CONCLUSIONS FROM EXPERIMENTS WITH LARGE TOROIDAL CURRENTS ON W7-A AND W7-AS

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1) Suppression of current disruptions on W7-A:
(data obtained in 1978/79)

2) Differences between W7-A and W7-AS

3) Pure bootstrap currents on W7-AS

4) Bootstrap currents increased by ohmic and NB driven currents

5) Influence of large toroidal currents on confinement

6) Conclusions

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1) Suppression of current disruptions on W7-A:

important parameters of W7-A:

conventional stellarator:
<u>toroidal field coils and l=2 helical windings</u>
5 toroidal field periods

elliptical plasma cross section, turning toroidally in accordance with the helix geometry
<u>vacuum field rotational transform $\iota_o \approx 0$ ..0.55 at $B_o \approx 3$ T,</u>
very low vacuum field shear

$R_o = 200$ cm, a = 8 .. 11 cm, depending on ι_o
<u>large aspect ratio, cylindrical approximation rather adequate</u>

<u>at the beginning: ohmic heating</u> the only heating method
→ stellarator/ tokamak hybrid experiment
necessarily <u>confronted with the problem of current disruptions</u>

<u>only later on</u> other heating methods: <u>NB heating and ECRH</u>

<u>with ohmic heating only:</u> current disruptions do no longer occur for suffiently large external transform: $\iota_o > 0.15$

explanation: helical fields improve the stability against current disruptions in two ways:

a) current disruption limit almost identical with m = 2 tearing mode stability limit

Figure 1

stabilization of m = 2 mode easy to understand on the basis of tearing mode theory

free potential energy of tearing modes given by:

$$2\,\delta W = -8\pi^2 R_o \int_0^b r\,dr \left[\left(\frac{d\Psi}{dr}\right)^2 + \frac{A}{r^2}\Psi^2\right]$$

$$A = m^2 + \frac{mr}{m\,\iota(r) - n}\,\frac{\mu R_o}{B_o}\,\frac{d\,j(r)}{dr}$$

$\Psi(r)$ is the perturbed helical flux function, from which the stability parameter Δ' is calculated

essential term which governs tearing mode stability:

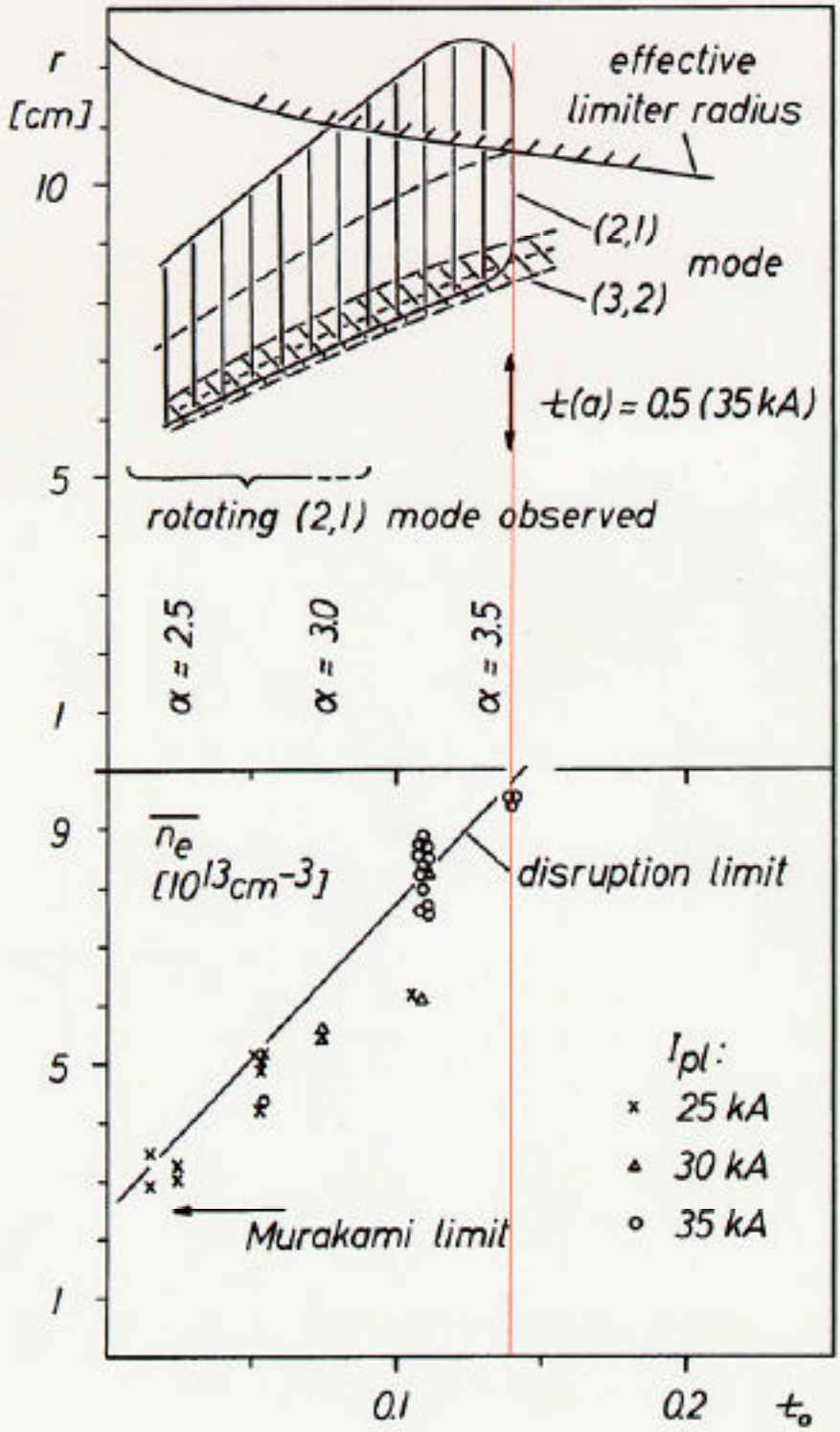
$$\frac{1}{m\,\iota(r) - n}\,\frac{d\,j(r)}{dr}$$

how changes this quantity under different conditions, at first for different ι_o ?

Figure 2,3

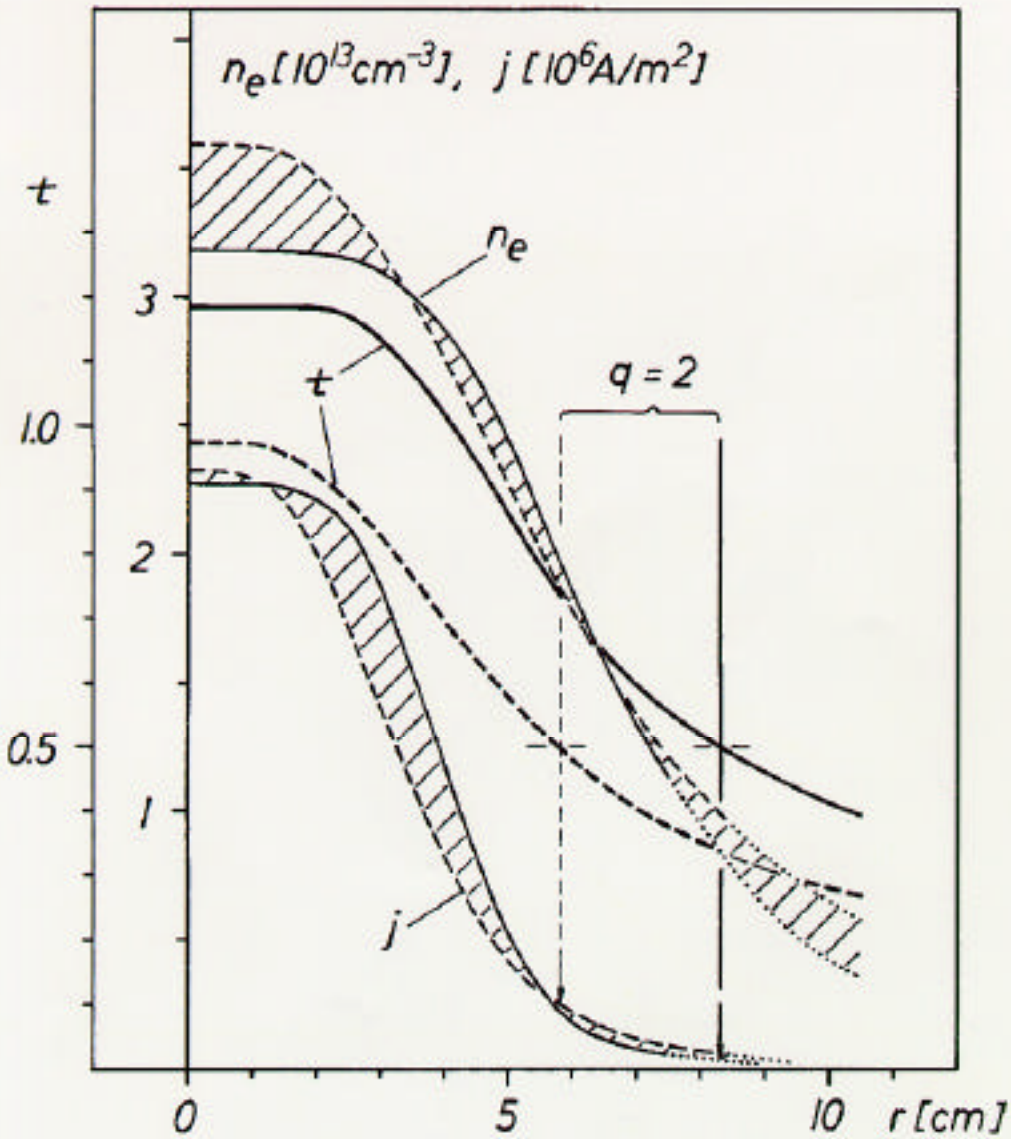
Disruption Limit on W7-A

B_0 = 3.5 T, ohmic heating



Stability of m=2 Tearing Modes on W7-A

similar $n_e(r)$ and $j(r)$, but different ι_0



--- $\iota_0 = 0.14$, $B_0 = 3.5$ T, $I_{pl} = 12.5$ kA, He

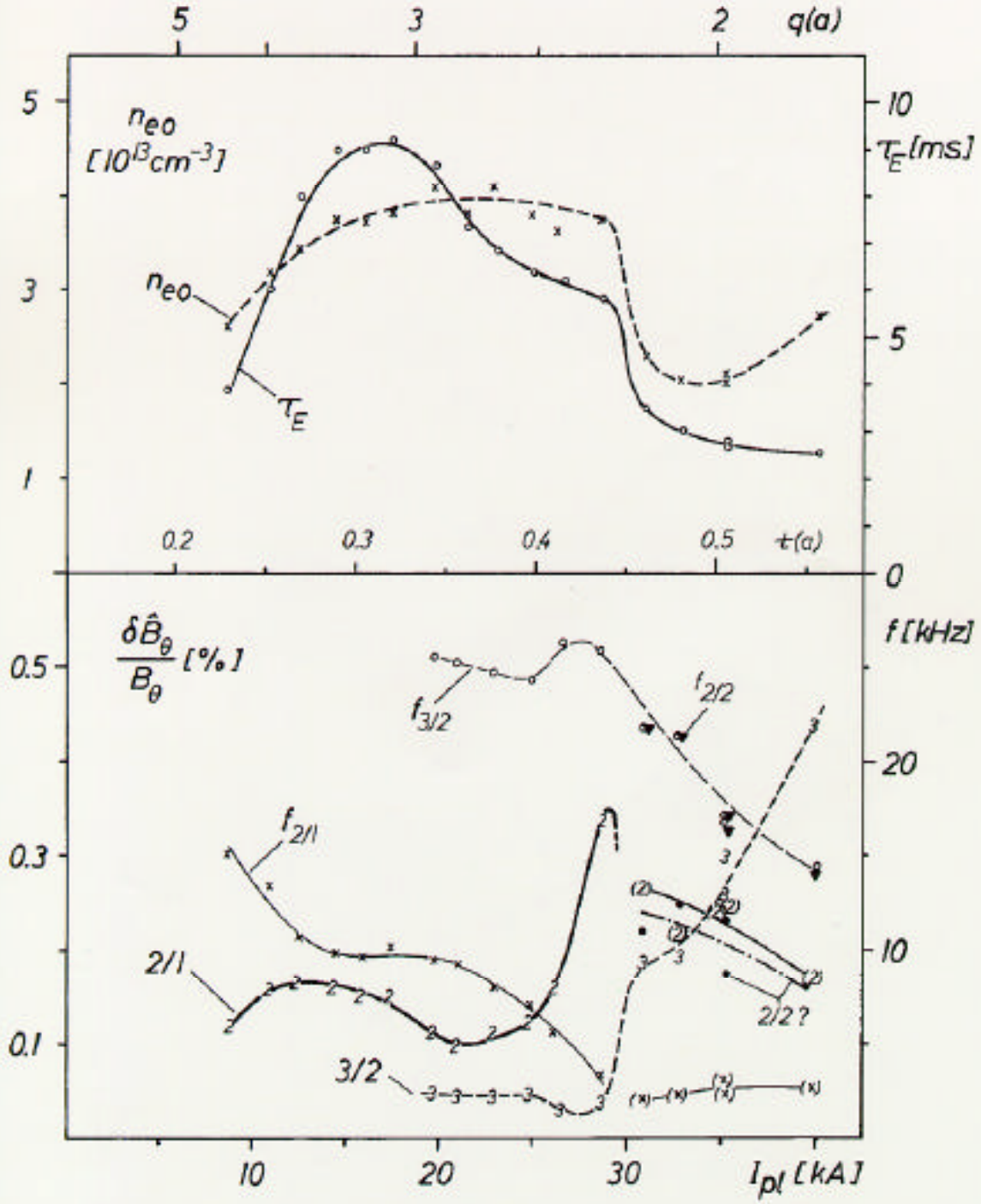
$f_2 = 9.7$ kHz, $\delta\hat{B}_{\theta 2}/B_\theta = 0.19$ %

—— $\iota_0 = 0.23$, $B_0 = 3.0$ T, $I_{pl} = 14$ kA, He

no m=2 tearing mode visible

Tearing Mode Stability on W7-A

plasma current scan



$B_0 = 3.5$ T, $\iota_0 = 0.14$, Helium

b) an external poloidal field that is fixed in space and that does not depend on the plasma position improves the positional stability of the plasma

tokamak: plasma equilibrium or horizontal plasma position depends sensitively on plasma current I_{pl}, vertical field B_z and plasma pressure p(r) fast B_z feedback control necessary

with sufficiently strong helical fields: no chain reaction leading to a current disruption possible: perturbation of confinement (e.g. by tearing modes) → plasma shifted inwards against limiter or wall → plasma cools down further .... an so on

W7-A and W7-AS: always operated with B_z = const, nevertheless horizontal plasma position changes only slightly with different p(r) and I_{pl}

another consequence of the absence of the above mentioned chain reaction: the amplitude of tearing modes can grow further and further

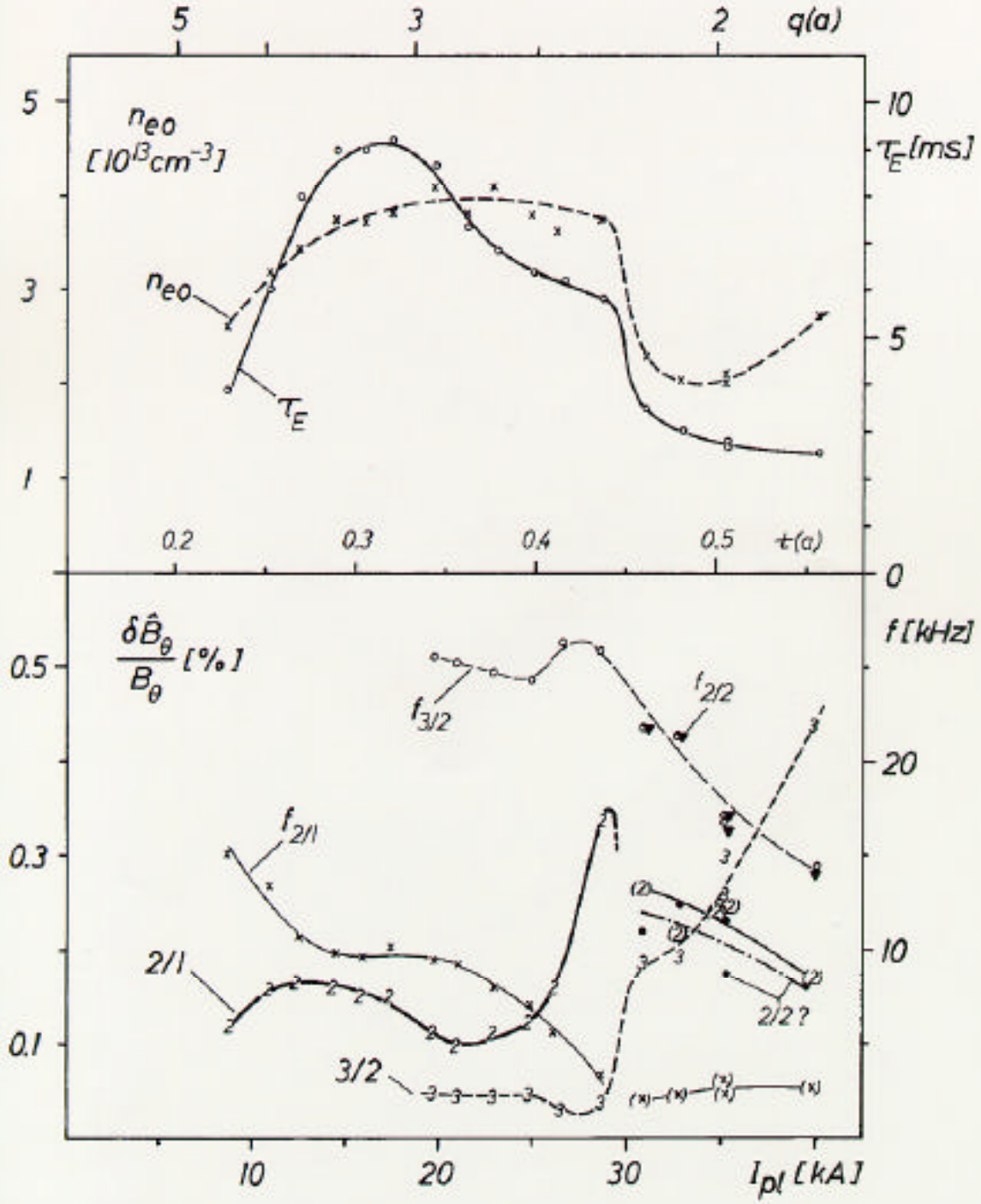
→ see especially results obtained on W7-AS

for very large currents: plasma confinement decreases quite often with increasing plasma current on W7-A: higher order tearing modes develop and the radius of the $\iota = 1$ surfaces increases more and more

Figure 4

Tearing Mode Stability on W7-A

plasma current scan



$B_0 = 3.5$ T, $\iota_0 = 0.14$, Helium

experiments with neutral beam heating on W7-A:

ohmically heated target plasma necessary for sufficient beam absorption (perpendicular injection, absorption length only 15 to 20 cm) → how to get rid of the plasma current?

first attempts: plasma current ramped down for constant $\iota_o \approx 0.23$ tearing modes (m = 2 and others) unstable, leading to "mini" disruptions and consequently to insufficient beam absorption

successful only when ramping up ι_o during the ramp down of the plasma current such that

$$\iota_{tot}(a) = \iota_o + \iota_{pl} > 1/2$$

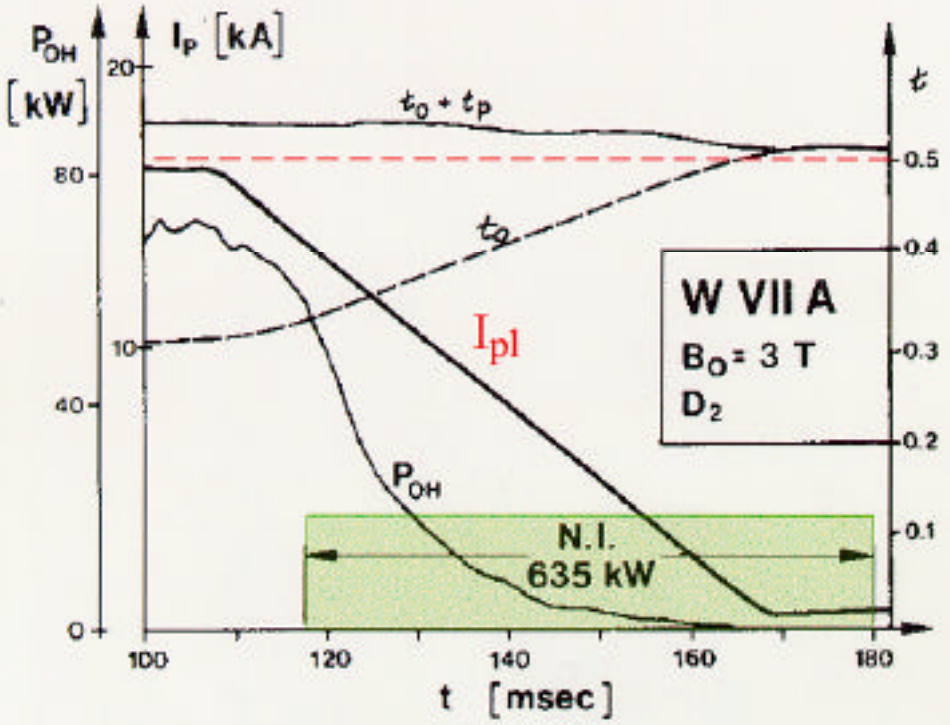
$\iota = 1/2$ surface always excluded from plasma

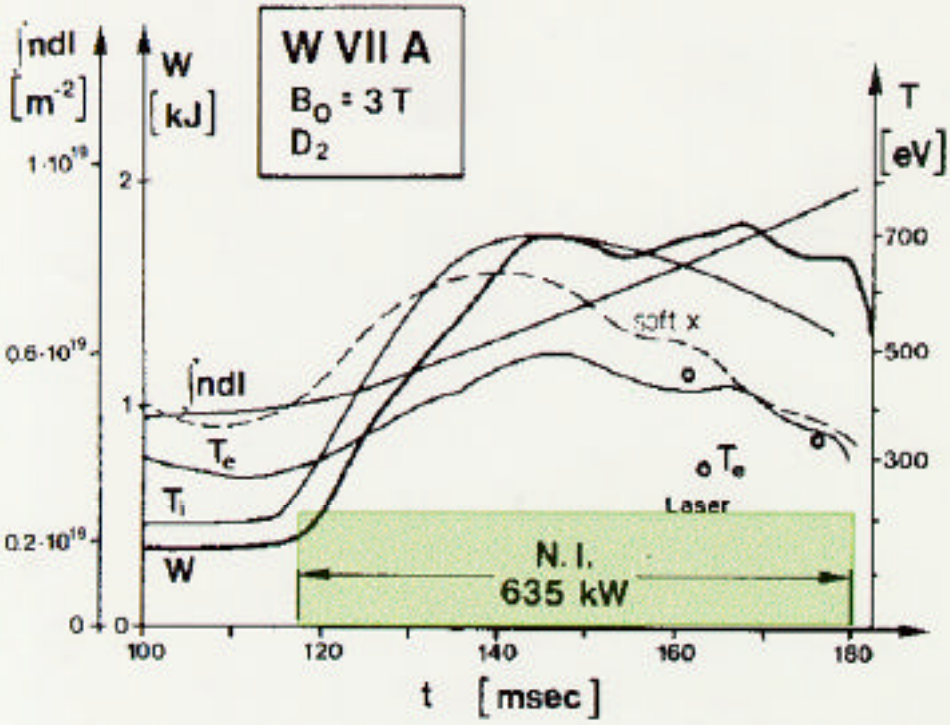
Figure 5

conclusion: NB heating changes current density profile and plasma pressure profile j(r) or dj/dr around resonant surfaces like $\iota = 1/2$ becomes a more independent quantity, no longer determined by ohmic heating alone → even more important effect for results obtained on W7-AS

Stability of m=2 Tearing Modes on W7-A

transition ohmic heating → NI heating





2) Differences between W7-A and W7-AS

important parameters of W7-AS:

confining magnetic field produced by <u>modular field coils</u> and a few toroidal field coils:
standart vacuum field rotational transform $\iota_o \approx 0.40$
can be changed by superimposed toroidal field from
$\iota_o \approx 0.30$ to ≈ 0.58 at $B_o \approx 2.5$ T

5 toroidal field periods, low vacuum field shear
$R_o = 200$ cm, $a < 18$ cm, <u>3D flux surfaces, deviating rather strongly from cylindrical symmetry</u>

<u>powerfull NB heating and ECRH from the very beginning</u>
almost no modifications to vertical field coils and ohmic heating transformer

general goal: to produce high temperature plasmas with significant plasma pressure ohmic heating transformer usually used to compensate the bootstrap current I_{BT}
= <u>net current free operation</u>

or to induce an <u>ohmic current</u> in a hot "target" plasma: such a current <u>does not heat the plasma</u>, it produces magnetic shear only and it is an energy source for driving instabilities

in addition: I_{BT} can increased/modified by
- ECCD
- Okhawa currents (almost tangential NB injection)

consequence for stability of tearing modes or the Δ' criterion:
dj/dr close to resonant surfaces like 1/2 almost arbitrary quantity
different tearing mode behaviour has to be expected compared with W7-A

3) Pure bootstrap currents on W7-AS

the neoclassical bootstrap current is driven by finite pressure, in the plateau and lmfp regime it is a complicated function of temperature, collisionality and magnetic field configuration (determining $E_r(r)$):

$$j_{BT}(r) \approx f(T_e, E_r) \quad p/B_o$$

due to the trapped particle effects calculations have to be performed with the 3D DKES code

experiments indicate that high electron temperatures are essential for large bootstrap currents - under these conditions a stationary state is reached only after a pulse length of several seconds

Figure 6,7

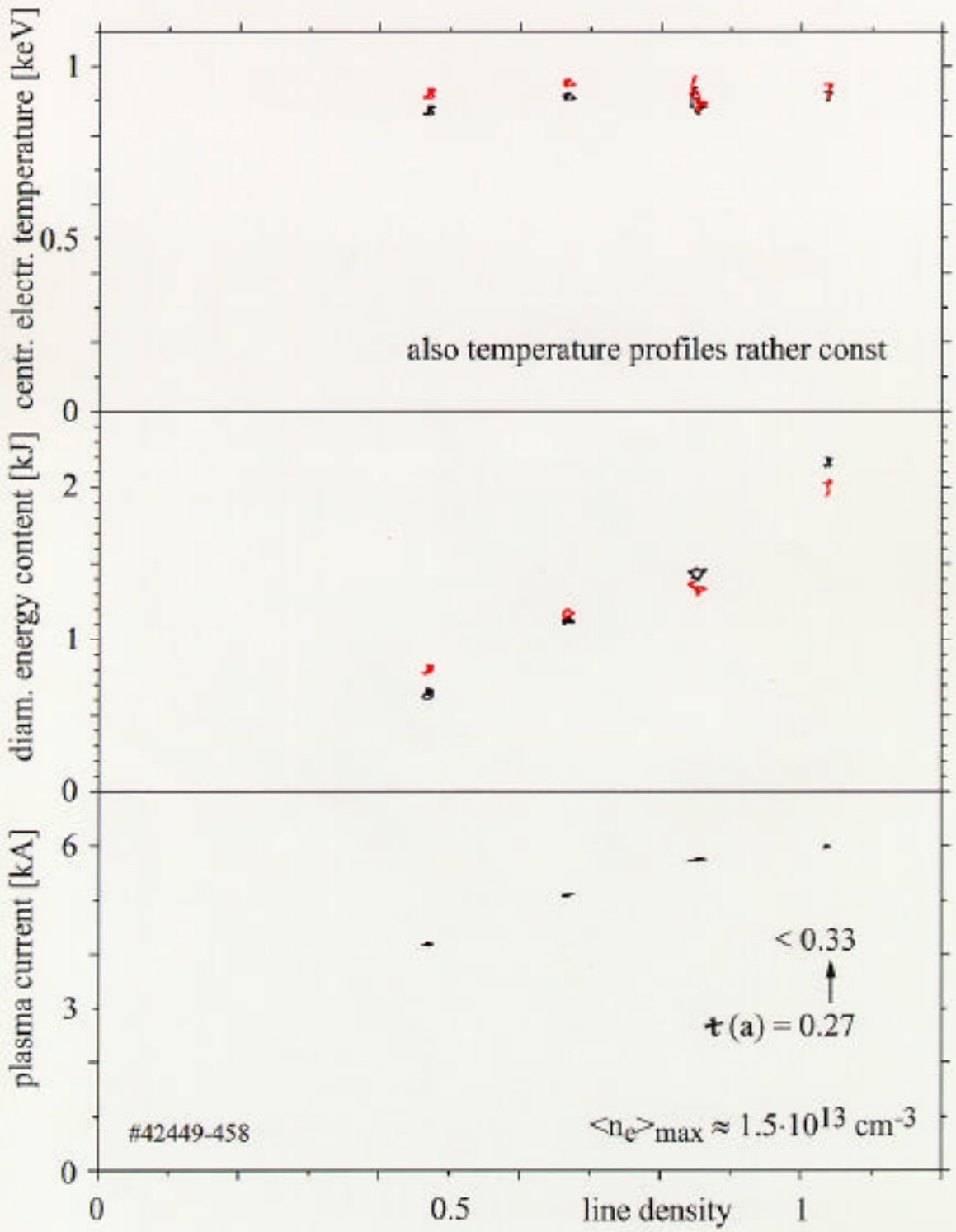
on W7-AS the ion bootstrap current is usually negligible, it is further suppressed by the negative E_r due to the "ion root"

the electron bootstrap current is enhanced by negative E_r, it is strongly reduced in the plasma center if the "electron root" feature occurs (positive E_r)

Figure 8

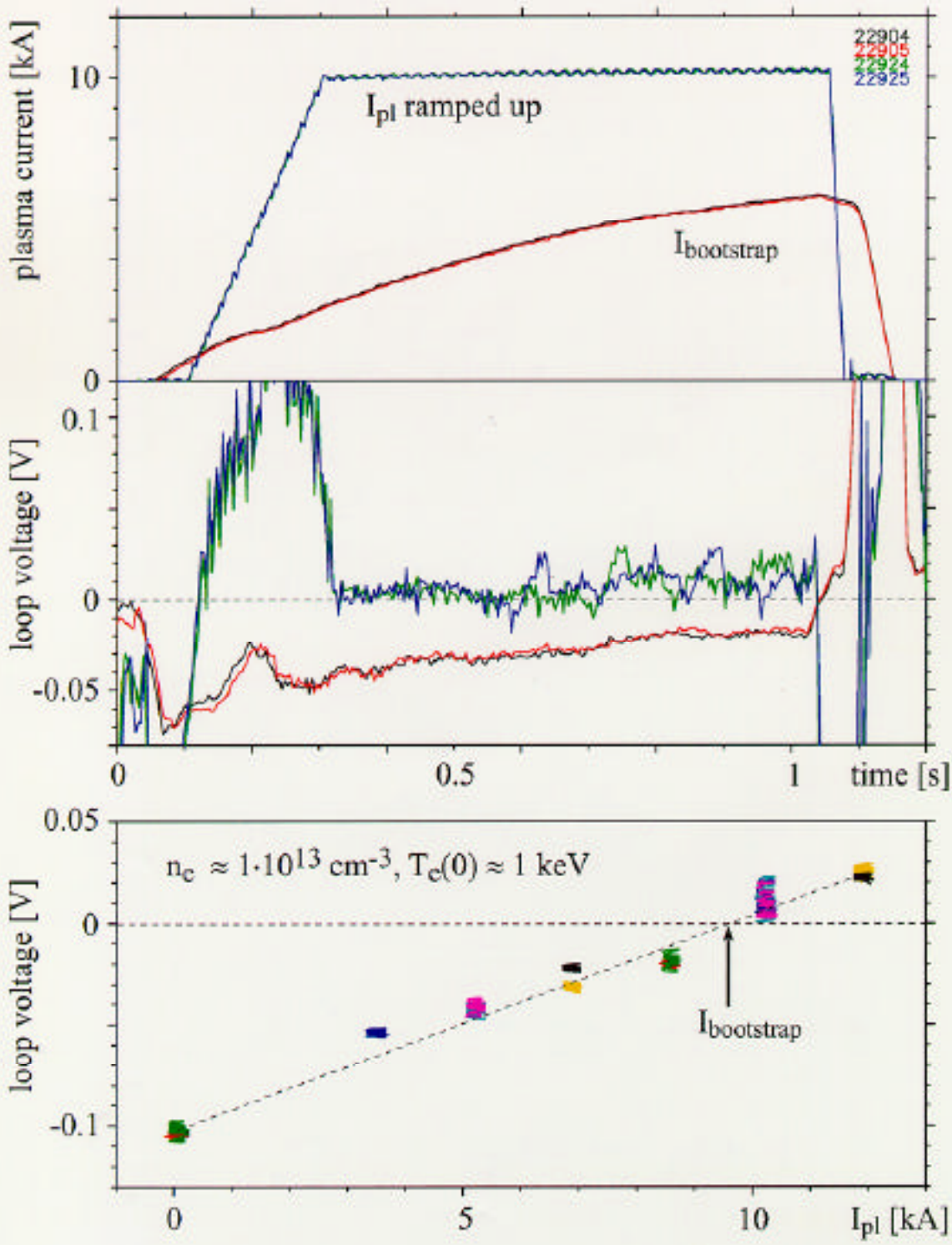
Bootstrap Current as a function of density

B_0 = 1.25 T, 350 kW ECRH, time ≈ 1 s



Determination of Bootstrap Current

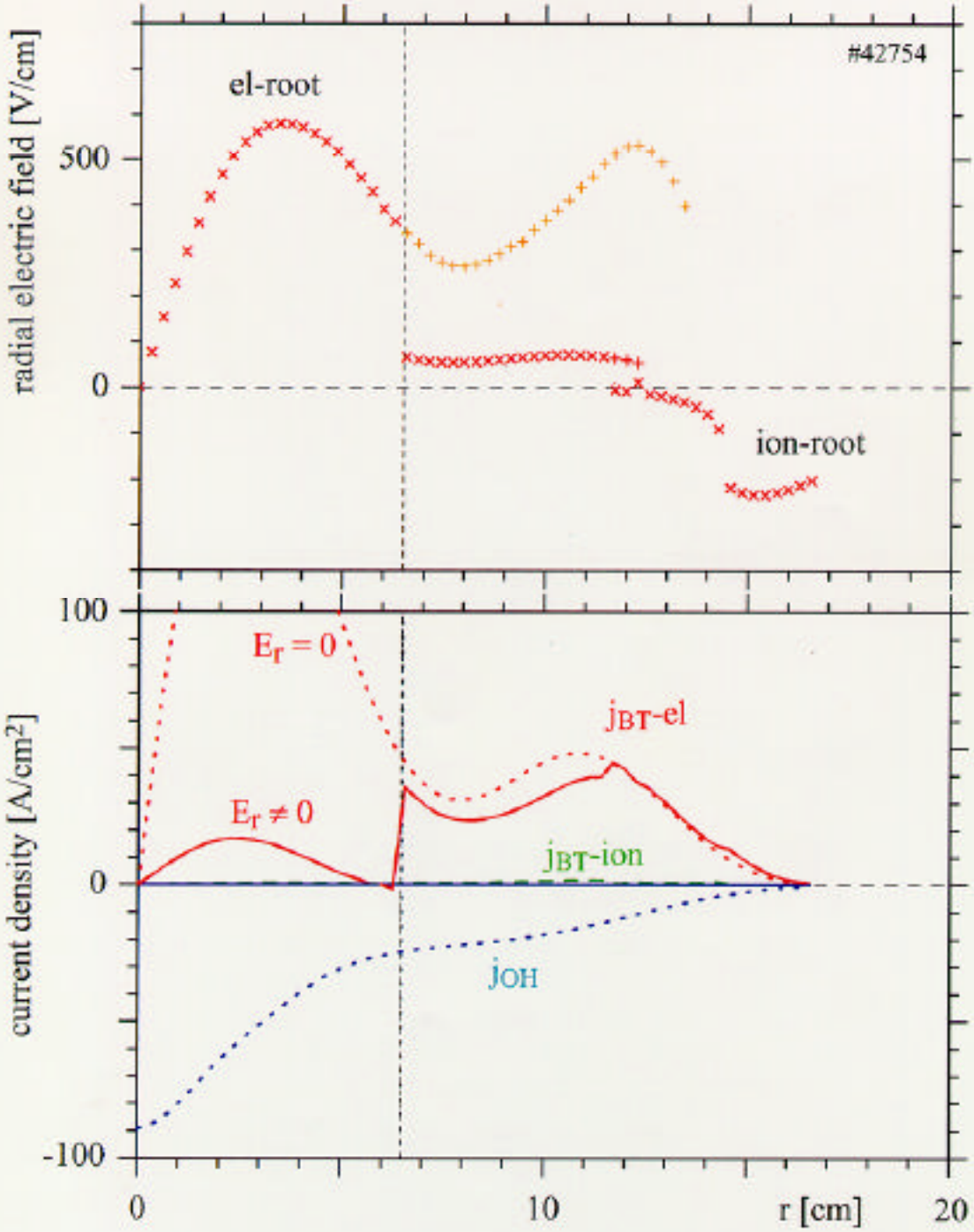
B_0 = 1.25 T, iota = 0.34, 350 kW ECRH



Bootstrap Current on W7-AS

effect of radial electric field, DKES Code

$B_0 = 2.5$ T, 1.3 MW ECRH, $T_e(0) \approx 5$ keV, $\langle n_e \rangle \approx 3 \cdot 10^{13}$ cm^{-3}



4) Bootstrap currents increased by ohmic and NB driven currents

to investigate the stability behaviour at large currents, several possibilities exist:

a) bootstrap currents increased by external loop voltage: in contrast to W7-A disruption-like phenomena occur on W7-AS

Figure 9

however: because of the improved positional stability, there always remains a confining magnetic field, even if the plasma is cooled down to the radiation barrier

Figure 10

causes for the temperature quench: almost locked m = 2 structure?

b) large bootstrap currents in the case of combined ECRH and co-NI, leading to high electron and ion temperatures at medium densities and some (unknown) amount of Okhawa current

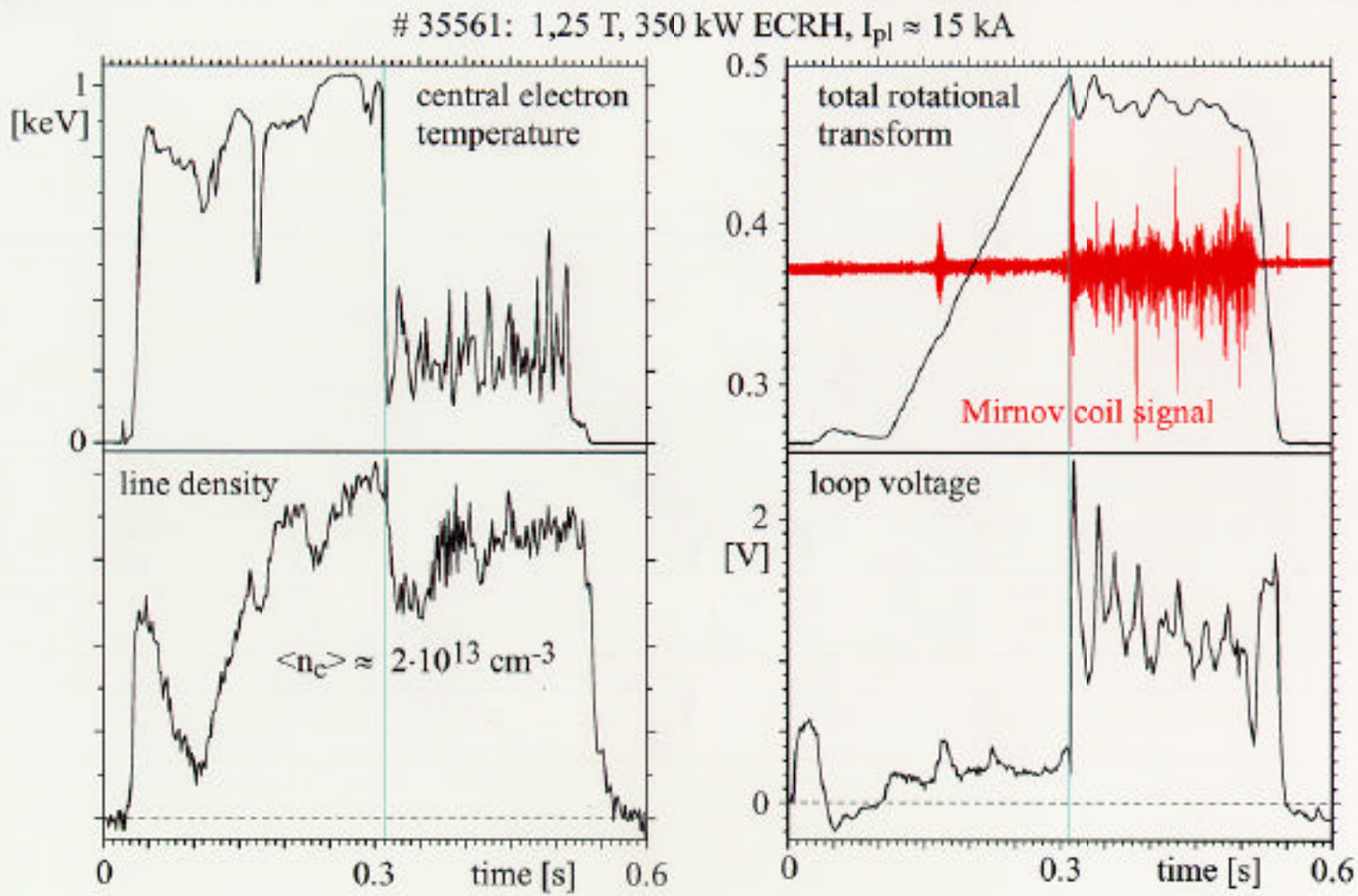
largest currents without external loop voltage achieved so far on W7-AS: almost 20 kA, corresponding to $\Delta\iota_{tot}(a) \approx 0.1$ at $B_o = 2.5$ T, not yet stationary after 1.2 s, pulse length limited by surface temperatures on limiters

Figure 11

c) bootstrap currents increased by ECCD: obtained up to 18 kA with 550 kW ECRH at $B_o = 1.25$ T $\Delta\iota_{tot}(a) \approx 0.2$
powerfull ECRH system needed, high efficiency at high electron temperatures (= low density?) only

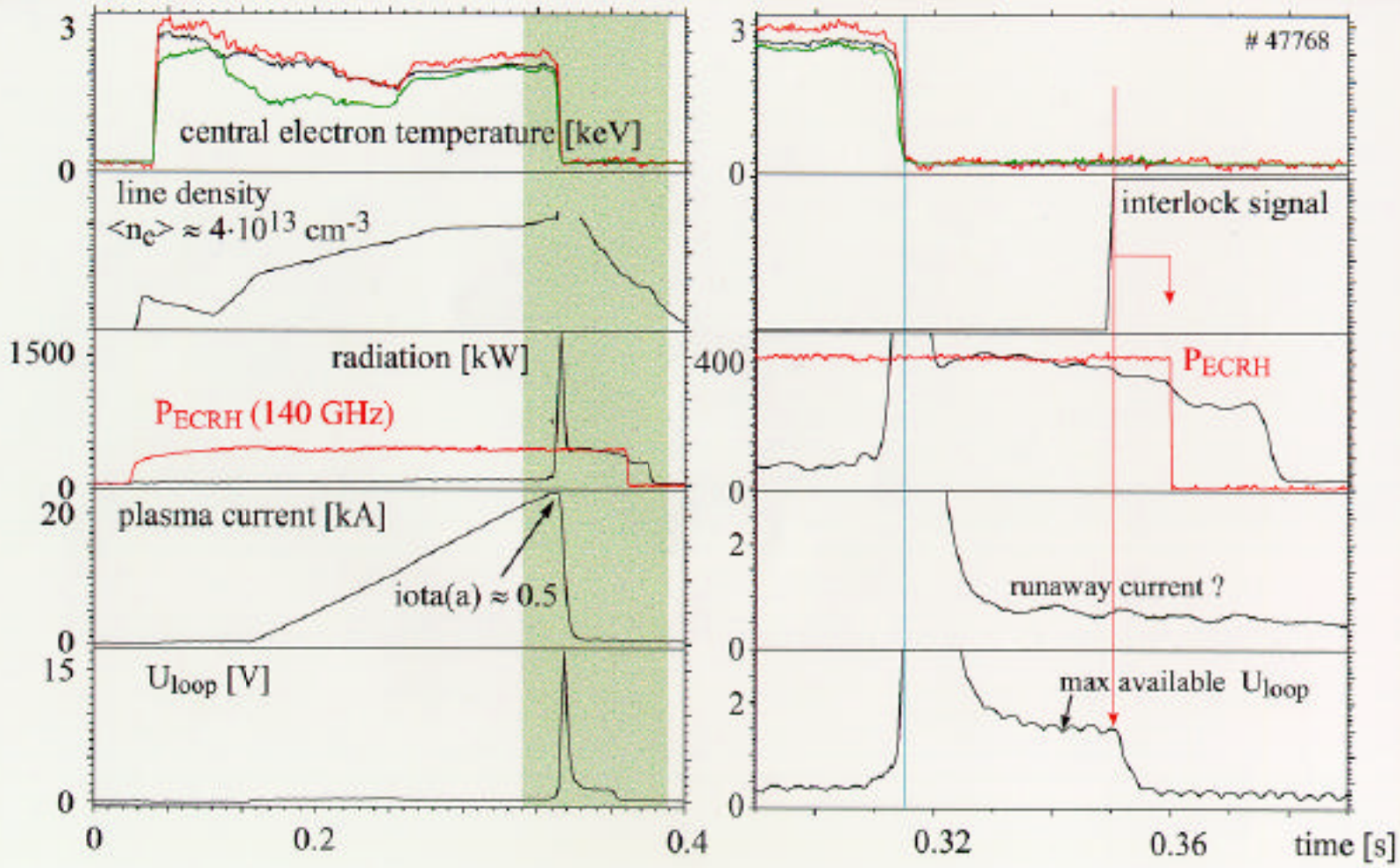
Disruption-like Phenomena in W7-AS (1)

cool, strongly fluctuating plasma with almost constant current



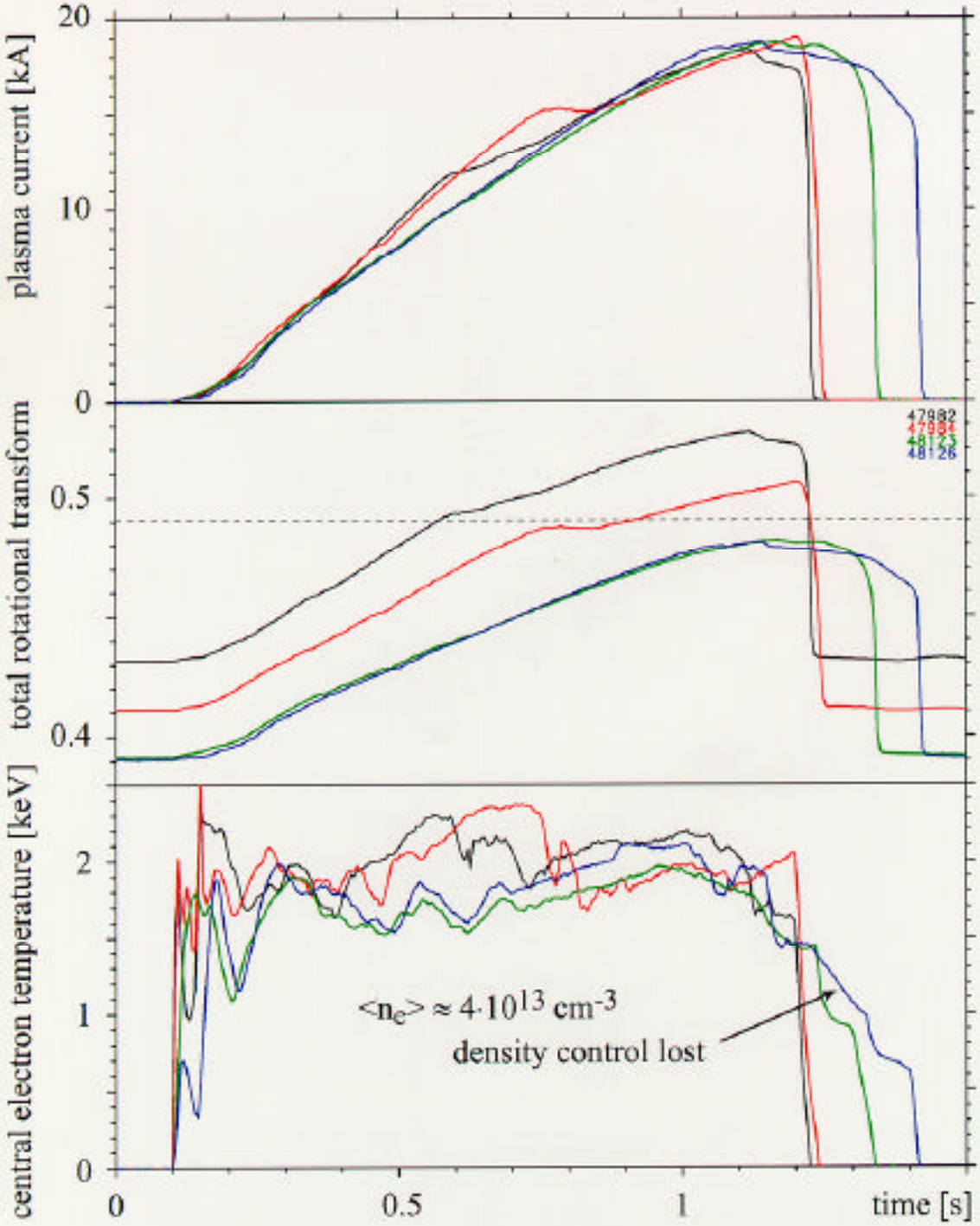
Disruption-like Phenomena in W7-AS (2)

B_0 = 2.5 T, plasma cools down to radiation barrier



Large Bootstrap and Okhawa Current

B_0 = 2.5 T, 400 kW ECRH + 2 co NI



5) Influence of large toroidal currents on confinement

problem with interpretation: in 3D geometry diamagnetic signals always perturbed to some (unknown) extent by toroidal plasma currents

a) small to medium toroidal currents: confinement follows roughly the results obtained for net current free discharges (a dependence that is at least partly understood)
just the changes of the boundary rotational transform $\iota_{tot}(a)$ and of the shear have to be taken into account

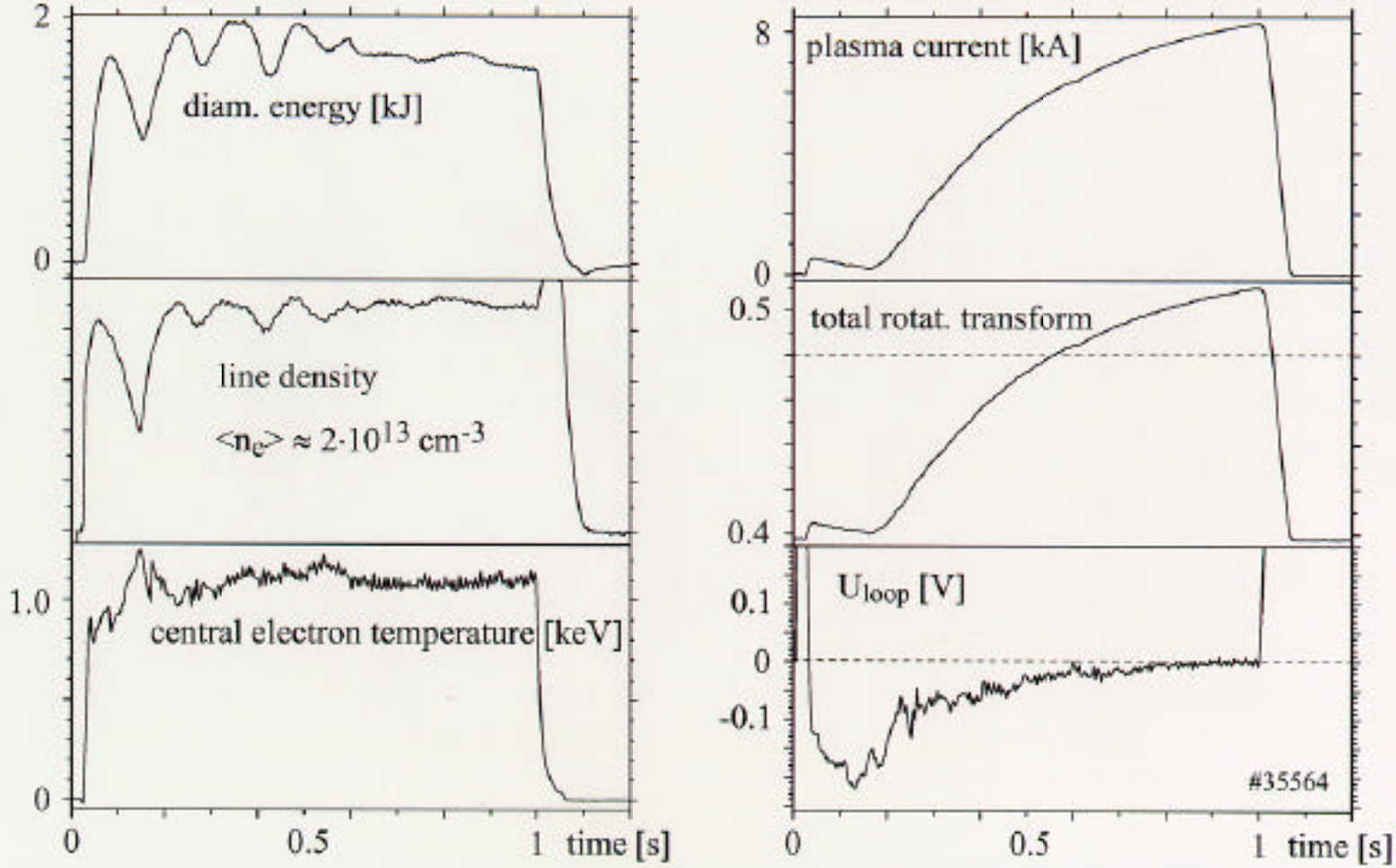
Figure 12

b) for discharges with large shear (large net currents, but also substantial internal currents e.g. at low density or high β):
no significant dependence of the confinement on $\iota_{tot}(a)$ or on the bootstrap current is observed or has to be expected
confinement no longer deteriorated by high order rational magnetic surfaces

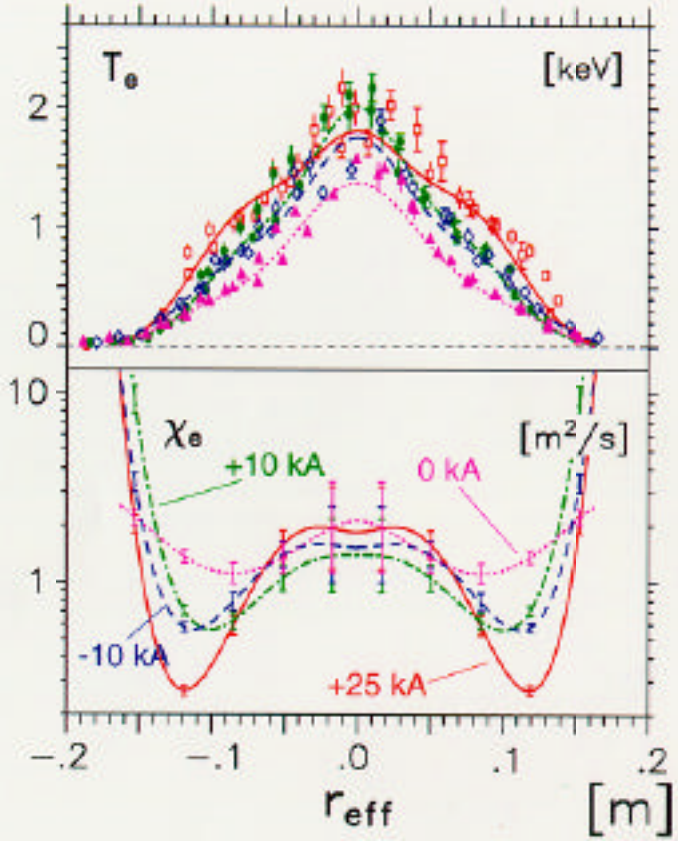
Figure 13,14

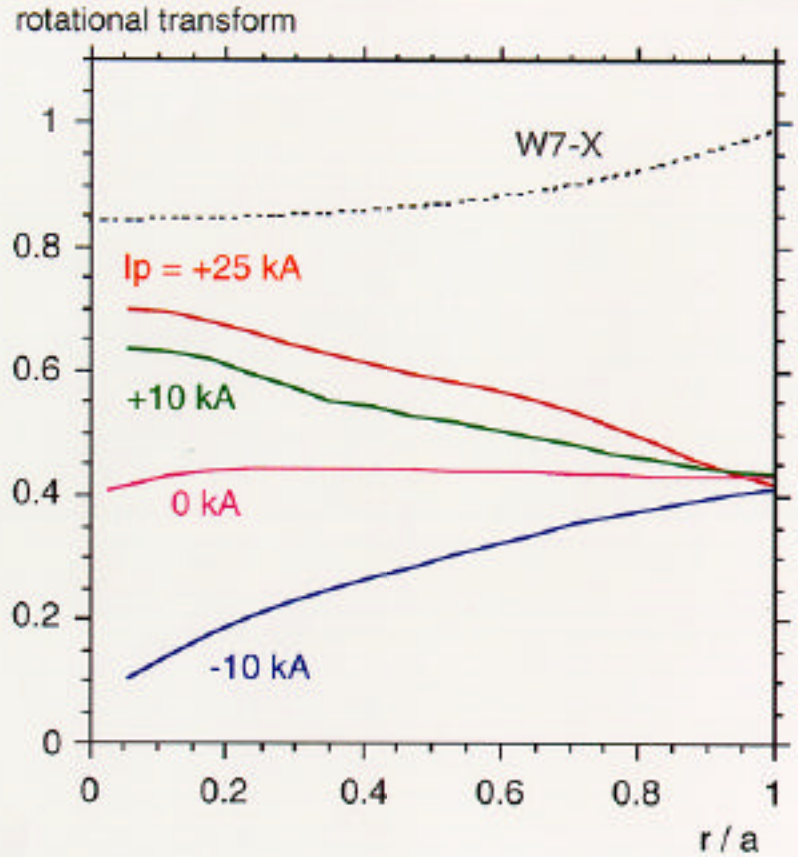
Variation of Confinement with increasing Bootstrap Current

B_0 = 1.25 T, 350 kW ECRH



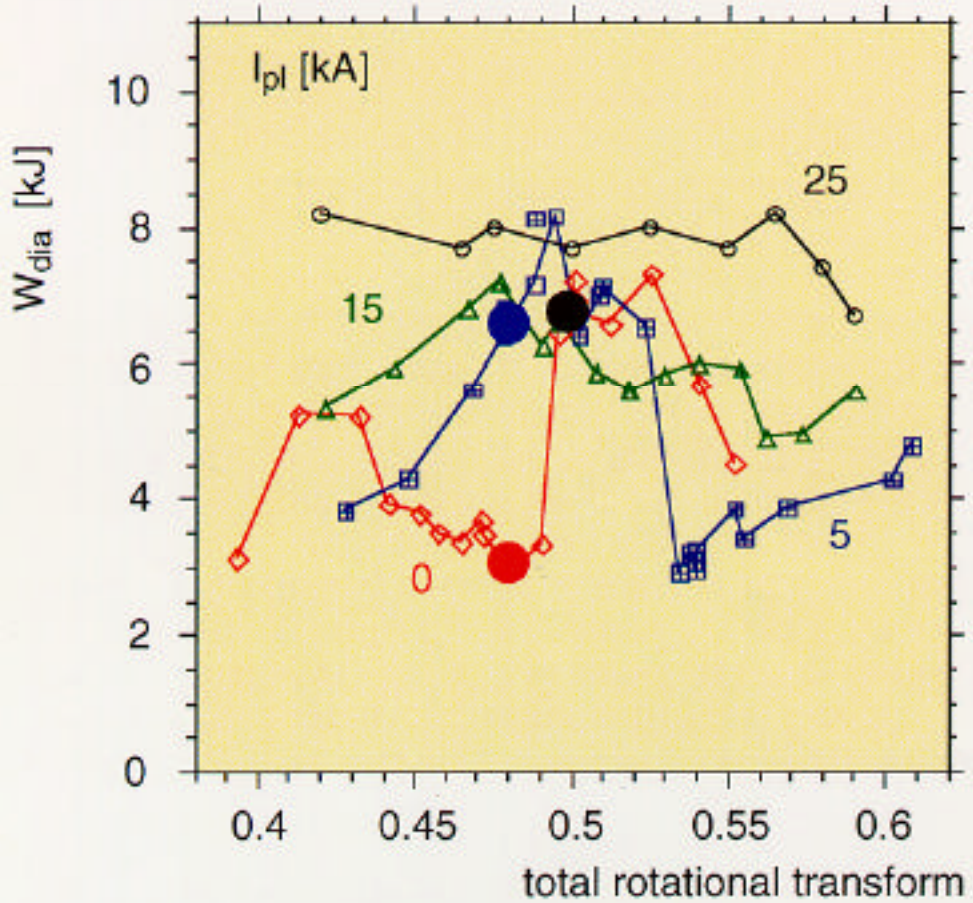
W7-AS: high shear by inductive currents

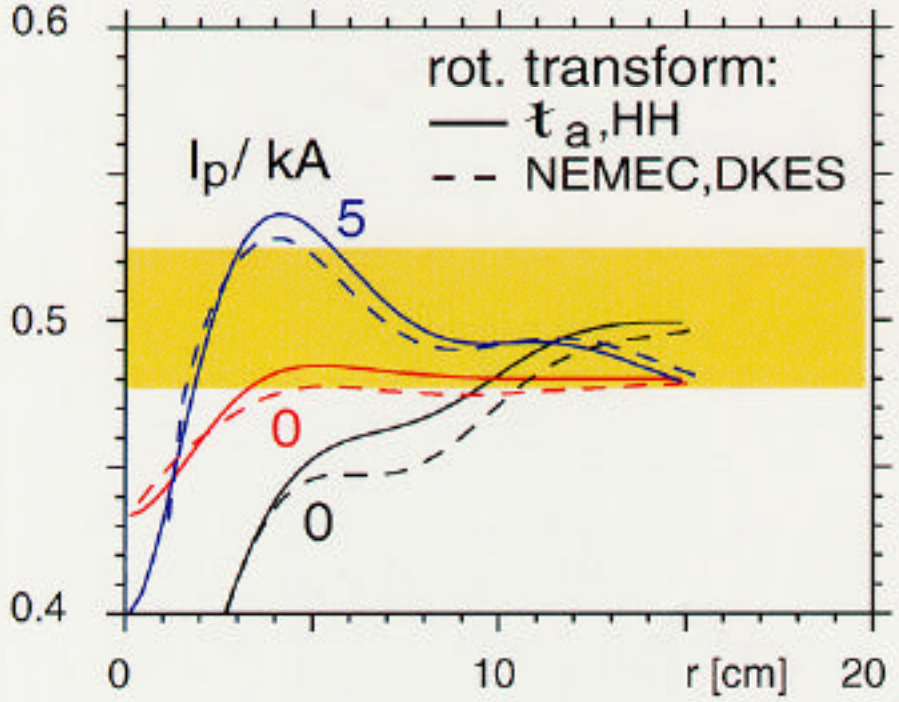




- magnetic shear improves degraded confinement (independent on sign)
- χ_e decreases by a factor of 5 to the neoclassical value at r/a = 0.7

W7-AS: confinement with increasing shear at iota around 0.5





6) Conclusions

consider the gedanken experiment: could it be possible to raise the total rotational transform starting from $\iota_o \approx 0.15$ to $\iota_{tot}(a) > 1/3$ just by the bootstrap current (or together with some amount of Okhawa current ..) <u>on W7-AS</u> ?

- $\iota_o \approx 0.15$ not accessible on W7-AS

- confinement at $\iota_o \approx 0.15$: somewhat worse than around 1/3 ?

- bootstrap current of about 40 kA necessary at $B_o = 2.5$ T: larger by a about factor of 2 than what has been obtained

- for large bootstrap currents high electron temperatures at medium densities are mandatory, can be achieved on W7-AS by ECRH only ? (improves also density control)

- pulse length of at least 2 to 3 s required: problems with density control at high heating power on W7-AS

- powerfull NB heating alone leads to high densities on W7-AS because of problems with density control and consequently to low temperatures and rather small bootstrap currents