NSTX

Supported by Office of Fusion Energy Sciences — Office of Science

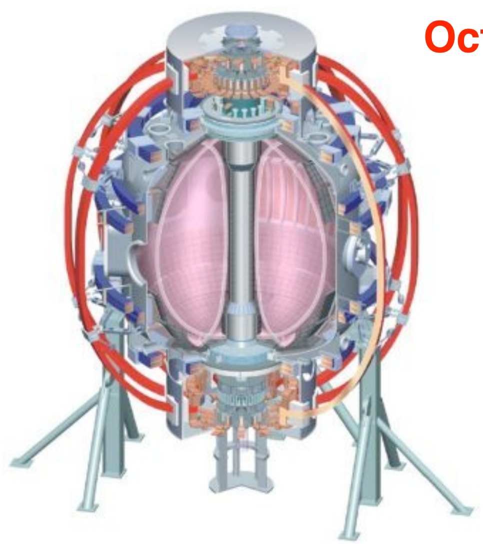
Overview of L-H power threshold studies in NSTX

D.J. Battaglia[1*], S.M. Kaye[2], R. Maingi[1]
and the NSTX team

[1] Oak Ridge National Laboratory, Oak Ridge, TN
[2] Princeton Plasma Physics Laboratory, Princeton, NJ

** Participant in the U.S. DOE Fusion Energy Postdoctoral Research Program administered by ORISE & ORAU*

International Spherical Torus Workshop
Madison, WI
Oct. 22-Oct. 24, 2009



College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Motivation for characterizing the L-H power threshold on NSTX

- H-mode operations provide access to a favorable regime for exploring ST physics
  - Reduced pressure peaking → increased β limits
  - Increased edge pressure gradient → larger bootstrap current
  - Improved energy confinement → reduced flux consumption

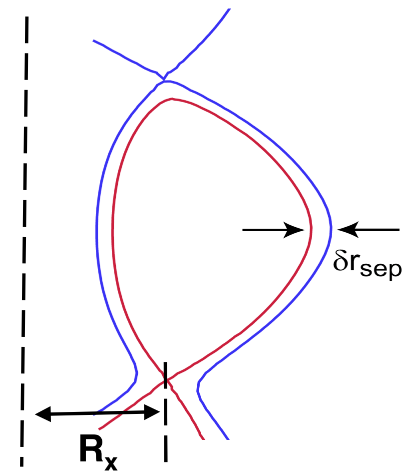
- Contribute to international P_{LH} research effort
  - P_{LH} and P_{HL} in ITER is an active concern
    - Prediction of transition requirements
    - Species dependence
    - Effect of 3D fields
  - NSTX has a wide range capabilities for L-H studies
    - Li pumping → effect of neutrals and collisionality
    - 3-D fields → rotation and edge magnetic field structure
    - Low-A → $B_\theta \sim B_\varphi$ at outboard, low B_T, diagnostic access
    - State-of-the-art diagnostics

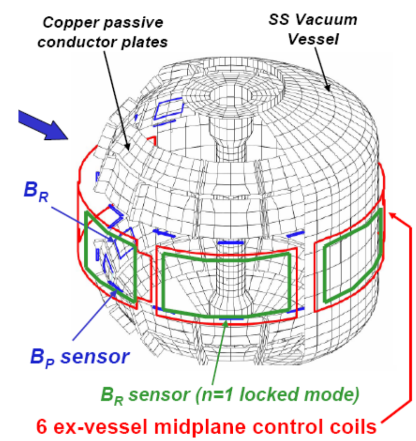
Characteristics of the L-H threshold on NSTX

P_{LH} is observed to …

- Increase with n_e ($n_e > 1.2 \times 10^{19}$ m^{-3}) *XP941*
- Increase with $|\delta r_{sep}|$
- Not vary strongly with R_x *XP909*
- Not vary strongly with plasma rotation
- Increase with an applied n=3 external field *XP936*
- Increase with I_p *XP922*
- Not vary between deuterium and helium *XP941*
- Decrease with lithium evaporation

** XP numbers indicate dedicated experiments in 2009*





VALEN Model of NSTX (Columbia Univ.)

Characteristics of the L-H threshold on NSTX

P_{LH} is observed to …

- Increase with n_e ($n_e > 1.2 \times 10^{19}$ m^{-3}) *XP941*
- Increase with $|\delta r_{sep}|$
- Not vary strongly with R_x *XP909*
- Not vary strongly with plasma rotation
- Increase with an applied n=3 external field *XP936*
- Increase with I_p *XP922*
- Not vary between deuterium and helium *XP941*
- Decrease with lithium evaporation

** XP numbers indicate dedicated experiments in 2009*

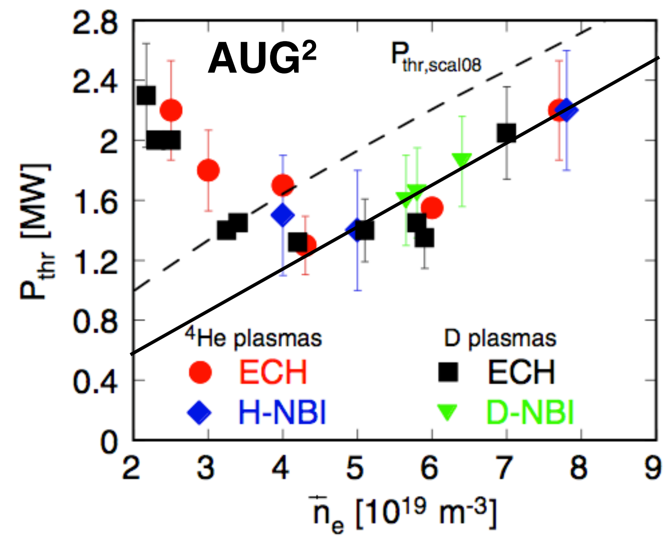
P_{LH} observed to scale linearly with n_e at high density

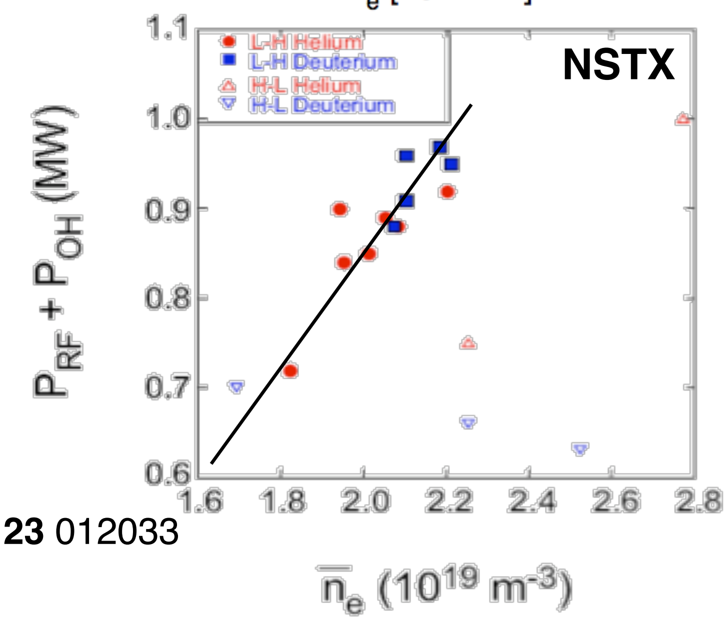
- Scaling relation[1] $P_{LH} \sim n_e$

  $$P_{LH} = 0.049\ n_{20}^{0.72}\ B_T^{0.8}\ S^{0.94}$$

- $P_{LH} \propto n_e$ at high density
  - Observed on a number of devices
  - P_{LH} minimum on NSTX at $n_e \sim 1.5 \times 10^{19}\ m^{-3}$

- Normalize P_{LH} by n_e in the high density regime
  - n_e not actively controlled on NSTX





1 Y.R. Martin, et. al., J. Phys.: Conf. Ser. (2008) **123** 012033
2 F. Ryter et. al., Nucl. Fusion **49** (2009) 062003

Characteristics of the L-H threshold on NSTX

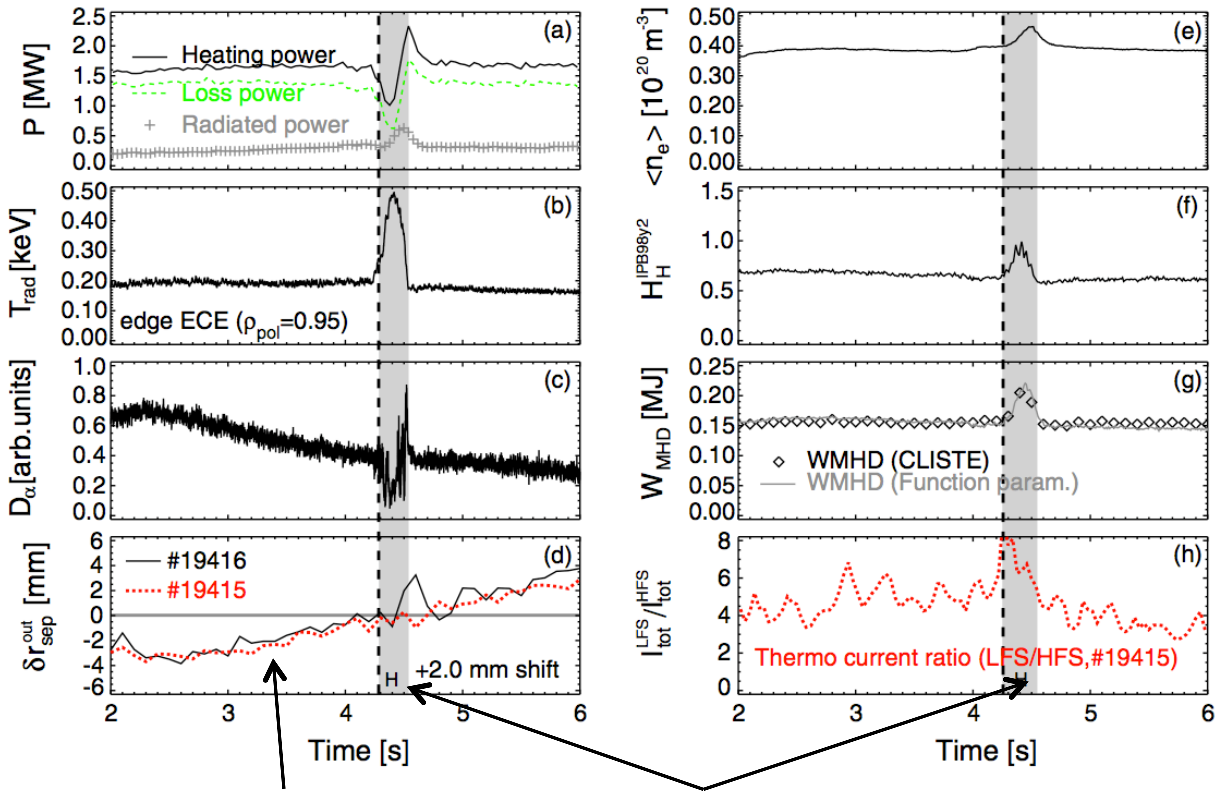
P_{LH} is observed to …

- Increase with n_e ($n_e > 1.2 \times 10^{19}$ m^{-3}) *XP941*
- Increase with $|\delta r_{sep}|$
- Not vary strongly with R_x *XP909*
- Not vary strongly with plasma rotation
- Increase with an applied n=3 external field *XP936*
- Increase with I_p *XP922*
- Not vary between deuterium and helium *XP941*
- Decrease with lithium evaporation

** XP numbers indicate dedicated experiments in 2009*

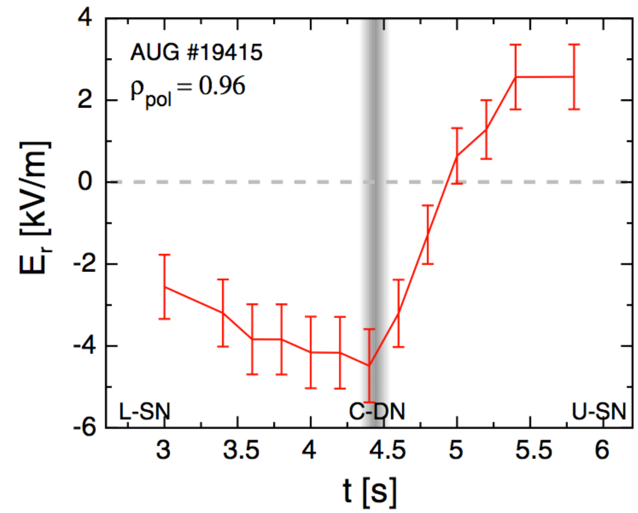
P_{LH} reduction with C-DN was observed on MAST, AUG and NSTX

ASDEX-Upgrade



Scan δ_r^{sep}

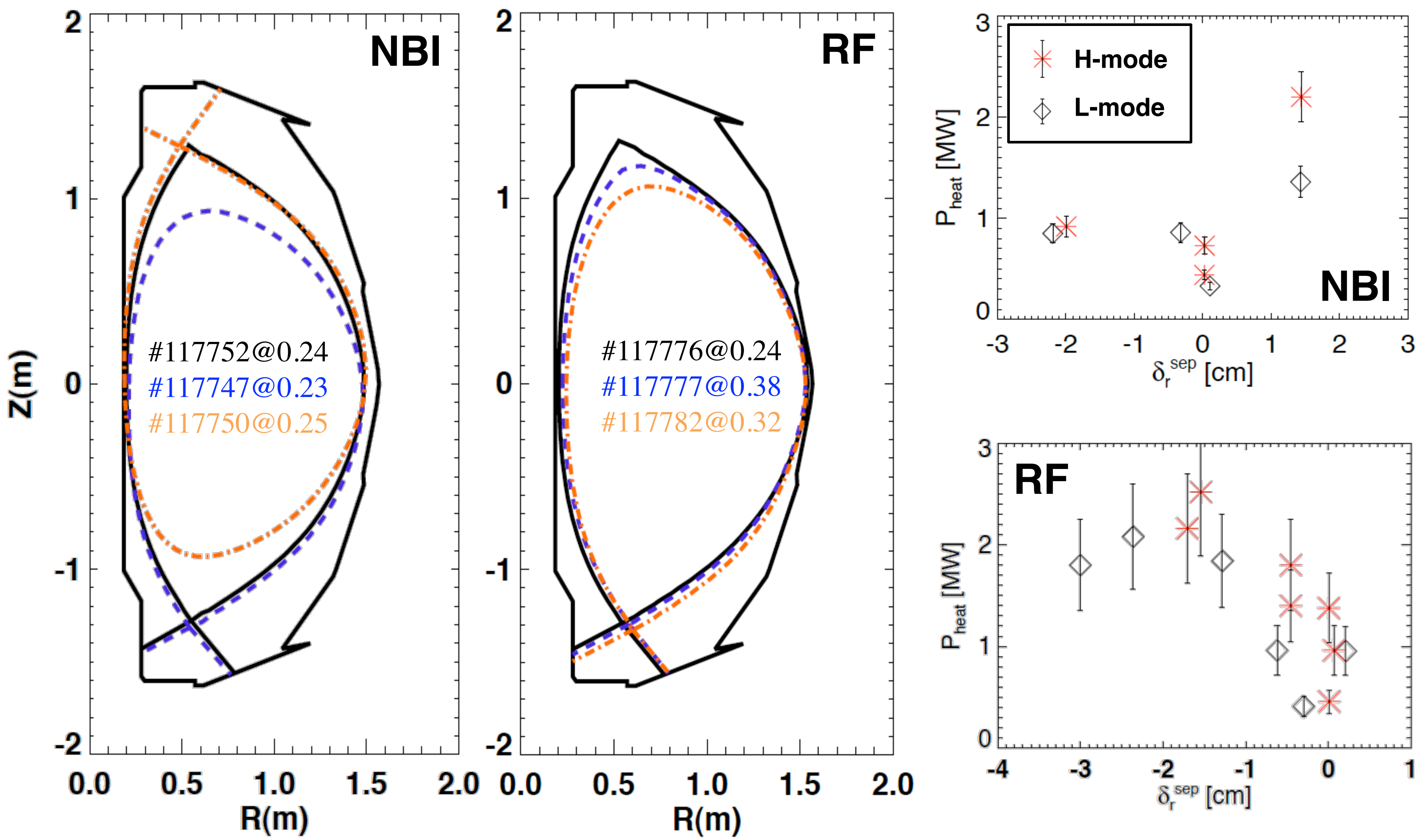
Brief H-mode period



E_r largest near C-DN

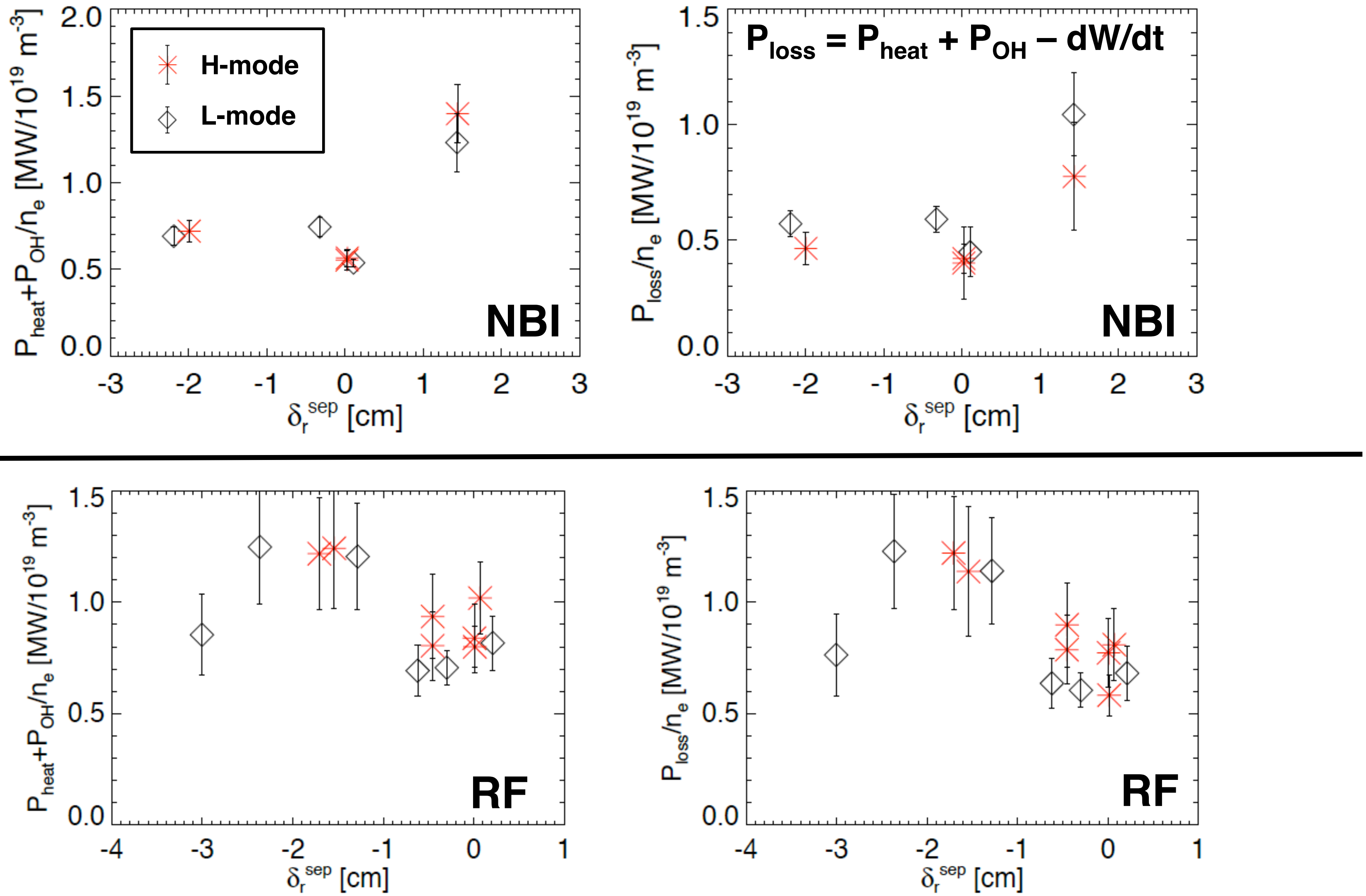
H. Meyer et. al., Nucl. Fusion **46** (2006) 64-72

L-H transition at lowest P_{heat} observed in DN



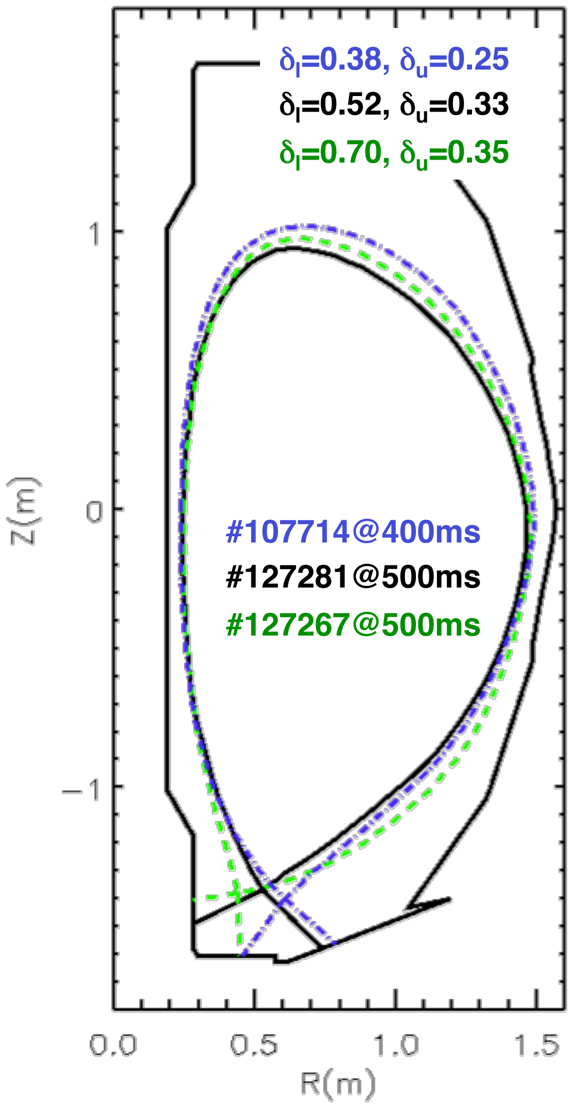
R. Maingi et. al., Nucl. Fusion, *In preparation*

P_{LH}/n_e shows less definitive scaling with δ_r^{sep}

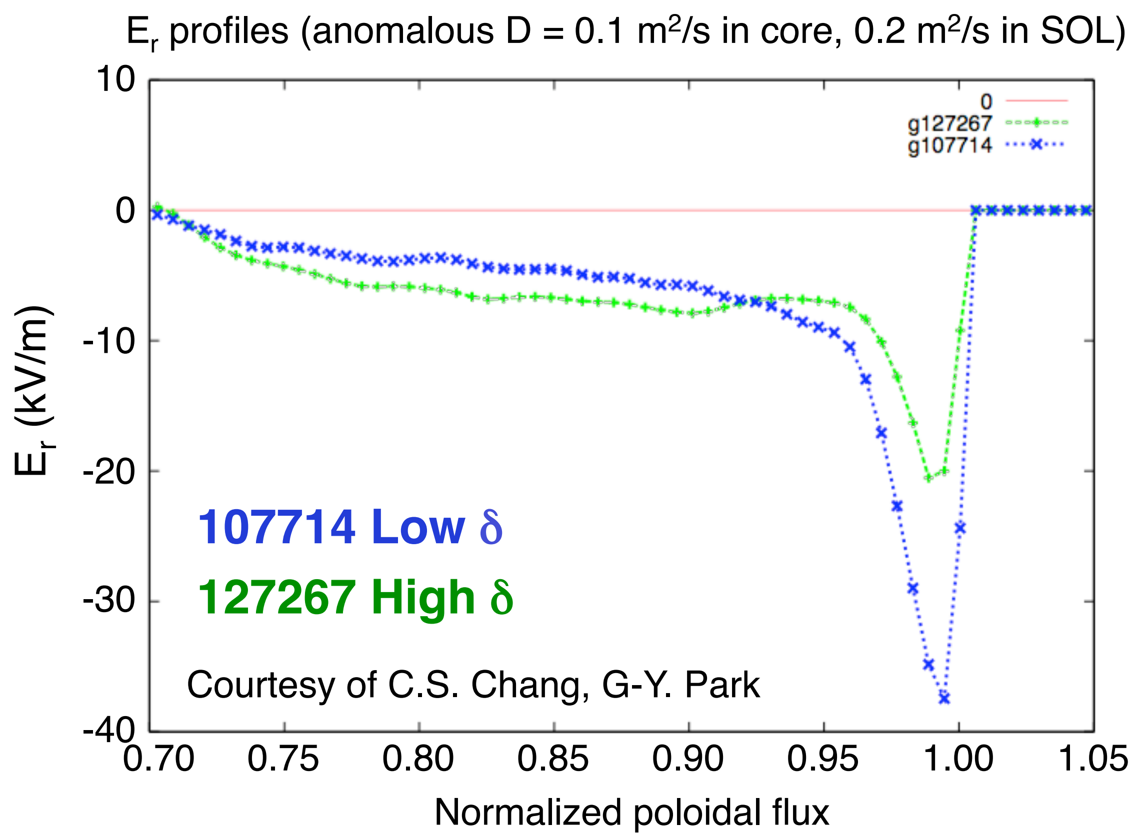


R. Maingi et. al., Nucl. Fusion, *In preparation*

XGC calculations suggest enhanced E_r & E_r' with increasing R_x

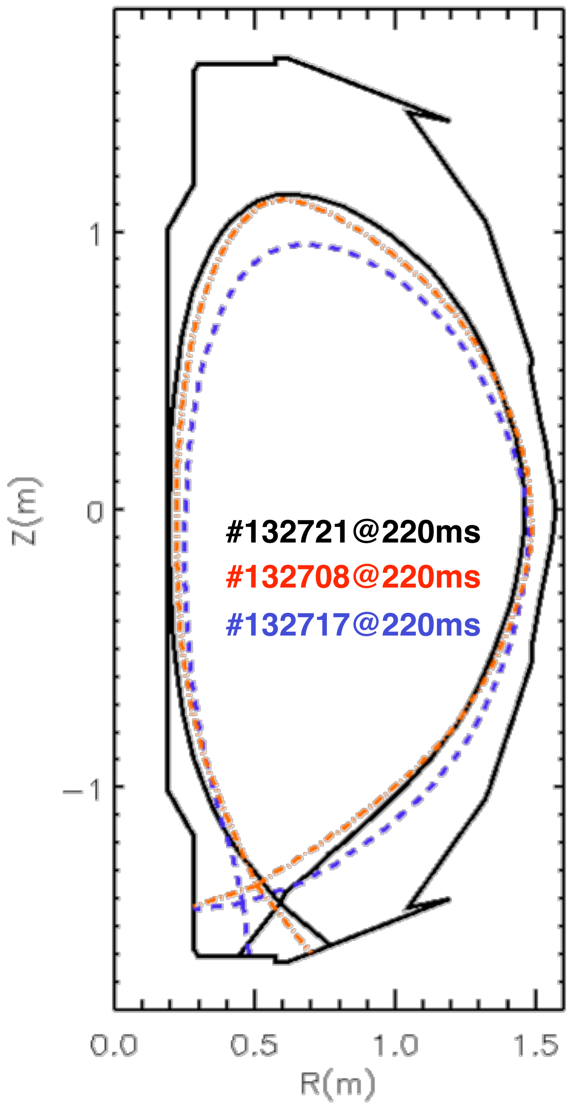


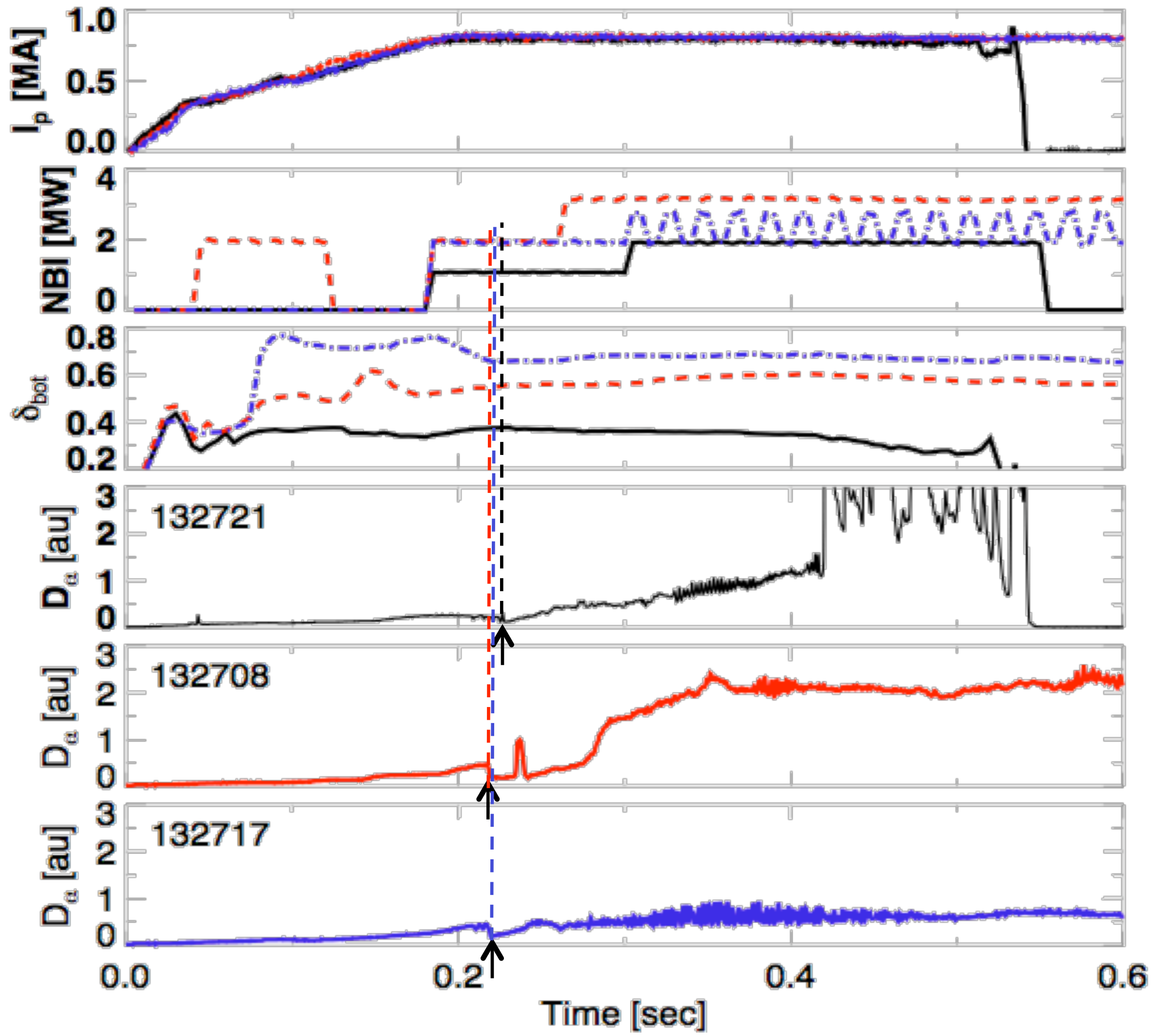
Enhanced E_r driven by ion loss near X-point



R. Maingi et. al., Nucl. Fusion, *In preparation*

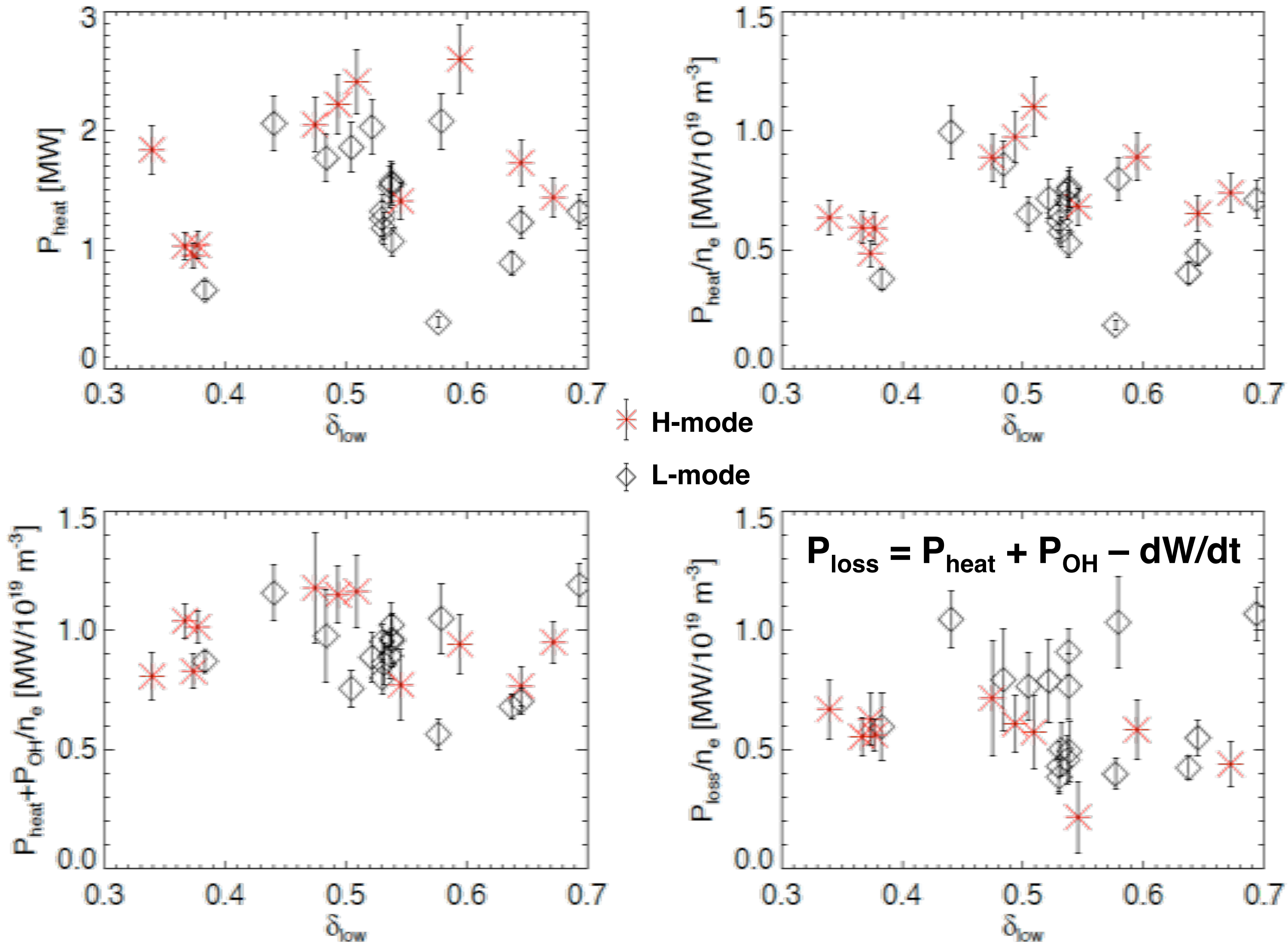
P_{NBI} lowest at largest R_x (lowest δ)





R. Maingi et. al., Nucl. Fusion, *In preparation*

P_{in} & P_{loss} do not vary strongly with δ_{low} (i.e., R_x)



R. Maingi et. al., Nucl. Fusion, *In preparation*

Characteristics of the L-H threshold on NSTX

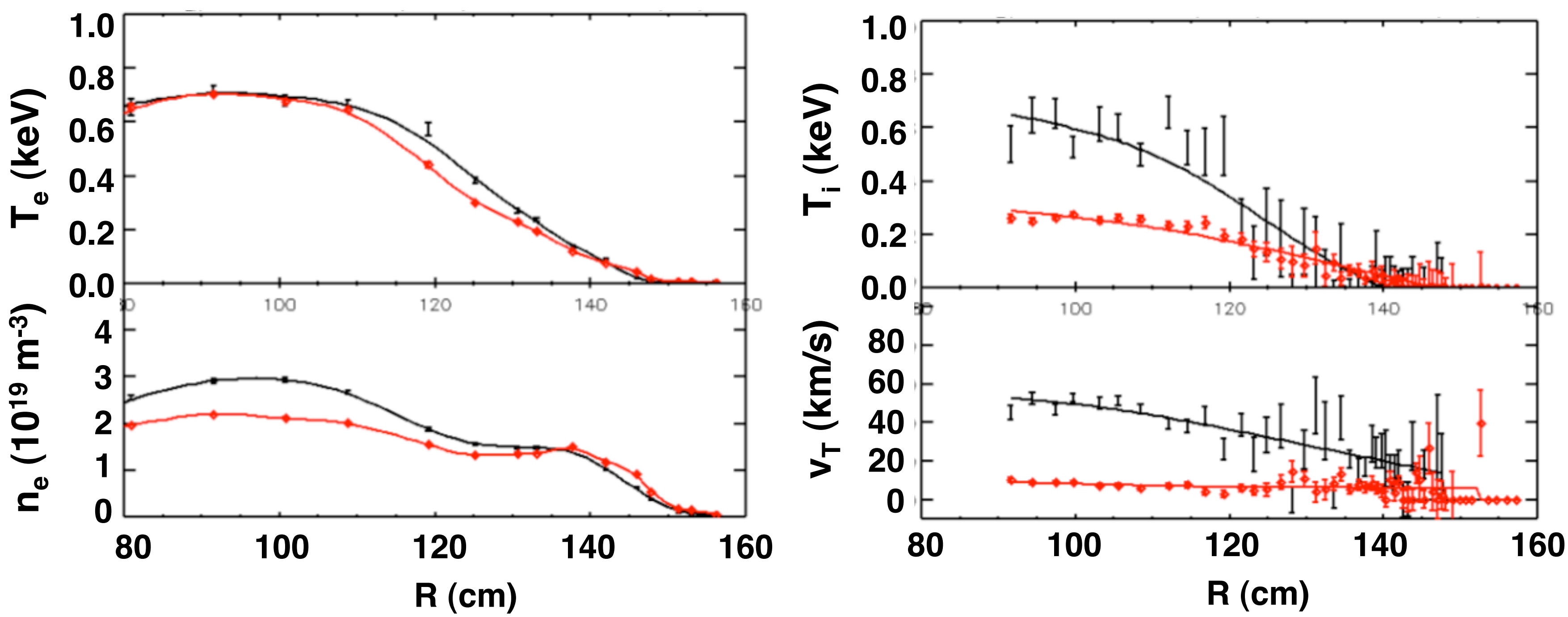
P_{LH} is observed to …

- Increase with n_e ($n_e > 1.2 \times 10^{19}$ m^{-3}) *XP941*
- Increase with $|\delta r_{sep}|$
- Not vary strongly with R_x *XP909*
- Not vary strongly with plasma rotation
- Increase with an applied n=3 external field *XP936*
- Increase with I_p *XP922*
- Not vary between deuterium and helium *XP941*
- Decrease with lithium evaporation

** XP numbers indicate dedicated experiments in 2009*

P_{LH} insensitive to plasma rotation

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



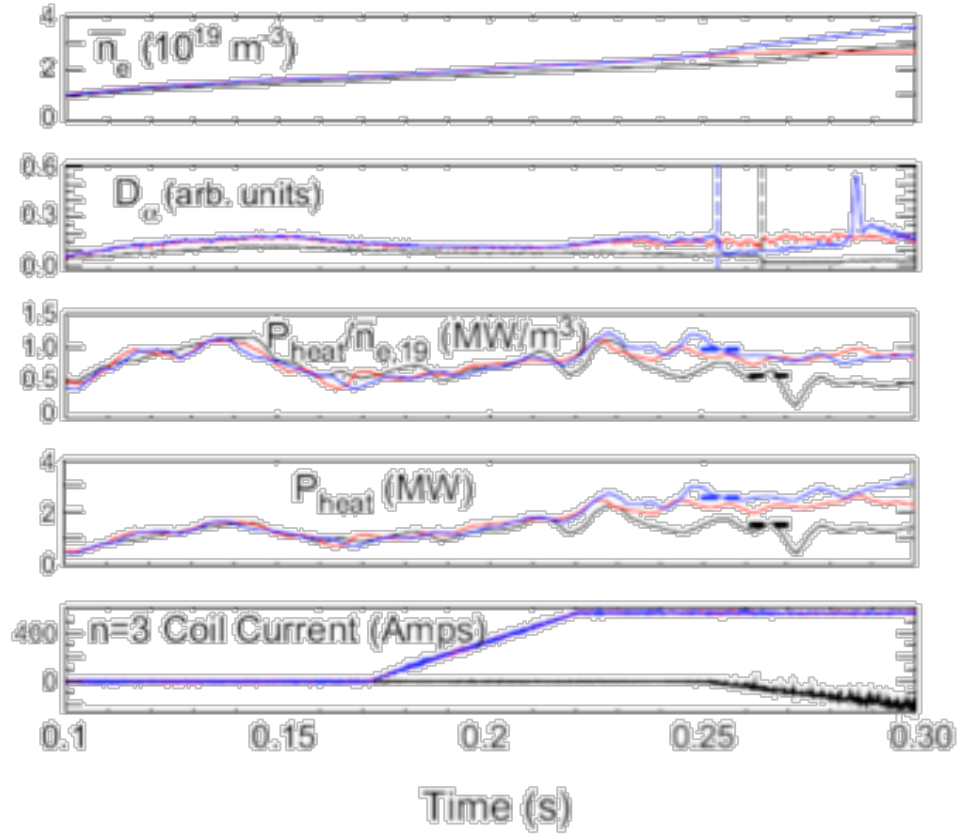
Both discharges transition when $P_{LH}/n_e \sim 0.5$ MW/10^{19} m^{-3} despite differences in core rotation and T_i/T_e

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

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

- Motivated by JET ripple, DIII-D torque scan results
- Recent MAST results showed delayed transition with increasing applied field amplitude
- Apply n=3 rotation braking to test effect on threshold power
  - Braking applied prior to L-H transition
- Found P_{LH}/n_e higher with larger applied n=3 field

P_{heat} increases from ~1.4 to 2.6 MW with higher n=3 current
(~65% increase for P_{heat}/n_e)



L-H Threshold Power Increases with I_p

- Observed over several years of operations
- P_{heat}/n_e almost a factor of 2 higher for 1 MA than for 0.7 MA
- Implies scaling relations should have an I_p dependence

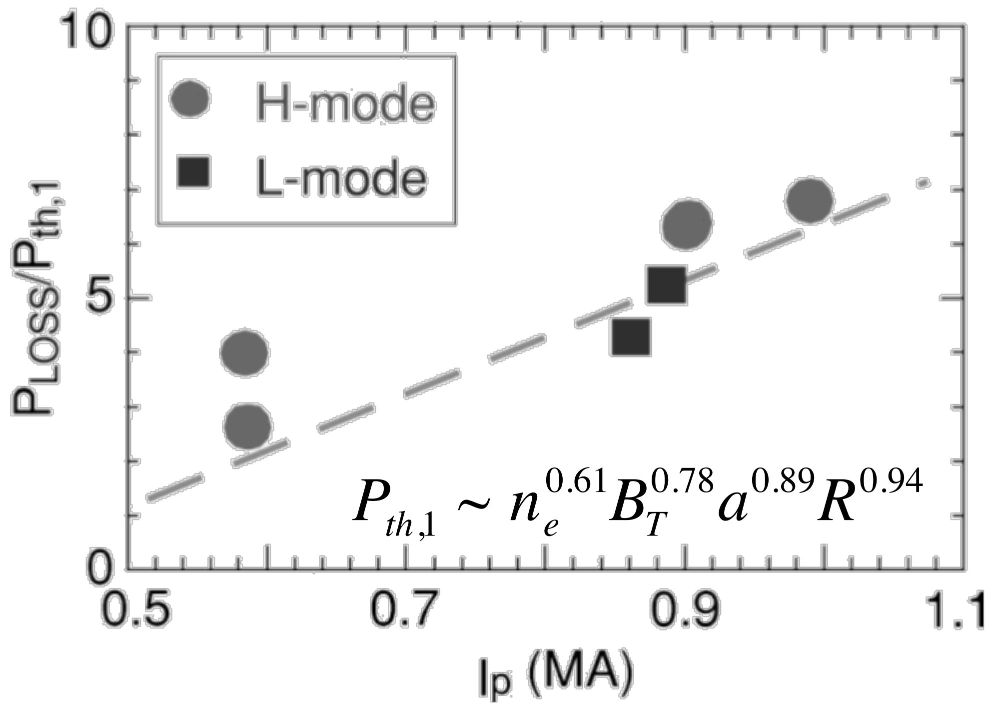
$$P_{LH} = 0.072\, n_{20}^{0.7}\, B_{out}^{0.7}\, S^{0.9}$$

T. Takizuka et. al., PPCF **46** (2004) A227

2009 NSTX

I_p = 0.7 MA: P_{LH} ~ 1.6 MW, $P_{heat}/n_{e,19}$ ~ 0.7 MW/m^{-3}

I_p = 1.0 MA: P_{LH} ~ 3.1 MW, $P_{heat}/n_{e,19}$ ~ 1.2 MW/m^{-3}



C.E. Bush, et. al., Phys. Plasmas **10** (2003) 1755

Characteristics of the L-H threshold on NSTX

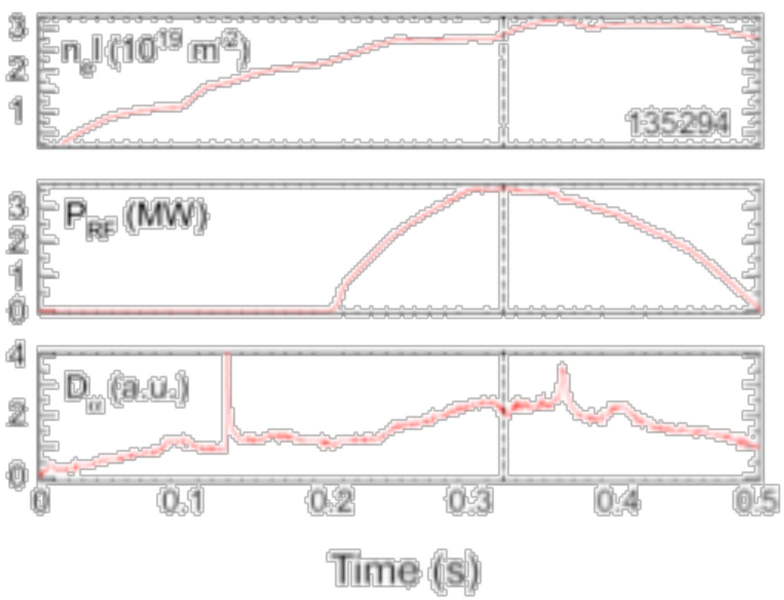
P_{LH} is observed to …

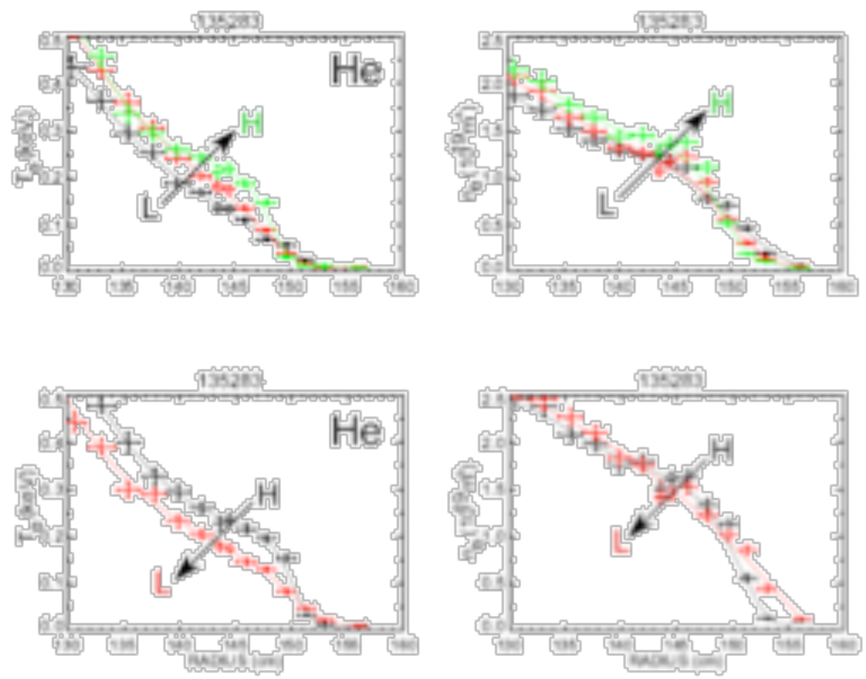
- Increase with n_e ($n_e > 1.2 \times 10^{19}$ m^{-3}) *XP941*
- Increase with $|\delta r_{sep}|$
- Not vary strongly with R_x *XP909*
- Increase with X-point height
- Not vary strongly with plasma rotation
- Increase with an applied n=3 external field *XP936*
- Increase with I_p *XP922*
- Not vary between deuterium and helium *XP941*
- Decrease with lithium evaporation

** XP numbers indicate dedicated experiments in 2009*

Fine scan of L-H/H-L power thresholds in pure He and D Plasmas using HHFW

- Use change in edge profiles to determine indication of L-H and H-L transitions
  - Transitions not always obvious in D_α signal with slow power scan
  - No D_α signal in pure He plasmas

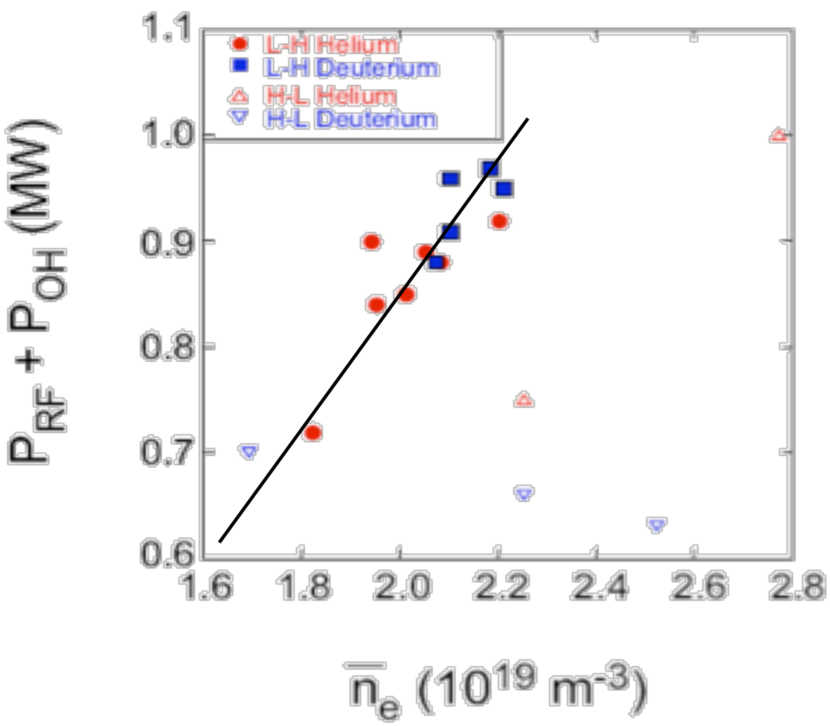


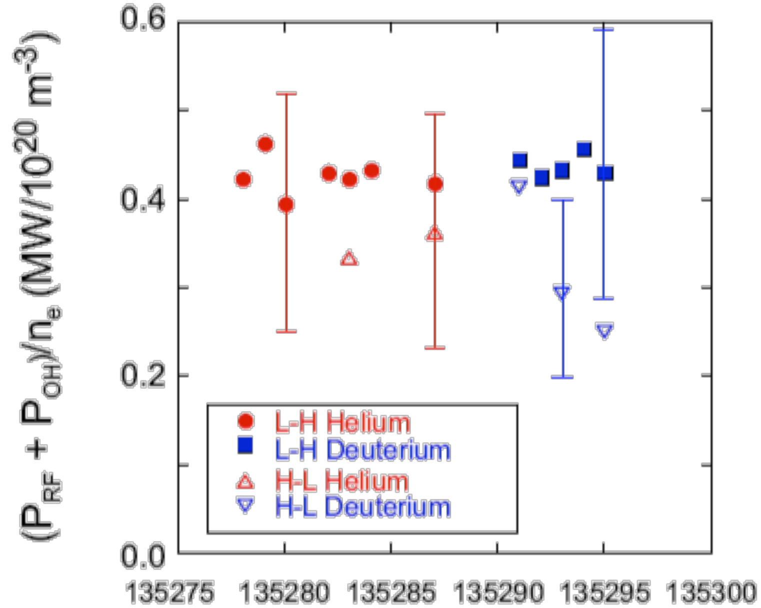


L-H power thresholds for He and D are similar

- $(P_{RF} + P_{OH})/n_e$ similar for P_{LH} thresholds with D and He
  - P_{HL} not effectively normalized by n_e
- H-L thresholds indicate some hysteresis

- Large error bars due to uncertainty in RF heating efficiency

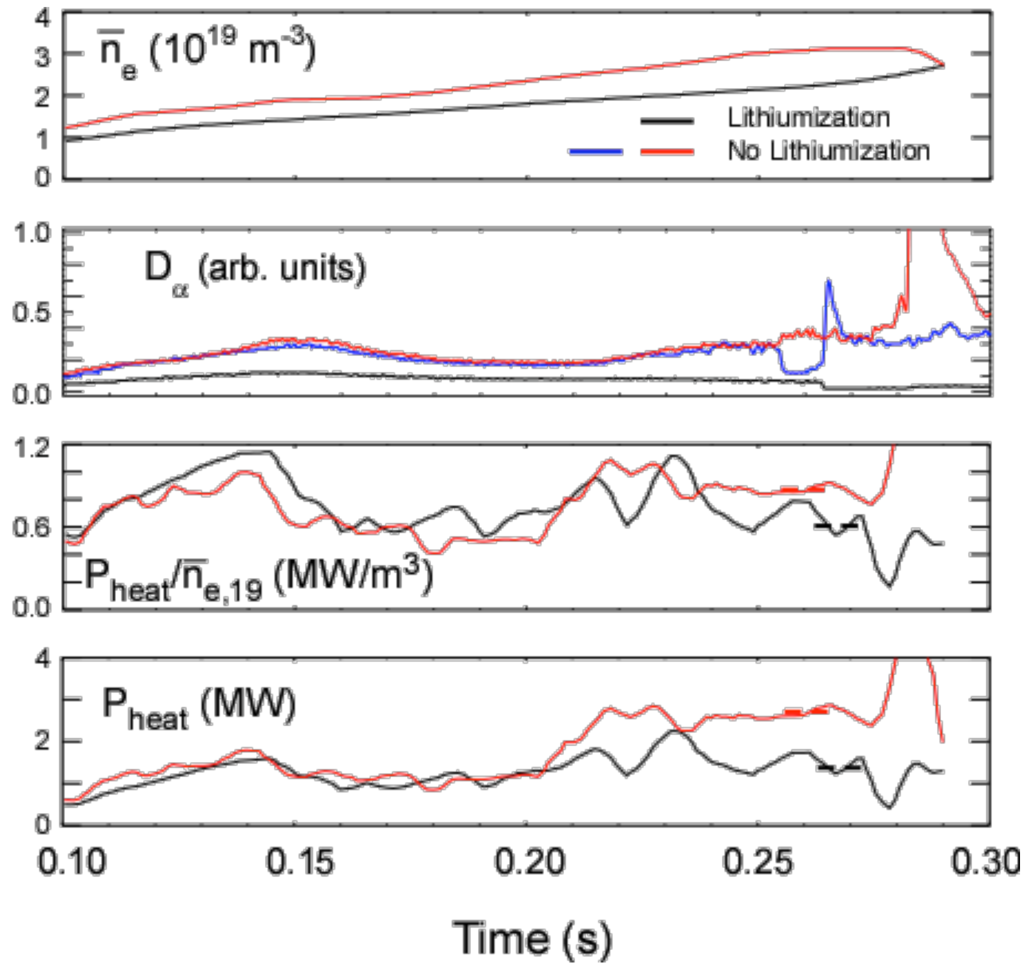




Lithium evaporation led to a significant reduction in L-H power threshold

P_{LH} ~ 2.7 MW NBI without Li evaporation (P_{heat}/n_e~0.9 MW/10^{19} m^3)

~ 1.4 MW NBI with Li evaporation (0.6 MW/10^{19} m^3)



Summary: P_{LH} dependences observed on NSTX

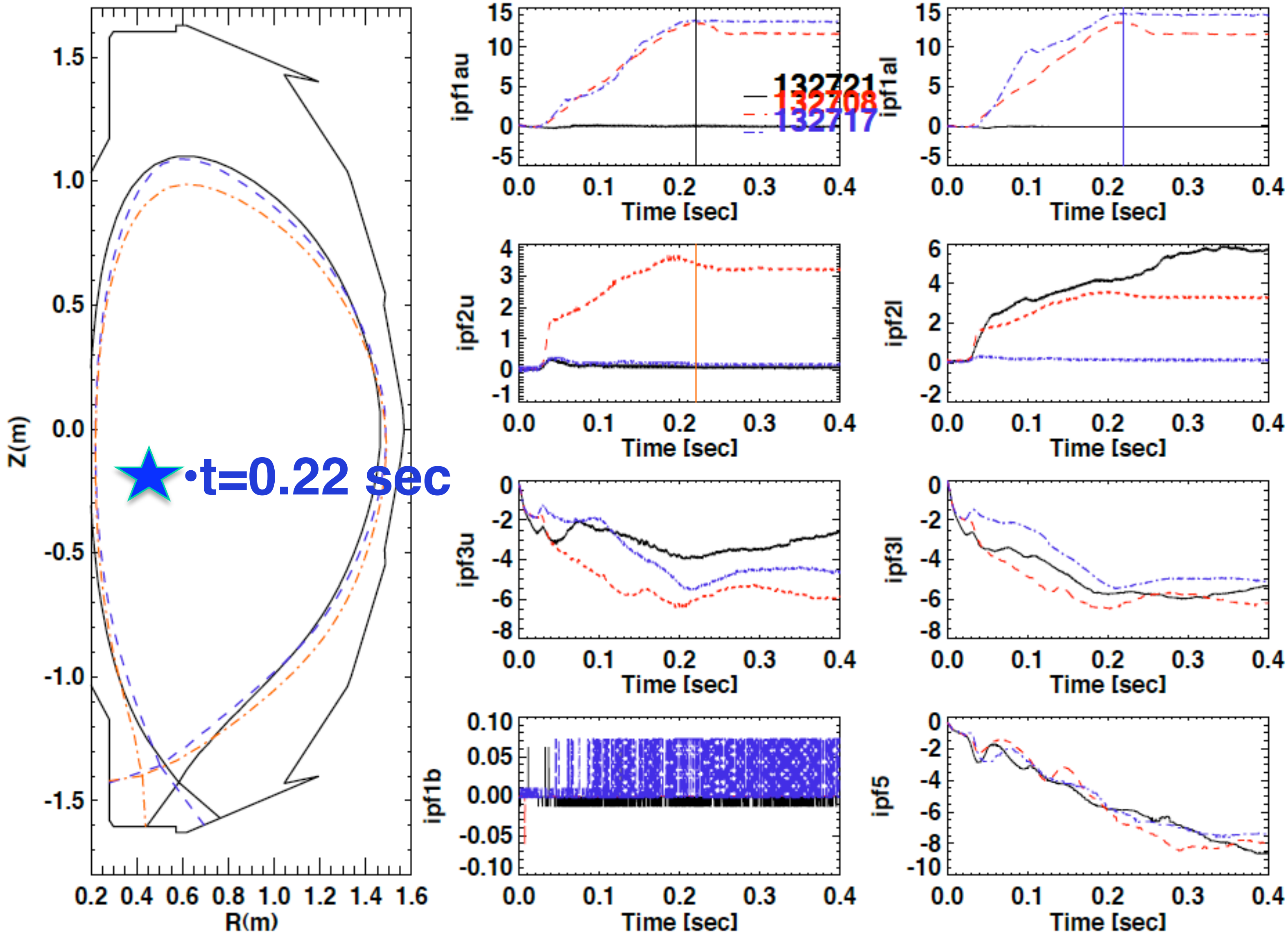
- Dependence on density
  - P_{LH} has linear dependence above a critical density
- Lowest P_{LH}/n_e near DN
  - $P_{LH}/n_e \sim 0.5$ MW/10^{19} m^{-3} for both RF and NBI heated plasmas
- Weak scaling of P_{LH}/n_e with R_X observed
  - May require discharges with similar P_{OH} and reduced dW/dt to cull out dependence
- Strong dependence on I_p
  - Observed on MAST and NSTX
  - May imply outboard B strength is important ($B_\theta \sim B_\varphi$ in an ST)

Summary: P_{LH} dependences observed on NSTX

- P_{LH} independent of plasma rotation
  - Elucidated using similar discharges with either RF or NBI heating
- Applying an n=3 increases P_{LH}
  - Past results imply rotation braking is not the root cause
  - Suggests edge magnetic field perturbation alters L-H dynamics
- No variation in P_{LH} with He
  - Reported $P_{LH,He}$: 1 - 1.8 times $P_{LH,D}$ in database
- Lithium wall conditioning appears to lower P_{LH}

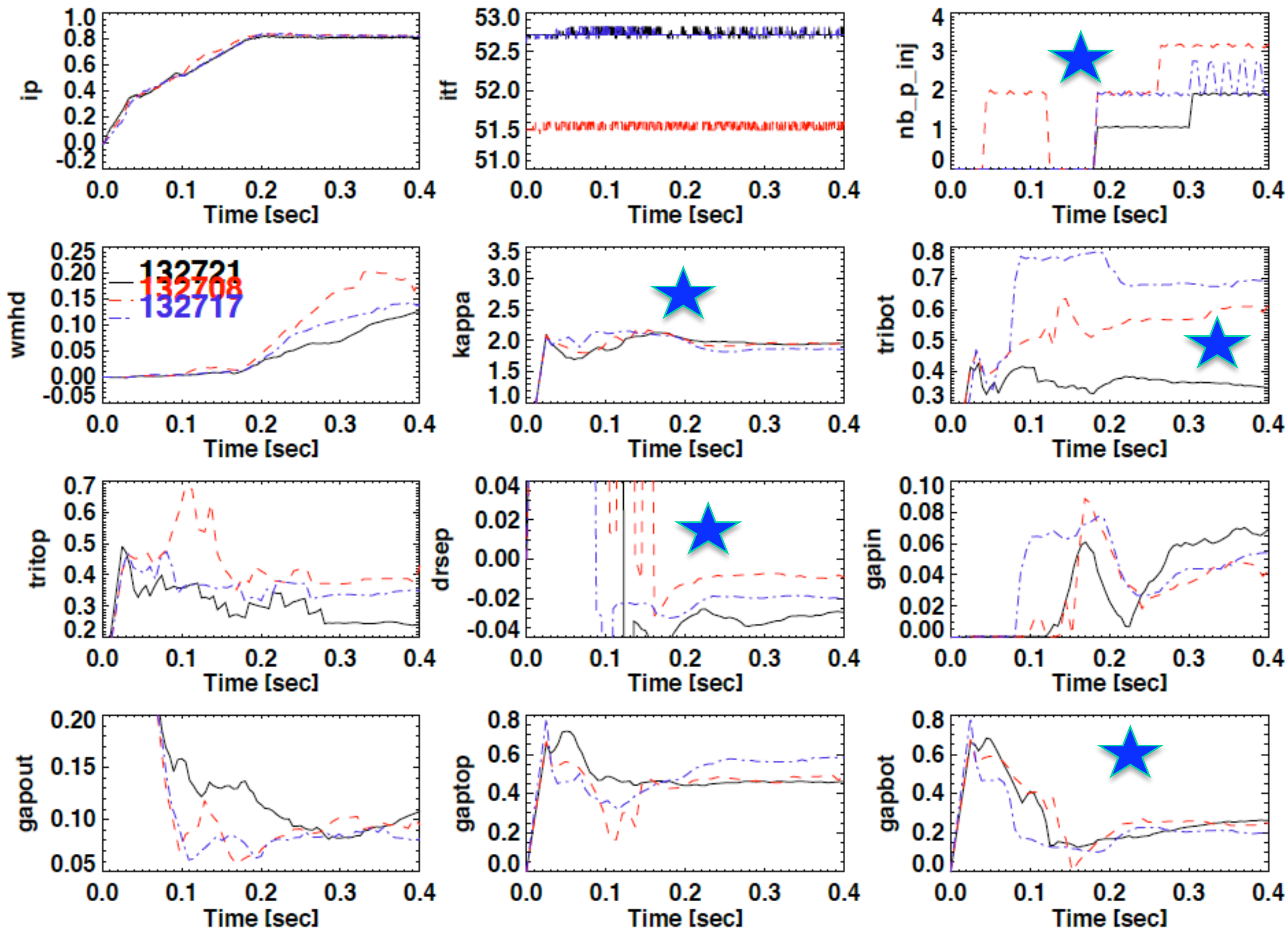
Backup Slides

•Three X-point radii and triangularities achieved

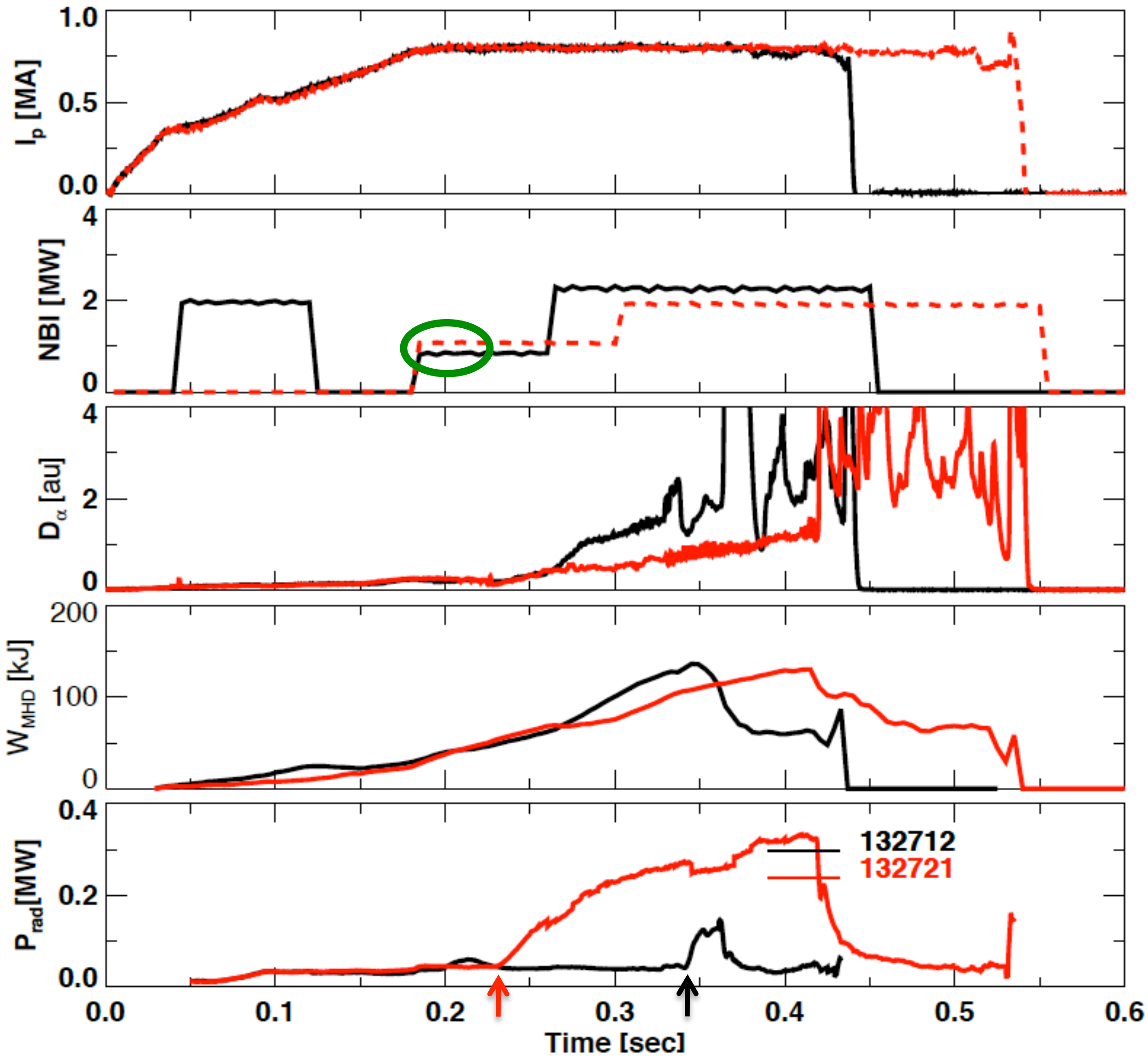


•κ, bottom gap relatively well matched at 0.2 s, but δ_r^{sep} different

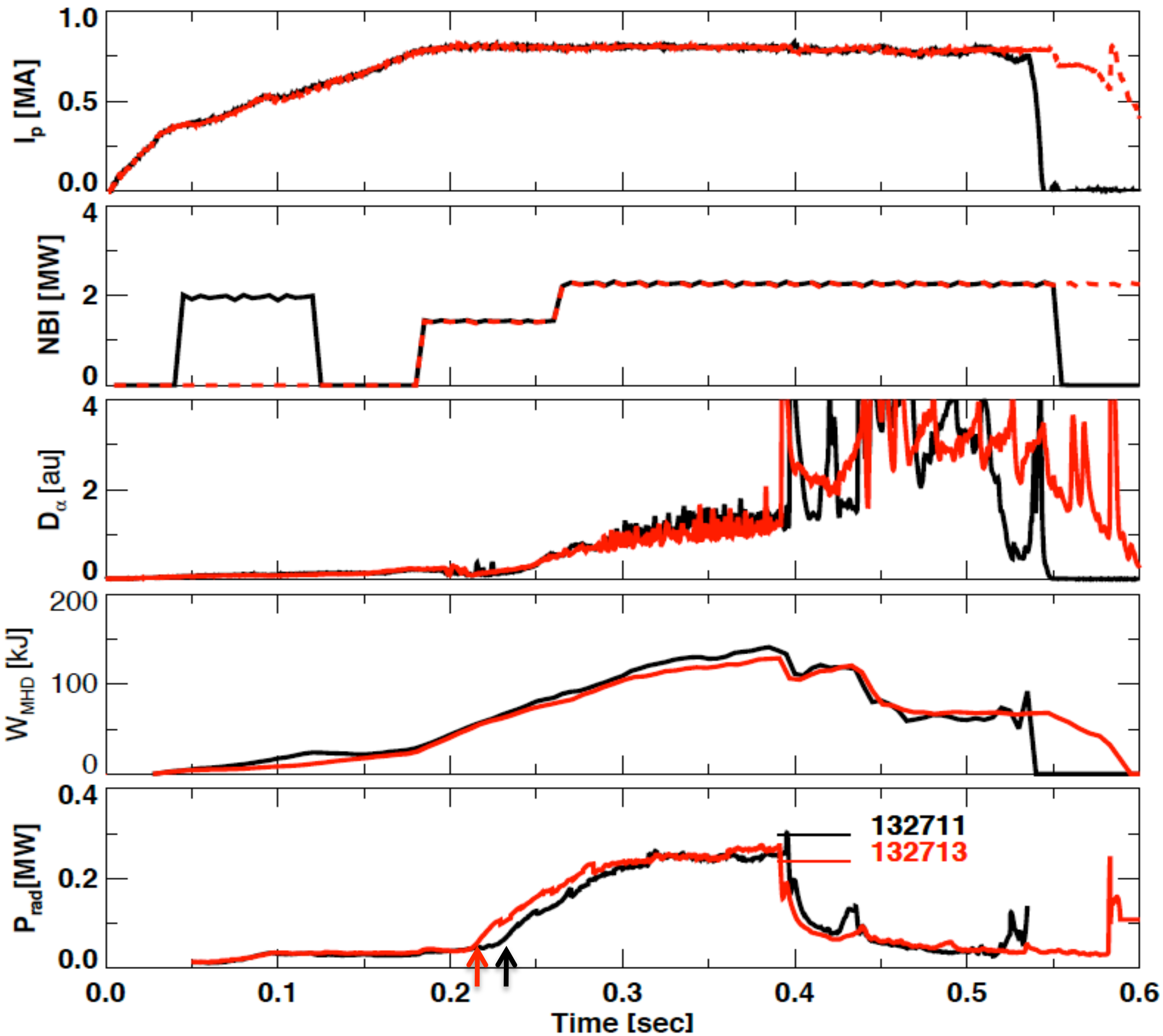
•P_{LH}^{NBI} lowest for $\delta_L \sim 0.4$ and comparable for higher δ_L



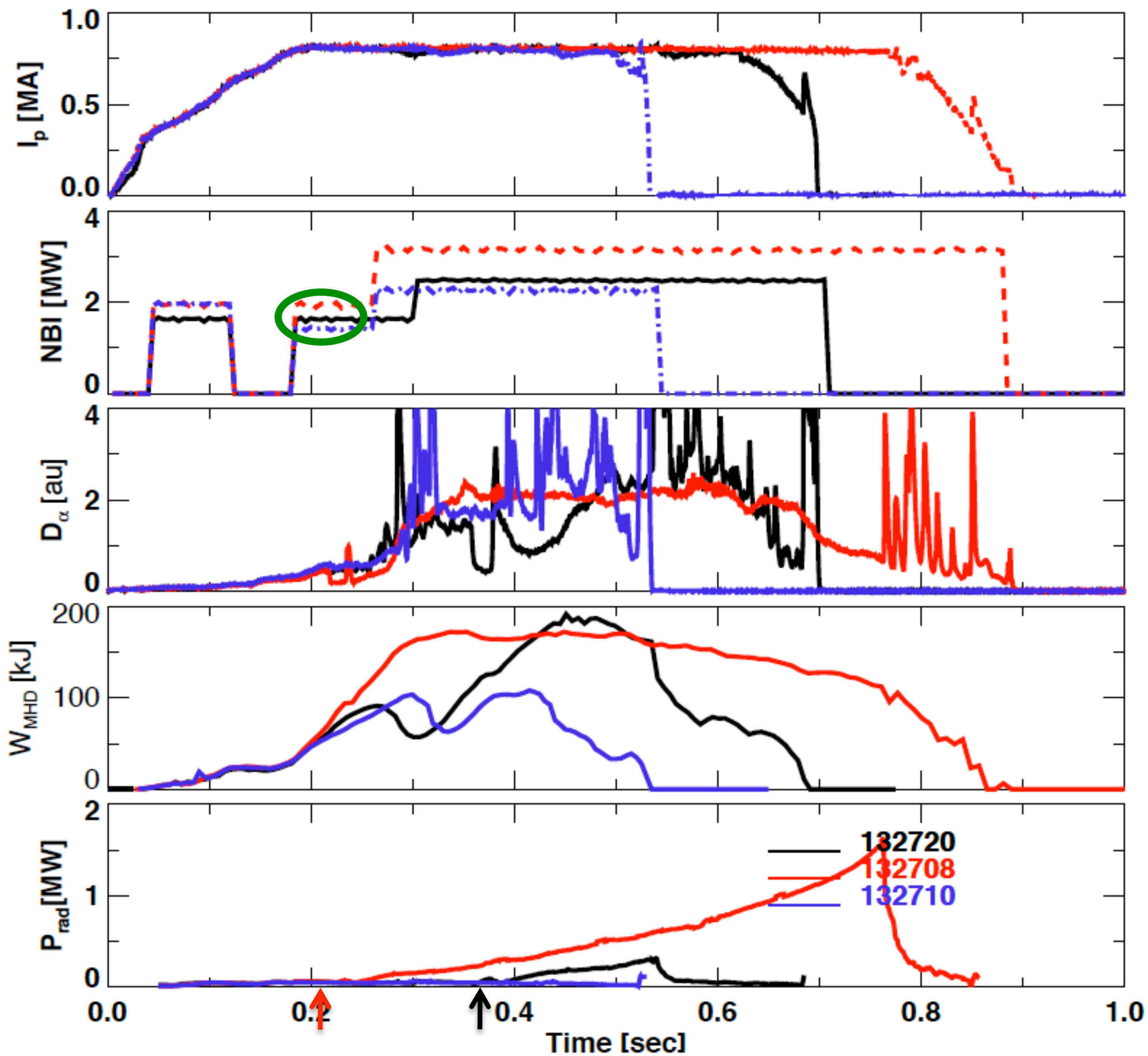
•Low δ_L~ 0.4 has P_{LH}^{NBI} < 1.1 MW



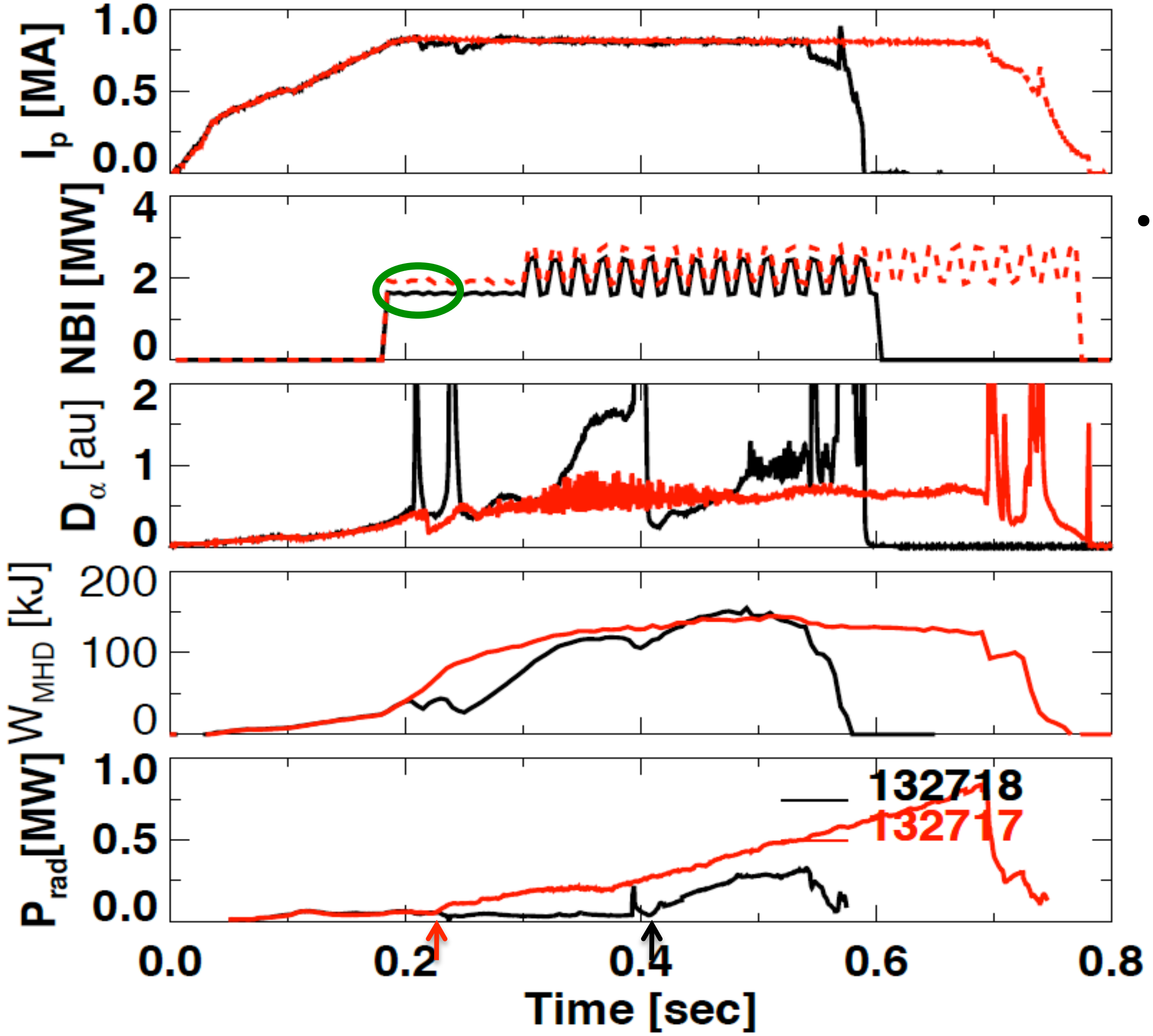
•Early heating does not affect P_{LH}^{NBI} (Low $\delta_L \sim 0.4$)



•Medium $\delta_L \sim 0.55$ has $P_{LH}^{NBI} \leq 2$ MW



•High $\delta_L \sim 0.7$ also has $P_{LH}^{NBI} \leq 2$ MW



- Locked modes affected LH timing in 132718

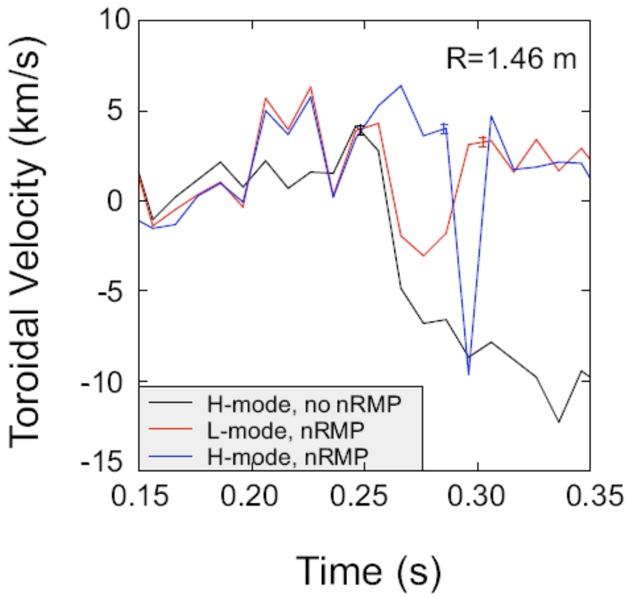
XP956: Reversed TF Results

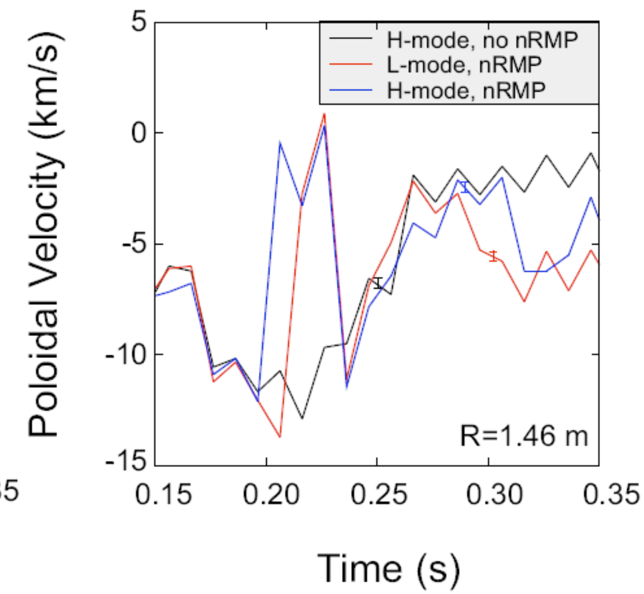
- D^+ plasmas with NBI used in this study
- USN vs LSN, no Li vs Li @ 200 mg/shot (4 cases)
- Have not yet done TRANSP calcs for P_{heat}, etc.
- Li has very strong effect, even in unfavorable ∇B drift direction

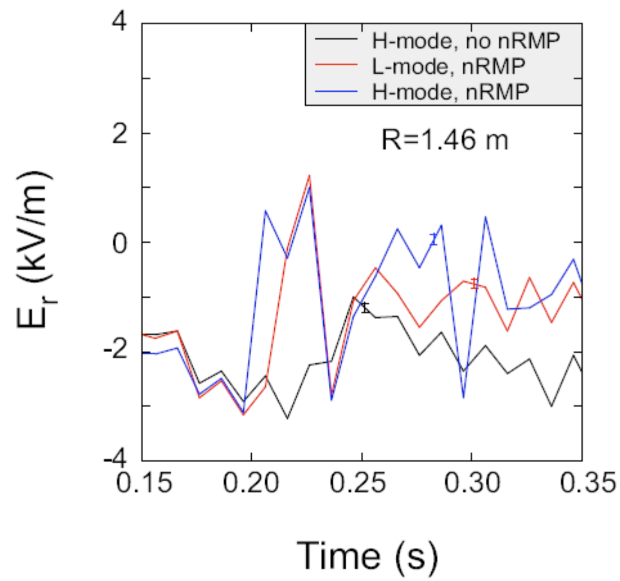
P_{inj}	USN	LSN
No Li	2.5 – 3.0 MW	2.9 – 3.2 MW
Li	0.4 – 0.6 MW	1.15 – 1.75 MW

•Similar to LSN with normal TF

Rotation/E_r shows Little Obvious Difference Between L and L→H



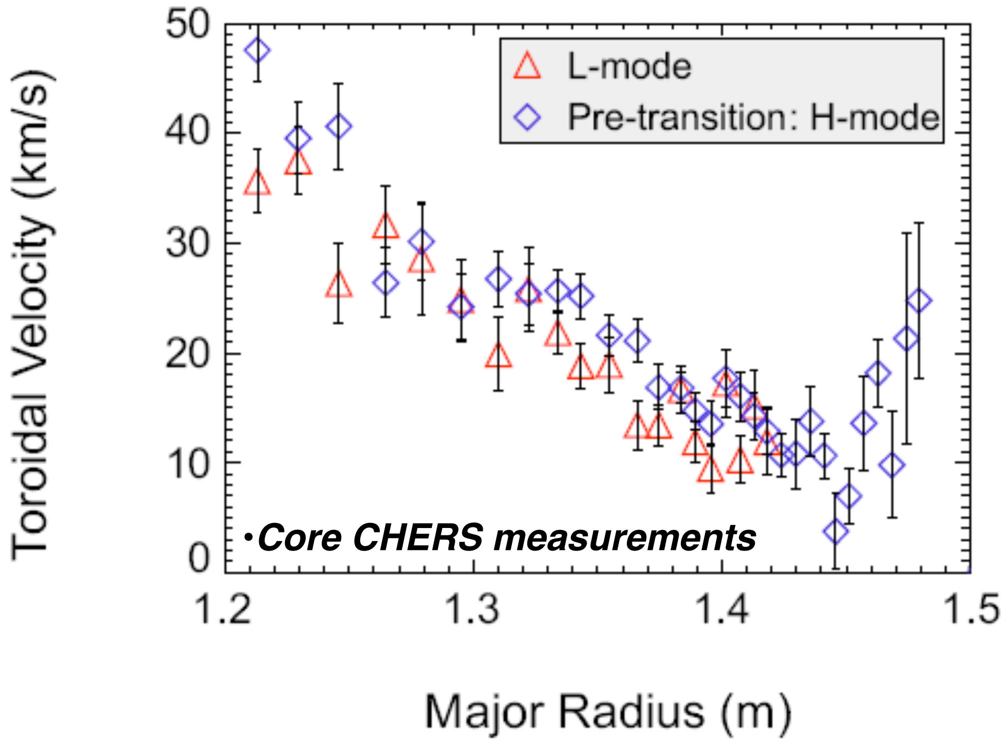




•3D effects appear to influence L-H threshold even in the absence of significant differences in rotation

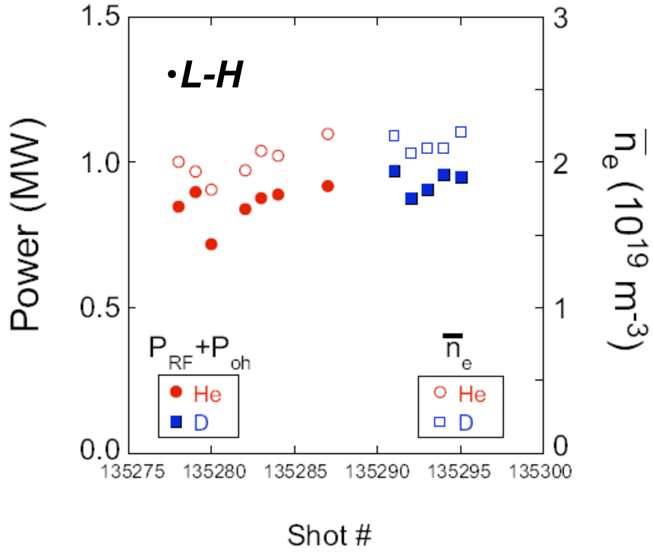
Rotation differences do not appear to play a major role

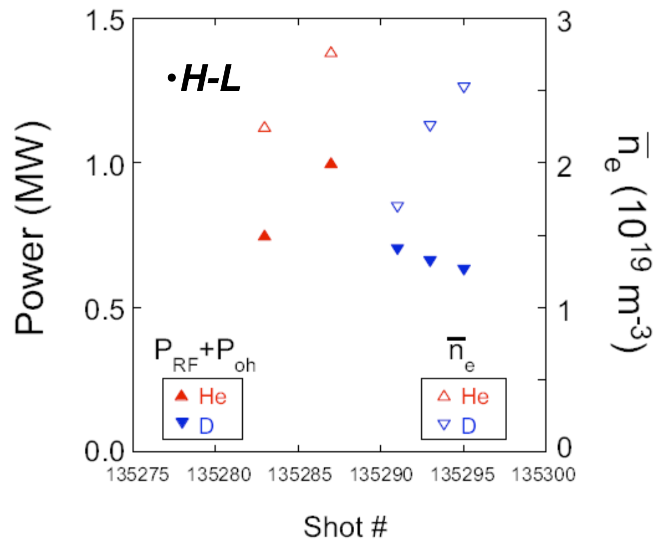
- Any difference in rotation does not appear to be key
  - Consistent with earlier RF vs NBI threshold expts.

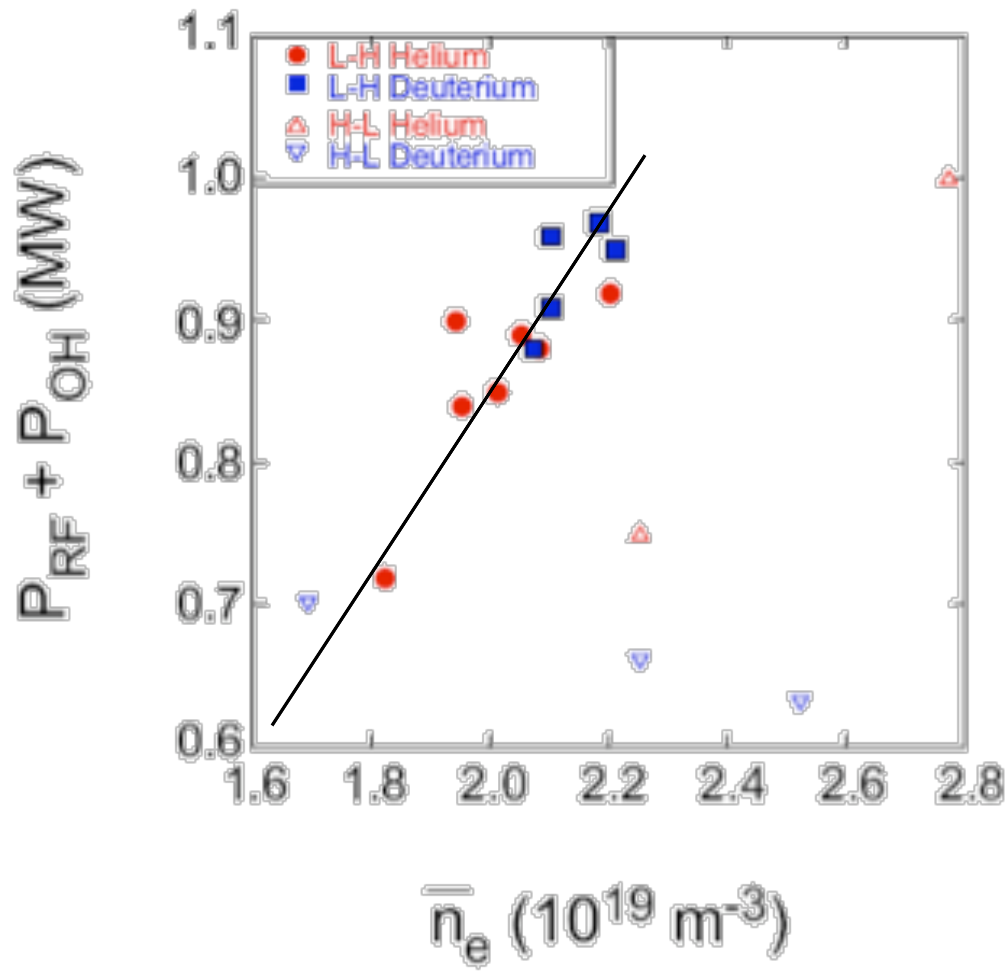


•How should I explain this?

L-H Transition Powers Linearly Dependent on Density; Not True for H-L Transitions







Lithium evaporation produced plasmas with long ELM-free durations

- 200 mg of Lithium evaporated between shots
- P_{NB} from 2 to 6 MW (H-mode accessible with P_{NB}<2 MW with Lithium)