MHD Control in JET

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* See the Appendix of M L Watkins et al, Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)

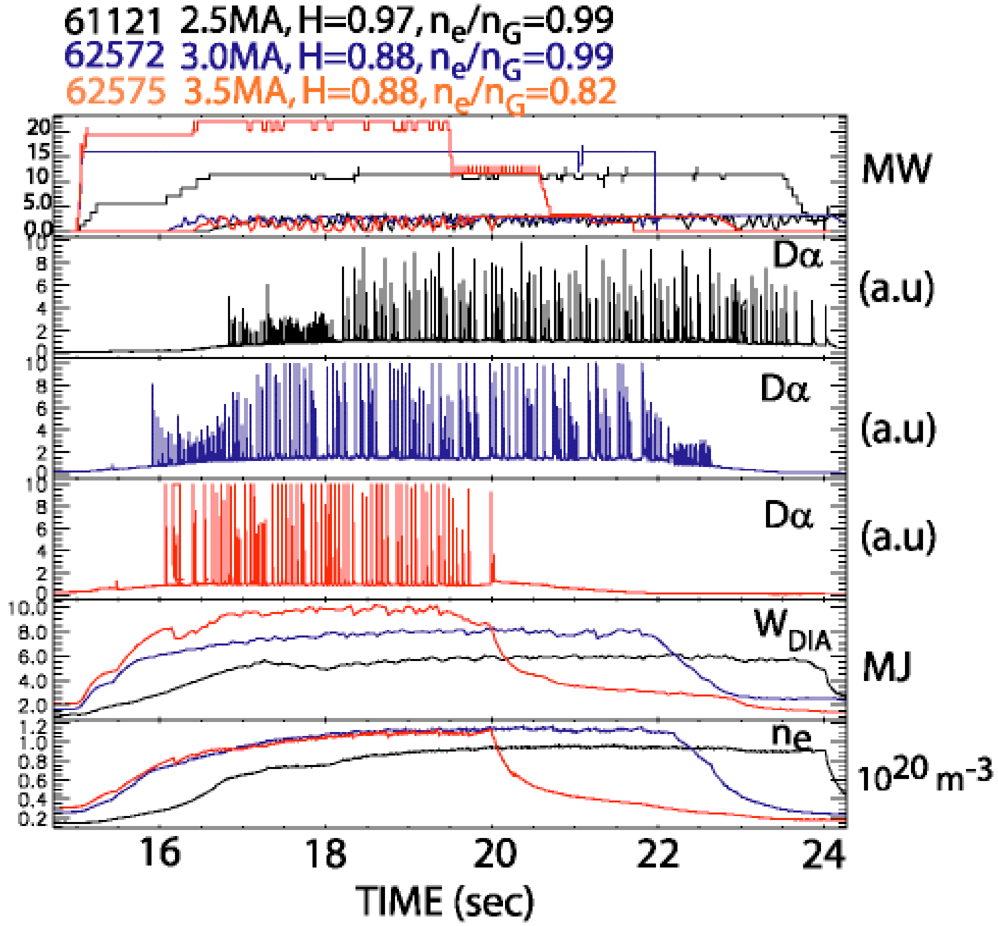
Outline

- NTM avoidance
    - Control of the sawtooth period
    - Destabilization of fast particle stabilized sawteeth
- NTM control
- Error field correction
- Active ELM control by $n=1$ perturbation fields

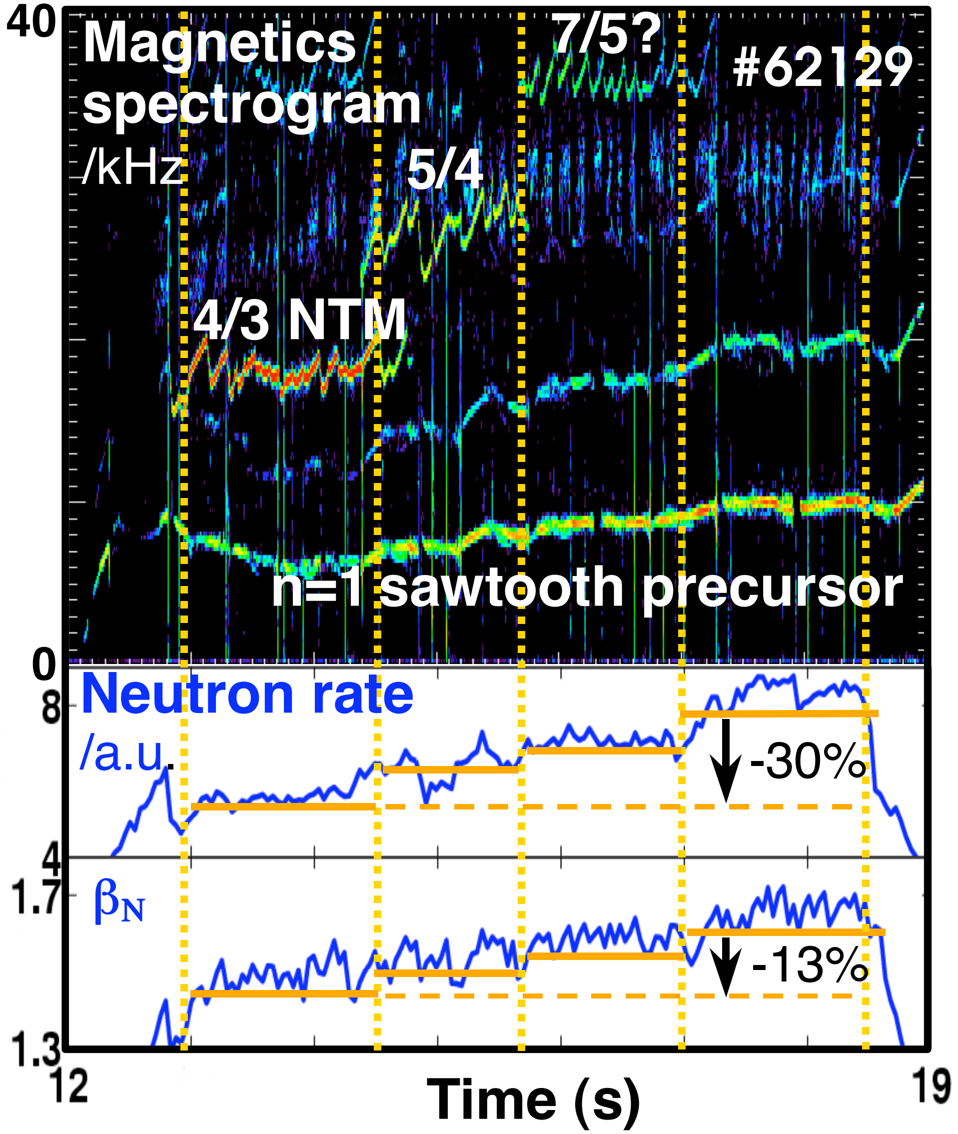
→ Support of ITER-relevant scenario development

NTM avoidance in JET high current plasmas

- ELMy H-mode discharges operate always in the metastable regime
- Metastability threshold is around β_N~0.8
- The initial phase of the discharge has to be tailored for NTM avoidance and first ELM amelioration.

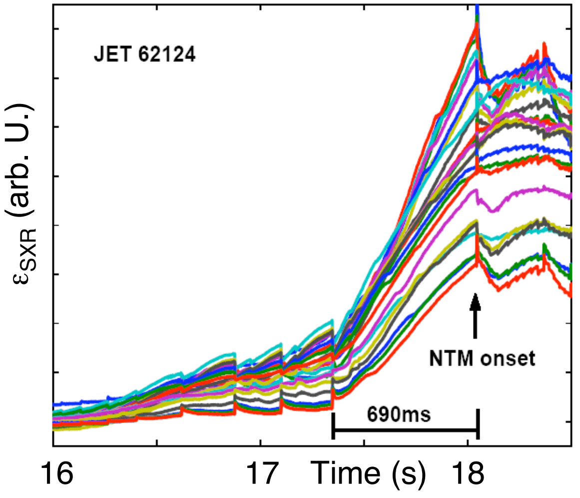


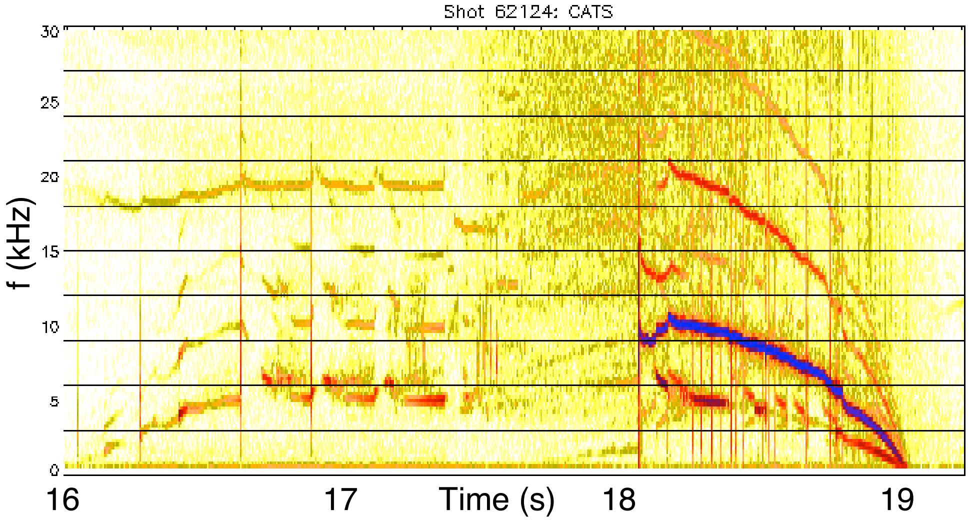
Which modes are a concern?

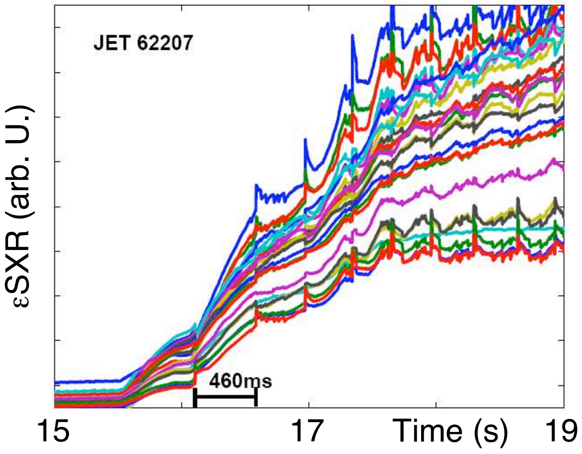


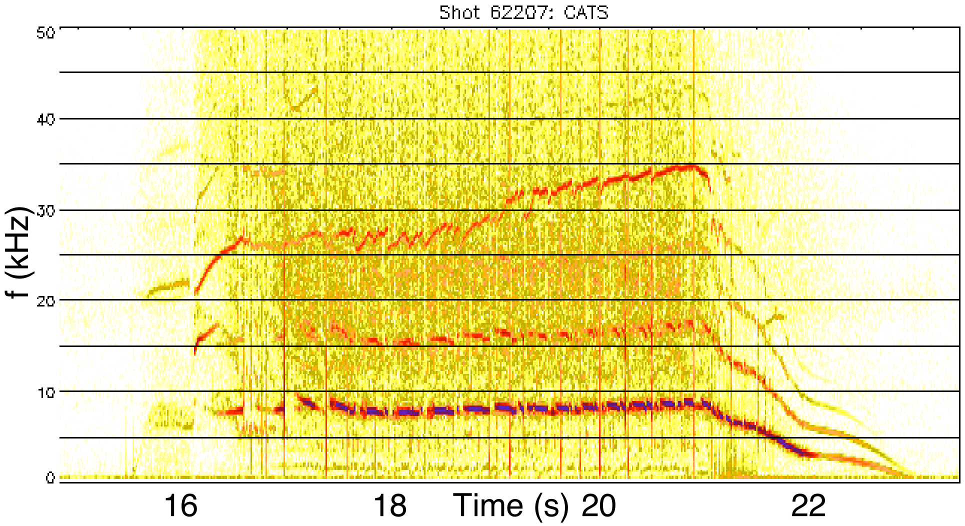
- 2/1 NTMs terminate performance & unacceptable in ITER
- 3/2 NTMs have a significant effect: typically 15-20% on confinement → ~ -30% in fusion power
- Higher m/n NTMs also impact fusion performance at low q_{95}
- E.g. 3.7MA, 2.9T, q_{95}=2.7
  - up to 13% decrease in confinement
  - up to 30% effect on neutrons

3/2 NTMs are triggered by long sawtooth after L-H transition









NTM avoidance scenario ⇒ lower density phase with high power, high q_{95} and lower δ ⇒ the final values of q_{95} and δ are reached only at high density

Status and ongoing work

- 3/2 mode : New start up phase has been developed which achieves less than 1/10 discharges with n=2 mode at q_{95}=3
- 4/3 mode is still present in a large fraction of the q_{95}=3 plasmas
- Improve understanding of avoidance *tools* to allow better scaling to different I_p/B_t combinations and shapes
- Investigate the application of LHCD to influence sawteeth / mode stability
- Use RT network to detect sawtooth period and act on heating / current waveforms

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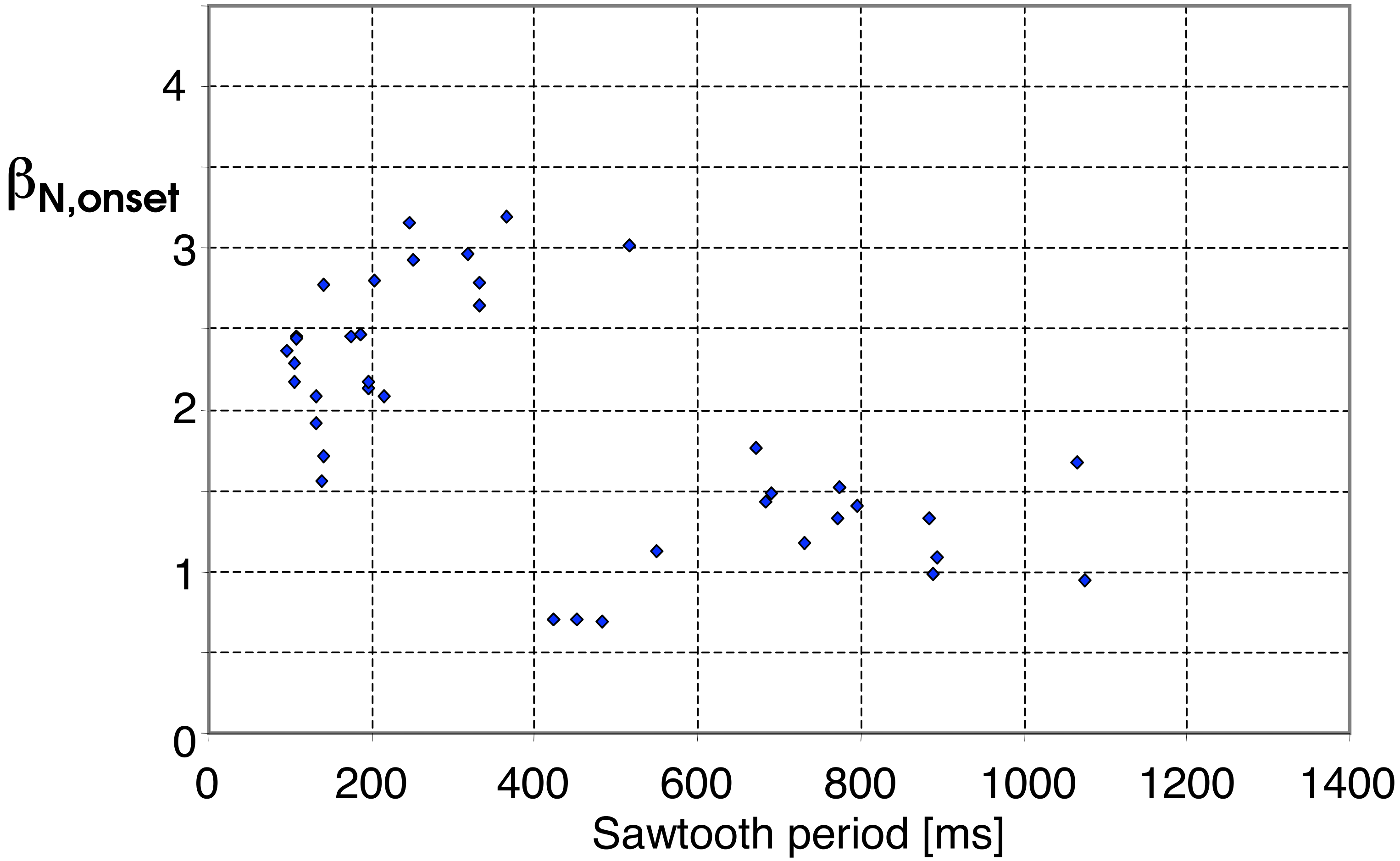
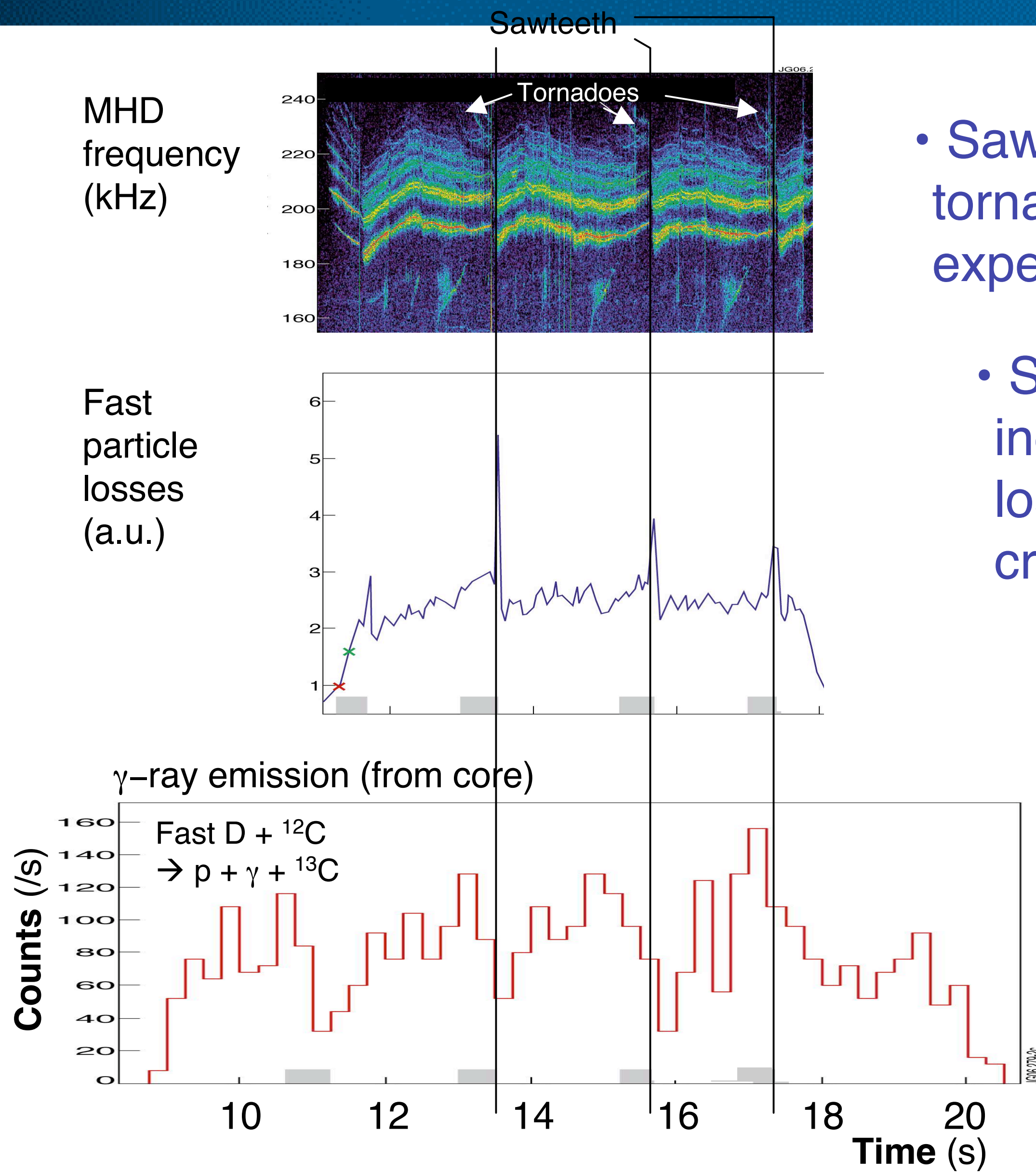
NTMs can be triggered at low β by long sawtooth



Fast particle stabilised sawteeth

- There is strong evidence that crashes of fast-ion induced long sawteeth can provide seed islands for NTMs
- One strategy for destabilising (i.e. shortening) the sawteeth is to apply ICCD near the $q=1$ surface to affect the local shear and induce a crash
- Experiment: two-colour ICRH
  - Create core fast ion population by applying central ICRH (+90 phasing) (*simulates α particles*)
  - Destabilise sawteeth by applying ICCD at the q=1 surface (-90 phasing)
  - The technique relies on using two different ICRH frequencies (H minority heating)

Loss of fast particles destablises sawtooth

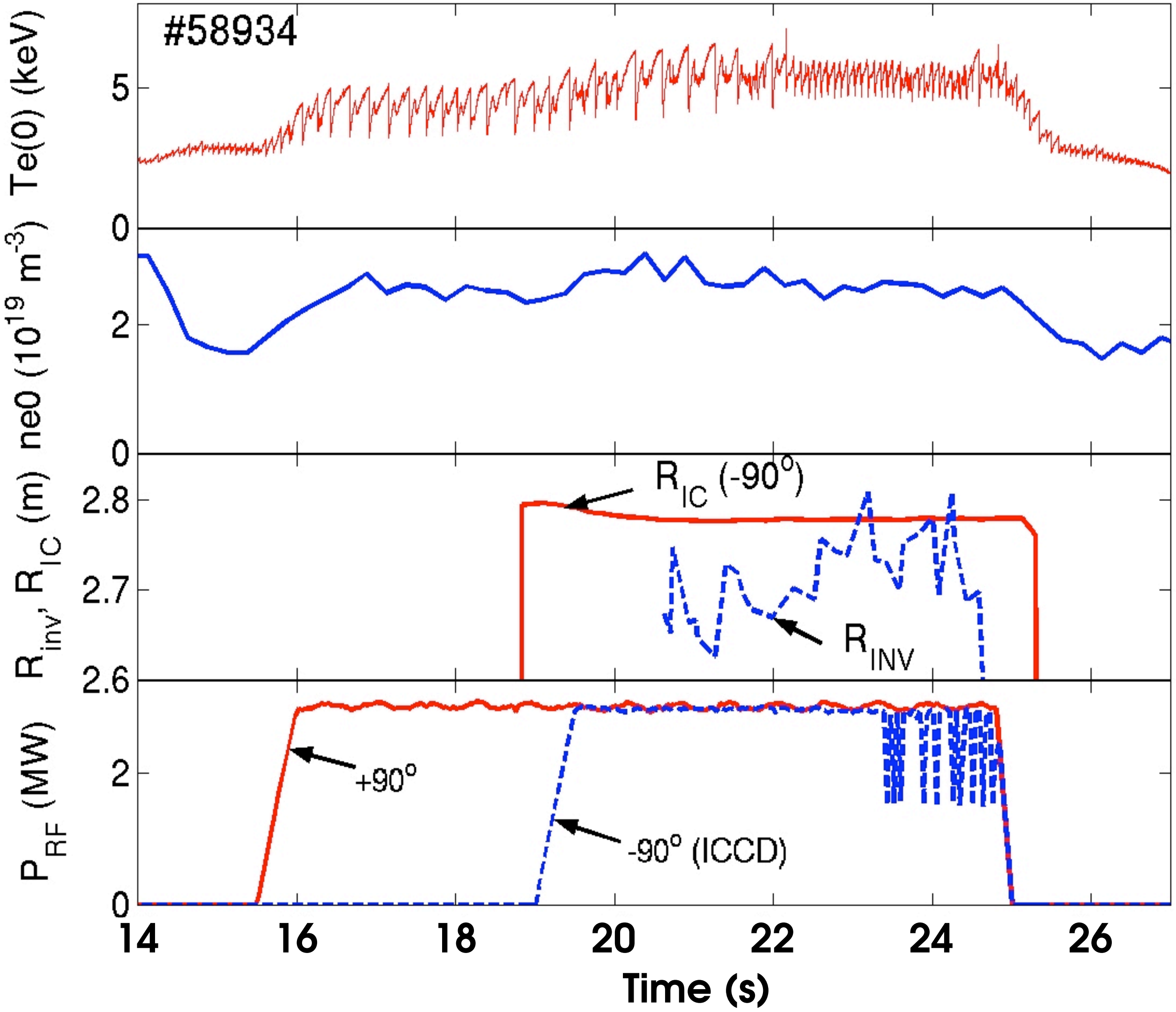


- Sawtooth crashes preceeded by tornado modes which are expected for q<1
  - Scintillator probe shows increasing fast particle losses *before* sawtooth crashes
    - γ–ray emission (from fast particle interaction with carbon) decreases *before* sawtooth crash

Fast-particle losses, due to tornado modes may play role in Sawteeth triggering

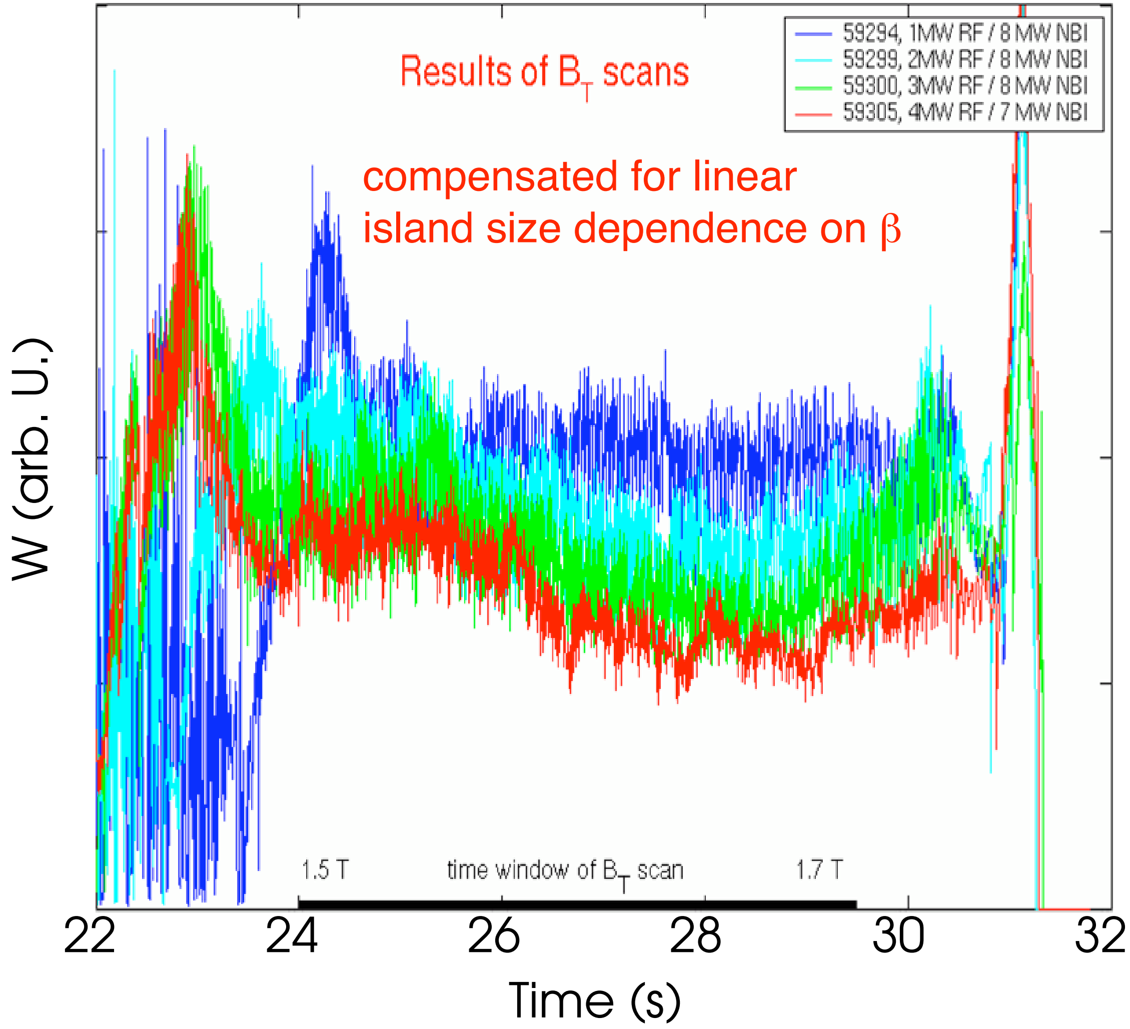
Control of fast particle stabilised sawteeth

- **This method of sawtooth control was successfully tested**
- **More experiments needed to get better statistics and proof reliability of the method**



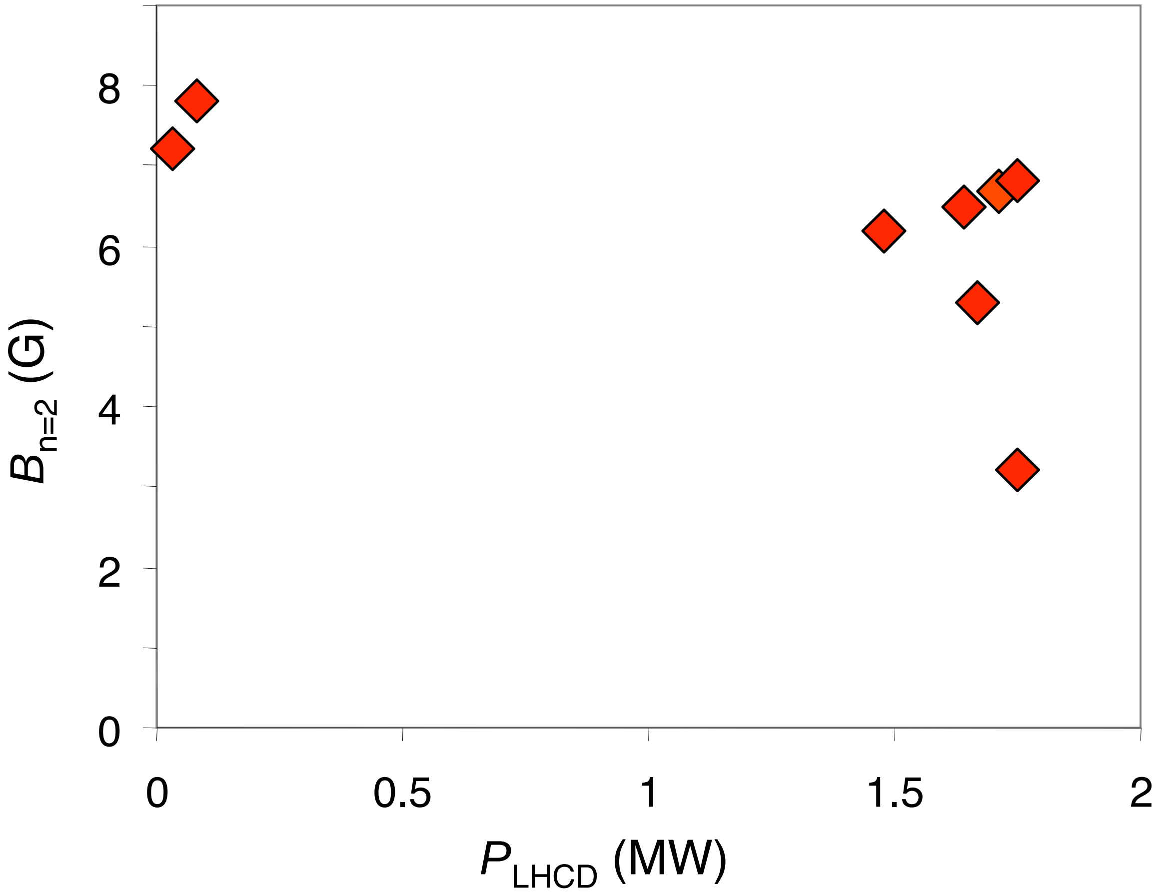
[L-G Eriksson et al. 2004 Phys. Rev. Lett. **92** 235004]

3/2 NTM stabilisation by ICCD



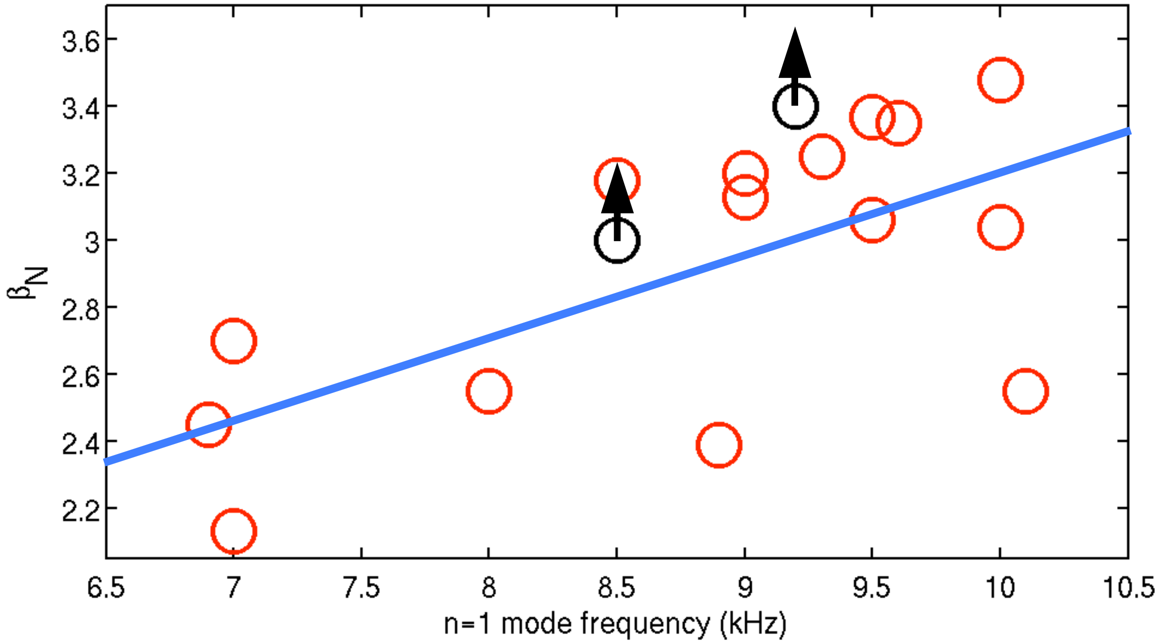
- TF / deposition scans show expected broad resonance
- Effect is relatively weak
- Dipole phasing had to be used to allow optimising ICRH (has theoretically same CD)

3/2 NTM stabilisation with LHCD



- Mode amplitude of saturated 3/2 NTM falls 15-60% with LHCD
- Complete stabilisation at higher LHCD power?

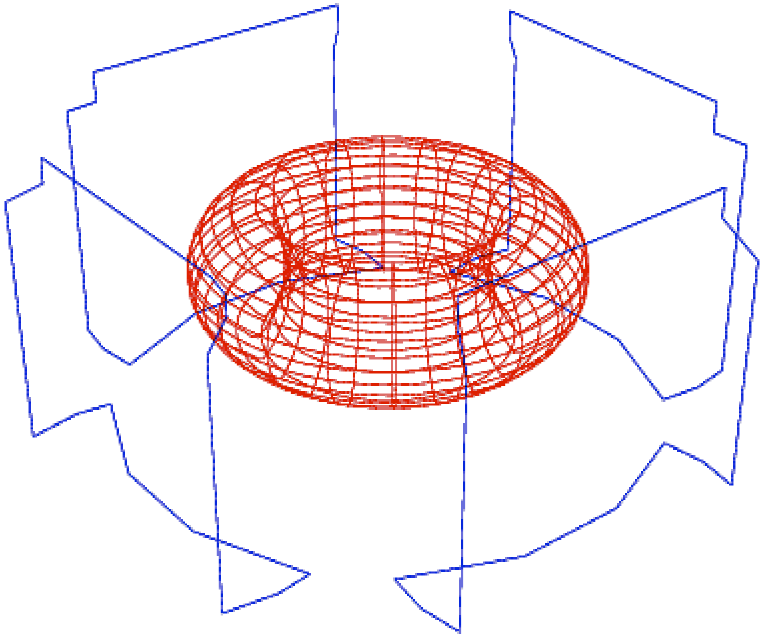
Rotation dependence of 3/2 NTM onset

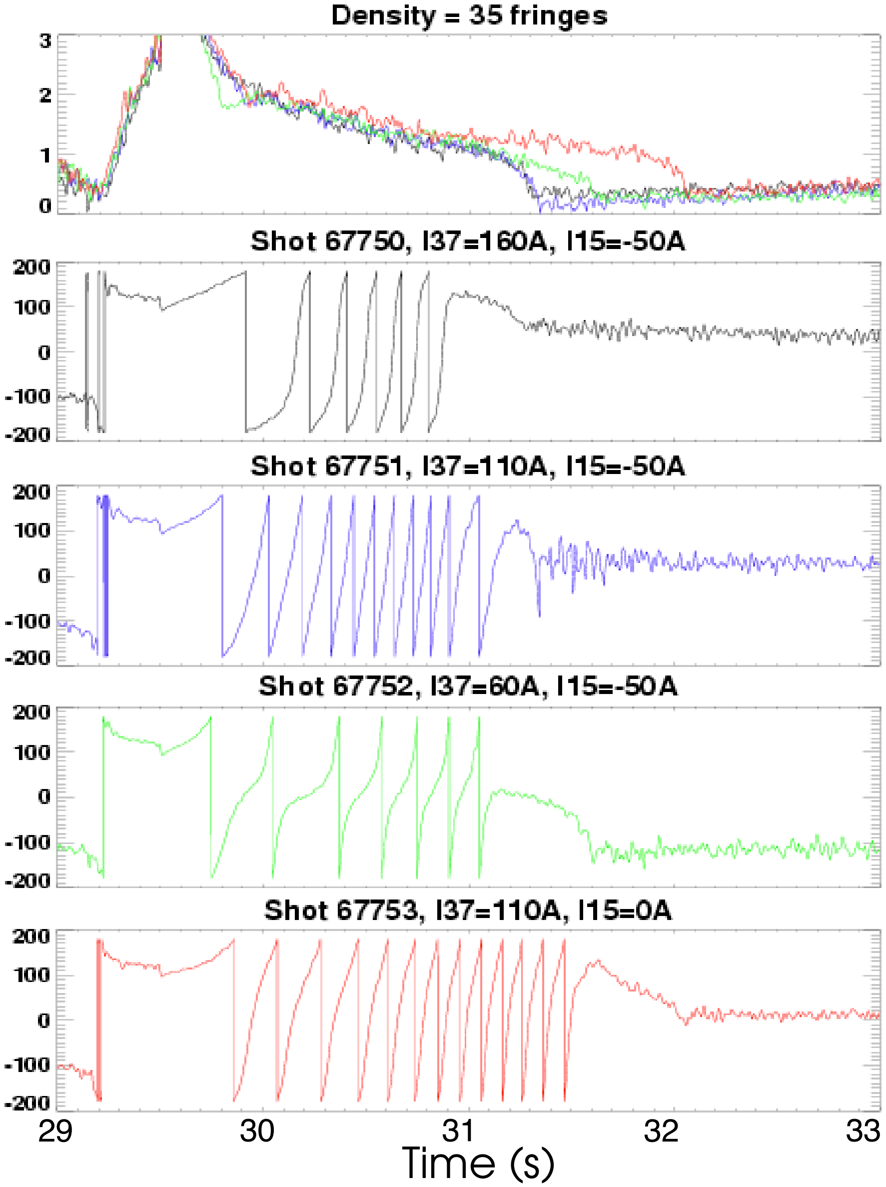


- Previous experiment replaced NBI power by ICRH
    - Influence from variation of sawtooth period
- New experiment uses various mix of tangential and normal ion sources to vary plasma rotation
- Data show slight trend of increasing threshold with rotation

Error field correction reduces risk of locked mode disruptions

- Optimal error correction results in spin-up of locked modes
- Rotating modes decay quickly
- Higher density is beneficial





Summary (I)

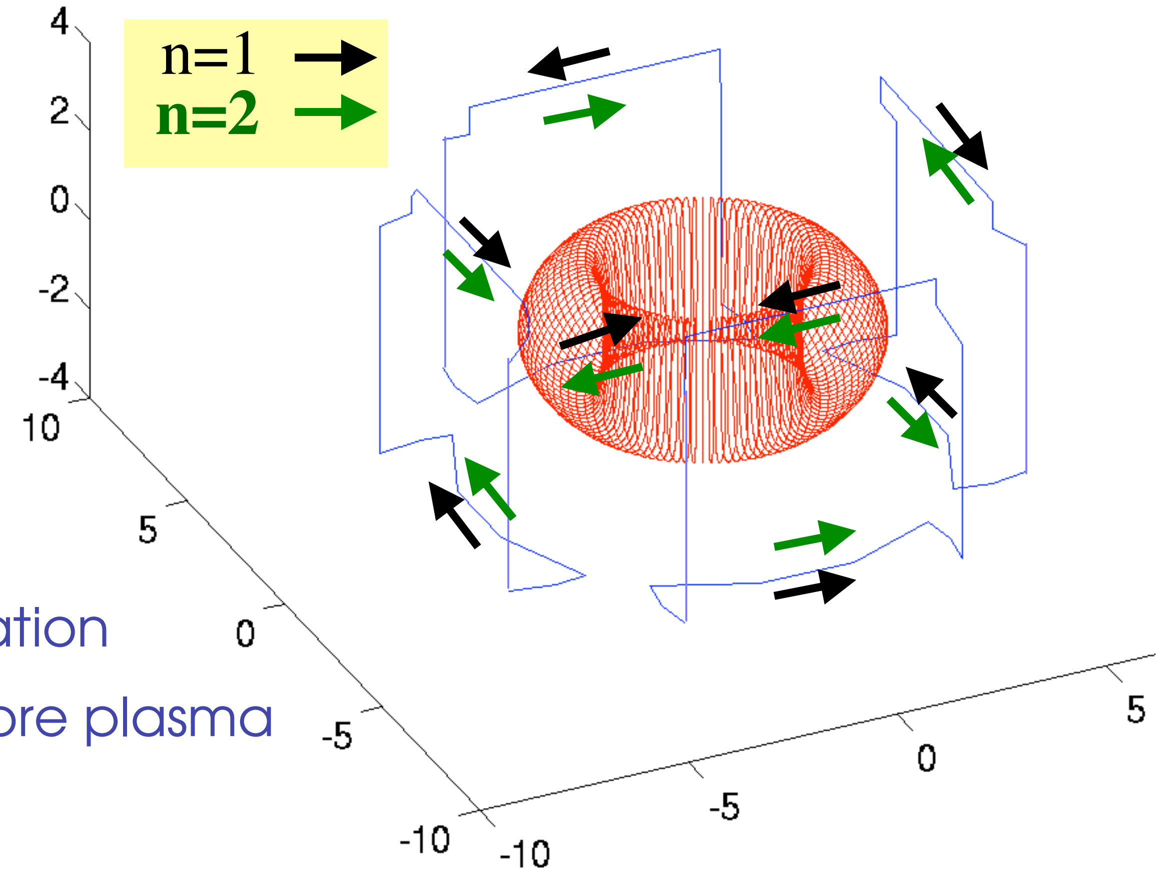
- 3/2 NTM avoidance is essential for scenario development
- Higher m/n NTMs also deteriorate fusion performance at high current
- Long sawteeth trigger NTMs even at low beta
- Losses of fast particles
- NTM threshold has a (weak) rotation dependence
  - Lower threshold may result in self-heated plasma
- LHCD has potential to stabilize NTMs
- ICCD showed small influence on island width
- Error field correction important to avoid locked mode disruptions

First results on active ELM control on JET

- Aim: Control type-I ELMs (heat loading)
- Tool: Error Field Correction Coils

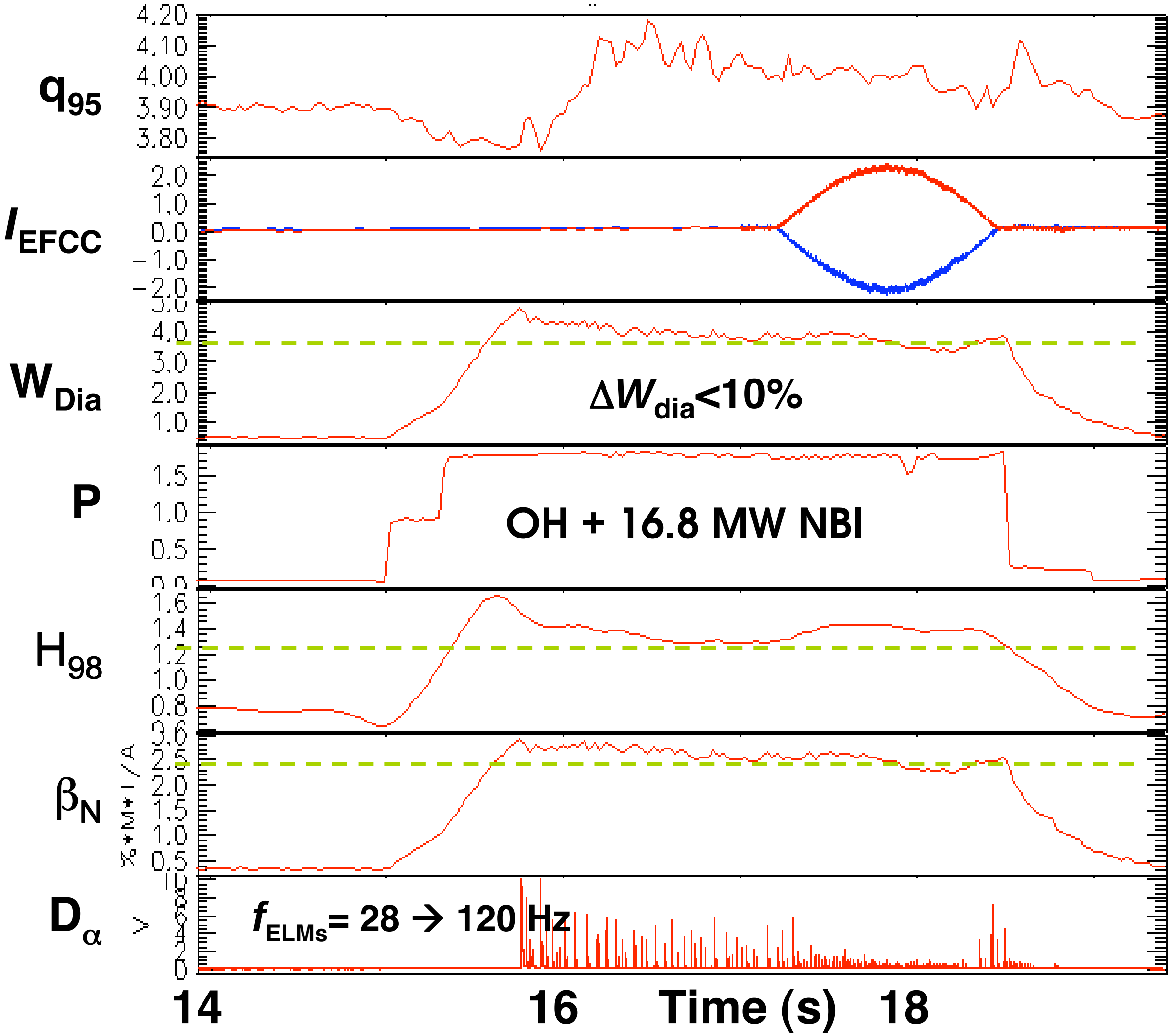
$I_{coil} \leq 3$ kA x 16 turns

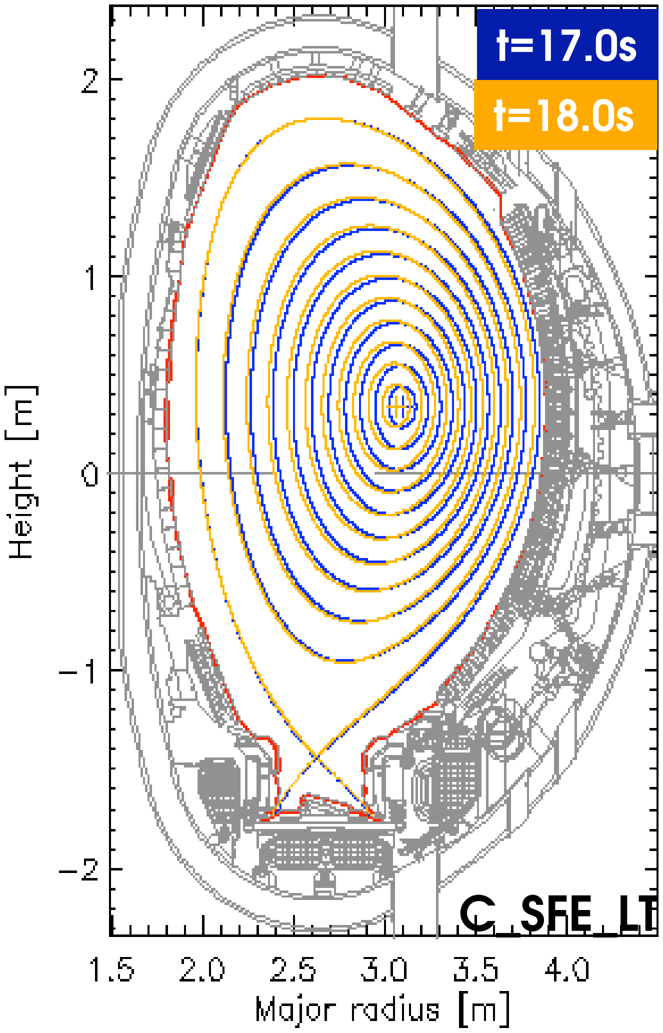
- *n*=1
  - Weak edge ergodisation
  - Plasma braking
  - Seeding of locked modes
- *n*=2
  - Good edge ergodisation
  - Small influence on core plasma



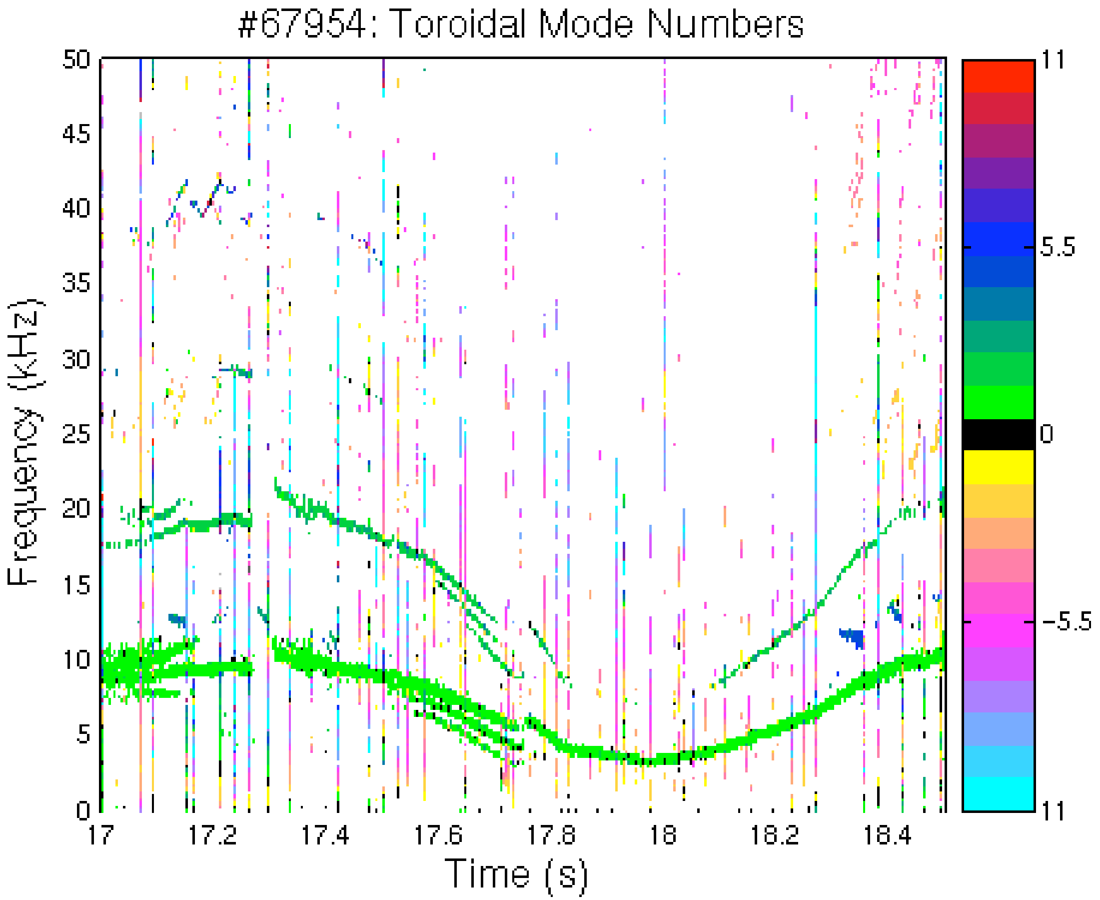
EFCC ELM mitigation experiment

#67954; I_p = 1.6 MA; B_t = 1.84 T; q_{95} ~ 4.0; δ ~ 0.3





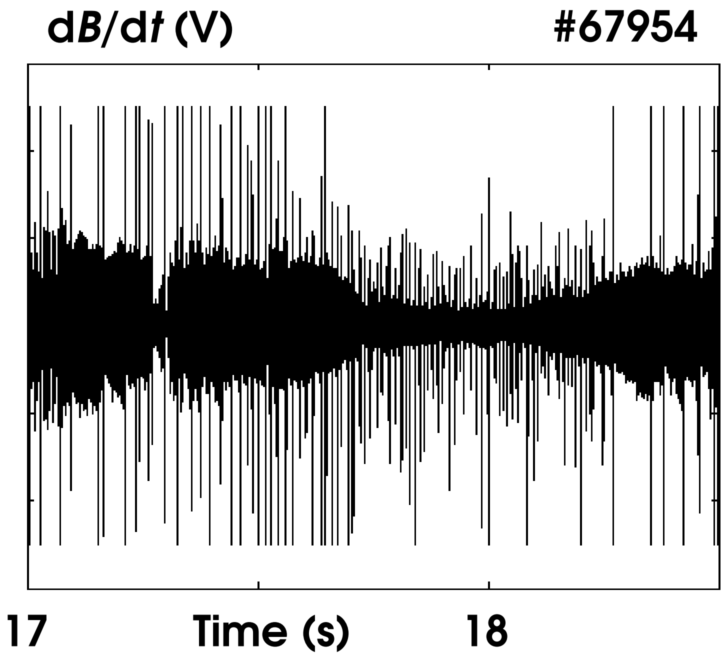
Influence of the *n*=1 field on MHD modes



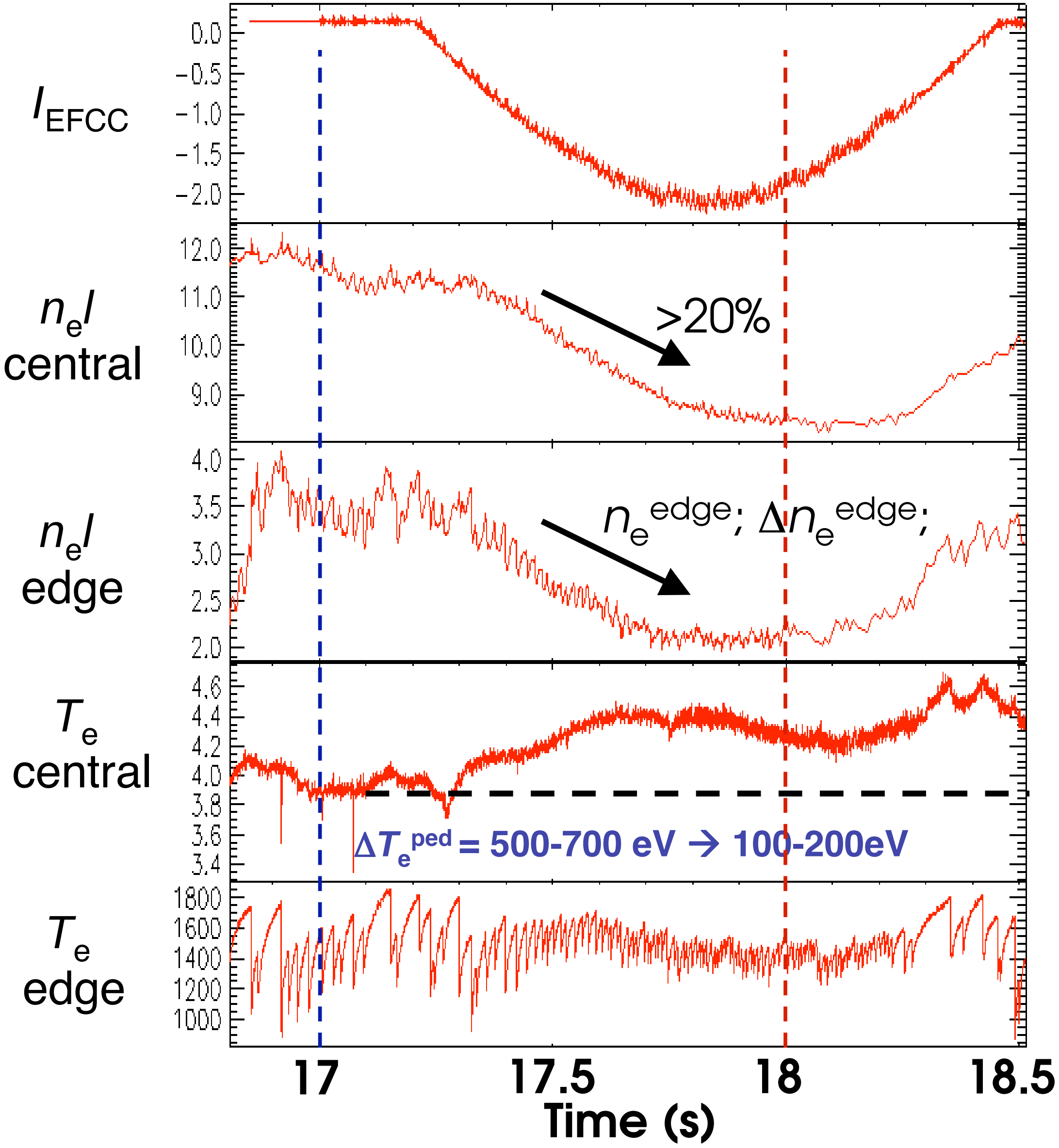
EFCCs break plasma rotation

No locked mode is observed

Amplitude of magnetic perturbations due to the ELM bursts is strongly reduced



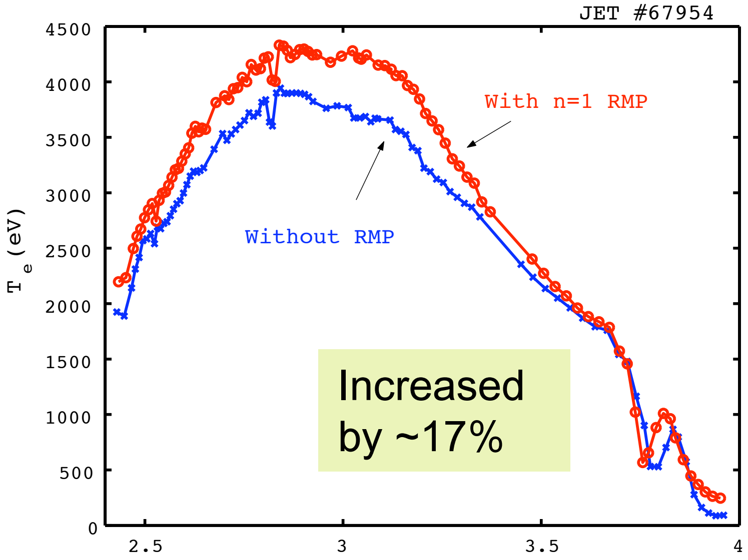
Influence of RMP (n=1) on n_e and T_e



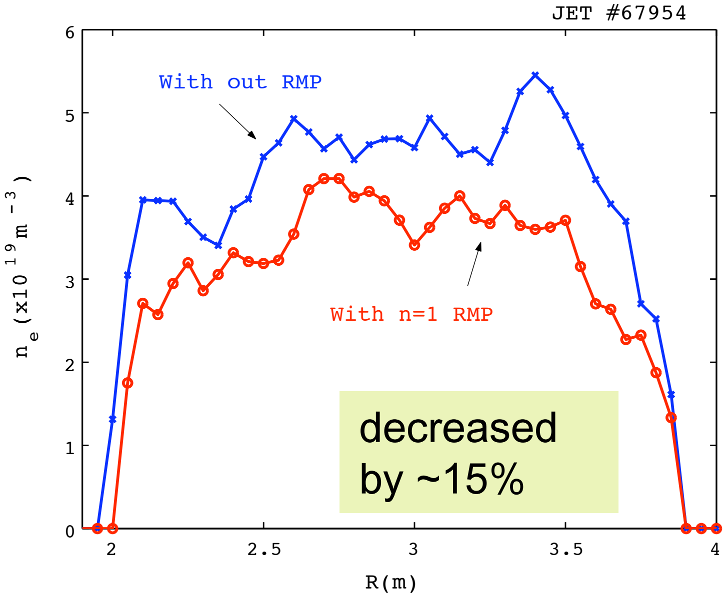
>20%

n_e^{edge}; Δn_e^{edge};

ΔT_e^{ped} = 500-700 eV → 100-200eV

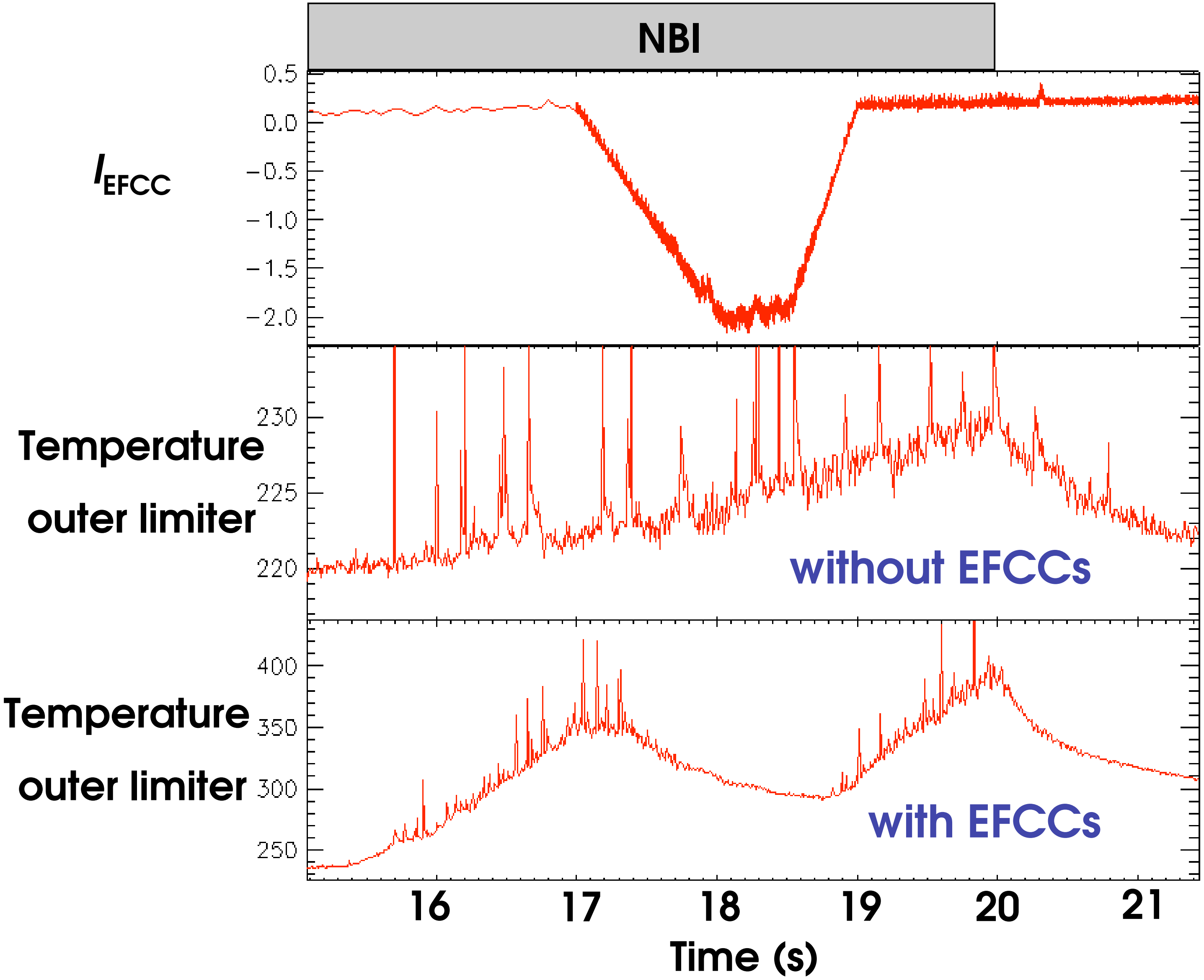


Increased by ~17%



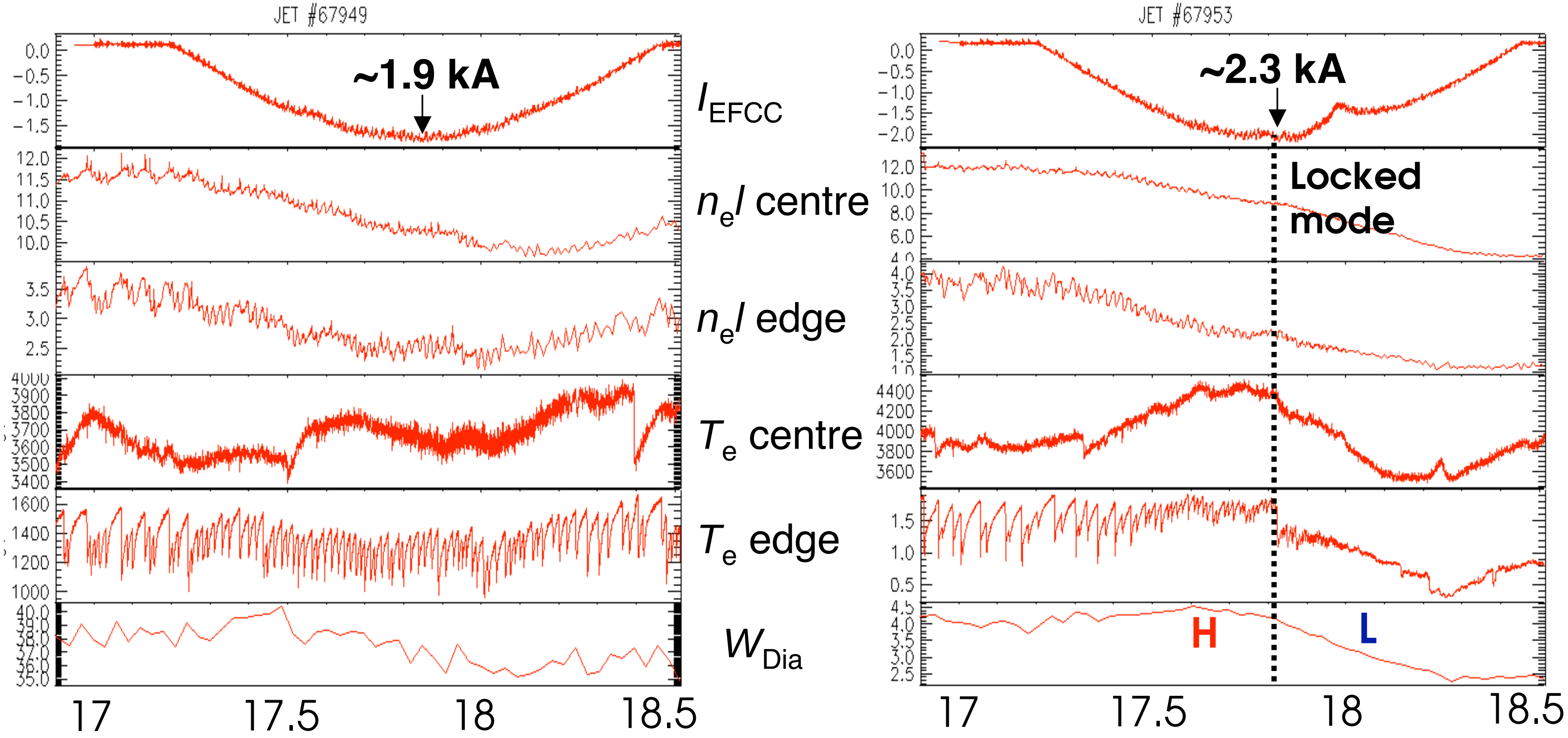
decreased by ~15%

Reduction in imiter heat loading



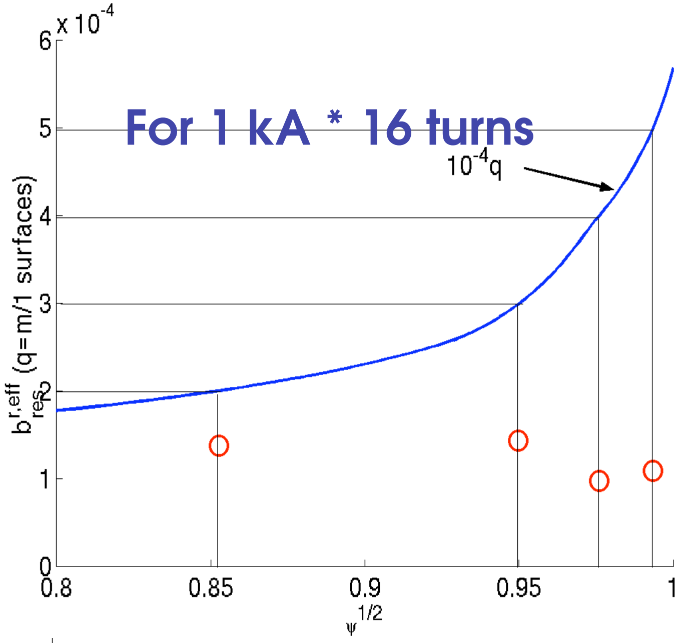
Operational window of the EFCCs

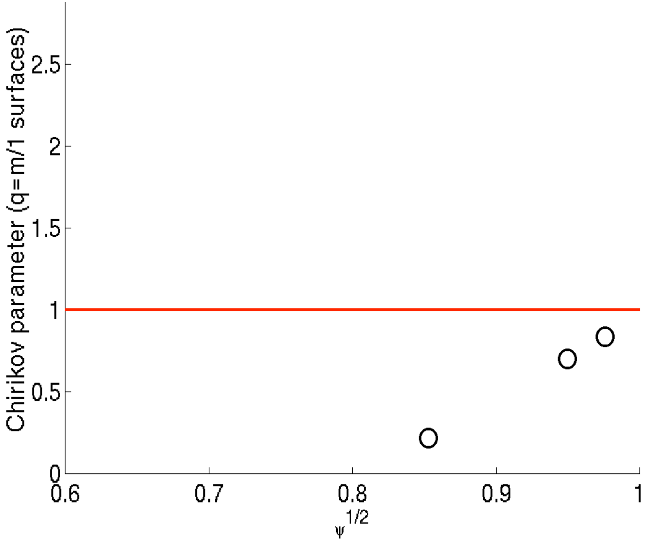
Less influence on ELMs (lower limit) ⟷ **Excitation of a locked mode (upper limit)**



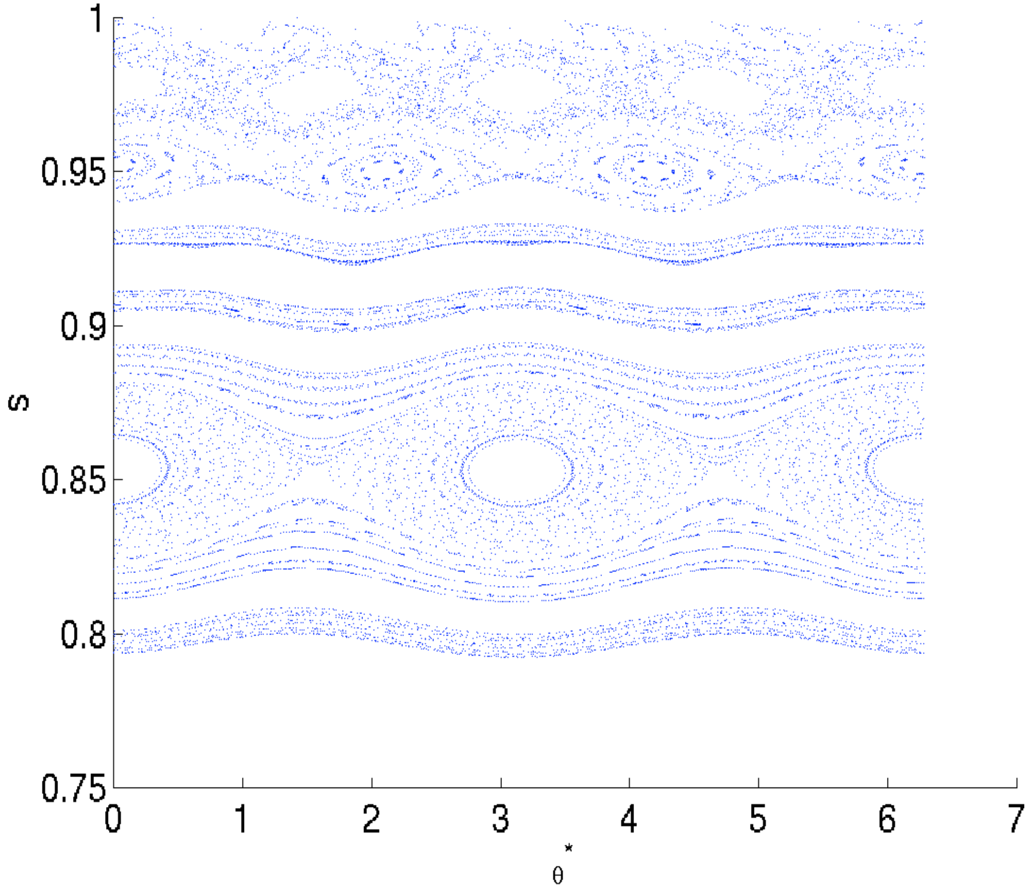
H-L back transition triggered by a locked mode induced by RMP (n=1)

Ergodisation?


For 1 kA * 16 turns

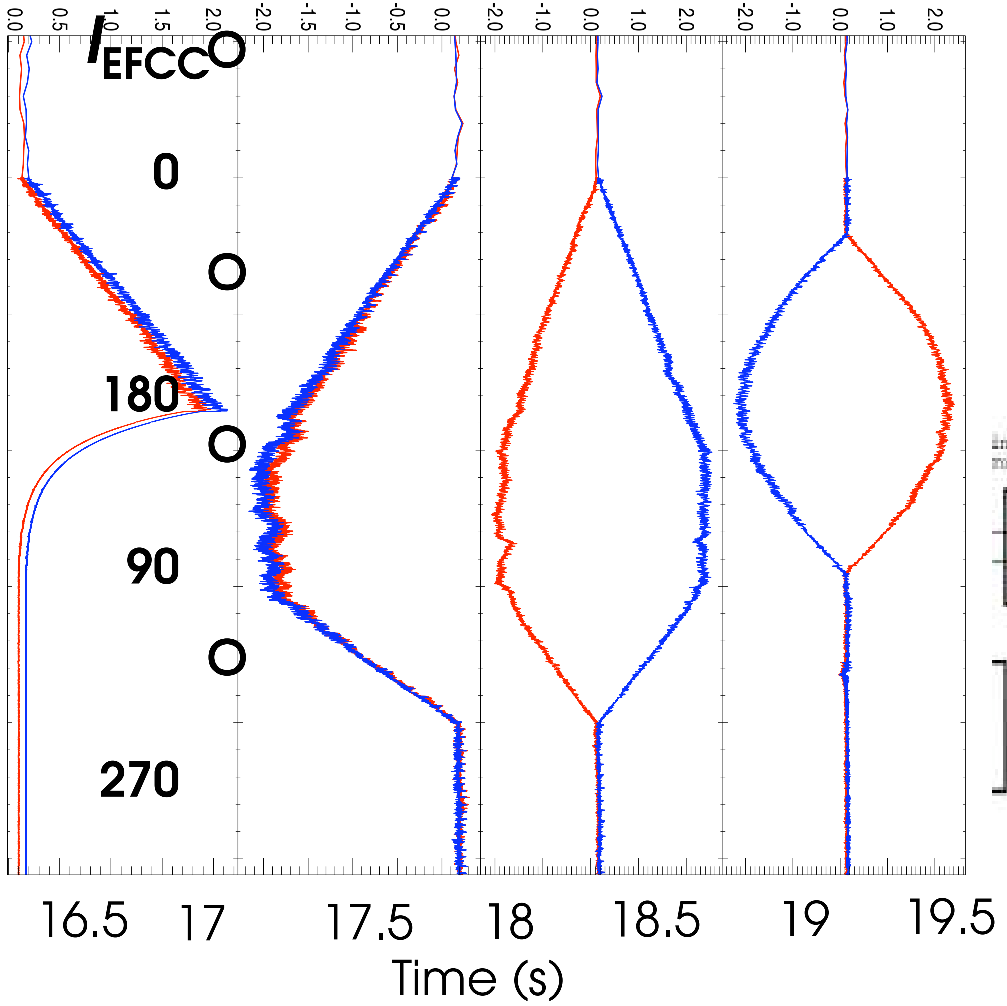


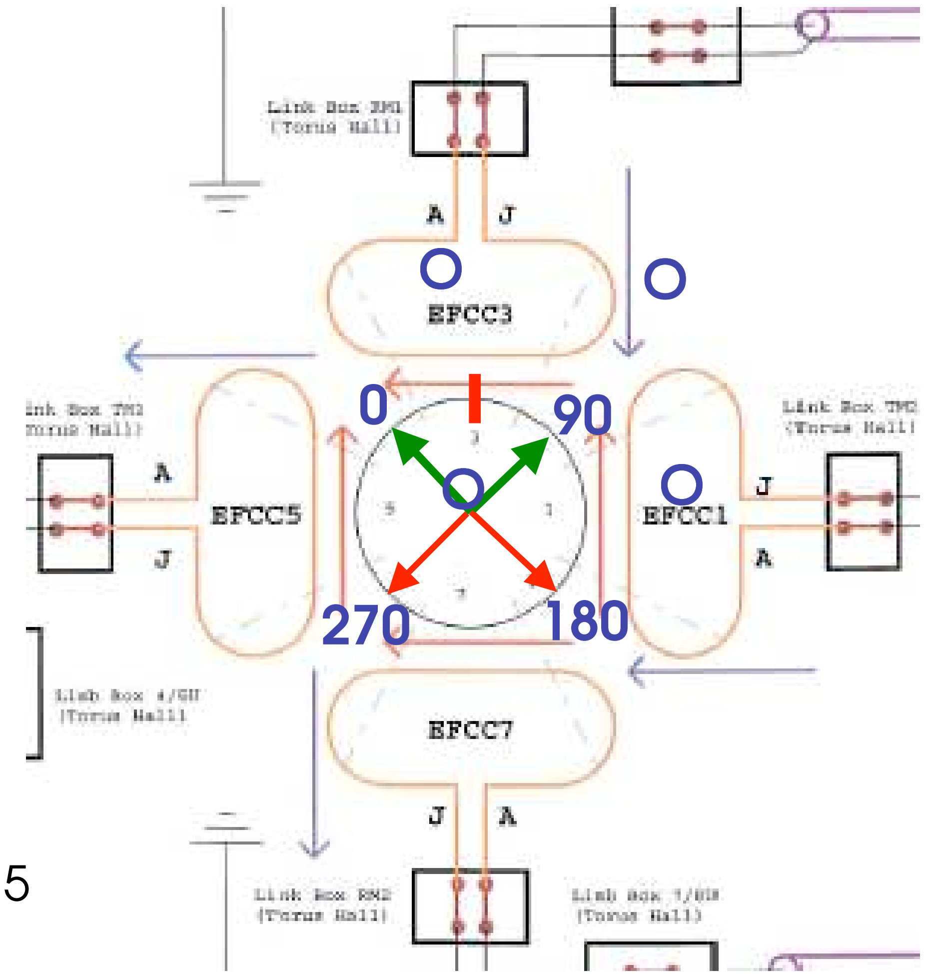
B_0 = 1.84 T, q_{95} = 3.95, δ = 0.5



[M. Bécoulet and E. Nardon, CEA]

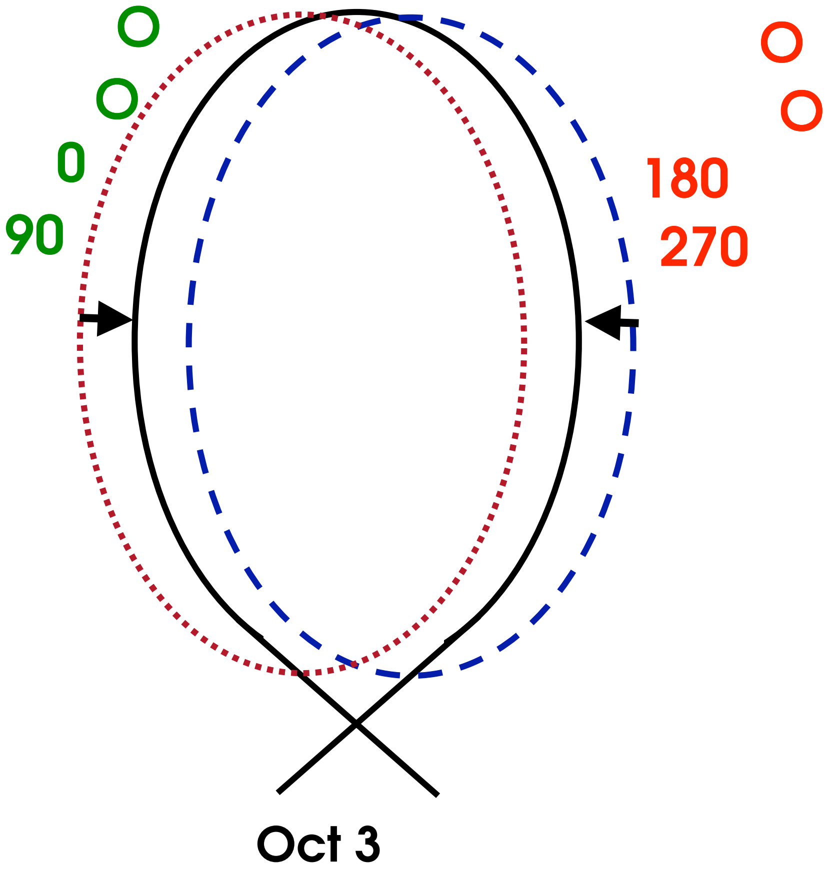
EFCC phase scan (I)

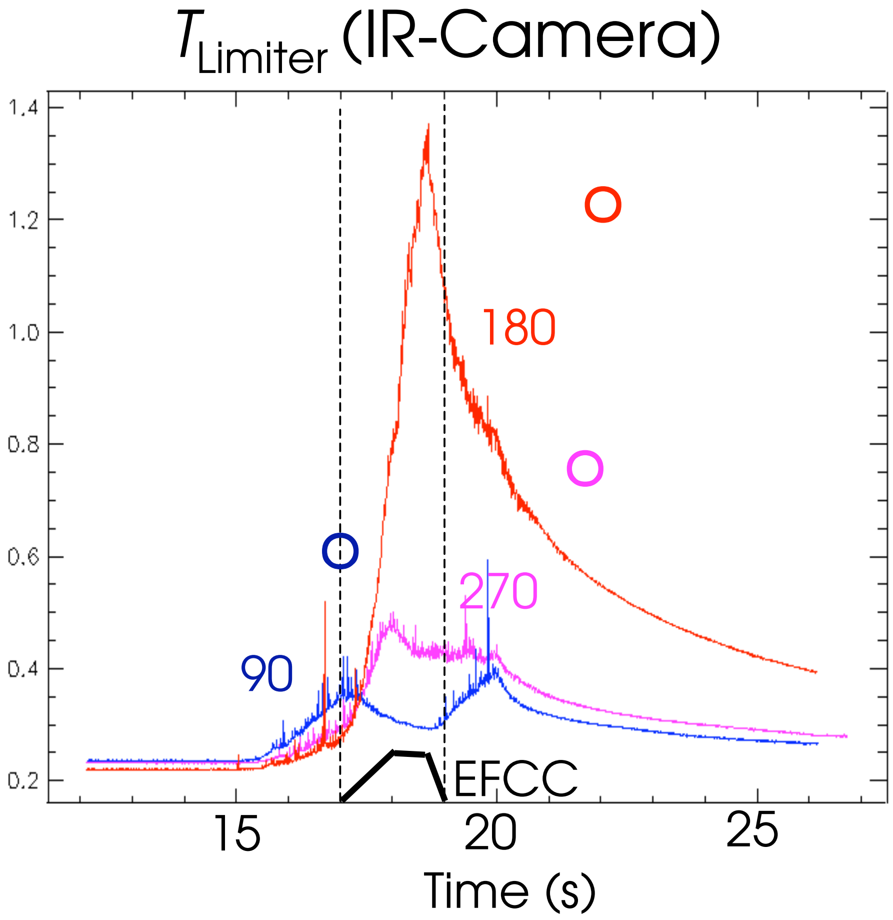




NB: *XLOC* uses coils in Oct 3 (and Oct 7)

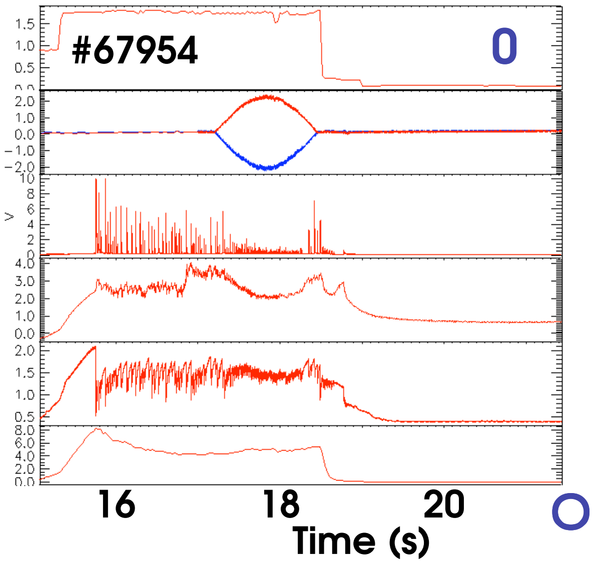
EFCC phase scan (II)





Shape control acts toroidally symmetric, but the effect of an n=1 perturbation field is toroidally asymmetric

Mitigation of type-I ELMs with difference phases of the n=1 perturbation field



P_{tot}

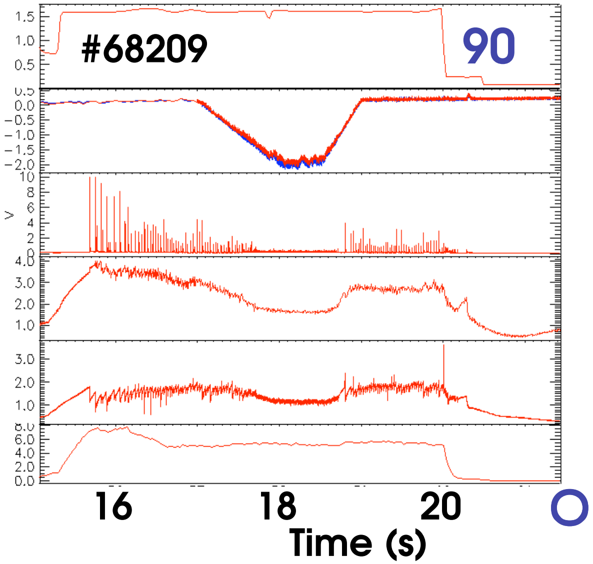
I_{EFCC}

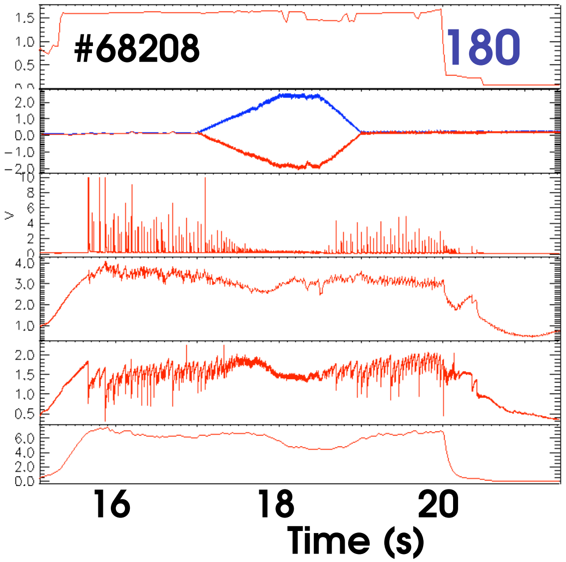
D_α

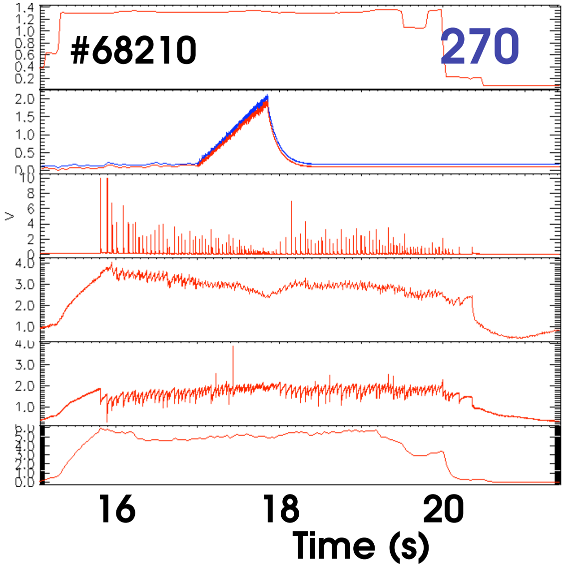
$n_e l$ edge

T_e edge

neutron rate







EFDA JET TFM

q_{95} scan

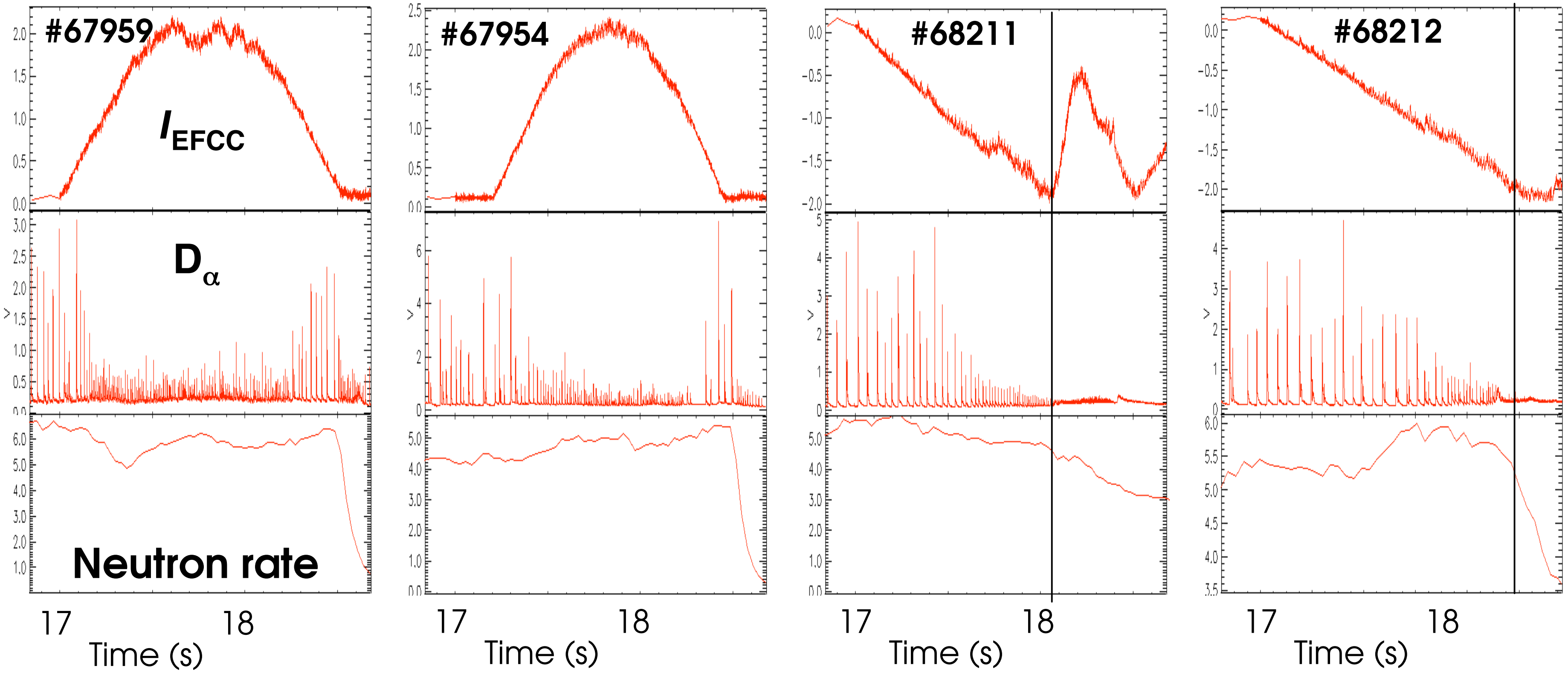
B_t=1.84 T; Plasma configuration: C_SFE_LT

I_p=1.4MA **q_{95}=4.8**

I_p=1.6MA **q_{95}=4.0**

I_p=1.8MA **q_{95}=3.5**

I_p=2.0MA **q_{95}=3.0**



Summary (II)

- First experimental results from JET show that type-I ELMs can be mitigated by the application of an $n = 1$ external perturbation field
- Static $n = 1$ perturbation induced by the EFCCs
  - ELM frequency increased from ~30 Hz to ~120 Hz
  - D_α intensity dropped by a factor of ~10
  - The drop in edge temperature during the ELM was reduced from 500 – 700 eV to 100 – 200 eV
  - The electron density in the centre and at the edge was reduced up to ~15%
  - The central electron temperature increased by ~15%, while the change of the edge temperature is less than a few percent

Summary (III)

- There is a wide range in q_{95} (4.8 – 3.0) in which ELM mitigation with the $n = 1$ external perturbation field has been observed
- Only weak degradation (< 10%) of global plasma performance (W_{dia}, β_N) is observed during the ELM mitigation phase
- The temperature of the outer limiter dropped during the EFCC phase
- ELM mitigation does not depend on the phase of $n = 1$ external field, however, there are *good* phases and *bad* phases with respect to the position and boundary control on JET
- The sawtooth frequency during the EFCC phase increases
- Breaking of the central rotation has been observed when the EFCCs were applied
- The effect on ELMs (lower bound) and the excitation of a locked mode (upper bound) form an operational window for EFCC usage for ELM mitigation