H-mode Access and Pedestal Characteristics at High Magnetic Field (7.8 T) in Alcator C-Mod Discharges

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H-mode at high B (7.8 T) merits increased analysis

- High magnetic field tokamak concepts (e.g. ARC, 9.2 T [1]) create a path to compact, less expensive reactors
- Experience with tokamak operation predominantly developed at lower magnetic field and lower values of pedestal pressure
- Set of experiments in last Alcator C-Mod run campaign elucidate behavior of:
  - I-mode at 7.8 T [2]
  - Super H-mode at 5.4 T— J.W. Hughes, Wednesday A.M.
  - H-mode threshold power at 7.8 T
  - H-mode regime access at 7.8 T
  - Pedestal parameters (height, width) at 7.8 T
- Results seen to be broadly consistent with experience at lower field

[1] B. Sorbom, et al., Fusion Engineering and Design 100, 378 (2015).
[2] A. E. Hubbard, et al., submitted to Nuclear Fusion

H-mode Threshold Power at 7.8 T

H-mode threshold physics depends on B

- L-H confinement transition occurs at threshold value, P_{th}, of loss power:

$$P_{Loss} = P_{OH} + P_{AUX} - \frac{dW_{MHD}}{dt}$$

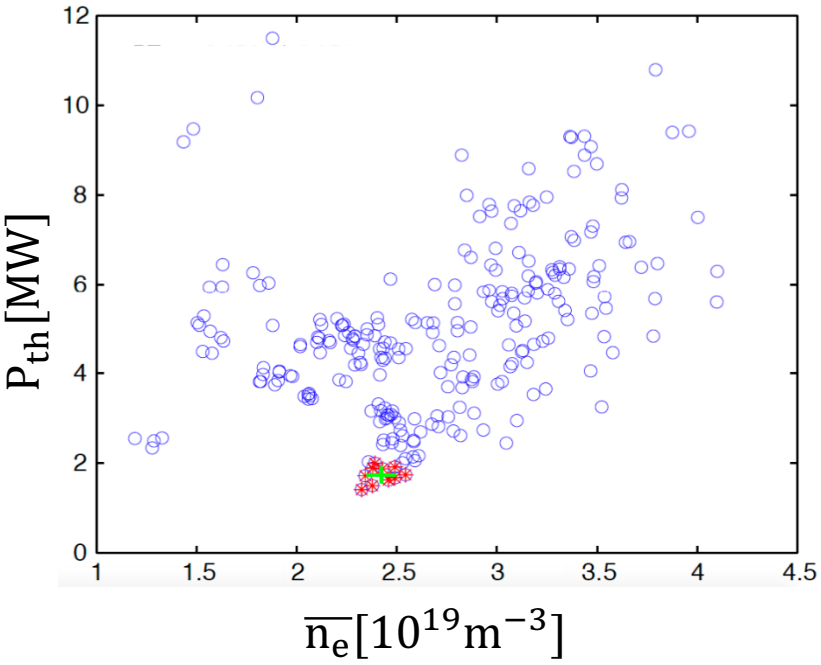
- ITPA scaling reads [1]:

$$P_{th} \sim {n_e}^{0.7} B^{0.8} S^{0.9}$$

- At fixed B and size, "low density branch" where P_{th} increases below characteristic value $n_{th,min}$:
  - E_r well is created by ion pressure gradient, but electrons are preferentially heated
  - Ryter scaling law for location of $n_{th,min}$ reads [2]:

$$n_{th,min}[10^{20}\, m^{-3}] \approx .07 I_p^{0.34} B_T^{0.62} a^{-0.95} \left(R/a\right)^{0.4}$$

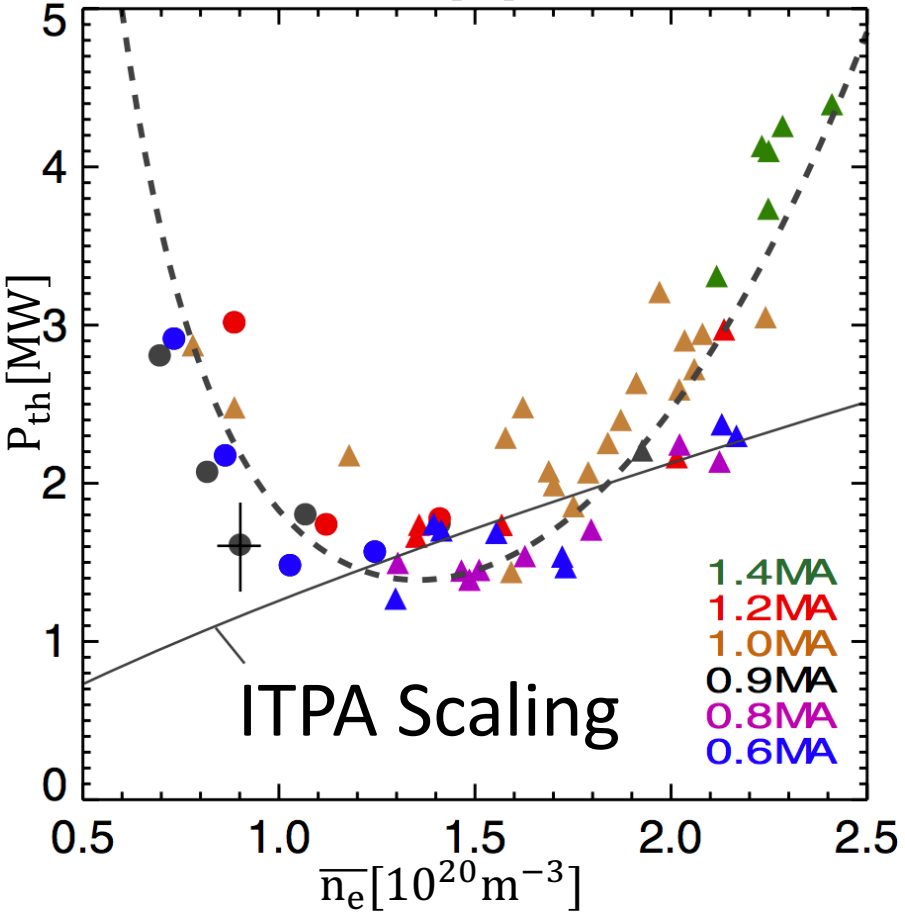
$P_{th}(\overline{n_e})$ for JET shots from 2.5 to 2.8 T [1]



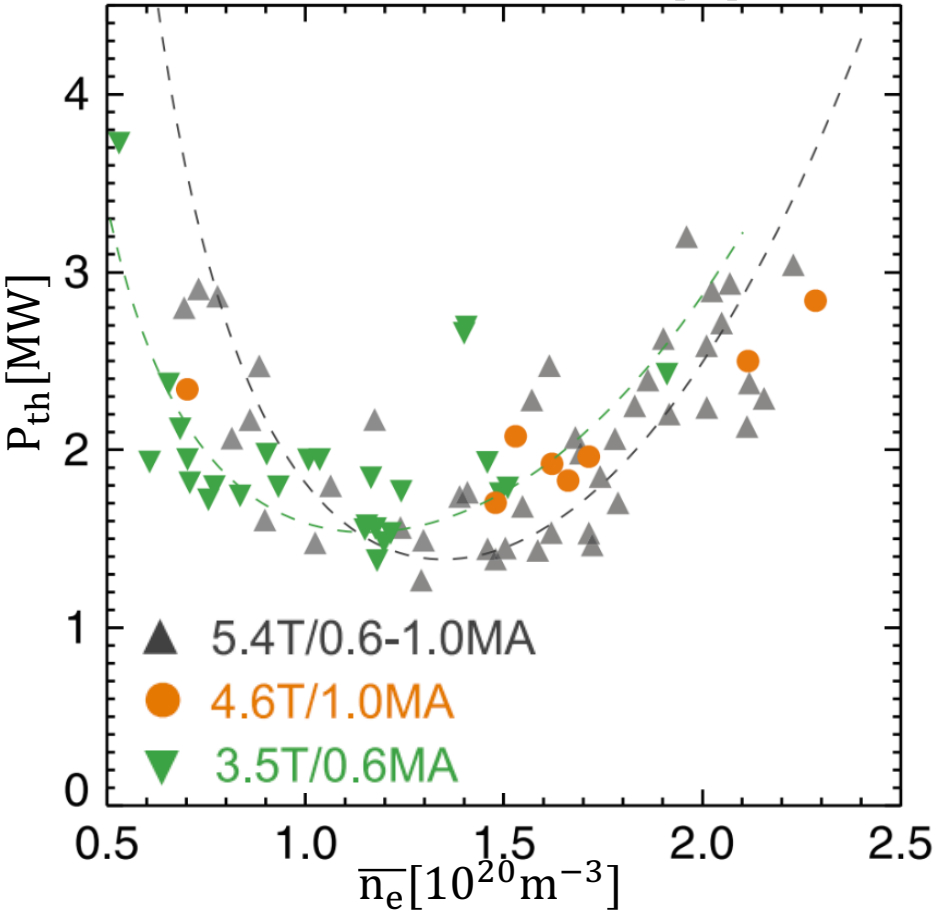
[1] Y.R. Martin, et. al., J. Phys.: Conf. Ser., 123 (2008).
[2] F. Ryter, et. al., Nuclear Fusion 54 (2014).

Previous C-Mod work at lower B explores scaling law behavior

$P_{th}(\overline{n_e})$ for C-Mod shots at 5.4 T [1]



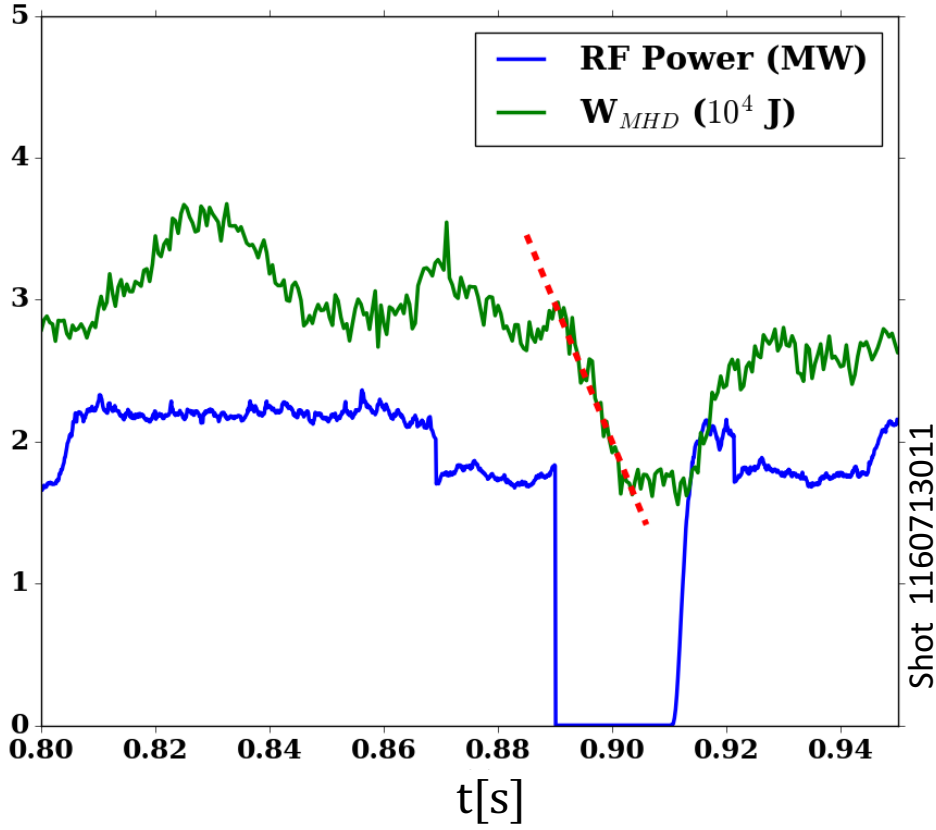
$P_{th}(\overline{n_e})$ for C-Mod shots at 3.5, 4.6, 5.4 T [1]



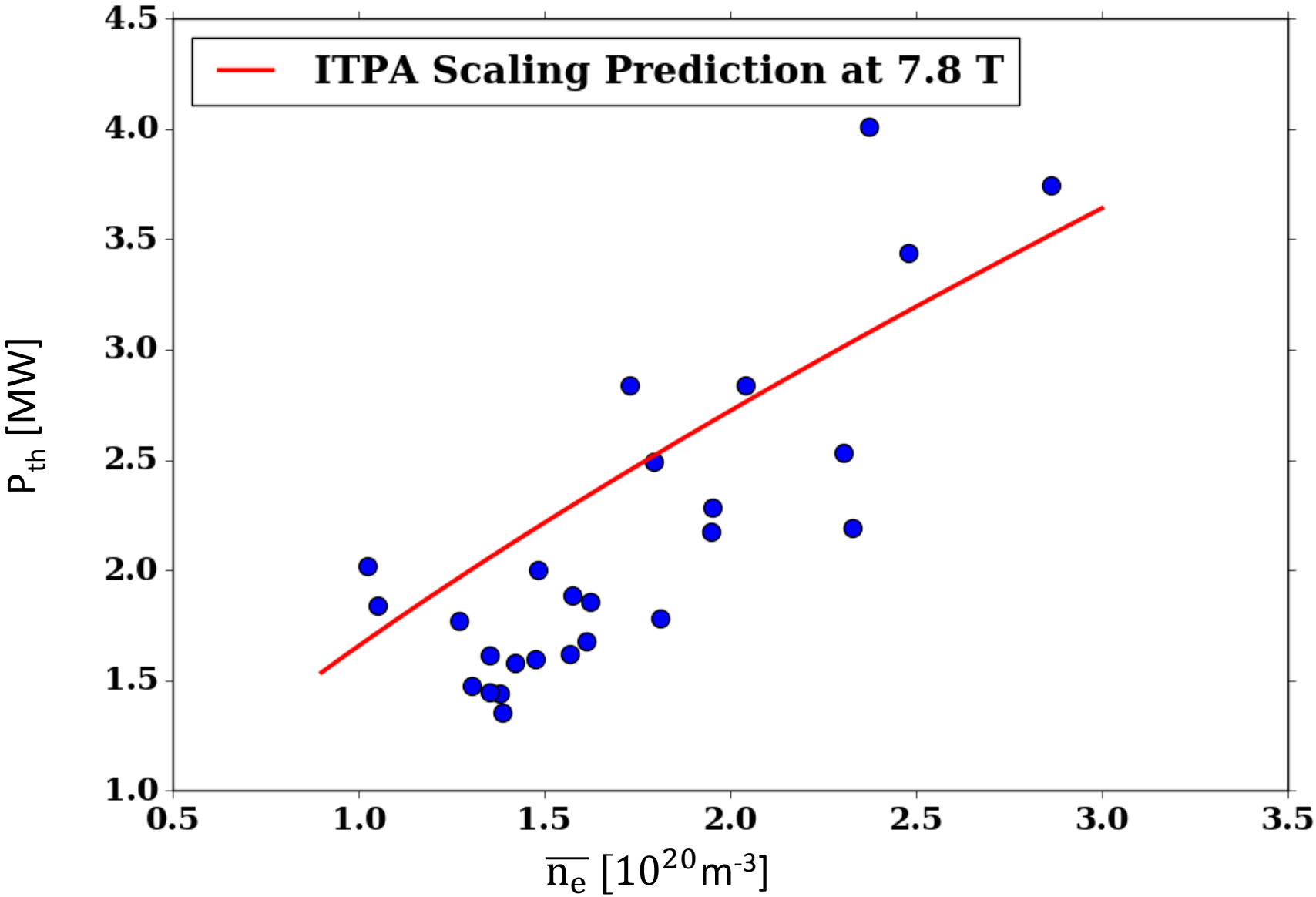
[1] Y Ma, et. al., Nuclear Fusion 52, 378 (2012).

Set of shots at 7.8 T analyzed to determine P_{th}

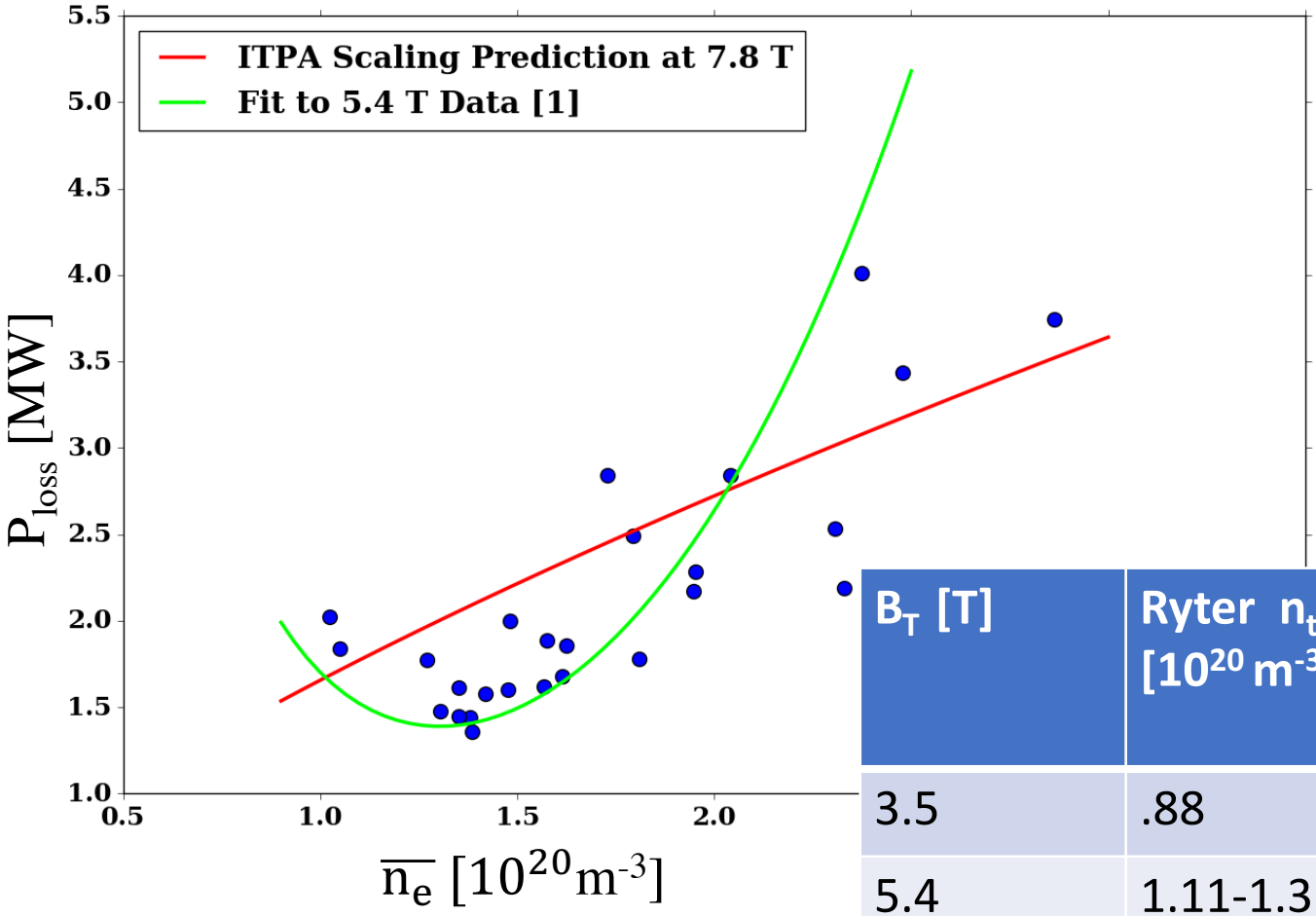
- Set of 26 shots from 2016 run campaign at 7.8 T analyzed to determine $P_{Loss} = P_{OH} + P_{AUX} - \frac{dW_{MHD}}{dt}$ at time of L-H transition
- All shots LSN with ion grad-B drift towards X-point
- High B operation requires lower-efficiency D(He^3) ICRF heating
- Efficiency estimated by using notch in ICRF power during L-mode
- $\eta_{RF} = \frac{dW_{MHD}/dt}{\Delta P_{RF}}$ = .5
- $P_{AUX} = \eta_{RF} P_{RF}$



H-mode transitions at 7.8 T occur near ITPA scaling



$n_{th,min}$ at 7.8 T lower than Ryter prediction; similar to 5.4 T value



B_T [T]	Ryter $n_{th,min}$ [10^{20} m^{-3}] [2]	Experiment $n_{th,min}$ [10^{20} m^{-3}]
3.5	.88	1.1 [1]
5.4	1.11-1.32	1.3 [1]
7.8	1.60-1.76	<1.5

[1] Y Ma, et. al., Nuclear Fusion 52, 378 (2012).
[2] F. Ryter, et. al., Nuclear Fusion 54 (2014).

7.8 T data can guide extrapolations to higher B

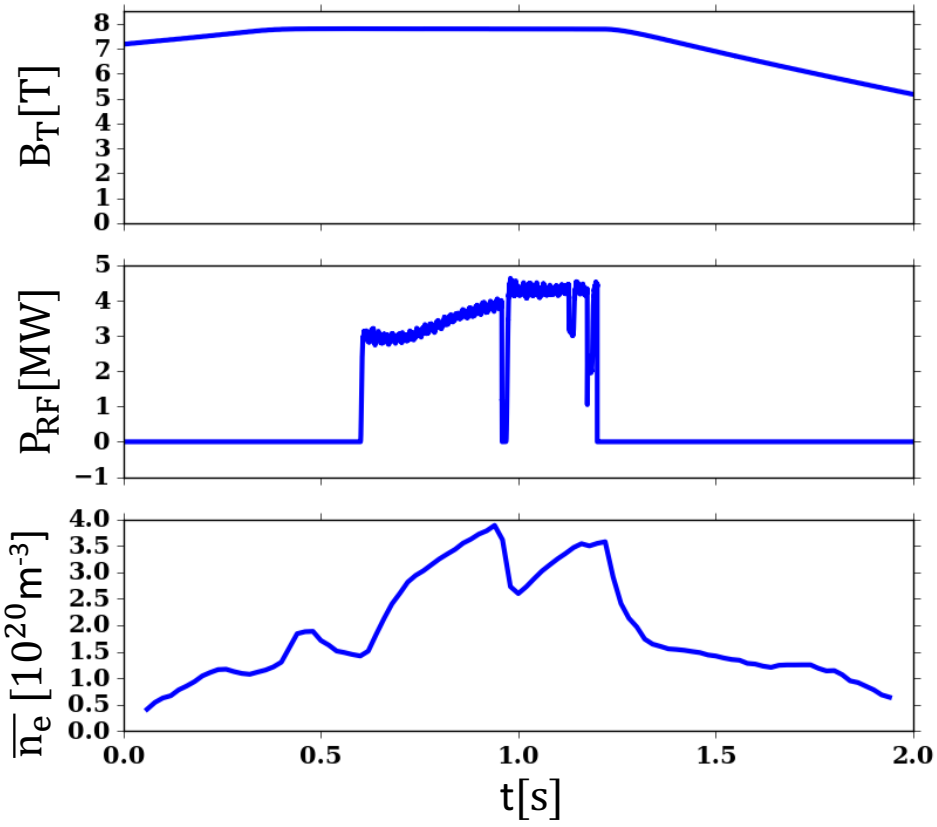
- ITPA scaling law well represents data at 7.8 T, and some parts of lower field data
- $n_{th,min}$ seen to increase weakly with magnetic field on C-Mod

[1] Y Ma, et. al., Nuclear Fusion 52, 378 (2012).

H-mode regime access at 7.8 T

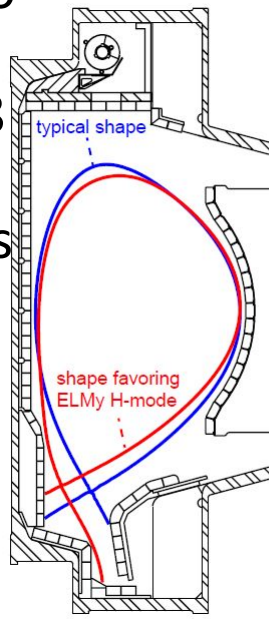
Standard 7.8 T H-mode was non-stationary ELM-free

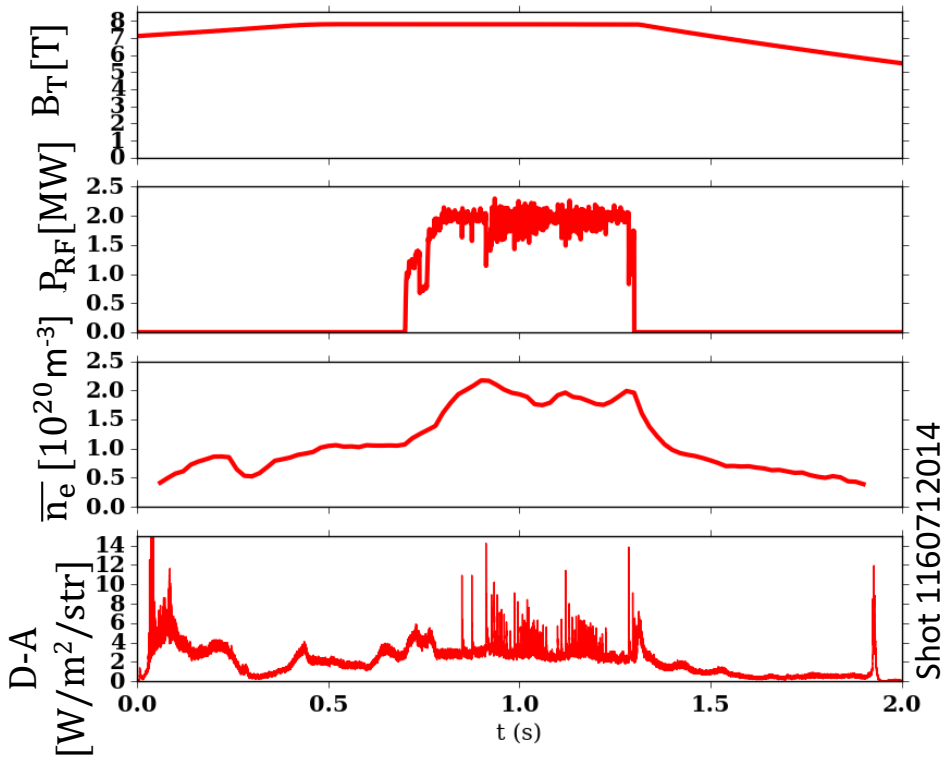
- ELM-free H-modes routinely obtained across all C-Mod fields
- These H-modes exhibit a continual rise in density and temperature ending in radiative collapse



ELMy H-modes extended to 7.8 T

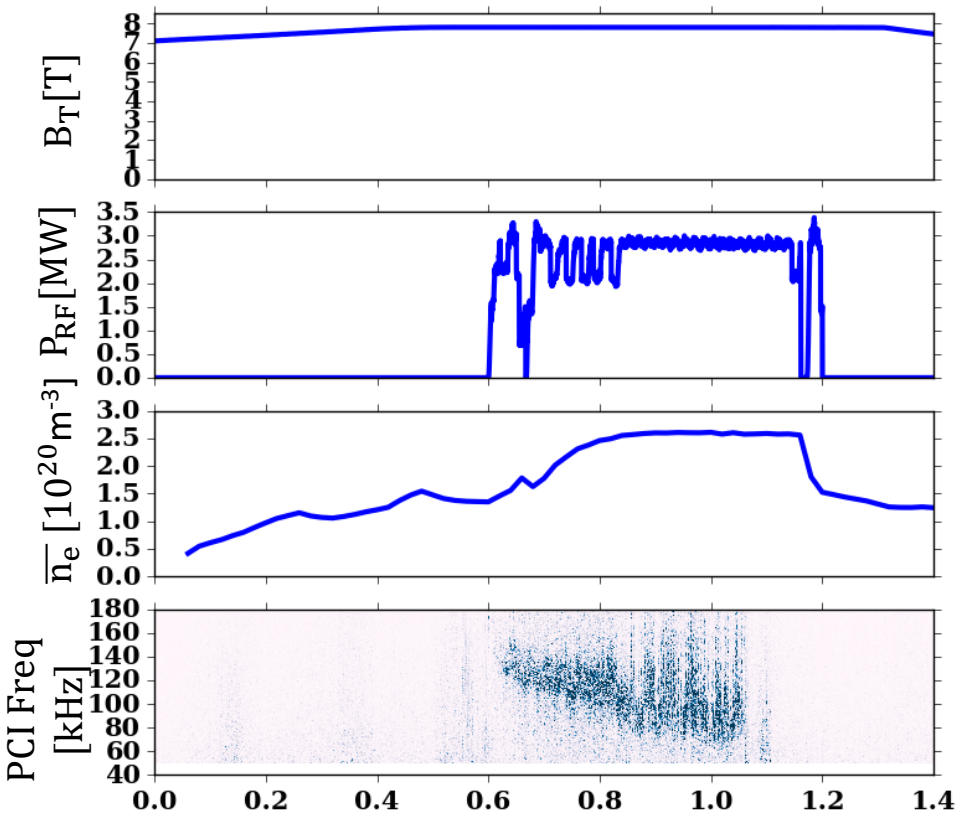
- ELMy H-Modes difficult to obtain on C-Mod
- Limited ELMy shots at 7.8 T prior to 2016 campaign
- Additional ELMy H-modes obtained at 7.8 T in 2016
- Weakly shaped equilibrium with divertor strike point used to optimize ELMy H-mode access



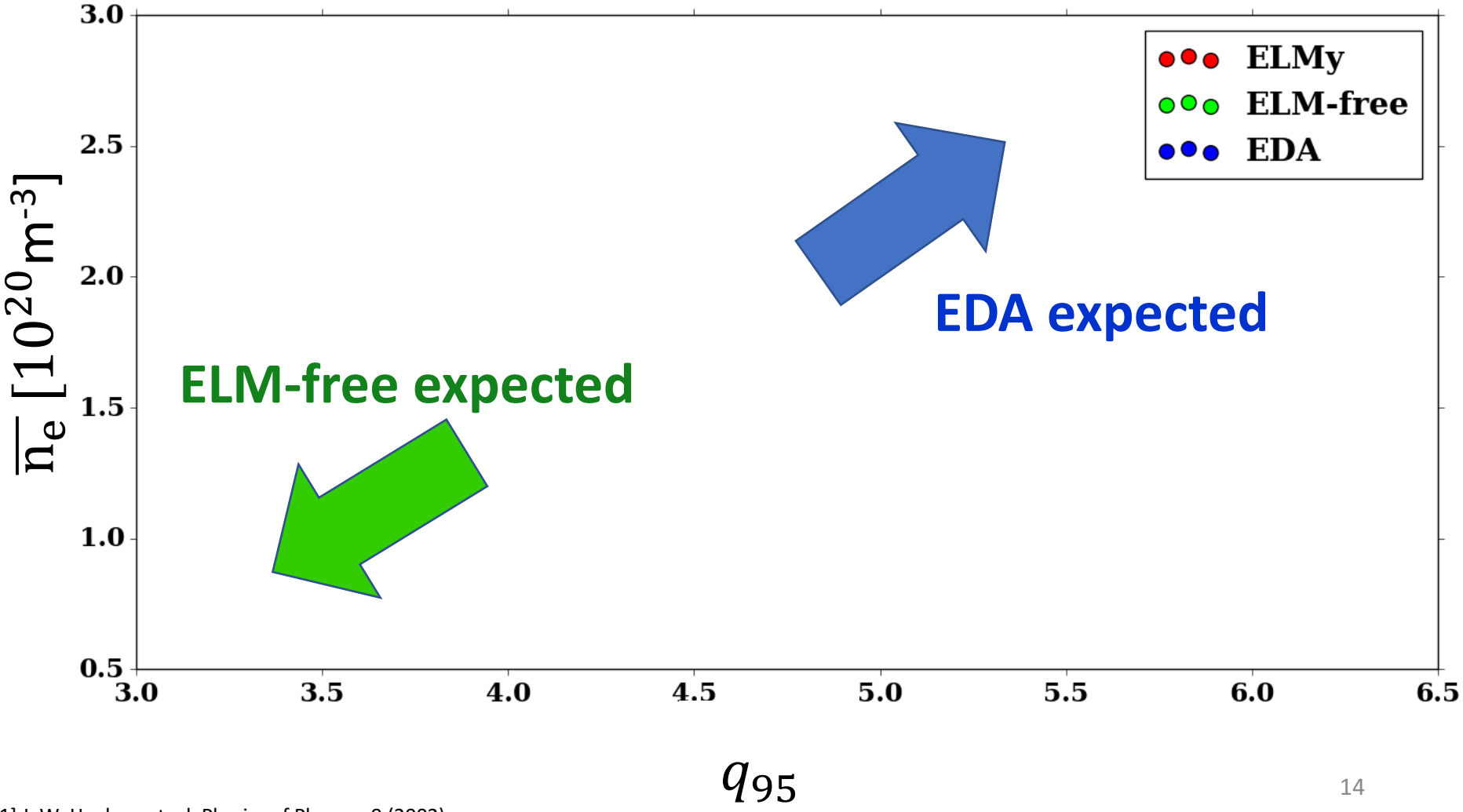


Stationary, ELM-suppressed EDA H-modes extended to 7.8 T

- C-Mod observes the steady state EDA (Enhanced D_α) H-mode at high density and q_{95}
- EDA characterized by quasi-coherent mode (QCM)
- EDA H-Mode obtained at high density
  - Elevated P_{th} creates heating challenges at high magnetic field
- First confirmed EDA H-mode at 7.8 T obtained in 2016



Operating space of H-mode regimes at 7.8 T follows lower-B intuition



[1] J. W. Hughes, et. al, Physics of Plasmas 9 (2002)

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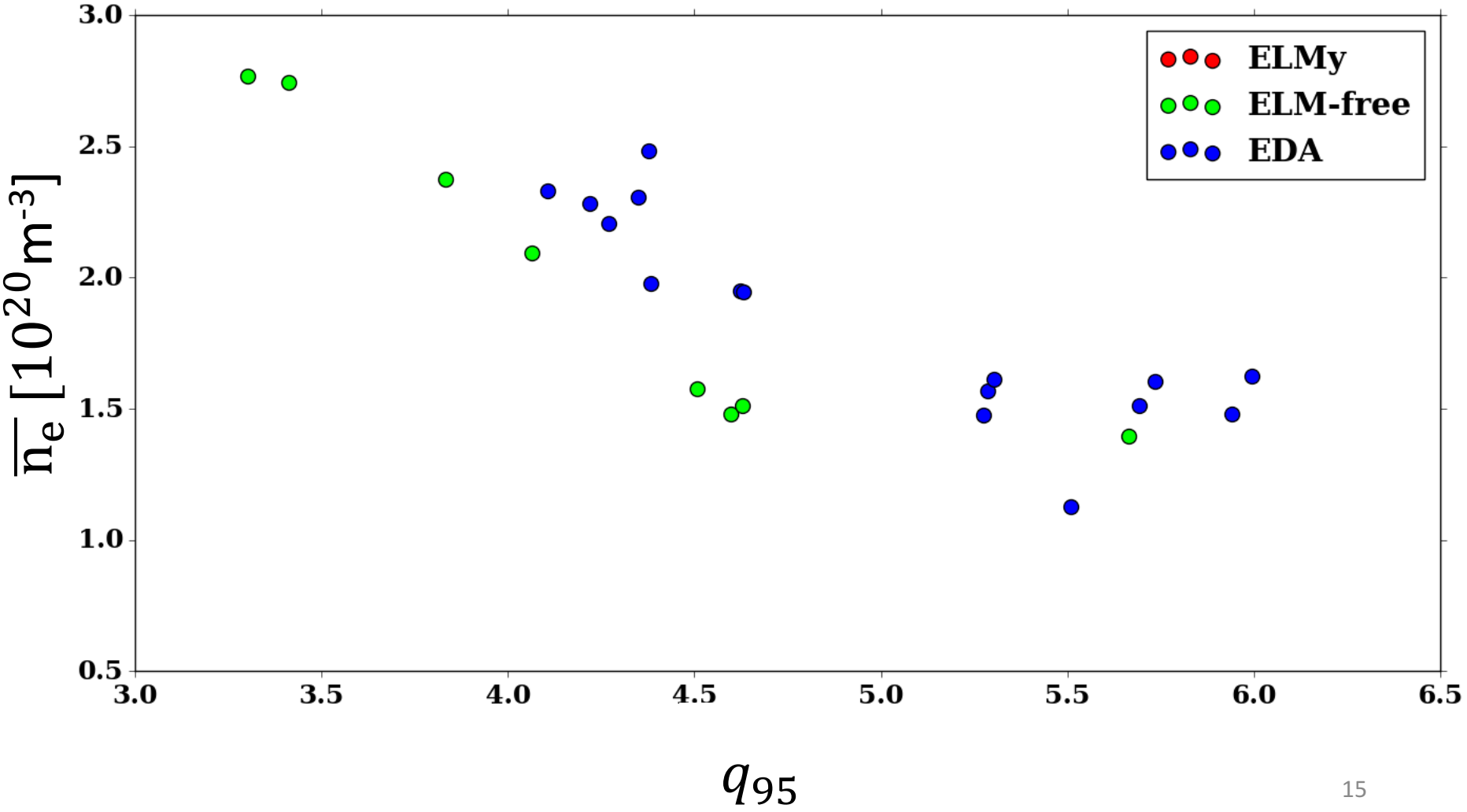

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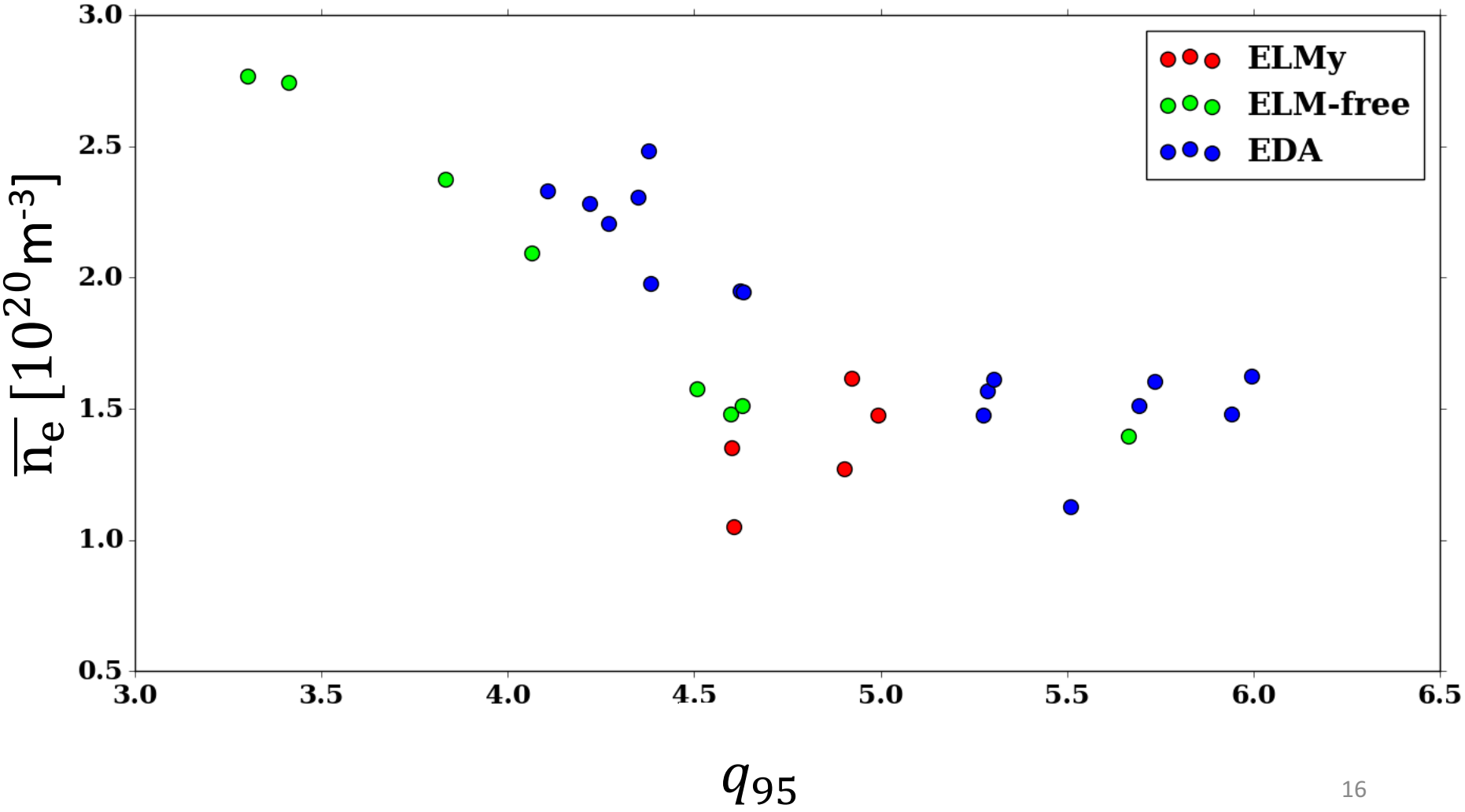


H-mode pedestal characteristics at 7.8 T

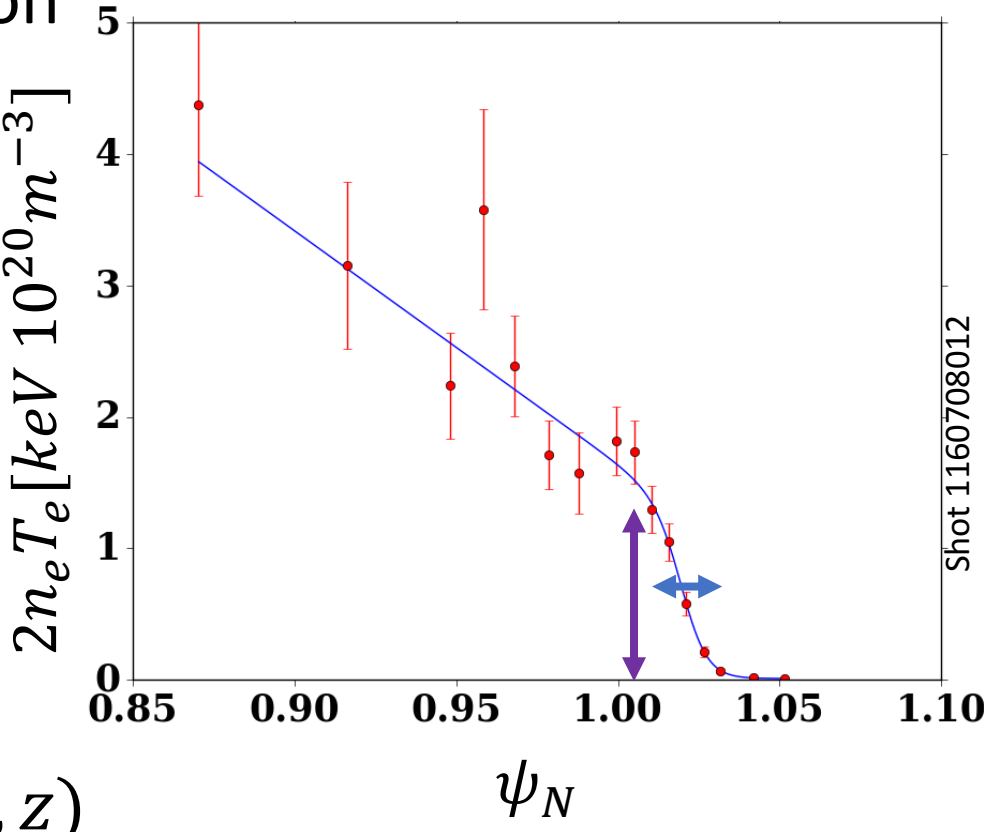
Pedestal structure quantified using mtanh function

- In order to consistently define pedestal location, width, and height, and baseline, Thomson profiles are fit with:

$$z(r) = \frac{r_0 - r}{\Delta/2}$$

$$mtanh(\alpha, z) = \frac{(1 + \alpha z)e^{z} - e^{-z}}{e^{z} + e^{-z}}$$

$$y(z) = \frac{b+h}{2} + \frac{h-b}{2} mtanh(\alpha, z)$$



ELMy H-mode pressure pedestals constrained by stability

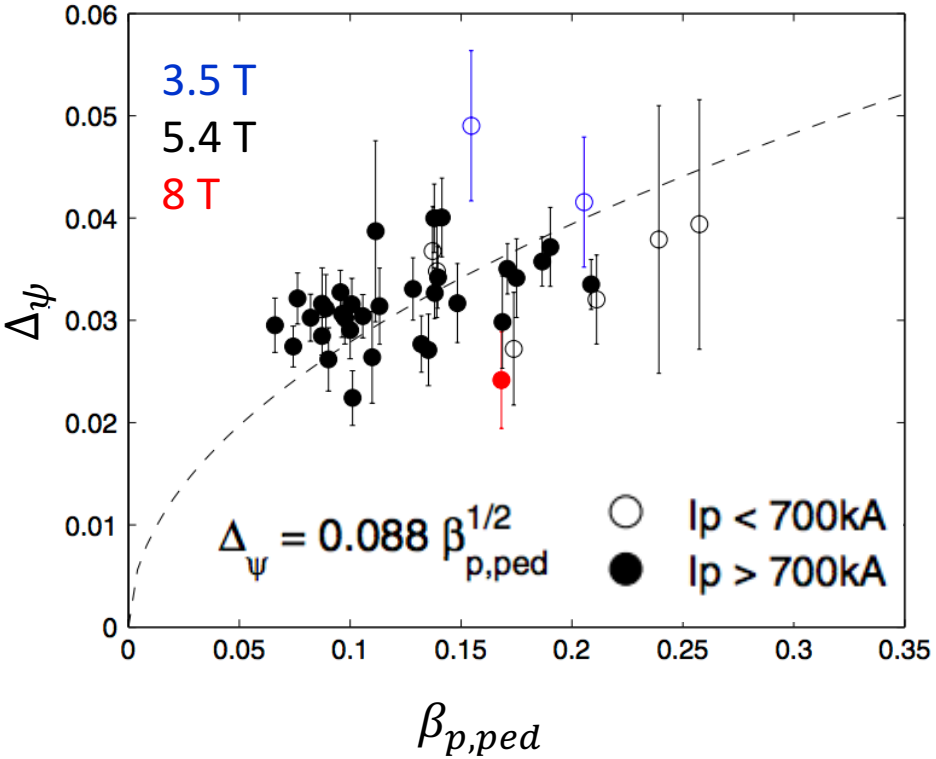
- Kinetic ballooning mode (KBM) onset condition gives condition constraining pedestal width [1]:

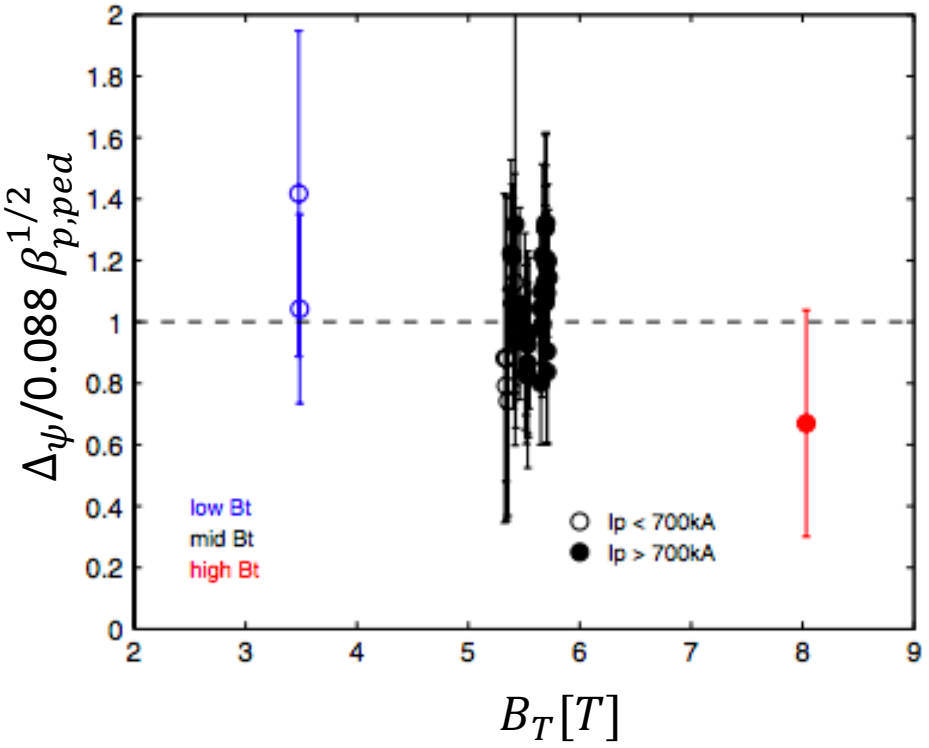
$$\Delta_\psi = c\beta_{p,ped}^{1/2}$$

$$\beta_{p,ped} = \frac{2n_{e,ped}T_{e,ped}}{\mu_0\langle B_p\rangle^2}$$

[1] P. Snyder, et. al., Physics of Plasmas, 16 (2009).

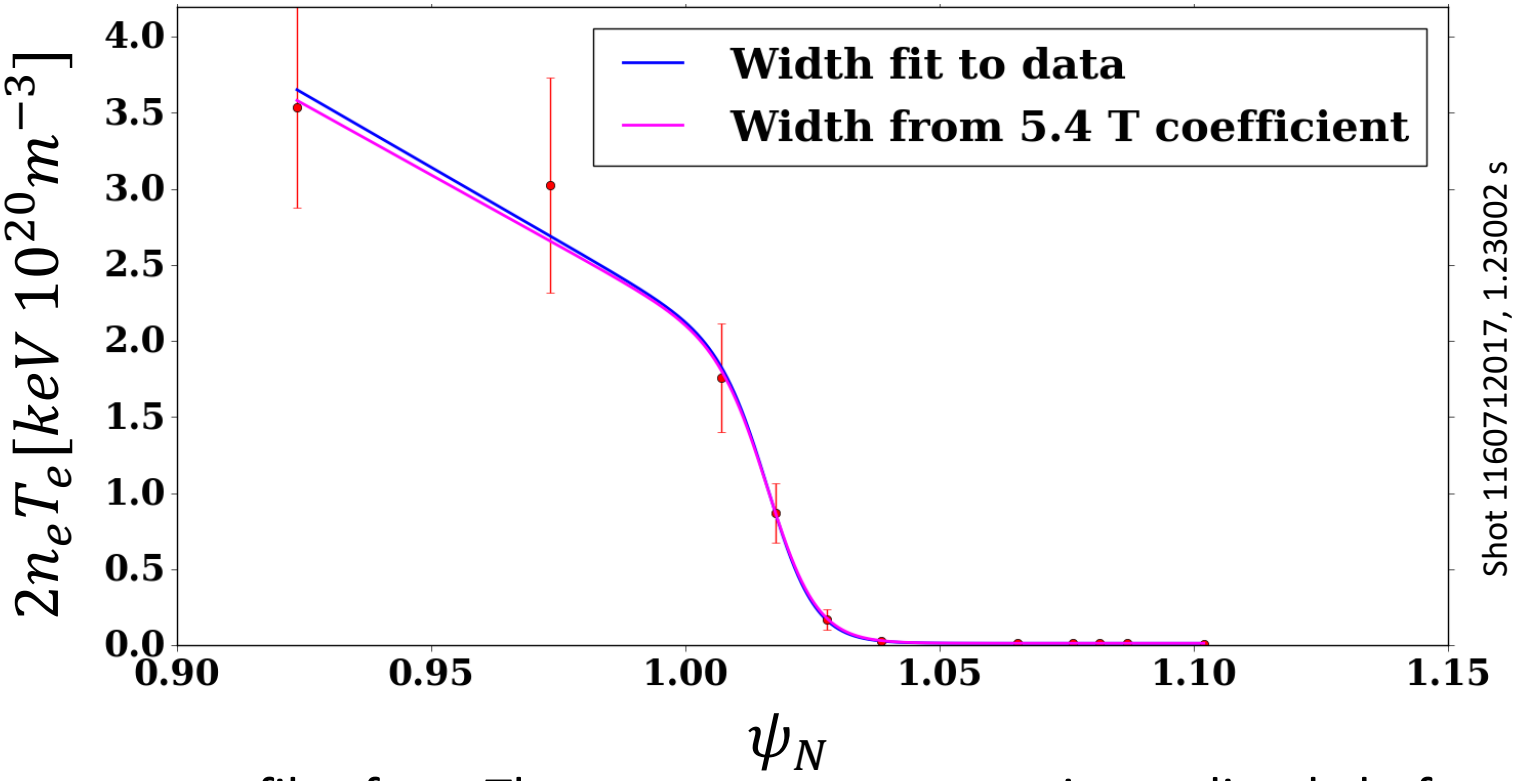
Limited previous data suggested narrowing of width at 7.8 T





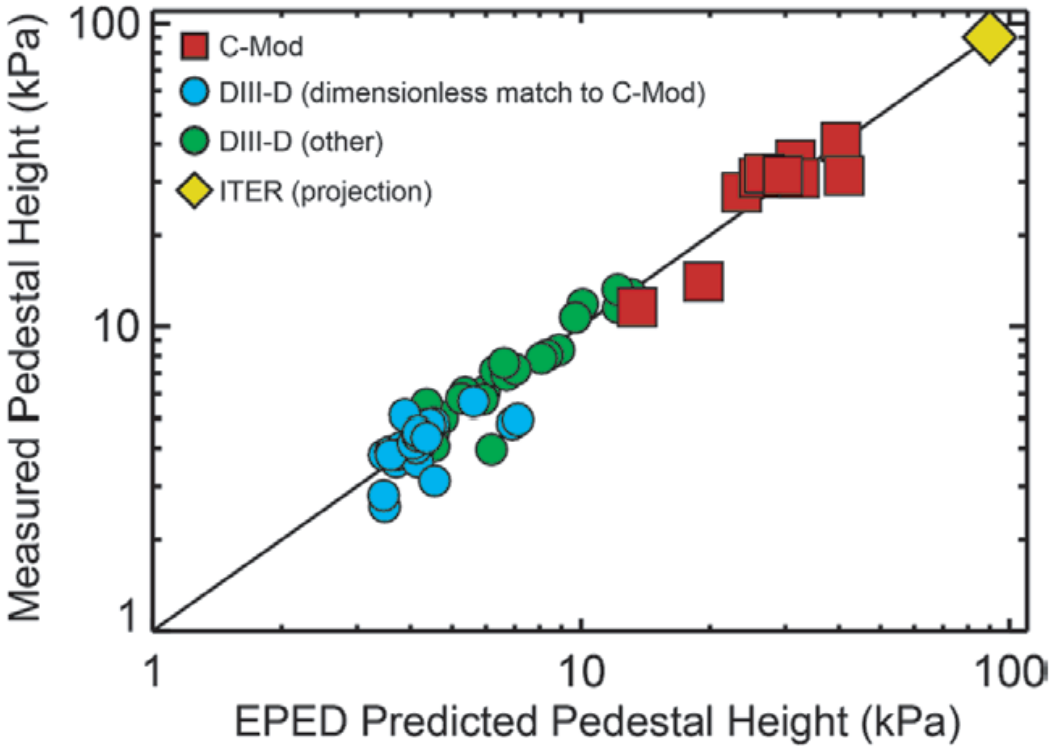
[1] J. Walk, et. al., Nuclear Fusion, 52 (2012).

Coefficient from 5.4 T shots fits 7.8 T data well



- Fit pressure profiles from Thomson measurements immediately before ELM in 7.8 T shots
- Width prediction using coefficient from data at mostly 5.4 T predicts the fit profiles at 7.8 T well
- Narrowing of pedestal suggested in previous work is not seen

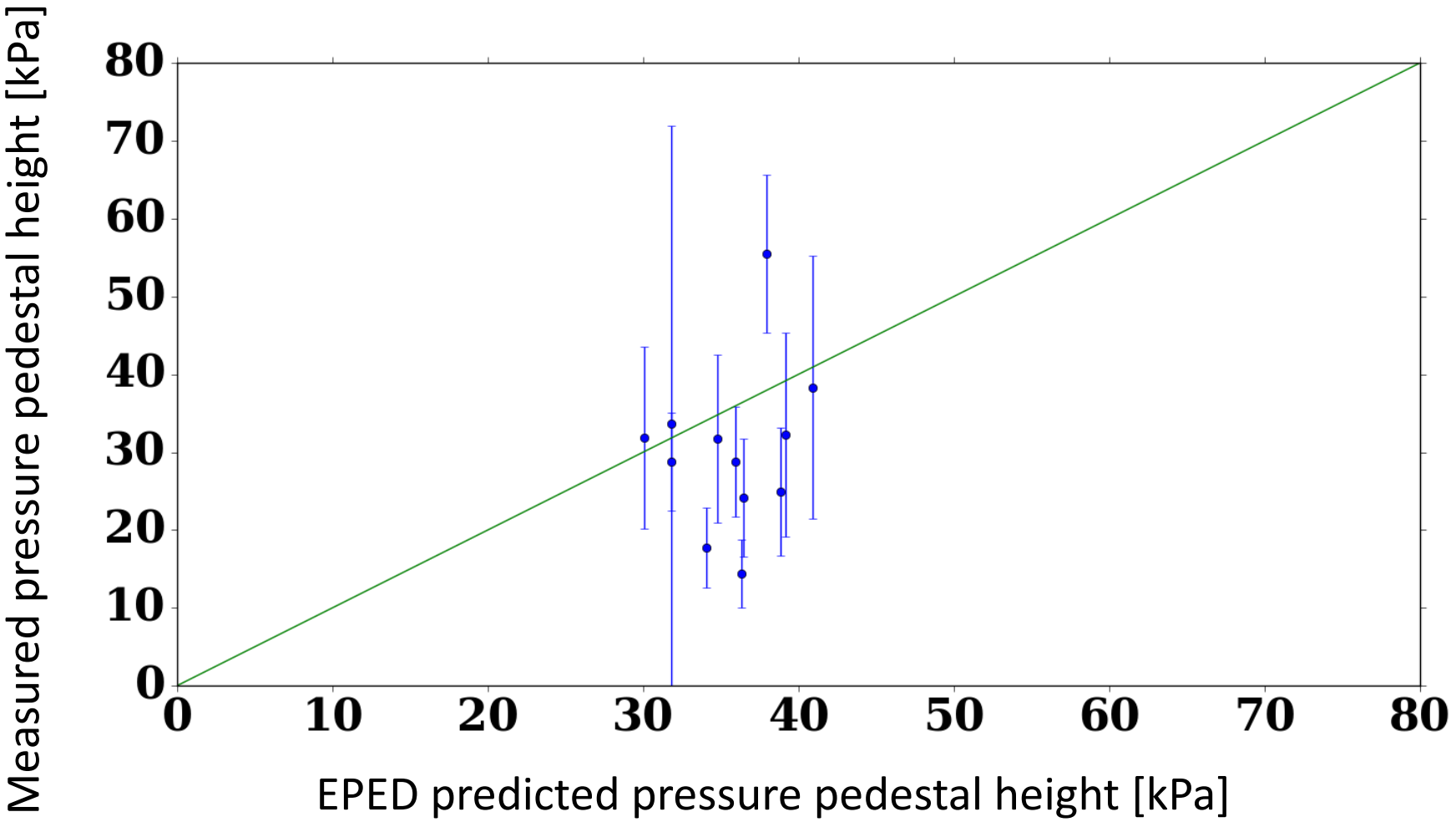
EPED couples KBM constraint with peeling-ballooning stability to predict pedestal



- EPED model couples KBM constraint with peeling ballooning-stability to predict pressure pedestal height— P. Snyder, Wednesday A.M.
- Previous work has compared EPED predictions with measured pressure up to 5.4 T [1]

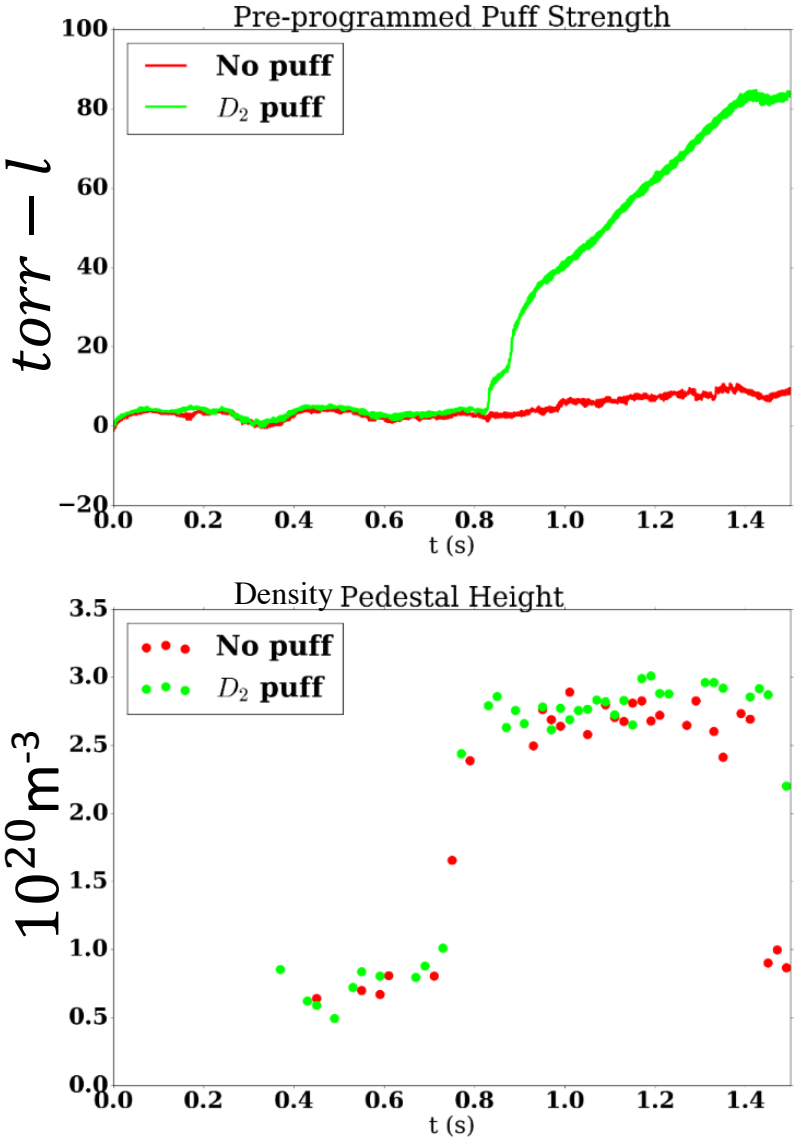
[1] J.W. Hughes, et al., Nuclear Fusion (2013).

Preliminary EPED results extend comparison to 7.8 T



EDA density pedestals determined by conditions before L-H transition

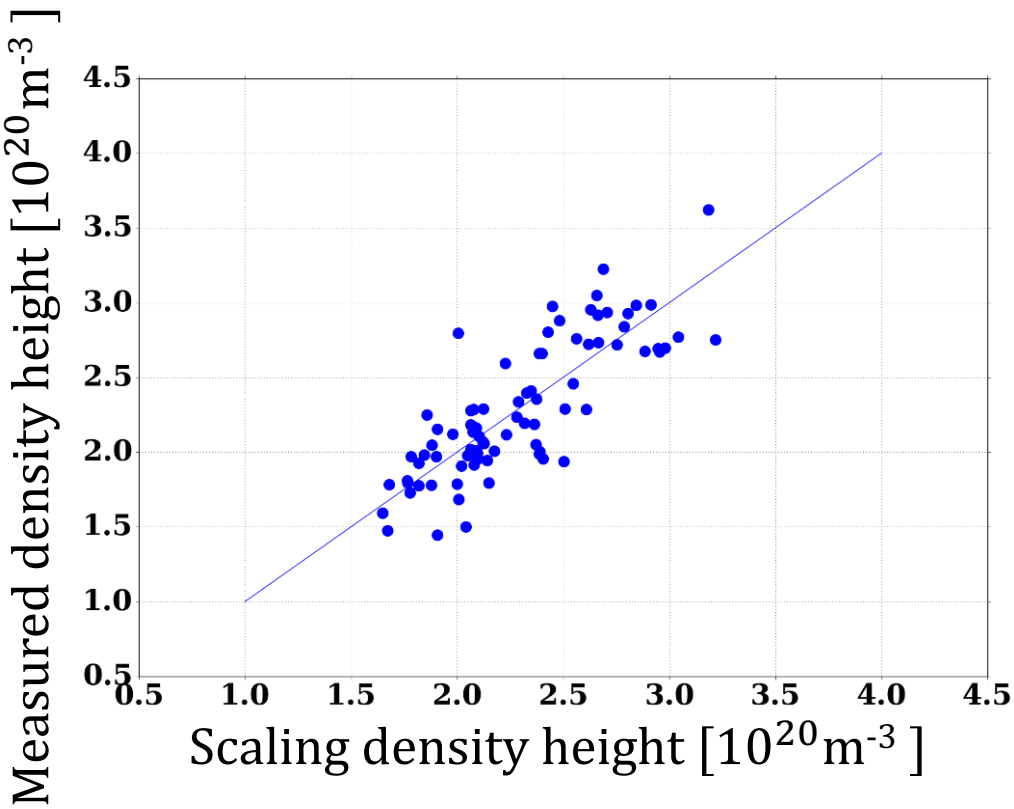
- EDA pressure pedestals are away from MHD stability boundaries [1]
- EDA pedestal displays characteristic quasi-coherent mode, which appears to fix density pedestal after L-H transition
- Density pedestal width previously observed to show little systematic variation with plasma parameters [2]



[1] J.W. Hughes, et. al., Nuclear Fusion 53 (2013).
[2] J. W. Hughes, et. al, Physics of Plasmas 9 (2002)

EDA density pedestal height dependent on magnetic field

- Analyze database of 85 C-Mod steady EDA H-Modes
  - Magnetic fields from 2.7 T to 7.8 T
  - q_{95} from 2.88 to 5.93
  - L-mode target density from .95 x 10^{20} m^{-3} to 2.31 x 10^{20} m^{-3}
- Resulting fit law reads:



$$n_{e,ped}[10^{20}m^{-3}] = 3.48\, I_P[MA]^{0.54}\, \overline{n_{e,L}}[10^{20}m^{-3}]^{0.52}\, B[T]^{-0.36}$$

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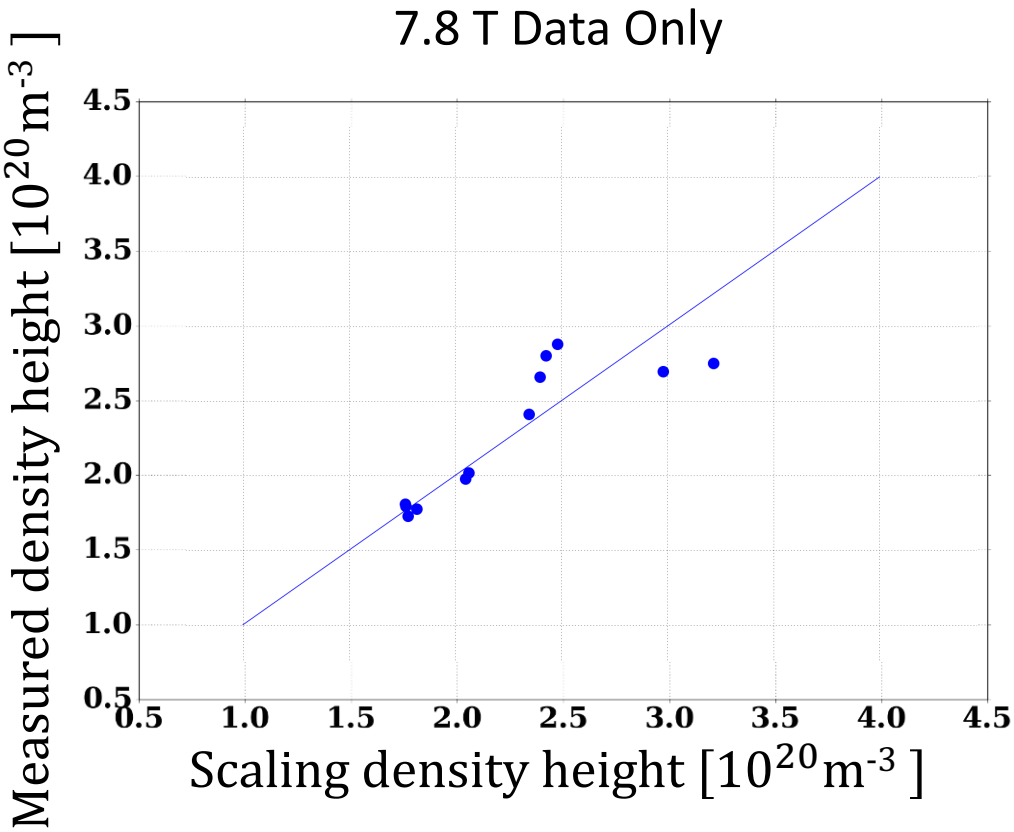

$$n_{e,ped}[10^{20}m^{-3}] = 3.48\, I_P[MA]^{0.54}\, \overline{n_{e,L}}[10^{20}m^{-3}]^{0.52}\, B[T]^{-0.36}$$

Conclusions: H-mode behavior at high magnetic field

- Most recent C-Mod run campaign extends H-mode experience at 7.8 T
- L-H transitions
  - L-H transitions at 7.8 T occur around ITPA scaling
  - Density corresponding to lowest P_{th} increases with magnetic field
- H-mode type
  - All types of H-mode routinely obtained on C-Mod can be obtained at 7.8 T
  - These types live in expected parameter space
- Pedestal characteristics
  - No evidence of ELMy pressure pedestal narrowing at high B
  - EDA scaling displays magnetic field dependence

Thomson scattering system

- Two Nd:YAG lasers fired vertically through machine
- Each laser is 50 Hz, so with full operationality the overall measurement is 100 Hz
- Scattered light collected by core and edge fibers running to polychromators
- Scattering volumes shown by green dots at right
- Vertical locations mapped to midplane by EFIT equilibrium reconstruction code

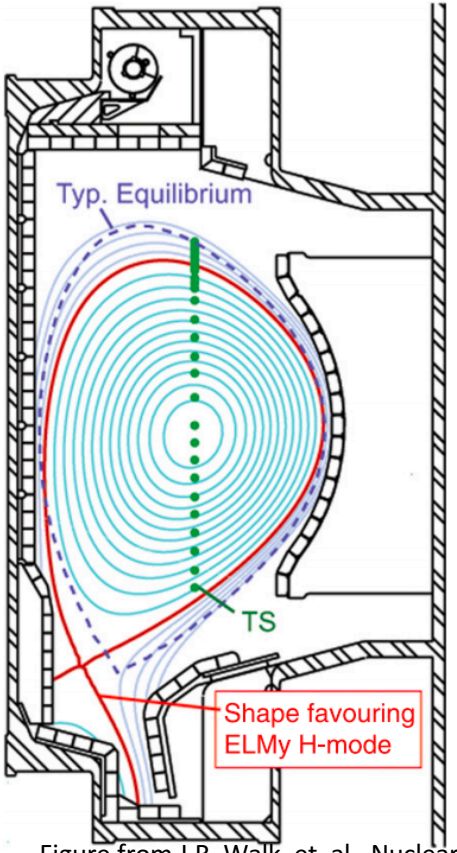

Figure from J.R. Walk, et. al., Nuclear Fusion 52 (2012).