1. Motivations

WHY STUDY also SHAPES different from ITER?
• Test of MHD and transport theory
• Negative triangularity improves confinement
• Confinement scales with \( I_n \), \( \beta_n \), \( \beta_B \) and fast ions, and \( I_{\text{max}} \) 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 \( \kappa \), triangularity \( \delta \), including negative, squareness
• aspect ratio R/a
• limited / divertor 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 containment 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 plasma scenario, e.g.: *e.g. sawtooth period \( \tau_{\text{ST}} \) depends strongly on plasma shape\r

2. TCV facility & Shaping achievements

Flexible plasma shaping ... matched by a flexible heating system, entirely based on ECRH
16 independent shaping coils

vertical stability requires broad current profiles

operational diagram limited by:
\( n=0 \) : vertical instability
\( n=1 \) : external kink \( \beta \)-limit

current limit at high \( \kappa \)

Ideal MHD predicts the current limit

Flexible plasma shaping

2. MHD and stability: \( q=1 \) sawteeth

- elongation
- Optim. of devices beyond ITER, innovative shapes
- Test of MHD and transport theory

- \( q=1 \) radius scaling: studied over a large \( \kappa \)-range

- Sawtooth period/stability central ECH (1.1<<2.1 and -0.2<<0.5)


- Sawtooth period/stability for -0.6<<0.3, OH...


- Sawtooth disappearance at high \( \kappa \)


- \( \kappa \)-limit depends strongly on plasma shape


- the limiting pressure inside \( q=1 \) is determined by shape

- \( \tau_{\text{ST}} \) follows ideal internal kink stability

- parallel to Mercier ideal stability over this shape range

- both triangularity signs are stabilizing (shorter sawteeth)

- \( \kappa \) and \( \delta \) show the same behaviour with \( \delta \) (min. close to \( \delta \approx -0.3 \))


3. MHD and stability: \( q=3 \) disruptions reduced by shaping, \( \kappa \)

\( q=3 \) disruptivity reduced by shaping

Twisted multi-separatrix ECH

\( \kappa \) and \( \delta \) shape

\( \kappa \) and \( \delta \) shape

\( \kappa \) and \( \delta \) shape

4. MHD & stability: modes & disruptions

\( q=3 \) disruptivity reduced by shaping

Disruptivity (disr./s) in Hugill diagram vs. \( \delta \) and \( \kappa \)

low disr./s-blue, high disr./s-red

\( q=3 \) high density distr. notch stabilized by \( \kappa, \delta \)-shaping

\( q=3 \)-events: 3 shape ranges: low, medium, high disrupt.

MHD modes leading to disruption

- 2/1: dominant mode leading to disruption.

- Locking of 3/1 to 2/1 correlates with the 2/1 becoming disruptive.

- Shaping reduces the 3/1 external mode \( \kappa=1.3, \kappa=0.2 \text{ (weak shaping) } \)

MHD modes: 3/1 & 2/1

- \( \kappa \)-stab predicts 2/1 stable in \( \kappa \)-ramp

- Thus wall stab. of the 3/1 mode is essential to avoid destab. of 2/1 by 2/1 & 3/1.

- 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 \( q=4,5, \ldots \)
5. Confinement and geometry

Ohmic confinement at medium densities ($v_{\text{eff}} \approx 2.5-10$)
- Strong $T_e$ increase with $\kappa$ ($\kappa \approx -2.3$)
- Mild decrease with $\delta$ ($\delta > 0$)

Is geometry sufficient to explain?

Heat transp: $Q_0$ (shape geom., flux surf. averaged $T_e$-gradients)

The SEF (shape enhancement factor) evaluates the part of $\tau_E$ variation due to the geometrical shape factor, keeping same diffusivity $\chi_E$ ($\kappa$) and $\tau_T$ ($\delta$)

SEF = $\text{shape}/\text{flux surf. av}$ with same $\chi_E$ (ASTRA)

keeping sawtooth inv. radius $\rho_s$ - const (for similar profiles)

SEF adequately accounts for $\tau_E$ variations with shape in OH medium density discharges ($v_{\text{eff}} \approx 2.5-10$)

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

Central ECH and covering a large $\delta$-range: $-0.6 < \delta < +0.5$
- Strong $\tau_E(\delta)$ dep. found, asymmetrical in $\delta$, unlike SEF
- No more explained by SEF only: $\chi_E$ must vary with $\delta$

6. Electron heat transport versus shape and collisionality

$T_e$ grad $T_e$-variation exps

Triangularity scan ($v_{\text{eff}} \approx 0.1-1$)

Triangularity and many parameters varied

Gyrokinetic simulations linear, global (LORB)

$\delta = 0.3$

Is $\tau_E$ at high $v_{\text{eff}}$ independent of $\delta$?

Transport with $\kappa$ and $\delta$ will depend on $v_{\text{eff}}$

Collisionality $\chi_E$

- $\chi_E$ depends on collisionality $v_{\text{eff}}$
- Rather than on $T_e$; $\tau_E$ and $R_L$ vary with $v_{\text{eff}}, 0.1 \times$ $\chi_E$, $T_{\text{eff}} \tau_E$ and $\kappa$

- $\tau_E$ varies with $\delta$ and $\kappa$

- As good as H-mode...

Transport simulations reflect exp. $\chi_E$ in TEM regime:
- Decrease of $\chi_E$ towards high $v_{\text{eff}}$ and negative $\delta$
- Triangularity effect on $\chi_E$: smaller at high $v_{\text{eff}}$
- But disagree for the radial dependence: possibly a global effect.

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 $\gamma$ of the mode
  2) enhances the local shear, increasing $k_\perp$ of the mode.

- Shapes effects on $\chi_E$ and $\tau_E$ depend on collisionality
- Collisionality unifies the description of OH & EC transport (different $v_{\text{eff}}$)

7. Innovative ideas, prospects, e.g.

Rotation inversion: $n_p$ is shape dependent

H-mode at negative triangularity

To study the effect of shape on:
- Confinement, transport, ELM/quesence regime, pedestal, $\beta$-limit & RWM at low power with ECH X3

$\tau_E$ at negative triangularity: better?

Transport with $\kappa$ will depend on $v_{\text{eff}}$ and instability ...

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 $\delta$, destabilized by high $\kappa$
- Suppression of $q=3$ ramp-up disruptions by plasma shaping: role of mode coupling ($3/1 \rightarrow 2/1$) and wall stabilization (of $q=3$, 4, 5, ...)
- Heat transport: Dominant role of geometrical factor (SEF) at high $v_{\text{eff}}$ important for $\chi$-changes
- Transport improves by a factor 2 in L-mode from $\delta = +0.4$ to $\delta = 0.4$ at low $v_{\text{eff}}$
- Central role of collisions, modifying $\chi_E$ with shape (here triangularity)
- Negative triangularity physical effect: 1) $\beta$-shear of $k_\perp$ and 2) trapped $e^-$ toroidal precession versus TEM mode frequency (decreasing $\gamma$ of the mode)
- Thus, shape effects on confinement & transport depend on collisionality, which determines the dominant micro-instability type and transport associated with collisionality:
- Exploration of - heat, momentum, particle transport - with shape
- Further shape studies:
  - Systematic exploration of plasma shape effects on H-mode properties
  - Impurity, particles transport with elongation and triangularity
  - Diverter 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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