Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

MHD Control in TEXTOR

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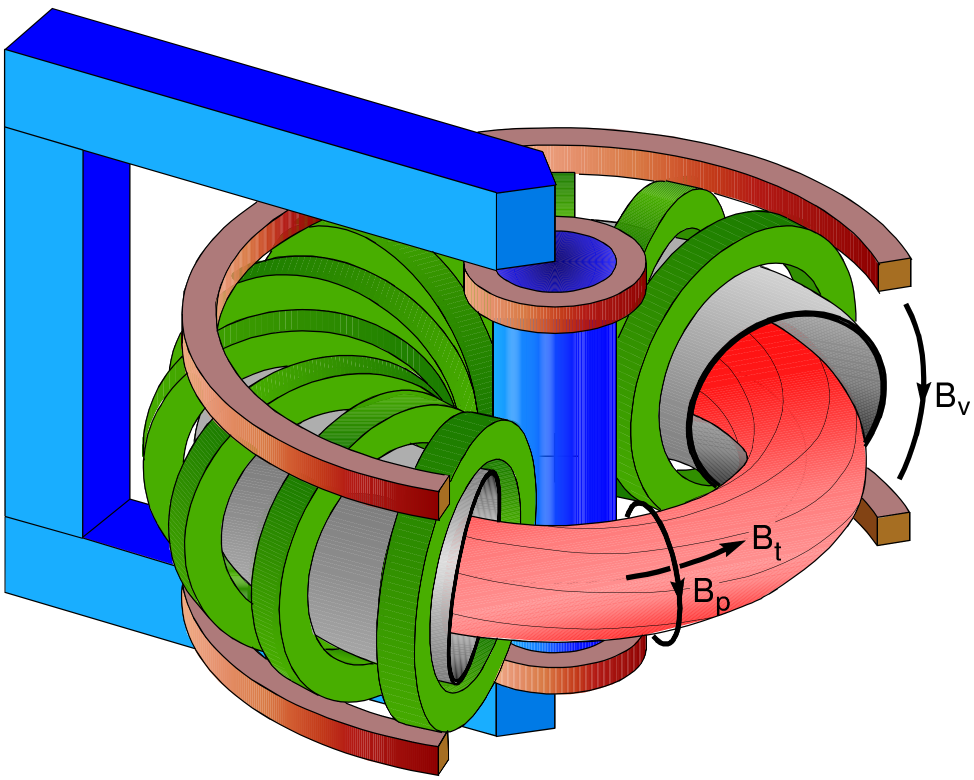
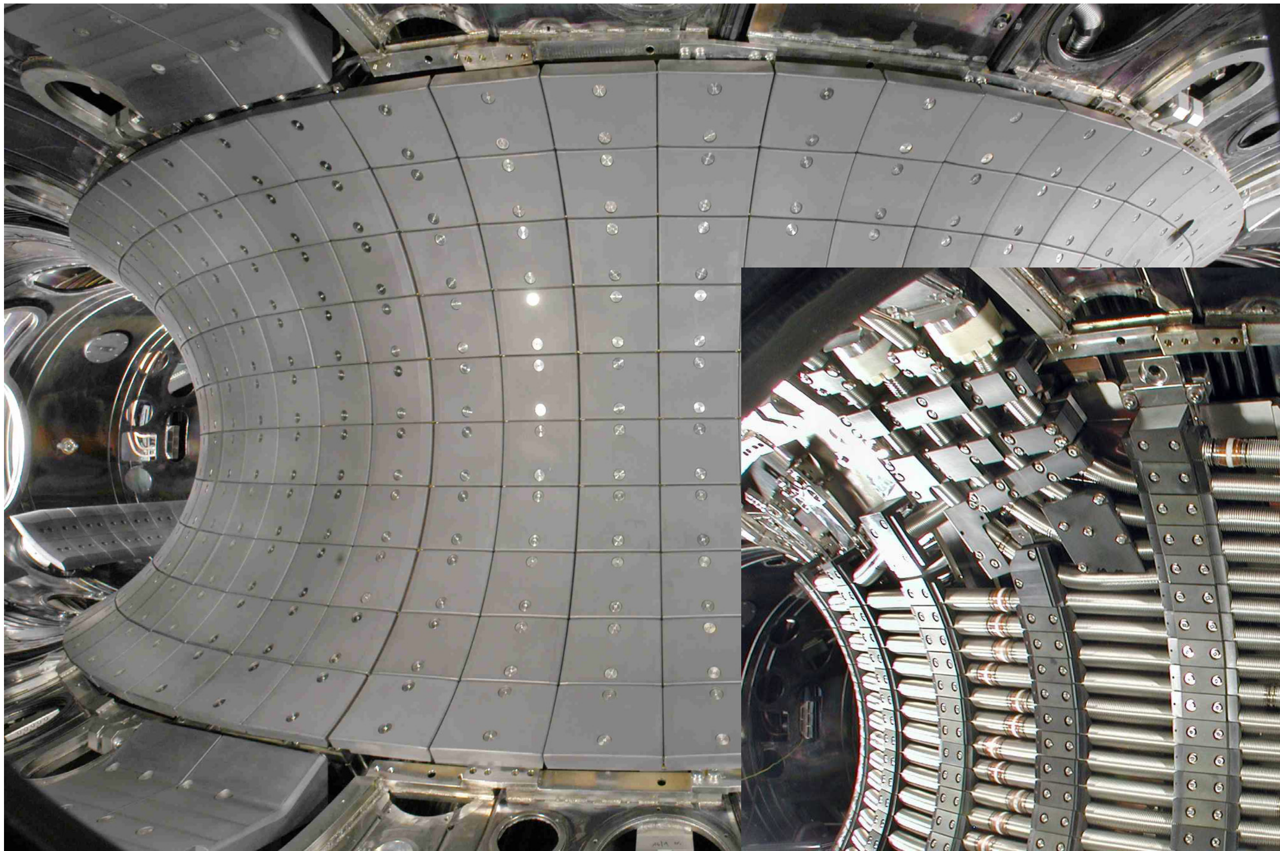
Tokamak EXperiment for Technology Oriented Research

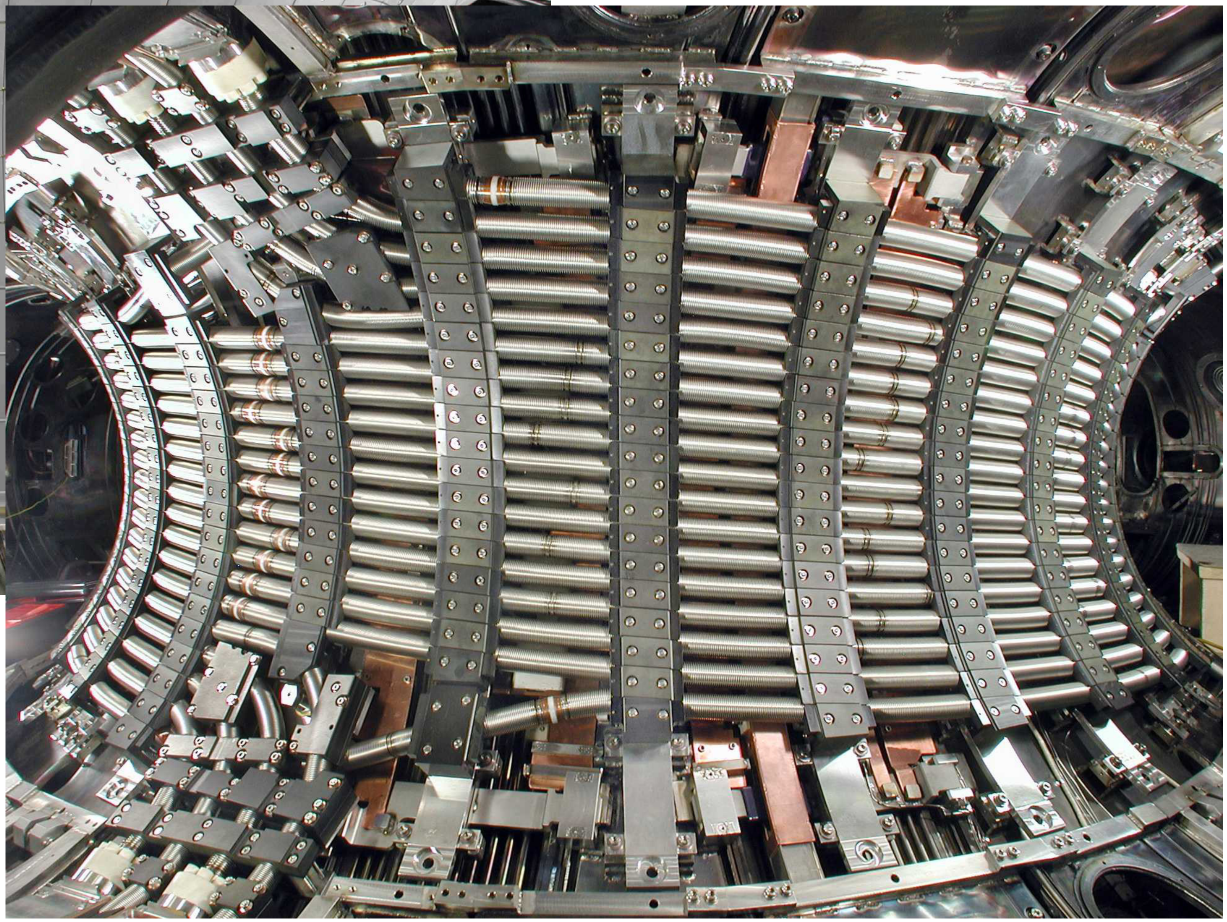


Circular cross section limiter tokamak

- R = 1.75 m, a = 0.46 m
- B_t < 2.8 T
- I_p < 600 kA
- t_{pulse} < 10 s
- **N**eutral **B**eam **I**njection heating
  - 2 ion sources (co- and counter-current direction)
  - 0 - 1.5 MW each
- **I**on **C**yclotron **R**esonance **H**eating
  - Up to 4 MW
- **E**lectron **C**yclotron **R**esonance **H**eating
  - 110 GHz, 400 kW, 200 ms
  - 140 GHz, 800 kW, 3 s

Dynamic Ergodic Divertor (DED)





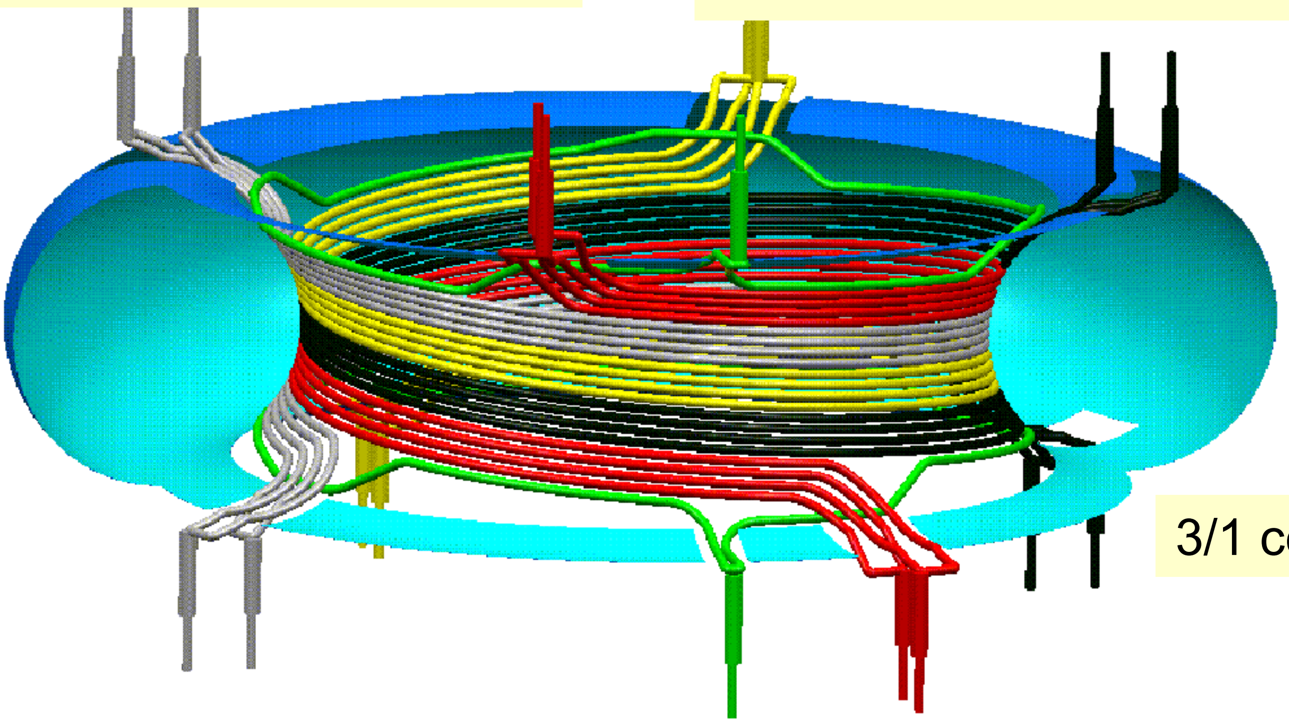
16 helical (+2 compensation) coils on the HFS

Helical pitch resonant to *q* = 3 field lines on HFS

DED parameters

- Configurations
  - 12/4 : PSI studies, island divertor properties
  - 6/2 : confinement studies
  - **3/1 : error field studies, mode stabilization**

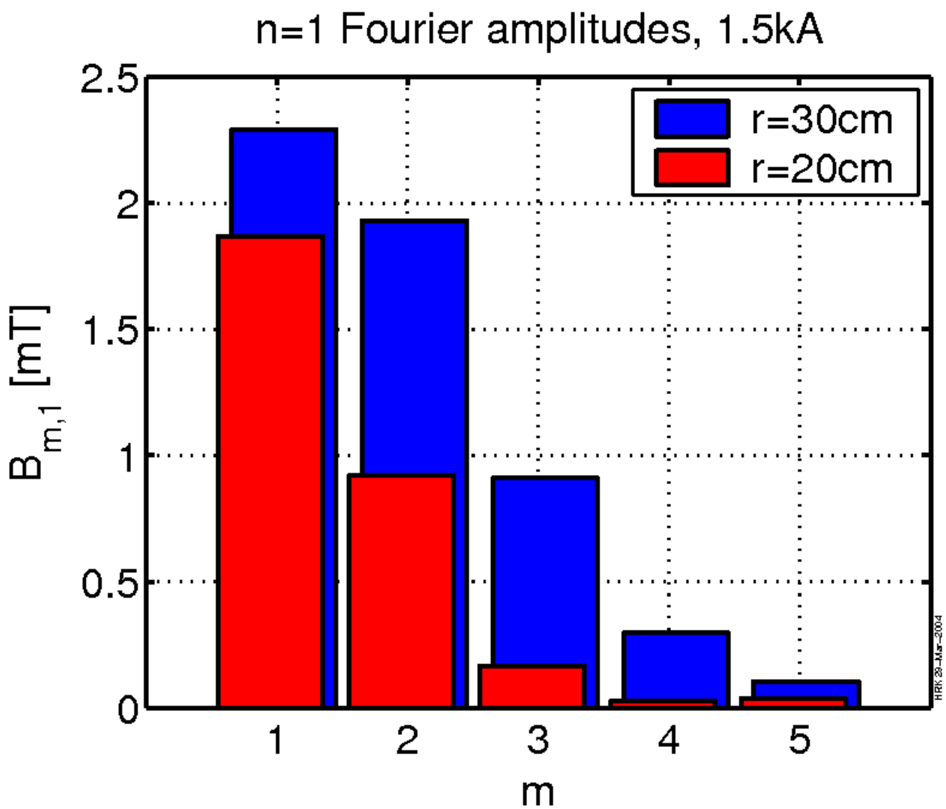
- Currents and Frequencies
  - Up to *n* * 3.75 kA / coil
  - dc or low frequency (2Hz)
  - ac (1 .. 10kHz)
  - Field rotation in co- and counter current direction



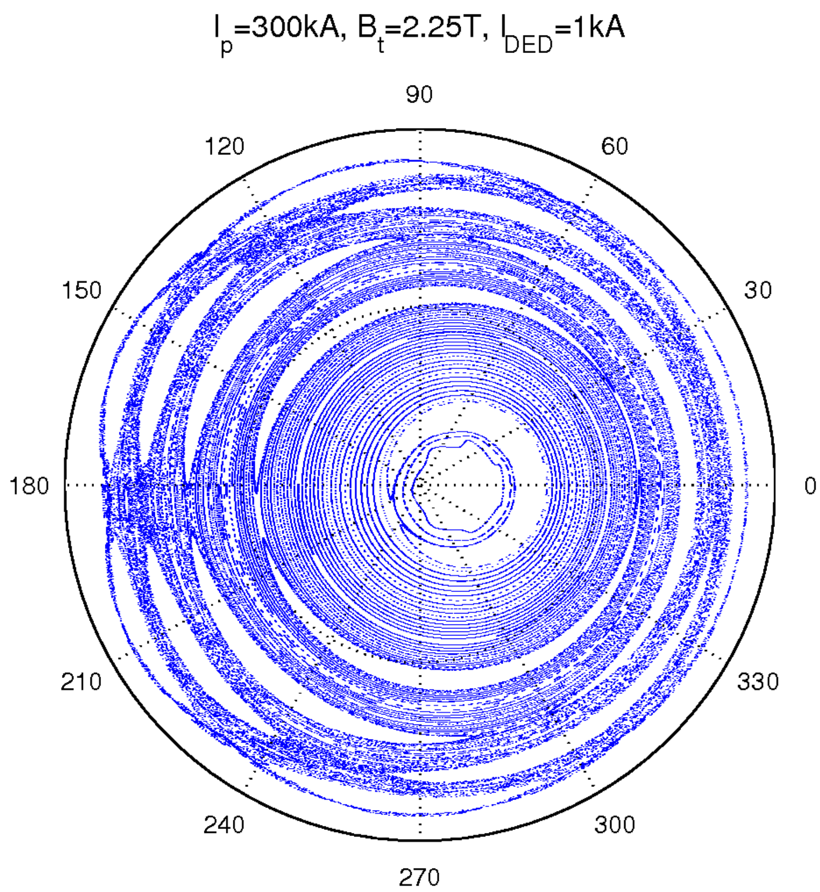
3/1 configuration

DED in 3/1 configuration has strong 2/1 sideband

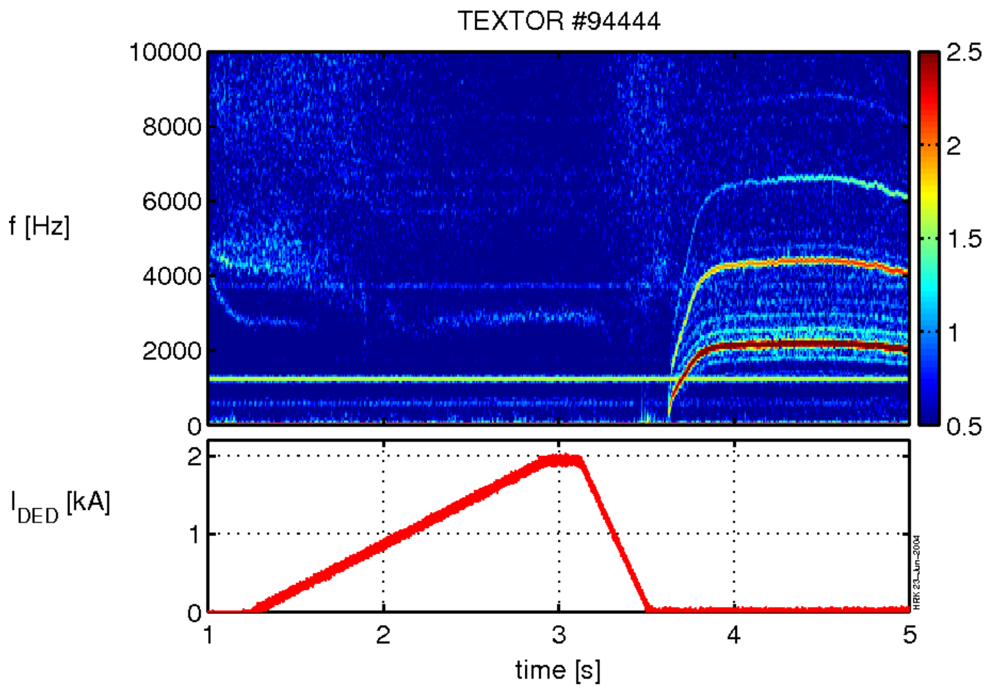
Amplitudes of the $n = 1$ Fourier components of the perturbation field

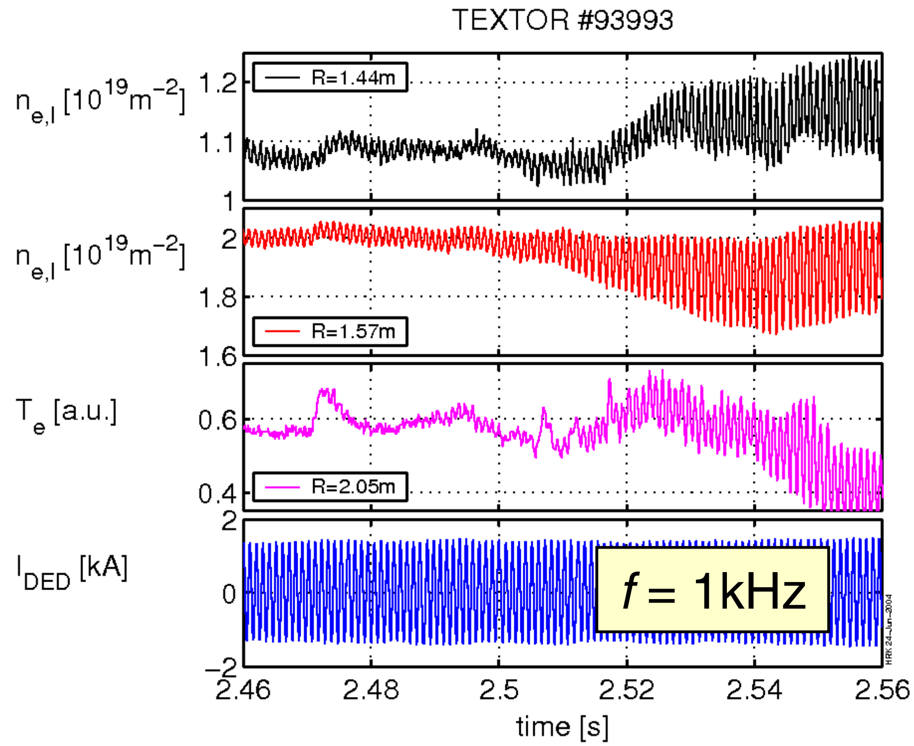


Standard plasma equilibrium + vacuum DED field ($q_a^{cyl}=4.5$)



Locked 2/1 tearing mode is excited by the DED



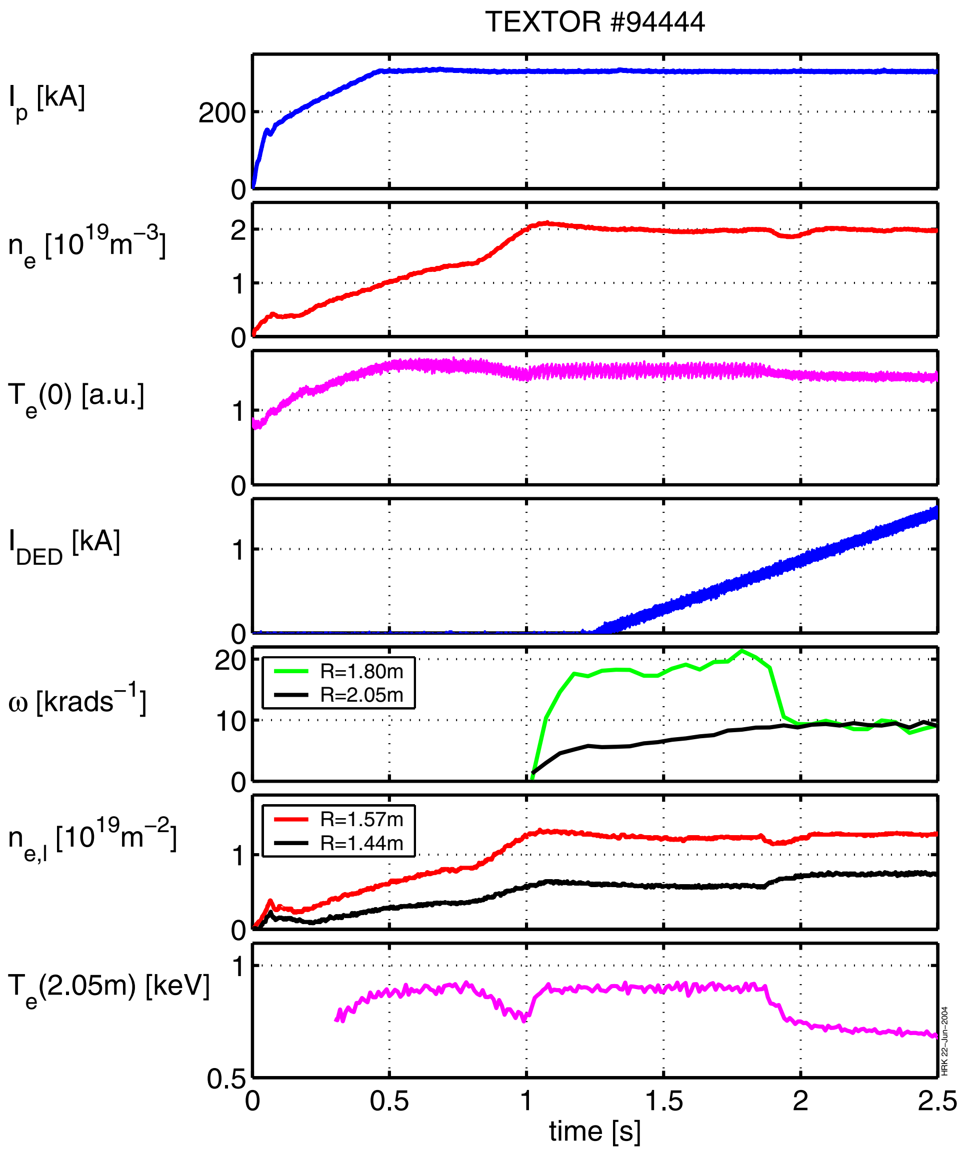


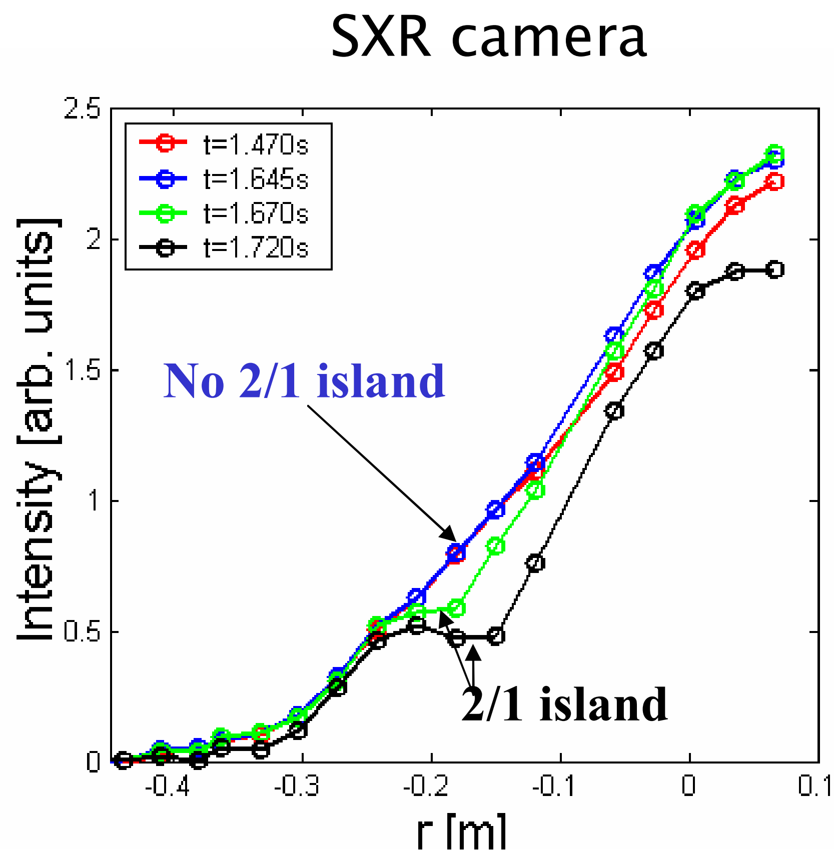
The DED allows to excite an initially locked 2/1 tearing modes

With DED in ac mode the tearing mode is “locked” to the external (rotating) perturbation

H R Koslowski et al 2004 *ECA* **28G** P1.124

Discharge scenario for mode excitation studies





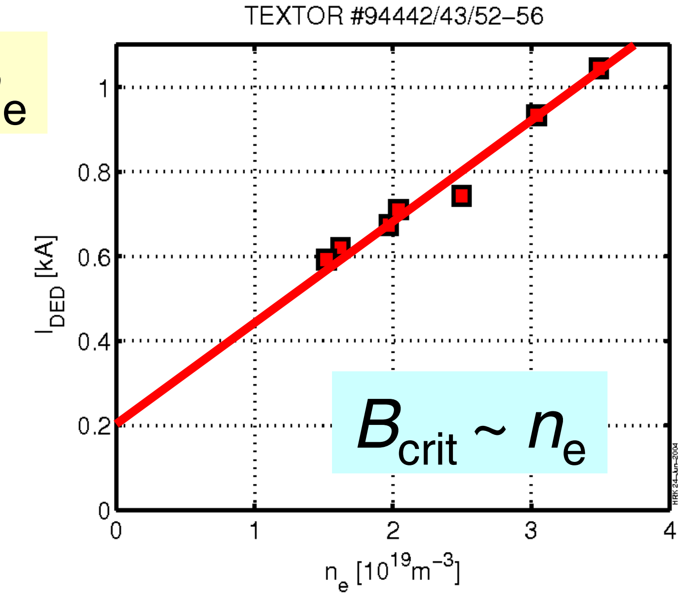
Saturated island width up to 17% of plasma minor radius

Tearing mode studies using the DED

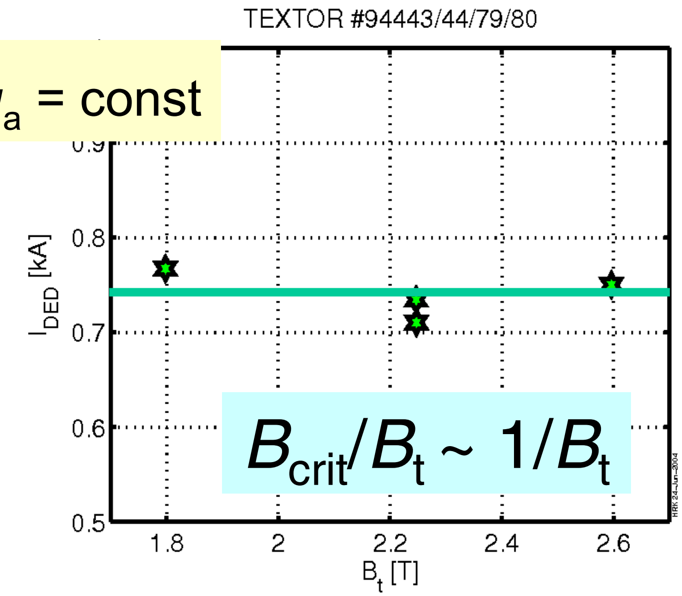
- DED in 3/1 configuration allows to create 2/1 tearing modes on purpose
- dc and ac operation at 1 or 3.75 kHz with co- and counter current rotation
- Mode is locked to external perturbation, i.e. mode rotates in the tokamak frame with the DED frequency
- Radial location of islands is well known
- Phase (X- and O-point of the island) is determined by external DED currents
- **Well defined experiments to study mode onset thresholds and mode stabilization by ECRH / ECCD can be performed on TEXTOR**

Parametric dependencies of perturbation field penetration

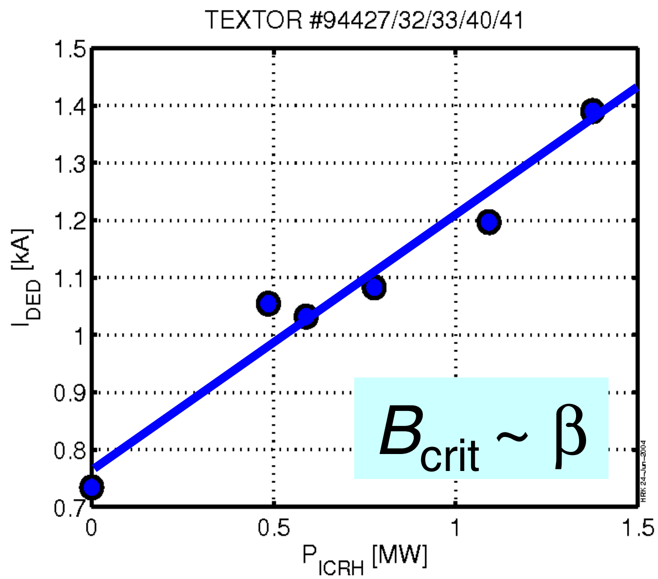
n_e



B_t, q_a = const



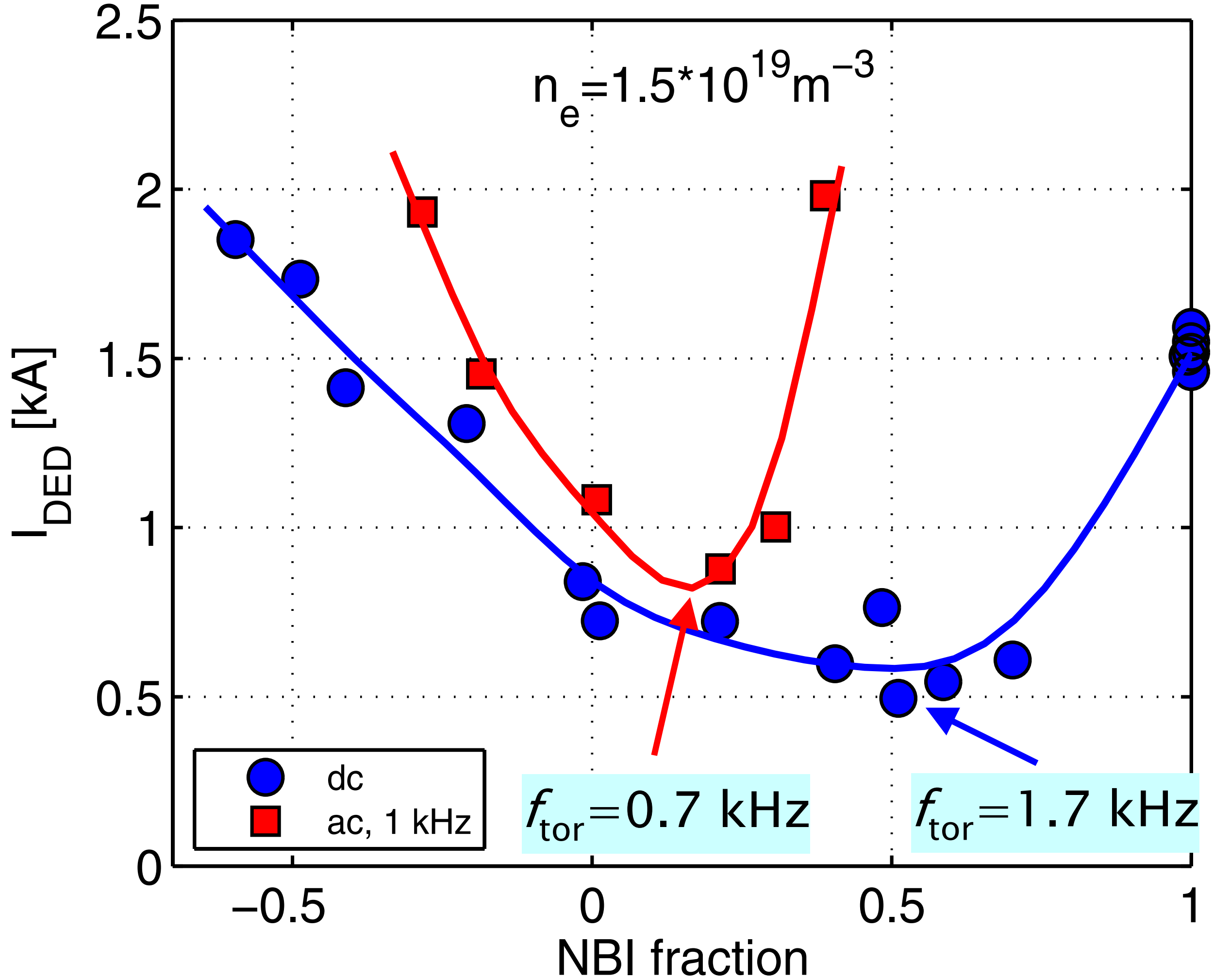
β



Almost *usual* behaviour of parametric dependencies of error field thresholds for tearing mode excitation

H R Koslowski et al 2004 *ECA* **28G** P1.124

Plasma rotation scan with dc and ac DED

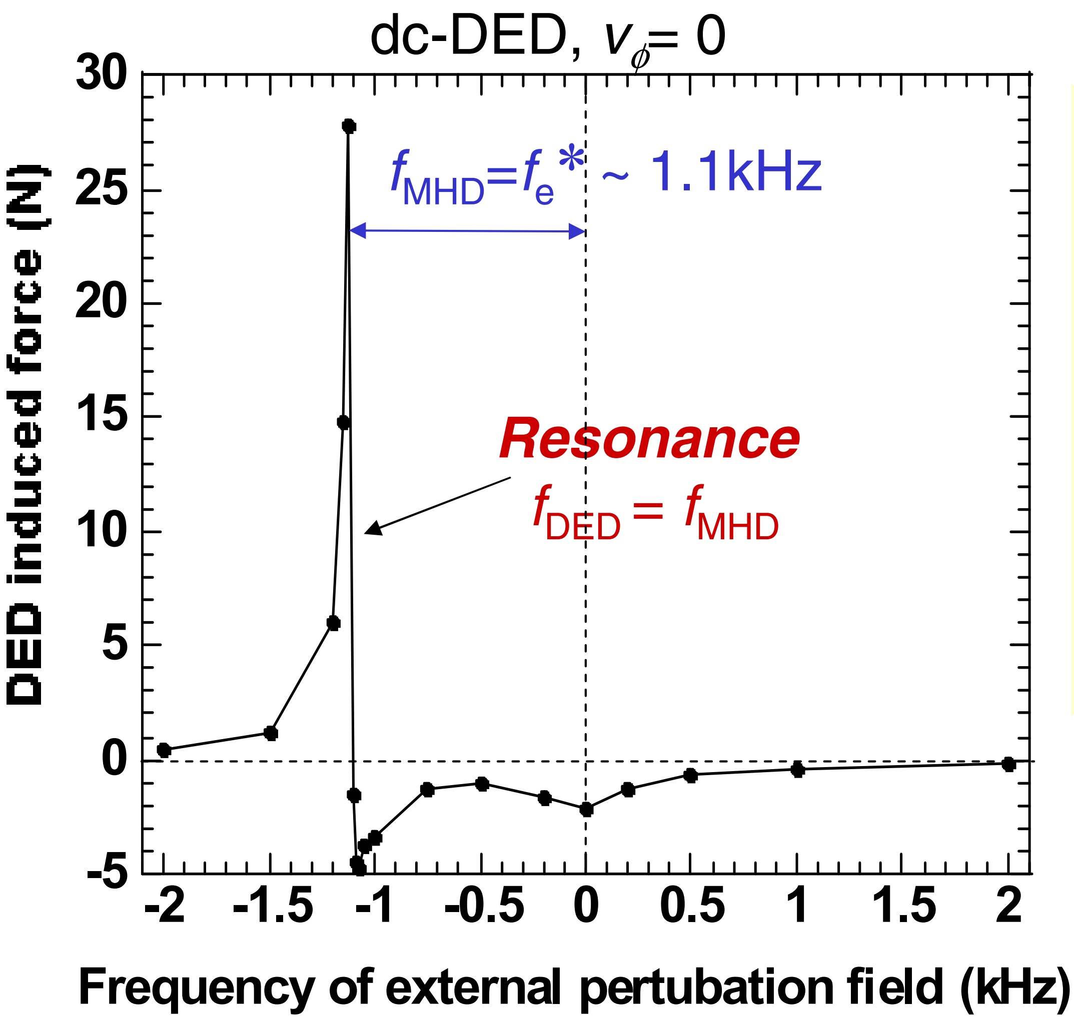


- P_{tot} = const
- β = const
- 2/1 mode
  - dc
  - +1 kHz ac (counter)
- no 2/1 mode
  - −1 kHz ac (co)
- Minimum shifts by DED frequency
- Resonance

NBI fraction = $(P_{co}-P_{cntr})/(P_{co}+P_{cntr})$

H R Koslowski et al 2006 *NF* **46** L1

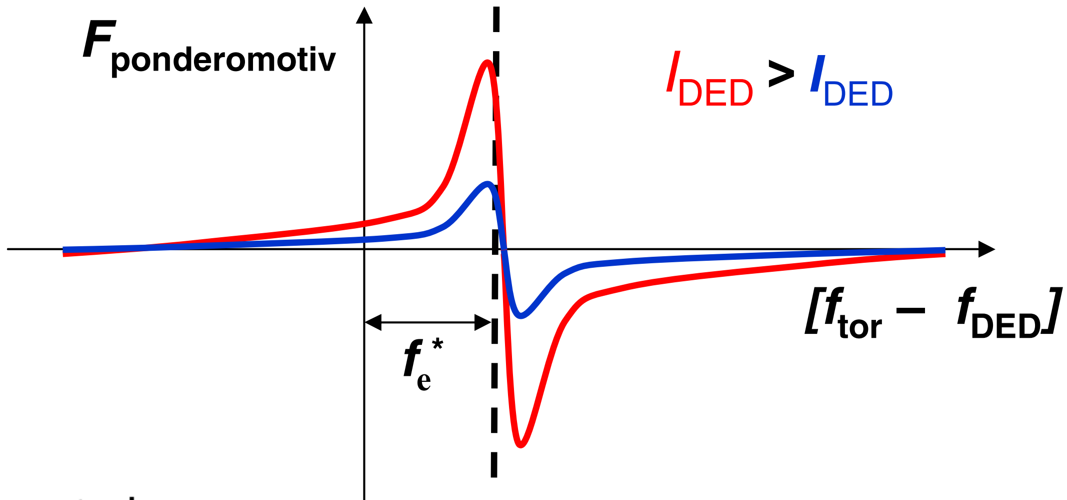
Dependence of the DED induced force on the MHD frequency



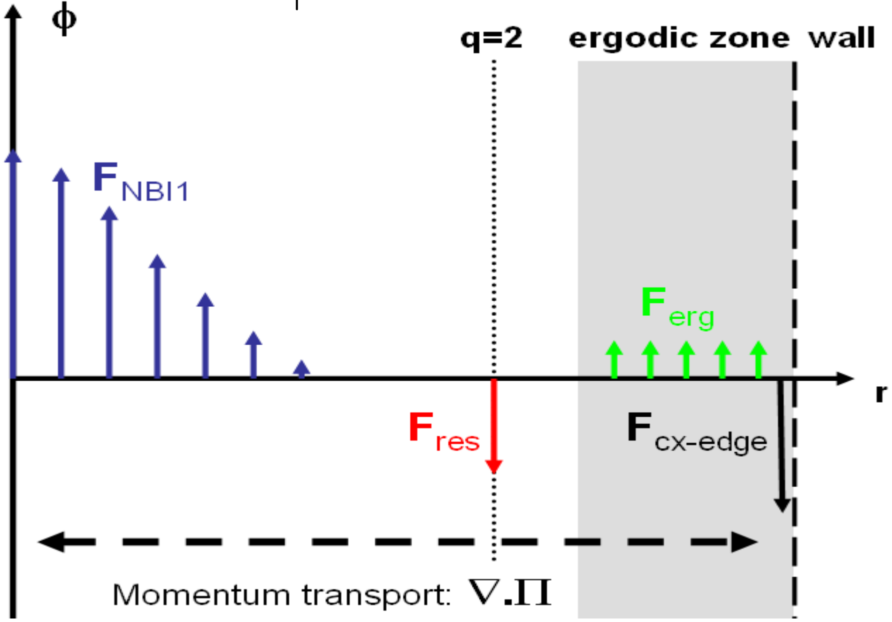
- Four-field MHD model ($A_{||}$, ϕ, n, $v_{||}$)
- linear cylindrical approximation
- single mode ($m/n = 2/1$)
- Force: $F = j \times B_r$

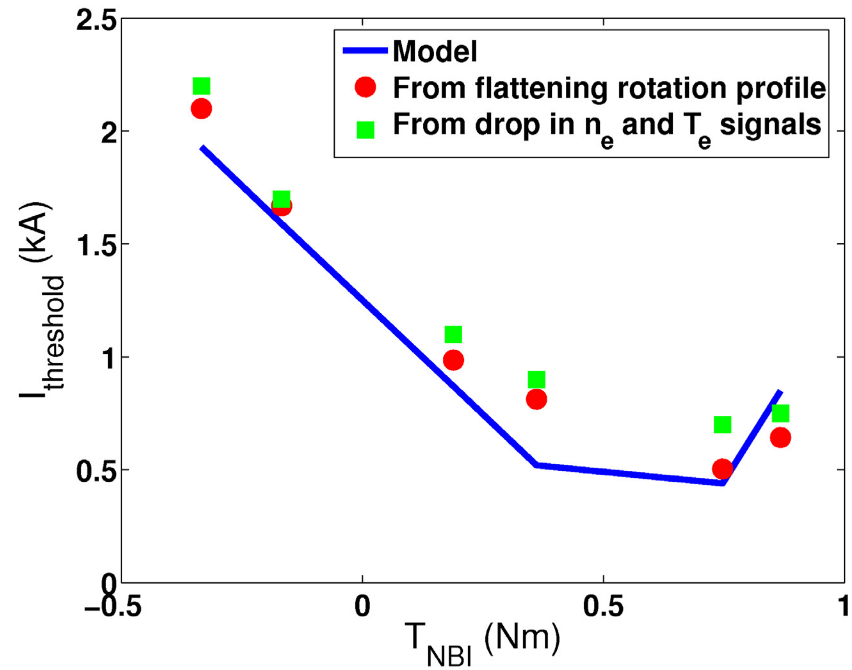
Y Kikuchi et al 2006 *ICPP*

Force balance explains measured threshold



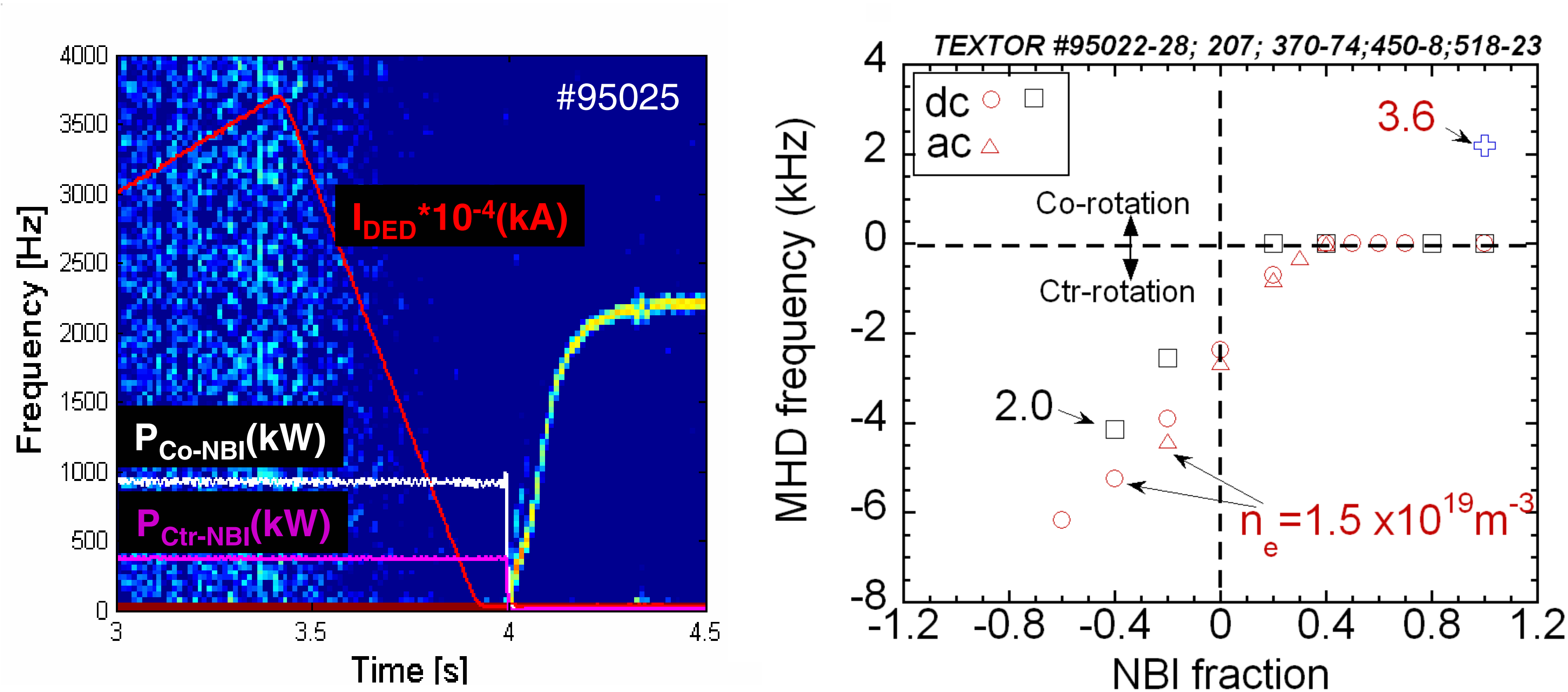
Simple model based on force balance gives good agreement with measurement





M de Bock 2007 *PhD Thesis* TU Eindhoven

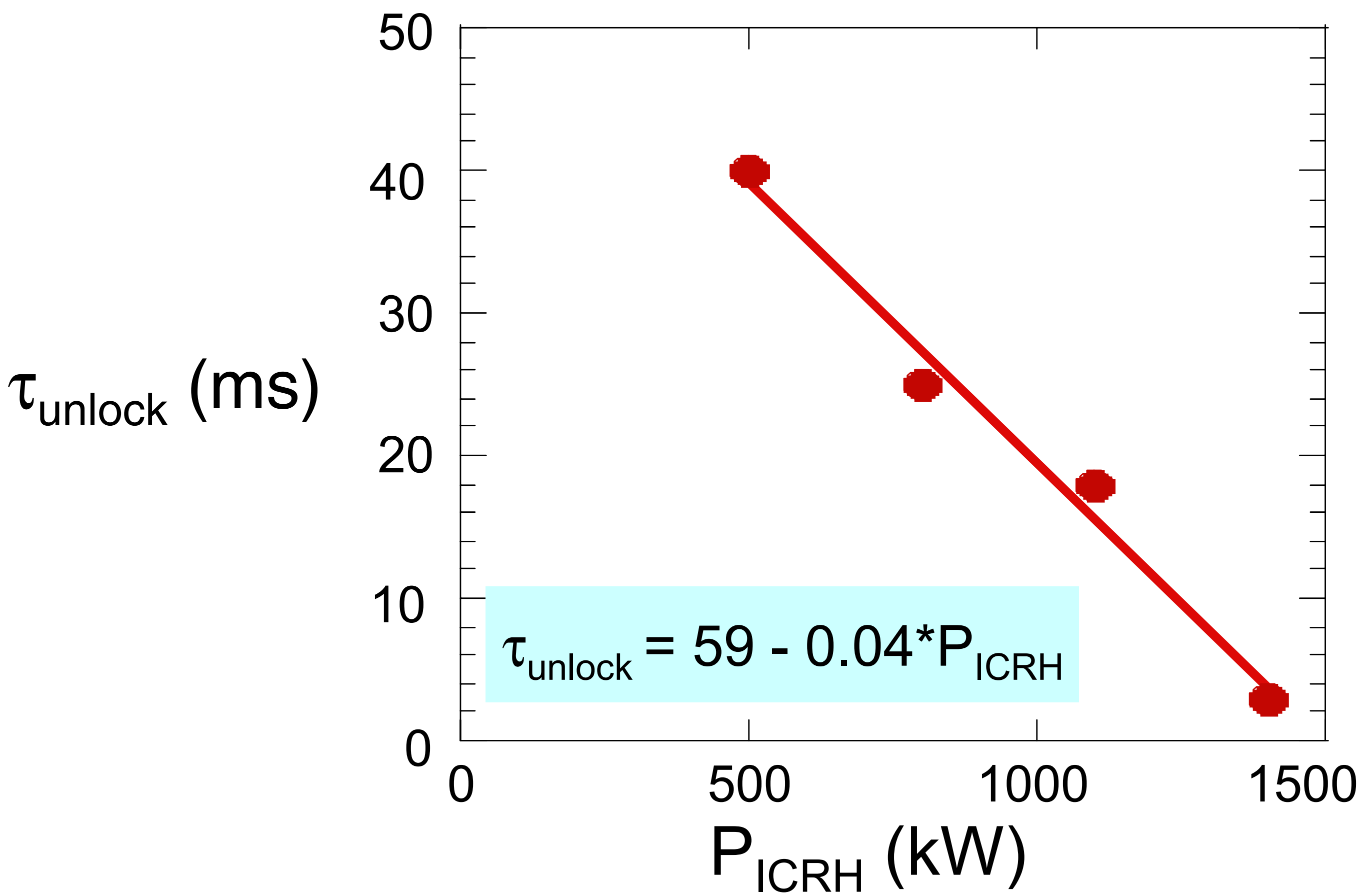
Tearing mode unlocks delayed with respect to the switch-off of the external perturbation field



Locked mode spins up when dominating co-NBI heating is switched off in low-density plasmas (n_e< 3.6x10^{19}m^{-3})

Y Liang et al 2005 *ECA* **29C** P4.060

Mode unlocking shows equivalent beta dependence as the mode onset threshold



I_p=300kA

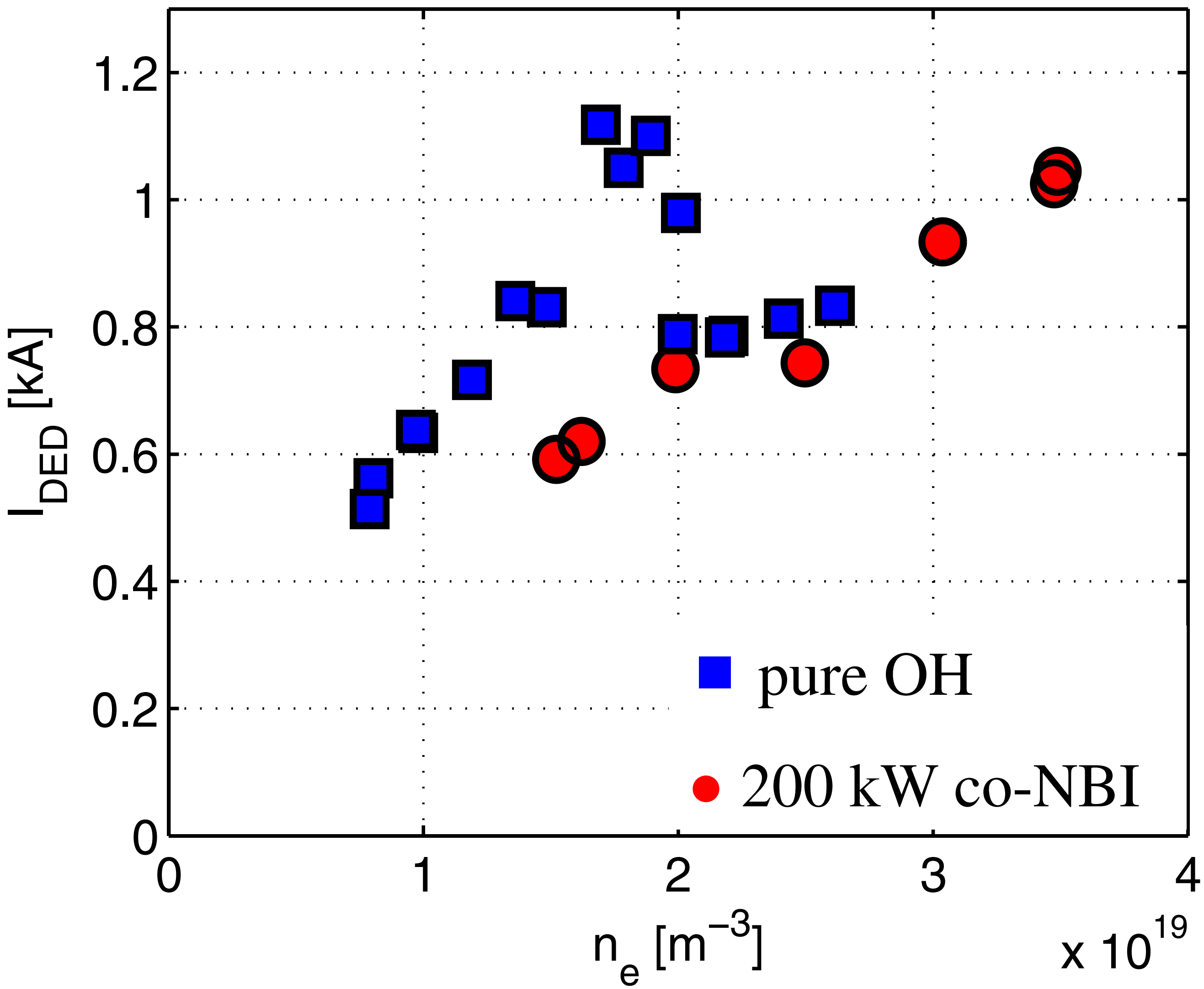
B_t=2.25T

n_e=2x10^{19}m^{-3}

This behaviour is most likely a rotation effect: f^* (in counter direction) increases with β and increases the threshold

Y Liang et al 2004 *ECA* **28G** P1.126

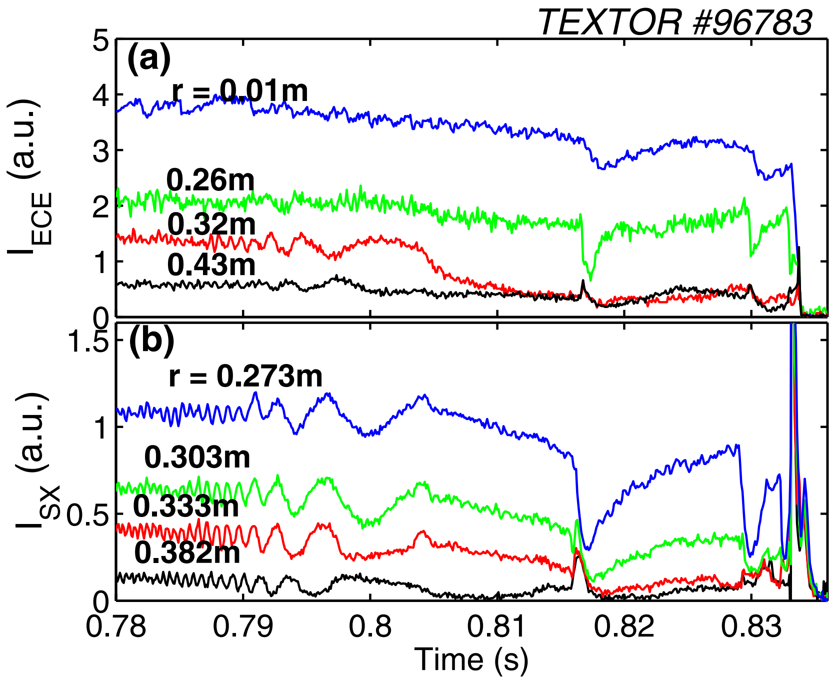
Density dependence of locked mode threshold

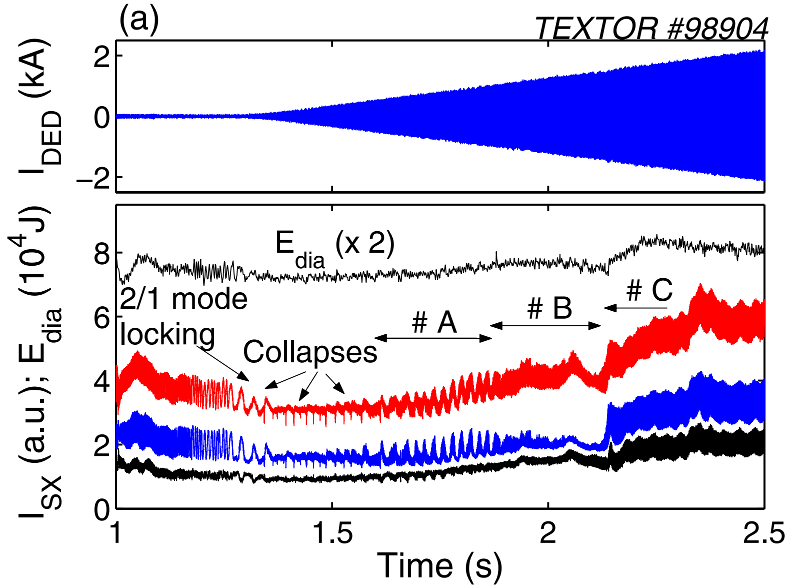


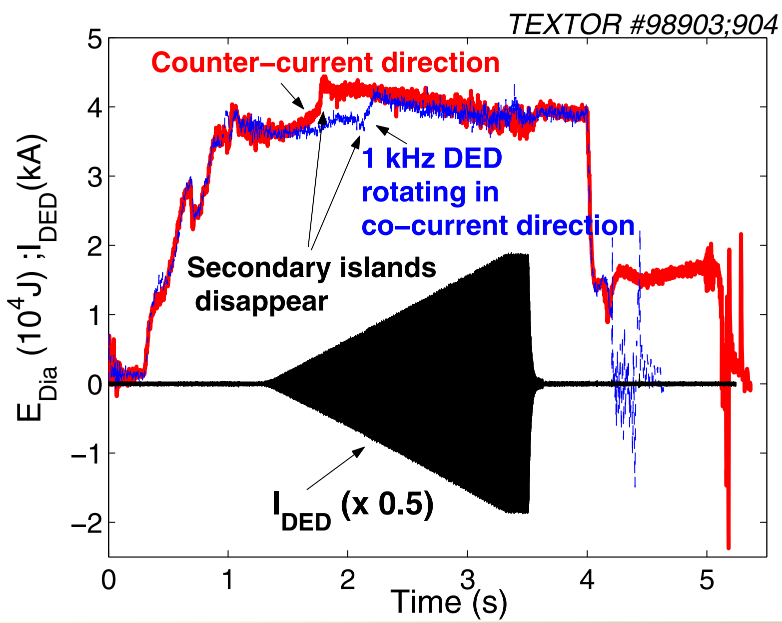
Resonance-like behaviour of mode excitation threshold at very low electron density

K Löwenbrück 2007 *PhD Thesis* U Bochum

Rotating perturbation fields can prevent locked mode disruptions







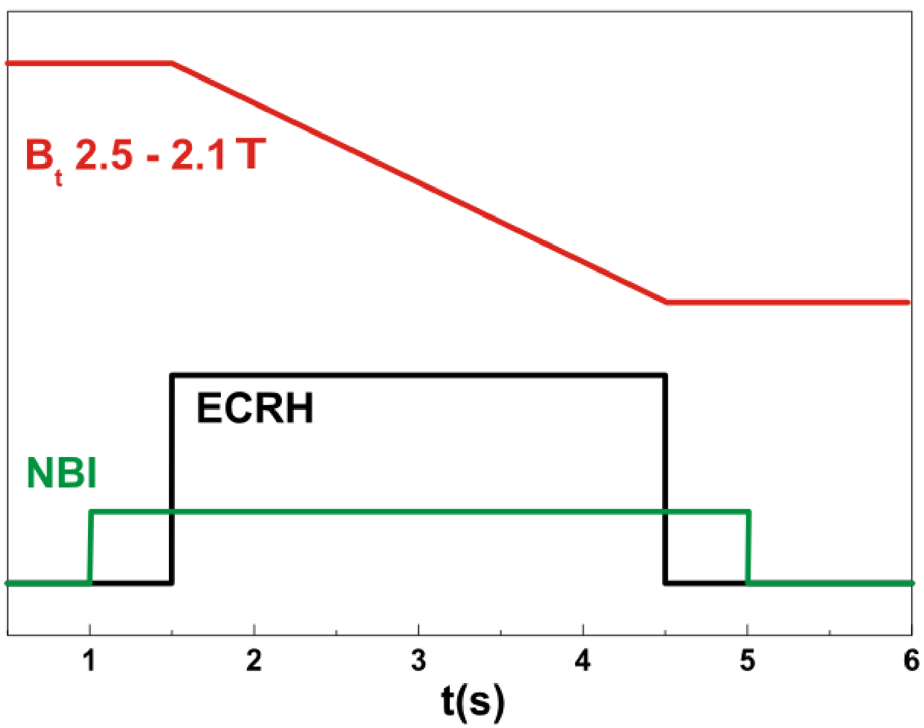
Application of rotating perturbation field spins up locked mode and stabilises discharge

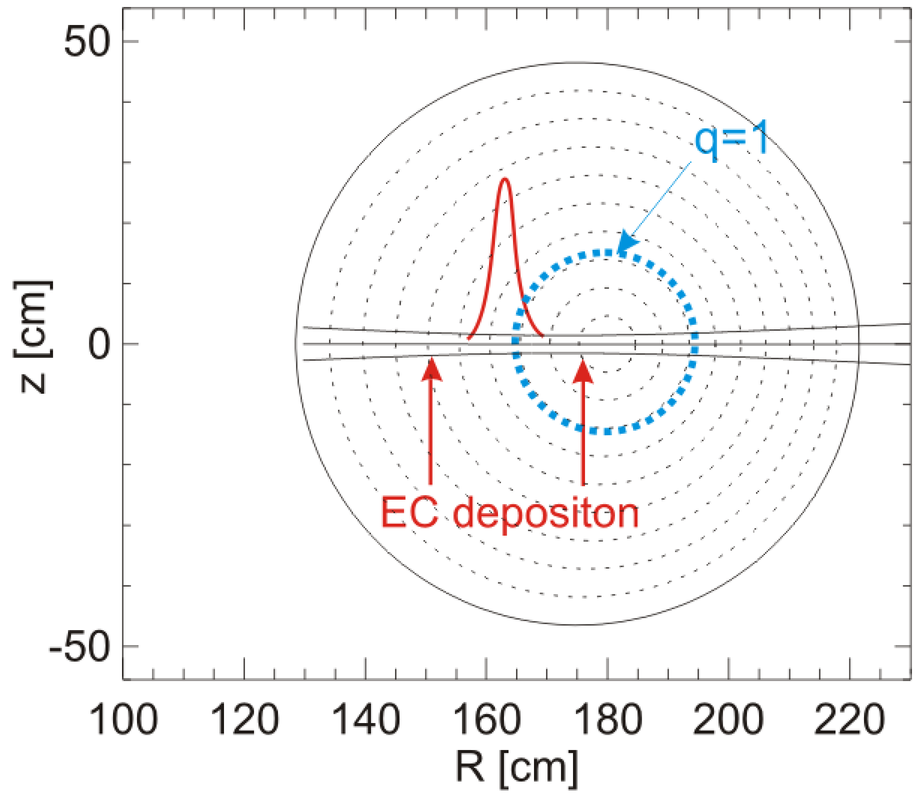
Rotating 2/1 mode does not lead to disruption

Y Liang et al 2006 *subm. To PRL*

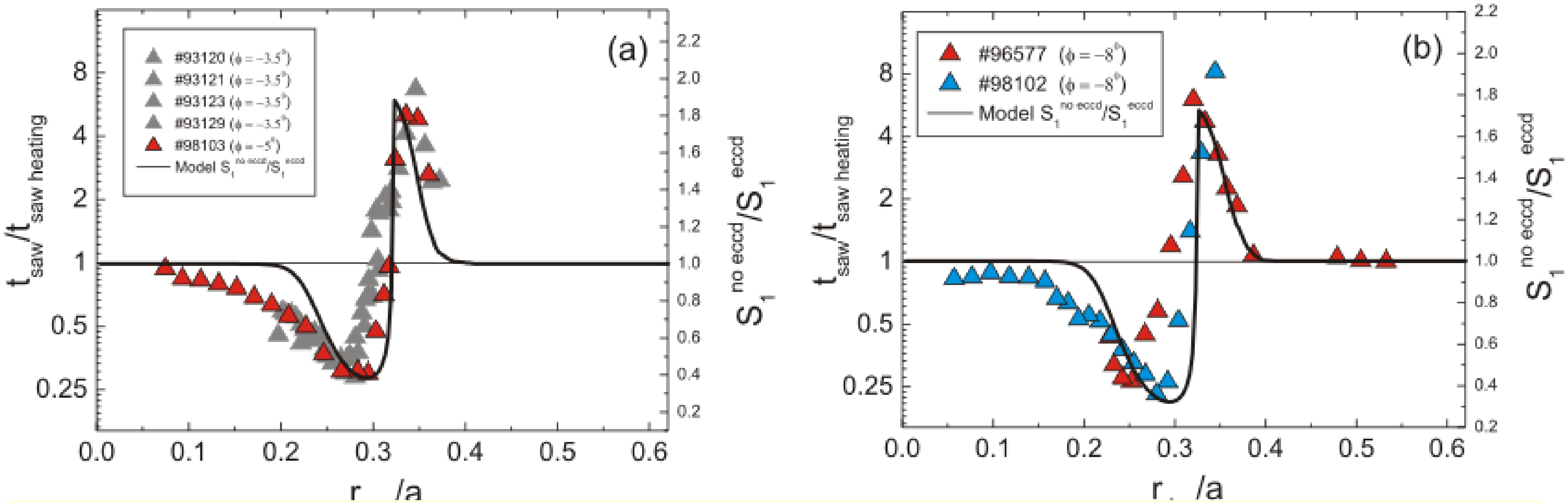
Sawtooth control experiments

- Slow magnetic field ramps to scan the EC deposition through the plasma
- Variation of toroidal injection angle to vary EC driven current





Example: co-current drive



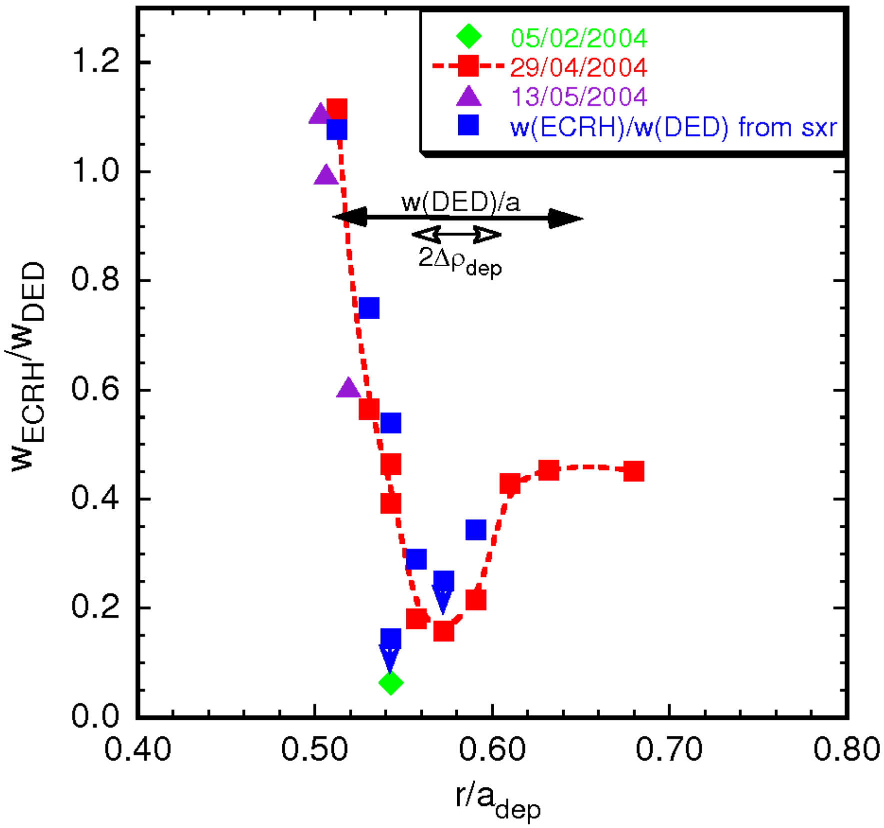
- Effect of current drive separated from effect of concurrent heating by normalization of sawtooth period response function on a discharge with pure heating
- Effect on sawtooth period proportional to effect on shear evolution
- In qualitative agreement with Porcelli's critical shear sawtooth model
- Required non-inductive current for sawtooth control scales like:

$$I_{cd} > 2\,(\Delta r/r_{q=1})^2\, I_{q=1}$$

A Merkulov et al 2004 *Proc. Int. Varenna Workshop* 279

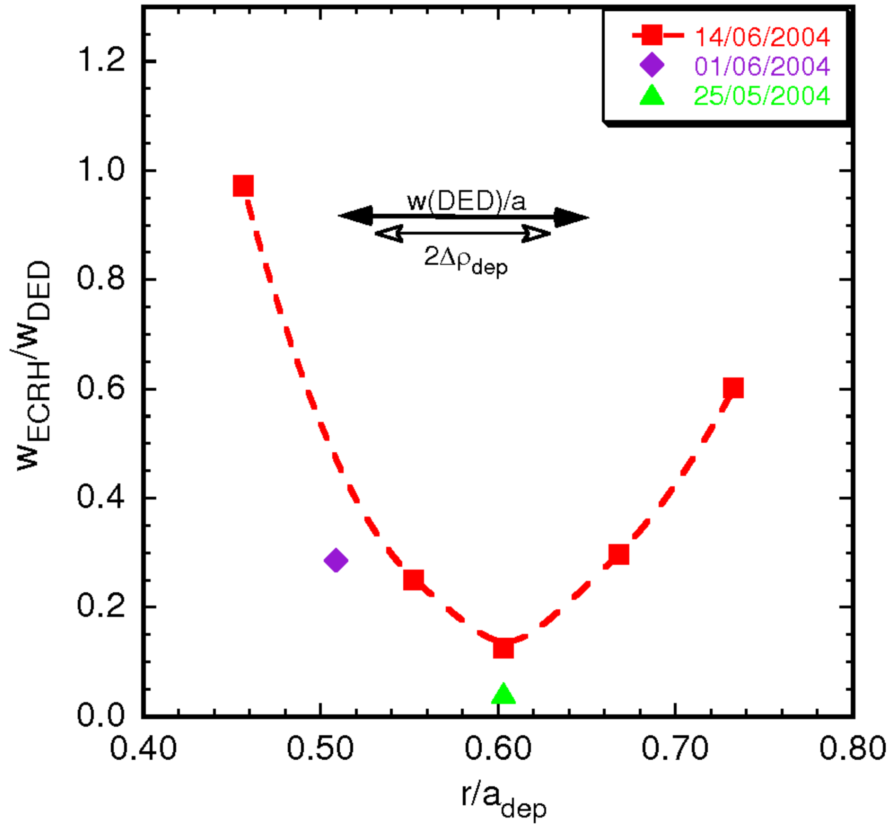
Tearing mode control: scan of deposition radius (dc ECRH/ECCD)

ECRH



Deposition scan by vertical injection angle

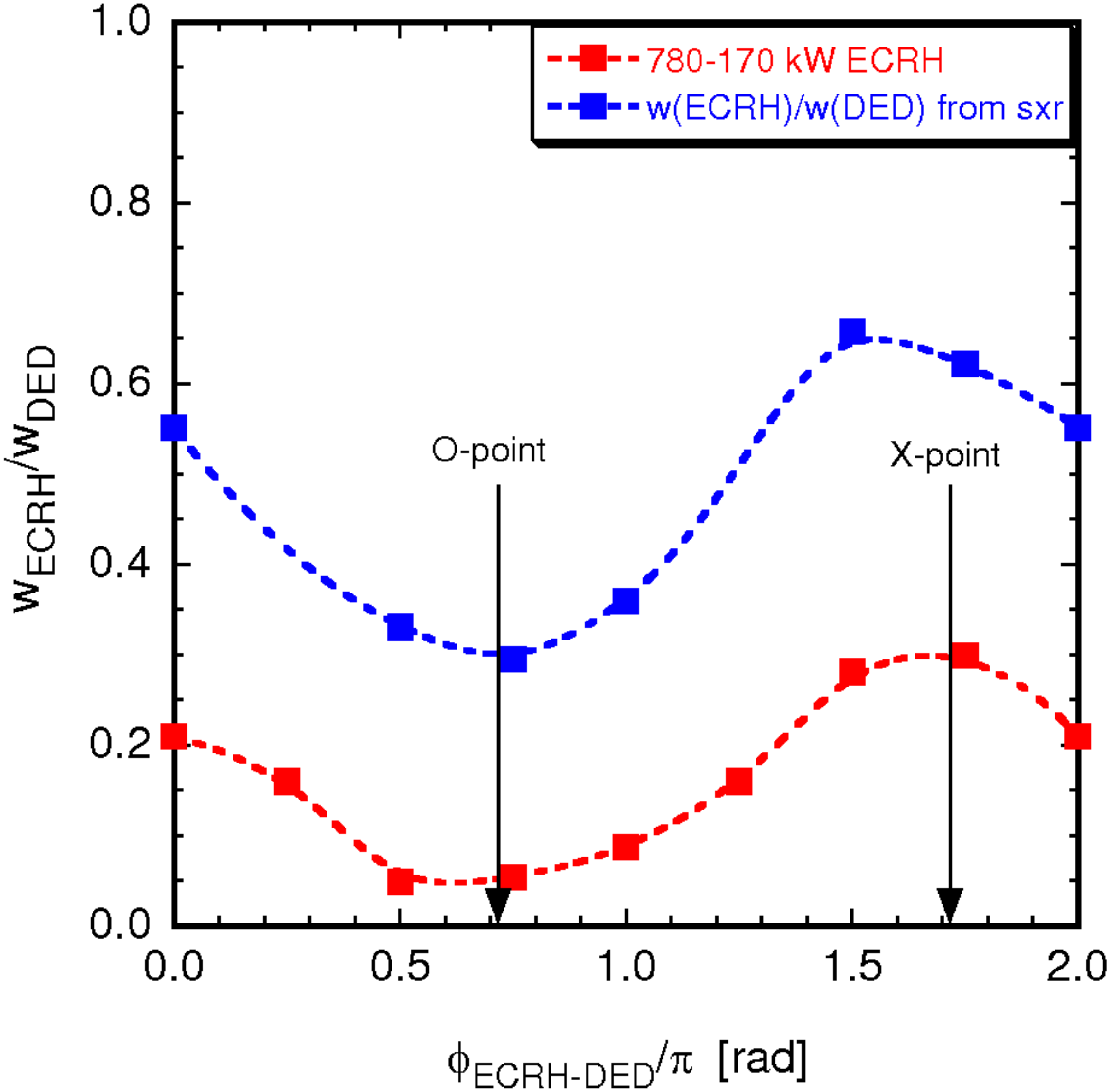
ECCD



$J_{cd,max}$ at q=2 is 6% of $J_{q=2}$

E Westerhof et al 2006 *subm. To NF*

Phase scan (ac ECRH/ECCD)



Island generated with DED and kept rotating at 1 kHz

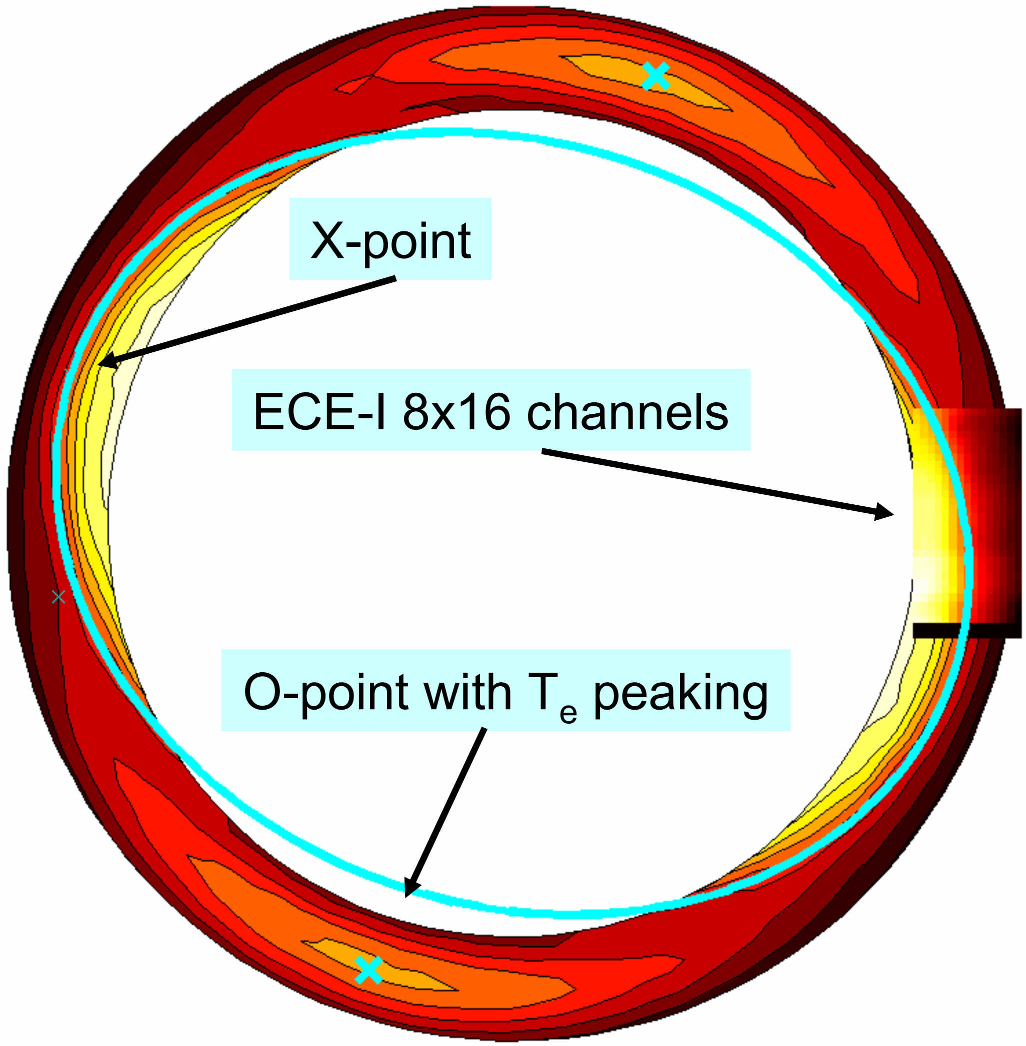
Phase derived from currents in DED coils

Heating inside the O-point of the island is more effective than heating at the X-point

E Westerhof et al 2006 *subm. To NF*

Main cause of stabilization is heating inside the island

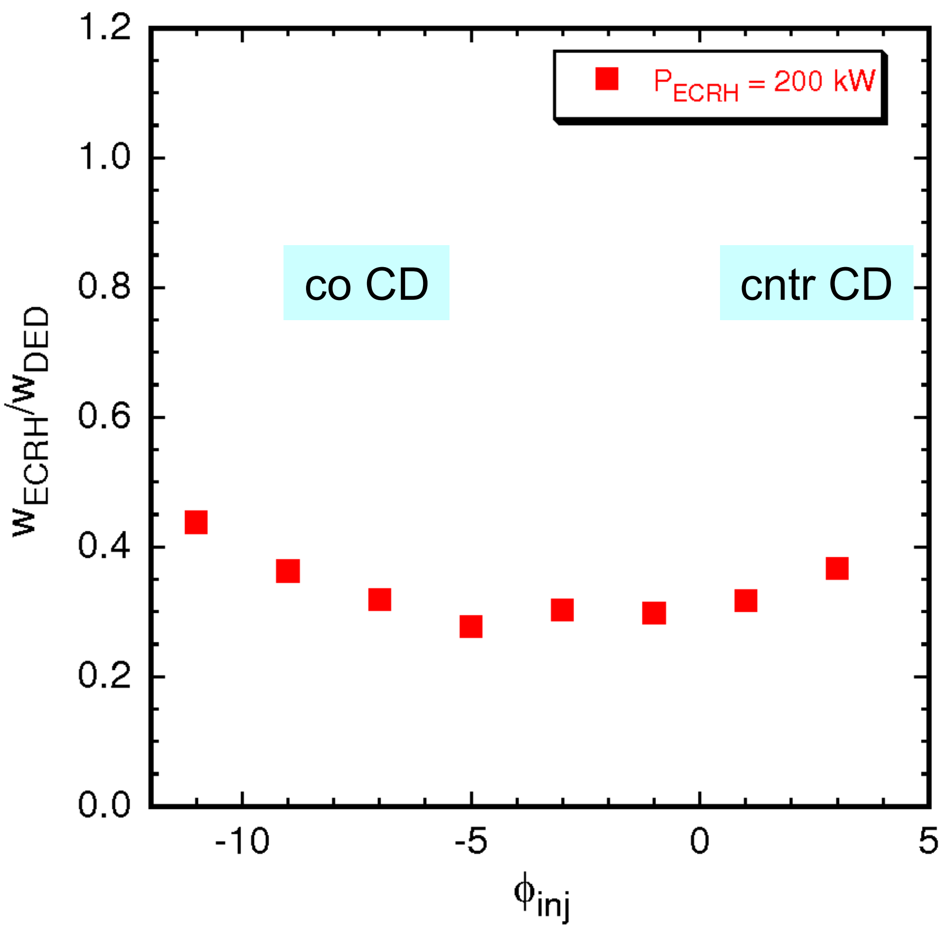
- Temperature peaking inside island has been observed by ECE-Imaging (and confirmed by Thomson scattering)
- A pronounced T_e peaking of ~ 10% (during first 10 ms after ECRH switch-on)



I Classen et al 2006 *Proc. EC-14*

Mechanism for ECRH / ECCD Mode stabilization

Reduced power (200 kW) enhances contrast



- $J_{cd,max}$ at q=2 is 3% of $J_{q=2}$
- Extrapolation to ITER
  - 20 MW ECRH system for NTM stabilization
  - Concurrent heating will especially help in the initial stage with large island width
  - For $\chi_e = 0.1\ m^2/s$, the temperature perturbation in the island is predicted to be ~1 keV, and the effect of the heating is as large as the effect of the ECCD
  - For $\chi_e = \chi_{e,q=3/2} = 0.5\ m^2/s$, still a 20% effect remains

E Westerhof et al 2006 *subm. To NF*

Summary and Conclusions

- TEXTOR with NBI, ECRH, ICRH and DED allows detailed studies of mode excitation by perturbation fields and mode stabilisation by electron cyclotron heating and current drive
- The frequency match between external perturbation field and MHD frequency of the mode determines the excitation threshold
- Dynamic (rotating) perturbation fields can stabilise locked modes and prevent disruptions
- Sawtooth control in qualitative agreement with Porcelli's model
- The 2/1 tearing mode is predominantly suppressed by heating inside the island and by the corresponding temperature increase in the O-point
- Heating inside the island will have a considerable influence on NTM stabilisation on ITER