The Physics of Sawtooth Stabilisation

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Fusion Working in Europe

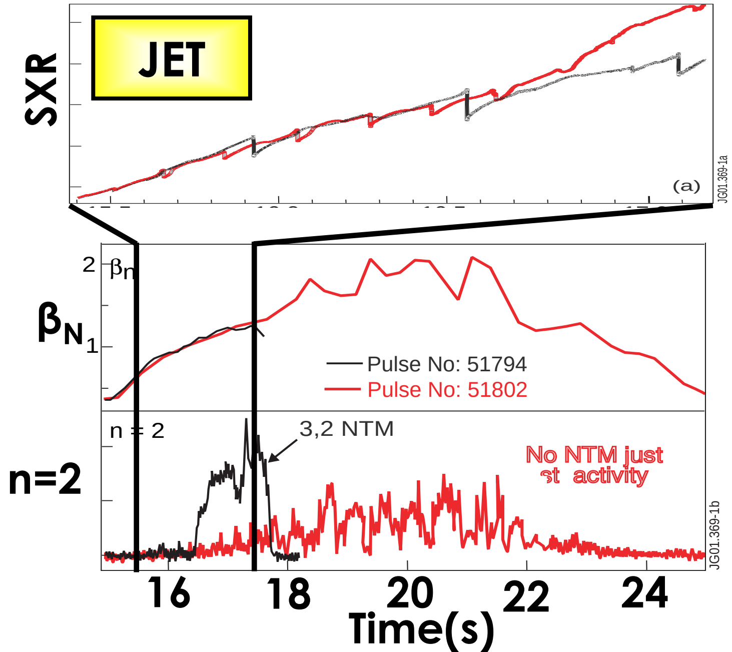
Outline – Sawtooth Stability

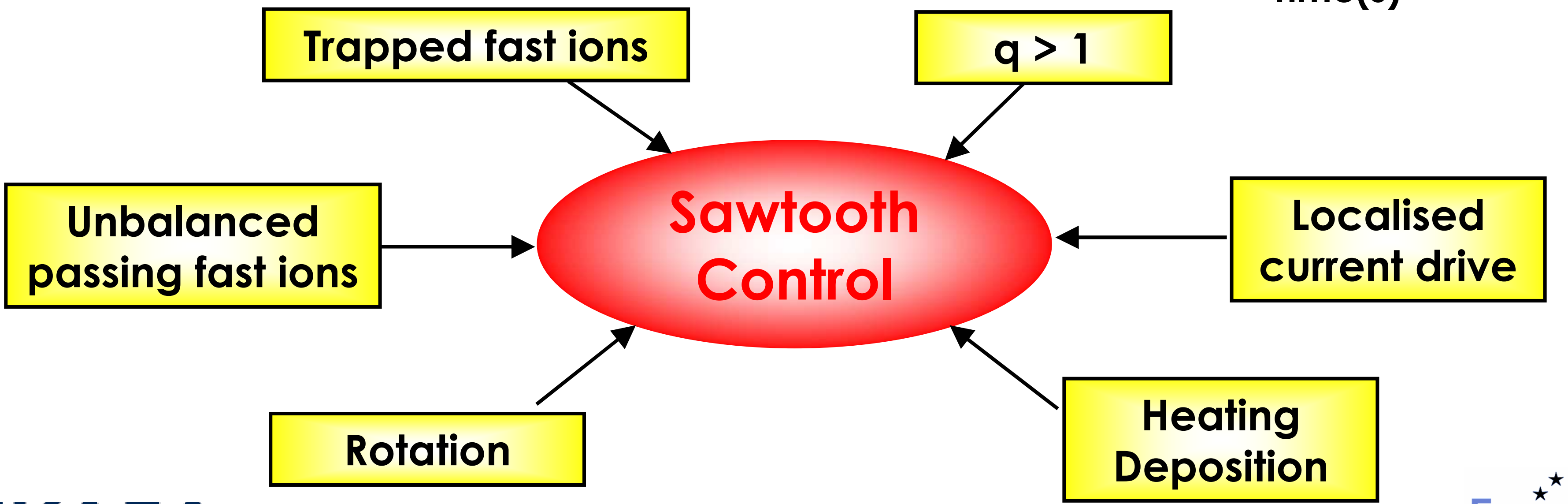
- **Motivation**
  - Sawteeth can trigger Neo-Classical Tearing Modes (NTMs)
- **Methods for Sawtooth Control**
- **Sawtooth Control Using Neutral Beam Injection**
  - MAST: Flow Effects
  - JET: Kinetic Effects
  - TEXTOR: Flow and Kinetic Effects
- **Sawtooth Control Using Ion Cyclotron Resonance Heating**
  - Experiments on JET
  - Physics Explanation
- **Sawtooth Control in ITER**
  - ECCD and Negative-ion Neutral Beam Injection

Motivation – Sawtooth Seeding of NTMs

- **Why are sawteeth important?**
  - Reduce thermal insulation of the core
  - Trigger other modes like ELMs or NTMs
    - **Short $\tau_{saw} \rightarrow$ no NTM**
    - **Long $\tau_{saw} \rightarrow$ NTM seeding**

*Sauter et al, PRL, **88**, 2002*





Methods for Sawtooth Control

- **MAST Neutral Beam Injection**
  - Flow Effects dominate
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  - Raise Magnetic Shear at q=1
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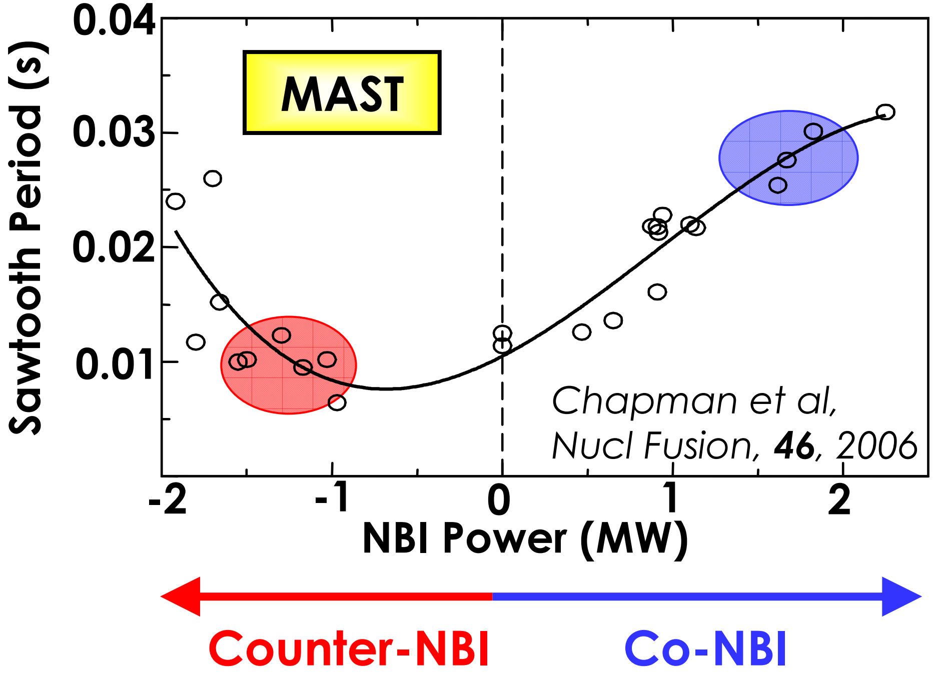
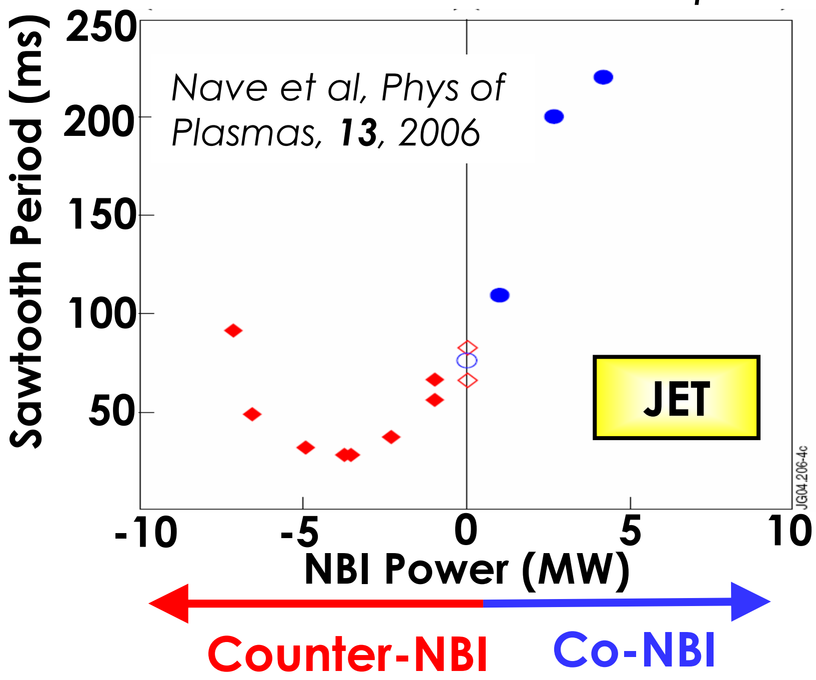
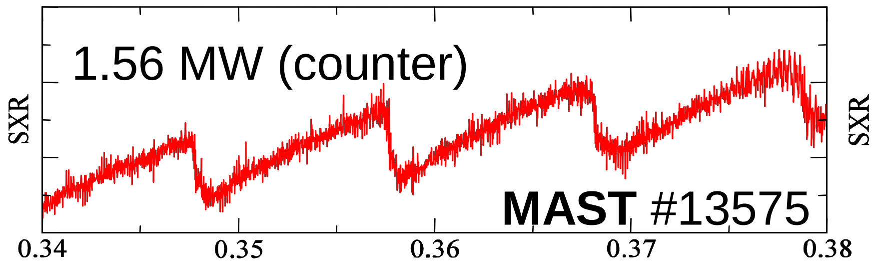
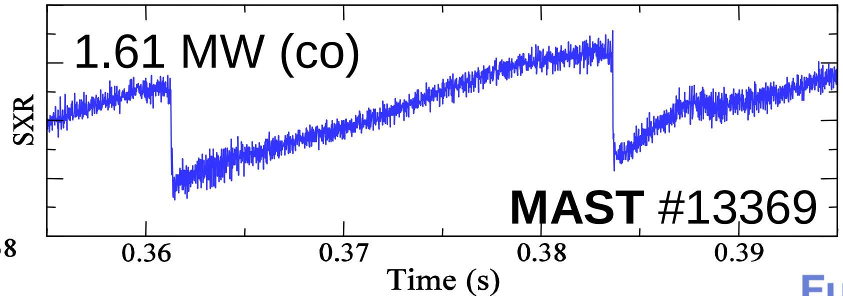
Sawtooth Control Using NBI

- **JET and MAST experiments show sawtooth control using NBI**
  - *NBI heating in **co**-current direction causes an **increase** in period*
  - *NBI heating in **counter**-current direction causes a **decrease** in period*



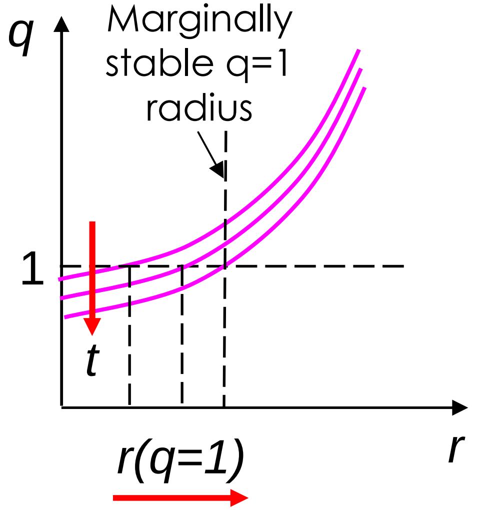


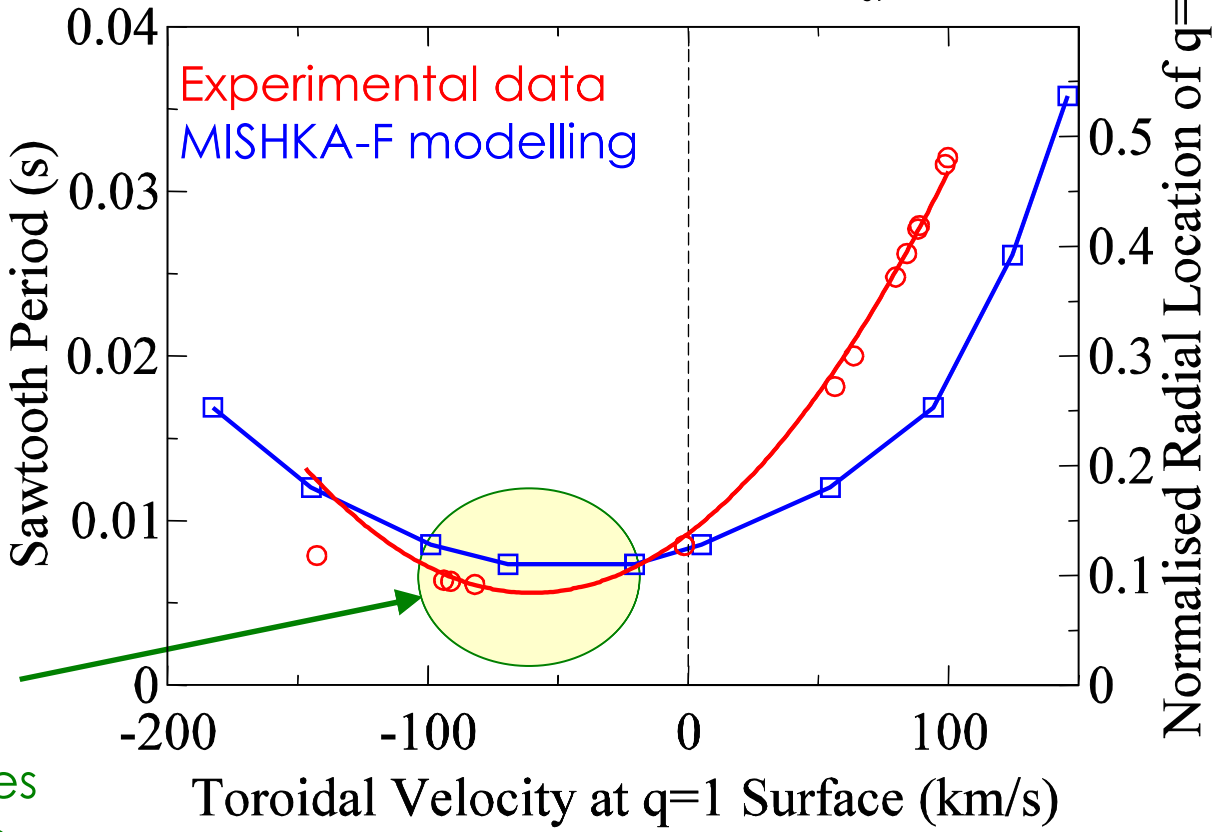




Modelling sawtooth stability with flow in MAST

- **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*

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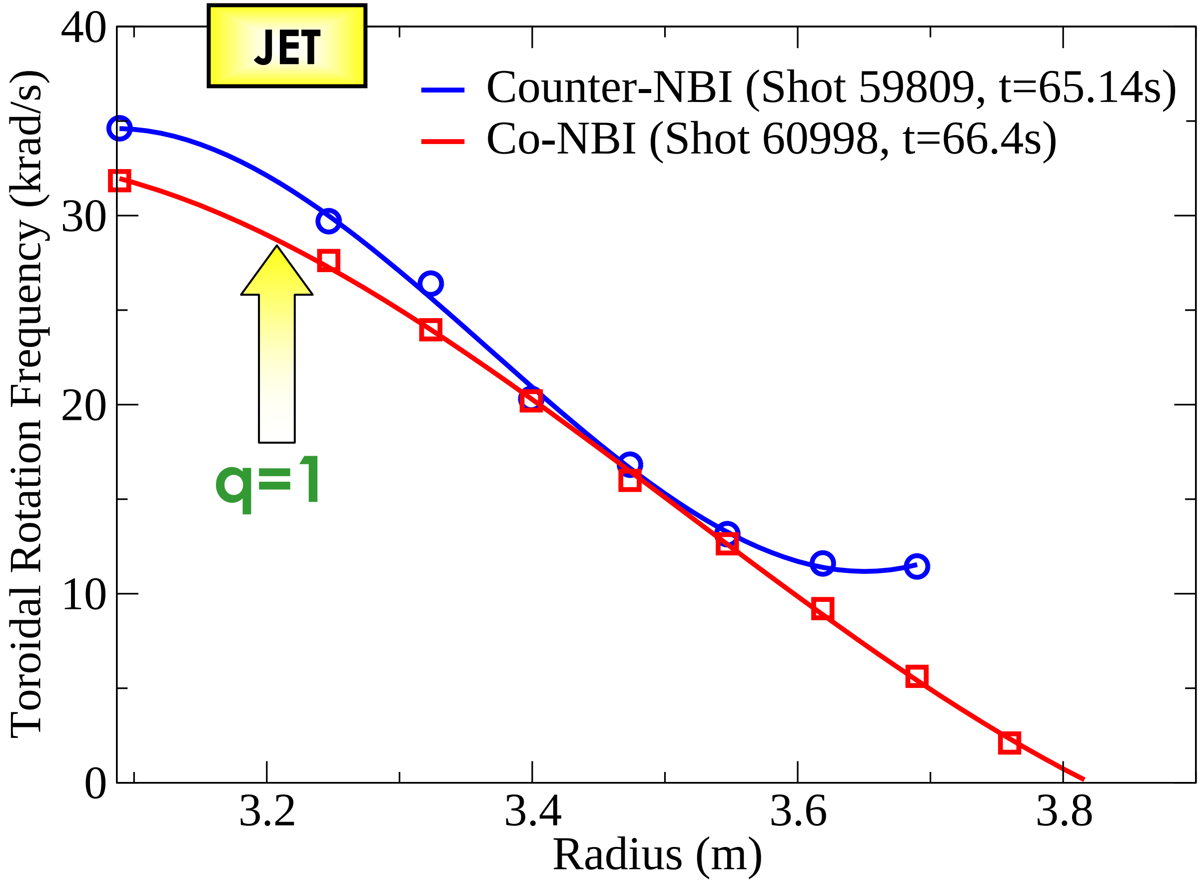
JET Rotation Profiles

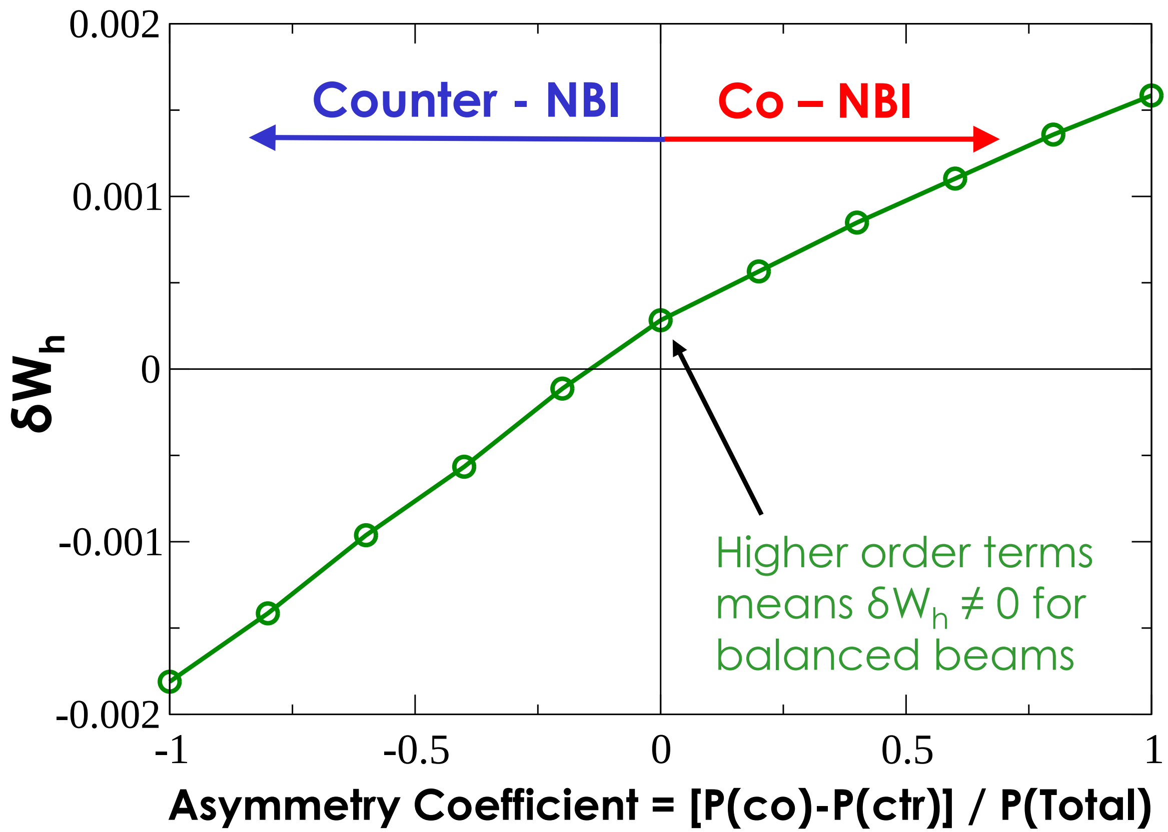
- **Toroidal Rotation is an order of magnitude smaller than MAST**
  - Much slower rotation speeds than MAST, only small effect on stability of kink mode
  - Strong flow ***shear*** at radial location of q=1 (compared to MAST)



(Rotation Profiles from Charge Exchange)

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]



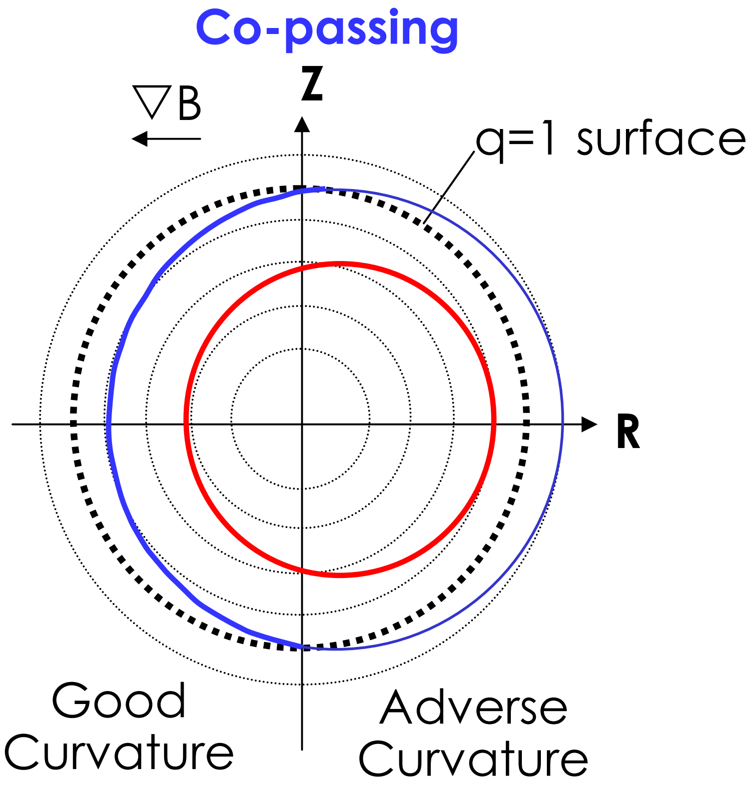
- **HAGIS code**
  - Drift Kinetic code for exploring wave-particle interactions
  - Calculates change in potential energy:

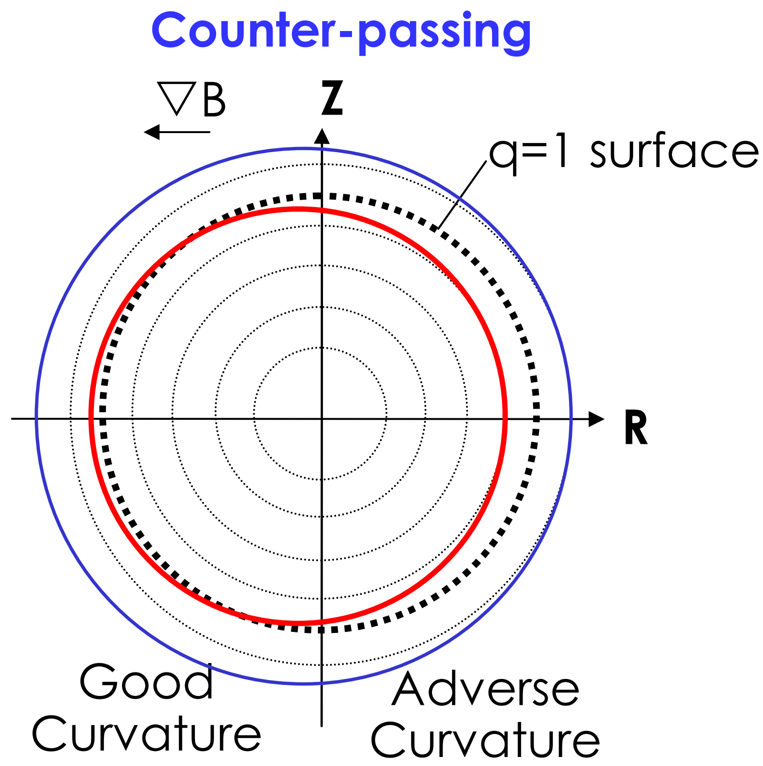
$$\delta W_h = \frac{1}{2}\int \left(mv^2 + \mu B\right) \delta f \;\; \kappa \cdot \xi^* d^3x\, d^3v$$

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

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

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

Effects of Flow Shear

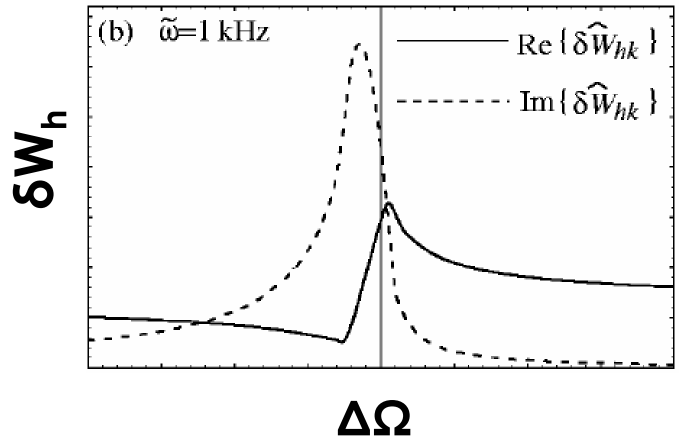
- Flows change the **electric field** by adding a factor:

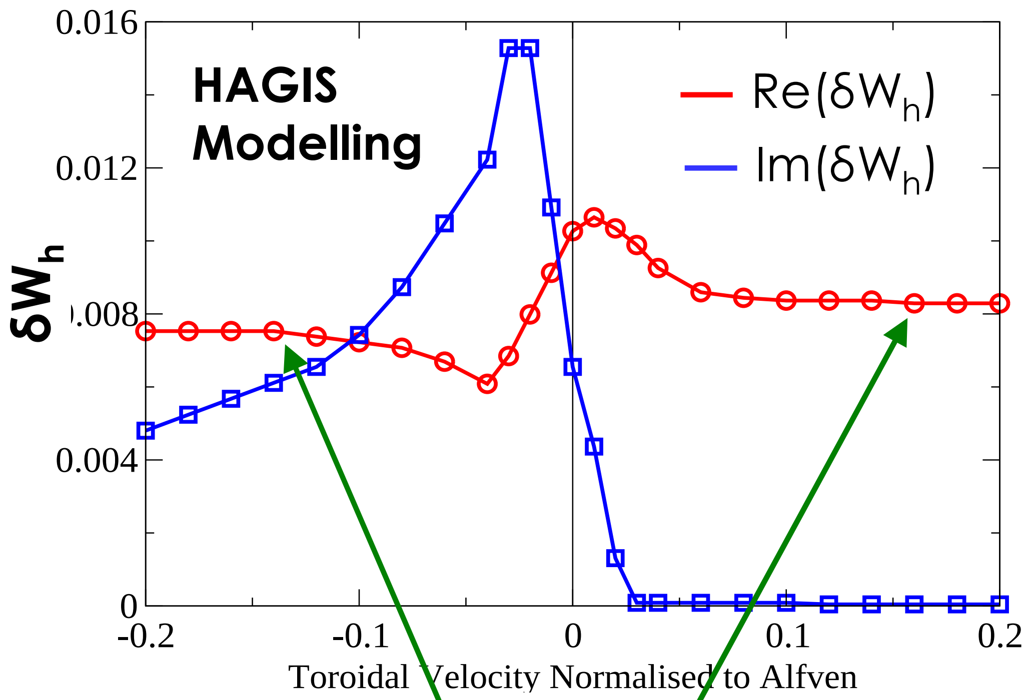
$rB_\theta\Omega$ ← NB: Electric potential depends

- The flow shear can change number of particles in resonance. $\delta W_h > 0$ when:

$$\langle \omega_d \rangle + \Delta\Omega - \left(\omega - \Omega_{r_1}\right) > 0$$

Graves, PPCF, ***42****, 2000*



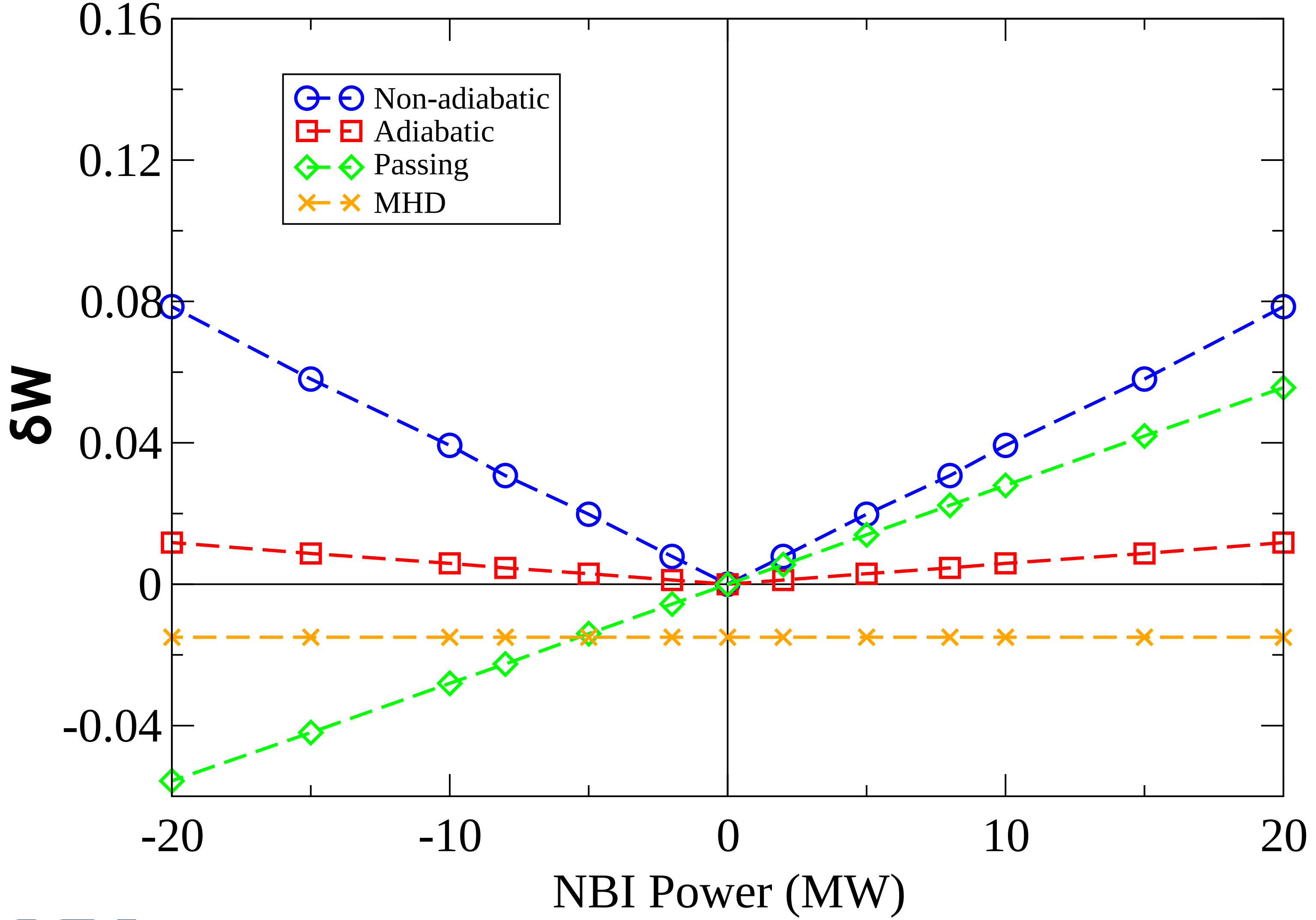


$$\delta W_h \sim \frac{\omega - \Delta\Omega - \omega_{*h}}{\omega - \Delta\Omega - \langle \omega_d \rangle} \xrightarrow{\Delta\Omega\uparrow} O(1)$$

  – At very large flows ($\Delta\Omega > \langle\omega_d\rangle$) flow shear dominates the numerator and denominator of expression for δW_h → asymptotic limit

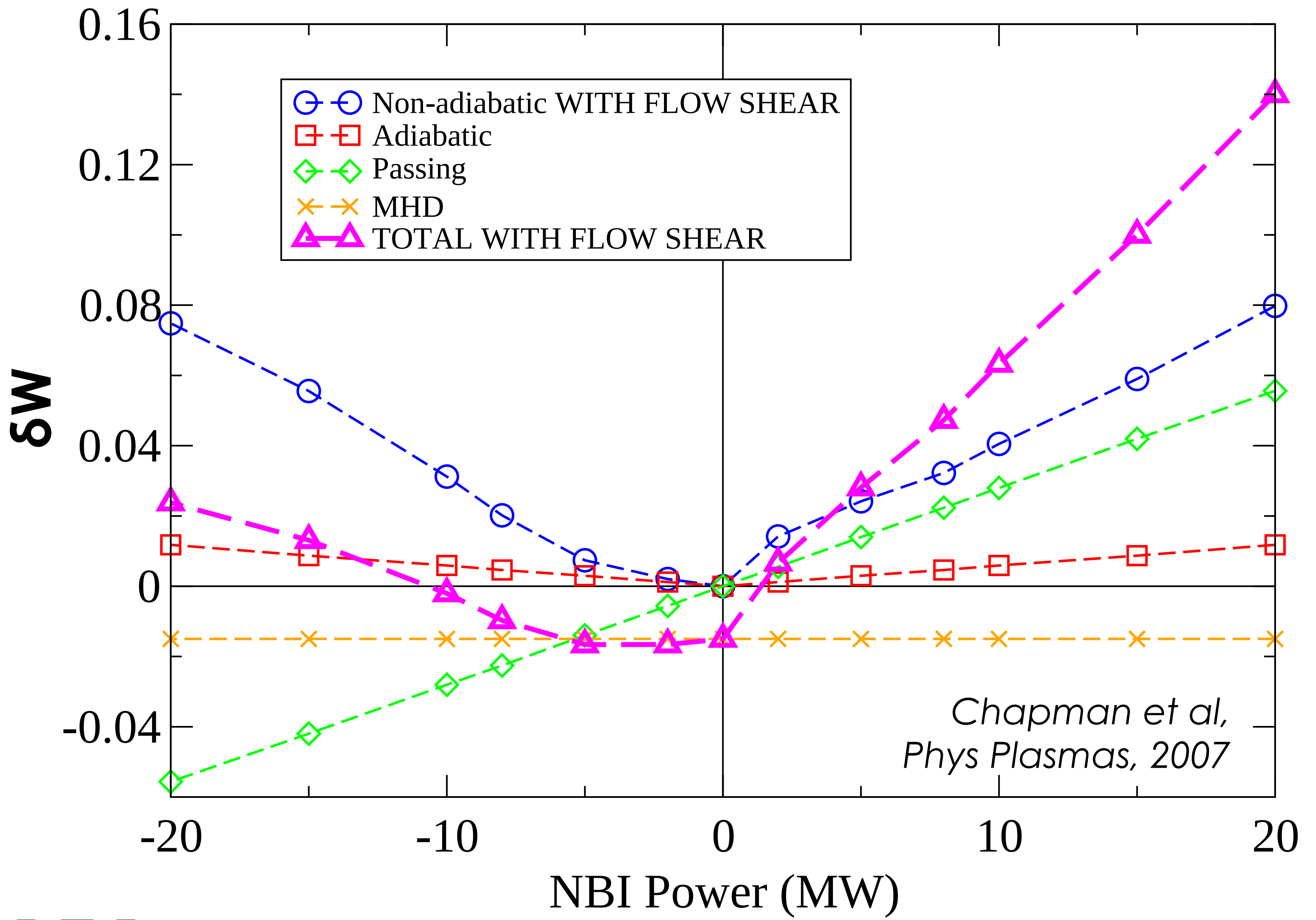
How does δW_h change with respect to beam power?

- **Modelling the effect of energetic particles on the ideal n=1 internal kink mode WITHOUT flow shear in JET:**

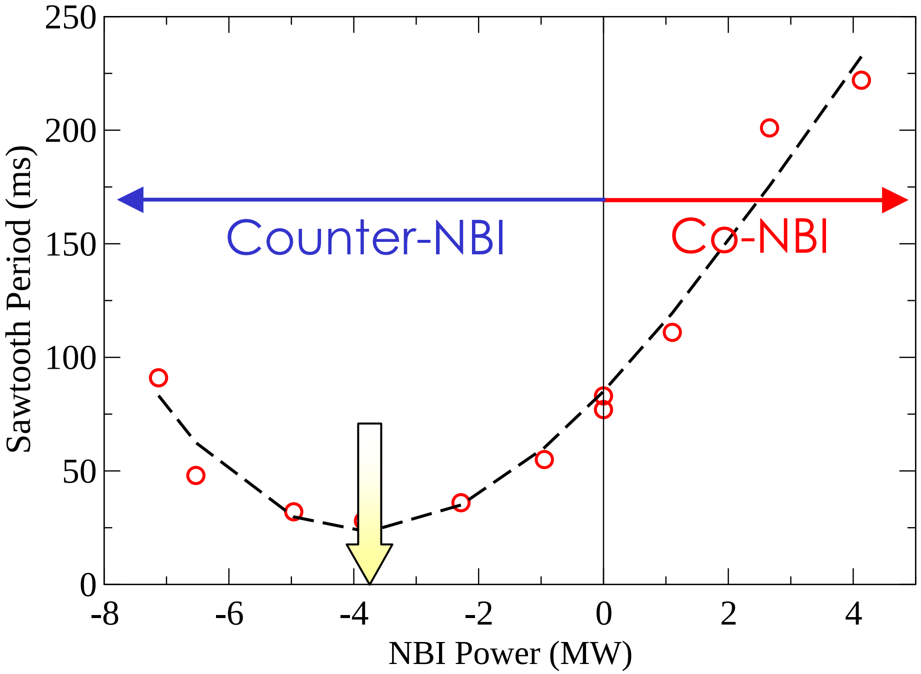


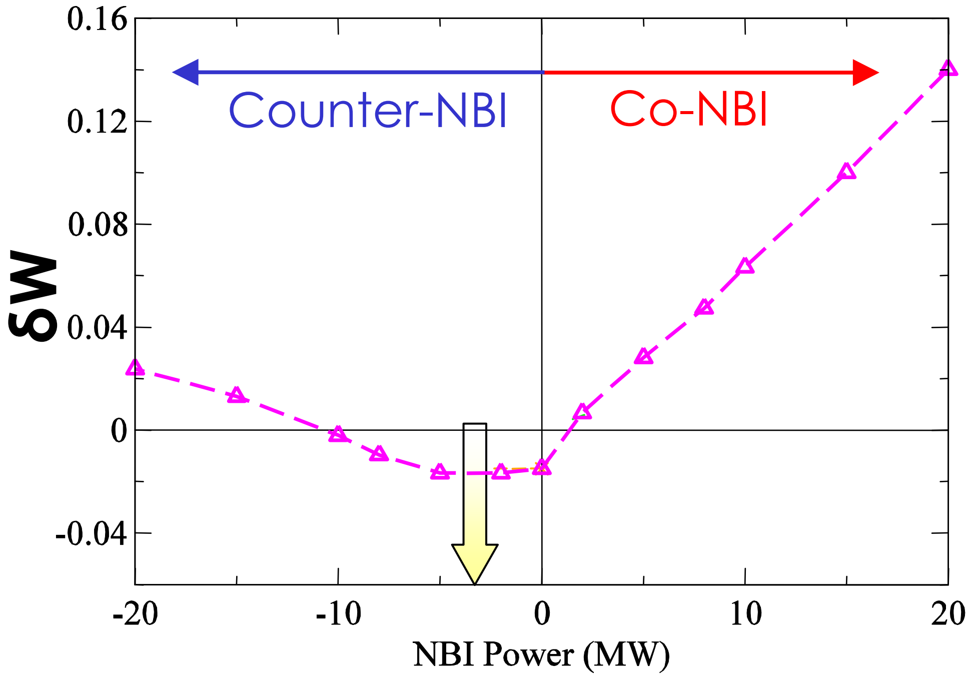
How does δW_h change with respect to beam power?

- **Modelling the effect of energetic particles on the ideal n=1 internal kink mode *WITH flow shear* in JET:**



eriment?





- Minimum in sawtooth period and δW_h agrees well (at ~ 4MW)
- Minimum in δW_h is dependent upon details of the distribution function and the exact rotation shear at q=1
- In **JET**, asymmetry and minimum is explained by **energetic particle effects**
- In **MAST**, asymmetry and minimum is explained by **flow effects**

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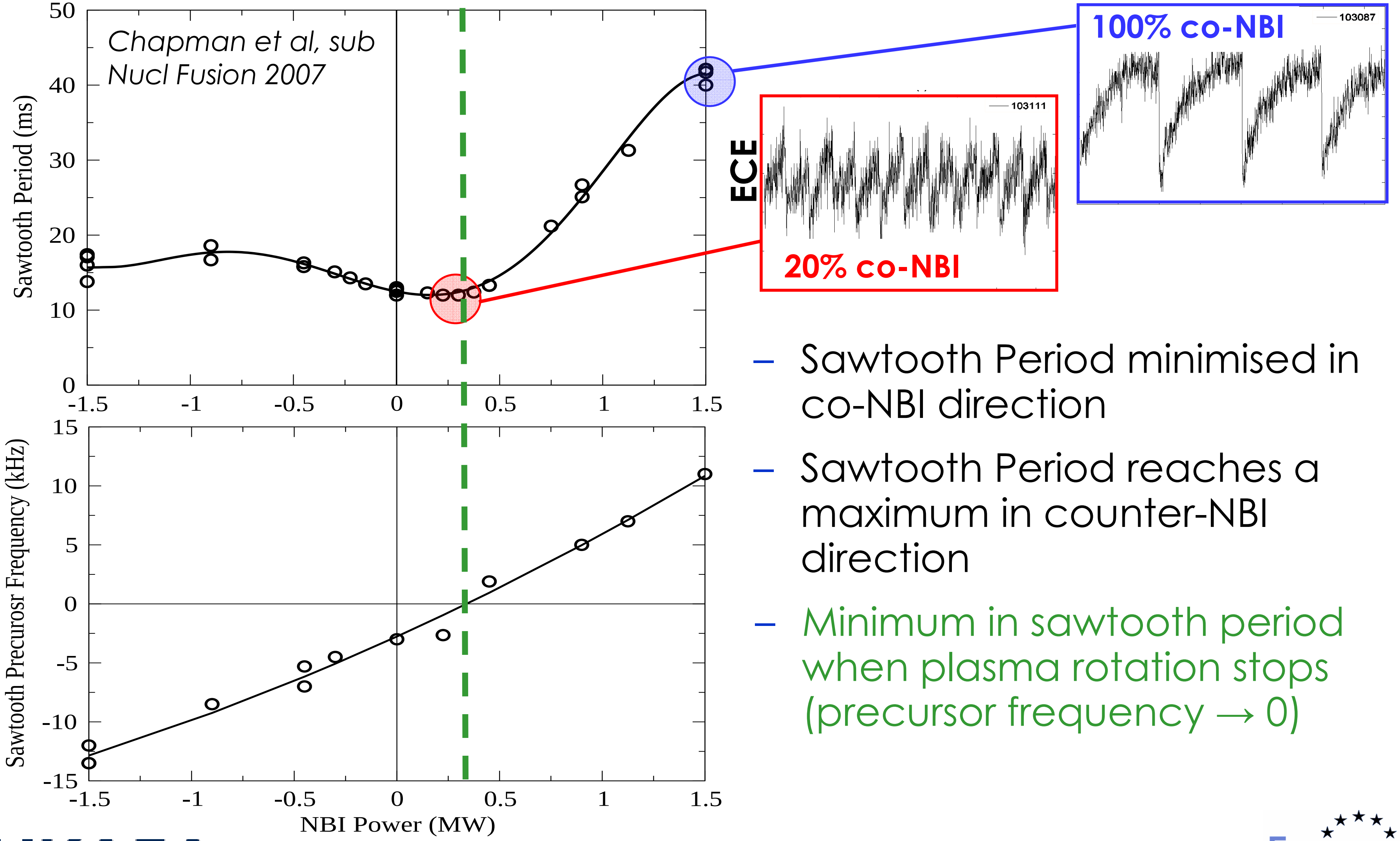
Sawtooth Control by NBI in TEXTOR

- **TEXTOR shows different behaviour of sawteeth with NBI heating**



- Sawtooth Period minimised in co-NBI direction
- Sawtooth Period reaches a maximum in counter-NBI direction
- Minimum in sawtooth period when plasma rotation stops (precursor frequency → 0)

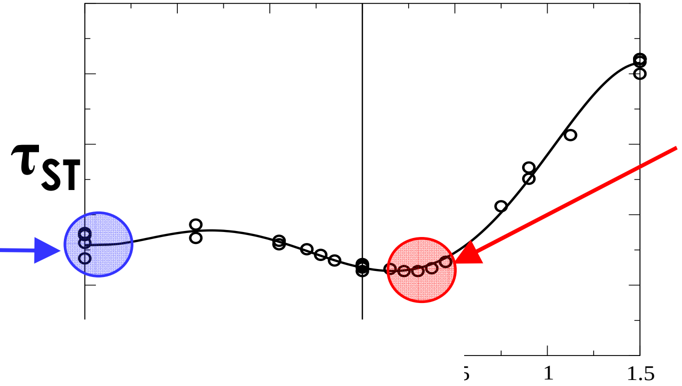
TEXTOR NBI Physics Explanation

- **Competition between gyroscopic and fast ion effects**

Kinetic Effects

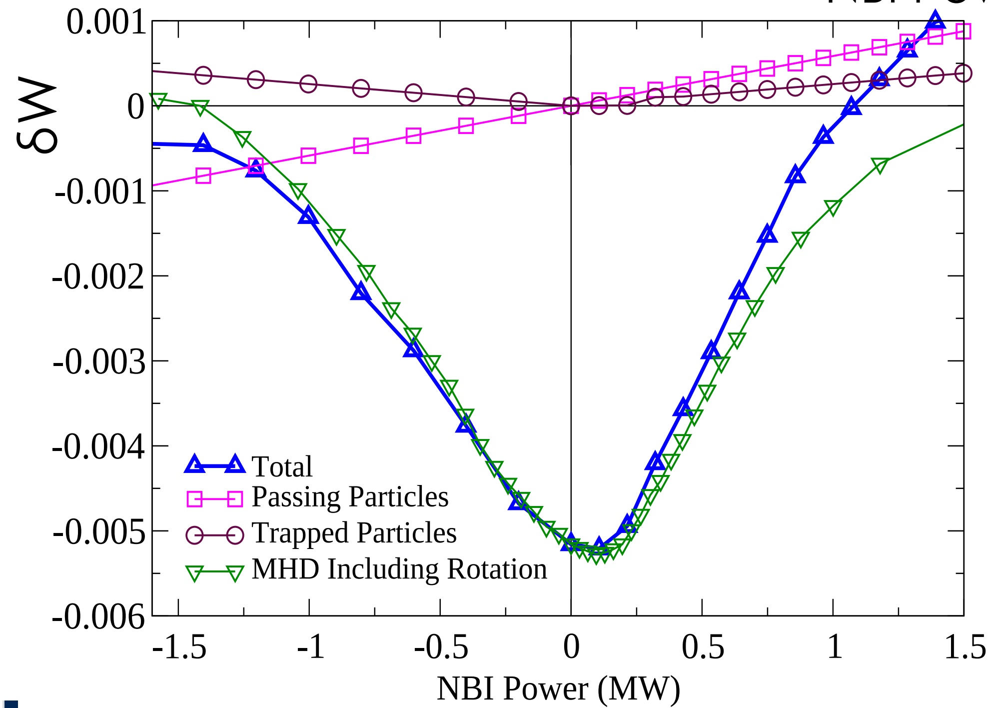
Counter-passing fast ions destabilise kink mode & dominate when flow tends to upper limit.

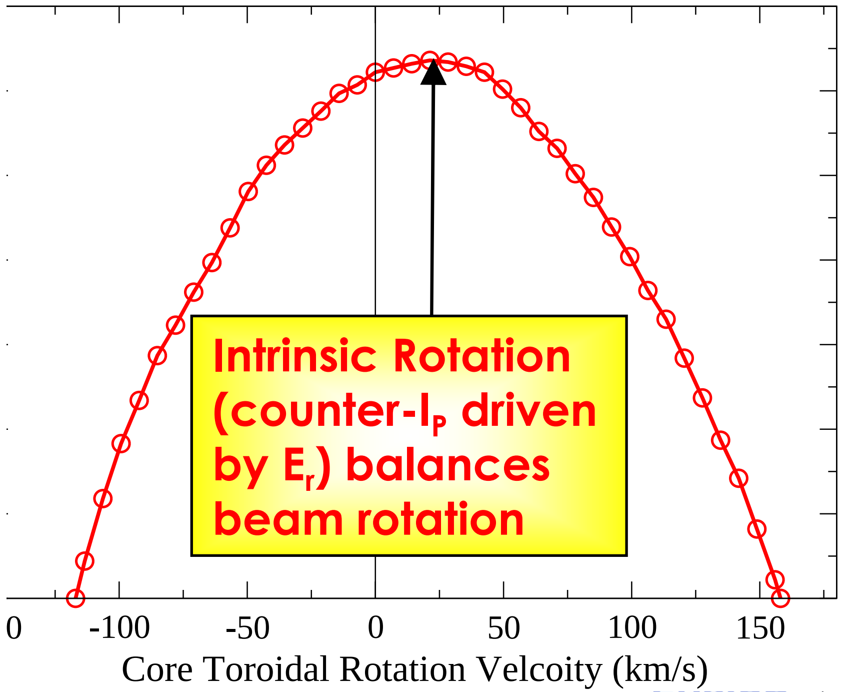
Co-passing and trapped



Flow Effects

Minimum τ_{ST} occurs when rotation stops. Strong toroidal flows stabilise mode, but rotation is not linear with respect to P_{NBI}





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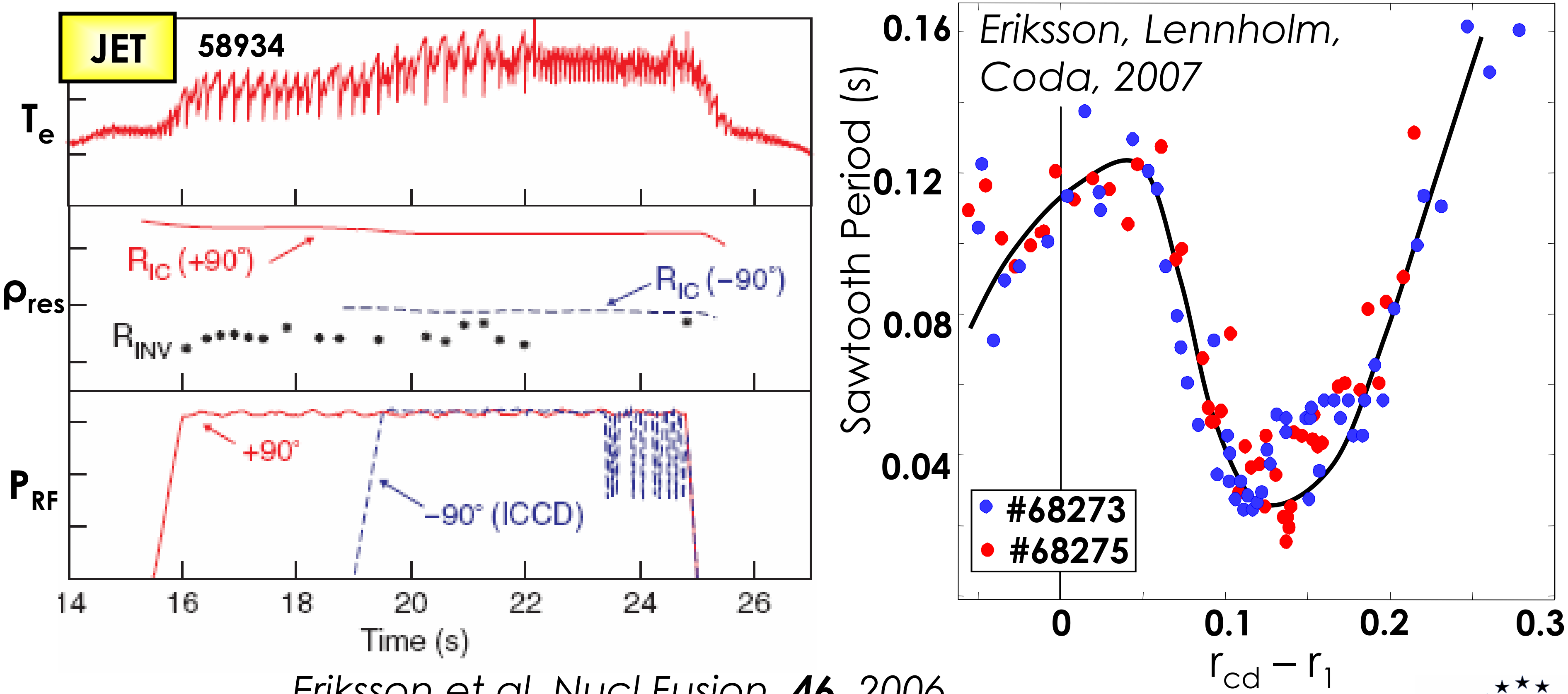
Sawtooth Control by ICRH in JET

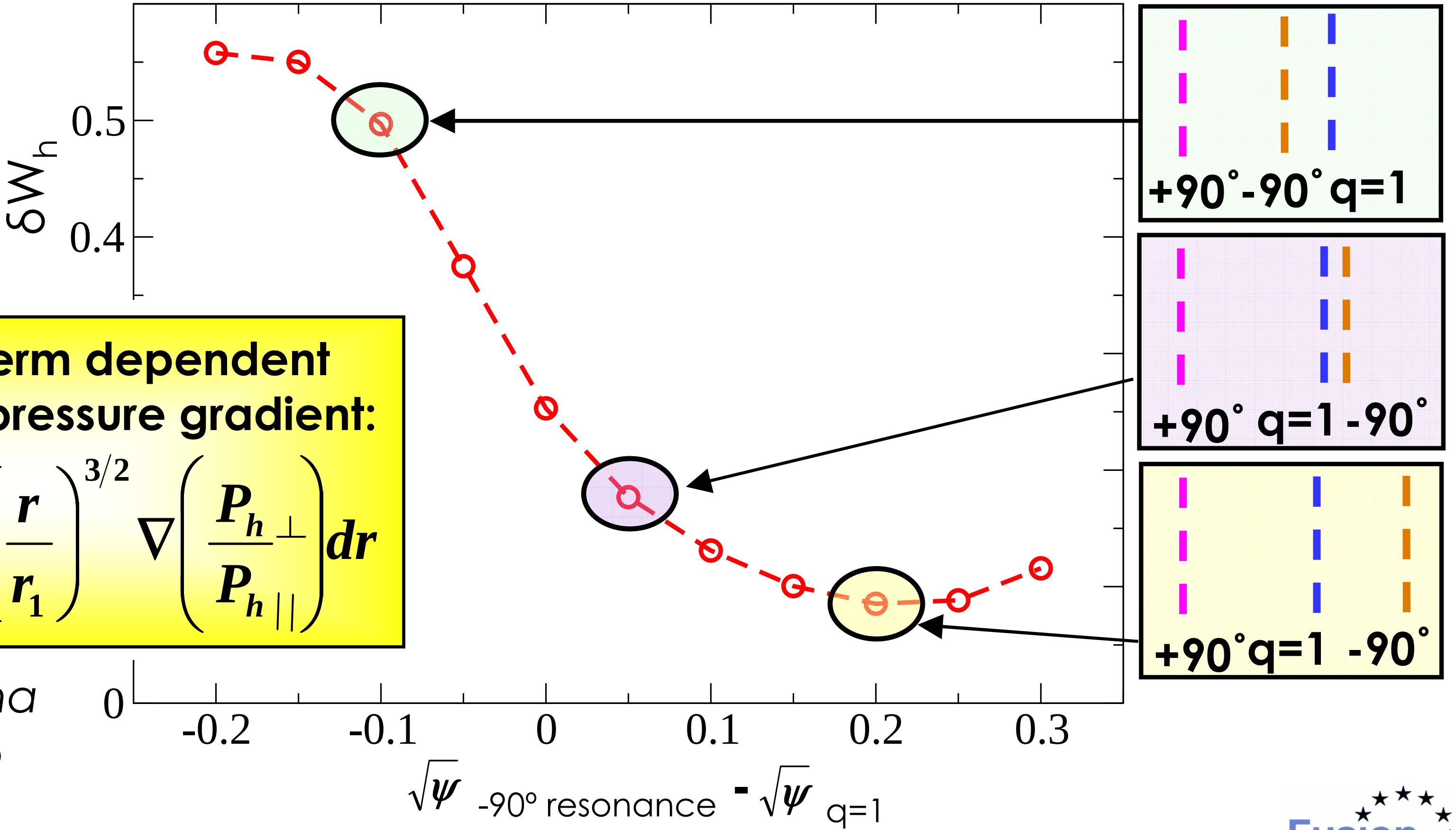
- **JET experiments show that ICRH can destabilise long sawteeth**
  - Sawtooth period increases with on-axis +90° phasing ICRH
  - Fast ion deposition near/outside q=1, -90° ICRH destabilises sawteeth
  - Sawtooth period v. sensitive to deposition location w.r.t. q=1 location



*Eriksson et al, Nucl Fusion, **46**, 2006*

Modelling Sawtooth Control Using ICRH

- **Modelling also exhibits dependence upon resonance location**
  - ICRH inside q=1 gives strong stabilising contribution to δW_h
  - Stabilisation is reduced as deposition moves outside $r_{q=1}$



δW_h has a term dependent upon hot ion pressure gradient:

$$\delta W \sim -\int_0^{r_1} \xi_1 \left(\frac{r}{r_1}\right)^{3/2} \nabla\left(\frac{P_{h\perp}}{P_{h||}}\right) dr$$

Graves, Varenna Lausanne, 2006

Physics of Sawtooth Control with ICRH

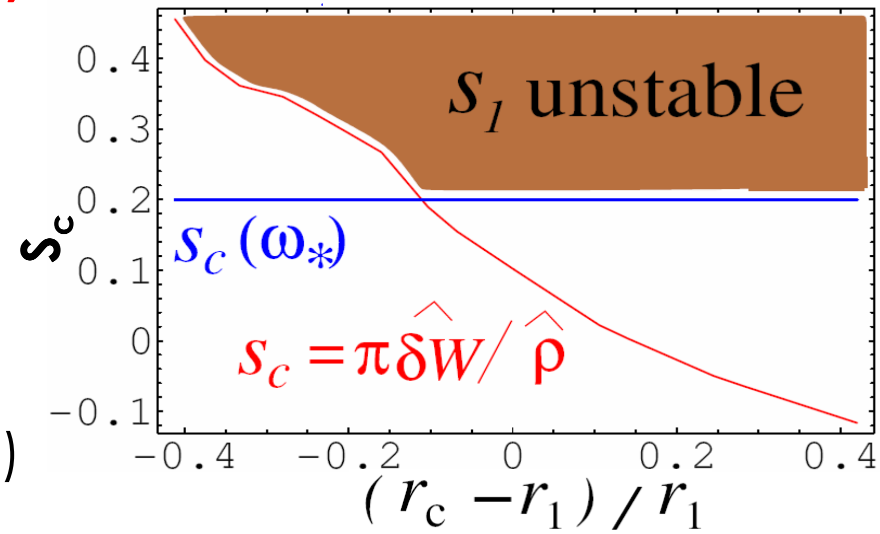
- **Sawtooth is triggered when one of three criteria is met** [Porcelli et al, PPCF, 38, 2163 (1996)]
  - Most relevant for plasmas with energetic ions is:

$$\pi \frac{\delta \hat{W}}{s_1} < c_\rho \frac{\rho}{r_1} \quad \text{and} \quad \gamma_\eta > c_\eta \sqrt{\omega_{*i}\omega_{*e}}$$

  - This can be written in terms of a critical magnetic shear:

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

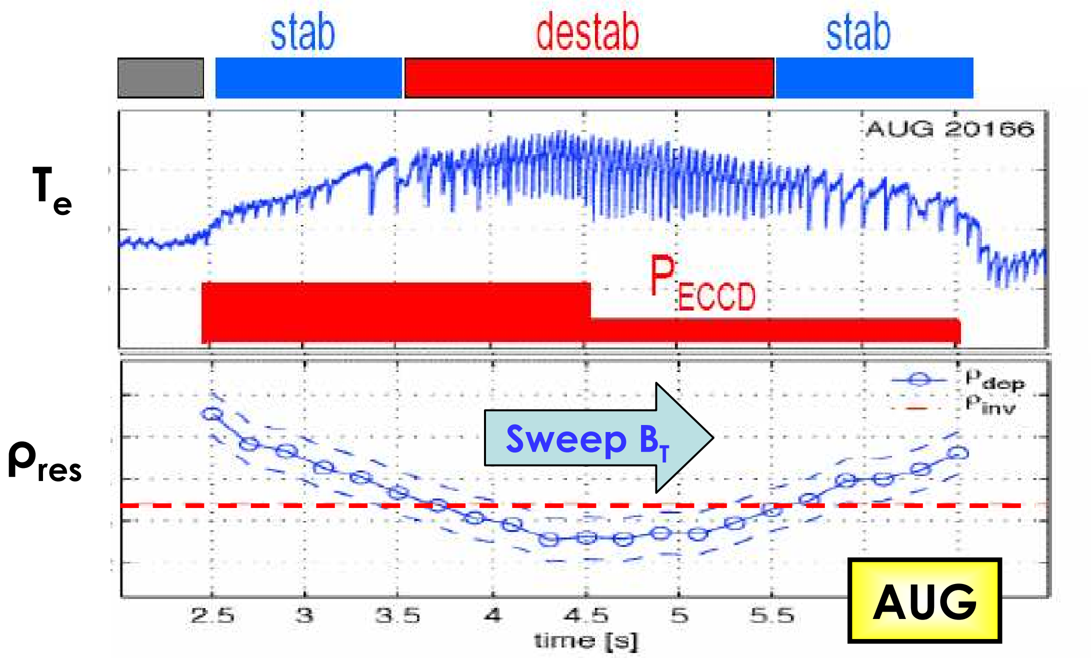
- **Effect of ICRH is two-fold:**
  1. **Reduce critical shear** from the large critical shear which occurs with on-axis fast ions
  2. ICCD **increases magnetic shear** (This is how ECCD destabilises sawteeth too [Mück, PPCF, 2005])



Graves, Conf. Active Control MHD, 2006

ITER Sawtooth Control with Negative-ion NBI

- **Sawtooth control even more important in ITER where the alpha particle population is likely to lead to long period sawteeth**
  - ECCD (and ICCD) has been proposed as a mechanism to destabilise sawteeth to a tolerably small period



*Mück et al, Plasma Phys Cont Fus, **47**, 2005*

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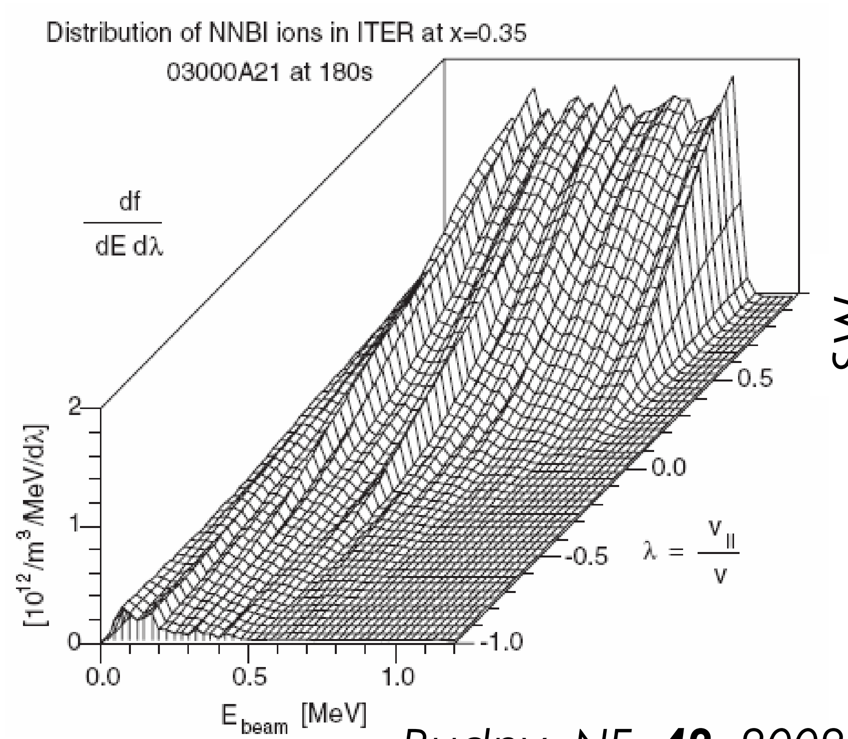
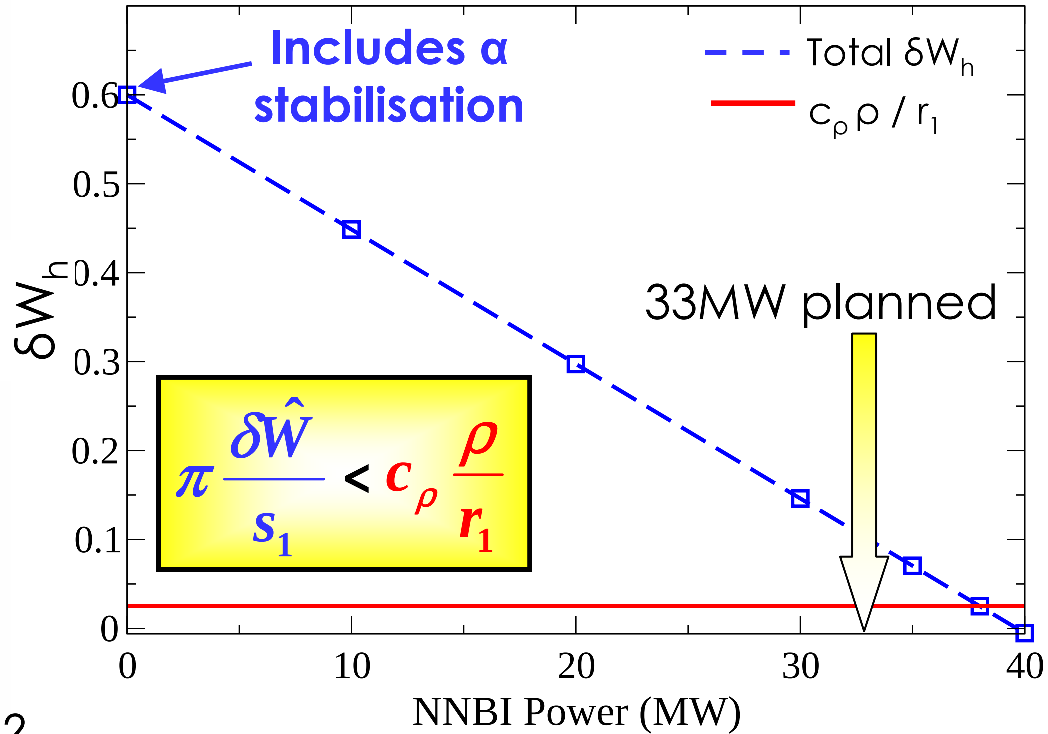
  - ECCD (and ICCD) has been proposed as a mechanism to destabilise sawteeth to a tolerably small period
  - Can off-axis NNBI co-passing ions be used?
    (ITER NNBI has a large passing fraction) [*Graves, PPCF, **47**, 2005*]



*Budny, NF, **42**, 2002*



Conclusions

- Sawtooth Control by different methods in different machines has been explained by a model including flow and kinetic effects

NEUTRAL BEAM INJECTION	FLUID EFFECTS	KINETIC EFFECTS
MAST	✓	
JET		✓
TEXTOR	✓	✓

RESONANCE HEATING	INCREASE S_1	REDUCE S_{crit}
ICRH	✓	✓
ECCD	✓	

- Achievable Sawtooth Control in ITER
  - Off-axis co-NNBI to destabilise internal kink mode
  - ECCD to raise magnetic shear at q=1