Cross-machine NTM physics studies and implications for ITER

Presented by R. J. Buttery[1],

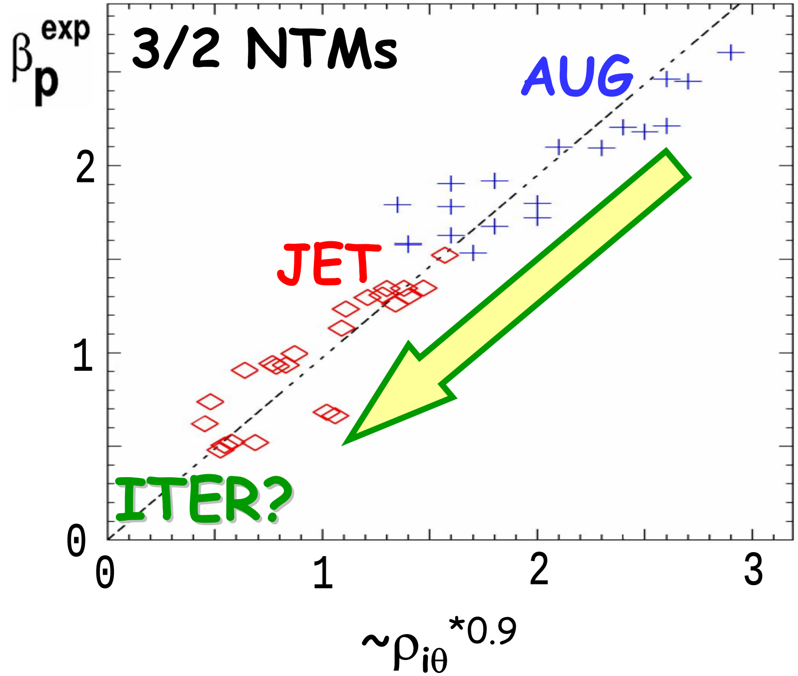
On behalf of: P. Belo[2], D. P. Brennan[3], S. Coda[4], L.-G. Eriksson[5], J. Graves[4], S. Günter[6], C. Hegna[7], T. C. Hender[1], D. F. Howell[1], H. R. Koslowski[8], R. J. La Haye[3], M. Maraschek[6], M. L. Mayoral[1], A. Mück[4], M. F. F. Nave[2], O. Sauter[4], E. Westerhof[9], C. Windsor[1], and the ASDEX Upgrade[6] and DIII-D[3] teams, and JET-EFDA contributors*.

[1]EURATOM/UKAEA Fusion Association
[2]Association EURATOM/IST
[3]General Atomics, San Diego
[4]CRPP, Association EURATOM-Confédération Suisse
[5]Association EURATOM-CEA, CEA-Cadarache
[6]MPI für Plasmaphysik, EURATOM Association
[7]Dept. of Engineering Physics, University of Wisconsin
[8]Association EURATOM-FZ Jülich IPP.
[9]FOM-Rijnhuizen, Ass. EURATOM-FOM.
*see annex 1, Pamela et al., Nuc Fus 43 (2003) 1540.

Are NTMs a problem for ITER?

- NTM physics is expected to scale with ρ^*
  - often observed in local β onset scalings
  - → *low threshold in ITER?*

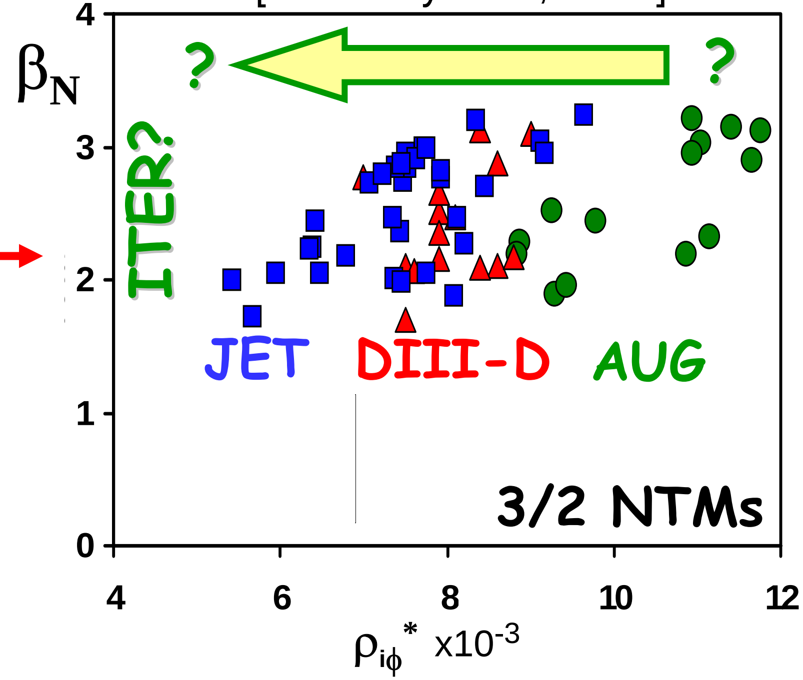
[M. Maraschek et al., EPS03]



Are NTMs a problem for ITER?

- NTM physics is expected to scale with ρ^*
  - often observed in local β onset scalings
  - $\rightarrow$ *low threshold in ITER?*
- But analyses in global β_N suggests another possibility
  - **which is it?**
- *Key aspect in resolving the onset is the seeding process...*

[R. Buttery et al., NF04]

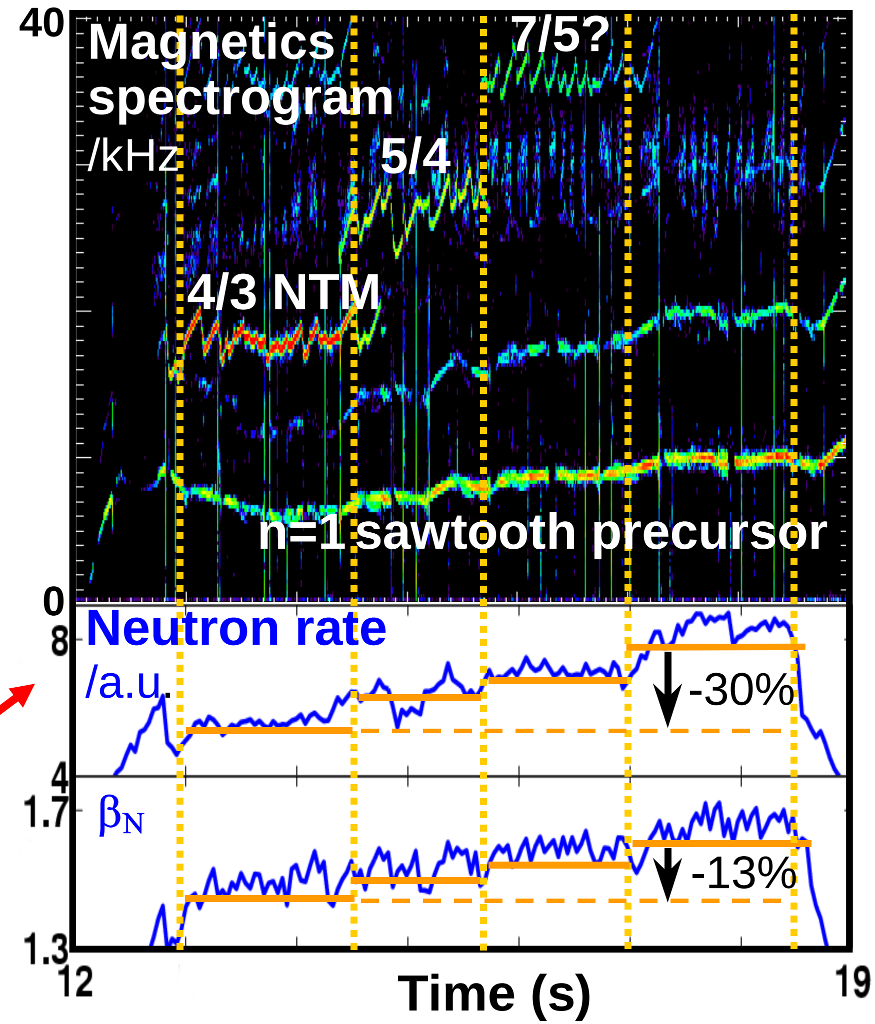


Which modes are a concern?

- 2/1 NTMs terminate performance & unacceptable in ITER
- 3/2 NTMs significant effect
  - typically 15-20% on confinement → ~ -30% in fusion power
  - trace Tritium experiments show consistent with ~50% fall in inward pinch in vicinity of island
- Higher m/n NTMs also impact fusion performance at low q_{95}

JET: 3.7MA, 2.9T, q_{95}=2.7:

- up to 13% effect on confinement
- up to 30% effect on neutrons

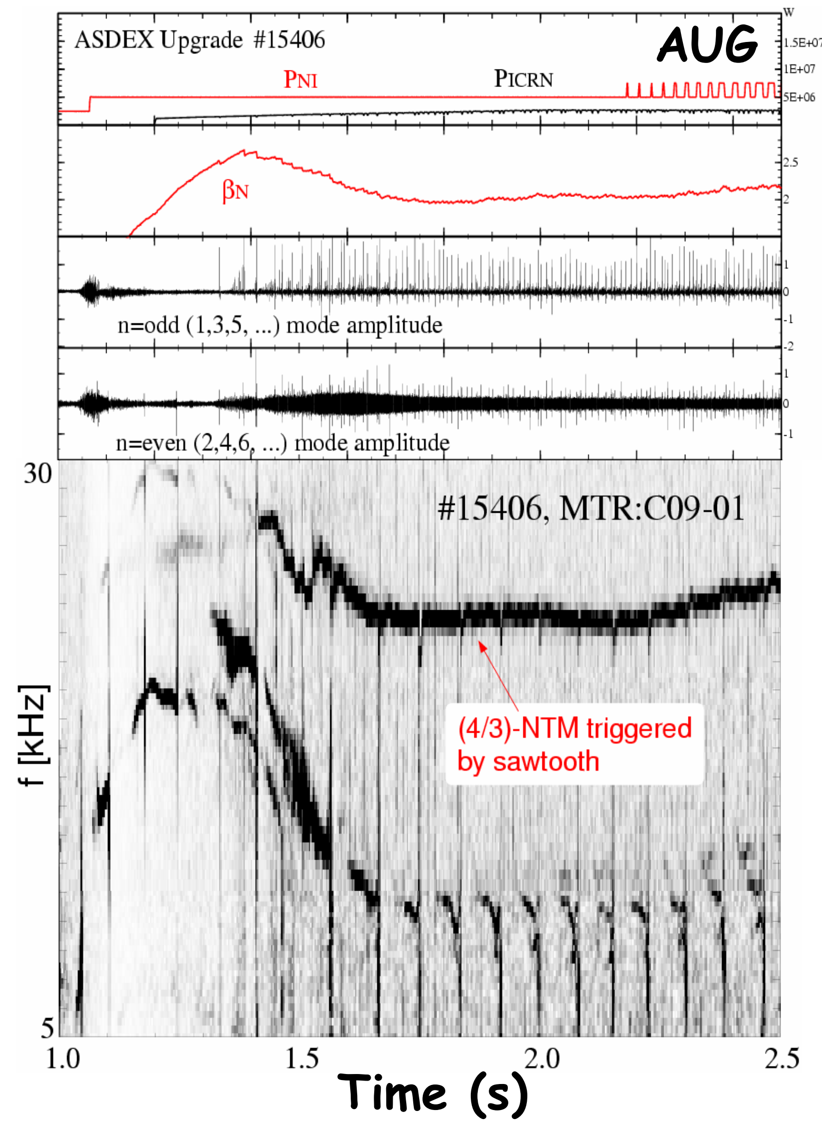


Which modes are a concern?

- 2/1 NTMs terminate performance & unacceptable in ITER
- 3/2 NTMs significant effect
  - typically 15-20% on confinement → ~ -30% in fusion power
  - trace Tritium experiments show consistent with ~50% fall in inward pinch in vicinity of island
- Higher m/n NTMs also impact fusion performance at low q_{95}

  JET: 3.7MA, 2.9T, q_{95}=2.7:
  - up to 13% effect on confinement
  - up to 30% effect on neutrons

  AUG: 4/3 NTMs at q_{95}=3.7:
  - up to 20% effect on stored energy

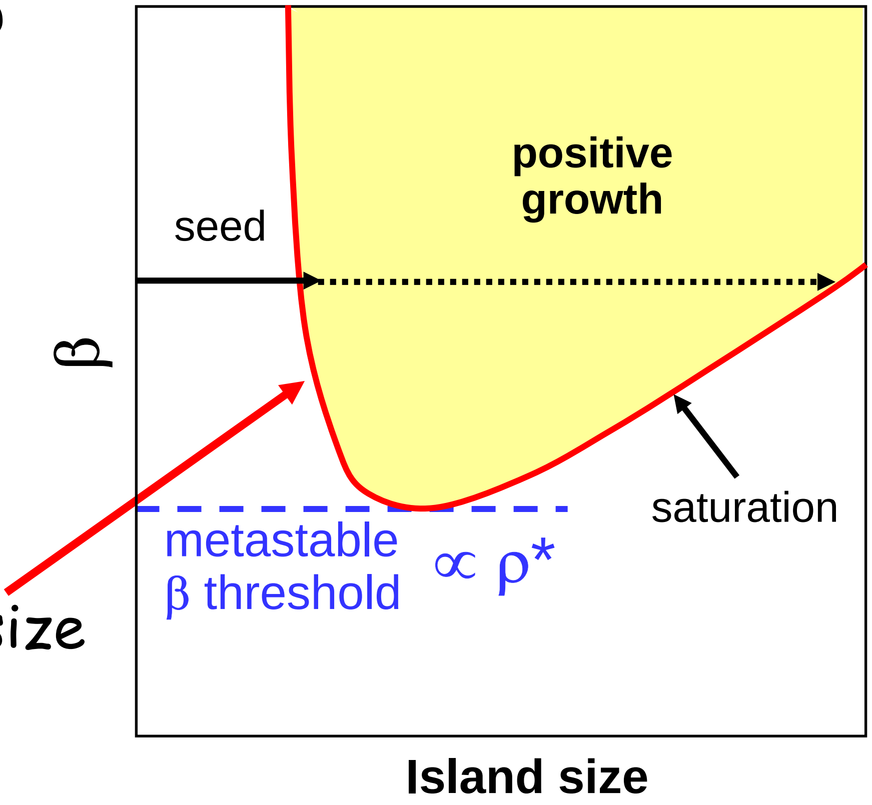


Content

- NTM ρ^* scalings:
  - Onset criteria for NTMs
  - How do the scalings do?
- Role of the seed: the Sawtooth
  - Influence on thresholds
  - Sawtooth control
  - Advances in sawtooth prediction
- The seeding process
  - Sawtooth coupling mechanisms
  - Other trigger mechanisms and effects
- Implications for ITER

NTM onset criteria

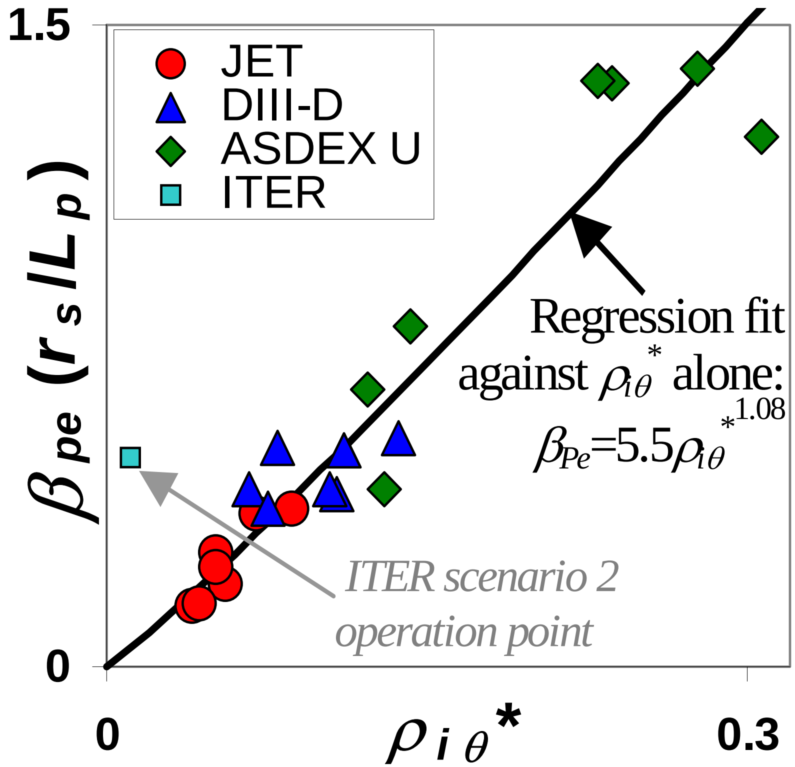
- NTMs driven by hole in bootstrap
  - but onset criteria depend on small island stabilisation effects
  - require a seed island to reach positive growth
  - these introduce a ρ^* dependence in the metastable threshold



- Onset β highly sensitive to seed size
  - scaling of seeding process may be the critical thing
  - uncertainties both in seed needed and seed obtained

How do the ρ* scalings do?

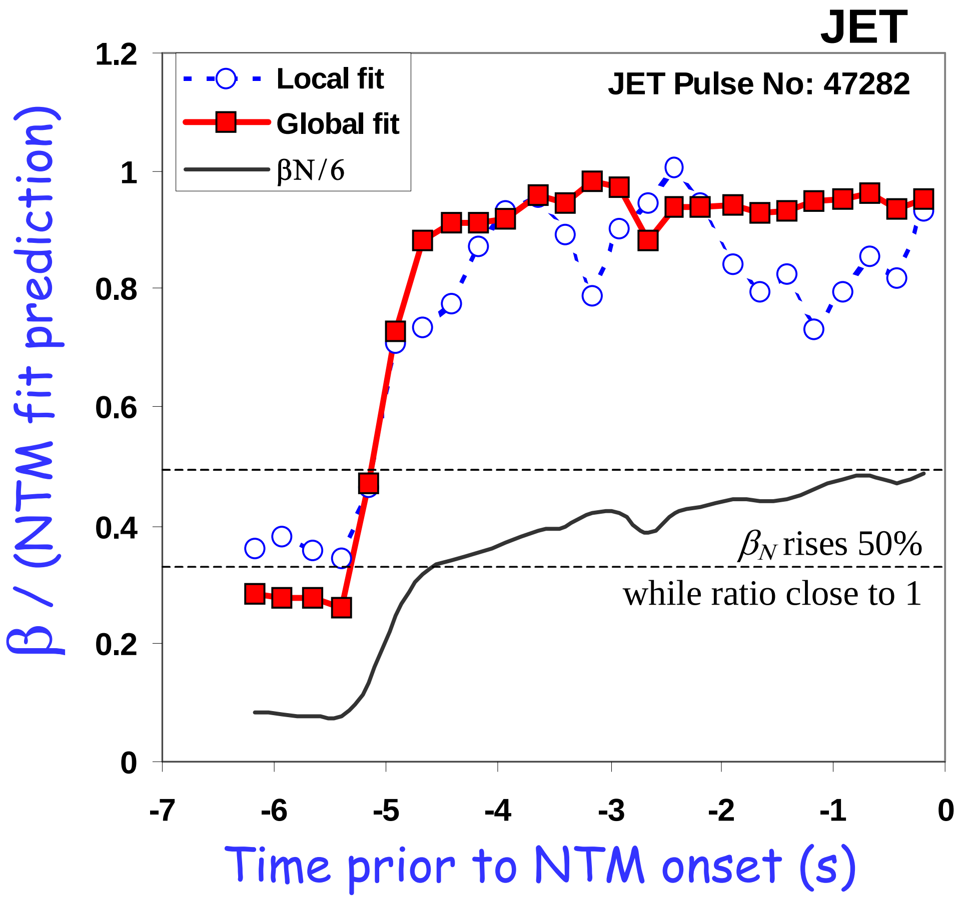
Pretty good in terms of underlying NTM physics and metastable threshold...



- power ramp-down experiments measure β at which 3/2 NTM self-stabilises
- **ITER baseline operation point deeply into metastable region**
  - small triggers can excite mode
  - mode removal requires driving island down to small sizes

How do the ρ* scalings do?

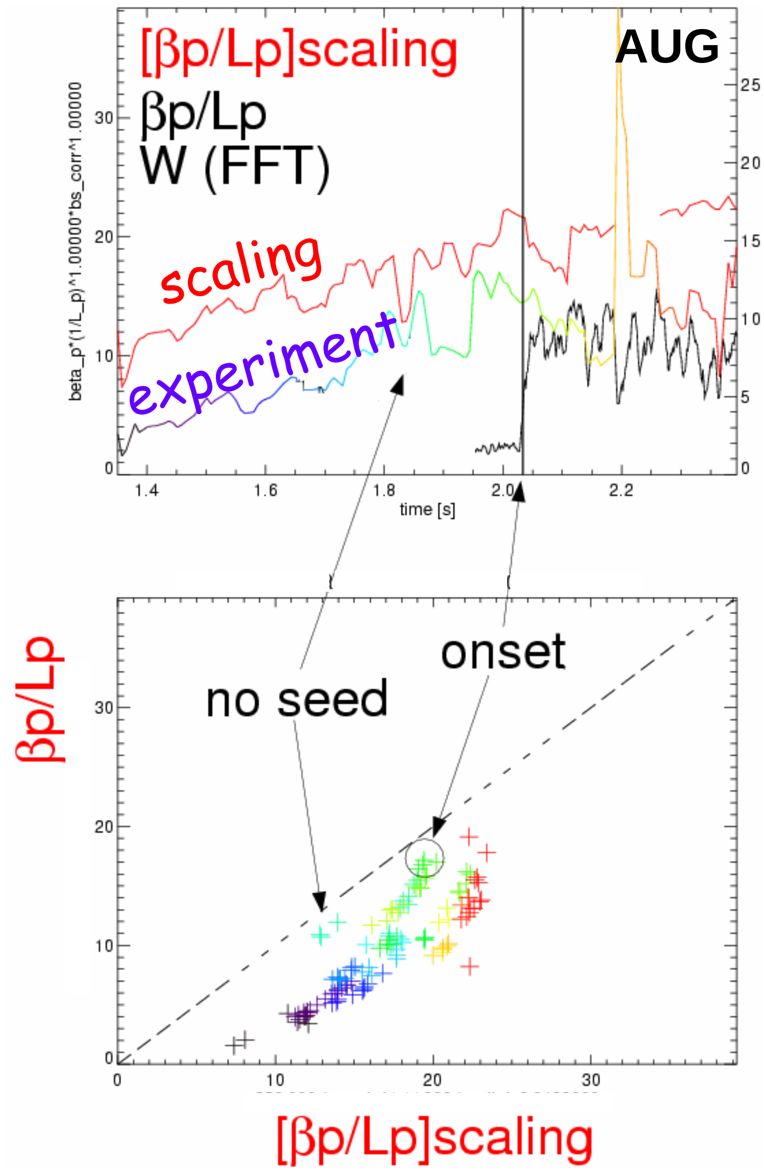
- But they are not predictive of NTM onset β and time on JET…



- β stays close to NTM onset scaling prediction once H-mode reached
  - ♦ for both local and global parameter fits

How do the ρ* scalings do?

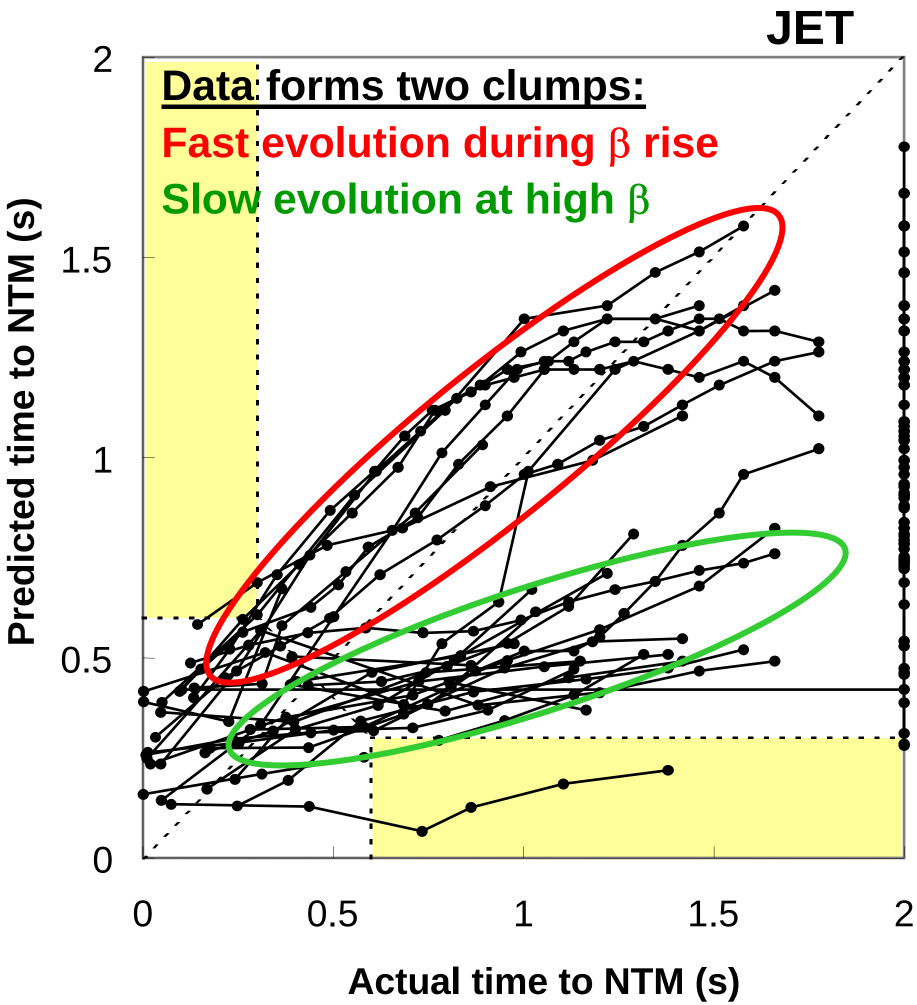
- But they are not predictive of NTM onset β and time



- β stays close to NTM onset scaling prediction once H-mode reached in JET
  - for both local and global parameter fits
- similarly on AUG:
  - proximity to scaling is a necessary-but-not-sufficient condition for NTMs
- there must be an extra control parameter...

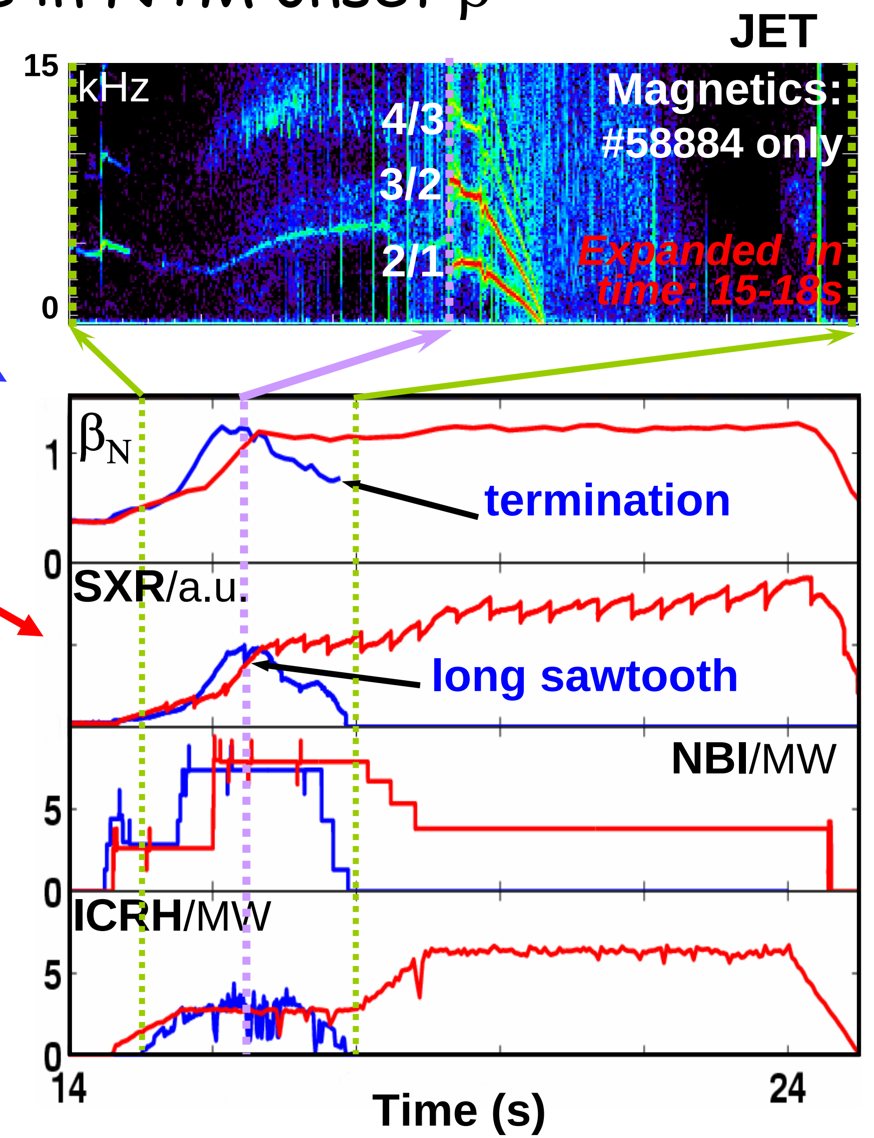
What is the hidden control parameter?

- Employ neural network to look for pattern in data...
  - automatic optimisation from choice of 27 input parameters
  - train to predict onset time
- Network successful →
  - predicts decreasing time to NTM as onset approached
    - *unlike ρ^* scaling!*
  - best network uses just β_N, ρ^* and sawtooth period
    - *period even more significant than ρ^**



Role of the sawtooth

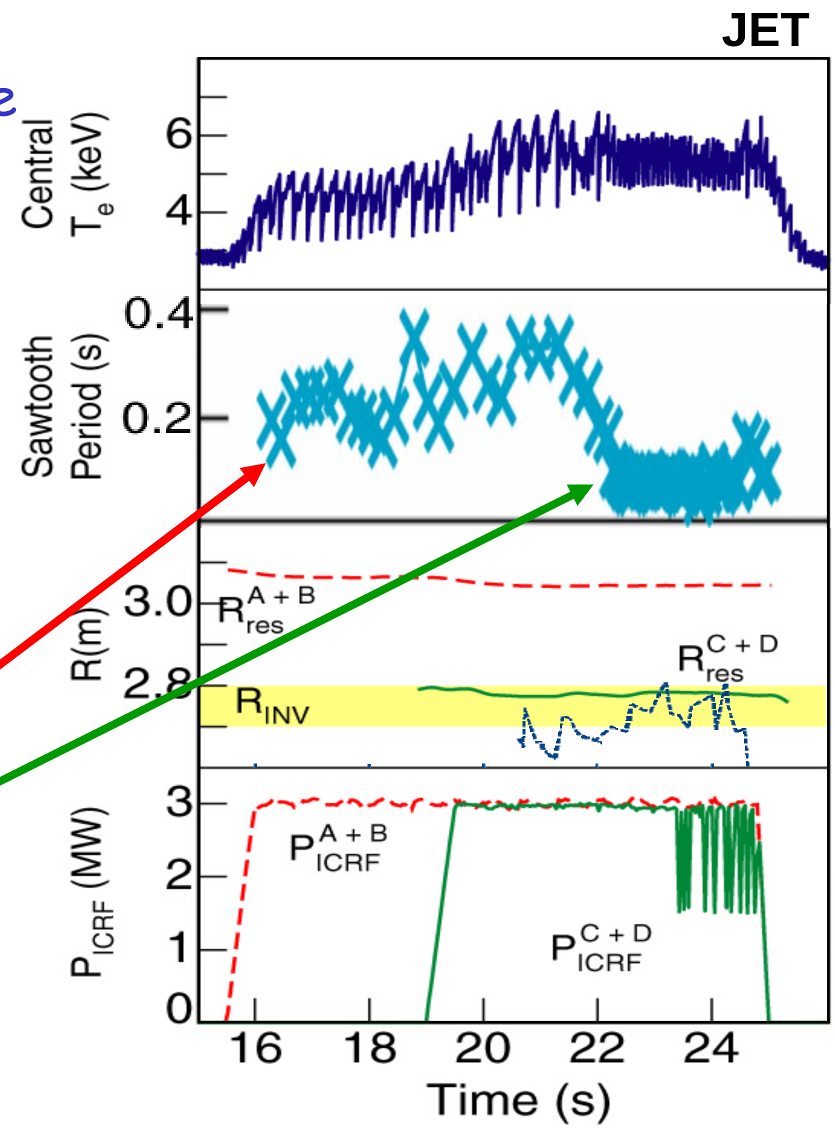
- Sawtooth period plays key role in NTM onset β
- Long sawteeth can lead to many low β modes (blue)
- Sawtooth control can offer substantial mitigation (red)
  - here achieved by:
    - ICRH phasing to avoid core pinch
    - establishing sawtoothing heated L-mode to avoid peaked profiles
  - avoids all modes, even with much more heating power



Sawtooth control in ITER

ITER has two possible strategies:

- early α production to stabilise sawtee
  - extend further with modified start up and current drive
  - but still limited and not steady state
- current drive destabilisation
  - ***is this possible for fast particle stabilised (ideal) sawteeth?...***



Destabilisation of fast particle stabilised sawteeth now achieved:

- core ICRH stabilises sawteeth
- ICCD destabilises as inversion radius is approached

Further progress with ECCD on AUG
→ see Maraschek talk today

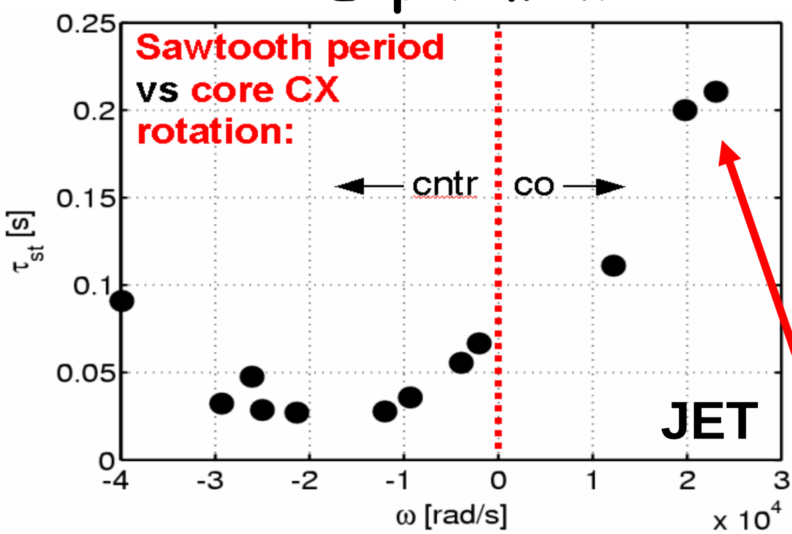
[*Porcelli et al, NF44, 362]

Sawtooth prediction is key

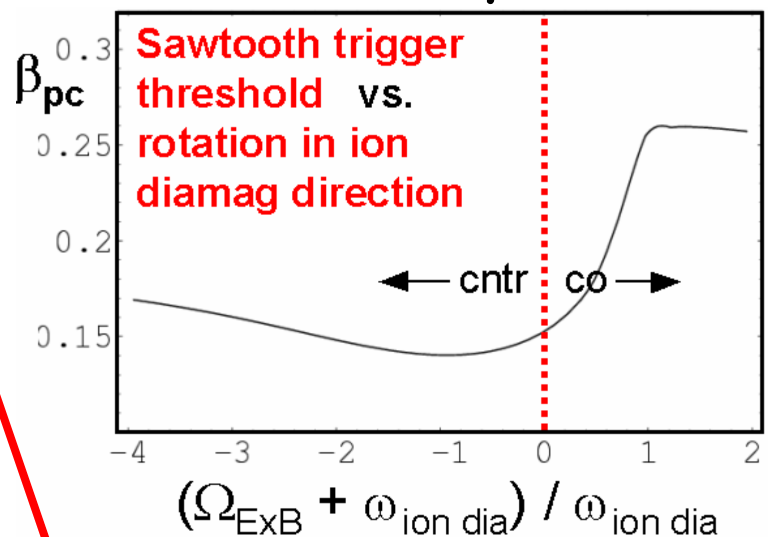
- Good progress in the theory...

eg: Rotation dependence on JET...

Experiment:



Theory:

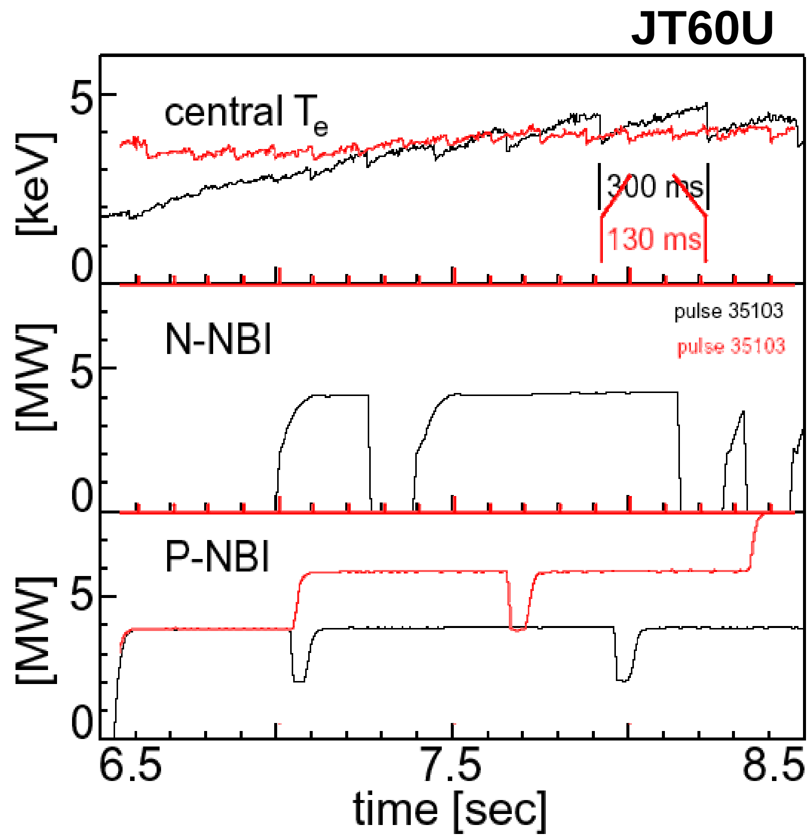


– kinetic effects stabilise sawteeth at high rotation

– important in reconciling data from present devices

Sawteeth with NNBI

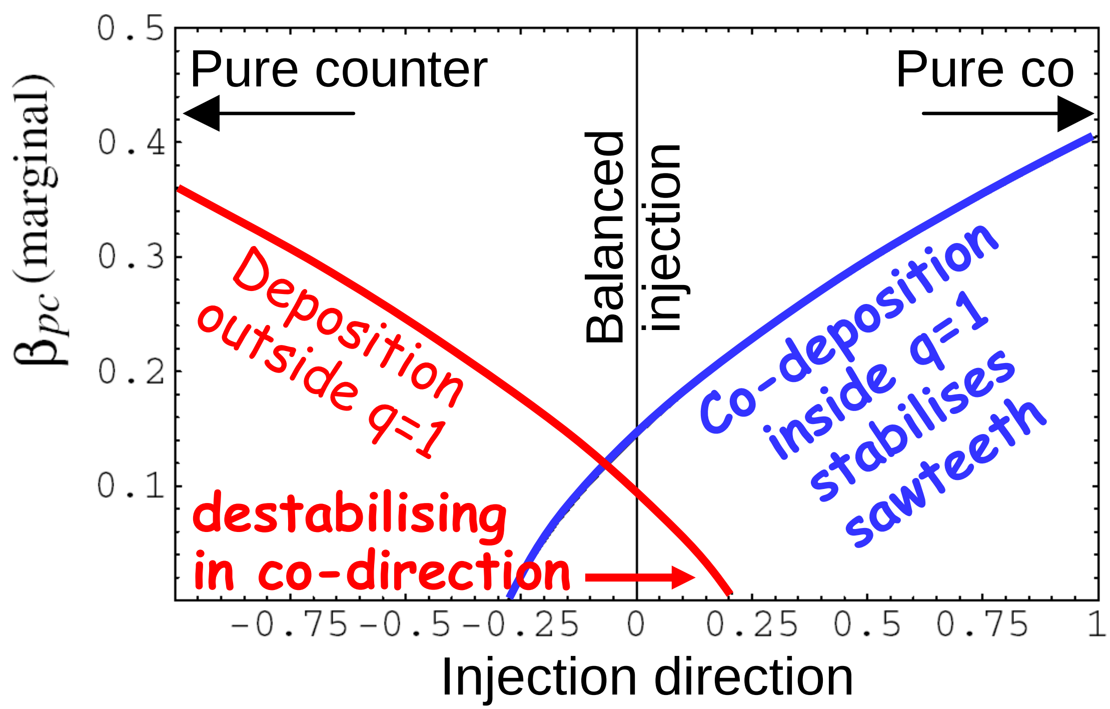
- JT60U also finds fast particles from energetic negative ion beams stabilising…
  - 350keV NNBI gives sawteeth of **300ms**
  - cf PNBI: **130ms**



[Kramer et al, NF40, 1383]

Sawteeth with NNBI

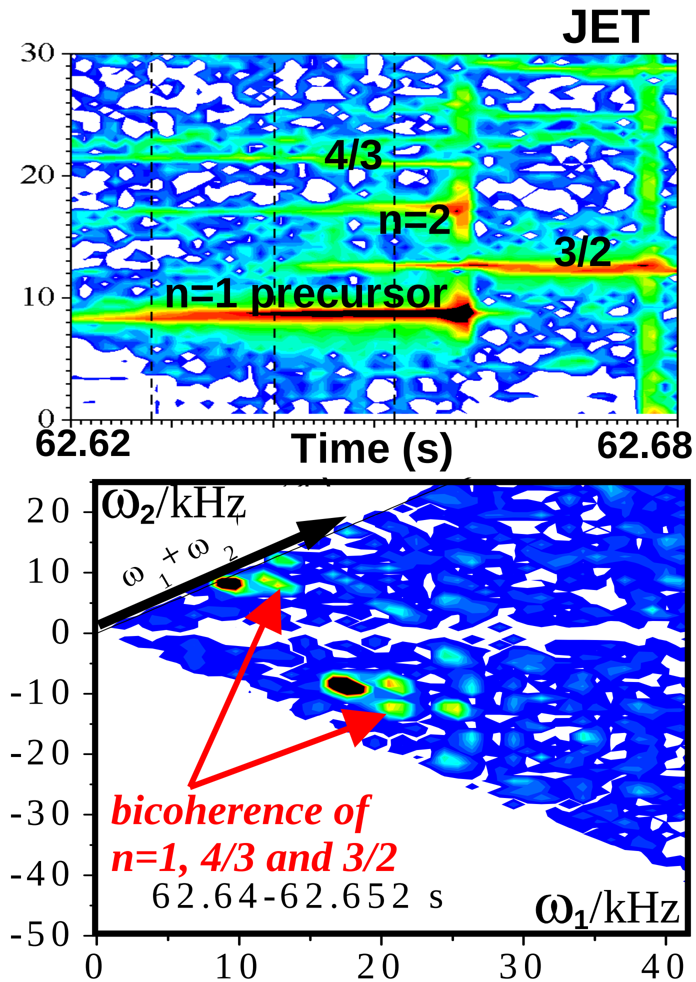
- JT60U also finds fast particles from energetic negative ion beams stabilising…
  - 350keV NNBI gives sawteeth of **300ms**
  - cf PNBI: **130ms**
- Explained by Graves:
  - finite ion orbit effects change free energy
  - depends on deposition location…
- *Possible mechanisms for sawtooth control in ITER?*



[Graves et al, PRL92, 185003]

How is initial seed made?

- Sawteeth often trigger 3/2 NTMs before the crash...
  - Magnetic coupling?
    - NTM often too slow for toroidal coupling to n=2
    - 3 wave seeding possible:
      - bicoherence analysis shows phase lock between driving (11+43) and 32 fields
    - but frequencies are not always consistent...
  - Ion polarisation effects?
    - MHD can change island rotation*
    - potential to lower/reverse ion polarisation effects enabling seeding
    - avoids need for frequency locking

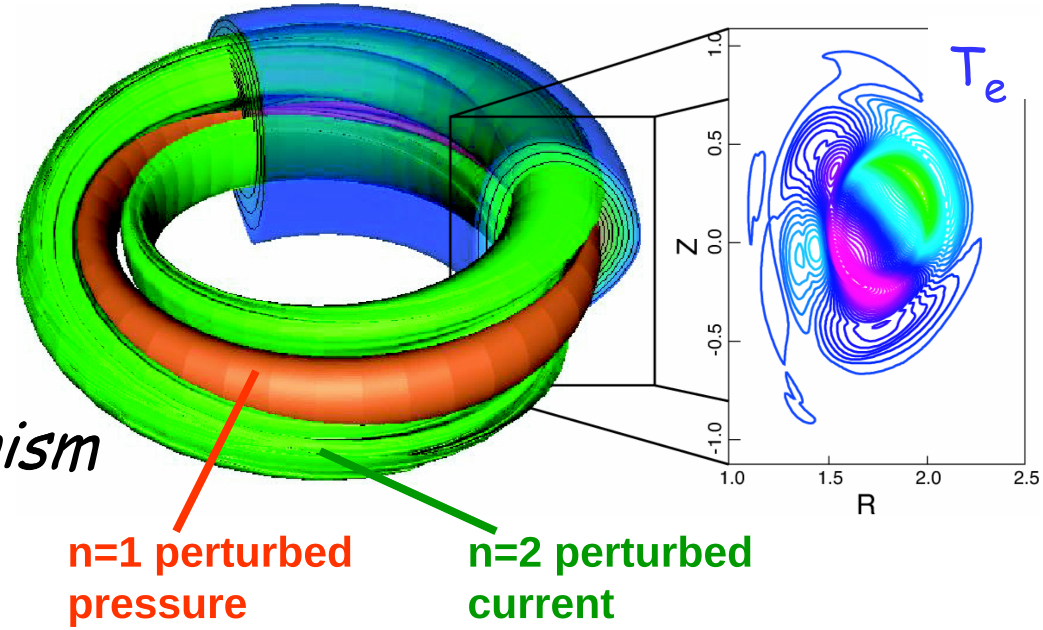


[*Hegna, Bull.Am.Phys.Soc.48, 280]

Forced reconnection at crash

- At low β, long sawteeth trigger NTMs directly at the crash
  - excite multiple NTMs & 2/1 much more likely → *concern for ITER*
  - codes such as NFTC and NIMROD now able to 3D model such processes in detail...

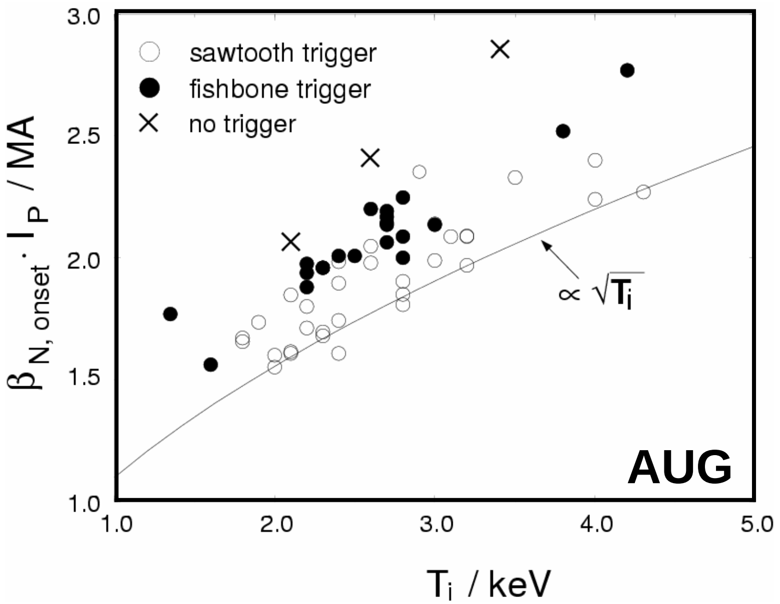
- Example: forced reconnection inducing a 3/2 in DIII-D
  - NIMROD simulation now includes rotation shear:
  - island is still destabilised by forced reconnection
  - but as island grows its structure becomes distorted by rotation



- *Shows viability of mechanism for NTM seeding*

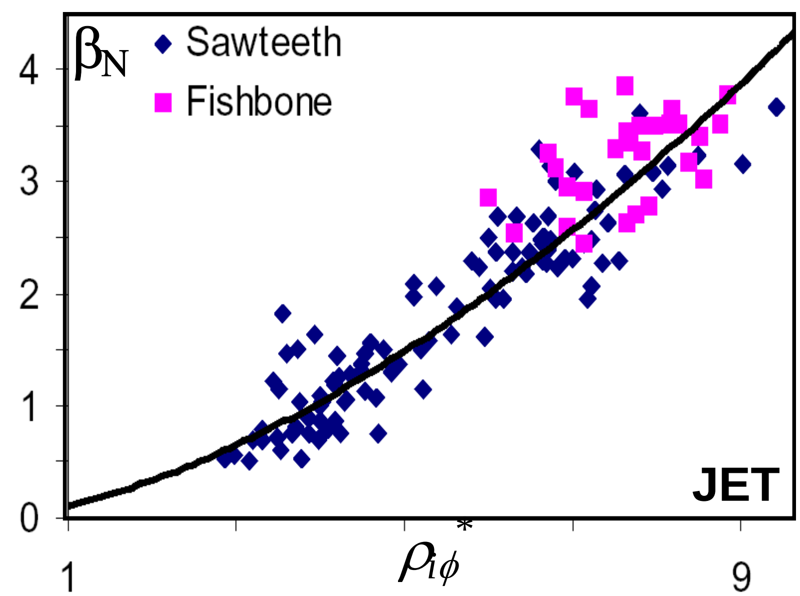
Fishbone triggers - at higher β_N?

- Fishbones also trigger NTMs
  - 3/2 NTM thresholds on AUG generally higher than for sawtooth

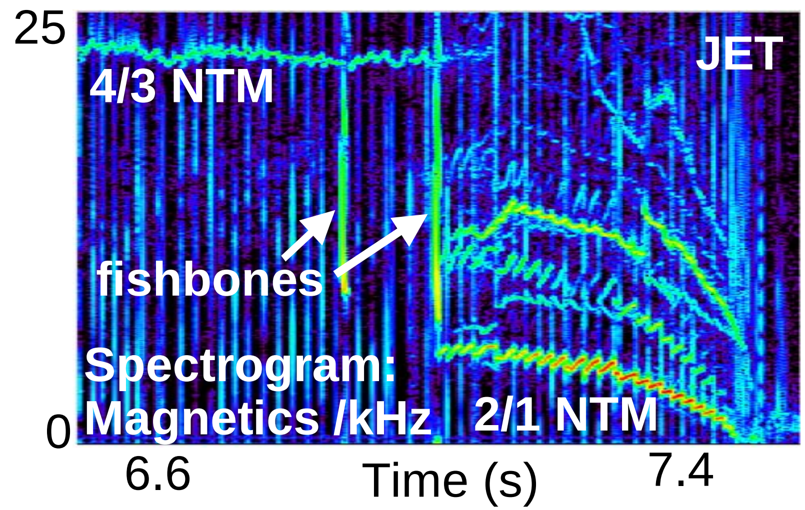


Fishbone triggers - at higher β_N?

- Fishbones also trigger NTMs
  - 3/2 NTM thresholds on AUG generally higher than for sawtooth
  - although on JET these do not extend to low β
    - unlike cases with fast particle stabilised sawteeth

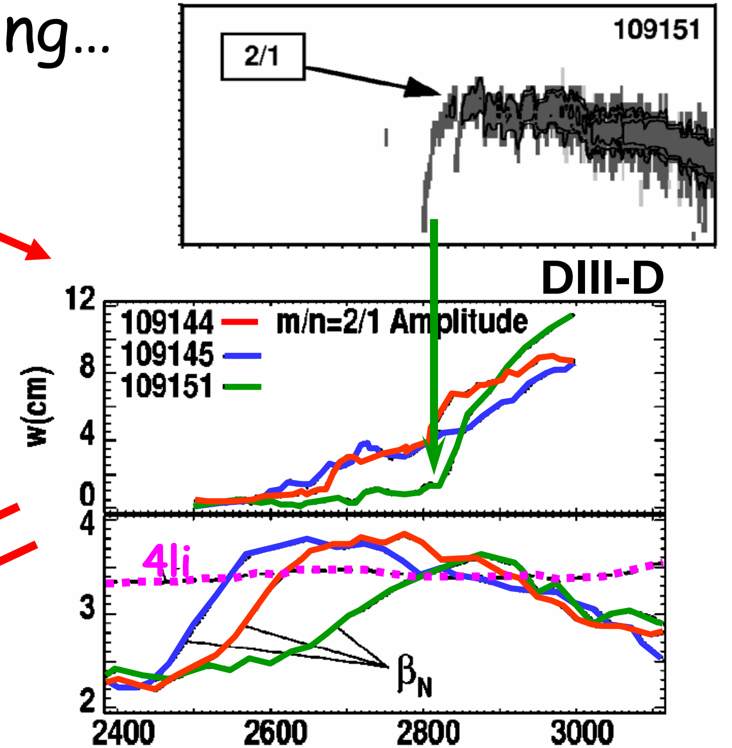


- Fishbones recently observed to also trigger 2/1 NTMs:
  - at β_N=2.5 on JET

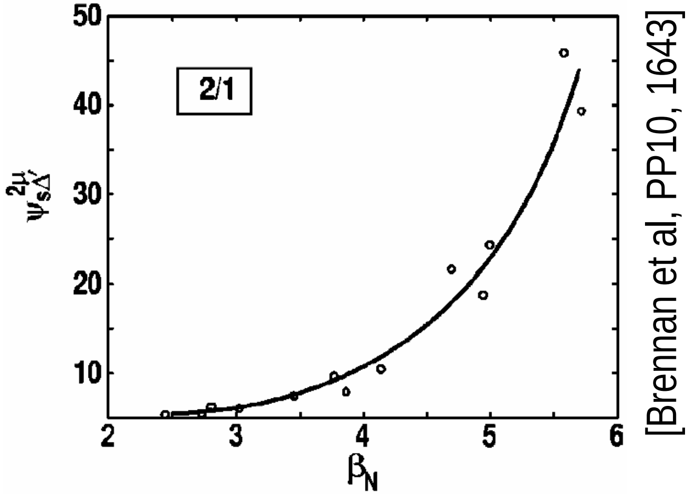


Ideal triggers at high β_N...?

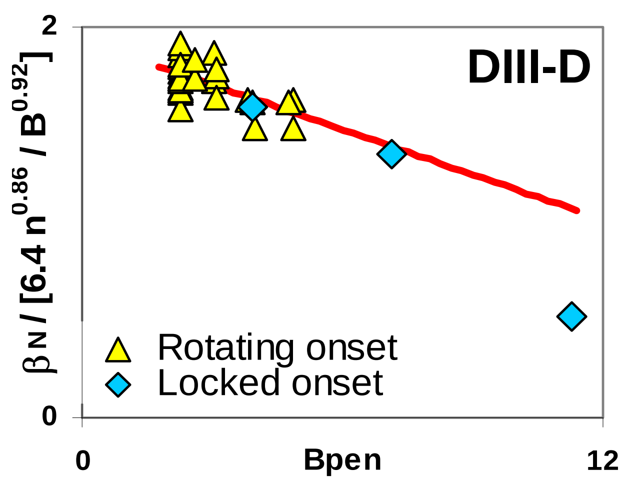
- At high β_N often see weak/no seeding...
  - modes often near ideal limit
  - a particular issue for hybrid scenario and 2/1 NTMs



- Modelling of DIII-D case shows poles in classical tearing stability:



- Separate studies show 2/1 NTM threshold lowered by error fields
  - ***possibly an ion polarisation effect...***



Conclusions for ITER on NTMs

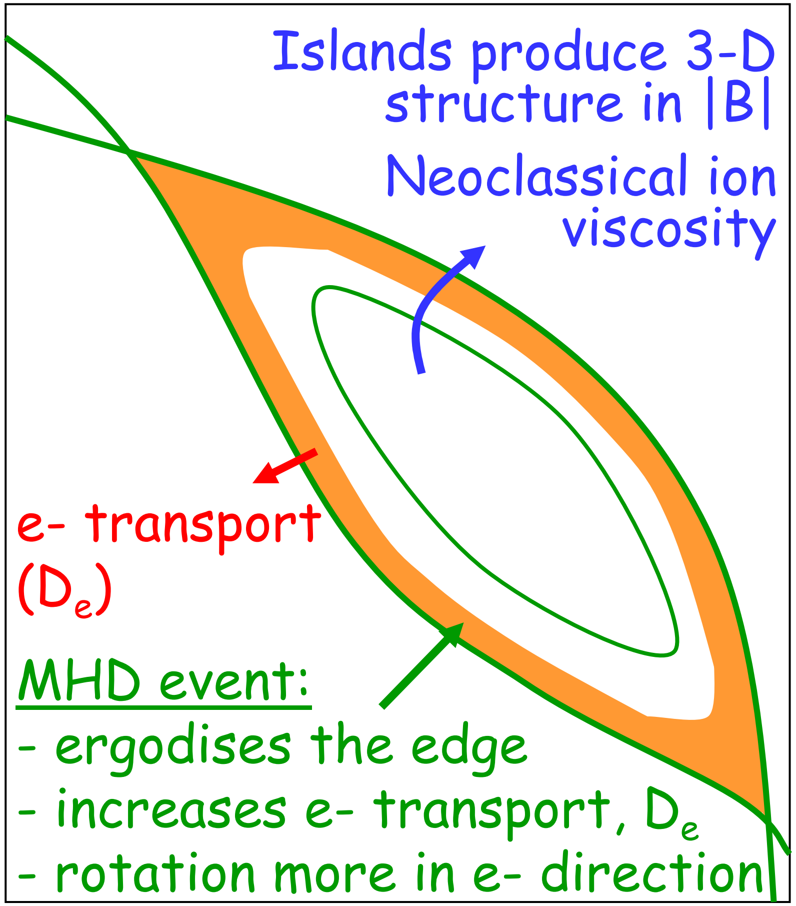
- ITER deeply metastable to NTMs, but tractable?
  - benign scalings for some NTM onset mechanisms
  - control of seeds possible for others
- Baseline scenario - ***key issues are fast particles & sawtooth***
  - further triggers at higher β_N may remain at high β_N
- Hybrid scenario - ***main concern is 2/1 NTM*** (3/2 fairly benign)
  - does 2/1 onset threshold fall with ρ^*? - mitigate with high q_{min}?
- However, caution required for ITER...
  - adverse NTM physics scalings and high fast particle populations
  - need to confirm scalings of high β_N modes, especially 2/1 NTMs
  - need to integrate control techniques into scenarios to develop ready to use tools (not lengthy research programmes) for ITER

Nevertheless, we now see the principal physics ingredients assembled, a new generation of codes identifying the effects, and good progress in control and predictive capability.

→ **Ongoing work is important to provide solutions for ITER**

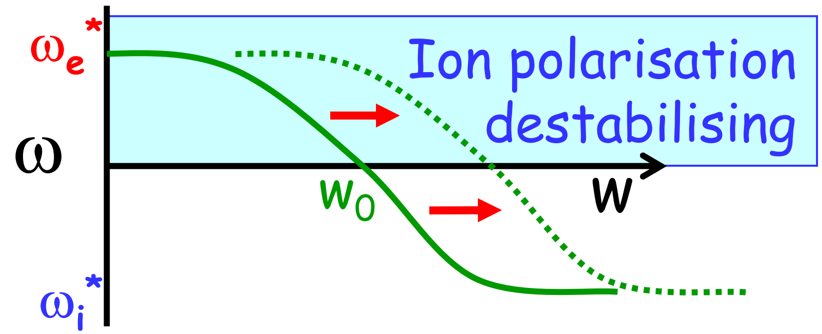
Transient transport events can seed NTMs

- Ion polarisation effects depend on island rotation - $a_{pol} \sim \omega(\omega - \omega^*_I)$



[Hegna, Bull.Am.Phys.Soc.48, 280]

Rotation from balance of ion and electron dissipation:



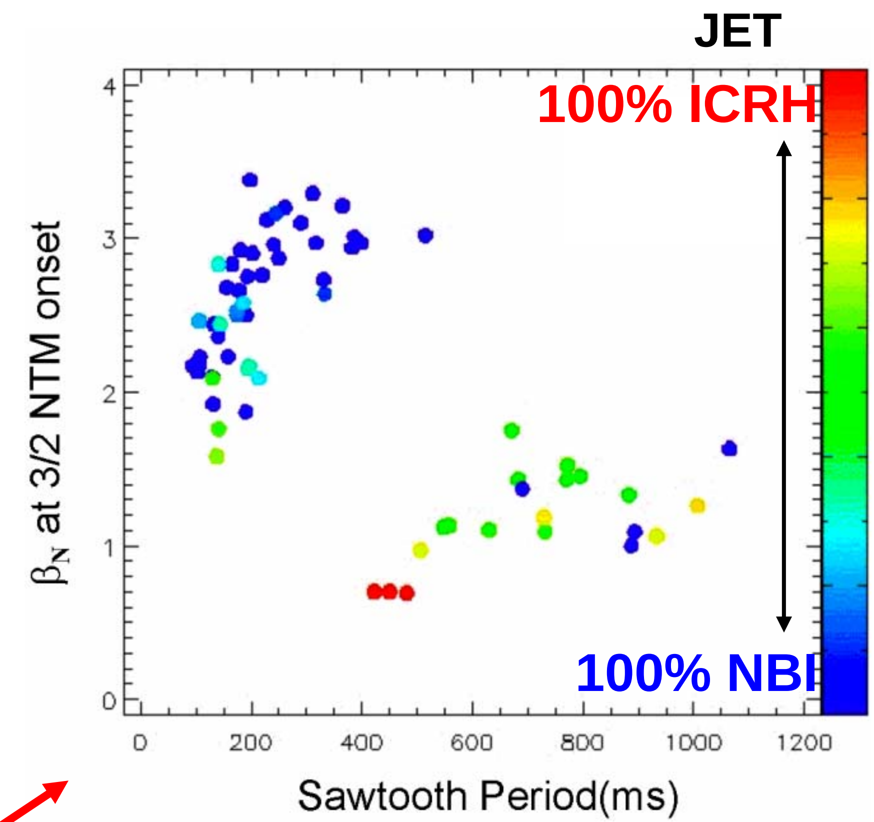
- naturally leads to small islands via ion polarisation effects
- higher e-dissipation raises $w_0 \sim (D_e)^{0.5}$

- *Does not require frequency matching between MHD modes and the island*
- *May explain error field effects*

What is the hidden control parameter?

- Employ neural network to look for pattern in data...
  - automatic optimisation from choice of 27 input parameters
  - train to predict onset time

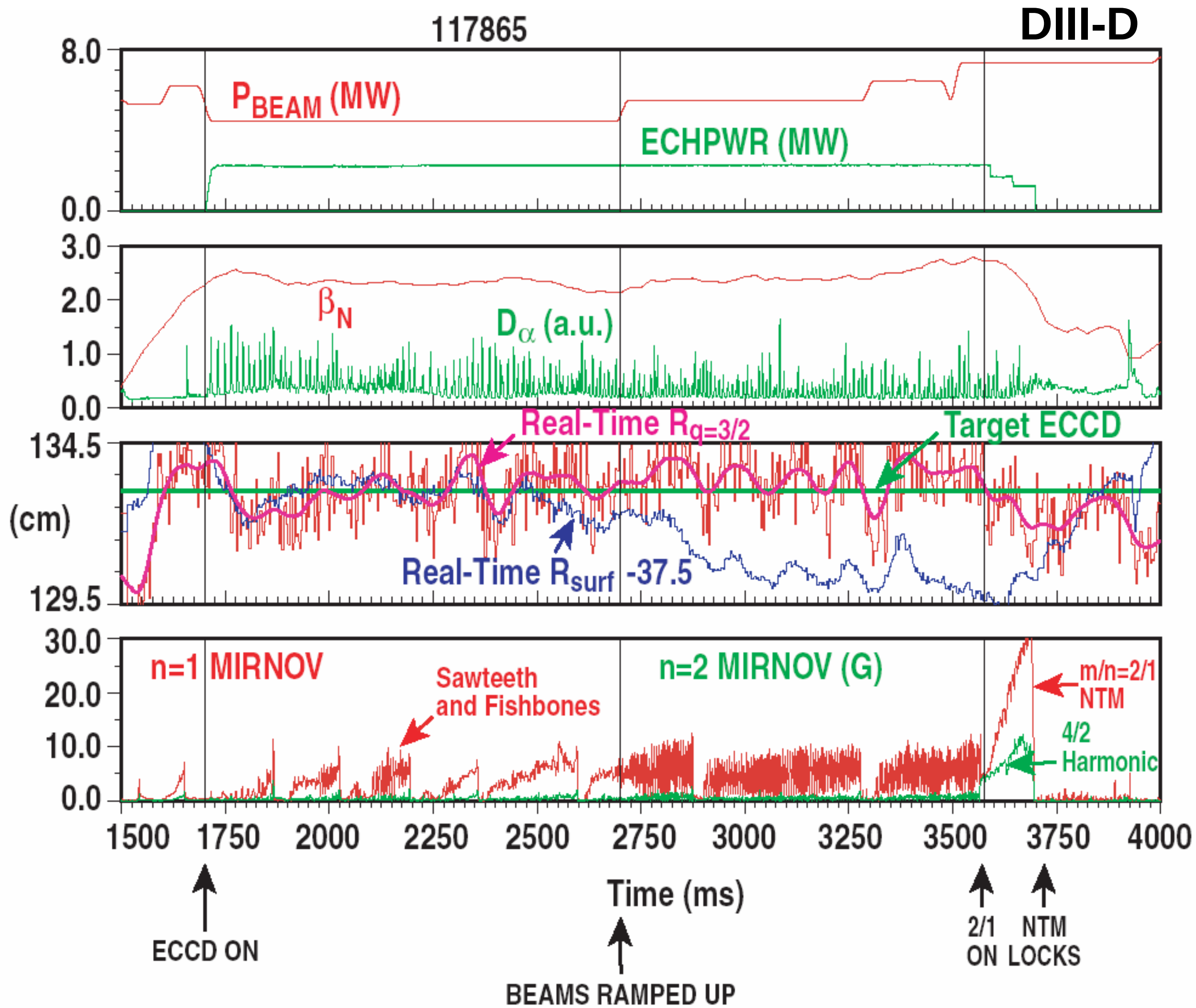
- Network successful
  - predicts decreasing time to NTM as onset approached
    - ♦ *unlike ρ* scaling!*
  - best network uses just β_N, ρ* and sawtooth period
    - ♦ *period even more significant than ρ**



- Sawtooth period plays key role in NTM onset β

Preemptive current drive on DIII-D

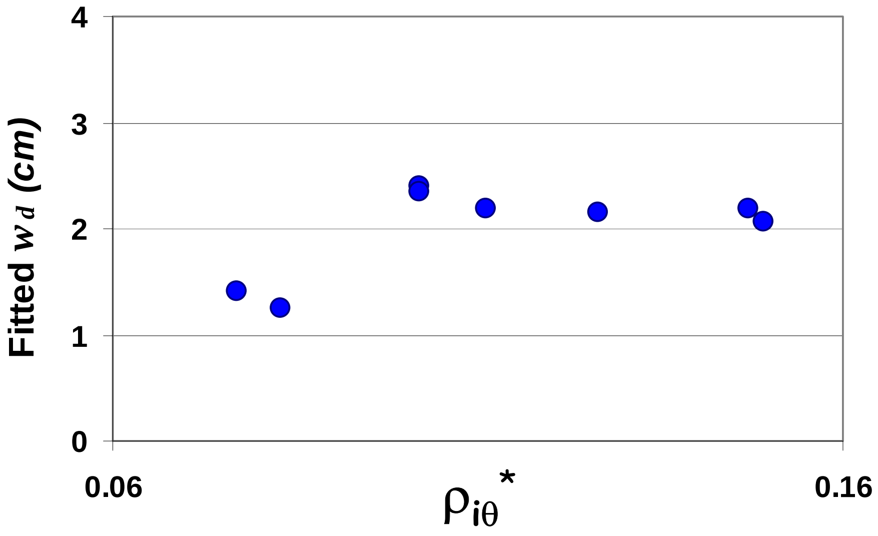
- Use real time MSE tracking to put ECCD on NTM resonant surface, raising NTM thresholds



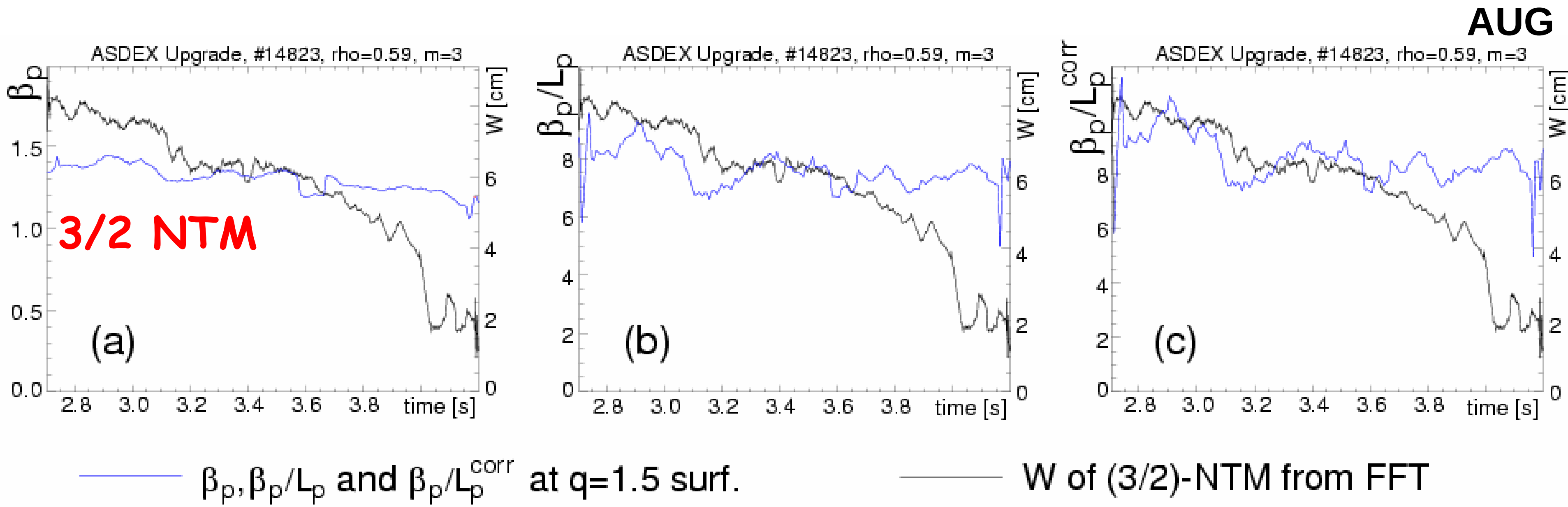
Mode removal in ITER

- Island evolutions show scale length of small island term, w_d, does not change much with ρ^*

- Mode removal in ITER will require driving islands down to similar size to those required in present devices

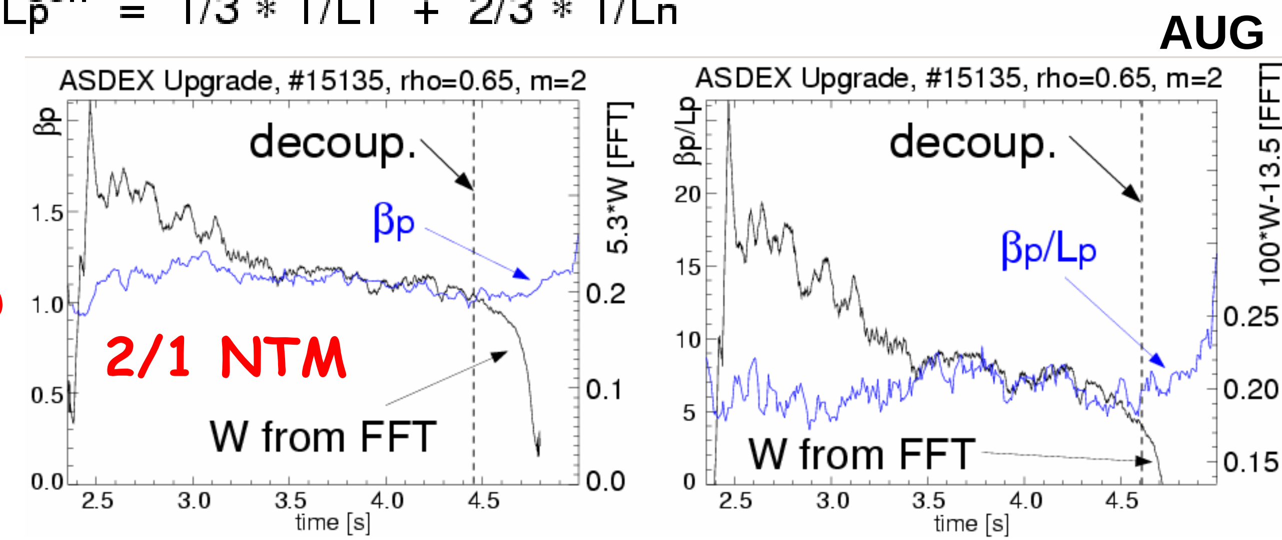


Use of correct local parameters



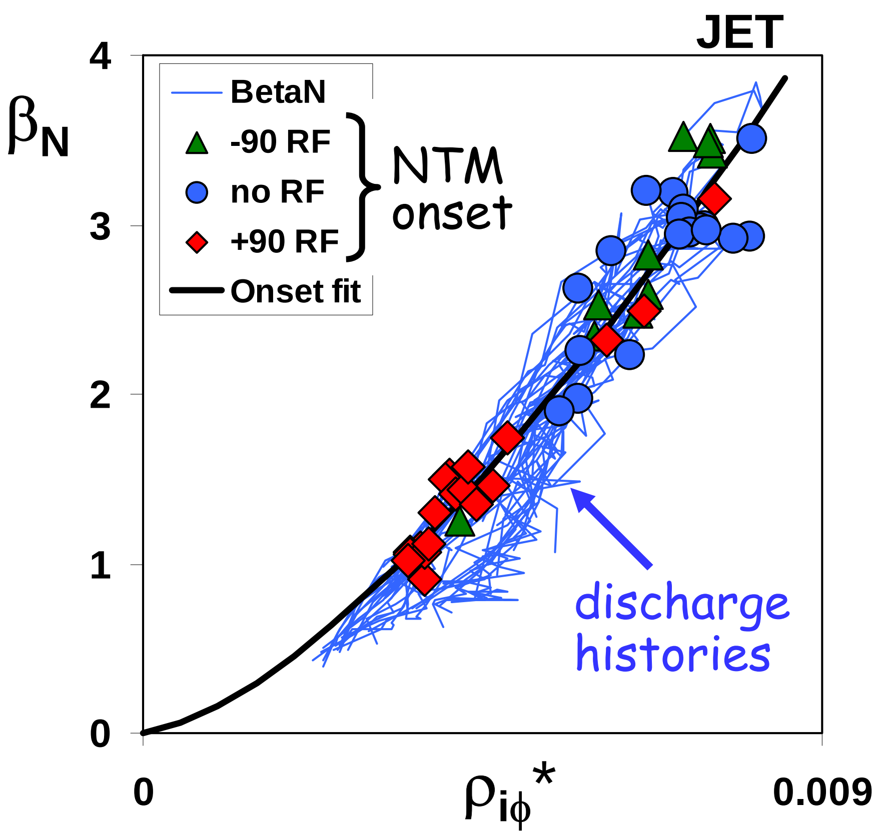
$$L_p^{corr} = 1/3 * 1/L_T + 2/3 * 1/L_n$$

- Studies on AUG show that NTMs track correctly calculated bootstrap parameter, better than β_p



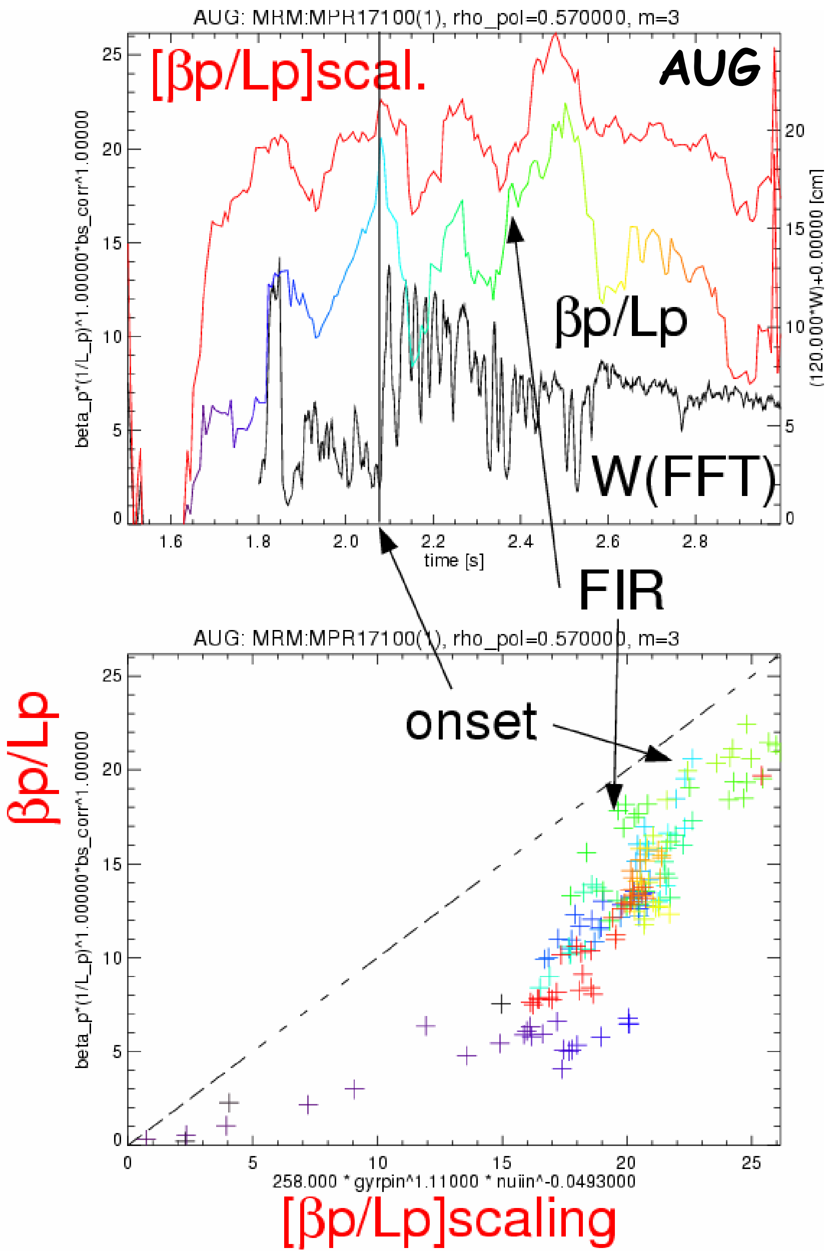
How do the ρ* scalings do?

- But they are not predictive of NTM onset β and time on JET…



- β stays close to NTM onset scaling prediction once H-mode reached
    - for both local and global parameter fits
- JET NTM onsets align well with natural discharge evolution
    - (clue: ICRH phasings)

ρ* scalings sometimes work for NTM onset



- AUG discharges sometimes approach scalings from below and get NTM when the scaling is reached

Formalism - origin of ρ^* scaling

- Evolution of island size *w* governed by modified Rutherford:

$$\frac{\tau_r}{r}\frac{dw}{dt} = r(\Delta' - \alpha w) + r\beta_P\left[a_{bs}\left(\frac{0.65\,w}{w^2+w_d^2}+\frac{0.35\,w}{w^2+28\,w_b^2}\right) - \frac{a_{GGJ}}{\sqrt{w^2+0.2\,w_d^2}} - \frac{a_{pol}\;w}{w^4+w_b^4}\right]$$

classical tearing

bootstrap

finite island transport

ion banana width

field curvature

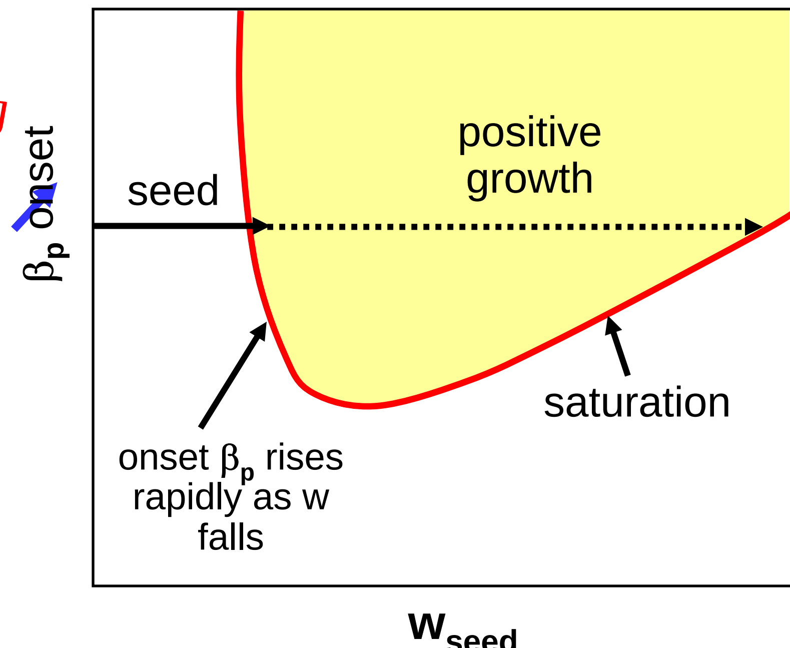
ion polarisation currents

small island terms stabilising - lead to minimum size and β for growth

- Example: ion polarisation term, $a_{pol} \propto f(\Omega)\; g(\nu,\varepsilon)\; \rho_{i\theta}^{2}$

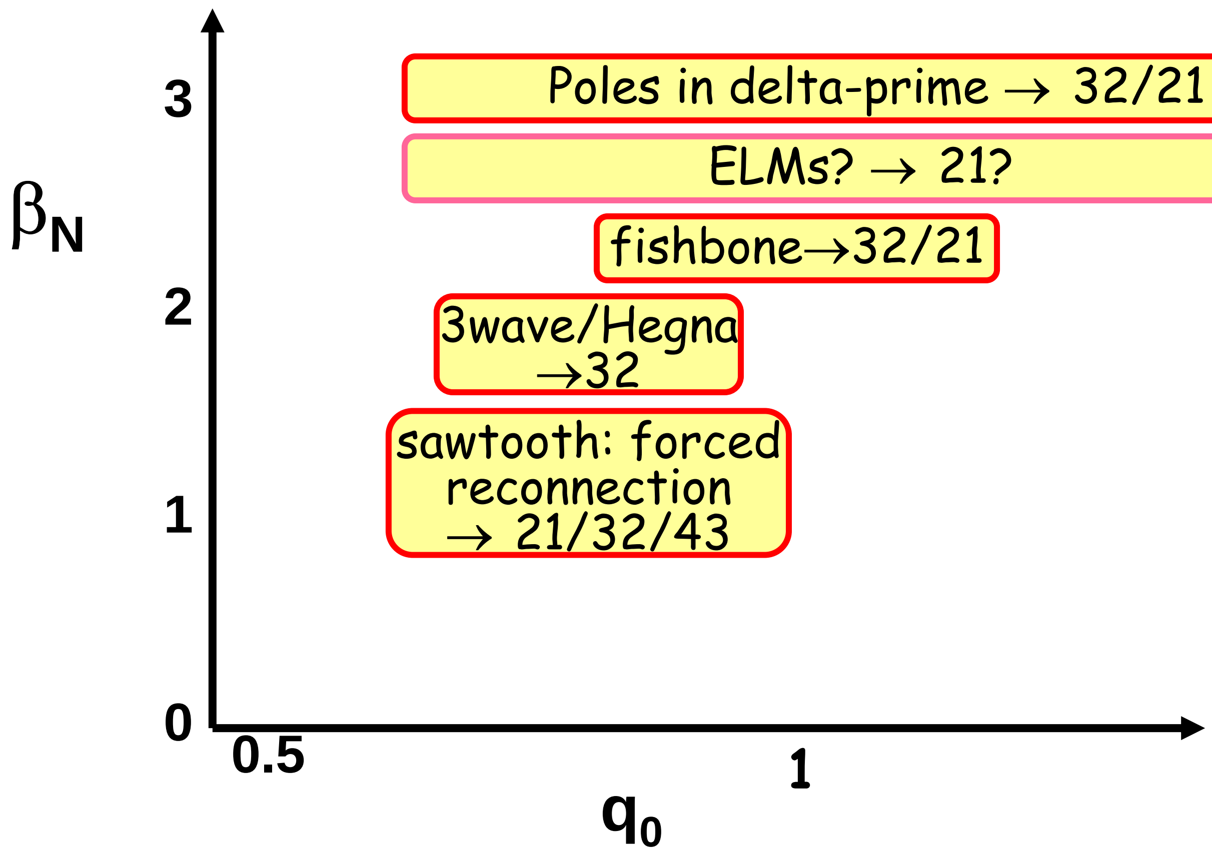
$$\Rightarrow \quad \beta_{p-onset} \propto -r_s\Delta' \cdot \rho^*_{i\theta} \cdot \frac{w_{seed}/\sqrt{a_{pol}}}{[1-(\sqrt{a_{pol}}/w_{seed})^2]} \cdot g$$

- seed get > seed need
- uncertainties in both



ITER possible figure?

- Possibly how it looks...

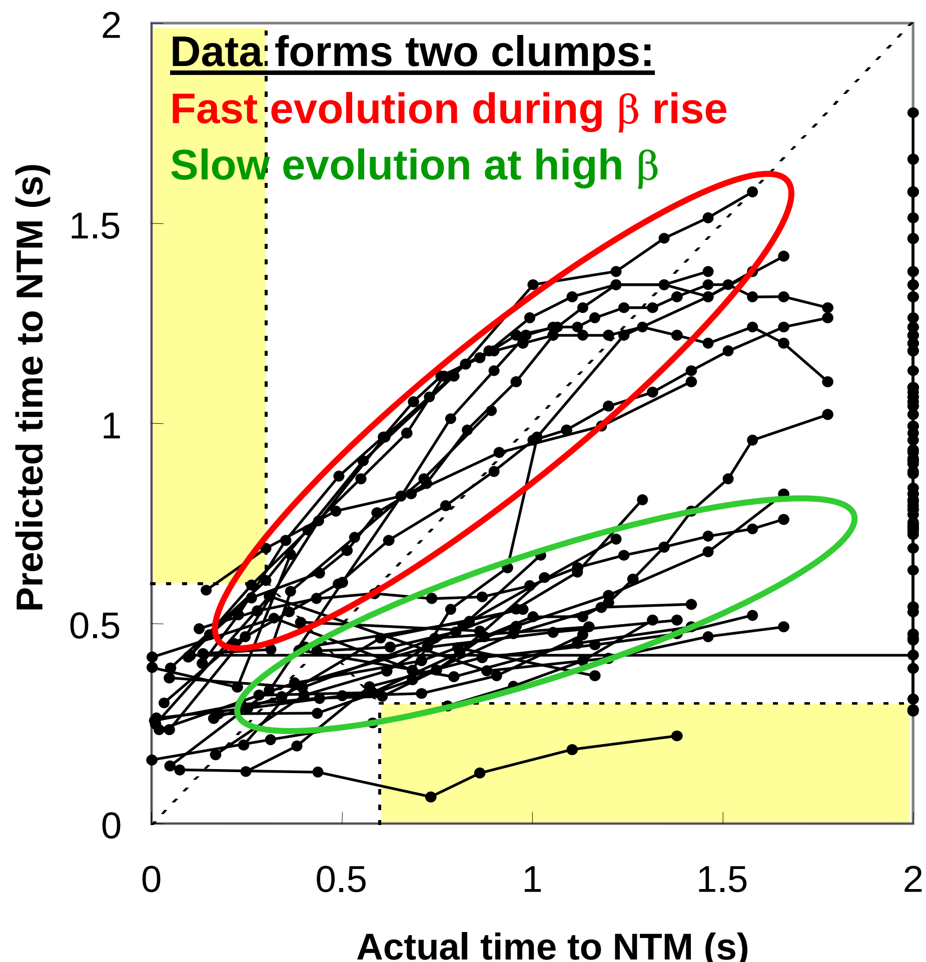


What is the hidden control parameter?

- Employ neural network to look for pattern in data...
  - automatic optimisation from choice of 27 input parameters
  - train to predict onset time
- Network successful
  - predicts decreasing time to NTM as onset approached
    - *unlike ρ^* scaling!*
  - best network parameters:

Parameters:	Residual†	Errors
β_N $\tau_{sawtooth}$ $\rho_{i\phi}^*$	34.3	17%
β_N $\tau_{sawtooth}$	34.4	20%
β_N $\rho_{i\phi}^*$	35.7	26%
β_N	35.9	31%
$\rho_{i\phi}^*$	37.5	29%

† $\Sigma(\textit{predicted} - \textit{actual time to NTM})^2$



- *Sawtooth period more useful than $\rho_{i\phi}^*$!*

Future work

- Continue good progress on sawtooth models
- Demonstrate sawtooth control with strong FP populations at high beta
- Explore NTM triggering mechanisms and ways to control them
- Find beta limit in hybrid scenario and how it scales
- Resolve NTM small island physics and its scaling - particularly for 2/1 modes