NSTX

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Characterization of the L-H power threshold on NSTX

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NSTX actively contributes to the international effort to characterize the L-H power threshold (P_{LH})

- ITER modeling need: projection for P_{LH}
  - Transition requirements
    - ITPA scaling database
    - First-principles model
  - Species dependence (D, H, He)
  - Effect of 3D fields prior to transitions

- NSTX has a wide range capabilities for L-H studies
  - Li pumping → effect of neutrals and collisionality
  - 3-D fields → rotation and edge magnetic field structure
  - NBI (7 MW) & RF (6 MW) for heating and current drive
  - Low-A → $B_\theta \sim B_\phi$ at outboard, high edge β, low B_t
  - Flexible shaping capability
  - State-of-the-art diagnostics with excellent access

Recent experiments on NSTX have aimed to characterize P_{LH} in the ST geometry

- P_{LH} is reduced with . . .
  - Smaller B_t at X-point
  - Lower I_p
  - Balanced double null

  All predicted to enhance edge ion loss, thus deeper E_r well

- P_{LH} does not scale with toroidal rotation

- P_{LH} is larger with . . .
  - Helium plasmas versus deuterium plasmas
  - Non-axisymmetric magnetic perturbations

- P_{LH} has strong dependence on edge pumping and fueling
  - Well-known "hidden variables" of P_{LH} scaling

Dependence of P_{LH} with I_p and B_t is well documented for toroidal devices

- ITER-like ITPA database scaling
  - Near-linear scaling with B_t
  - No significant scaling with I_p

$$P_{LH} = 0.0488\, n_{e20}^{0.717}\, B_t^{0.803}\, S^{0.941} \quad [1]$$

- Low-A devices exhibit I_p scaling
  - $B_\theta \sim B_t$ at outboard midplane at low-A
  - May imply P_{LH} scales with |B| at outboard midplane

$$P_{LH} = 0.072\, n_{e20}^{0.7}\, B_{out}^{0.7}\, S^{0.9} \quad [2]$$

$P_{LH} = P_{OH} + P_{abs} - dW/dt - P_{floss}$

P_{OH}: Ohmic heating power

P_{abs}: Absorbed heating power

dW/dt: Change in plasma stored energy

P_{floss}: Power lost by fast ions

P_{LH}: Minimum loss power needed for LH transition

n_{e20}: Line-averaged density (10^{20} m^{-3})

B_t: On-axis toroidal magnetic field (T)

S: Plasma surface area (m^2)

B_{out}: Mag field at outboard midplane

1 Y.R. Martin et. al., *J. Phys.: Conf. Ser.* **123** (2008) 012033
2 T. Takizuka et. al., *PPCF* **46** (2004) A227

I_p and B_t scaling of P_{LH} may be described by their relationship to the edge shearing rate and E_r

- Hypothesis: LH transition at a critical E_r x B shearing rate
  - E_r x B shear rate increases prior to the formation of a pedestal
  - Shearing exceeds a critical value → suppresses turbulence → triggers a positive feedback loop

$$\omega_{ExB} = \frac{(RB_\theta)^2}{B}\left(\frac{\partial}{\partial\psi}\right)\frac{E_r}{RB_\theta}$$

- From force balance: $E_r = v_\theta B_\phi + v_\phi B_\theta - \nabla(n_i T_i)/Z_i e n_i$
  - NSTX measurements: core $E_r \sim v_\Phi B_\theta$, edge $E_r \sim \nabla P_i / Z_i n_i$
  - Edge pressure gradient related to power lost across separatrix
  - XGC-0 calculations: edge n_i and ∇n_i influenced by ion orbit losses
    - Result: magnetic geometries that enhance ion orbit losses require smaller edge pressure gradients to trigger LH transition

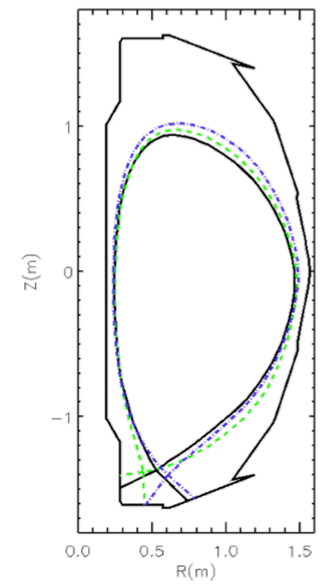
Equations from: K.H. Burrell, *Phys. Plasmas,* **4** (1997) 1499

XGC-0 calculations show the edge E_r well is larger with smaller B_t at X-point

- Consider matched discharges with different X-point radii
  - B_t at X-point: $B_{tX} \sim 1/R_X$
  - Low-A geometry enhances the difference in B_{tX}

- B_{tX} impacts ion loss at X-point
  - XGC-0 calculation for H-mode profiles
  - Lower B_{tX} →

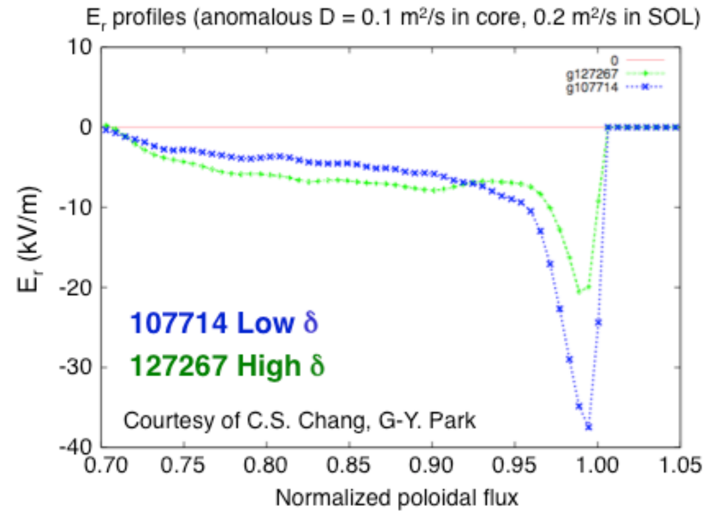
    Larger ion gyroradius →
    Enhanced ion loss at X-point →
    Larger E_r well → Reduced P_{LH}
  - Agrees qualitatively with ITPA P_{LH} scaling with B_t



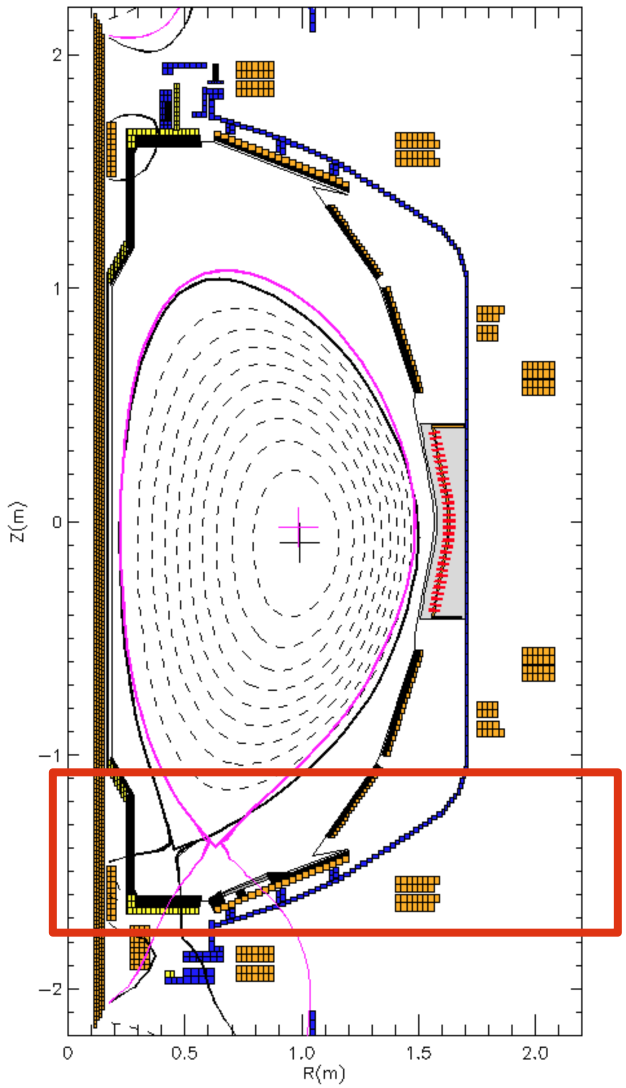
#107714@400ms
δ_l=0.38, δ_u=0.25

#127281@500ms
δ_l=0.52, δ_u=0.33

#127267@500ms
δ_l=0.70, δ_u=0.35

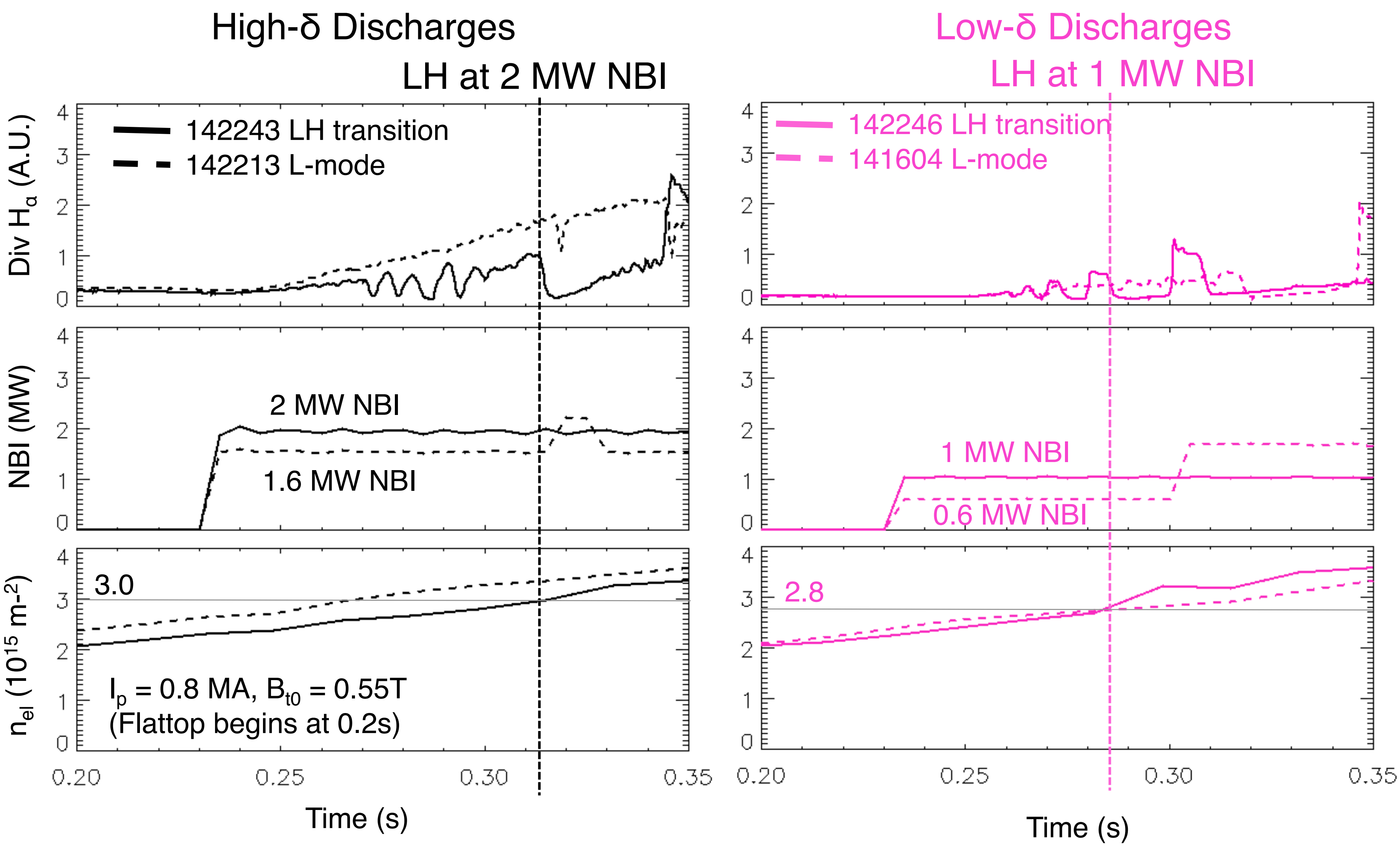


Recent experiments on NSTX examine the dependence of P_{LH} on B_t at X-point



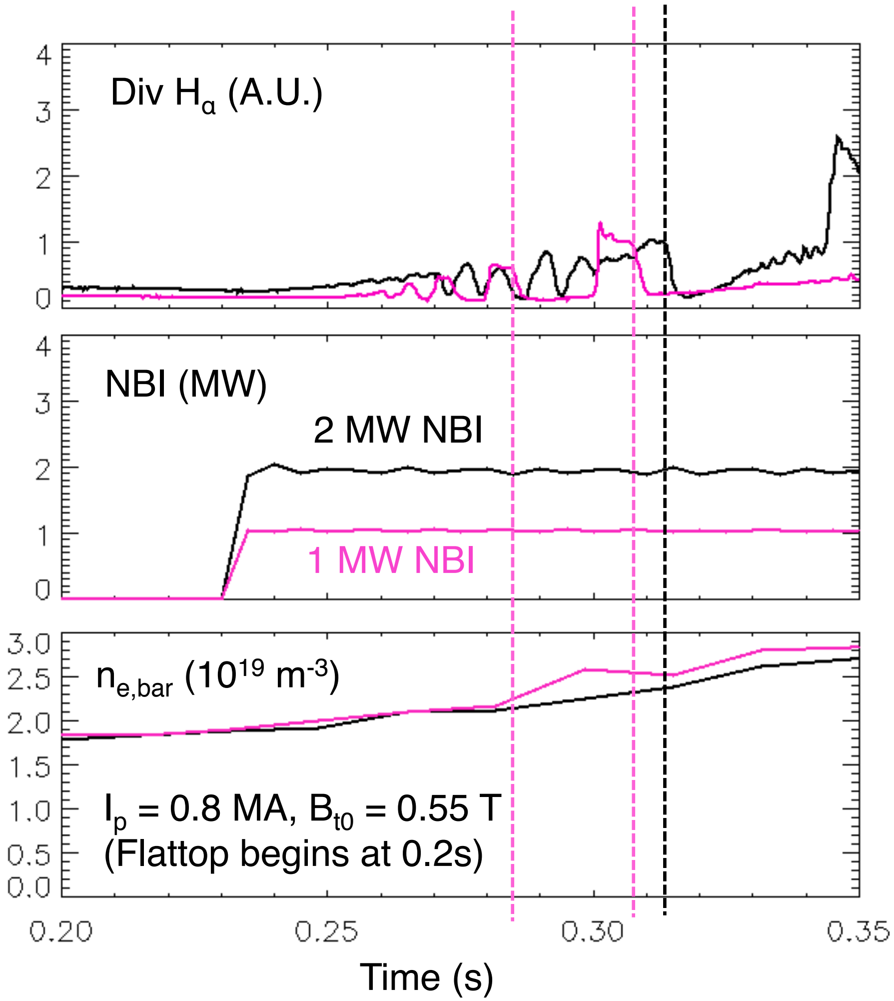
- With the same TF coil current …
  - Match inboard B_t (i.e., inner gap)
  - Match outboard |B| (i.e., outer gap and I_p)
  - Match B_{t0} (same R_0)
- Try to match other P_{LH} variables . . .
  - Line-averaged density
  - X-point height
  - Plasma surface area
  - HFS and LFS neutral fueling
- Scan R_x
  - Low triangularity: R_x = 0.64 (δ_L = 0.36)
  - High triangularity: R_x = 0.47 (δ_L = 0.64)
  - B_{tX} ratio (low-δ_L / high-δ_L) = 0.73

High-δ shape requires more NBI power than low-δ shape to achieve H-mode



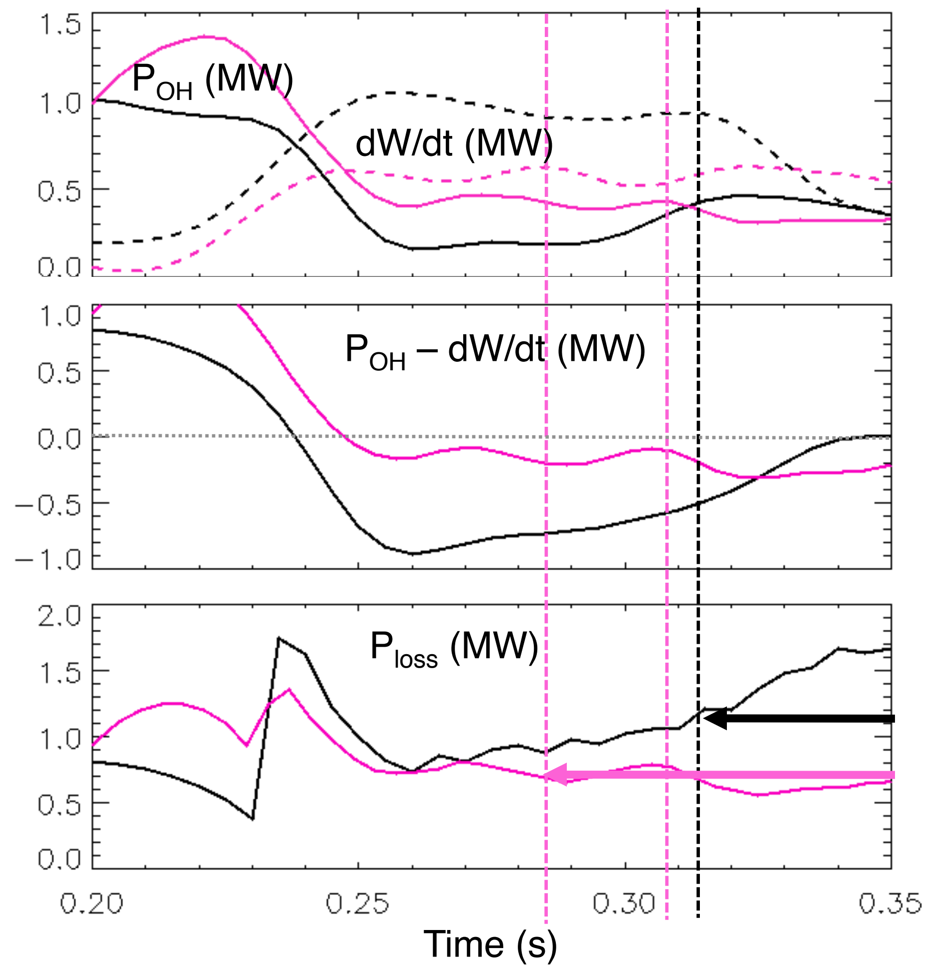
LH transitions occur during periods of steady P_{OH} and dW/dt

142243 R_X = 0.47 (High δ)
142246 R_X = 0.64 (Low δ)

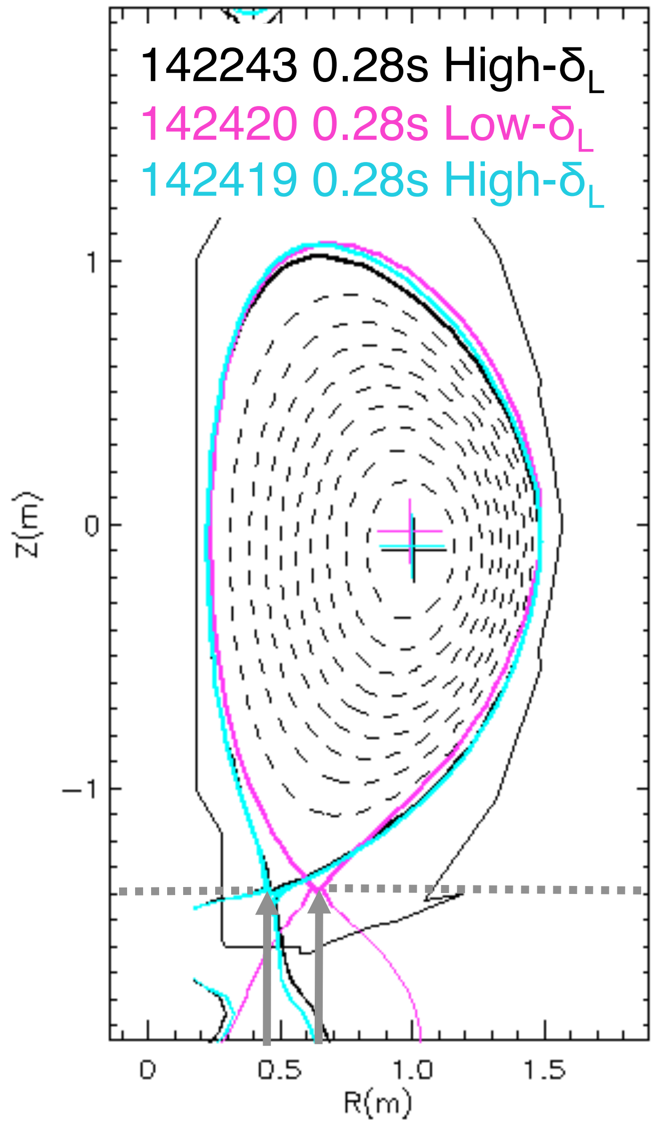


$$P_{loss} = 0.85\ P_{NBI} + P_{OH} - dW/dt$$

Average efficiency for similar discharges analyzed using TRANSP



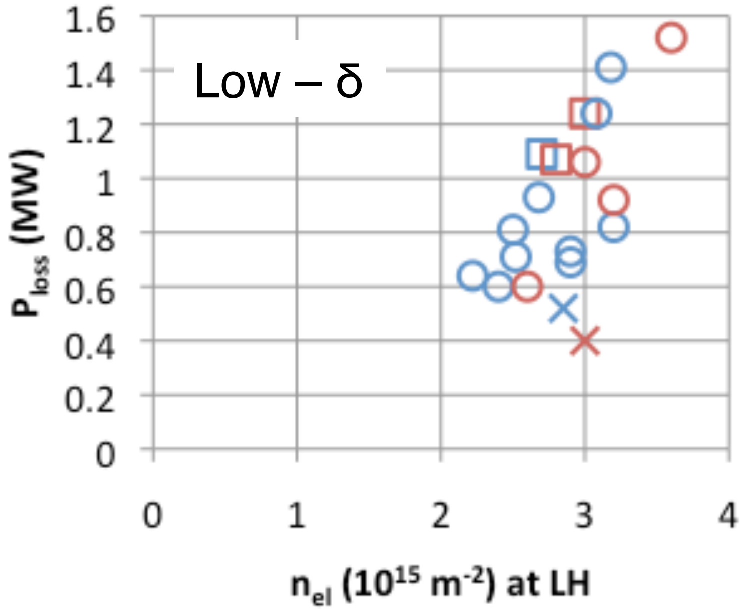
P_{LH} is similar for both shapes when B_{tX} is matched



- TF current reduced for high-δ shape to match B_{tX}
  - P_{LH} very similar to low-δ shape
- Dataset implies $P_{LH} \sim B_{tX}^{1.0-2.0}$
  - 22% - 27% reduction in B_{tX} gives …
  - 22% - 45% reduction in P_{LH}

B_{t0} (T)	R_X (m)	B_{tX} (T)	P_{NBI} (MW)	P_{LH} (MW)
0.55	0.47	0.86	1.9	1.1
0.55	0.64	0.63	1.0	0.7
0.40	0.47	0.63	1.0	0.6

P_{LH} vs B_{tX} experiment ran both shapes over a wide range of fueling and pumping conditions

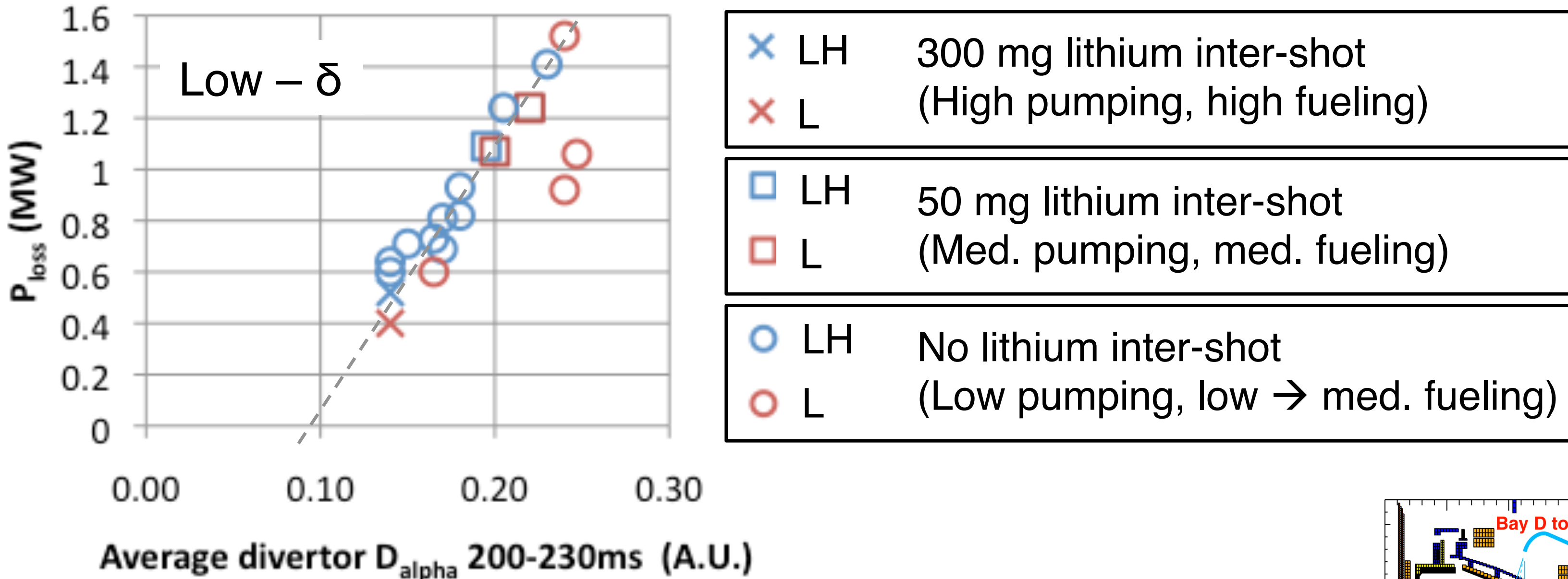


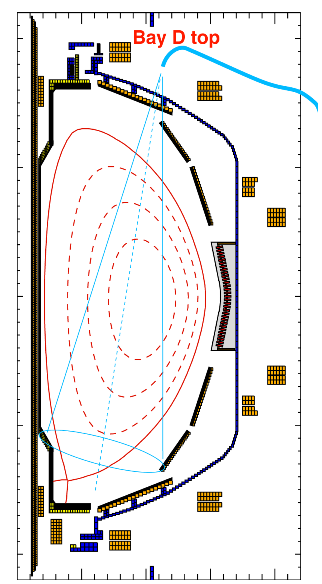
Preliminary P_{loss} calculation assumes P_{heat} / P_{NBI} ~ 85% for all discharges

- 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}

- Future analysis: focus on scaling with edge parameters

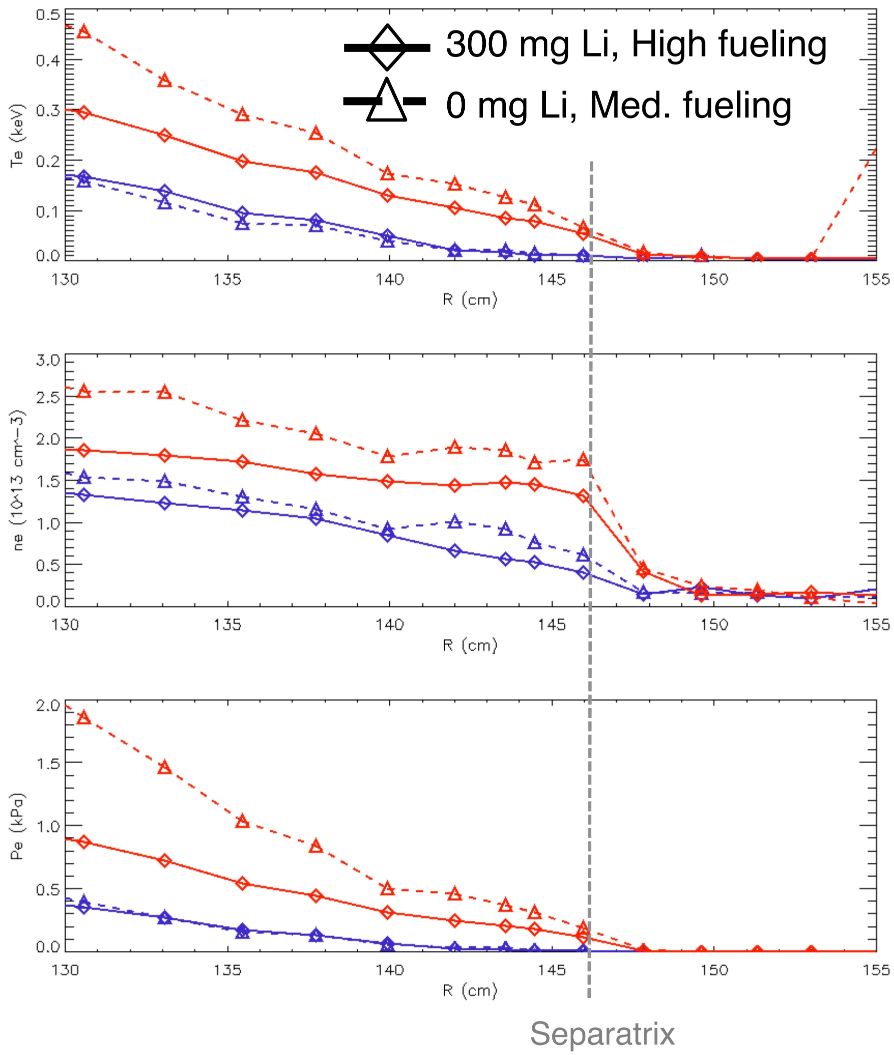
Preliminary observation: P_{LH} scales linearly with initial divertor D_α intensity

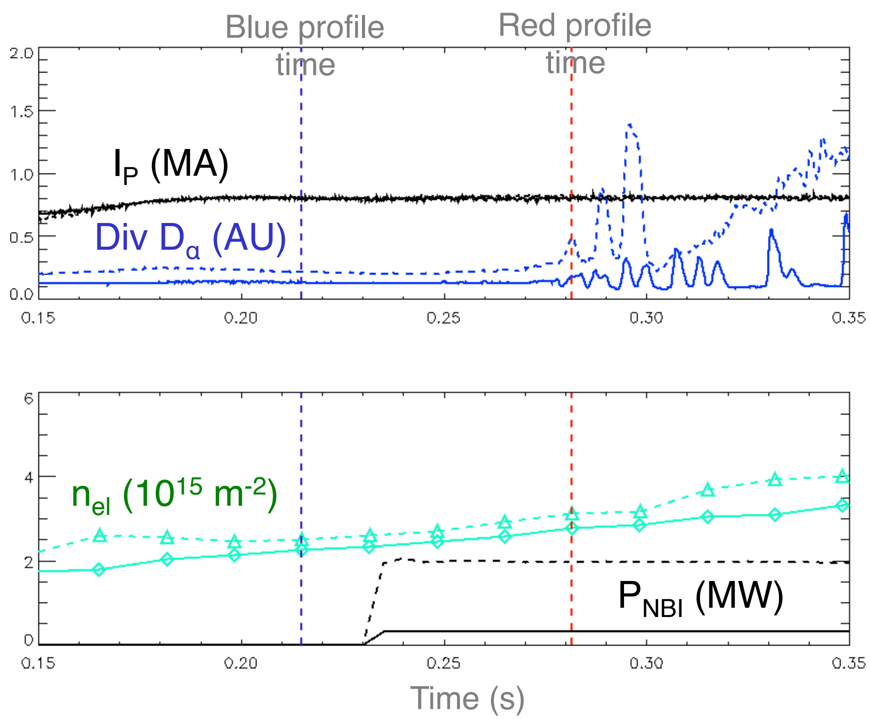




- P_{LH} increases with pre-NBI divertor D_α signal
  - May be proportional to initial edge neutral density (n_N)
- Indicates n_N is important in P_{LH} calculations
  - NBI heating efficiency depends on n_N
  - Neutrals impact LH trigger (ion – neutral collisions)

Profiles indicate that the scaling with divertor D_α is not solely an effect of changes to the NBI efficiency

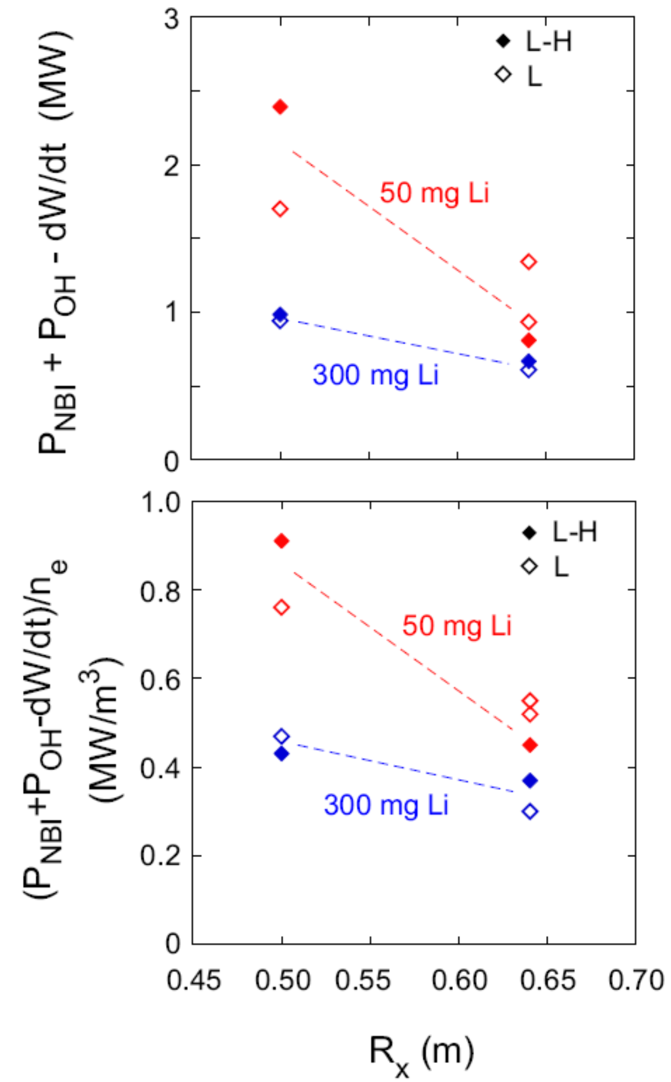




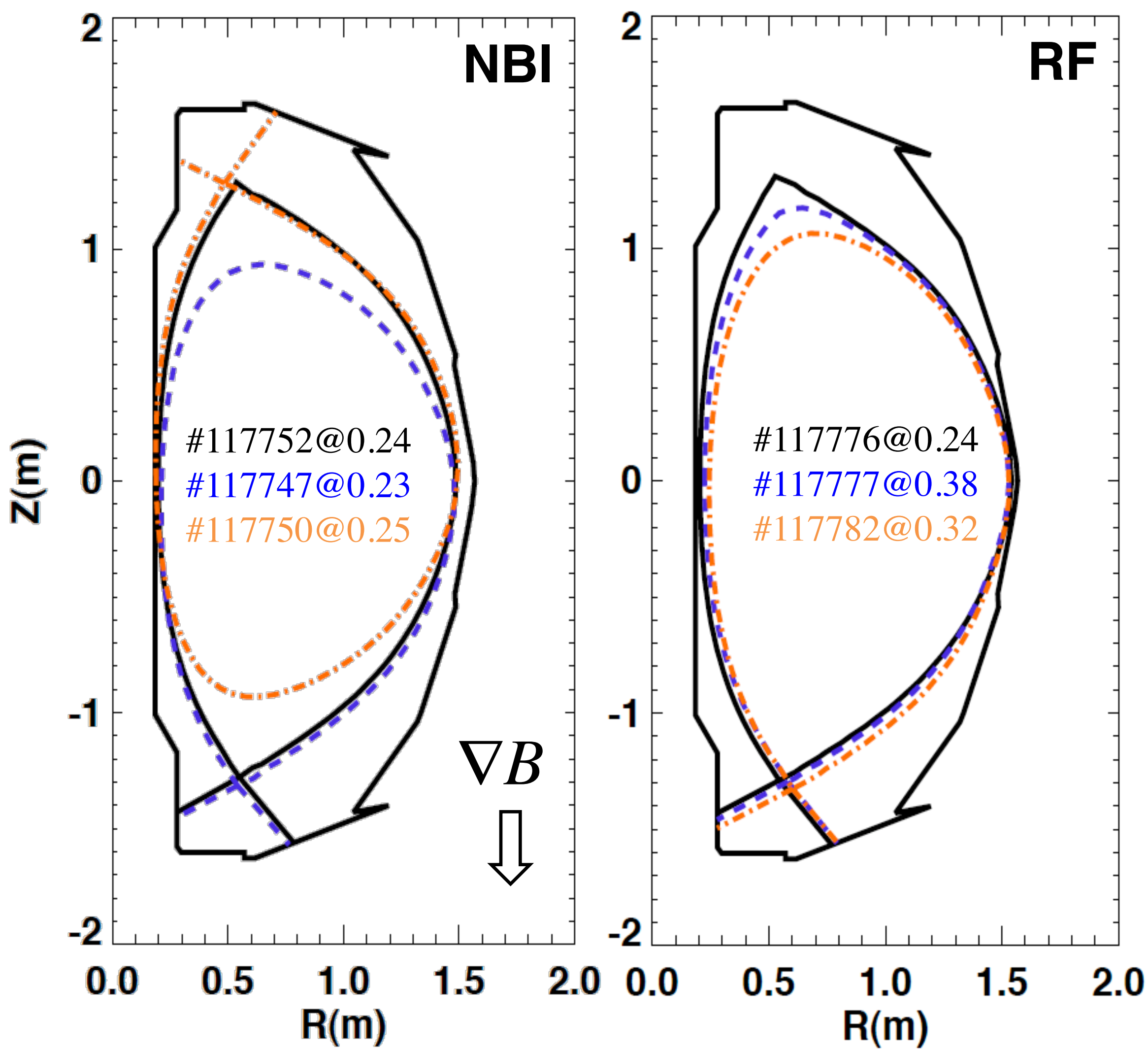
- L-mode profiles matched before NBI, but not during
  - Expect profiles to be similar if P_{abs} was the same despite different P_{NBI}

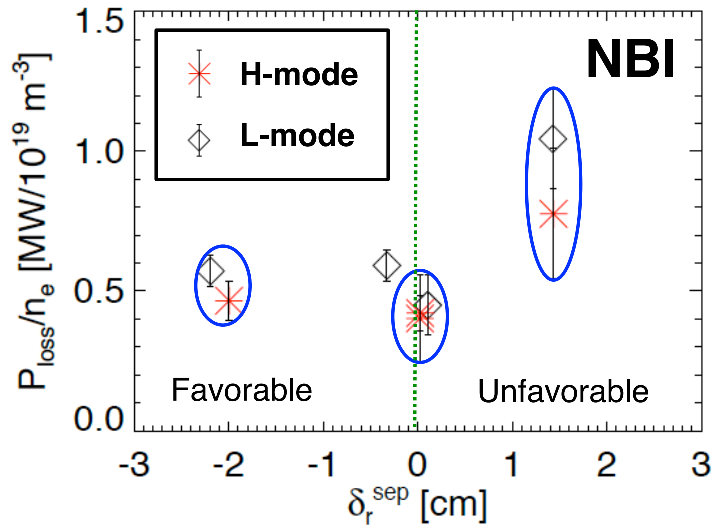
P_{LH} for both shapes strongly influenced by edge fueling and pumping

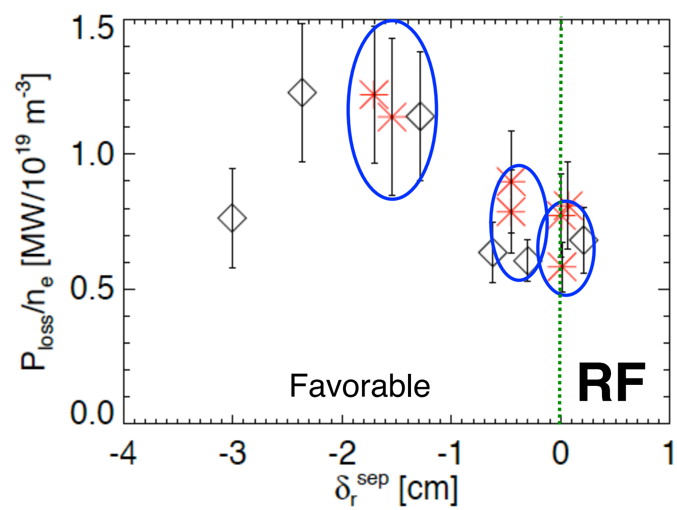
- Full TRANSP analysis of six discharges
  - Matched B_t, I_p, Z_X
  - Nearly matched n_{el}
    - Required more fueling for high Li shots
    - Divertor D_α larger for low Li case
    - TRANSP accounts for effect of estimated n_N on P_{heat}
- Change in edge fueling has a large effect on P_{LH}
  - 20% - 40% change with geometry vs 30% - 40% change with edge fueling



P_{LH} is a minimum for DN geometry, consistent with prediction that E_r well is deepest in DN



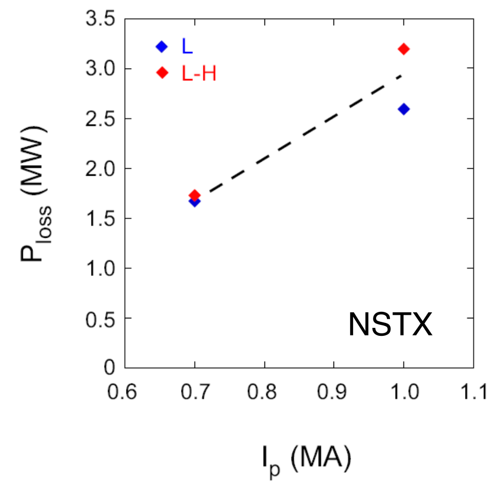


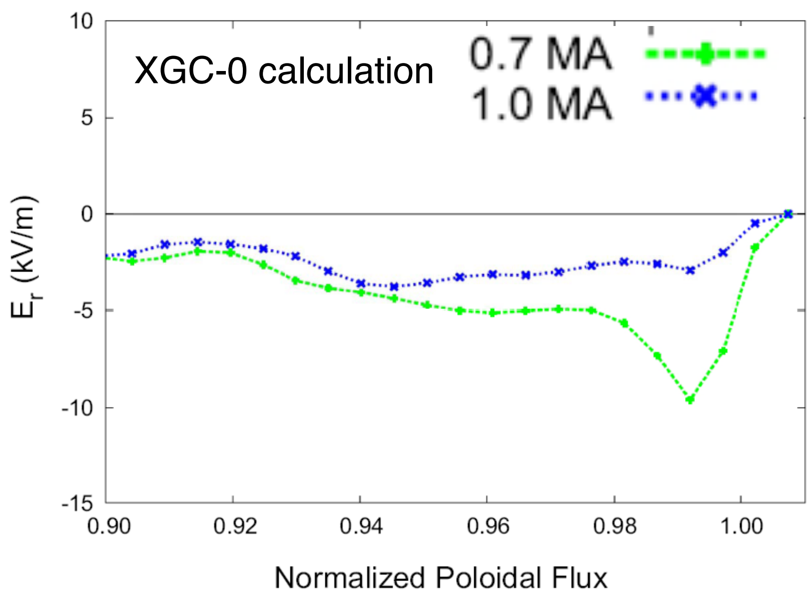


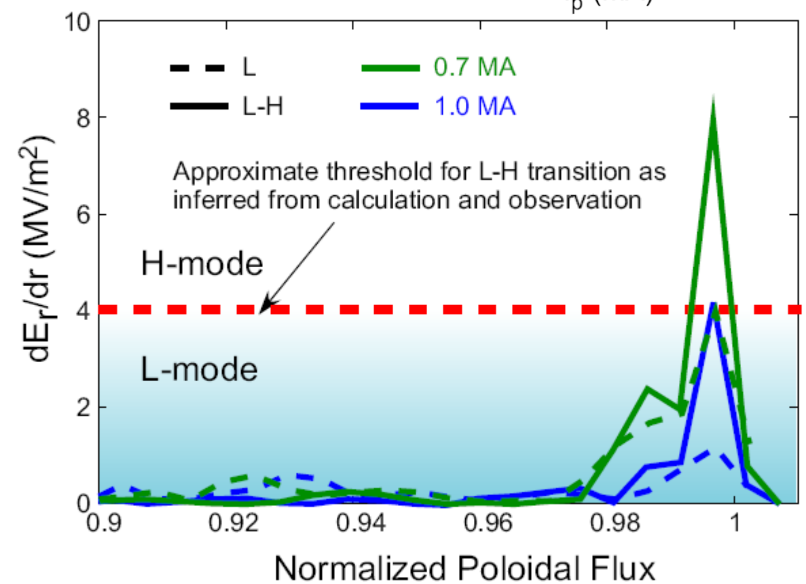
R. Maingi et. al., *Nucl. Fusion,* **50** (2010) 064010

XGC-0 calculations predict edge E_r well is deeper at lower I_p in the ST geometry

- Low energy ions are lost more readily at low I_p plasmas in an ST
  - Leads to a deeper E_r well at the plasma edge
  - Result is consistent with I_p dependence of P_{LH} in low-A geometry



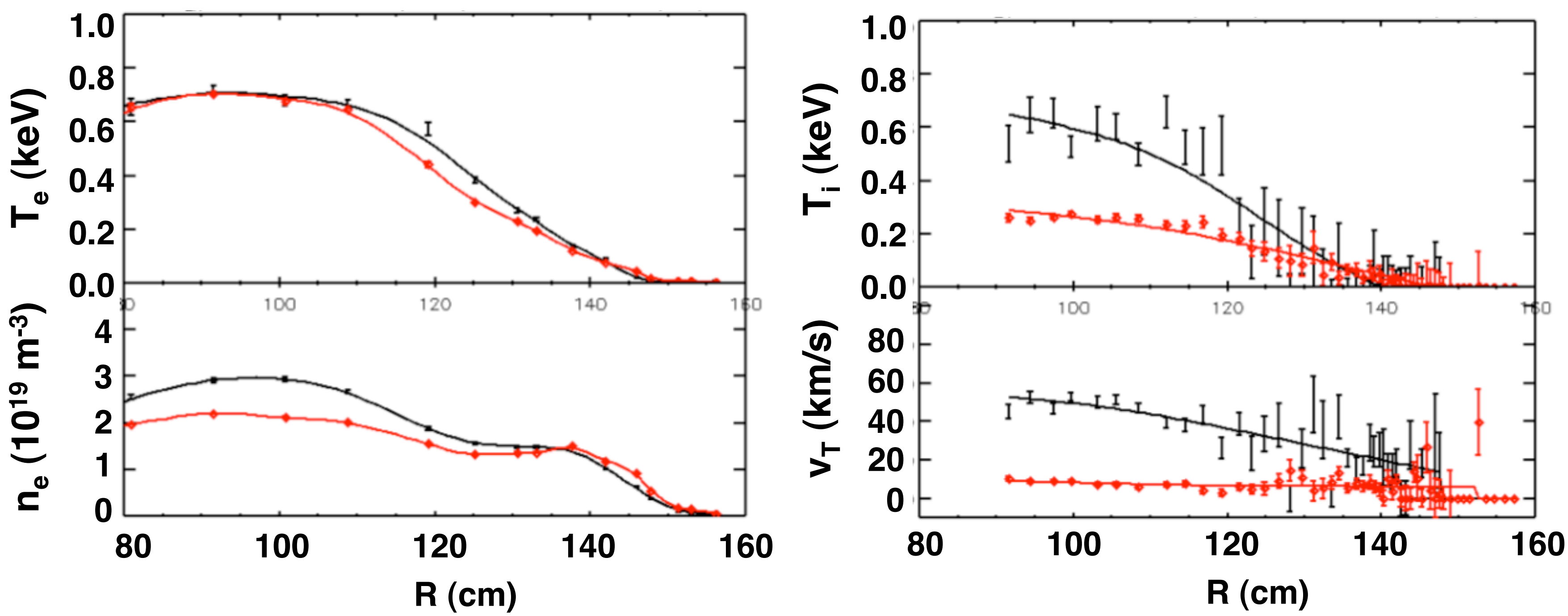




S. Kaye et. al., *Nucl. Fusion, to be submitted*

P_{LH} insensitive to plasma rotation on NSTX

Radial profiles for **NBI** and RF heated DN discharges prior to LH transition

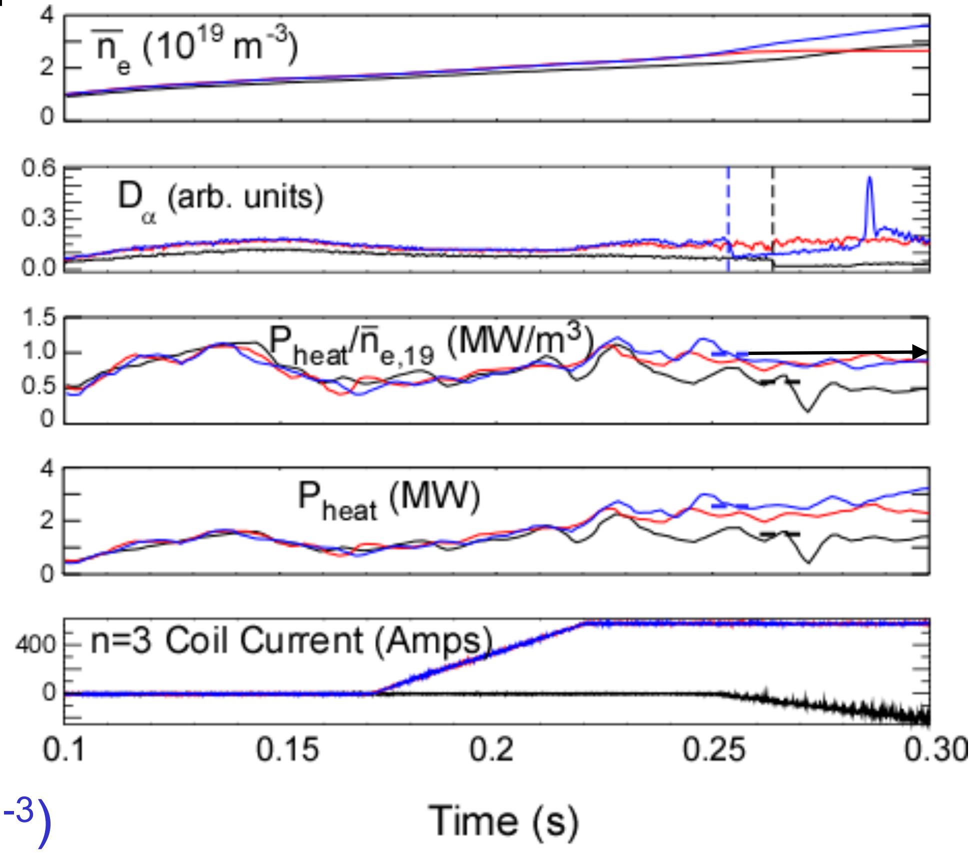


Both discharges transition when $P_{LH} / n_e \sim 0.5$ MW/10^{19} m^{-3} despite differences in core rotation and T_i / T_e

T.M. Biewer, et. al., EPS, Rome June, 2006

Application of n=3 fields results in larger P_{LH}

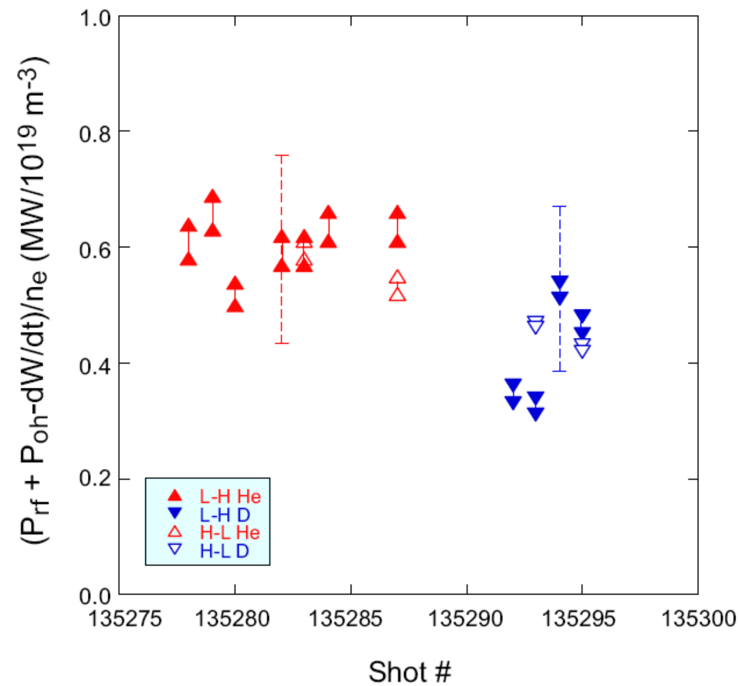
- Motivated by recent JET and MAST results
- Apply n=3 field in addition to error field correction
  - Applied prior to L-H transition
  - Only small change in toroidal rotation observed
- Found P_{LH}/n_e higher with larger applied n=3 field
  - P_{heat}: 1.5 → 2.6 MW
  - P_{heat}/n_e: 0.6 → 1.1 MW/(10^{19} m^{-3})



S. Kaye et. al., *Nucl. Fusion, to be submitted*

P_{LH} and P_{HL} are larger for helium plasmas than deuterium plasmas

- HHFW power provides "fine-scale" determination of P_{LH} and P_{HL}
  - 2009: Current drive phase RF
  - 2010: Heating phase RF
    - Reduces uncertainty in heating efficiency calculation
    - Analysis is ongoing – but experiment was hindered by limited RF power



S. Kaye et. al., *Nucl. Fusion*, *to be submitted*

- P_{LH} (He) ~ 1.2 to 1.4 P_{LH} (D)
  - $P_{HL} \sim P_{LH}$
  - Consistent with ITPA scaling: $P_{LH} \sim M^{0.5}$

Summary

- P_{LH} observed to scale with B_{tX}
  - Consistent with XGC-0 calculations that link the ion orbit loss at the X-point to the E_r well depth
  - May contribute to the scaling of P_{LH} with B_t seen in all toroidal devices
    - ST geometry can decouple B_{tX} from B_{t0} through small changes in R_X
  - Data is 2.5 weeks old → analysis is ongoing

- Recent dataset taken over a range of edge fueling and pumping conditions
  - Initial observation: P_{LH} scales linearly with the pre-beam divertor D_α
  - Lithium coatings are a powerful tool for altering edge fueling & P_{LH}
  - Changes in NBI heating efficiency do not fully describe scaling, implies effect of neutral density on LH dynamics

Summary

- P_{LH} depends on the magnetic balance of X-points and I_p
  - XGC-0: E_r well is deeper for lower I_p due to low-energy ion losses
  - MAST results: E_r well is deeper for balanced double null geometry
  - Both low I_p and $|d_{rsep}|$ reduce P_{LH} on NSTX
- P_{LH} appears to be insensitive to toroidal rotation on NSTX
  - Suggests the ion pressure gradient is the dominant term in E_r at the plasma edge
  - P_{LH} is larger with n=3 fields applied, but the effect does not seem to be attributed to a change in the plasma rotation
- P_{LH} is 1.2 – 1.4 times larger in He plasmas than D plasmas

Acknowledgement

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