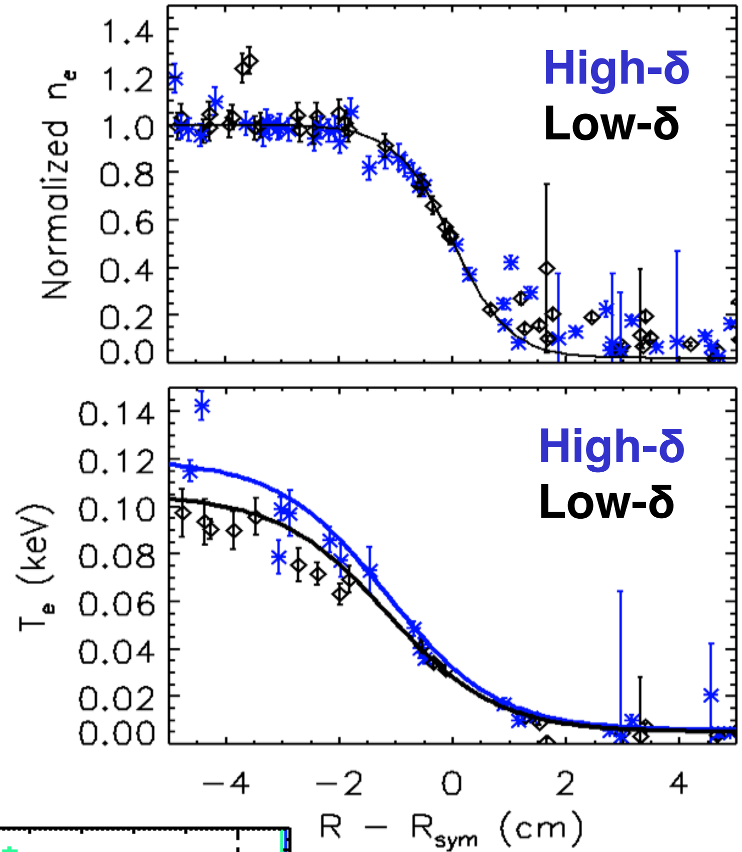
P_{loss} calculation assumes

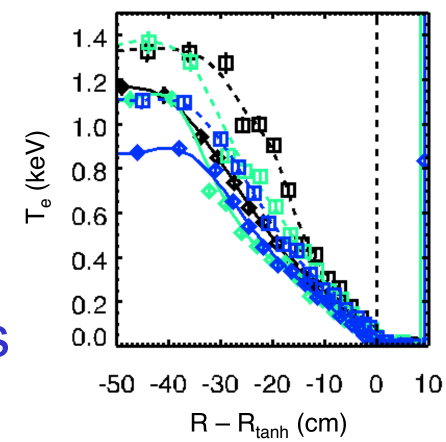
P_{heat} / P_{NBI} ~ 85% for all discharges

- P_{LH} trends higher with line-integrated density
  - Qualitatively agrees with ITPA scaling
  - Yet, P_{loss} varies over a factor 3 at n_{el} ~ 3 x 10^{15} m^{-2}
- P_{LH} increases with pre-NBI divertor D_α signal
  - May be proportional to initial edge neutral density (n_N)
  - Impacts NBI efficiency and ion-neutral collisional losses

Electron profiles at L-H are similar despite large range in heating power and neutral fueling

- n_e from last 2 or 3 L-mode profiles
  - n_e normalize to $n_{e,ped}$
  - All profiles roughly fit tanh profile with ~ 1 cm width
- T_e plotted with R axis normalized to tanh symmetry point (~ 1.47 m)
  - Only last L-mode profile before L-H plotted at right
  - High-δ has ~ 10% larger T_e at top of density pedestal
- Central T_e follows NBI heating
  - But $T_{e,ped}$ are very similar for all cases





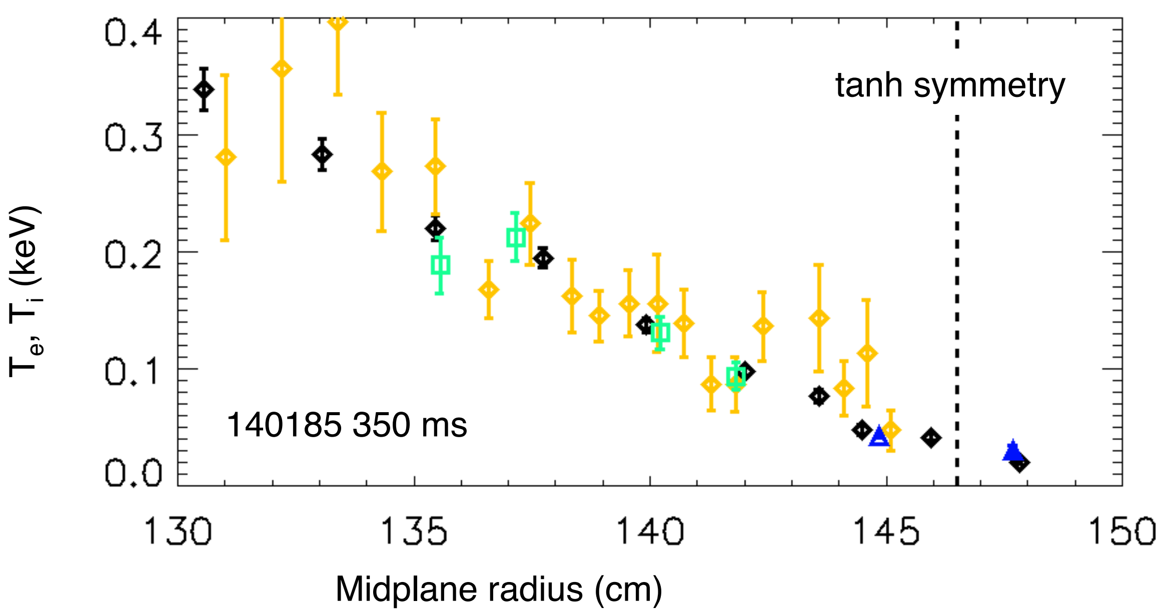
Dash: High-δ
Solid: Low-δ

Black: No Li, Med fuel
Green: No Li, Small fuel
Blue: Li, Large fuel

Ion measurements difficult in L-mode edge of NSTX

- Poor L-mode Carbon confinement, marginal NBI, and lithium coated windows conspire against CHERs

- Could infer $T_i \sim T_e$ in L-mode edge
  – Thermal equilibration time < electron thermal confinement
  – Limited edge T_i data lines up fairly well with T_e L-mode profile



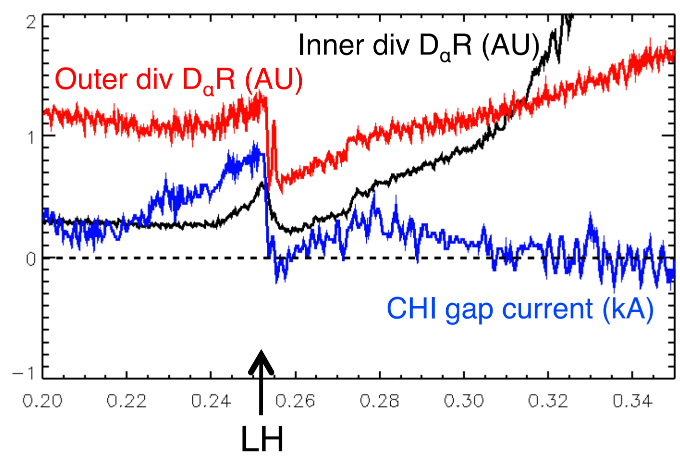
Example of L-mode T_e, T_i close to L-H transition

T_e (MPTS)
T_i (CVI CX Spectroscopy)
T_i (CVI intrinsic emission inverted)
T_i (CIII intrinsic emission)

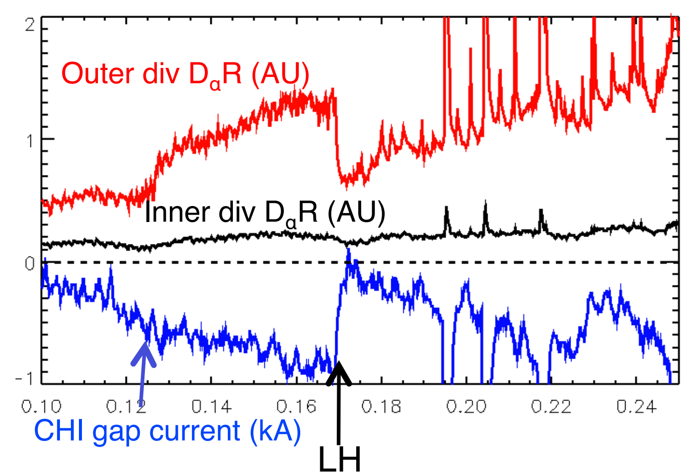
L-H transition on NSTX "always" preceded by an increase in the divertor D_α and CHI gap current

- NSTX: D_α increases prior to L-H
  - Favorable: biggest change in inboard div
  - Unfavorable: biggest change in outboard div
- NSTX: Divertor current prior to L-H
  - Direction of current follows grad-B direction
- L-mode: Divertor current saturates & decays, D_α continues upward trajectory
- Dithers and L-H: D_α and divertor current quickly drop in ~ 1 ms

Favorable grad-B



Unfavorable grad-B



Summary of experimental observations

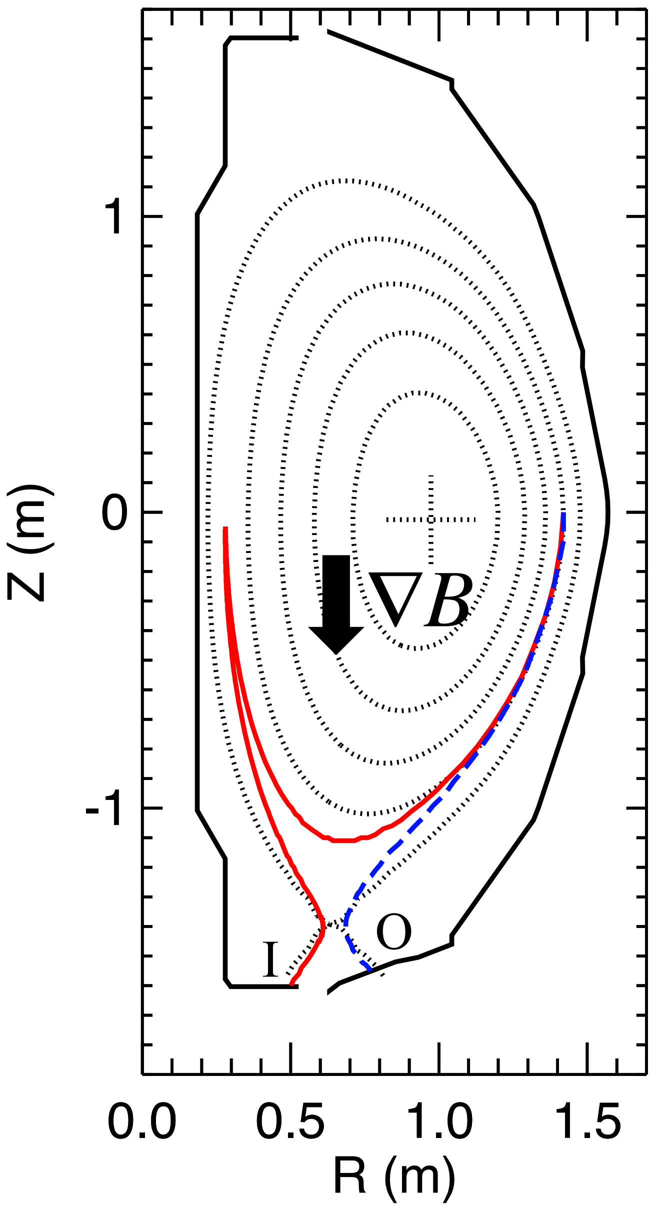
- P_{LH} varies 20 – 40% over range of triangularity
  - Edge T ~ 10% difference over range of R_X
  - Remaining energy probably goes to ion-neutral collisions
- P_{LH} increases with inferred neutral density
  - Consistent with ion-neutral collisions consuming energy
- T_e, n_e at L-H pretty similar despite large range in heating power (NBI: 0.3 – 2.6 MW) & neutral fueling (D_α: 0.15 – 0.25)
  - Large divertor pumping leads to broad T_e profile (i.e., low peaking)
  - Ion edge temperature and rotation are not well constrained
- Before L-H transition …
  - Dithering phase is longest at lowest P_{heat} (or smallest neutral density)
    - Very few dithers observed at largest neutral fueling cases
  - Always see increase in D_α and divertor current
    - Changes character with grad-B direction

Connecting experimental results to theory and simulation

- What do these results say about the L-H trigger?
  - Pick a theory … Diamond … FM^3 … Burrell …
  - Most propose non-linear mechanisms for suppressing turbulence
  - Most theories say (more or less) that the transition will be more likely as the E × B flow shear increases
  - … and that the mechanisms are not direct functions of grad-B, R_X, n_N
  - … the mean equilibrium profiles are a function of these things

- Goal: use a self-consistent simulation of edge to examine dependence of $E_r \times B$ flow shear, edge gradients, separatrix parameters, etc. versus grad-B, R_X, n_N …
  - How well could these computed scalings explain the observed P_{LH} scaling with "hidden variables?"
  - XGC0: full-f of pedestal and SOL; ion, electron & neutrals; real 2D or 3D edge geometry; sheath physics

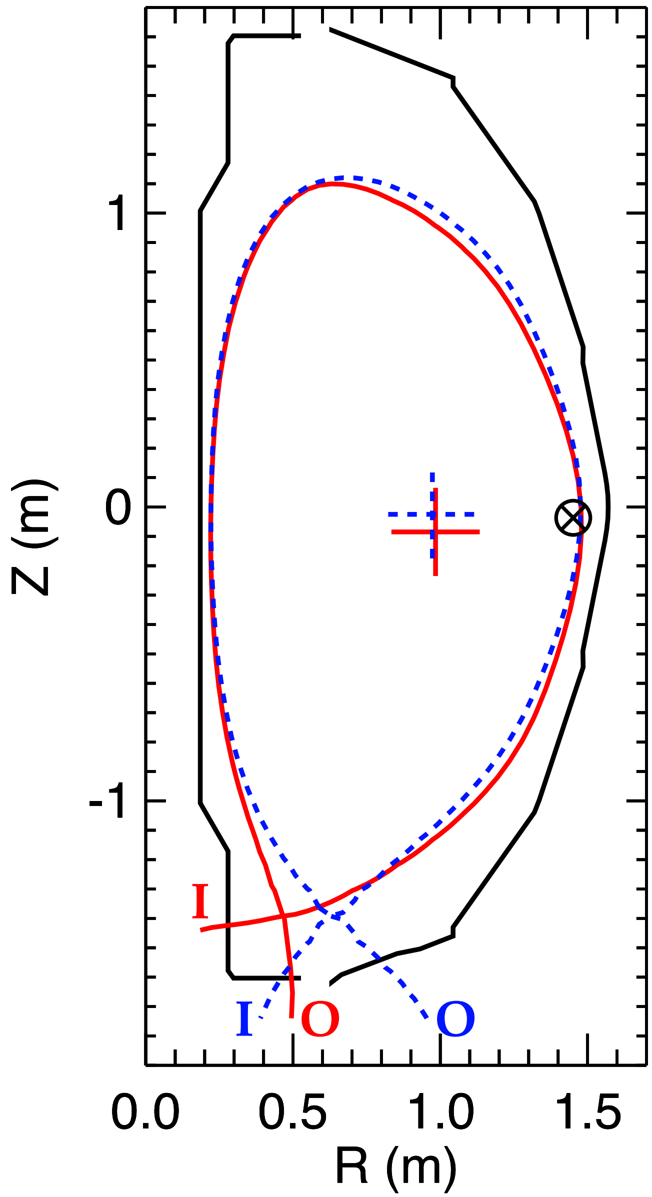
X-transport: suppression of non-ambipolar transport of ions on neoclassical orbits contributes to the edge E_r



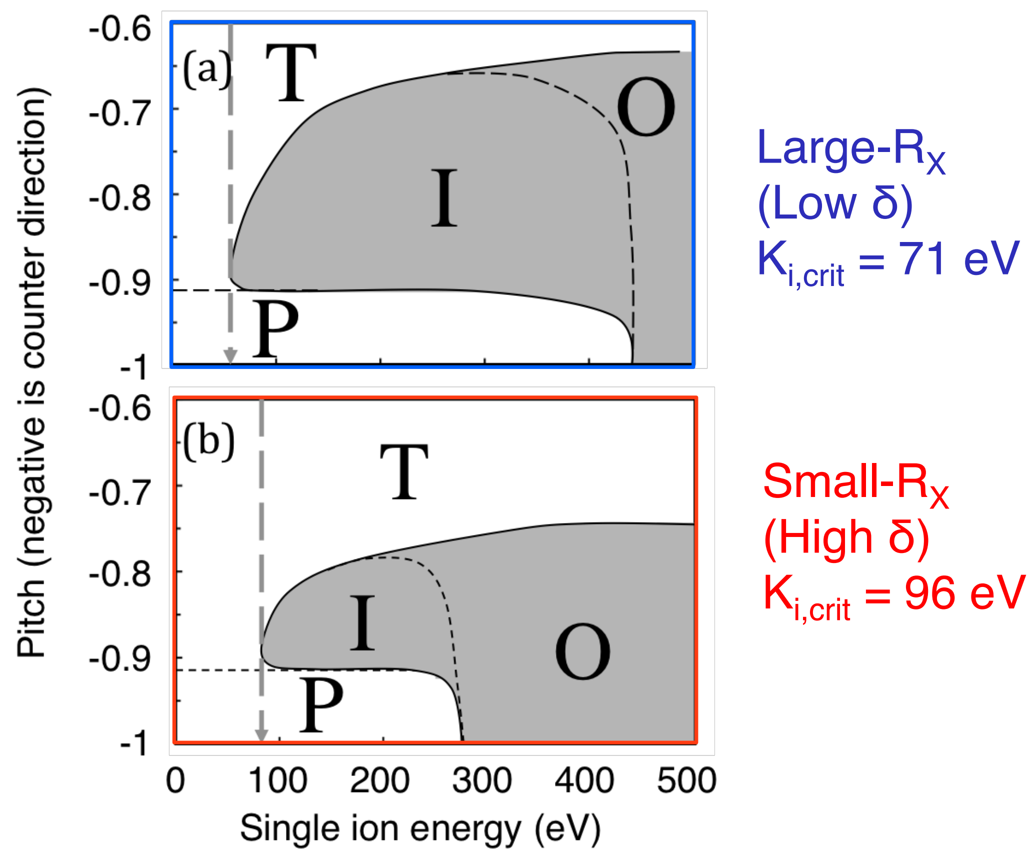
- X-point amplifies grad-B drift
  - X-point: low B_θ, slows poloidal transit
  - Non-ambipolar: ion drift >> electron drift
- Lowest energy loss orbits:
  - Start at outboard midplane
  - Bounce at inboard midplane
  - Lost to inner divertor leg in favorable grad-B
- Negative E_r acts to confine ions
  - Constraint on E_r: must be negative enough to nearly suppress non-ambipolar ion loss

C.S. Chang, S. Ku, H. Weitzner, *Phys. Plasmas*, **9** (2002)

Critical energy for ion loss increases as R_X decreases



ψ_N = 0.96 (~1 cm from separatrix) at midplane

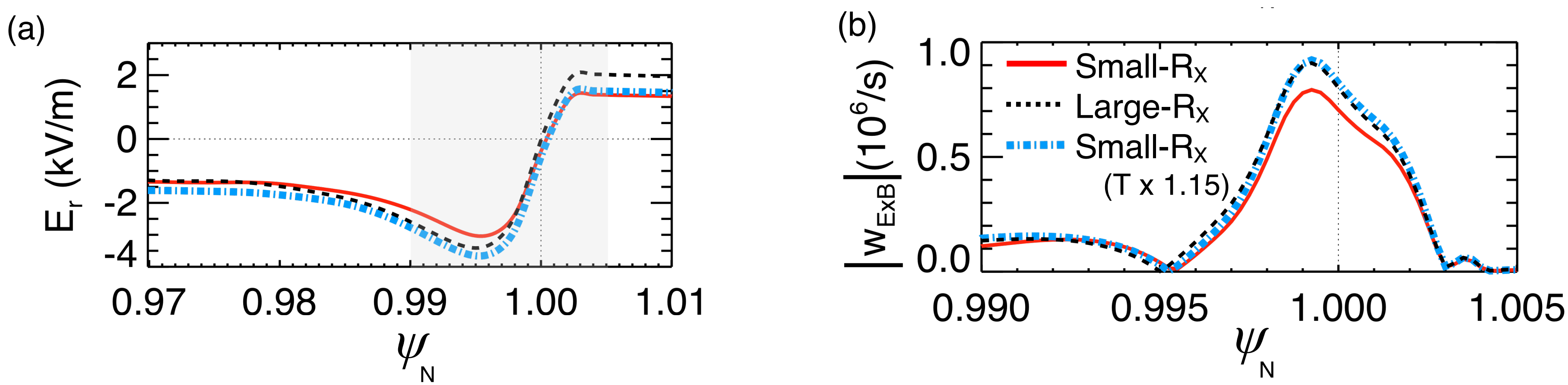


- Critical energy increases ~35% as R_X moves in: 0.64 → 0.47 m

Guiding-center orbit tracing code:
S. Ku, H. Baek, C. S. Chang, *Phys. Plasmas* **11** (2004)

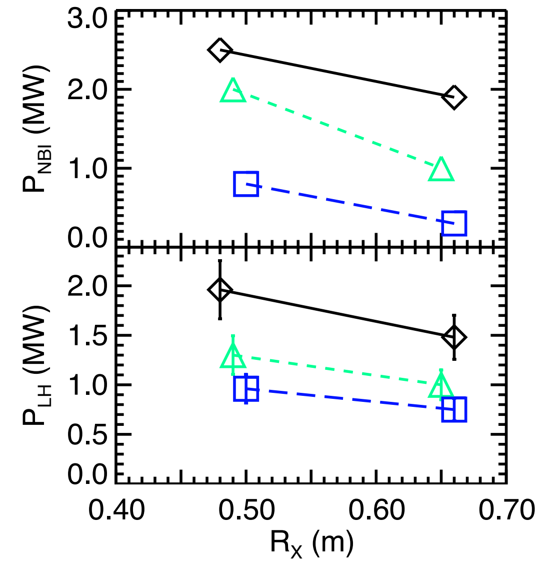
Preliminary XGC0 results indicate the ion-orbit loss hole does impact E_r close to the separatrix

- Self-consistent E_r calculation with D^+, e^- and D^0
  - Start with L-mode T_e (= T_i) and n_e, 99% recycle rate, no impurities
  - Core heat and particle source to maintain profiles
    - About 5 - 10% larger core heat needed for low-δ shape
  - No anomalous transport (kinetic neoclassical)
    - Initial profiles steepen
    - E_r well is 20 – 40% deeper for low-δ shape
  - Include anomalous transport (~0.06 m^2/s)
    - Profiles held constant for a few ms
    - E_r well is only about 10% deeper for low-δ shape

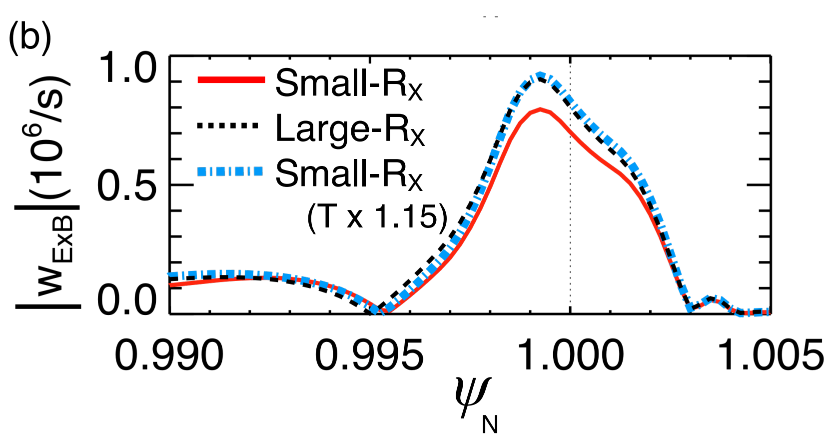


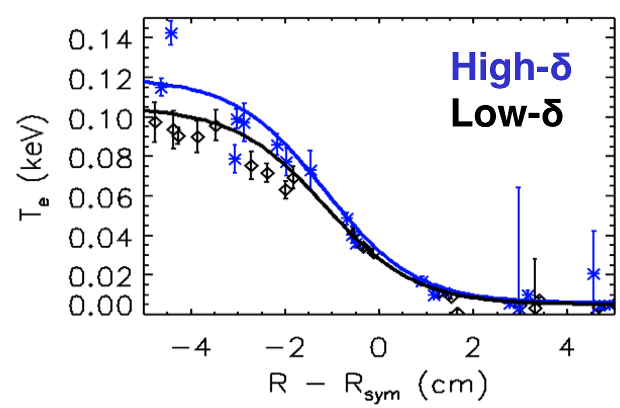
XGC0 is providing insight into the mechanisms that lead to P_{LH} varying with R_X on NSTX

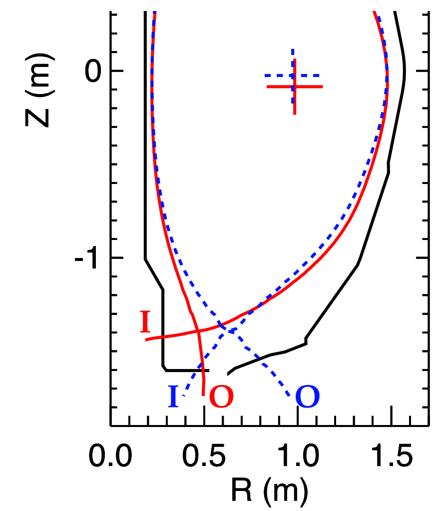
- XGC0: ~ 25% more core heating needed in high-δ shape to match $E_r \times B$ flow shear
  - ~ 15% larger T_i to offset X-transport effect
  - ~ 10% due to increased ion-neutral losses
  - Does the L-H trigger physics depend on R_X?



- XP: P_{LH} is 20 – 40% larger for high-δ shape
  - Nice connection between model and experiment, but results are preliminary



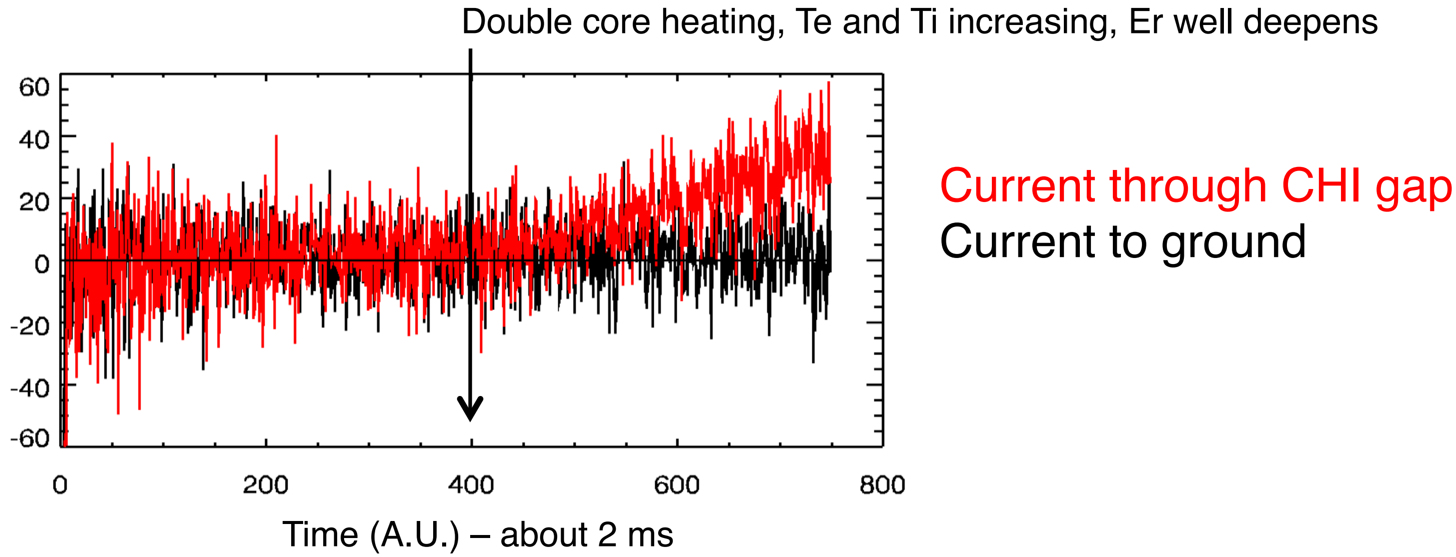




Some other preliminary observations with XGC0 that correlate with experimental results

- Reduced recycling deepens E_r well
  - Neutral density has biggest impact on T_i via CX losses
    - Smaller impact on T_e
  - Fueling changes height of density pedestal, but not the width much
    - L-mode n_e pedestal width is primarily set by anomalous transport rate

- Code can probe dynamic solutions approaching L-H



On-going work

- Turbulence measurements in this data set
  - Any signatures during dithers or just prior to L-H?
  - What would L-H trigger theories predict for this dataset?
- Working with CPES team to resolve curiosities in first runs with XGC0
  - Goal is to quantitatively compare to experiment using synthetic diagnostics built around XGC0 calculations
- Impact of grad-B drift direction, magnetic balance of X-points
  - These have large impacts on P_{LH} (factors of 2 or 3)
  - Potentially the highest impact connection between model and experiment
- Supporting DIII-D boundary group with XGC0 runs

Summary

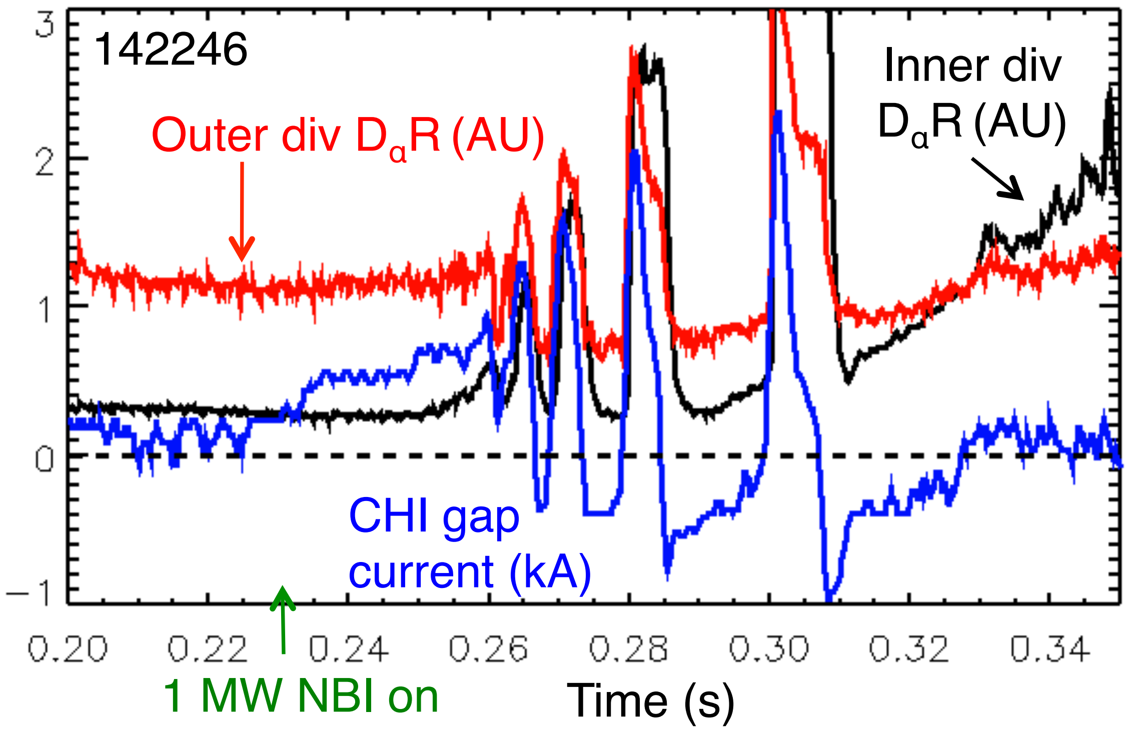
- P_{LH} increases 20 – 40% as triangularity increases
  - About half of this power goes into achieving the larger T_e &T_i needed for comparable $E_r \times B$ shear
    - Due to single-ion orbit loss hole near separatrix
  - Other half lost to ion-neutral collisions
    - Presumably due to changes in the divertor connection lengths, flux expansion …

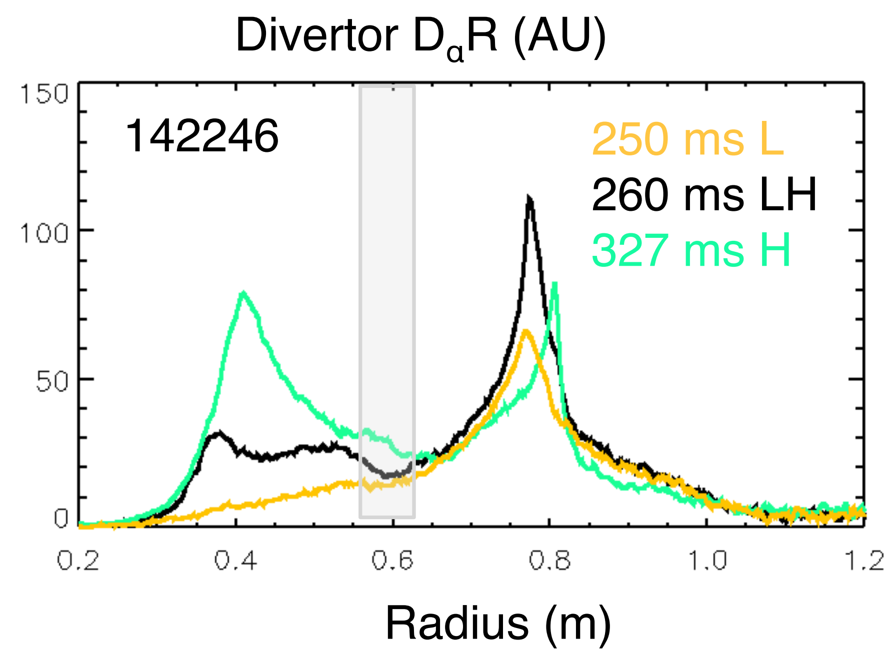
- P_{LH} varied over a factor of 2 via lithium coatings
  - Consistent with P_{LH} increasing with the inferred divertor recycling
  - On-going XGC0 work will explore ion-neutral dynamics

- I'll be back … hopefully with …
  - Impact on P_{LH} from grad-B drift, dynamic solutions approaching L-H, scaling with different threshold conditions, turbulence characteristics around dithers and L-H

BACKUP

Prior to LH, increase in inboard divertor D_α and a finite current across divertor gap





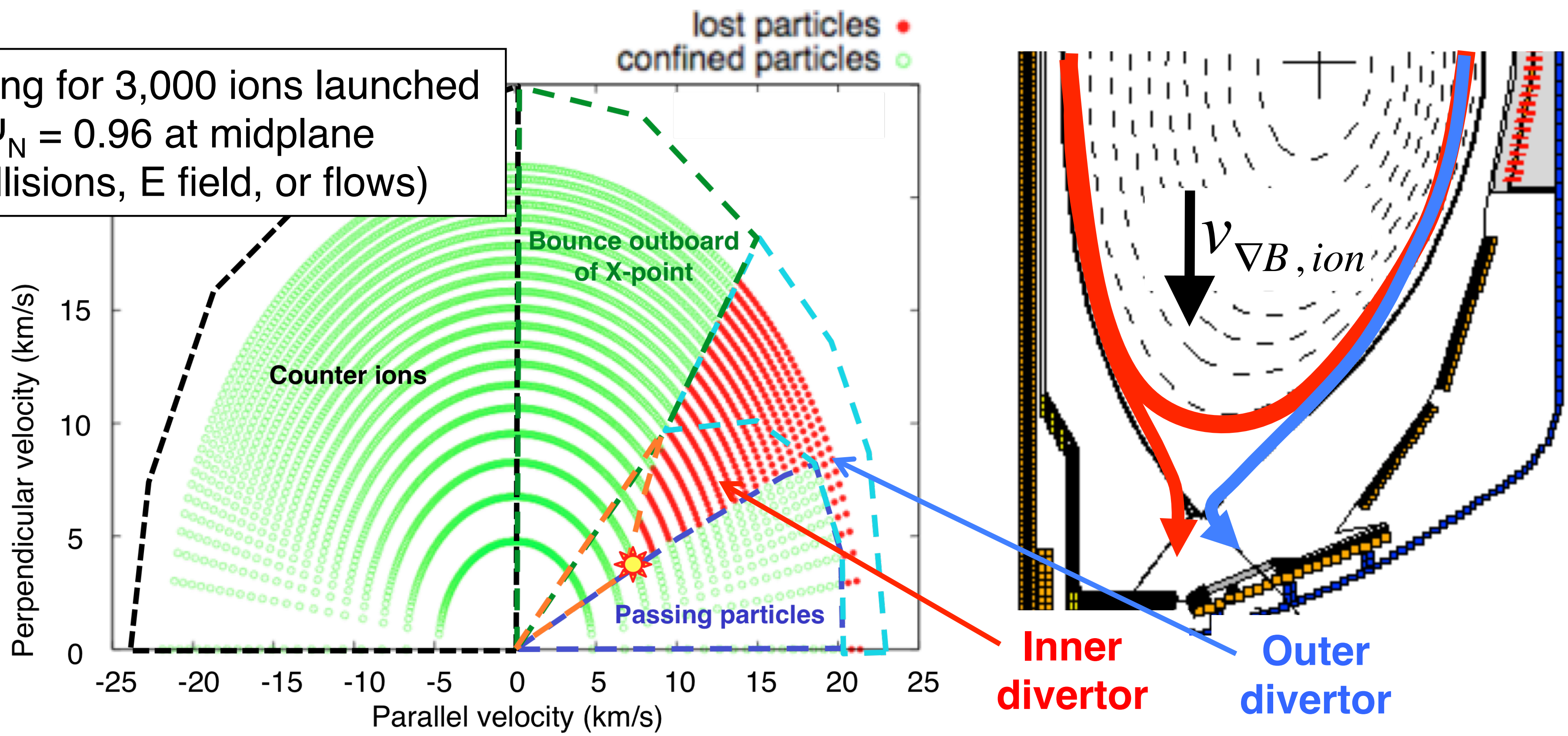
- As $P_{loss} \rightarrow P_{LH}$ …
  - Significant increase in inboard div D_α
    - Broad D_α through private flux region (ions grad-B drift)
  - Current across CHI insulating gap toward outer divertor
    - Suggests increase in ion current to inboard divertor
- Observed in NBI heated and ohmic-only discharges

X-point geometry enhances ion-orbit loss, primary loss is to the inner divertor plate

- Low B_p above X-point enhances grad-B drift toward divertor
- Collisionless orbits lost through X-point
  - Lowest energy ion on loss orbit bounces at inboard midplane, lost to inner divertor

C.S. Chang, S. Ku, H. Weitzner, PoP **9**, 3884 (2002)

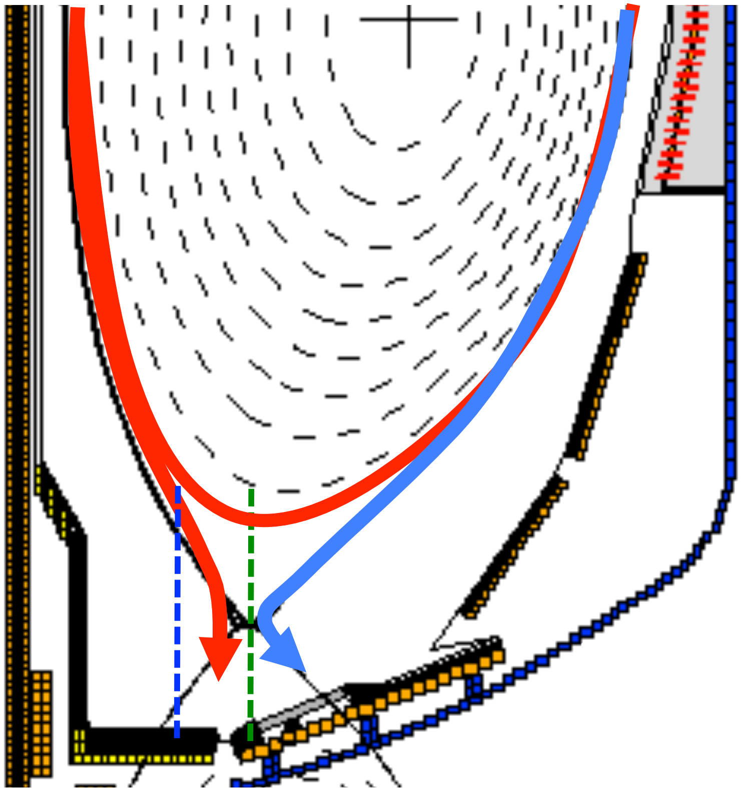
Orbit tracing for 3,000 ions launched at Ψ_N = 0.96 at midplane (No collisions, E field, or flows)



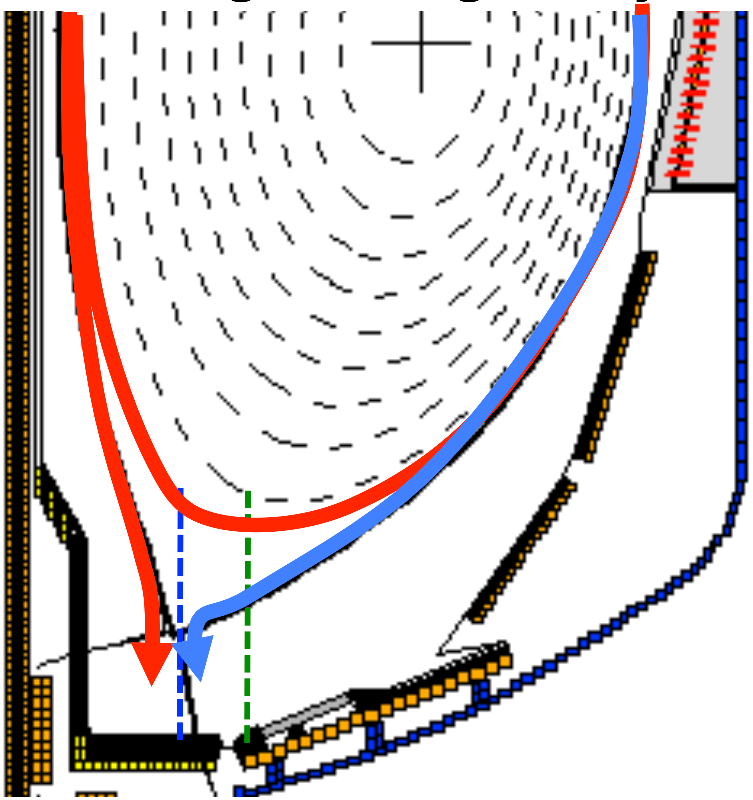
Ion-orbit loss is sensitive to the X-point geometry

- Move large R_X (δ_{low} ~ 0) to small R_X (high δ_{low}) …
  - Shorten inboard loss orbits → increase critical T_i for loss
  - Lengthen outboard loss orbits → decrease critical T_i for loss
  - More trapped ions will bounce inboard of X-point

Low Triangularity

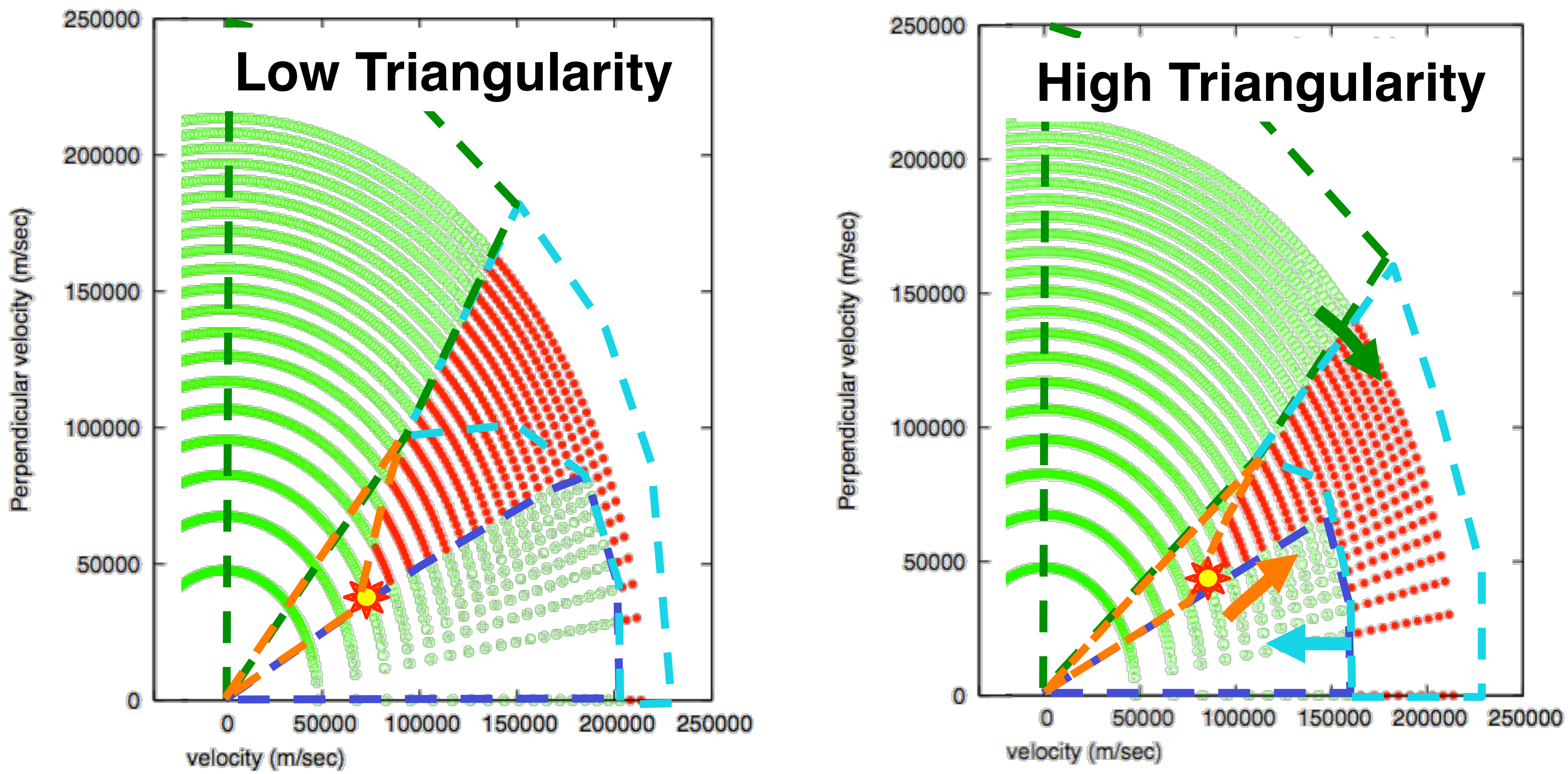


High Triangularity



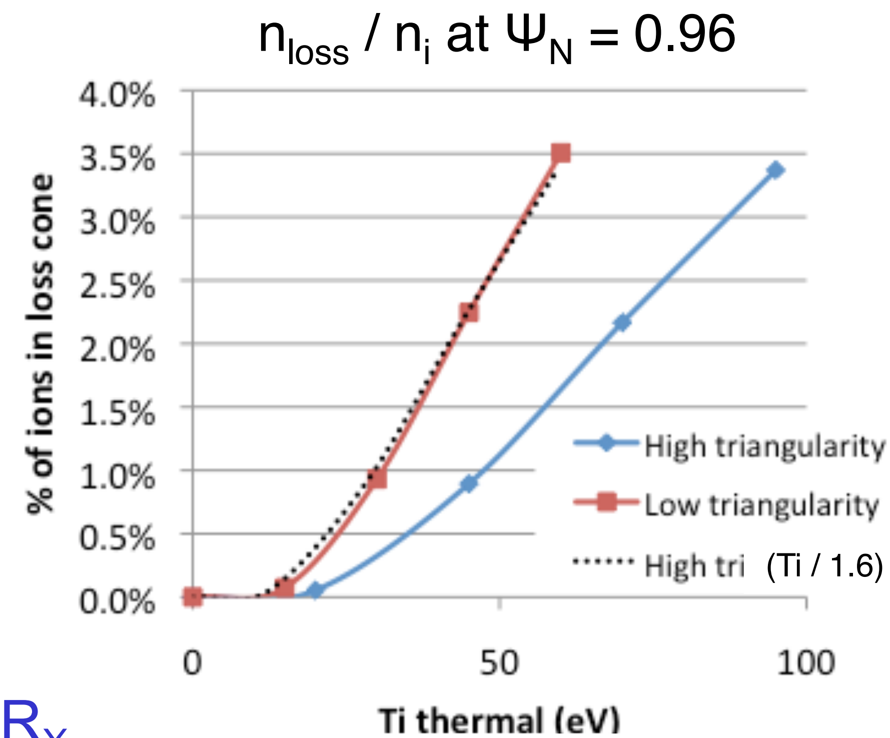
High-δ shape has a larger critical T_i and smaller loss cone for type-I orbit loss

- Move large R_X (δ_{low} ~ 0) to small R_X (high δ_{low}) …
  - Shorten inboard loss orbits → increase critical T_i for loss
  - Lengthen outboard loss orbits → decrease critical T_i for loss
  - More trapped ions will bounce inboard of X-point



High-δ shape reduces the number of collisionless loss orbits for a given T_i profile compared to low-δ

- Size of loss cone in Maxwellian ion distribution increases with thermal T_i
  - Majority of loss orbits are to inner divertor
  - Loss rate depends on rate ions are scattered into hole
  - E_r, flows reduce loss rate, but maintain dependence on R_X

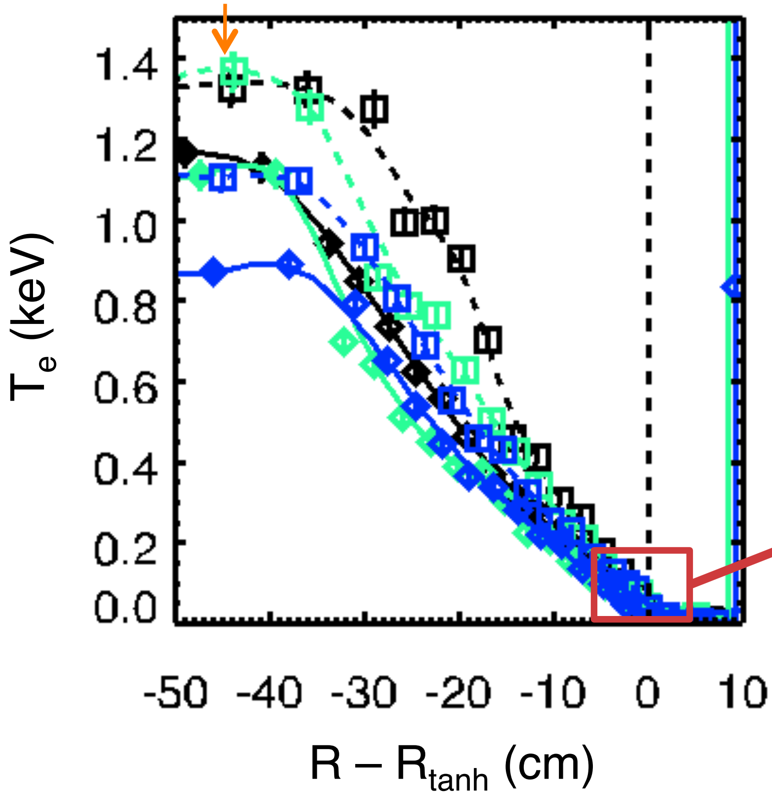


- High-δ shape requires ~ 1.6 higher T_i than low-δ to match the size of the loss cone in the Maxwellian distribution

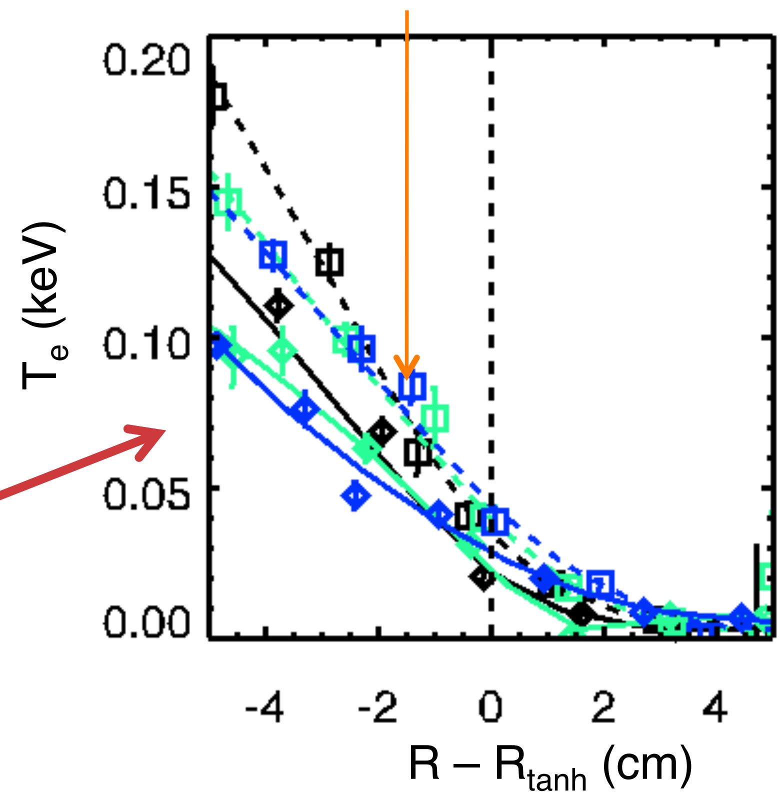
Slowly varying profiles provide good constraint to L-mode electron profiles right before L-H transition

Last T_e profile before LH transition
(X-axis normalized to density tanh symmetry point)

T_{e0} follows NBI heating…



while $T_{e,ped}$ follows R_X

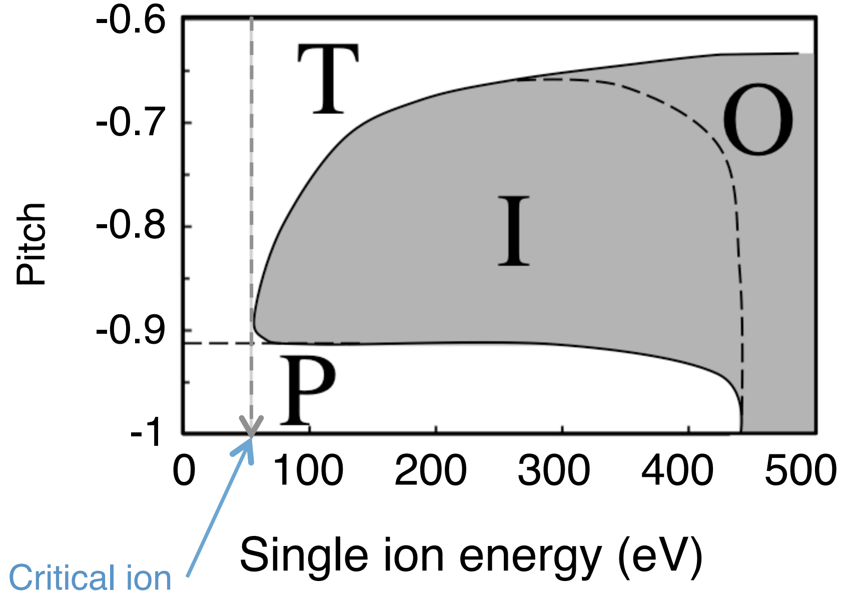


300 mg Lithium, Large fueling	0 mg Lithium, Small fueling	0 mg Lithium, Medium fueling
Small R_X: dotted (0.6 MW)	Small R_X: dotted (2.0 MW)	Small R_X: dotted (2.5 MW)
Large R_X: solid (0.3 MW)	Large R_X: solid (1.0 MW)	Large R_X: solid (2.0 MW)

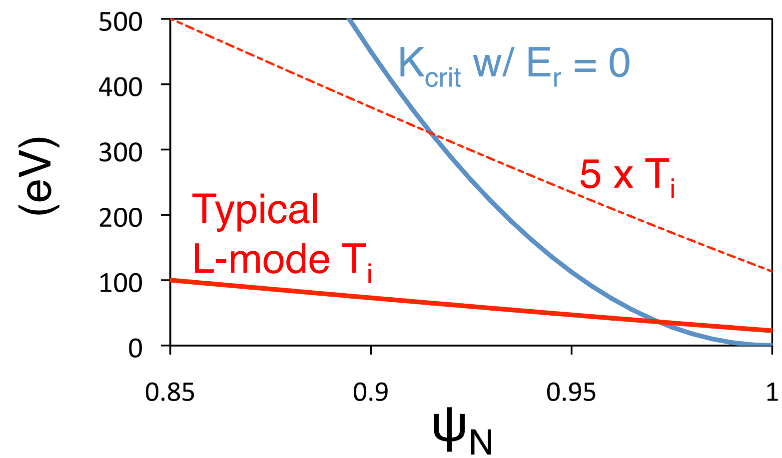
Ion velocity loss hole has a critical energy near ion thermal energy in edge region when $E_r = 0$

- Single particle guiding-center orbit tracing with $E_r = 0$, no collisions
  - White: Confined orbits
    - T: Trapped, P: Passing
  - Gray: Unconfined orbit
    - I: Strike inner div
    - O: Strike outer div

ψ_N = 0.96 (~1 cm from separatrix) at midplane



- K_{crit} within Maxwellian T_i in edge
  - X-transport important only in edge pedestal region
  - Negative E_r pushes K_{crit} curve to higher energies



Guiding-center orbit tracing code:
S. Ku, H. Baek, C. S. Chang, *Phys. Plasmas* **11** (2004)

Analytical model for ion orbit loss with E_r = 0 illustrates impact of plasma parameters on K_{crit}

- K_{crit}: Critical energy for collisionless ion loss with E_r = 0
  - B, B_X, B_B: Magnetic field at launch point, bounce point & X-point
  - $\Delta\psi = \psi_X - \psi_{launch}$, $\Delta r = R_{out} - R_{launch}$ on midplane

$$K_{crit} = \frac{1}{8}\left(\frac{e}{\pi c}\right)^2 \frac{Z^2}{M_i}\Delta\psi^2\left[\frac{1}{B}\sqrt{1-\frac{B}{B_B}}+\frac{1}{B_X}\sqrt{1-\frac{B_X}{B_B}}\right]^{-2}$$

A.V. Chankin, G.M. McCracken, *Nucl. Fusion* **33** (1993)

$$\sim \frac{Z^2}{M_i}(\Delta r)^2\left(\frac{I_P}{C_P}\right)^2 \underbrace{\left[\sqrt{1-\frac{R_{in}}{R_{out}}}+\frac{R_X}{R_{out}}\sqrt{1-\frac{R_{in}}{R_{out}}}\right]^{-2}}_{}$$

Launch at outboard midplane, E_r = 0
(Large aspect ratio approximation)

D: 0.5
H: 1.0
He: 1.0

K_{crit} ~ 2.5 times larger as R_X goes from R_0 to R_{in}
K_{crit} decreases with aspect ratio, provided $B_{\Phi,out} \gg B_{\theta,out}$

K_{crit} increases with larger I_p and smaller plasma circumference (C_p)

Acknowledgements

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