Sawteeth and Fast Particle Control

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JET

Outline

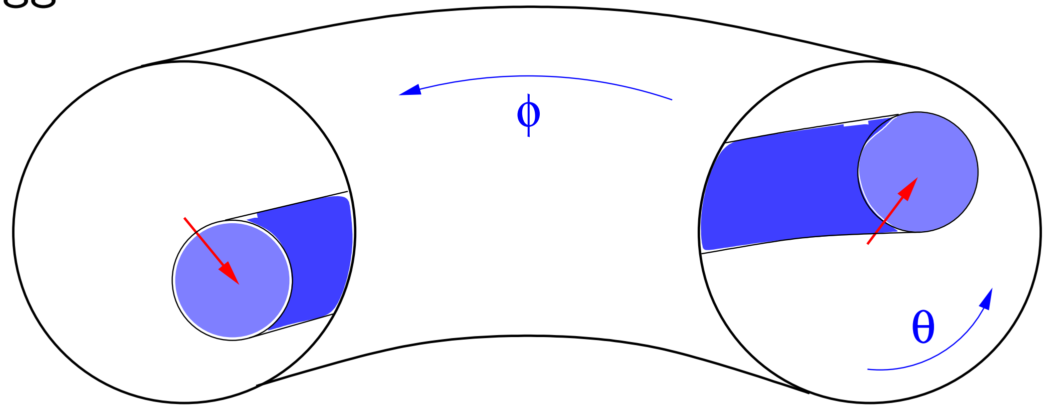
- Phenomenology of Sawteeth
- Sawtooth seeding of NTMs.
- Sawtooth model - critical dependence on magnetic shear.
- ECRH simulations and experiments in TCV.
- ICRH and ICCD in JET.
- Counter-NBI and toroidal rotation in JET.
- Negative ion based NBI in JT-60U.
- Conclusions.

The Sawtooth Instability

Sawtooth cycle divided into three phases:

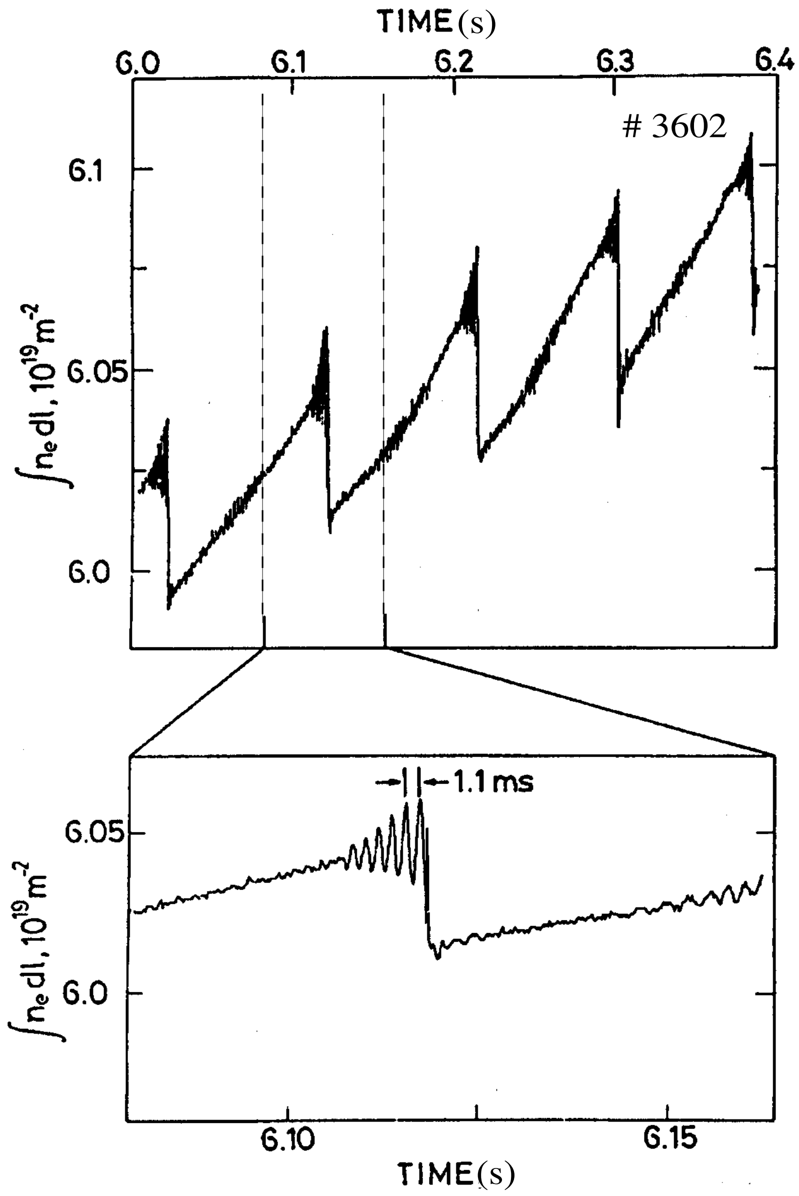
(i) Sawtooth ramp: density, temperature and current density increase in the core.

(ii) Precursor phase: macroscopic instability triggered.



Tilt and shift plasma displacement ~exp(iθ −iφ −iωt)

(iii) Collapse phase: density, temperature and current return rapidly to smaller values.



Sawtooth Seeding of NTMs

NTMs are triggered by sawteeth even though β_N small.

Successive sawteeth excite seed islands as shown here in MAST.

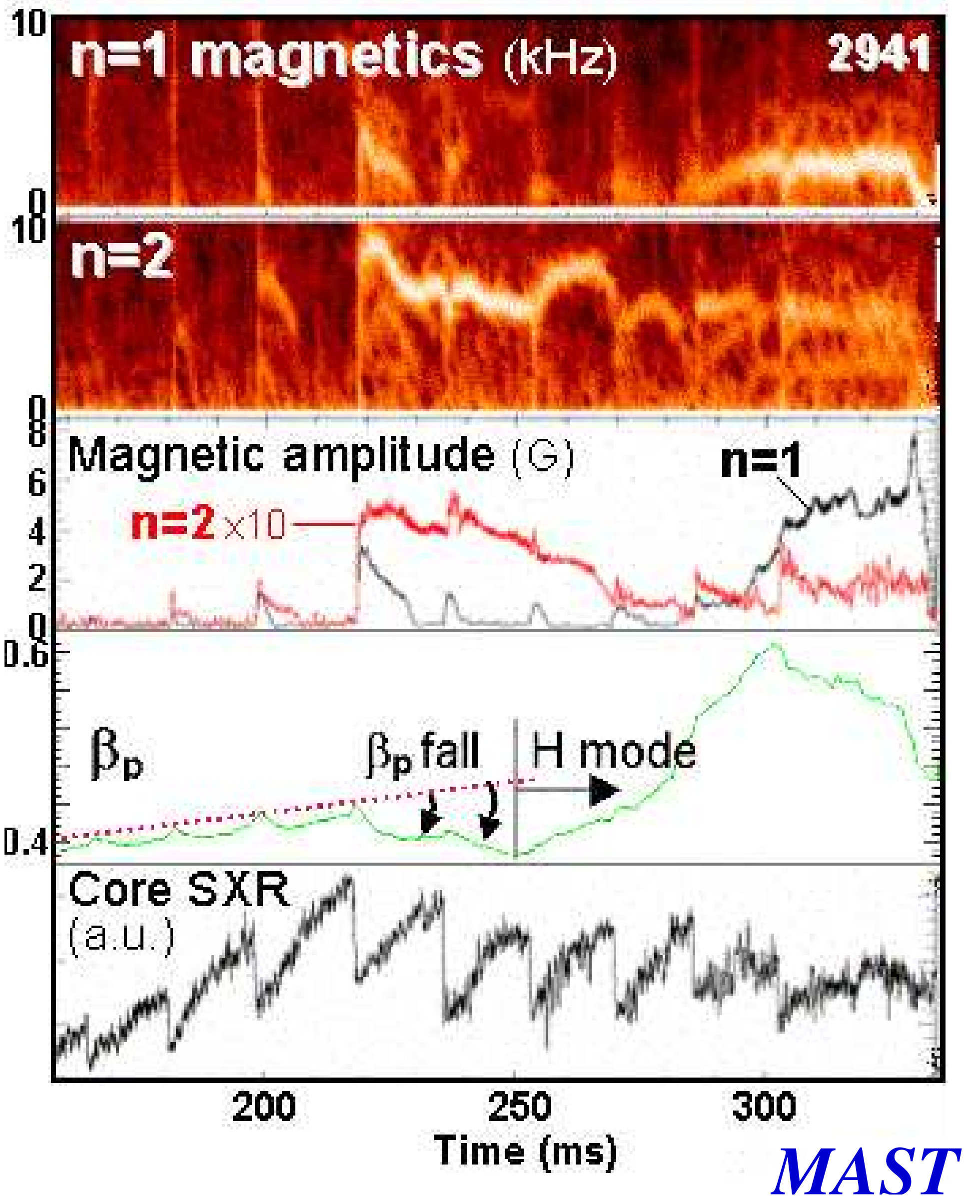
NTMs expected to limit performance of ITER.

- ▷ Optimise auxiliary heating schemes to:

  (i) produce high performance plasmas.

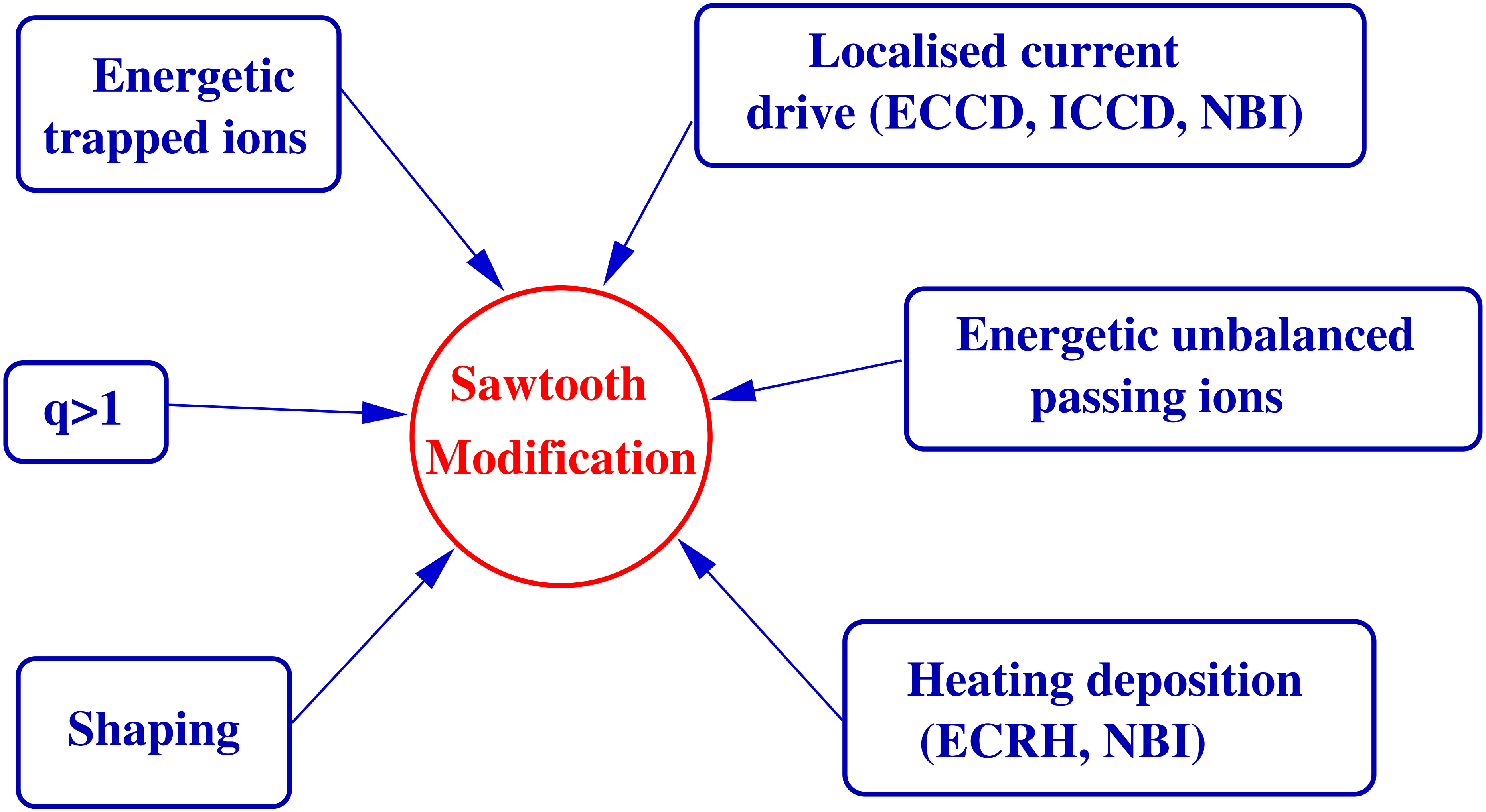
  (ii) control NTMs.

  (iii) control sawteeth.



R. J. Buttery, Phys Rev Lett 88, 125005 (2002)

Control of Sawteeth



Energetic trapped ions

Localised current drive (ECCD, ICCD, NBI)

q>1

Sawtooth Modification

Energetic unbalanced passing ions

Shaping

Heating deposition (ECRH, NBI)

Sawtooth Trigger - Dependence on s_1

The trigger mechanism depends on the regime [F. Porcelli *et al* PPCF 38, 2163 (1996)]:

In a plasma without energetic minority ions, with high κ, small δ, the ideal instability threshold is relevant:

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

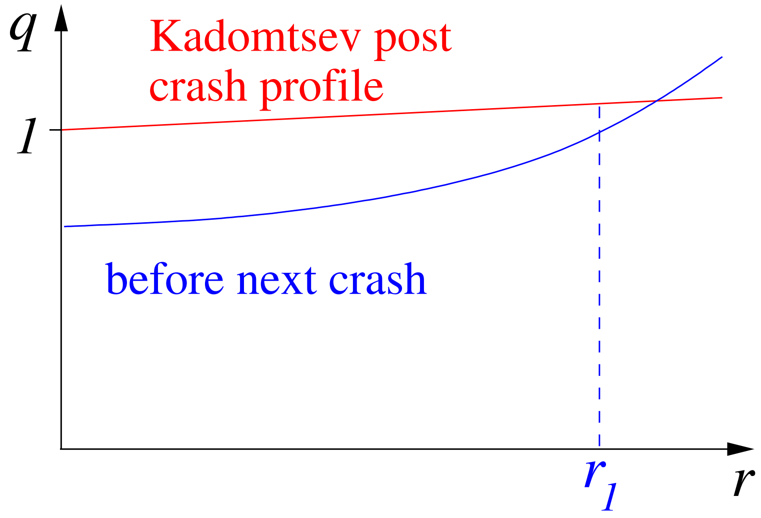
Most relevant for auxiliary heated discharges is linear resistive two fluid [L. Zakharov *et al* Phys. Fluids B 5, 2498 (1993)] and [F. Porcelli *et al* PPCF 38, 2163 (1996)]:

$$\pi\frac{\delta\hat{W}}{s_1} < \hat{\rho} \ \ \text{and} \ \ \gamma_\eta > c_\eta(\omega_{*i}\omega_{*e})^{1/2}$$

This latter threshold for instability can be written as a criterion in the shear at $q = 1$:

$$s_1 > \text{max}\left\{ s_c = \pi\frac{\delta\hat{W}}{\hat{\rho}} \ , \ s_c(\omega_*) \right\}$$

Sawtooth Control: Modifying resistive diffusion



Sawtooth period partially governed by evolution of magnetic shear at $q = 1$:

$$s = \frac{r}{q}\frac{\partial q}{\partial r}.$$

Low dimensional transport codes use MHD equations:

$$\frac{\partial B_\theta}{\partial t} \approx \frac{\partial E_\phi}{\partial r} \quad , \quad E_\phi \approx \eta j_{Ohm} \quad \text{and} \quad \mu_0(j_{Ohm} + j_{cd}) \approx \frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)$$

The resulting equation for $B_\theta(r,t)$ can be written in terms of rate of change of the shear following a crash:

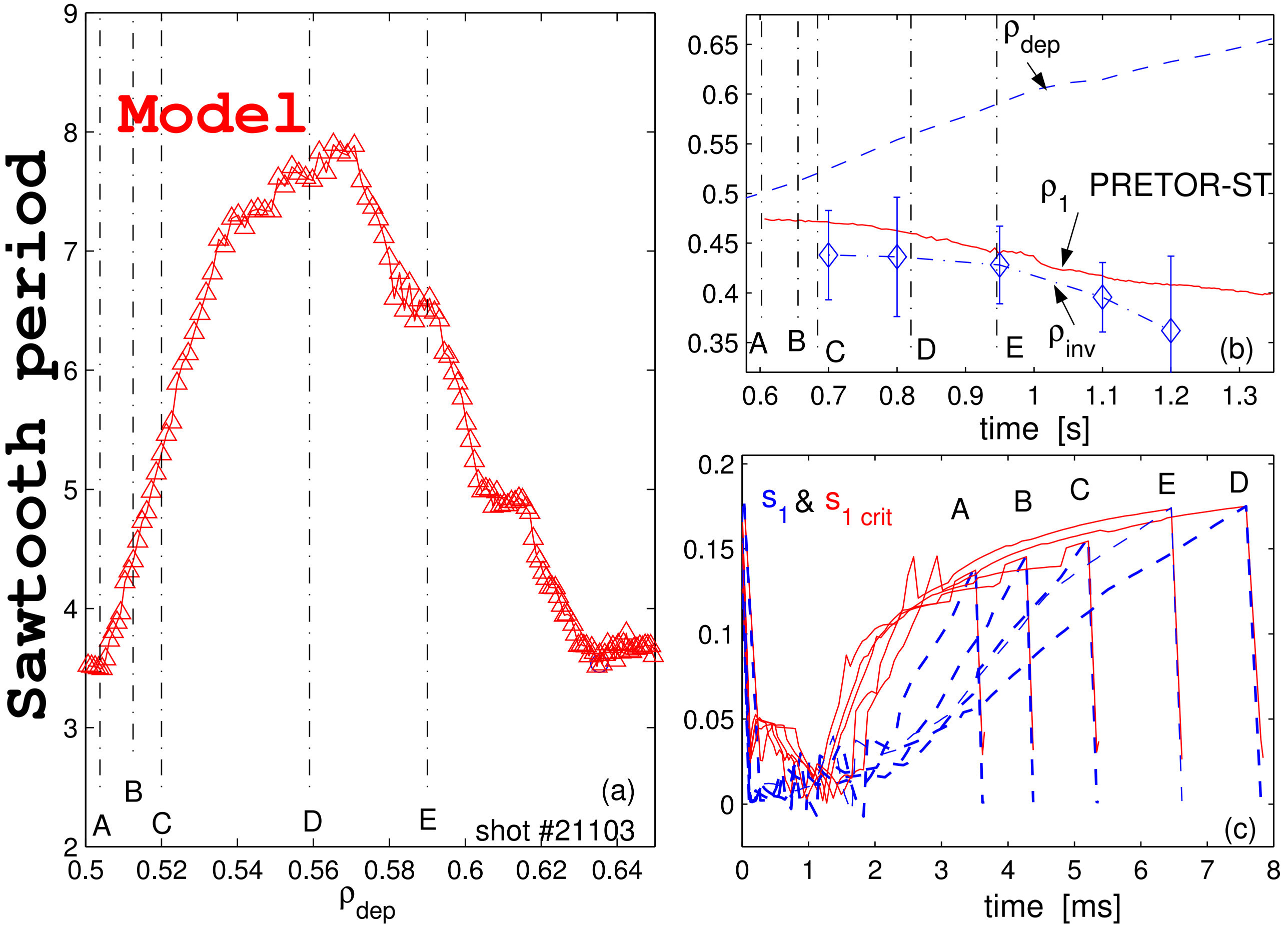
$$\frac{\partial s}{\partial t} = \frac{1}{\mu_0 r}\left[1 - r\frac{\partial}{\partial r}\right]\left[(2-s)\eta' - (s - s^2 + rs')\frac{\eta}{r}\right] - \frac{qR_0}{rB_0}[(1-s)(\eta j_{cd})' - r(\eta j_{cd})'']$$

Control sawtooth period by adjusting $\eta \propto T_e^{-3/2}$ and j_{cd} profiles on rational surface.

Localised ECRH IN TCV

Flexible ECRH set-up in TCV permits accurate investigation into most stabilising heating location.

- ds_1/dt modified by moving resonance location.
- $s_1 > s_c(\beta)$ controls trigger.
- PRETOR-ST simulates sawtooth cycle.
- s_1 evolves most slowly towards almost saturated $s_c(\beta)$ at the optimum location (D).



C. Angioni, NF 43, 455 (2003).

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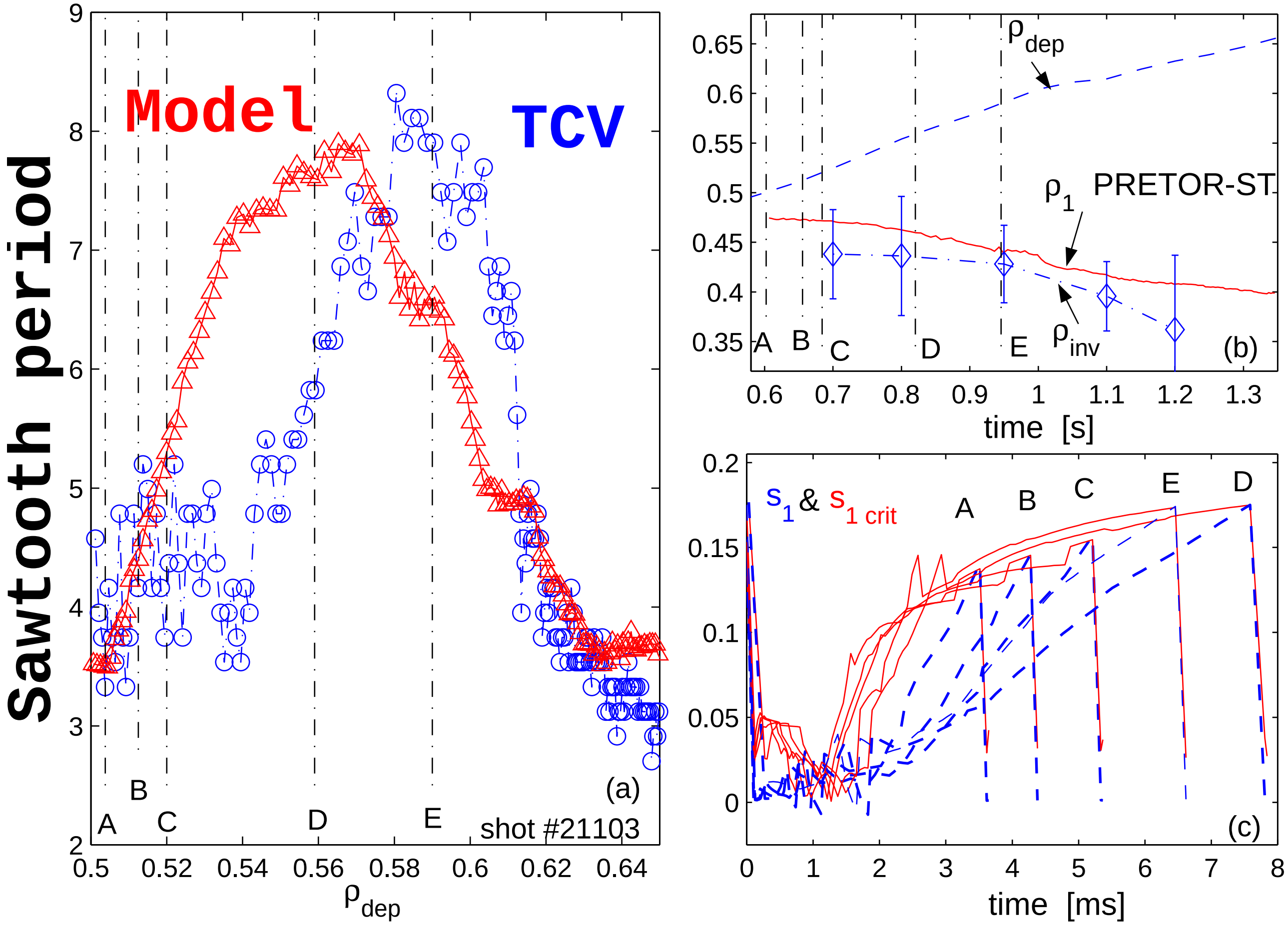


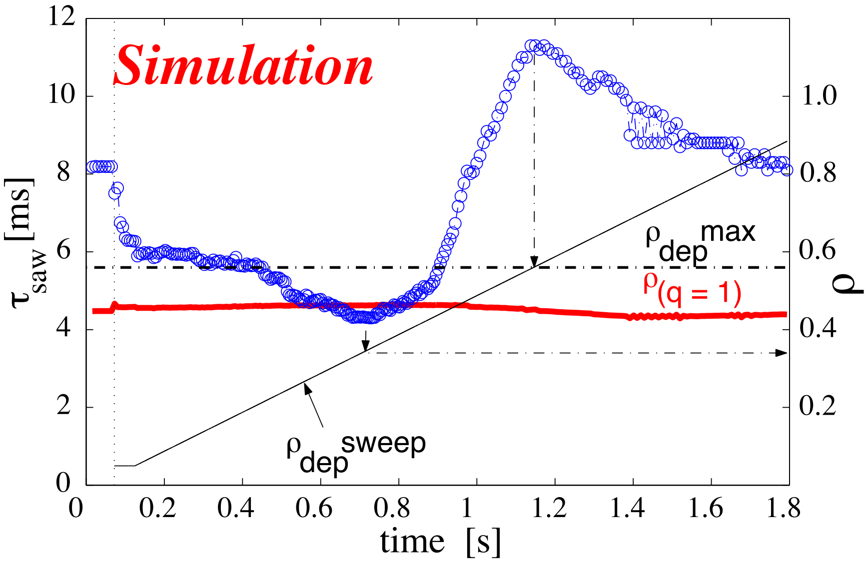
C. Angioni, NF 43, 455 (2003).

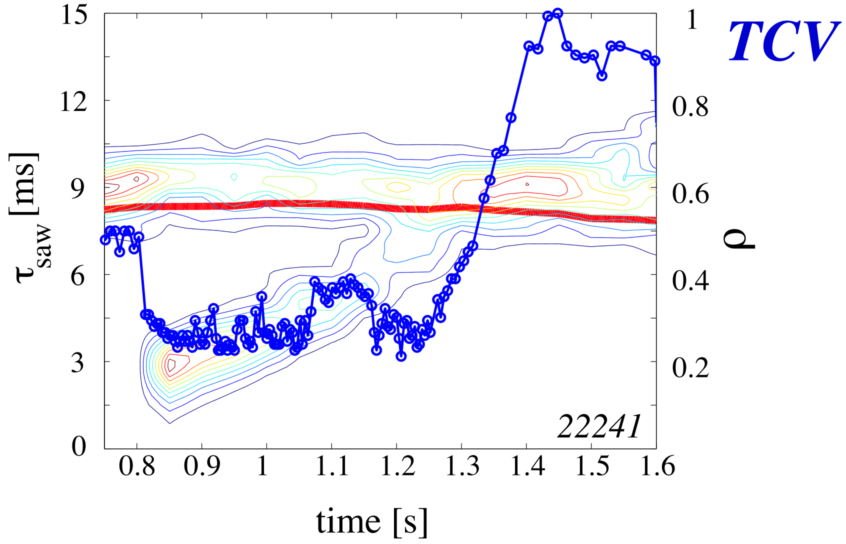
Sawtooth Destabilisation with ECRH

- PRETOR-ST predicts optimum location for sawtooth destabilisation.

- Initial ECH beams stabilise sawteeth.

- Another ECH beam swept through $q = 1$.
  - heating inside $q = 1$ significantly reduces τ_{saw}.
  - sensitive stability transition around $q = 1$.



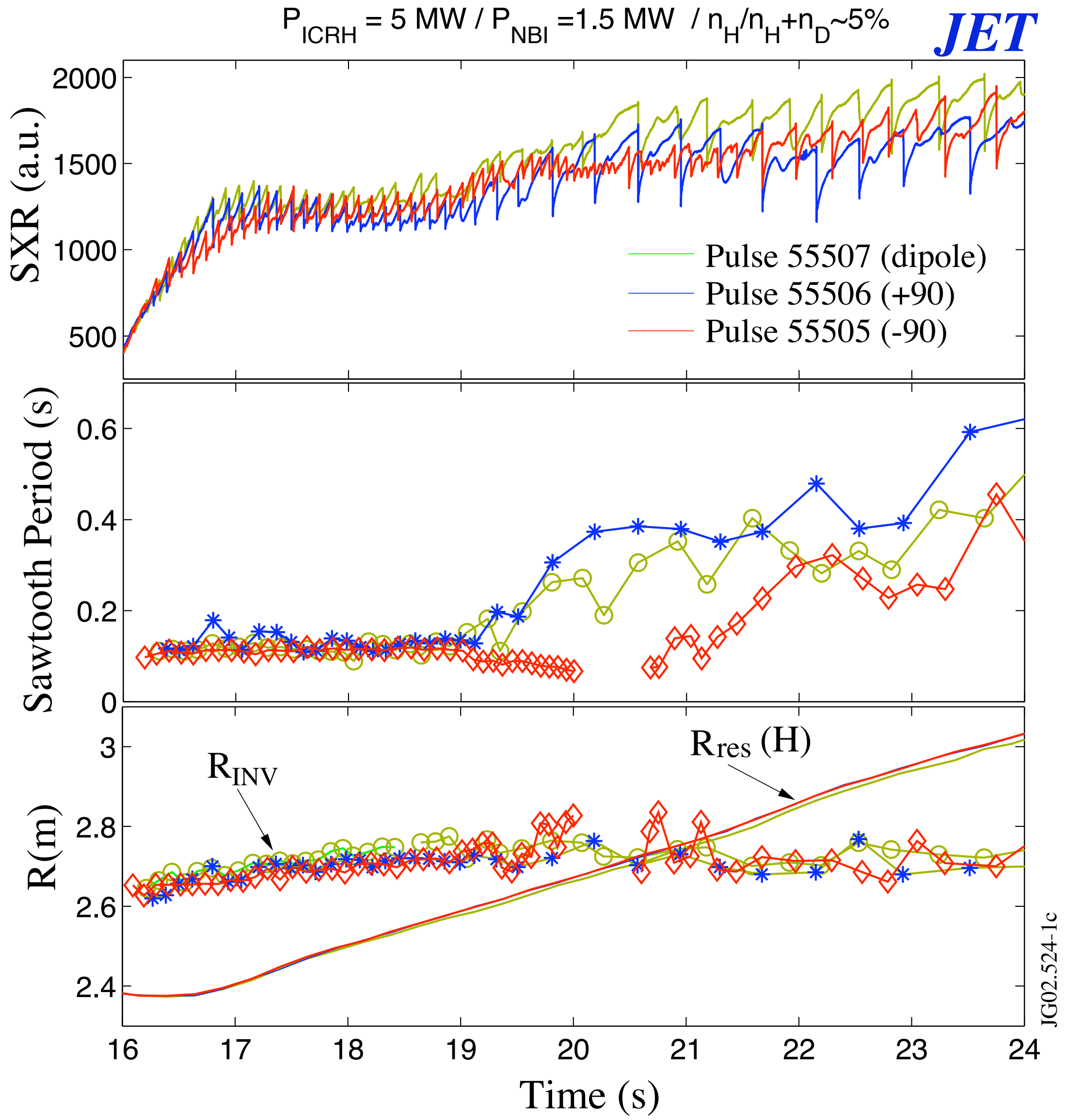


C. Angioni, NF 43, 455 (2003).

Fundamental Harmonic ICRH/ICCD in JET

B and ramp of D(H) ICRH on HFS

- Current drive perturbations from different antenna phasings.
- $+90^\circ$ stabilises sawteeth as $R_{\text{res}} \rightarrow R_{INV}$.
- -90° destabilises sawteeth as $R_{\text{res}} \rightarrow R_{INV}$.
- All stabilised by kinetic effects as R_{res} approaches centre.
- Similar results seen with ITER-relevant second harmonic [M. Mantsinen, PPCF 44, 1521 (2002)].



M.-L. Mayoral: PoP 11, 2607 (2004)

Control of Fast Ion Stabilised Sawteeth

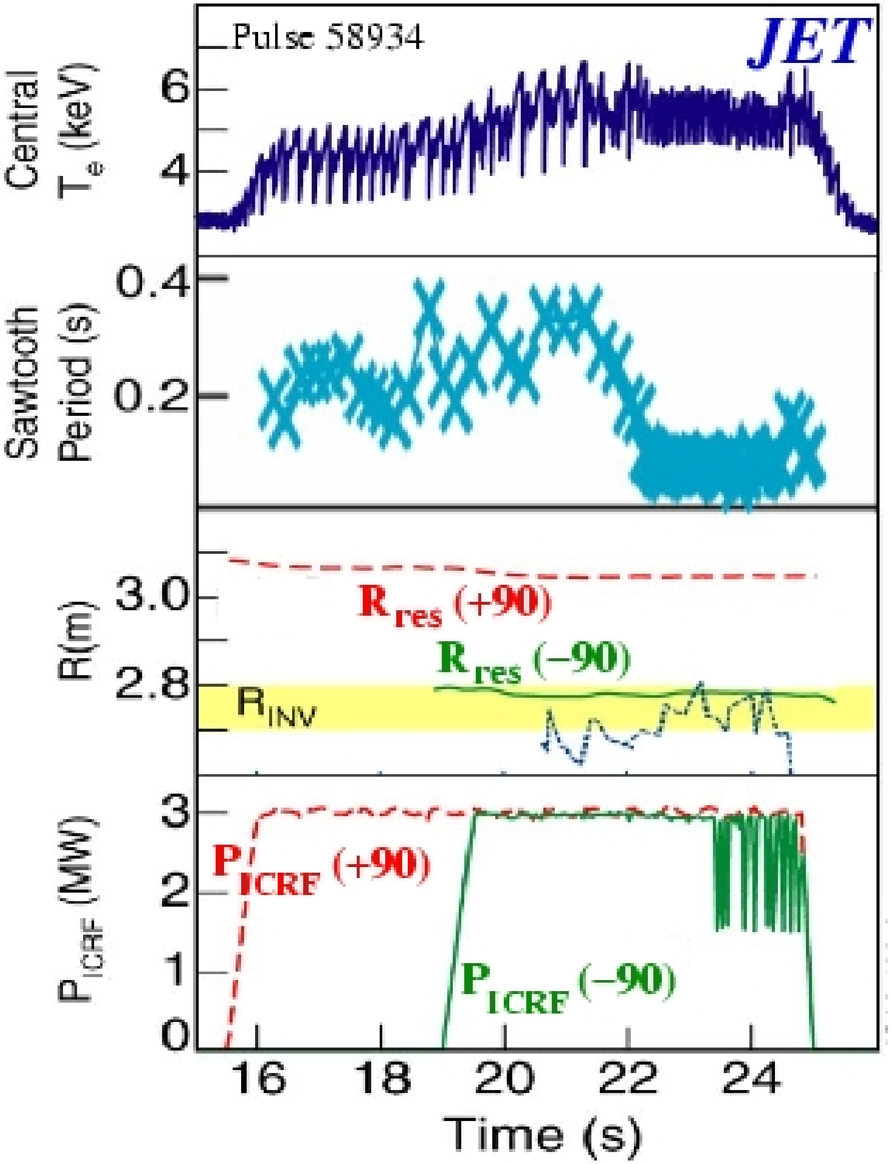
- ICRH $+90^\circ$ pinches trapped fast ions towards magnetic axis. This creates large stabilising energy sink δW_h.

- A second antenna with -90° used to heat same species (H) but with resonance location near $q = 1$.

- The localised current drive enhances local resistive diffusion. Hence shortening sawteeth.

- It is hoped Localised current drive could compensate stabilising role of alpha's in ITER.

- Detailed modelling of combined fast ion stabilisation and current drive is required.

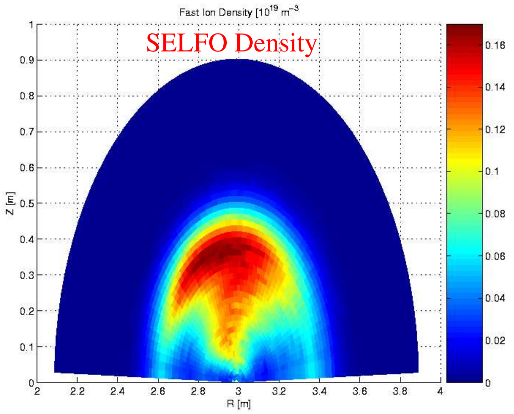


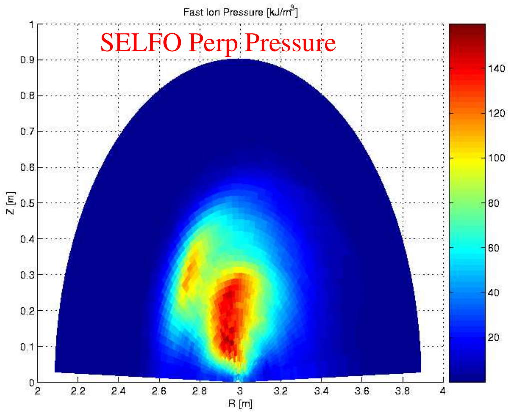
L.-G. Eriksson: PRL 92, 235004 (2004)

Modelling ICRH

Modelling the Distribution Function

3D Fokker Planck solutions from SELFO [J. Hedin, *et al*, Nucl. Fusion 42, 527 (2002)] provide the distribution function of two ICRH populations of JET discharge 58934.





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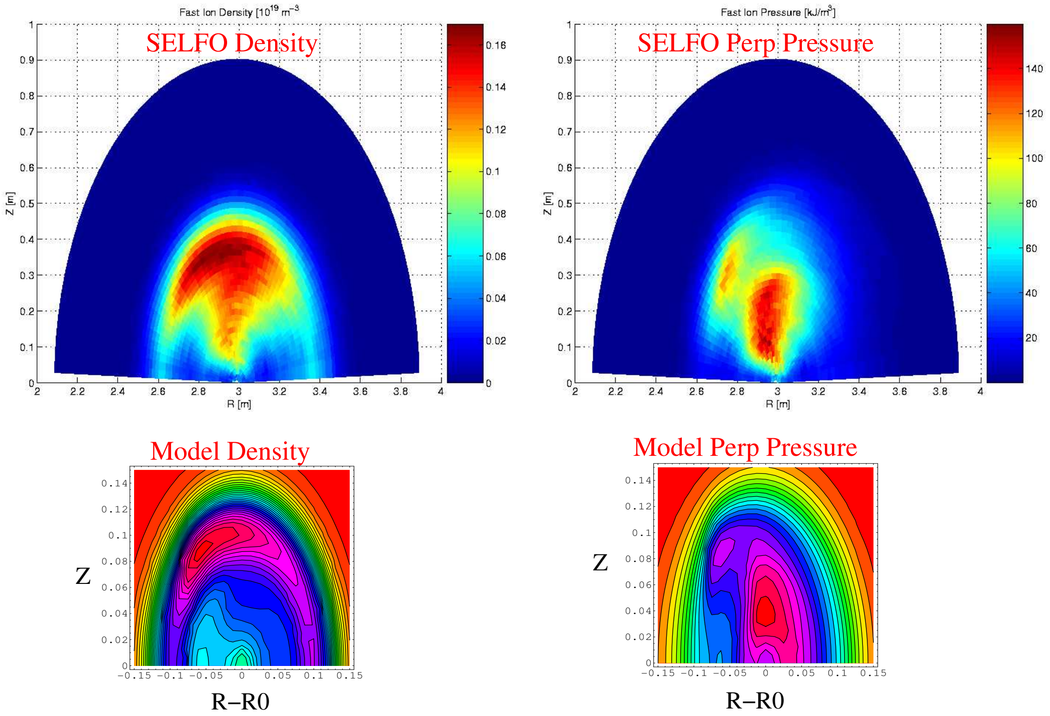
The distribution is written in terms of a bi-Maxwellian in $v_{\|}$ and $v_{\perp}$ [W.A. Cooper, J P Graves *et al* Nucl. Fusion 46, 683 (2006)].

This model distribution permits analytical evaluation of its moments in terms of local magnetic field B:



J P Graves, *et al* Varenna Proceedings 2006

$$F=\left(\frac{m}{2\pi}\right)^{3/2}\frac{n_c(r)}{T_{\perp}(r)T_{\|}^{1/2}(r)}\exp\left[-\frac{\mu B_c}{T_{\perp}(r)}-\frac{|\mathcal{E}-\mu B_c|}{T_{\|}(r)}\right].$$

Kinetic and Fluid anisotropic contributions to δW are analytically tractable.

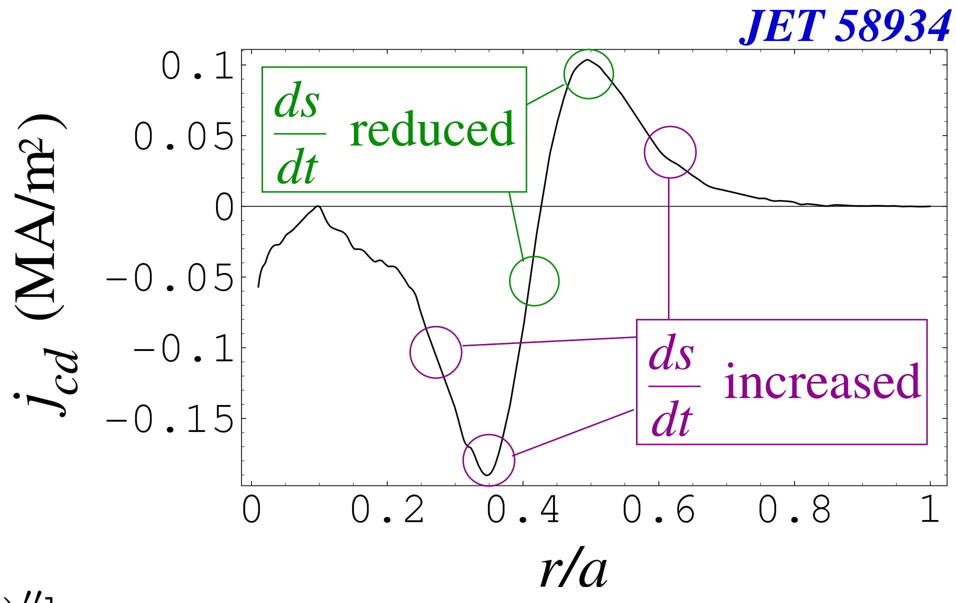
Modelling ICCD

Modelling the Current Drive

The current drive profile is again taken from SELFO simulations [L.-G. Eriksson, NF, 5951 (2006).]

Evolving shear modelled assuming initial q profile was fully reconnected inside r_1:

$$\frac{\partial s}{\partial t} = \left.\frac{\partial s}{\partial t}\right|_{\text{no } j_{cd}} - \frac{qR_0}{rB_0}[(1-s)(\eta j_{cd})' - r(\eta j_{cd})''].$$



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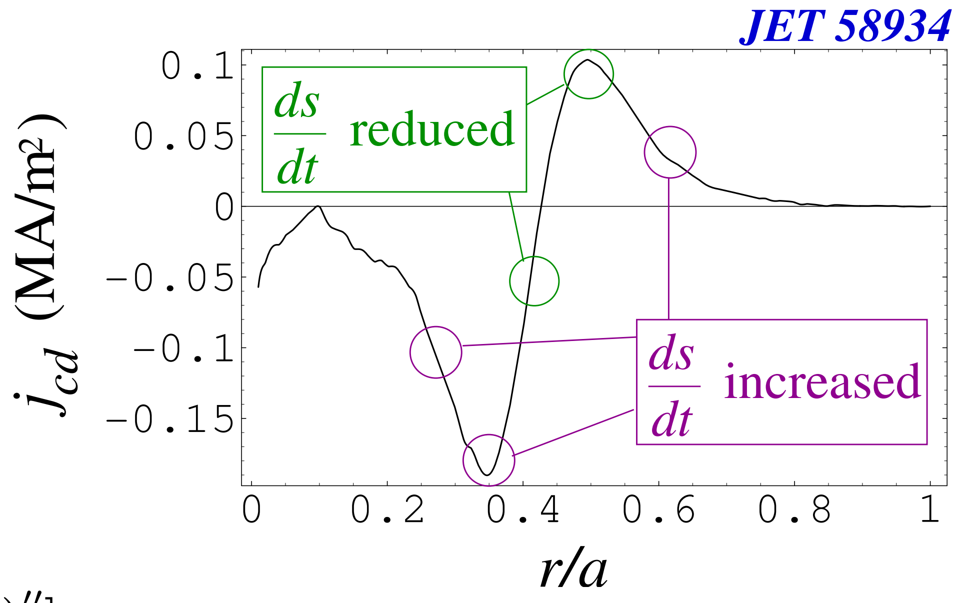
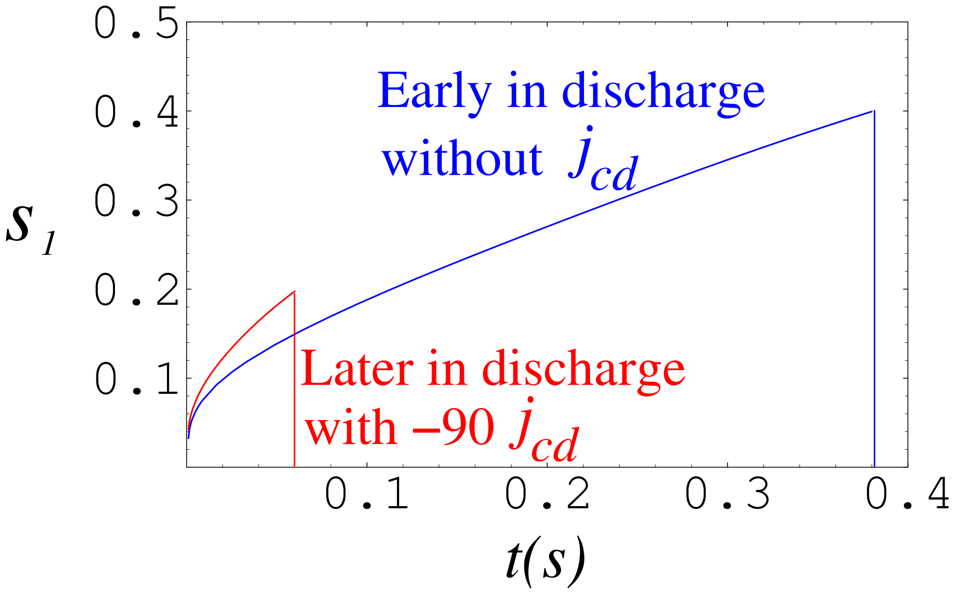
For early part of discharge (without -90 ICCD) the critical shear is given by $s_c = \pi\delta\hat{W}/\hat{\rho}$.

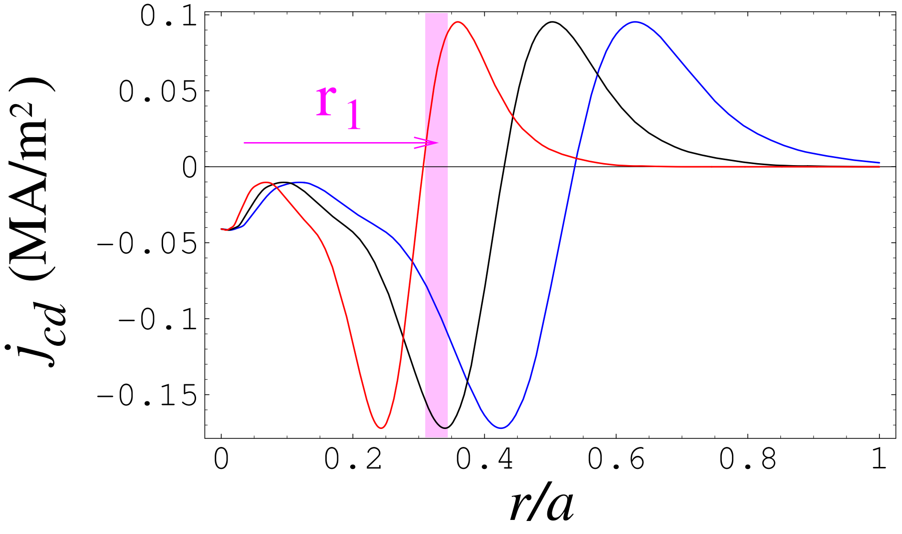
In later part of discharge, -90 population diminishes $\delta\hat{W}$. Thus critical shear given by $s_c(\omega_*) \approx 0.2$.





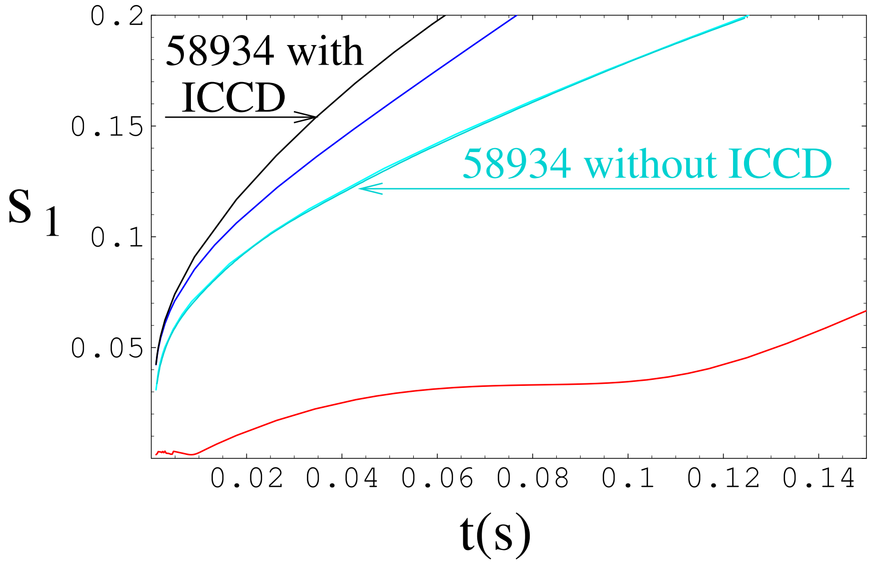
Effect of ICCD localisation

Effect of moving resonance location r_c



As seen, ds_1/dt controlled by first and second derivatives in j_{cd}:

$$\frac{\partial s}{\partial t} = \left.\frac{\partial s}{\partial t}\right|_{\text{no } j_{cd}} - \frac{qR_0}{rB_0}[(1-s)(\eta j_{cd})' - r(\eta j_{cd})'']$$



This means that as resonance location is moved inside r_1, the rate of change of s_1 is reduced markedly.

This feature is partially responsible for the transition from very short to long sawteeth.

Combined ICRH and ICCD localisation

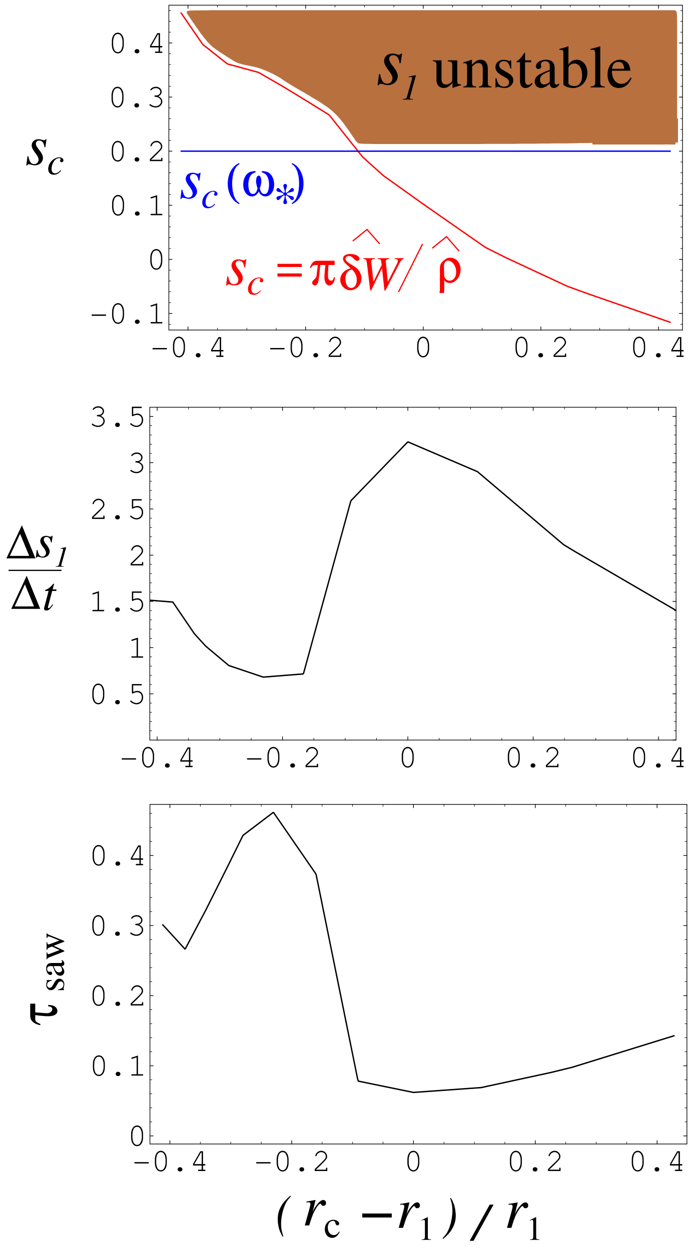
Effect of moving resonance location r_c

Calculations suggest that in JET discharge 58934, the -90 off-axis population almost cancels the kinetic stabilising contribution δW from the co-existing on-axis $+90$ ion population.

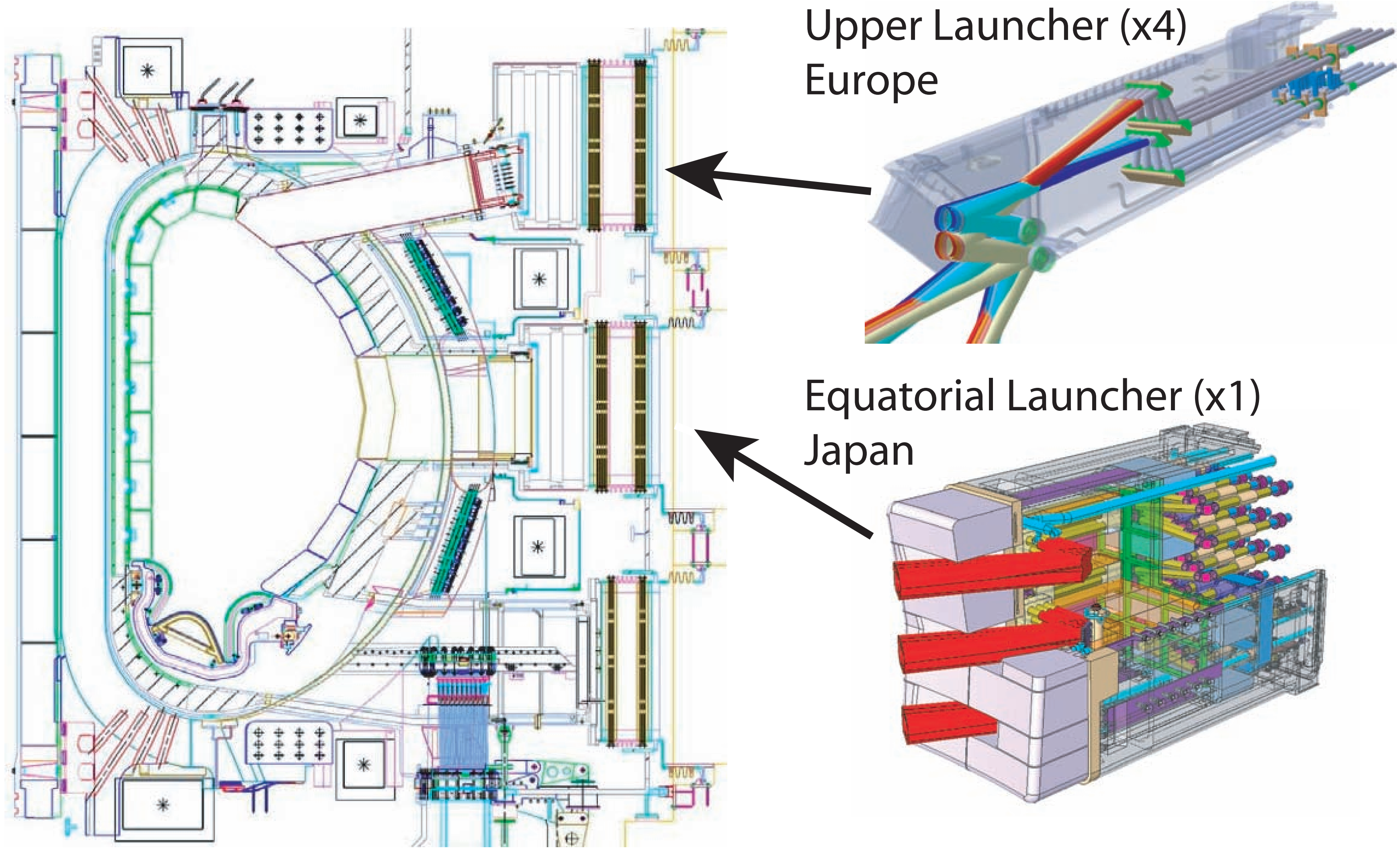
Nevertheless, to be sure of this, very accurate knowledge of F_h, j_{cd} and r_1 is required.

- ▷ If the resonance location r_c is moved inside r_1, the -90 fast ion population provides a stabilising contribution to δW.

An important question may remain: Can localised current drive destabilise sawteeth effectively where there is significant fast ion stabilisation? .



ITER EC Launchers

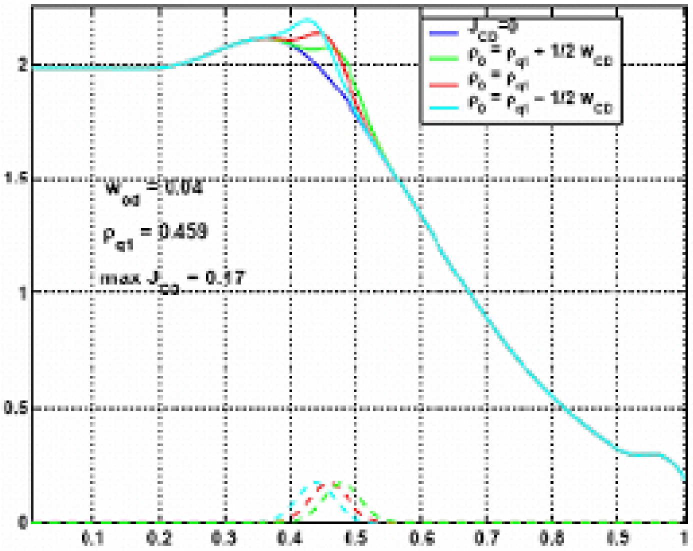


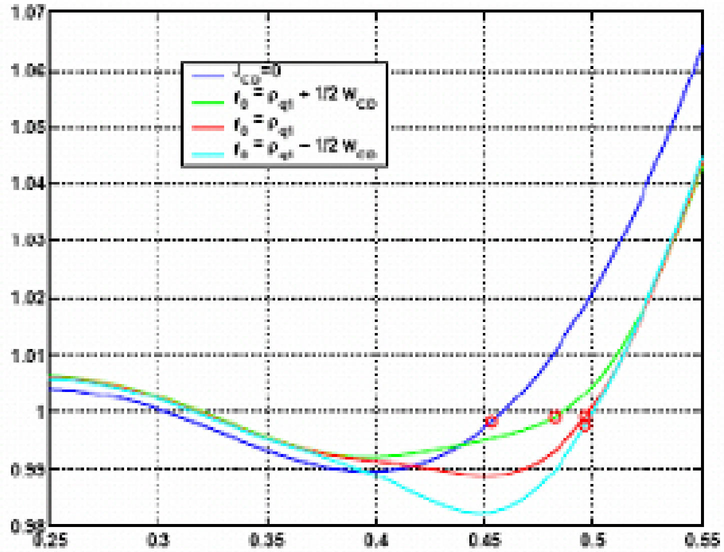
Upper Launcher (x4)
Europe

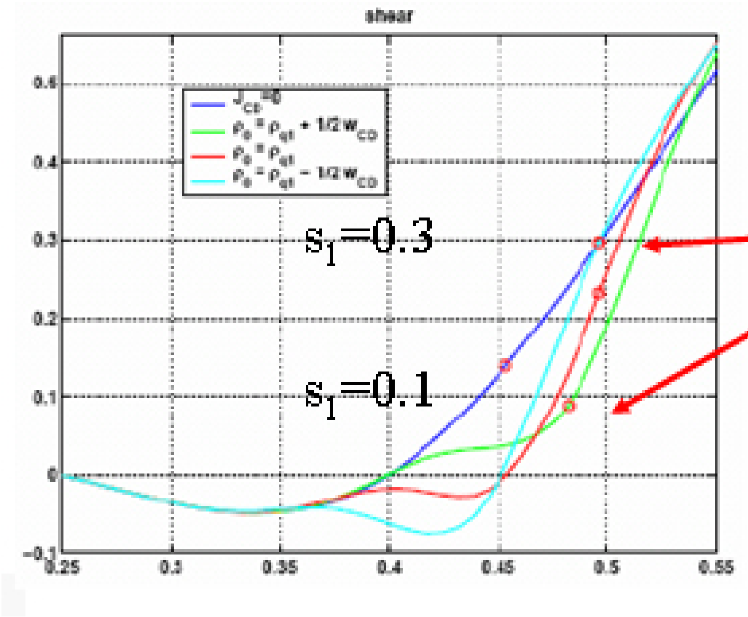
Equatorial Launcher (x1)
Japan

M. Henderson et al

Shear Control using Upper Launcher





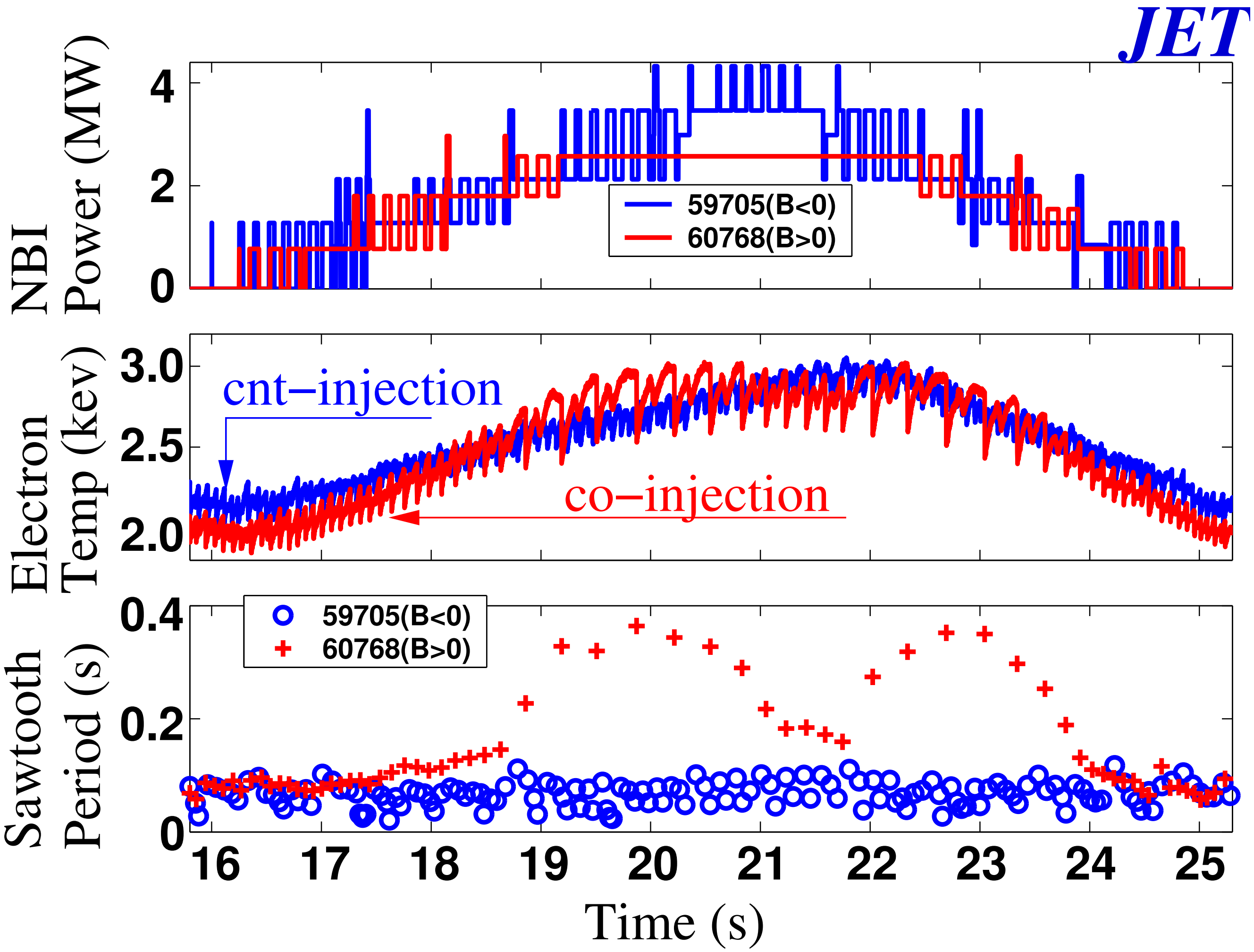


Adding 120kA to hybrid scenario allows changing s_1 by factor 3

Thus can stabilise sawteeth with $s_1<0.2$, or at least significantly delay 1st sawtooth in hybrid?

Courtesy O. Sauter, C. Zucca, M. Henderson et al

Counter NBI in JET



J. P. Graves, S. Coda, H. R. Koslowski, M. M. F. Nave *et al*, PPCF 47, B121 (2005)

M. M. F. Nave *et al*, POP 13, 014503 (2006)

- Otherwise similar co- and cntr-NBI ramping discharges are compared.
- Toroidal rotation has changed direction relative to I and B.

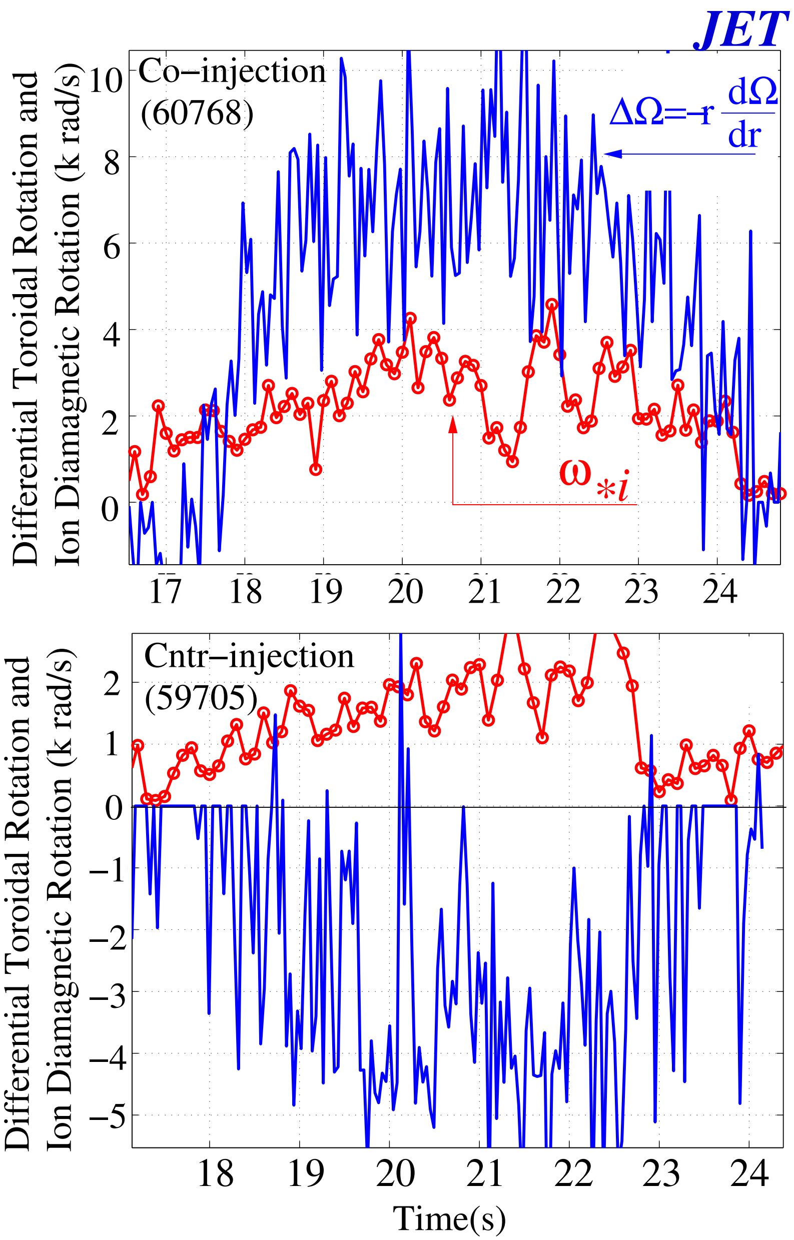
Sheared Toroidal Rotation

- Plasma rotation Ω up to $12\,\mathrm{krad/s}$ for cntr-NBI.

- Differential flow of the order of the ion diamagnetic frequency:

$$\Delta\Omega \equiv -\,r\frac{d\Omega}{dr}\bigg|_{r_1} \approx \pm 2\omega_{*pi}(r_1)$$

- Such small flows do not modify MHD stability.

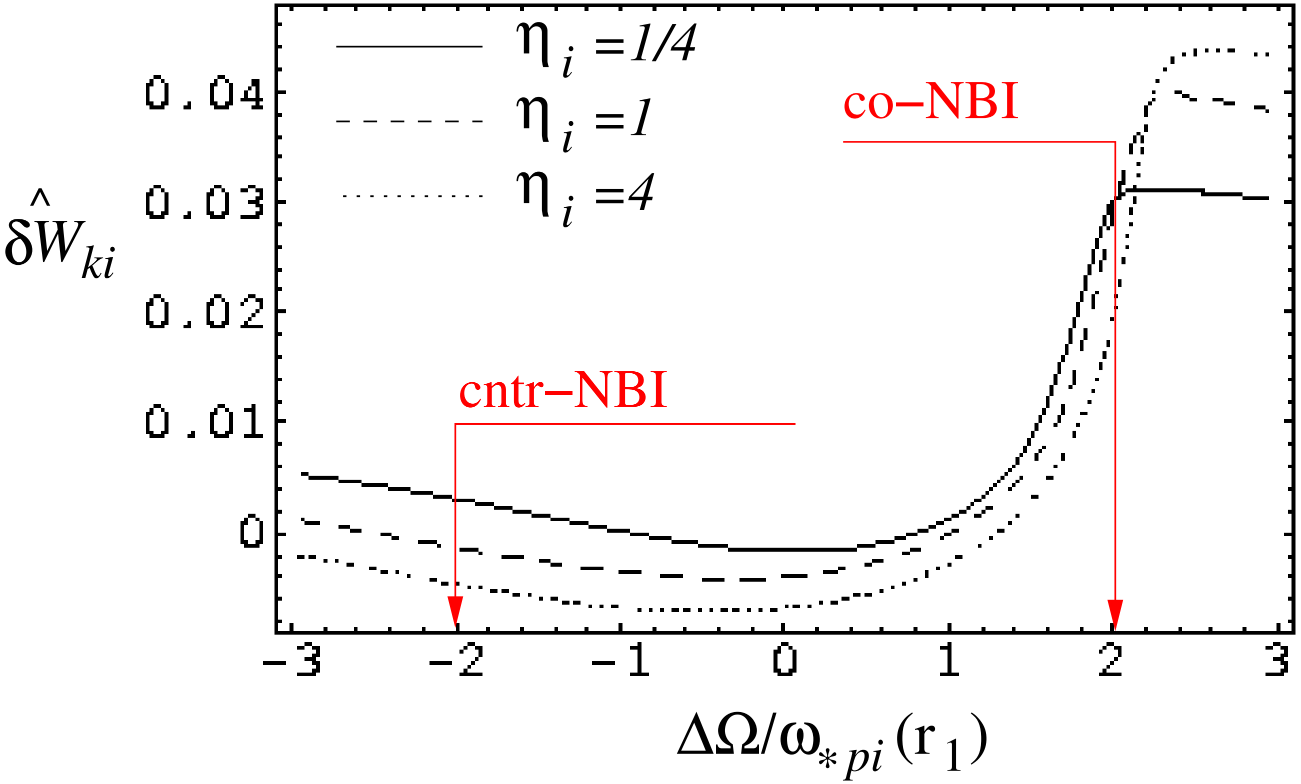


Collisionless Trapped Thermal Ions

Collisionless trapped ions are strongly stabilising if:

$$\tilde{\omega} \sim \omega{*}i \ll \langle \omega_{md} \rangle + \Delta\Omega.$$

- In JET, NBI fast ions stabilising.
- Collisionless trapped thermal ions depend on $\Delta\Omega$.



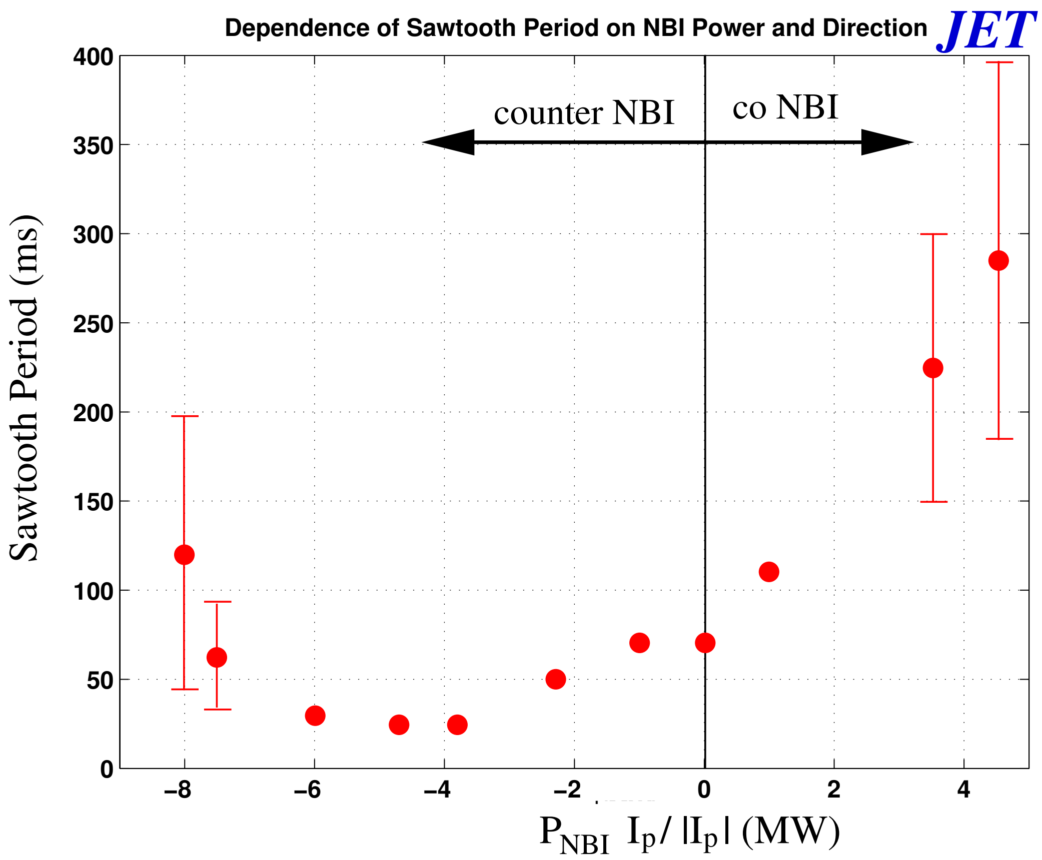
Graves, Hastie, Hopcraft, PPCF <u>42</u>, 1049 (2000).

Normal Cntr-NBI in JET

- 8 MW Cntr-NBI kinetically stabilises sawteeth.
- Sawtooth period smaller than Ohmic sawteeth with deep penetration of NBI. Modification of $\eta(r)$?
- Similar trends observed in:

  TEXTOR [Koslowski, Fus. Sci. Tech. 47, 260 2005]

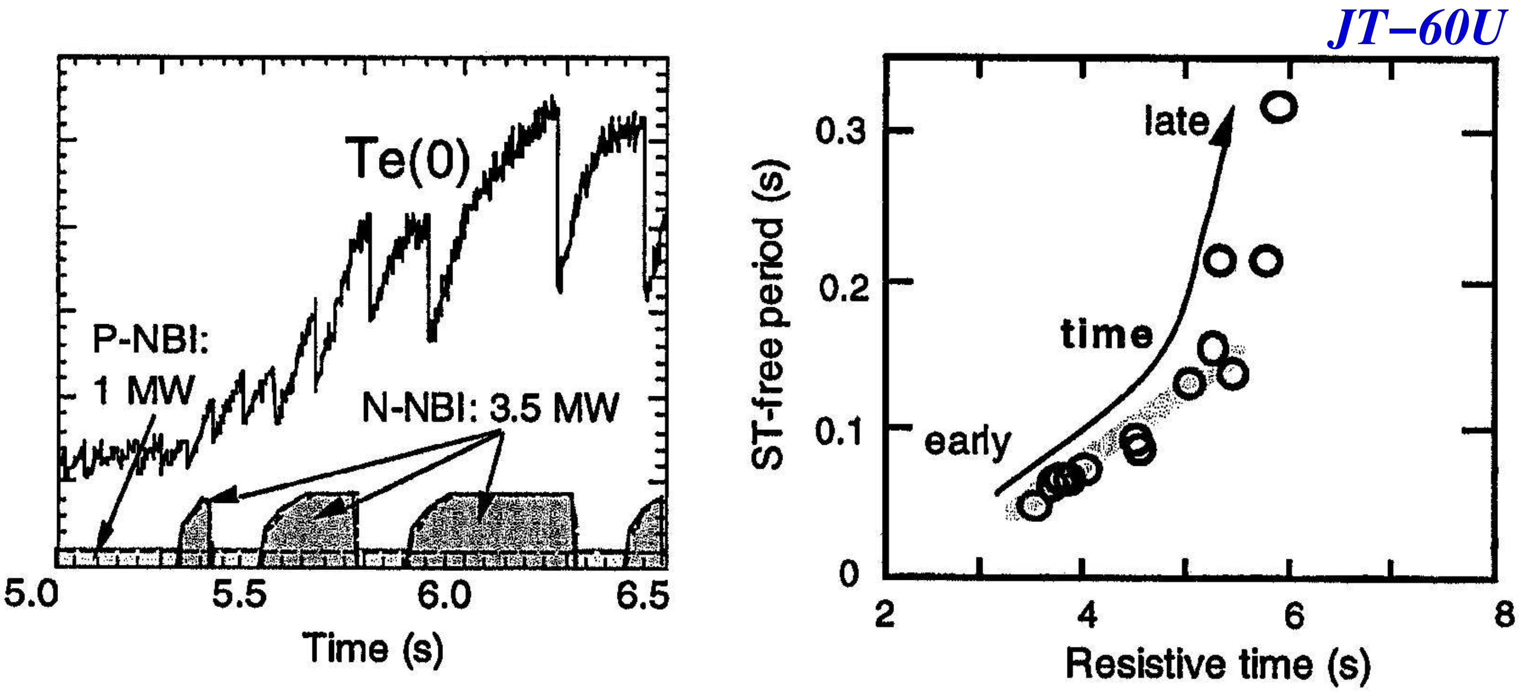
  MAST [I. Chapman, accepted NF].



- MAST: flows order of magnitude larger than JET. Centrifugal effects and kinetic effects from NBI fast ions could be important.
- ITER: momentum induced shear flow is expected to be small.

Sawteeth in JT-60U with Asymmetric NNBI

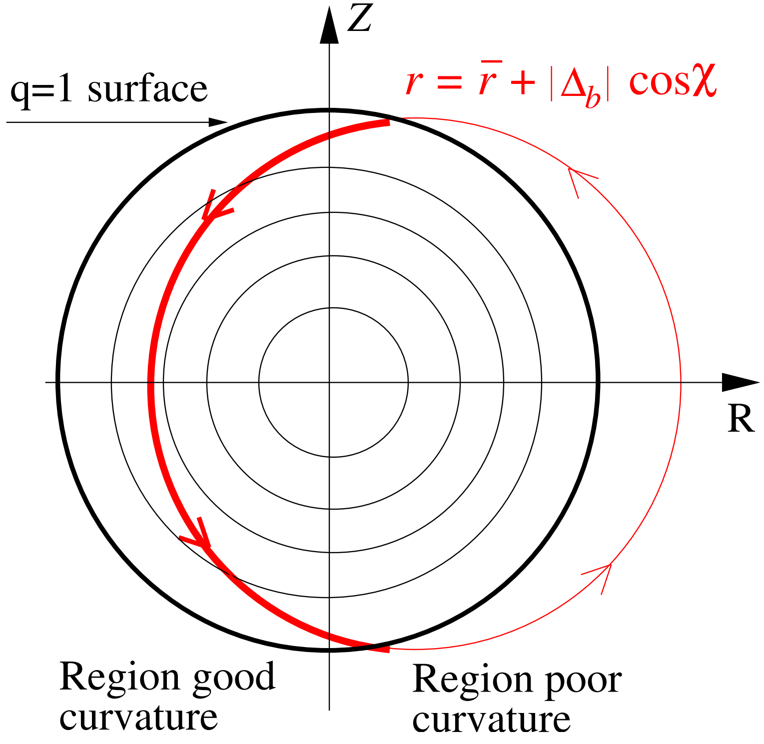
- Highly tangential unbalanced injection (350 keV in JT-60U) is employed. Passing fraction of particles is very large.
- The sawtooth period does not simply increase linearly with the resistive diffusion time.



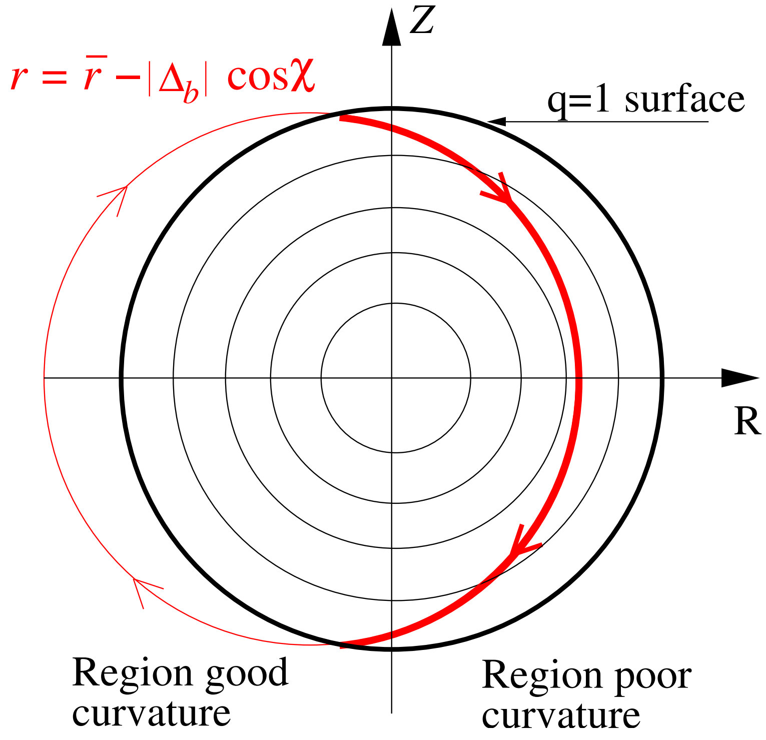
K. Tobita *et al*, Proc. 6th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement (1999)

NNBI Kinetic Stabilisation

Co−transiting ions

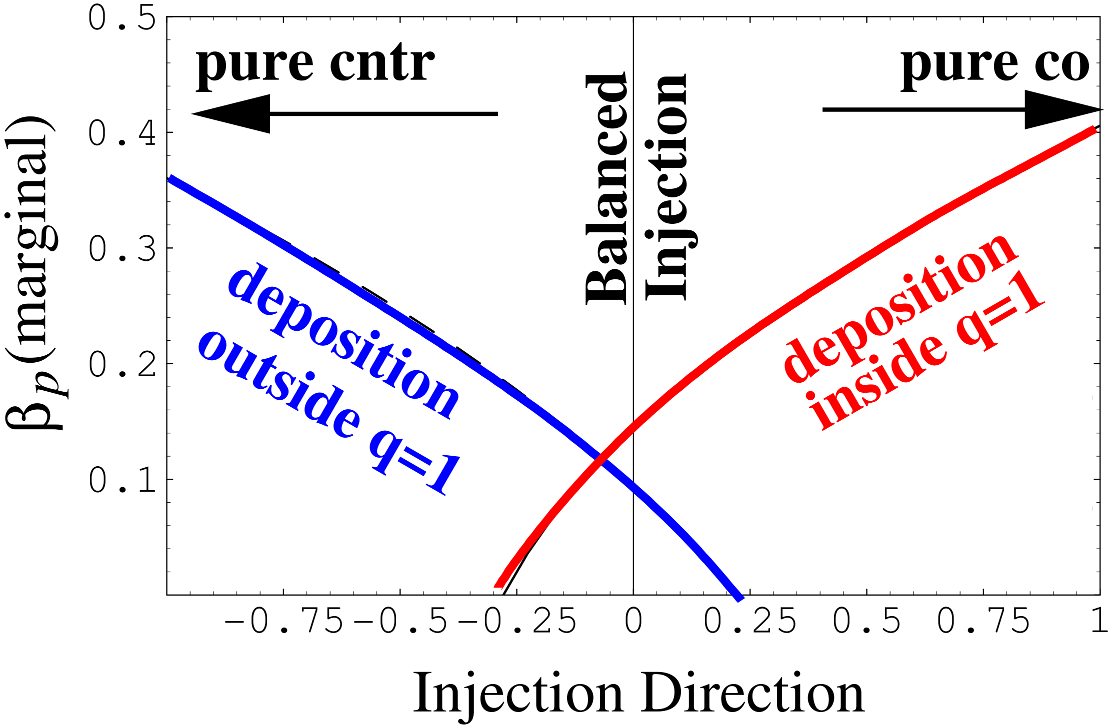


Counter−transiting ions



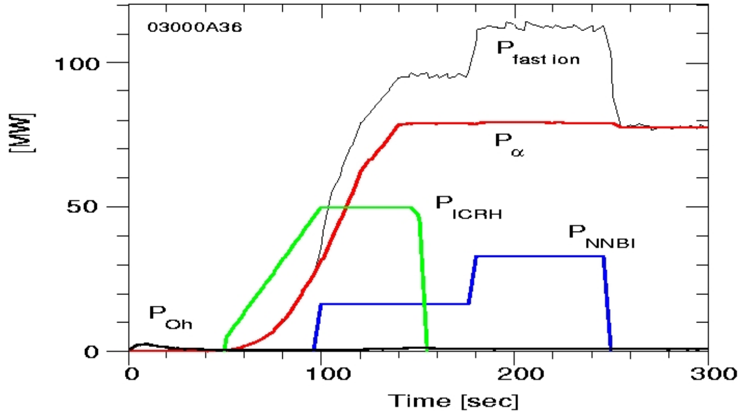
NNBI Kinetic Stabilisation

- Evaluate marginal β_p for internal kink mode.
- Finite orbit effects in collisionless kinetic terms modify free energy.
- Dependent on injection direction.
- Dependent on deposition location.
- Not related to toroidal plasma rotation.



J. P. Graves, Phys. Rev. Lett. 92, 185003 (2004)

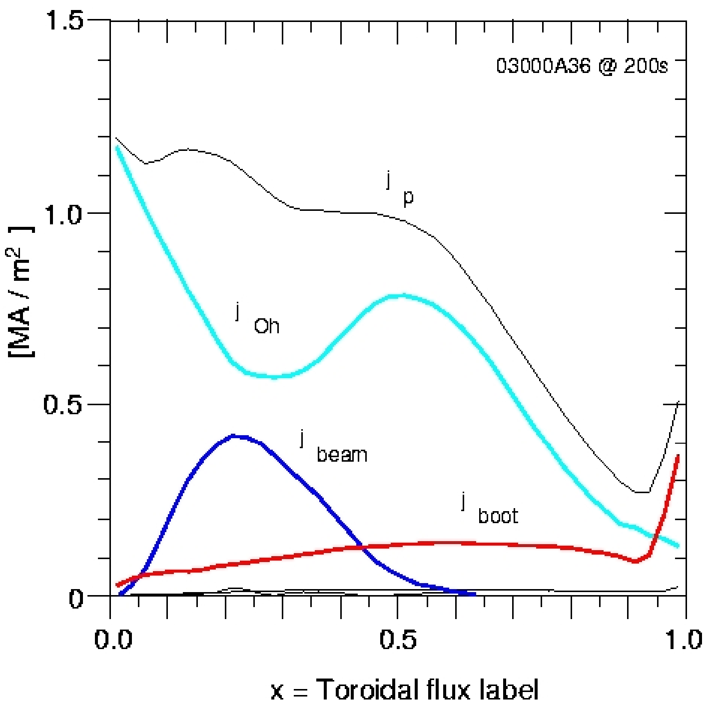
NNBI in H-Mode ITER-FEAT

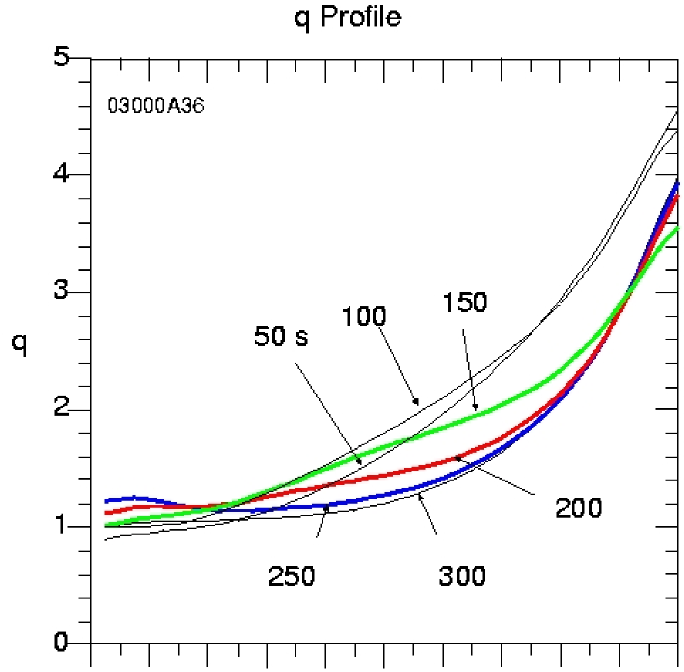


For small shear:

$$\frac{\partial q}{\partial t} \approx \left.\frac{\partial q}{\partial t}\right|_{\text{no cd or boot}} + \frac{q}{B_p}\frac{\partial}{\partial r}(j_{cd}\,\eta + j_{boot}\,\eta).$$

Hence off-axis current drive could significantly slow down current penetration in core.





R. Budny, 8th IAEA Technical Meeting on Energetic Particles, General Atomics, San Diego, CA, Oct 6-8, 2003

Conclusions

Great deal of progress has been made in Sawtooth Control

- Localised ECRH and ECCD.
- Localised ICRH and ICCD (first and second harmonic).
- Neutral Beam injection.
- Localised ICCD effective even with stabilising energetic ion population in core.

These results are promising for ITER

- Localised current drive expected to provide crucial sawtooth control.

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