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Physics Insight & Performance Benefit in MHD & Energy Transport...

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1. Motivations

WHY STUDY also SHAPES different from ITER?

- Test of MHD and transport theory
- Negative triangularity improves confinement
- Confinement scales with I_p (τ_E, n_e, β, fast ions...), and $I_{p\ max}$ can be increased by plasma cross-section shaping at constant magnetic field
- Many parameters depend on plasma shaping and reciprocally, active plasma shaping offers a mean to control these parameters
- Optim. of devices beyond ITER, innovative shapes

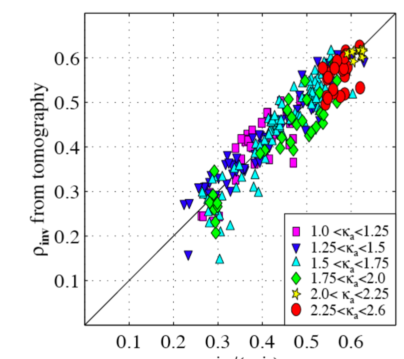
SHAPING VARIABLES

- elongation κ, triangularity δ, including negative, squareness
- aspect ratio R/a
- limited / diverter shape

SHAPE INFLUENCES ...

- **MHD** stability (sawteeth, modes, disruptions, ELMs, TAE damping & gaps)
- **Confinement**, edge transport barrier, performance
- **Transport** (electron heat, rotation)
- ***Integrated approach** of plasma shaping **needed**: several phenomena* with crucial impact on plasma containement *are influenced by shape, e.g.:*
  - e.g. ELMs(*shape*) can destroy ITBs (e.g. JET)
  - Sawteeth(*shape*) can trigger NTMs
- ***Some effects of plasma shaping can differ with plama scenario, e.g.:***
  - $\tau_E(\delta)$ increases towards *neg* δ in L-mode (core) increases towards *posit* δ in H-mode (pedestal)

3. MHD and stability: *q*=1 sawteeth

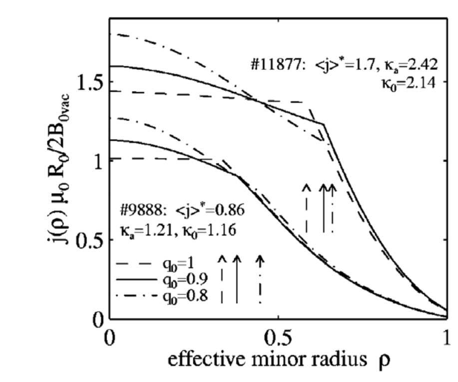


q=1 radius scaling: studied over a large κ-range

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

$\rho_{inv} \approx 2\ (q_{eng}\ (\kappa_0+1/\kappa_0))^{-1}$, with $q_{eng}=5abB / RI_p$

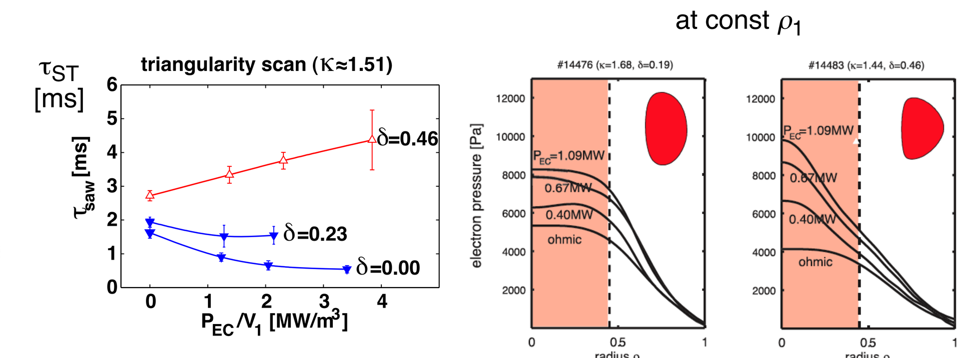
Weisen NF02, PPCF98



At fixed $q(a)$, ρ_{inv} and $\langle j\rangle$ increase with shaping, κ

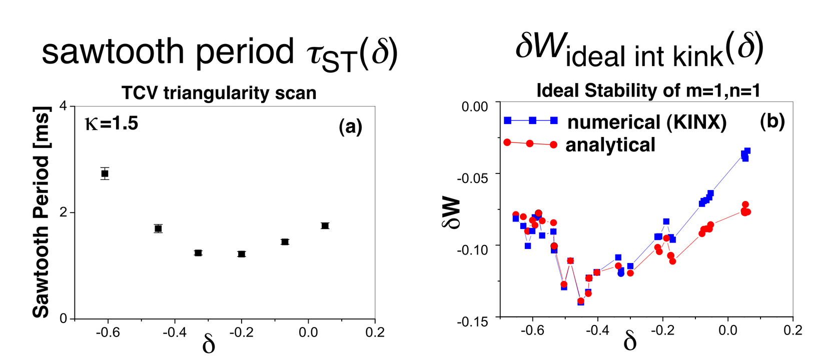
Sawtooth period/stability central ECH (1.1<κ<2.1 and -0.2<δ<+0.5) Reimerdes PPCF00

- τ_{ST} depends strongly on plasma shape



- the limiting pressure inside q=1 (β_{Bussac}) is determined by shape
- τ_{ST} follows ideal internal kink stability
- parallel to Mercier ideal stability over this shape range

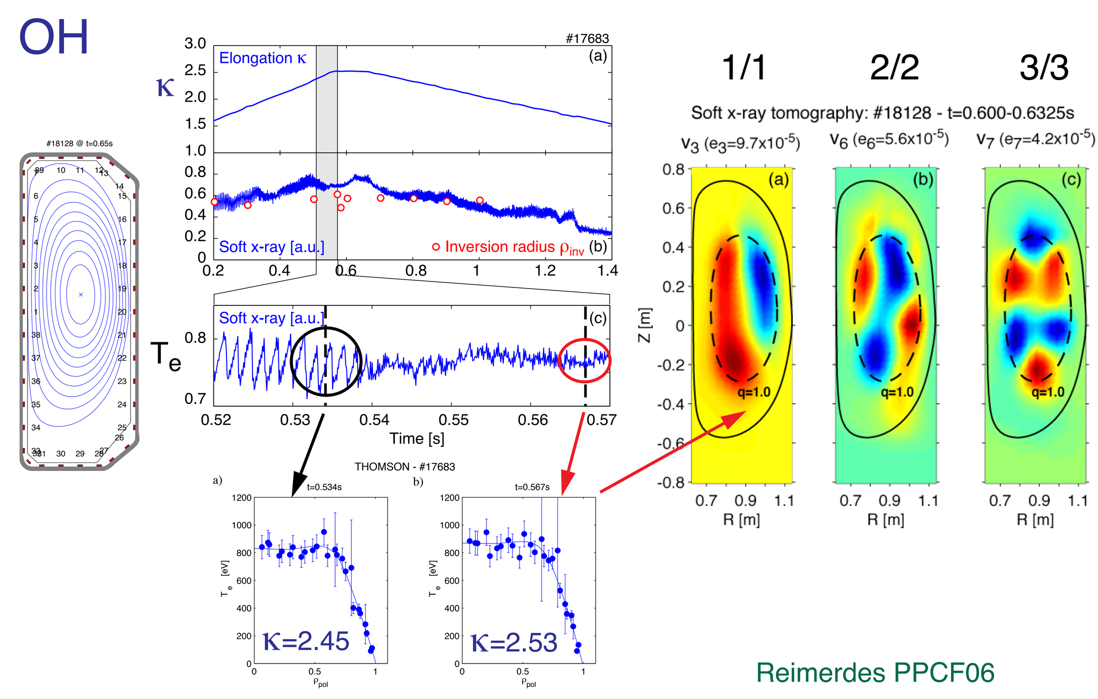
Sawtooth period/stability for -0.6<δ<+0.3, OH Martynov PPCF05



- both triangularity signs are stabilizing (shorter sawteeth)
- $\delta W_{ideal\ int\ kink}$ and τ_{ST} show the same behaviour with δ (min. close to $\delta\sim$-0.3)

—> ideal internal kink

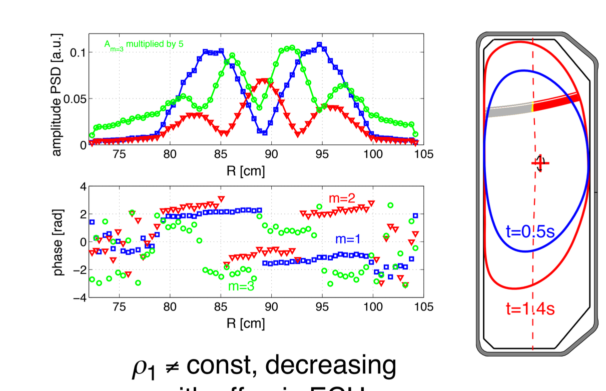
Sawtooth disappearance at high κ>2.3 - 2.6, in OH ...



At very high κ & l_i<0.7, sawteeth disappear ($\gamma_{ideal\ int\ kink} > \omega_{*i}/2$), replaced by m/n=1 multi-harmonic modes on q=1 keeping a flat central pressure profile with ρ_1 unchanged *(infernal, interchange modes?)*

Reimerdes PPCF06

... and at lower κ with off-axis ECH



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

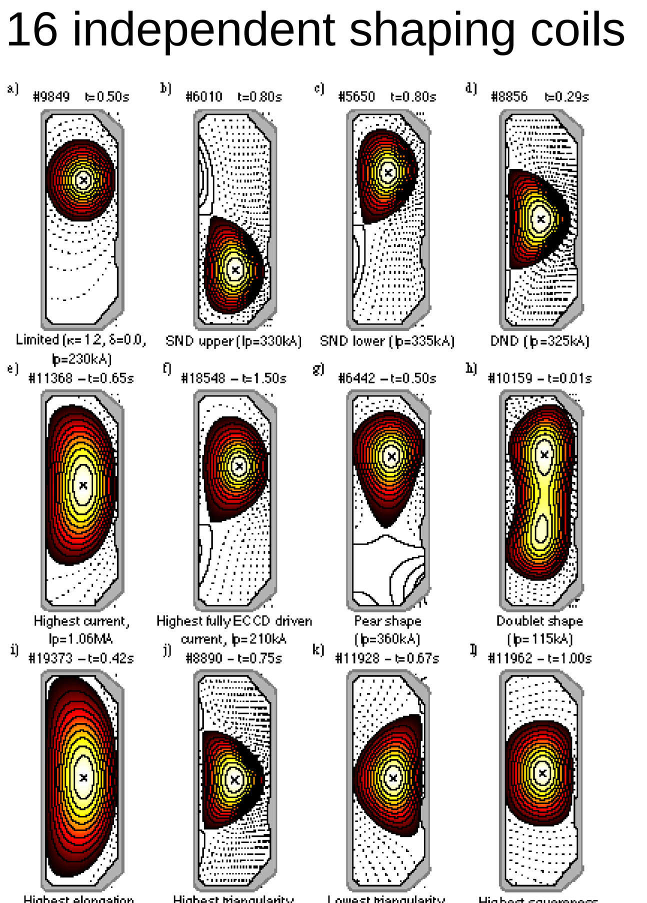
multi-harmonics m=1,2,3 on q=1 with off-axis ECH current profile broadening, as in high I_N OH discharges

Scarabosio thesis06

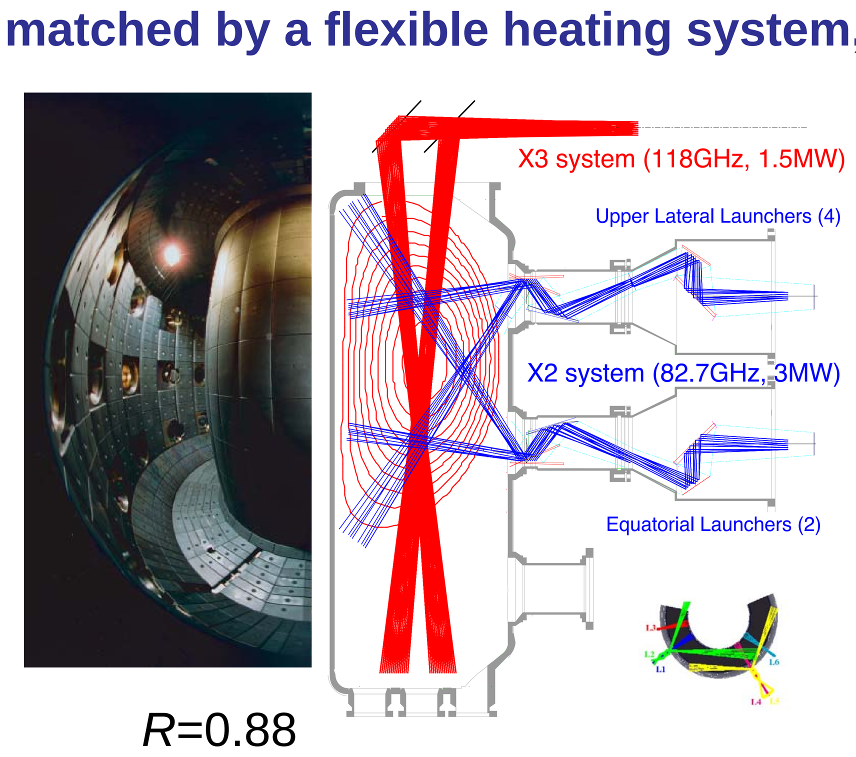
2. TCV facility & Shaping achievements

Flexible plasma shaping

16 independent shaping coils



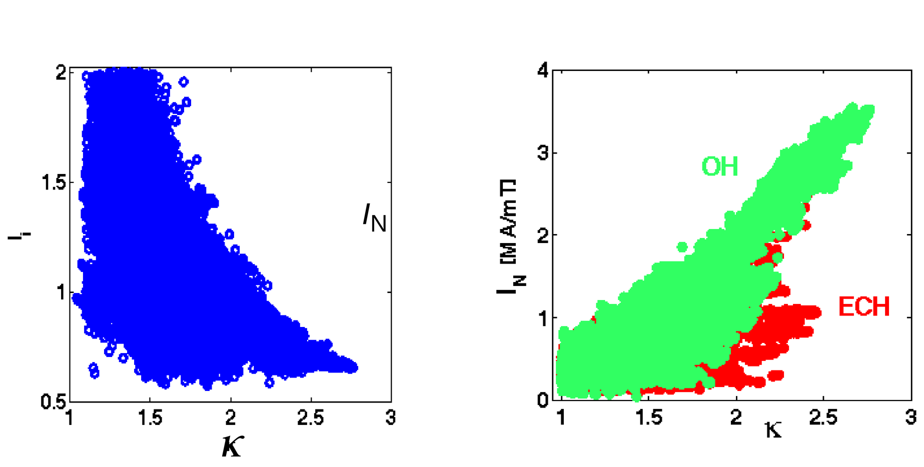
... matched by a flexible heating system, entirely based on ECRH



- X2, 2nd harm., 82.7GHz, 3MW, 6 LFS launchers, steerable during discharge
- X3, 3rd harm., 118GHz, 1.5MW
- Cut-off densities:
  X2 : 4.2 10^{19} m^{-3}
  X3: 11.1 10^{19} m^{-3}

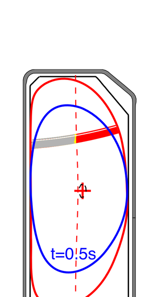
R=0.88 m, a=0.25m, R/a~3.5
B<1.54T, I_p<1MA
0.9 < κ < 2.8
- 0.7 < δ < +1

vertical stability requires broad current profiles



operational diagram limited by :
n=0 vertical instability
n=1 external kink (I_N & β-limit)

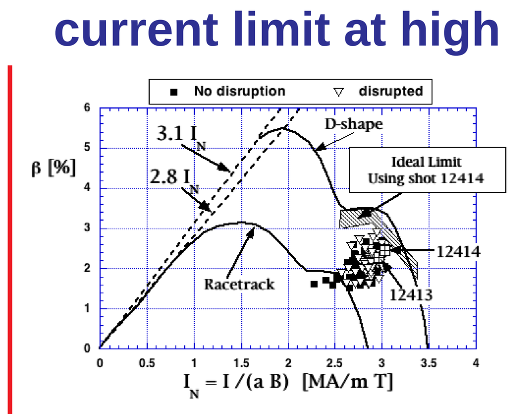
Hofmann PPCF01



κ=2.5 at low I_N, with off-axis ECH

Pochelon NF01
Camenen NF07
Paley PPCF07

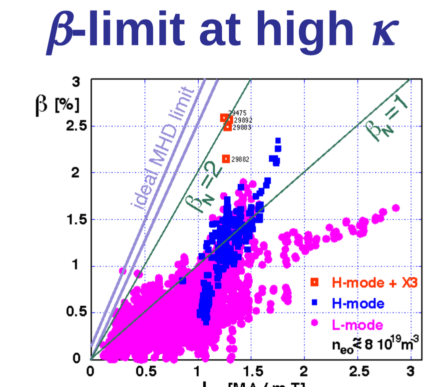
current limit at high κ



Ideal MHD predicts the current limit

Hofmann PRL97

β-limit at high κ

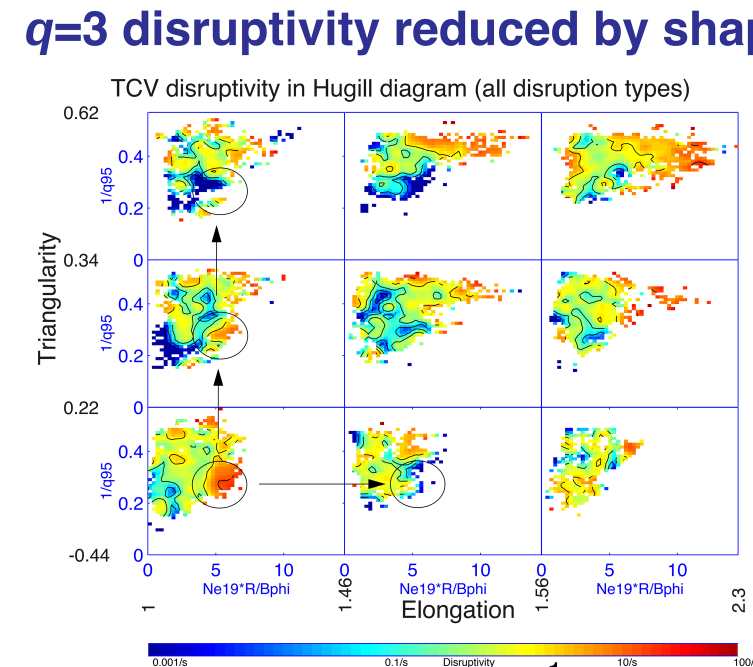


β_N~2 reached with 1.5MW X3 at κ_{95}~1.6 in H-mode
More power needed to test the β-limit at high κ!

Porte NF07, Alberti JoPh05, Pochelon SMP05

4. MHD & stability: modes & disruptions

q=3 disruptivity reduced by shaping Scarabosio NF07



Disruptivity (disr./s) in Hugill diagram vs δ and κ
low disr.=blue, high disr.=red

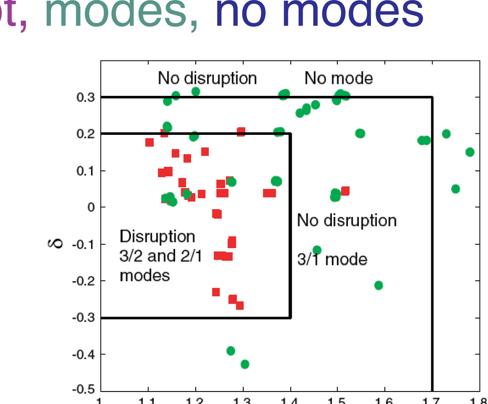
q=3 high density disr. notch stabilized by (κ,δ)-shaping

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

disrupt, modes, no modes

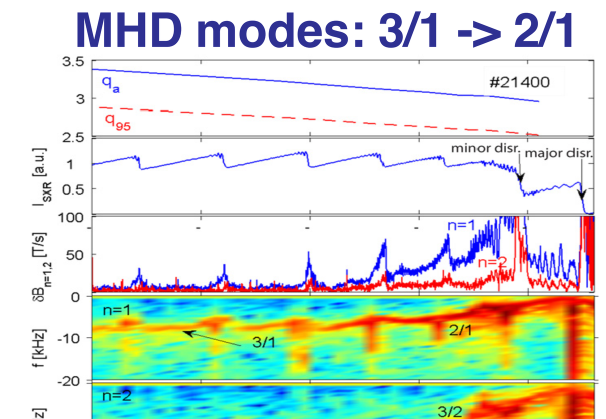
MHD modes leading to disruption

- 2/1: dominant mode leading to disrupt.
- Locking of 3/1 to 2/1 correlates with the 2/1 becoming disruptive
- ***Shaping reduces the 3/1 external mode***



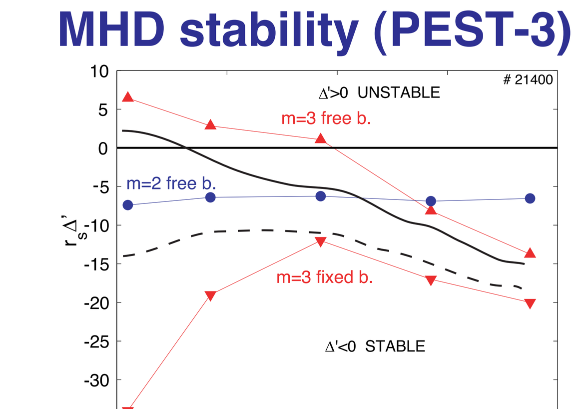
κ=1.3, δ=0.2 (weak shaping)

MHD modes: 3/1 -> 2/1



ext.-mode with m/n=3/1~q_a
—> coupling to int. mode 2/1

MHD stability (PEST-3)



- Δ'-stab predicts 2/1 stable in I_p-ramp
- Thus wall stabil. of the 3/1 mode is essential to avoid destab. of 2/1 by 2/1

- 2/1-Δ'-stability does not improve, even deteriorates towards high κ!
- Essential role of mode coupling (from exp. and th.)
- Thus other mechanisms acting like wall stab. of external mode 3/1,
  - and coupling with higher q integer vacuum flux surfaces q= 4, 5, ...

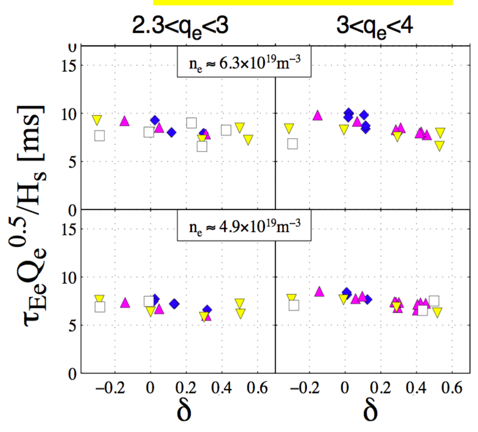
1 University of Warwick, UK 2 Keldysh Institute, Moscow, RF 3 General Atomics, San Diego, CA, US 4 IPP Garching, Germany 5 CEA-Cadarache, France 6 RRC Kurchatov Institute, Moscow, RF

... from plasma Shaping Experiments in the TCV tokamak

5. Confinement and geometry

Ohmic confinement at medium densities ($\nu_{eff} \sim 2.5$-10)

- Strong τ_{Ee} increase with κ, (κ<~2.3)
- Mild decrease with δ (δ>0)



Is geometry sufficient to explain?

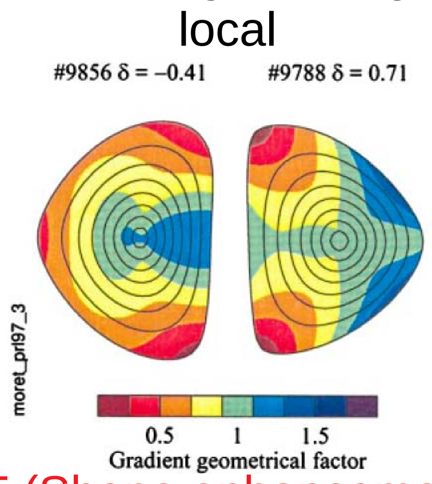
Moret PRL97, Weisen NF97

Heat transp Q_e (shape geom., flux surf. averaged T_e-gradients)

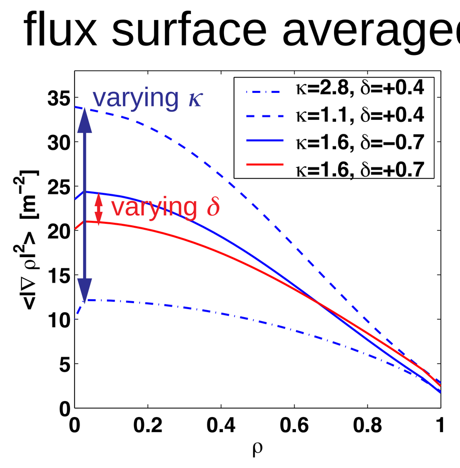
$$Q_\alpha = -n_\alpha \chi_\alpha \left\langle |\nabla \rho|^2 \right\rangle \frac{\partial T_\alpha}{\partial \rho}$$

gradient geometrical factor

local — flux surface averaged



Moret PRL97

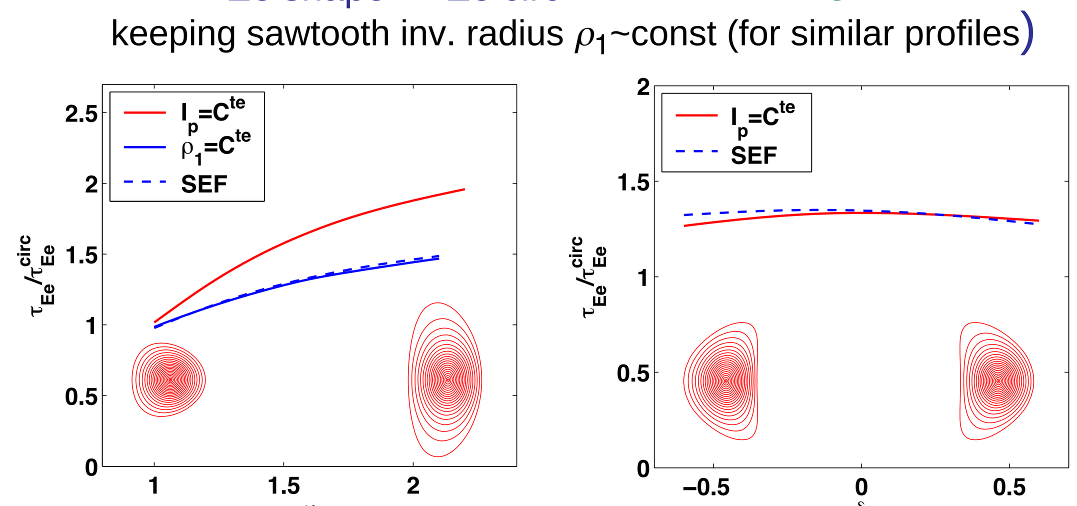


Camenen thesis06

The SEF (Shape enhancement factor) evaluates the part of τ_{Ee}-variation due to the geometrical shape factor, keeping same diffusivity $\chi_e(\rho)$ (and $\nabla T_e(\rho)$)

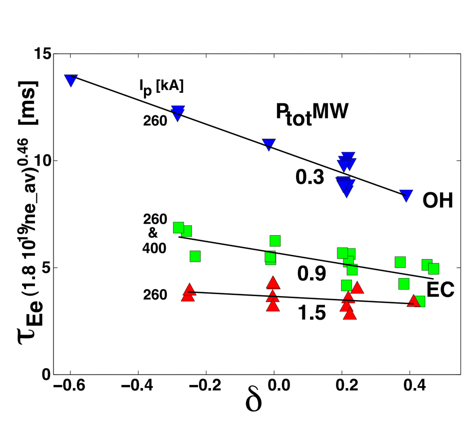
SEF=$\tau_{Ee\ shape}$ / $\tau_{Ee\ circ}$ with same χ_e (ASTRA)

keeping sawtooth inv. radius ρ_1~const (for similar profiles)



SEF adequately accounts for τ_{Ee}-variations with shape in OH medium density discharges ($\nu_{eff} \sim 2.5$-10)

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



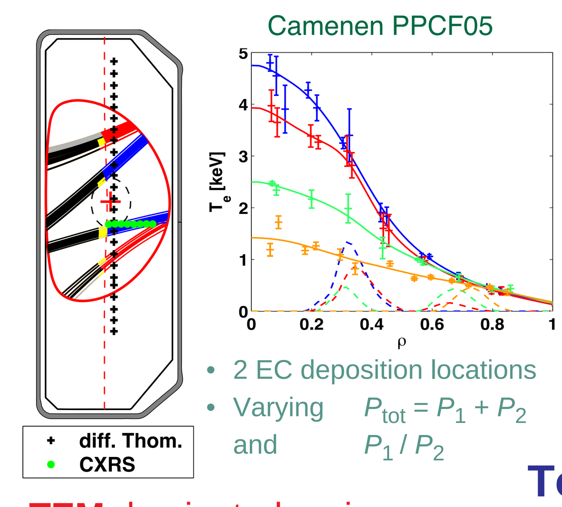
Central ECH and covering a large δ-range: $-0.6 < \delta < +0.5$

- Strong $\tau_{Ee}(\delta)$ dep. found, asymmetrical in δ, unlike SEF
- No more explained by SEF only: χ_e *must vary with* δ.

Pochelon EPS99 — Coda 98, Pochelon NF99, Weisen NF98

6. Electron heat transport versus shape and collisionality

T_e, gradT_e-variation expts



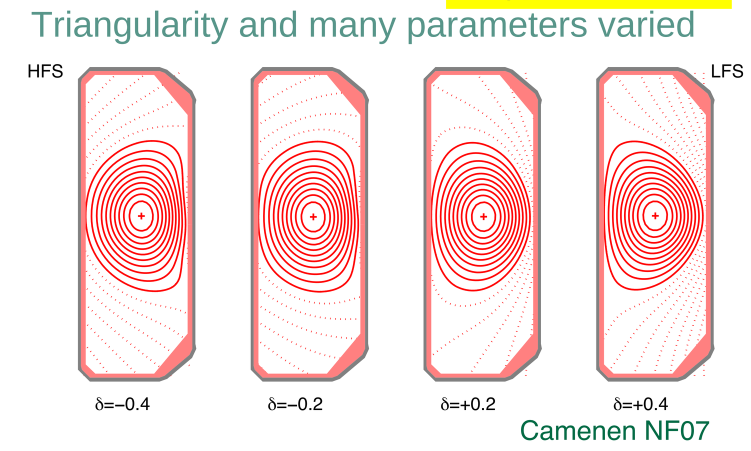
Camenen PPCF05

- diff. Thom.
- CXRS
- 2 EC deposition locations
- Varying $P_{tot} = P_1 + P_2$ and P_1 / P_2

TEM dominated regime (no ETG in 0.2<ρ<0.7 range, due to high Z_{eff} & high T_e/T_i)

Triangularity scan ($\nu_{eff} \sim 0.1$-1)

Triangularity and many parameters varied

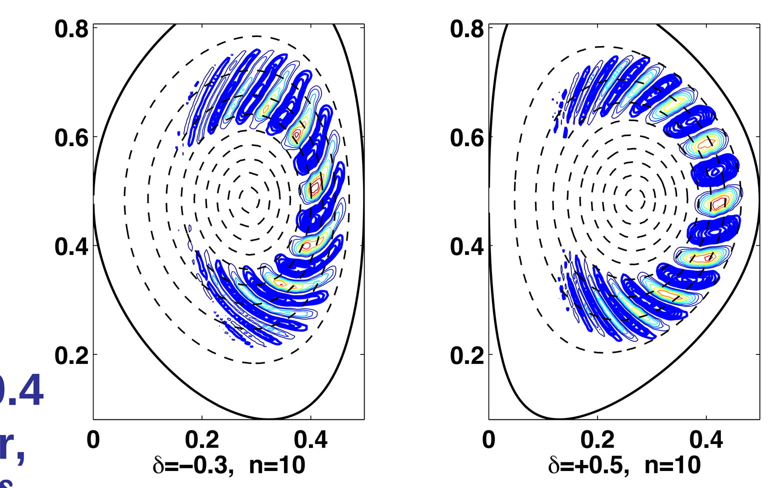


Camenen NF07

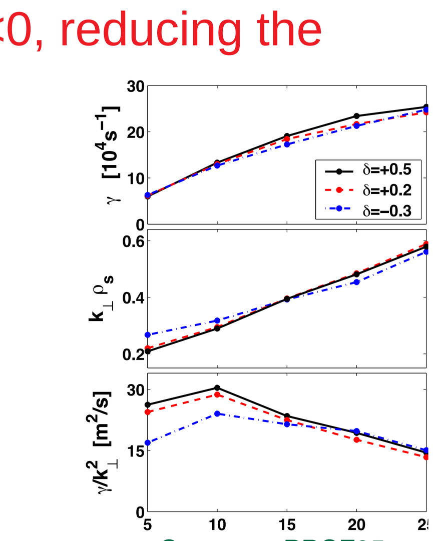
To sustain the same pressure profile at δ=-0.4 than at δ=+0.4 demands only half the power, due to the reduction of χ_e toward negative δ.

Gyrokinetic simulations linear, global (LORB)

δ = - 0.3 — Camenen NF07 — δ=+0.5



larger $k_\perp$ at δ<0, reducing the mixing length transport $\gamma/k_\perp^2$ at low n



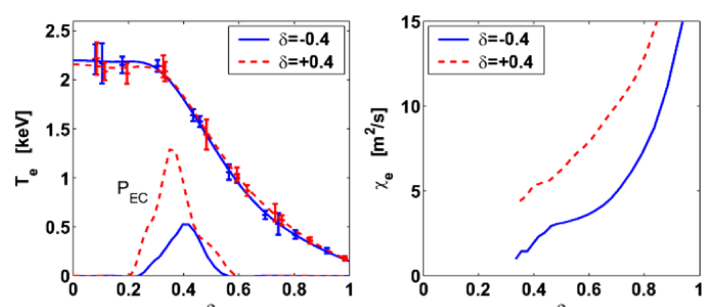
Camenen PPCF05

Collisionality ν_{eff}

Camenen PPCF05

- χ_e-depends on collisionality ν_{eff}, rather than on e.g.: T_e, n_e, or R/L_{Te}, with ν_{eff}= 0.1R n_e Z_{eff} / T_e^2 = ν_{ei}/ω_{De}, where ω_{De} = curvature drift frequency.
- and χ_e decreases with collisionality ν_{eff}

Angioni PoP03

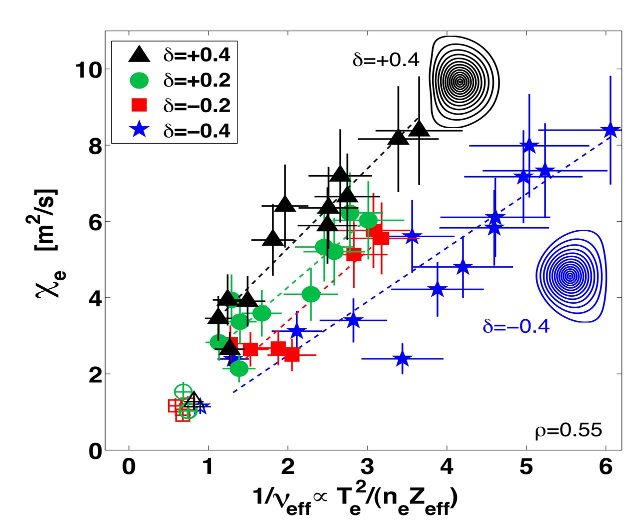


- As good as H-mode...

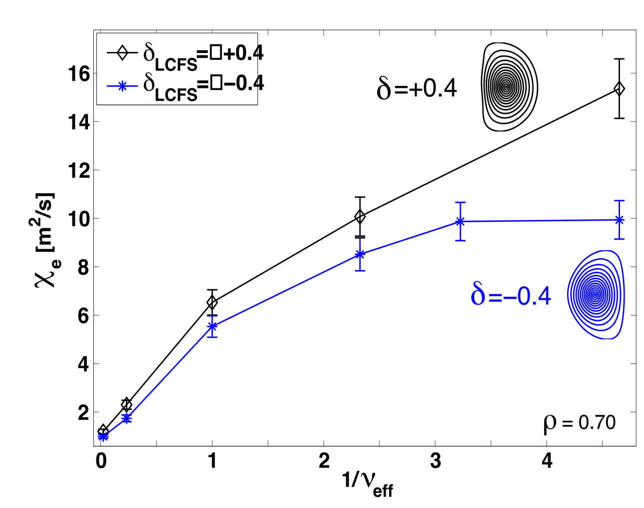
Camenen PPCF05, Thesis06, NF07

Triangularity and collisionality dep. (in TCV L-mode, TEM-dominated)

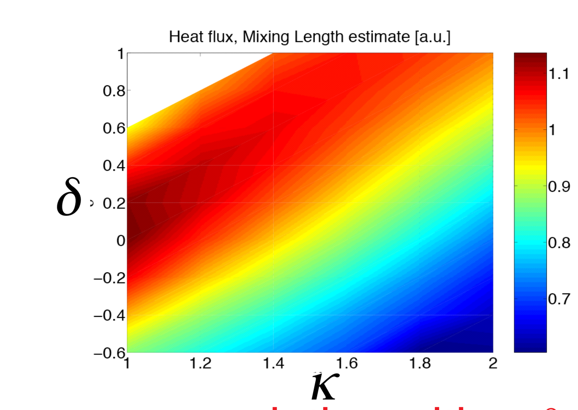
Camenen NF07



Non-linear gyrokinetic local collisional (GS2)



Marinoni subPPCF 08 — **GS2 linear**



$\chi_{e\ ml}$ -variation with κ,δ

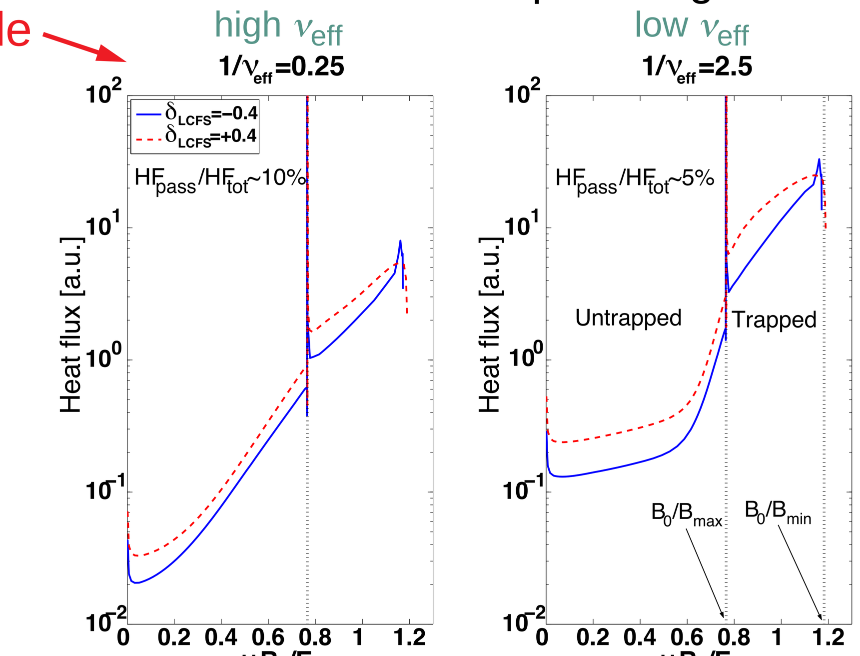
Marinoni subPPCF 08

Transport simulations reflect exp. χ_e in TEM regime:

- decrease of χ_e towards high ν_{eff} and negative δ
- triangularity effect on χ_e smaller at high ν_{eff}, see also vs. pitch-angle
- but disagree for the radial dependence: possibly a global effect.

GS2 non-linear

heat flux versus pitch angle



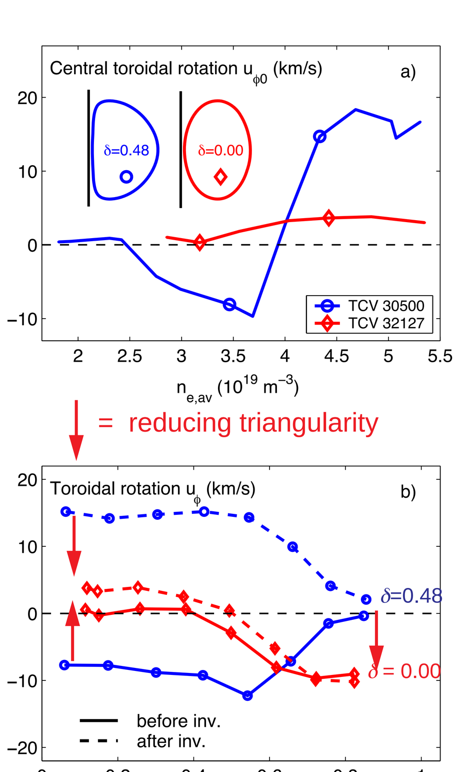
Marinoni subPPCF 08

Linear and non-linear GK simulations of heat transport

- Negative triangularity
  1) modifies the resonance between the toroidal precessional drift frequency of trapped electrons and the mode frequency, *reducing the growthrate γ of the mode*
  2) enhances the local shear, *increasing $k_\perp$ of the mode*.
- Shapes effects on χ_e and τ_{Ee} depend on collisionality
- Collisionality unifies the description of OH & EC transport (different ν_{eff})

7. Innovative ideas, prospects, e.g.

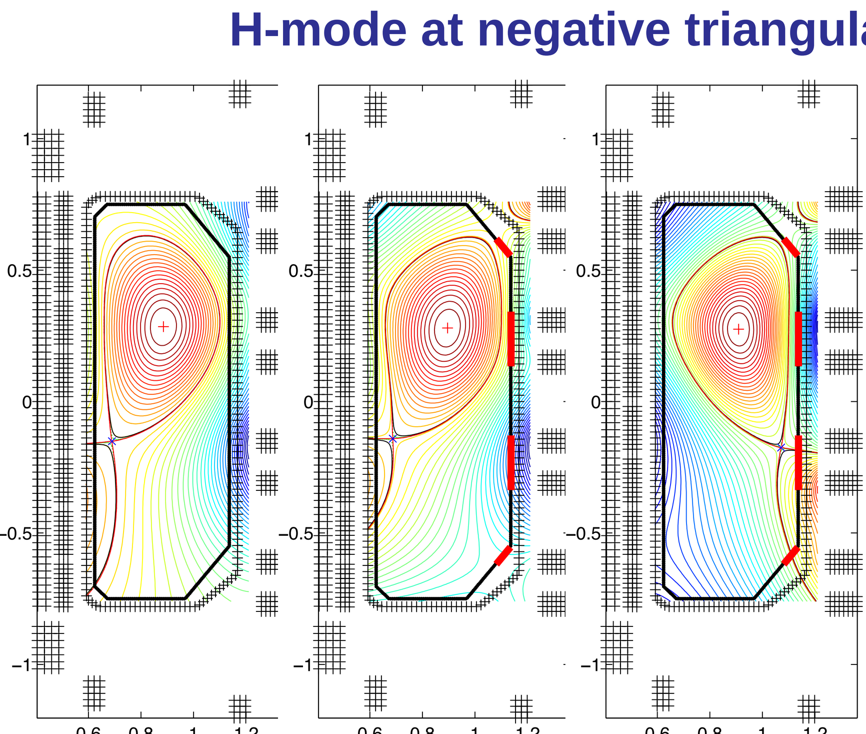
Rotation inversion vs. n_e is shape dependent



Shaping, by changing χ_e, T_e, T_i , T_e/T_i, Z_{eff}, wall-contact, etc... , gives an opportunity for untangling the underlying physic, in particular the change of dominant TEM turbulence with ν_{eff}.

Bortolon PRL06 Duval PPCF07 PP08

H-mode at negative triangularity



Medvedev EPS 08

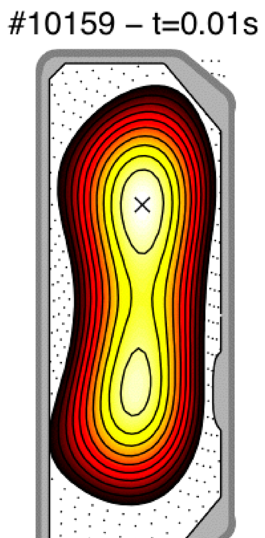
To study the effect of shape on:
- confinement,
- transport,
- ELM/quiescent regime,
- pedestal,
- β-limit & RWM at low power with ECH X3

eITB at negative triangularity: better?

Transport with κ, will depend on ν_{eff} and instability ...

Doublet

#10159 – t=0.01s

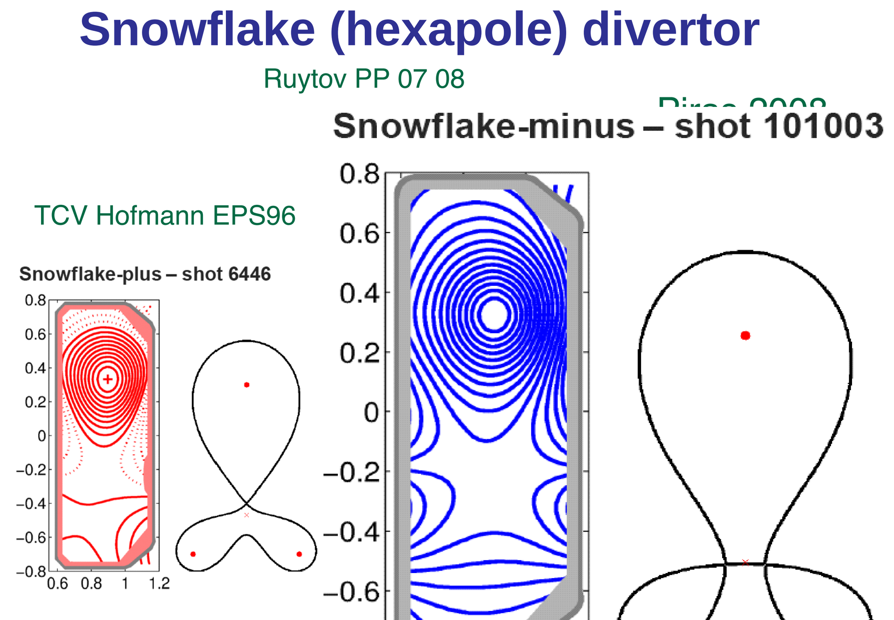


Doublet shape

Hofmann EPS 96

Snowflake (hexapole) divertor

Ruytov PP 07 08



8. Conclusions

- **TCV plasma shaping** acts as a stringent **test bench for theories**, validation of models, by gradually changing parameters and extending their covered range .
  - **MHD:** Sawtooth period/internal kink stability: stabilized by ±δ, destabilized by high κ
  - Supression of q~3 ramp-up disruptions by plasma shaping: role of mode coupling (3/1 —> 2/1) and wall stabilization (of q~3, 4, 5...)
  - **Heat transport:** Dominant role of geometrical factor (SEF) at high ν_{eff}, important for κ-changes
  - Transport **improves by a factor 2** in L-mode from δ =+0.4 to δ =-0.4 at low ν_{eff}
  - Central role of collisions, modifying χ_e with shape (here triangularity)
  - Negative triangularity physical effect: **1)** role of **shear (increasing $k_\perp$)** and **2) trapped e$^-$ toroidal precession versus TEM mode frequency (decreasing γ of the mode)**
  - Thus, **shape effects on confinement & transport depend on collisionality,** which determines the dominant micro-instablity type and transport associated
  - exploration of - heat, momentum, particle transport - with shape
- **Further shape studies:**
  - ***Systematic exploration of plasma shape effects on* H-mode properties** (also at *negative triangularities*: test of models over broader range of shapes)
  - **improved eITB** properties at negative triangularity with lower transport?
  - **impurity, particles** transport with elongation and triangularity
  - **divertor** with low shear to reduce heat load and study transport
- **Shape is related to vital issues in ITER and to concept improvement in view of DEMO**

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