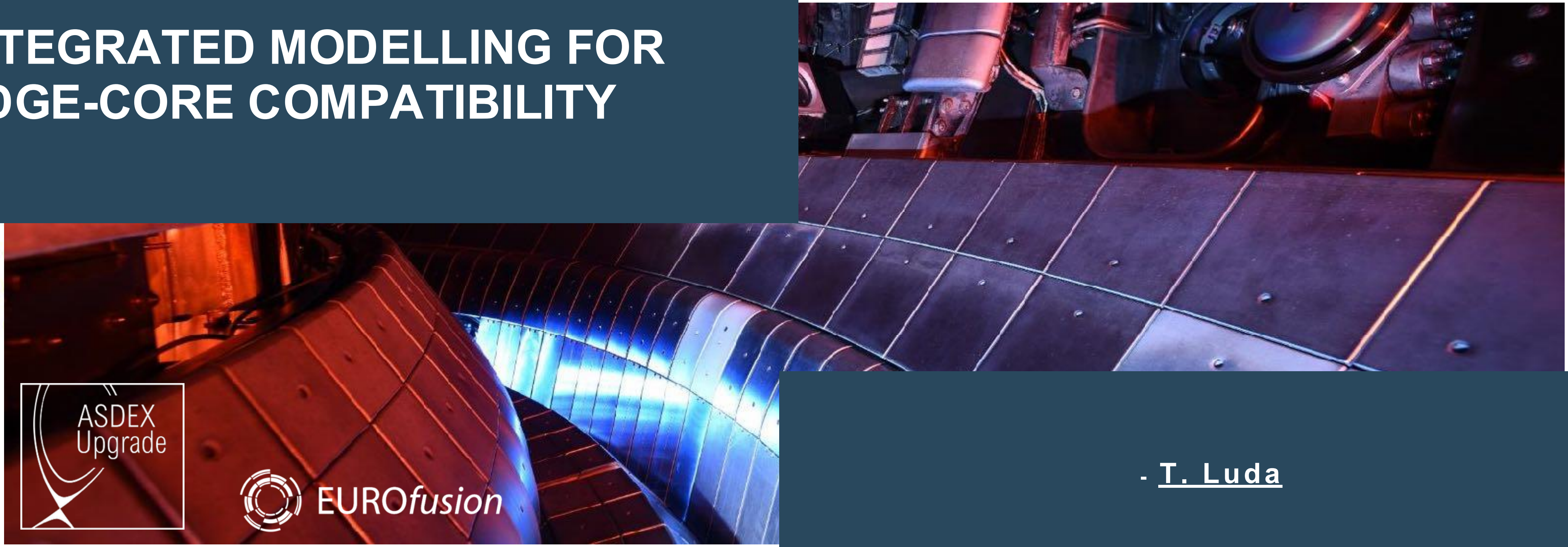
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

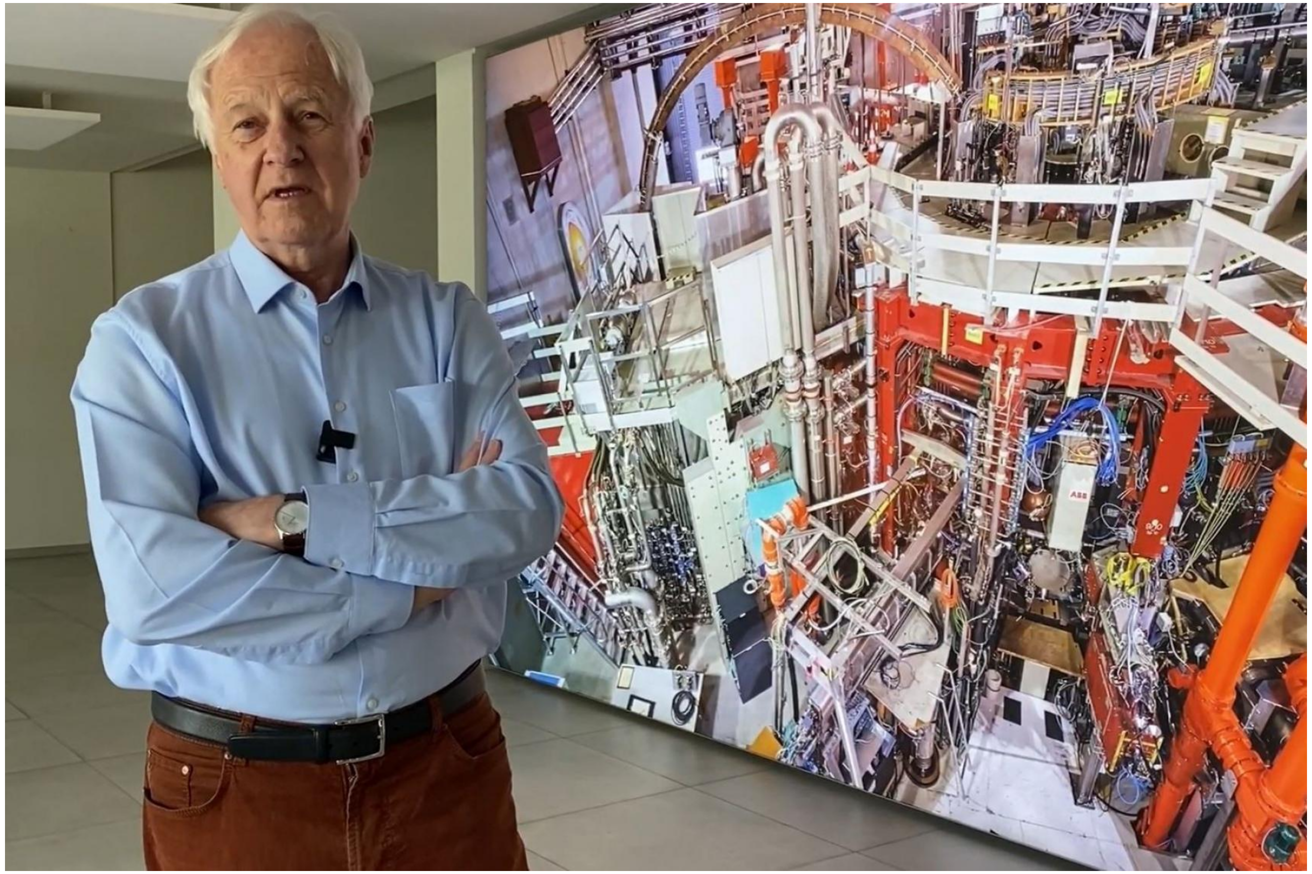
INTEGRATED MODELLING FOR EDGE-CORE COMPATIBILITY



- **T. Luda**

THE H-MODE REGIME AND THE PEDESTAL

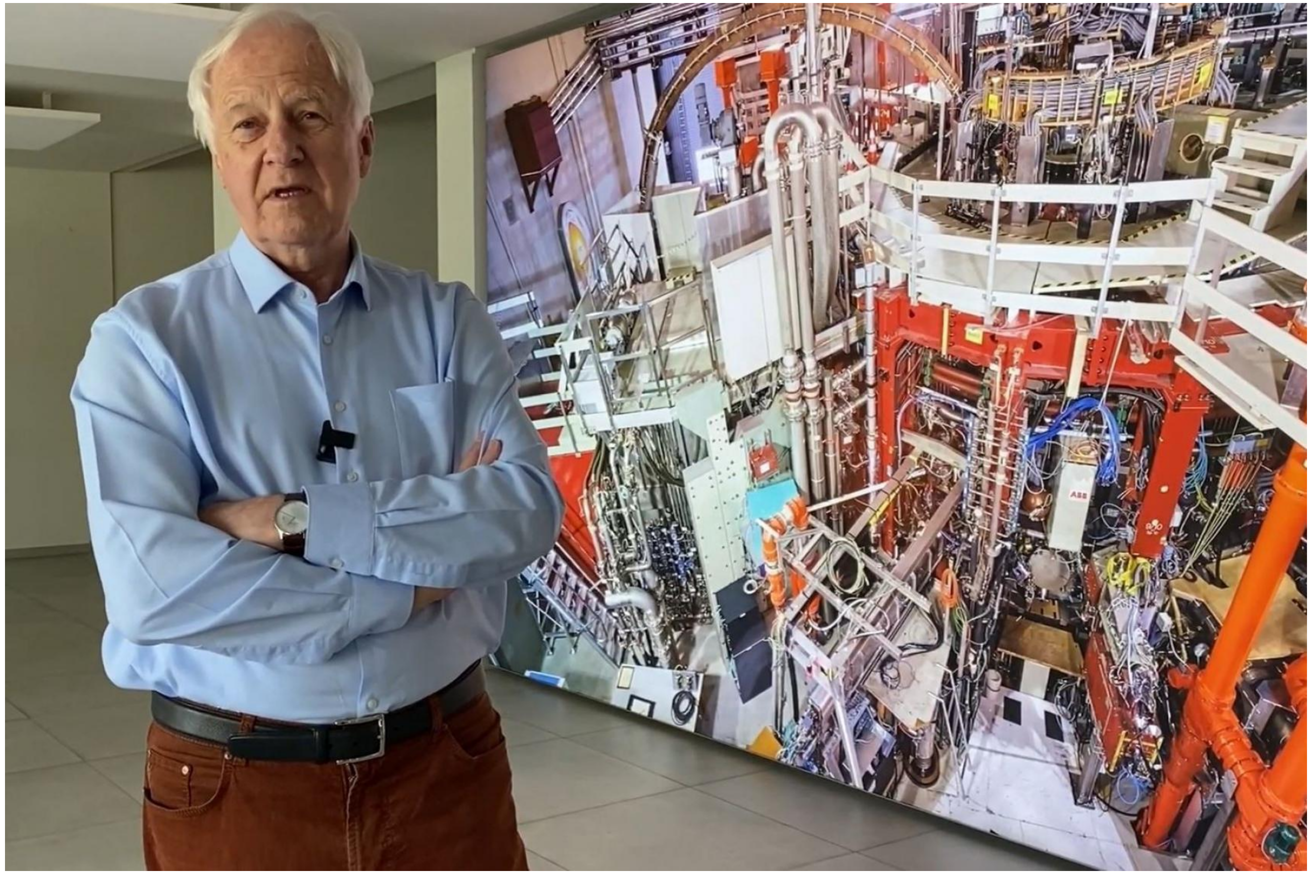
On February 1982, in Garching, Germany, Friedrich Wagner discovered the **H-mode** in the ASDEX tokamak



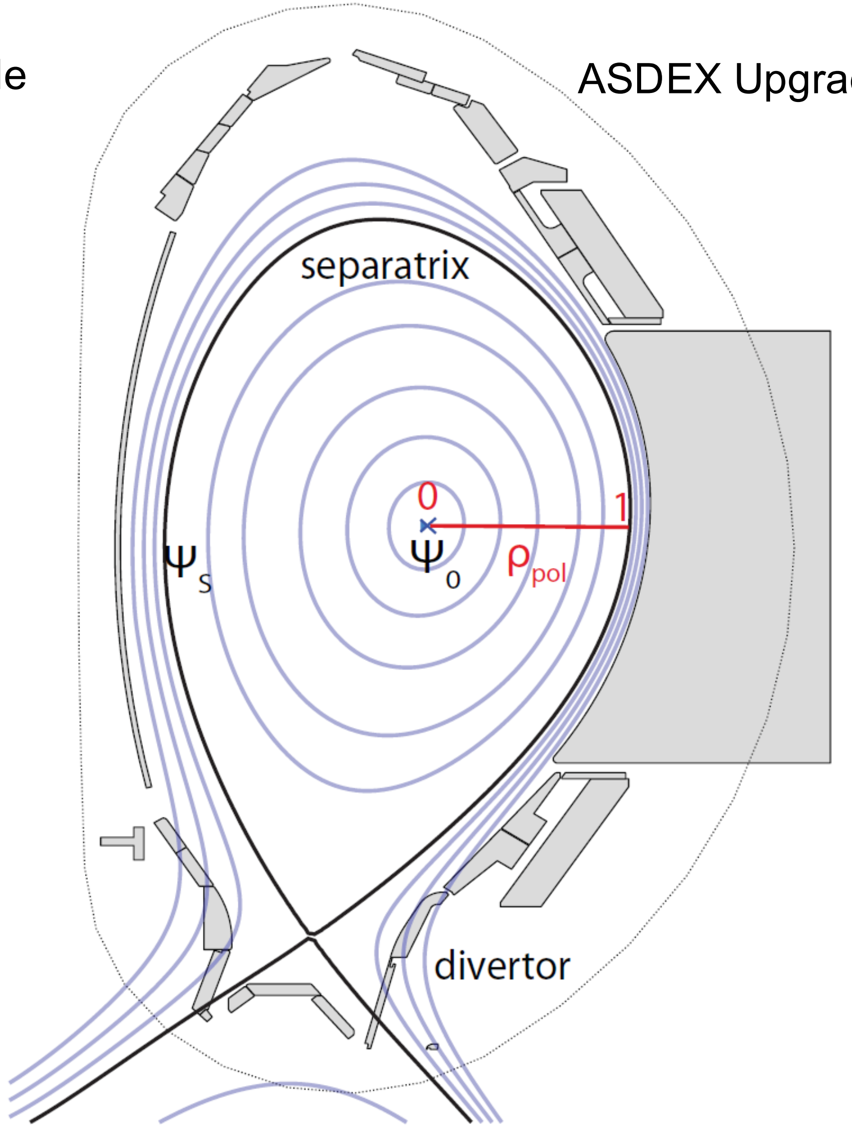
ASDEX

THE H-MODE REGIME AND THE PEDESTAL

On February 1982, in Garching, Germany, Friedrich Wagner discovered the H-mode

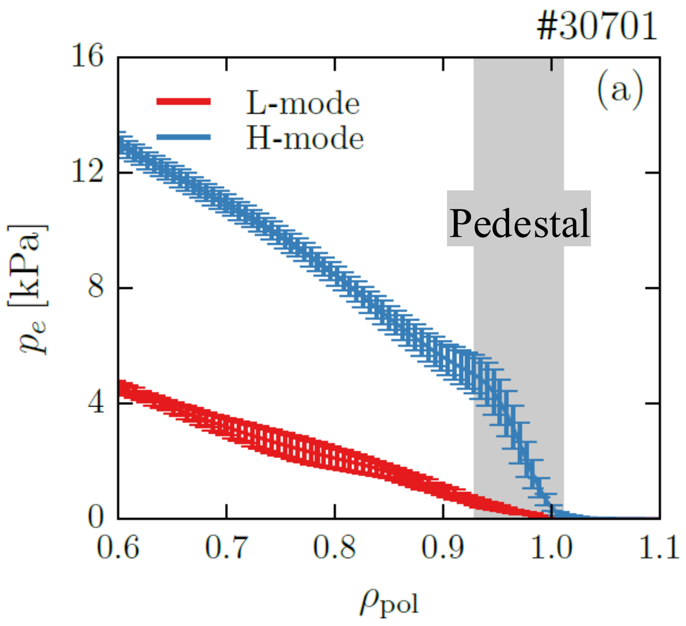


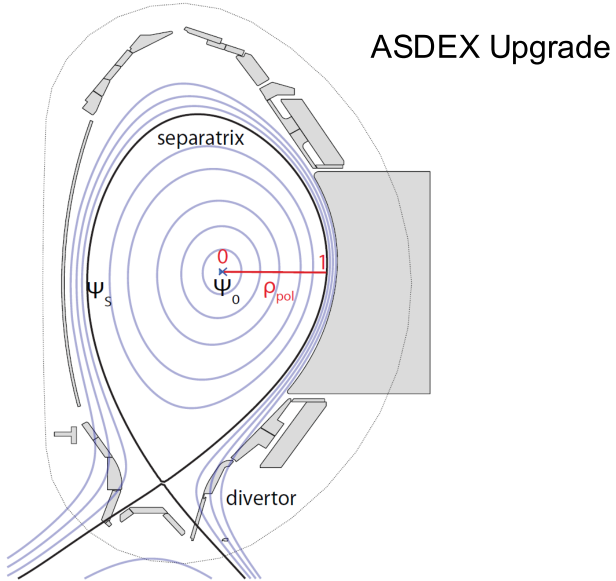
ASDEX Upgrade



THE H-MODE REGIME AND THE PEDESTAL

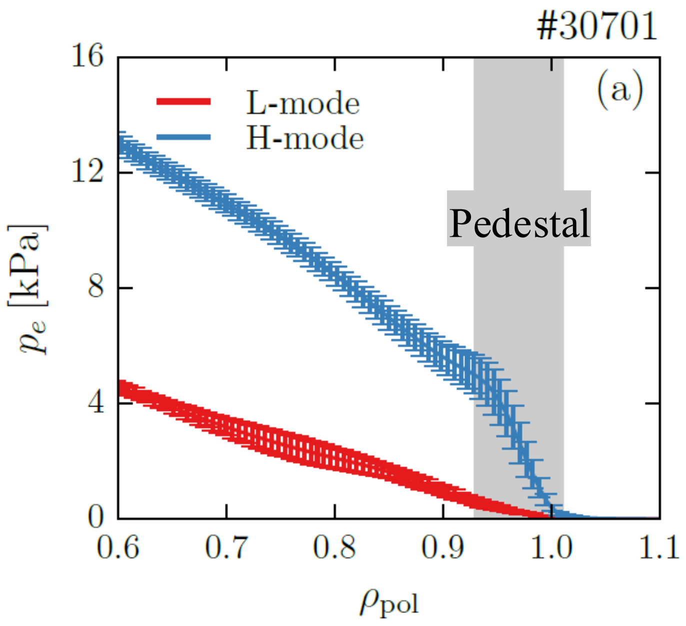
- With sufficient heating power, a **transport barrier** develops in the edge of the plasma
- Suppression of turbulence reduces transport and allows the transition to the **H-mode** regime
- Formation of steep gradient region: **the pedestal**

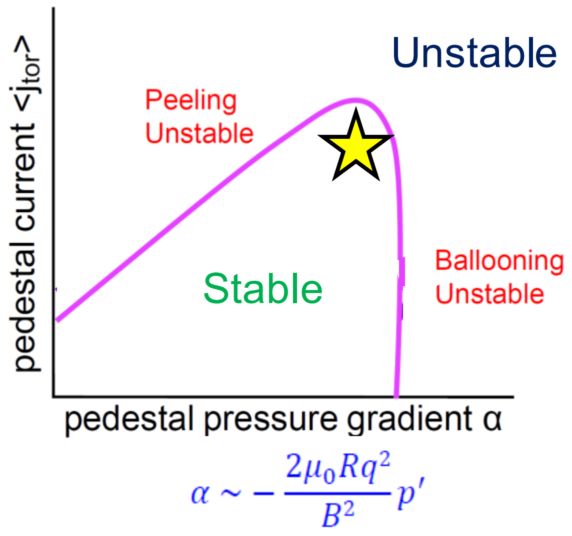




THE H-MODE REGIME AND THE PEDESTAL

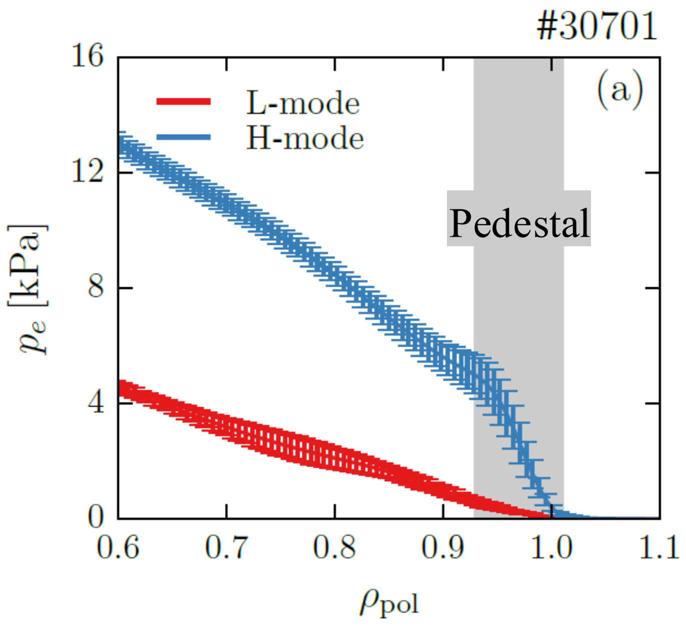
- With sufficient heating power, a **transport barrier** develops in the edge of the plasma
- Suppression of turbulence reduces transport and allows the transition to the **H-mode** regime
- Formation of steep gradient region: **the pedestal**
- Height of the pedestal limited by **MagnetoHydroDynamic (MHD) instabilities:** peeling-ballooning model [H. R. Wilson *PoP* 1999, 2002, P. Snyder *PoP 2002, 2004*]

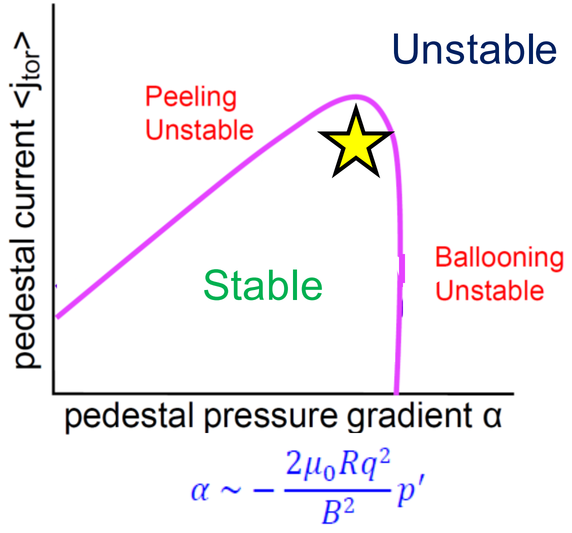




THE H-MODE REGIME AND THE PEDESTAL

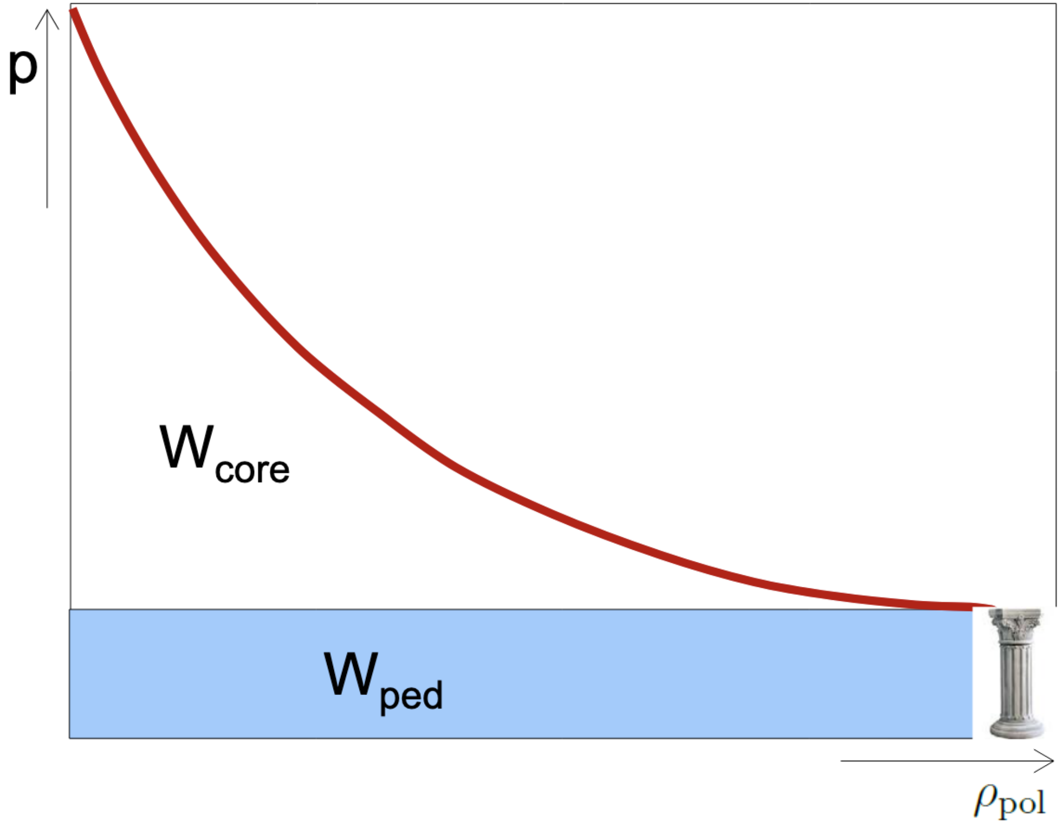
- With sufficient heating power, a **transport barrier** develops in the edge of the plasma
- Suppression of turbulence reduces transport and allows the transition to the **H-mode** regime
- Formation of steep gradient region: **the pedestal**
- Height of the pedestal limited by **MagnetoHydroDynamic (MHD) instabilities:** peeling-ballooning model [H. R. Wilson *PoP* 1999, 2002, P. Snyder *PoP 2002, 2004*]
- Due to its **high confinement** properties, the H-mode is the regime foreseen for ITER and future reactors





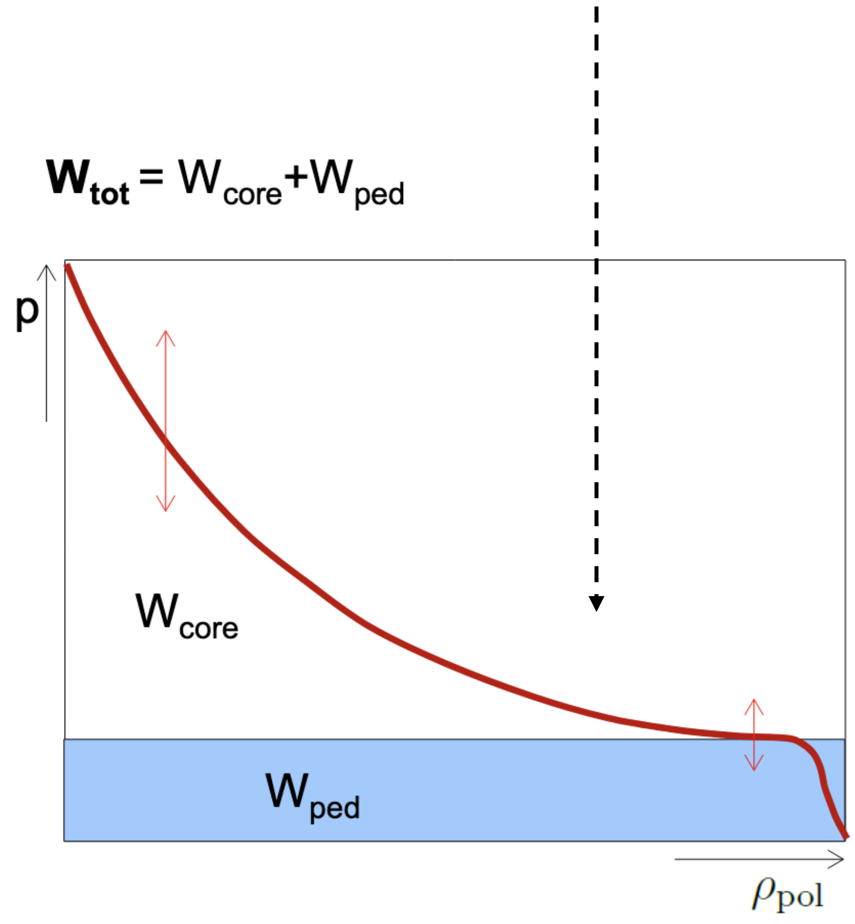
H-MODE PEDESTAL STORES ADDITIONAL ENERGY

$$W_{tot} = W_{core} + W_{ped}$$



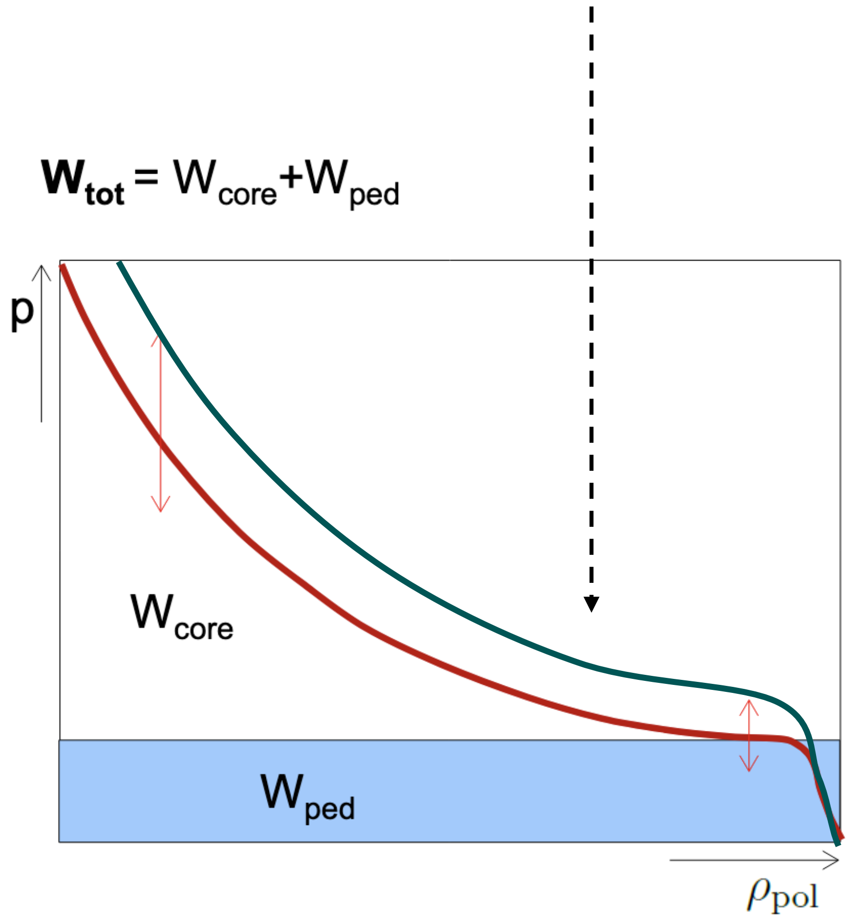
PLASMA ENERGY PROPORTIONAL TO PEDESTAL ENERGY

Due to the nature of turbulent transport in the core of the plasma, the central temperature is proportional to the pedestal temperature



PLASMA ENERGY PROPORTIONAL TO PEDESTAL ENERGY

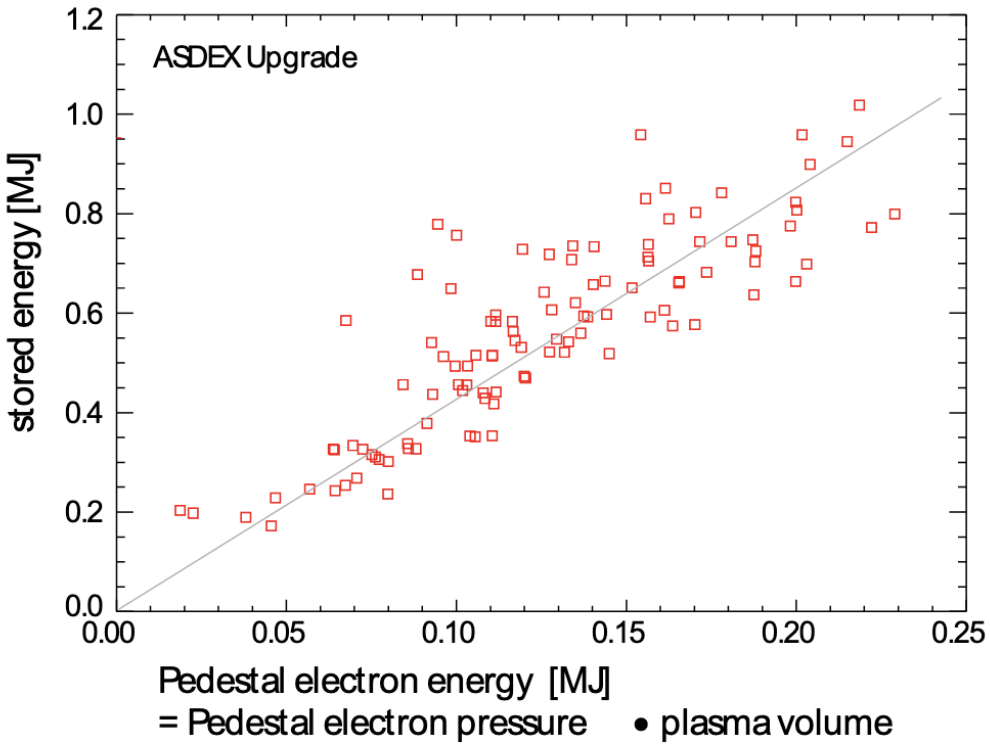
Due to the nature of turbulent transport in the core of the plasma, the central temperature is proportional to the pedestal temperature



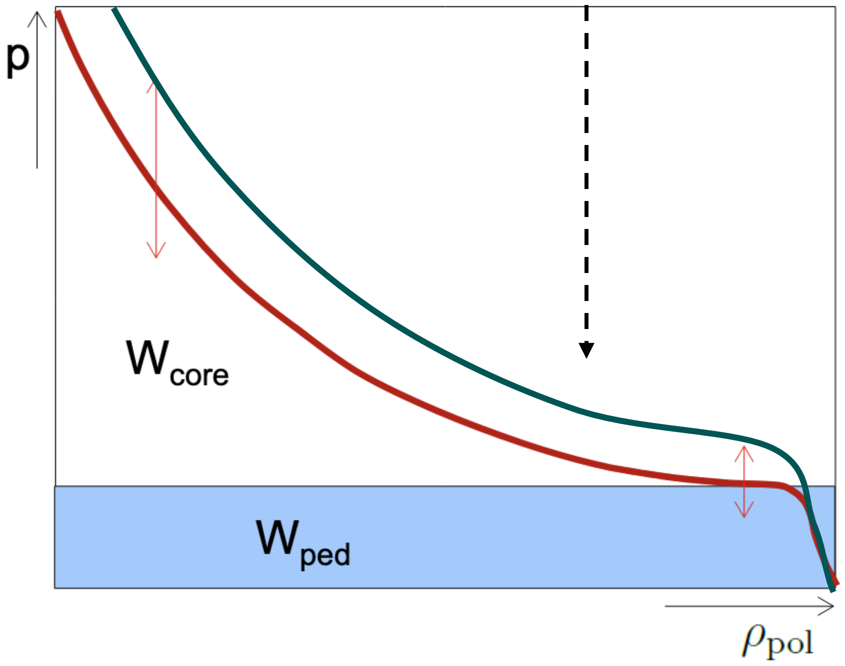
PLASMA ENERGY PROPORTIONAL TO PEDESTAL ENERGY

Due to the nature of turbulent transport in the core of the plasma, the central temperature is proportional to the pedestal temperature

ASDEX Upgrade database
(varying heating power, ...)



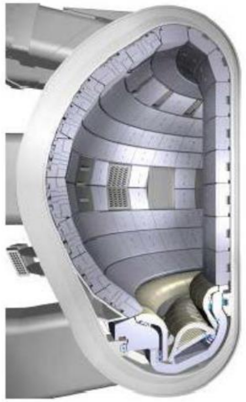
$\mathbf{W_{tot}} = W_{core} + W_{ped}$

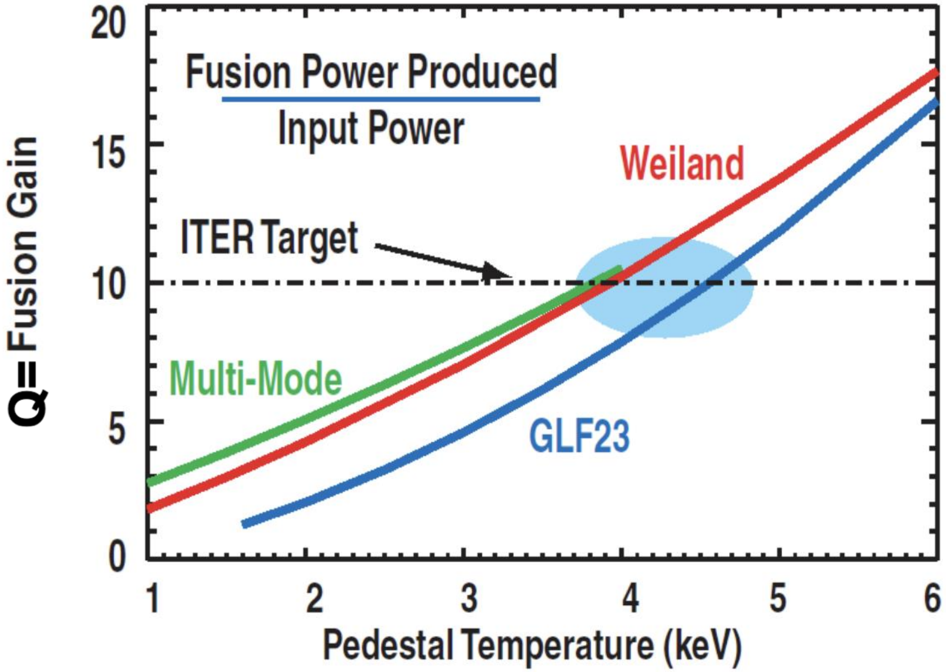


ITER: REQUIREMENT OF PEDESTAL TEMPERATURE

Fusion power ∝ central pressure → fusion power ∝ pedestal pressure!

In ITER pedestal density limited by Greenwald limit → fusion power ∝ pedestal temperature





Transport models predict pedestal temperature needed for fusion gain
Q=10 (ITER target)

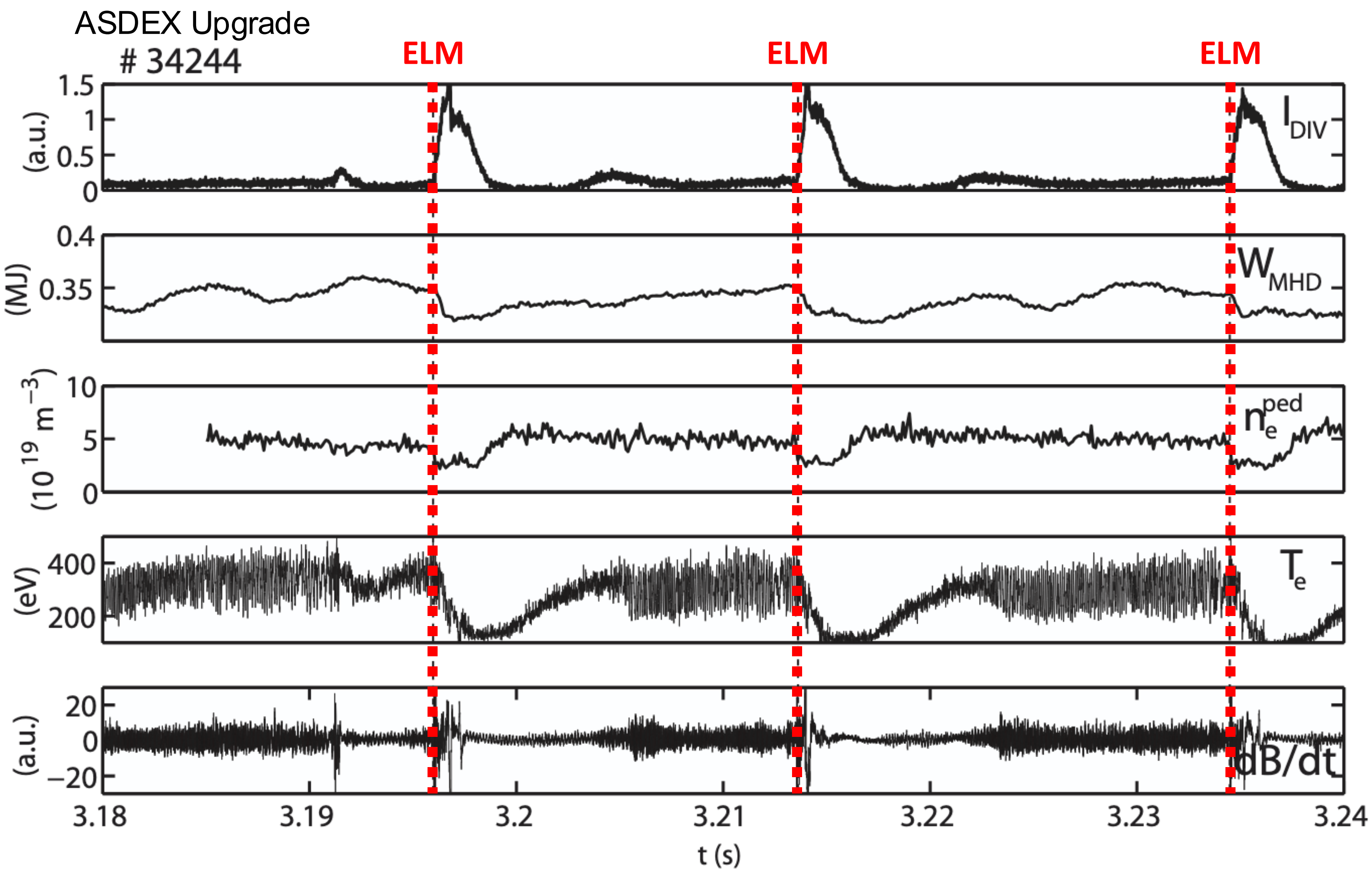
M Wade, SOFT 2008

T_{ped} ~ **3.8 – 4.5 keV**
(depending on model)

THE ELM CYCLE

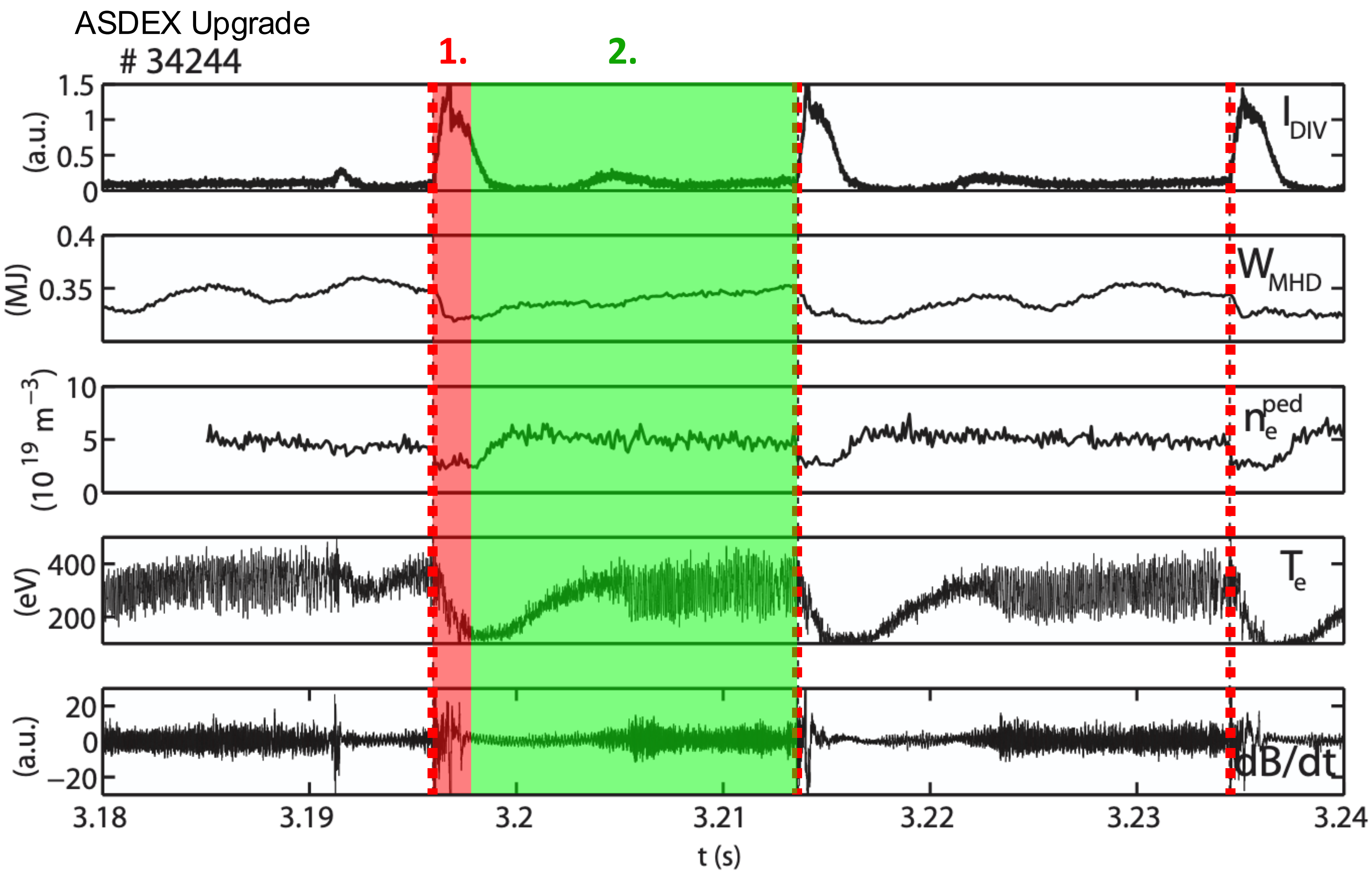
- Height of the pedestal limited by MHD instabilities:
  the Edge Localized Mode (ELM)

- When the **ELM** is triggered, it causes a crash in the pedestal pressure

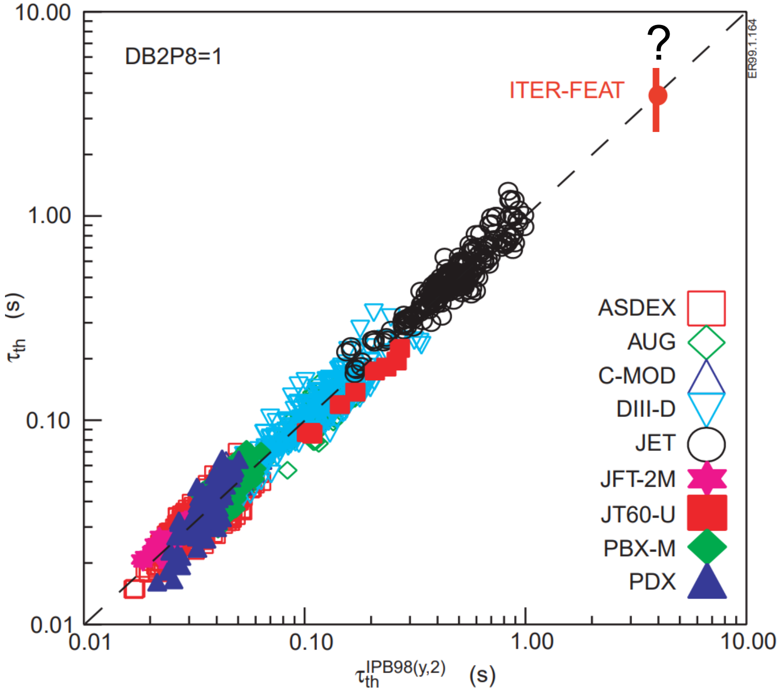


THE ELM CYCLE

- Height of the pedestal limited by MHD instabilities:
  the Edge Localized Mode (ELM)
- When the **ELM** is triggered, it causes a crash in the pedestal pressure
- The pedestal evolves in time through the ELM cycle, consisting of two phases:
  1. **ELM crash**
  2. **Recovery phase**
- The pedestal stays most of the time very close to the pre-ELM conditions
- **For fusion power predictions:** no need to describe the time evolution → the important is the pre-ELM conditions!



HOW TO PREDICT CONFINEMENT FOR H-MODE PLASMAS

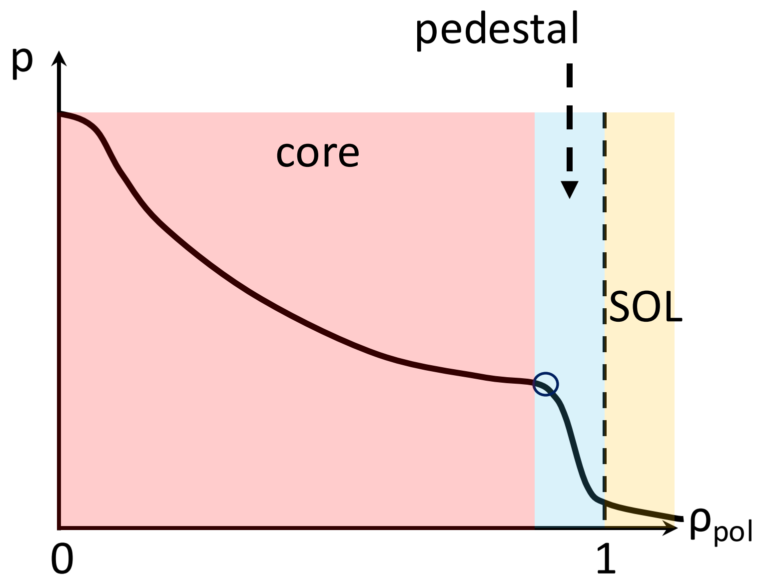


[*ITER Physics Basis Editors 1999 Nucl. Fusion*]

$$\tau_{\mathrm{th}}^{\mathrm{IPB98(y,2)}} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \epsilon^{0.58} \kappa^{0.78}$$

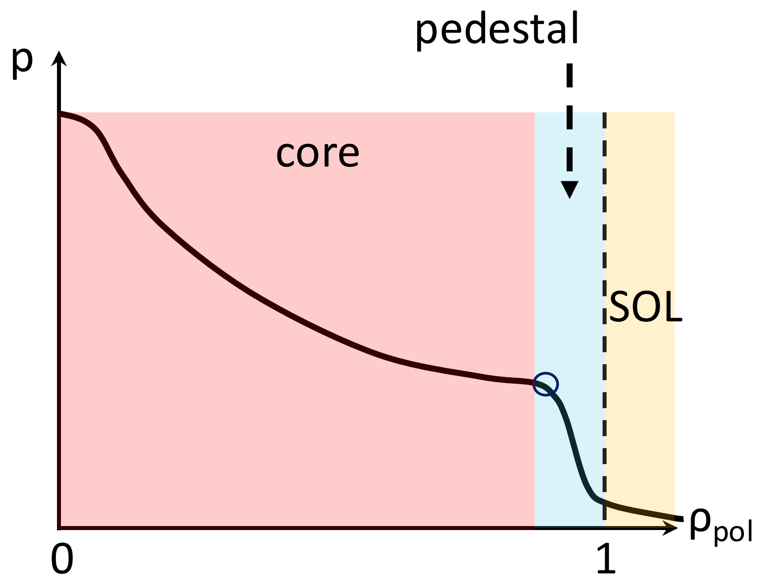
- Scaling laws (statistical regressions):
  - Simple, based on main engineering parameters
  - Robust to capture dominant dependencies (e.g. I_p)
  - Do not capture other “hidden” dependencies (e.g. n_e)
  - Limited extrapolation capabilities

HOW TO PREDICT CONFINEMENT FOR H-MODE PLASMAS



- Scaling laws (statistical regressions):
  - Simple, based on main engineering parameters
  - Robust to capture dominant dependencies (e.g. I_p)
  - Do not capture other “hidden” dependencies (e.g. n_e)
  - Limited extrapolation capabilities
- Integrated models NOT coupling edge-core:
  - Predict kinetic profiles (T_e, T_i, n_e, n_i)
  - Theory-based description of core transport
  - Pedestal top pressure often set from measurements or to match global confinement scaling
  - Transport models from core to plasma boundary can include empirical elements
  - Limited coupling between core, pedestal and SOL effects

HOW TO PREDICT CONFINEMENT FOR H-MODE PLASMAS



- Scaling laws (statistical regressions):
  - Simple, based on main engineering parameters
  - Robust to capture dominant dependencies (e.g. I_p)
  - Do not capture other “hidden” dependencies (e.g. n_e)
  - Limited extrapolation capabilities
- Integrated models NOT coupling edge-core:
  - Predict kinetic profiles (T_e, T_i, n_e, n_i)
  - Theory-based description of core transport
  - Pedestal top pressure often set from measurements or to match global confinement scaling
  - Transport models from core to plasma boundary can include empirical elements
  - Limited coupling between core, pedestal and SOL effects

➢ **Solution:** integrated modeling coupling edge-core!

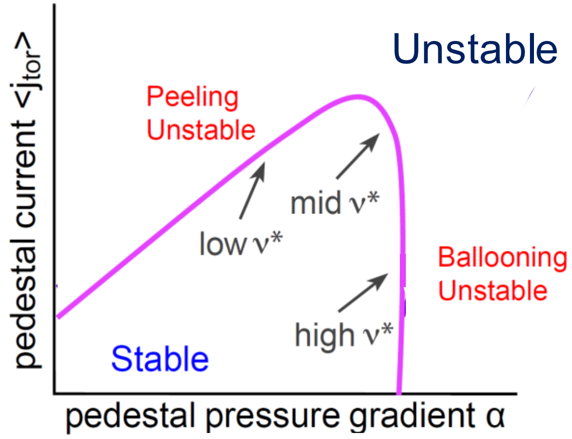
INTEGRATED MODELING FOR EDGE-CORE COMPATIBILITY

- Integrated modeling coupling edge-core provides the **highest fidelity predictions**

- Enables the study of **compatibility between core and edge**: compromise between high confinement/fusion power and reduced heat loads at the divertor target

INTEGRATED MODELING FOR EDGE-CORE COMPATIBILITY

- Integrated modeling coupling edge-core provides the **highest fidelity predictions**
- Enables the study of **compatibility between core and edge**: compromise between high confinement/fusion power and reduced heat loads at the divertor target
- High confinement requires high pedestal pressure BUT this means low separatrix density in ballooning limited pedestals (mid/high collisionality)



$$\alpha \sim -\frac{2\mu_0 R q^2}{B^2} p'$$

INTEGRATED MODELING FOR EDGE-CORE COMPATIBILITY

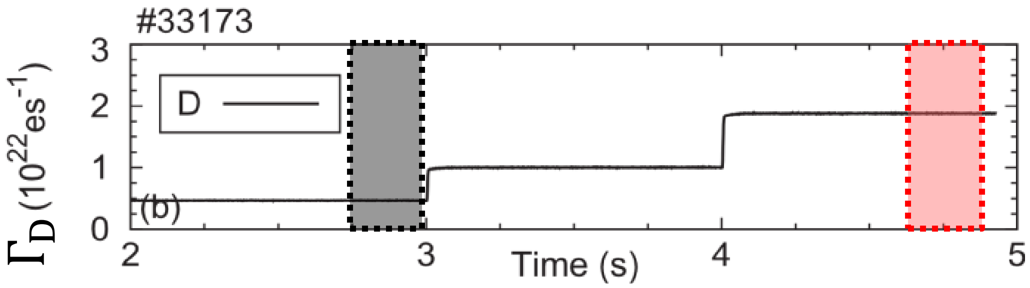
- Integrated modeling coupling edge-core provides the **highest fidelity predictions**
- Enables the study of **compatibility between core and edge**: compromise between high confinement/fusion power and reduced heat loads at the divertor target
- High confinement requires high pedestal pressure BUT this means low separatrix density in ballooning limited pedestals (mid/high collisionality)
- Low separatrix density means higher divertor head loads, detachment is achieved only at sufficiently high separatrix density

INTEGRATED MODELING FOR EDGE-CORE COMPATIBILITY

- Integrated modeling coupling edge-core provides the **highest fidelity predictions**
- Enables the study of **compatibility between core and edge**: compromise between high confinement/fusion power and reduced heat loads at the divertor target
- High confinement requires high pedestal pressure BUT this means low separatrix density in ballooning limited pedestals (mid/high collisionality)
- Low separatrix density means higher divertor head loads, detachment is achieved only at sufficiently high separatrix density
- Important to model core, pedestal, SOL at the same time to **address edge-core compatibility!**

NEGATIVE IMPACT OF SEPARATRIX DENSITY ON PLASMA CONFINEMENT

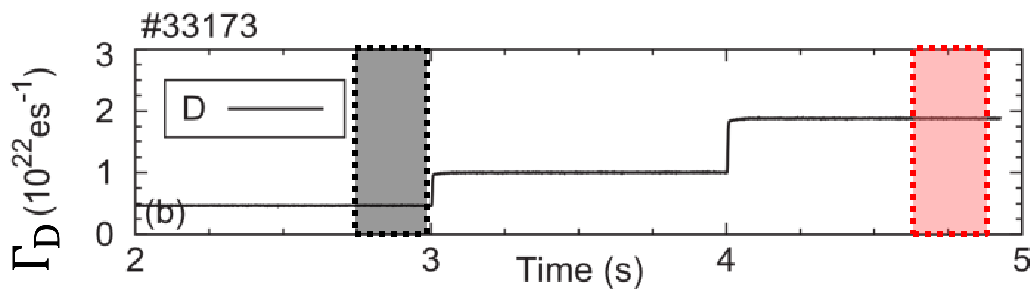
Experimental scan in fueling rate Γ_D shows the typical confinement degradation with gas puff



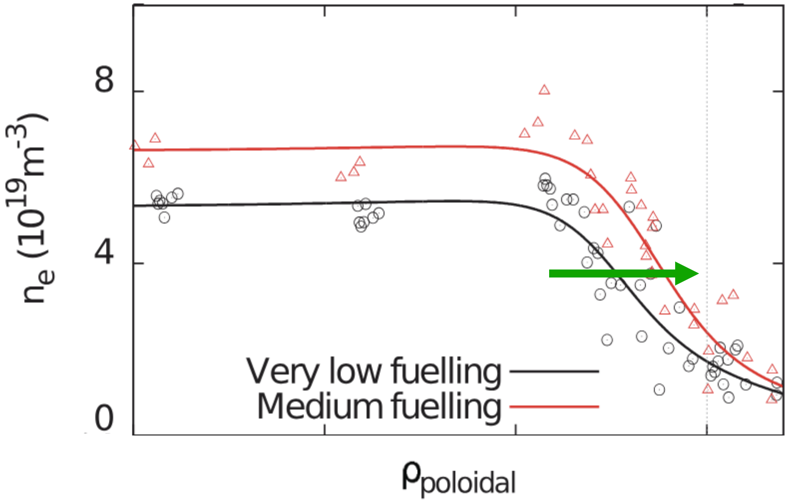
[M G Dunne et al 2017 Plasma Phys. Control. Fusion]

NEGATIVE IMPACT OF SEPARATRIX DENSITY ON PLASMA CONFINEMENT

Experimental scan in fueling rate Γ_D shows the typical confinement degradation with gas puff



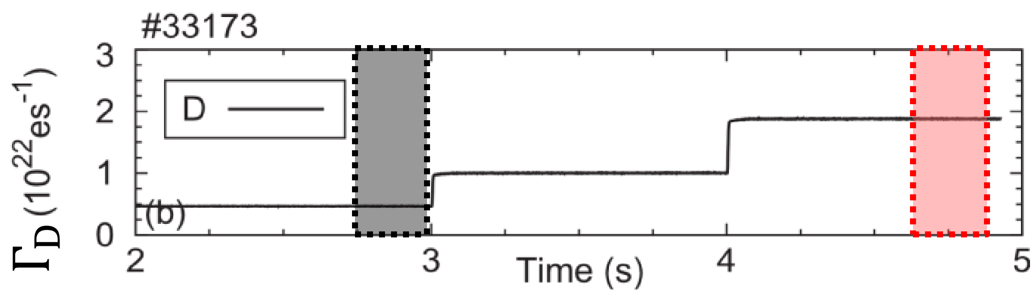
[M G Dunne et al 2017 Plasma Phys. Control. Fusion]



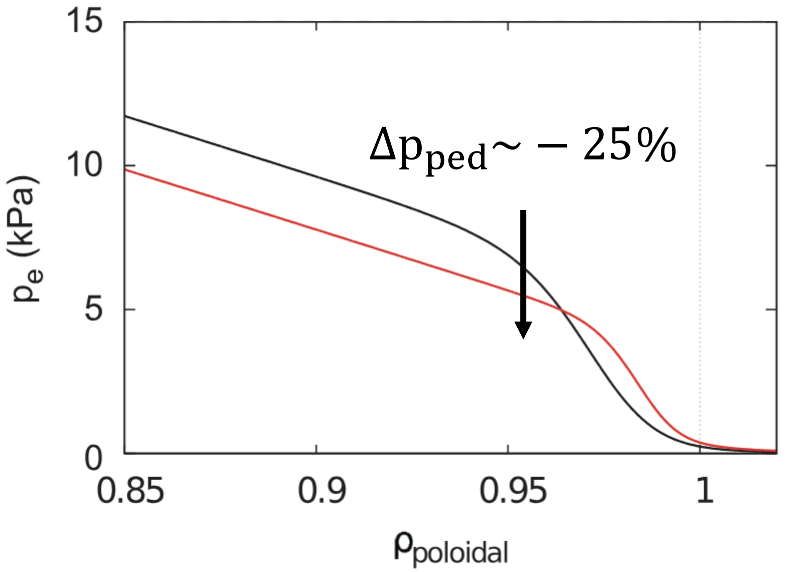
1. The increase in fuelling causes an **increase in $n_{e,sep}$** and shifts the density profile **outwards**

NEGATIVE IMPACT OF SEPARATRIX DENSITY ON PLASMA CONFINEMENT

Experimental scan in fueling rate Γ_D shows the typical confinement degradation with gas puff



[M G Dunne et al 2017 Plasma Phys. Control. Fusion]

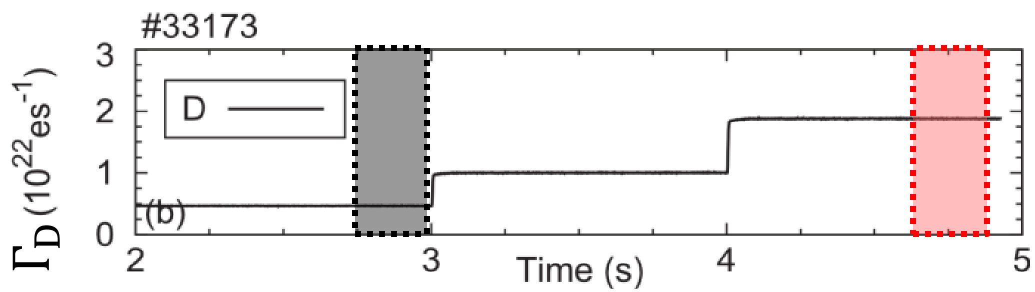


1. The increase in fuelling causes an **increase in $n_{e,sep}$** and shifts the density profile **outwards**

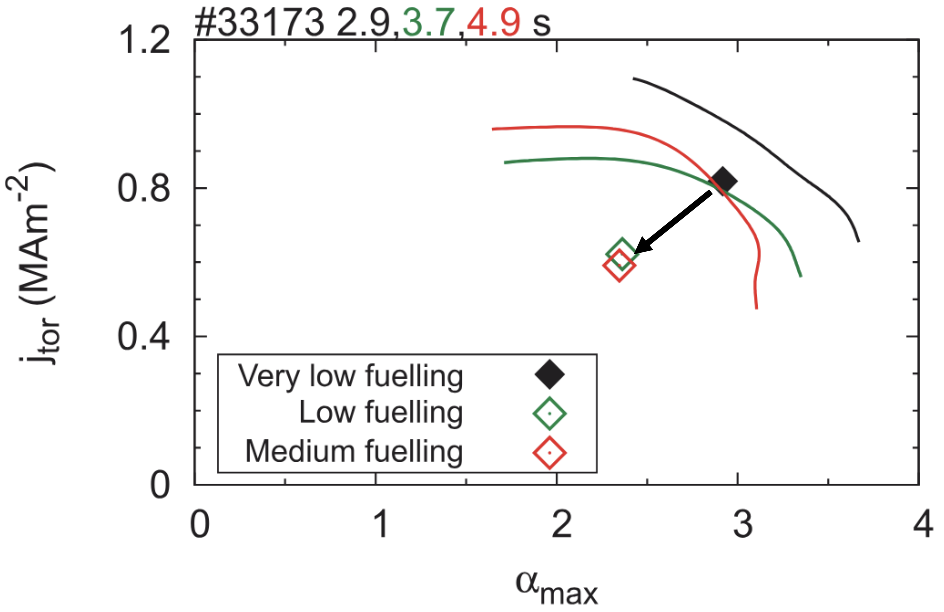
2. This shift is also evident in the gradients of the pressure profile, and this has a strong impact on the ballooning stability → the **pedestal pressure decreases**

NEGATIVE IMPACT OF SEPARATRIX DENSITY ON PLASMA CONFINEMENT

Experimental scan in fueling rate Γ_D shows the typical confinement degradation with gas puff



[M G Dunne et al 2017 Plasma Phys. Control. Fusion]

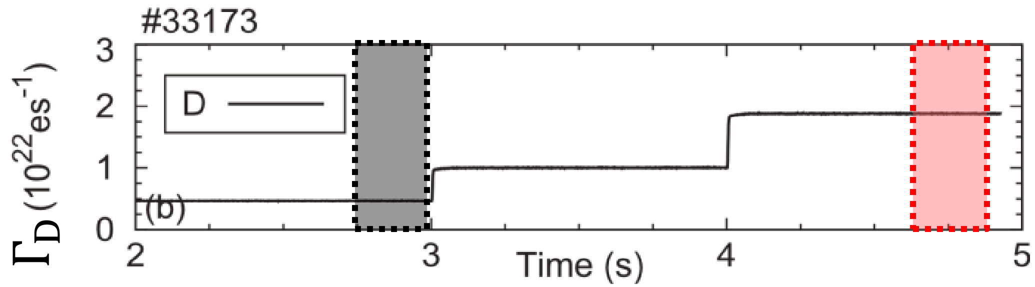


1. The increase in fuelling causes an **increase in $n_{e,sep}$** and shifts the density profile **outwards**

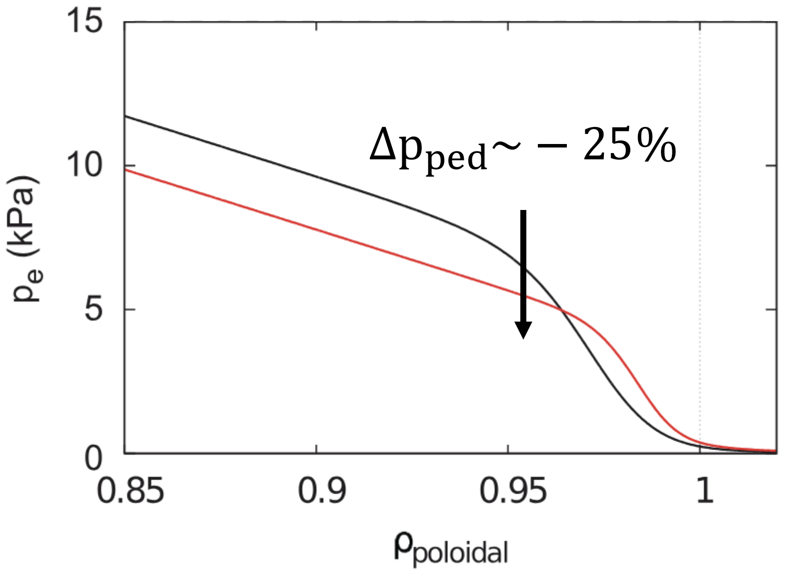
2. This shift is also evident in the gradients of the pressure profile, and this has a strong impact on the ballooning stability → the **pedestal pressure decreases**

NEGATIVE IMPACT OF SEPARATRIX DENSITY ON PLASMA CONFINEMENT

Experimental scan in fueling rate Γ_D shows the typical confinement degradation with gas puff



[M G Dunne et al 2017 Plasma Phys. Control. Fusion]



1. The increase in fuelling causes an **increase in $n_{e,sep}$** and shifts the density profile **outwards**

2. This shift is also evident in the gradients of the pressure profile, and this has a strong impact on the ballooning stability → the **pedestal pressure decreases**

3. Corresponding to the increase in $n_{e,sep}$, the pedestal pressure has decreased by ~**25%**

NOW A LITTLE QUESTIONS BREAK

Everything clear so far?

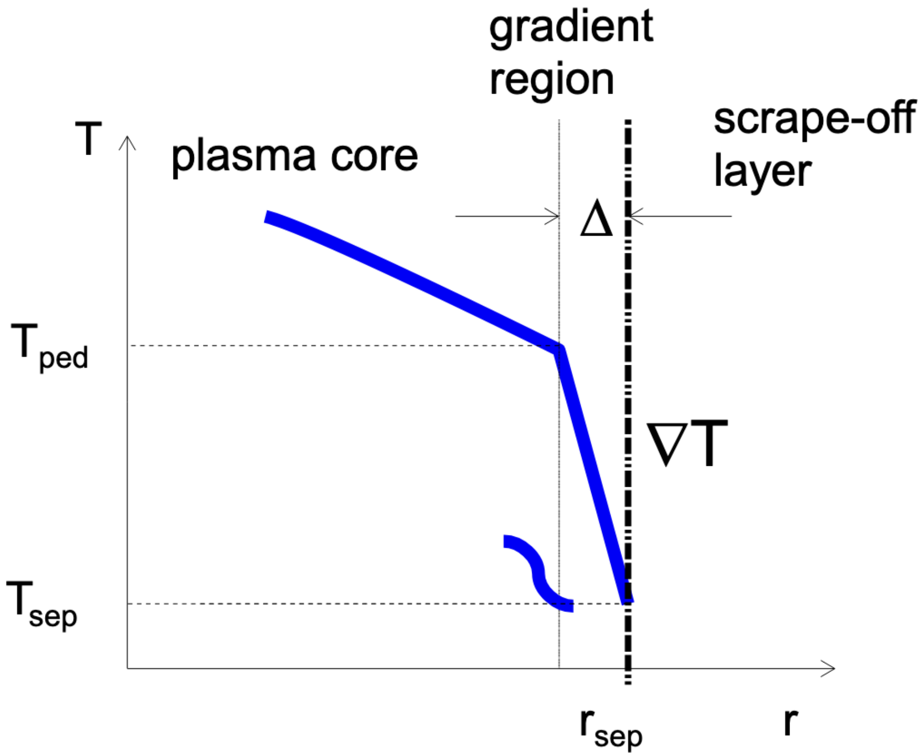
…feel free to ask anything!

PREDICTIVE PEDESTAL MODELS

How can we predict the pedestal?
Two ingredients are required:

- **Transport model:**
  describe width (Δ) and height

- **MHD stability limit:**
  describe critical pressure gradient

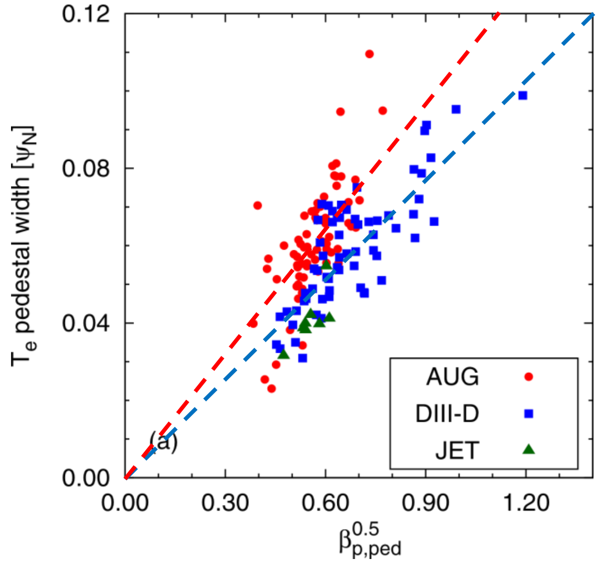


Cartoon:

$$T_{ped} \sim T_{sep} + \nabla T * \Delta$$

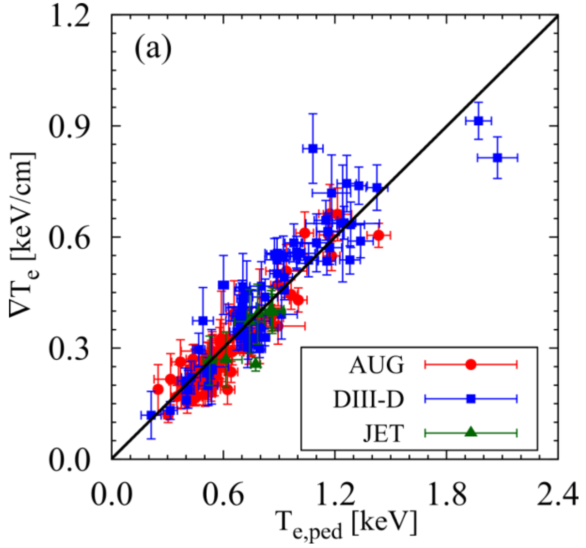
PEDESTAL TRANSPORT MODELS

- The EPED pedestal model: [P. B. Snyder *et al* 2009 *PoP*]
  - assumes: $\Delta\Psi_N \sim (0.076, 0.11)\beta_{p,ped}^{0.5}$
  - requires $n_{e,top}$ as input
  - assumes $T_{e,top} = T_{i,top}$



- The IMEP pedestal model: based on common feature from AUG and DIII-D pedestals:

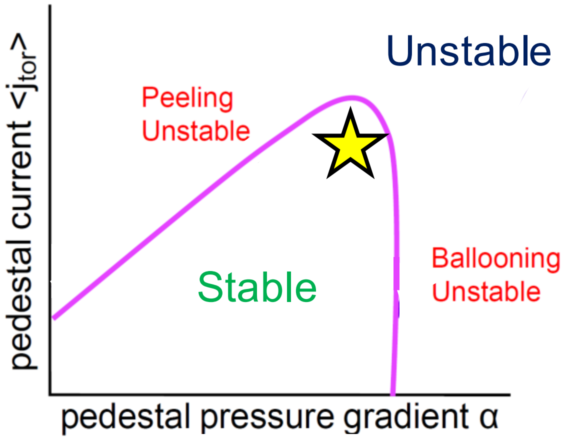
$$\frac{\mathbf{R} < \nabla \mathbf{T_e} >}{\mathbf{T_{e,top}}} = -\mathbf{82.5}$$



[P.A. Schneider *et al* 2013 *NF*]

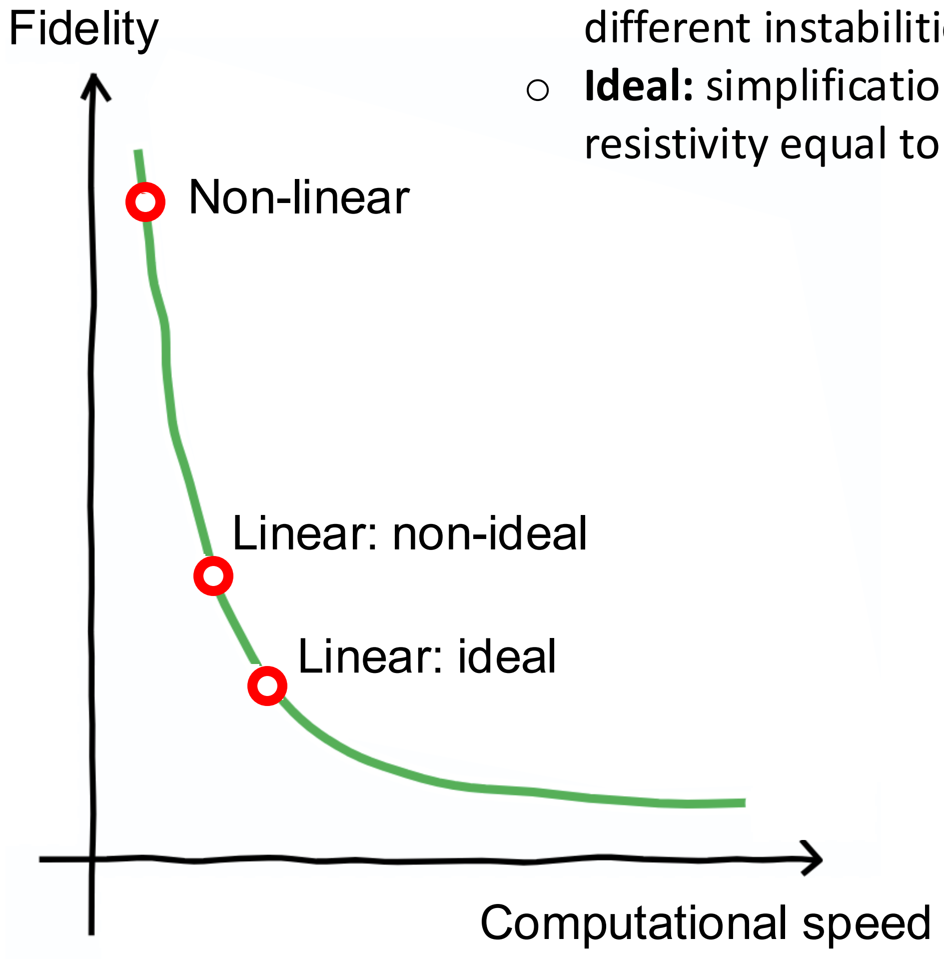
MHD STABILITY CODES

Calculate Peeling-Ballooning (PB) modes stability



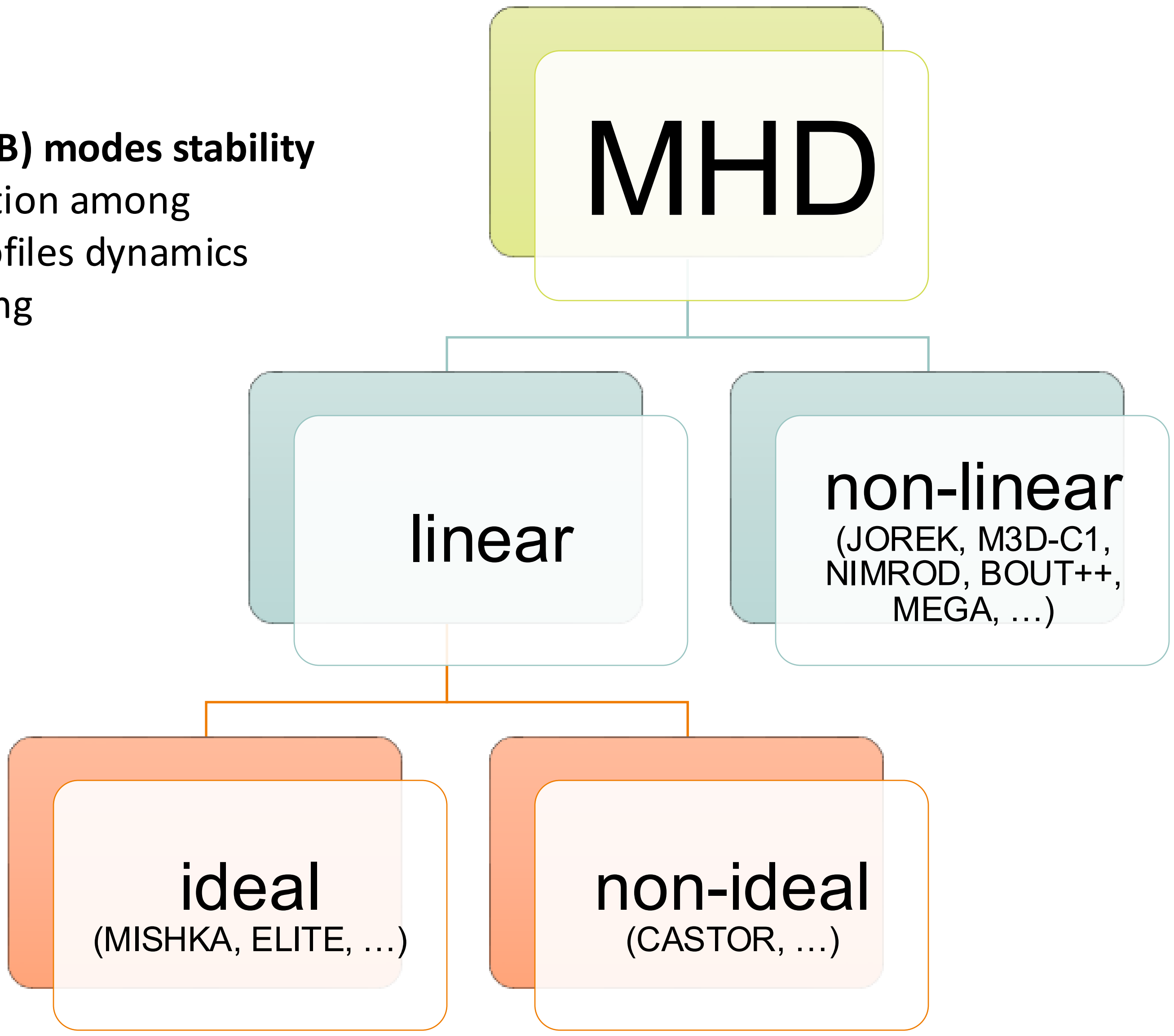
$$\alpha \sim -\frac{2\mu_0 R q^2}{B^2} p'$$

MHD STABILITY CODES



Calculate Peeling-Ballooning (PB) modes stability

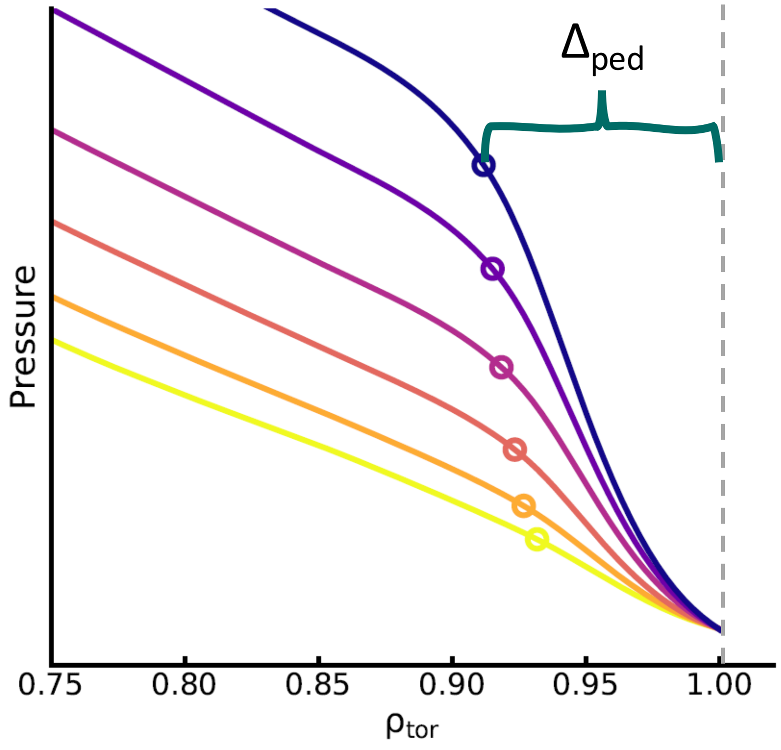
- **Non-linear:** describe interaction among different instabilities and profiles dynamics
- **Ideal:** simplifications assuming resistivity equal to zero



COUPLING OF TRANSPORT AND MHD STABILITY

$$\Delta_{ped} = 0.076\ \beta_{p,ped}^{0.5}$$

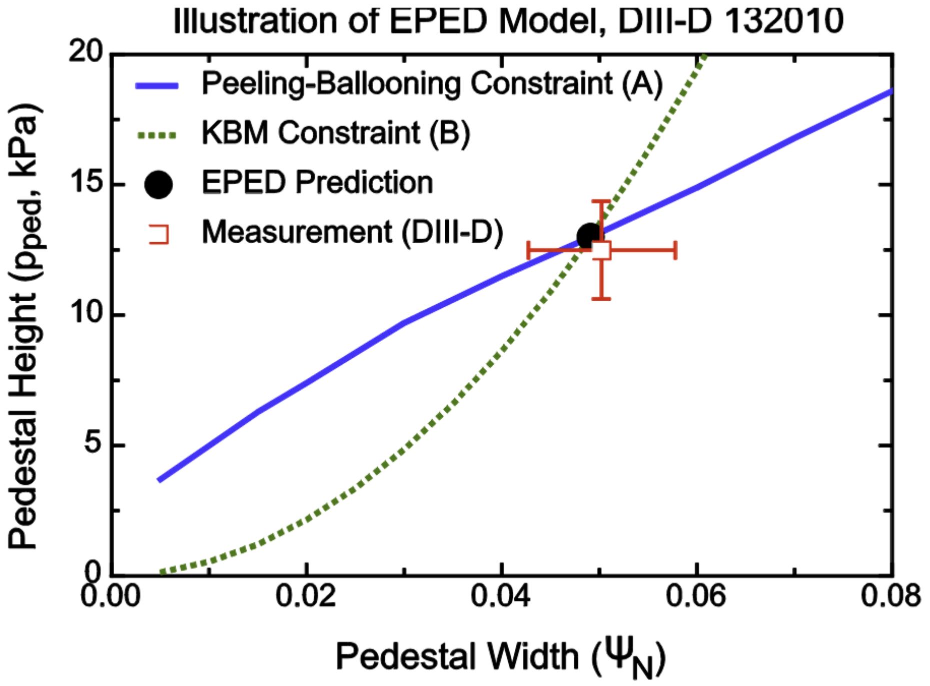
Create profiles with different widths and heights consistent with transport constraint



COUPLING OF TRANSPORT AND MHD STABILITY

Create profiles with different widths and heights consistent with transport constraint

P.B. Snyder et al. PoP 2009

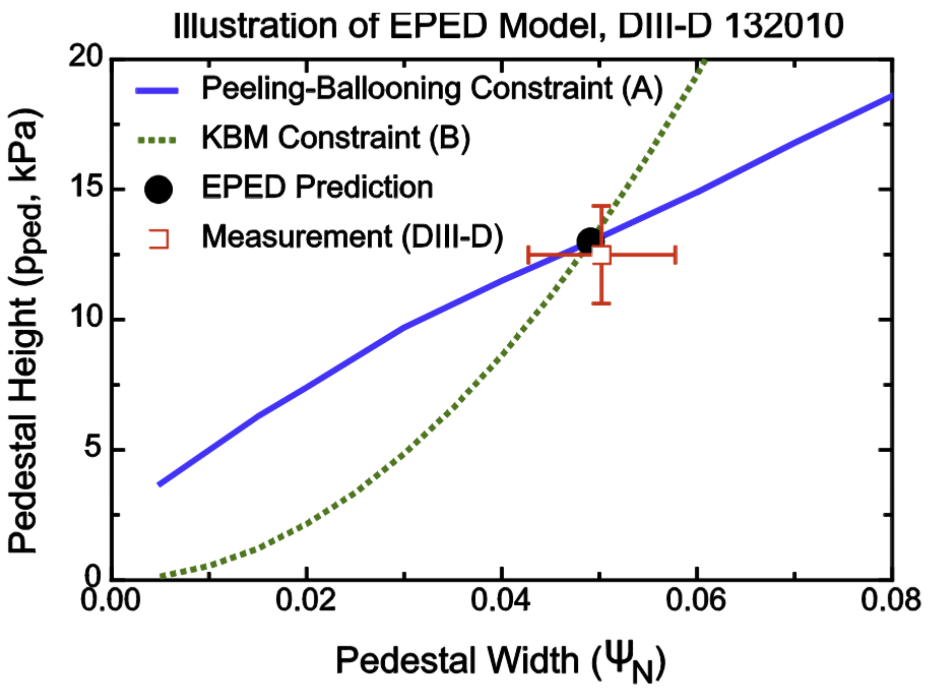


COUPLING OF TRANSPORT AND MHD STABILITY

Create profiles with different widths and heights consistent with transport constraint

Calculate MHD stability for each point

P.B. Snyder et al. PoP 2009



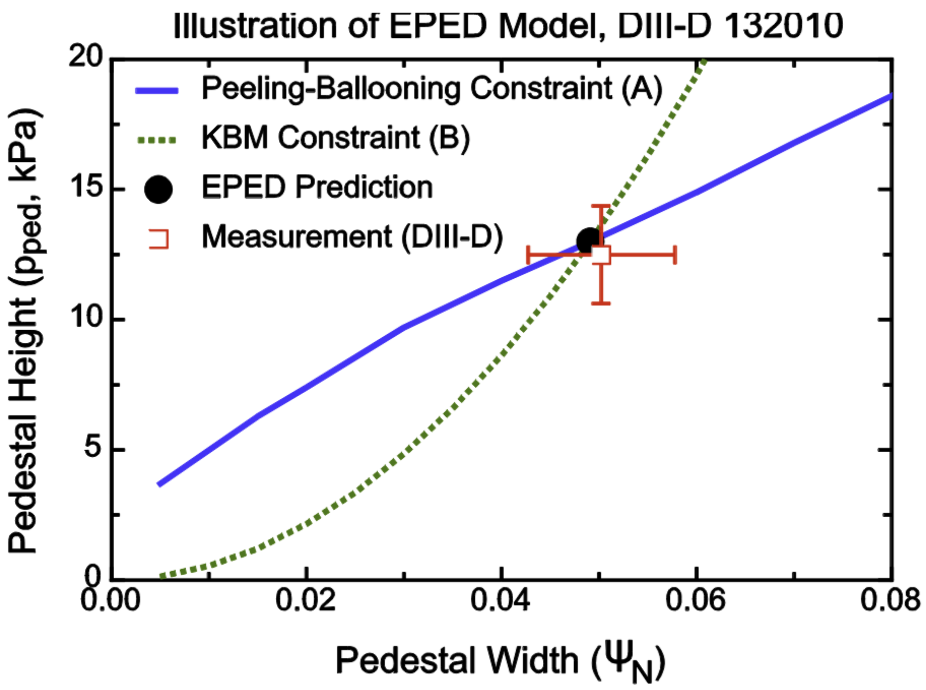
COUPLING OF TRANSPORT AND MHD STABILITY

Create profiles with different widths and heights consistent with transport constraint

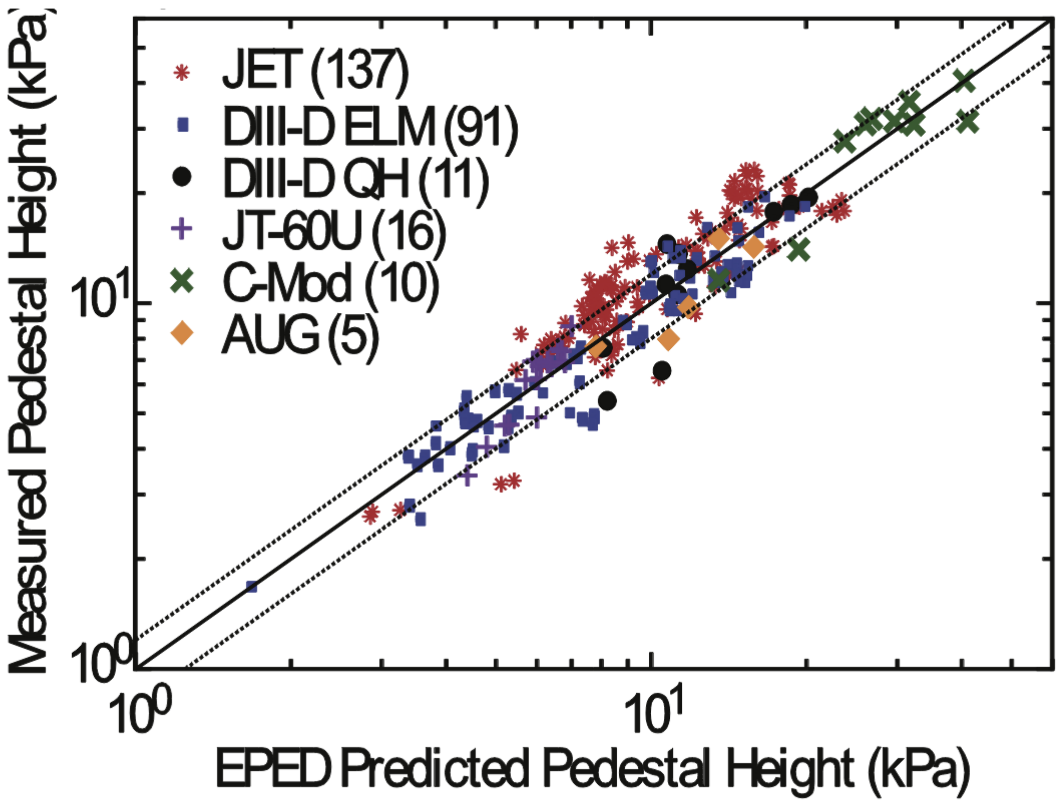
Calculate MHD stability for each point

Find highest stable pedestal pressure
→ **final result**

P.B. Snyder et al. PoP 2009



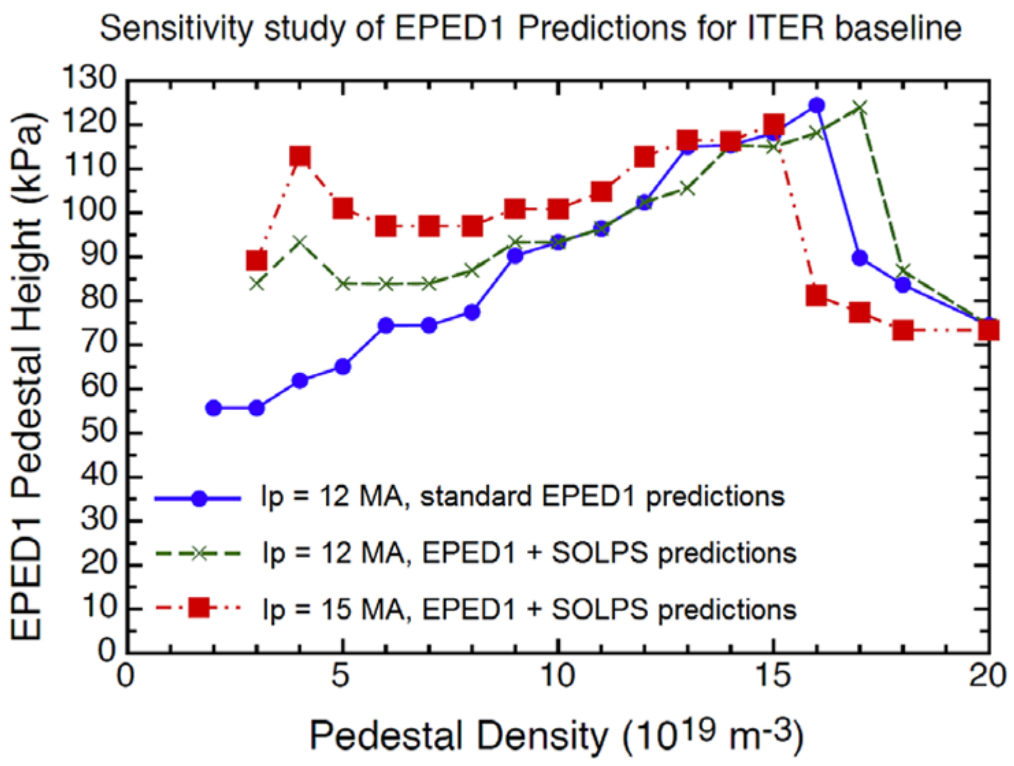
VALIDATION OF EPED ON MULTIMACHINE DATABASE



P.B. Snyder et al. IAEA 2012
R.J. Groebner et al. IAEA 2012

EPED AND THE ITER PEDESTAL

[A. Polevoi *NF* 2015]



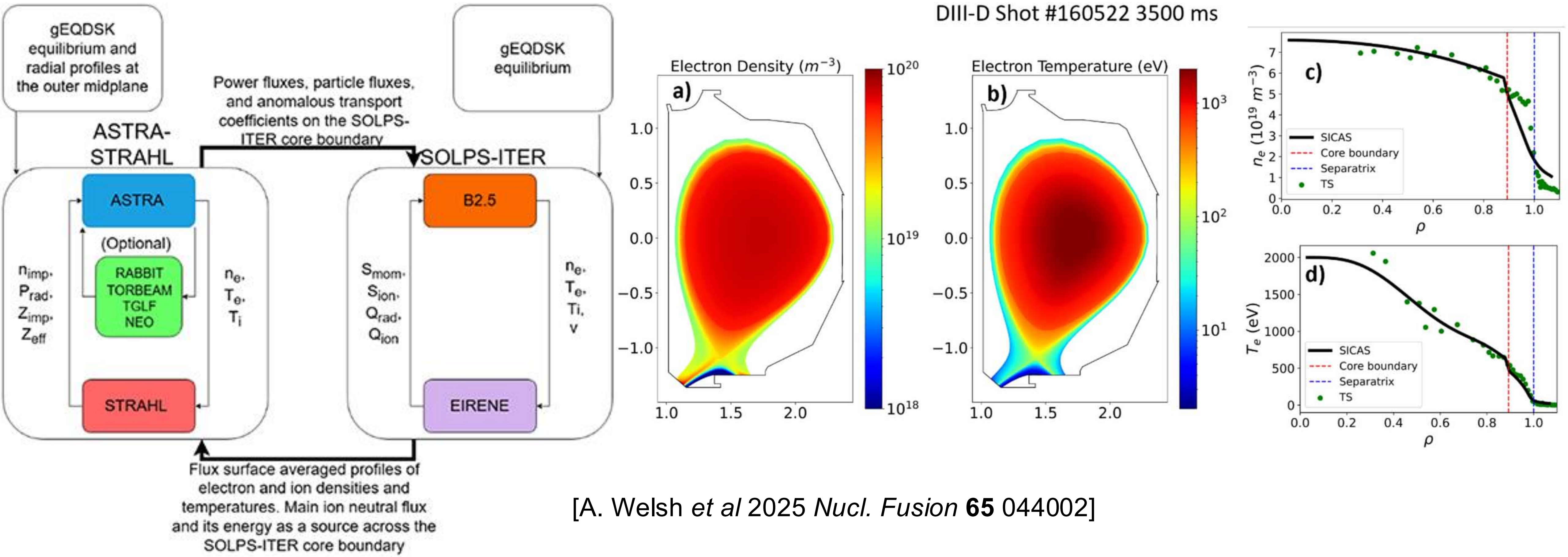
Standard EPED1 predictions:
assumes $n_{e,sep} = 1/4\ n_{e,ped}$

EPED1 + SOLPS predictions:
assumes $n_{e,sep} = 1/2\ n_{e,ped}$

<u>The edge can have an important impact on the pedestal pressure</u>

THE SICAS INTEGRATED MODEL

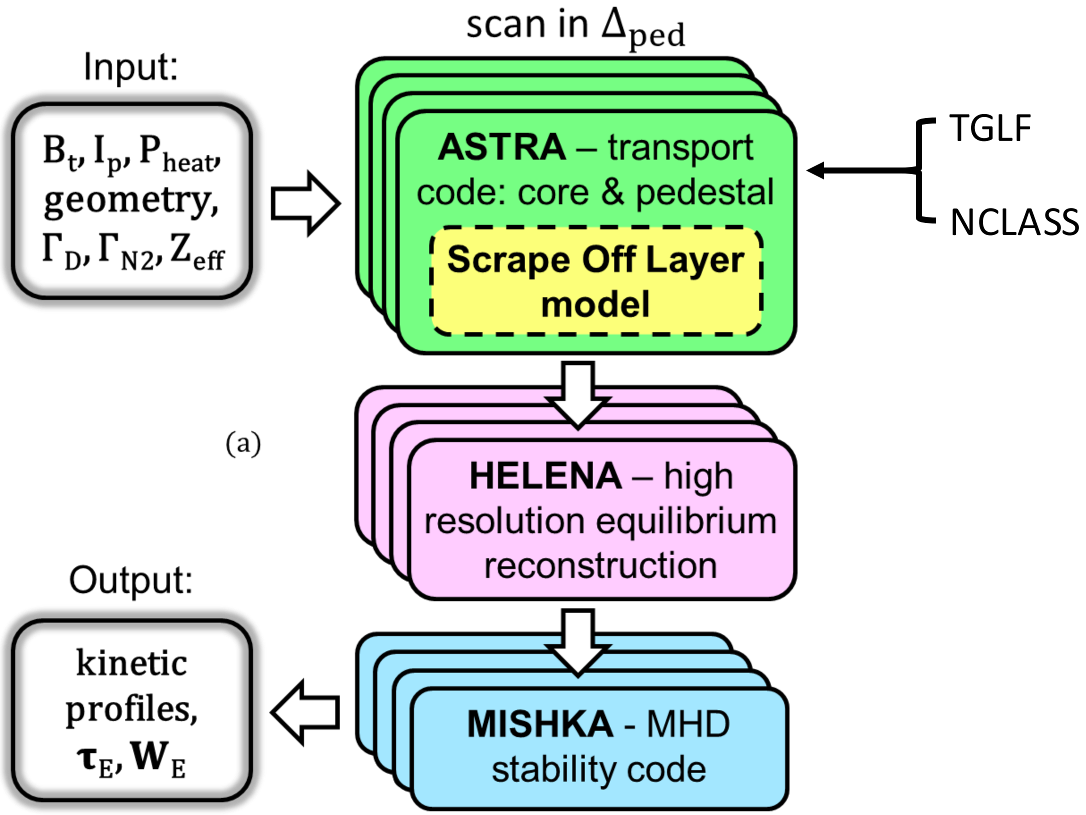
ASTRA + SOLPS-ITER but pedestal scaled to match experimental profiles so far → coupling to EPED planned



[A. Welsh *et al* 2025 *Nucl. Fusion* **65** 044002]

IMEP: INTEGRATED MODEL BASED ON ENGINEERING PARAMETERS

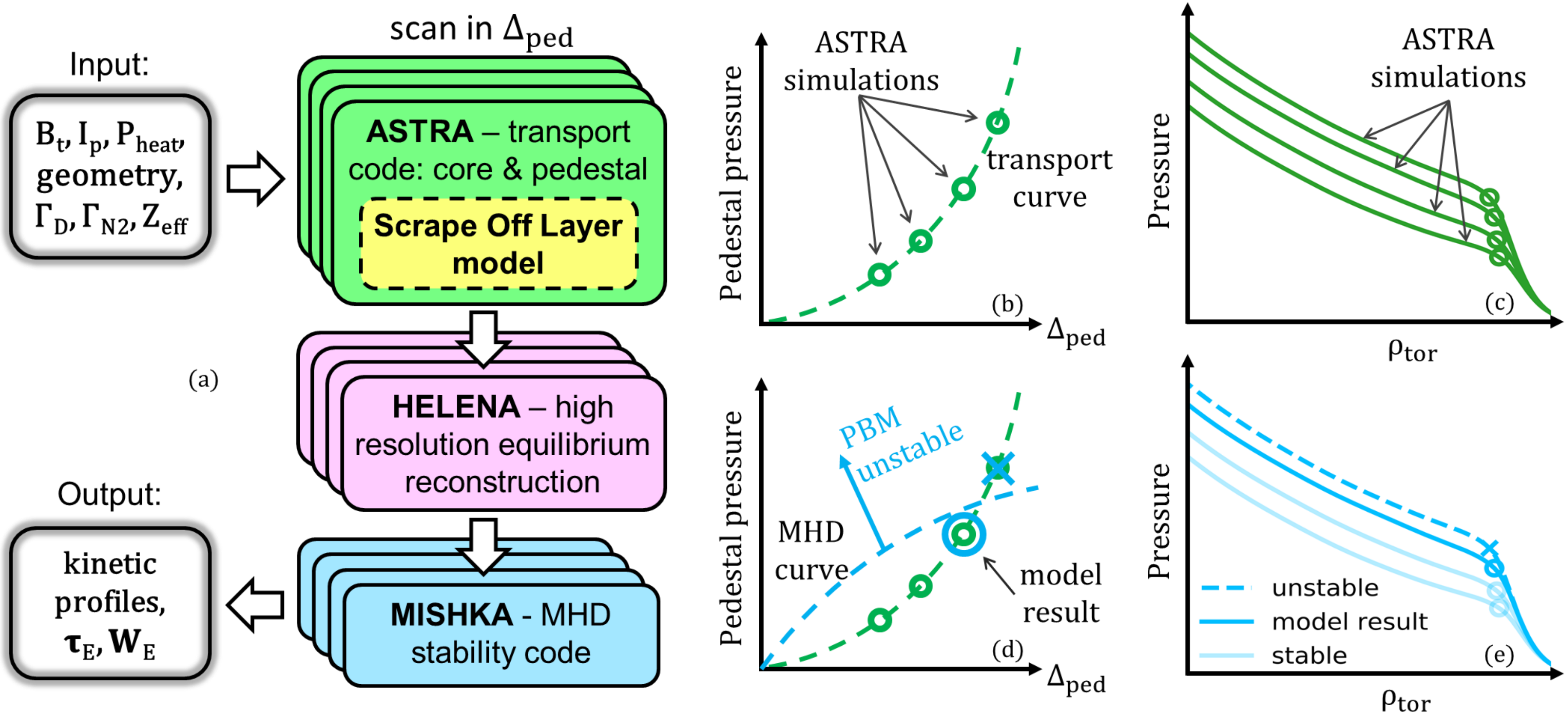
<u>GOAL</u>: **predict H-mode plasma confinement** with more accuracy than empirical scaling laws, using only engineering parameters



[T. Luda *et al* **2020** *NF*, T. Luda *et al* **2021** *NF*, T. Luda *et al* **2023** *PPCF*]

IMEP: INTEGRATED MODEL BASED ON ENGINEERING PARAMETERS

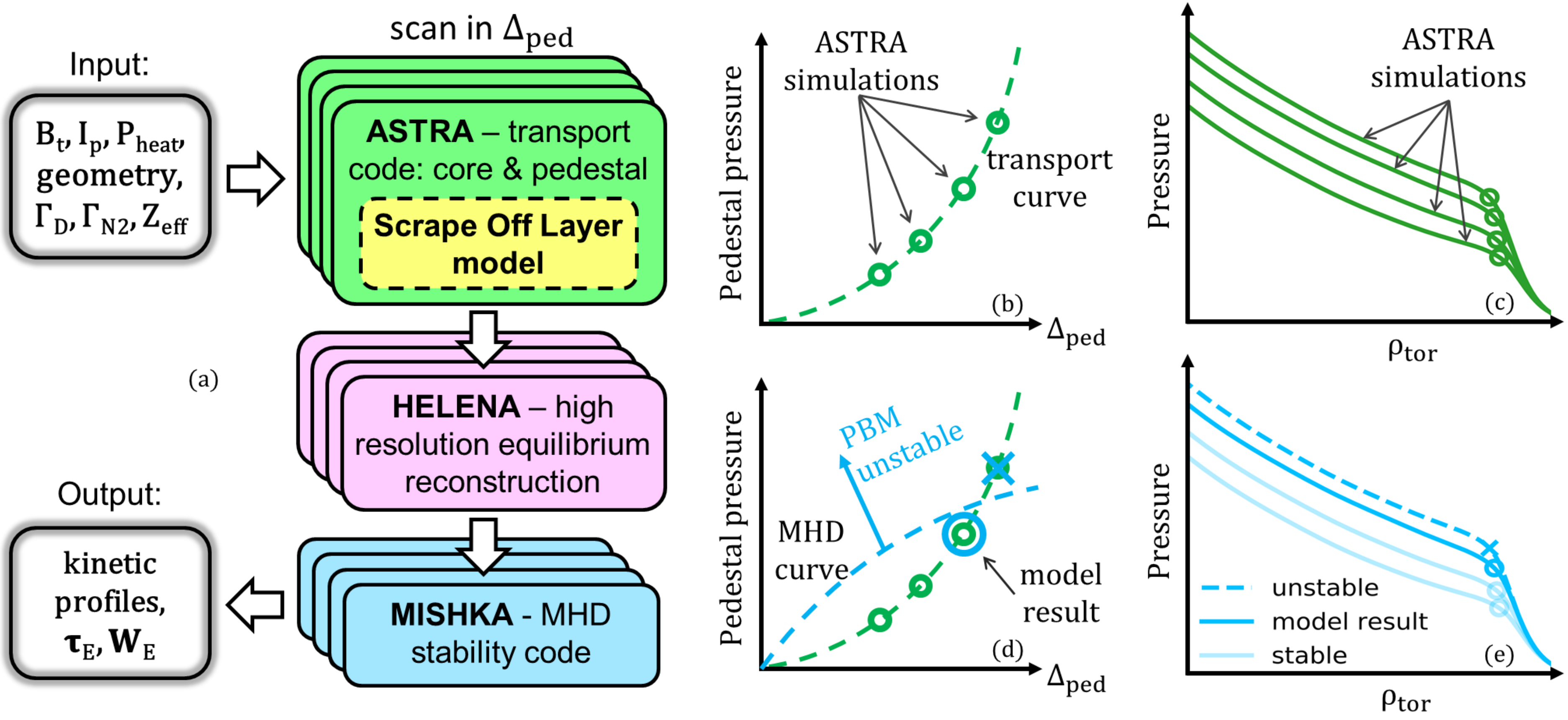
GOAL: **predict H-mode plasma confinement** with more accuracy than empirical scaling laws, using only engineering parameters



[T. Luda *et al* **2020** *NF*, T. Luda *et al* **2021** *NF*, T. Luda *et al* **2023** *PPCF*]

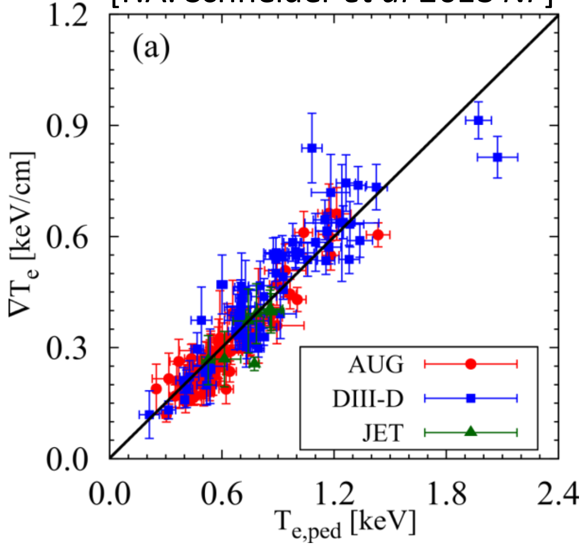
IMEP: INTEGRATED MODEL BASED ON ENGINEERING PARAMETERS

GOAL: **predict H-mode plasma confinement** with more accuracy than empirical scaling laws, using only engineering parameters



[T. Luda *et al* **2020** *NF*, T. Luda *et al* **2021** *NF*, T. Luda *et al* **2023** *PPCF*]

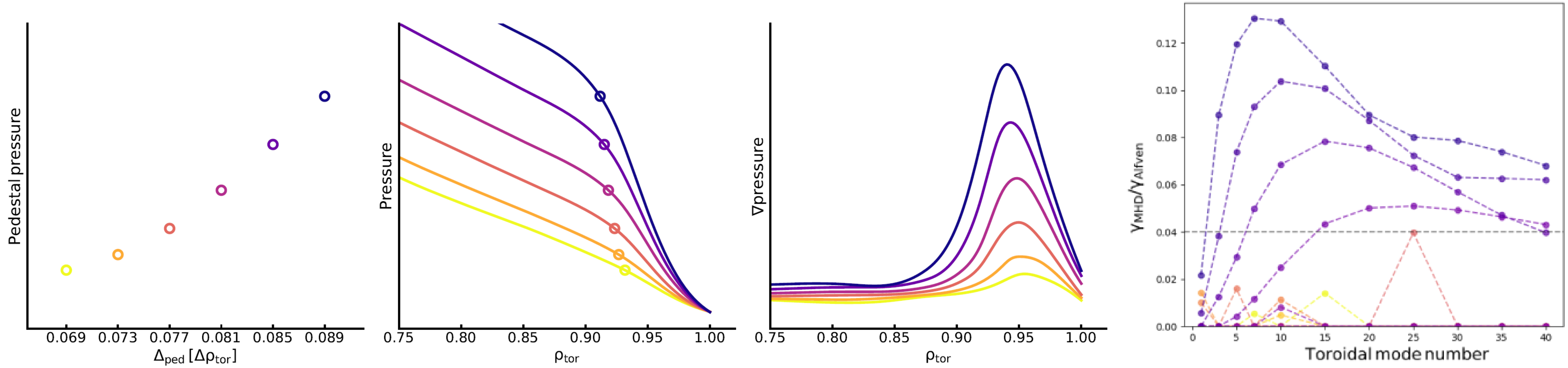
[P.A. Schneider *et al* 2013 *NF*]



$$\frac{R < \nabla T_e >}{T_{e,top}} = -82.5$$

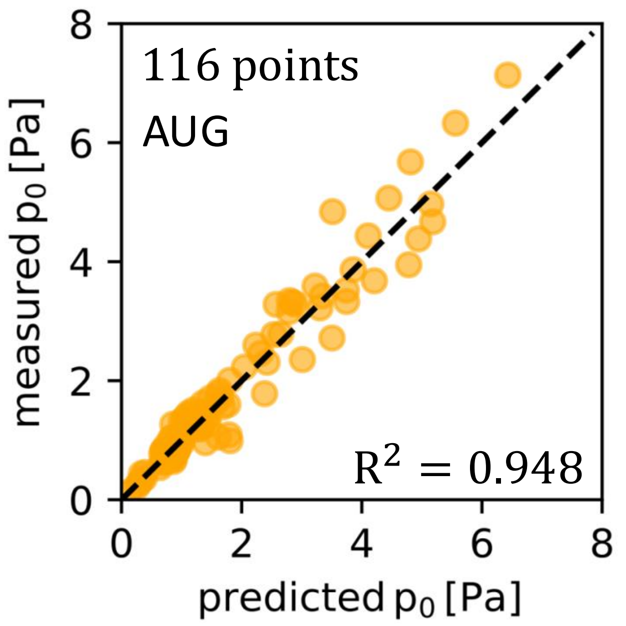
PEDESTAL TRANSPORT MODEL → $p_{top} \propto \Delta_{PED}$

- For every Δ_{ped} of the scan, ASTRA changes $\boldsymbol{\chi_{e,ped}}$ until $\frac{\langle \nabla T_e \rangle}{T_{e,top}} = -0.5$ is satisfied
- The obtained $\chi_{e,ped}$ is used to evaluate $\chi_{i,ped}$: $\boldsymbol{\chi_{i,ped} = \chi_{e,ped} + \chi_{i,NEO}}$
- Modelling of the electron density: $\mathbf{D_{n,ped} = c_{D/\chi}\chi_{e,ped} + D_{n,NEO}}$
- $c_{D/\chi} = 0.06$ and $C_{n,ped} = -0.05$ [m/s] obtained with an **optimization** procedure trying to match different experimental pedestal density profiles



SOL MODEL

Scrape Off Layer model
Gives a relation between gas puffing, separatrix density, and incoming neutral particles



$$\mathbf{p_0} = 0.174\mathbf{\Gamma_D}^{0.63}\mathbf{\Gamma_{N2}}^{-0.057}P_{NBI}^{0.33}v_{pump}^{-0.67}$$

From the 2-point model:

$$\mathbf{T_{e,sep}} = \left(\frac{7P_{sep}\pi q_{cyl}R}{3k_0k_z}\right)^{2/7}$$

[A Kallenbach *et al* 2018 *Nuclear Materials and Energy*]

$$\mathbf{n_{e,sep}} = 0.35\left(\frac{P_{sep}B}{3\pi < \lambda_{q,HD} >< B_p >}\right)^{3/14} \cdot R^{-0.5}(\gamma \sin\alpha)^{-\frac{1}{2}}\left(\frac{2k_0k_z}{7\pi q_{cyl}}\right)^{\frac{2}{7}}\frac{2}{e}\left(\frac{m_D}{2}\right)^{0.5} \cdot \left(1.5 \cdot 10^{23}\,\mathrm{Pa}/(\mathrm{at\,m^{-2}s^{-1}})\right)^{0.5}\mathbf{p_0}^{1/4}$$

Divertor neutral pressure → $\mathbf{p_0}$

$$\mathbf{\Gamma_{0,sep}} = \alpha\left(f_R\mathbf{\Gamma_{e,sep}} + c_{div,wall}\left(\Gamma_D - \Gamma_{pump}\right)\right)$$

α: ionization and CX procceses considering Franck-Condon neutrals ($T_0 = 5$eV)

IMEP MORE ACCURATE THAN IPB98(Y,2) ON AUG

This modeling workflow is tested by simulating **50** H-mode stationary phases from ASDEX Upgrade discharges covering wide variations in:

$\mathbf{B_t}$ = 1.5 - 2.8 [T] $\mathbf{I_p}$ = 0.6 – 1.2 [MA]

$\mathbf{P_{net}}$ = 2 – 14 [MW] $\mathbf{q_{95}}$ = 3 - 8

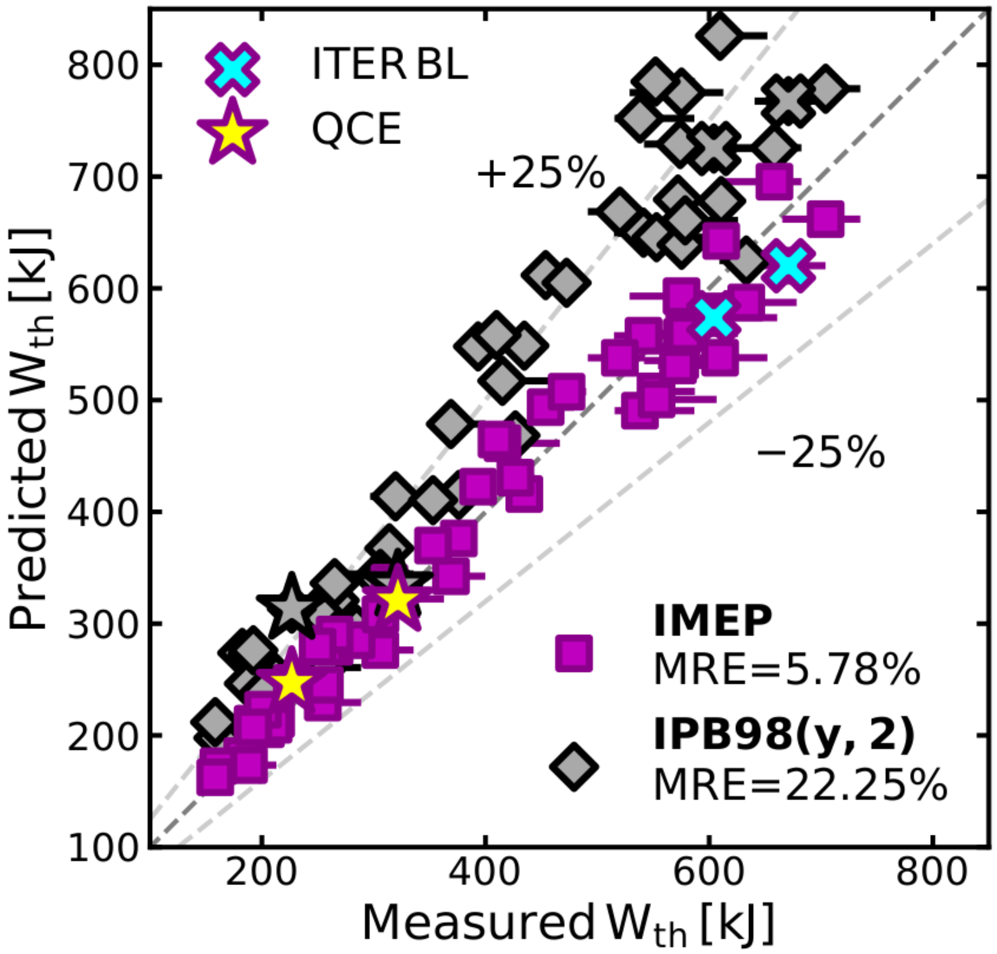
$\mathbf{\Gamma_D}$ = 0 – 8 x 10^{22} [e/s]

$\boldsymbol{\delta}$ = 0.19 – 0.42

$\mathbf{V_{NBI}}$ = 42 - 92 [kV]

IMEP:
- ✓ is **more accurate** with respect to the IPB98(y,2) scaling law
- ✓ can accurately **capture the effect** of the different operational parameters

[T. Luda *et al* **2021** *NF*]



PEDESTAL ENERGY PREDICTED BETTER THAN CORE ENERGY

This modeling workflow is tested by simulating **50** H-mode stationary phases from ASDEX Upgrade discharges covering wide variations in:

B_t = 1.5 - 2.8 [T] **I_p** = 0.6 – 1.2 [MA]

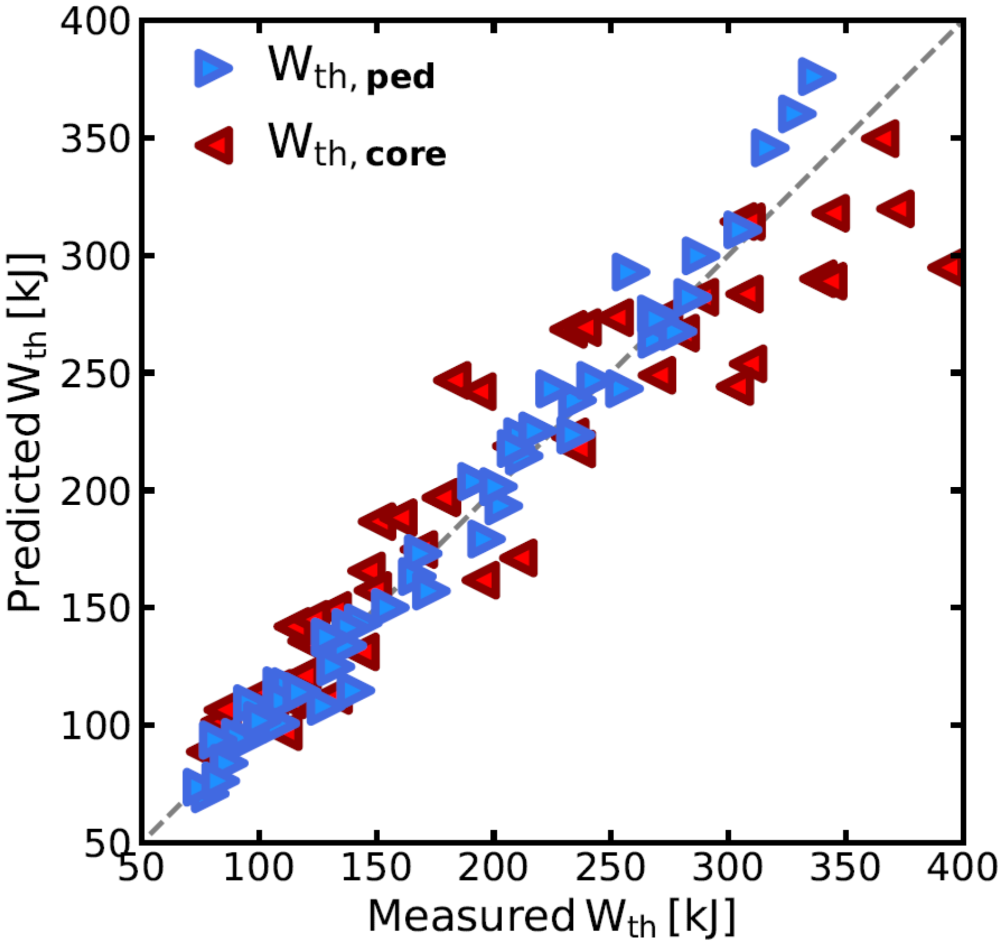
P_{net} = 2 – 14 [MW] **q_{95}** = 3 - 8

Γ_D = 0 – 8 x 10^{22} [e/s]

δ = 0.19 – 0.42

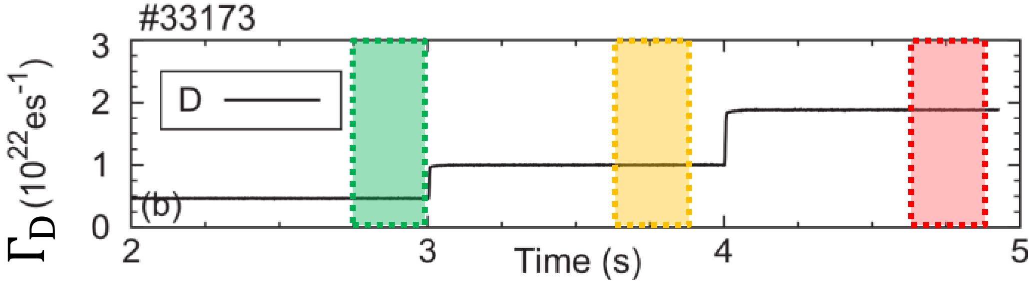
V_{NBI} = 42 - 92 [kV]

This approach can accurately predict the **pedestal energy**, and can describe the effect of the different parameters on pedestal confinement for this database

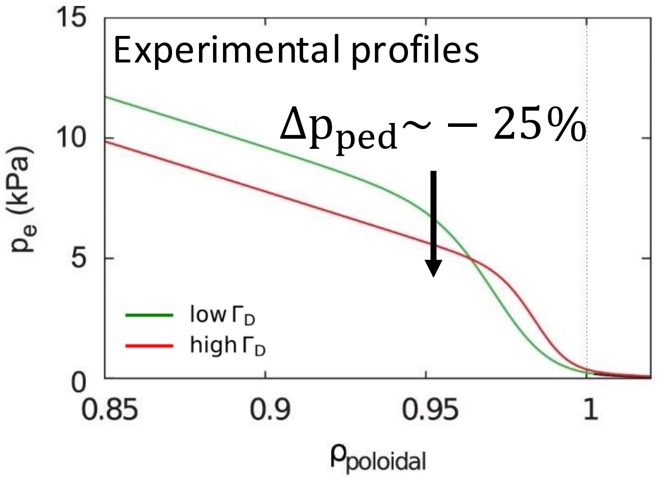


NEGATIVE IMPACT OF FUELING RATE ON PLASMA CONFINEMENT

We focus on an **experimental scan in fueling rate Γ_D**, which shows the typical confinement degradation with gas puff



[M G Dunne et al 2017 Plasma Phys. Control. Fusion]

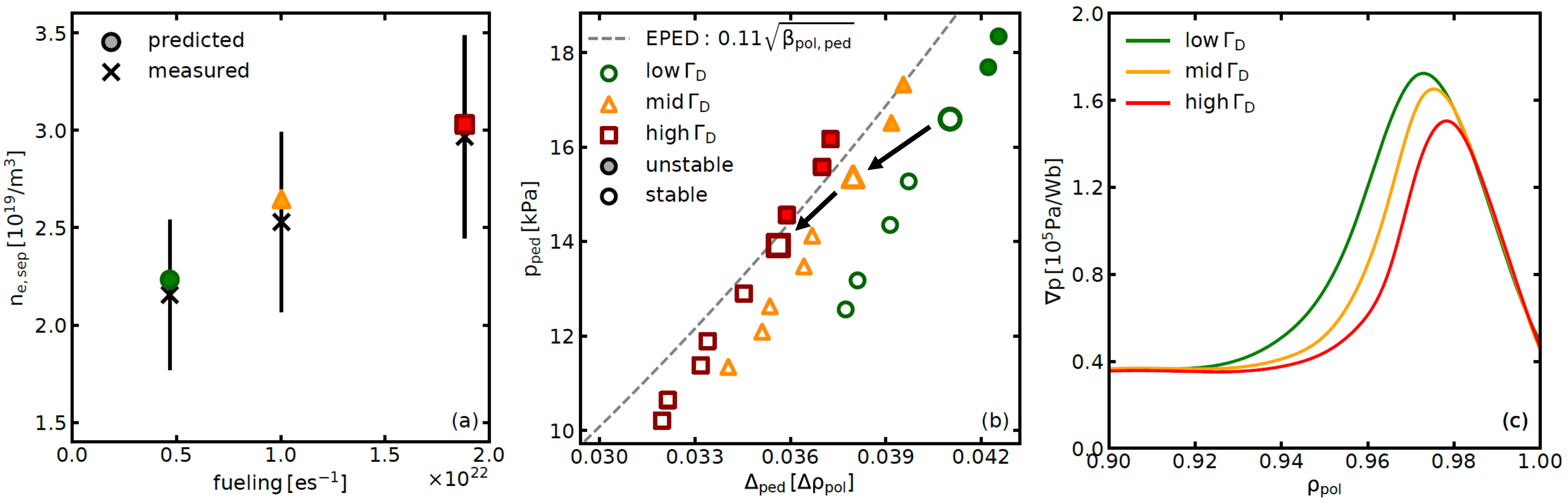


1. The increase in fuelling causes an **increase in $n_{e,sep}$**, and shifts the density profile outwards

2. This shift is also evident in the gradients of the pressure profile, and this has a strong impact on the ballooning stability → the **pedestal pressure decreases**

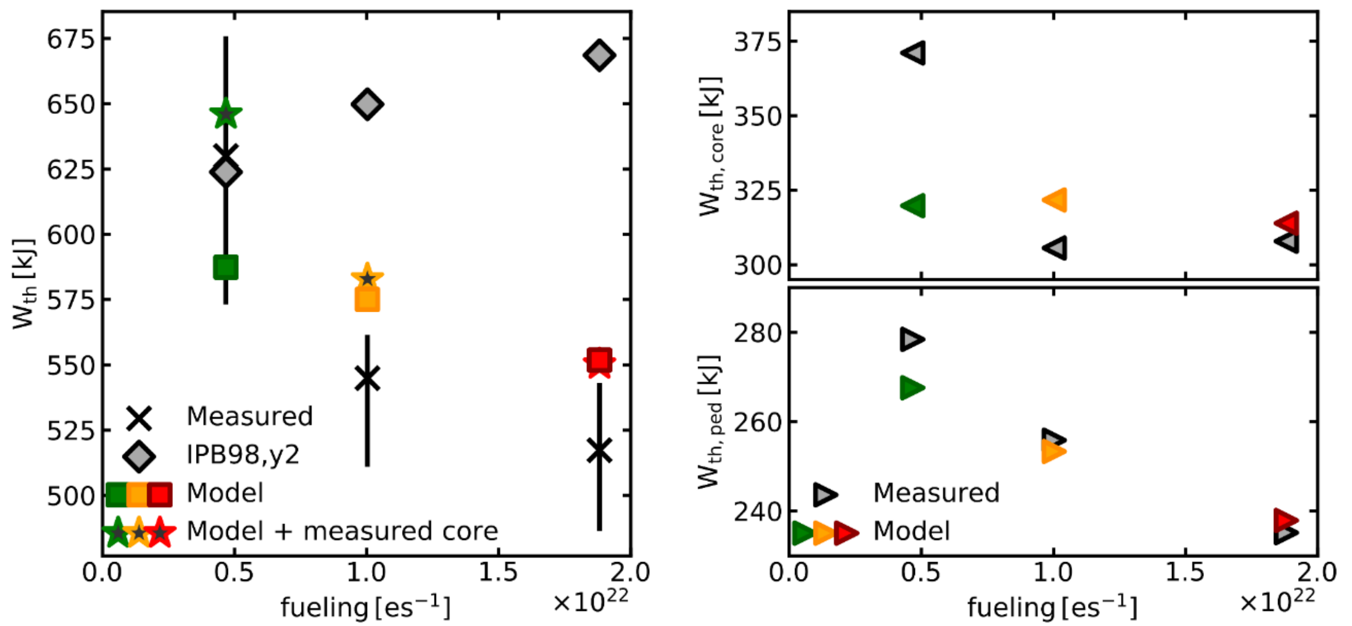
NEGATIVE IMPACT OF FUELING REPRODUCED BY INTEGRATED MODELING

Simulations results



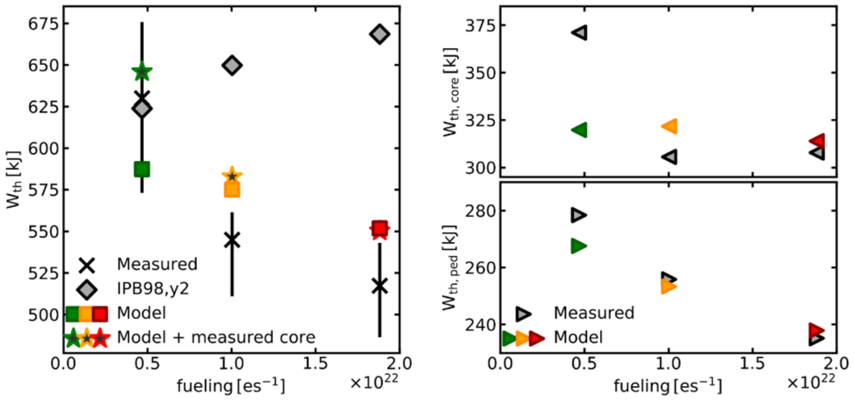
1. The SOL model describes correctly the $n_{e,sep}$ increase with fueling
2. The predicted p_{ped} decreases with increasing fueling
3. This is because of the shift in the peak of the pressure gradients

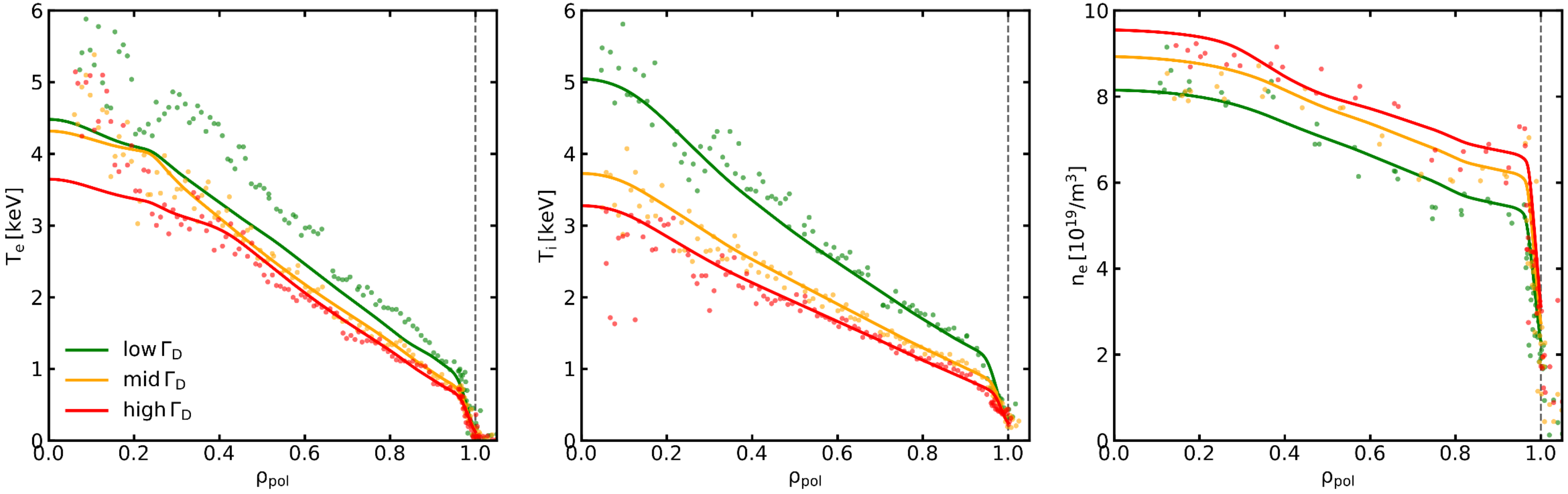
BEYOND THE POSSIBILITIES OF EMPIRICAL SCALING LAWS



4. The change in pedestal energy is well reproduced by the model
5. At lowest fueling the core energy is underpredicted by TGLF
6. Using experimental core profiles we get a very good agreement on W_{th}
7. The IPB98(y,2) scaling law instead predicts an increase in W_{th} due to the positive dependence on the density $\tau_{E,th(IPB98)} \propto n^{0.41}$

CAPTURING THE IMPACT OF FUELING RATE ON THE KINETIC PROFILES





The integrated model also allows us to understand the physics of interdependencies connecting the different plasma regions: **SOL** ⇄ **pedestal** ⇄ **core**

REPRODUCING OTHER SUBTLE EFFECTS: V_{NBI} SCAN

NBI voltage scan: 2 similar discharges with

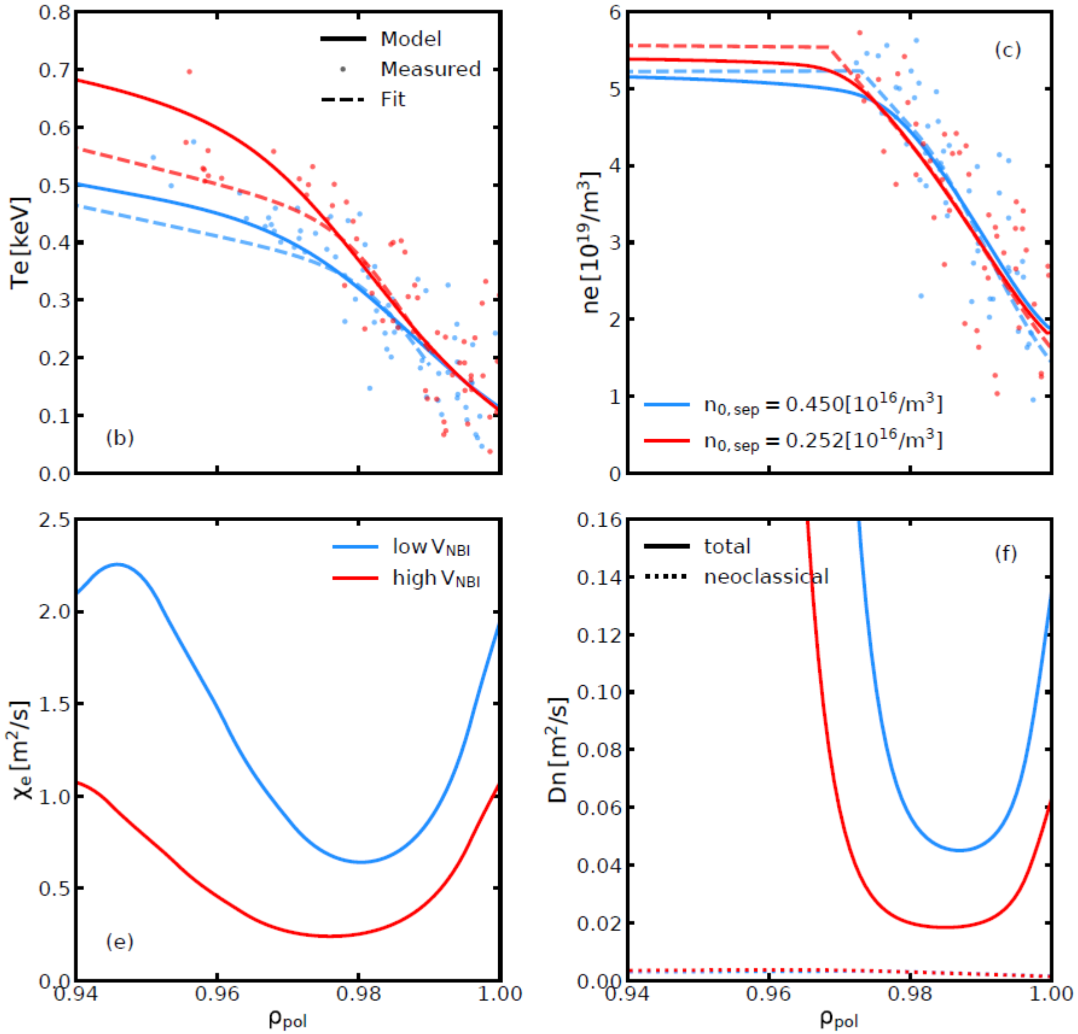
P_{NBI} = 5 [MW], **V_{NBI} = 42 [kV],** **V_{NBI} = 92 [kV],** $S_{n,\ V=42[kV]} \approx 2x S_{n,\ V=92[kV]}$

8 NBI sources **3 NBI sources**

REPRODUCING OTHER SUBTLE EFFECTS: V_{NBI} SCAN

NBI voltage scan: 2 similar discharges with

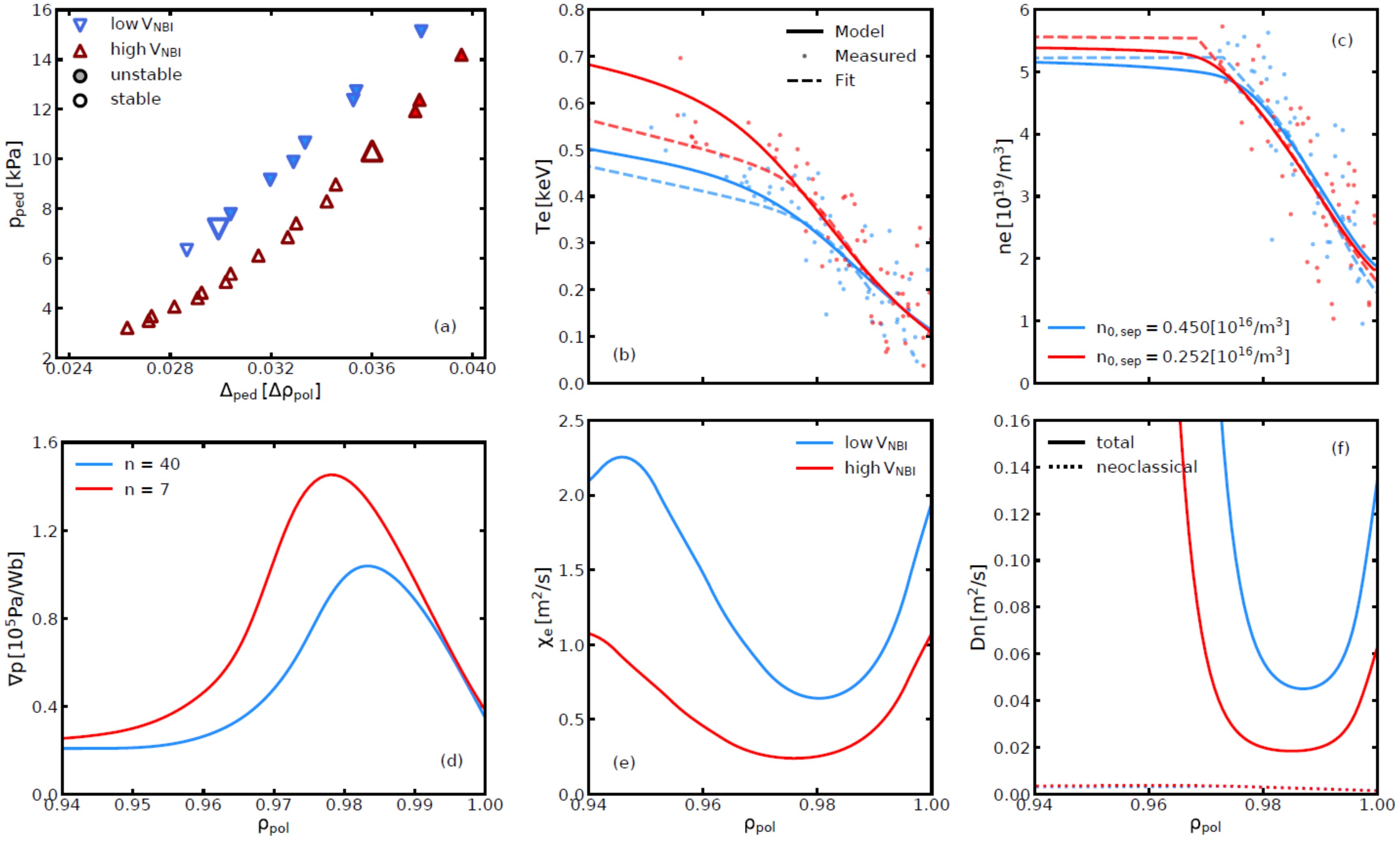
P_{NBI} = 5 [MW], V_{NBI} = 42 [kV], V_{NBI} = 92 [kV], $S_{n, V=42[kV]} \approx 2xS_{n, V=92[kV]}$



REPRODUCING OTHER SUBTLE EFFECTS: V_{NBI} SCAN

NBI voltage scan: 2 similar discharges with

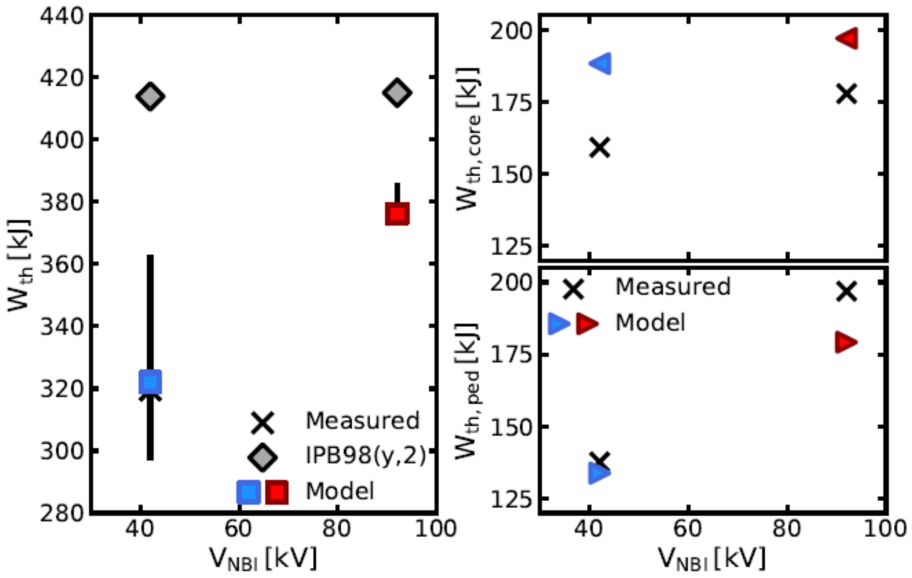
P_{NBI} = 5 [MW], V_{NBI} = 42 [kV], V_{NBI} = 92 [kV], $S_{n, V=42[kV]} \approx 2xS_{n, V=92[kV]}$



REPRODUCING OTHER SUBTLE EFFECTS: V_{NBI} SCAN

NBI voltage scan: 2 similar discharges with

P_{NBI} = 5 [MW], **V_{NBI} = 42 [kV],** **V_{NBI} = 92 [kV],** **$S_{n, V=42[kV]}$** ≈ 2x**$S_{n, V=92[kV]}$**



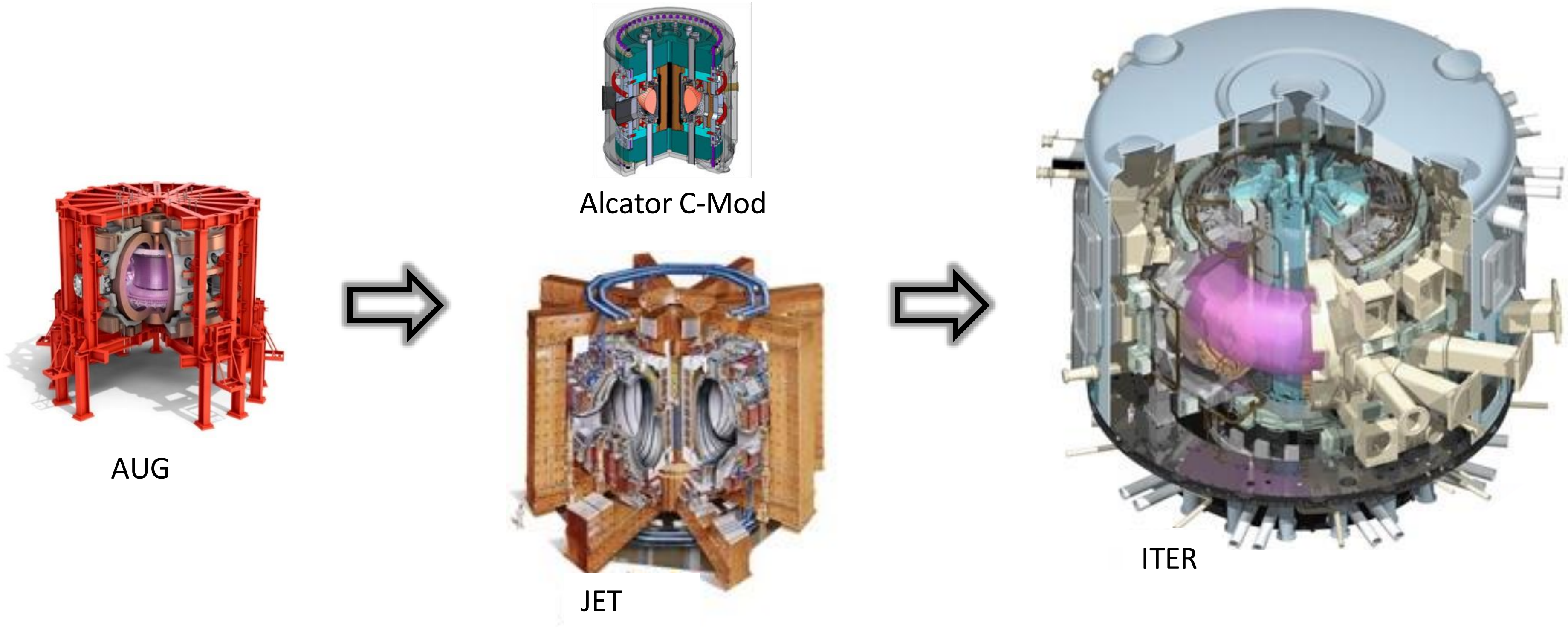
The model **well captures** the change in confinement caused by the NBI voltage scan

IPB98(y,2) predicts **no change** in confinement with V_{NBI}

This case demonstrates again of how important it is to take into account core, pedestal, and SOL effects self-consistently: **SOL** ⇄ **pedestal** ⇄ **core**

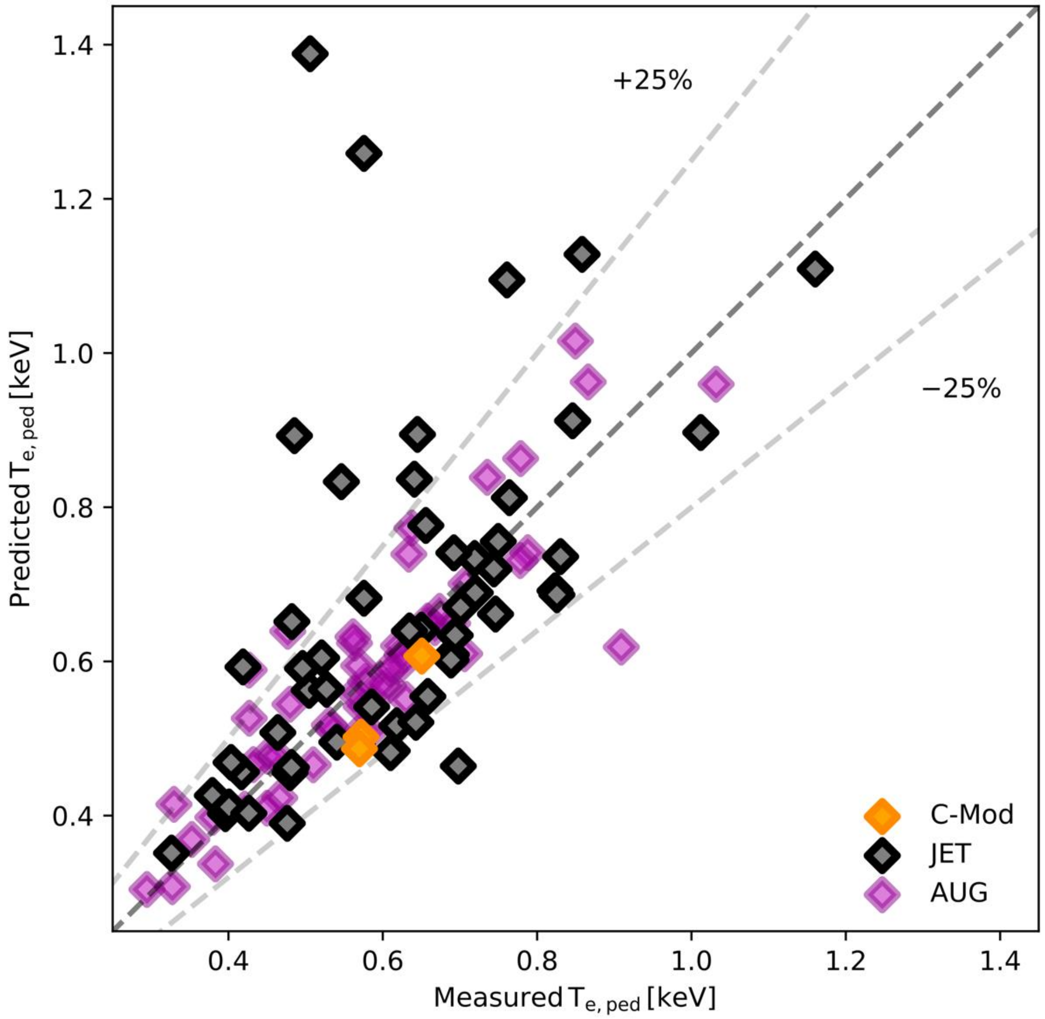
Change in core particle **transport** and **sources** with different V_{NBI} ⇒ Change in SOL **neutrals** via recycling ⇒ Change in **pedestal** MHD stability and global **confinement**

EXTENSION OF IMEP TO OTHER DEVICES



The application to C-Mod and JET allows the inclusion of a large variation of **machine size** (R) to further validate IMEP in order to make more accurate predictions for ITER and DEMO

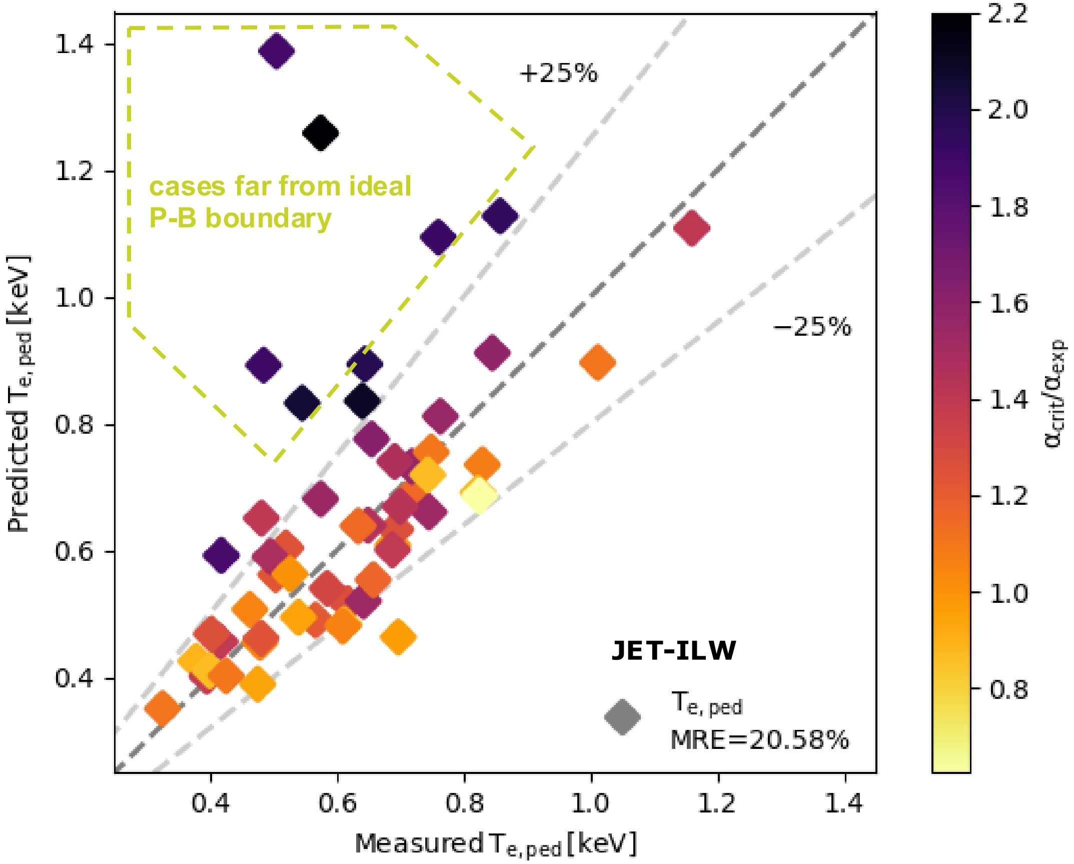
PEDESTAL TOP TEMPERATURE PREDICTION: C-MOD, AUG, JET



Similar accuracy in Te,ped prediction for AUG, C-Mod and JET-ILW ELMy H-modes, except for a few cases…

[T. Luda *et al* **2023** *PPCF*]

PEDESTAL TOP TEMPERATURE PREDICTION: JET-ILW



Highly overpredicted cases are far from ideal P-B boundary → correspond to $\frac{\alpha_{crit}}{\alpha_{exp}} > 1.6$

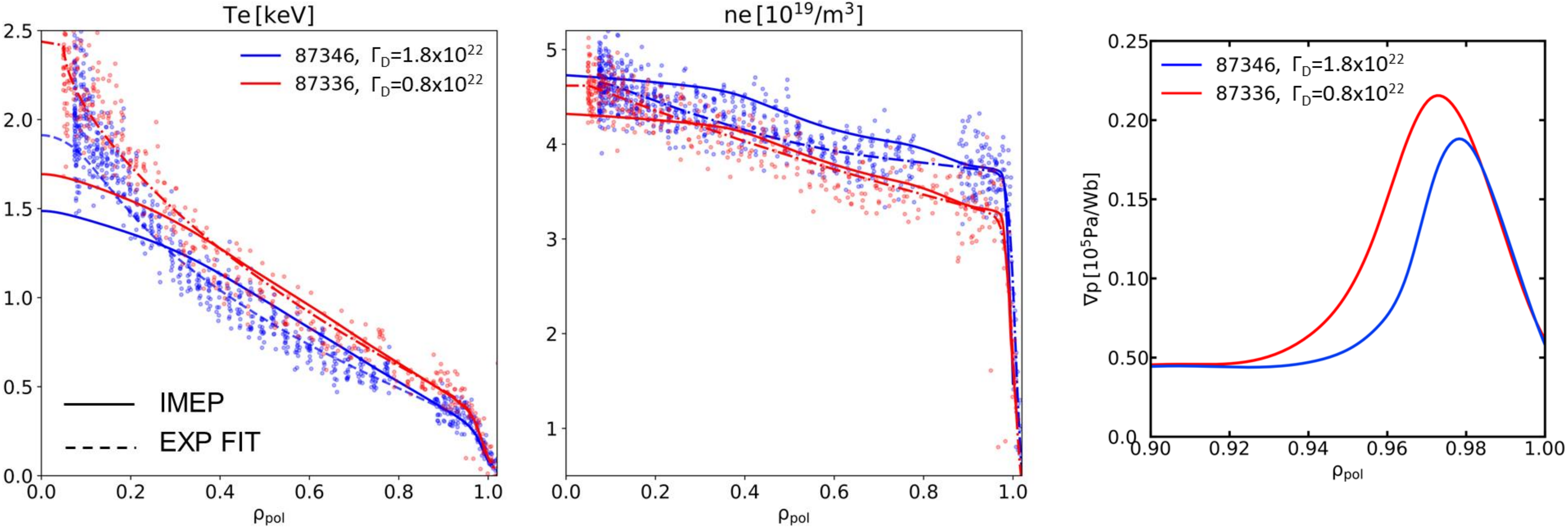
$$\alpha = -2 \times \frac{Rq^2}{B^2}\frac{dp}{dr}$$

$\alpha_{crit}/\alpha_{exp}$ values from stability analysis as in L. Frassinetti IAEA paper [Frassinetti *NF* 2021]

Cases at high $\alpha_{crit}/\alpha_{exp}$ correspond to high resistivity → ideal MHD (MISHKA) not sufficient → resistive MHD (CASTOR) reproduces experimental pedestal pressure [Nystrom *NF* 2022]

Coupling CASTOR to IMEP to improve accuracy

JET FUELING SCAN AT 1.4MA/1.7T – NBI 4.7 MW

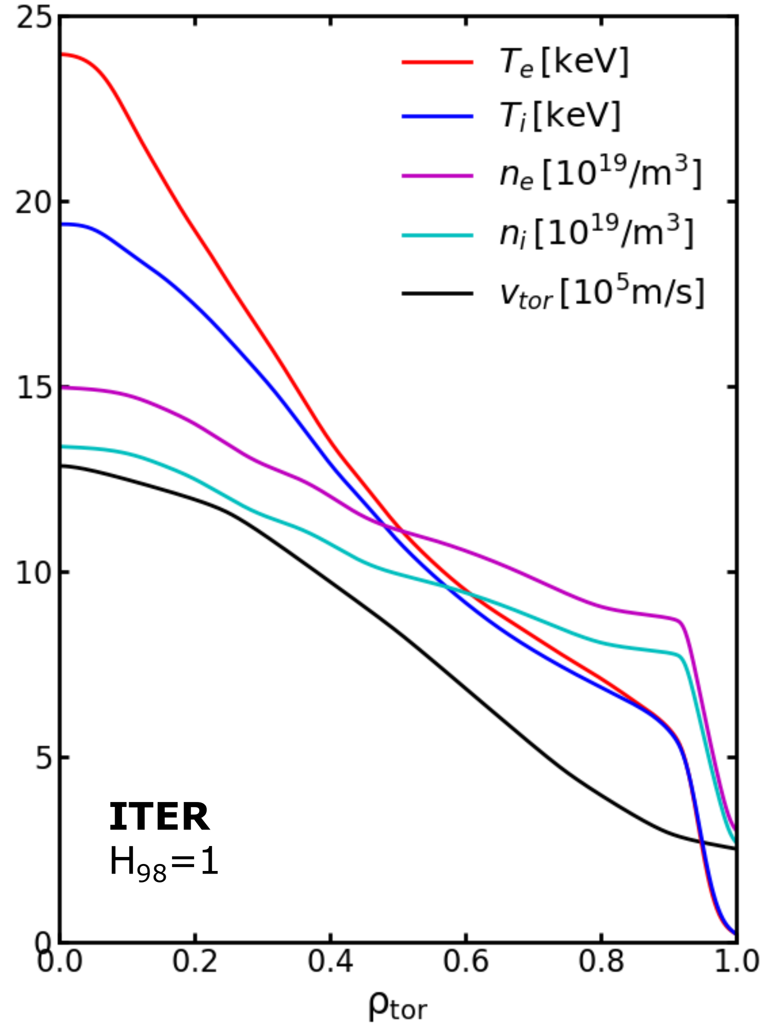


– Higher fueling rate causes the density profile to **shift outwards** (closer to the separatrix)

– Peak of pressure gradient shifts outwards, **destabilizing ballooning modes**

– **Decrease of pedestal pressure** with higher fueling rate, consistent with stability analysis from [Maggi *NF* 2015]

ITER Q=10 SCENARIO PREDICTION



Prediction for **ITER** 15MA baseline (B_t=5.3T, R=6.2m):

- separatrix values (similar to SOLPS simulation results):

  $\mathbf{n_{e,sep}}$ = 3 [10^{19}/m^3] $\mathbf{T_{e,sep}}$ = $\mathbf{T_{i,sep}}$ = 200 [eV]

- $\mathbf{n_{e,top}}$ = 8.5 [10^{19}/m^3]

- $\mathbf{P_{ECRH}}$ = 20 [MW] $\mathbf{P_{NBI}}$ = 30 [MW]

- **Pellets** given by Gaussian centered at ρ_{tor} = 0.85

- **50/50 DT**, $\mathbf{c_{He}}$ = 5%, $\mathbf{c_B}$ = 1%, $\mathbf{c_W}$ = 10^{-5} → $\mathbf{P_{rad}}$ = 39 [MW], $\mathbf{Z_{eff}}$ = 1.4

- Toroidal rotation profile $\mathbf{v_{tor}}$ from [C. Chrystal **2020** *NF*]

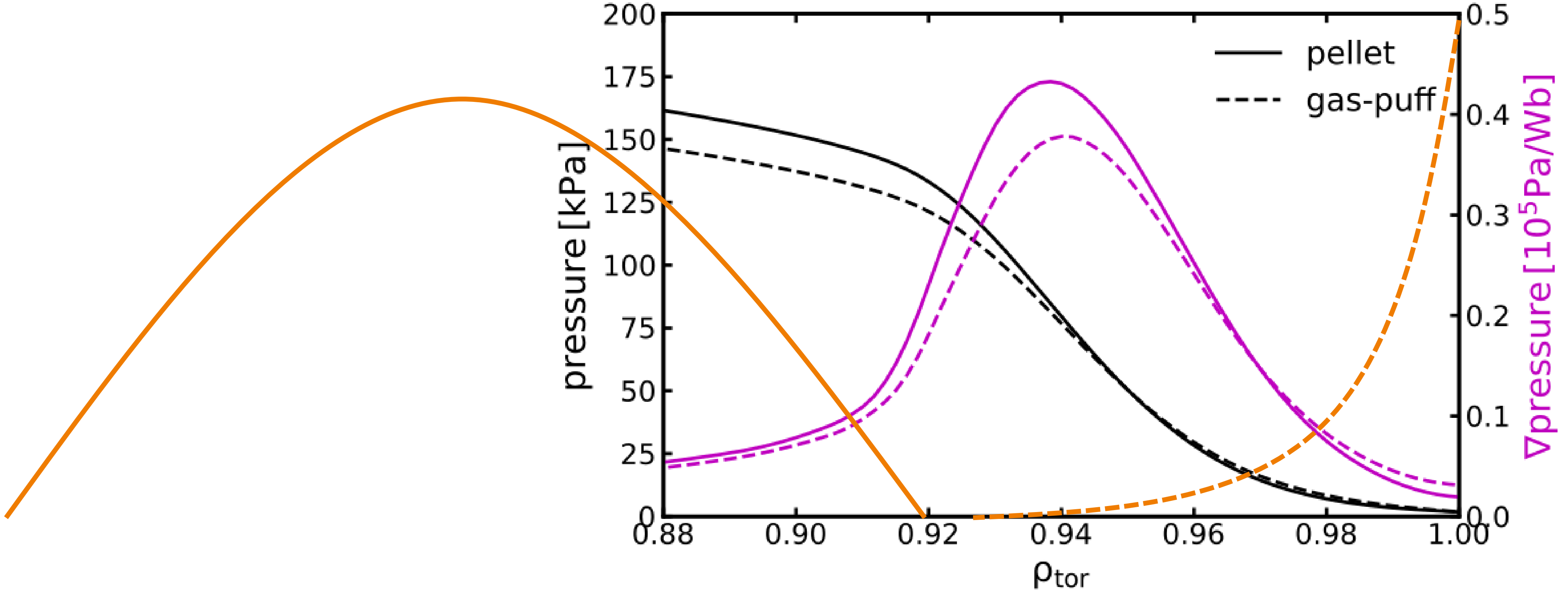
- Pedestal top pressure $\mathbf{p_{top}}$=141kPa (similar to EPED, also similar Δ_{ped}),

  $T_{e,top}$= $T_{i,top}$ =5.5keV, H_{98}=1, $\mathbf{P_{fus}}$=600MW, and **Q=12**

ITER Q=10 SCENARIO PREDICTION – PARTICLE SOURCE

Effect of **particle source location** on pedestal pressure (in these simulations):

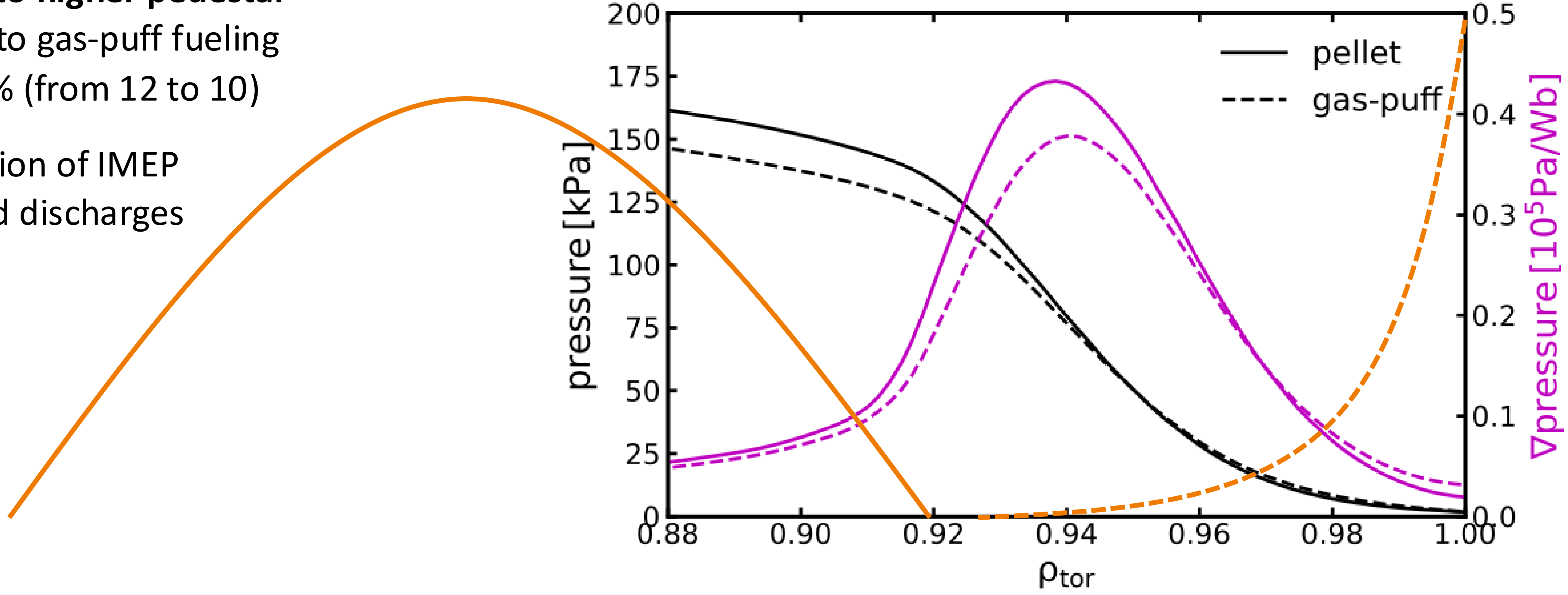
– Pellet source localized near pedestal top (solid), gas-puff source localized near separatrix (dashed)



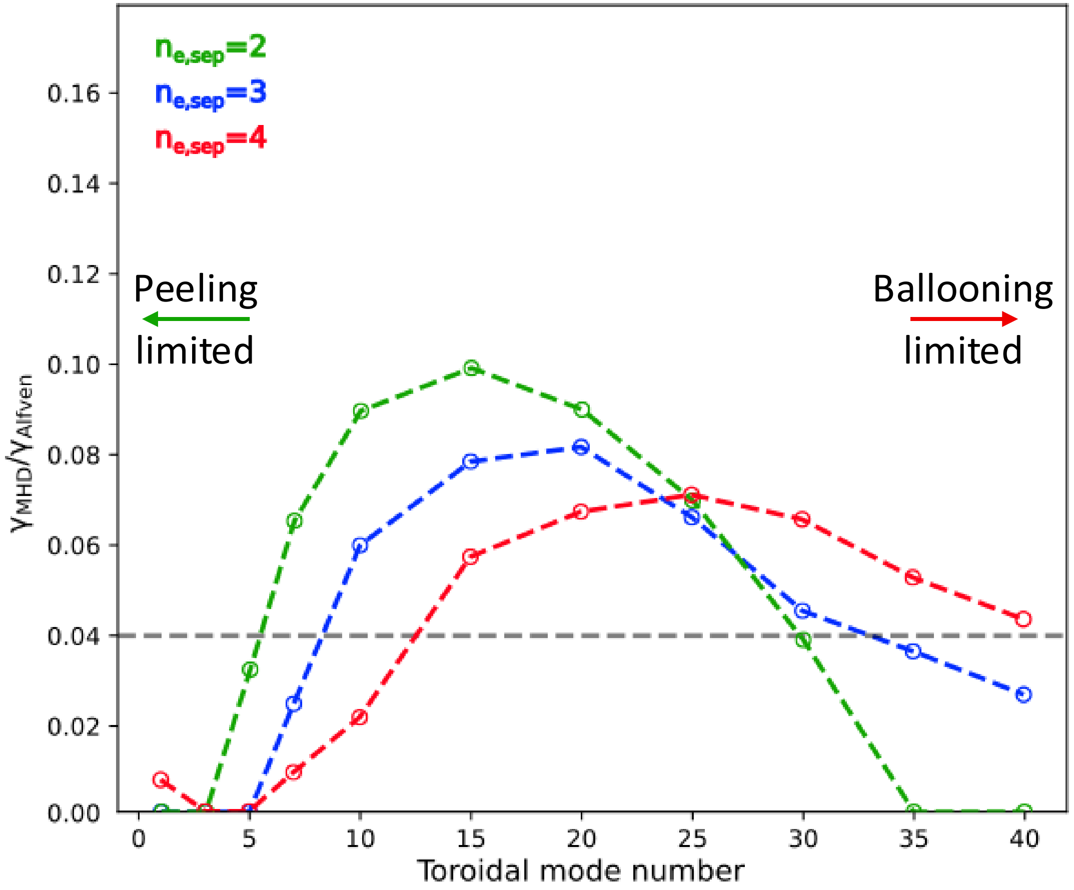
ITER Q=10 SCENARIO PREDICTION – PARTICLE SOURCE

Effect of **particle source location** on pedestal pressure (in these simulations):

- Pellet source localized near pedestal top (solid), gas-puff source localized near separatrix (dashed)
- Change in location changes **shape of pedestal density profile**: switching from gas-puff to pellets → peak of pressure gradient moves towards pedestal top (density shift) → stabilize ballooning modes → increase pedestal pressure
- **Pellet fueling leads to higher pedestal** pressure compared to gas-puff fueling → Q changes by 20% (from 12 to 10)
- Future work: validation of IMEP on AUG pellet fueled discharges



ITER Q=10 SCENARIO PREDICTION – SEPARATRIX DENSITY



- Scan in separatrix density $n_{e,sep} \in \{2,3,4\}$x10^{19}m^{-3}
- Pedestal pressure remains unvaried p_{ped}=141kPa
- Pedestal becomes more ballooning unstable: $n_{e,sep} \uparrow \rightarrow \nu_{eff} \uparrow, \nabla n \downarrow \rightarrow j_{BS} \downarrow$
- Further reduction of $n_{e,sep}$ does not change spectra → possible saturation of j_{BS} with ν_{eff} [P. Maget *NF* 2013]
- ITER pedestal is found to be more ballooning than peeling limited (consistent with [P. Maget *NF* 2013], [S. Saarelma *NF* 2012])

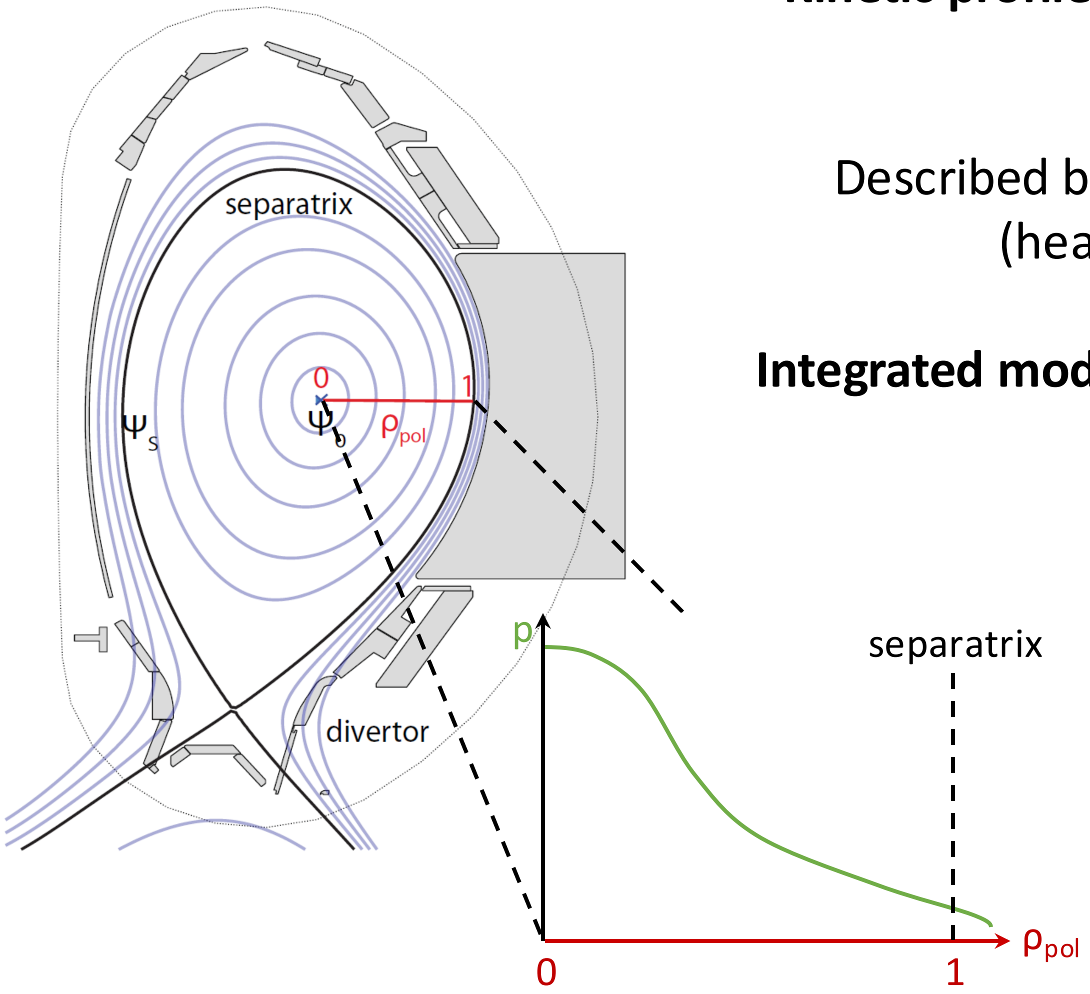
SUMMARY

- Fusion power strongly depends on pedestal top pressure due to stiff core transport
- Pedestal pressure can strongly depend on separatrix density
- Separatrix density also strongly affects power exhaust
- Important to model edge, pedestal, core self consistently in integrated models to find core-edge compatibility → many many examples existing of integrated models I did not mention!
- Predictive pedestal models can reasonably well reproduce experimental pedestals from present tokamaks → current predictions for future machines from different models are in good agreement
- Exciting times for integrated modeling → looking forward to see future developments also thanks to **your efforts!**


…feel free to ask
anything!

BACKUP

PLASMA PROFILES



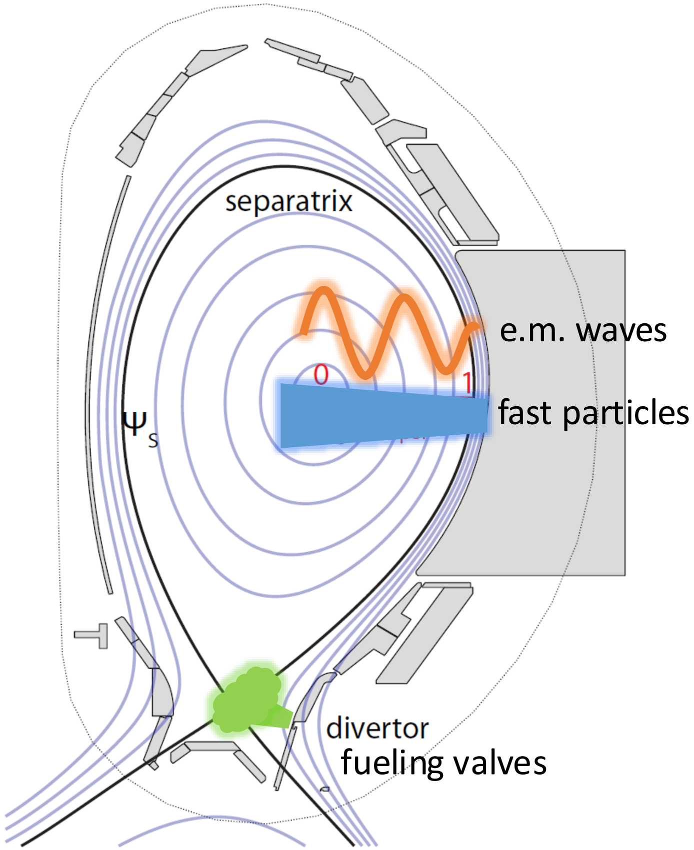
Kinetic profiles (p,n,T,v) determined by balance between sources and transport

Described by **1D equations** → transport code (heat, particle, momentum transport)

Integrated models combine different modules to simulate the confined plasma:

- Magnetic **equilibrium** reconstruction

PLASMA PROFILES



Kinetic profiles (p,n,T,v) determined by balance between sources and transport

Described by **1D equations** → transport code (heat, particle, momentum transport)

Integrated models combine different modules to simulate the confined plasma:

- Magnetic **equilibrium** reconstruction

- Realistic description of **sources**

- Models for calculation of **transport coefficients** (neoclassical and turbulent transport)