NSTX

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L-H power threshold scaling with magnetic geometry on NSTX and the role of ion orbit loss

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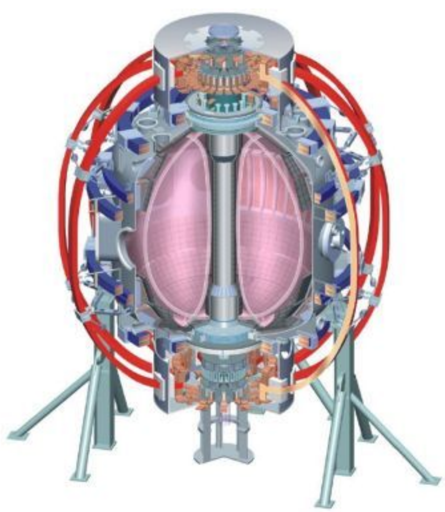

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Outline

- X-transport: suppression of neoclassical ion orbit loss is a constraint on the edge E_r
  - Constraint on E_r scales with T_i and magnetic geometry, especially R_X
  - $E_r \times B$ shear predicted to play a role in L-H transition
- NSTX results: lend strong support for the X-transport theory
  - Critical edge T_i, and thus P_{LH}, increase as R_X moves inward
    - Increase in T_i nearly matches increase in calculated critical ion loss energy
  - Critical T_i mostly independent on divertor pumping and CS fueling
    - But large variation in P_{LH} → these things impact coupling between core heating and edge T_i
- X-transport should be included in L-H transition models
  - "Hidden variables" of L-H transition qualitatively consistent with X-transport physics

Connection between E_r and L-H transition

- Steady-state E_r maintains ambipolar transport

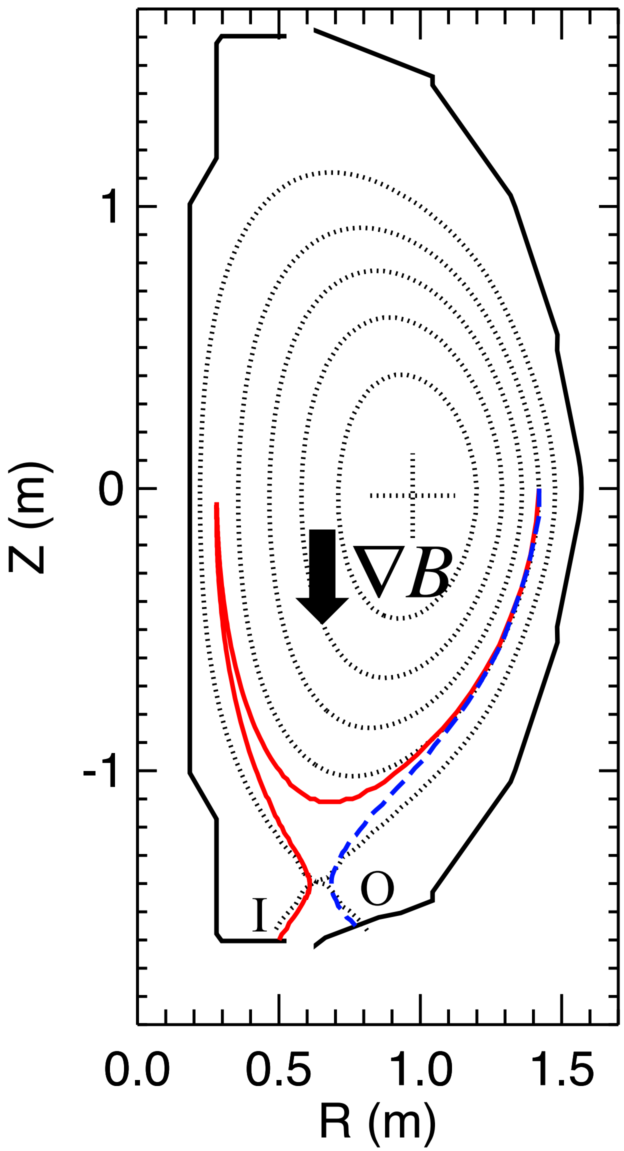
$$\varepsilon \frac{\partial}{\partial t} E_r = e\left[\Gamma_e\left(E_r\right) - \Gamma_i\left(E_r\right)\right] = 0$$

- Self-consistent E_r calculation must consider all non-ambipolar transport processes
  - X-transport: significant non-ambipolar process near plasma edge

- Edge E_r × B shear thought to play a role in L-H transition
  - Transport suppression mechanism still under investigation
    - Possible: decorrelation of turbulent eddies by E_r × B flow shear [1]
    - Possible: interaction of mean and turbulent driven E_r × B flow shear [2]
  - May be a critical E_r × B shear for triggering L-H transition
    - E_r × B shear ~ minimum in E_r well

[1] K.H. Burrell, Phys. Plasmas, **4** (1997) 1499-5185
[2] G.D. Conway, et. al. Phys. Rev. Lett. **106** (2011) 065001

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



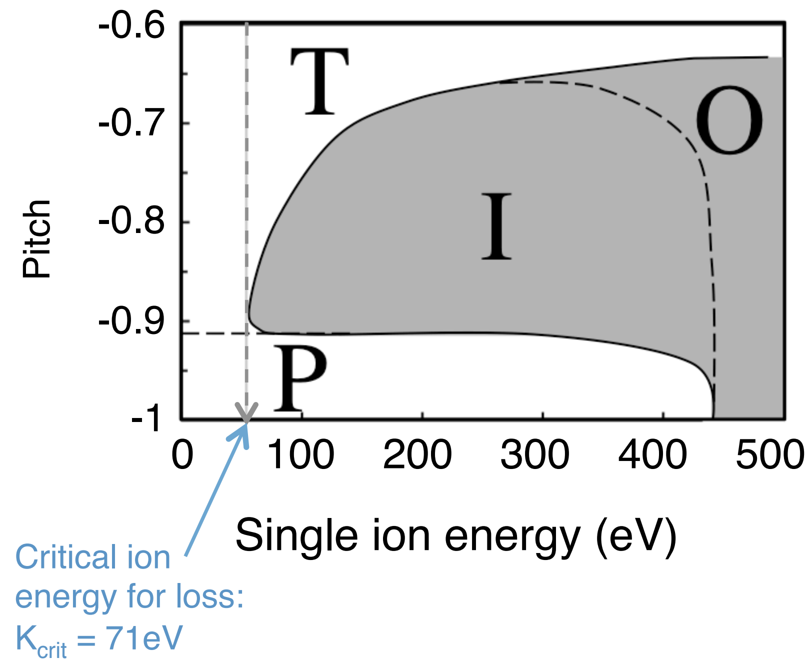
- X-point amplifies grad-B drift
  - X-point: low B_θ, slows poloidal transit
  - Non-ambipolar: ion drift >> electron drift
- Lowest energy loss orbits:
  - Start at outboard midplane
  - Bounce at inboard midplane
  - Lost to inner divertor leg in favorable grad-B
- Negative E_r acts to confine ions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

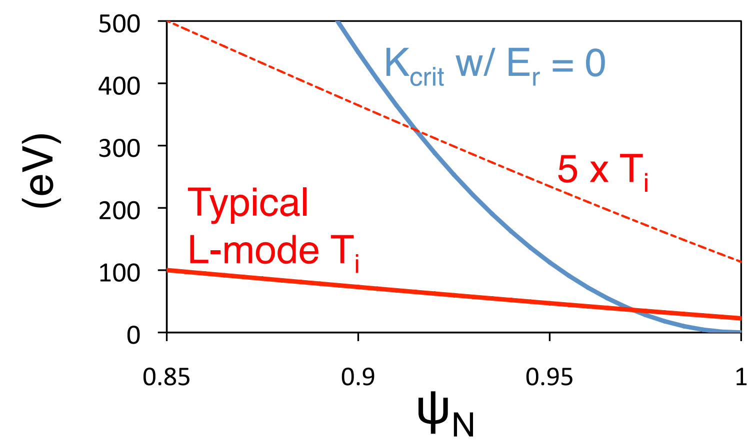
Ion velocity loss hole has a critical energy near ion thermal energy in edge region when $E_r = 0$

- 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

$\psi_N = 0.96$ (~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)

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

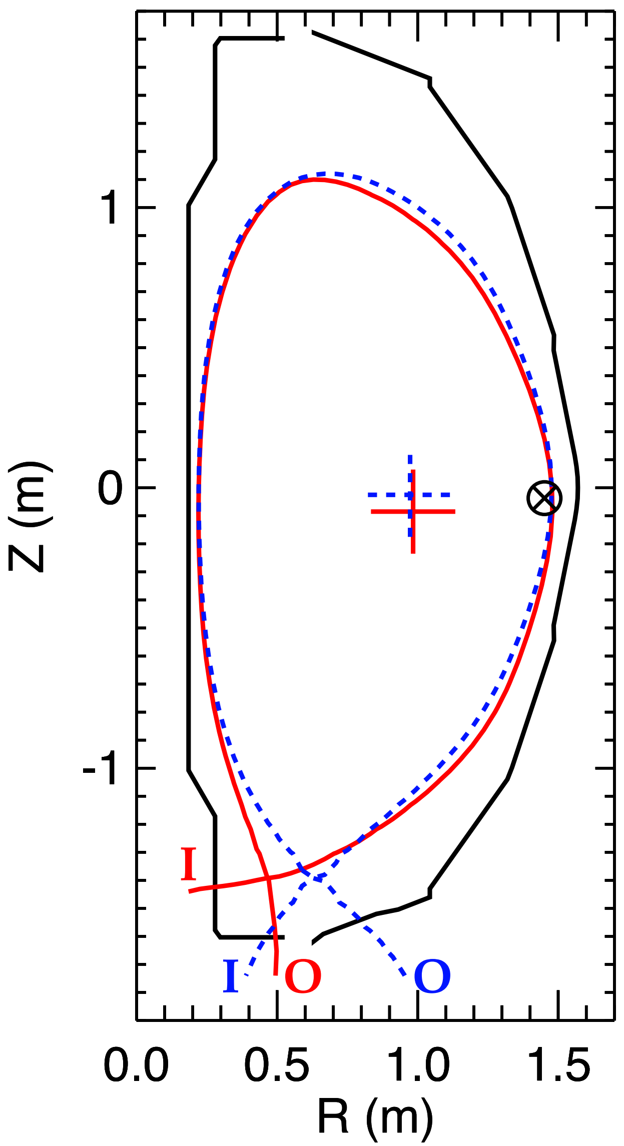
Launch at outboard midplane, $E_r = 0$
(Large aspect ratio approximation)

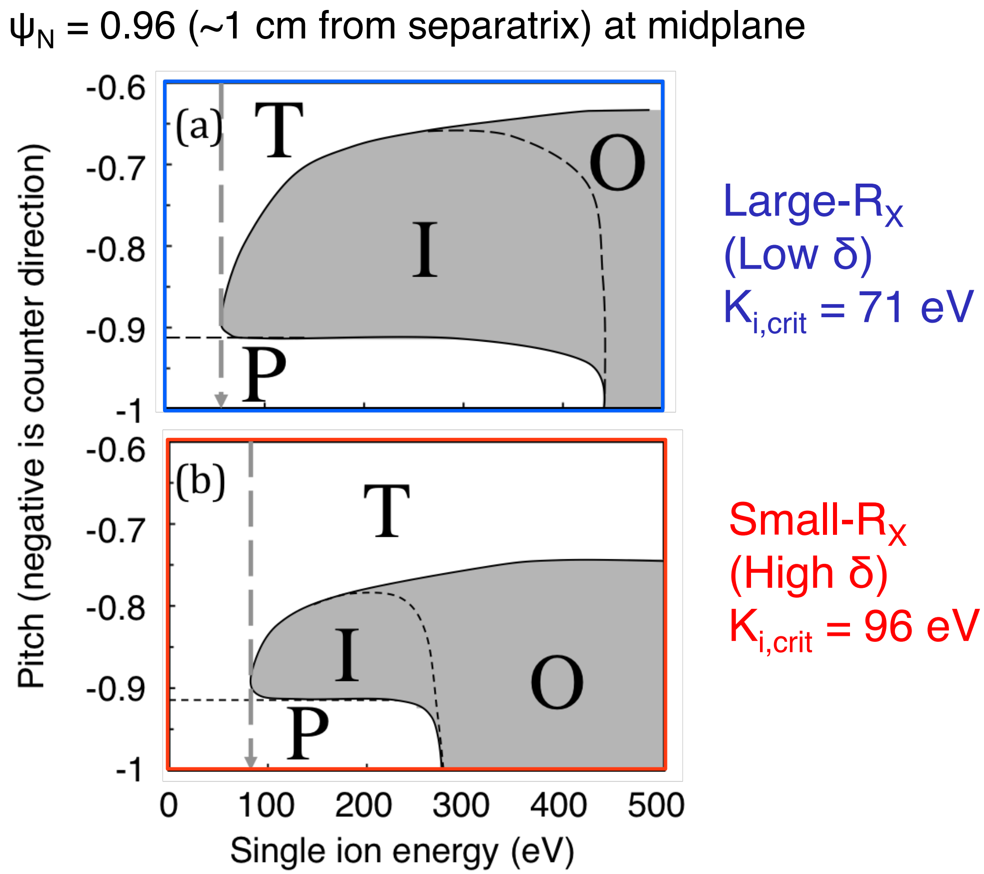
D: 0.5
H: 1.0
He: 1.0

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

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

Critical energy for ion loss increases as R_X decreases





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

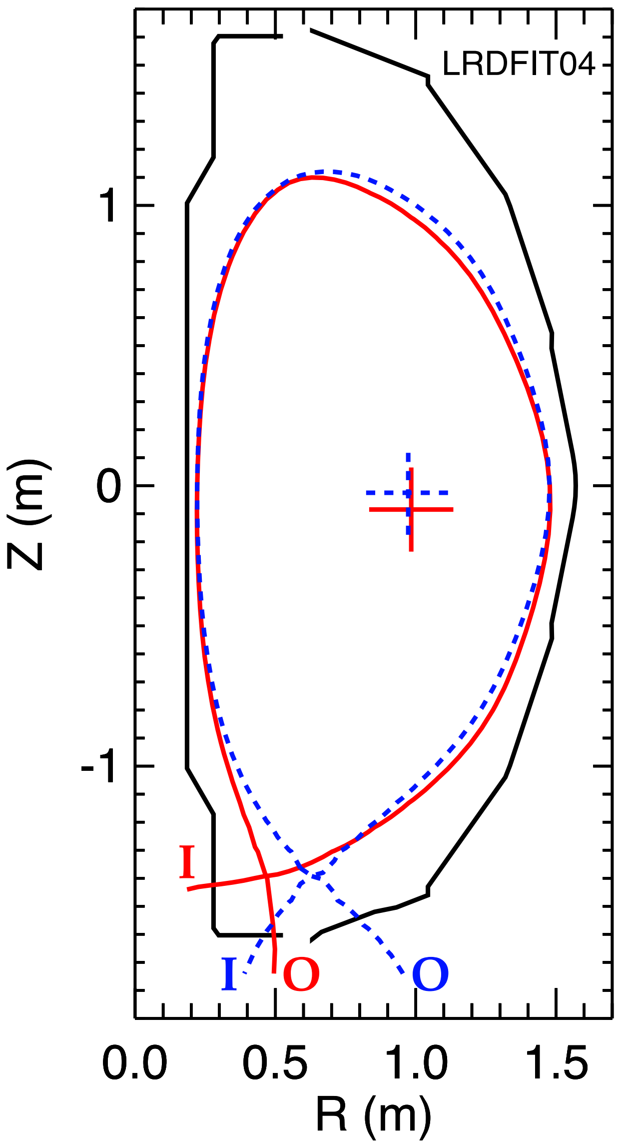
Full self-consistent E_r solution must consider collisions

- Low collisionallity regime (ion loss time * ν_{ii} << 1)
  - Ions scattered into loss hole are lost on collisionless orbits
  - Increase collisionallity: more ions scattered into loss hole → more negative E_r
- High collisionallity regime
  - Ions scattered into loss hole to not complete collisionless orbit
  - Increase collisionallity: fewer collisionless ion loss orbits → more positive E_r
- Ion loss time impacts edge E_r
  - Grad-B drift direction: longer ion loss orbit time in unfavorable
  - X-point region: large null region (snowflake) increases ion loss time

Connection between X-transport theory and L-H transition

- Ion loss hole makes a significant contribution to E_r at edge
  - Contribution scales with T_i (Neoclassical scales with grad-T_i)
- For a given T_i, if K_{crit} is lowered, E_r becomes more negative
- More negative E_r leads to a deeper E_r well
  - Larger dE_r/dr → increased shearing rate
- If L-H transition at critical dE_r/dr, then transition at critical T_i
  - Critical T_i depends on plasma geometry and collisionality
  - Expect edge T_i and heating power to be connected → P_{th}

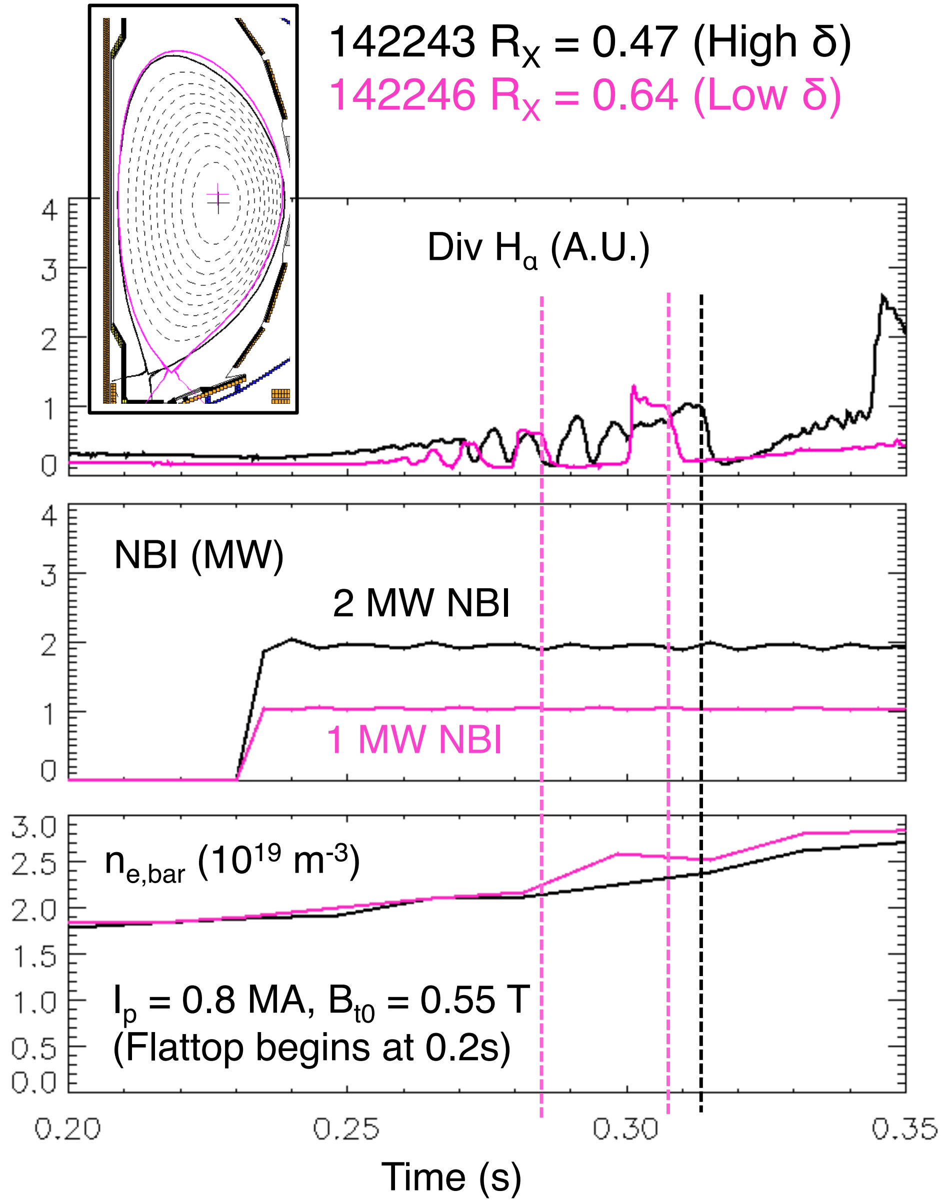
X-transport predictions motivated a dedicated P_{LH} versus R_X experiment on NSTX



- Goal: quantify P_{LH} vs R_X on NSTX
  - Match R_{IN}, R_{OUT}
  - Nearly match X-point height, surface area, B_{T0}, B_{OUT}, density
  - Reproduce shapes under different pumping & fueling conditions
  - Shot-to-shot change in NBI < 300 kW
- Delay L-H to > 40 ms after NBI turn-on to reduce error in P_{LH}
  - P_{OH} – dW/dt slowly varying

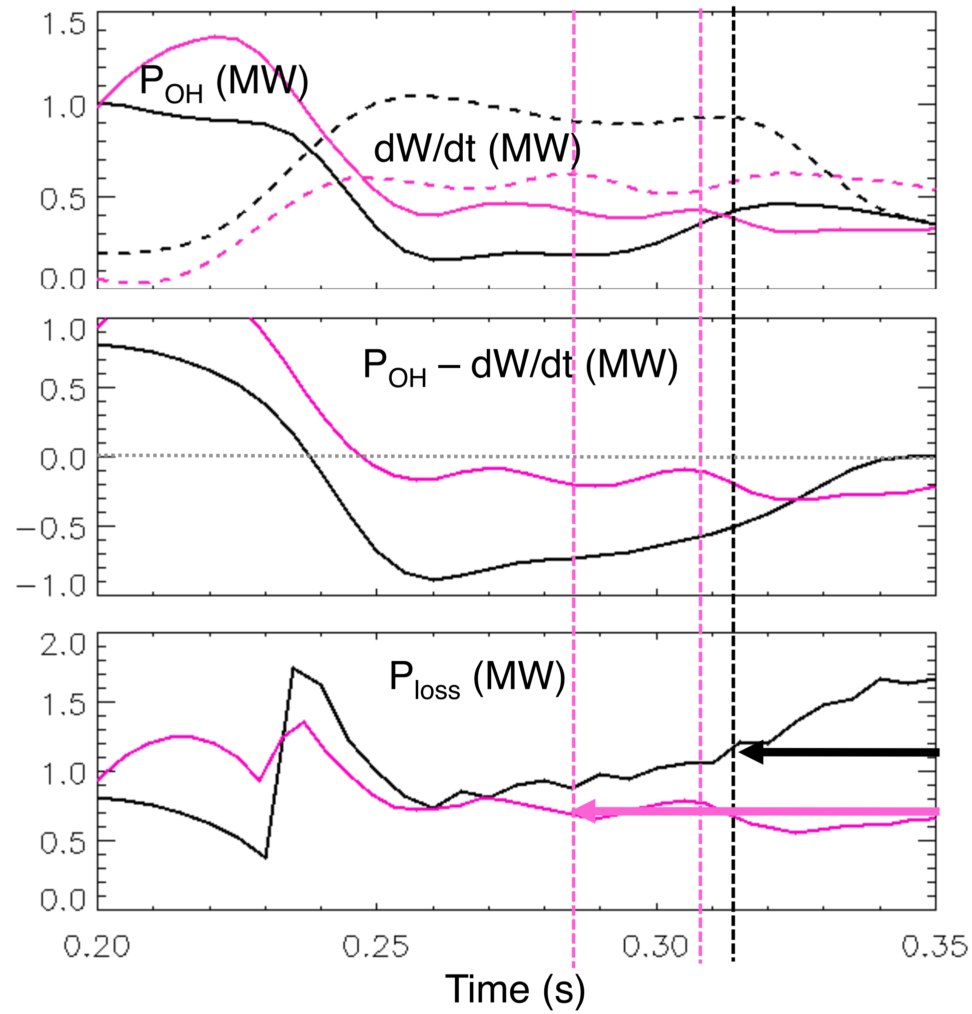
First results reported in: R. Maingi, et. al. *Nucl. Fusion* **50** (2010)

LH transitions occur when P_{OH} – dW/dt is slowly varying



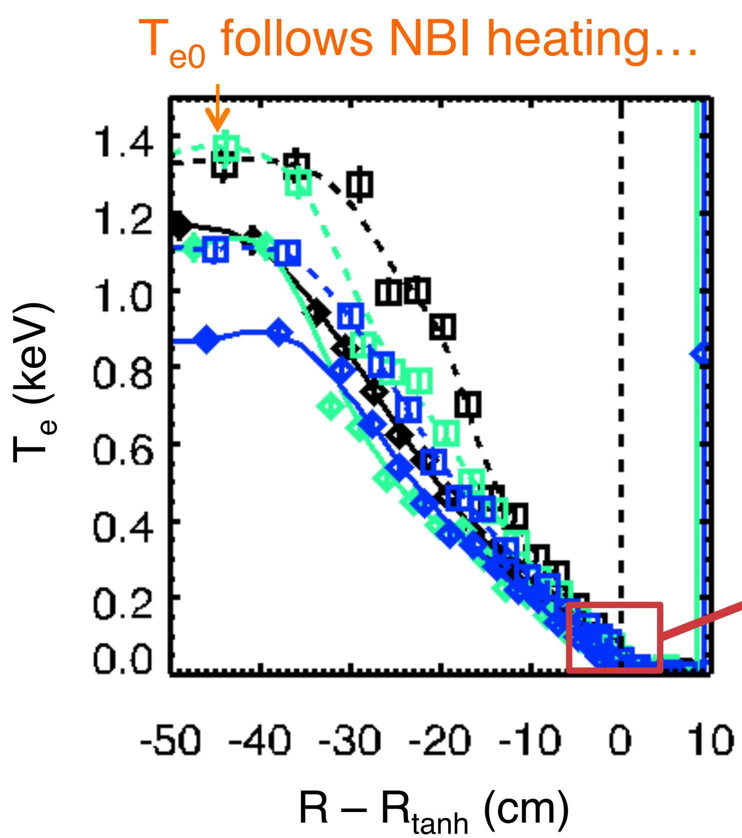
$$P_{loss} = 0.85\ P_{NBI} + P_{OH} - dW/dt$$

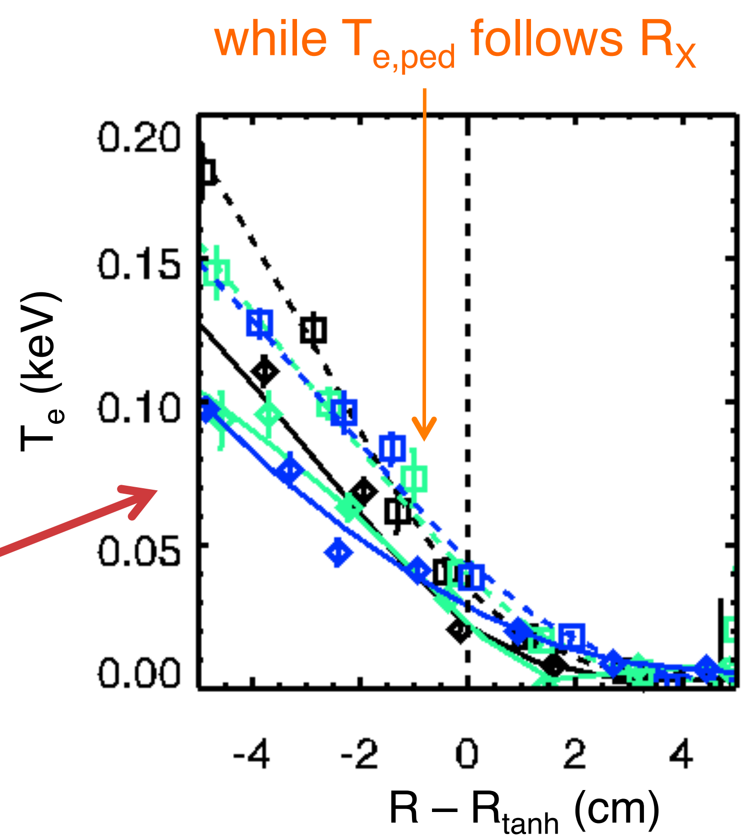
Average efficiency for similar discharges analyzed using TRANSP



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)

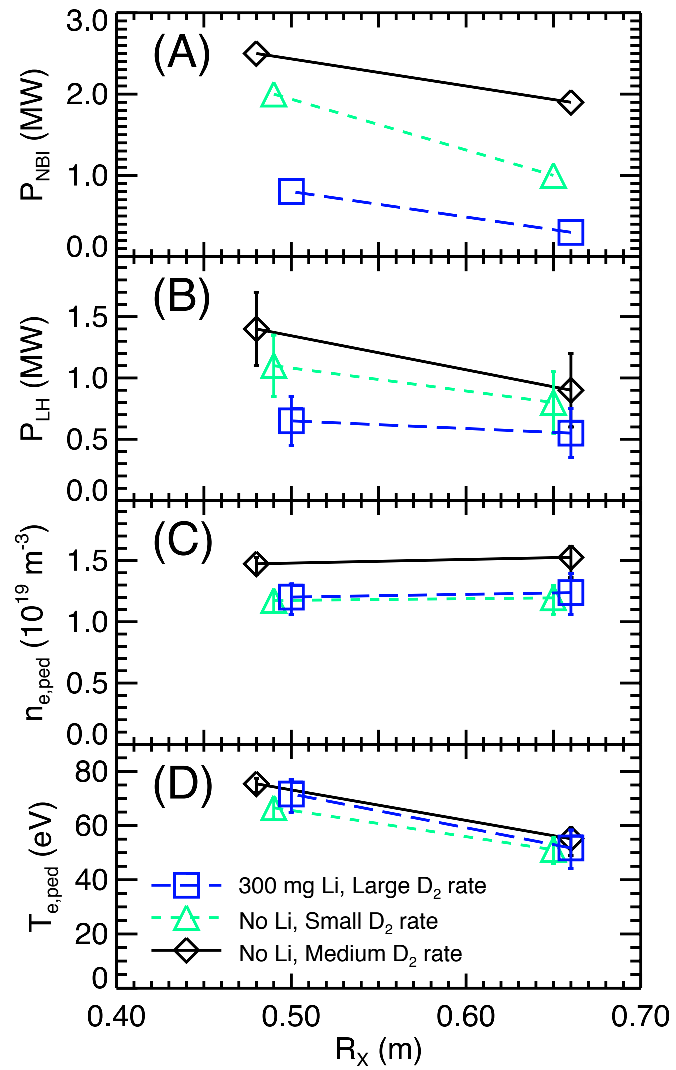




300 mg Lithium, Large fueling	0 mg Lithium, Small fueling	0 mg Lithium, Medium fueling
Small R_X: dotted (0.6 MW)	Small R_X: dotted (2.0 MW)	Small R_X: dotted (2.5 MW)
Large R_X: solid (0.3 MW)	Large R_X: solid (1.0 MW)	Large R_X: solid (2.0 MW)

Edge temperature prior to LH transition larger for small-R_X than large-R_X over wide range of heating and pumping

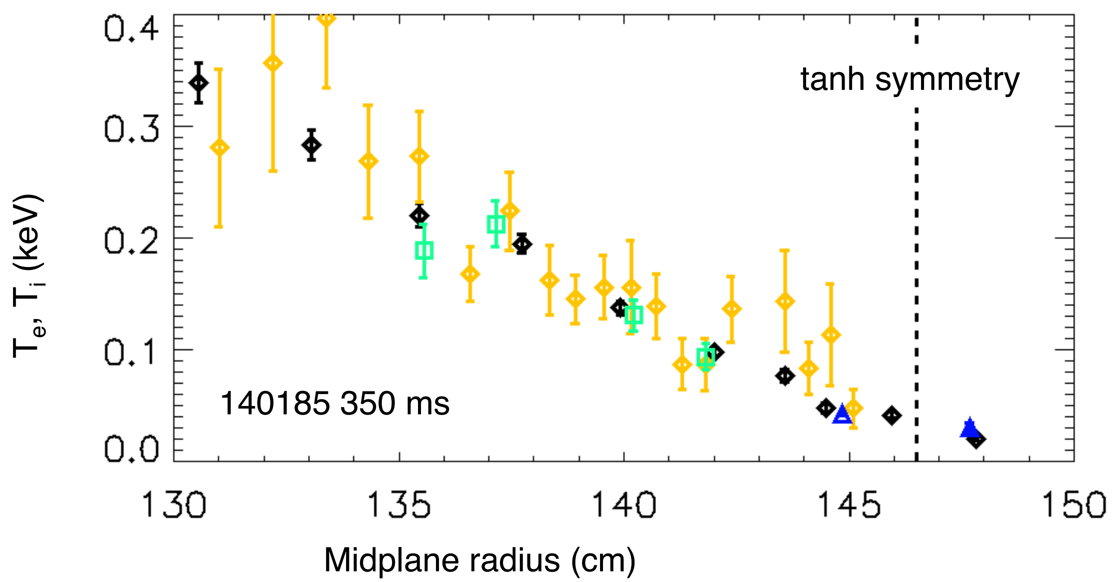
- Three pumping & fueling conditions
  - Divertor pumping on NSTX varied using inter-shot Lithium deposition rates
- P_{LH} increases with…
  - Less divertor pumping
  - Higher $n_{e,ped}$ and/or HFS fueling rate
  - Smaller R_X
- Pedestal T_e near L-H time …
  - Nearly independent of pumping, fueling density, NBI power
  - Increases ~40% as R_X 0.64 → 0.37 m
  - Unfortunately, T_i not available for all shots



D.J. Battaglia, et. al., PRL, *submitted*

T_e can be used as a proxy for T_i in the L-mode edge of NSTX

- Infer $T_i \sim T_e$ in L-mode edge
  - Thermal equilibration time < electron thermal confinement
  - T_i is the critical parameter in X-transport theory
- Thus, $T_{i,LH}$ increases ~40% as R_X: 0.64 → 0 .47
  - Leads to 20 – 60% larger P_{LH}



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

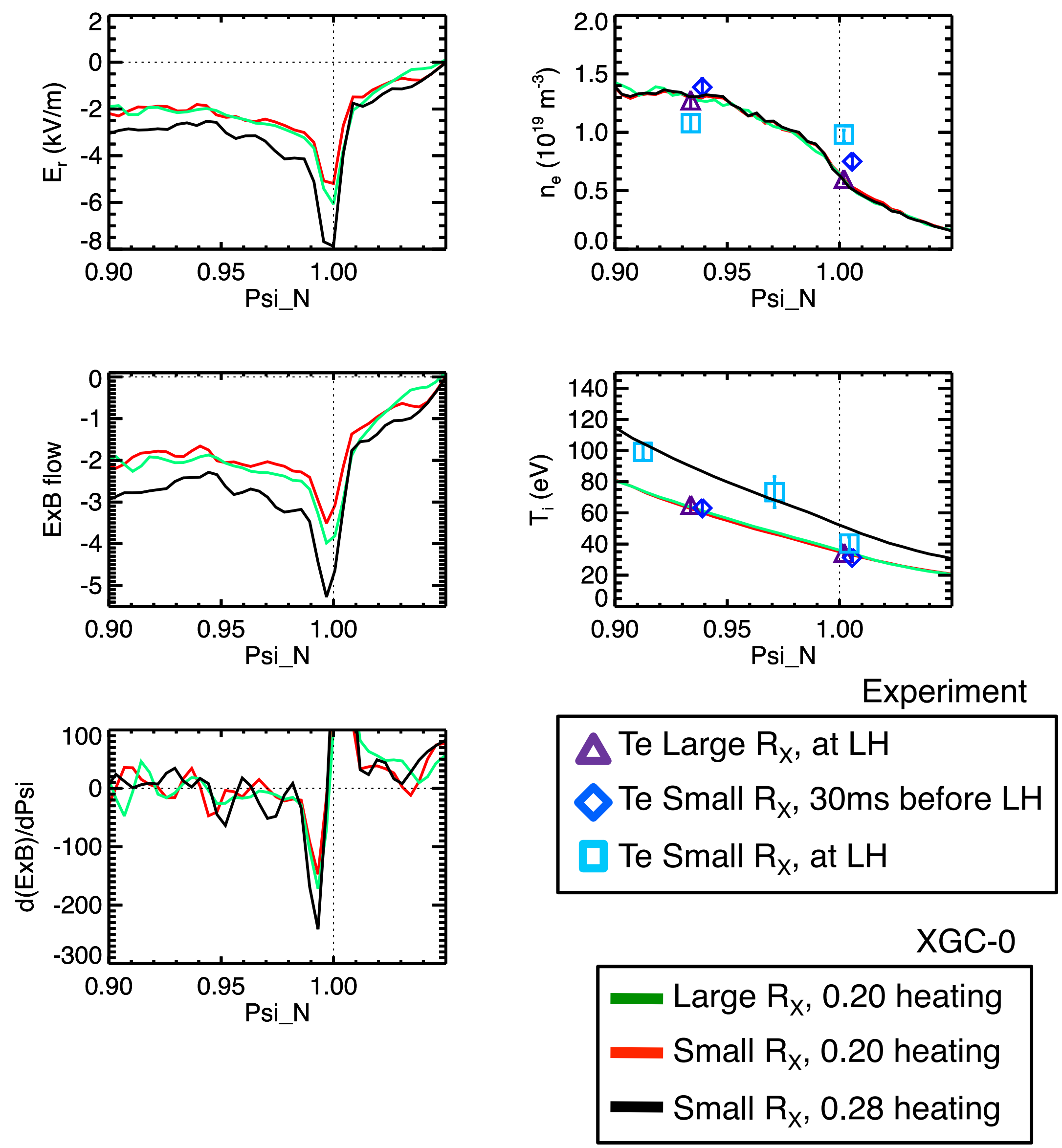
Experimental data is consistent with X-transport model

- Increase in T_i matches increase in K_0
  - As R_X: 0.64 → 0.47 m …
    - K_0 increases 35% (guiding center calculation)
    - Edge T_i increases 40% (derived from measurements)
  - Full self-consistent E_r calculations needed to confirm quantitative agreement
- P_{LH} dependence on pumping and fueling
  - T_i similar for all three conditions … but P_{LH} varies considerably
  - Recycling cools edge → need larger core heating to reach critical T_i
- Does change in strike points with R_X impact div. recycling?
  - Most likely and it will have an effect on P_{LH}
  - But it should not effect $T_{i,LH}$ (since it appears insensitive to large changes in divertor recycling)

Preliminary self-consistent calculations of E_r using XGC-0

- XGC-0 simulations
  - 5D ion & electron + neutrals kinetic model
  - Divertor sheath and recycling models
- Tailor model parameters to match L-mode profiles
  - Inboard heating, outboard neutral fueling, anomalous transport rate
- E_r well deeper for large-R_X shape with matched profiles

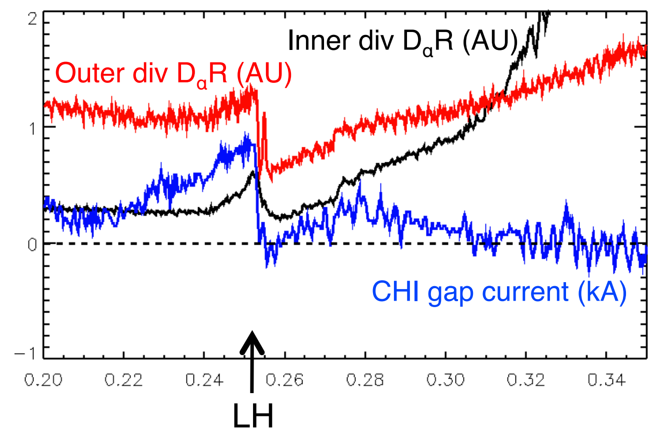
Preliminary results. No electron physics included.



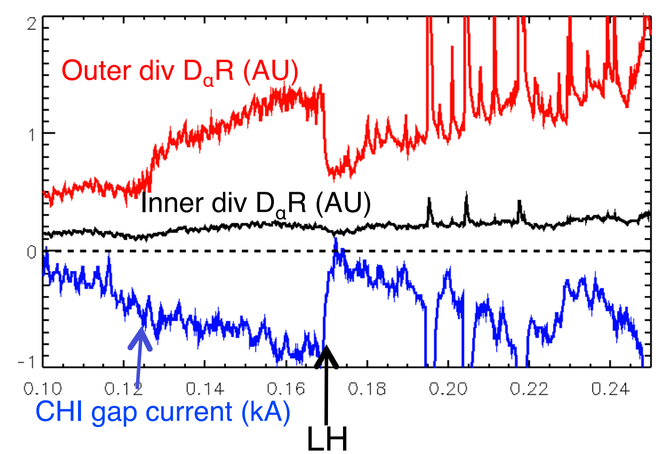
Measurements may suggest there is finite ion orbit loss to the divertor

- 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
- Are ions lost on neoclassical orbits?
  - Signals consistent with ions lost on neoclassical orbits to the divertor
  - Large ion loss not expected in steady state, but may be possible in a dynamic solution
- Use XGC-0 to explore L-H dynamics and impact on SOL / divertor

Favorable grad-B



Unfavorable grad-B



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