Sawteeth

Physics of ITER
DPG Advanced Physics School
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O . Sauter

CRPP – EPFL, Lausanne, Switzerland

With contributions in particular from:

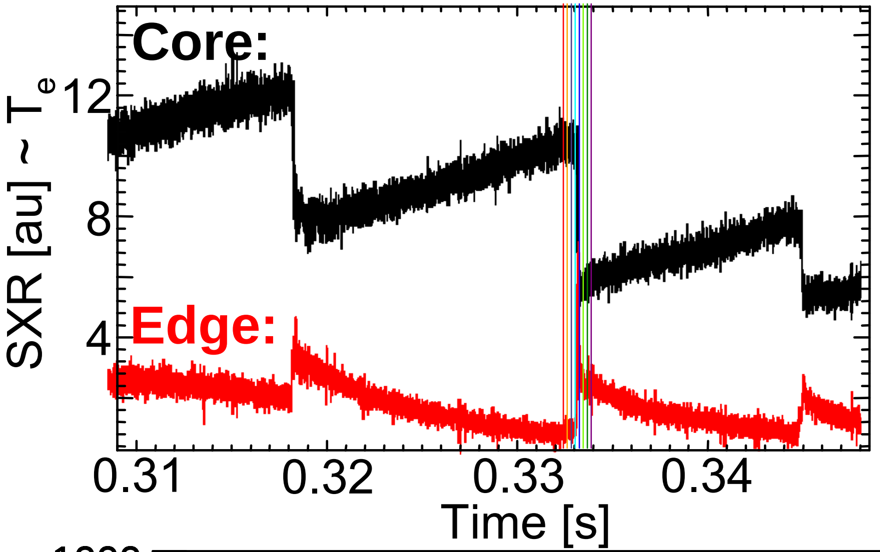
J. Graves, T. Goodman, D. Kim, I. Chapman, T. Nicolas

Outline

- Sawtooth Modeling
- The 3 criteria
- Ideal versus Resistive regime from TCV experiment
- Critical shear condition and CD control (TCV, JET)
- Sawtooth period prediction test (TCV)
- Fast particle stabilisation (JET)
- NTMs controlled through ST period control
- ST control on ITER
- Conclusions

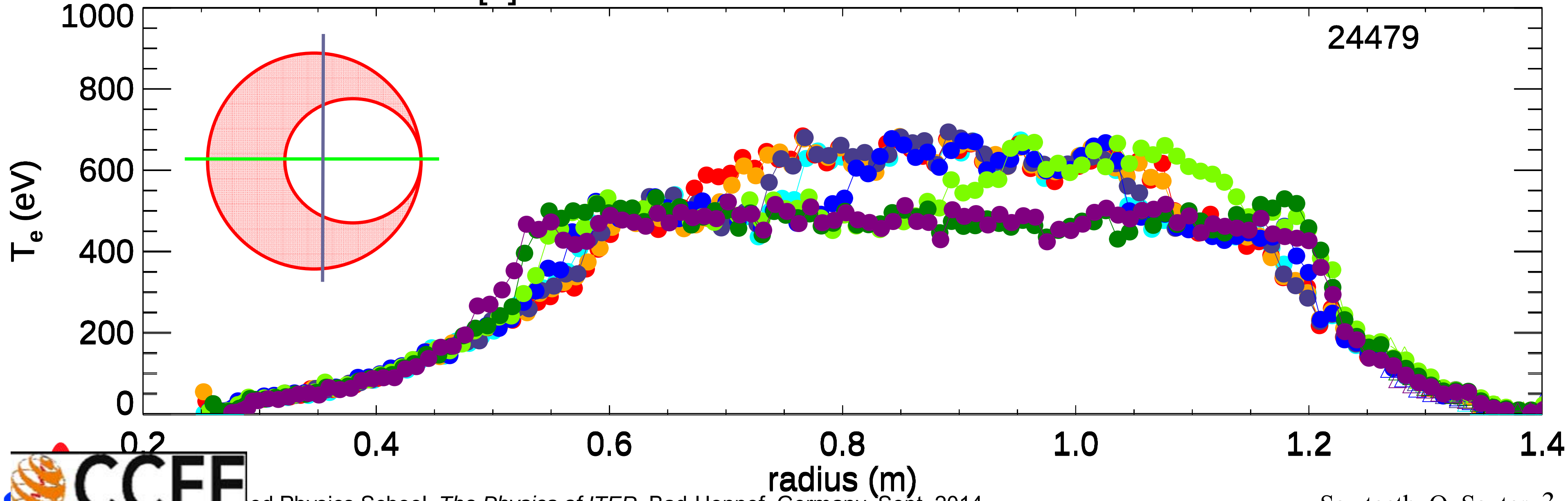
Reconnection in the Plasma Core

Sawtooth oscillations cause rapid, periodic temperature collapse

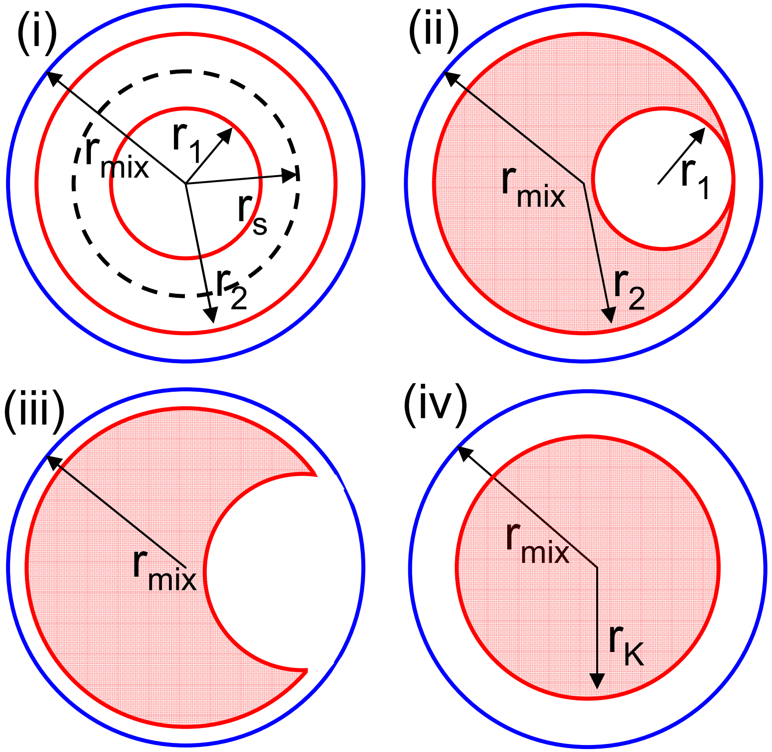


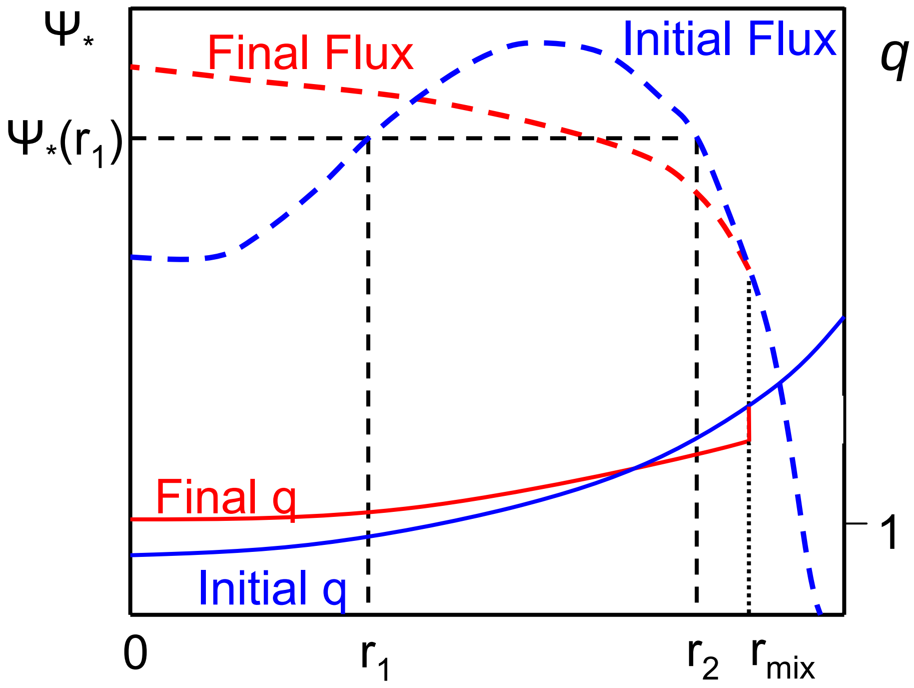
Insight into reconnection process from <1cm Thomson Scattering diagnostic on MAST

IT Chapman et al, PRL, 2010



Kadomtsev Model





- Full reconnection model
  - Current density in core rises, q drops below 1 => 1/1 kink unstable
  - Island grows pushing hot core to cooler plasma, flux reconnects
  - Island growth predicts periodic collapse
  - q<1; crash too fast compared to Sweet-Parker reconnection time

Kadomtsev, Sov J Plasma Phys 1975

Sawtooth modeling

Based on Porcelli model (PPCF 1996)

- Need coupled 1D transport and 2D equilibrium codes
- Transport code with good enough coefficients to reproduce T(ρ,t), n(ρ,t) profiles evolution from post-crash to pre-crash
- Equilibrium recalculated at each transport time-steps to have self-consistent plasma and shear profiles
- Key from model is crash criteria and possibility to have different regimes. It is not the assumption of full reconnection
- At present, one free parameter in model, being coeffs or level of reconnection=>mainly relative results are relevant

Sawtooth modeling (2)

Based on Porcelli model (PPCF 1996)

- 1st criteria: "usual" ideal internal kink

$$\gamma_{\text{ideal}} = -\delta\hat{W} \quad > \quad 0.5\,\omega_{*i}\,\tau_A$$

- 2nd: ideal internal kink "stabilised" by fast particles

$$\delta\hat{W} = \delta\hat{W}_{\text{core}} + \delta\hat{W}_{\text{fast}} \qquad \text{or} \qquad -\delta\hat{W}_{core} \quad > \quad c_h\,\omega_{Dh}\,\tau_A$$

- 3rd: resistive "global" internal kink *(Actually 2 possible crash cond.)*

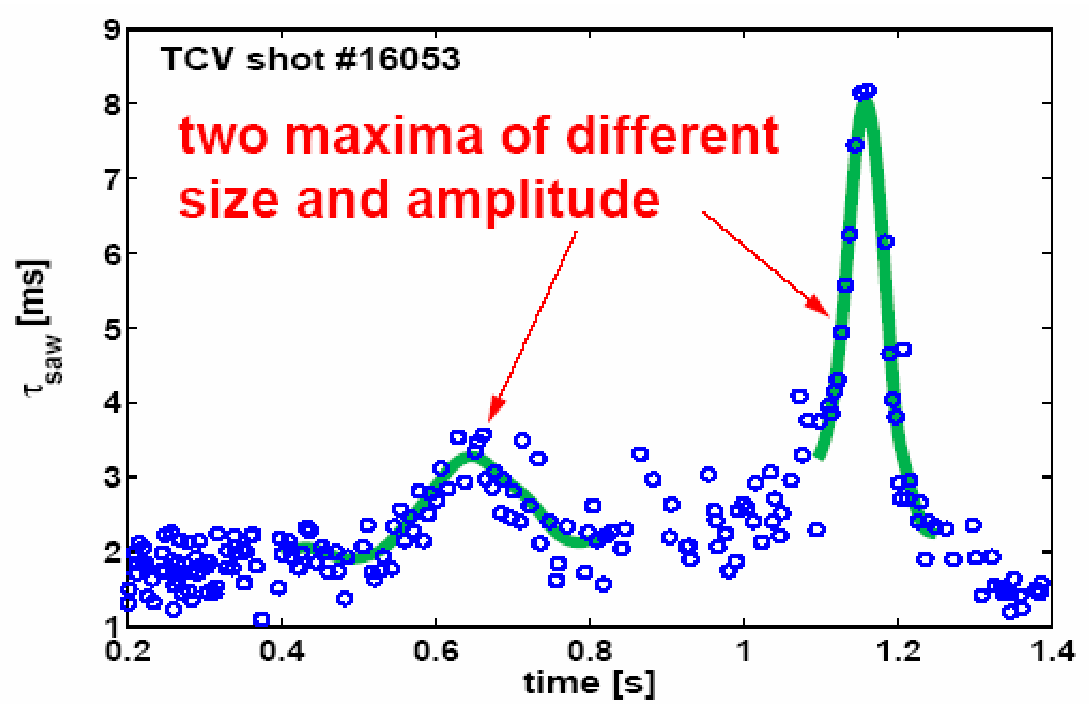
$$-c_\rho\,\hat{\rho} \;\boxed{<}\; -\delta\hat{W} \quad < \quad 0.5\,\omega_{*i}\,\tau_A$$

and

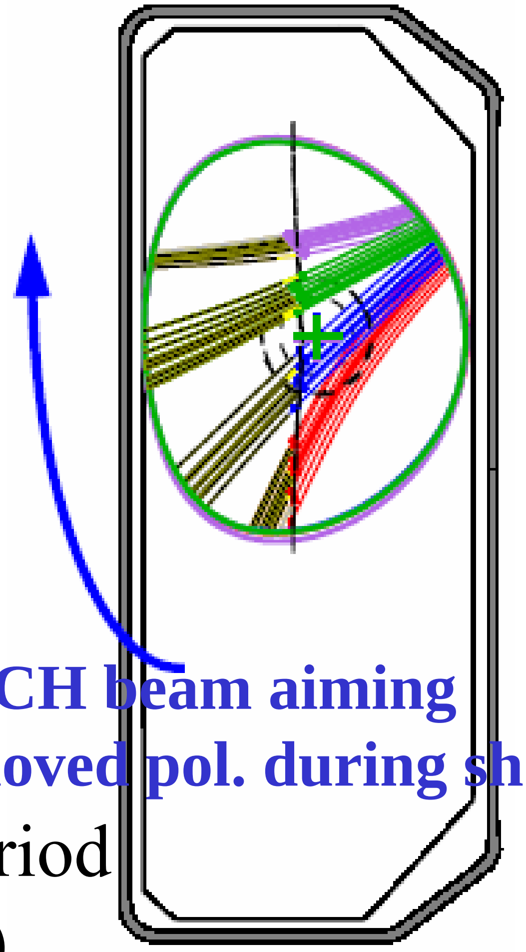
$$\gamma_{\text{eff}} = \max(\gamma_\rho, \gamma_\eta) \;\boxed{>}\; c_r\,(\omega_{*i}\omega_{*e})^{1/2}$$

$$\gamma_{res} \propto s_1 \Rightarrow \qquad s_1 > s_{1,crit}(\boldsymbol{profiles})$$

Critical shear condition (resistive regime)



two maxima of different size and amplitude



ECH beam aiming moved pol. during shot

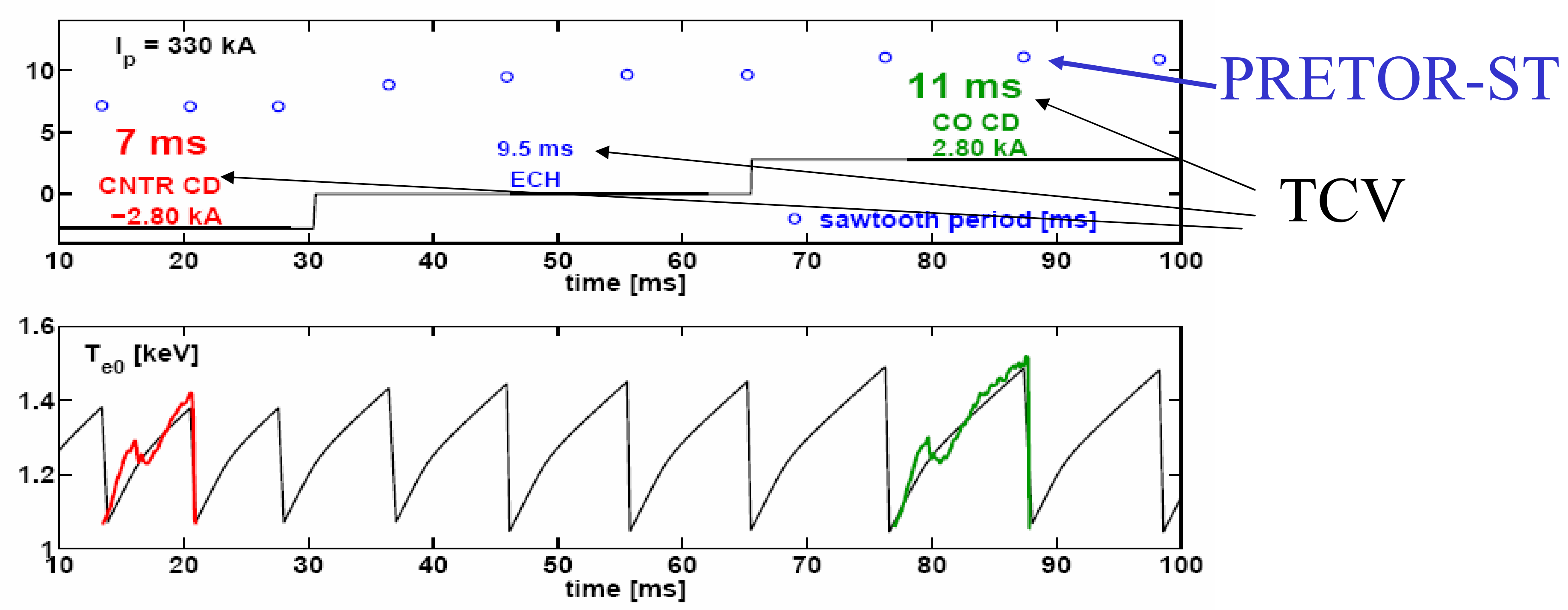
Basic demonstration in TCV:

Asymmetry in poloidal sweep for ST period

Measured in TCV (Goodman, EPS 1999)

ST period VERY sensitive to local CD
(well explained by Angioni et al NF 2003)

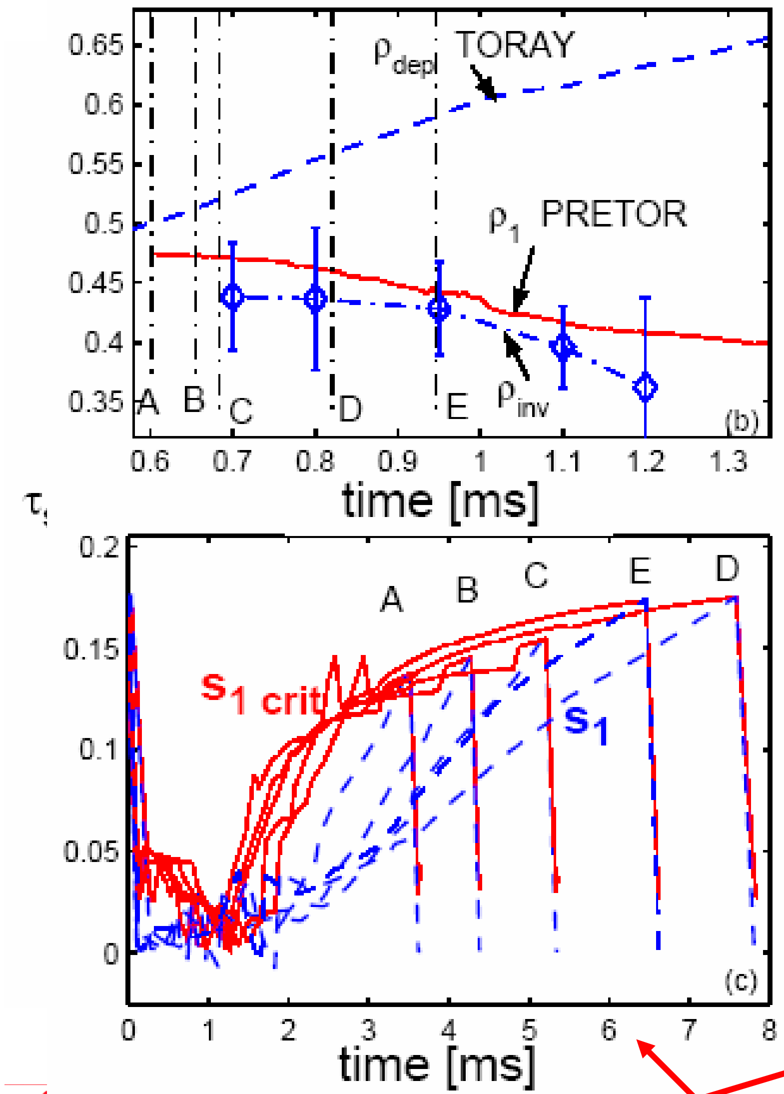
Small toroidal angle scan changes significantly ST period



Sensitivity well reproduced by PRETOR-ST with $s_1>s_{1,crit}$

1 free parameter normalised in ohmic phase (c_r)

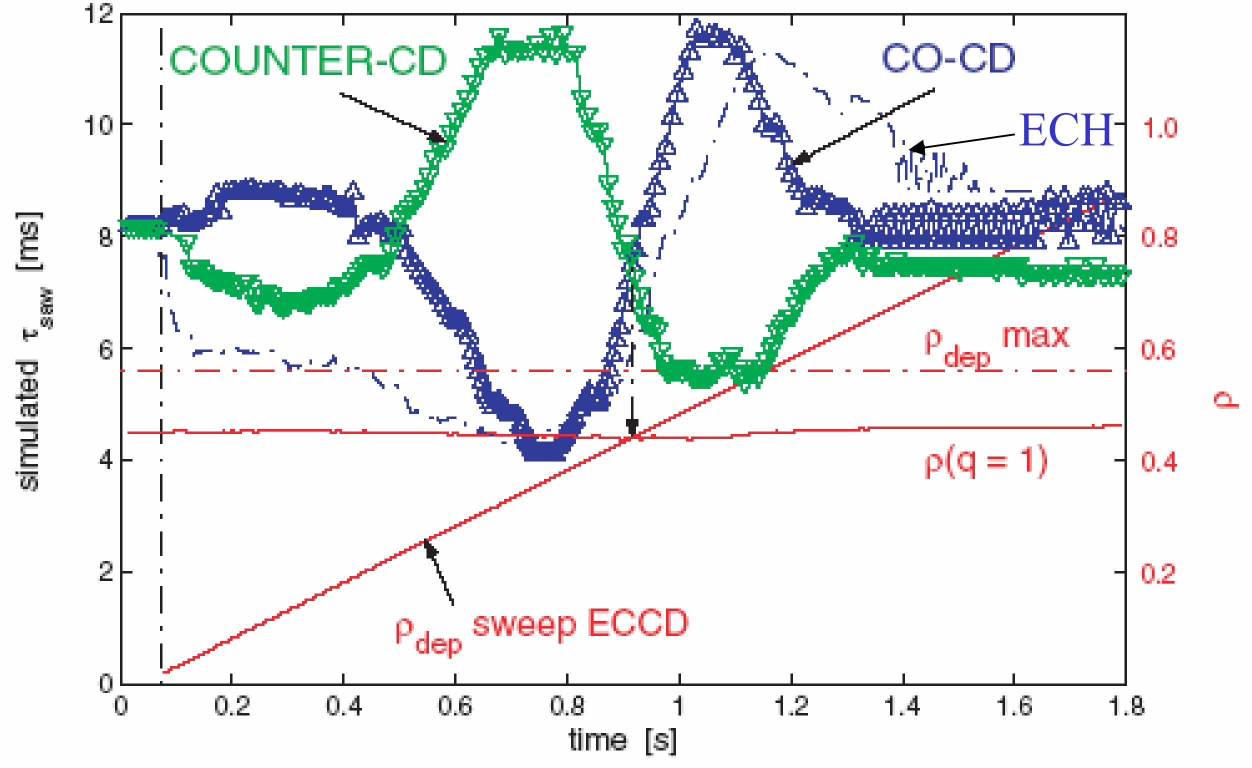
Modeling allows detailed understanding



- $s_{1,crit}$ depends on n_e, T_e, thus evolves on local confinement time scale
- s_1 evolves on resistive time scale
- Changing local CD or power deposition alters mainly time evolution of s_1, thus ST period
- Location of maximum ST period well defined and well predicted (down to equilibrium reconstruction errors)

notice fine radial scale

Effects of localised heating and CD when $\gamma>c_r(\omega_{*e}\ \omega_{*i})^{1/2}$ crash criteria determines ST



Dependence of ST period versus radial sweep of local co-CD, cnt-CD **or** heating

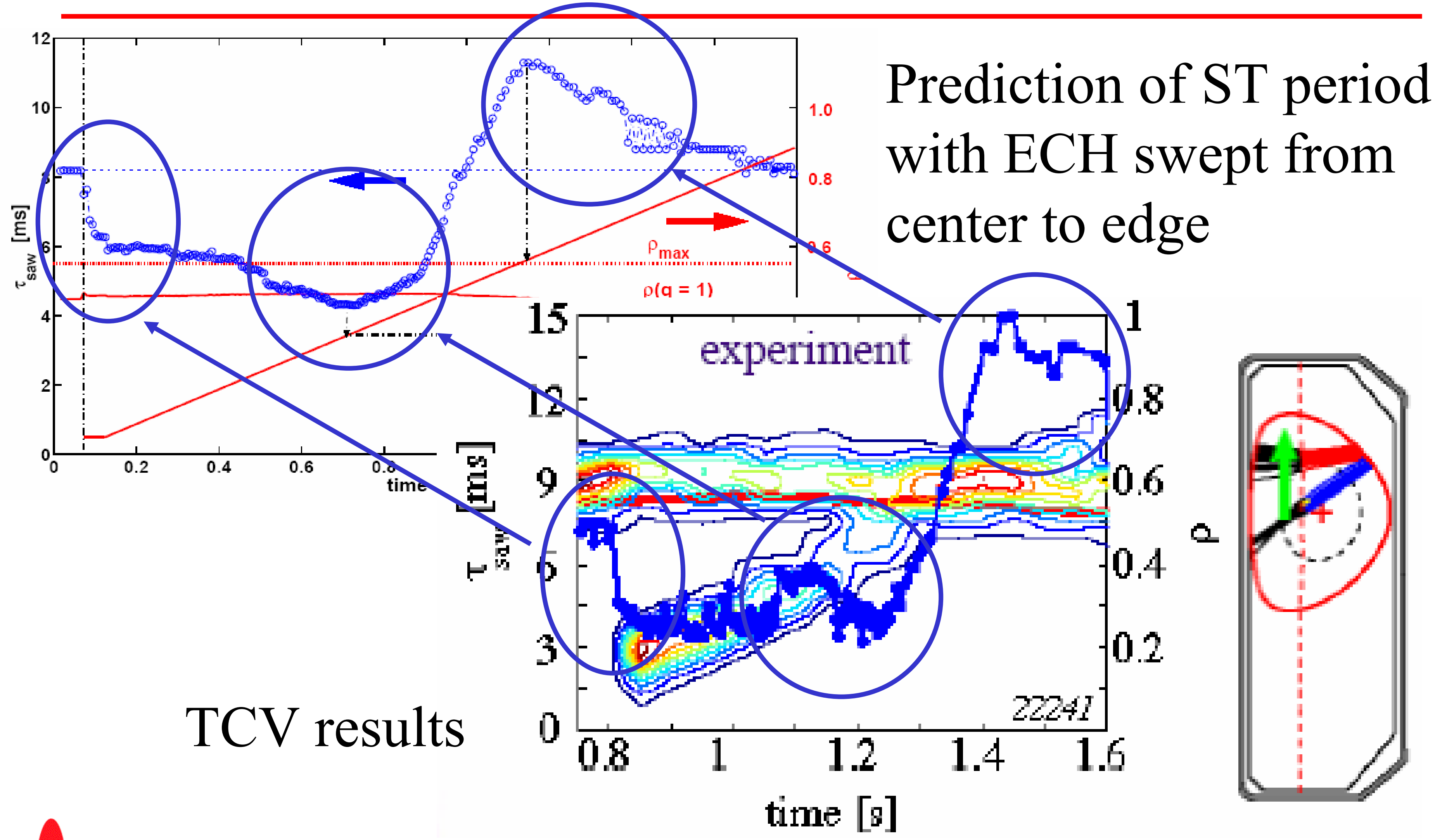
Simulation allows CD effects decoupled from heating

Symmetry around q=1 recovered

All experiments with heating and CD can be understood from "adding up" the above effects

Prediction "exercise"

Experimental set-up simulated before exp. performed



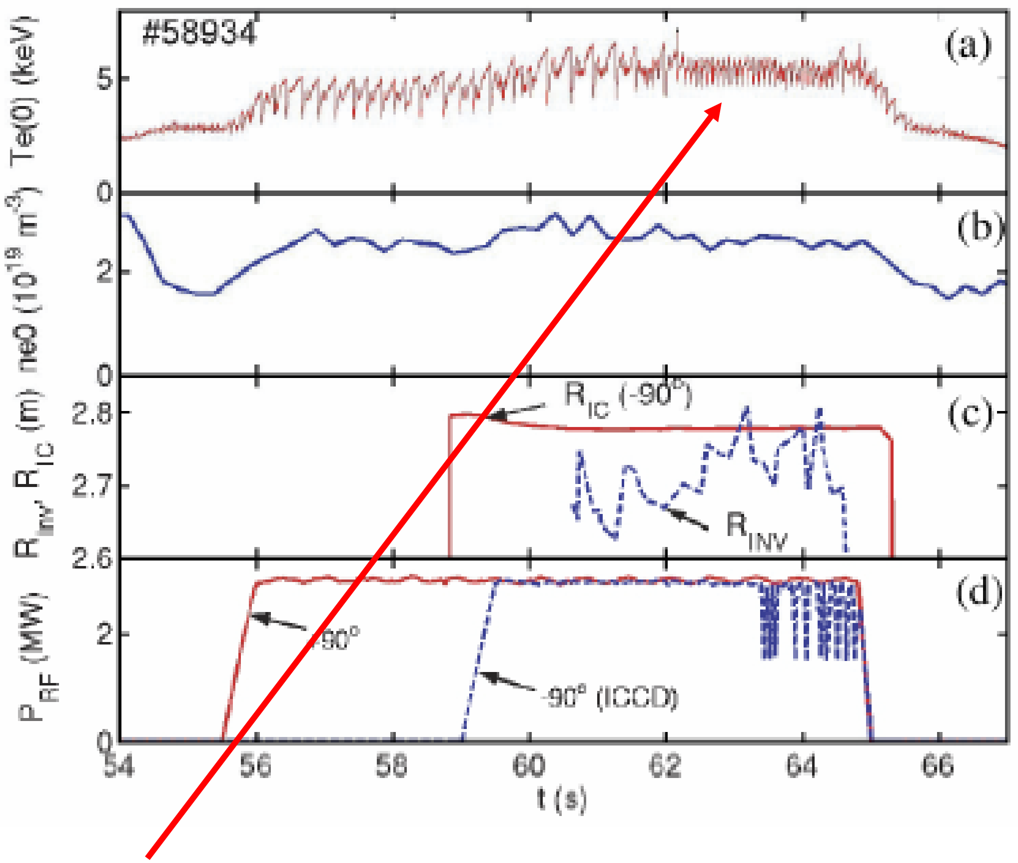
Prediction of ST period with ECH swept from center to edge

TCV results

ICRF fast particles also stabilise sawteeth

$$\delta W_{fast} \sim p'_{fast}/s_1$$

Thus can modify stabilised ST by altering s_1 in same way as with CD and $s_1 > s_{1,crit}$ regime or modifying p_{fast}



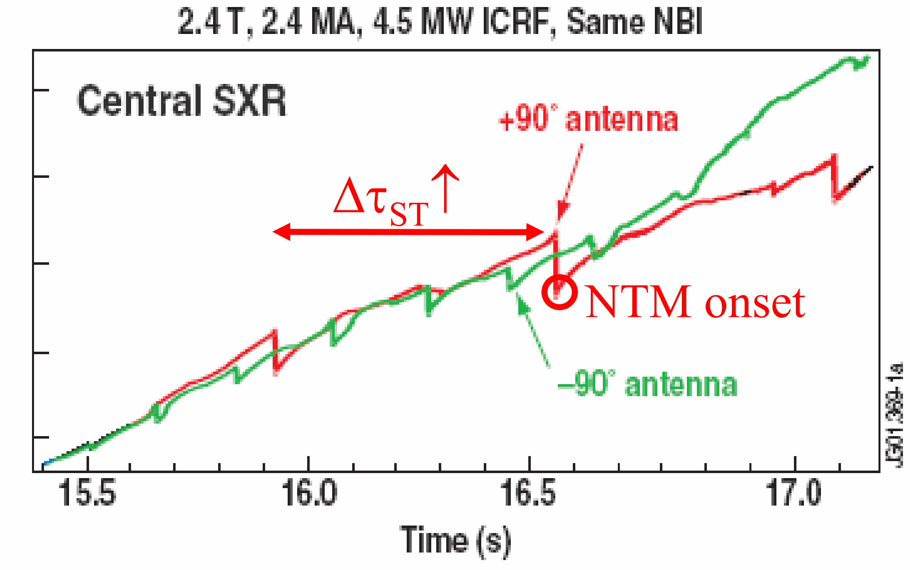
Very small ST period obtained despite central ICRH

Eriksson et al, PRL 2004

Controlling sawtooth period changes significantly onset β of NTMs

Understanding of sawtooth control used for NTMs control

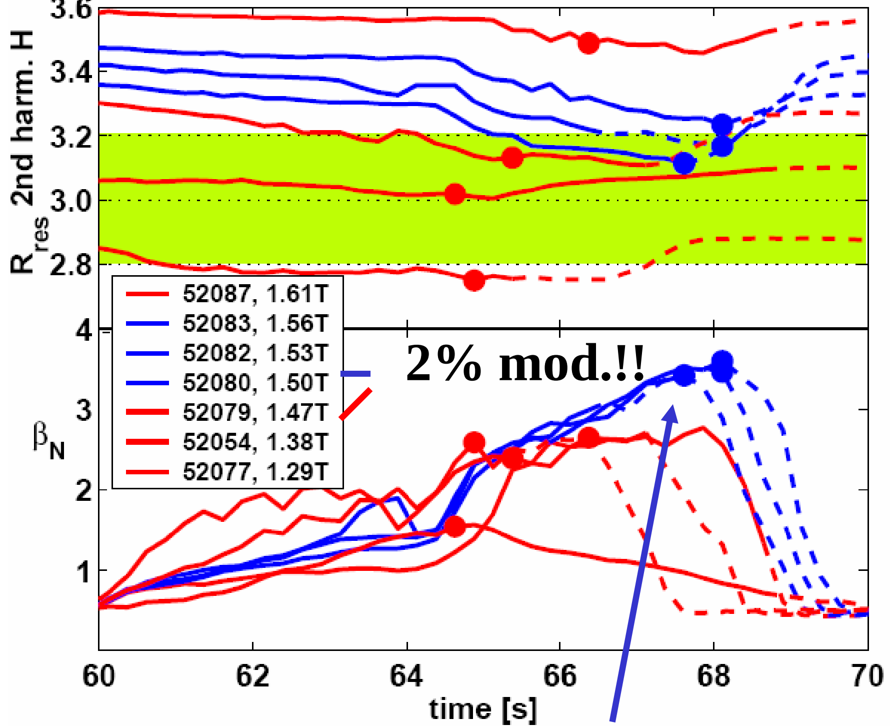
1st harmonic minority ICRH



+90: phase: $\beta_{N,onset}\approx1$

-90: No NTM with β_N up to 2

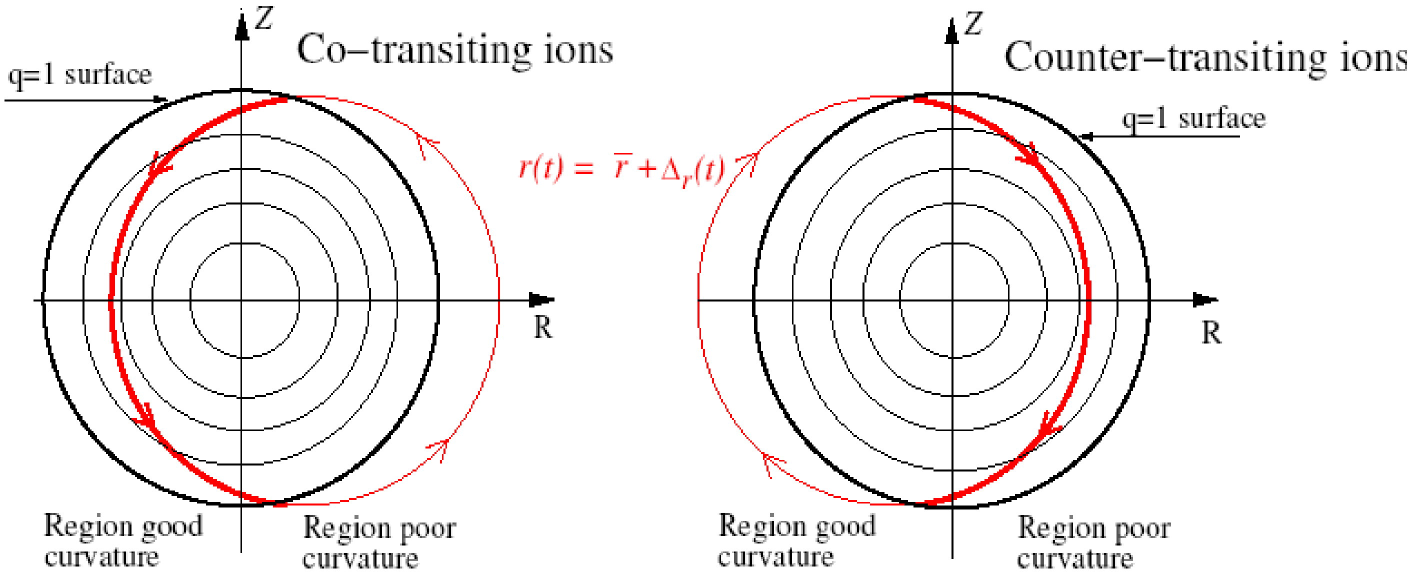
2^{nd} harmonic



β_N~3.5

Sauter et al, PRL 2002

Effect of Passing Energetic Ions



[Graves, PRL, 92, 2004]

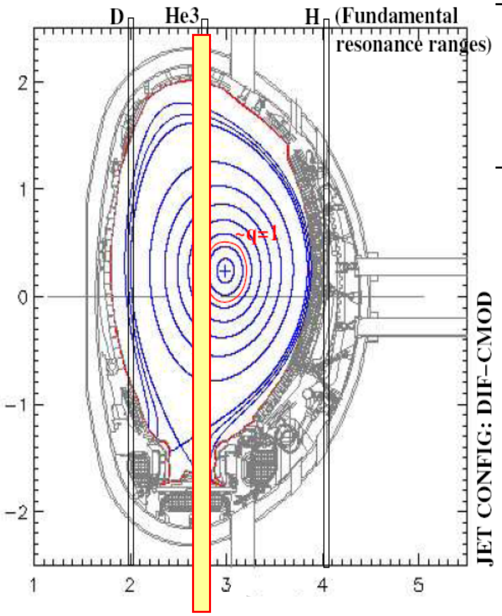
- Only get net effect on stability when distribution asymmetric:

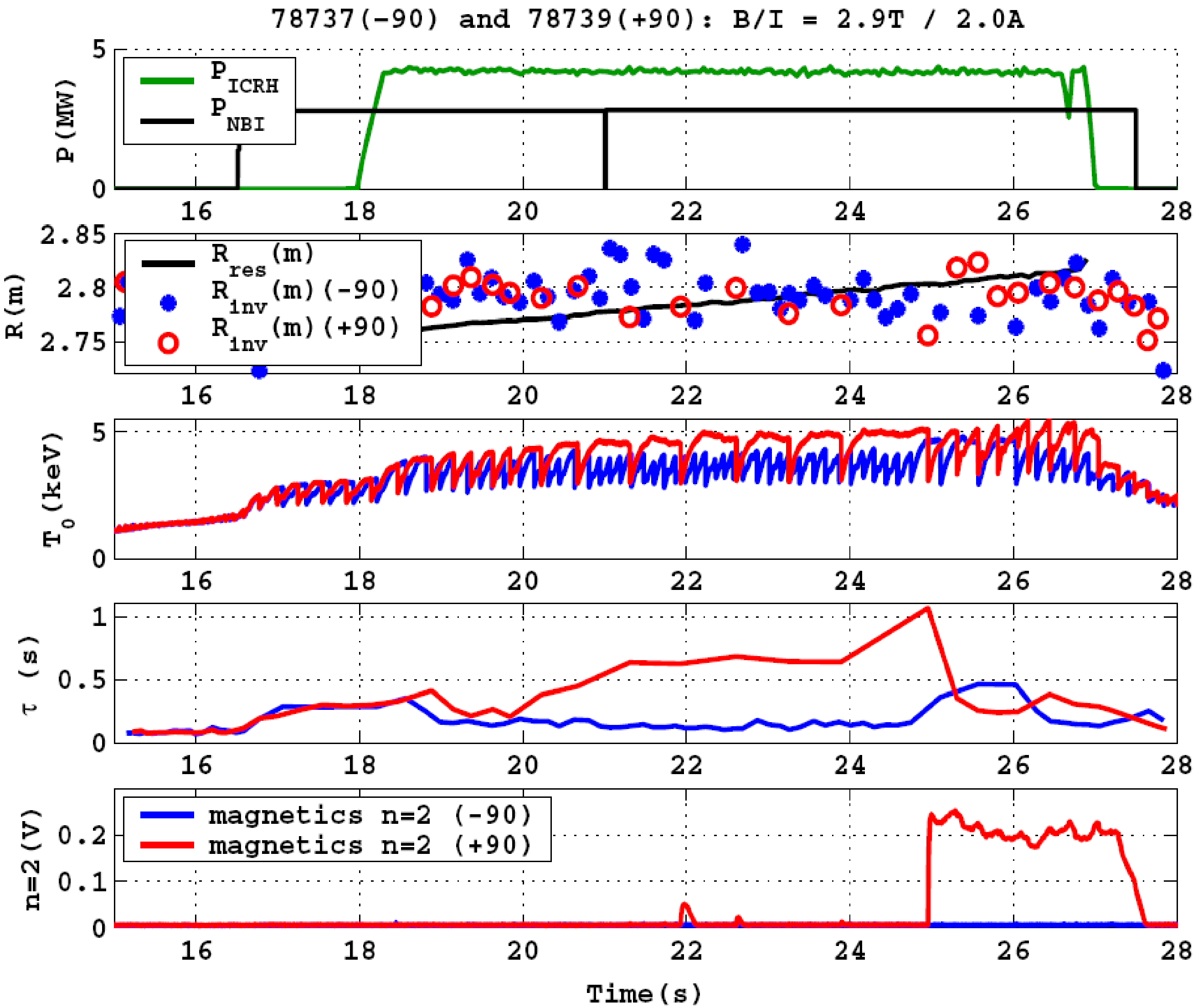
$$F_h(v_{||}^{+}) \neq F_h(v_{||}^{-})$$

- Effect increasingly strong for increasing Δ_r(increasing fast ion energy)
- Destabilisation for: $F_h(v_{||}^{+}) > F_h(v_{||}^{-})$ and $\nabla F_h|_{r1} > 0$

  or: $F_h(v_{||}^{+}) < F_h(v_{||}^{-})$ and $\nabla F_h|_{r1} < 0$

HFS ICRH control in JET





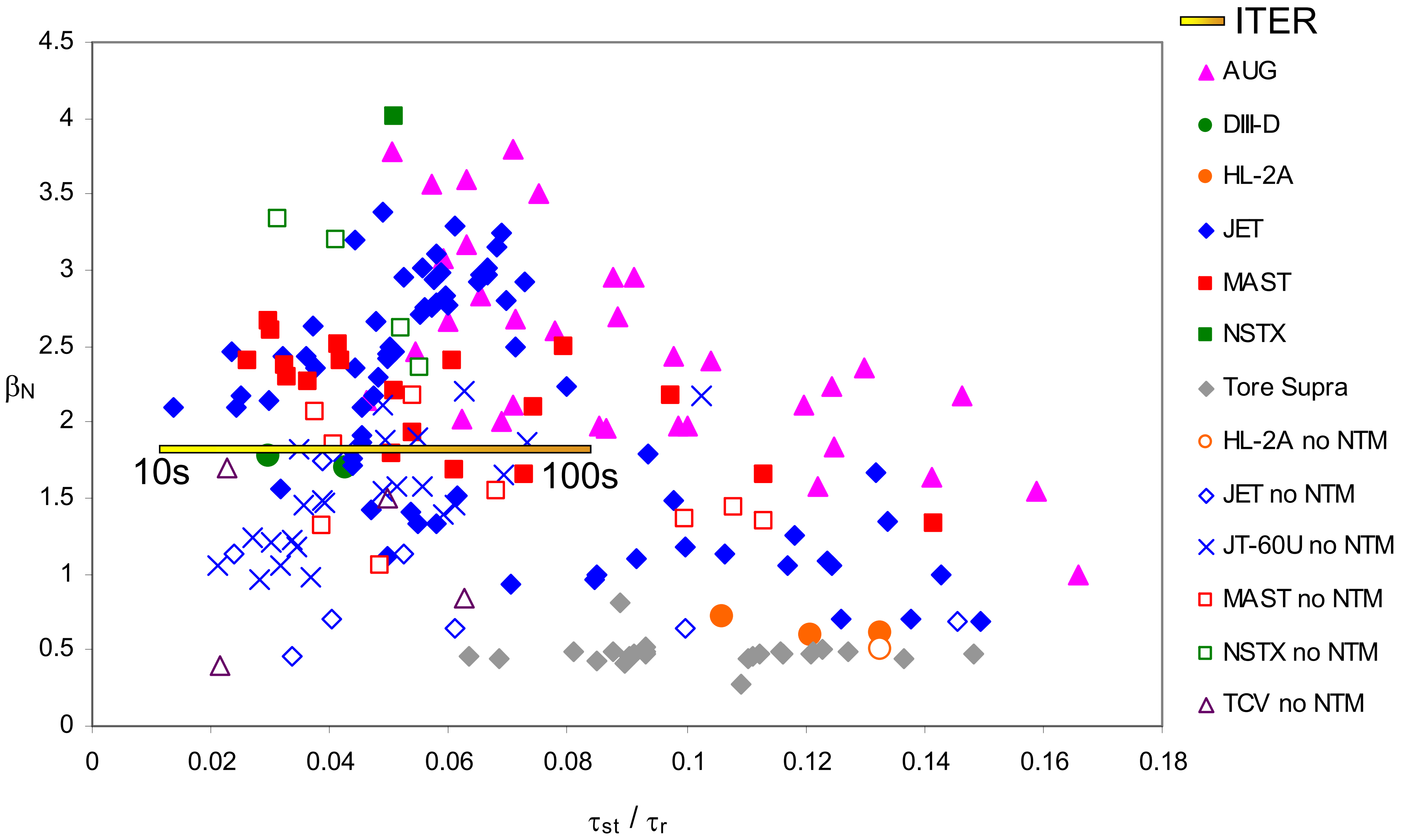
Sawtooth lengthening or shortening depended on antenna phasing.

Resonance position has to be deposited very close to q=1 (3 percent minor radius), or 1 percent field variation!

Technically challenging, RTC required for routine use.

Graves et al, NF 2010, Nature Comm. 2012

Link between ST period and NTMs

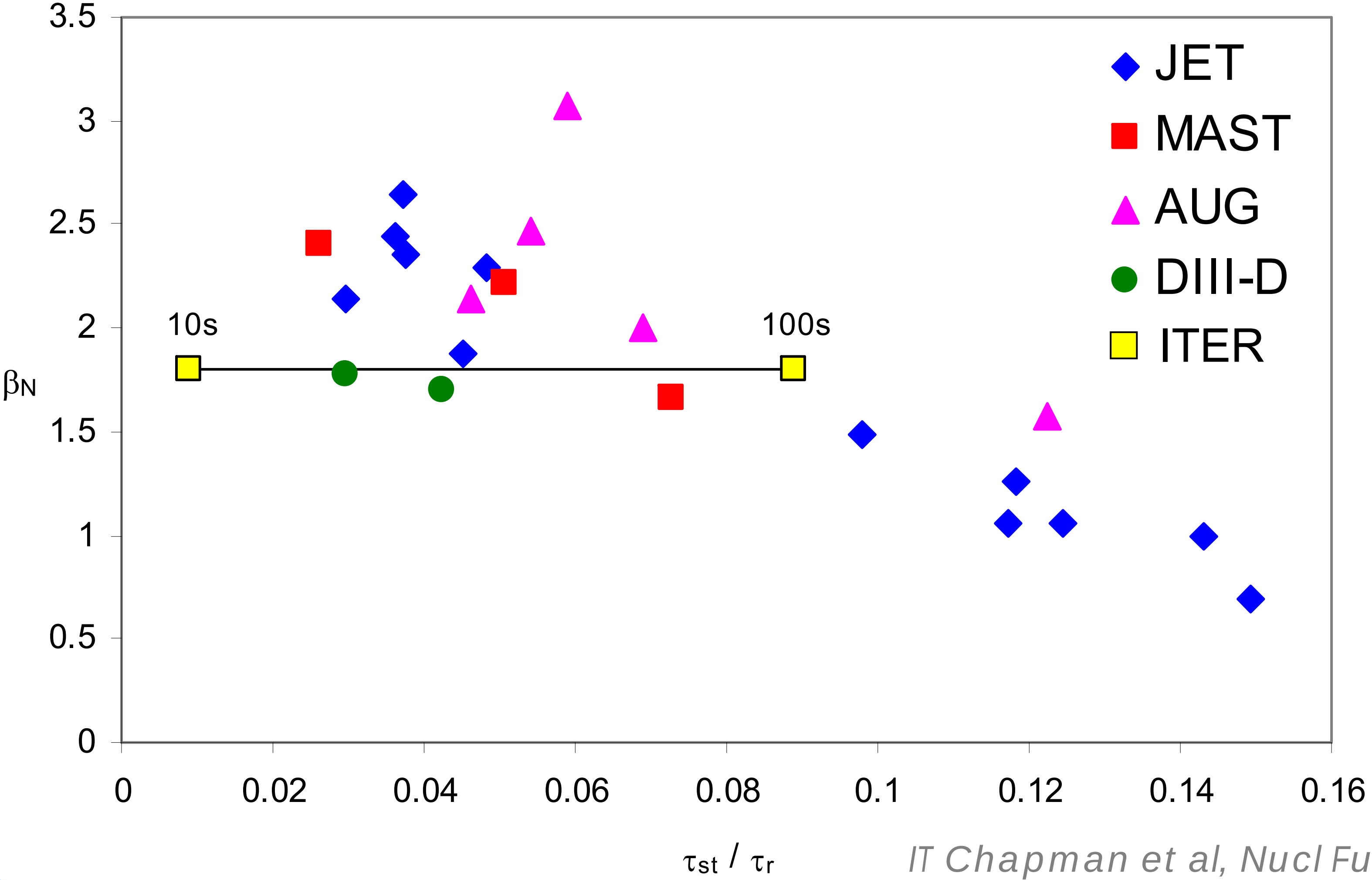


IT Chapman et al, Nucl Fusion, 2010

ITER-like Data Set

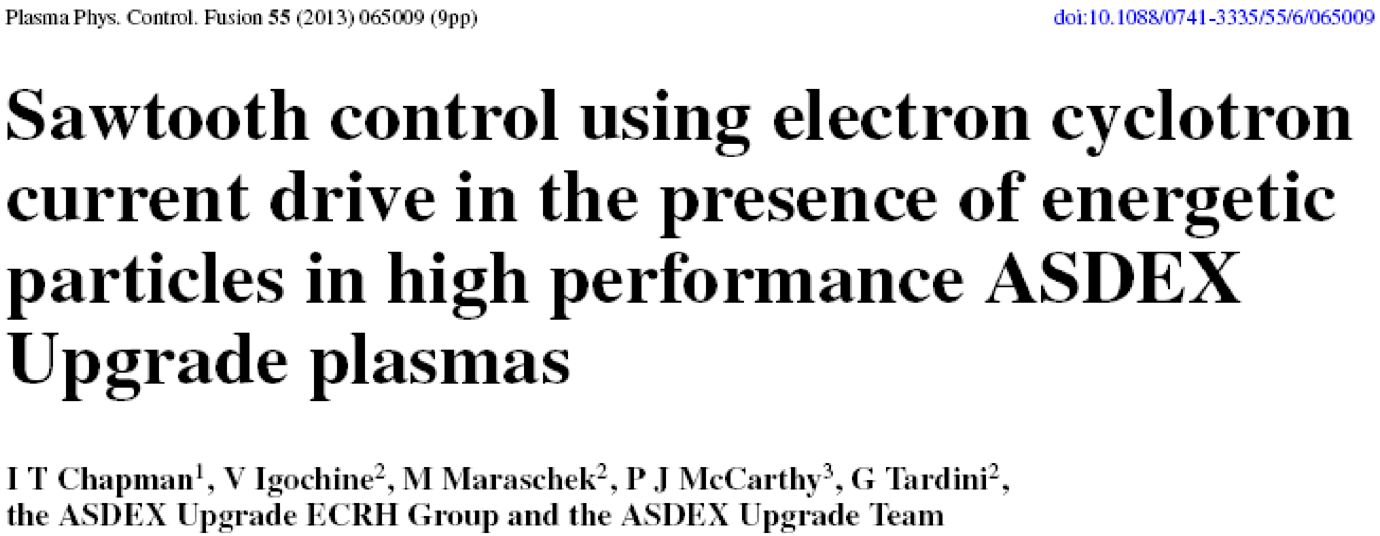
- Trimming data to include only:

$\delta \in[0.3,0.4]$, $\kappa\in[1.65,1.85]$, $r_1/a\in[0.3,0.45]$, $P_{aux}/P_{L\text{-}H}\in[1.3,1.7]$



IT Chapman et al, Nucl Fusion, 2010

Sawtooth Control ITER related



Plasma Phys. Control. Fusion **55** (2013) 065009 (9pp) doi:10.1088/0741-3335/55/6/065009

Sawtooth control using electron cyclotron current drive in the presence of energetic particles in high performance ASDEX Upgrade plasmas

I T Chapman[1], V Igochine[2], M Maraschek[2], P J McCarthy[3], G Tardini[2], the ASDEX Upgrade ECRH Group and the ASDEX Upgrade Team

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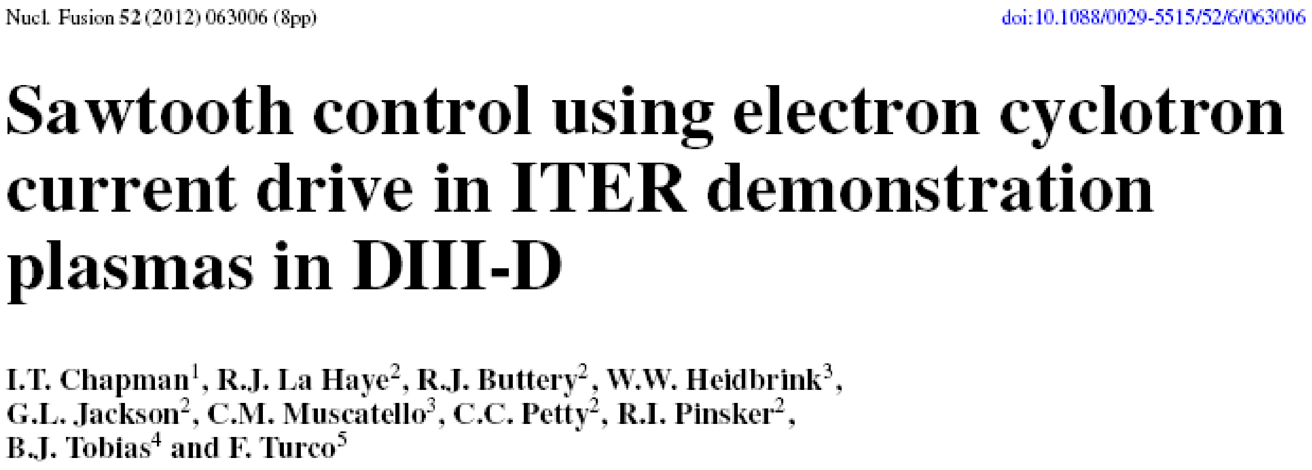
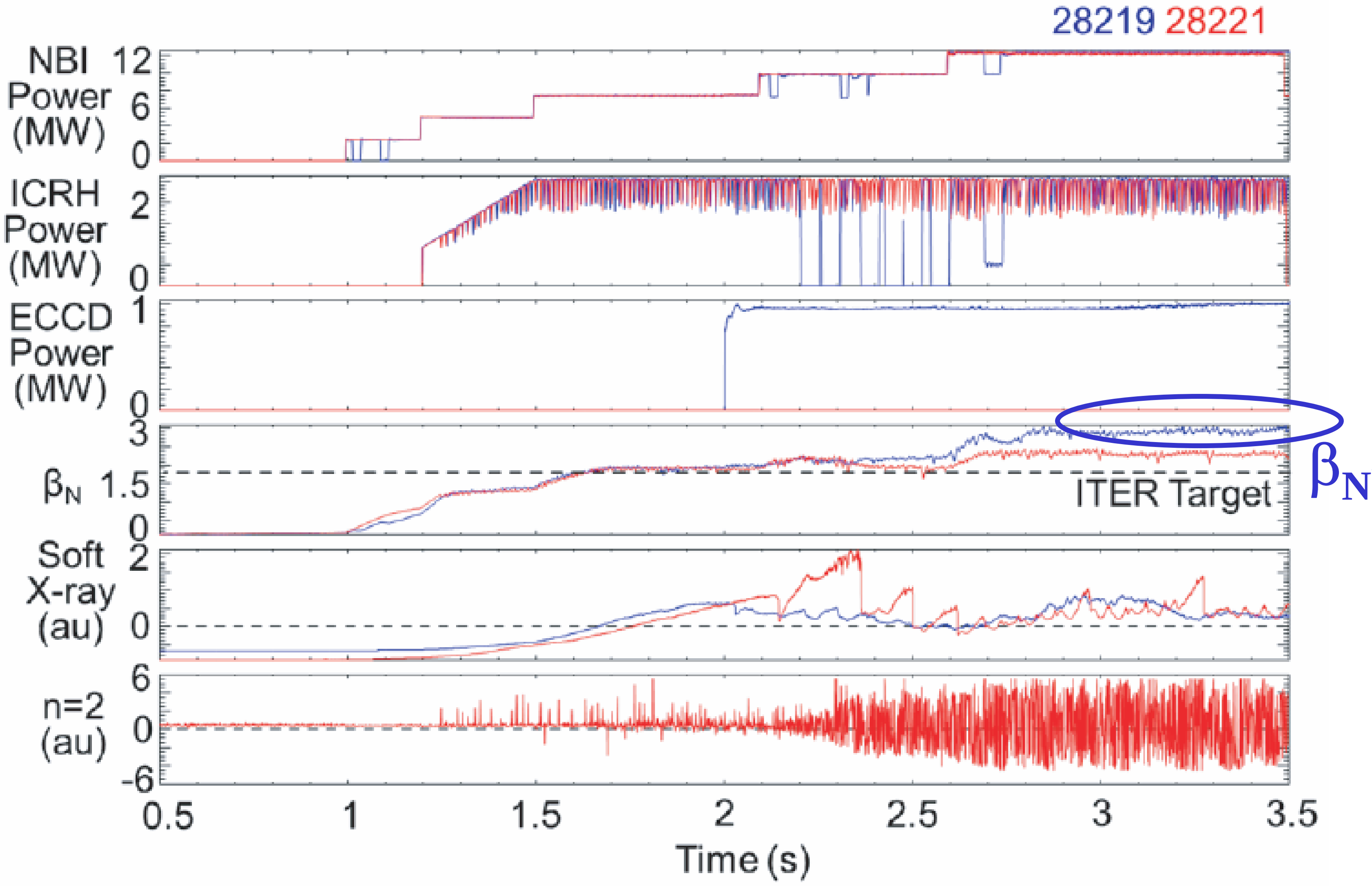


Nucl. Fusion **52** (2012) 063006 (8pp) doi:10.1088/0029-5515/52/6/063006

Sawtooth control using electron cyclotron current drive in ITER demonstration plasmas in DIII-D

I.T. Chapman[1], R.J. La Haye[2], R.J. Buttery[2], W.W. Heidbrink[3], G.L. Jackson[2], C.M. Muscatello[3], C.C. Petty[2], R.I. Pinsker[2], B.J. Tobias[4] and F. Turco[5]

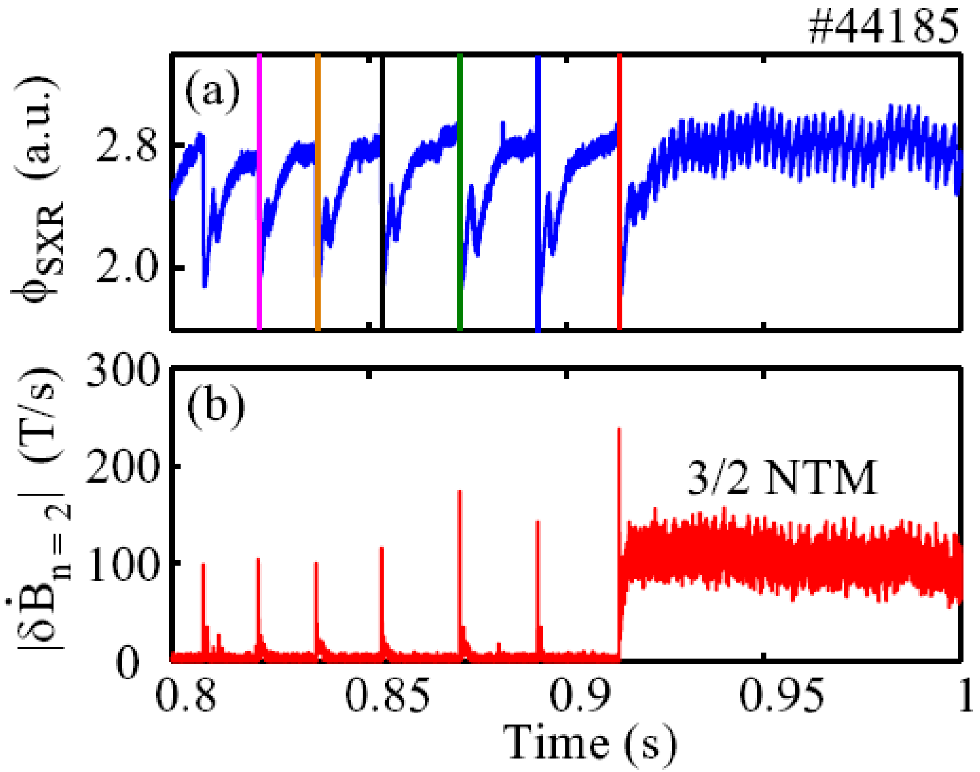
High β_N with Sawtooth Control on AUG



β_N~3

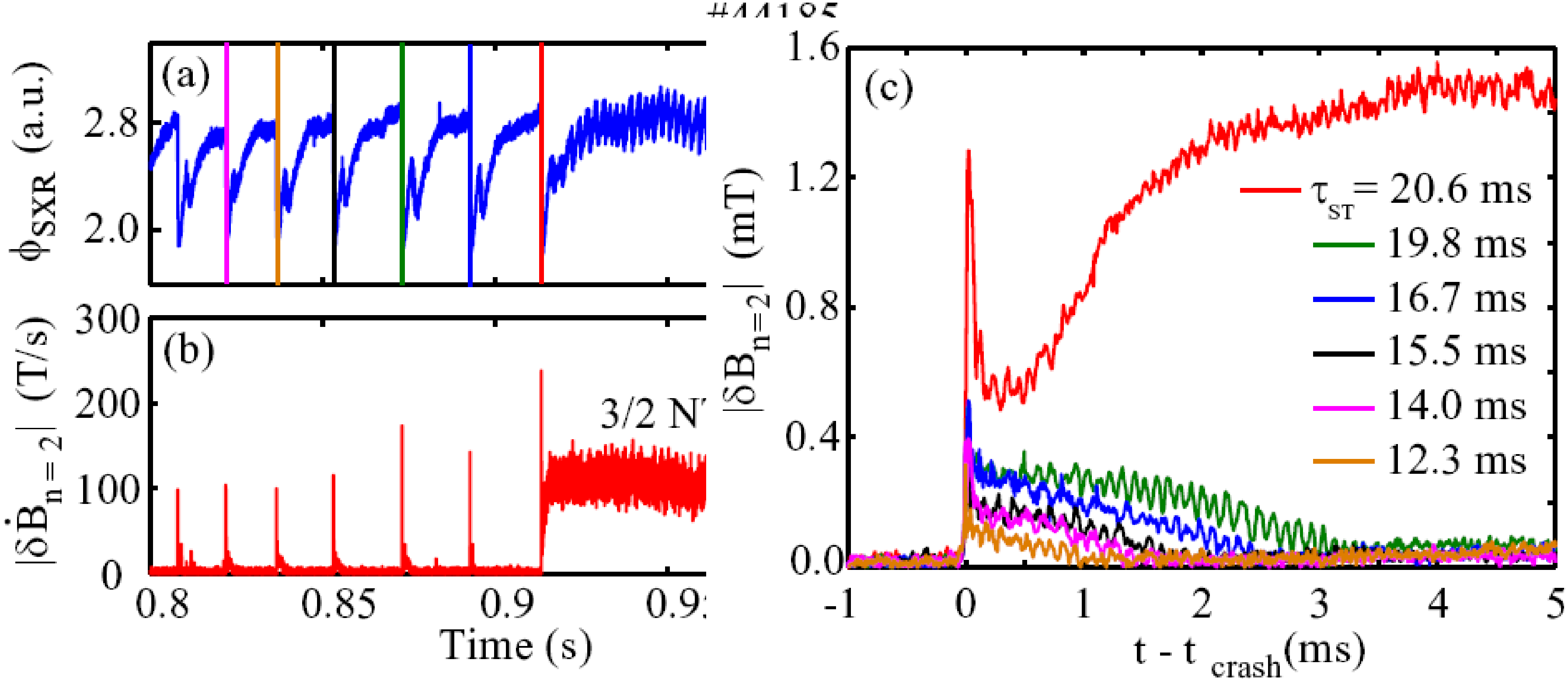
Chapman et al, PPCF 55 (2013) 065009

Sawteeth Can trigger NTMs at ST crash



Canal et al, NF 53 (2013) 113026

Sawteeth Can trigger NTMs at ST crash



Canal et al, NF 53 (2013) 113026

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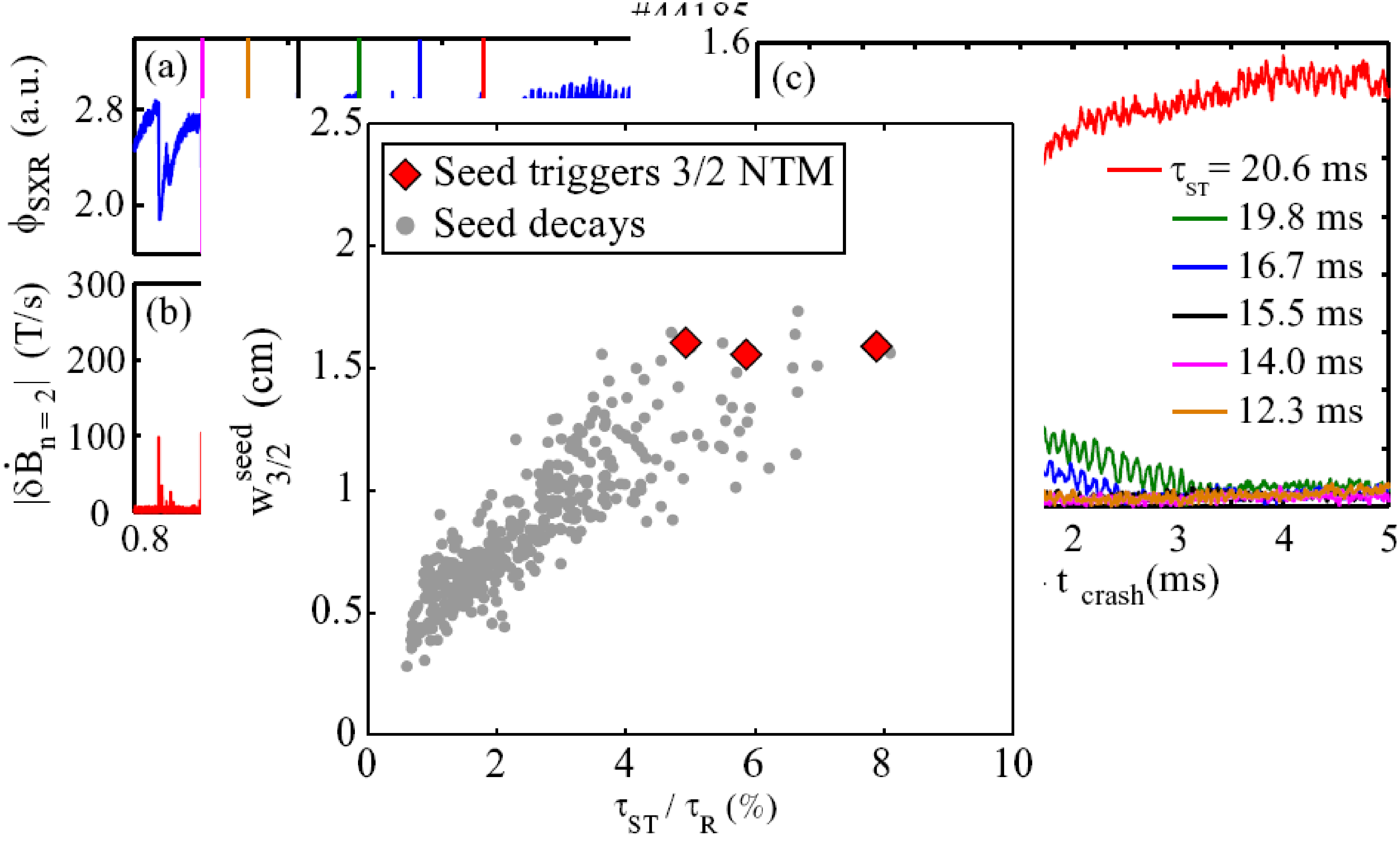
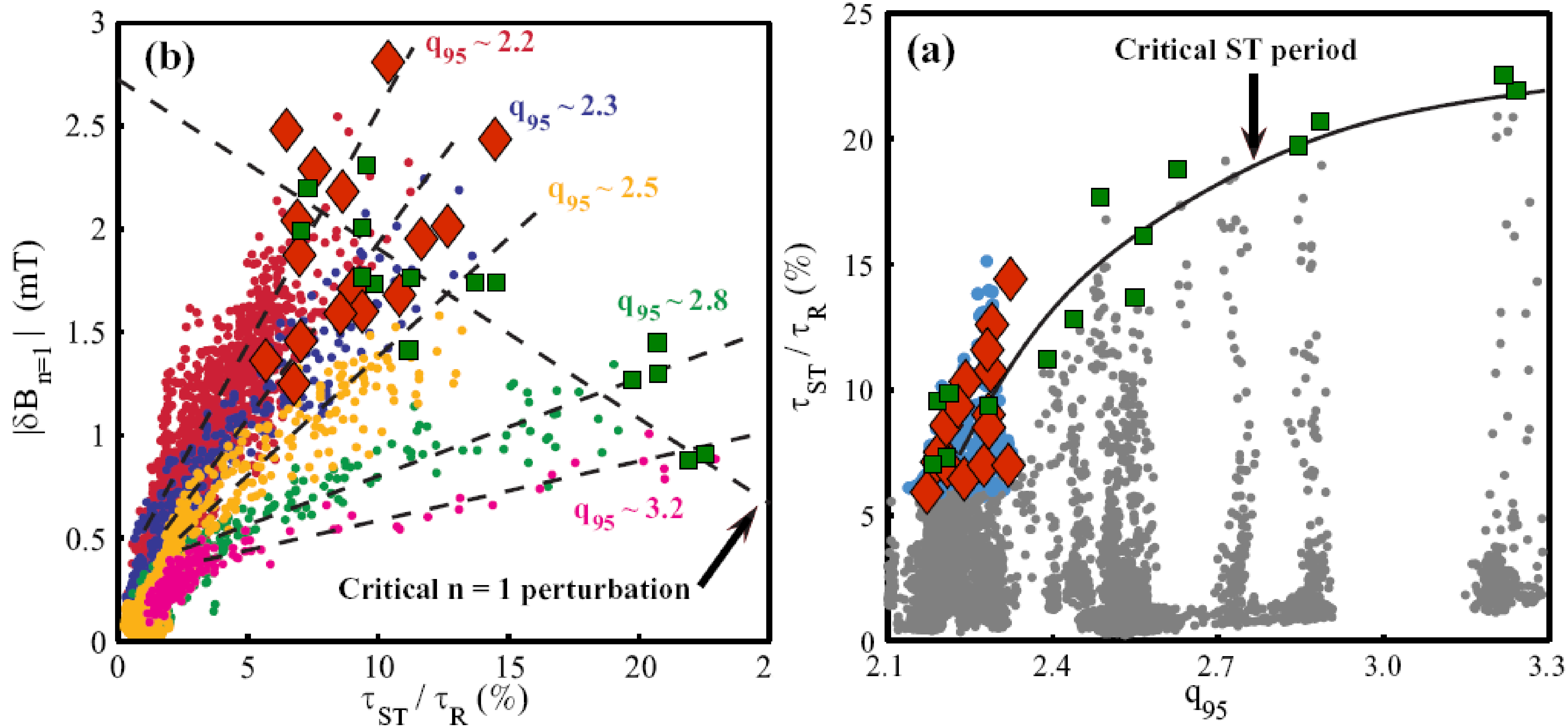


Canal et al, NF 53 (2013) 113026

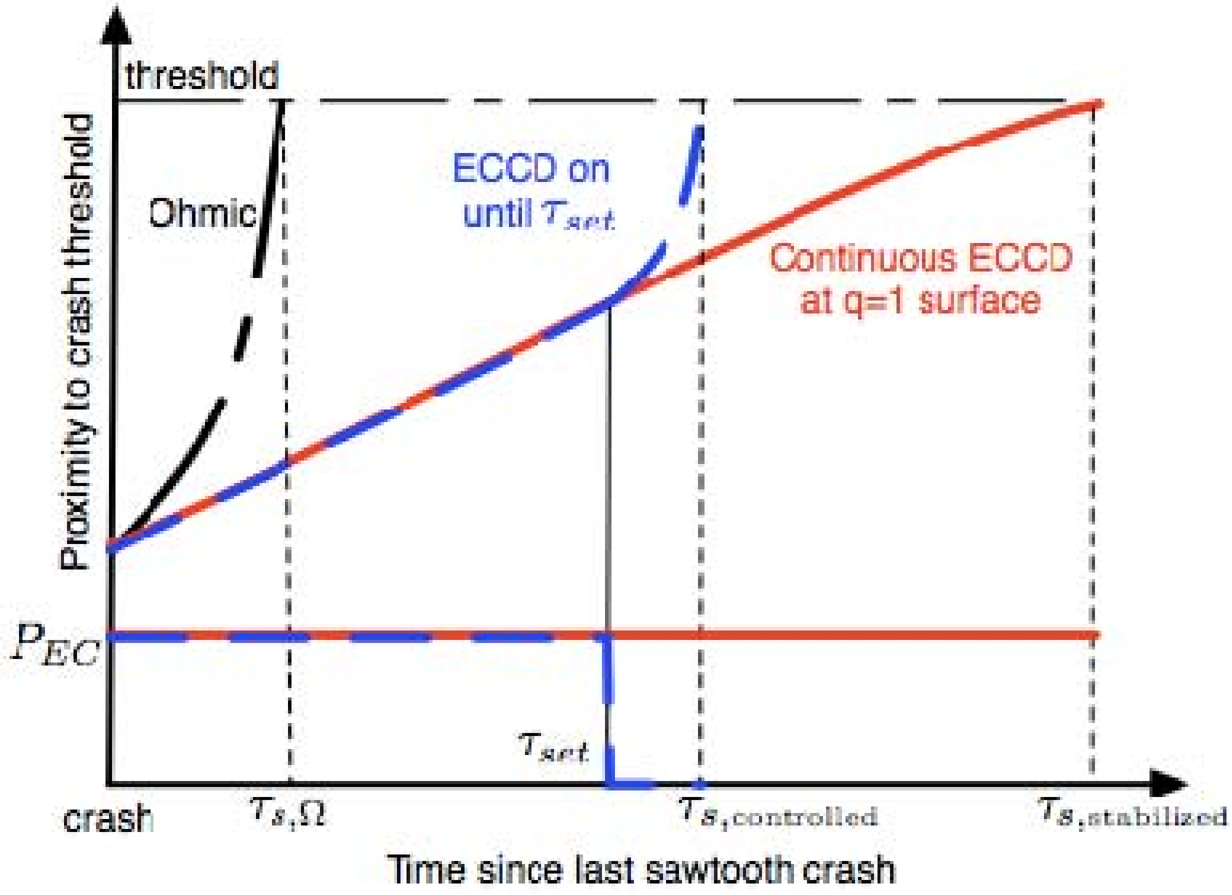
Perturbation depends on ST period and q_{95}



- This explains (after-facts) why we did L-H at high q_{95} in JET to avoid NTMs after 1st (*unique*) long ST period

Canal et al, NF 53 (2013) 113026

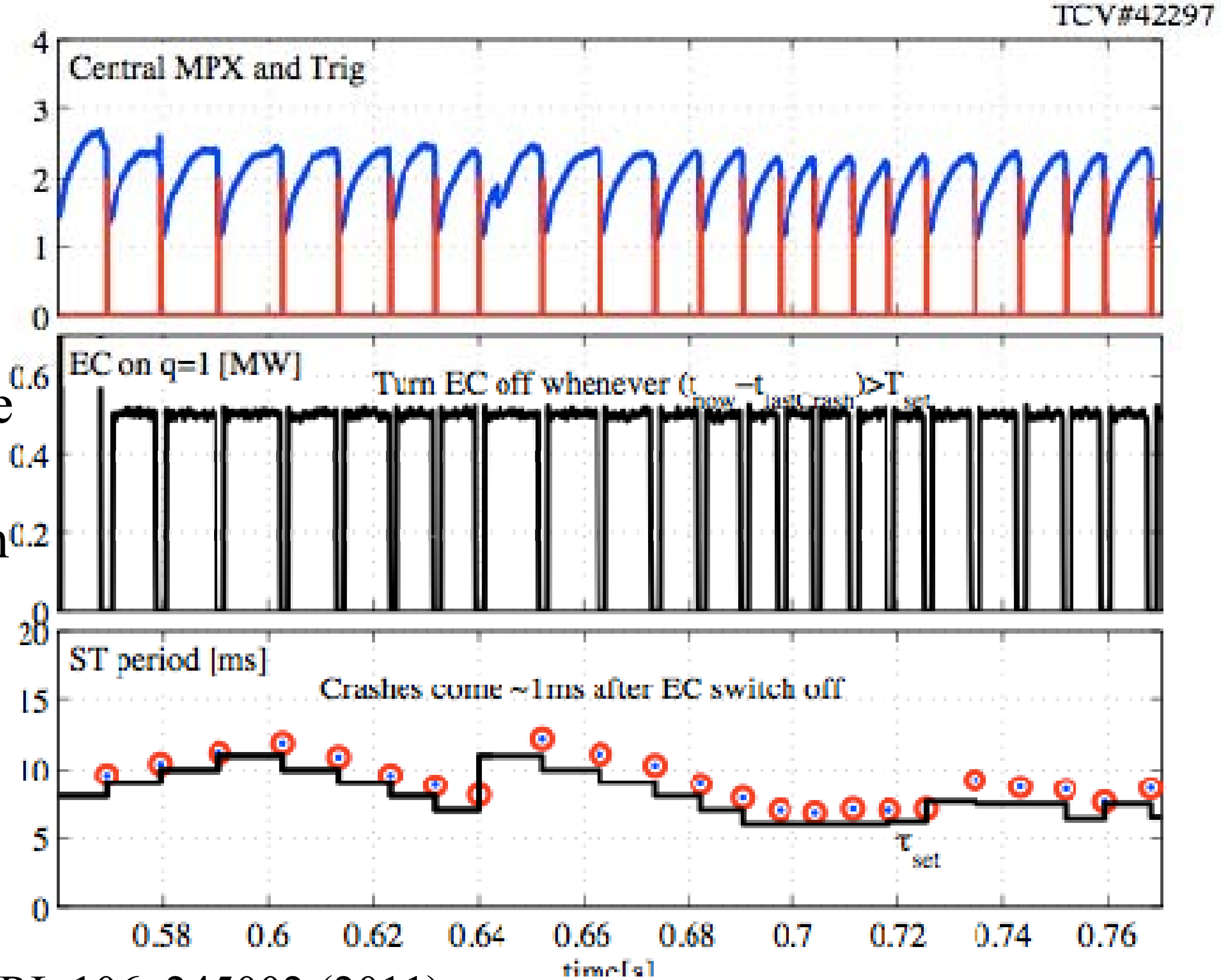
Simple ST control (in real-time)



- Use known effects of ECCD on sawteeth as "on/off" control knob
- Leads to sawtooth PACING and sawtooth LOCKING control

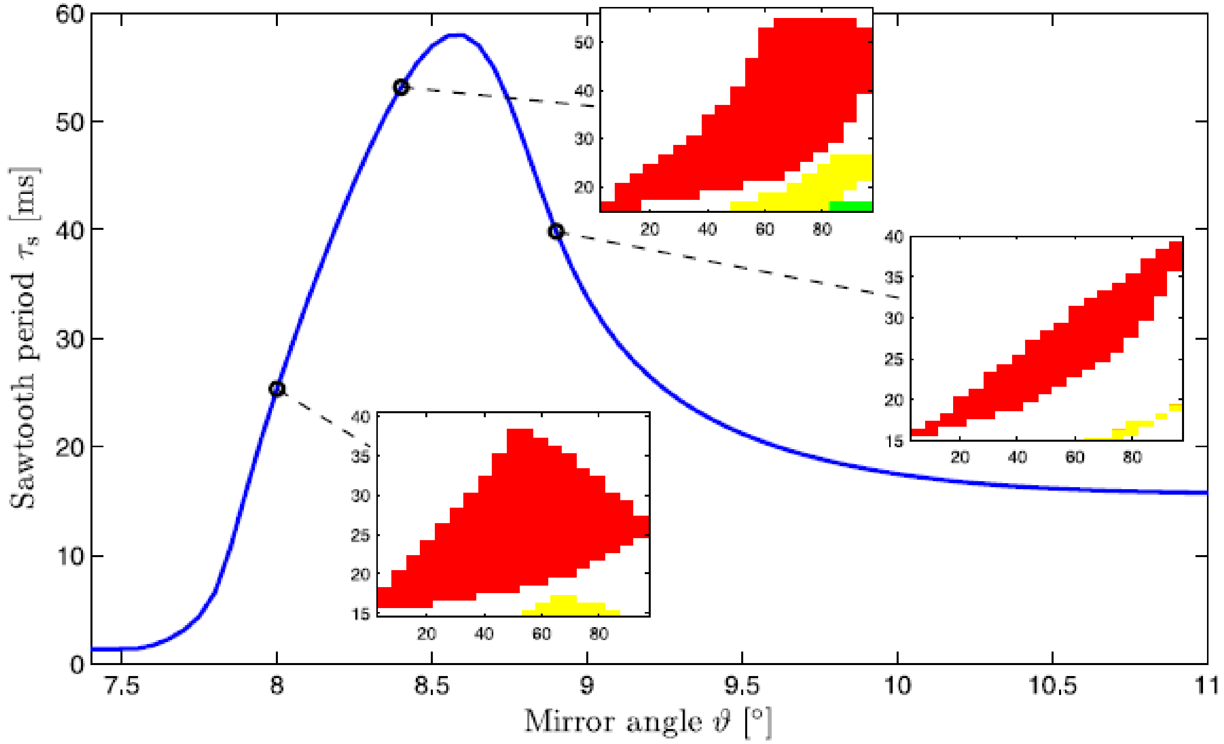
Sawtooth pacing demonstrated on TCV

- Pre-program a sequence of τ_{set}, one value per crash
- Has an immediate effect on the *ongoing* sawtooth
  - – One can not expect for a faster response than this



Goodman et al, PRL 106, 245002 (2011)

Sawtooth locking predicted by modeling then expt



Witvoet et al, NF 51, 103043 (2011)

Lauret et al, NF 52, 062002 (2012)

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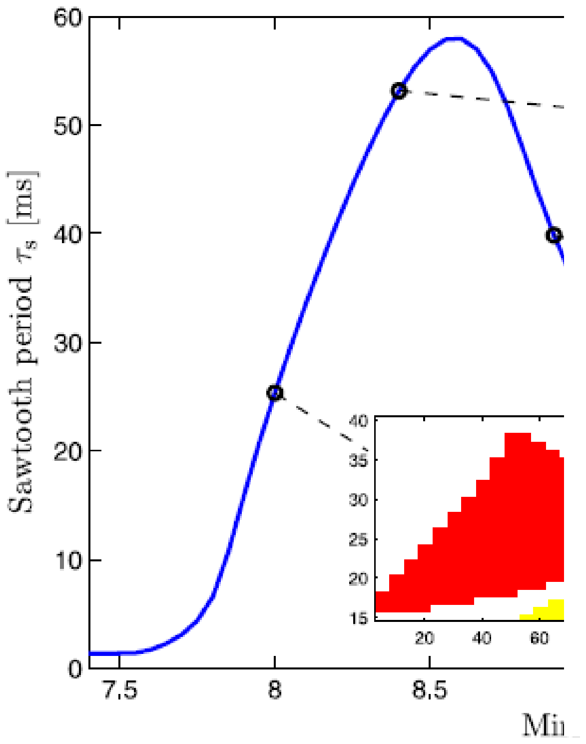

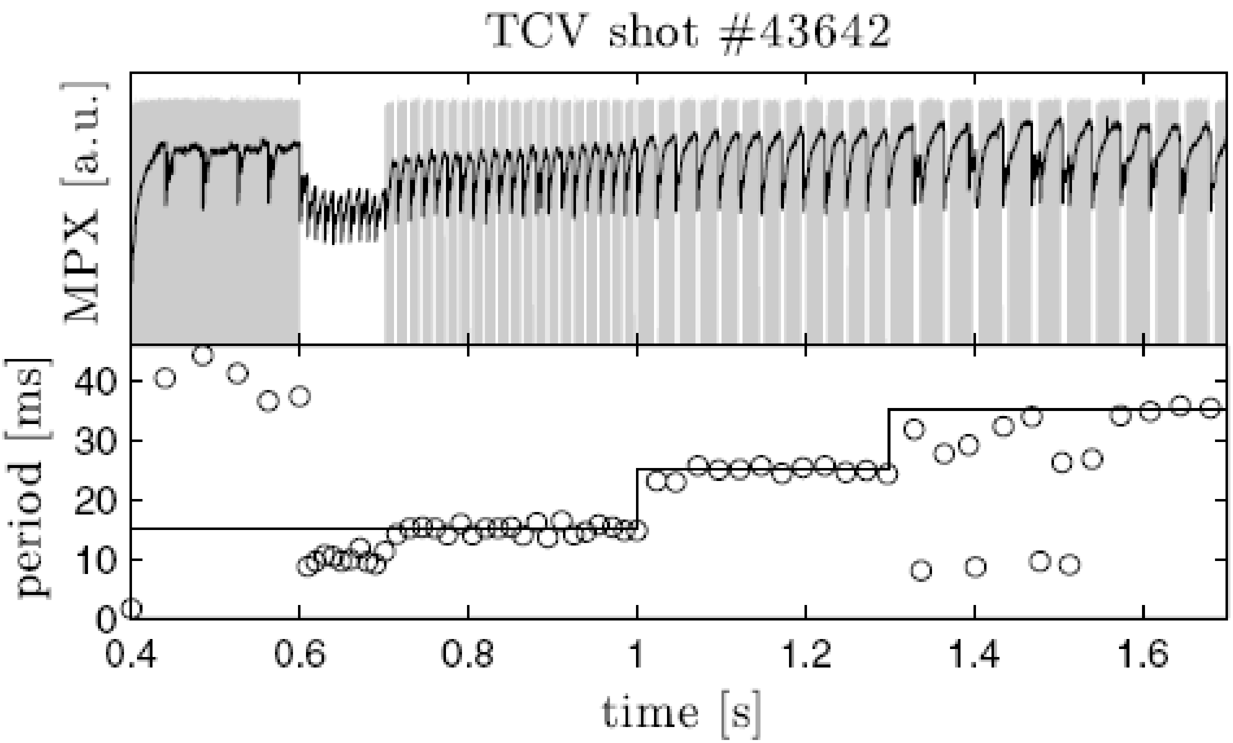

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Expt on TCV proposed by NL group

Lauret et al, NF 52, 062002 (2012)

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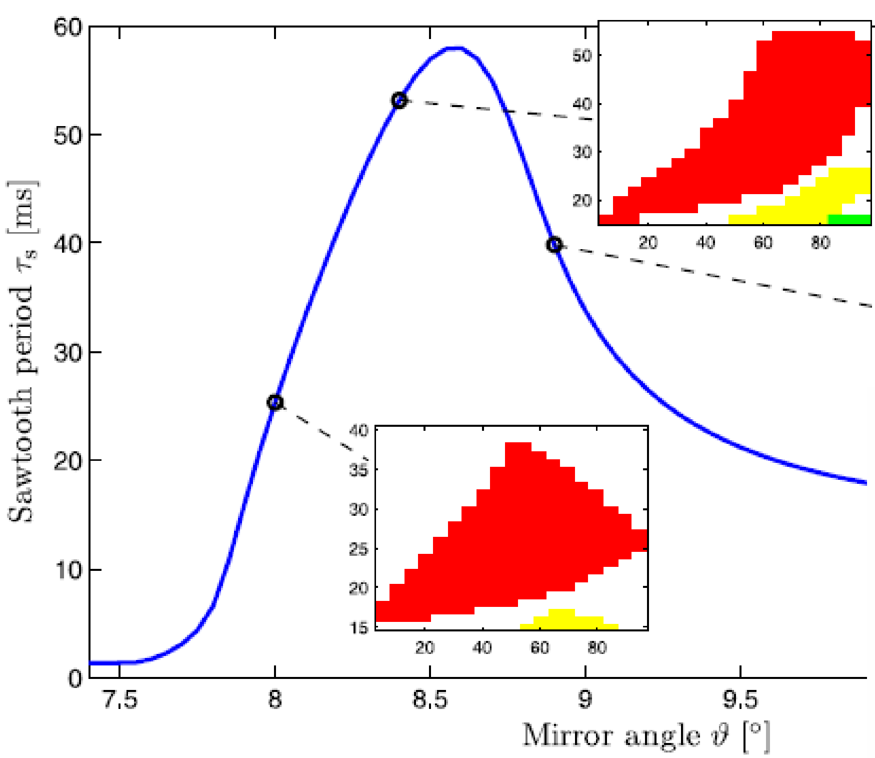
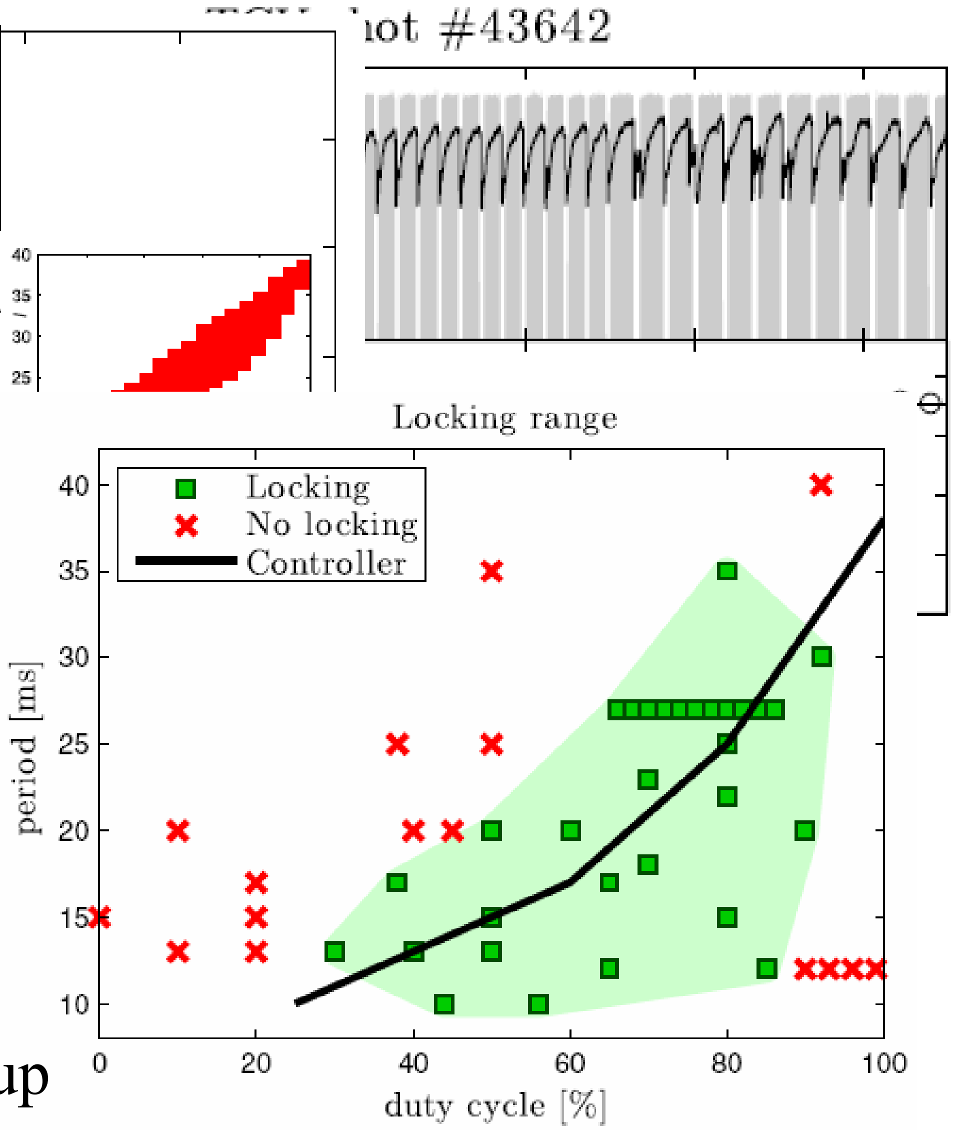


Witvoet et al, NF 51, 103043 (2011)



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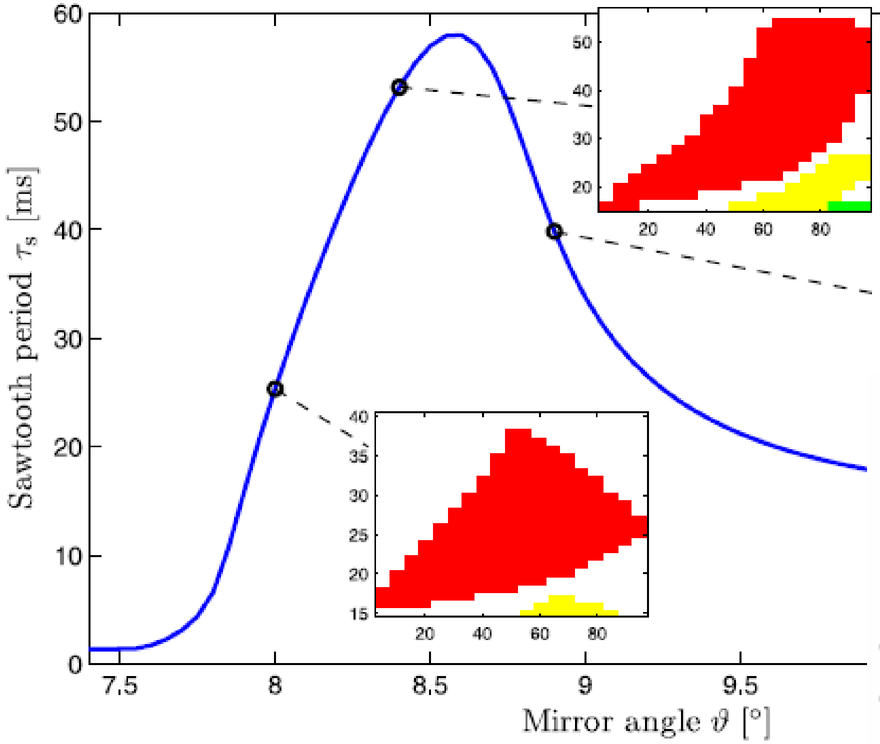
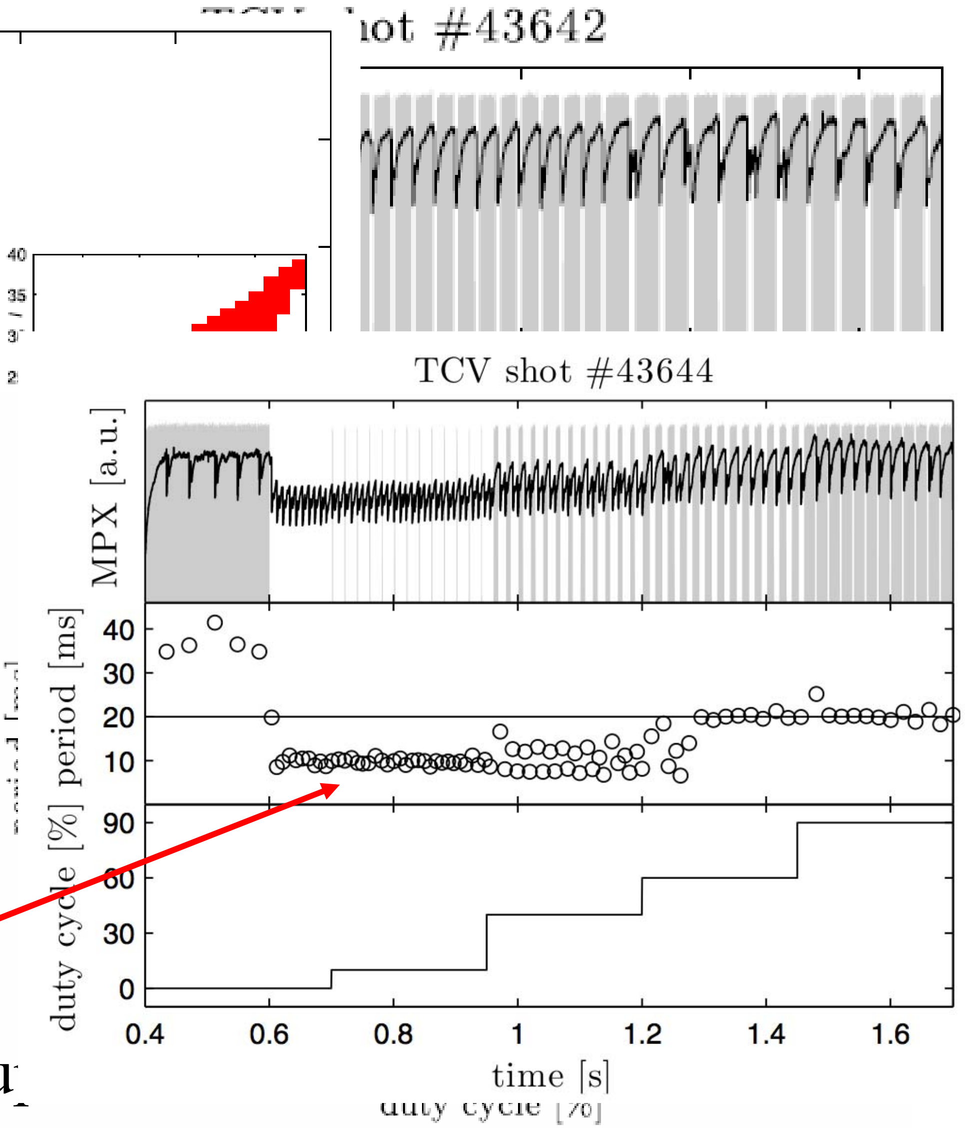


Witvoet et al, NF 51, 103043 (2011)

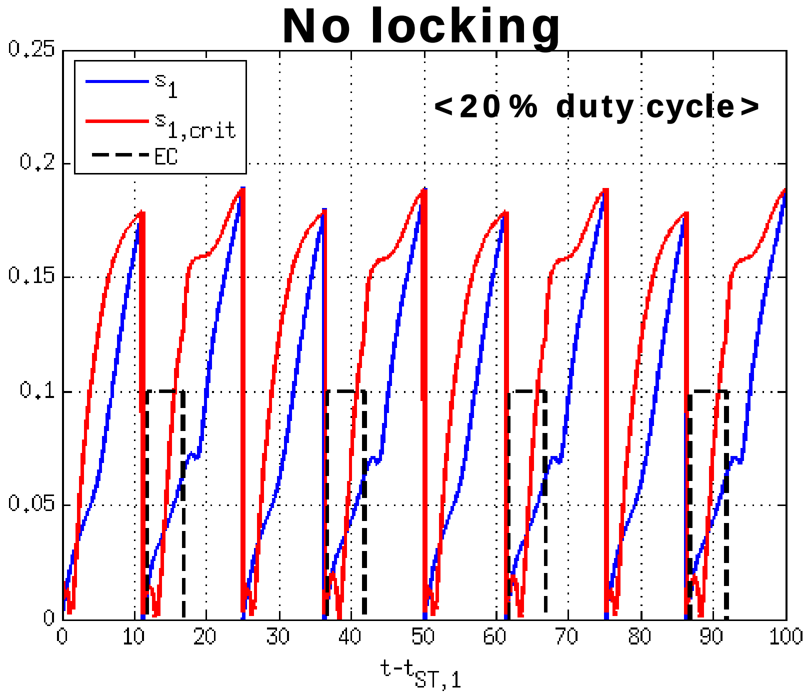


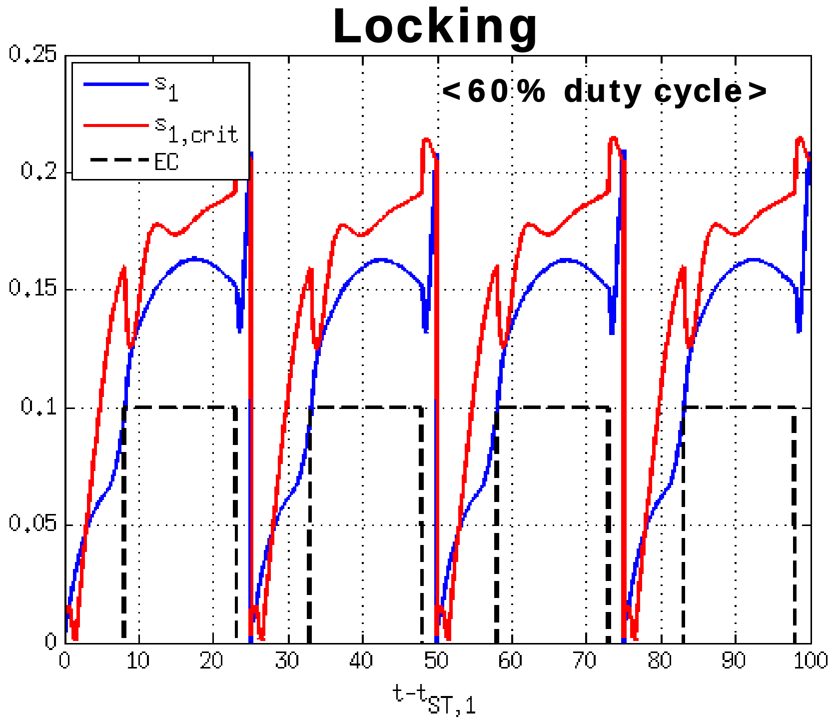
Can also "lock" at half period

Expt on TCV proposed by NL grou

Lauret et al, NF 52, 062002 (2012)

Simulation provides details about time evolution/locking

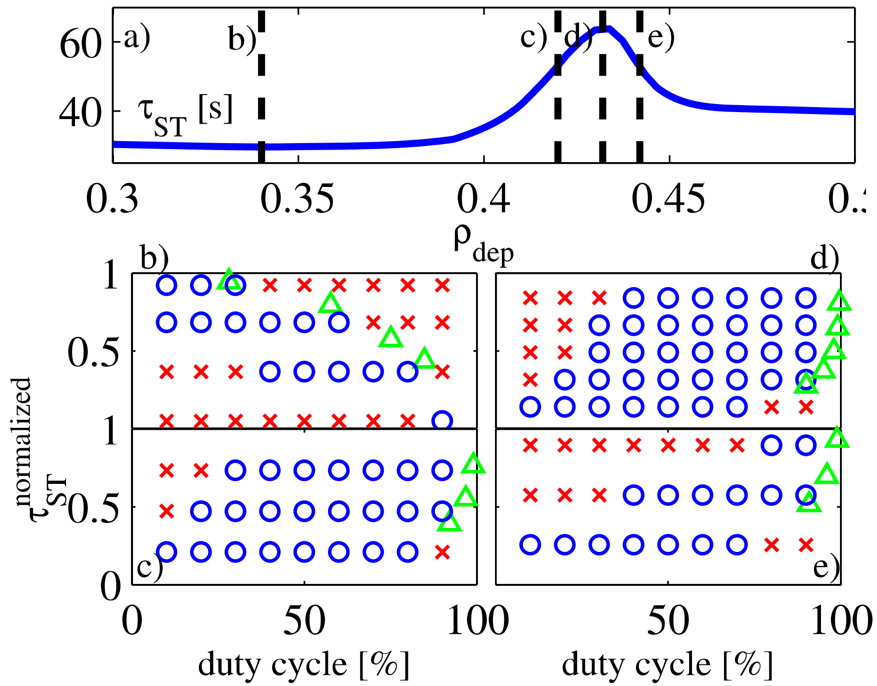


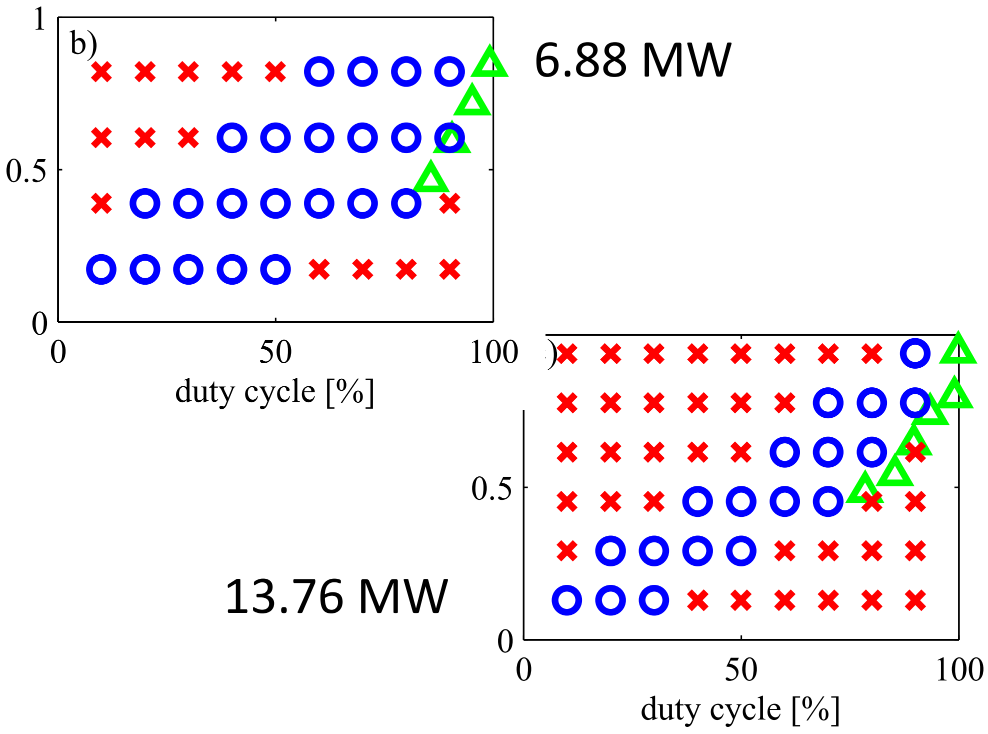


- Time evolution of shear (~dq/dr) at q=1 key for sawtooth control with ECCD.
- Can have complex behavior with off-axis ECCD

Sawtooth locking simulation – ITER

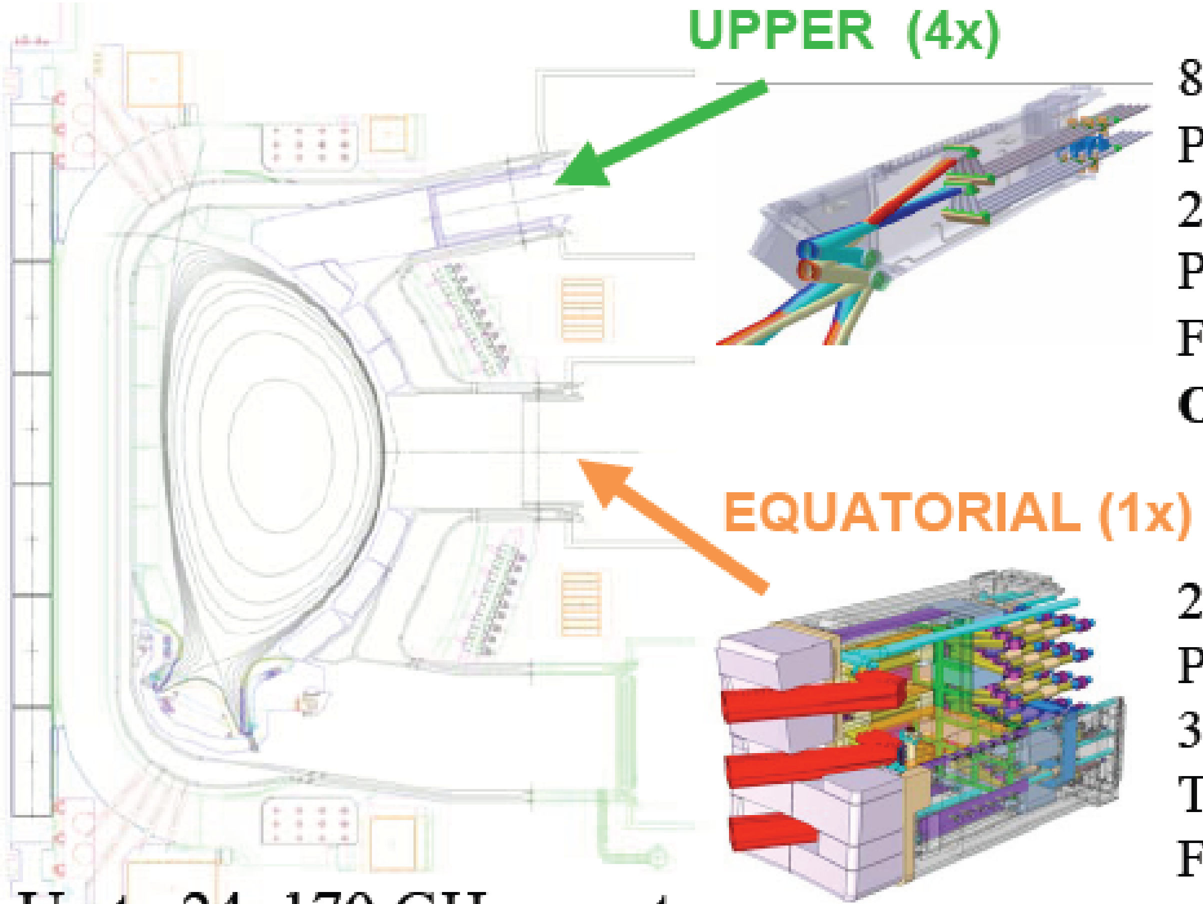
D. Kim *et al.* PoP 201414





- Locking range depends on the deposition position – locking with both stabilisation (left, c-e) and destabilisation (left, b) are possible.
- As well as deposition position, locking range is affected by the EC power (right).
- Pacing (green) always works and at high duty cycle (by construction) s

ITER launchers lead to more complex situation

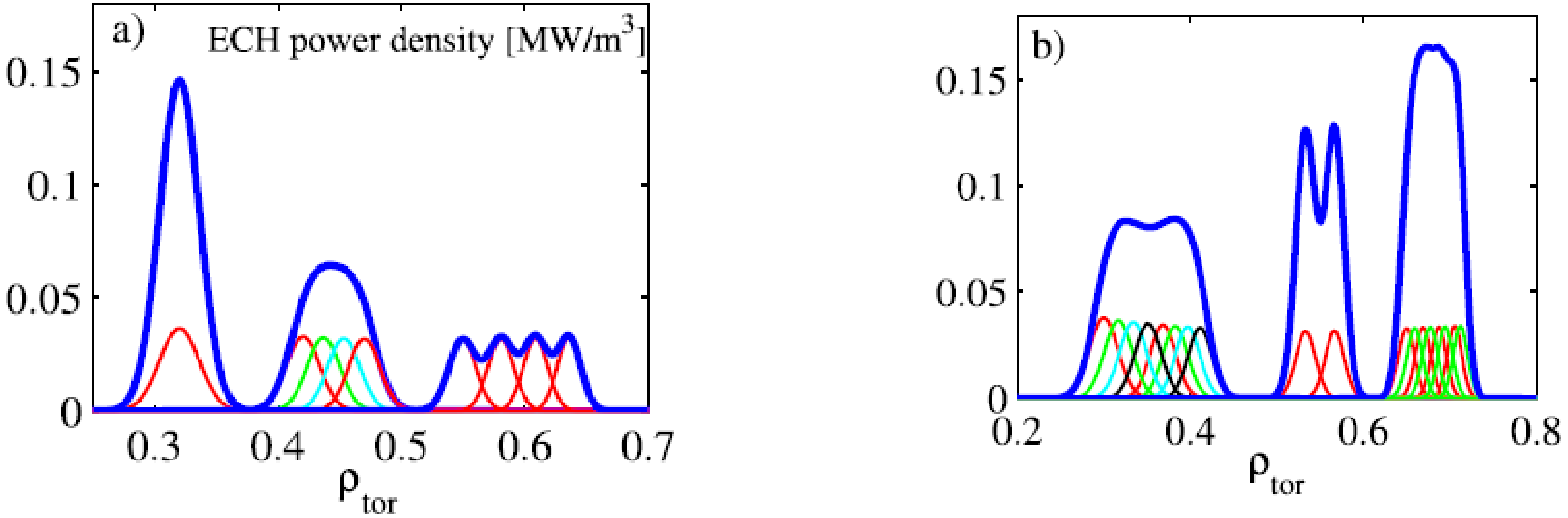


8 beams/port
P_{in} = 2.0MW/beam
2 steering mirrors
Poloidal scan $\Delta\theta$=24°
Fixed toroidal angle ϕ~20°
Optimised for peak j_{CD}

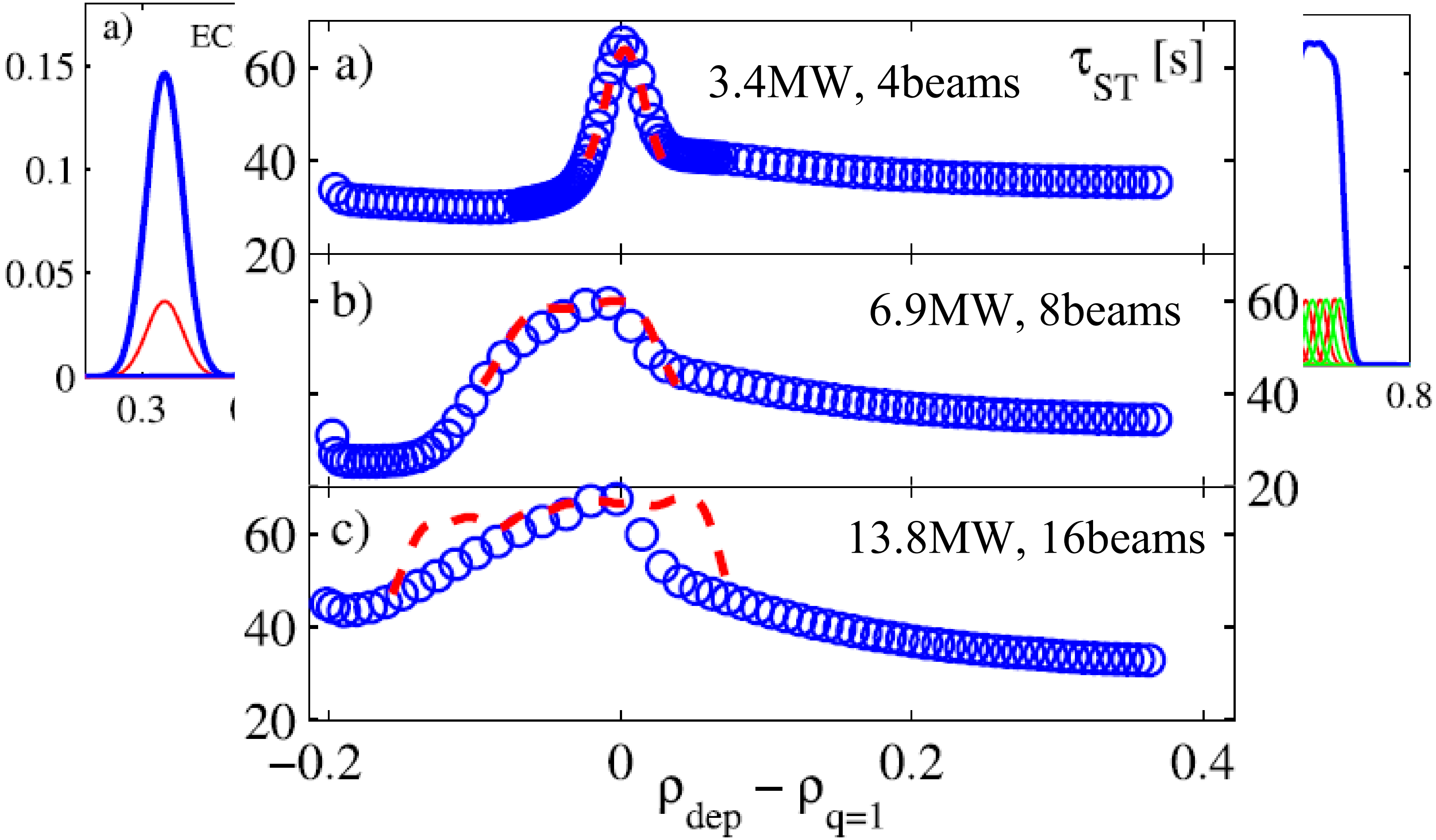
24 beams/port
P_{in}=1.0MW
3 steering mirrors
Toroidal scan $\Delta\phi$=25°
Fixed poloidal angle θ=0°
Optimised for maximum I_{CD}

Up to 24, 170 GHz gyrotrons
$P_{\mathrm{ECH}} = 20\mathrm{MW}$

ITER: Higher power means broader deposition



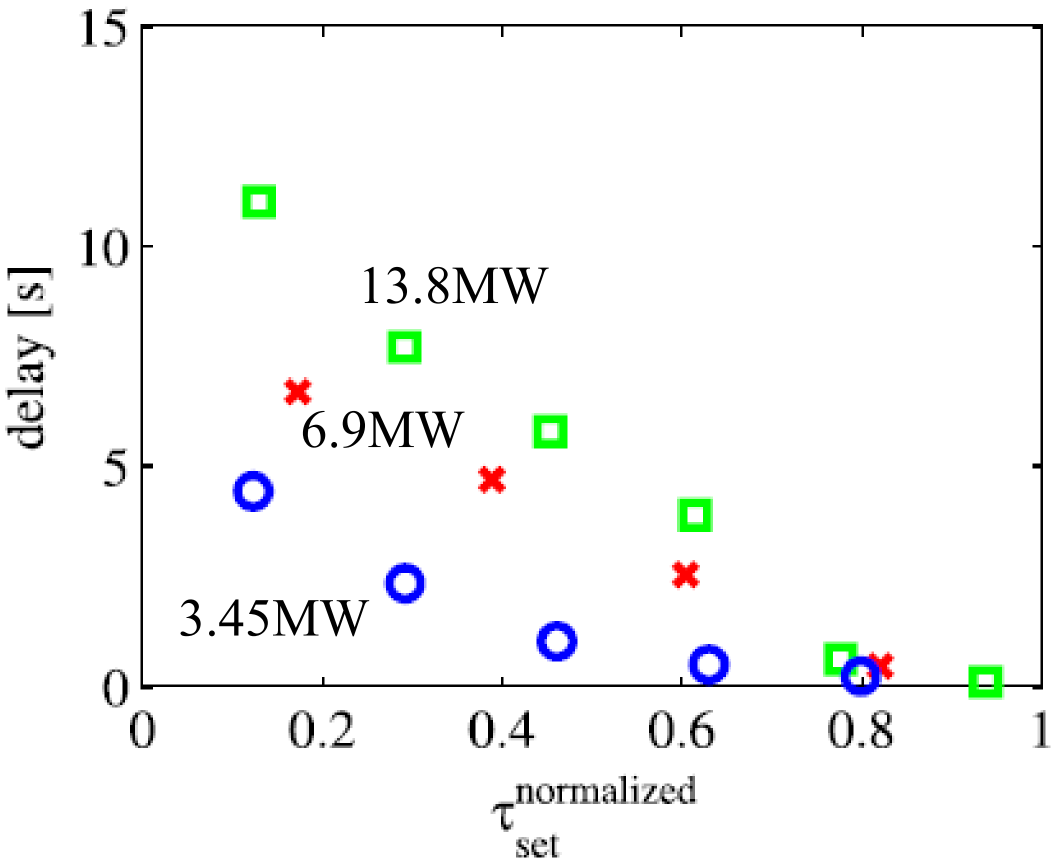
ITER: Higher power means broader deposition



Higher power does not lead to longer max. sawtooth period (can be the same for NTM control => design opt. For NTMs)

Delay up to ST crash important for actuator sharing

Predicted delay after turn-off of ST control ECCD power



Delay does not depend on model (symbols)

Delay **DOES** depend on power

D. Kim *et al.* PoP 21, 061503, 2014

Need ~1-2s to go from q=1 radius to 3/2 or 2/1 position and preempt or stabilize an NTM triggered by a ST crash

Sawteeth and NTM control

$$\delta W_{mhd} + \delta W_{fast} < \hat{\rho} \qquad \delta W_{fast} \sim -\nabla p_{fast} / s_1$$

large and positive in burning plasmas

ICRH to change num.
ECCD to increase s_1

1. Destabilize ST and "hope" seed island too small to trigger NTM *(most probably since β_N in ITER relatively small)*
2. If cannot avoid triggering from ST crashes:
   1. Stabilize fully ST for long pulse at high performance
   2. Pace ST crashes and coordinate with preemption of NTM

- **Need central heating from EC, thus can use it for ST control (ECCD does do ECH as well)**
- **Avoid off-axis EC (NTM control) since in bad confinement region**

Some conclusions and words of caution

- Porcelli-type sawtooth model tested in many experiments
- Sawtooth simulations used to understand and predict control of sawtooth period in many experiments with heating, current drive and/or fast particles stabilisation
- Key to model is crash criteria, not post-crash reconnection state
- Existence of pre-cursors "decoupled" from crash
- Other modes might be unstable and observed (see Furno et al e.g.) during sawtooth ramp. But linear drive from global internal kink seems dominant term for crash itself. Thus linear instability of global mode (which gives crash criteria) key for "time of crash"
- 2D/3D evolution can alter sawteeth. E.g. lead to "funny" sawtooth shape (Furno et al), but less important for sawtooth period, except now with impurity control
- Level of reconnection, full or partial, certainly can change for various scenarios. Not a reason to disregard model, rather a reason to enhance accuracy of model (may be new regimes)

Some conclusions and words of caution

- The simulations are now good enough for predictive capabilities of relative effects.
- The model not yet ready for accurate absolute value of sawtooth period. (But transport properties not predicted either)
- Accurate (enough) formula for γ_{ideal} now available (Martynov, PPCF 2005)
- Lots of work still needed, mainly in 2 regimes:
  a) $\gamma_{res} > c_r (\omega_{e*}\ \omega_{i*})^{1/2}$
  b) Effects of fast particles, dependence on shear s_1
- Main uncertainties/unknown
  - Relation (a) is ad-hoc (Sauter et al, Varenna 1998: **s_1>0.2**)
  - Resistive growth rate formulas are approximate in (a)
  - Full/partial reconnection
- Effects of crash itself: heat pulse and triggering of NTMs e.g. not well studied yet (need 2 fluids 3D MHD)