Integrated Improved Performance with Negative Triangularity

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Outline

• Negative triangularity: a long history for TCV
• Effects on core and edge profiles
• Improved confinement
• Gyrokinetic simulations
• Pedestal pressure predictions
• Towards a NTT-Demo?
(κ, δ) effects on MHD and confinement
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\[ \beta_N = \frac{\beta[\%]}{I_p/\alpha B_0} \]

- Troyon limit:

[O. Sauter, 24th EFPW, Poland, Nov. 2016]
(κ, δ) effects on MHD and confinement

TCV design calculations: prediction

- Troyon limit: \[ \beta_N = \frac{\bar{\beta} \text{[\%]}}{I_p / a B_0} \]
- TCV design: \( \beta_N \) decreases for \( \kappa > 2.5 \) before \( q_{95} = 2 \)

[F. Troyon et al., PPCF (1984)]
[A. Turnbull et al., NF (1988)]
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- TCV results: \( \beta_N \) does decrease for \( \kappa > 2.2 \) before \( q_{95} = 2 \)

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[F. Hofmann et al., PRL (1998)]
(κ, δ) effects on MHD and confinement

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[F. Hofmann et al., PPCF (2001)]
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TCV: Shape enhancement factor explains most confinement improvements at high kappa, negative delta

$$H_s \propto \frac{dr}{d\psi} \nabla \psi$$

#9856 $\delta = -0.41$  #9788 $\delta = 0.71$

[J.-M. Moret, et al., PRL (1997)]
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- TCV results: \( \beta_N \) does decreases for \( \kappa > 2.2 \) before \( q_{95}=2 \)
- TCV: \( \tau_{Ee} \sim (-\delta) \)

\[
\begin{align*}
& q_a = 2.4 \rightarrow 3.1 \\
& q_a = 3.3 \rightarrow 3.9 \\
& n_e = 8.2 \times 10^{19} \text{m}^{-3} \\
& n_e = 6.4 \times 10^{19} \text{m}^{-3} \\
& n_e = 5.0 \times 10^{19} \text{m}^{-3}
\end{align*}
\]

- TCV: improv. saturates at high \( \kappa \)

[J.-M. Moret, et al., PRL (1997)]
(κ, δ) effects on MHD and confinement

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- TCV results: \( \beta_N \) does decreases for \( \kappa > 2.2 \) before \( q_{95} = 2 \)
- TCV: \( \tau_{Ee} \sim (-\delta) \)
- All shapes overlay essentially
- TCV: improv. saturates at high \( \kappa \)

[J.-M. Moret, et al., PRL (1997)]
Improved conf. at negative triangularity

- Ohmic and EC heated L-modes show improved conf at high coll.

[Y. Camenen, et al., NF (2007)]
Improved conf. at negative triangularity

- Same profiles at half the power for $\delta<0$
  - Factor 2 global confinement improvement

[Y. Camenen, et al., NF (2007)]
Collisionality dependence

- Main difference at low collisionality (when TEM more dominant?)

[Y. Camenen, et al., NF (2007)]
Highly resolved measurements of $T_e$ and $n_e$ profiles localise changes of gradients and scale lengths

- Center dominated by sawtooth
- Core by stiffness
- Edge gradients increase with $I_p$ ($P$, $n_{el}$, …)

[O. Sauter, et al., PoP (2014)]
Highly resolved measurements of $T_e$ and $n_e$ profiles localise changes of gradients and scale lengths

- Linear with $\rho_v$ in edge region
- Gradient increasing with $I_p$, $P$, $n_{el}$, …
“Core” profiles also remain stiff with $\delta$ modifications

- Same input power with positive and negative $\delta$ with good radial resolution
- Almost whole profile self-similar…except edge (next VG)

[O. Sauter, et al., PoP (2014)]
Role of edge for $\delta$ effects on transport

- $T_e(\rho_v=0.8)$ increases with negative $\delta$ because of increased gradient in edge region 0.8-1.0
- Consistent with previous simulations (Marinoni et al)

[O. Sauter, et al., PoP (2014)]

O. Sauter, 24th EFPW, Poland, Nov. 2016
Nonlinear local gyrokinetic simulations at $\delta<0$

- Ratio of $\chi_e$ between positive/negative $\delta$ explained outside $\rho=0.7$

[A. Marinoni, et al., PPCF (2009)]

O. Sauter, 24th EFPW, Poland, Nov. 2016
Relative density fluctuations are lower at negative $\delta$

- Reduction of turbulence with $\delta_{\text{LCFS}} < 0$, confirmed by extensive Phase Contrast Imaging measurements

[Z. Huang et al. Proceedings 41th EPS Conf.(2014)]
Equilibrium effects with change in delta

- Elongation “penetration” or shear different for diff. edge $\delta$

[A. Marinoni, et al., PPCF (2009)]
Equilibrium effects with change in delta

- $q$ and $\delta$ profiles are related

- Main changes for $f_t$ and Shafranov shift

$\delta$ effects on $f_t$ reproduced by new formula in [O. Sauter, FED 2016]
Role of $\delta$ revisited with local gyrokinetics

- No change in core
- $\delta<0$ better at outer radii
- Less stiff near edge
- Linear critical gradients increase with decreasing $\delta$

[G. Merlo, et al., PPCF (2015)]
Link between core and edge and stiffness

- How to get same profiles with $\frac{1}{2}$ power with $\delta<0$?
- Local runs hint towards change in critical gradients near the edge
- Local runs not sufficient to explain experimental heat fluxes
Simulation tool

Inclusion of finite machine size effects appears to be the key missing element. Finite $\rho^*$ expected to:

1. Capture the effect of negative $\delta$ at all radii
2. Reproduce the experimental transport level

Second goal very challenging (profile stiffness vs. computational cost), the first can be met even if the second is not.


The GENE code (http://genecode.org):

- Eulerian nonlinear gyrokinetic code.
- Arbitrary number of species.
- Radially local and global approaches.
- Electrostatic and electromagnetic fluctuation (here only $A_y$).
- Linearized Landau-Boltzmann collision operator.

All following simulations are global, electromagnetic ($\exp. \beta$), collisional, carried out considering fully gyrokinetic ions and electrons with realistic mass ratio and assuming experimental plasma geometry.

Grids up to $n_z \times n_x \times n_{ky} \times n_z \times n_y \times n_\mu = 3 \times 512 \times 96 \times 32 \times 110 \times 48$ points.

Global simulations – full radius

- Less agreement than only core results.
- Highly unrealistic deposition profiles.
- Need to include carbon impurities.
- Core very sensitive to electron density gradient.

416x48x32x140x68 = $10^{10}$ grid-points per species
$dt = 10^{-4}$

[G. Merlo, PhD (2016)]
Global simulations – change discharge

- Consider experimentally better diagnosed easier than playing with the profiles. Available only a δ scan carried out at constant power.

- With C ongoing

\[\text{512x64x32x110x60} = \sim 10^{10} \text{ grid-points per species}\]
\[\text{dt}= 10^{-4}\]

[G. Merlo, PhD (2016)]

O. Sauter, 24th EFPW, Poland, Nov. 2016
Effect of carbon – local runs

Ion heat flux

\[ Q_i \cdot S[MW] \]

- No C
- No C + rotation
- C from Vloop
- C from CXRS

Electron heat flux

\[ Q_e \cdot S[MW] \]

- Inclusion of carbon suppresses ITG (ion channel) and lowers TEM (electron channel)
- Similar behaviour for other shape
Negative Triangularity Tokamak: NTT Demo

- For ITER, $\delta_l > 0$ and $\delta_u > 0$.
- For NTT, $\delta_l < 0$ and $\delta_u \simeq 0$. 
Advantages of NTT Demo

By moving the X-point to the low-field side (LFS) and thus to larger values of $R$,

+ The divertor wetted area is larger $\Rightarrow$ reduction of the heat flux
+ The magnetic field amplitude at the divertor coils is smaller $\Rightarrow$ allows innovative divertor concepts like the snowflake divertor
+ [TCV] Confinement is enhanced
+ [TCV] individual ELM losses are reduced
  - Plasmas are more vertically unstable
  - Scrape-off layer width is smaller in GBS simulations [Riva et al.]
TCV ELM$	ext{y}$ H-modes with negative $\delta_t$
TCV ELMy H-modes with negative $\delta_t$

- Type I ELMs from power dependence
- Negative $\delta$ increases ELM frequency and decreases relative ELM power loss

[A. Pochelon, et al, PFR (2012)]
Basic trend of pedestal height recovered by EPED-CH

Experimental data from TCV #43872 at \( t = 0.7 \) and 1.8 s

- EPED1 predicts a drop in \( T_{e,ped} \) of about 200 eV for \( \delta < 0 \)
- This is in qualitative agreement with the experimental data
- Effect of \( \delta \) only: both \( \overline{n_e} \) and \( n_{e,ped} \) are constant during the scan
- No reliable experimental measurement of the pedestal width (\( \Delta \))

[A. Merle et al, PPCF submitted, Varenna 2016]
Pedestal height/width versus triangularity

- Double scan in $\delta_u, \delta_l$ (analytical equilibria, no X-pt)

- $p_{ped}$ seems to depend mostly on the average $\delta = (\delta_u + \delta_l)/2$
- At constant $\delta$, $p_{ped}$ scales unfavorably with $|\delta_u - \delta_l|/2$
- $p_{ped}$ seem to reach a minimum when $\delta < -0.2$

[A. Merle et al, PPCF submitted, Varenna 2016]
Ideal limit is very different

[A. Merle et al, PPCF submitted, Varenna 2016]
No 2\textsuperscript{nd} stability region with negative $\delta$

Using standard pedestal stability analysis (fixed $\Delta$)

- Scale $p'$ and $I_\parallel$ independently in the pedestal region
- Compute finite-$n$ and infinite-$n$ stability boundaries

- The “nose” disappears for negative $\delta$, preventing access to the high $\alpha$ region. Linked with the absence of the second stability region for ballooning modes.

[S. Medvedev, NF 2015]
Thus little effect of beta on $p_{ped}(\delta<0)$

- Large beneficial effect of $\beta$ on $p_{ped}$ for $\delta > 0$
  $\Rightarrow$ linked with easier access to 2nd stability and “longer nose”
- $p_{e,ped}$ only weakly increasing with $\beta$ for $\delta < 0$

[A. Merle et al, PPCF submitted, Varenna 2016]
Conclusion: Integrated solution NTT demo

- $R_0=9m$, $a=3m$, $B_0=5T$, $I_p=15MA$
- $\delta_l=-0.85$, $\delta_u=0$, $\kappa=1.8$
- Stable up to $\beta_N=2.9$
- Compatible with low $p_{ped}$ ($\delta<0$) and $R/L_{Te}\sim10$

[M. Kikuchi et al., JPS Conf. Proc. 1 (2014)]
[S. Medvedev et al., IAEA (2016) ICC/P3-47]
Conclusion: Integrated solution NTT demo

• Potential for improved core transport with $\delta<0$
• Use “MHD” to limit upper bound => no single large events

• $R_0=9m$, $a=3m$, $B_0=5T$, $I_p=15MA$
  $\delta_1=-0.85$, $\delta_u=0$, $\kappa=1.8$
• Stable up to $\beta_N =2.9$
• Compatible with low $p_{ped}$ ($\delta<0$) and $R/L_{Te} \sim 10$