Sawtooth Control

SD Pinches[1]

IT Chapman[1], JP Graves[2], RV Budny[3], VG Igochine[4], I Jenkins[1], T Johnson[5], HR Koslowski[6], M Lennholm[7], Y Liang[6], M Maraschek[4], G Tardini[4], M Turnyanskiy[1], C Wahlberg[8], the ASDEX Upgrade, MAST & TEXTOR Teams and JET-EFDA Contributors*

[1] EURATOM/CCFE Fusion Association, Culham Science Centre, Oxon, UK
[2] CRPP, Association EURATOM/Confédération Suisse, EPFL, 1015 Lausanne, Switzerland
[3] PPPL, Princeton University, PO Box 451, Princeton, NJ 08543, USA
[4] MPI fur Plasmaphysik, EURATOM-Ass D-85748 Garching, Germany
[5] Association EURATOM/VR, EES, KTH, Stockholm, Sweden
[6] Association EURATOM/FZ Jülich, IPP, D-52425 Jülich, Germany
[7] JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK
[8] EURATOM/VR, PO Box 515, Uppsala University, SE-751 20, Sweden
* See the Appendix of F Romanelli et al., IAEA FEC Geneva 2008

This work was partly funded by UK EPSRC and EURATOM. The work was partly carried out within the framework of the European Fusion Development Agreement

CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority**

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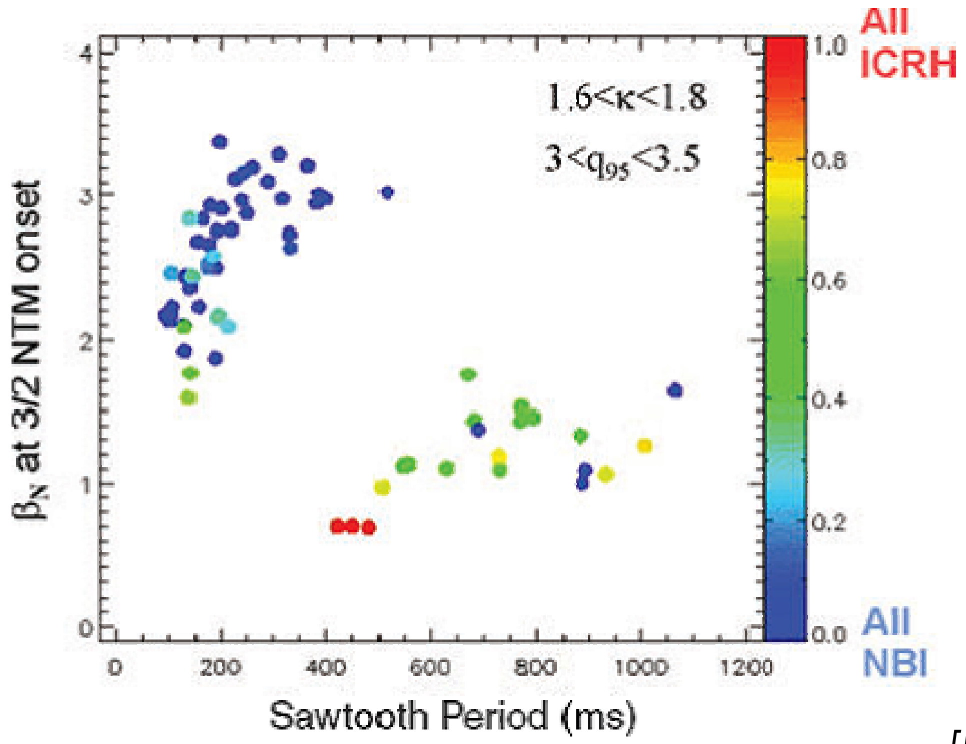
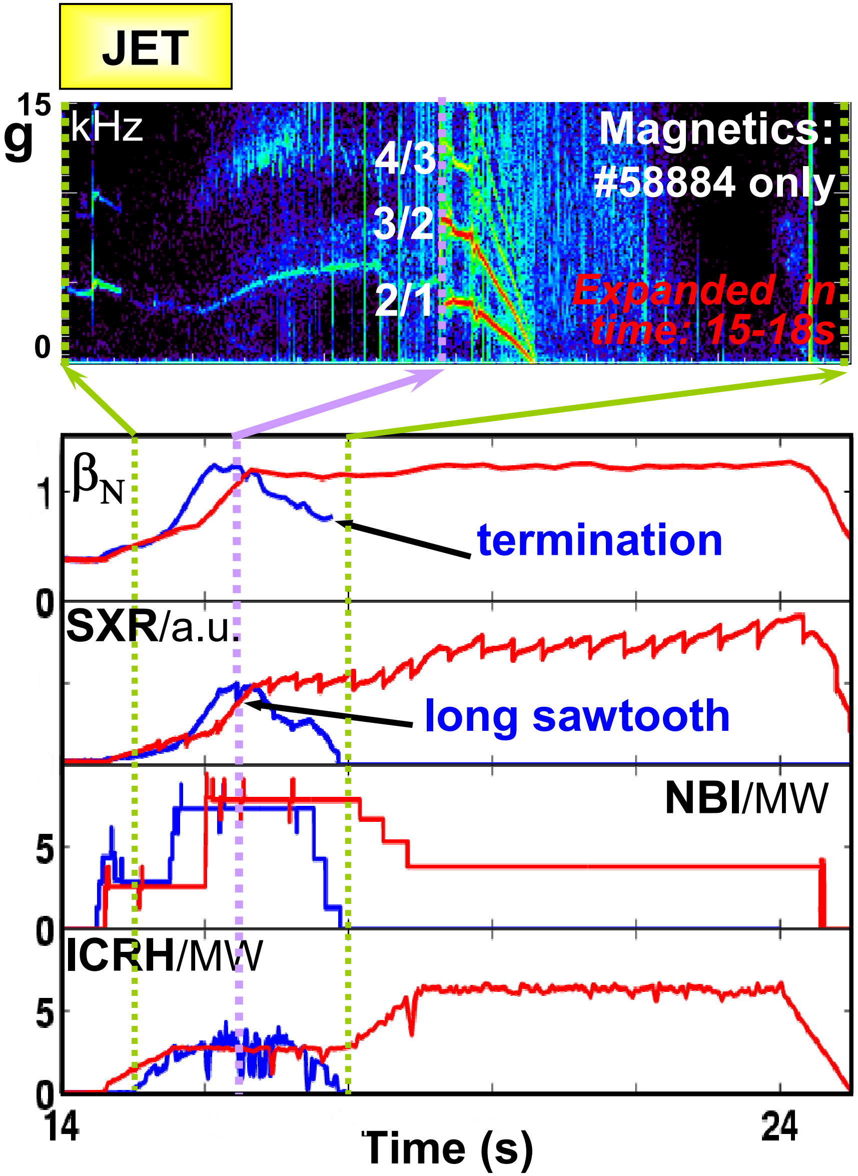
Why do we need to control sawteeth?

- **Long Period Sawteeth** have been shown to **trigger Neo-classical Tearing Modes** (NTMs)
  - Long Sawteeth → NTMs
  - Short Sawteeth → Avoid NTMs



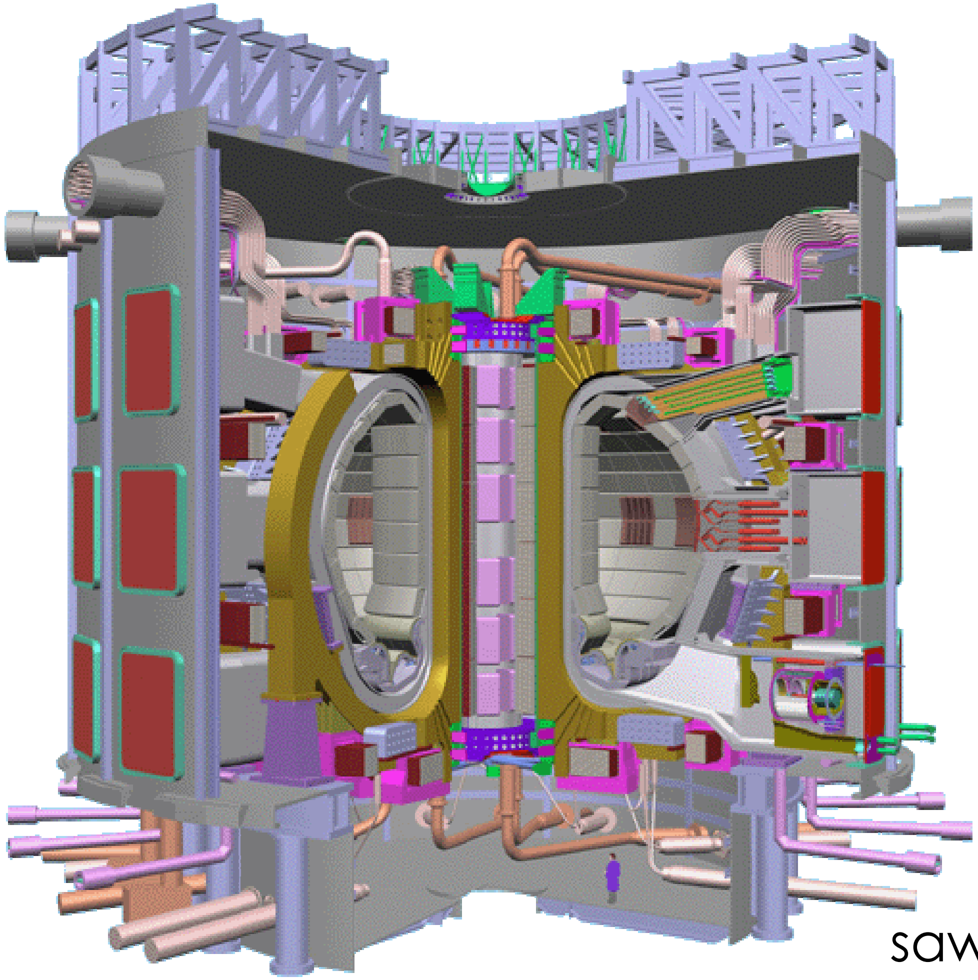
[Buttery, Nucl Fusion, **44**, 2004]



[Buttery, IAEA FEC, EX/7-1, 2004]
[Sauter et al, PRL, **88**, 2002]

Sawteeth are a bigger problem in ITER

- **NTMs degrade plasma confinement or even cause terminations**



ITER will have lots of fusion-born alpha particles in the core

↓

Long sawtooth periods

↓

Trigger NTMs and cause confinement degradation

↘ **Keep sawteeth small and frequent**

↙ Deliberately stabilise sawtooth so it's longer than the pulse – is this possible?

Outline – Sawtooth Control

- **Motivation**
  - Sawteeth can trigger Neo-Classical Tearing Modes (NTMs)
  - Methods for Sawtooth Control
- **Developments in our understanding of sawtooth stability**
  - Co/Counter NBI Experiments on JET, MAST and TEXTOR
  - Effect of passing ions and sheared flows
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When will a sawtooth crash happen?

- **Sawtooth is triggered when one of following criteria is met** [Porcelli et al, PPCF, 38, 2163 (1996)]
  - Resistive instability:

Change in potential energy of internal kink mode

Ion Larmor radius

$$\pi \frac{\delta \hat{W}}{s_1} < c_\rho \frac{\rho}{r_1}$$

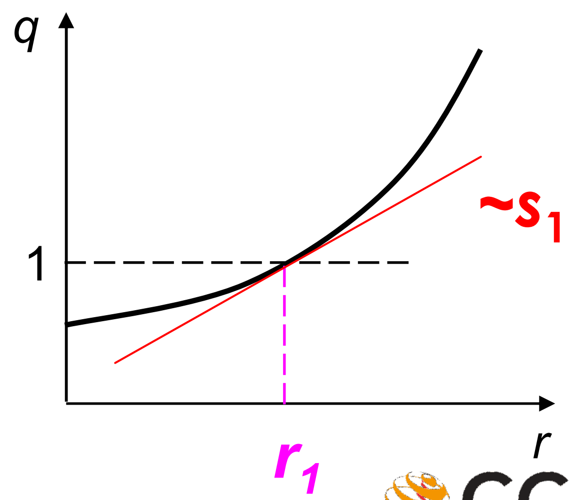
Magnetic shear at q=1 surface

Radius of q=1 surface

  - Ideal Instability:

$$\pi \frac{\delta \hat{W}}{s_1} < -\frac{\omega_{*i}\tau_A}{2}$$

- **So a sawtooth crash occurs when:**
  - The potential energy of the kink mode is sufficiently small
  - The magnetic shear at q=1 is sufficiently large



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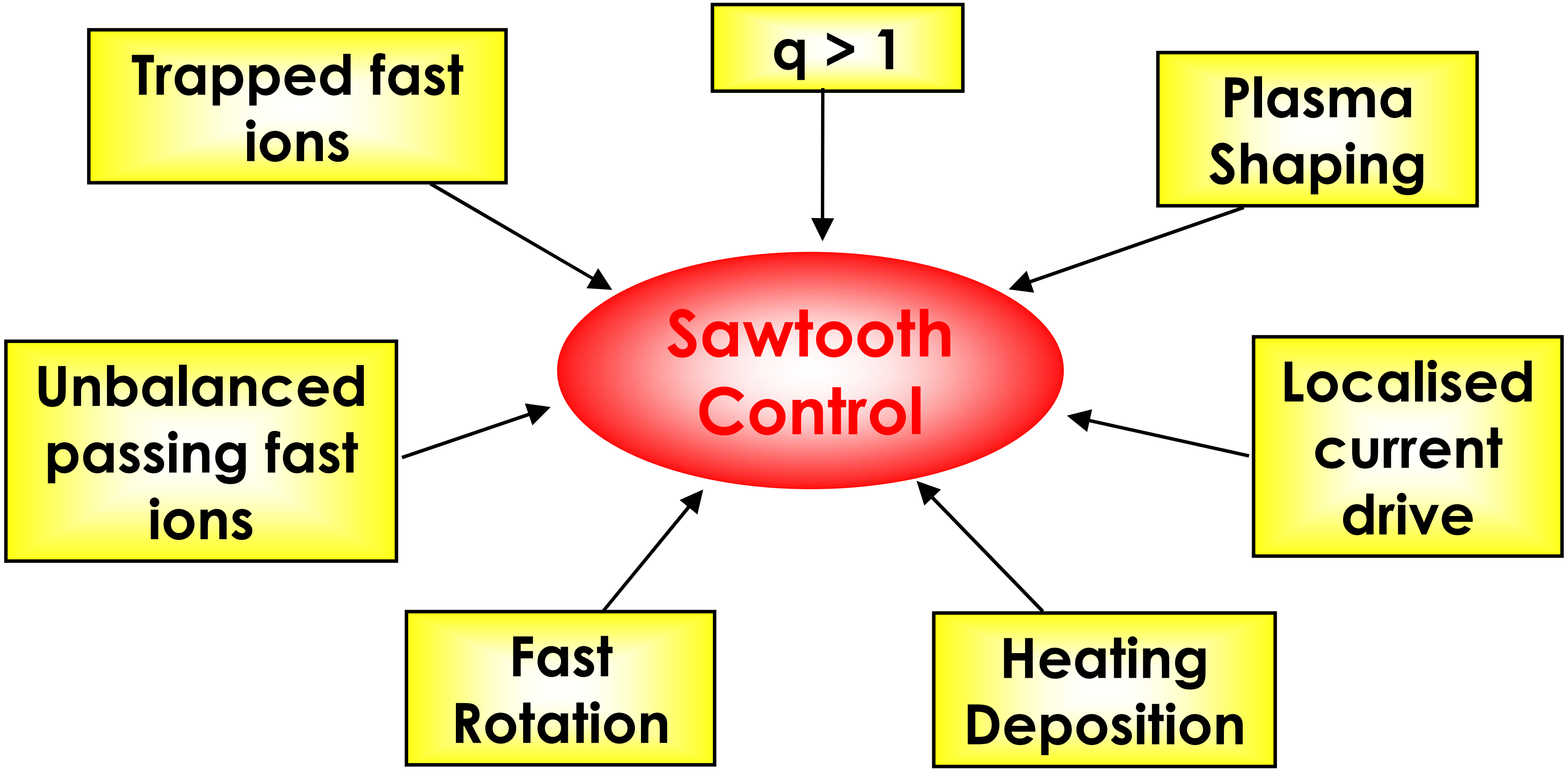
How can we control sawteeth?



- **Two main techniques:**
  - Drive current near q=1 surface to change magnetic shear
  - Introduce energetic ions to change mode potential energy

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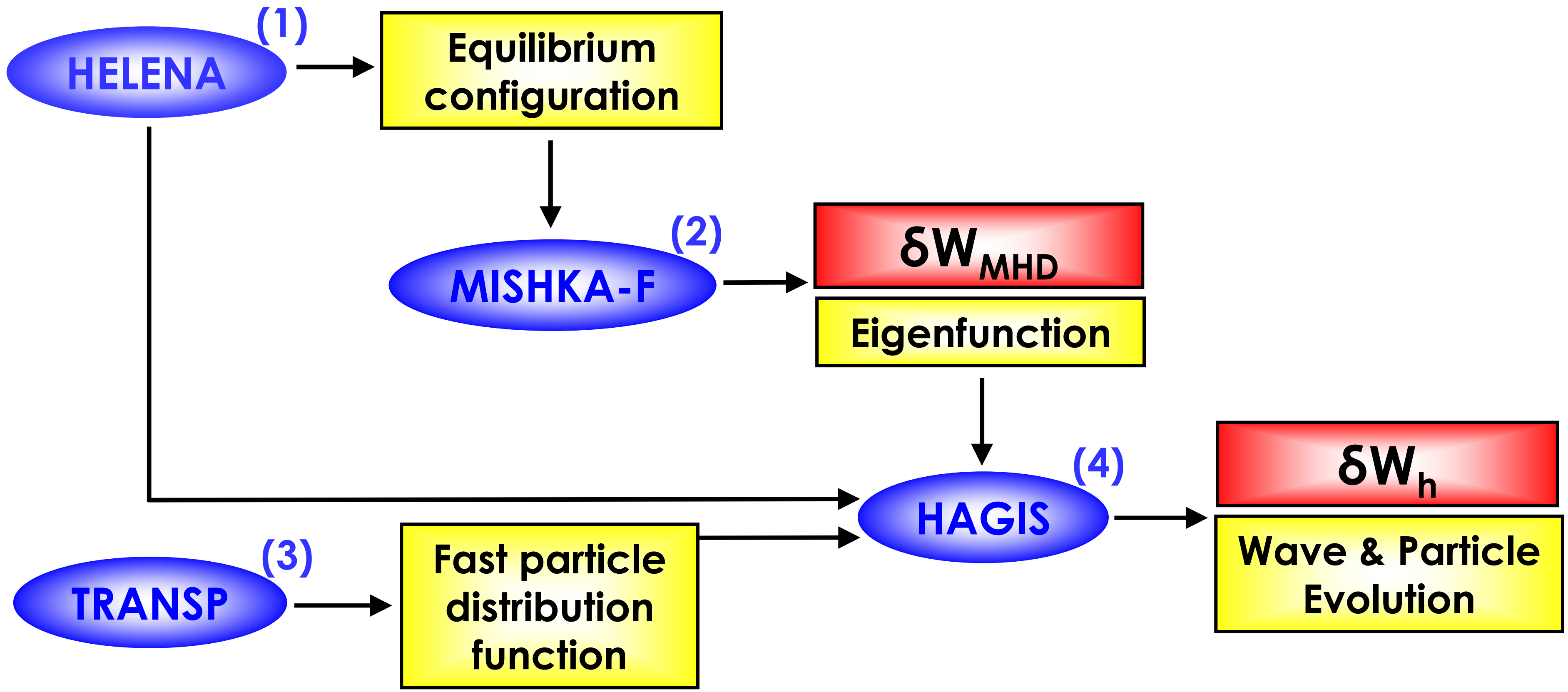
Modelling Sawtooth Stability

- **Model Stability of *n*=1 internal kink mode**



(1) *Huysmans et al*, CP90 Conf on Comput Phys, *p371 (1990)*
(2) *Chapman et al*, Phys Plasmas, ***13***, *062511 (2006)*
(3) *Budny et al*, Nucl Fusion, ***32***, *429 (1992)*
(4) *Pinches et al*, Comput Phys Commun, ***111***, *133 (1998)*

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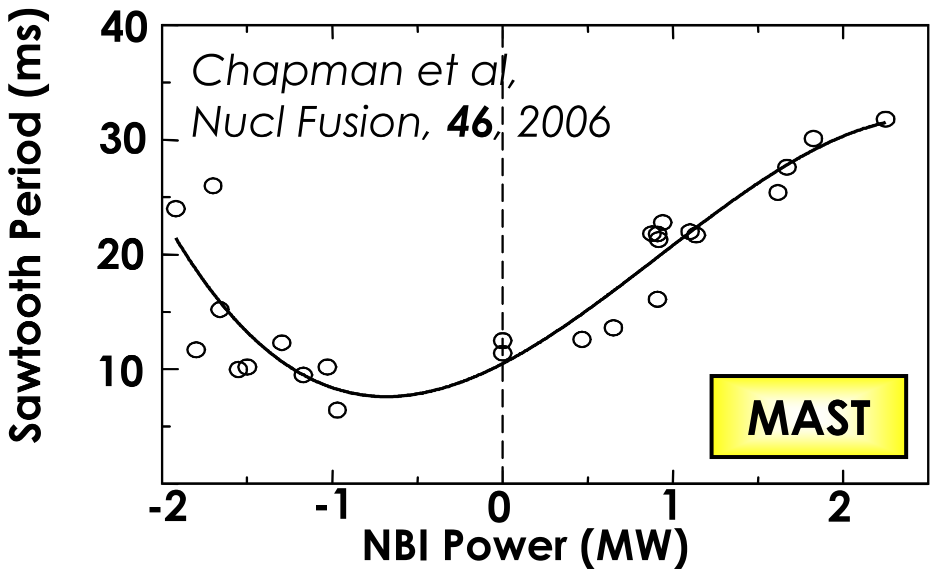
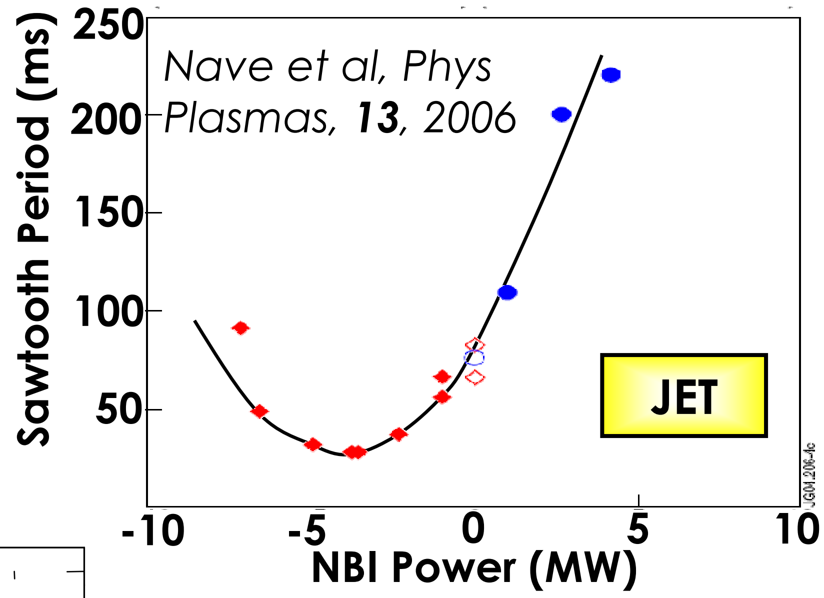
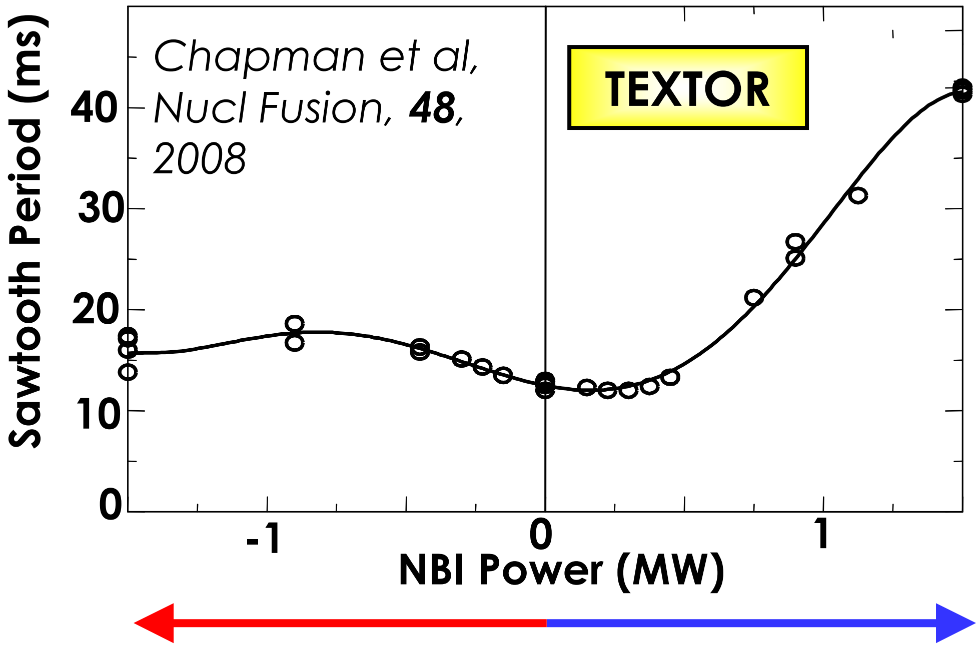
Asymmetry in NBI-heated plasmas





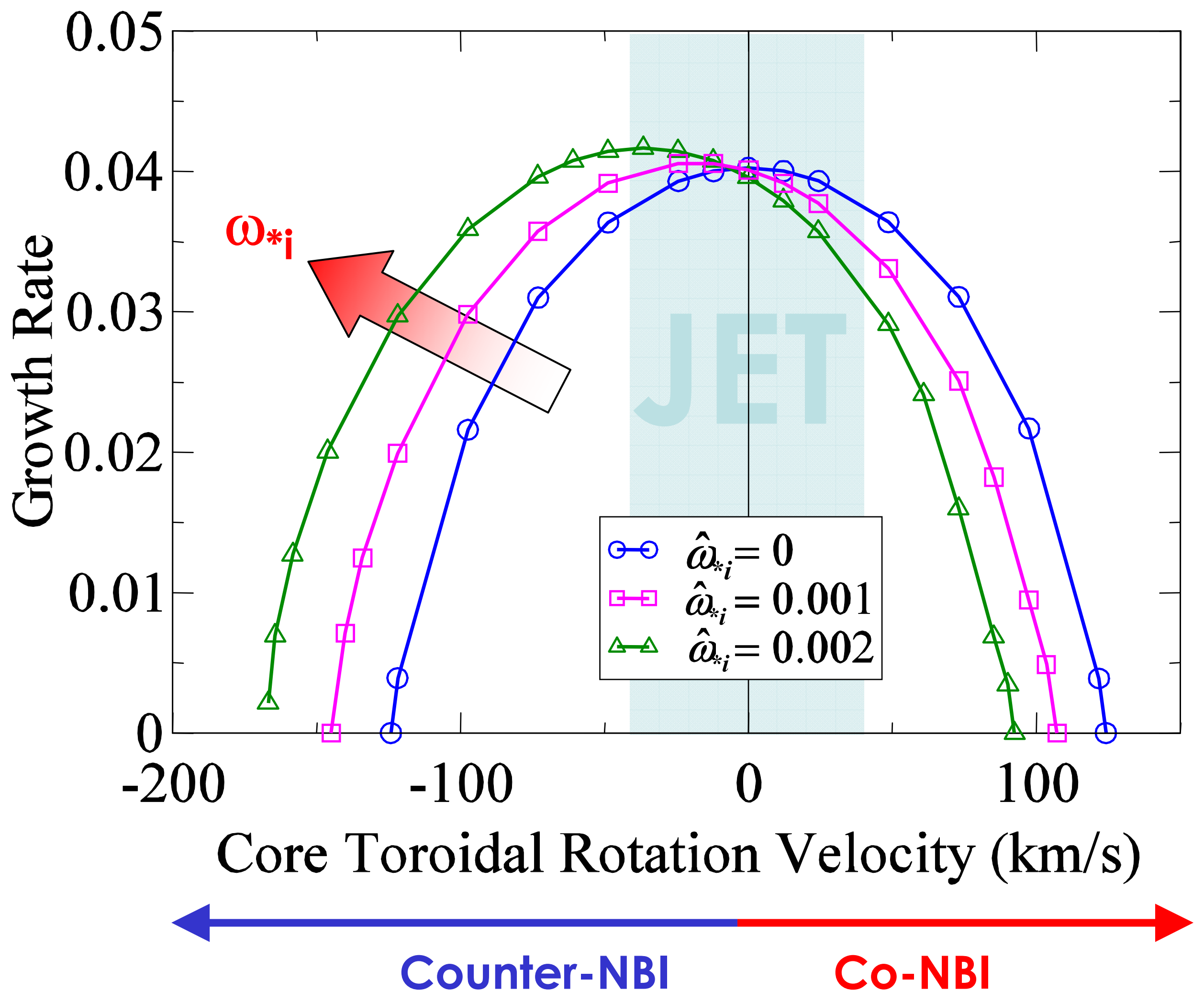


Counter-NBI Co-NBI

- **Co v Counter Studies**
  - Asymmetric behaviour
  - Minimum is not in Ohmic plasmas

Stability of n=1 kink mode at finite ion diamagnetism

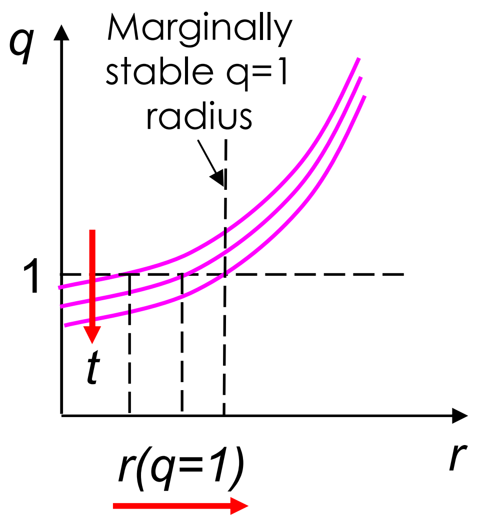
- **Modelled the effect of toroidal flow on the ideal n=1 internal kink mode with finite ion diamagnetic frequency in MAST:**

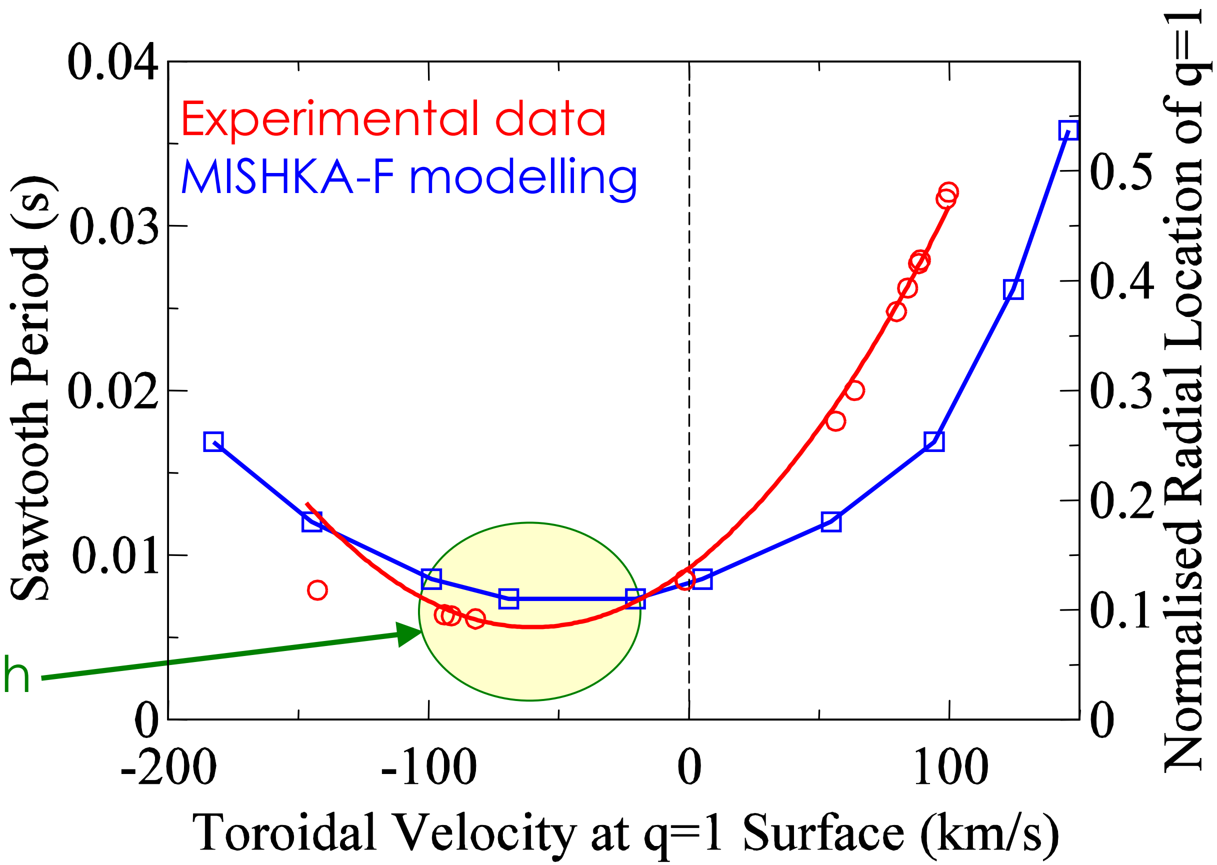


Chapman et al, NF, 46, 2006

Modelling sawtooth stability with flow in MAST

- **Kink mode stabilised by strong toroidal rotation**
  - As sawtooth period, τ_{st}, increases, radial location of q = 1 increases
  - Marginally stable q = 1 radius expected to correlate with τ_{st}



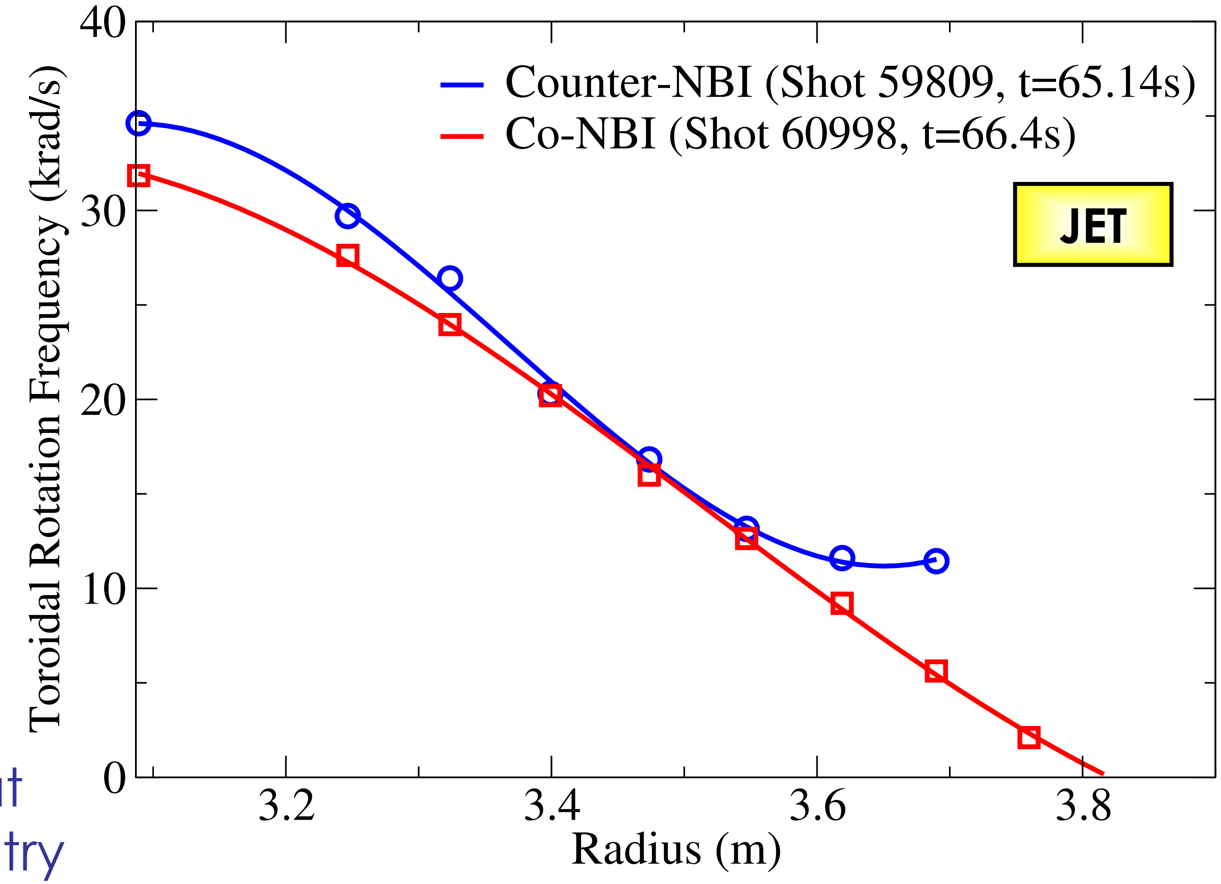


Toroidal velocity at which q = 1 radius for marginal stability is minimised agrees with minimum in sawtooth period

[Chapman et al, Nucl Fusion, **46**, 2006]

JET Rotation Profiles

- **Toroidal Rotation is an order of magnitude smaller than MAST**
  - Much slower rotation speeds than MAST, only small effect on stability of kink mode
  - Strong flow ***shear*** at radial location of q=1 (compared to MAST)

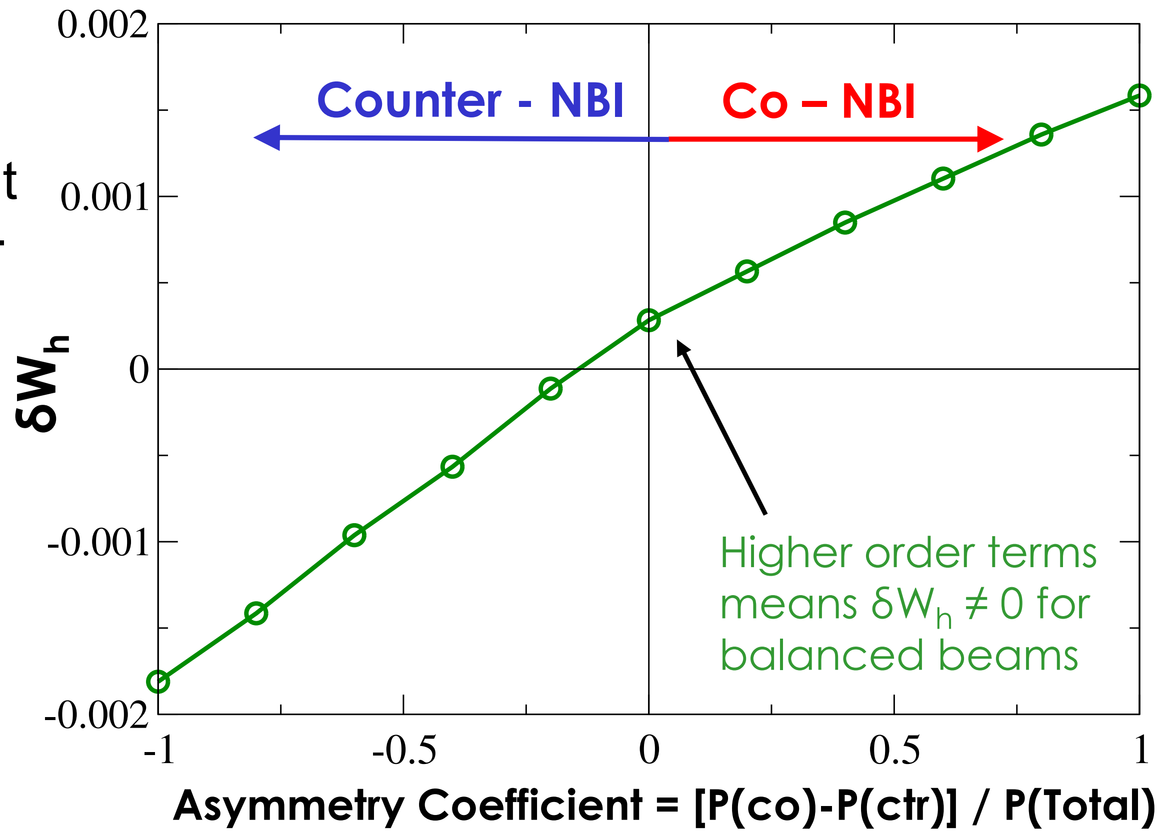


(Rotation Profiles from Charge Exchange)

⇨ At slower flows, what causes the asymmetry in sawtooth period in JET experiments?

What is the rôle of trapped and passing particles?

- **Sawtooth stabilisation by energetic particles is usually attributed to the presence of trapped fast ions** *[Porcelli, PPCF, 33, 1991]*
  - In JET, fast beam ions are **mainly passing**
  - Passing ions can be stabilising when co-NBI, but destabilising when counter-NBI.
    [Graves, PRL, **92**, 2004]



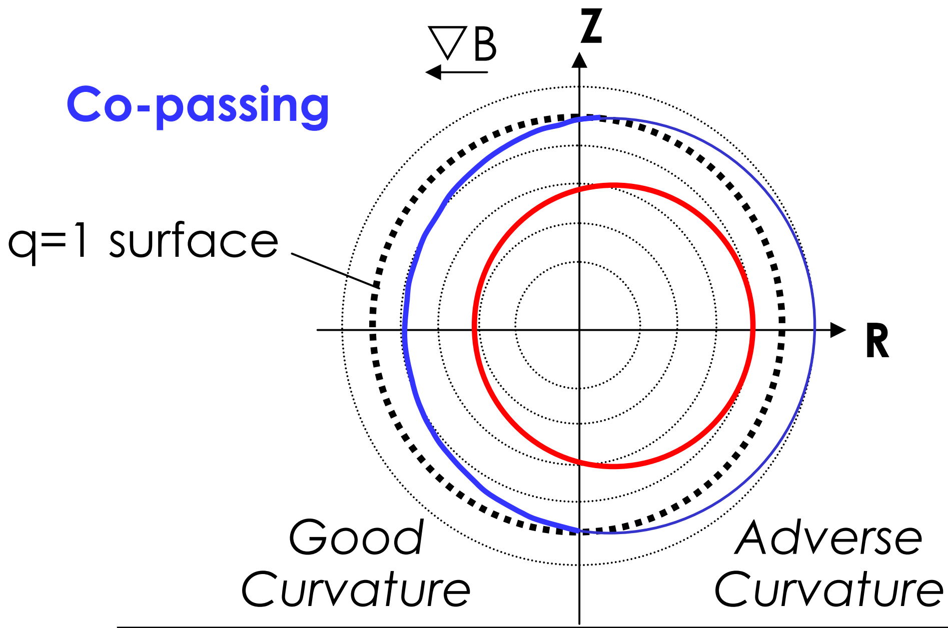
- **HAGIS code**
  - Drift Kinetic code for exploring wave-particle interactions
  - Calculates change in potential energy:

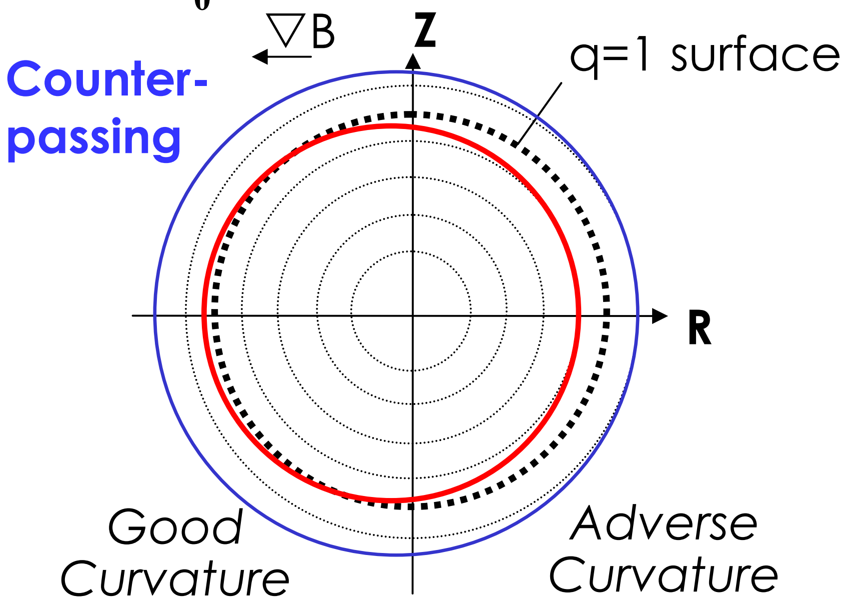
$$\delta W_h = \frac{1}{2}\int \left(mv^2 + \mu B\right) \delta f \;\; \kappa \cdot \xi^* d^3x\, d^3v$$

*Pinches, CPC, **111**, 1998*

Passing Particle Stabilisation Mechanism

δW has a term dependent upon curvature: $\delta W \sim -\int_0^{r_1} \left(\xi \cdot \nabla \langle P_h \rangle\right)\left(\xi \cdot \kappa\right) dr$





Co-pass, $\langle P_h \rangle' \|_{r_1} < 0 \rightarrow$ stabilising	Ctr-pass, $\langle P_h \rangle' \|_{r1} < 0 \rightarrow$ destabilising
Co-pass, $\langle P_h \rangle' \|_{r1} > 0 \rightarrow$ destabilising	Ctr-pass, $\langle P_h \rangle' \|_{r1} > 0 \rightarrow$ stabilising

- **Increasing effective orbit width leads to large passing ion effect**
  - Large thermal velocity (NNBI, ICRH)
  - Large fraction of barely passing ions (JET NBI, ICRH)

Graves, PRL, **92**, *2004*

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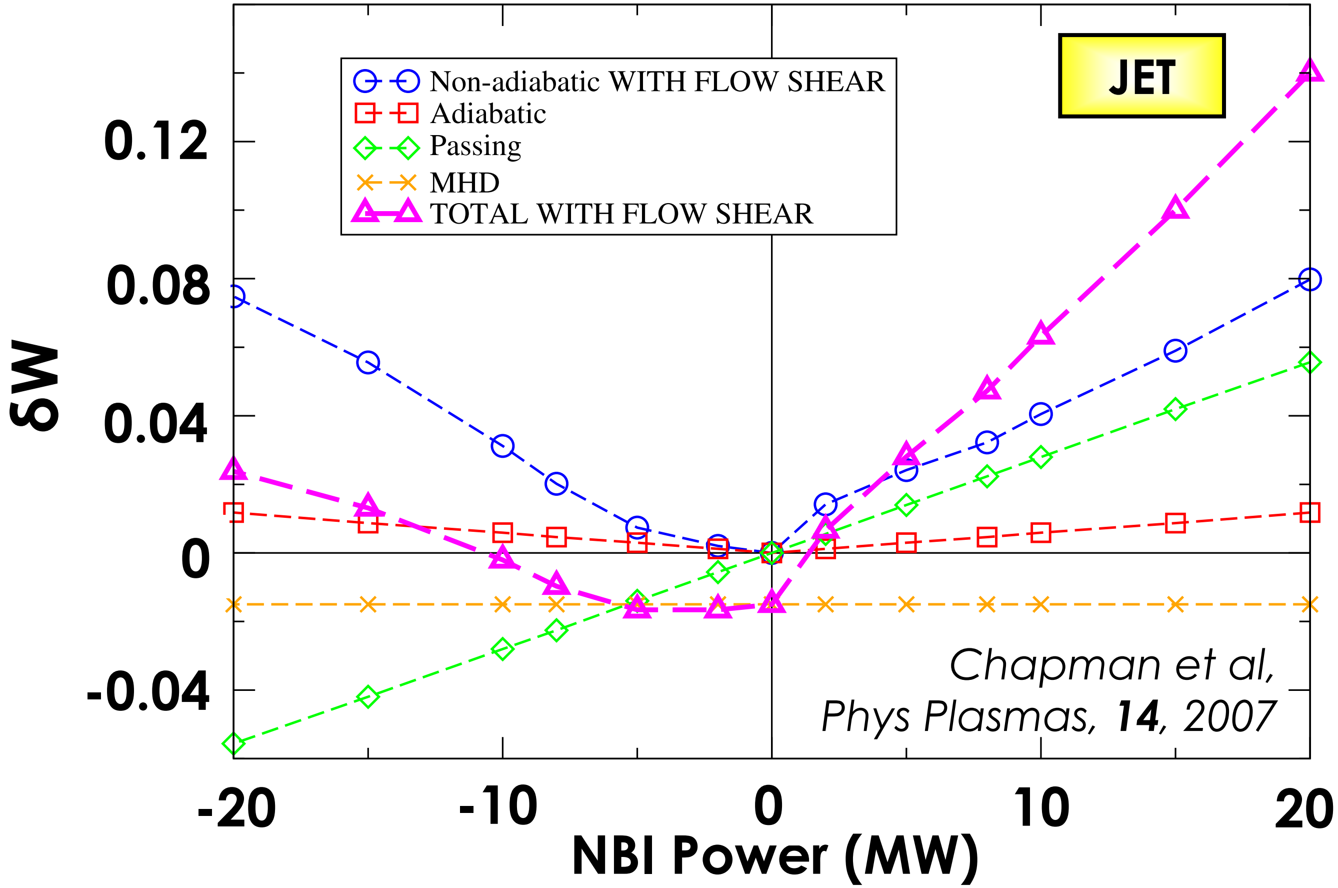
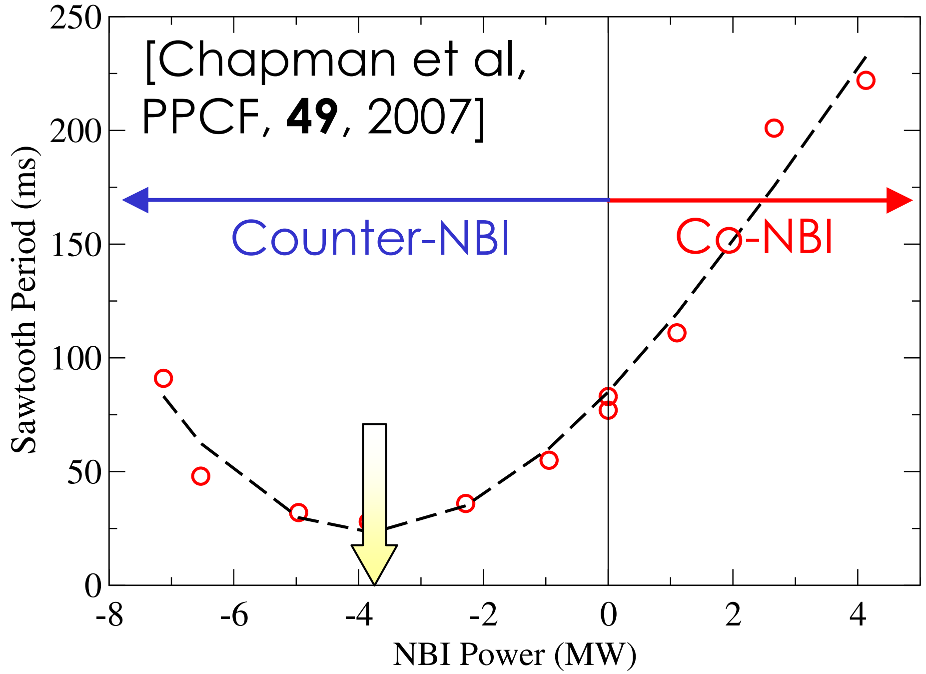
Do passing fast ions explain JET result (low rotation)?

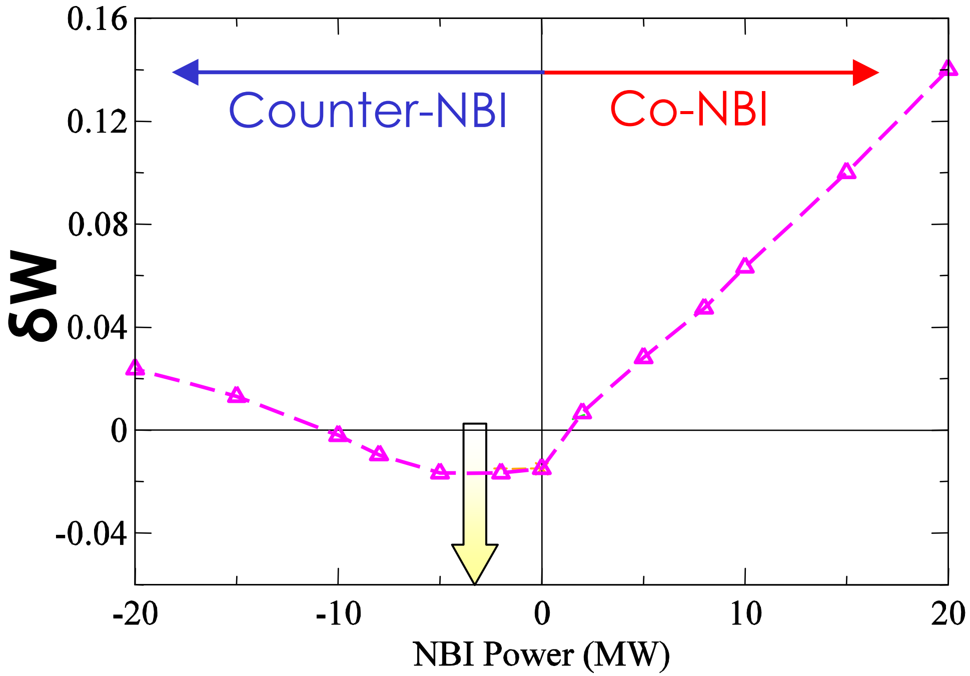
- **Modelling the effect of fast ions on *n*=1 kink mode**



- **New understanding about fast ions and sawtooth behaviour:**
  - **Passing fast ions play a key role** (low v_{ϕ} & NBCD) [*Graves PRL 2004*]
  - Effect of trapped ions influenced by flow shear [*Graves PPCF 2000*]

How does it compare to experiment?

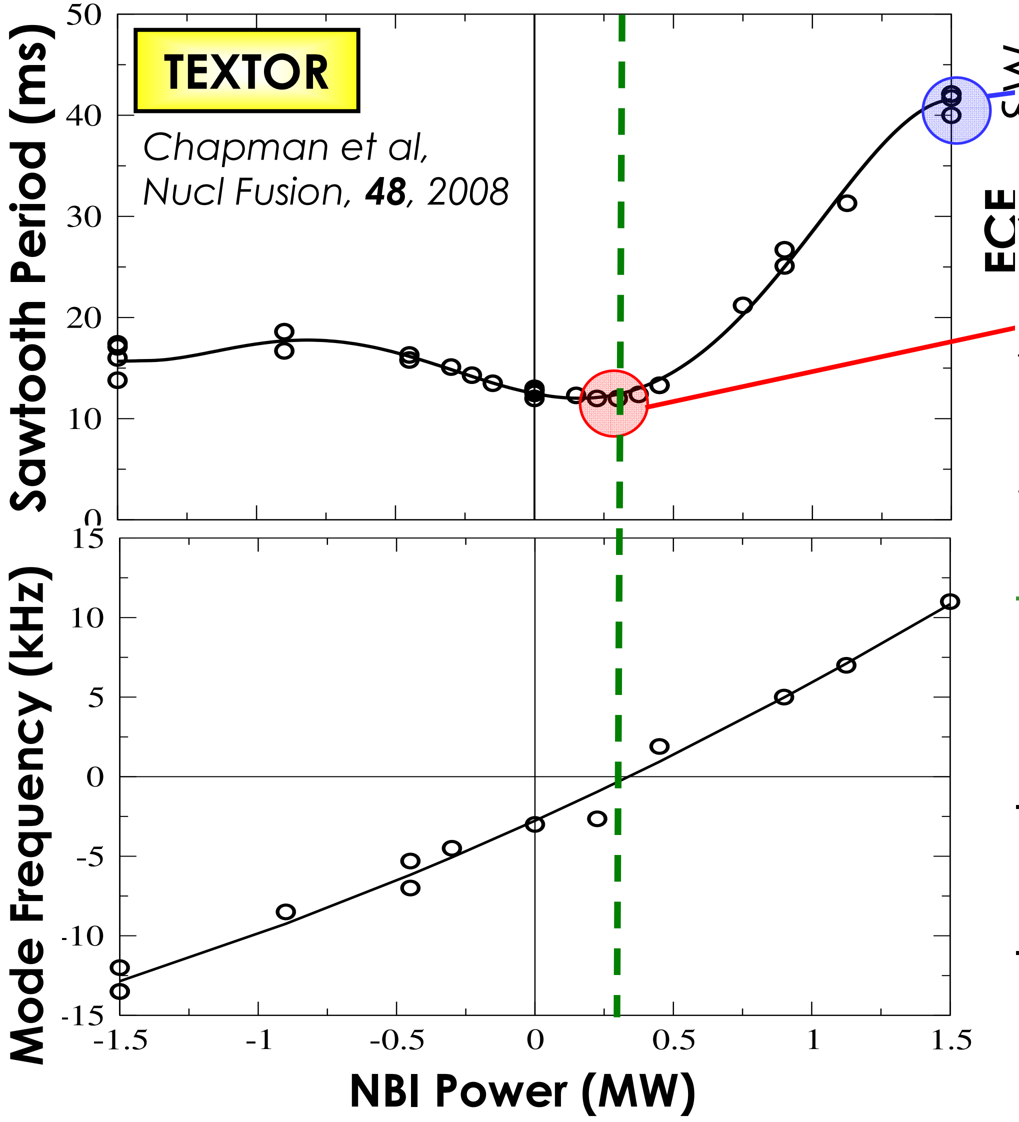


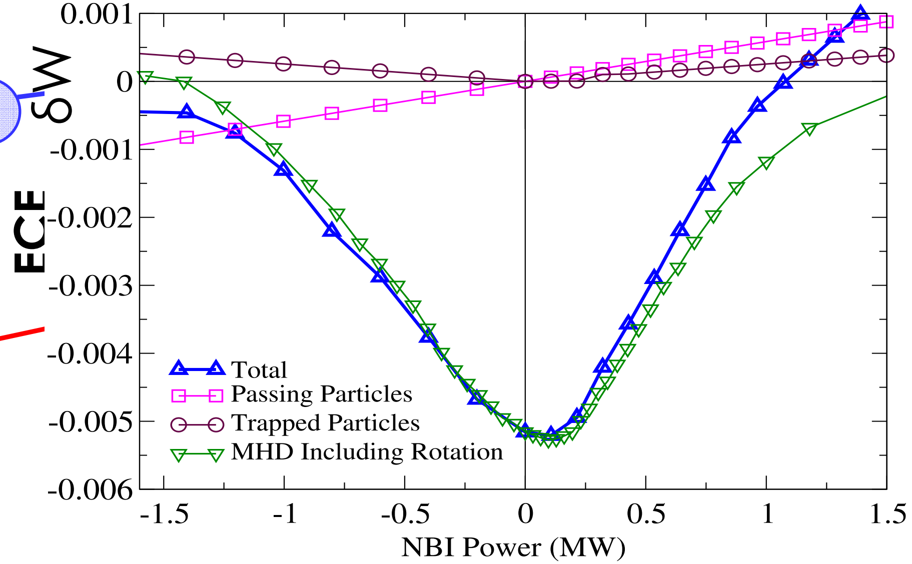


- Minimum in sawtooth period and δW_h agrees well (at ~ 4MW)
- In **JET**, asymmetry and minimum is explained by **energetic particle effects**
- In **MAST**, asymmetry and minimum is explained by **flow effects**

Sawtooth Behaviour with NBI in TEXTOR

- **TEXTOR exhibits different sawtooth behaviour with NBI**





- Minimum in sawtooth period when plasma rotation stops (precursor frequency → 0)
- Minimum τ_{ST} occurs when NBI rotation balances intrinsic flow
- Counter-passing fast ions destabilise kink mode & dominate when flow tends to upper limit

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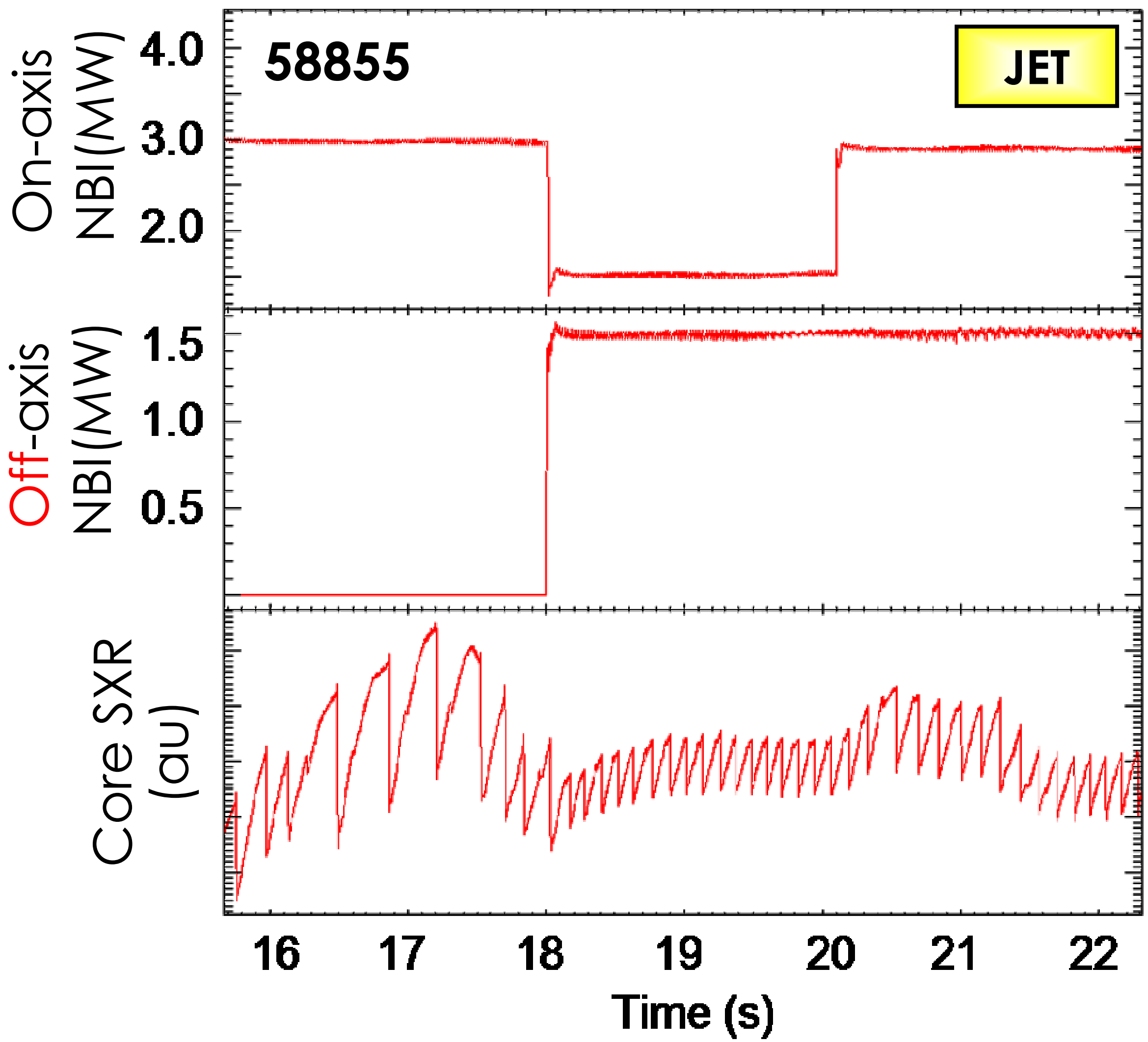
Sawtooth Control Using Off-Axis Co-NBI

- **Sawtooth period can be shortened by applying off-axis NBI**



– Off-axis NBI can control sawteeth which have been stabilised by on-axis NBI

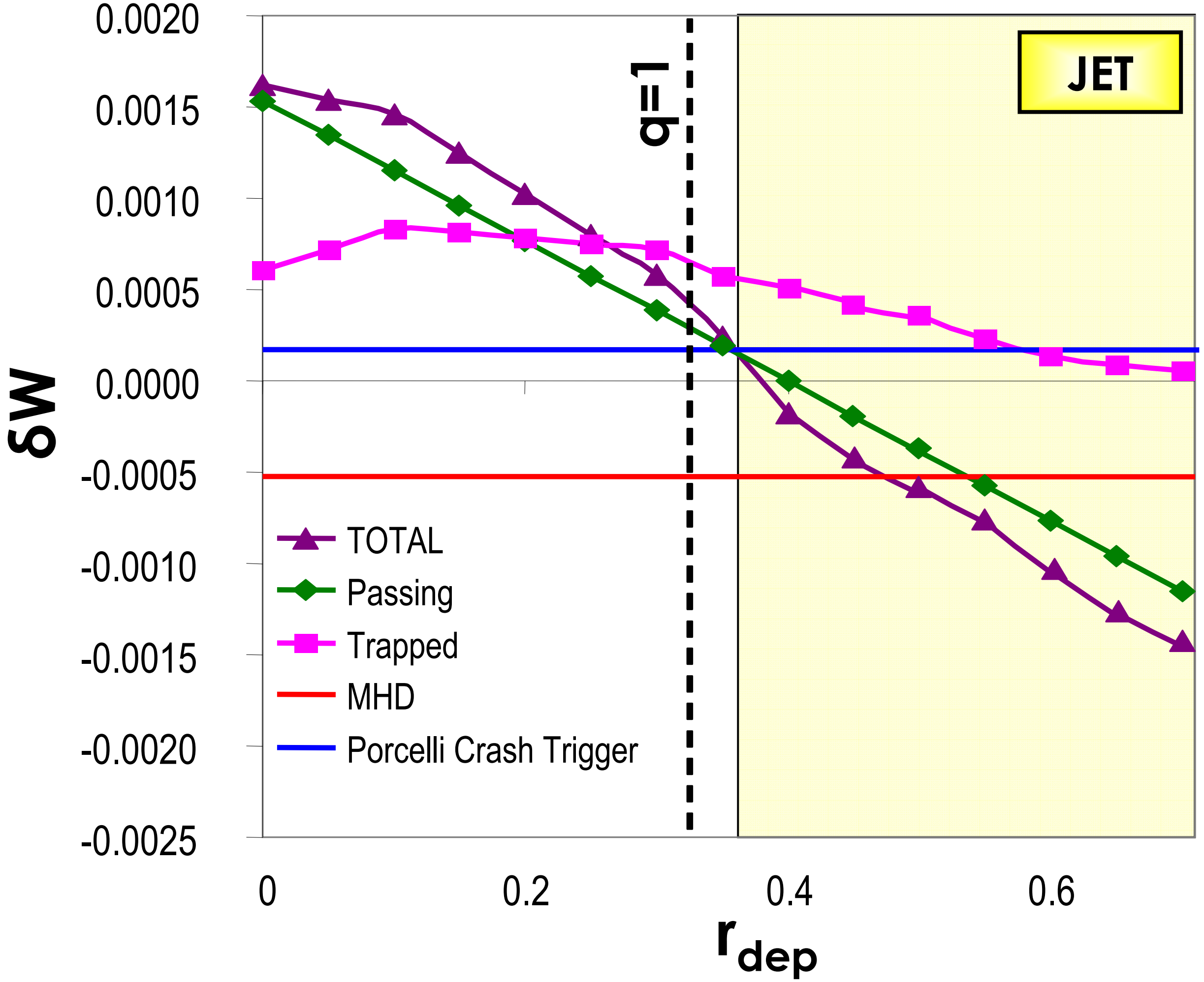
– Explained by destabilising contribution from passing fast ions born outside q=1

– Modelling shows fast ion effects dominate and NBCD effect is very small

[*Chapman et al, Nucl Fus **49** 2009*]

Modelling Off-axis NBI Effects

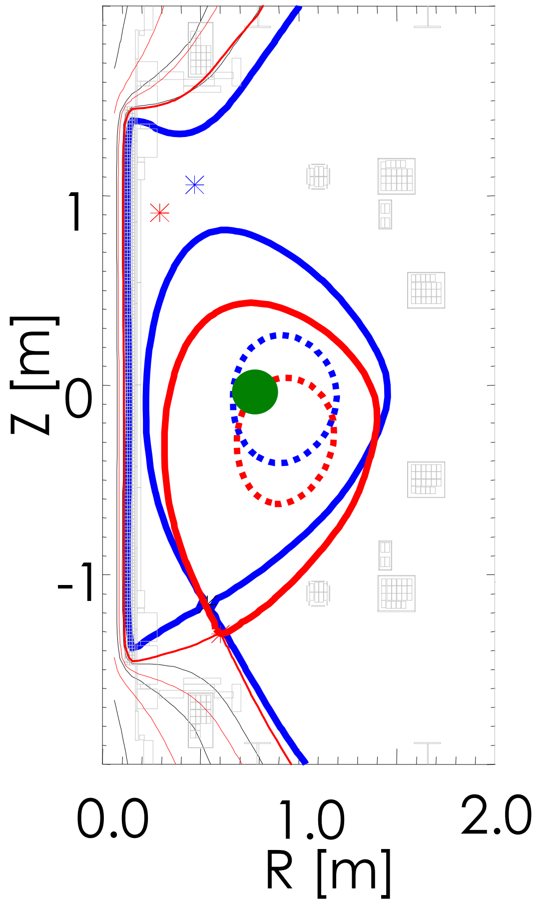
- **Move deposition location of peak of fast ion distribution wrt *q*=1**
  - When fast ions peaked just outside *q*=1, kink mode unstable

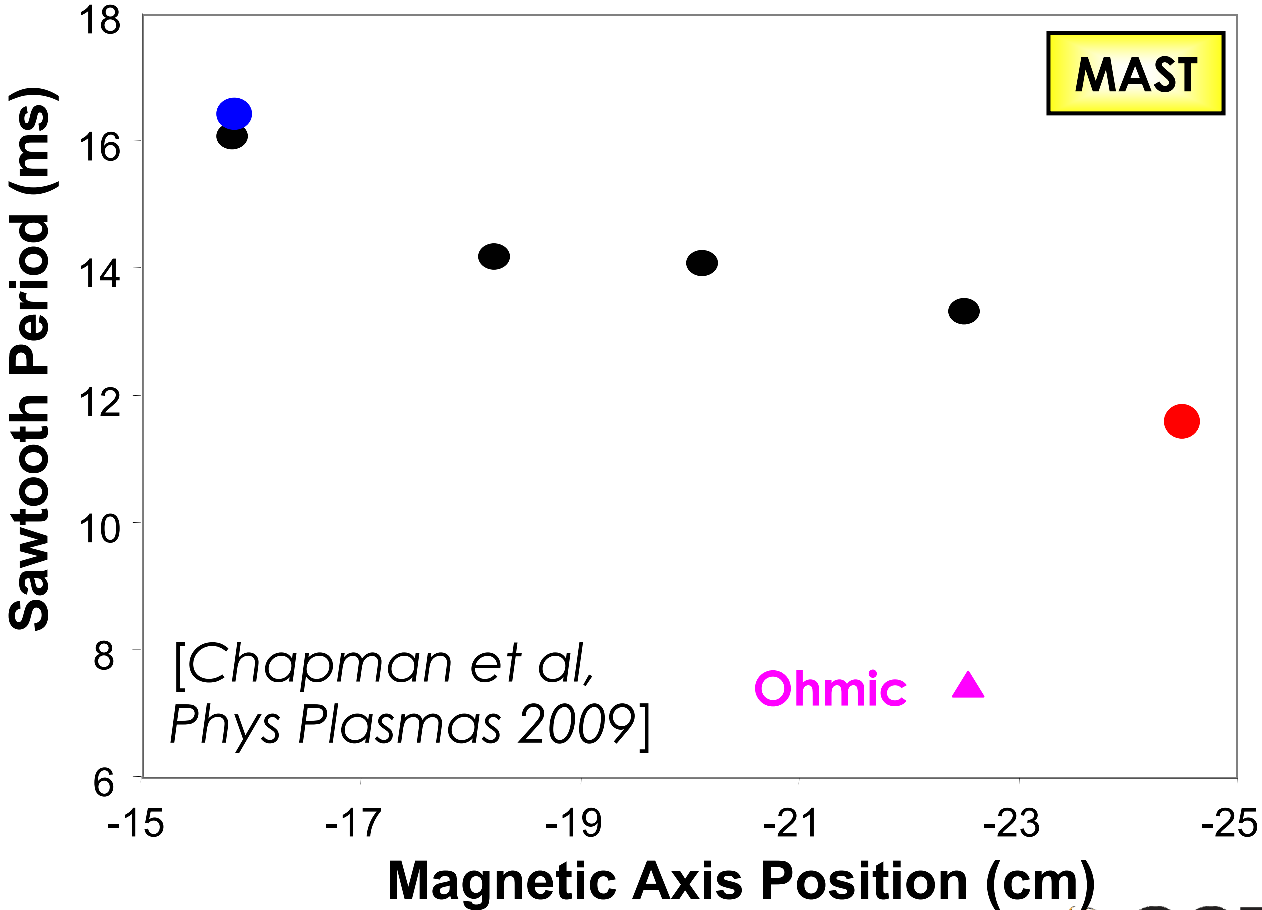


Chapman et al, PPCF, ***50****, 2008*

Off-axis NBI Effects in MAST

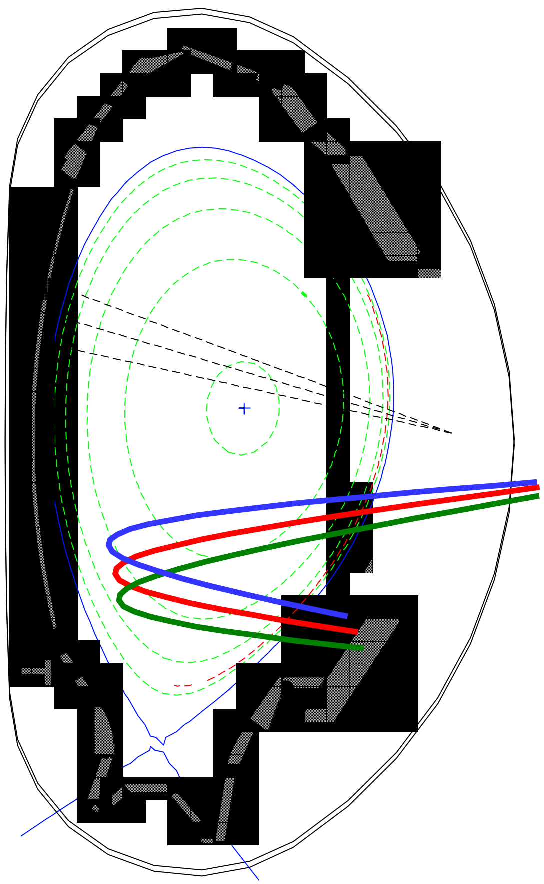
- **Scan the deposition location by moving plasma vertically**
  - Sawtooth behaviour affected by deposition location relative to *q*=1
  - Passing ion effects dominate over change in NBCD, v_ϕ, shape etc

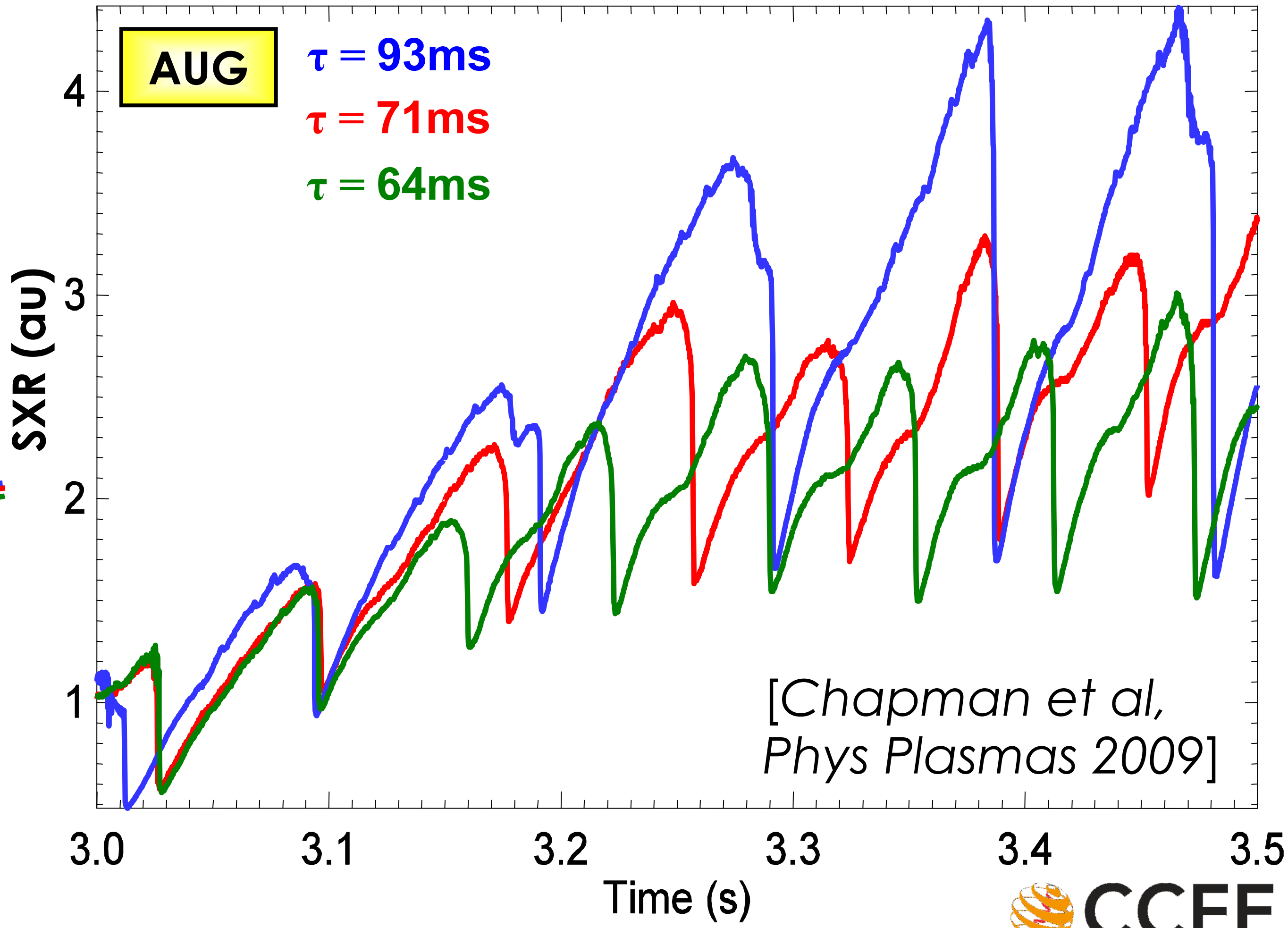




Off-axis NBI Effects in ASDEX Upgrade

- **Off-axis NBI affects sawtooth behaviour**
  - As f_h moves further outside q=1, τ_s decreases by ~50%
  - Modelling again shows passing ions dominate over NBCD





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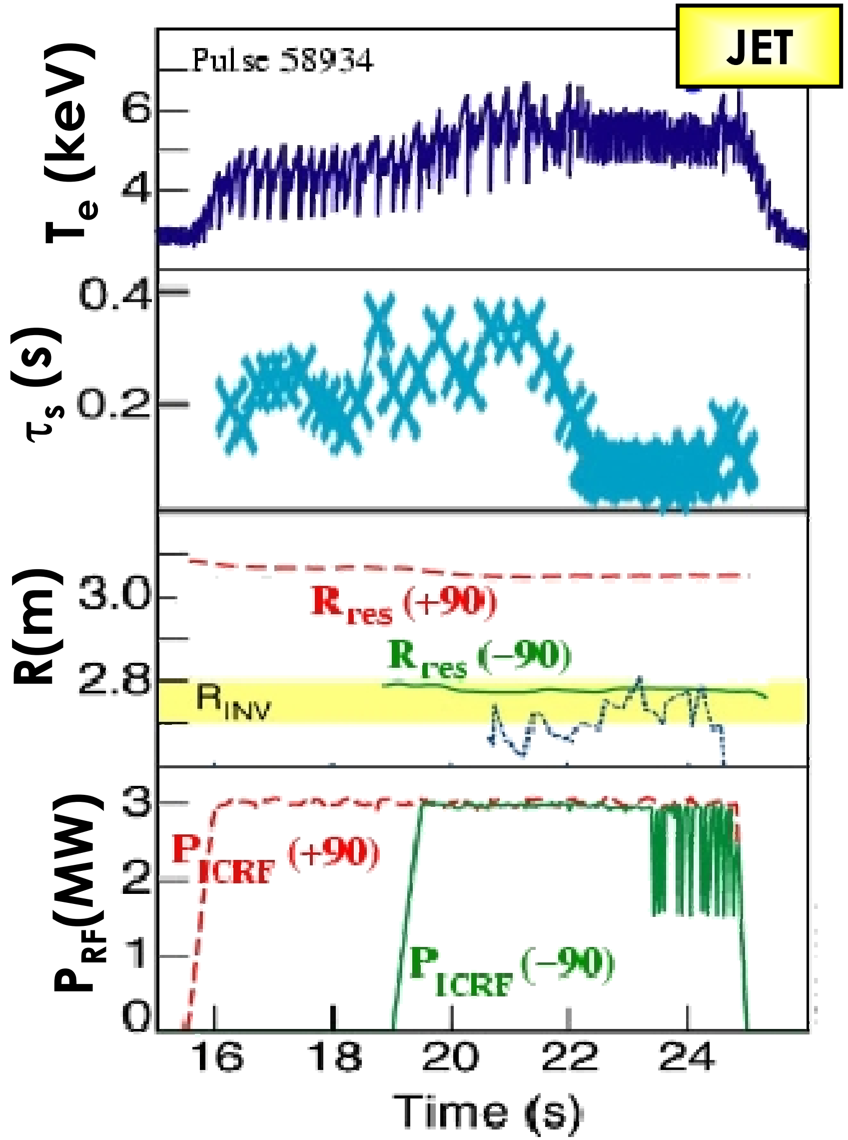
ICRH Sawtooth Control in JET



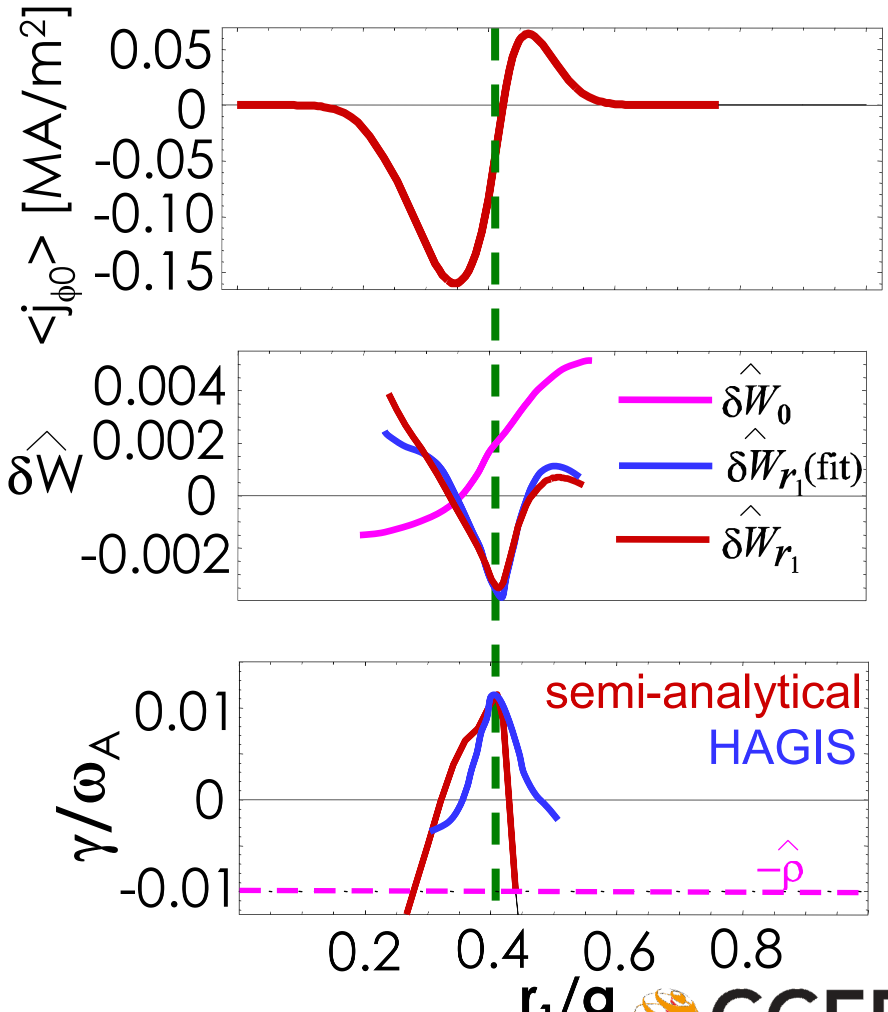
Eriksson, PRL, **92,** *235004 (2004)*

- On Axis ICRH strongly stabilises sawteeth due to hot trapped ions [*Campbell, White, Porcelli et al*]
- Off Axis Counter-propagating ICRH (-90) **destabilises long sawteeth** (which were stabilised by on-axis fast ion population)
- Initially **expected** that control mechanism would be from **shear modification at *q*=1**
- Modelling of recent JET discharges [*Coda, EPS 2007*] confirms that **change to shear from -90 ICRH is typically small**

ICRH Sawtooth Control in JET

- New theory shows that **<u>control is determined by the asymmetry in $v_{\parallel}$ of passing ion distribution</u>**
- Fast ion growth rate is proportional to the radial gradient of the passing fast ion current density profile at *q*=1
- Results confirmed using SELFO code (for f_h^{RF}) and HAGIS (for δW)
- In He^3 minority scenarios in ITER an **electron drag current** results in small change to shear but **does not affect fast ion mechanism** [*Laxåback, Nucl Fusion*, ***45*** *2005*]

$$\delta\hat{W}_{r_1} \approx -\frac{2^{1/2}}{\pi\epsilon_1^2}\frac{1}{Z\Omega_c}\left(\frac{2\mu_0}{B_0^2}\right)T_\perp^{1/2}T_\parallel^{1/2}\left.\frac{d < j_{\phi 0} >}{dr}\right|_{r_1}$$



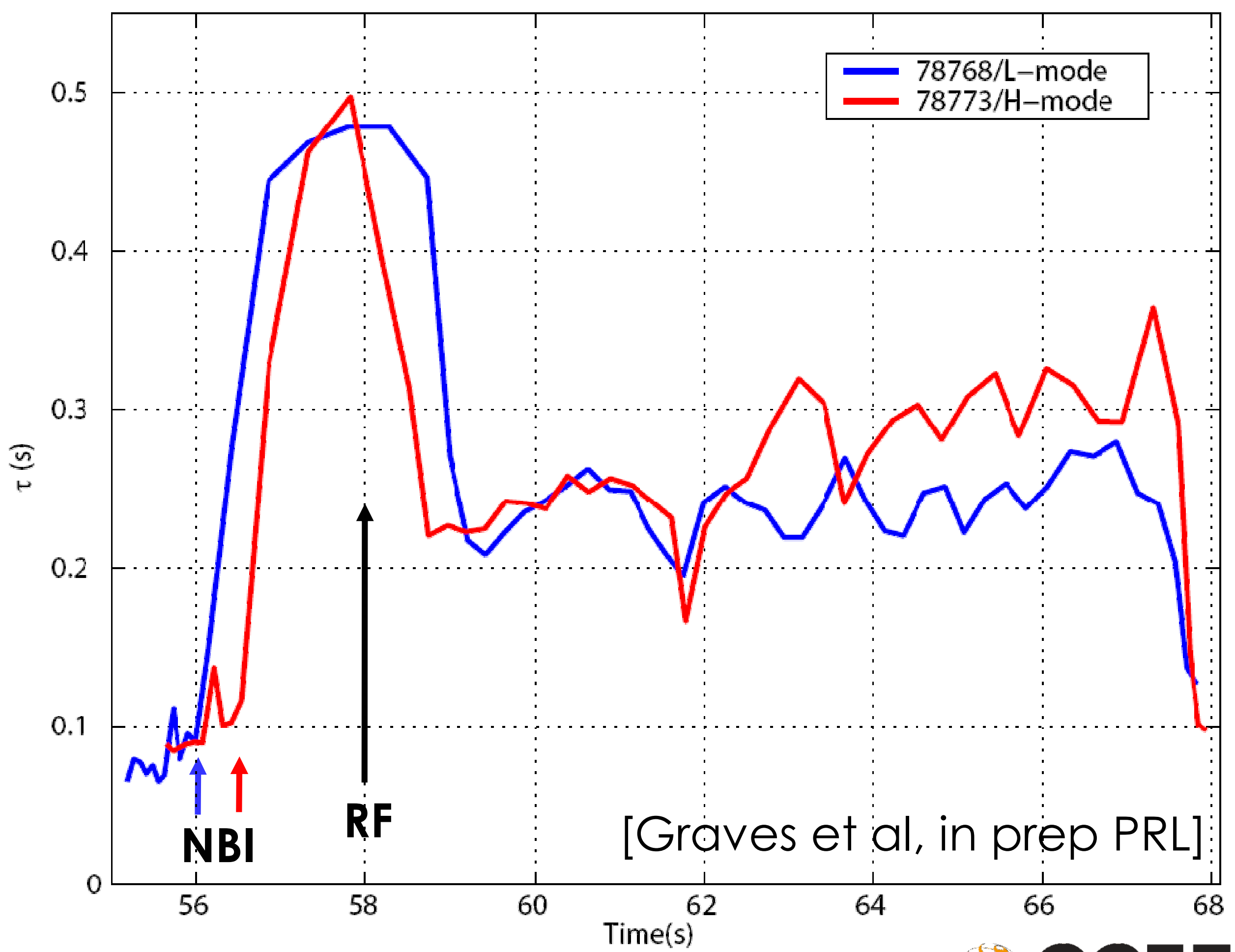
JP Graves et al, PRL (2009)

Sawtooth Control with ICRH in JET (and ITER?)

- **Control with ICRH shown to be fast ion effect**
  - Use ^{3}He minority as electron drag results in negligible ICCD

- **Can significantly destabilise long period sawteeth**
  - Stabilised by NBI (as ITER-like ICRH not available)
  - Decreased τ_{saw} by factor of 2, even in H-mode plasmas
  - Direct evidence of importance of control - get NTMs with long s.t. period

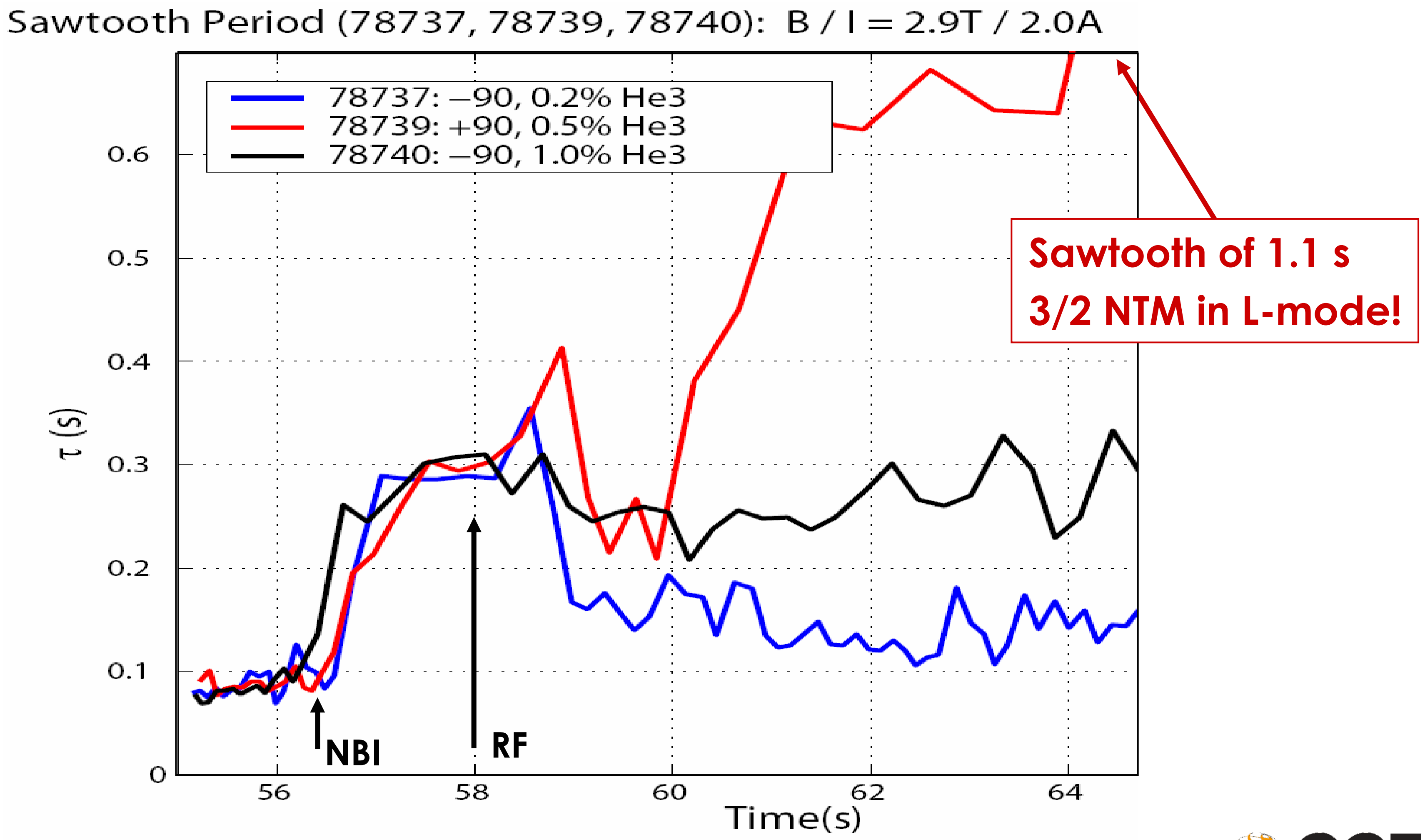
Period Control of Fast ion stabilised Sawteeth



[Graves et al, in prep PRL]

Sawtooth Control with ICRH in JET (and ITER?)

- Lower ^{3}He concentration → shorter τ_{saw} (high energy ions in distribution tail)
- Co-propagating waves are stabilising, counter-propagating are destabilising



[Graves et al, in prep PRL]

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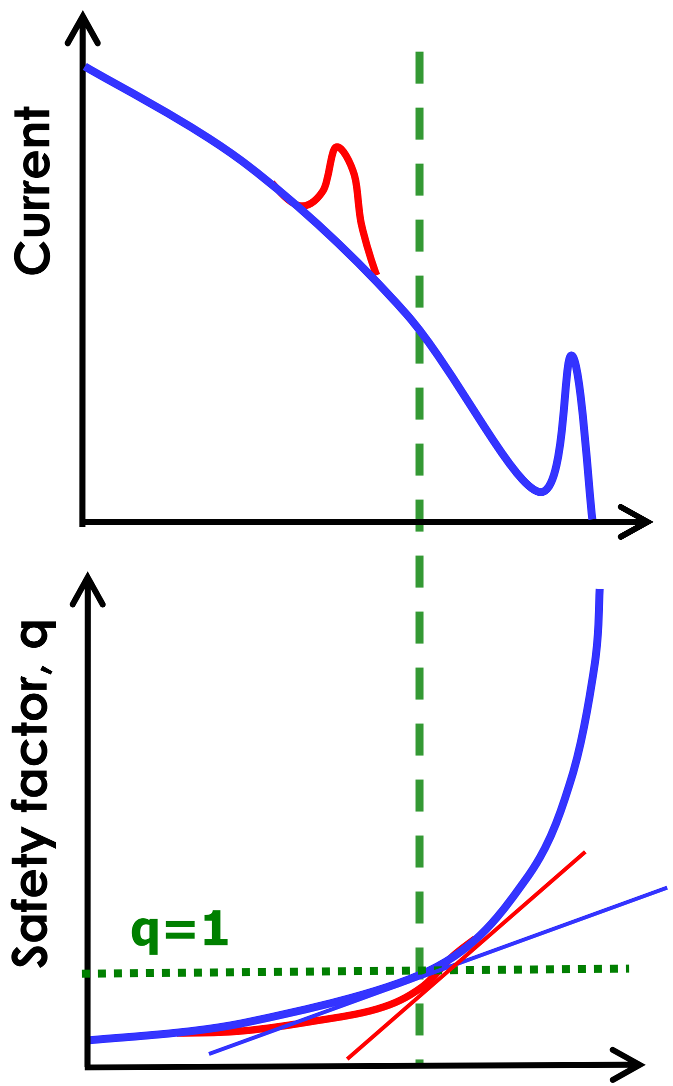
How does driving current trigger sawteeth?



- **Trigger condition:** $\pi \dfrac{\delta \hat{W}}{s_1} < c_\rho \dfrac{\rho}{r_1}$

A perturbation is applied to the initial current profile (inside q=1)

⇓

More current means more poloidal field, so q drops

⇓

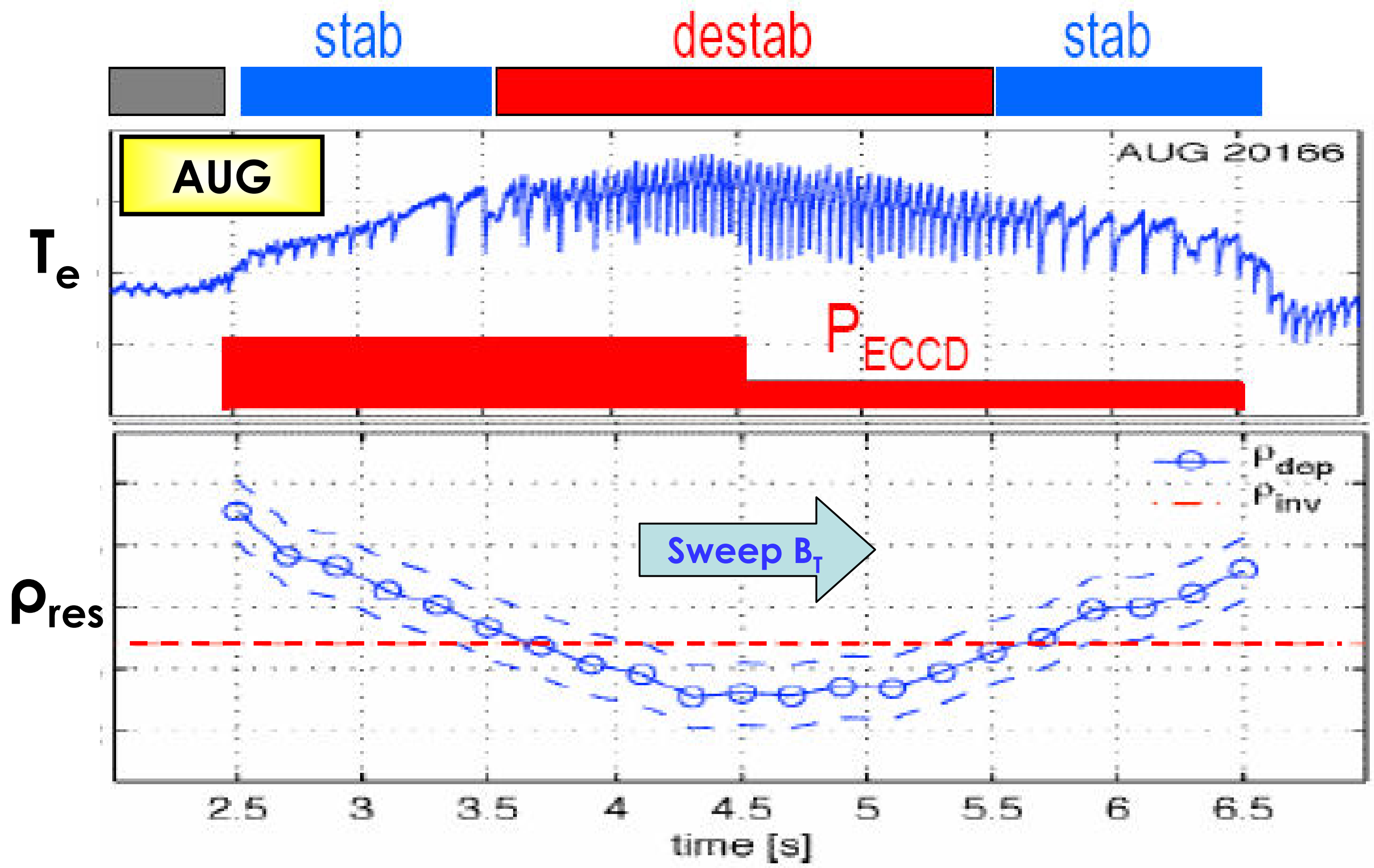
q=1 is moved outwards

⇓

Magnetic shear at q=1, s_1 (~gradient of q) increases

Current drive can shorten sawtooth periods

- **Current drive shown to destabilise sawteeth in ASDEX Upgrade, DIII-D, TEXTOR, JT-60U, TORE SUPRA, TCV, HL2A…**



Mück et al, Plasma Phys Cont Fus, ***47****, 2005*
Manini et al, 14th Joint Workshop on ECE and ECRH , Santorini, 2006

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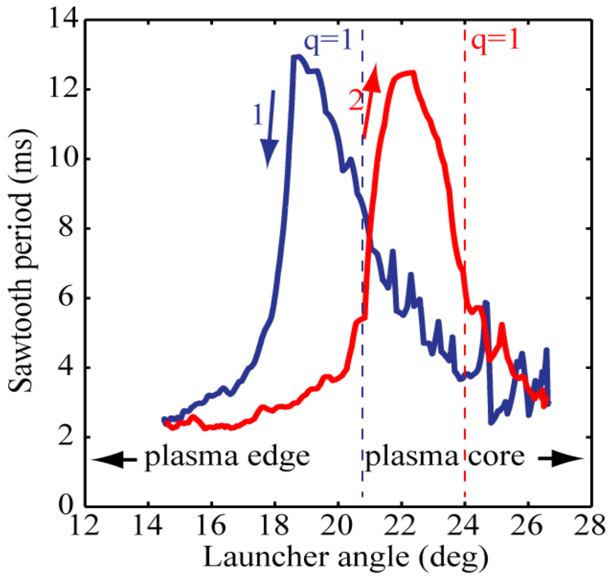
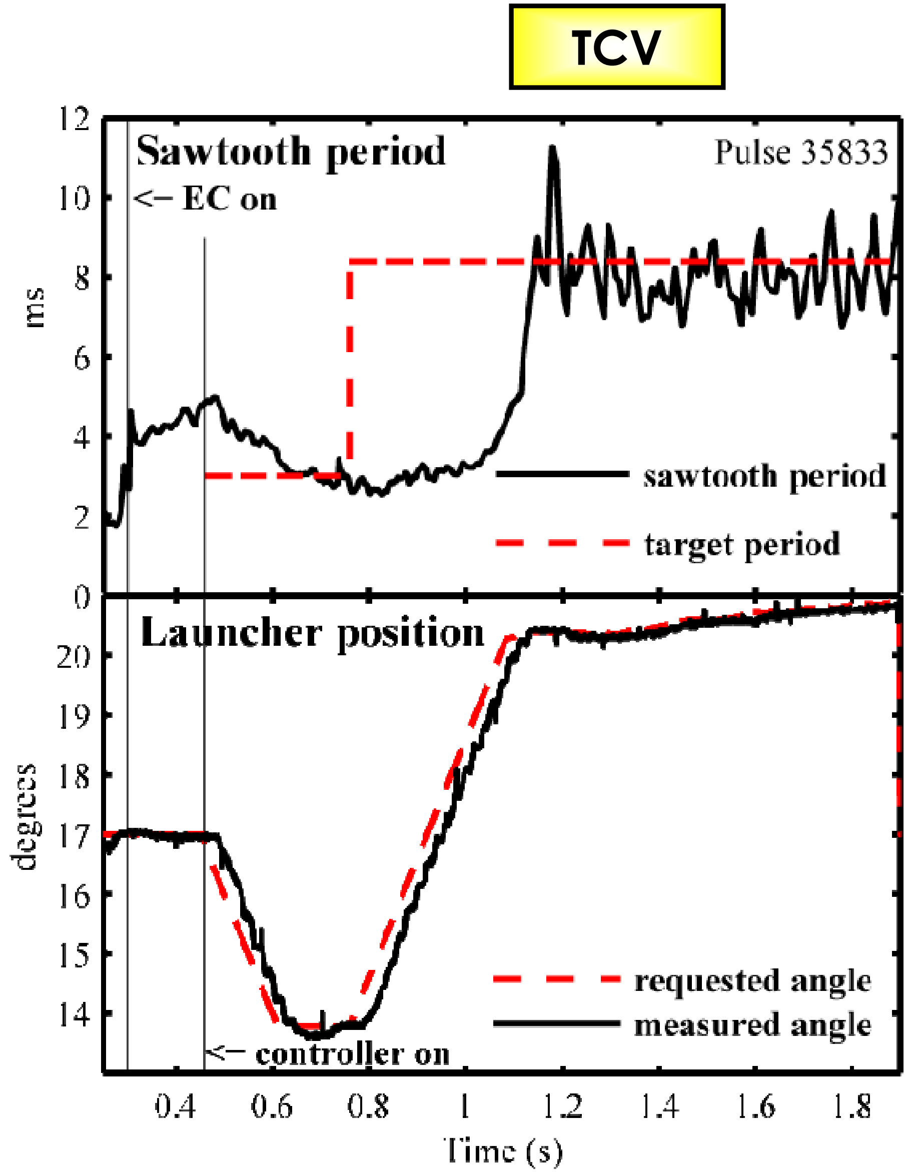
ECCD Real-time control in TCV

- Controller obtains and tracks target reference period by tailoring EC deposition to be just outside *q*=1
  - Launcher moved to larger angle to increase period, smaller angle to decrease
- Maximum period acquired and tracked despite changing plasma conditions

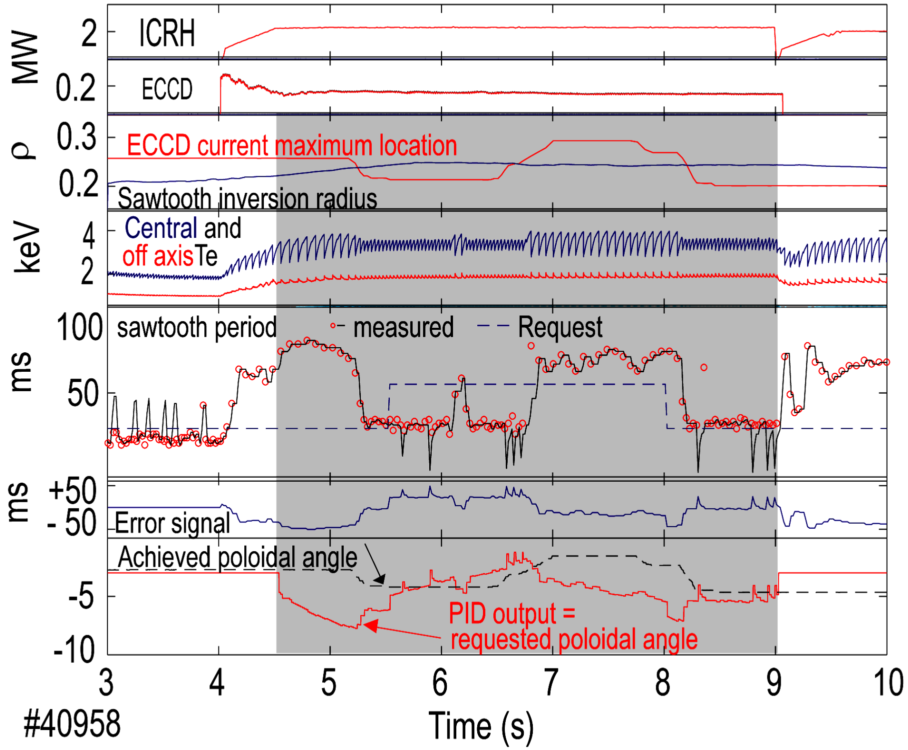




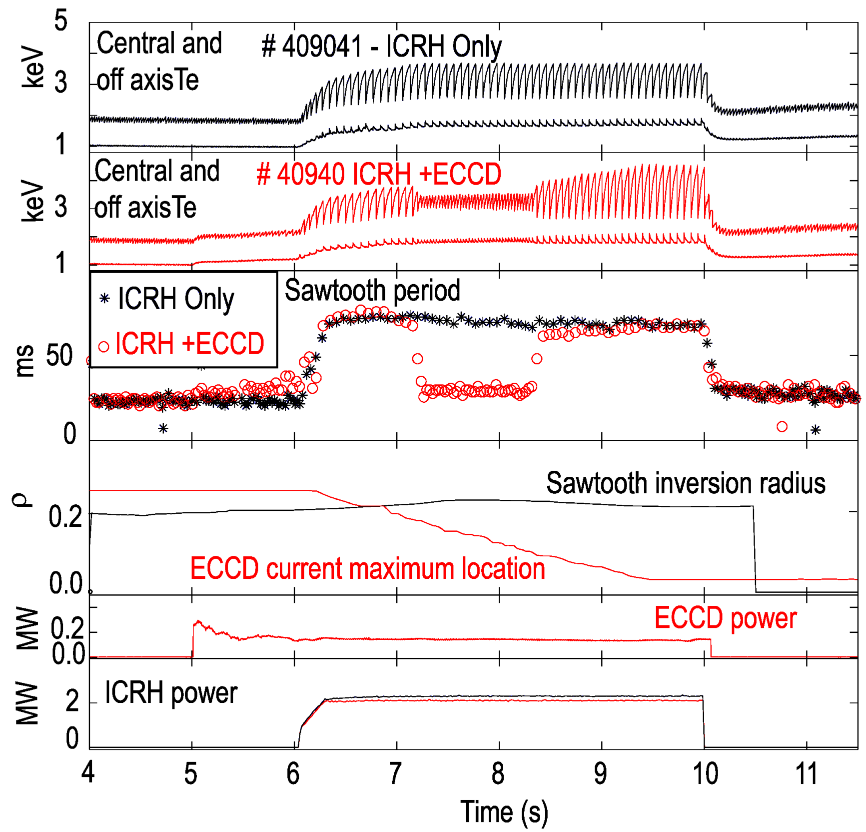
[J.I.Paley *et al.* PPCF 51 (2009) 055010]

ECCD control in TORE SUPRA with fast ions

- **Open loop – ICRH + scan ECCD**
  - 2MW ICRH: τ_{saw}=70ms (τ_{Ohm}=30ms)
  - Add 300kW ECCD: τ_{saw}=30ms
  - Abrupt change in period
    - Tentative explanation due to s_{crit} trigger dependence upon fast ions



[M Lennholm et al, PRL, **102** (2009)]



- **Progress with RT control**
  - Can maintain distance between sawtooth inversion radius and ECCD location using real time inversion radius measurement

Sawtooth Control

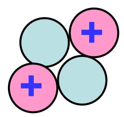
- **Motivation**
  - Sawteeth can trigger Neo-Classical Tearing Modes (NTMs)
  - Methods for Sawtooth Control
- **Developments in our understanding of sawtooth stability**
  - Co/Counter NBI Experiments on JET and MAST
  - Effect of passing ions and sheared flows
- **Sawtooth Control Using Off-axis Co-NBI**
  - Experiments on JET, MAST and ASDEX Upgrade
- **Sawtooth Control Using ICRH**
  - Explained by kinetic effects. Experiments on JET
- **Sawtooth Control Using ECCD**
  - Current drive effect. Experiments on AUG and Tore Supra
- **Sawtooth Control in ITER**

General Comments on Sawtooth Control in ITER

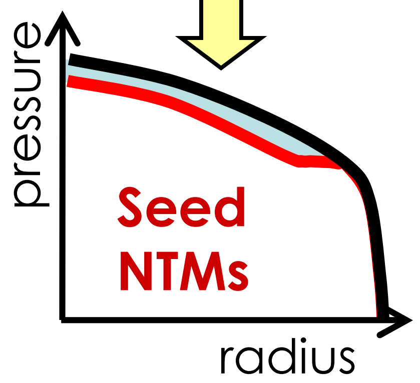
- **Triggering criteria for resistive *n*=1 kink** [Porcelli, PPCF, 1996]

$$\pi \frac{\delta \hat{W}}{s_1} < c_\rho \frac{\rho}{r_1}$$

In ITER, ρ will be small and r_1 will be large



Alpha particles will stabilise the internal kink, increasing τ_{saw}



Planned control via ECCD to increase local shear

Promising first results from TORE SUPRA [Lennholm et al, PRL 2009]

Passing ions from ICRH can destabilise sawteeth [Graves et al, PRL, 2009]

NB: He^3 minority ICRH in ITER will not drive sufficient current, but kinetic effects will help

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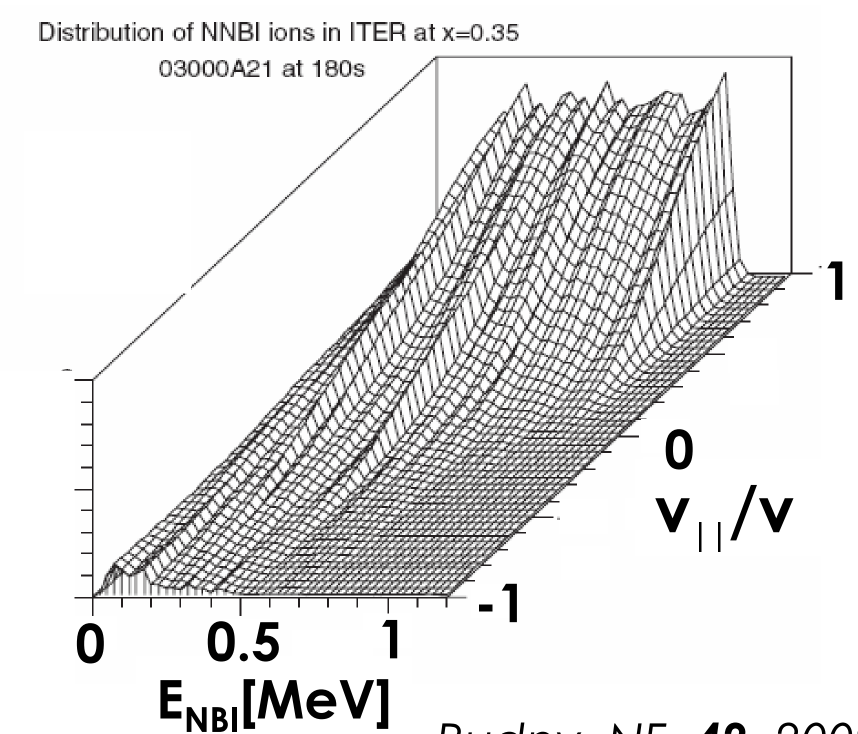
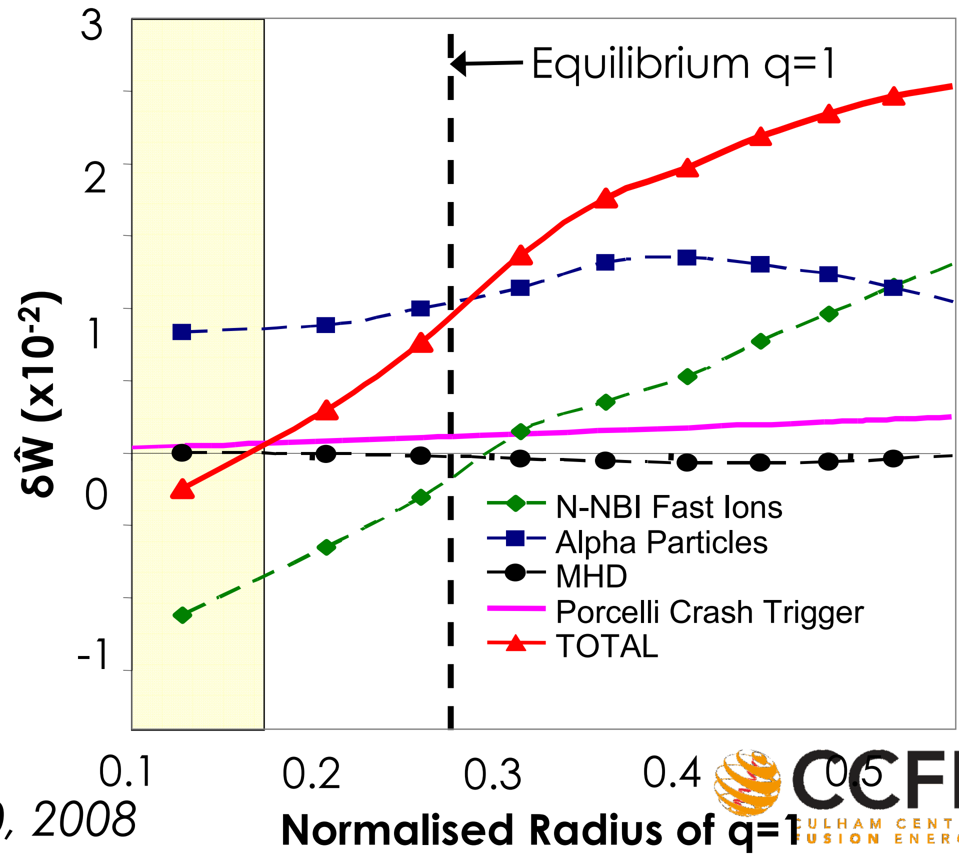
ITER Sawtooth Control with NBI

- **Sawtooth control even more important in ITER where the α particle population is likely to lead to long period sawteeth**
  – Could off-axis NNBI co-passing ions be used?
  – Passing NNBI ions significantly influence sawtooth stability
    - Only destabilising if q=1 is very core localised ($r_1/a < 0.2$)
    - With broad q=1 expected in Scenario 2, NNBI ions strongly stabilising!



*Budny, NF, **42**, 2002*
*Chapman, PPCF, **50**, 2008*



ITPA MHD Working Group

- **MHD Group has initiated high priority near-term ITER tasks**
  - WG3: Assessment of the power requirements for ECRH and ICRH for control of sawteeth (Chair: Ian Chapman)
- **Sawtooth control strongly influenced by fast ions**
  - Need accurate fast ion distribution function arising from ICRH (i) in the core for heating and (ii) near q = 1 for mode control
    - Early assessments made using SELFO code (T Johnson)
  - Need accurate fast ion distribution function arising from N-NBI in core
    - Early assessments made using TRANSP code (R Budny)
- **Sawtooth control achieved by changing magnetic shear at q=1**
  - Need assessment of local current drive at q = 1 achievable with ECCD
    - Some work using GRAY code (C Zucca, O Sauter)

The future for sawtooth control research

- **ECCD Control <u>in presence of fast ions</u>**
  - Need robust experimental verification that ECCD can destabilise sawteeth in the presence of fast ions (eg ICRH to represent α particles)
  - Initial assessment made on TORE SUPRA
    - Though still some unexplained behaviour
  - Also to be addressed on ASDEX Upgrade, DIII-D, KSTAR…
- **Will require real-time feedback in ITER (if ECCD control works)**
  - Some positive signs that real-time feedback can be achieved
  - Need to show robust *minimisation* of sawtooth period
  - Work continuing on TCV, AUG, TORE SUPRA, FTU…

Conclusions

- **Sawtooth Behaviour in different machines has been explained by a model including flow and kinetic effects**
  - **Local effects of passing fast ions found to be very important**
  - Flow shear can affect kink mode stability as well as trapped ion response

ON-AXIS NBI HEATING	FLUID EFFECTS	KINETIC EFFECTS
MAST	✓	
JET		✓
TEXTOR	✓	✓

SAWTOOTH CONTROL	INCREASE S_1	REDUCE δW_{hot}
ECCD	✓	
ICRH		✓
OFF-AXIS NBI	?	✓

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