MAX PLANCK GESELLSCHAFT

ASDEX Upgrade

IPP Max-Planck-Institut für Plasmaphysik

Experimental Evidence of Magnetic Flux Pumping at ASDEX Upgrade

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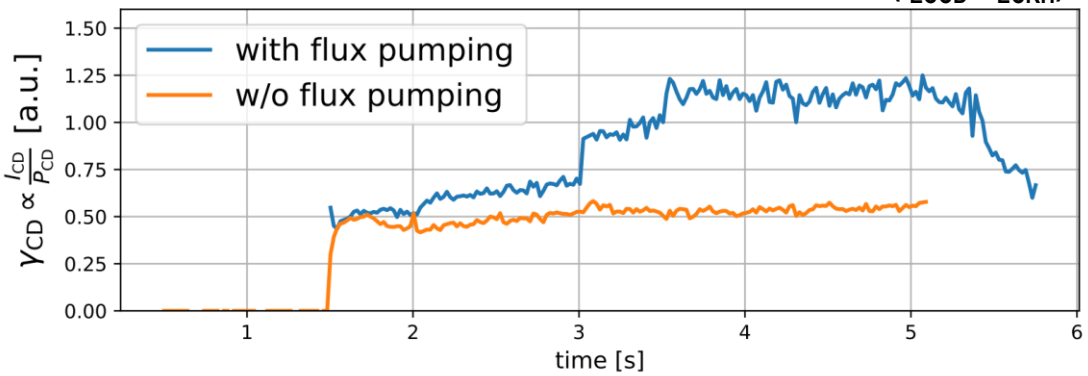
Motivation

- **Tokamaks pulsed ➔ high non-inductive current fraction desirable**
- **Sawteeth undesirable:**
  - flatten core pressure ➔ reduced fusion power
  - can trigger deleterious modes

see also:
[Turco et al, PoP 22, 056113 (2015)]

- **Flux pumping:**
  - clamps central q to unity ➔ no sawteeth
  - high confinement
  - high current drive efficiency

Current drive efficiency (I_{ECCD}/P_{ECRH})



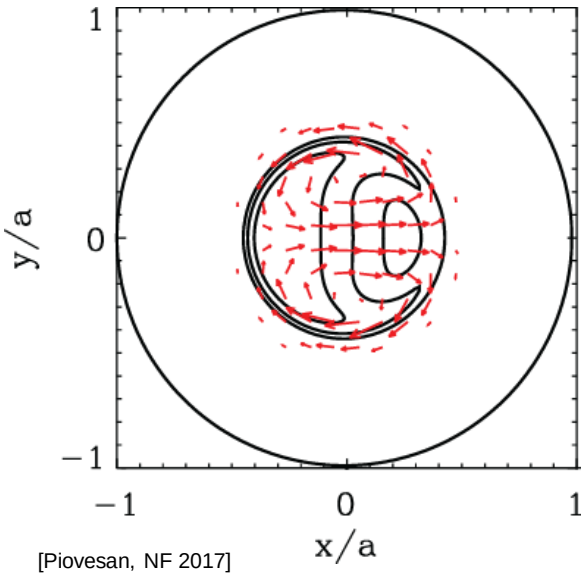
Flux pumping mechanism

- **At DIII-D: flux pumping observed with 3/2 mode, and 1/1 RMP-induced helical core**
- **Here, n=1, m=1 "natural" helical core**
- **In presence of q_0 just above 1 and low shear:**
  - Quasi-interchange (1/1) instability can develop

[Petty, PRL 2009, Piovesan, NF 2017]

[Jardin, PRL 2015]

mode flux surfaces (poloidal cut)
associated flows



[Piovesan, NF 2017]

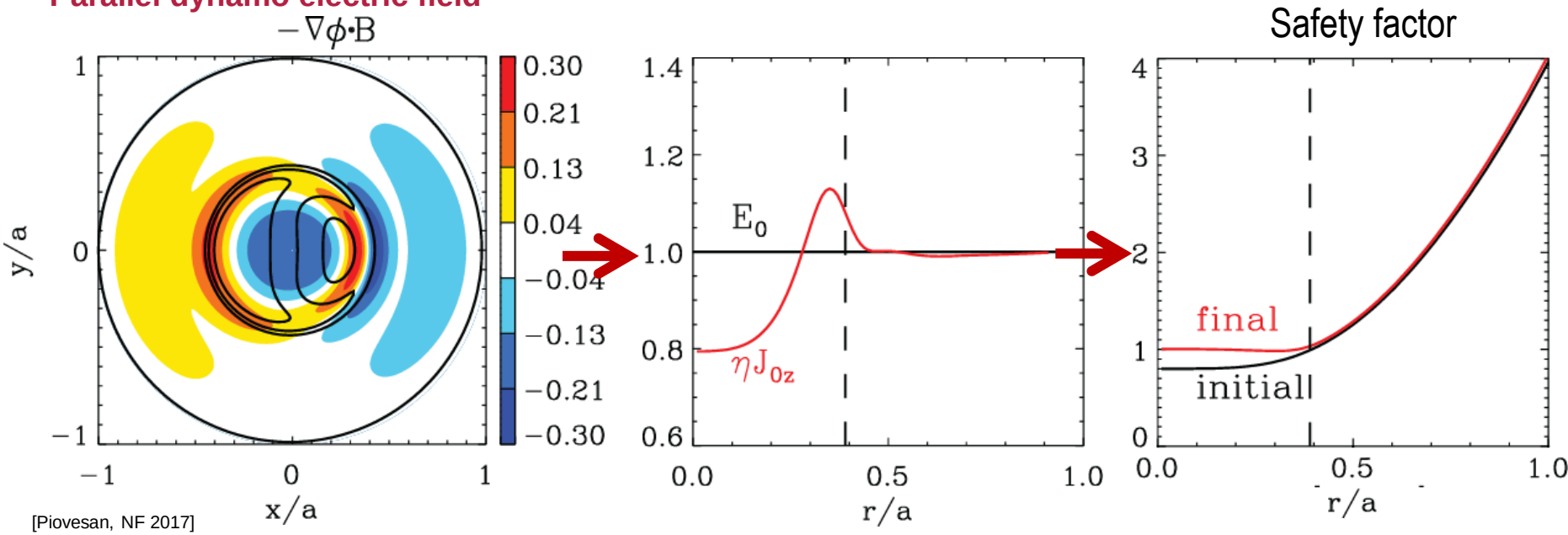
Flux pumping mechanism

- **At DIII-D: flux pumping observed with 3/2 mode, and 1/1 RMP-induced helical core**
- **Here, n=1, m=1 "natural" helical core**
- **In presence of q_0 just above 1 and low shear:**
  - Quasi-interchange (1/1) instability can develop
- **Dynamo loop voltage from flows and magnetic field (negative in plasma center)**
- **Dynamo field drives q_0 up and clamps it to unity**

[Petty, PRL 2009, Piovesan, NF 2017]

[Jardin, PRL 2015]

Parallel dynamo electric field

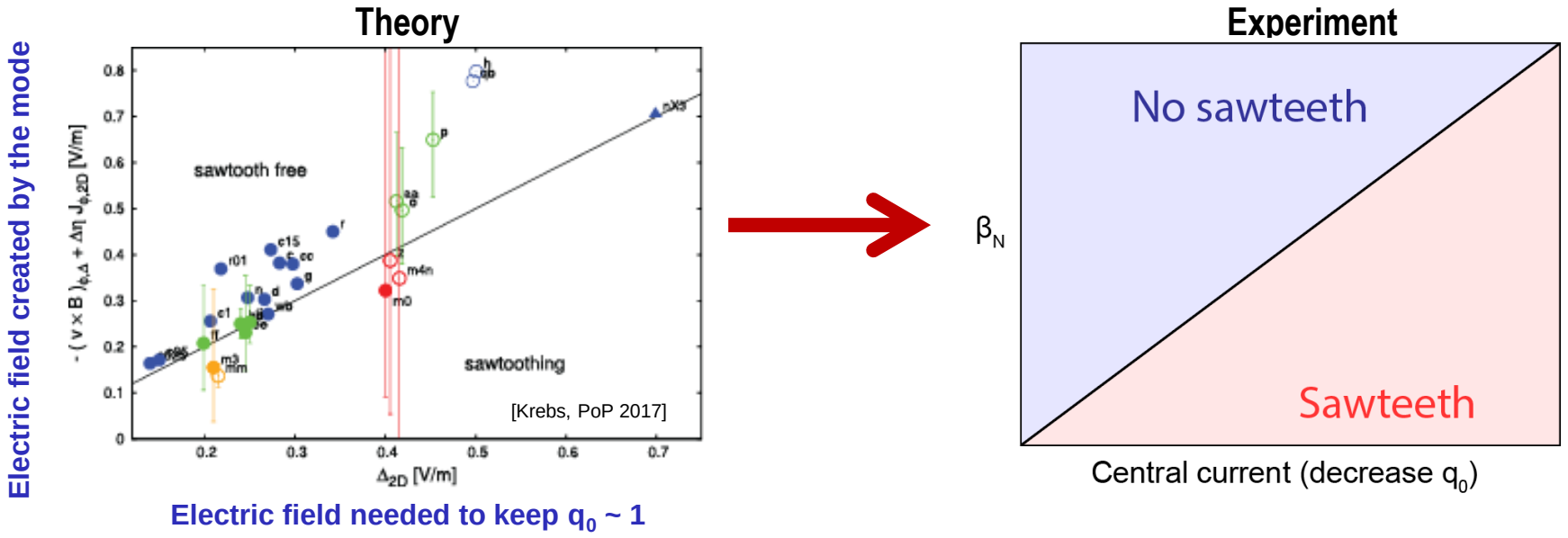


[Piovesan, NF 2017]

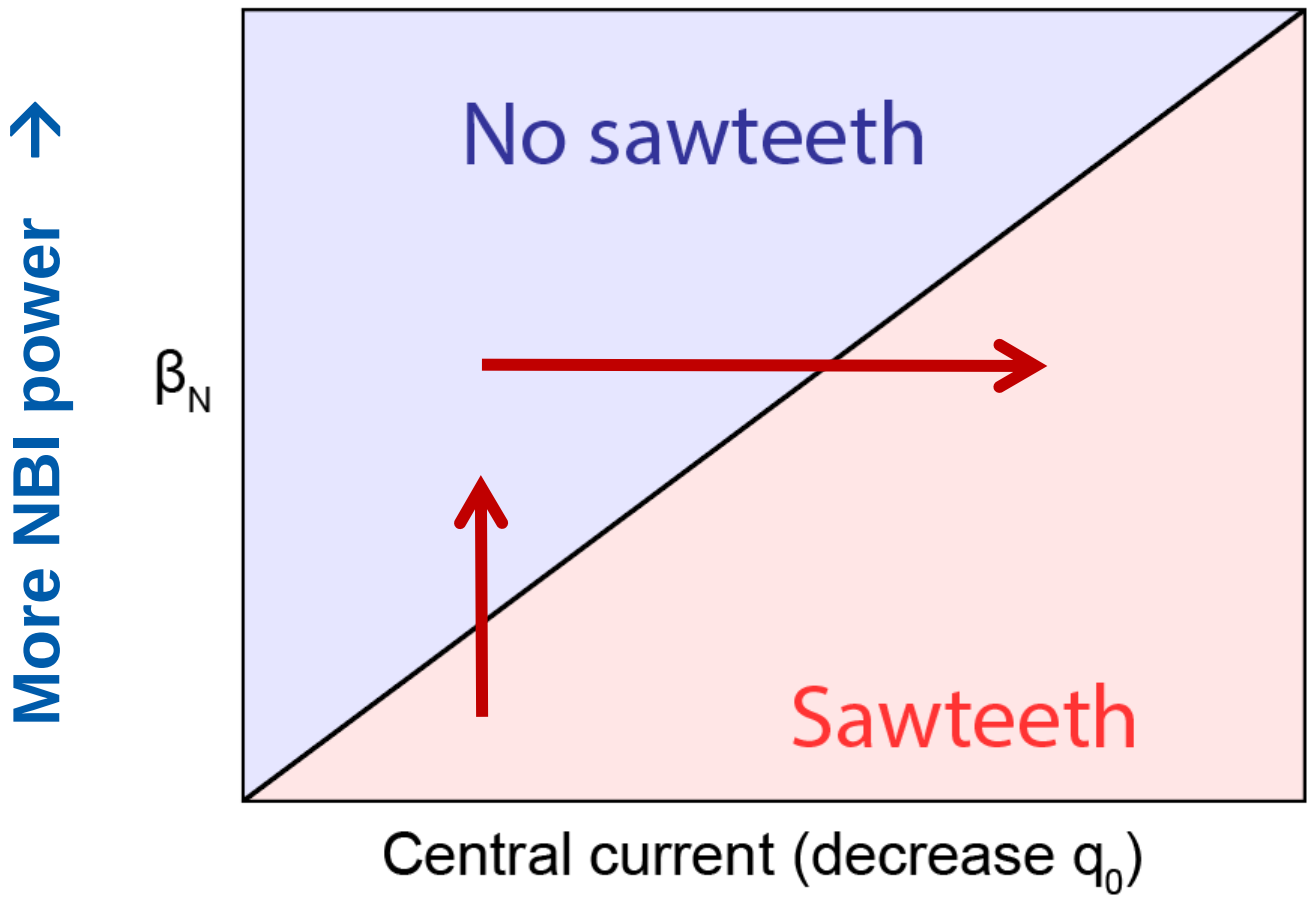
Experimentally testing the predicted flux pumping

- **Magnetic flux pumping with 1/1 mode investigated theoretically** [Krebs, PoP 2017]
- **Simulations with varying inputs reveal dependency on:**
  - Core pressure ➔ drives the mode, more flux pumping, $q_0 \sim 1$
  - Current peaking ➔ drives q_0 under 1. If too peaked, FP not sufficient to keep q_0 at unity

- **Can be tested experimentally by varying current peaking and β**

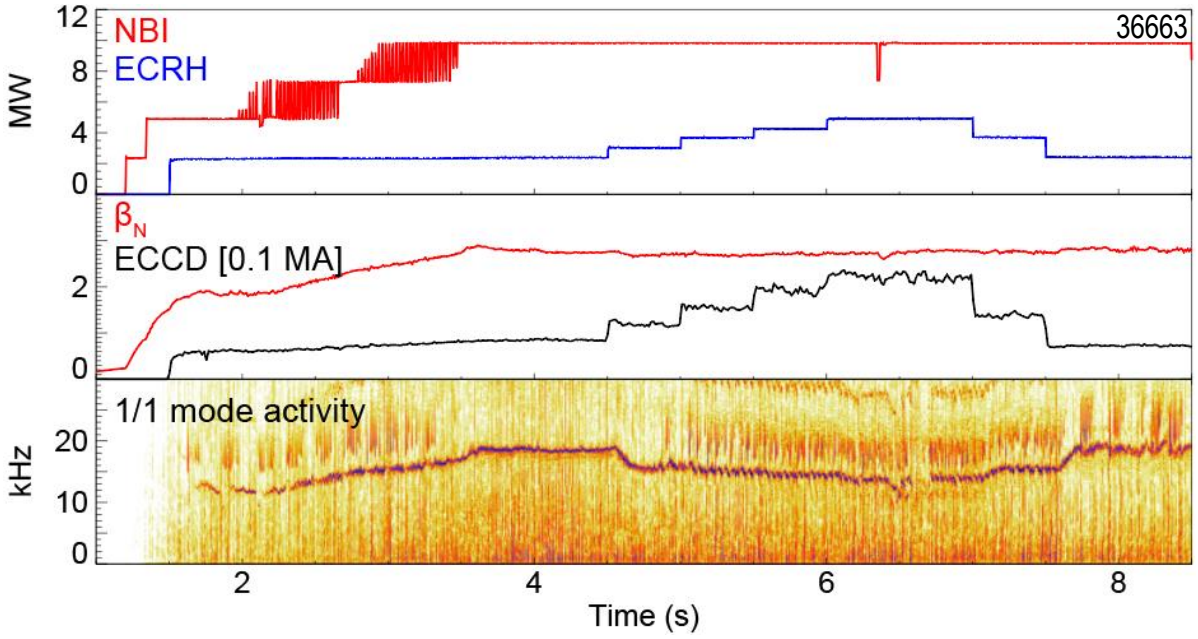


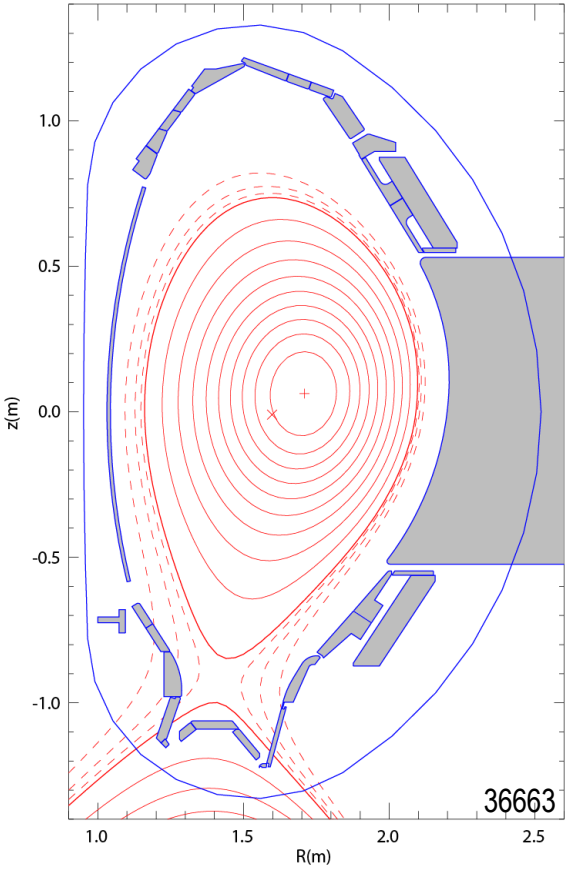
Experiment planning



Scenario overview

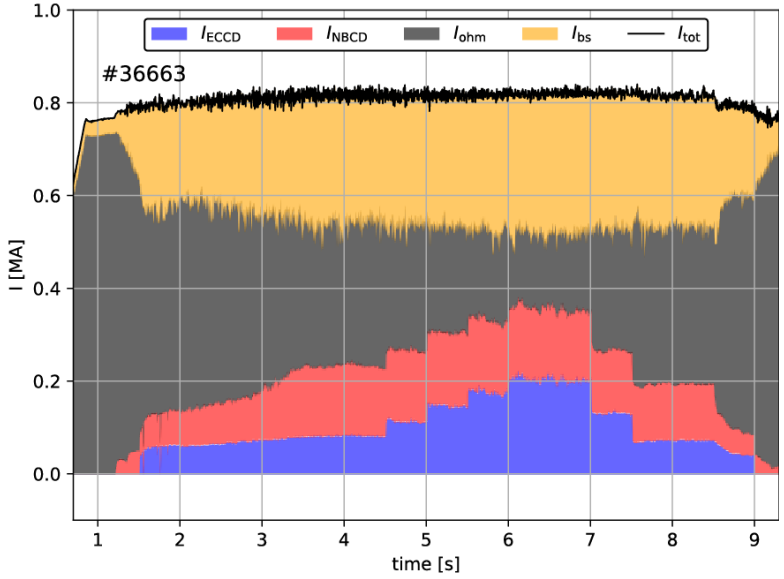
- 0.8MA / -2.5T / Lower single null, deuterium
- Line averaged density ~5.6x$10^{19}$$m^{-3}$
- 10MW NBI, up to 5MW ECRH (over 200kA ECCD)
- achieved β_N: ~2.9
- Strong 1/1 mode visible in magnetics after 1.6s

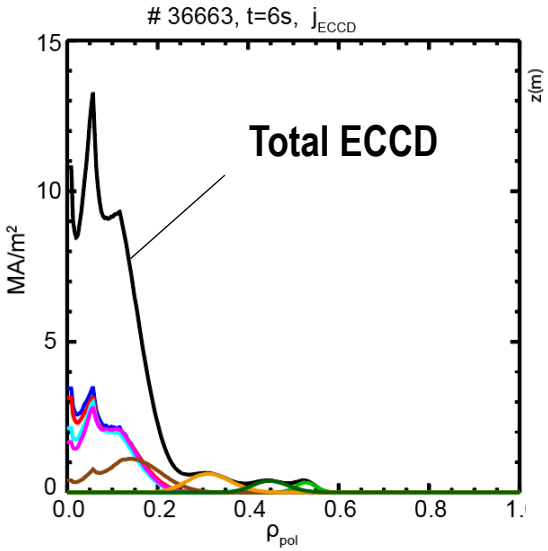


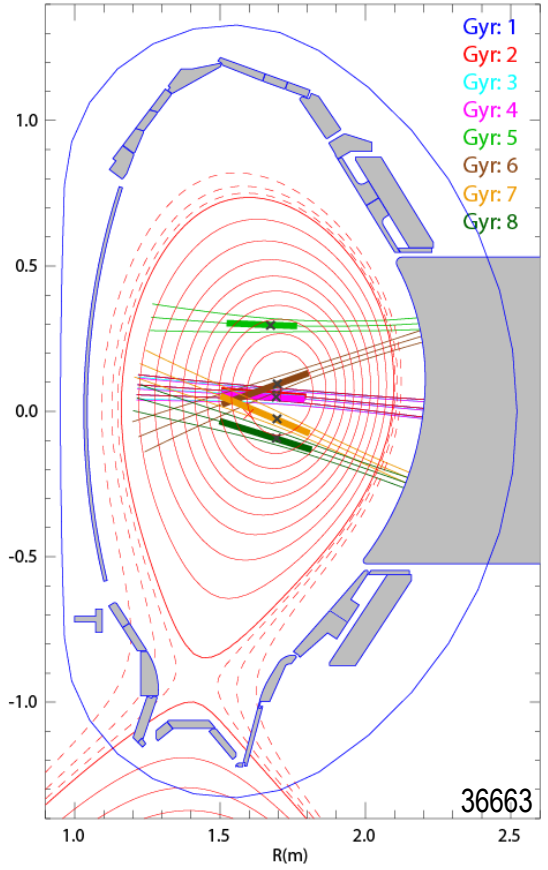


Scenario overview

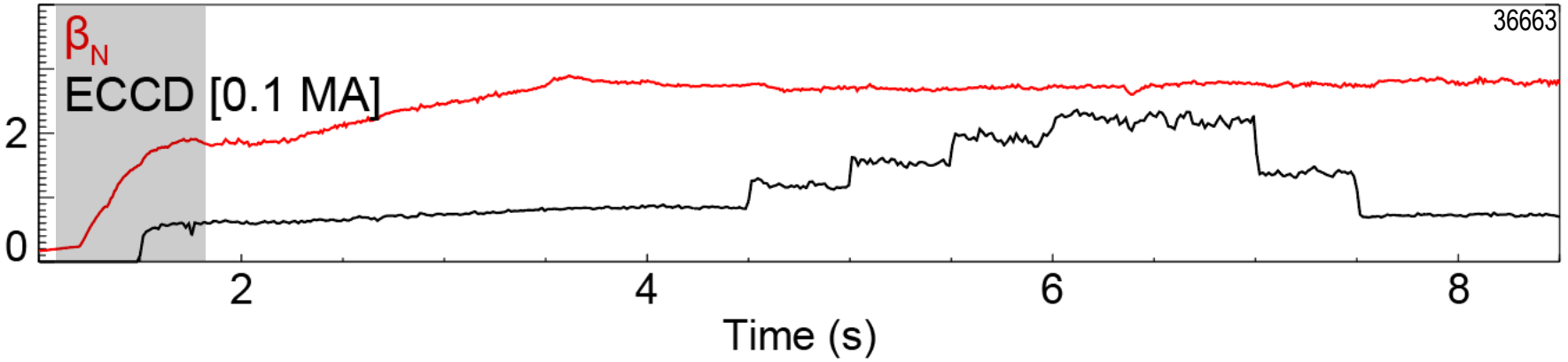
- **Max driven current (NBI + ECCD): 0.35MA**
- **With Bootstrap: close to non-inductive**

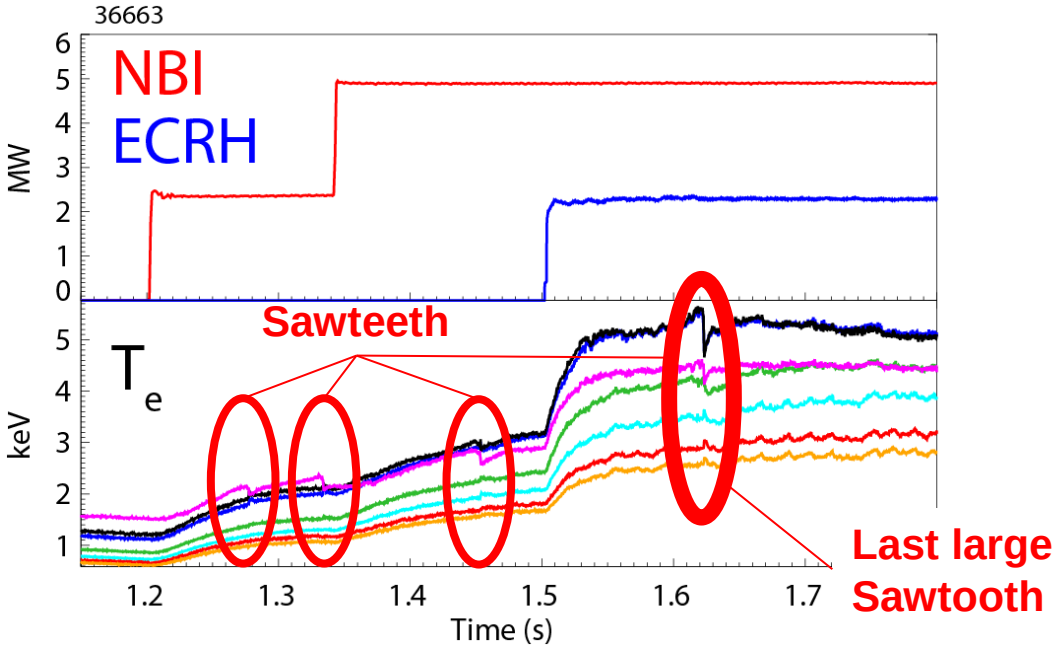




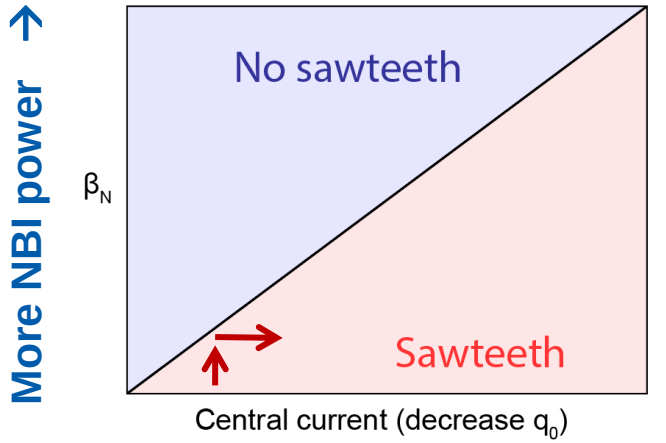


Large sawteeth present at first



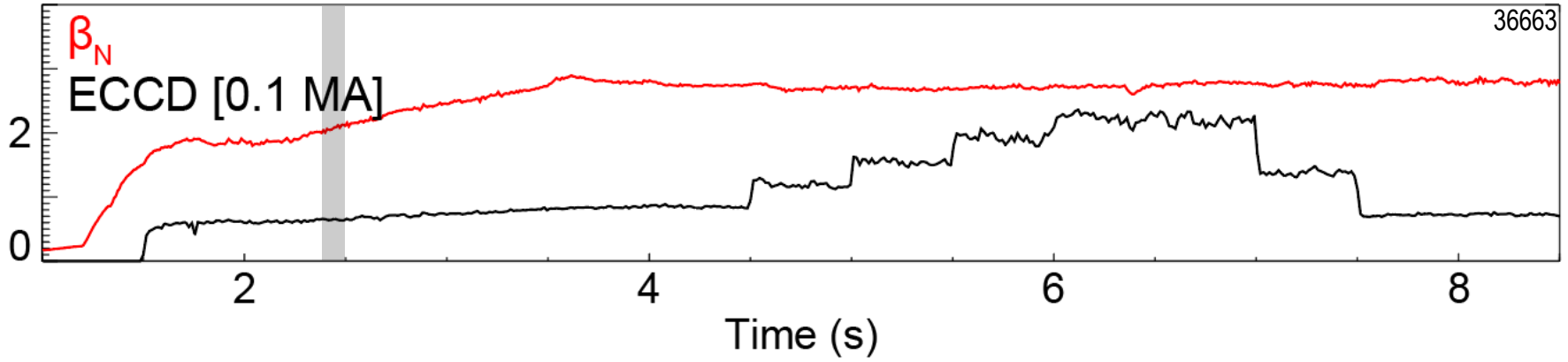


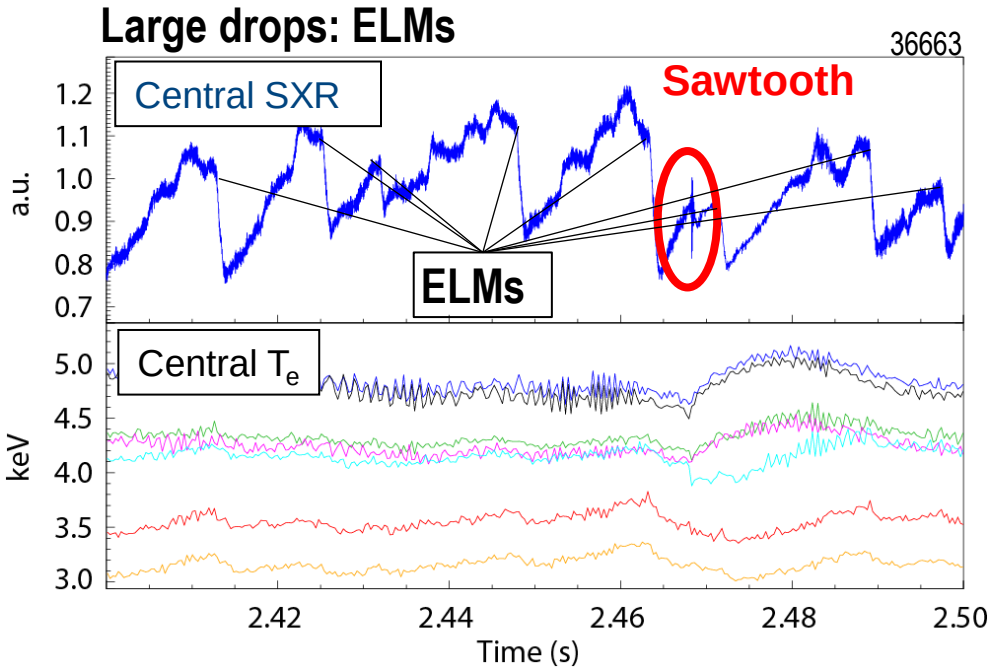
Last large Sawtooth

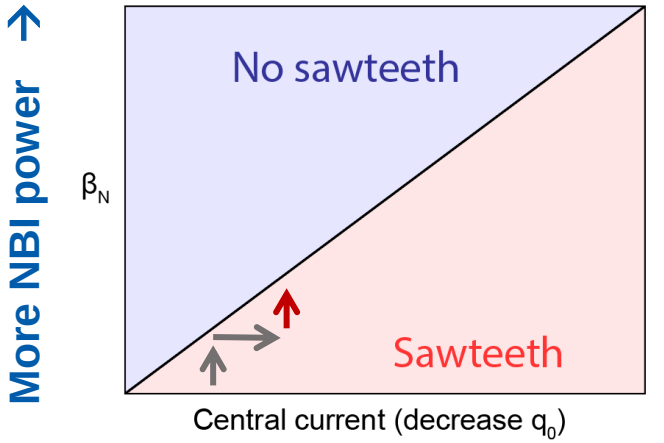


Co-current on-axis ECCD →

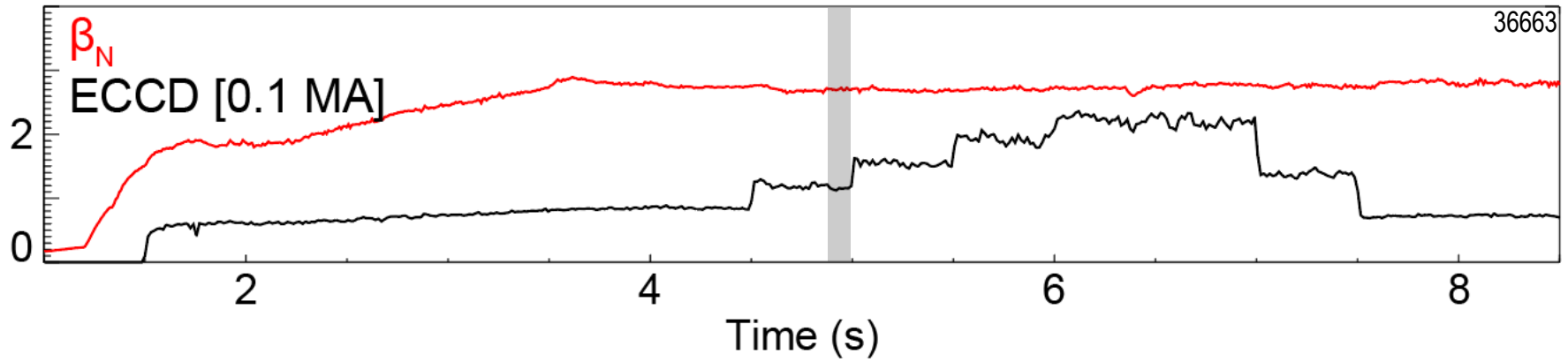
Smaller sawteeth after 1/1 onset



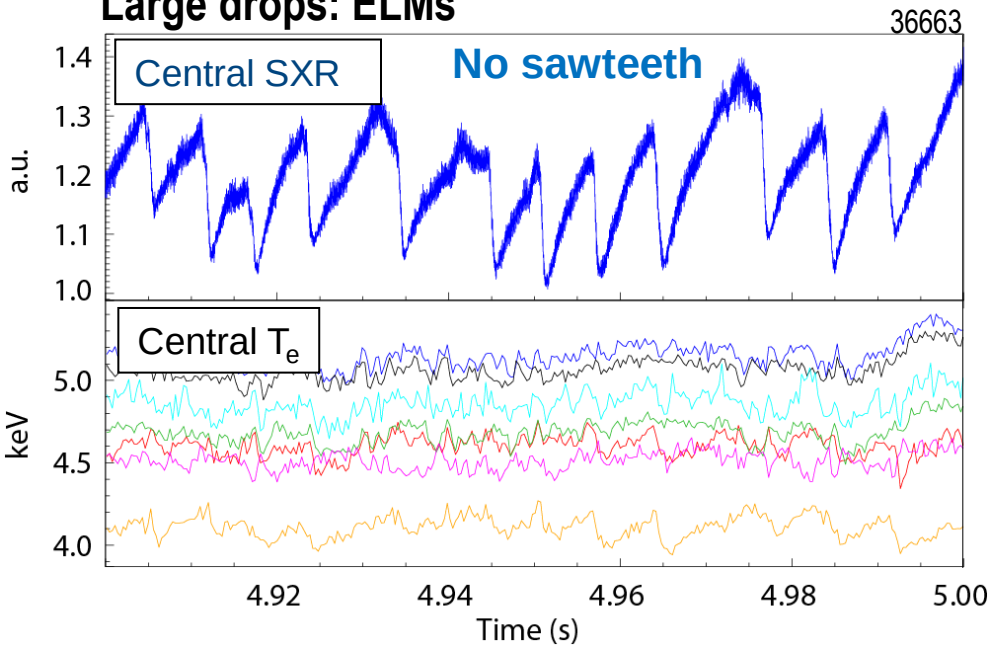


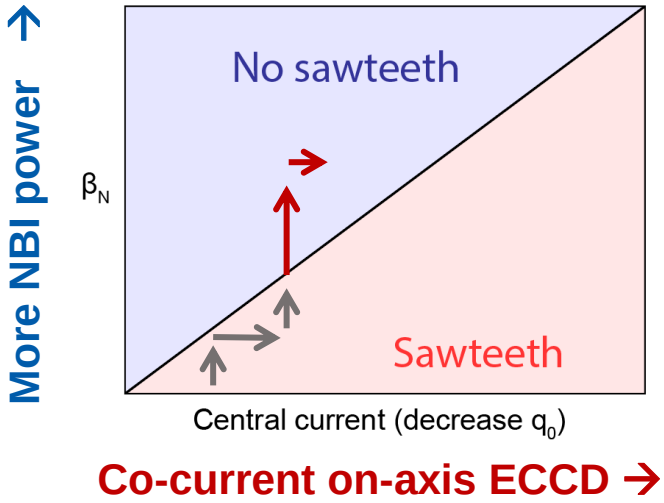


Sawteeth suppressed at high β

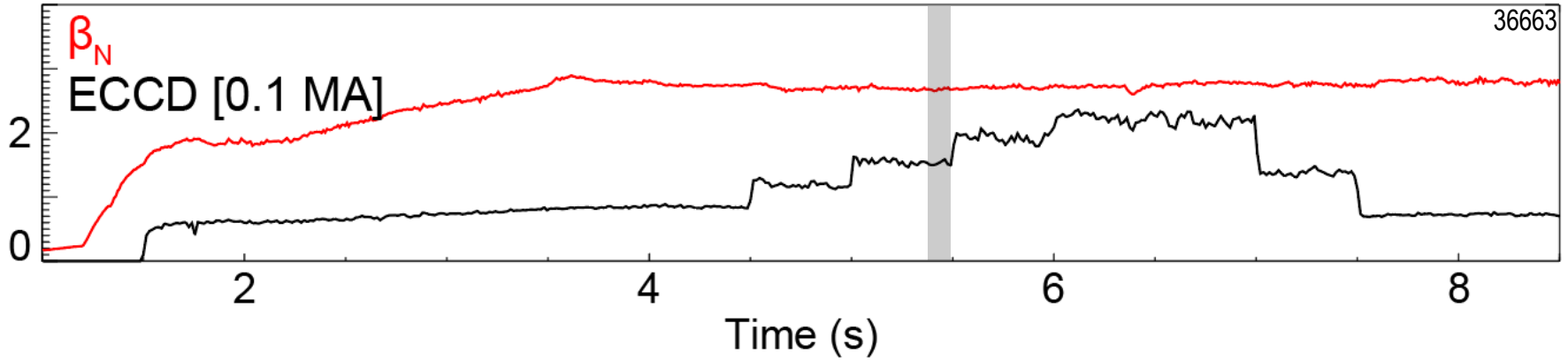


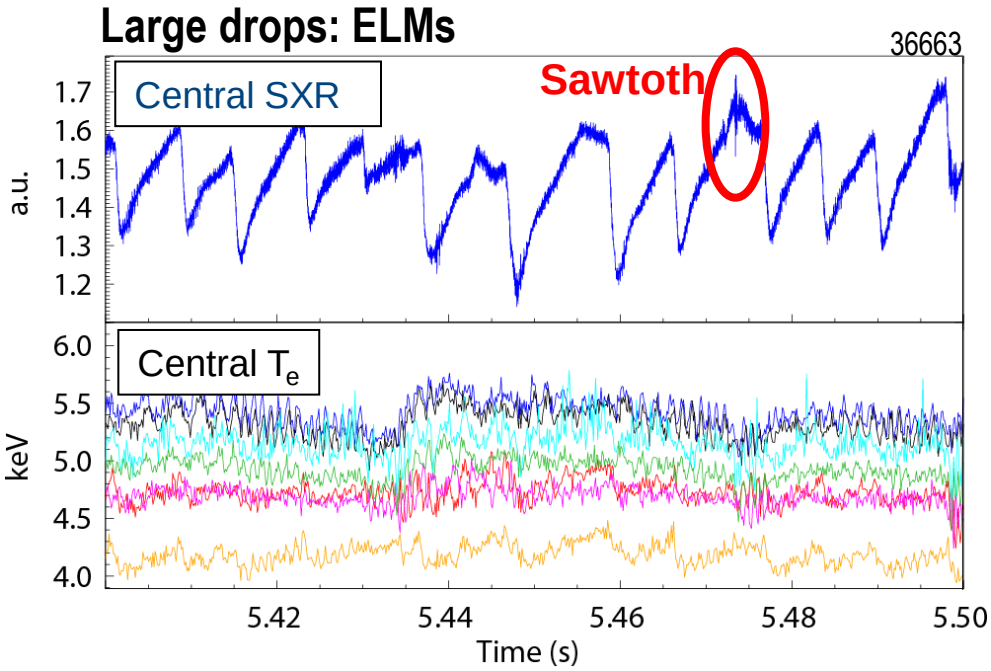
Large drops: ELMs

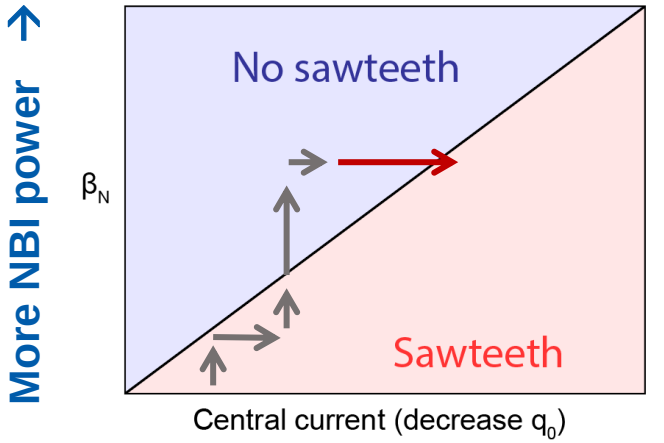




Sporadic sawteeth return at higher ECCD

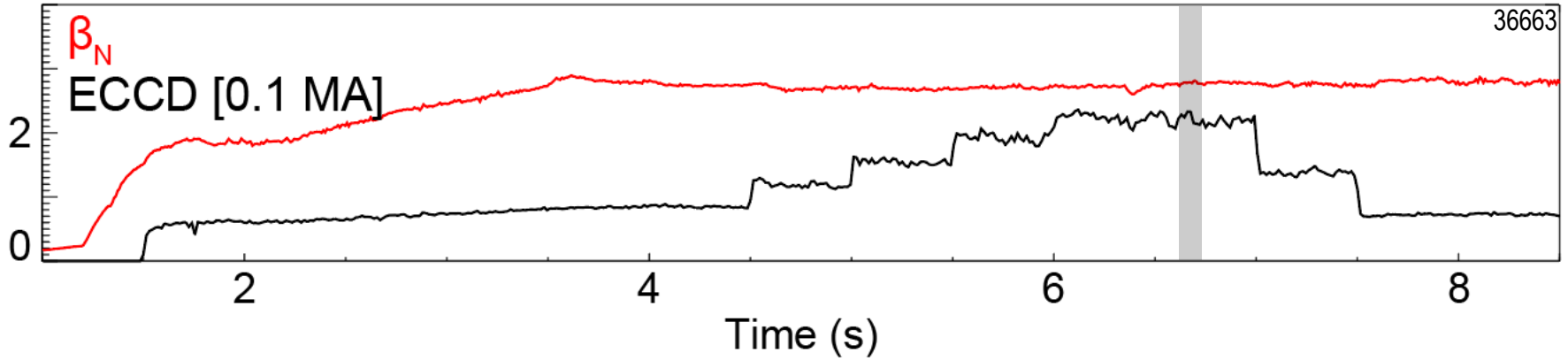




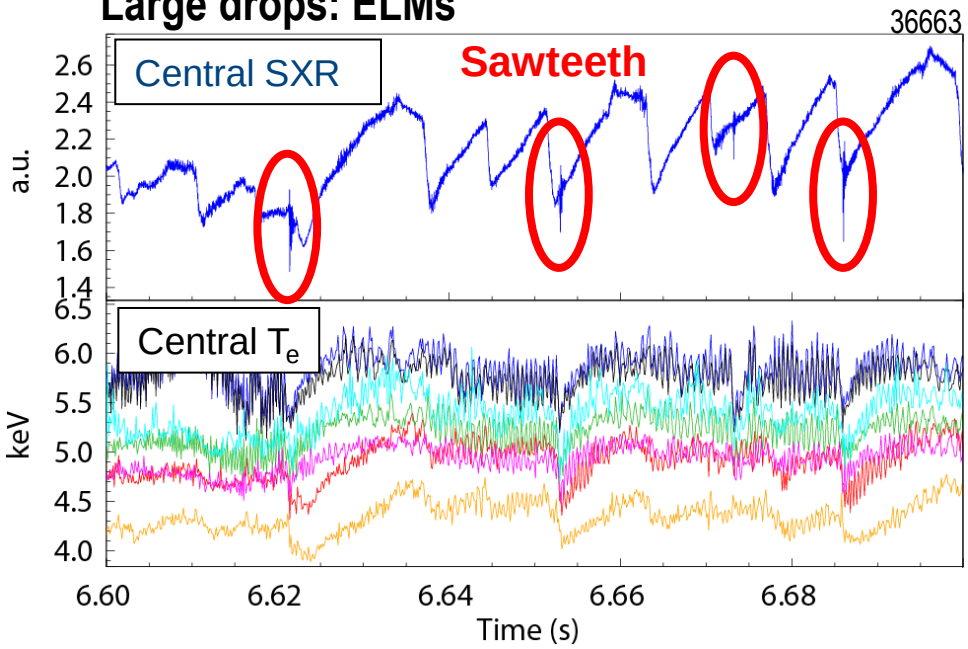


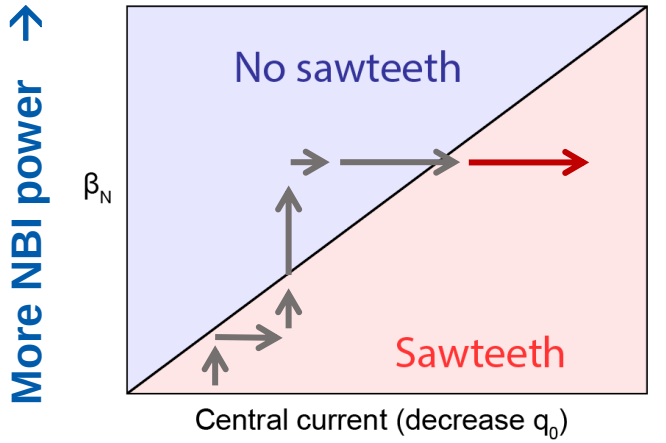
Co-current on-axis ECCD →

Sawtooth freq. and ampl. increases with ECCD



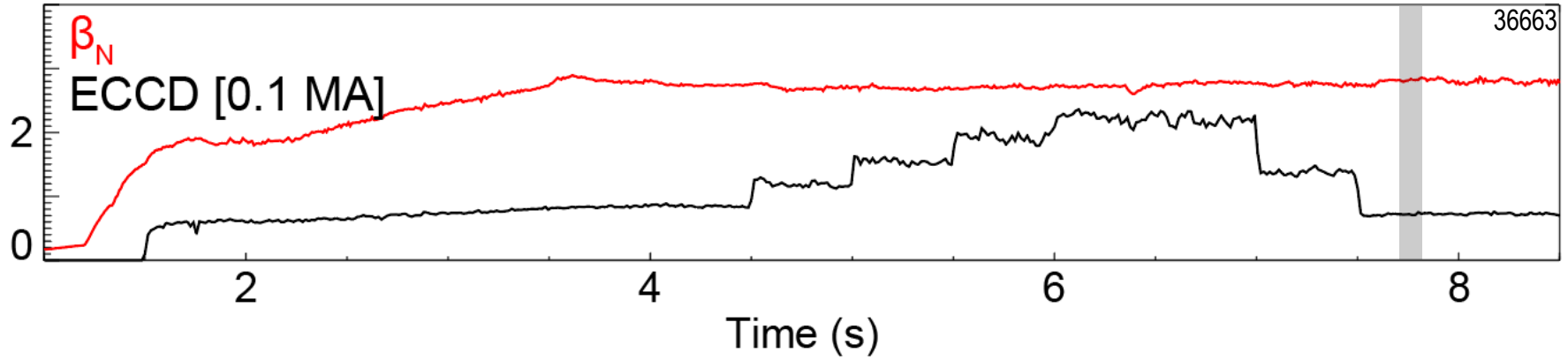
Large drops: ELMs



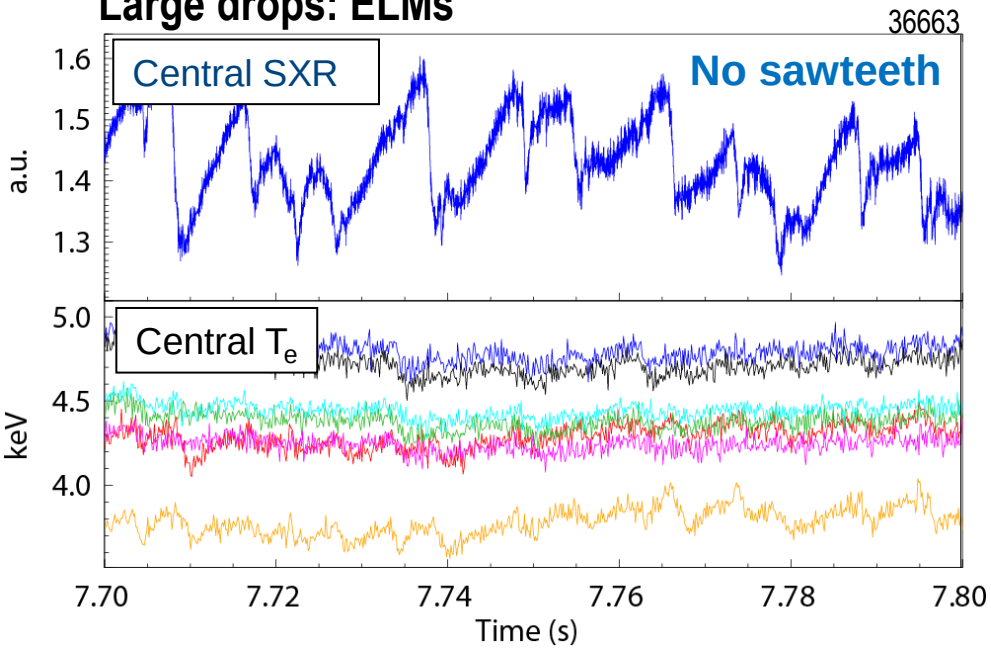


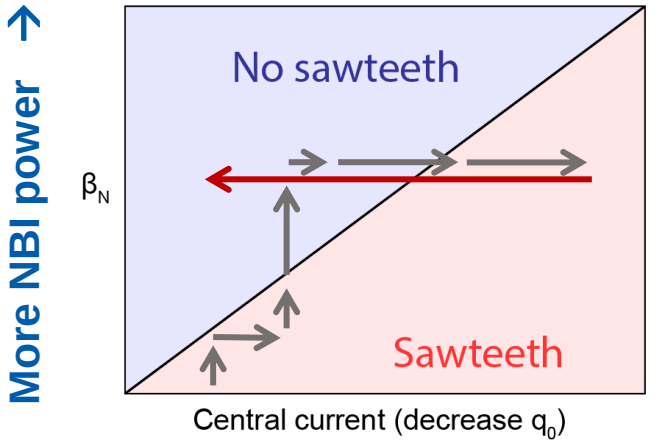
Co-current on-axis ECCD →

Sawteeth suppressed when reducing ECCD



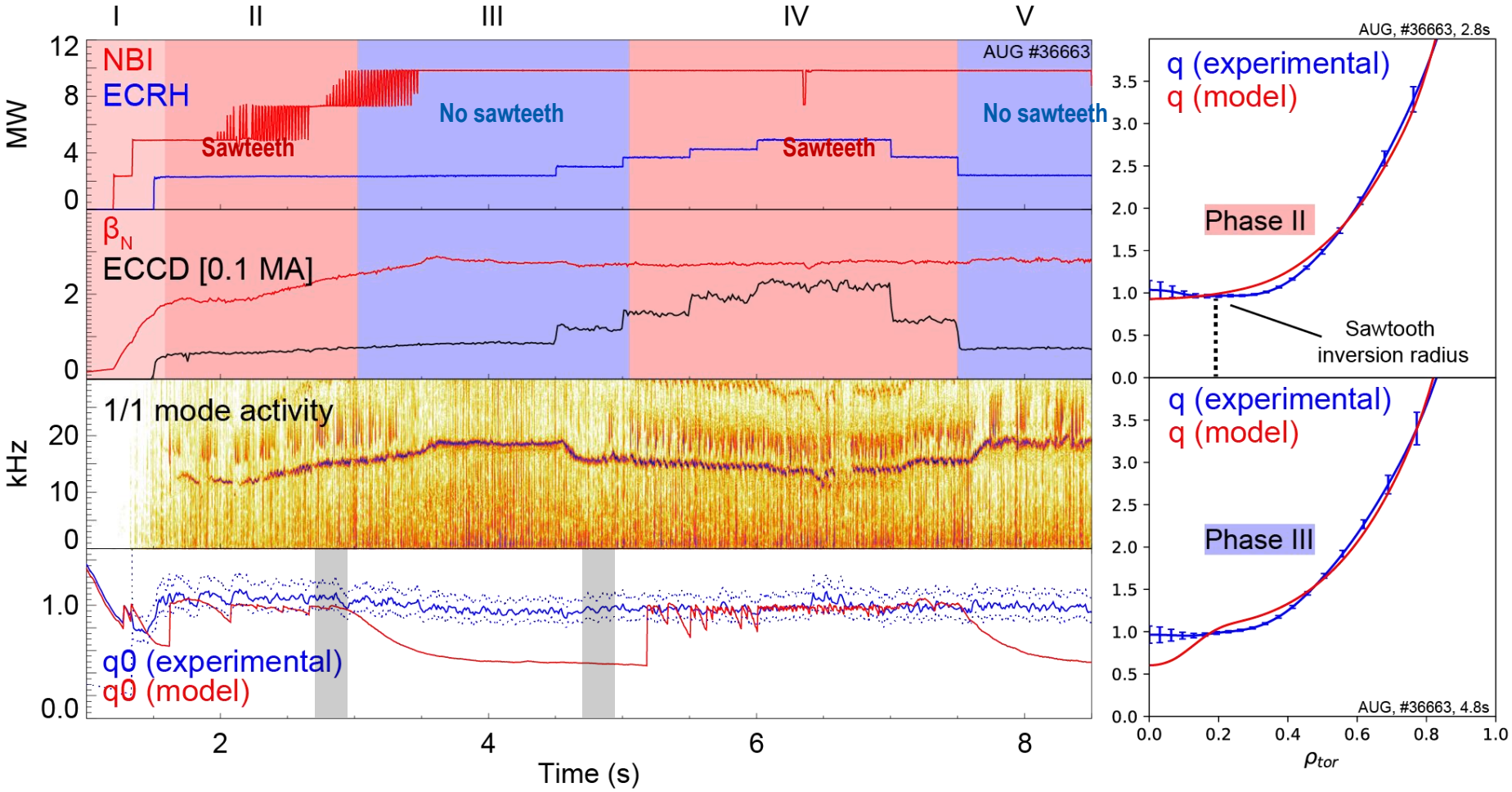
Large drops: ELMs





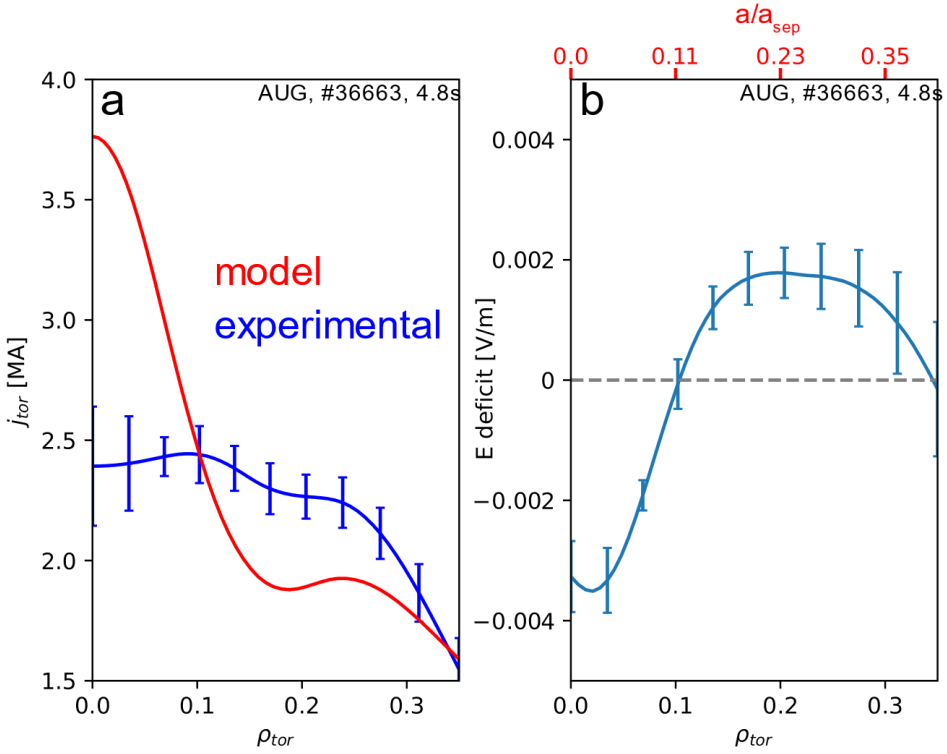
Co-current on-axis ECCD →

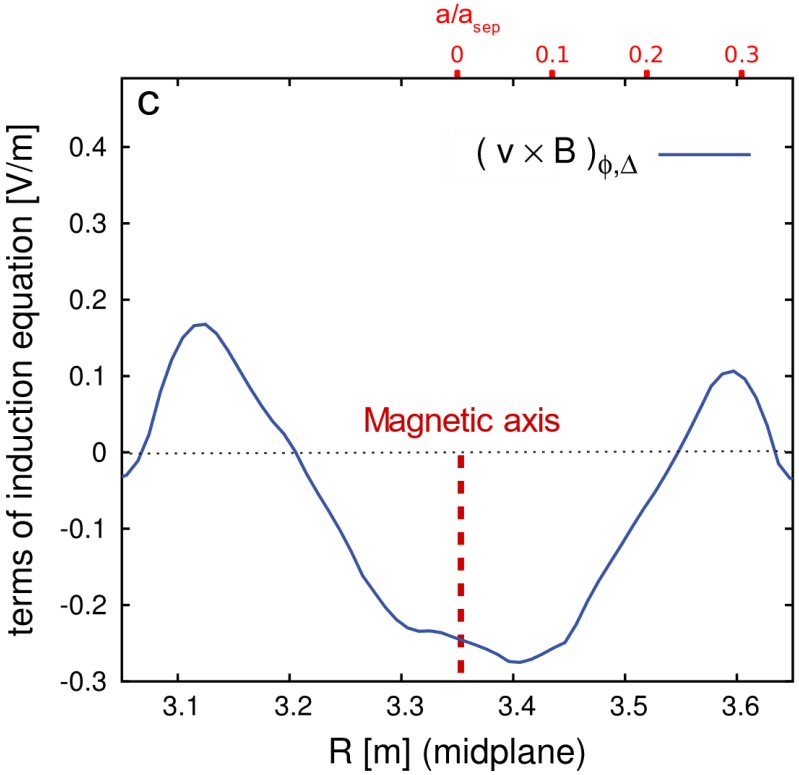
Measurements suggest q_0 stays close to 1



Qualitative agreement with theory

- **Modelled** current much more peaked than **measured**
- E-field deficit can be interpreted as produced by flux pumping
- Qualitative agreement with 3D non-linear MHD simulations





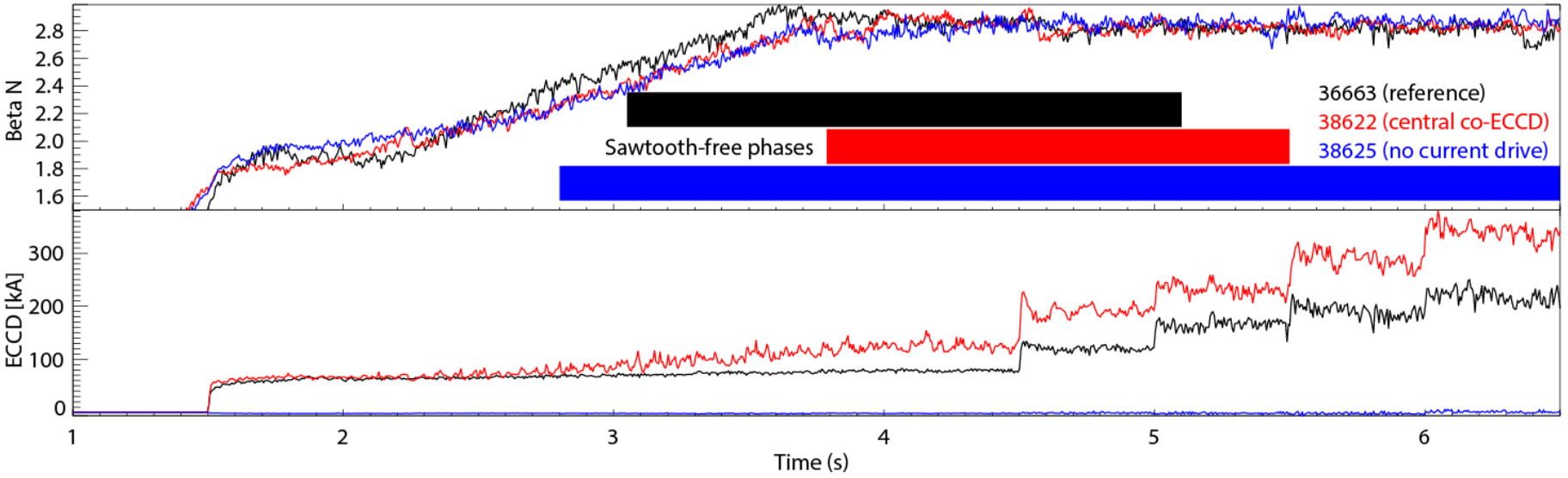
Modified from [Krebs, PoP 2017]

Repeat, more central co-ECCD and no ECCD

- **Parameter scan, 2 extremes: high on axis ECCD, only ECRH no current**

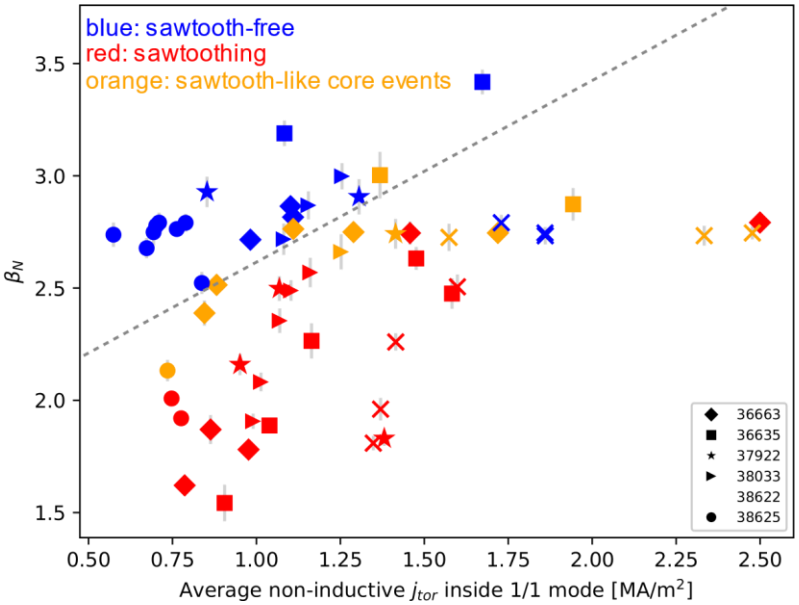
- **More co-ECCD, further on axis than reference**
  - sawtooth suppression occurs later, but ends at higher co-ECCD

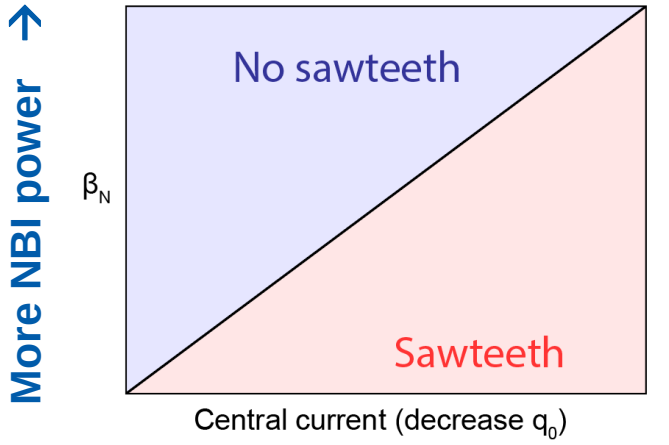
- **Without current drive but same ECRH power**
  - sawteeth disappear early and remain absent



Central current vs beta

- **x-axis: volume-averaged non-inductive j inside 1/1 mode (radius from SXR)**
- **y-axis: keep β_N as mode drive**
- **High β_N ➔ ST suppression**
  High j_{tor} ➔ ST reappear





Conclusion

- **Reactors need high current drive, high confinement, no instabilities**
  - advanced tokamak scenarios attractive, especially with flux pumping
    ➔ high current drive efficency, high beta, no sawteeth
- **New theoretical flux-pumping model tested experimentally, at high β in the presence of 1/1 mode:**
  - q-profile evolution does not follow neoclassical current diffusion
  - central q clamped around unity (IMSE measurements, no sawteeth)
- **Exp. findings with combination of various NBI and ECCD levels:**
  - co-current ECCD does not drive q_0 down as we would expect
  - at higher β the effect is stronger (similar to theory)
  - at high non-inductive central current: effect not strong enough to keep q_0 at unity (in theory, β-threshold dependent on central current peaking)
- **Theoretical non-linear 3D MHD simulations (JOREK) based on experimental AUG data are underway**