EUROfusion

# Joint experiments tailoring the plasma evolution to maximise the pedestal performance

IT Chapman[1], A Merle[2], S Saarelma[1], R Cesario[3], S Coda[2], J Connor[1], E de la Luna[4], R Fisher[6], L Garzotti[1], C Ham[1], RJ Hastie[1], J Hobirk[5], A Kirk[1], C Maggi[1], O McCormack[7], M Peterka[8], O Sauter[2], R Scannell[1], J Simpson[1], E Solano[3], A Thornton[1], H Urano[9], W Wright[10], JET Contributors*, the MAST Team[1], the TCV Team[7], and the EUROfusion MST1 team

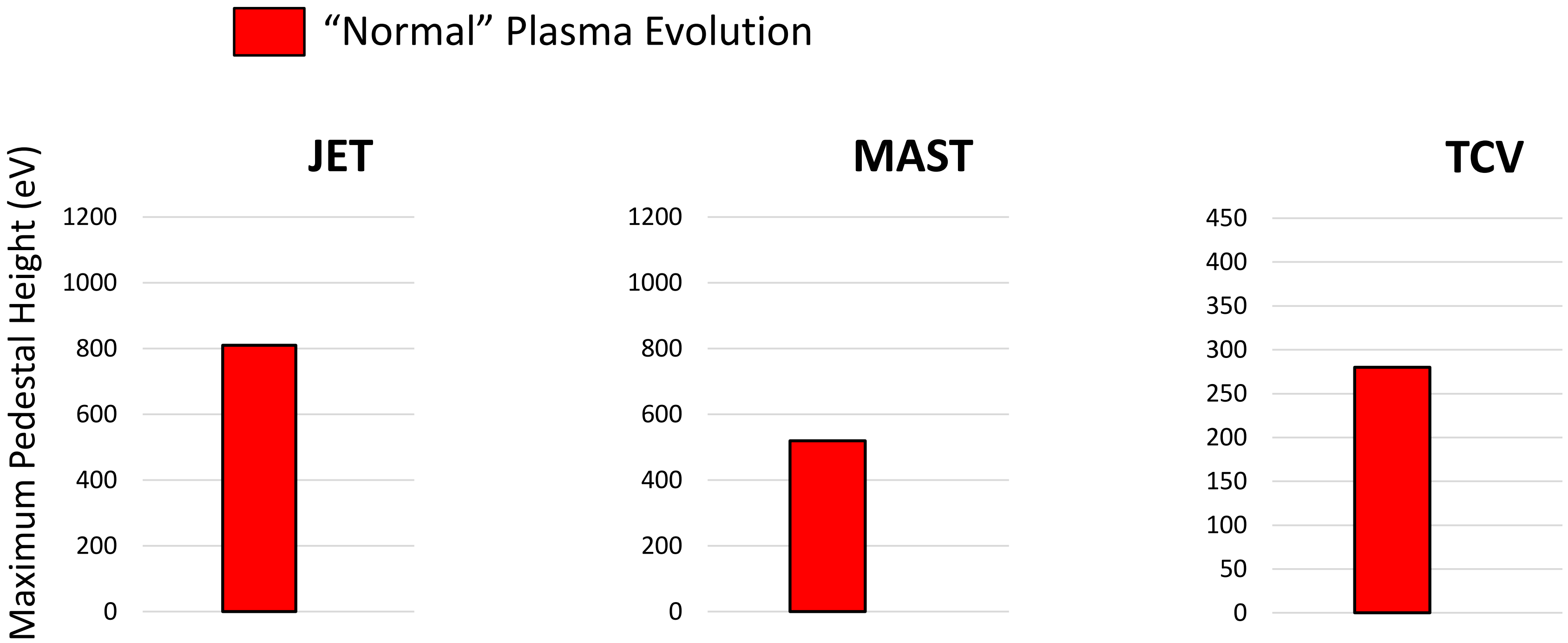
*EUROfusion Consortium, JET, UK; [1] CCFE, UK Atomic Energy Authority, UK; [2] ENEA Frascati, Italy; [3] Swiss Plasma Centre, EPFL, Switzerland; [4] Laboratorio Nacional de Fusión, CIEMAT, Spain; [5] Max-Planck-Institut für Plasmaphysik, Garching, Germany; [6] University of Bath, UK; [7] Consorzio RFX, Padova, Italy; [8] Institute of Plasma Physics of the CAS, Prague, Czech Republic; [9] QST, Naka, Japan; [10] Durham University, UK*

** See appendix of X Litaudon et al Proc 26th IAEA Fusion Energy Conference 2016*

JET SWISS PLASMA CENTER CCFE CULHAM CENTRE FOR FUSION ENERGY

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

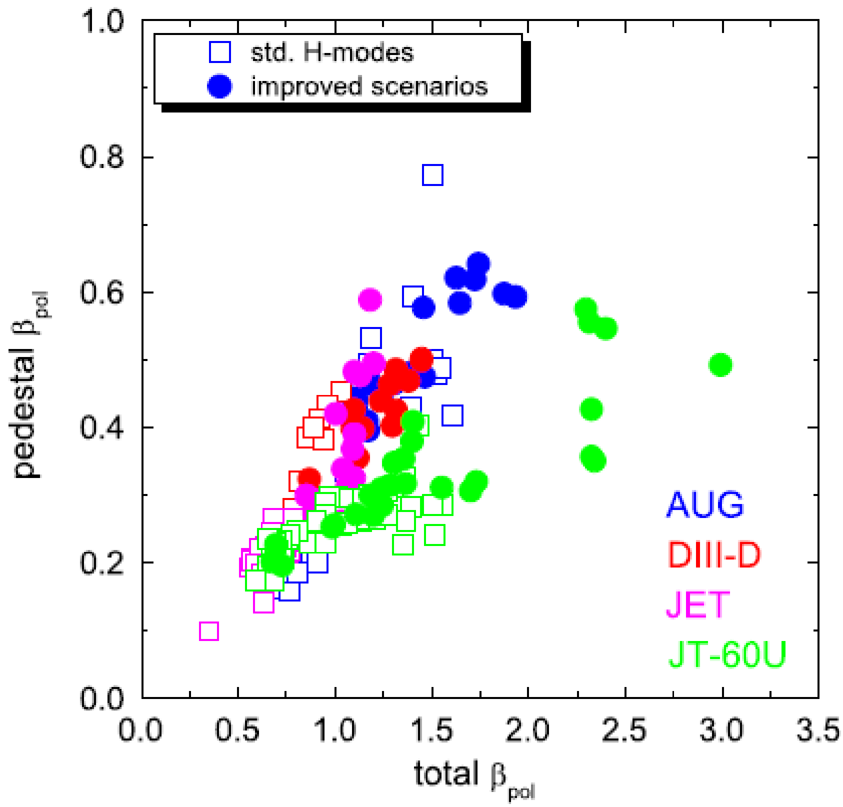
# Achieved significant increase in pedestal height by tailoring plasma evolution



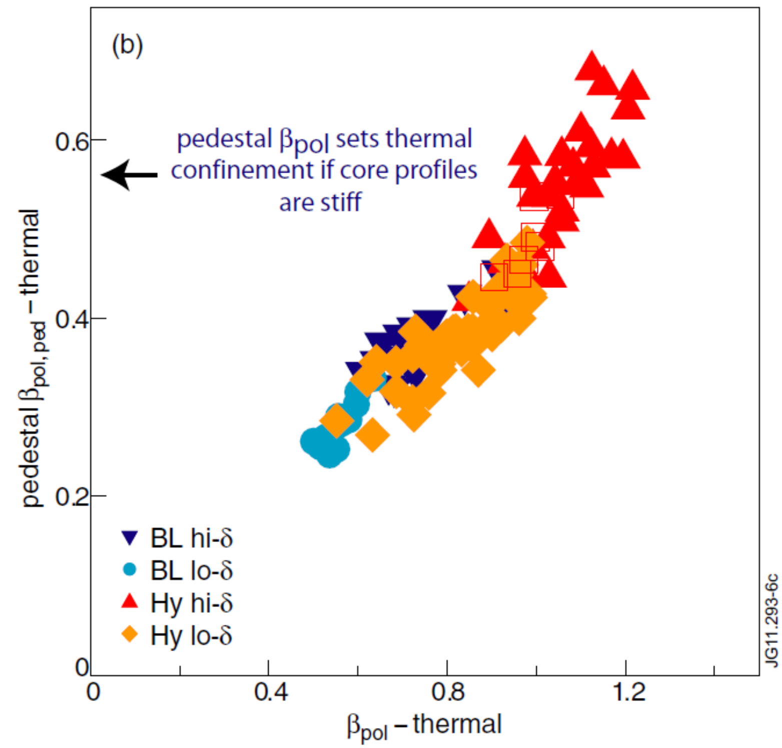

- The maximum pedestal height achieved can be increased by increasing the core pressure <u>before</u> accessing H-mode

# Link of pedestal and core pressure

- Pedestal pressure and core pressure correlated – causality?
- β varied here by change in field / current / shape / power



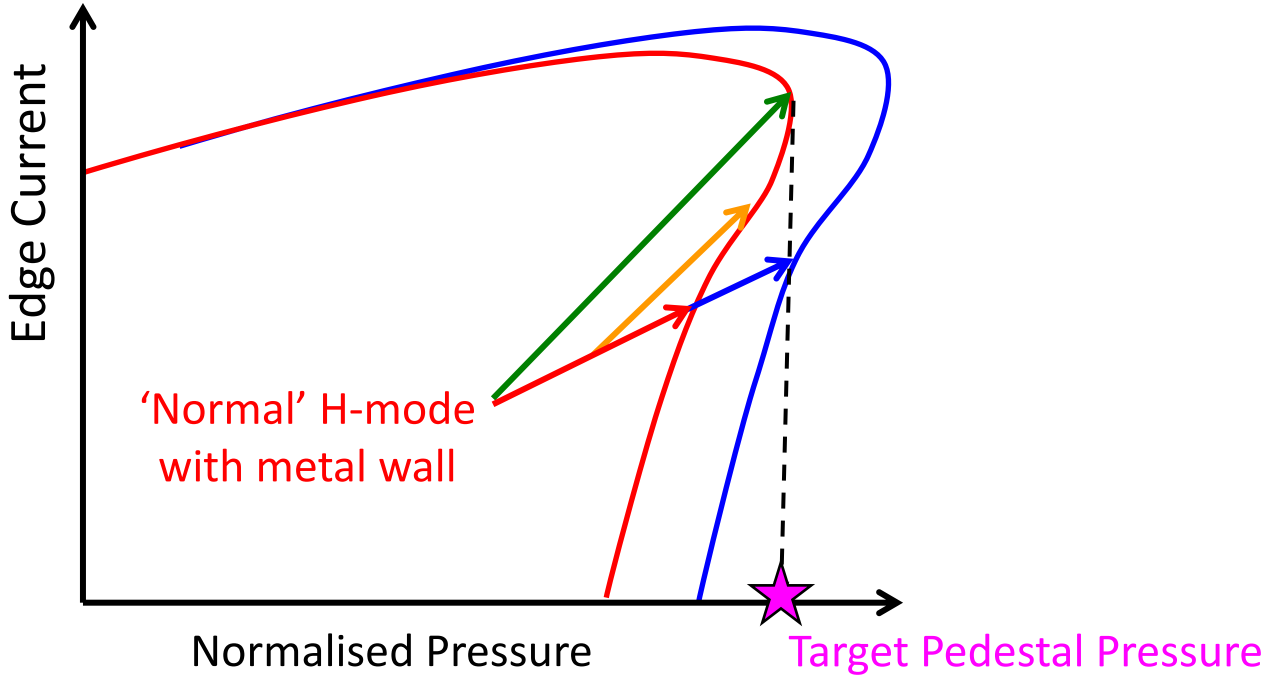

Maggi et al, *Nucl. Fusion* 2007




Beurskens et al, *Nucl. Fusion* 2013

# How to achieve higher pedestals?

- For fixed heating power & plasma shape, simplistically there are 3 ways to improve pedestal from stability constraints:
  1. Decrease collisionality, increase bootstrap current [C-wall recipe]
  2. Increase edge current [difficult or transient]
  3. Move ballooning boundary to higher critical pressure gradient



# Improved pedestals by tailoring plasma evolution

- How can we improve the “ballooning boundary”?
  - Analytic theory explaining effect of core pressure
  - Predictive pedestal model Europed

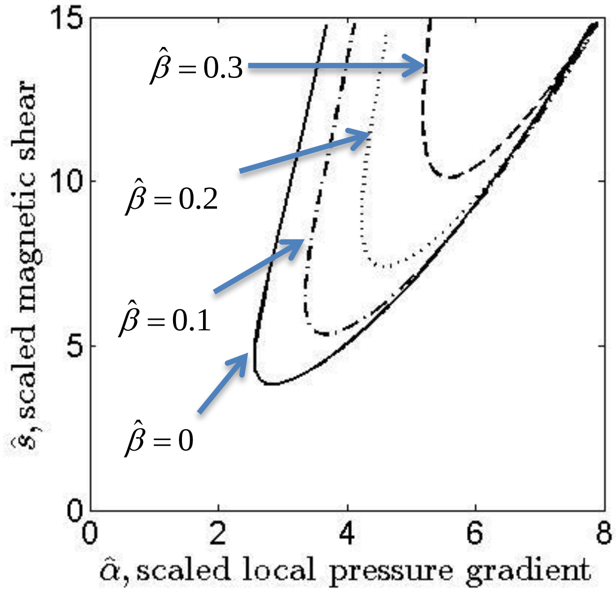
- Demonstration that core pressure affects the achievable pedestal height in EU devices
  - Exploiting magnetic flexibility of MAST/TCV to increase core $\beta$
  - Changing divertor configuration in JET to increase core $\beta$
  - Sustaining the improved pedestal height

- Implications for ITER
  - Integrated modelling of achievable pedestal in ITER

# Analytic study on core pressure and ballooning

- Analytic equilibrium including Shafranov shift, plasma shaping and toroidicity
- Used in ballooning equation to examine effects on the $s$- $\alpha$ diagram at low magnetic shear
- Stability improves with plasma beta through the effect on both Shafranov shift and ellipticity

Ellipticity at edge, E(a)=0.4

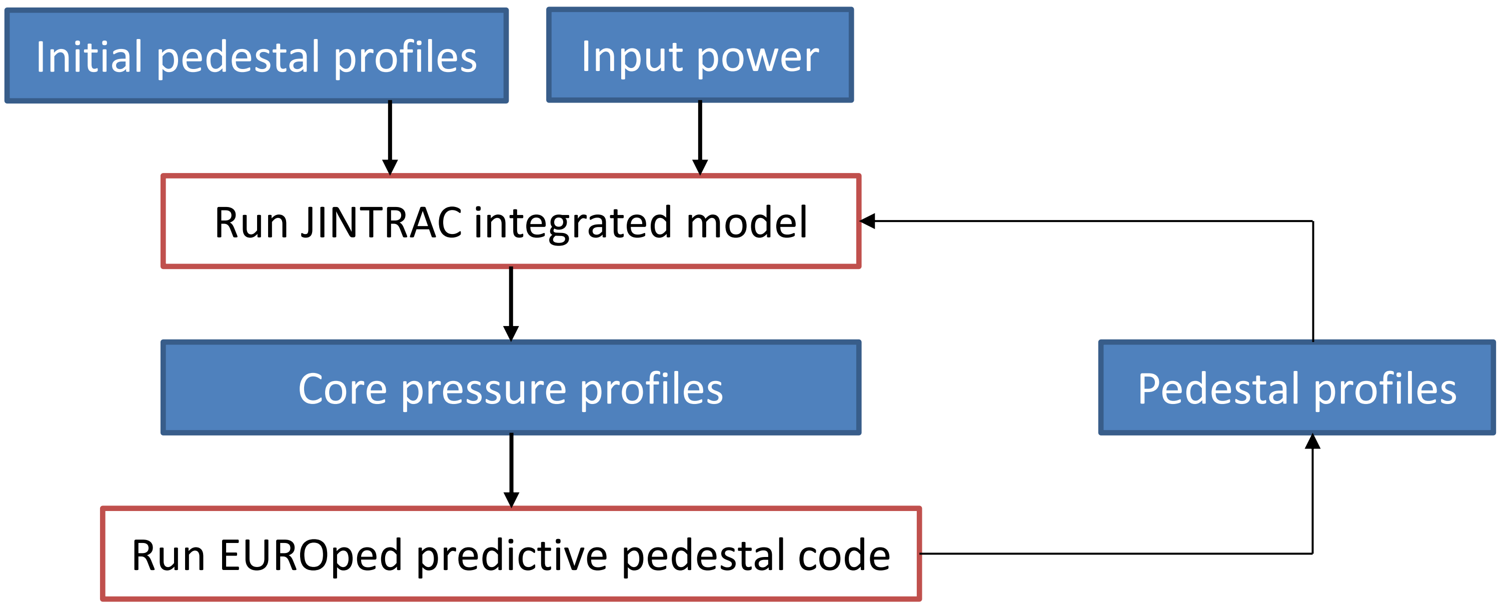



The stability diagrams are presented as universal curves for any toroidicity by appropriate scalings of parameters

J W Connor et al, *Plasma Phys. Control. Fusion* 2016

# Predictive pedestal model not constrained by giving core pressure as an input

- Pedestal predictions often constrained to give the core pressure and density as an input
  - However, these strongly determine pedestal height
- Developed an iterative loop to take power as input:




Saarelma et al, sub *PPCF*, 2016

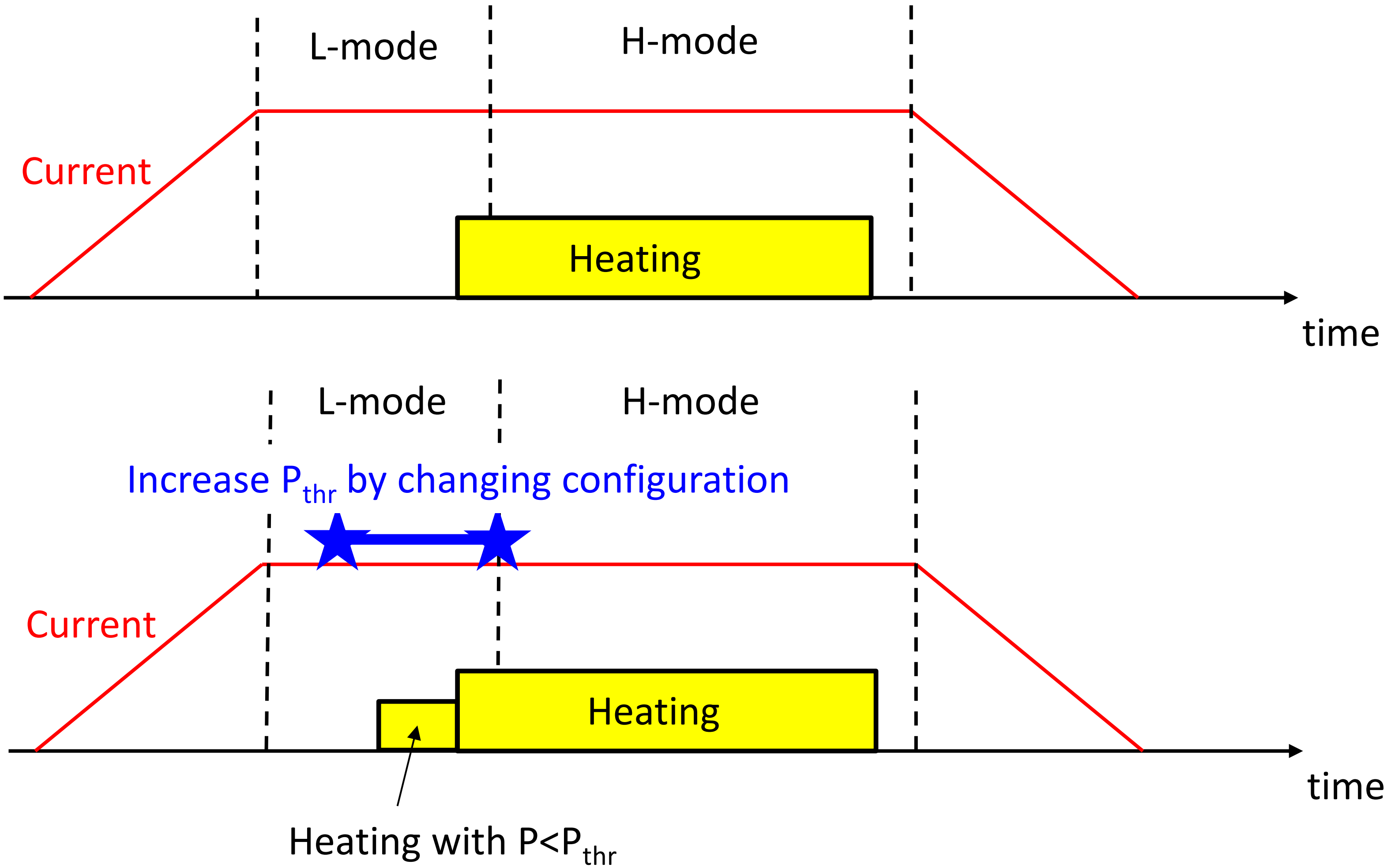
# Improved pedestals by tailoring plasma evolution

- How can we improve the “ballooning boundary”?
  - Analytic theory explaining effect of core pressure
  - Predictive pedestal model Europed

- Demonstration that core pressure affects the achievable pedestal height in EU devices
  - Exploiting magnetic flexibility of MAST/TCV to increase core β
  - Changing divertor configuration in JET to increase core β
  - Sustaining the improved pedestal height

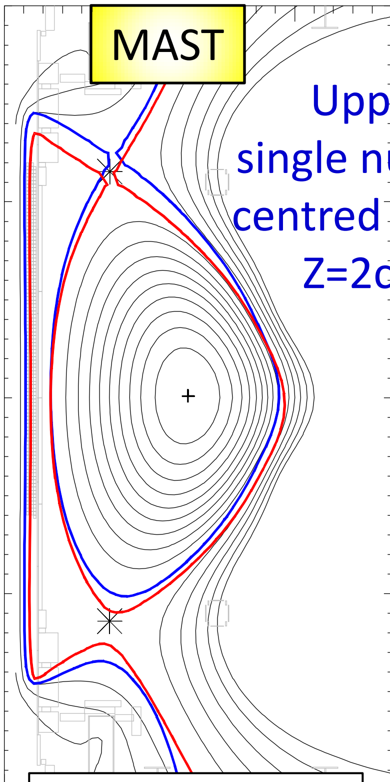
- Implications for ITER
  - Integrated modelling of achievable pedestal in ITER

# How to tailor the plasma evolution

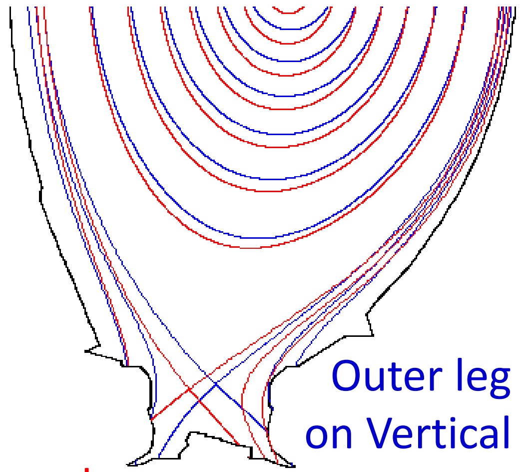


# How to increase the core pressure?

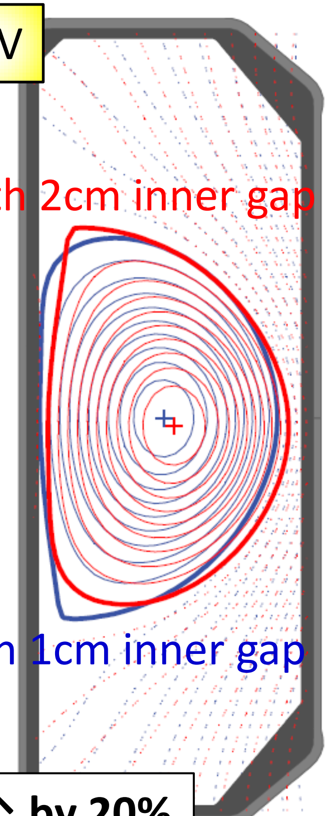
- Suppress the L-H transition by changing magnetic configuration to increase $P_{thr}$ then heat to increase $\beta$
- Trigger H-mode by changing back magnetic configuration




$\beta_{core}$ ↑ by 36%



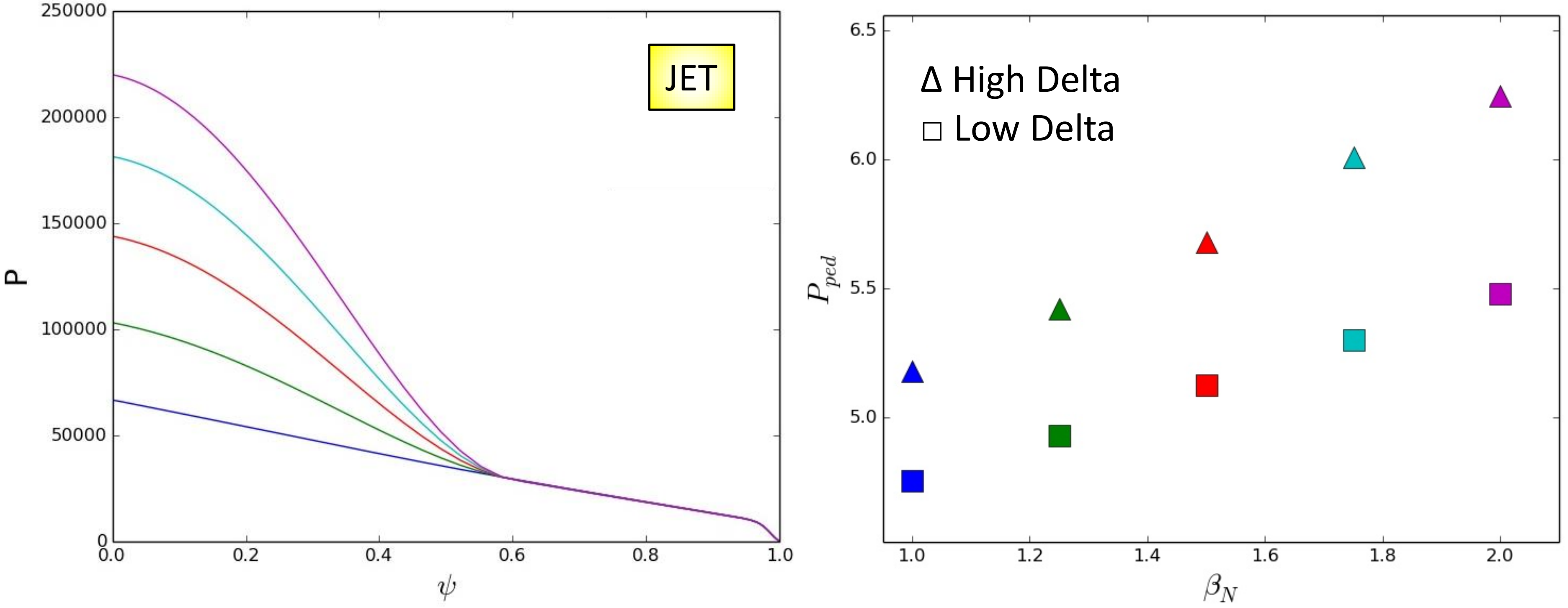

$\beta_{core}$ ↑ by 70%




$\beta_{core}$ ↑ by 20%

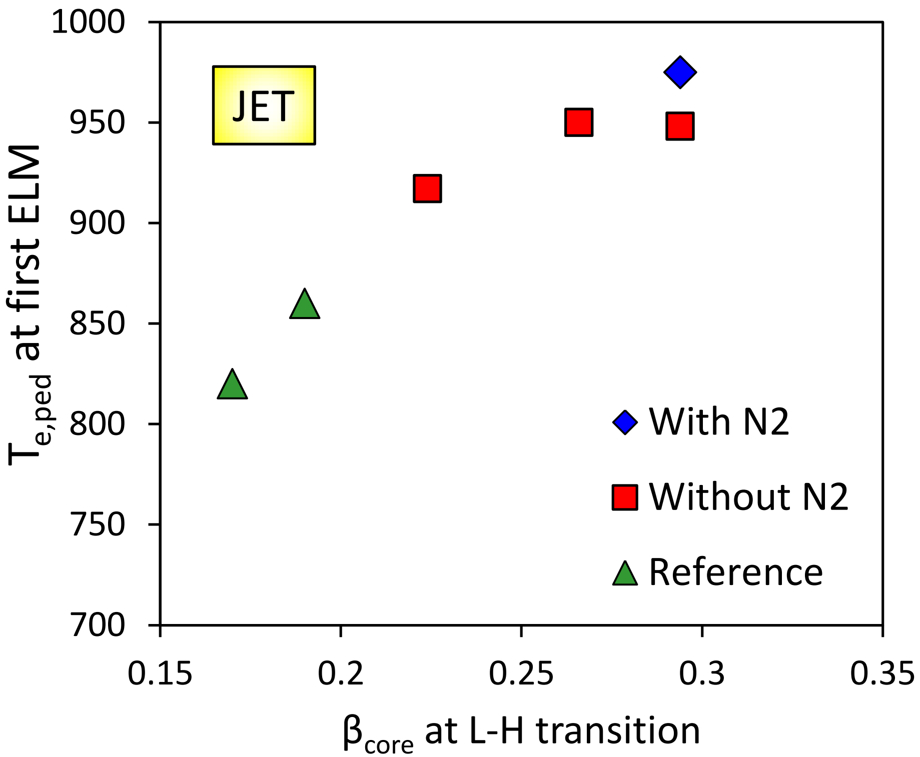
# Predictions of core pressure effect

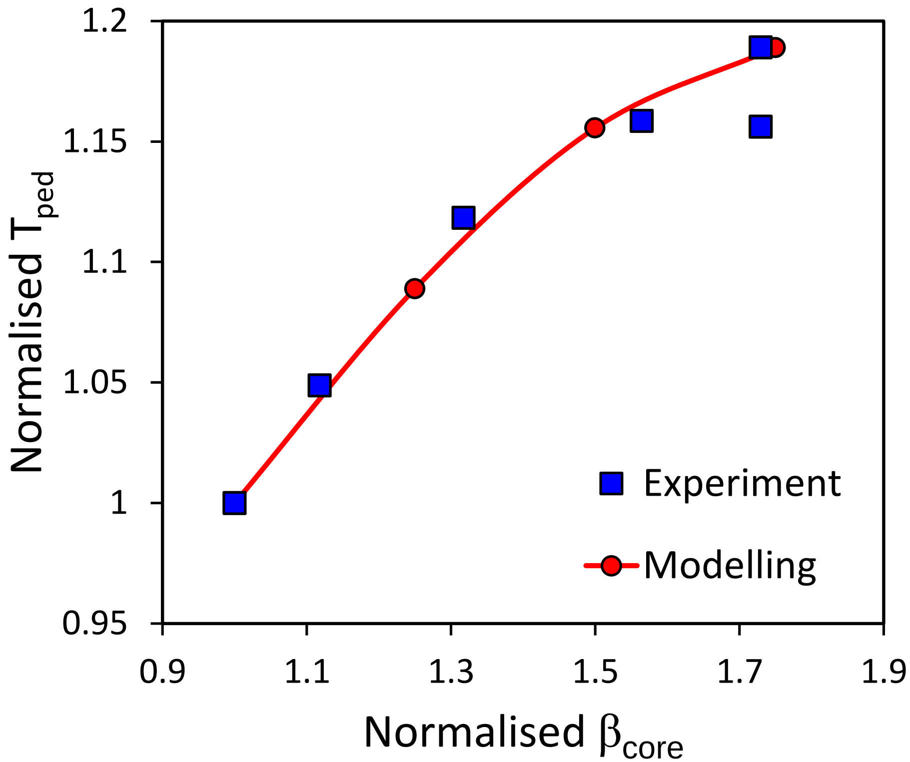
- Achievable increase in $\beta_{core}$ in JET predicted to increase the pedestal height by ≈20%



# Effect of core pressure with JET metal wall

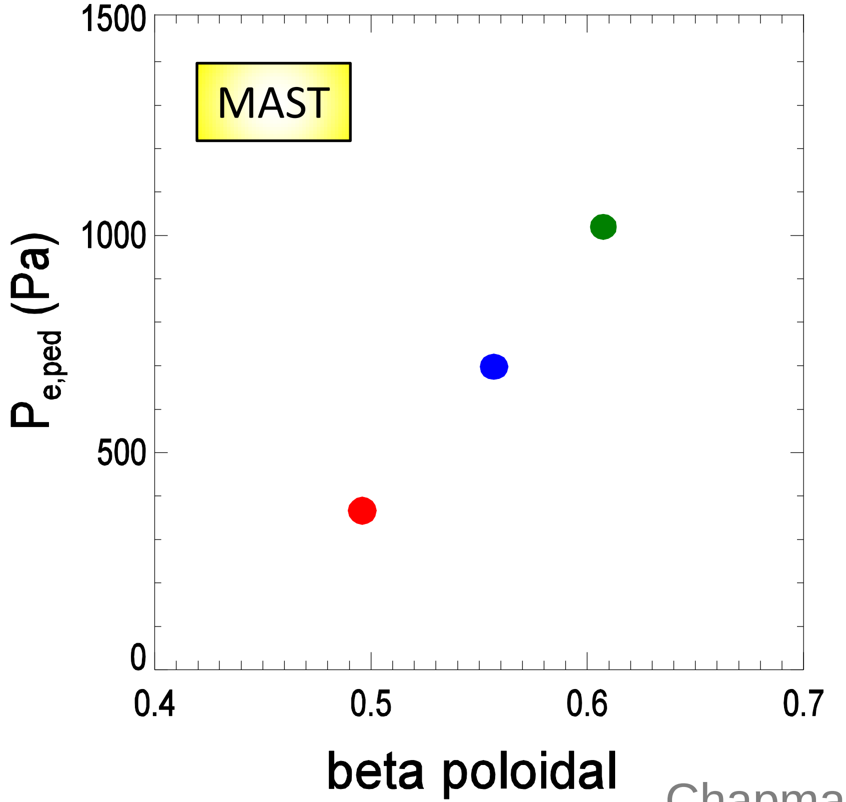
- 72% increase in the $\beta_{core}$ in JET stabilises ballooning modes
- This results in 19% increase in $T_{ped}$ at the first ELM



# Massive increase in MAST pedestal height

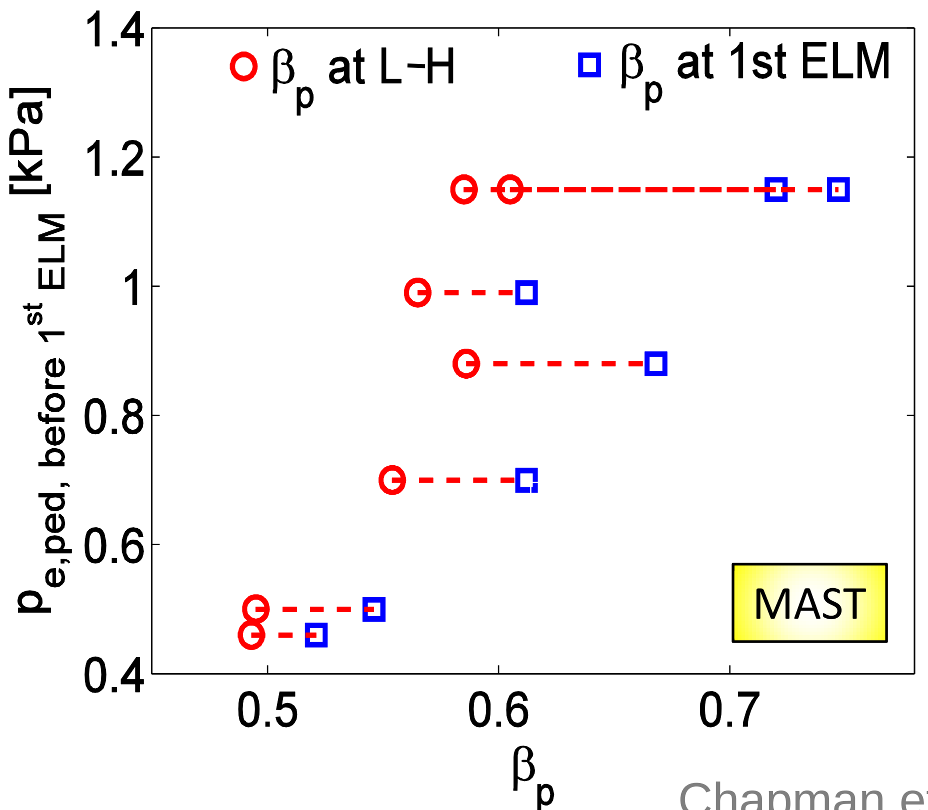
- 36% increase in $\beta_{core}$ in MAST stabilises ballooning modes
- Pedestal height at first ELM is **more than double** the "normal" pedestal




Chapman et al, *Nucl. Fusion* 2015

# Massive increase in MAST pedestal height

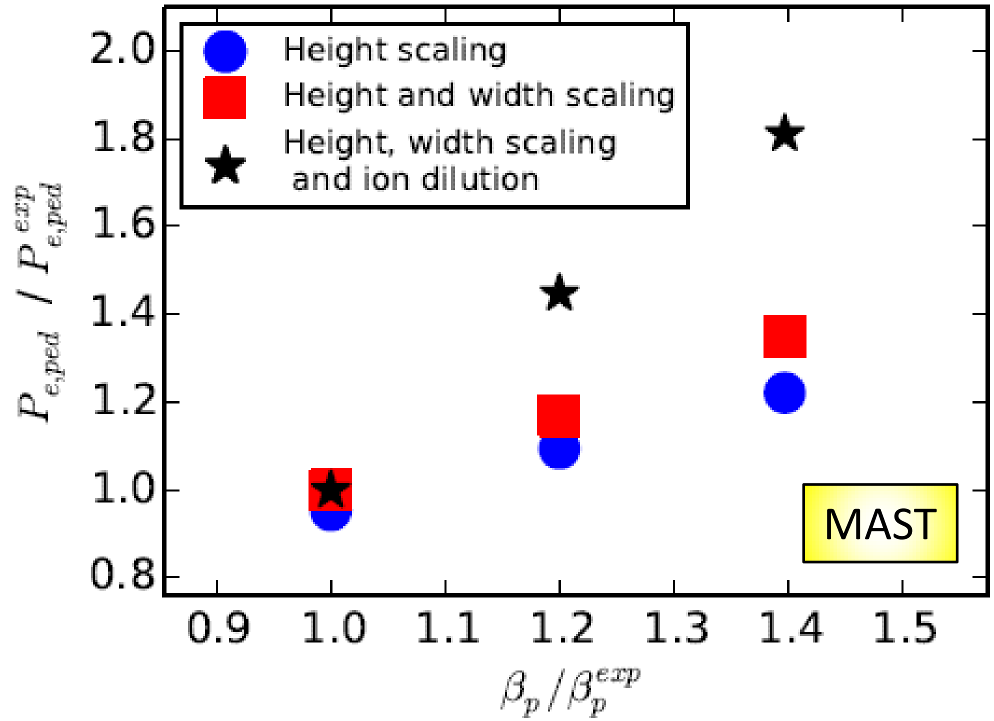
- This leads to positive feedback loop
  - High $\beta_{core}$ stabilises ballooning modes, so increases $T_{ped}$
  - Higher $T_{ped}$ gives larger β, which further stabilises ballooning modes




Chapman et al, *Nucl. Fusion* 2015

# Understanding pedestal increase in MAST and TCV

- In MAST & TCV pedestals are much higher than predictions
- Increasing critical pressure to trigger an ELM increases the pedestal height, but also increases the time between ELMs
- In MAST this leads to significant C influx before first ELM
- Including the ion dilution from impurity influx and increase in pedestal width (scales with √β) matches experiment data

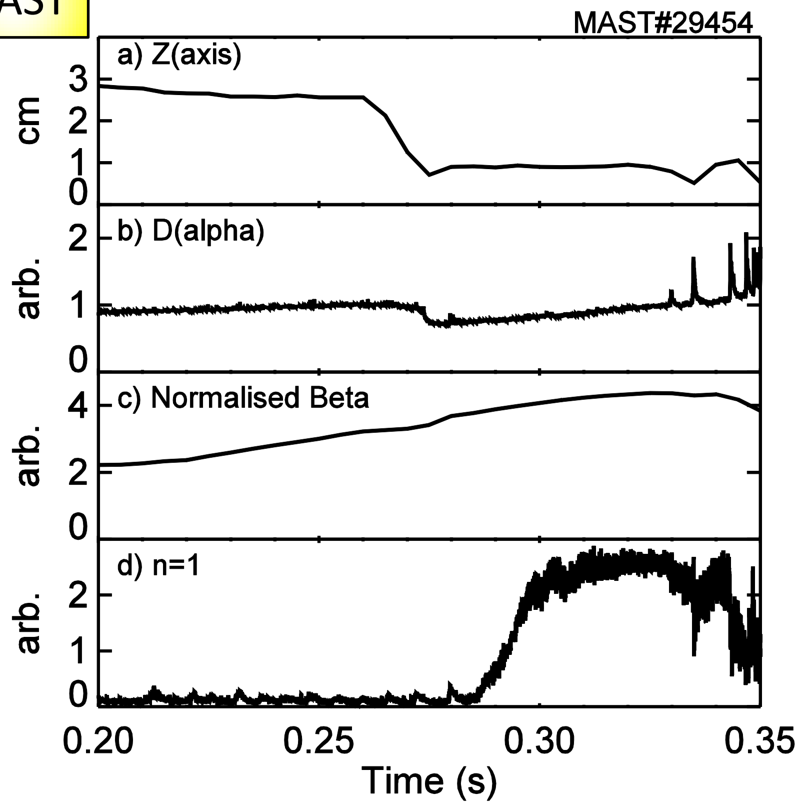



Simpson et al, sub *PPCF*, 2016

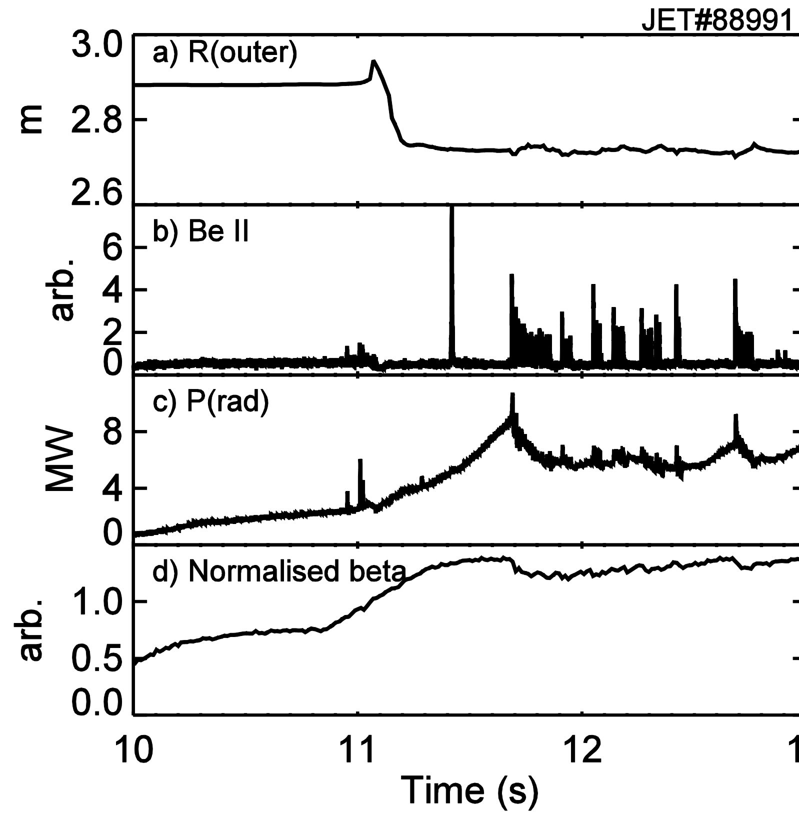
# Can we sustain the pedestal improvement?

- Stabilising ballooning modes gives low ELM frequency
  - MAST: Carbon influx means β increases too much & NTM triggered
  - JET: Tungsten influx results in too much radiation

MAST



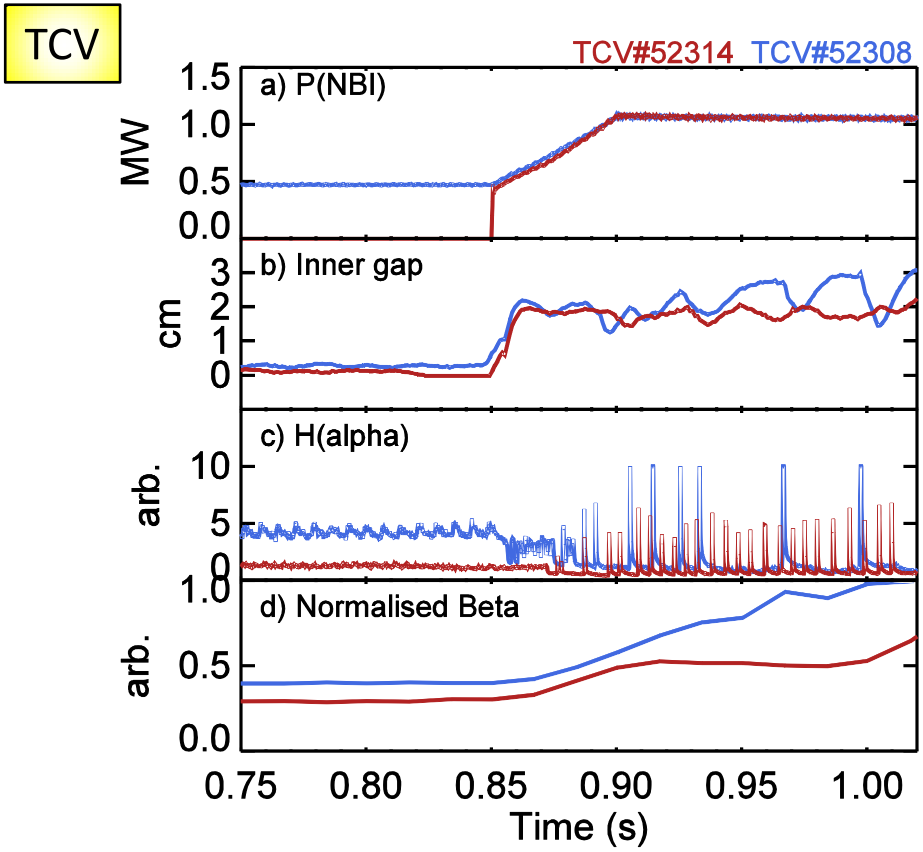

JET




JET CCFE CULHAM CENTRE FOR FUSION ENERGY SWISS PLASMA CENTER

# Sustaining improved pedestals

- In TCV the increase in pedestal height can be sustained for many ELM cycles compared to “normal shot”

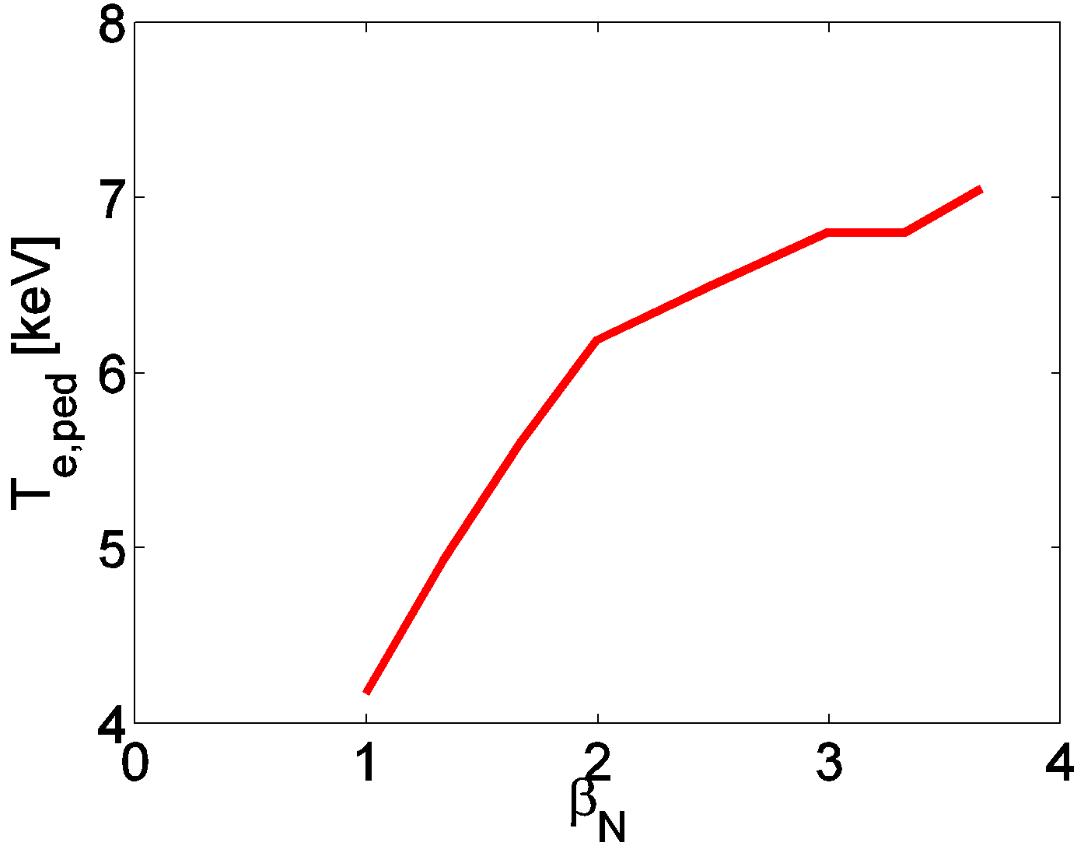


# Improved pedestals by tailoring plasma evolution

- How can we improve the “ballooning boundary”?
  - Analytic theory explaining effect of core pressure
  - Predictive pedestal model Europed
- Demonstration that core pressure affects the achievable pedestal height in EU devices
  - Exploiting magnetic flexibility of MAST/TCV to increase core β
  - Changing divertor configuration in JET to increase core β
  - Sustaining the improved pedestal height
- Implications for ITER
  - Integrated modelling of achievable pedestal in ITER

# Prediction of ITER pedestal improvement

- Significant improvement in ITER pedestal height achievable by tailoring an increase in core pressure



# Future work required to apply to ITER

- Controlling the ELMs
  - Need to sustain improved performance after the first large ELM
  - Need to assess compatibility with ELM control techniques

- Using ITER relevant recipes to increase the core pressure in L-mode phase
  - Unlikely to use the magnetic geometry techniques applied here
  - Application of RMPs known to increase $P_{thr}$, so this technique should be assessed
  - Exacerbate effects by increasing shaping or seeding

# Conclusions

- The pedestal height can be increased by maximising the core pressure in the L-mode phase
  - This stabilises the ballooning modes, allowing access to a higher pedestal before ELMs occur
  - The improved pedestal can be sustained for subsequent ELM cycles

# Other affects in prelude heating

- Varied ICRH:NBI fraction in preheat, changing rotation and impurity content in pedestal
- More NBI --> Hotter $T_e^{ped}$