Physics Insight from Plasma Shaping of TCV Tokamak Plasmas - focus on Electron Heat Transport

(TCV = Tokamak à Configuration Variable)

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1. Motivations for plasma shaping
2. TCV tokamak facility
3. Confinement and electron heat transport vs. shape
   3a. Confinement shape enhancement factor (OH, high collisionality)
   3b. Electron heat transport (ECH, low collisionality)
4. Conclusions on heat transport
5. Outlook on innovative divertors / shapes
1. MOTIVATIONS of SHAPE STUDIES

WHY STUDY also SHAPES different from ITER?

- Test and validation of MHD and transport theory
- New: negative triangularity *improves confinement* (in L-mode!)
- Confinement of $\tau_E$, $n_e$, $\beta$, fast ions... scales with plasma current $I_p$
  and $I_{p\,\text{max}}$ can be increased by plasma cross-section shaping
  *without increasing the magnetic field*
- Many other parameters depend on plasma shaping
- Reciprocally, active plasma shaping offers a way to control
  plasma parameters
- What plasma shape, what divertor for a device beyond ITER?
  to maximize performance, and reduce heat loads
Shaping variables

- elongation $\kappa$
- triangularity $\delta$, including negative (D- and inverse-D-shaped)
- squareness
- limited / various diverted, innovative geometry
- single plasmas / doublets plasmas ...
- beyond TCV: aspect ratio $R/a$

**TCV:**

\[ R = 0.88 \text{ m}, \ a = 0.25 \text{ m}, \ R/a \sim 3.5 \]
\[ B < 1.54 \text{T}, \]
\[ I_p \leq 1 \text{MA} \]

elongation \quad 0.9 < \kappa < 2.8
triangularity - 0.7 < \delta < 1

(reached parameters)
Many parameters, effects, are influenced by plasma shape

Direct influence of shape ...
• MHD stability sawteeth, modes, NTM, disruptions, TAEs, ELMs, ...
• Transport electron heat, momentum (particle...)
• Confinement pressure limits, edge transport barrier, performance

Indirect influence ...
• ELMs(shape) [can destroy ITBs (e.g. JET), etc...]
• Sawteeth(shape) [can trigger NTMs]

Dependence on the plasma confinement regime ...
• $\tau_E(\delta)$ increases towards negative $\delta$ in L-mode (through core transport)
  increases towards positive $\delta$ in H-mode (through pedestal height)
2. TCV FACILITY and SHAPING ACHIEVEMENTS

- **Limited**
  - $\delta = 0$, $I_p = 230\text{kA}$
  - $T = 1.5\text{s}$

- **SN upper**
  - $I_p = 330\text{kA}$
  - $T = 0.5\text{s}$

- **SN lower**
  - $I_p = 335\text{kA}$
  - $T = 0.3\text{s}$

- **DN**
  - $I_p = 325\text{kA}$
  - $T = 0.42\text{s}$

- **Highest squareness**
  - $\lambda = 0.5$
  - $I_p = 1.06\text{MA}$
  - $T = 0.67\text{s}$

- **Highest current**
  - $I_p = 230\text{kA}$
  - $T = 0.65\text{s}$

- **Highest fully ECCD driven current**
  - $I_p = 210\text{kA}$

- **Pear shape**
  - $I_p = 360\text{kA}$

- **Doublet shape**
  - $I_p = 115\text{kA}$

- **Highest elongation**
  - $k = 2.8$

- **Lowest triangularity**
  - $\delta = -0.77$

- **Snowflake**
  - $I_p = 230\text{kA}$
Flexible plasma shaping ... 
16 independent shaping coils 

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

Total: 4.5 MW at 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic
Cut-off densities: 4.2 \textsuperscript{19} m\textsuperscript{-3} and 11.5 \textsuperscript{19} m\textsuperscript{-3}

TCV FACILITY

X3 system (118GHz, 1.5MW)
Upper Lateral Launchers (4)

X2 system (82.7GHz, 3MW)
Equatorial Launchers (2)
3a. CONFINEMENT vs. SHAPE / Ohmic, high collisionality densities ($\nu_{\text{eff}} \sim 2.5-10$)

- $\tau_{\text{Ee}}$ increases strongly with $\kappa$
- Mild decrease with $\delta$, in $\delta>0$-range
- Interpretation in terms of a confinement Shape Enhancement Factor (SEF):

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

heat diffusivity: depends on collisions, shape, etc...

gradient geometrical factor, expresses flux surfaces sep., metric term

Moret PRL97, Weisen NF97
Gradient geometrical factor

Gradient geometrical factor

local

#9856 $\delta = -0.41$

#9788 $\delta = 0.71$

fluct surface averaged

$\kappa = 2.8$, $\delta = +0.4$

$\kappa = 1.1$, $\delta = +0.4$

$\kappa = 1.6$, $\delta = -0.7$

$\kappa = 1.6$, $\delta = +0.7$

Moret PRL97
SEF: when confinement only due to flux surface separation ($\chi_e=$cst)

$\tau_{Ee}$ shaped plasma / $\tau_{Ee}$ circular plasma with same $\chi_e$ (ASTRA calculations)

![Graph showing comparison between shaped and circular plasmas with SEF]

Important to keep sawtooth inv. radius $\rho_1$~const (self-similar profiles)

SEF found adequate to account for $\tau_{Ee}$ variations with shape in OH, at medium densities

Camenen thesis06
ECH confinement at low densities ($\nu_{\text{eff}} \sim 0.2-1$)

Central ECH, large $\delta$-range, positive and negative triangularity

- Strong $\tau_{\text{Ee}}(\delta)$ dependence, improvement towards $\delta<0$
- Asymmetry in triangularity not explained by SEF alone:
  $\rightarrow$ does also $\chi_\varepsilon$ vary with shape?

Coda 98, Pochelon NF99, EPS99, Weisen NF98
3b. ELECTRON HEAT TRANSPORT vs shape / EC low $n_e$ ($\nu_{\text{eff}} \approx 0.2-1$)

$T_e$-variation, grad$T_e$-variation experiments

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

Camenen PPCF05
Microinstability types in EC plasmas

Type of micro-instabilities (GLF, LORB)

EC plasmas:
High \( R/L_{Te} > 7 \), in high \( T_e/T_i \),
low collisionality:

**TEM** dominated regime

(no ETG in \( 0.2 < \rho < 0.7 \) range, due to high \( Z_{eff} \) & high \( T_e/T_i \))

Camenen PPCF05, Thesis06
Collisionality effect demonstrated

- The effect of $T_e$, $n_e$, $Z_{\text{eff}}$, when combined, show a clear dependence of $\chi_e$ on collisionality $\nu_{\text{eff}}$
- $\nu_{\text{eff}} = 0.1 R n_e Z_{\text{eff}} / T_e^2$
  $= \nu_{\text{ei}}/\omega_{\text{De}}$  De: curvature drift
- Diffusivity $\chi_e$ reduces with increasing collisionality

Camenen NF07
How to decrease transport by a factor 2 in L-mode?

1) change triangularity from positive to negative:
   \[ \delta = +0.4 \rightarrow -0.4 \]

2) adapt additional power to keep the same \( T_e, n_e \) and \( q \)-profiles
   \[ \rightarrow \text{Result: heat transport is halfed at mid-radius,} \]
   an effect of negative triangularity

Camenen NF07
Shape and collisionality effects separated

• Collisionality lowers $\chi_e$
• At same $\nu_{\text{eff}}$, negative $\delta$ reduces $\chi_e$
• At high $\nu_{\text{eff}}$, vanishing $\delta$-effect
• Taking account of collisionality $\nu_{\text{eff}}$ explains the different $\delta$-dependence of OH and EC data

Camenen NF07
Global TEM micro-instabilities simulations

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

Camenen PPCF05

Electrostatic potential fluctuations

Negative $\delta < 0$:  
- stronger tilt of eddies at LFS equator!  
- higher $k_\perp$  
- lower mixing-length transport

$\delta = -0.3, \ n = 10$  
$\delta = +0.5, \ n = 10$
**GS2 linear, local, gyrokinetic calculations**

χe mixing length as a function of (κ, δ)

GS2 (gyrokinetic, linear, local)

As in above δ–scan expts, χ_e_{GS2} reduces monotonically towards δ<0

Marinoni PPCF 09
GS2: local, non-linear gyrokinetic calculations, with collisions

**Effect of shape and collisionality**

**GS2**

\[ \chi_e \propto \frac{1}{\nu_{\text{eff}}} \]

\[ \rho = 0.55 \]

\[ \delta = 0.4 \]

\[ \delta = -0.4 \]

**TCV**

\[ \chi_e \propto \frac{T_e^2}{n_e Z_{\text{eff}}} \]

\[ \rho = 0.55 \]

\[ \delta = 0.4 \]

\[ \delta = -0.4 \]

Marinoni PPCF 09

Transport simulations reflect experimental \( \chi_e \) in TEM regime:

- decrease of \( \chi_e \) towards high \( \nu_{\text{eff}} \) and negative \( \delta \)
- triangularity effect on \( \chi_e \) smaller at high \( \nu_{\text{eff}} \)
- but disagree for the radial dependence: possibly a global effect.
$T_e$-fluctuations decrease with collisionality (corr-ECE diag.)

fluctuation spectra decrease with density
Ohmic, $q \sim 10$, $\kappa \sim 1.4$, $\delta \sim 0.3$

fluctuation amplitude $\left( \frac{\delta T_e}{\langle T_e \rangle} \right)^2$
averaged over $<30\text{-}130\text{kHz}>

$T_e$-fluctuations amplitude decrease with collisionality $\nu_{\text{eff}}$

- $\rho = 0.55$ on LFS equator
- $n_e$ increasing

Udintsev & Fable US-TTF09

de Meijere: talk 15h (534, in place of 504)
More on turbulence measurements in TCV
Fluctuation amplitude decrease with $\nu_{\text{eff}}$, as predicted by GS2

$T_{e-}$ & $n_{e-}$-fluctuations from GS2 decrease with $\nu_{\text{eff}}$ (as in experiment)

$\chi_{e-GS2}$ decreases with $\nu_{\text{eff}}$, as $\chi_{e-PB}$ from experiment

consistent with TEM ampl. reduction with collisions ($e^-$ collisional detrapping)

Udintsev, Fable US-TTF09
Evaluating turbulence correlation length with «corr-ECE diag»

Change of eddy geometry with triangularity
to be measured by correlation-ECE measurements

How close/different are the experimental results
to the linear (or non-linear) global gyrokinetic calculations?
4. CONCLUSIONS on heat transport / shape

- **Role of metric** (flux surface separation)
  SEF, evidenced at high $\nu_{\text{eff}}$ (where $\chi_e$ weakly dependent on shape)
  Confinement improves with elongation

- **Role of collisionality ($\chi_e$)**
  Effect of collisionality evidenced varying triangularity (where SEF~const.)
  At low $\nu_{\text{eff}}$, $\tau_e$ and $\chi_e$ are not found symmetric in $\delta$,
  Confinement improving towards negative $\delta$ (in TEM dom. transp.)

- **TEM dominated transport**
  - $\chi_e$ decreases with $\nu_{\text{eff}}$ (electron de-trapping)
  - $<\delta T_e/T_e>^2$ decreases with $\nu_{\text{eff}}$
  - role of triangularity in (de)tuning resonance between $\omega_D$ and $\omega_{\text{TEM}}$
  - global GK calculations show larger $k_\perp$ at $\delta<0$, thus smaller $\chi_{e_{\text{ml}}} \sim \gamma/k_\perp^2$
    - an effect of magn. curvature & Shafranov shift
  - to be identified at the turb. level (e.g. corr-ECE)
5. OUTLOOK on INNOVATIVE SHAPES: 5.1 Snowflake divertor

On the search of reduction of divertor power heat loads:

- standard quadrupole null $\rightarrow$ hexapole null (= SF divertor)

- larger magn. flux expansion (factor 2-3 over standard X-point) $\rightarrow$ heat load reduction

- increased magnetic shear $\rightarrow$ improves edge ideal stab., change ELM and H-mode properties?

Pitzschke: next talk 502 on edge ideal-MHD stability

Ryutov PP 07 08
Snowflake divertor concept first tested in TCV

Investigation of SF and neighbour configurations (SF+, SF, SF-) :
- distrib. of power on div. legs
- distrib. of power on the walls
- maximisation of radiation power
- H-mode properties ...

Piras PPCF 09
5.2 Towards H-mode at negative triangularity

To learn more about H-mode properties by extending to negative triangularity:

from MHD modeling:
- pedestal seems lower
- smaller ELM regimes?
- $\beta$-limit & RWM studies at lower power with ECH X3

Medvedev EPS09
5.3 Doublet configuration: an innovative shape, a divertor concept?

... on the search of configurations - with good confinement and enhanced edge radiation properties - quiescent edge in H-mode scenarios...

a possible scenario (model calculation)

double ECH breakdown using 2 gyrotron beams (Piras July 2009)

... under development at TCV
TCV, a flexible, variable shape tokamak
to develop new shapes
to improve models

for concepts improvement
and for ITER

Thank you
CRPP-Lausanne talks / Plasma Physics Session

- 14h30, 502
  Pitzschke
  MHD stability calculations for H-mode plasmas with Snowflake divertor configuration

- 15h00, 534 (repl. 504)
  de Meijere
  Measurements of electron density fluctuations in TCV

- 17h00, 508
  Furno
  Turbulence and transport in TORPEX

- 17h15, 509
  Federspiel
  Observation of a critical pressure gradient for the stabilization of interchange modes in TORPEX
SPARES
Stability limits (Ohmic)

Using high $I_N$, elongation up to $\kappa=2.8$

Operation at high $\kappa$ limited by
$n=0$ vertical instability $\rightarrow$ broad $j(r)$ required: low-$q$, high-$I_N$ + fast int. coil
$n=1$ external kink $\rightarrow$ high current limit ($I_N$ & $\beta$-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 $\kappa=2.5$ at $I_N \sim 1$

off-axis ECH power at constant quadrupole field $\rightarrow \kappa$ increase

Pochelon NF01, Camenen NF07, Paley PPCF07
Current limit at high $\kappa$

Ideal MHD predicts correctly the current limit as often, resistive modes ($m/n = 4/3, 3/2, 2/1$) are found just below the ideal limit.

Current limit at high $\kappa$

Shape influences the $\beta$-limit

Hofmann PRL97
However, more power is needed to test the $\beta$-limit in various TCV shapes —> foreseen to double the installed X3 power

$\beta$ reached at $\kappa \sim 1.6$
with 1.5MW X3

TCV provides the highest $\beta$-values in the inter-machine spontaneous rotation database (J.Rice NF07)

Hofmann PPCF01

Porte NF07, Alberti JoPh05, Pochelon SMP05