Safety factor impact on the radial electric field in gyrokinetic simulations
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Safety factor impact on the radial electric field in gyrokinetic simulations

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Acknowledgments:

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<table>
<thead>
<tr>
<th>D2.5</th>
<th>Report including statements on the relative impact of some separate ingredients playing a role in the radial electric field formation (orbit losses, ripple, turbulence, neutrals, limiter...)</th>
<th>report or paper submitted, conference contribution</th>
<th>X. Garbet, R. Varennes, L. Vermare, G. Falchetto, P. Donnel</th>
<th>12/2022</th>
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[R. Varennes – PRL 2022]
[R. Varennes – PPCF in resubmission]
+ presented in 8 conferences

| M2.9 | Study the development of a radial electric field in response to key parameters such as injected power, collisionality and safety factor, using the GYSELA and ORB5 codes including simplified limiter/SOL - comparison with fluid code results | L. Vermare, X. Garbet, R. Varennes, P. Donnel | 06/2022 |
Strong impact of plasma current on edge radial electric field in experiment

- Plasma current $I_P$ scan performed in WEST discharges
- $I_P \propto 1/q$
- $|E_r|$ ↗ at the edge when $I_P$ ↗ (observed in Tore Supra and MAST)
- Effect more significant in USN compared with LSN

What are the mechanisms at play?

Robin Varennes, TSVV Workshop, 27-28 September 2022
GYSELA as a tool to assess the safety factor effect

GYSELA: kinetic code solving

Fokker-Planck: \[ \frac{dF}{dt} = C(F) \]

Poisson: \[ \varepsilon_R \nabla^2 \phi = - \sum_{\text{species}} e \int F d^3 v \]

Does GYSELA contain enough physical ingredients to retrieve the deepening of \( E_r \) when \( q \) decreases?

[V. Grandgirard – CPC 2016]
Simulations to isolate the effect of the safety factor

- Reference simulation $q_{1.0}$ close to Tore Supra #45511 discharge
- Supplementary simulations $q_{0.5}$ / $q_{1.5}$ to isolate only the effect of the safety factor
- As in WEST experiments, same magnetic shear in all simulations
Same trend as the experiment retrieved on the radial electric field

- Simulations run for ~ 150 000 $\omega_c^{-1}$
  - in a saturated turbulent state
- Thermodynamical gradients similar for each case
- $|E_r|$ observed to increase with $I_P$ near the edge qualitatively similar to experiment

Radial electric field $E_r$ profiles

Robin Varennes, TSVV Workshop, 27-28 September 2022
The turbulence intensity increases with the safety factor.

- Turbulent intensity $\uparrow$ with $q$
  - Expected from theory/experiment
    - $[T.\ Dannert – PoP 2005]$  
    - $[C.C \ Petty – PoP 2004]$  

- Non linear evolution $\rightarrow$ saturation
  - $[R.E. \ Waltz – PoP 1997]$  

- Effect of turbulence less important in low $q$ case ?
  - $\rightarrow$ Neoclassical effect prevails ?

Robin Varennes, TSVV Workshop, 27-28 September 2022
Neoclassical effects alone seem negligible

- Same simulations performed with artificially killing all turbulent modes
- No significant effect of $q$ on these neoclassical simulations

**Temporal evolution of the flux-averaged electric potential $\phi_{00}$**

Average between $0.75 < r/a < 0.85$

Non-turbulent simulations

Robin Varennes, TSVV Workshop, 27-28 September 2022
However, synergy between neoclassic and turbulent effect may still matter

- Neoclassical effects can modify the turbulent drive

\[ \partial_t V_P = -\nabla \cdot \Pi_{r\theta} - \nu_{\theta} (V_P - V_{\text{neo}}) \implies V_{P,eq} = \frac{-\nabla \cdot \Pi_{r\theta}}{\nu_{\theta}} + V_{\text{neo}} \sim E_r/B \]

[T.A. Giannakon – PoP 2002]
The flow structure generated by turbulence observed to depend on $I_P$

- Observed in simulations:
  - At low $q$: static zonal structures
  - At high $q$: high frequency events

Spatio-temporal evolution of $E_r$
Turbulence feeds Zonal Flows and GAMs differently depending on $q$

- Zonal Flows are quasi-static poloidal flows generated by turbulence
- GAMs $\rightarrow$ oscillations of $\phi$ due to toroidal curvature … that can be driven by turbulence

Average between $0.75 < r/a < 0.85$

[Angelino – PPCF 2006]
[Miyato – PoP 2004]
[Conway – NF 2022]
- $E_r$ frequency spectra in the range $0.75 < r/a < 0.85$

- Same “available” energy in each simulation

- GAMs $\rightarrow$ strongly driven by turbulence in the high $q$ case

- Low $q$: weak turbulent intensity & weak GAM drive $\rightarrow$ energy has to aliment ZF?

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The location of zonal flow source coincide with the $E_r$ well

- $\nabla \cdot \Pi_{r\theta} \rightarrow$ Turbulent source
- Zonal Flows and GAMs $\rightarrow$ with $\nabla \cdot \Pi_{r\theta}$
- Low $q \rightarrow$ Turbulence feeds ZF
  - ZF responsible for internal transport barriers that reduce turbulence
- High $q \rightarrow$ Turbulence feeds GAMs
  - GAMs less efficient to quench turbulence

[K. Miki – NF 2011]
Conclusion

- Experiments on WEST show that edge $E_r$ when $I_p \uparrow$ so when $q \downarrow$

- This effect is retrieved qualitatively with gyrokinetic simulations

- Neoclassical processes are negligible regarding the $E_r$ well formation

- Main effect seems to be the **turbulent energy transfer** that favor either the **zonal flows** or the **GAMs** depending on the safety factor value

- Further study → ‘advanced’ signal processing tools (bicoherence…)

The work in ongoing …
0D model for the $q$ scaling of energy transfer

- 0D model from Miki & Diamond → energy transfer between turbulence/GAMs/ZF
  [K. Miki – NF 2011]
- Exploratory model → simplified version … but with main $q$ dependences
- Lot of unknown parameters set ah-hoc → not for precise quantification

\[
\begin{align*}
\text{Turbulent energy:} & \quad \partial_t I &= I I_L - I^2 - C_0 I \varepsilon_0 - C_G I \varepsilon_G \\
\text{ZF energy:} & \quad a_0 \partial_t \varepsilon_0 &= \varepsilon_0 I - \varepsilon_0 I_0 - \varepsilon_0^2 \\
\text{GAM energy:} & \quad a_G \partial_t \varepsilon_G &= \varepsilon_G I - \varepsilon_G I_G - \varepsilon_G^2
\end{align*}
\]
Multiple equilibriums allowed

- 4 types of stationnary solutions
  - No flows $I \neq 0$, $\mathcal{E}_0 = \mathcal{E}_G = 0$
  - ZF only $I \neq 0$, $\mathcal{E}_0 \neq 0$, $\mathcal{E}_G = 0$
  - GAMs only $I \neq 0$, $\mathcal{E}_0 \neq 0$, $\mathcal{E}_G = 0$
  - Mixed ZF/GAM $I \neq 0$, $\mathcal{E}_0 \neq 0$, $\mathcal{E}_G \neq 0$

- Only accounted dependence with safety factor
  - Normalized growth rate $I_L = \bar{I}_L \sqrt{q}$ (Observed in simulations)
  - ZF damping rate $I_0 = \bar{I}_0 q$ (Neoclassical friction)
  - GAMs damping rate $I_G = \bar{I}_G q^5 \exp \left(-\frac{11}{4} q^2\right)$ (Collisionless prediction)

Work in progress
Reasonable $q$-scaling of energies

- With the scaling $I_0 \ll I_L \ll I_G$, the simulations behavior is retrieved.
- Lot of assumptions in the model … but still encouraging

/!/ Work in progress /!

ZF energy

GAM energy

Turbulent energy
Transition zones

\[ I_L = I_G + C_0(I_G - I_0) \]

- \( I_L \)
- \( I_0 \)
- \( I_G \)

Normalized growth/damping rates vs. Safety factor \( q \)

- ZF only
- Mixed
- GAMs only

Robin Varennes, TSVV Workshop, 27-28 September 2022