XP1029: P_{LH} dependence on R_X

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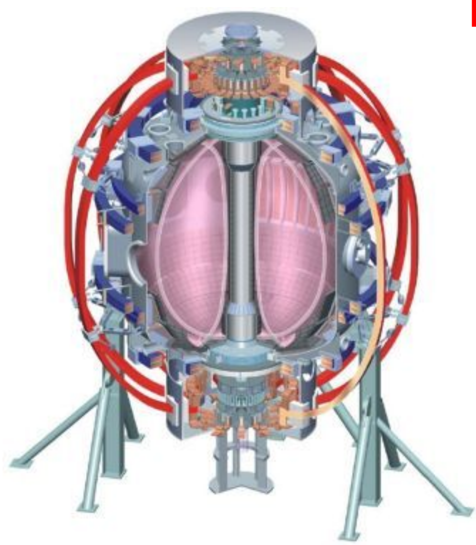
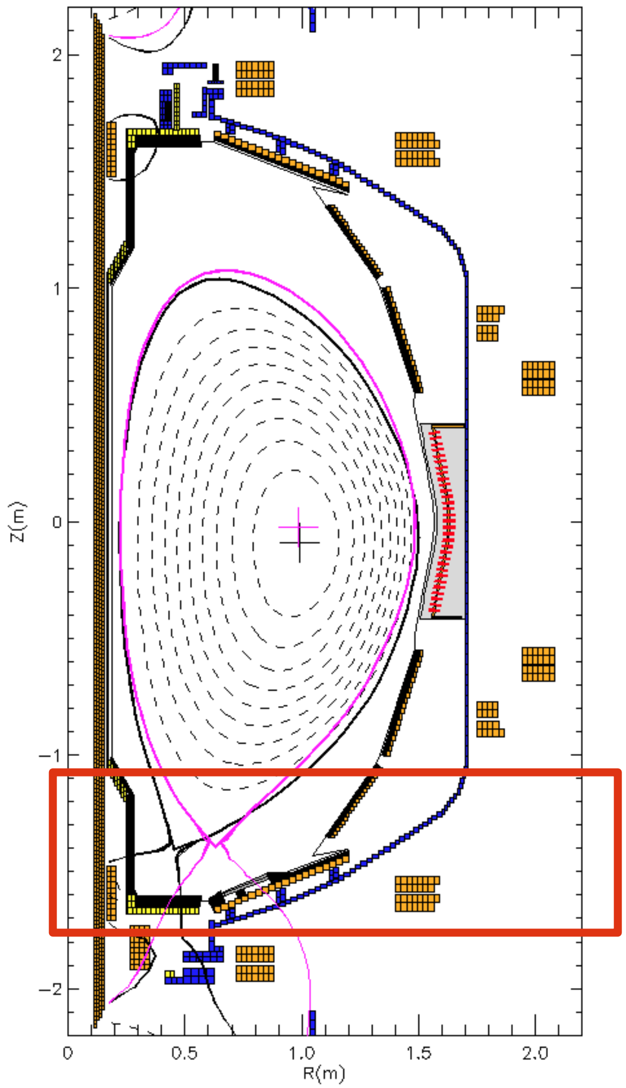
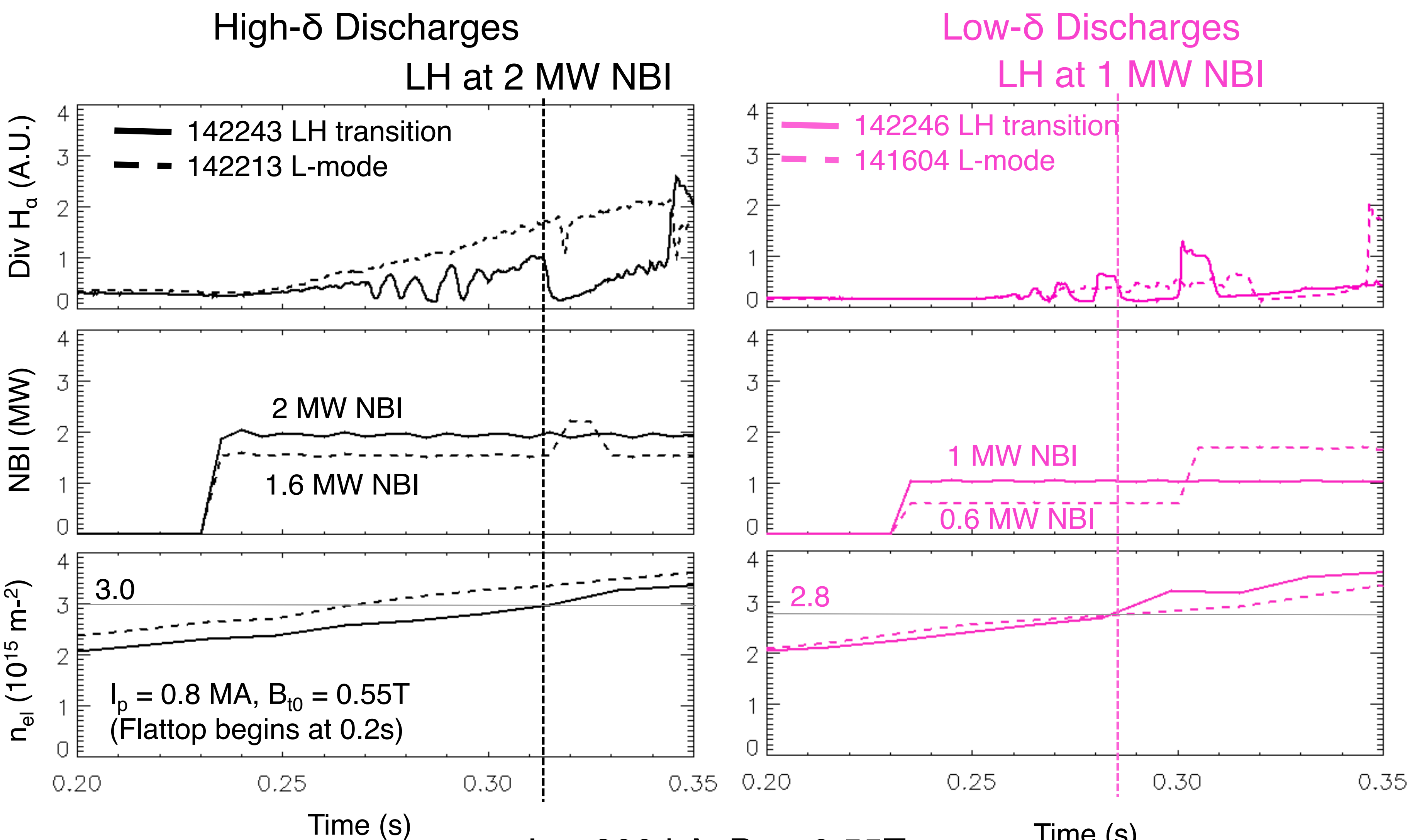


XP1029: Examine the dependence of P_{LH} on R_X



- 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
- Transition with P_{OH} & dW/dt nearly constant
- Scan R_x
  - Low triangularity: $R_x = 0.64$ ($\delta_L = 0.36$)
  - High triangularity: $R_x = 0.47$ ($\delta_L = 0.64$)
  - 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



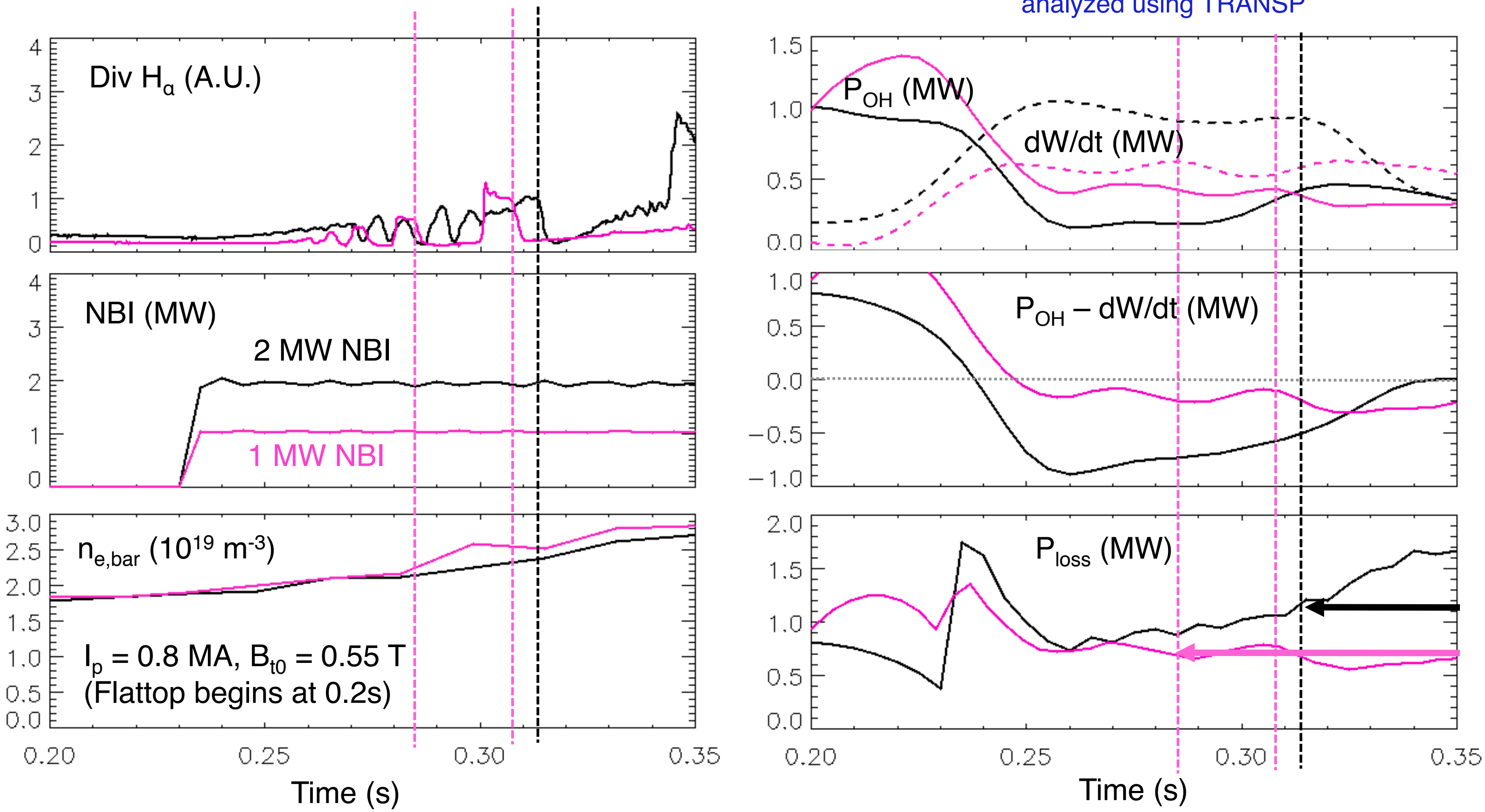
I_p = 800 kA, B_T = 0.55T

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

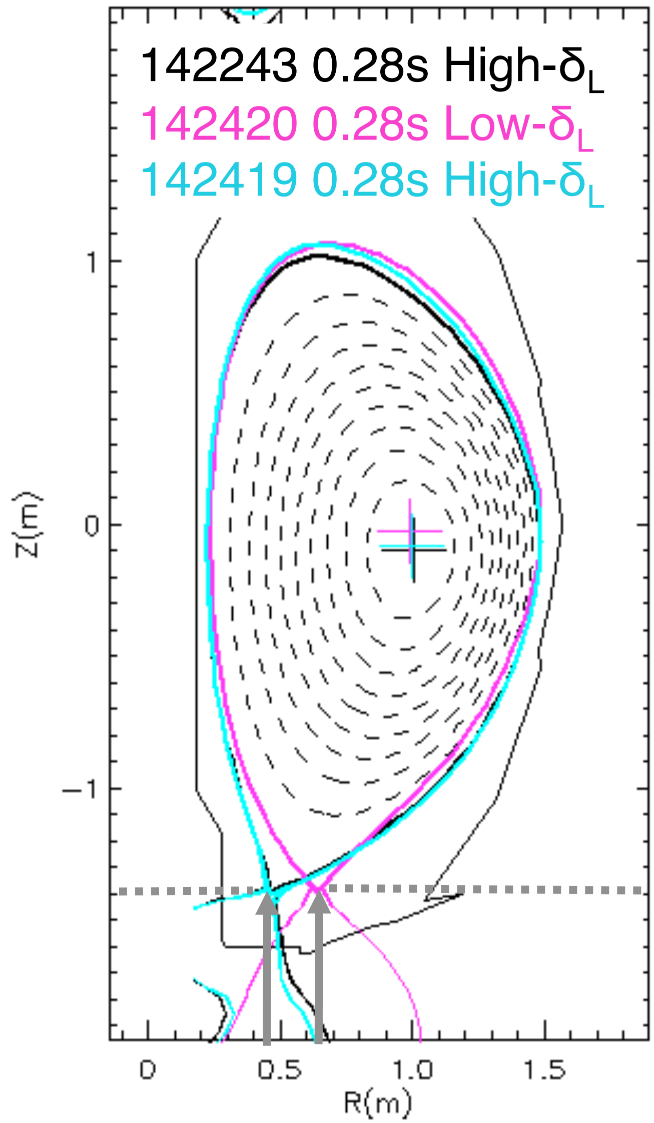
142243 $R_X = 0.47$ (High δ)
142246 $R_X = 0.64$ (Low δ)

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

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

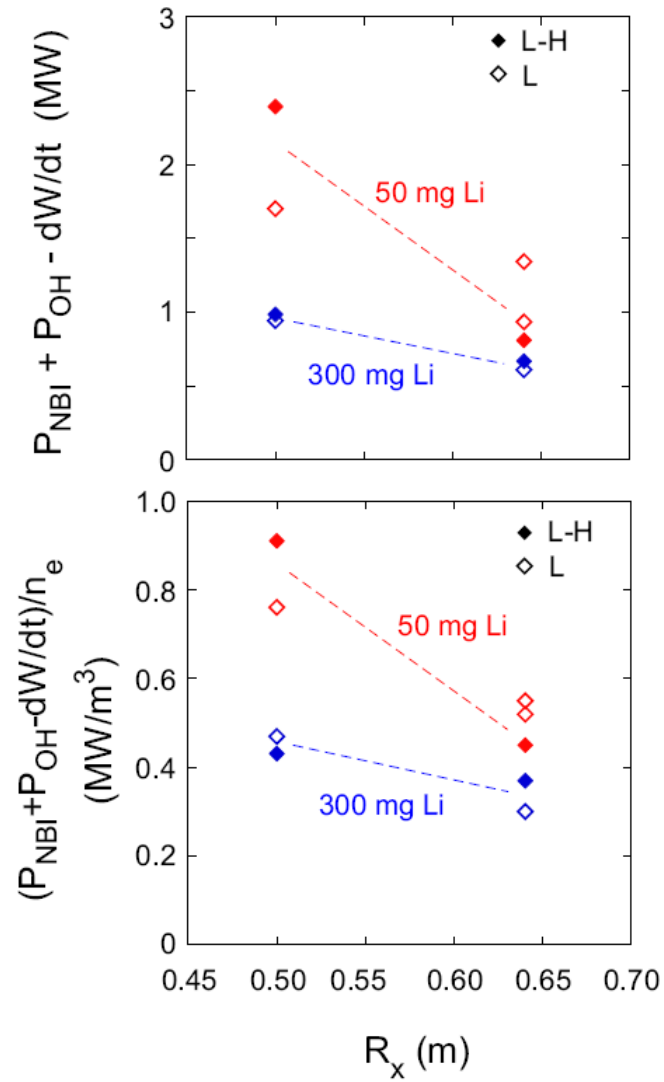
- Dataset implies $P_{LH} \sim B_{tX}^{1.0-2.0}$
  - 22% - 27% reduction in B_{tX} gives …
  - 22% - 45% reduction in P_{LH}

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

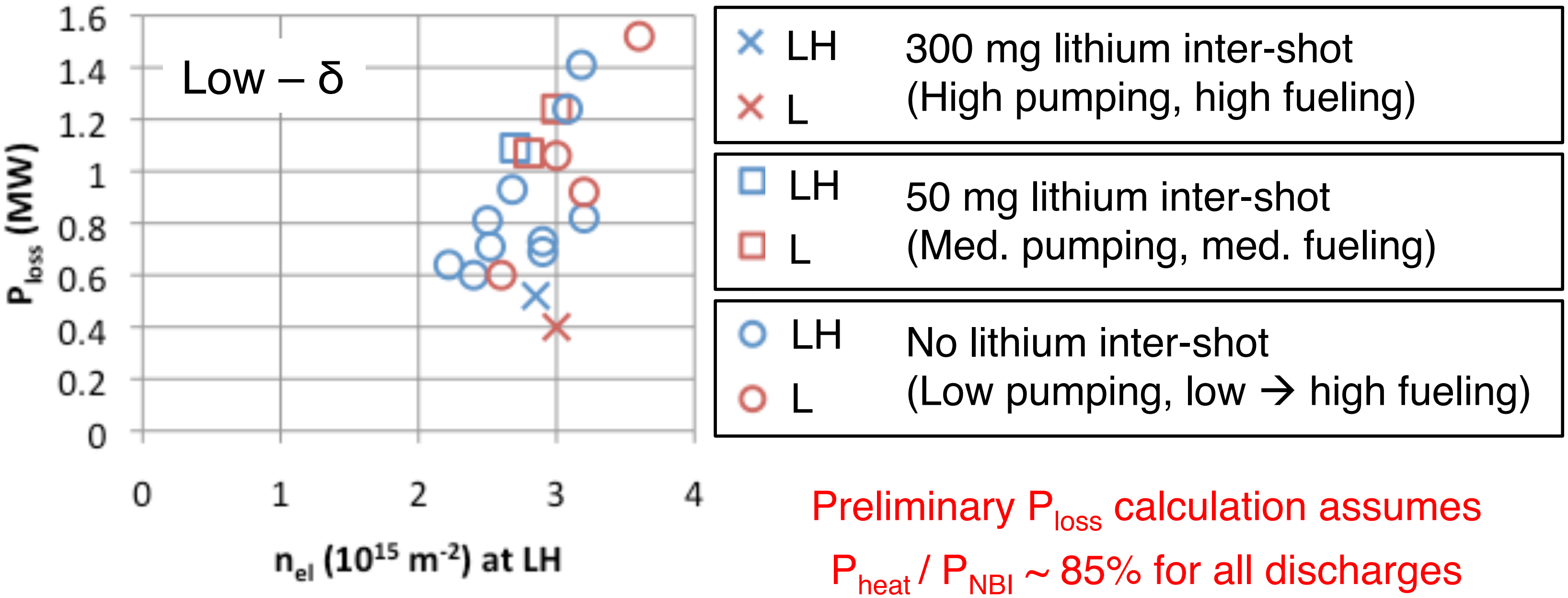
P_{LH} for both shapes strongly influenced by edge fueling and pumping

- Full TRANSP analysis of six discharges
  - Matched B_t, I_p, Z_X
  - Nearly matched n_{el}
    - Required more fueling for high Li shots

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

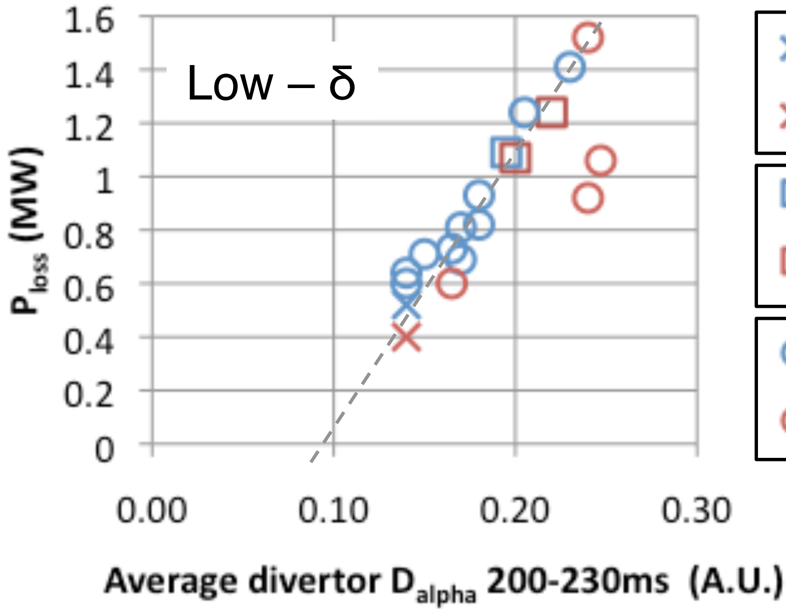


Preliminary P_{loss} calculation assumes P_{heat} / P_{NBI} ~ 85% for all discharges

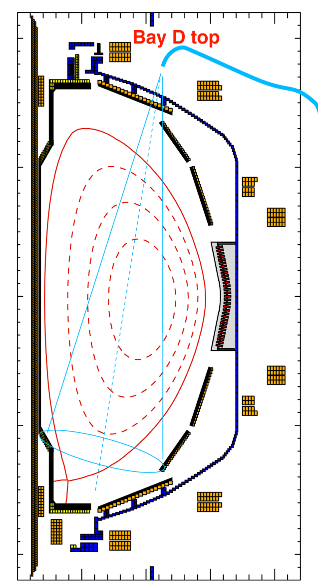
- P_{LH} trends higher with line-integrated density
  - Qualitatively agrees with ITPA scaling
  - Yet, P_{loss} varies over a factor 3 at n_{el} ~ 3 x 10^{15} m^{-2}

- Future analysis: focus on scaling with edge parameters

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



Symbol	Condition
× LH × L	300 mg lithium inter-shot (High pumping, high fueling)
□ LH □ L	50 mg lithium inter-shot (Med. pumping, med. fueling)
○ LH ○ L	No lithium inter-shot (Low pumping, low → med. fueling)



- 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)

XP1029 Summary

- P_{LH} observed to scale with B_{tX}
  - Consistent with XGC0 calculations that link the ion 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

- P_{LH} measured over a range of 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}

- Future work
  - XGC0 calculations of E_r in L-mode for both shapes
  - TRANSP calculations of full dataset
  - Use dataset to consider critical local variables for LH transition

XP1036: P_{LH} vs ionic species

- Deuterium: P_{RF} ~ 600 kW for LH transition with 180° phasing
  - 3 L-mode shots at 450 and 560 kW
  - 5 LH transitions at 625 and 700 kW
  - Locked mode about 50ms after flattop
  - Used combo of HFS and LFS fueling
  - P_{LH} higher with only LFS fueling
- Helium: No LH transition observed
  - Started with discharge that transitioned at 1.5 MW early in run
  - Tried up to 2 MW of RF with only LFS fueling
  - Tried up to 1.2 MW of RF with HFS D_2 and LFS He
  - Tried a number of tricks to lower P_{LH} to no avail

Backup

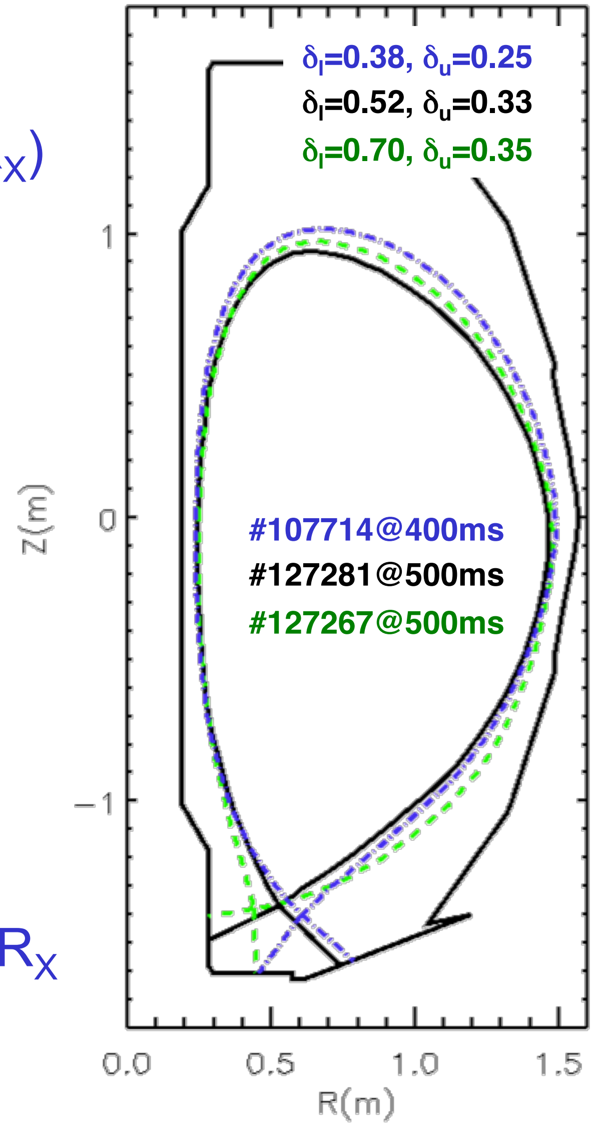
Ion loss mechanisms at the X-point depend on R_X

- Orbit losses
  - Ion gyro-orbit (ion loss decreases with $B_T \sim 1/R_X$)

- Grad-B drift
  - Low $v_{||}$ ions have slow poloidal procession
    - Ions can grad-B drift out of plasma

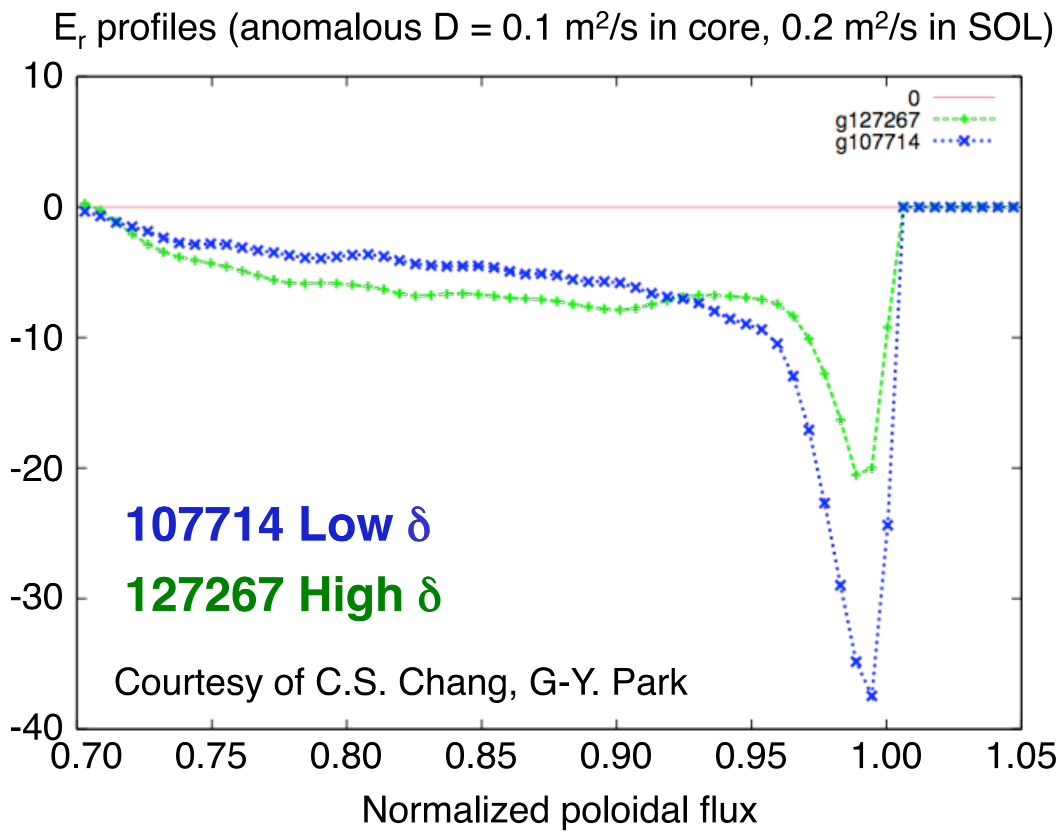
$$v_{||} B_p / B_T < v_{\nabla B}$$

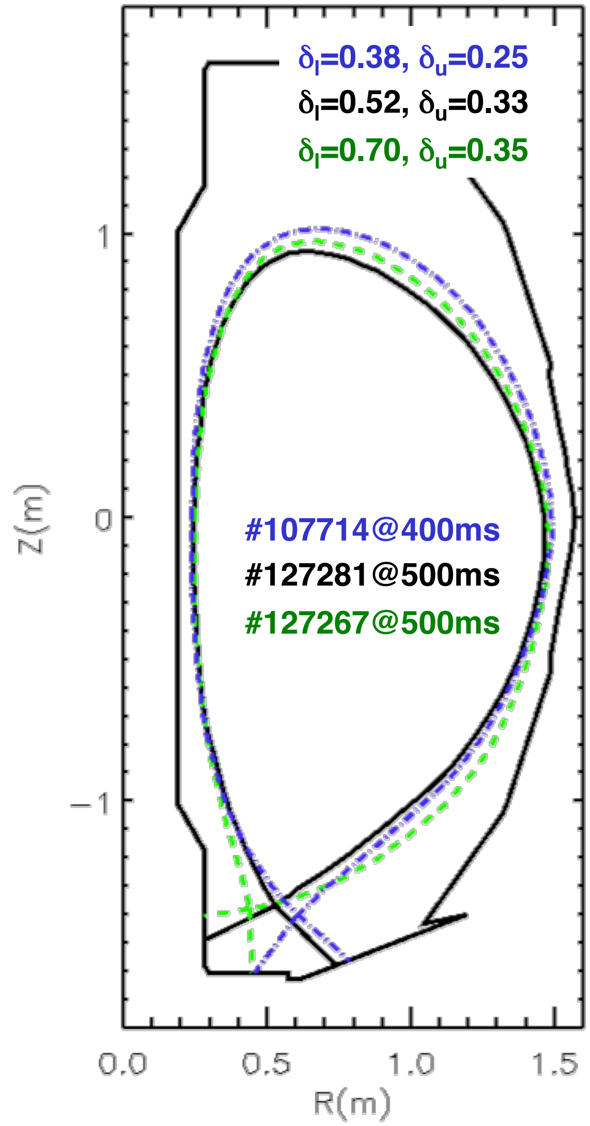
  - More complex relation to R_X
    - Smaller R_X → smaller B_p/B_T
    - But fewer low energy ions due to banana orbits
  - Used to describe DIII-D dependence of P_{LH} on R_X
    - C.S. Chang, S. Kue, H. Weitzner, PoP **9** (2002)



Edge E_r develops in response to ion losses at X-point

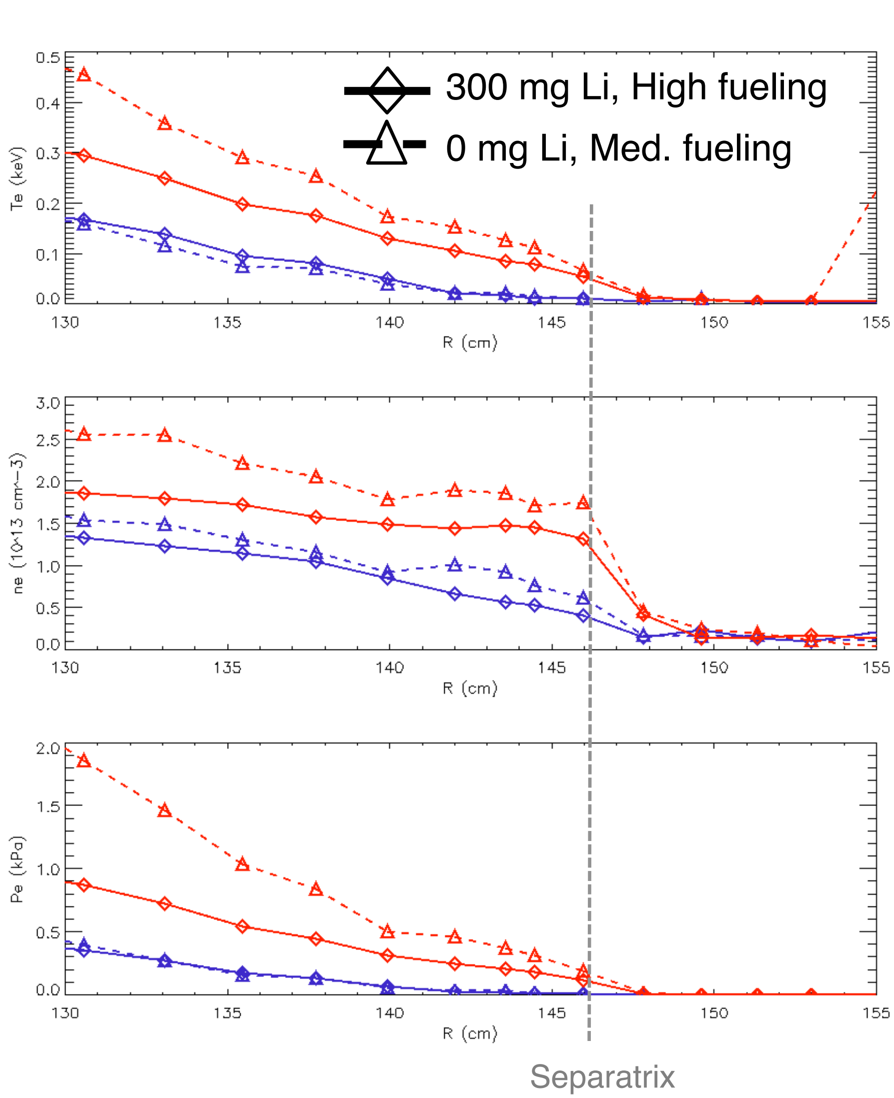
XGC0: NSTX H-mode profiles

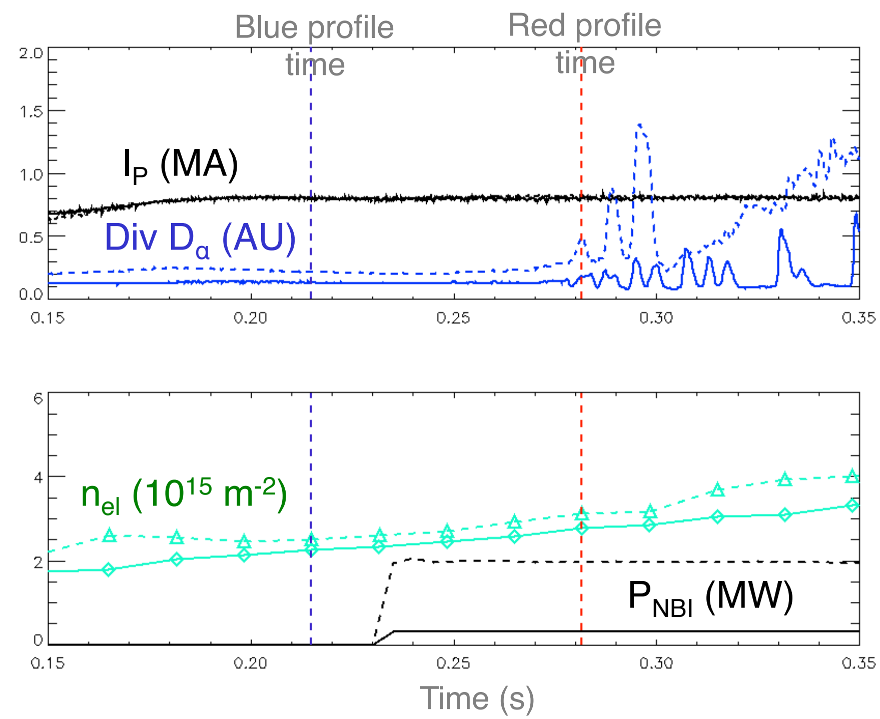




R. Maingi et. al., *Nucl. Fusion,* **50** (2010) 064010

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}

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

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

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

P_{OH}: Ohmic heating power

P_{abs}: Absorbed heating power

dW/dt: Change in plasma stored energy

P_{floss}: Power lost by fast ions

- 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}: 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

Acknowledgement

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