Control of NTM onset and sawteeth in JET

Richard Buttery*, L-G Eriksson[1], D. F. Howell*, T. C. Hender*, R. J. La Haye[2], M. Mantsinen[3], M. L. Mayoral*, S. Parris[4], O. Sauter[5], C. G. Windsor*, and JET-EFDA contributors[6].

*EURATOM/UKAEA Fusion Association, Culham Science Centre, United Kingdom.
[1] Association Euratom-CEA, DRFC, Cadarache, France.
[2] General Atomics, San Diego, USA.
[3] Helsinki University of Technology, Association Euratom-Tekes, Finland.
[4] Clare College, Cambridge, United Kingdom.
[5] Centre de Recherches en Physique des Plasmas, EPFL, Lausanne, Switzerland.
[6] Annex 1 of Pamela, J., 2003 Proc. 19th Int. Conf. on Fusion Energy (Lyon, 2002, IAEA).

Outline

- Many discharges on JET 'marginal' to NTM onset scalings
- What is hidden variable triggering NTM?
  - role of the sawtooth...
- How do we control NTM onset?
  - Sawtooth control with ICCD
  - fast particles, monster sawteeth and their control
  - Tailoring sawteeth without ICCD
- Other influences on NTM onset
  - error fields
  - rotation
- Conclusions

Expect NTM scalings to go with ρ*

- Modified Rutherford equation:

$$\frac{\tau_r}{r_s^2}\frac{dw}{dt} = \Delta' + a_{bs}\varepsilon^{1/2}\left(L_q / L_p\right)\frac{\beta_P}{w}\left(\frac{1}{1+w_d^2/w^2} - \frac{w_{pol}^2}{w^2}\right)$$

Small island effects such as ion polarisation introduce a ρ* dependence:

$$w_{pol} \approx [\, g(\nu,\varepsilon)\,(L_q/L_p)\,\varepsilon\,]^{0.5}\,\rho_{i\theta}$$

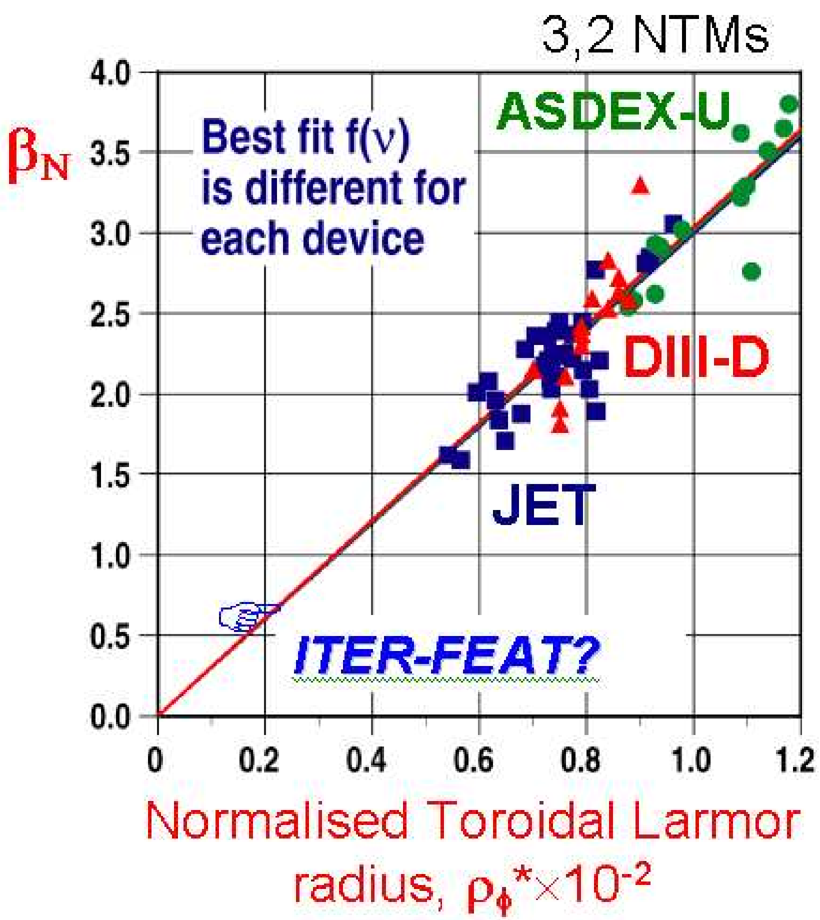
- …leads to a β~ρ* onset criteria:

$$\sqrt{\frac{L_q}{L_p}}\,\beta_{p-onset} = -r_s\Delta' . \rho_{i\theta}^{*} . \frac{w_{seed}/w_{pol}}{[1-(w_{pol}/w_{seed})^2]} . g(\nu,\varepsilon)$$

- *Usually assumes a given seed size*

(Similar form is possible for finite island transport model)

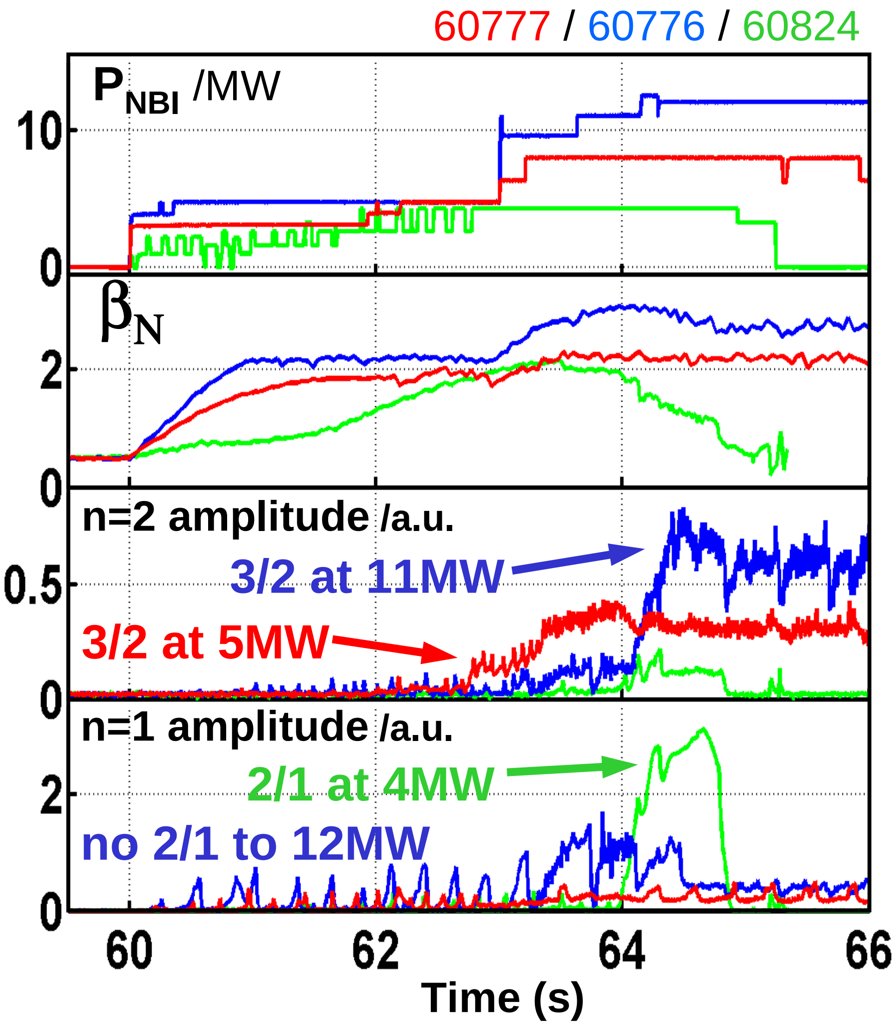
ρ* scaling appear to do a good job



- **Each experiment exhibits linear scaling**
  - *Collisionality dependence has been scaled out*
  - *scalings align at chosen ν value*

[La Haye et al., Phys. Plasmas 7 (2000) 3349]

Initial questions in JET data

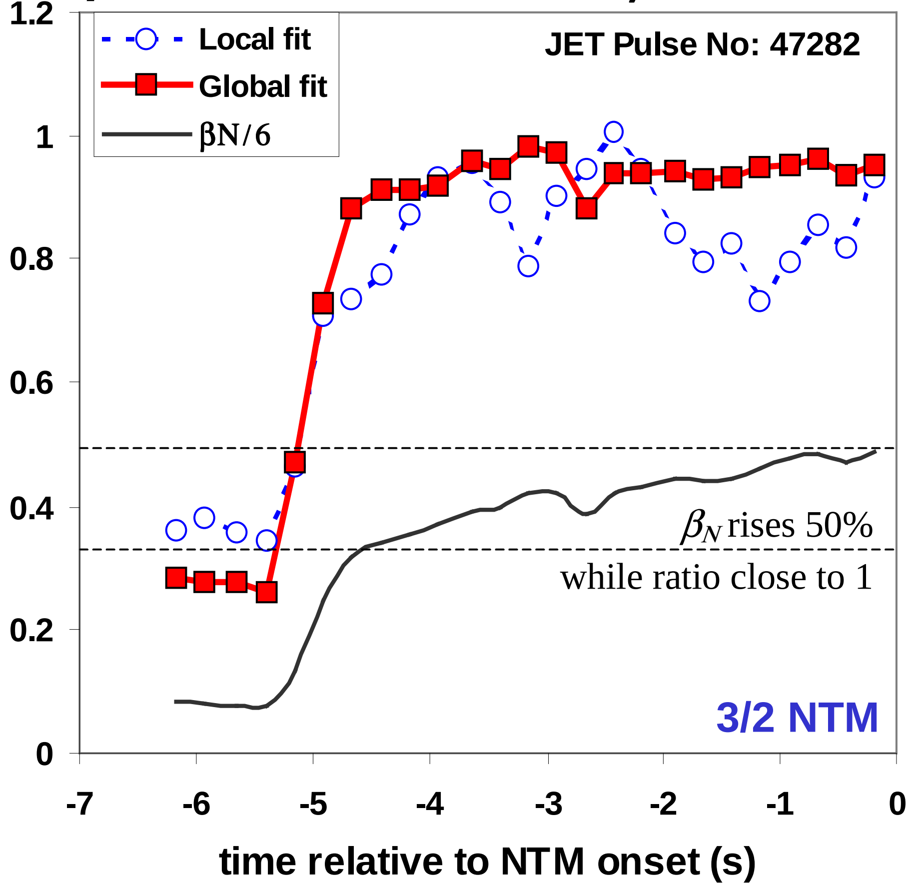


- Slightly different NBI ramps lead to very different thresholds for 3/2 mode (red and blue)
- Further modification triggers 2/1 at 4MW compared to 12MW with no-NTM in blue

Some cases stay at marginality

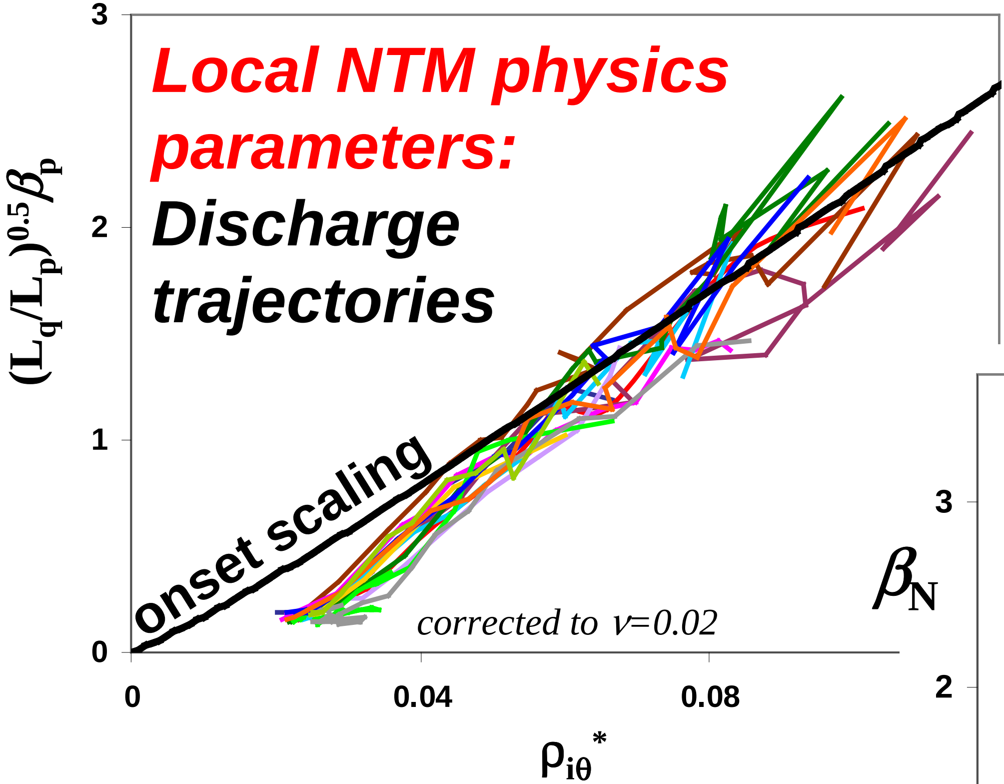
Ratio of experimental β to predicted NTM onset β:

using ρ*-ν based onset fits

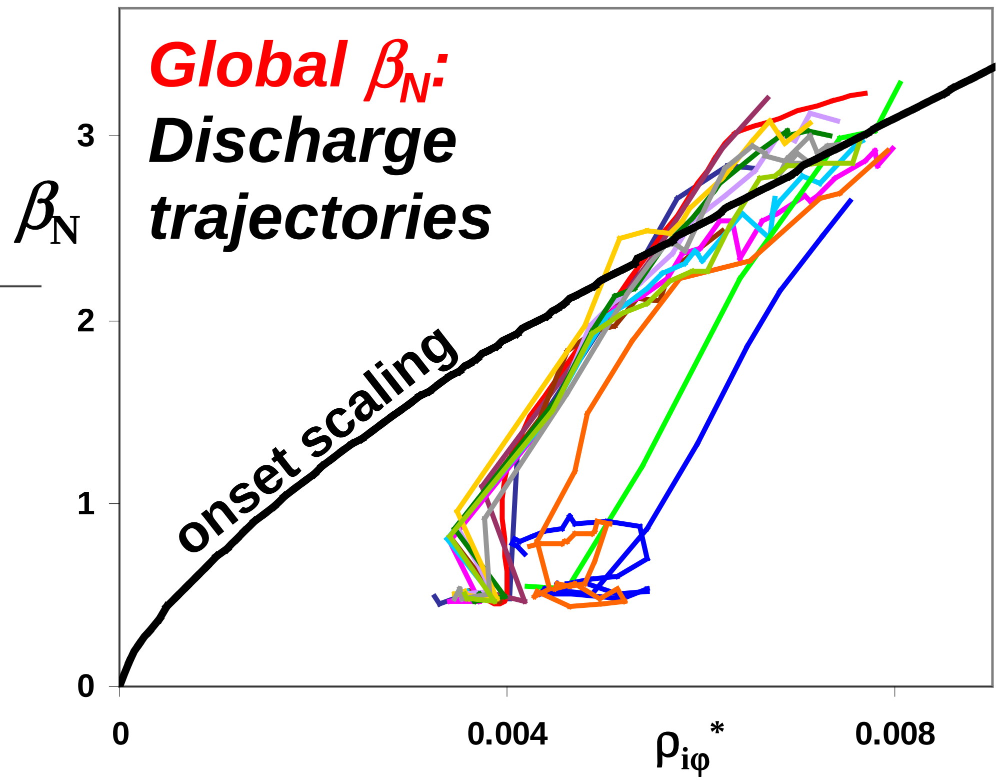


- Discharge reaches predicted onset level early
  - in both local parameter and global parameter fits
  - stays close to marginality while β rises 50%

Many discharges run along scalings



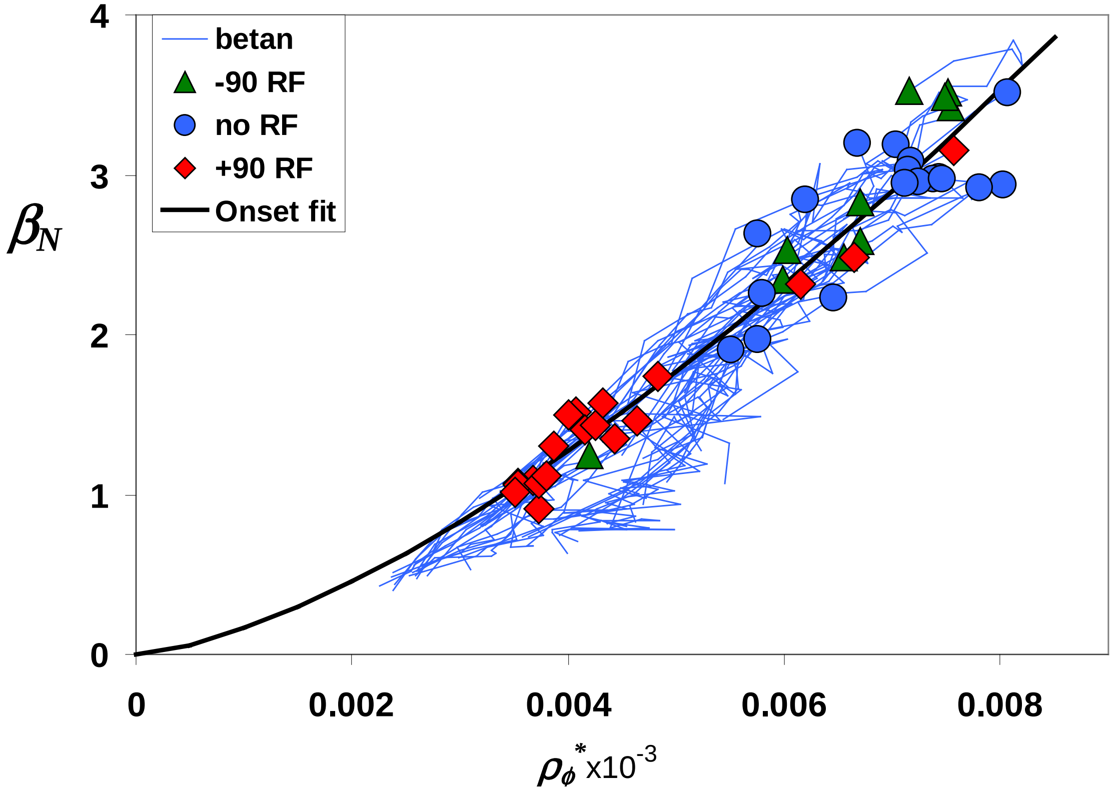
- *Shots follow scaling once H mode initiated*



All from one dedicated NBI-only NTM onset experiment in 1999

We know that changing sawtooth affects NTM threshold

- *Include ICCD q=1 sawtooth modification experiments:*



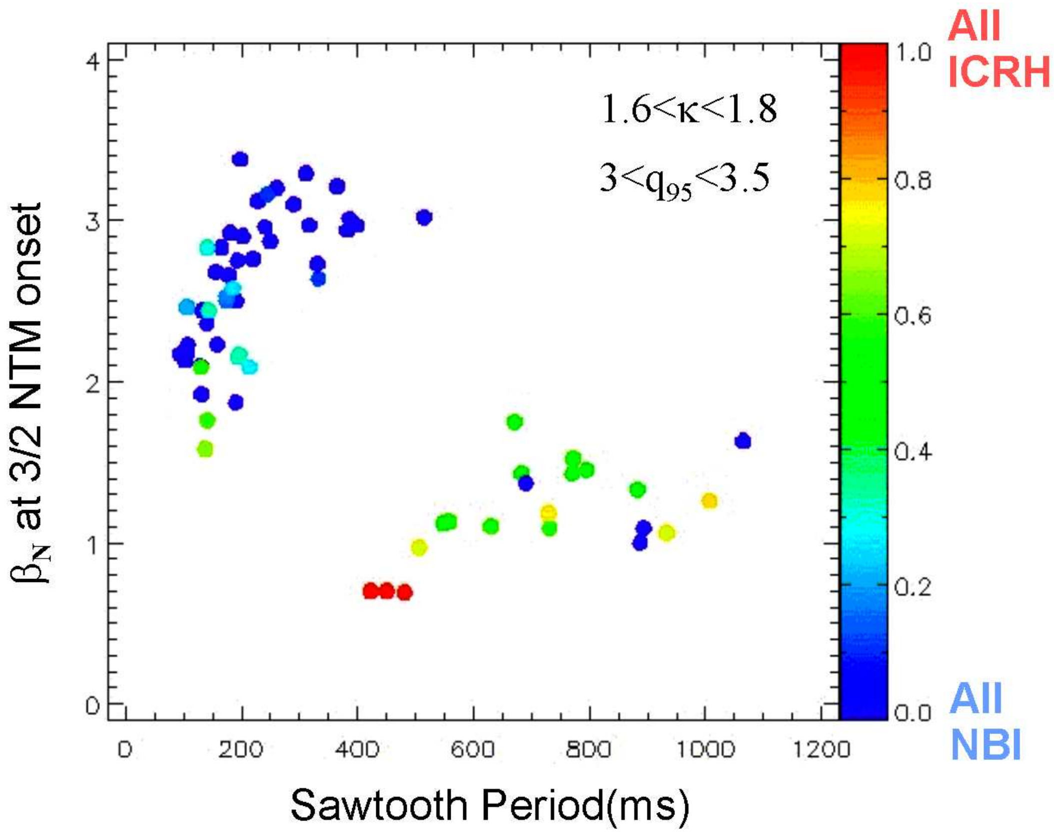
- **NTM onsets largely lie along trajectories**
  - *some -90 cases follow different path at low ρ* due to strong RF*
- Overall dependence is steeper than NBI only fits:

$$\beta_N \sim \rho_{i\phi}^{*1.5}$$

  - wider data set

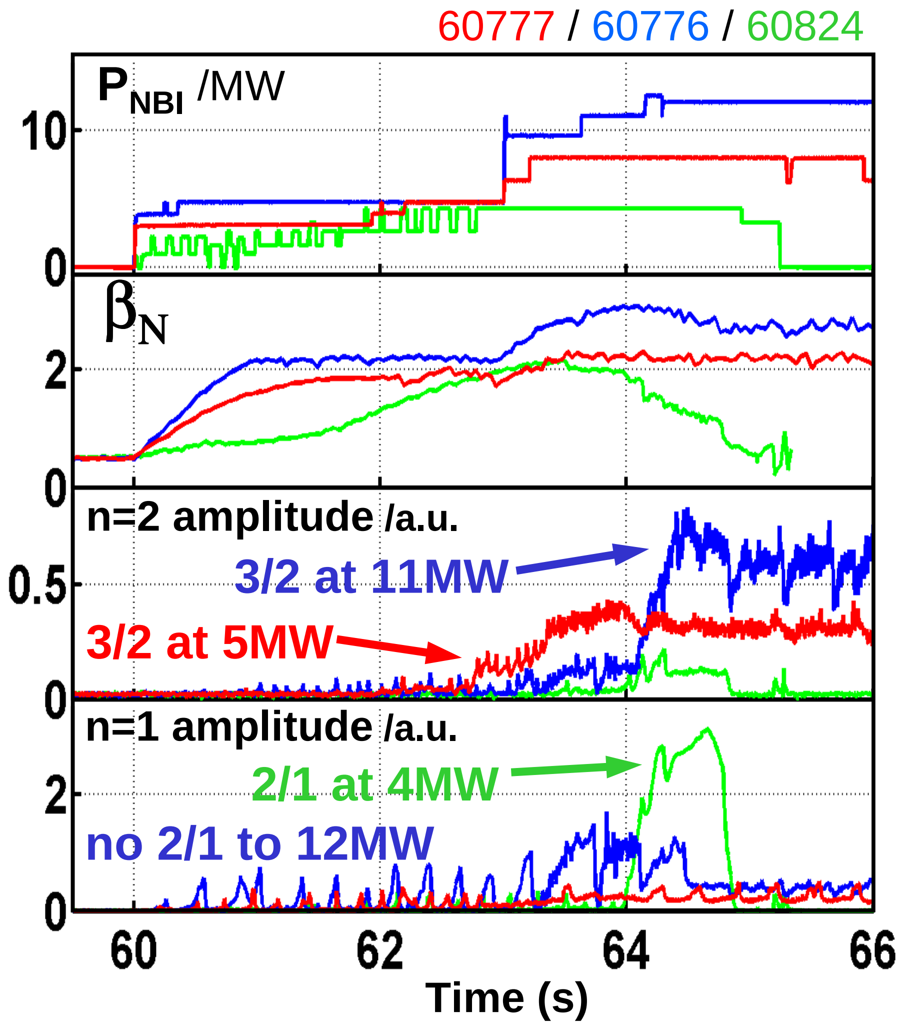
NTM onset dictated by how sawteeth evolve?

Low NTM thresholds with long sawteeth



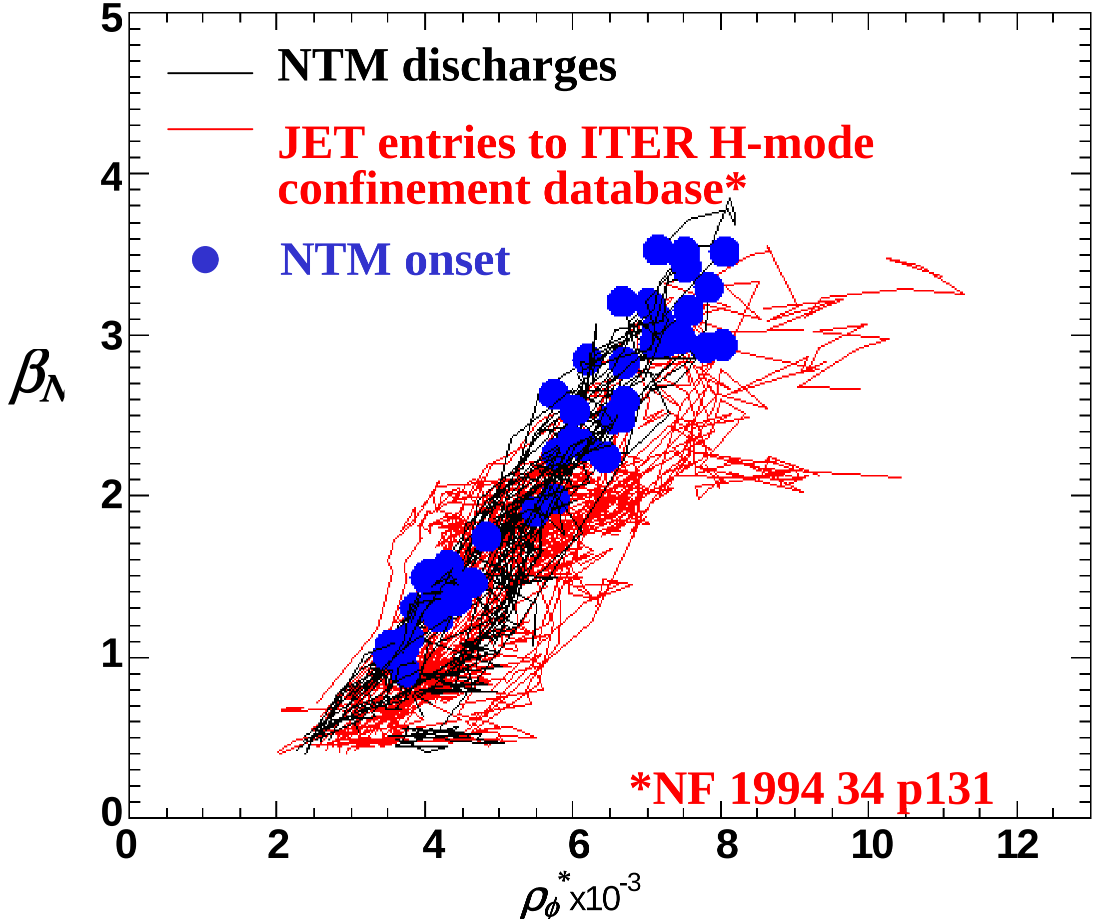
- **Long sawteeth from:**
  - ICRH induced fast particle
  - or long ‘first’ sawtooth on entry into H mode
- Sawteeth >400ms trigger NTMs easily

...but not so obvious in NBI only data



- Sawtooth periods similar for all cases
- If anything sawtooth amplitude larger in high 3/2 NTM threshold case (blue)

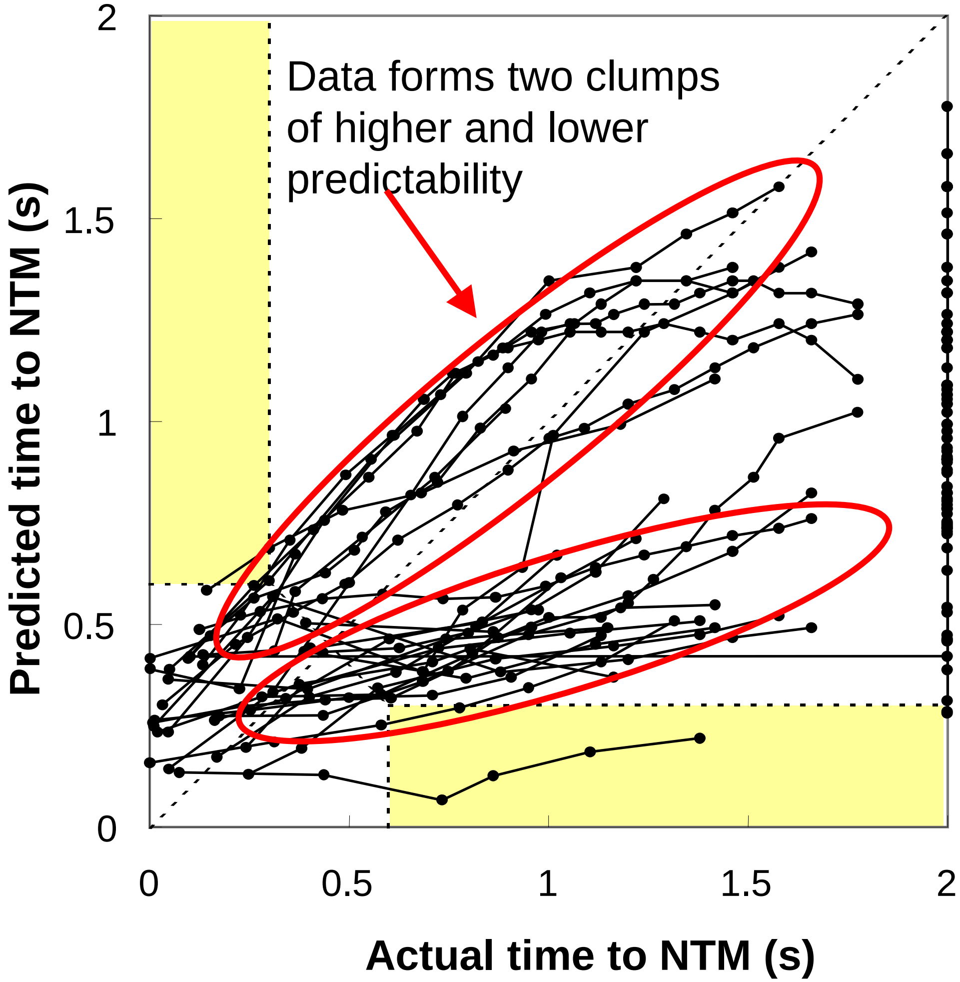
Comparison with JET ITER database



- Cut for approx match to:
  - $3.1<q_{95}<3.6$
  - $1.5<\kappa<1.65$
  - $0.2<\delta<0.33$
- ITER database entries occupy surprisingly narrow range in parameter space, when cast against local ρ_φ*
  - indicates density dependence on ρ*
- Similar to NTM discharge evolutions

Problem of collinearity of discharge evolutions and NTM thresholds is widespread...

Neural network analysis



- *Identify hidden parameters with neural network:*
  - *use NBI-only β ramp shots*
  - *predict time to NTM*
  - *optimise choice of 27 input parameters for best network performance*
- ***Best network needed just 3 parameters!***
  - ρ^* β_N τ_{ST}
- ***Network does better than fits***
  - ***trend in correct direction***
  - *(lower clump from slower evolving high β shots)*

Neural network - key parameters

Parameters used in network	Value of test residual
$\beta_N \quad \tau_{sawtooth} \quad \rho_{i\phi}^*$	34.31
$\beta_N \quad \tau_{sawtooth}$	34.41
$\beta_N \quad \rho_{i\phi}^*$	35.68
β_N	35.87
$\rho_{i\phi}^*$	37.45
$\tau_{sawtooth}$	48.85
$\tau_{sawtooth} \quad \rho_{i\phi}^*$	37.46
$\beta_N \quad \nu \quad \rho_{i\phi}^*$	35.67

Removing ρ* has little impact on network performance!

Sawtooth period more important than ρ* !

but some measure of heating power needed

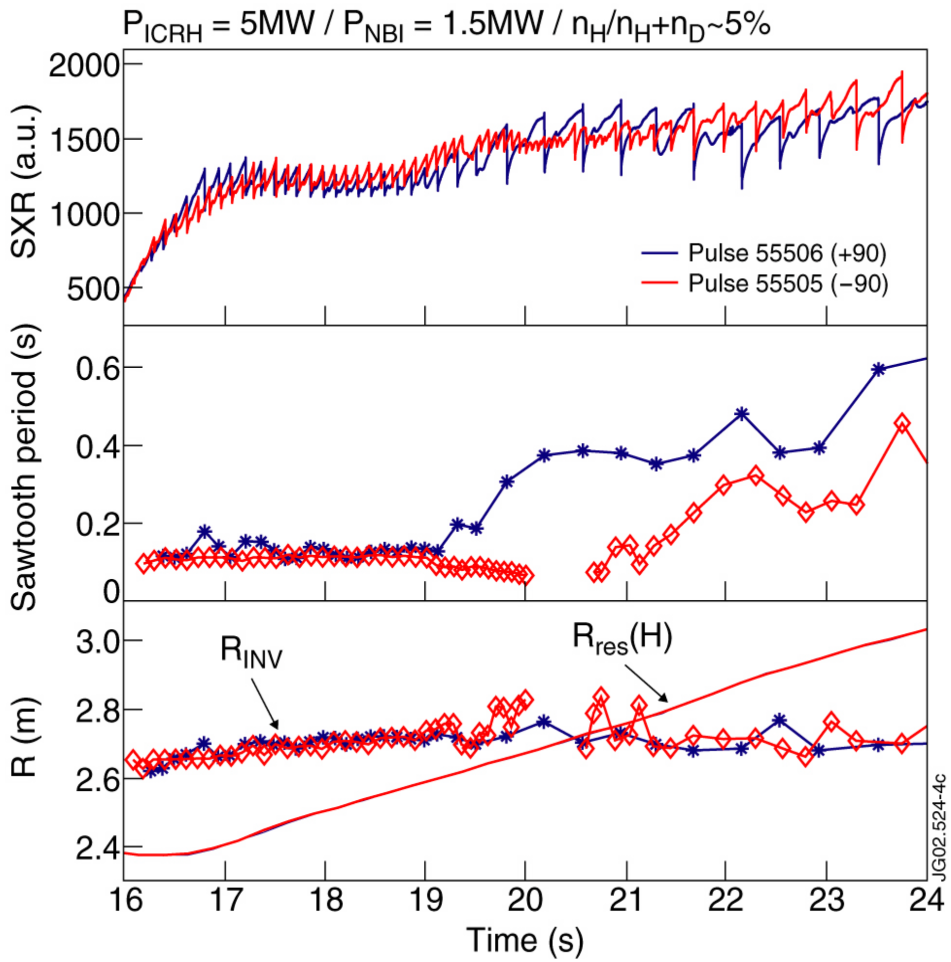
Collisionality offers no benefit

– *consistent with JET dependencies*

- So how to use this to control the NTM...?
  - Well, lets first review some ICRH techniques...

Sawtooth control by ICRF waves

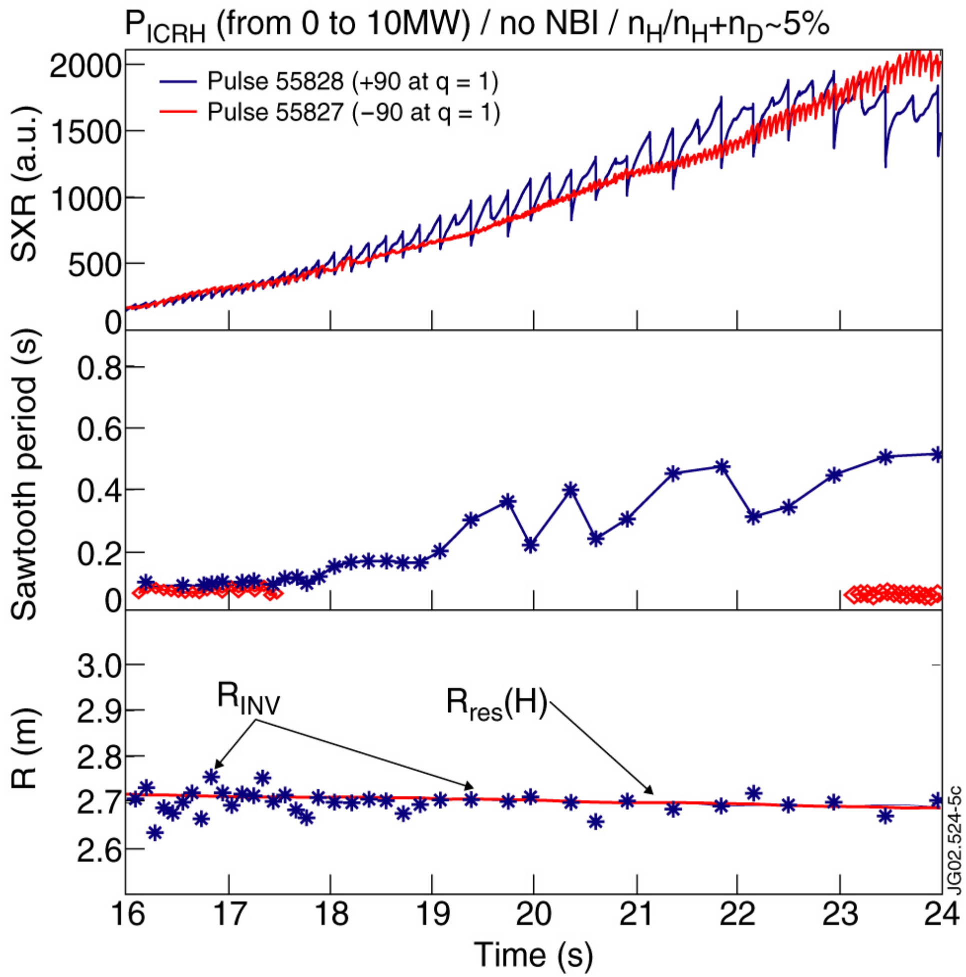
H minority heating



- Sweep deposition from inner side to centre
- Sawtooth destabilisation with - 90º phased waves at inversion radius
- Sawtooth stabilisation with:
  - + 90º phased waves at inversion radius
  - + 90º and -90 º in core: fast particle pressure increase

Sawtooth control by ICRF waves

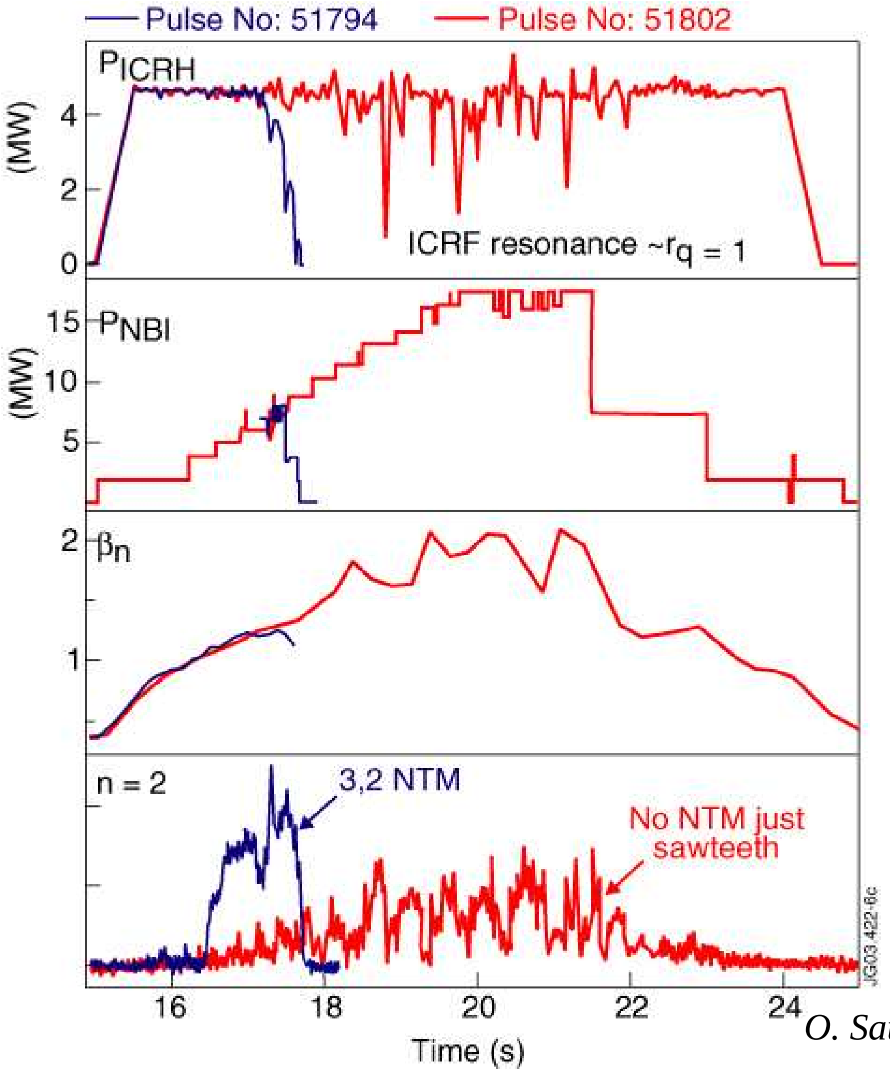
H minority heating

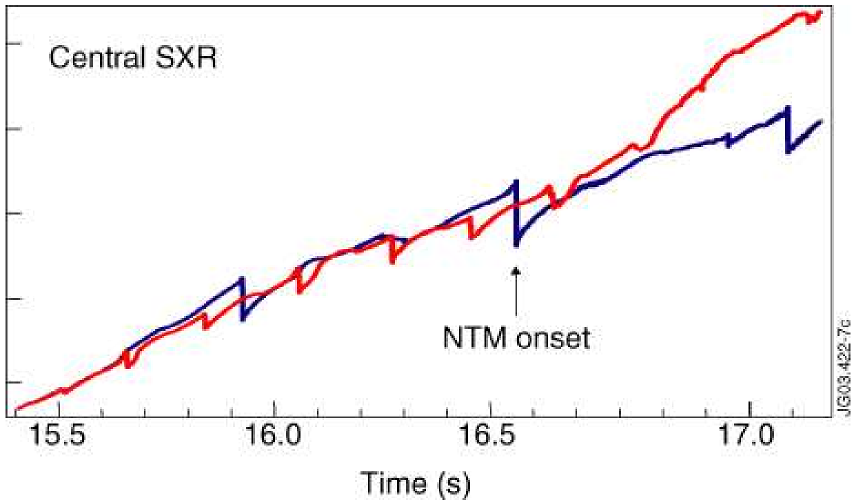


- Sweep deposition from inner side to centre
- Sawtooth destabilisation with - 90º phased waves at inversion radius
- Sawtooth stabilisation with:
  - + 90º phased waves at inversion radius
  - + 90º and -90 º in core: fast particle pressure increase
- P_{ICRF} ramp from 0 to 10 MW
  - Sawtooth activity small throughout
  - Optimal effect for P_{ICRF} = 4 to 6 MW

Sawtooth control by ICRF waves

NTM control





ICCD sawtooth destabilisation

⇩

Keep seed island of NTMs small

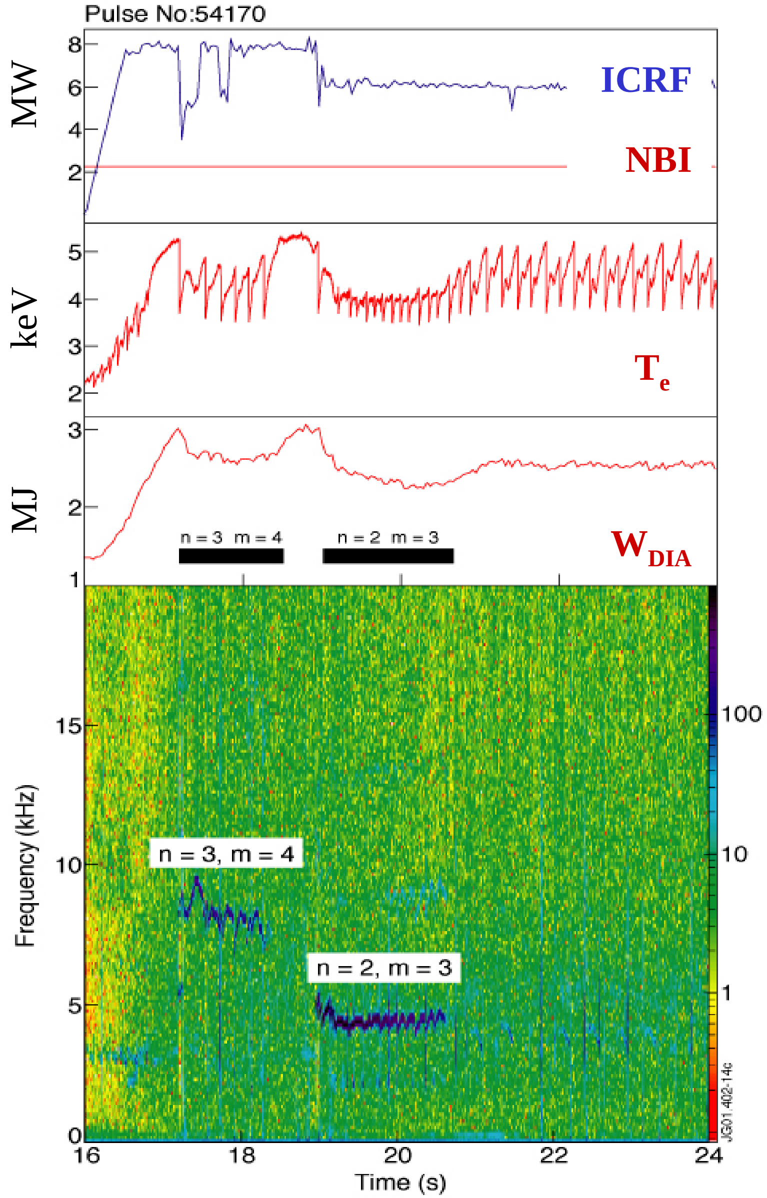
⇩

Larger plasma beta without triggering NTMs

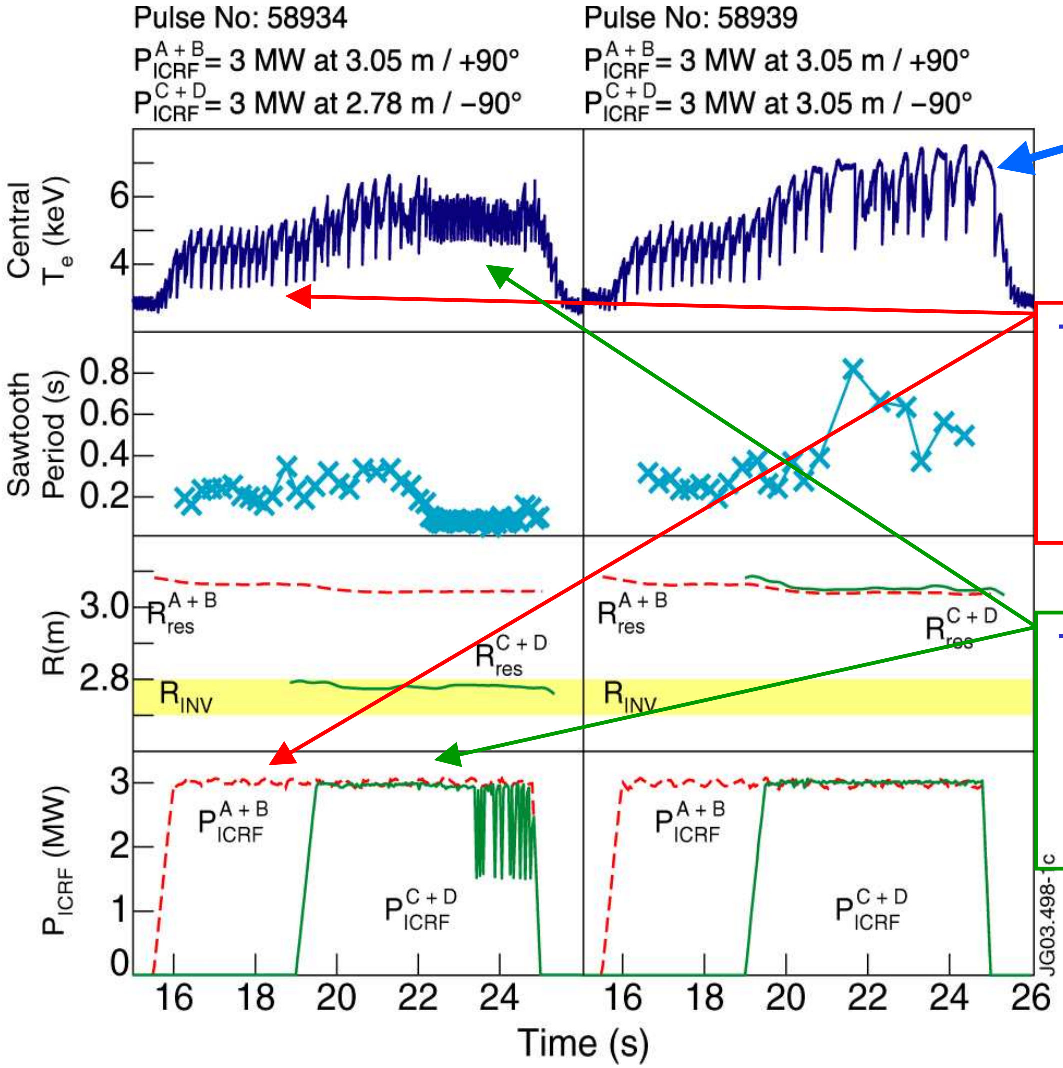
O. Sauter et al., PRL 2000

ITER will have monster sawteeth

- In JET 4He accelerated 4He ions to MeV energy range
  - makes fast alphas
- Fast alpha particles make long sawteeth :
  - Provide seed island large enough for NTM destabilisation
  - Concern for ITER D-T plasmas
- This is direct observation that fast alphas will lead to low NTMs thresholds
  - ITER will need monster sawtooth control!



Control of ‘monster’ sawteeth with ICRF waves



With all ICRH in core get monster sawteeth

Two antennas at 42 MHz and +90º:

- R_{res}(H) in centre
- Fast ions stabilised sawtooth

Two antennas at 47 MHz and -90º:

- $R_{res}(H) \sim R_{inv}$
- ICCD sawtooth destabilisation

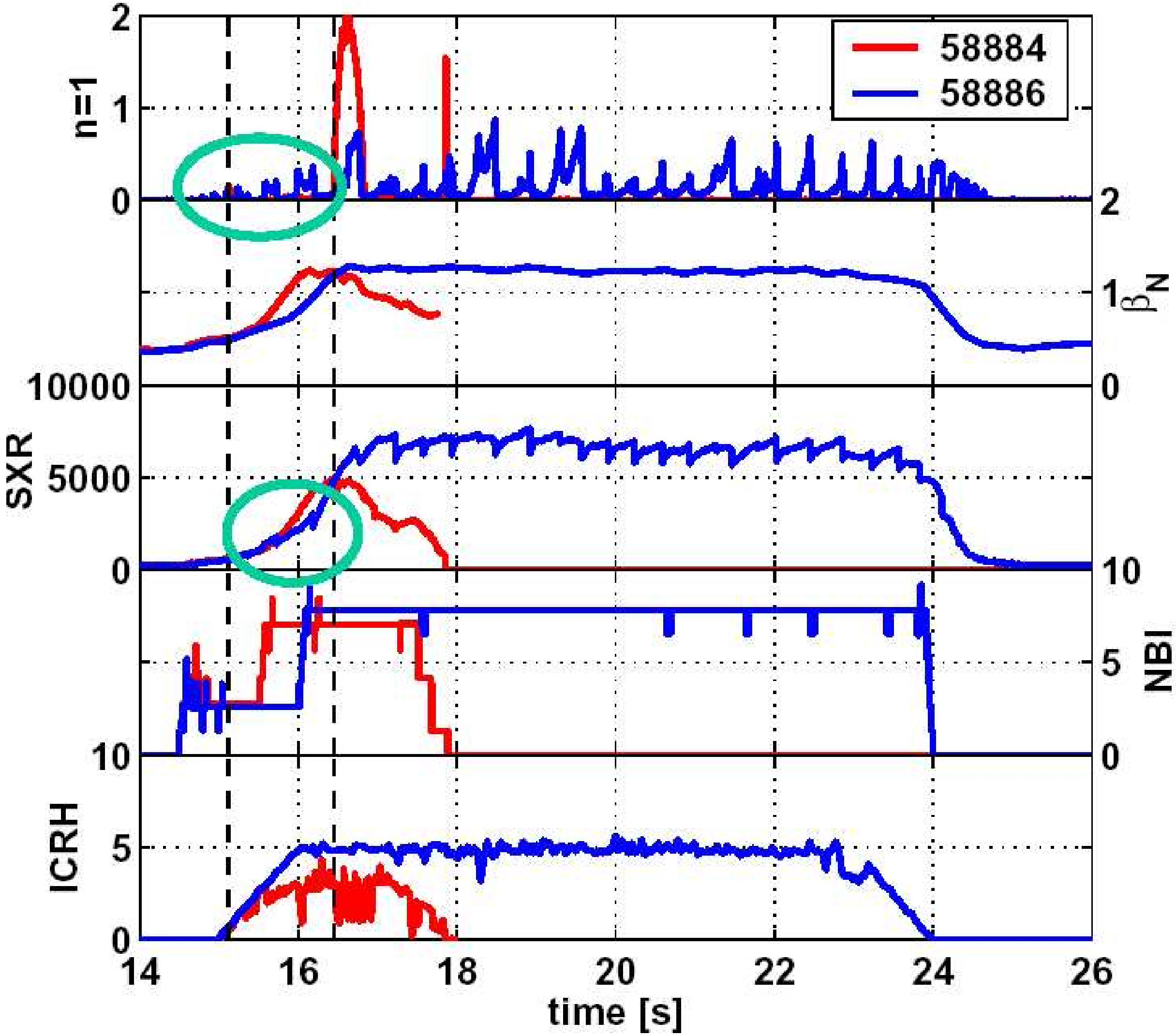
Essential technique for ITER

L.-G. Eriksson et al., to be submitted

- Application…
  - strategies used in a ‘real’ JET session that ran into unexpected NTM problems

Example case with 2/1 NTM at 3MW ICRF

- Typical ELMy H mode plasma for confinement studies:

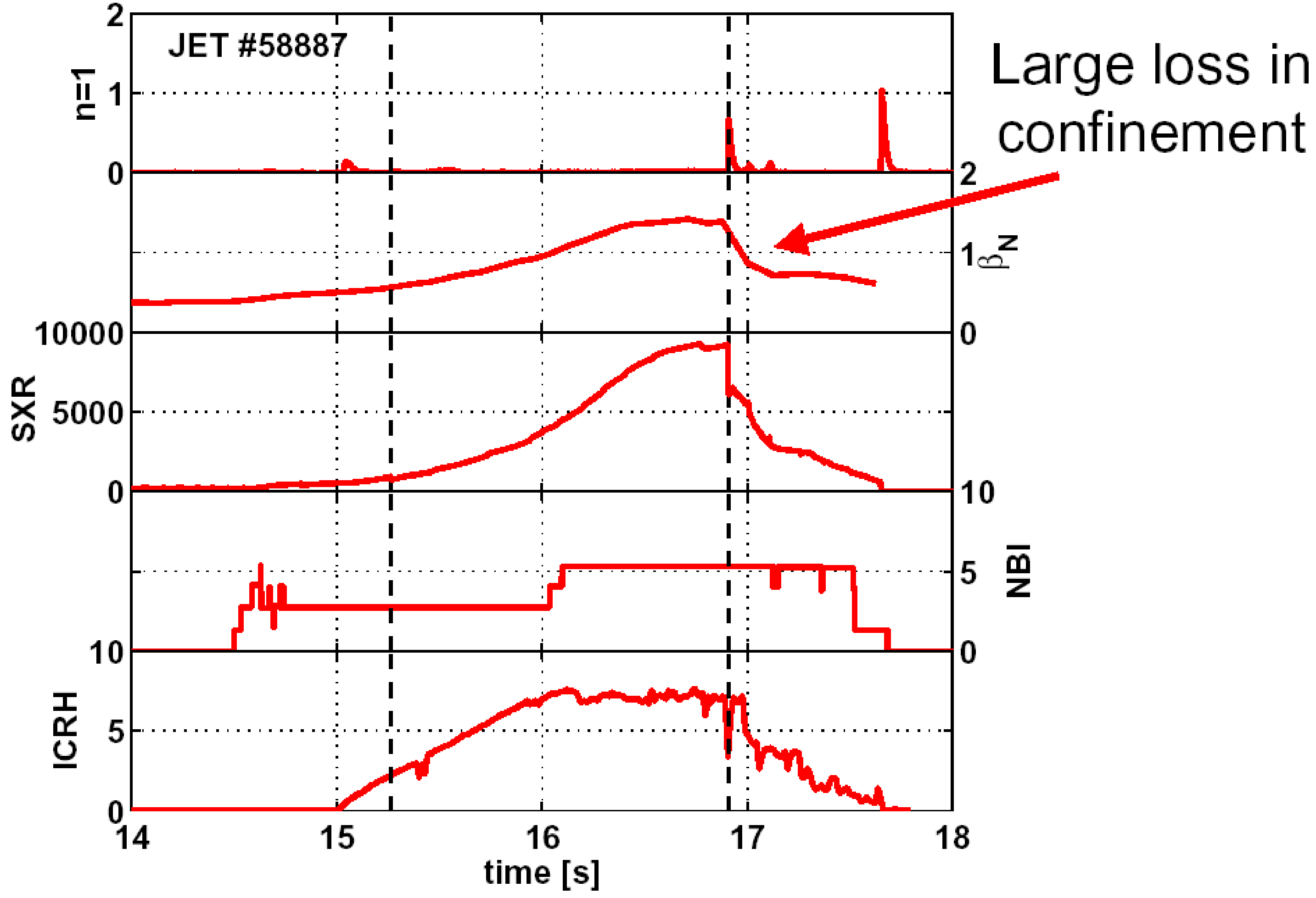


Actions

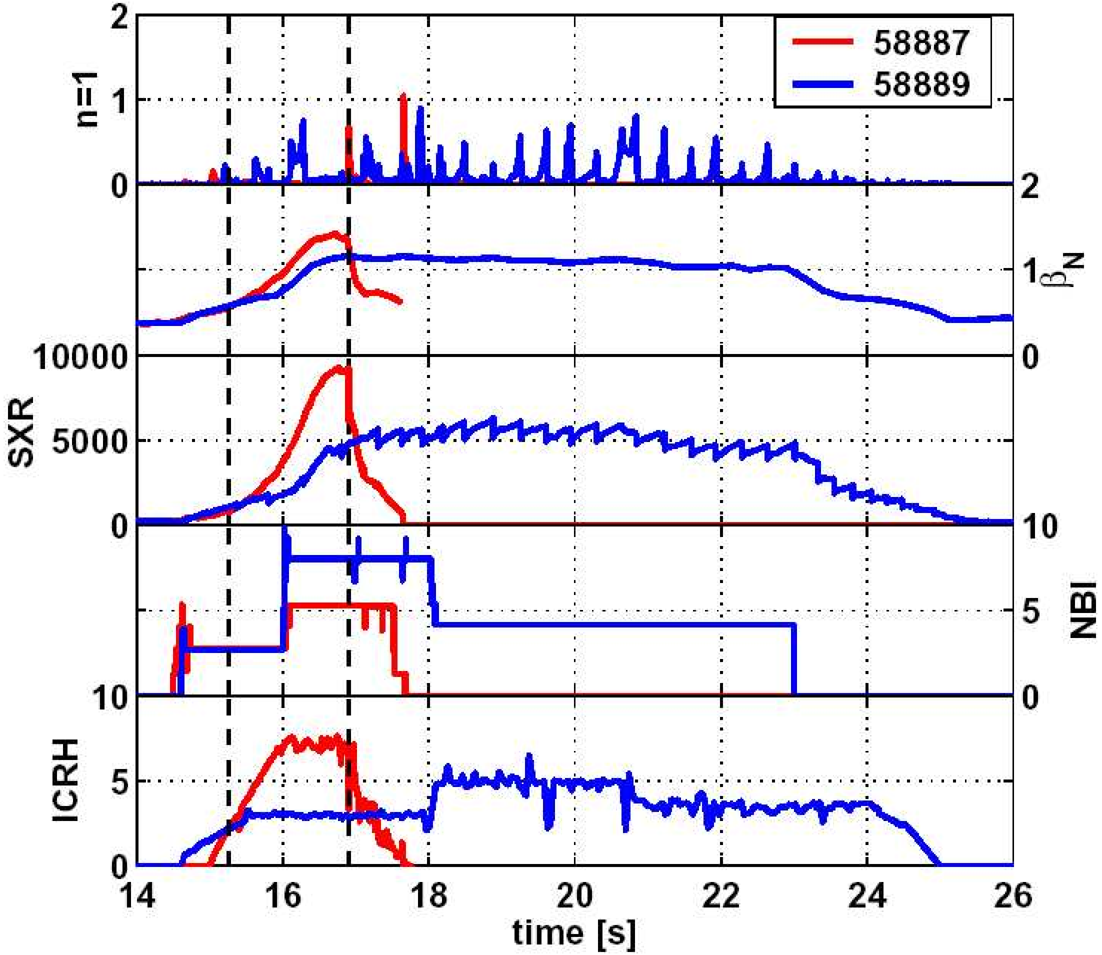
- **Changed RF to –90 phasing**
- **Modified NBI ramp-up waveform to have sawteeth before final ramp into H-mode**

2nd strategy also adopted in high shaping high current expts: 1st NBI plateau just below L-H threshold

Next pulse: more RF, long first sawtooth and 2/1 NTM



Strategy: delay RF ramp, long first sawtooth and 2/1 NTM



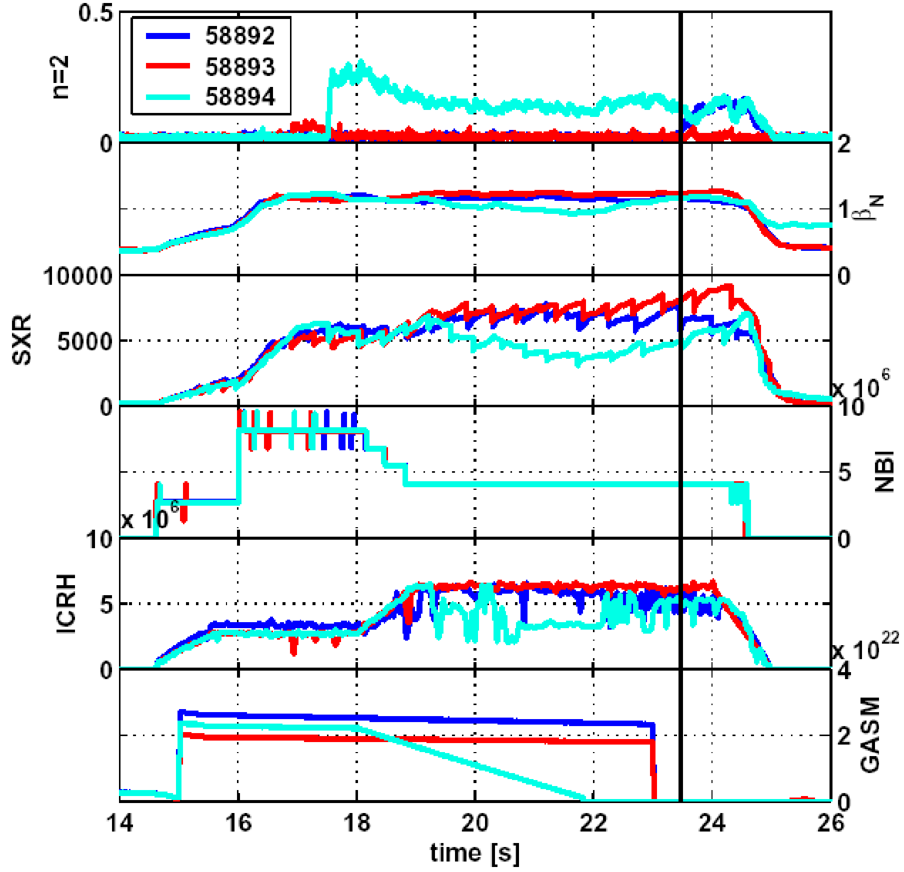
It worked !!!

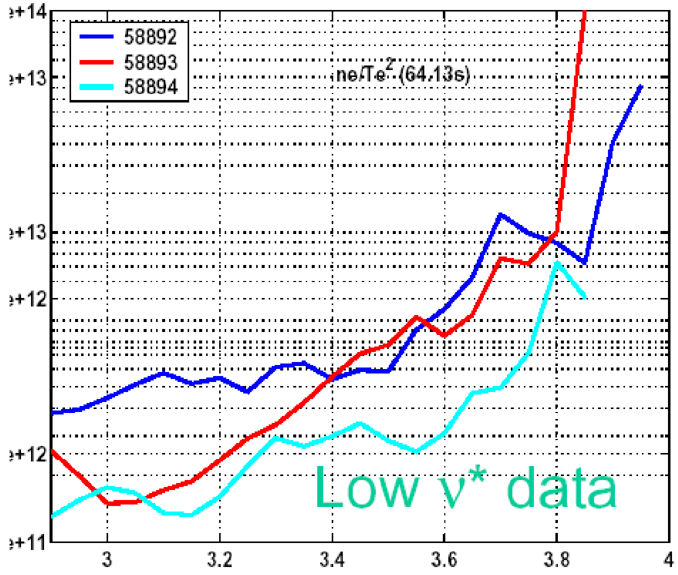
Still marginal for 1st ST period.

Thus some of following pulses had mode (but only 3/2) and some had none

Final optimisation

- So got from 3MW ICRF 2/1 disruption to 7MW RF occasional 3/2 mode by tailoring ramp-up



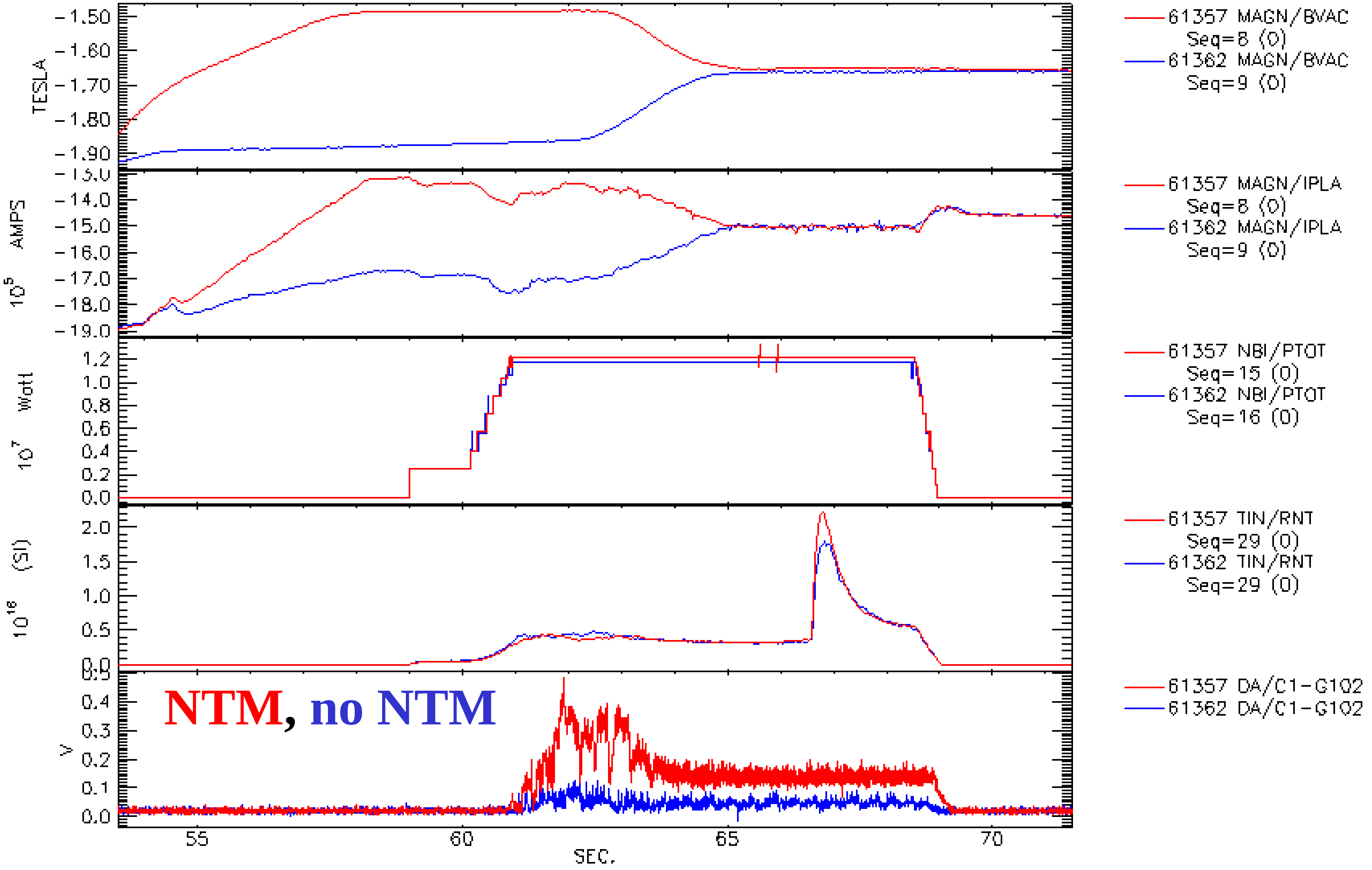


- Further development: lowering initial ICRH power avoided mode completely for later Trace Tritium session

Summary of avoidance techniques

- Get plasma sawtoothing while at low power
  - preferably before L-H - avoids broadening current profile
  - allows plasma density to rise before high heating
- Avoid strong fast particle population
  - +90 and dipole ICRH phasings trap fast particles from ICRH in the core
  - -90 phasing ejects fast particles
  - more fuelling helps
- Use q=1 current drive (-90 phasing)
- 2/1 NTMs particularly prevalent with monster sawteeth and low q_{95}
- Also more recently: get power on at higher field and current and then ramp to desired...

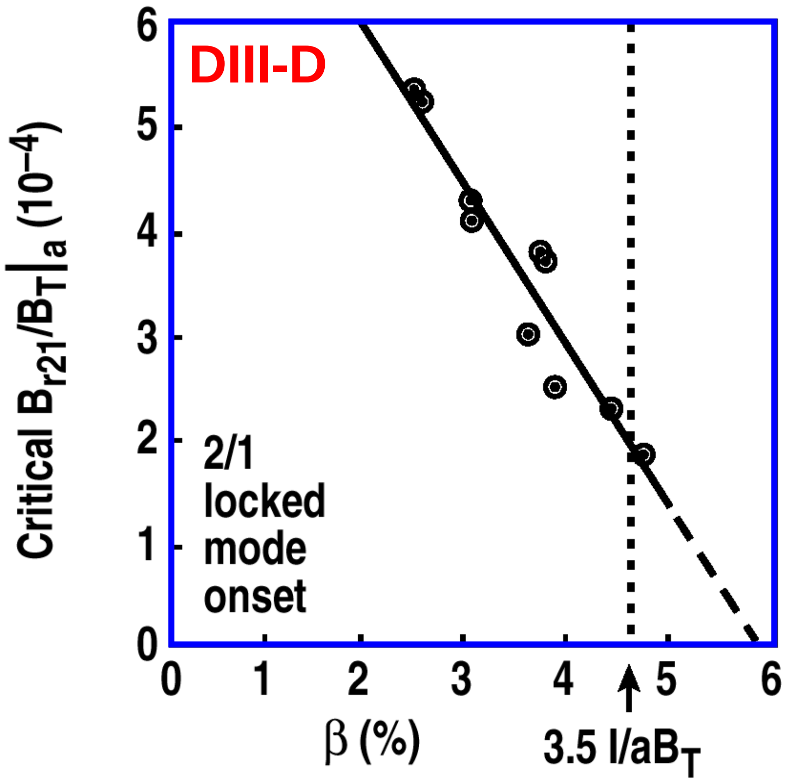
Controlling NTM onset with TF ramp



- Other parameters affecting NTMs...

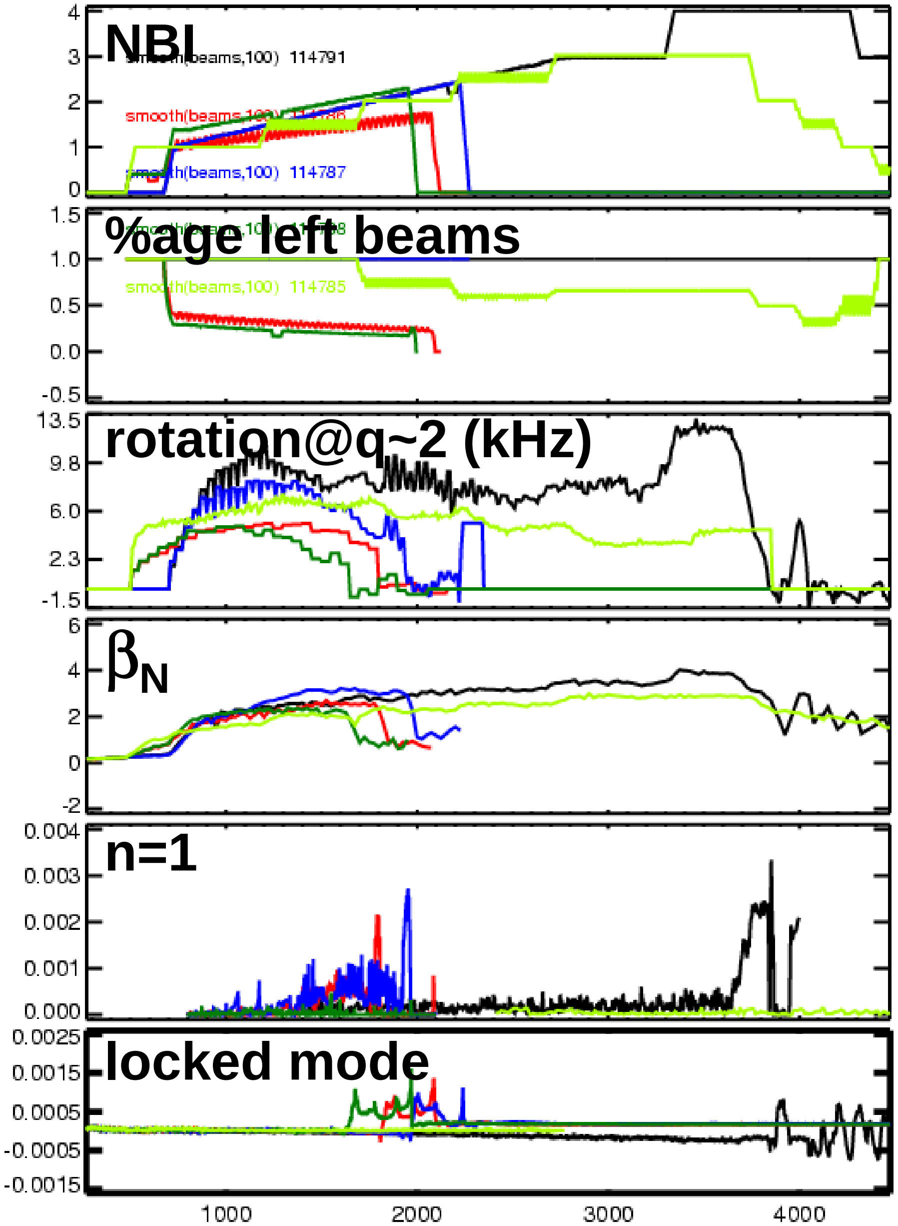
What about error field effects?

- Old result from DIII-D shows thresholds fall as ideal limit approached
  - generally locked modes
  - error field amplification effect?



1992 La Haye experiments

NTMs at lower β with pre-existing errors



- Pre-existing error field in coloured cases **(not black)**
- Leads to 2/1 NTMs or error field modes during beam ramp up
  - plasma slows first
  - goes rapidly to locked mode
- Using ‘left’ beams helps avoid modes

DIII-D

Why no mode for light green?

Error fields also lower thresholds

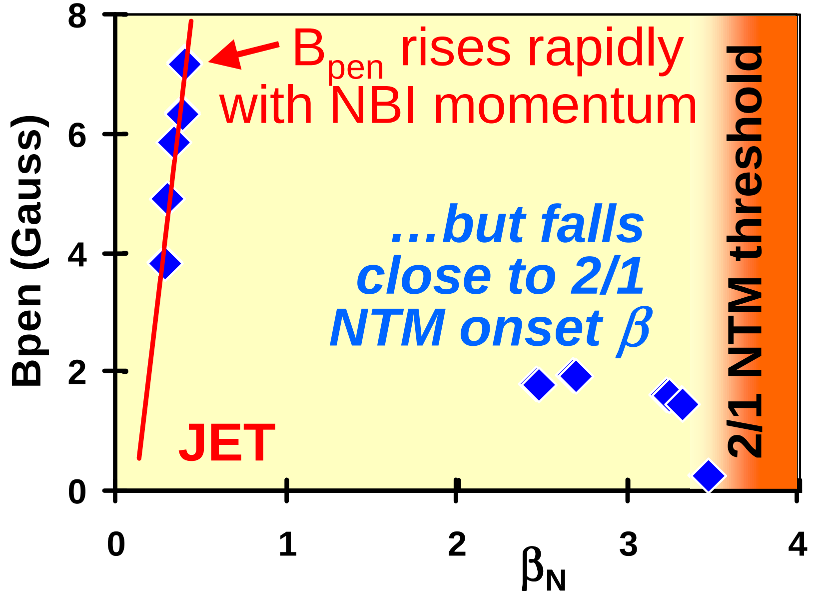
- Error field thresholds fall close to the 2/1 NTM onset β on JET

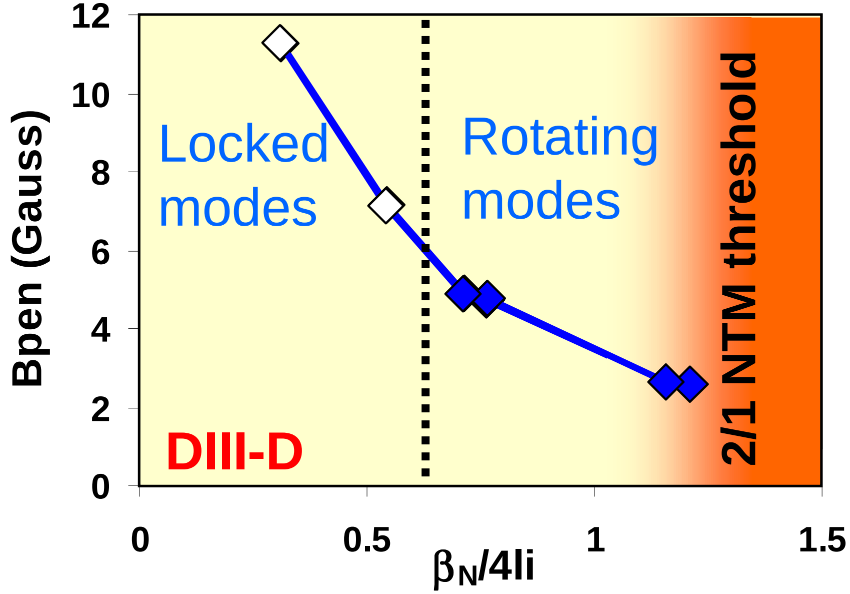
  ⇒ increased error field sensitivity

- Also observed on D3D…

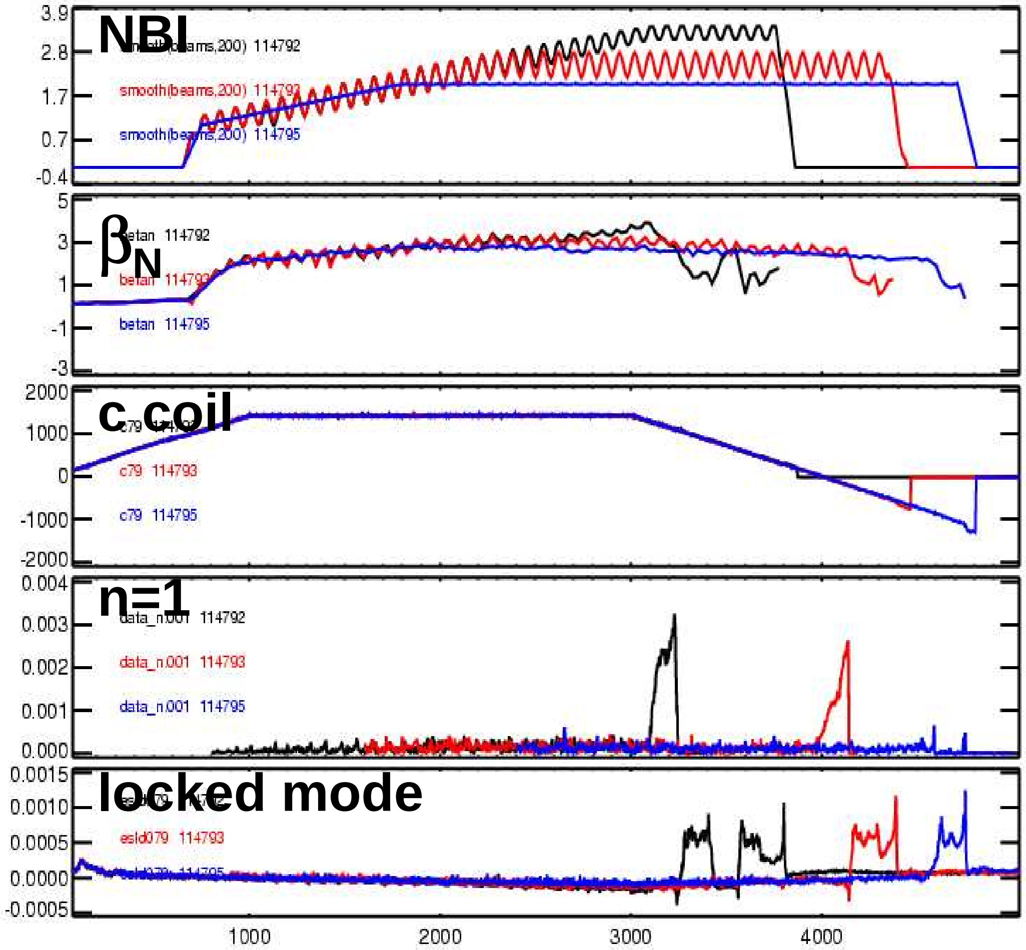
  – here modes formed rotating at intermediate β_N

  ⇒ EF is directly assisting NTM onset mechanism





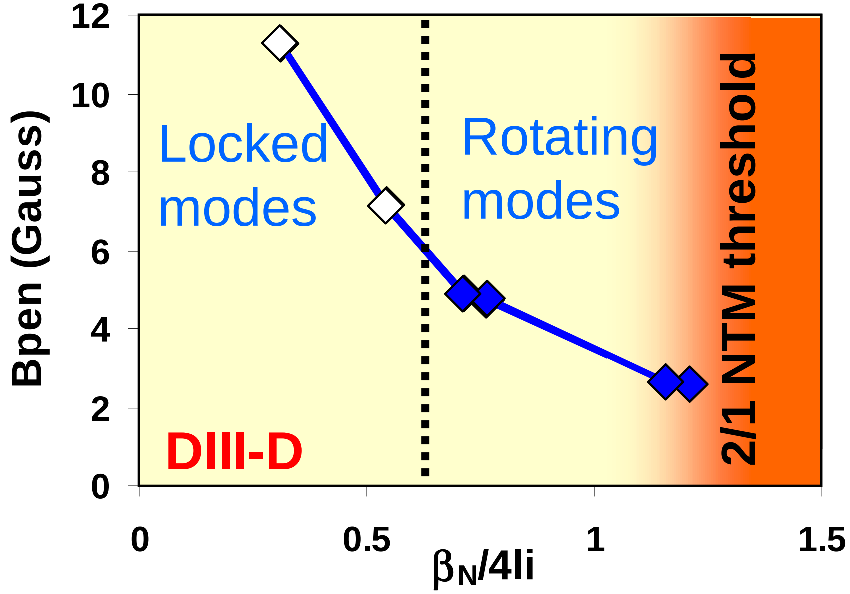
DIII-D: error field - NTM interplay



- Fix at subcritical β
  - apply EF ramp

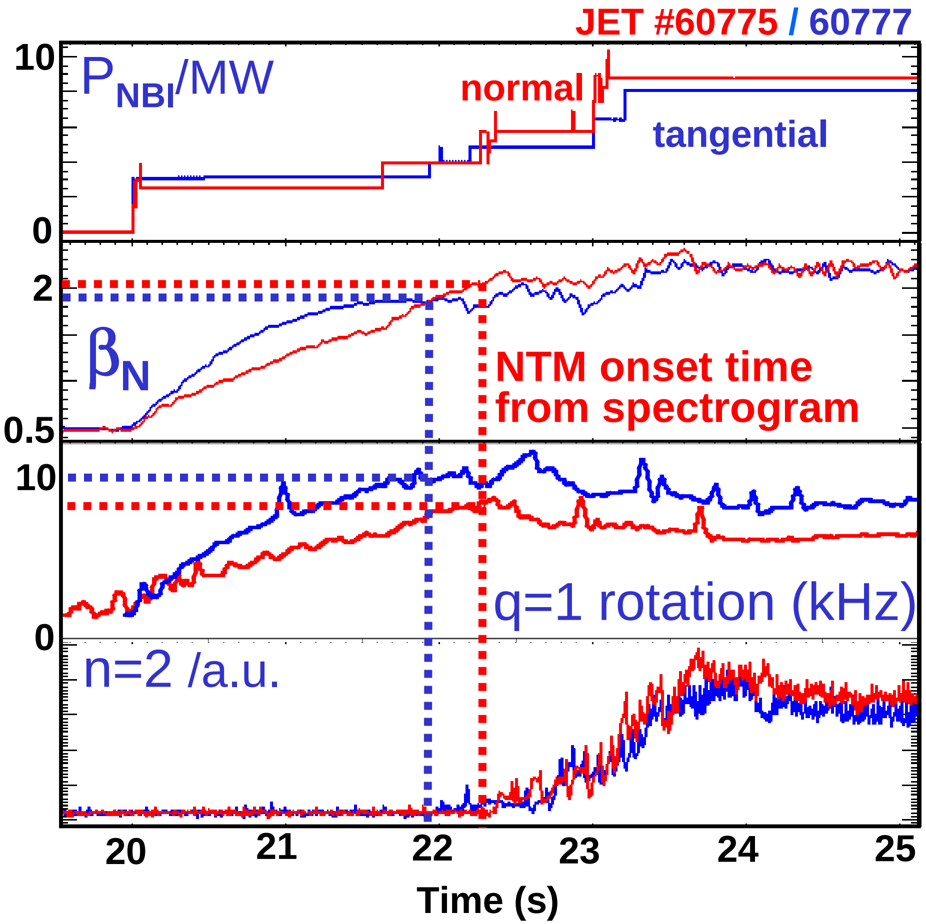
⇒EFs assist NTM onset

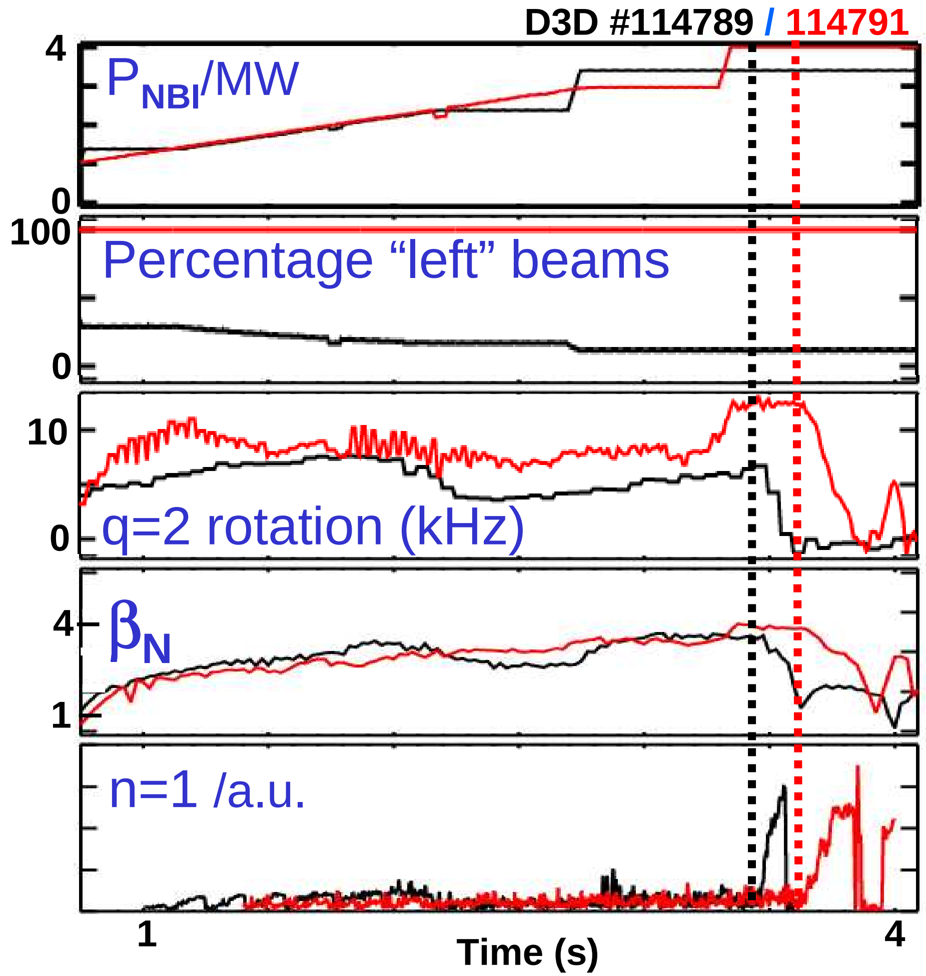
  - at medium β modes born rotating - NTMs
  - low β: standard locked modes



...but rotation has a weak effect

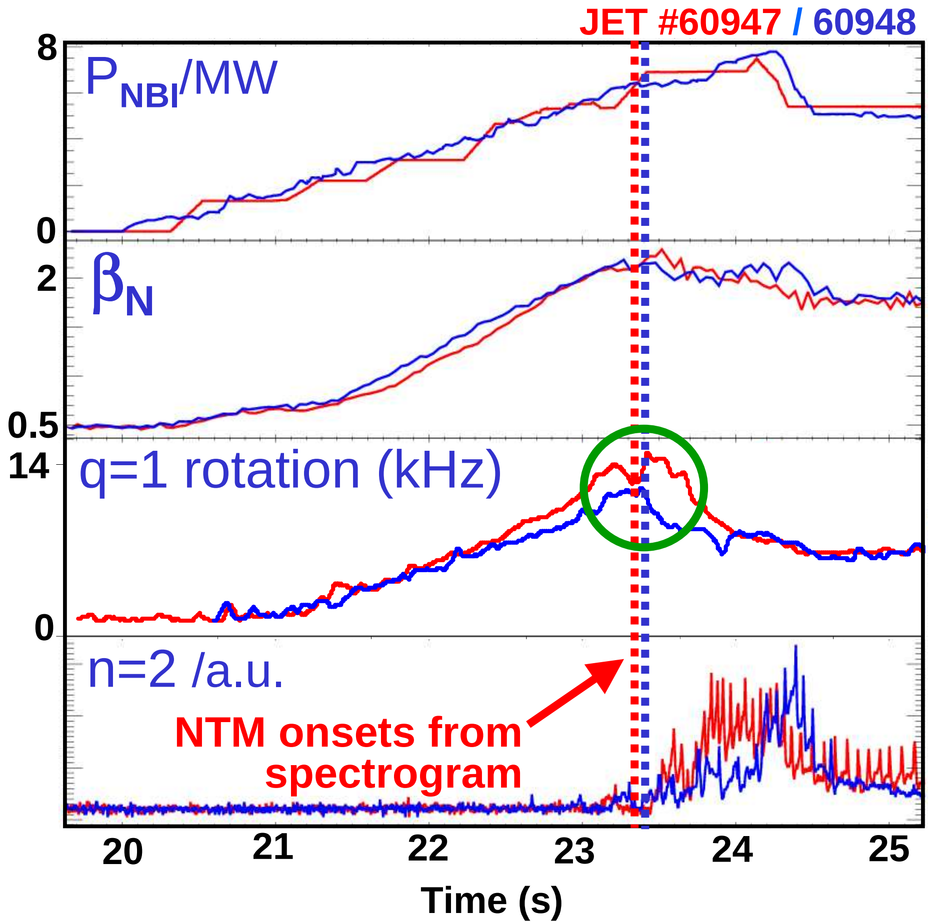
- Vary beam momentum:
  - similar 3/2 NTM β_N threshold on JET:
  - 10% higher 2/1 NTM onset β_N threshold on DIII-D:





JET: try more reproducible ramp

- Vary beam momentum:
  - rotation dip leads to same threshold!



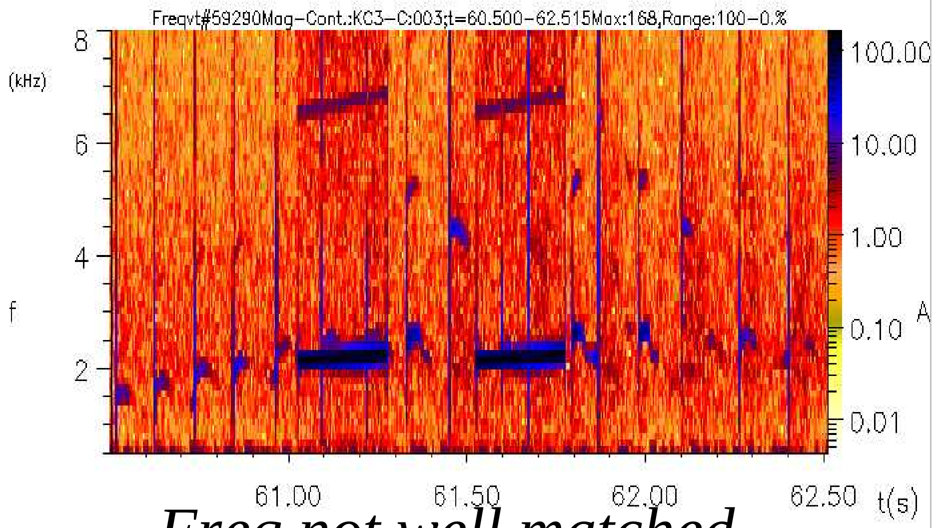
Conclusions

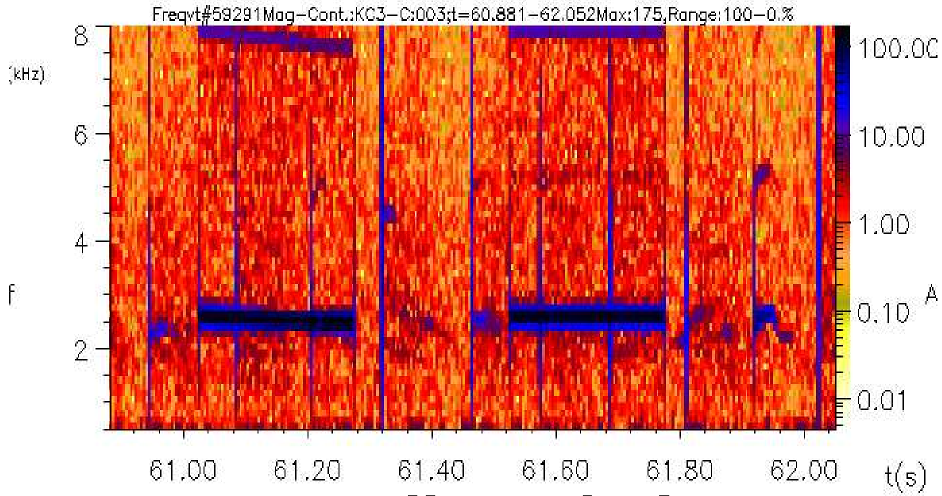
- NTM ρ^* - ν based onset scalings are non-predictive of NTM onset time on JET
  - discharges extremely sensitive to detailed form of heating power ramp-up
  - sawtooth period (not ρ^* values) is the hidden parameter
- NTM thresholds can be controlled via the sawtooth
  - direct control by ICCD can lower period and raise NTM onset β
  - fast particles stabilise sawteeth, lowering NTM thresholds
  - 'monster' sawtooth control uniquely demonstrated on JET
  - changing heating power ramp-up
- Error fields can lower 2/1 NTM threshold
- Rotation has weak effect

} *insight into seeding process*

Testing sawtooth island triggering

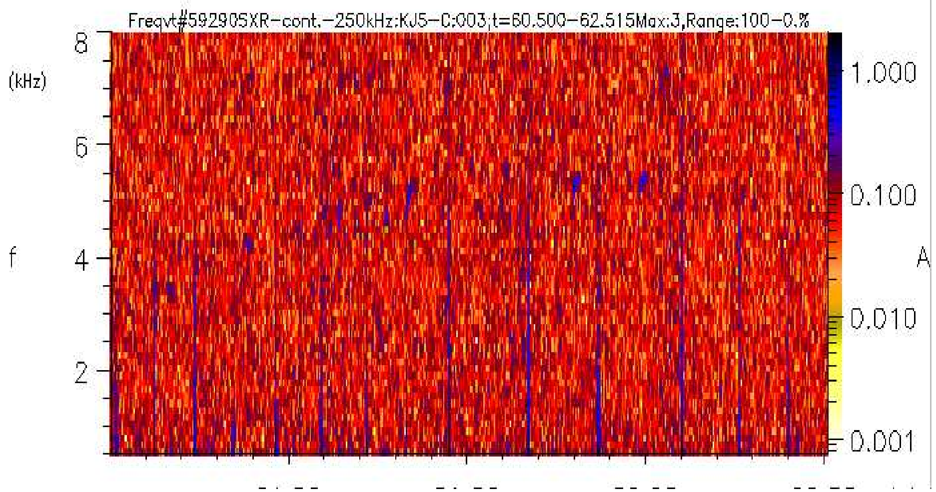
Apply saddle fields to couple through to 1/1 mode...

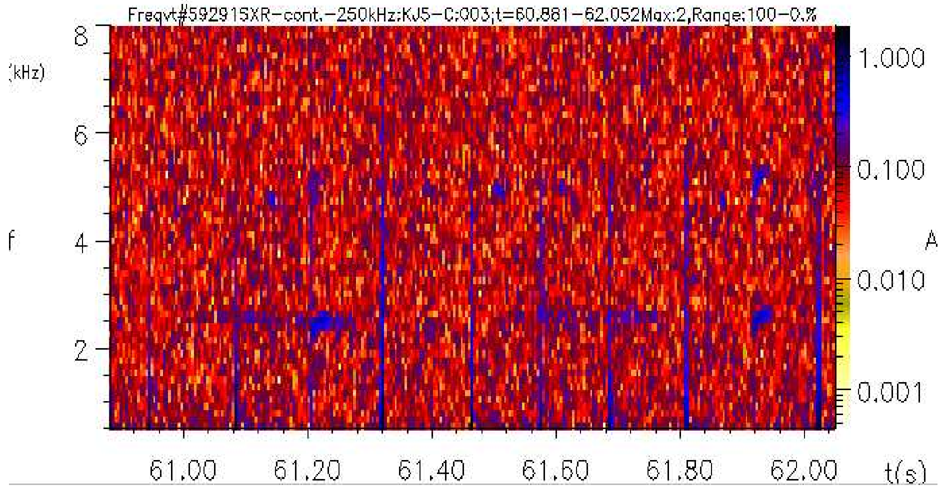




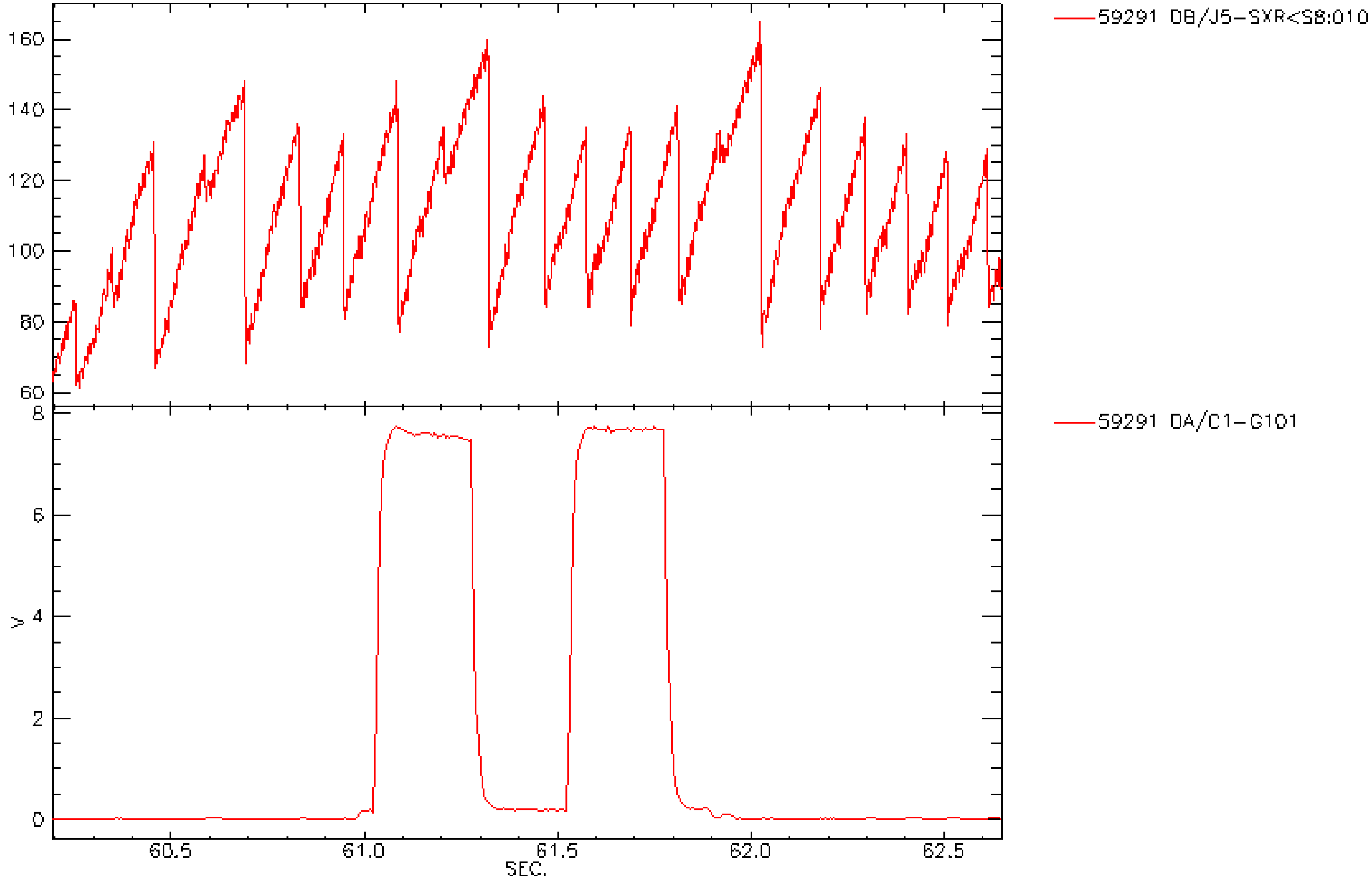
Freq not well matched

Freq well matched





No effect on sawteeth in well matched case



Evidence against/lack of validation of Gimblett Hastie model!