Physics insight from Plasma Shaping Experiments in MHD, heat transport, and EBWH in the TCV Tokamak

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more specially about Shape and Rotation:
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OUTLINE

1. Motivations of shape studies
2. TCV facility and shaping achievements
3. MHD at q=1
4. MHD disruptions & modes / disruptivity
5. Confinement vs. shape / OH at medium density (ν_{eff} ~ 2.5-10)
6. Electron heat transport vs. shape / EC at low density (ν_{eff} ~ 0.2-1)
7. Plasma rotation
8. Conclusions for the effect of shape on MHD and transport
9. Electron Bernstein Wave Heating

1. MOTIVATIONS of SHAPE STUDIES

WHY STUDY SHAPES different from ITER?

- Confinement of τ_E, n_e, β, fast ions... scales with plasma current I_p and $I_{p\ max}$ can be increased by plasma cross-section shaping *without increasing the magnetic field*
- *Improve confinement* using negative triangularity (in L-mode!)
- Test of MHD and transport theory
- Many parameters depend on plasma shaping
- Reciprocally, active plasma shaping offers a way to control these parameters
- Optimization of devices beyond ITER, exotic shapes...

Shaping variables

- elongation κ
- triangularity δ, *including negative*
- squareness
- limited / diverted, S/DN
- single plasmas / doublets
- beyond TCV: aspect ratio R/a

TCV:

$R = 0.88$ m, $a = 0.25$ m, $R/a \sim 3.5$
$B < 1.54$T,
$I_p \leq 1$MA
elongation $0.9 < \kappa < 2.8$
triangularity $-0.7 < \delta < 1$
(parameters reached)

Parameters influenced by shape

- MHD stability	sawteeth, modes, NTM, disruptions, TAEs, ELMs, ...
- Transport	electron heat, rotation
- Confinement	pressure limits, edge transport barrier (ITB?), performance

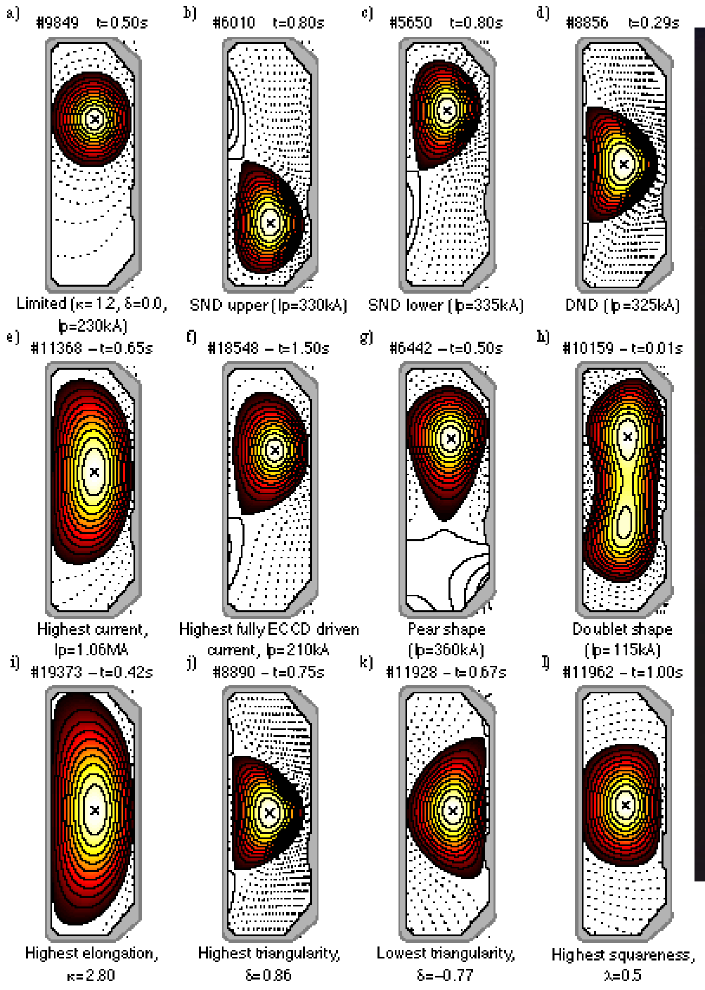
- *Several phenomena* having a crucial impact on plasma confinement are *influenced by shape*:
  - ELMs(*shape*) can destroy ITBs (e.g. JET), etc...
  - Sawteeth(*shape*) can trigger NTMs
- *Effect of plasma shape can depend on the plasma regime*:
  - $\tau_E(\delta)$ *increases towards negative* δ in L-mode (core transport)
    increases towards positive δ in H-mode (pedestal height)

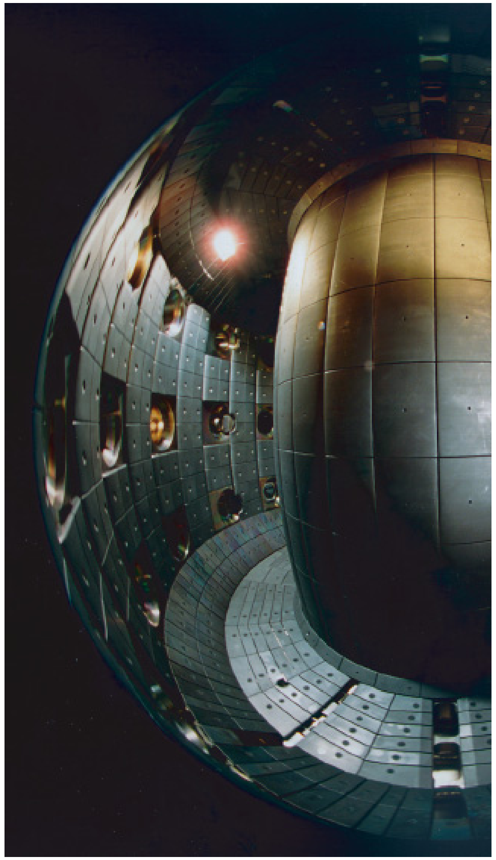
2. TCV FACILITY AND SHAPING ACHIEVEMENTS

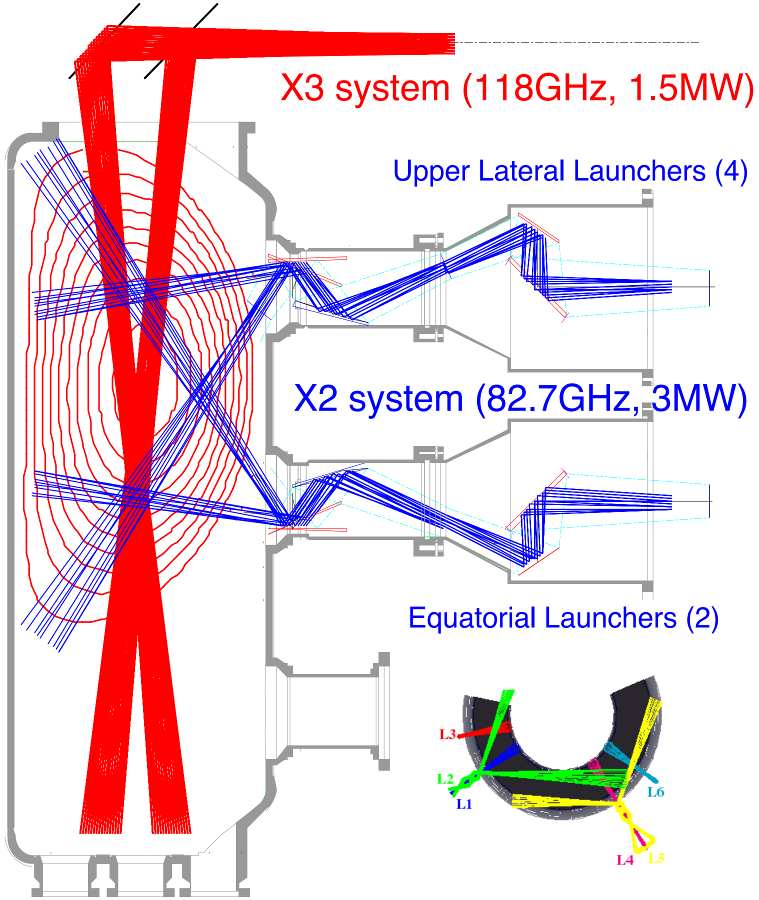
Flexible plasma shaping ...

16 independent shaping coils

... matched by a flexible heating system, entirely based on ECRH







X3 system (118GHz, 1.5MW)

Upper Lateral Launchers (4)

X2 system (82.7GHz, 3MW)

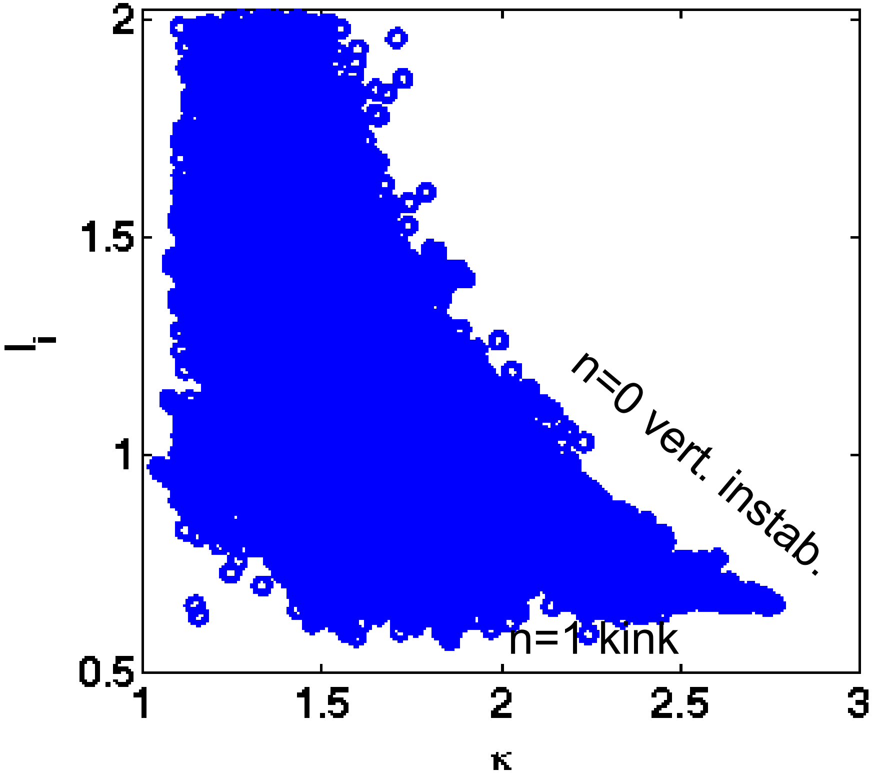
Equatorial Launchers (2)

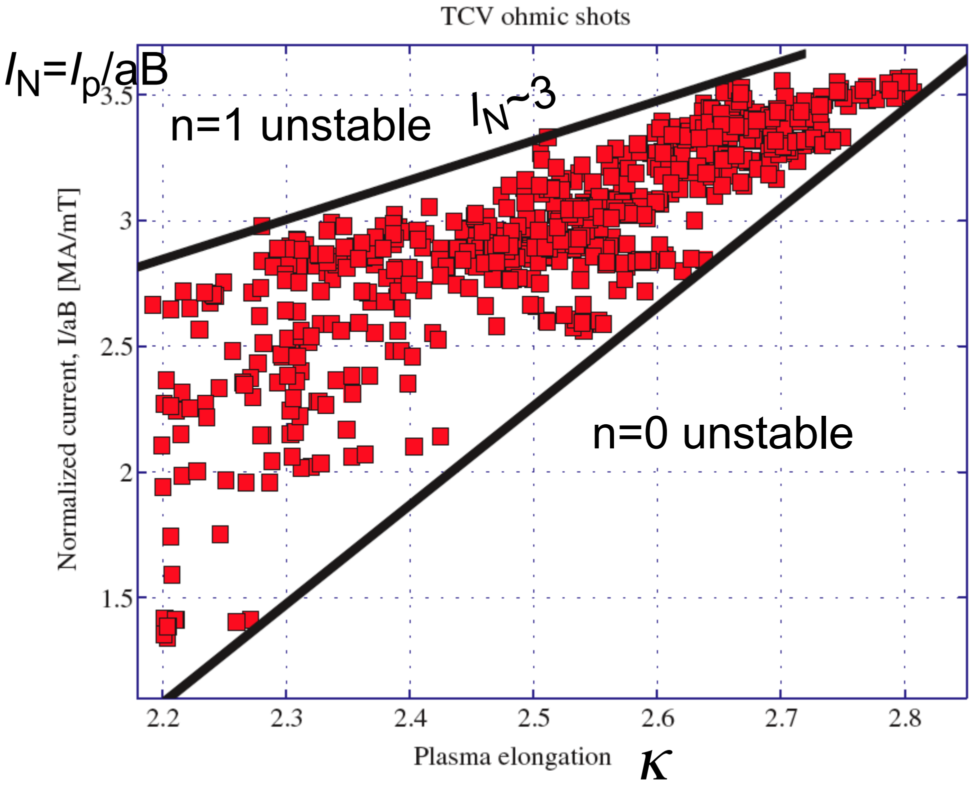
Total: 4.5 MW at 2nd and 3rd harmonic

Cut-off densites: 4.2 and 11.5 10^{19} m^{-3}

High elongation stability limits (Ohmic)

Using high I_N, elongation up to k=2.8





Operation at high κ limited by

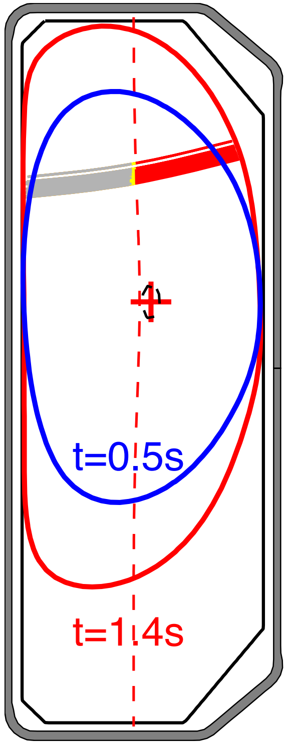
n=0 vertical instability —> needs broad *j*(*r*) (=low-*q*, high-I_N) + fast int. coils

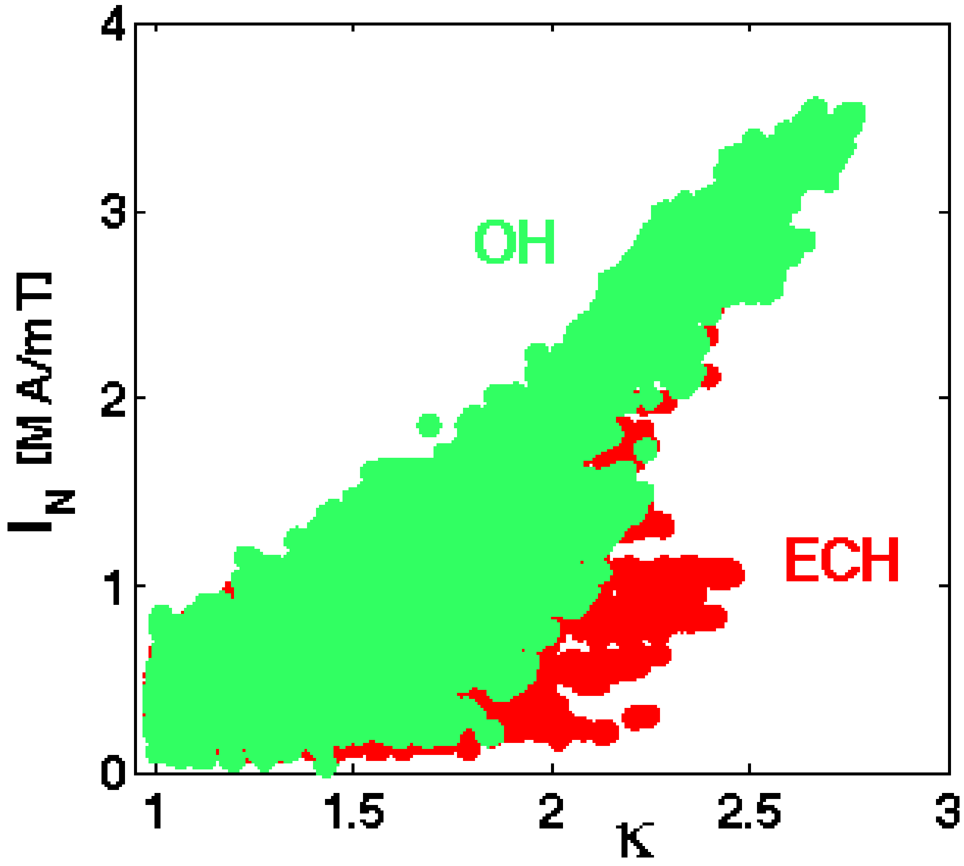
n=1 external kink —> high current limit (I_N & β-limit)

Hofmann PPCF01

High elongation stability limits (off-axis ECH)

At low I_N, vertical stability requires broadening the current profile, done using off-axis ECH, allows reaching κ=2.5

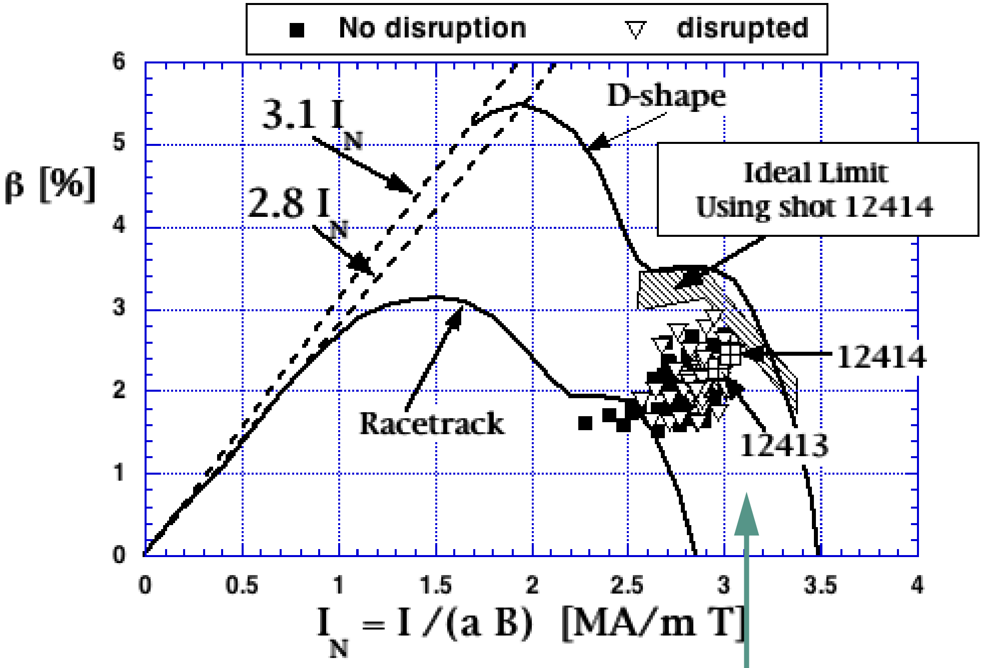


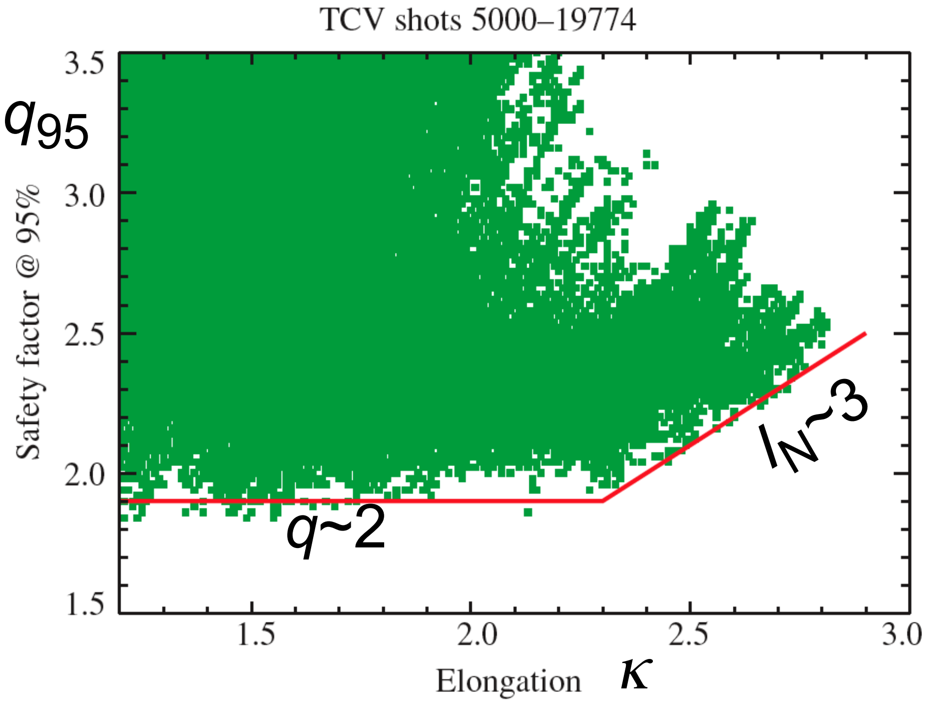


off-axis ECH power,
constant quadrupole field
—> *κ increases*

Pochelon NF01, Camenen NF07, Paley PPCF07

Current limit at high κ





current limit at high κ

shape influences the β-limit

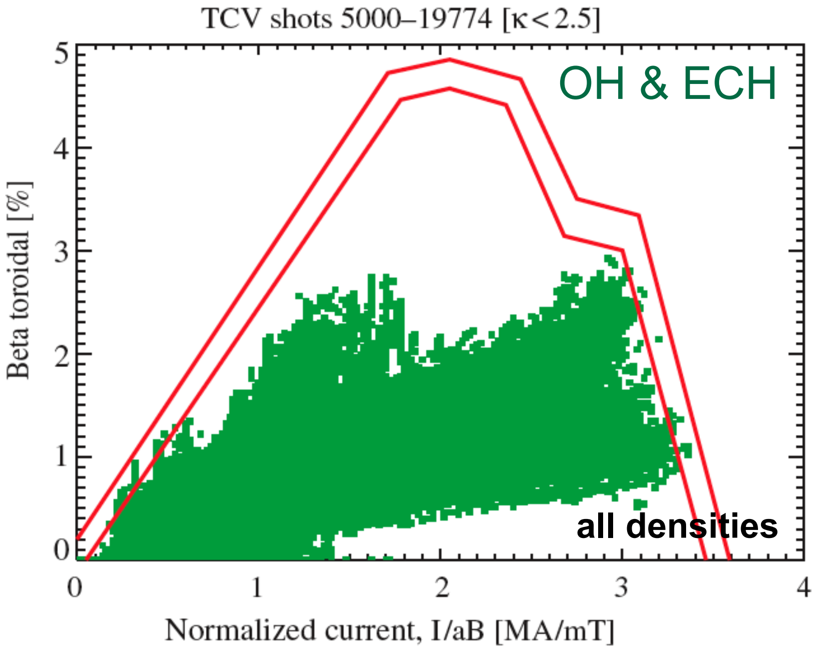
"q~2" limit increases with κ
for $\kappa > 2.3$
(the I_N~3 limit)

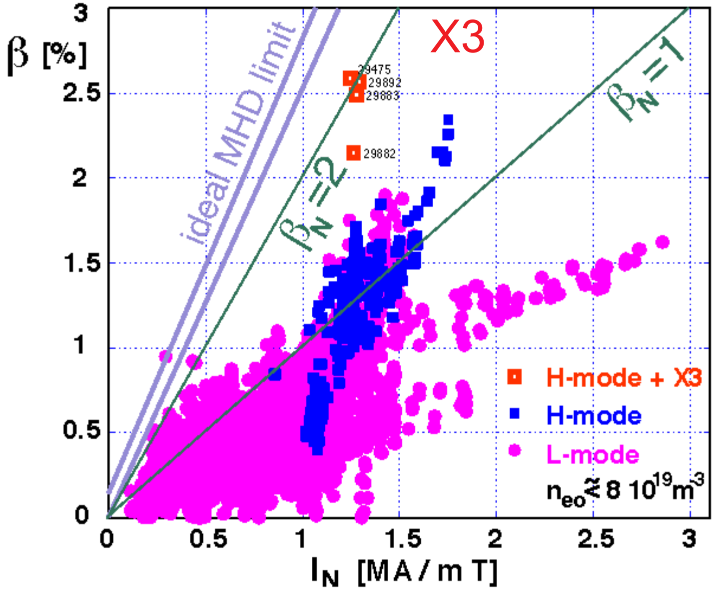
Ideal MHD predicts the current limit

resistive modes m/n = 4/3, 3/2, 2/1 appear just below the ideal limit

Hofmann PRL97

β-limit at high κ ...





β reached at κ~1.6
with1.5MW X3

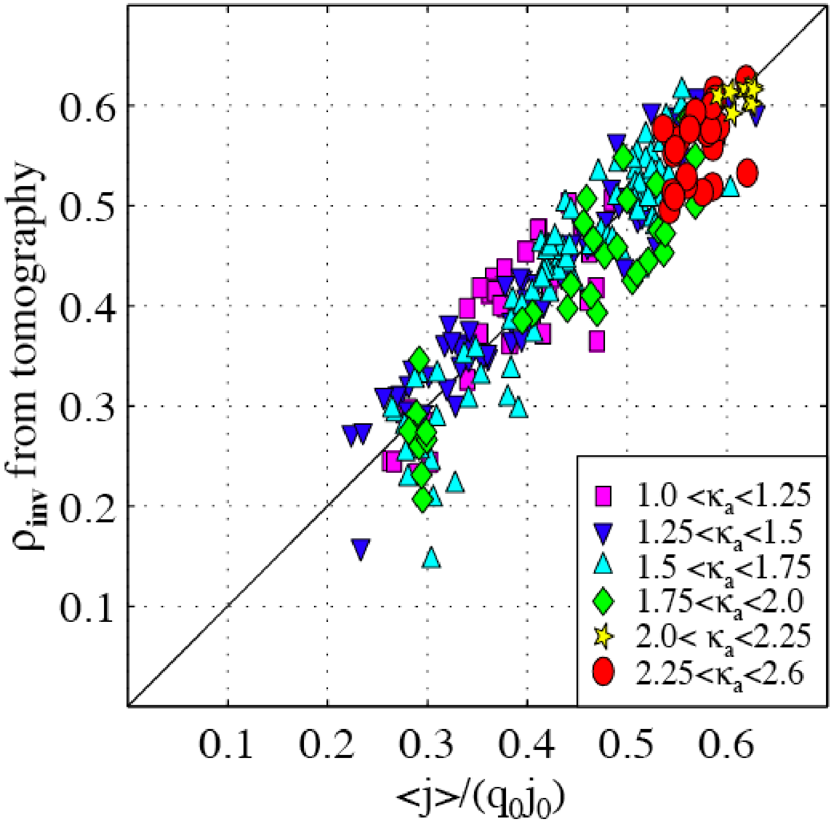
TCV provides the highest β-values in the inter-machine spontaneous rotation database by J. Rice NF07

More power needed to test the β-limit in various shapes in TCV —> doubling installed X3 power foreseen

Hofmann PPCF01 Porte NF07, Alberti JoPh05, Pochelon SMP05

3. MHD at q=1

Scaling of q=1 radius, ρ_{inv}, at various κ ...



q=1 radius: regression from a large range of shapes ($1<\kappa<2.6$)

$\rho_{inv} = \langle j \rangle / (q_0 j_0)$ inversion radius

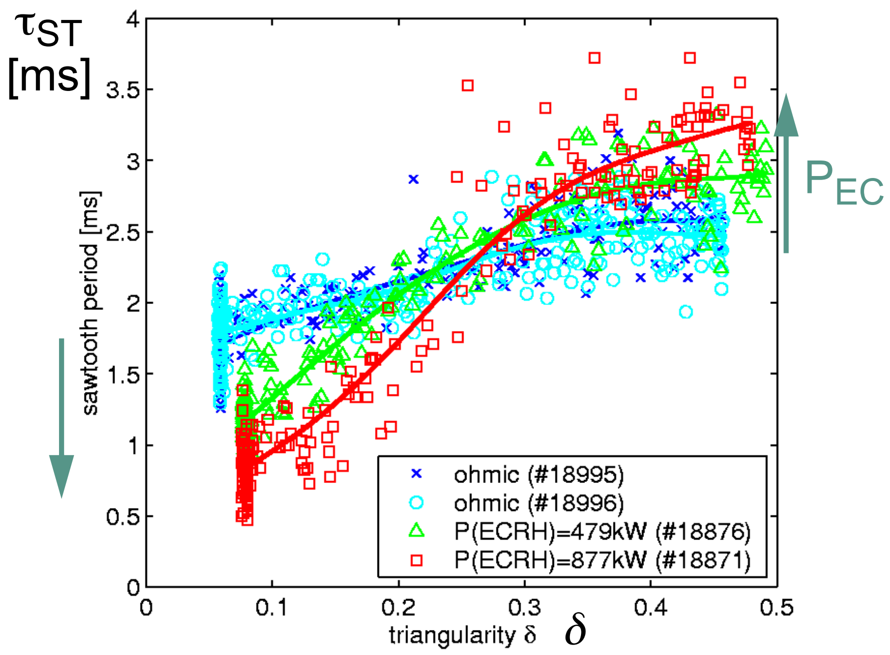
$$\rho_{inv} \approx 2\,(q_{eng}\;(\kappa_0+1/\kappa_0))^{-1}$$

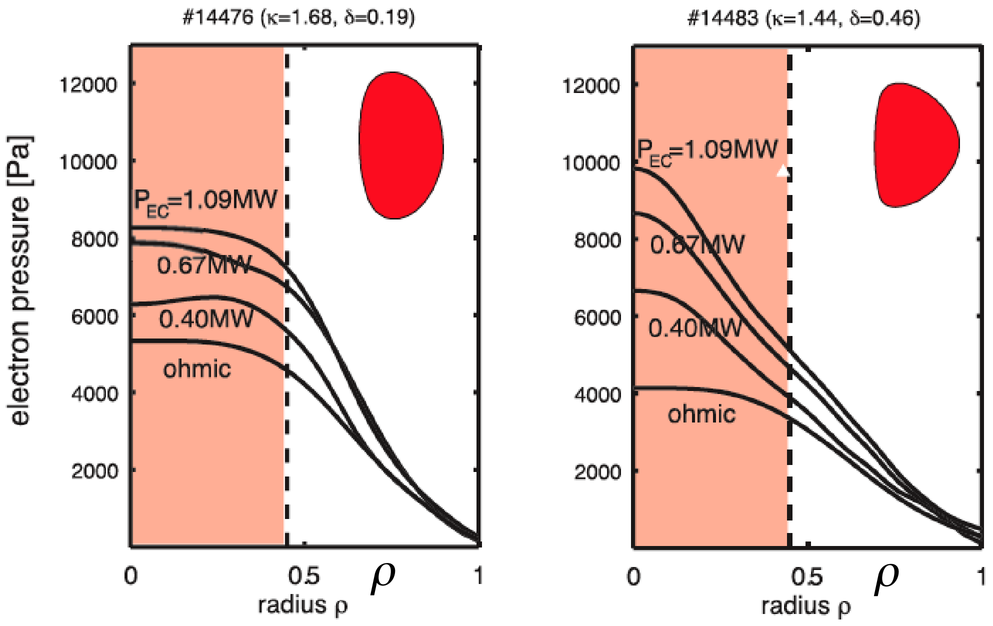
where $q_{eng}=5\,abB/RI_p$

Weisen NF03

Centrally heated sawteeth (1<κ<2.1, δ>0)

sawtooth period/stability for 1.1<κ<2.1 and -0.2<δ<+0.5, central ECH





τ_{ST} shortening at δ<0.25
lengthening at δ>0.25

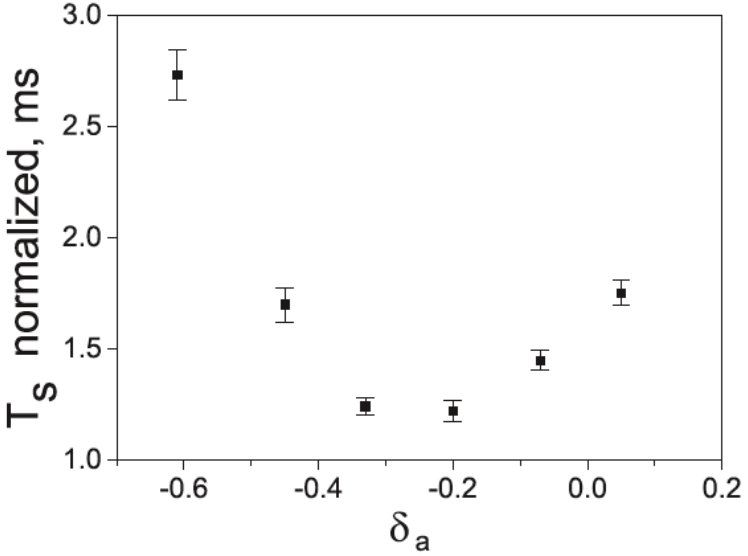
τ_{ST} follows Mercier ideal stability,
limiting pressure inside q=1
(β_{Bussac}) at low δ and high κ
triangularity stabilizes
elongation destabilizes

Reimerdes PPCF00

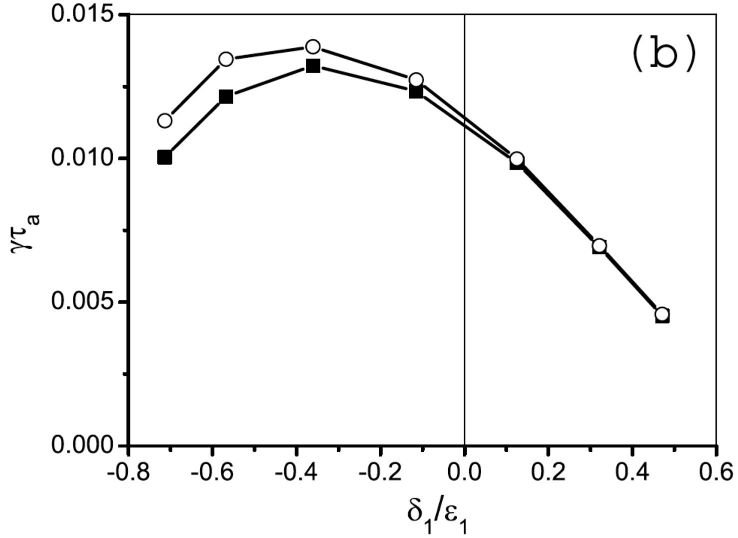
OH heated sawteeth (positive and negative δ)

triangularity scan $-0.6<\delta<+0.3$

sawtooth period



internal kink $\gamma\,\tau_a$

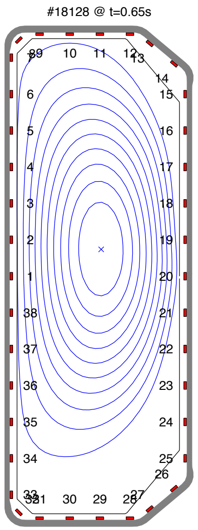


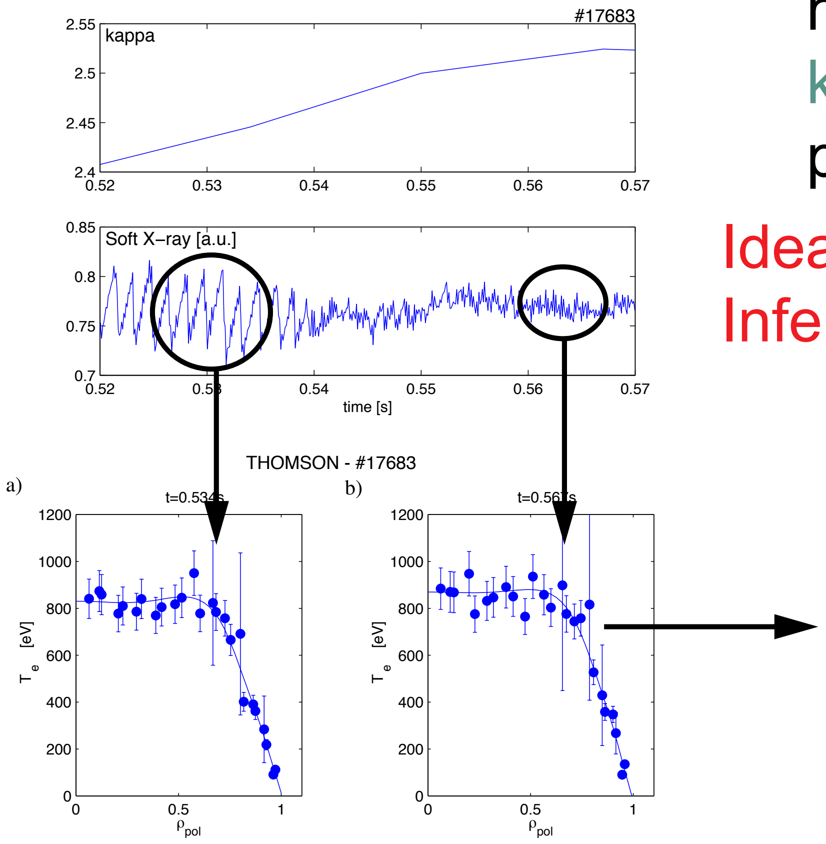
- both pos. and neg. triangularity are stabilizing
- minimum τ_{ST} close to δ=0 (δ_a~-0.2, δ_1~-0.05)
- maximum $\gamma_{\text{ideal int kink}}$ at similar δ_1/ε_1~-0.4
- (in contrast to $\gamma_{\text{res int kink}}$: indep. of δ)
- ideal MHD description

Martynov PPCF05

Sawtooth disappearance at high I_N, high κ >2.3 - 2.6

OH





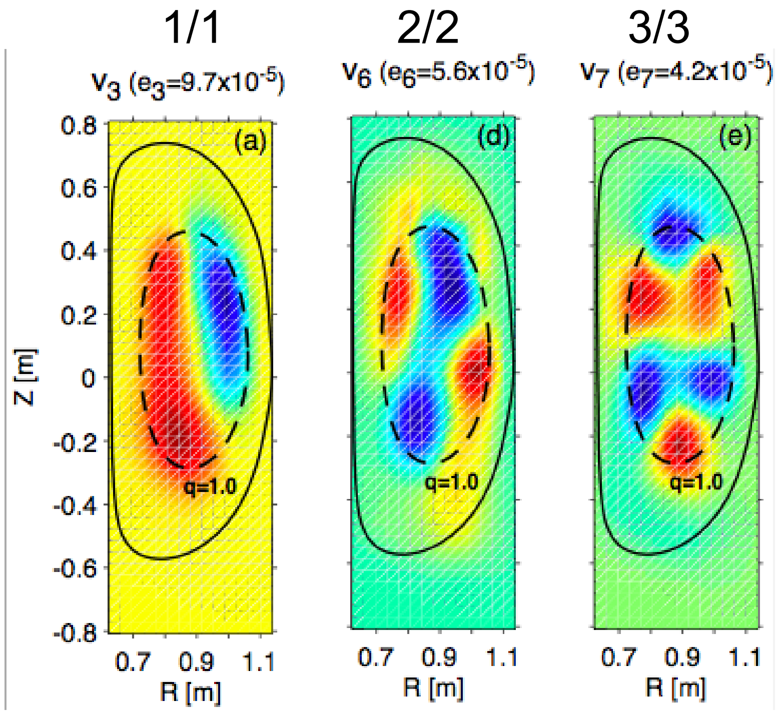
with sawteeth

with modes

At very high κ, l_i<0.7, sawteeth are replaced by m/n=1 harmonic modes on q=1, keeping a flat central pressure profile, with ρ_1 unchanged

Ideal internal kink: $\gamma_{\text{ideal int kink}}$ > const

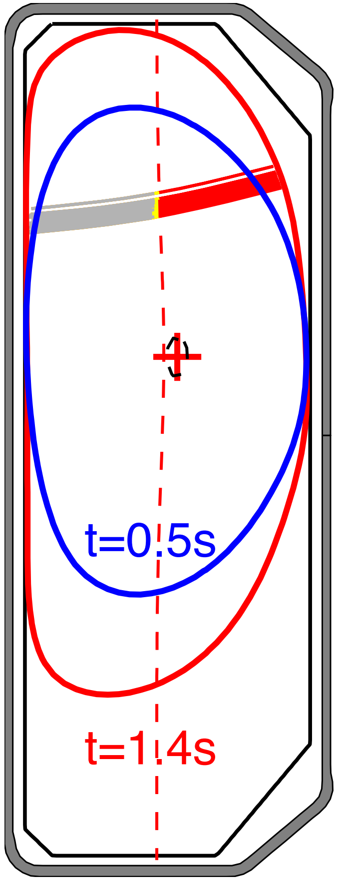
Infernal mode?



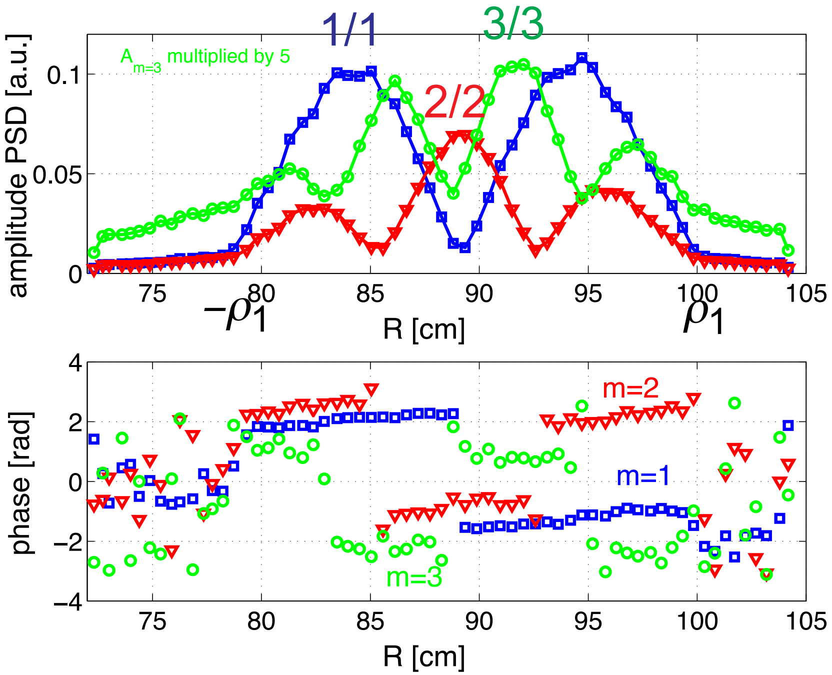
Reimerdes PPCF06

Similar harmonic modes on q=1 at lower I_N with off-axis ECH

off-axis ECH



soft X-rays



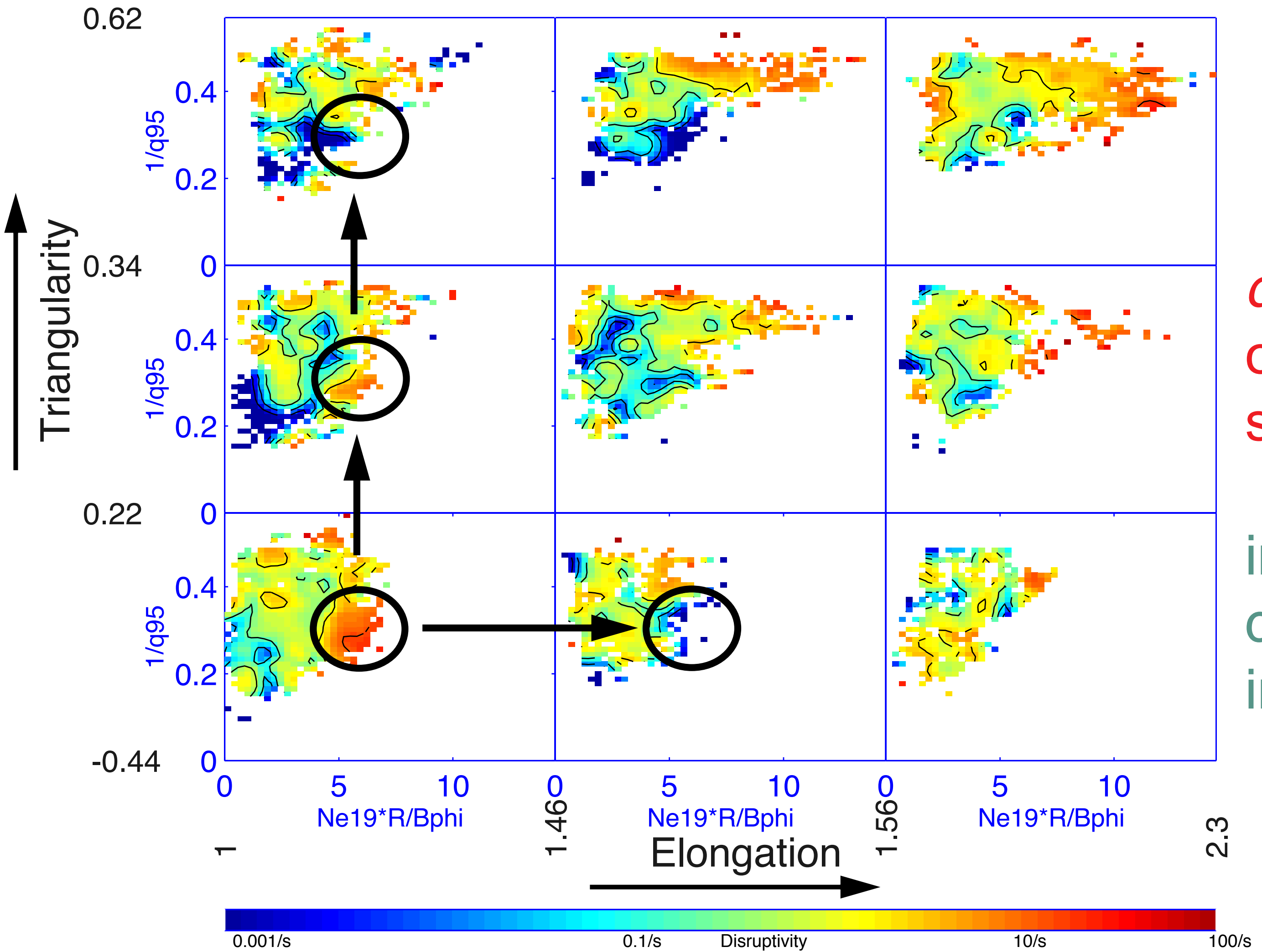
$\rho_1 \neq$ const, decreasing
with off-axis ECH

multiharmonics on q=1
in off-axis EC heated high κ discharges,
as in high current high κ OH discharges

Scarabosio thesis06

4. MHD DISRUPTIONS & MODES / TCV discharges disruptivity

Hugill diagram for different (δ, κ)-ranges

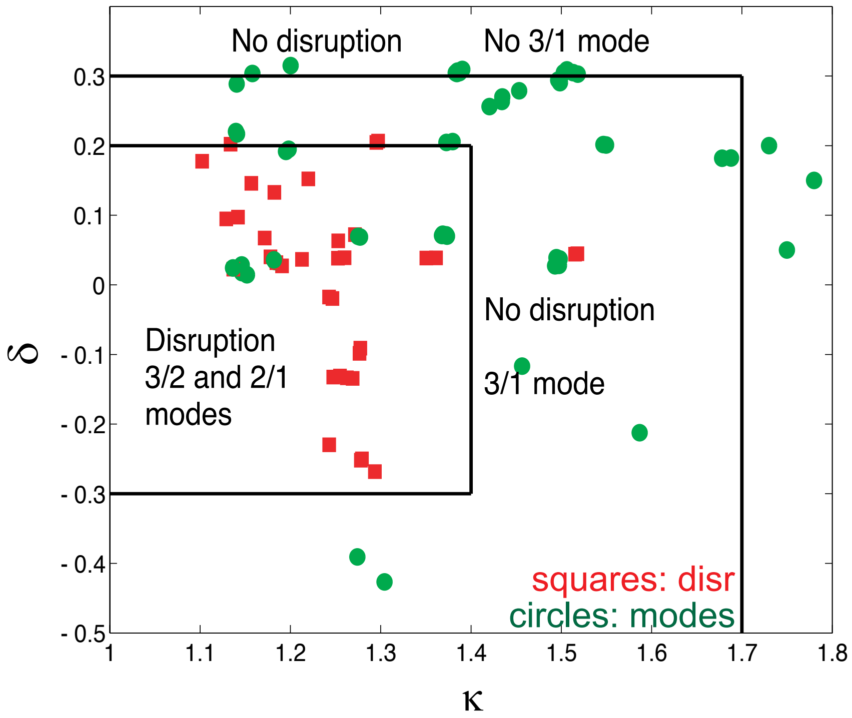

TCV disruptivity in Hugill diagram (all disruption types)

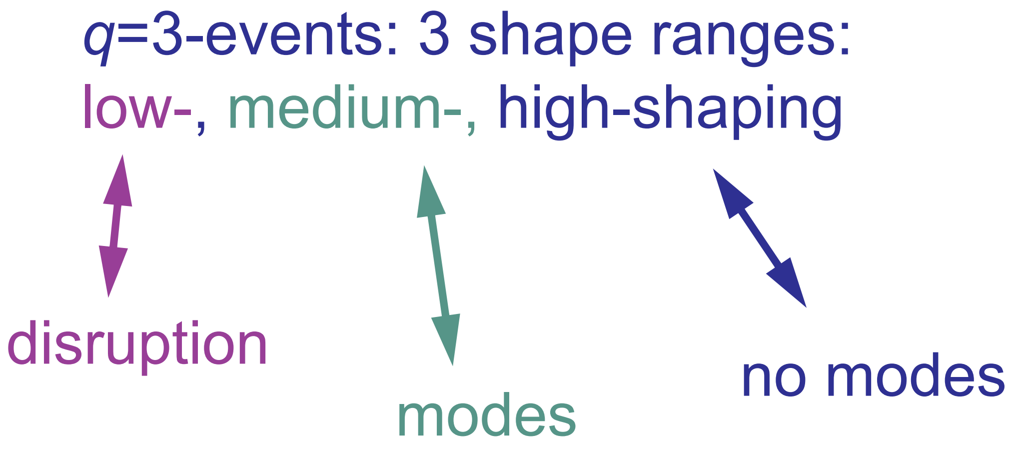
disruptivity [disr./s] :
high disr.=red,
low disr.=blue

q=3 high density notch occuring at low shape stabilized by δ, κ shaping

important for current ramp-up in low-*q* operation

Current rise q=3 events vs shaping





q=3-events: 3 shape ranges:
low-, medium-, high-shaping

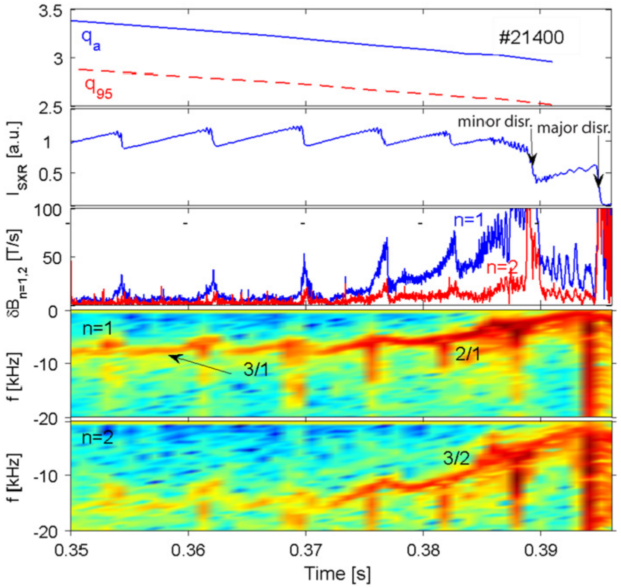
from experiment :

- The 2/1 is the dominant instability leading to disruption
- The locking of 3/1 to 2/1 correlates with whether or not the 2/1 becomes disruptive
- Shaping stabilizes the external 3/1 mode.

Scarabosio NF07

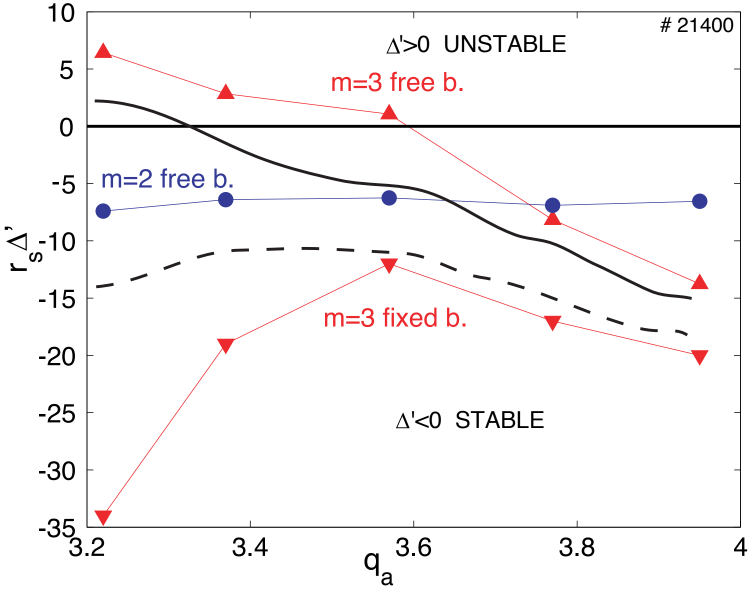
MHD modes leading to disruption

MHD modes: 3/1 -> 2/1



weak shaping
κ=1.3, δ=0.2

MHD stability (PEST-3)



ext.-mode with (*m*/*n*)=(3/1)~q_a
destabilizing internal (2/1) mode
(mode coupling)

The 2/1 mode is always stable
(no coupling in PEST)
Wall stab. of 3/1 mode essential
—> coupling essential!

- Dominant role of mode coupling
- In fact, *2/1-Δ'-stab. of single TM does not improve* with increased shaping!
- -> other stab. mechan.: - wall stab. of ext. 3/1mode (shaping helps!),

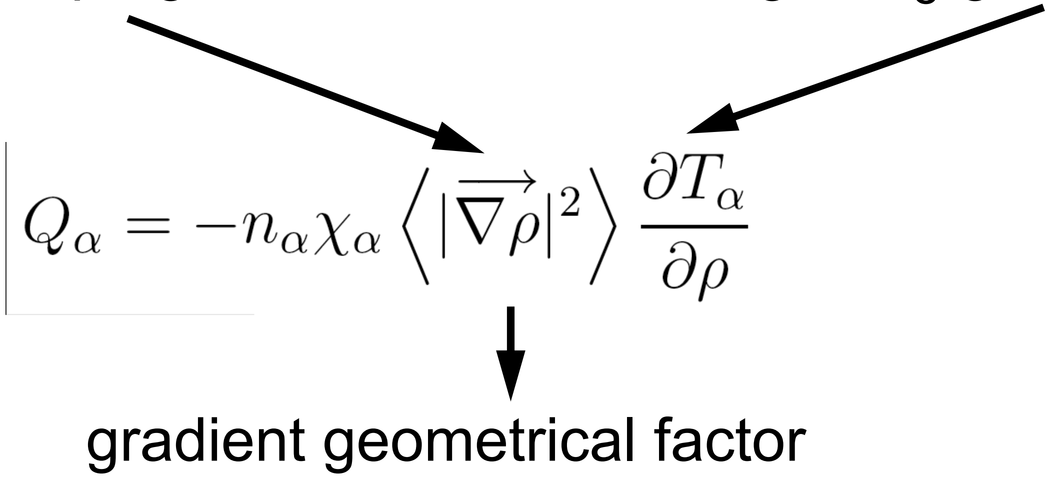
  - coupling with vacuum flux surfaces *q*=3, 4, 5,...

Scarabosio NF07

5. CONFINEMENT vs. SHAPE / OH medium density (ν_{eff}~2.5-10)

Ohmic confinement at medium densities (ν_{eff} ~ 2.5-10)

- Strong τ_{Ee} increase with κ, up to κ~2.3
- Mild decrease with δ, in δ>0-range
- Interpreted in terms of Shape Enhancement Factor (SEF): Transport χ_e(shape geom., flux surf. averaged T_e-gradients)



$$Q_\alpha = -n_\alpha \chi_\alpha \left\langle |\overrightarrow{\nabla \rho}|^2 \right\rangle \frac{\partial T_\alpha}{\partial \rho}$$

gradient geometrical factor

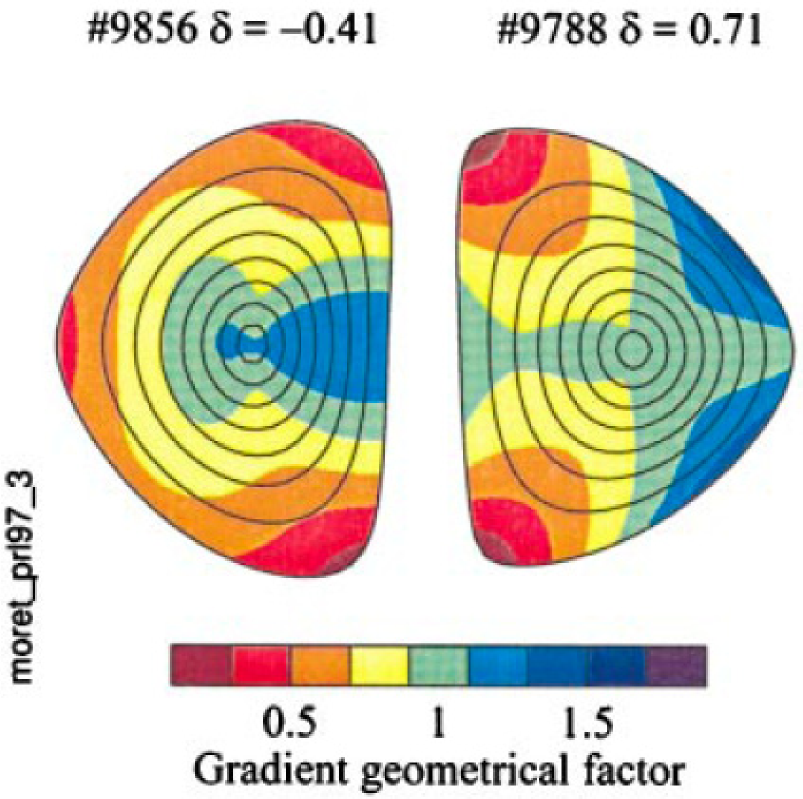
Moret PRL97, Weisen NF97

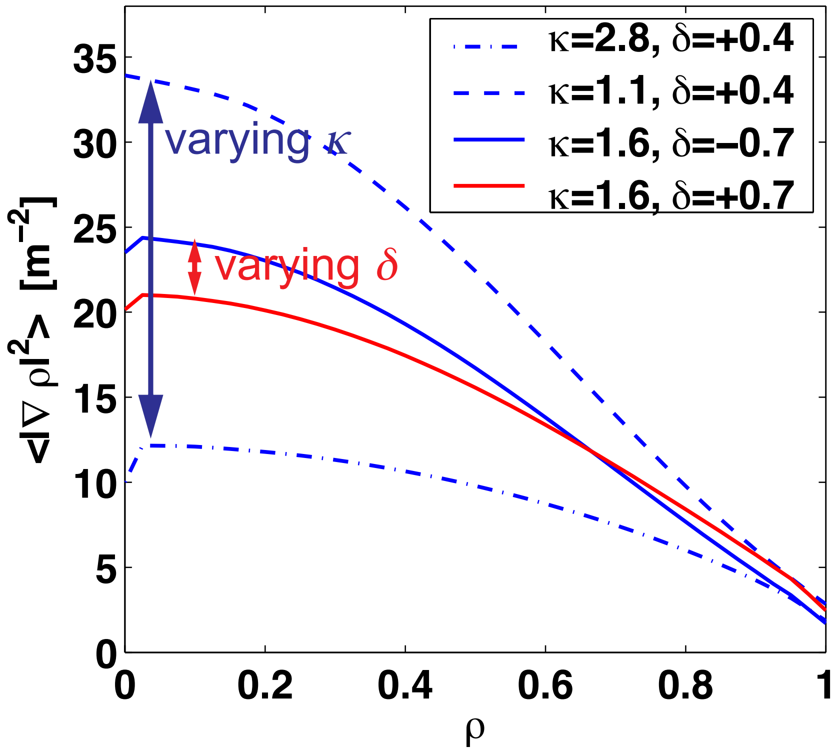
Gradient geometrical factor

gradient geometrical factor

local

flux surface averaged

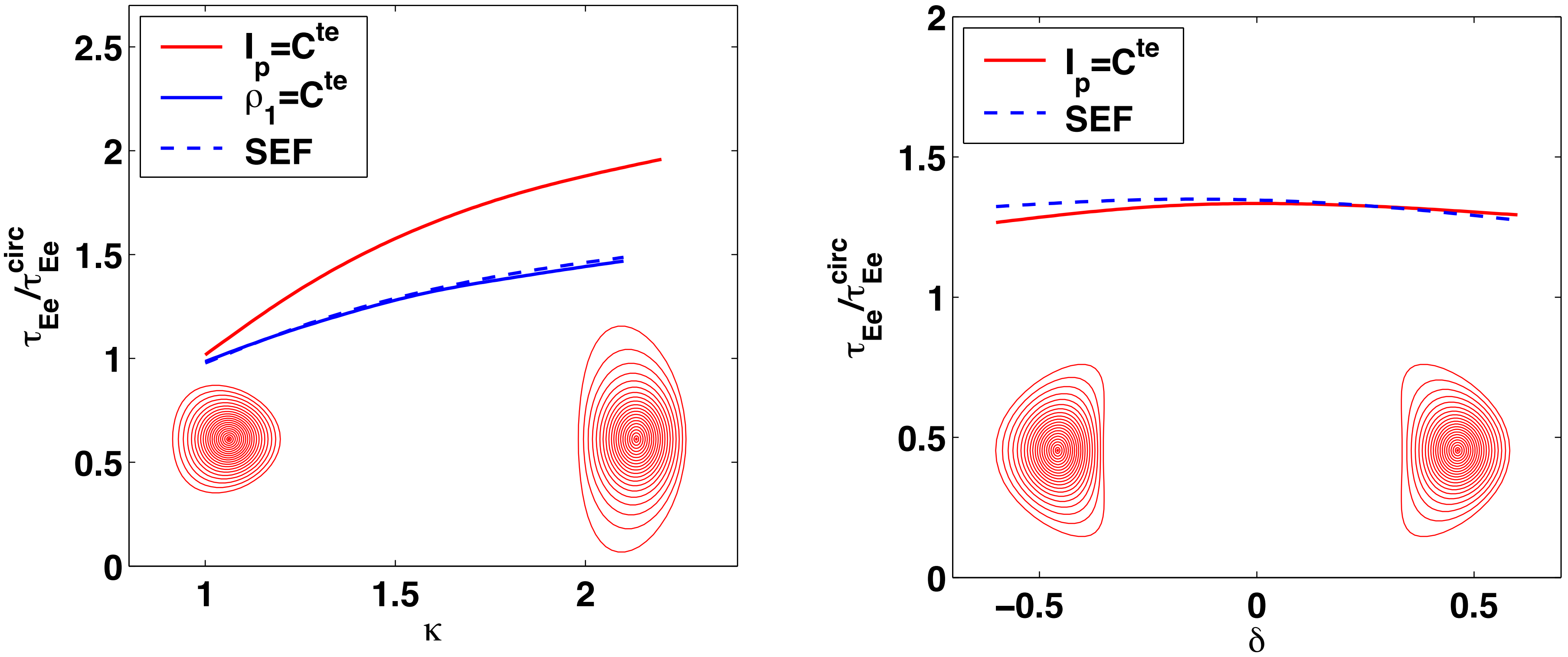




Moret PRL97

If confinement due to pure geometrical effects only (χ_e=const)

ASTRA: $\tau_{\mathrm{Ee\ shape}} / \tau_{\mathrm{Ee\ circ}}$ with same χ_e



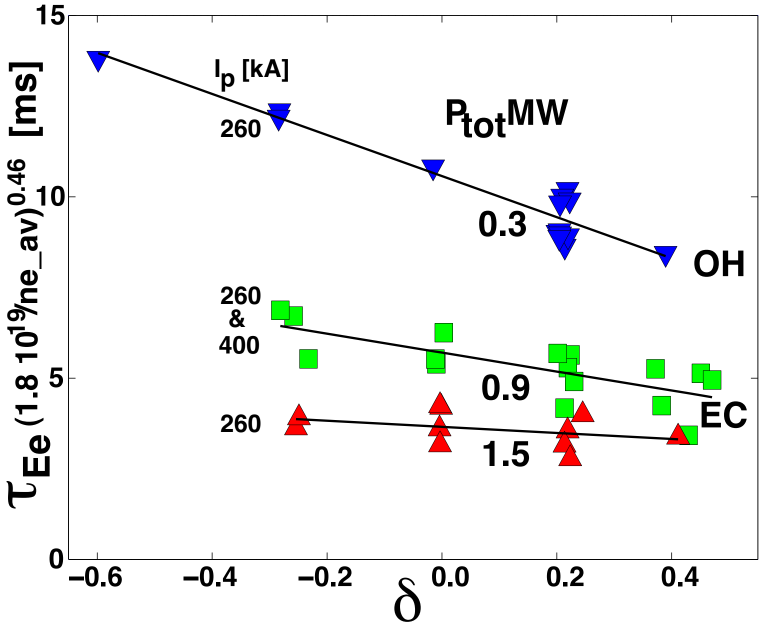
Important to keep sawtooth inv. radius ρ_1~const (self-similar profiles)

SEF adequate to account for τ_{Ee} variation with shape in OH, at medium densities

Camenen thesis06

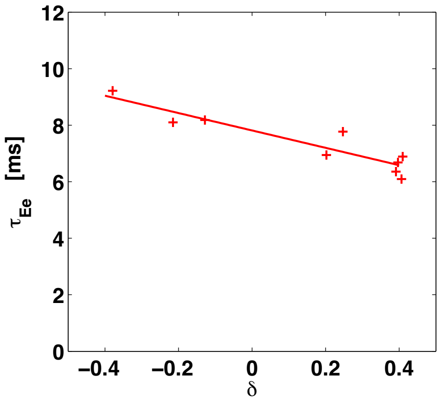
EC confinement at low densities ($\nu_{eff} \sim 0.2\text{-}1$)

Central ECH, large δ-range, including $\delta<0$



- Strong $\tau_{Ee}(\delta)$ dependence, improvement towards $\delta<0$
- Not explained by SEF

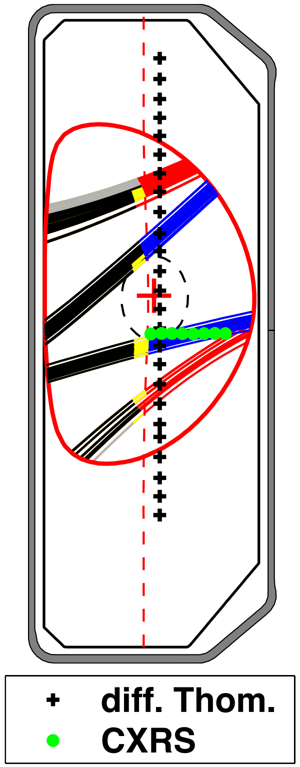
Does then χ_e vary with shape?

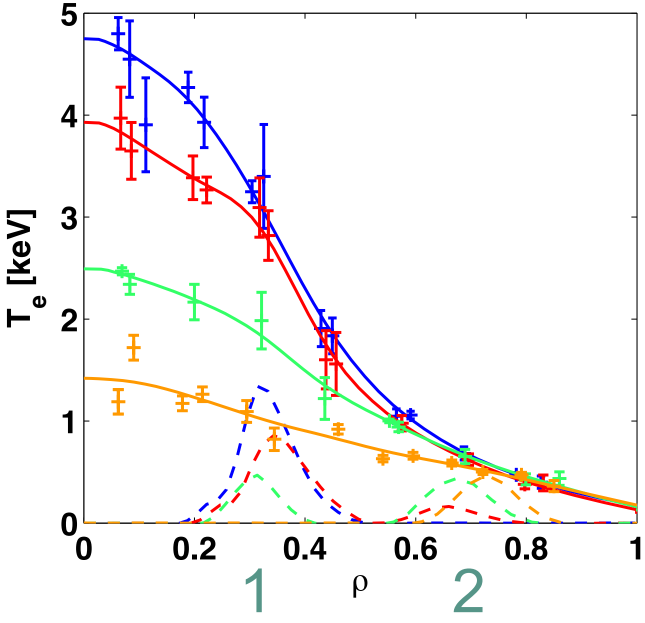


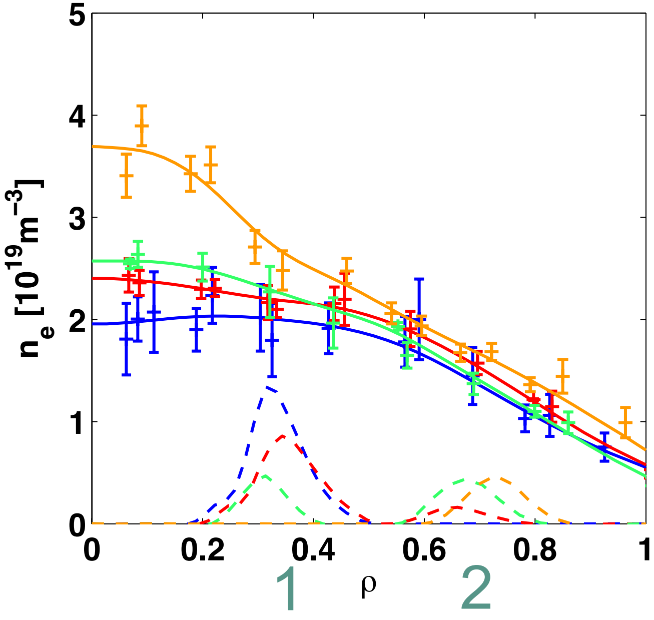
Coda 98, Pochelon NF99, EPS99, Weisen NF98

6. ELECTRON HEAT TRANSPORT vs shape / EC low n_e (ν_{eff}~0.2-1)

T_e-variation, gradT_e-variation experiments





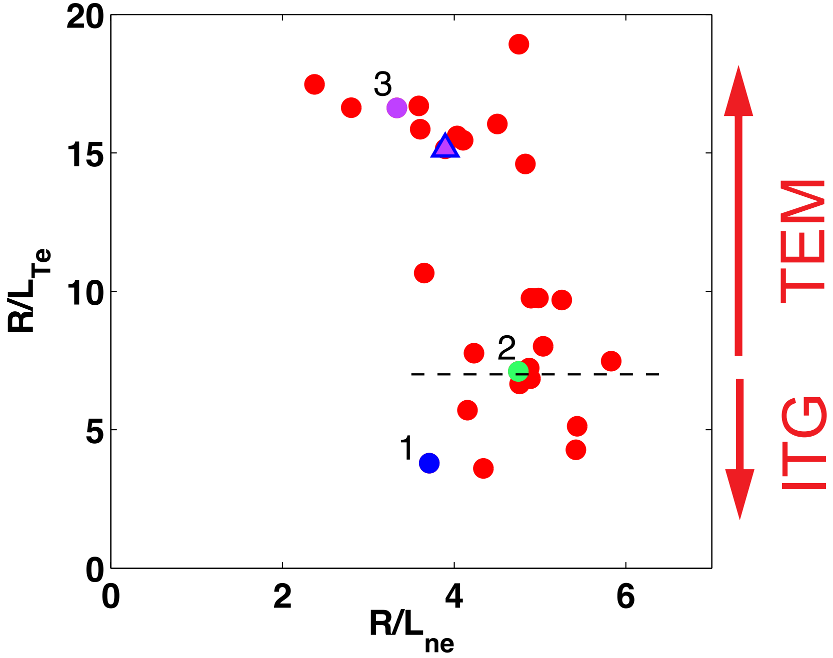


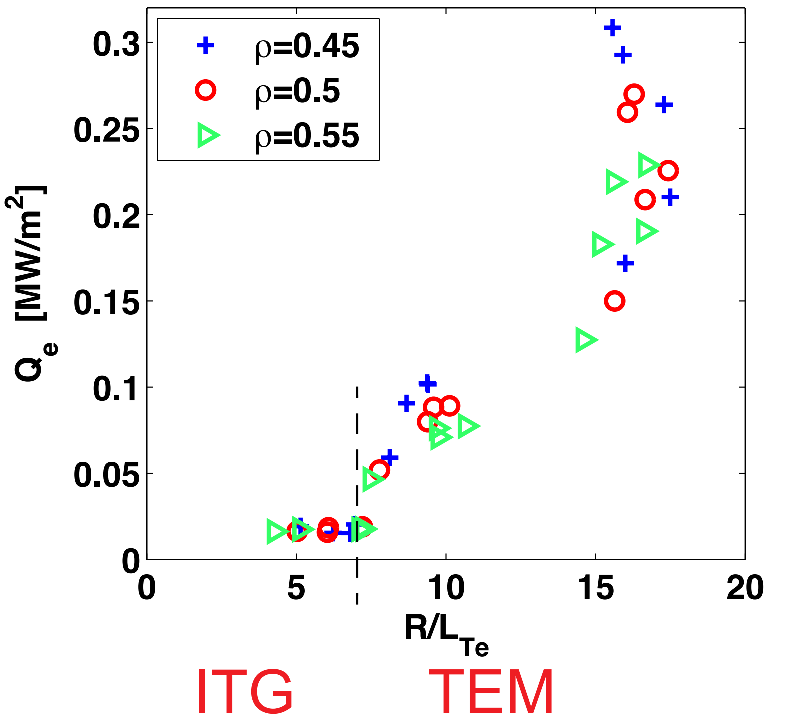
- 2 deposition locations 1 and 2
- Varying $P_{tot} = P_1 + P_2$
  and P_1 / P_2

Camenen PPCF05

Microinstability types in EC plasmas

Type of micro-instabilities (GLF, LORB)



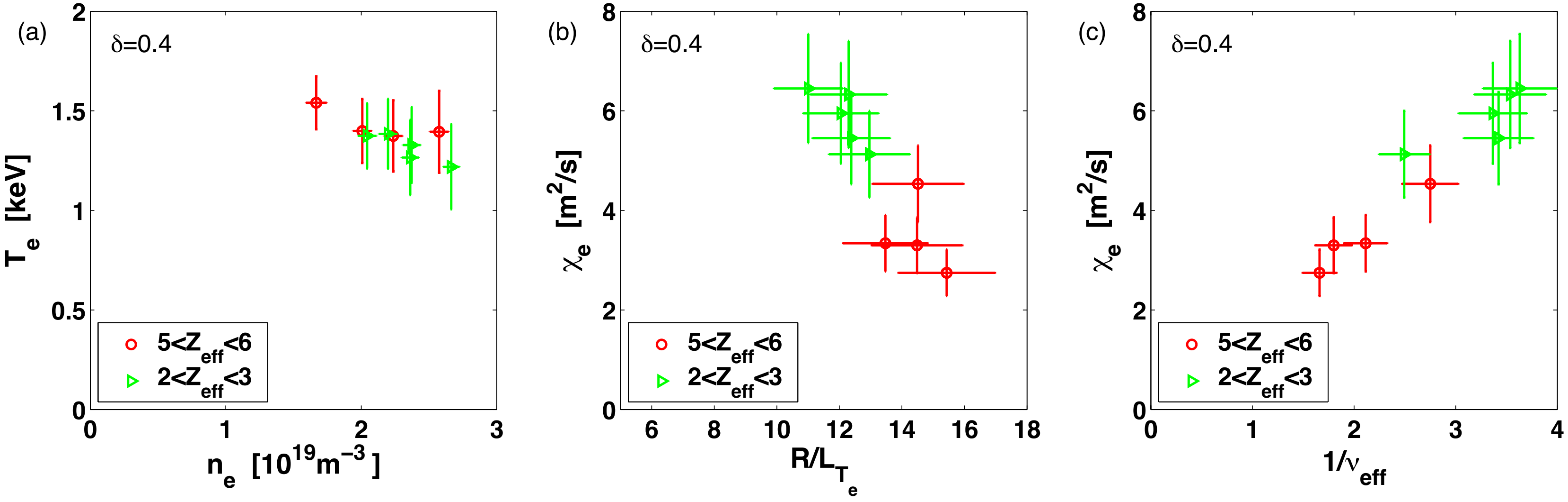


EC plasmas:
High *R*/*LT*$_e$>7, in high *T*$_e$/*T*$_i$, low collisionality: TEM regime

(no ETG in $0.2<\rho<0.7$, due to high *Z*$_{eff}$ & high *T*$_e$/*T*$_i$)

Camenen PPCF05, Thesis06

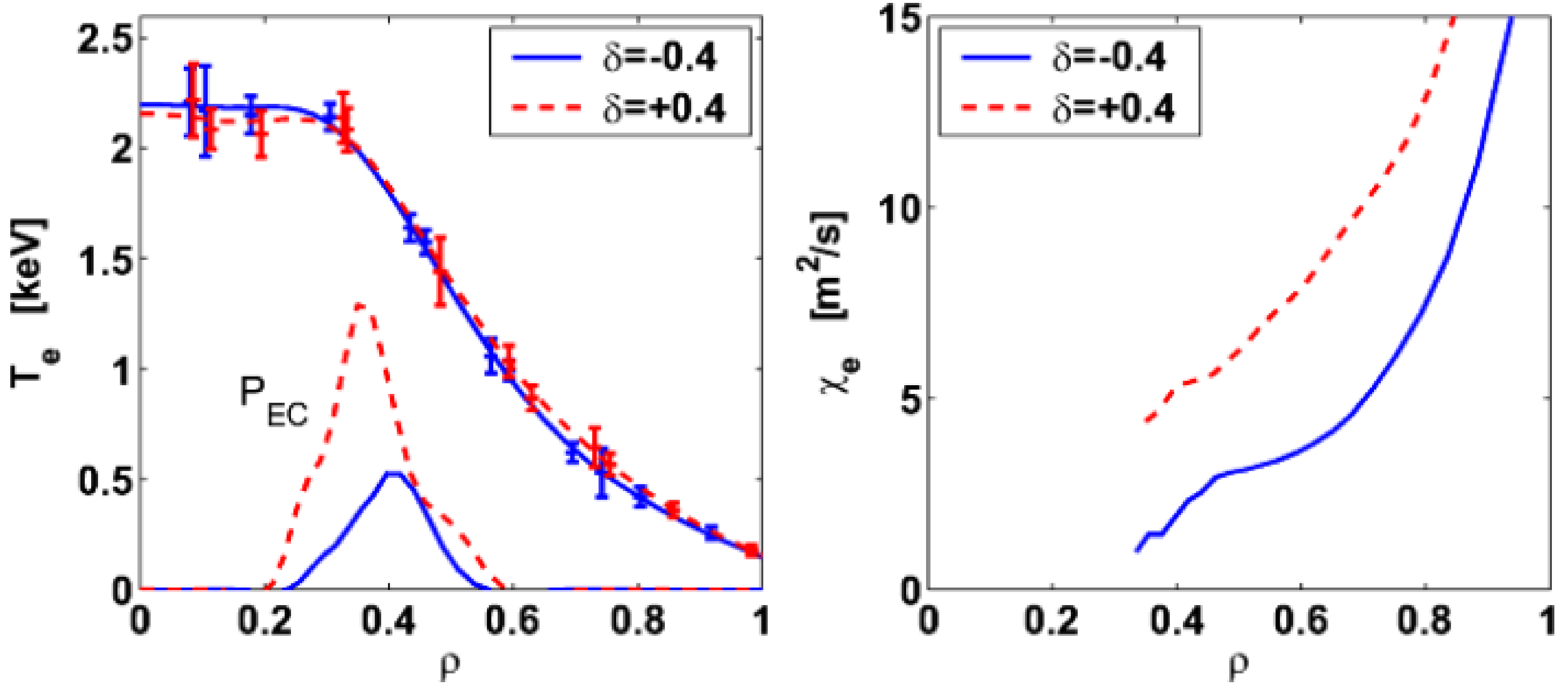
Collisionality effect demonstrated



- The effect of T_e, n_e, Z_{eff} combined
  show a clear dependence of χ_e on collisionality ν_{eff}
- $\nu_{eff} = 0.1R\, n_e\, Z_{eff} / T_e^2$
  $= \nu_{ei}/\omega_{De}$ De: drift due to curvature
- Diffusivity χ_e reduces with increasing collisionality (i.e. towards low $1/\nu_{eff}$)

Camenen NF07

How to double confinement in L-mode?



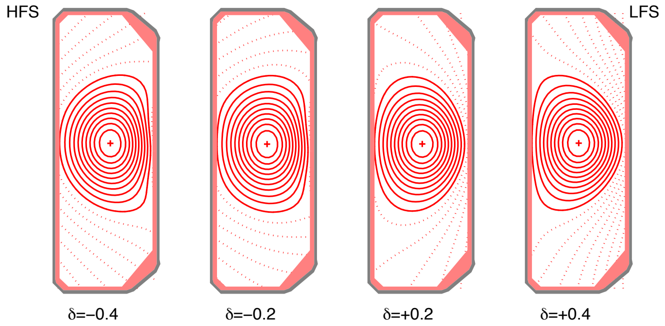
- Just change from positive to negative triangularity:

$$\delta = +0.4 \longrightarrow -0.4$$

- similar q and n_e profiles at both triangularities
- Transport halfed at mid-radius

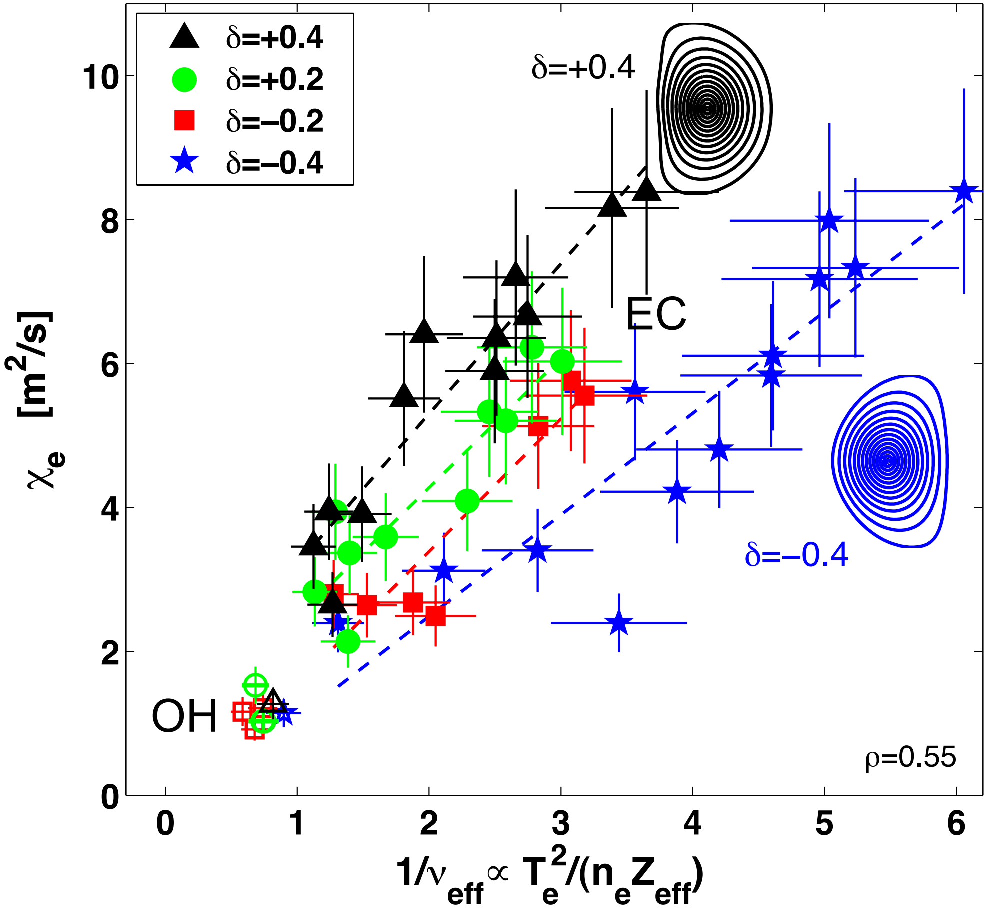
Camenen NF07

Shape and collisionality effects separated



Triangularity and many parameters varied

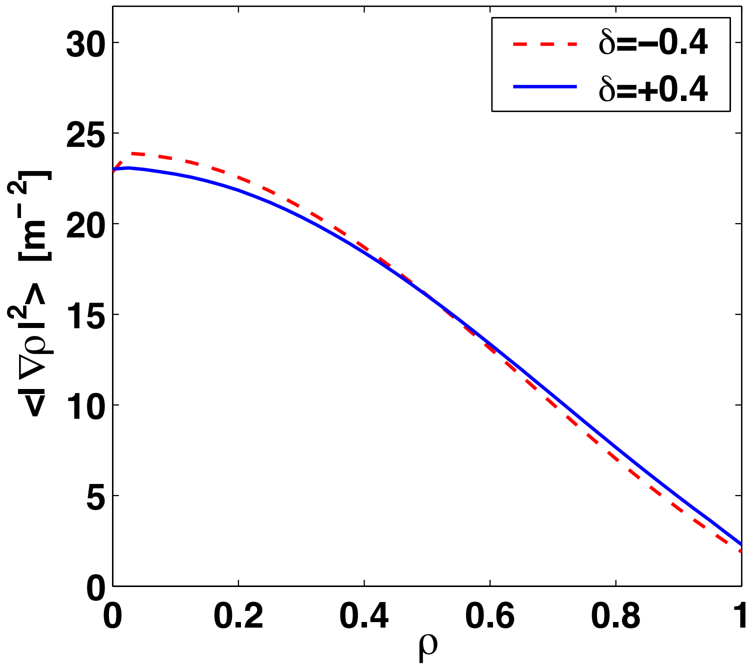
- Unifies OH-EC data (low,high ν_{eff})
- Collisionality lowers χ_e
- At same ν_{eff}, negative δ reduces χ_e



Camenen NF07

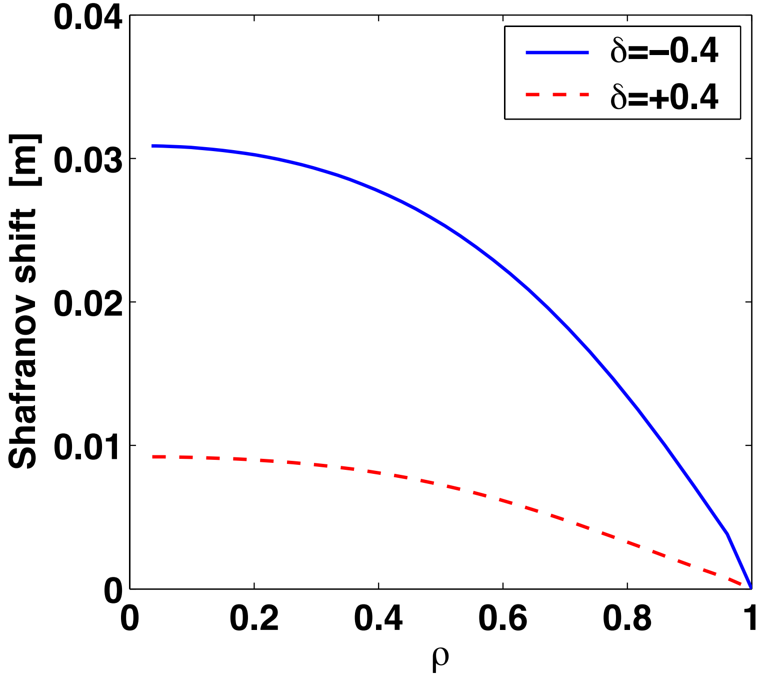
SEF, Shafranov shift effect?

Shape effect does not rely on SEF



SEF invariant with δ

Shafranov shift effect?

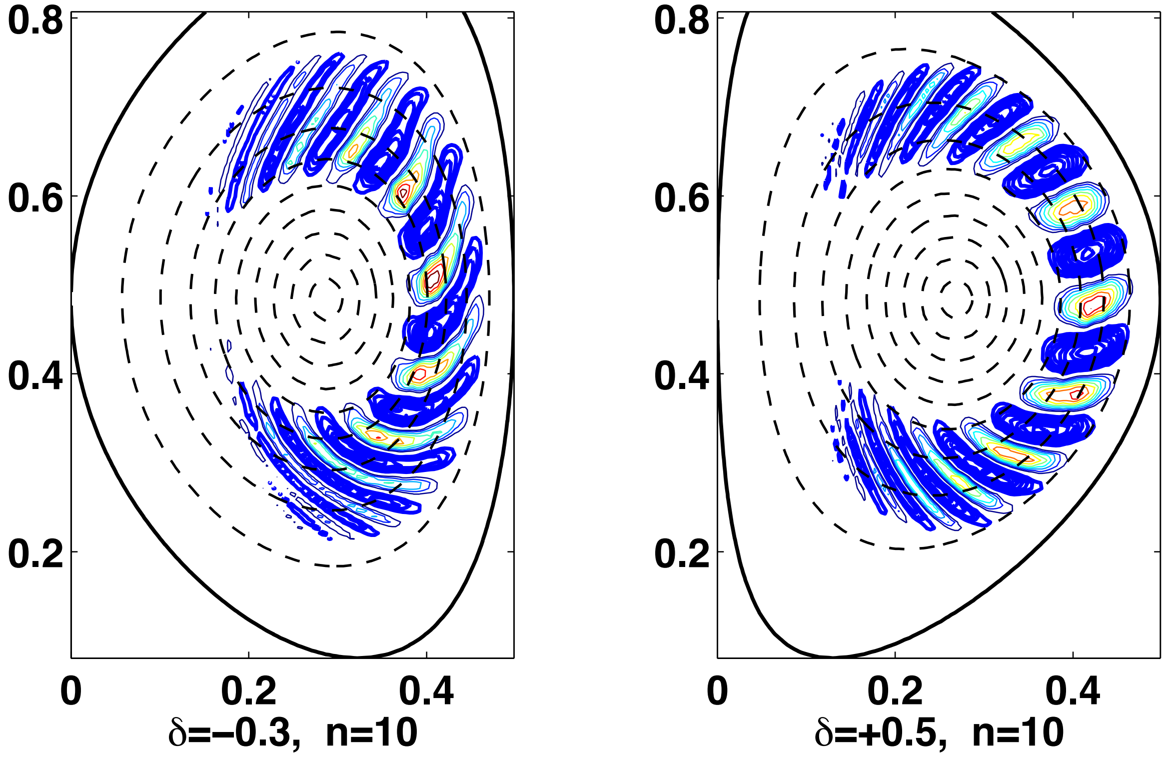


Shafranov shift important for $\delta<0$, stabilizing TEM should only be important at high pressure?

Camenen NF07

Global TEM micro-instabilities simulations

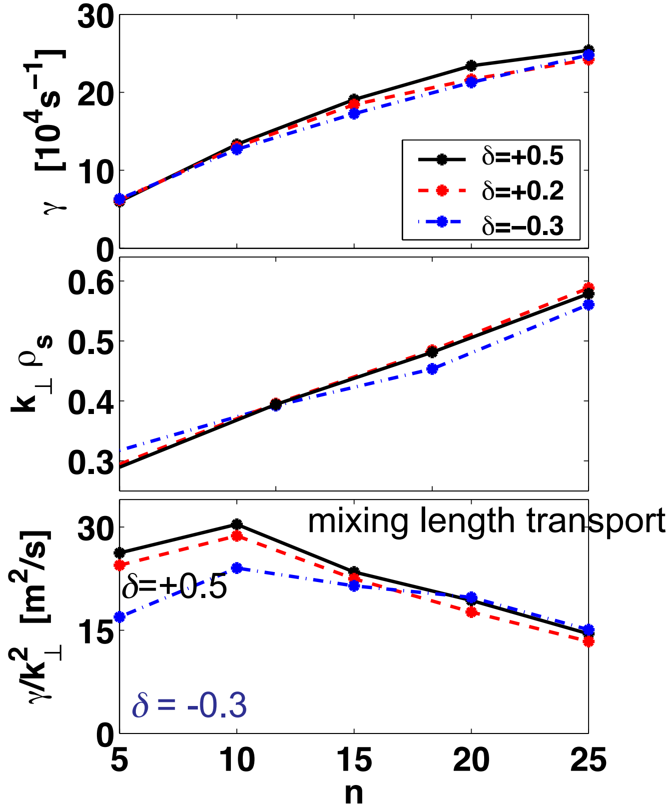
LORB simulations (gyrokinetic, linear, global, no collisions)



δ=−0.3, n=10

δ=+0.5, n=10

electrostatic potential fluctuations

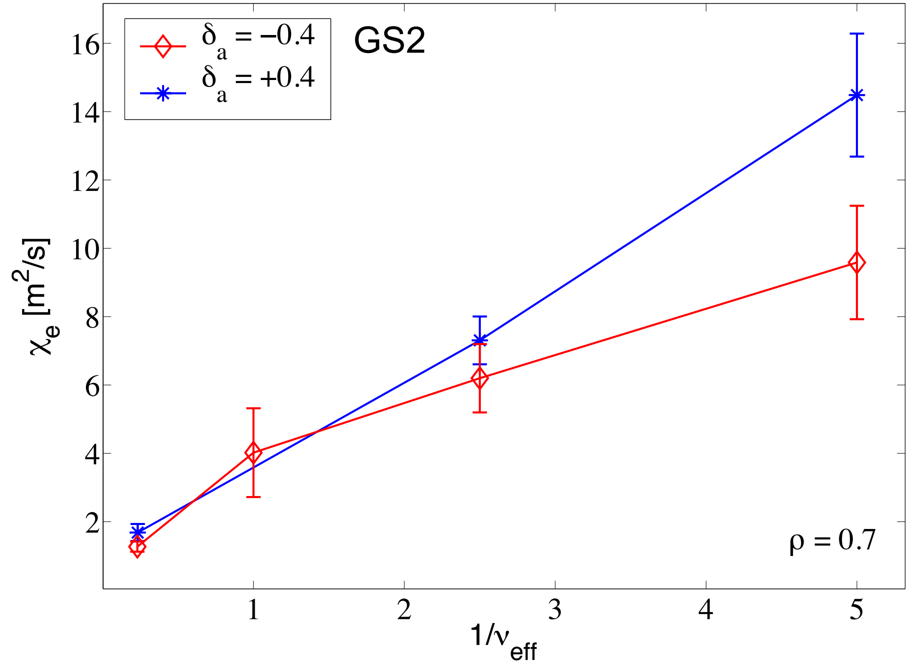


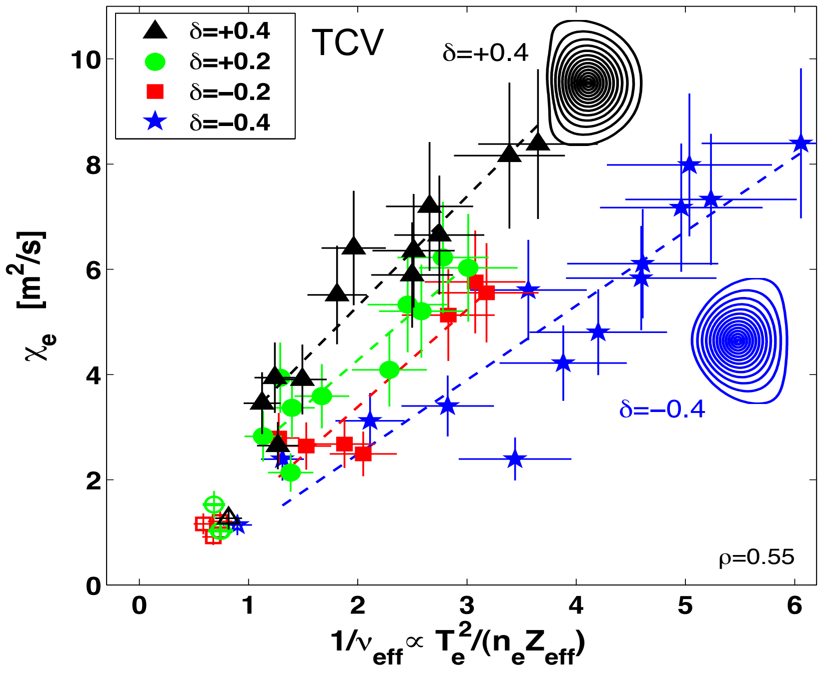
larger low-*n* transport at δ<0
An effect of curvature tilting eddies?

Camenen PPCF05

GS2: non-linear gyrokinetic collisional calculations

effect of shape and collisionality


Collisionality impact on different δ

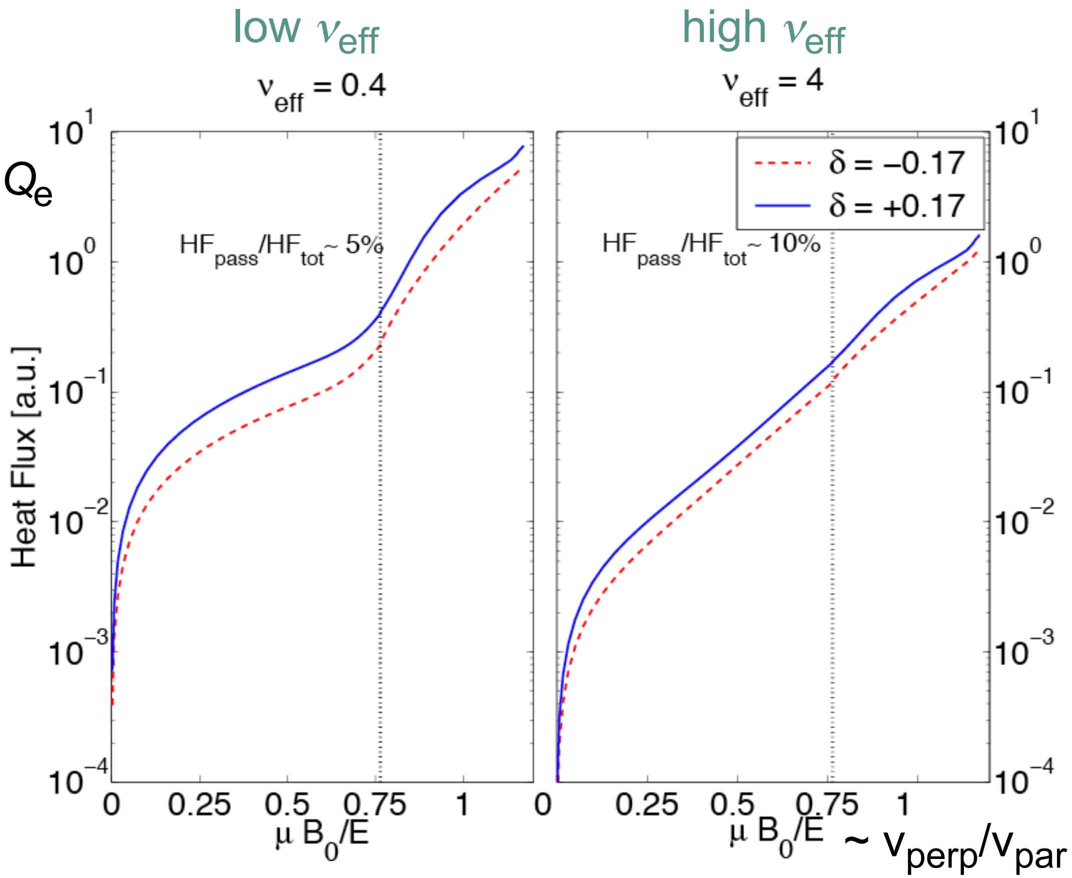


- small χ_e at negative δ (where larger k_{perp})
- similar χ_e difference at high ν_{eff} for different δ, as in TCV
- predicted χ_e (δ, ν_{eff}) at least in excellent qual. agreement with exp.

Marinoni EPS07

GS2 continued

heat flux integrated over pitch angle



- TEM are responsible for the transport
- barely trapped e⁻ contribute most to electron heat flux Q_e at low ν_{eff}

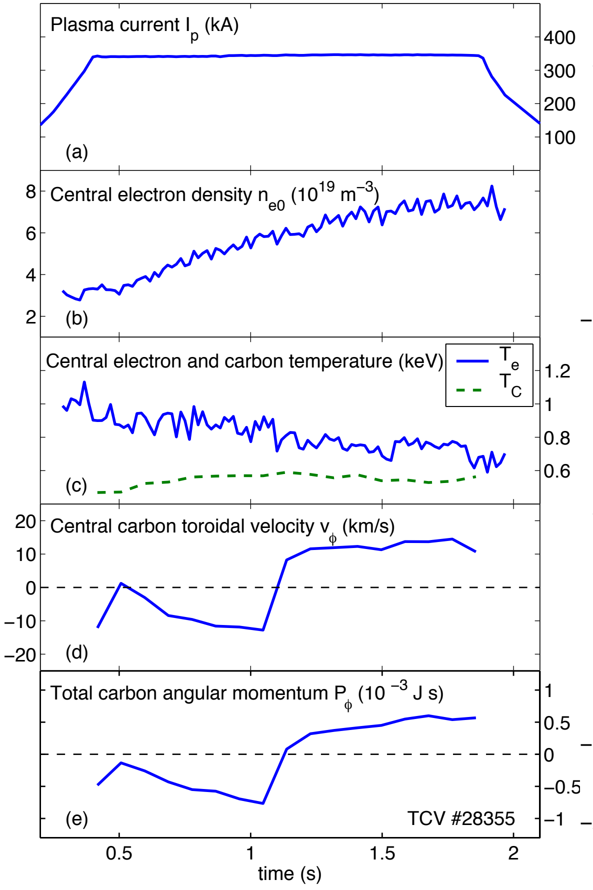
Marinoni EPS07

Some conclusions on heat transport

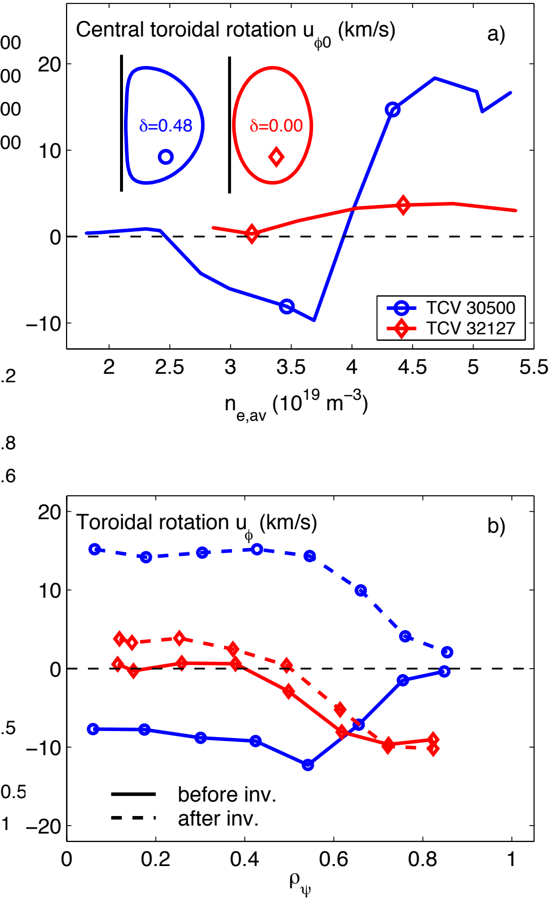
- Untangles transport dependences on **triangularity** and **collisionality**
- Collisionality unifies apparently contradictory δ-dependences in OH and ECH confinement studies (high, low ν_{eff})
- At same ν_{eff}, negative δ, shows reduced χ_e, a genuine effect of turbulence, rather than geometry
- Confirms TEM stabilization reduces transport
- Heat flux dependence on triangularity simulated (non-lin gyrokin)
- And **elongation**? What contribution of SEF, or also “genuine” χ_e?
- **Allows doubling confinement at negative triangularity** in low collisionality range
  (as good as H-mode!)

7. PLASMA ROTATION versus triangularity

Plasma toroidal rotation inverts above a critical density (co -> counter I_p)



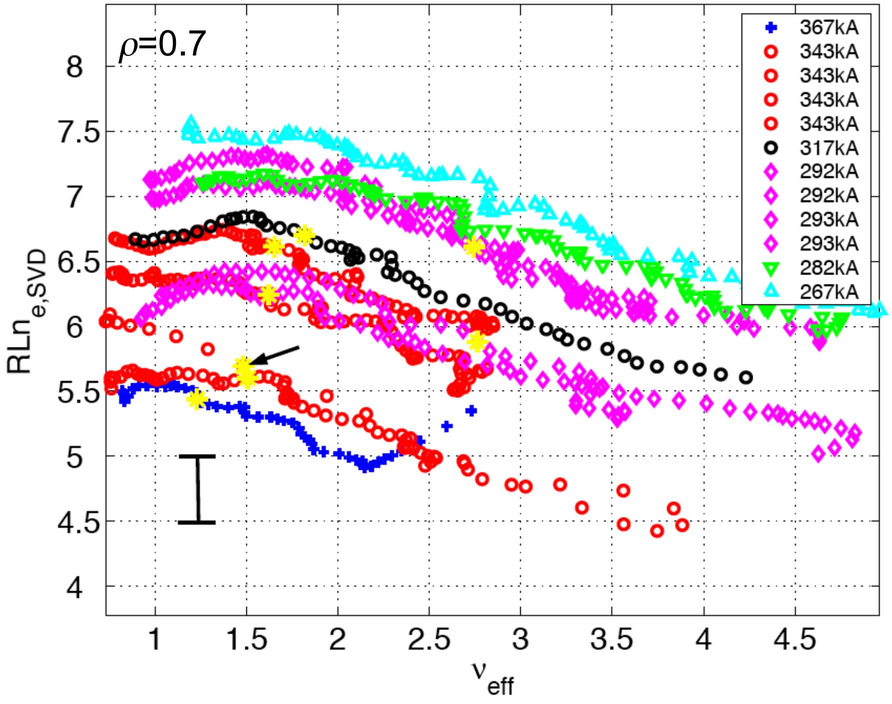
This rotation inversion gradually changes with plasma triangularity

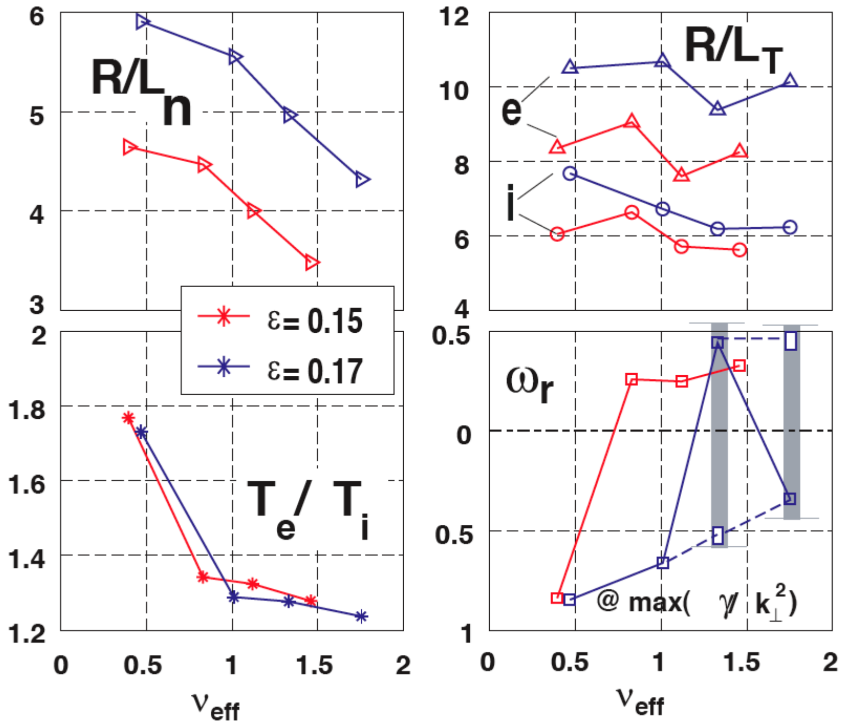


- Shaping modifies many parameters: χ_e, T_e, T_i , their gradients, T_e/T_i, contact with wall, etc...
- As for other studies in TCV, shape changes allow an extension of the plasma parameters covered, a chance for untangling the underlying physics!

Bortolon PRL05 Bortolon US-TTF07 Duval PPCF07 sub

Rotation inversion and micro-turbulence





Density ramps at different currents:
rotation inversion at 1<ν_{eff}<2,
corresponding to TEM/ITG transition at ρ~0.6

rotation inversion
= transition from
TEM to ITG.
True for more
than this case?

Scarabosio & Angioni ITPA-Trans07

8. CONCLUSIONS and PROSPECTS for the effect of SHAPE

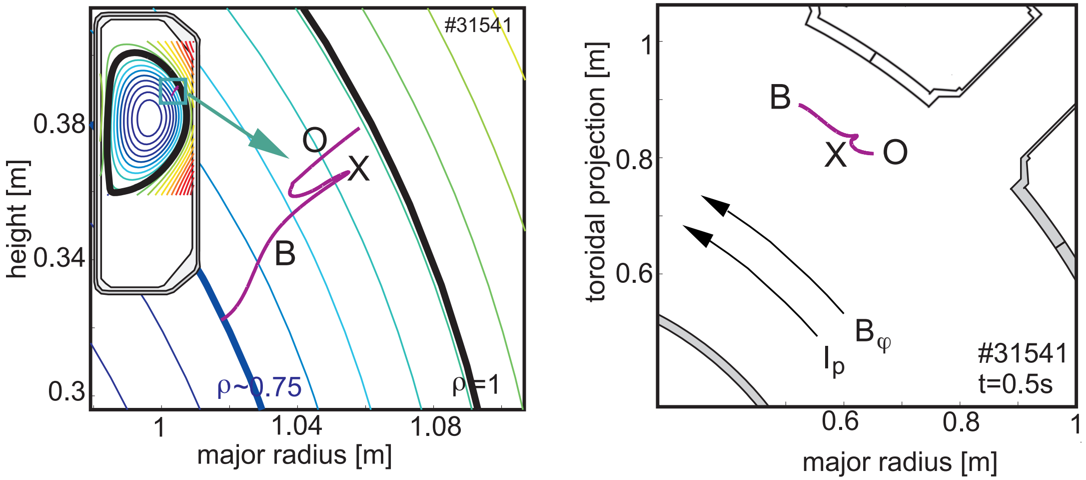
- β-current-limit at high κ (ideal ext. kink preceded by res. modes)
- Sawtooth period/internal kink stability:
  stabilized by $\pm\delta$, destabilized and suppressed at high κ
- Supression of q~3 ramp-up disruptions using shaping,
  dominant role of mode coupling in q~3-events (3/1 —> 2/1)
- Untangling the role of triangularity and collisionality in electron heat transport :
- Shape effect on confinement and transport depends on collisionality, which determines the dominant micro-instablity type, and χ_e for TEMs
- Benefit of negative triangularity: identical pressure profile achieved with half the power ! Doubling confinement : as good as H-mode!
- Using the tool of plasma shaping in intrinsic rotation studies may be as helpful as in electron heat transport studies to the reveal the underlying physics

Prospects for H-mode explored vs shape

- Systematic exploration of plasma shape effects on H-mode properties
  (also at *negative triangularities*: terra incognita!)
- L-H threshold, ELM, stationarity of H-mode
- Confinement, β-limits, transport, pedestal height:
  would H-mode also benefit of improved confinement at negative triangularity as the L-mode does? TCV should explore it.
- Many studies in TCV have profited of the additional button of shape, which by extending the parameter range covered, allows deeper insight
- Intrinsic rotation at high β
- ITB accessibilty at negative triangularity easier due to lower energy transport?

9. ELECTRON BERNSTEIN WAVE HEATING

First step: EBH deposition chosen far off-axis
(to avoid sawteeth perturbations)



Mueck PRL07
Mueck FST07
Pochelon NF07

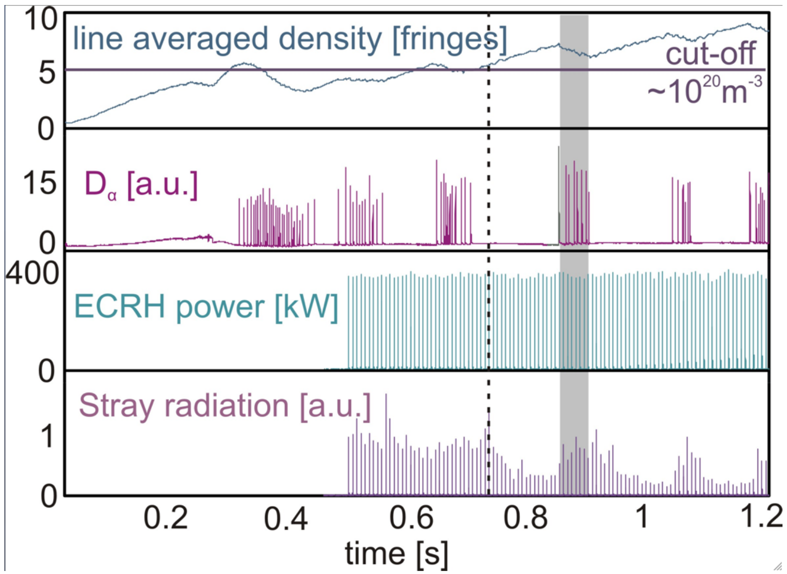
O-X-B scheme from LFS
high poloidal injection angle
$\rho_1\sim0.5 \;<\; \rho_{dep}\sim0.7 \;<\; \rho_{cut\text{-}off}\sim0.9$
$(\rho_{dep\_ART}\sim0.8)$

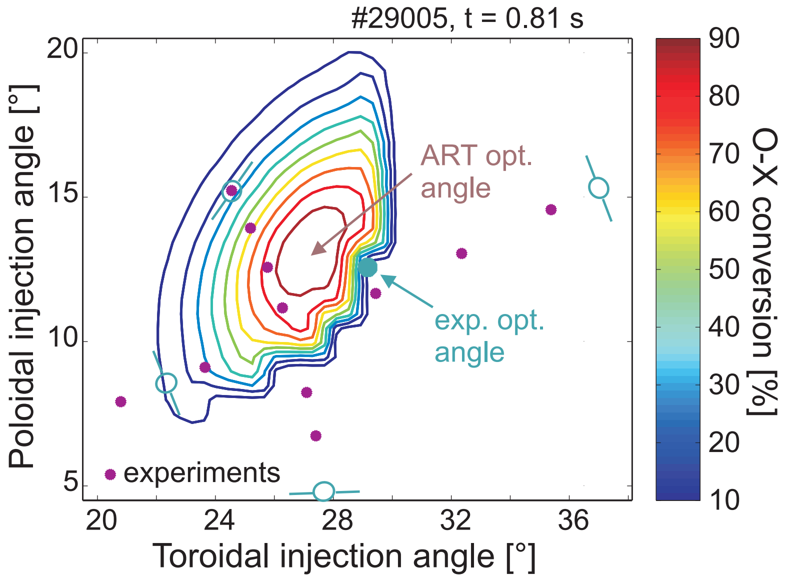
H-mode:
κ=1.8
δ=0.55
$q_{95}\sim2.3$
Steep n_e-gradients:
low q, high δ, high P

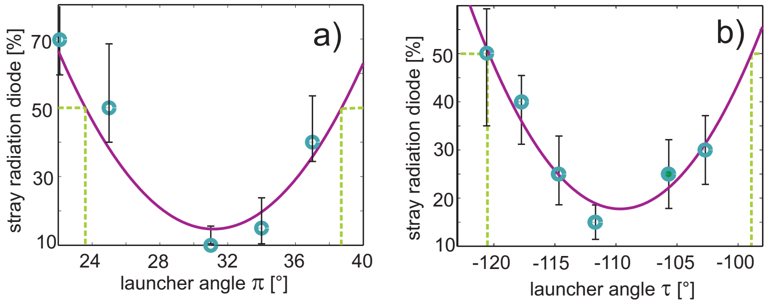
EBH demonstrated in a standard aspect ratio tokamak

Optimization of O-X-(B) coupling

minimize stray field to find optimal injection angle



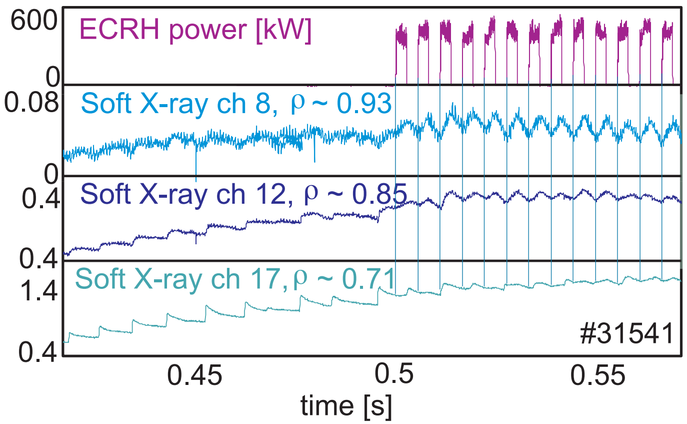




Experimental optimum angle within 2^{o} of ART prediction

Experimental angular transmission window larger than predicted one

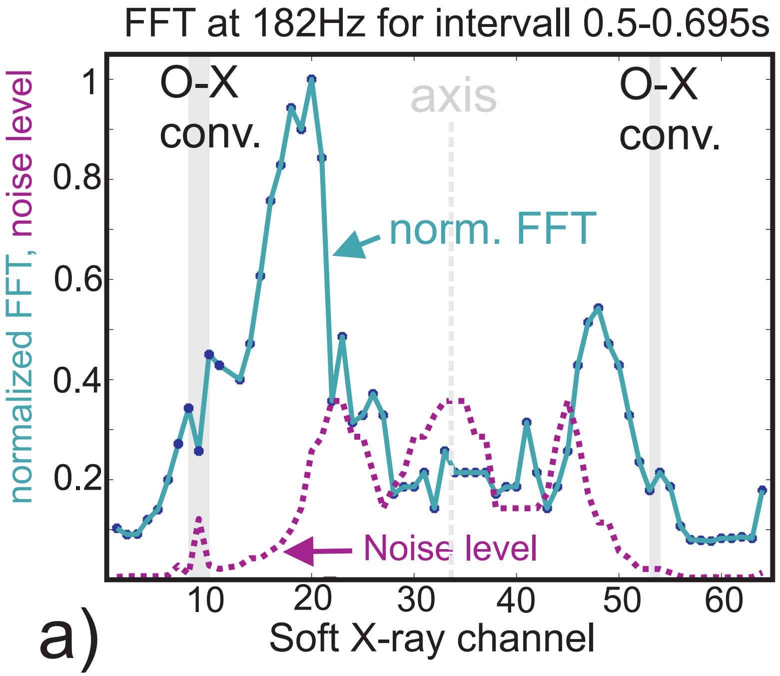
Power deposition location and coupling

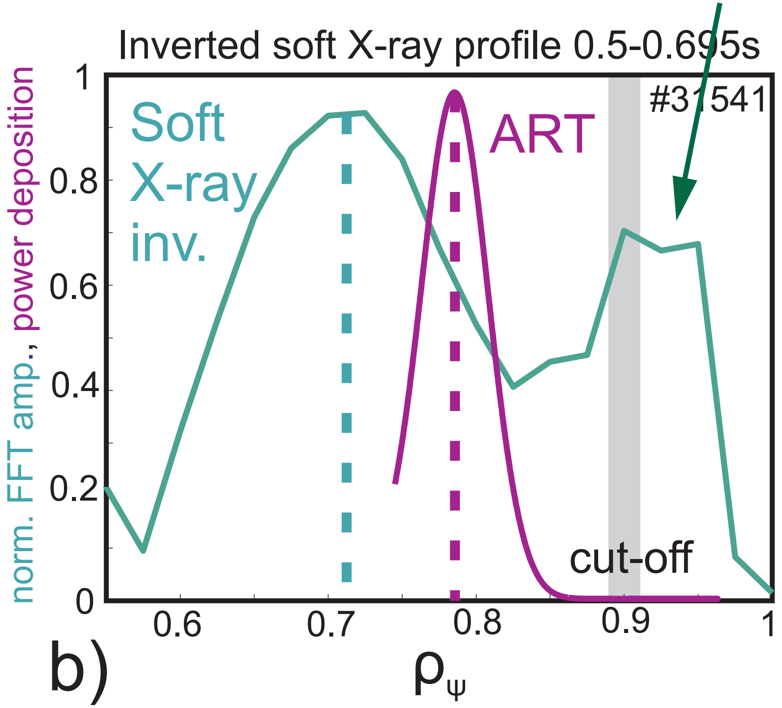


64 channel SXR —> local deposition at overdense location

Diamagnetic loop —> ≤ 60% power deposition

Outside deposition could be due to:
- scattered X2 power
- LH parametric decay
- collisional damping (cf. NSTX & Urban)



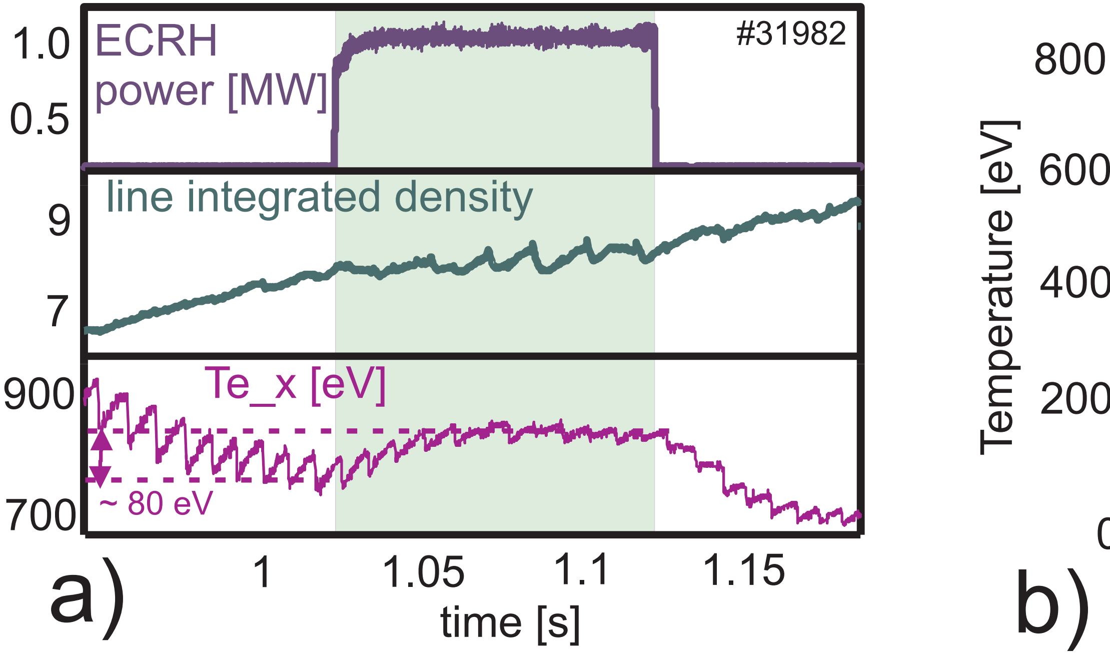


EBH deposition at overdense location, close to ART prediction

Higher power experiments

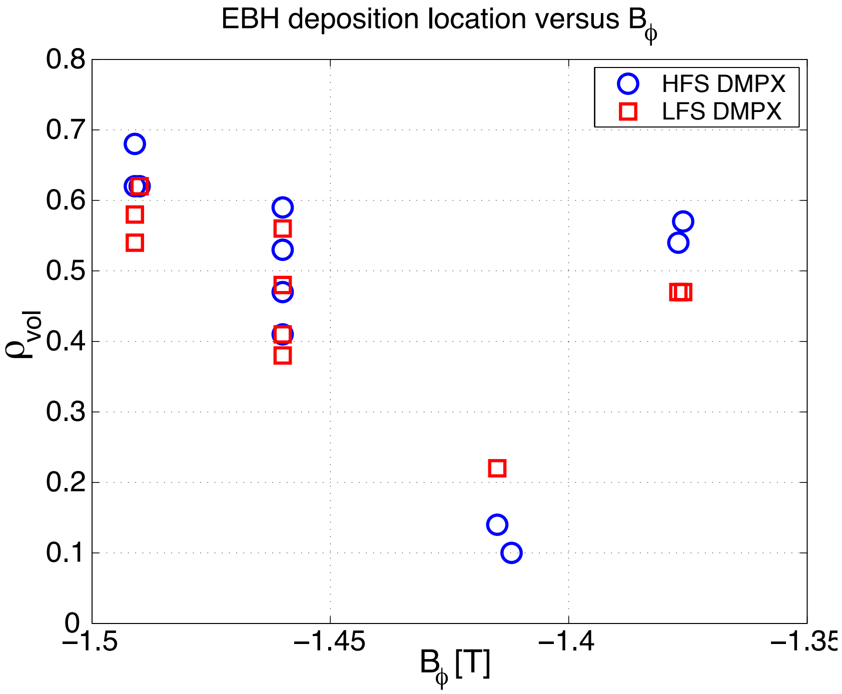
1 MW EBH pulse ($\tau_{pulse} > \tau_E$~50ms)
on top of 1MW EBH CW

$\rho_{dep\_ART} \sim 0.4$



Central temperature increase, at constant density

Second step: optimizing central deposition



Curchod EPS07

Determination of deposition location

- FFT, SVD perturbed by sawteeth
- adequate: slope-breaking method

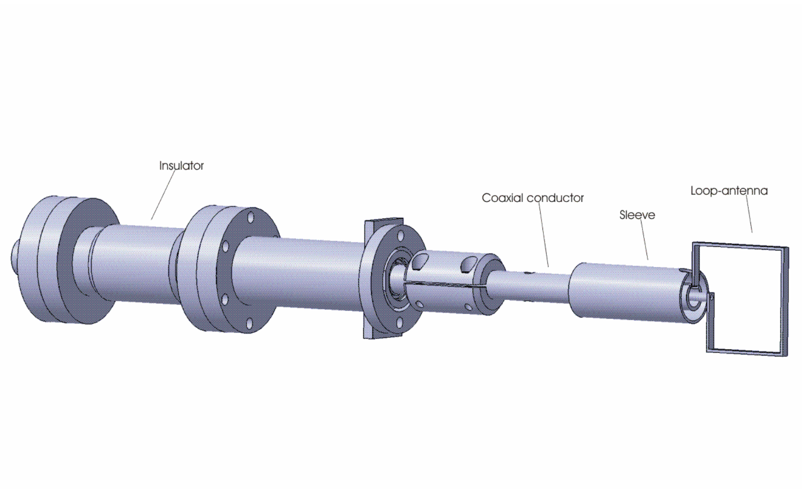
Results

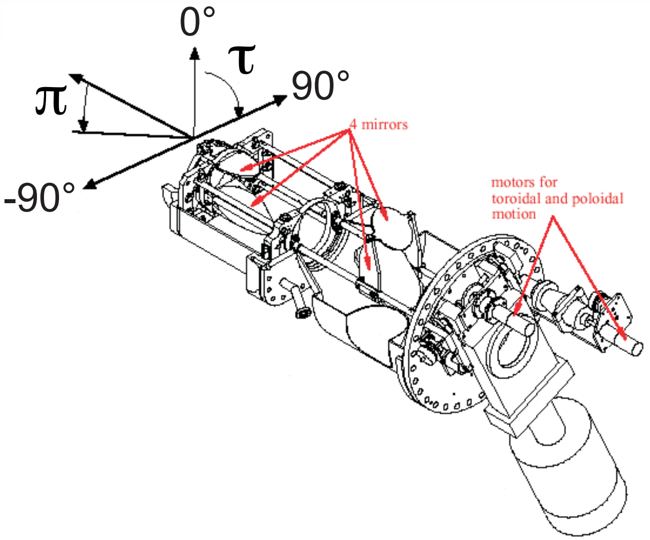
- central deposition found
- large differences in ρ_{dep} with ART ray tracing
- good opportunity to test relativistic ray traycing (GENRAY, LUKE-DKE, ...)

Aim

- central deposition at high power

Prospects





Diagnostics

- LH parametric decay probe Curchod
- EBE with additional “launcher” in reception mode

Aim

- maximize coupling, minimize losses
- possible use of vibrating mirror for feedback on mirror angle (as for X3, Alberti JoPh05, Arnoux PPCF05)

Conclusions on EBH

- Heating of a standard aspect ratio tokamak
- Good correspondance of experiment / ART in off-axis deposition, oblique launch
- Up to 2 MW of injected power in O-X-B

- Improve coupling (≤60%) / minimize losses (new diagnostics)
- Started central deposition at low power
- Now increase centrally deposited power to study the effects of high power EBH