Role of the radial electric field in the confinement of energetic ions in the Wendelstein 7-X stellarator

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1. Motivation

Good fast-ion confinement is an essential requirement for a fusion reactor. The magnetic configuration of the Wendelstein 7-X (W7-X) stellarator is optimized in this regard in a reactor-relevant scenario: when β is high and the effect of the radial electric field is negligible.

The experimental validation of this is difficult since achieving high β under appropriate conditions is challenging. Moreover, the radial electric field also makes fast ions precess, playing a stronger role than in a reactor [1].

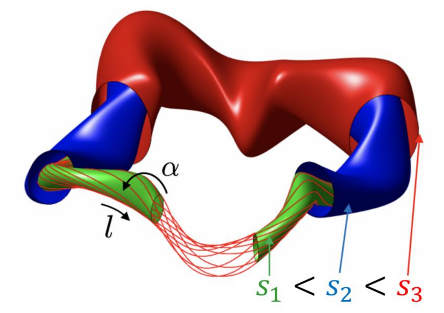
In W7-X, good fast-ion confinement is expected at high β and small radial electric field as a result of the combination of three effects:
(i) the orbit-averaged radial drift is small,
(ii) the diamagnetic effect causes the radial variation of $B \equiv |\mathbf{B}|$ to increase at high β and
(iii) the poloidal precession caused by this radial variation improves fast-ion confinement.

Given that (i) and (ii) have already been experimentally observed (indirectly) [2,3], **only (iii) still needs to be validated**.

In this work we show that the radial electric field produces an analogous effect on fast-ion confinement to β. **We aim to use this for an experimental validation of W7-X optimization strategy**, namely, the improvement of fast-ion confinement thanks to poloidal precession.

2. Coordinates and theoretical background

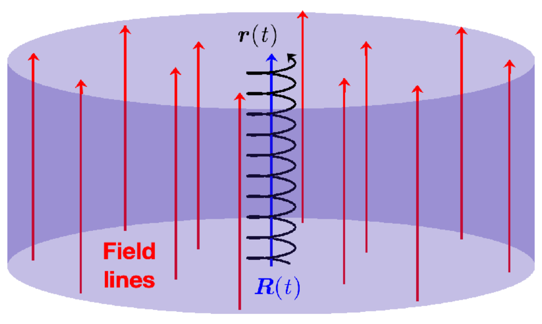
Spatial coordinates:
- $s = \Psi/\Psi_{LCFS}$.
- $\alpha = \theta - \iota\zeta$.
- l, which is the arc-length along the field line.



The guiding-center velocity is

$\dot{\mathbf{R}} = v_\parallel \mathbf{b} + \mathbf{v}_d$,

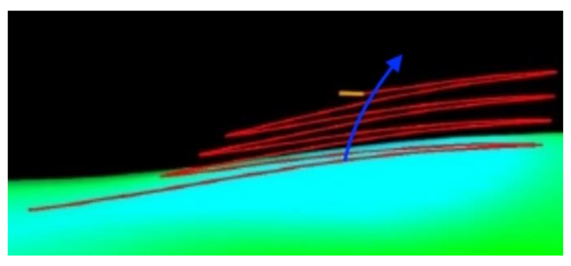
where $\mathbf{v}_d = \mathbf{v}_M + \mathbf{v}_E$ and $|\mathbf{v}_d/v_\parallel| \sim \rho_* \ll 1$.



At 0th order in ρ_*, two possible dynamics:
- Passing fast ions, which are able to circulate around all the torus.
- Trapped fast ions, which will reach a point in which $v_\parallel = 0$ and bounce back.

At 1st order in ρ_*, and in the absence of collisions and turbulence, **passing particles are exactly confined**, whereas **trapped particles are not**.

The motion of trapped particles can be characterized by the bounce average of the radial and tangential drifts.



Good confinement is expected [4,5] if $|\overline{\mathbf{v}_d \cdot \nabla s}| \ll |\overline{\mathbf{v}_d \cdot \nabla \alpha}|$, where

$$\bar{f} = \frac{2}{\tau_b}\int_{l_{b_1}}^{l_{b_2}} f \frac{\mathrm{d}l}{|v_\parallel|} \quad \text{and} \quad \tau_b = 2\int_{l_{b_1}}^{l_{b_2}} \frac{\mathrm{d}l}{|v_\parallel|}.$$

$\lambda \equiv \frac{\mu}{\mathcal{E}}$; $\mu \equiv$ magnetic moment, $\mathcal{E} \equiv$ total energy

Tangential drifts:
- $\overline{\mathbf{v}_E \cdot \nabla\alpha} = -E_s/\Psi_{LCFS}$, where $\mathbf{E} = E_s \nabla s$.
- $\overline{\mathbf{v}_M \cdot \nabla\alpha} = \overline{\frac{2\mathcal{E}}{Ze\Psi_{LCFS}}\left(1 - \frac{\lambda B}{2}\right)\frac{\partial_s B}{B}}$.

Well-known diamagnetic effect: $\frac{\partial_s B}{B} \approx \frac{\partial_s B_{vac}}{B_{vac}} - \frac{\partial_s \beta}{2}$ [6]

Parabolic profiles: $\partial_s \beta = -2\langle\beta\rangle$

We can rearrange the expression for the tangential drift:

$$\overline{\mathbf{v}_d \cdot \nabla\alpha} = I_0 + I_{\langle\beta\rangle}\langle\beta\rangle + I_{E_s}E_s \quad (1)$$

Therefore, with respect to $\overline{\mathbf{v}_d \cdot \nabla\alpha}$, a large $I_{E_s}E_s$ is equivalent to a large $I_{\langle\beta\rangle}\langle\beta\rangle$, and both can lead to a decrease in losses. Hence, we propose **a controlled scan on $I_{E_s}E_s$ for the validation of the enhanced fast-ion confinement at large $\overline{\mathbf{v}_d \cdot \nabla\alpha}$ in W7-X.**

3. Simulation details

The fast-ion loss fraction is computed via collisional guiding-center simulations of fast-ion trajectories, using the ASCOT5 orbit-following code. For each case, the trajectories of 10^4 hydrogen nuclei ($^1\mathrm{H}^+$) in the KJM (high mirror) configuration of W7-X are simulated.

We use three initial distributions, all of them isotropic in velocity, with an initial energy of 50 keV and with initial positions uniformly distributed on one flux-surface. We choose the surfaces with $\rho_0 = \{0.25, 0.50, 0.71\}$, where $\rho \equiv \sqrt{s}$ is the radial variable we will use from now on.

Markers are simulated until they escape or thermalize.

The magnetic configuration for each case is computed with the VMEC code.

In the simulations of Section 5, the radial electric field profiles are computed via the SFINCS code.

4. Ideal scan

In order to illustrate the equivalence between the effects of the radial electric field and $\langle\beta\rangle$ on fast-ion confinement, we choose academic analytical profiles.

Density profiles

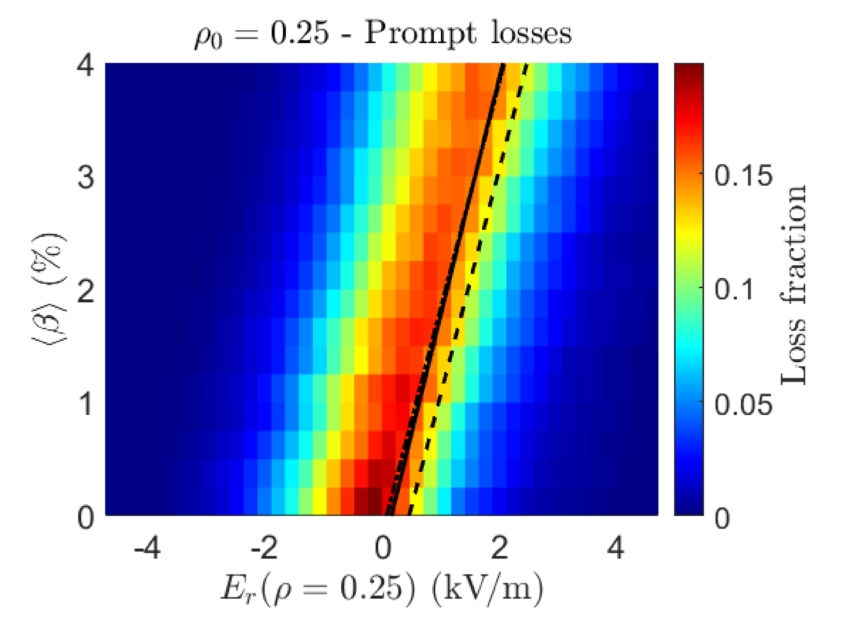
$n_e = n_{e0}\sqrt{1-\rho^2}$
$n_i = n_{i0}\sqrt{1-\rho^2}$
$n_{i0} = n_{e0}$

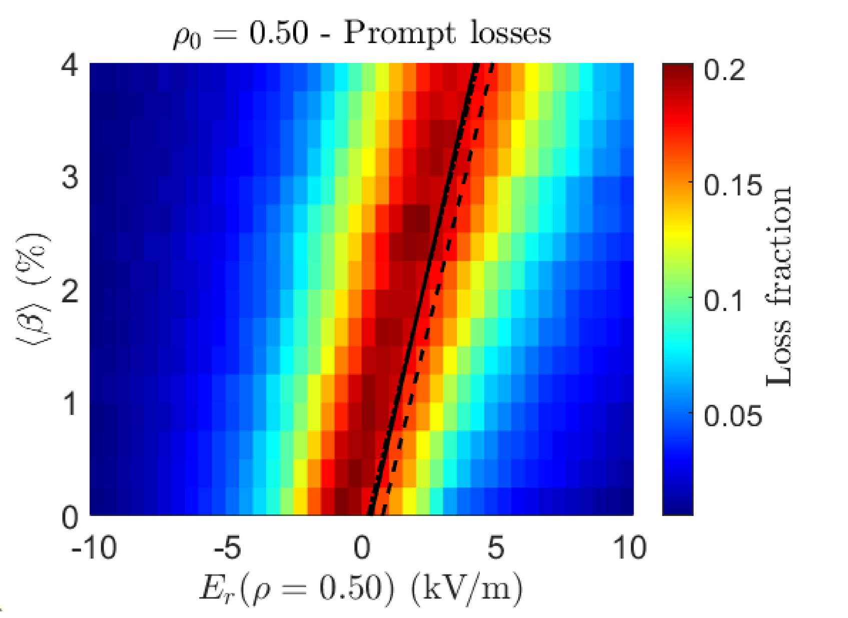
Temperature profiles

$T_e = T_{e0}\sqrt{1-\rho^2}$
$T_i = T_{i0}\sqrt{1-\rho^2}$
$T_{e0} = 3.0$ keV ; $T_{i0} = 1.5$ keV

Radial electric field profiles

$\mathbf{E} = E_s\nabla s = E_r\nabla r$
$E_s = E_{s0}\left(1 - e^{-\rho^2/C}\right)$
$C = 0.02$; $E_r = (2\rho/a)E_s$





By assigning different values to n_{e0} and E_{s0}, a scan on $\langle\beta\rangle$ and on E_r is carried out, performing the simulation of fast-ion trajectories and computing the prompt losses (the losses occurring within 10^{-3} s after the birth of the fast ions) for each scenario.

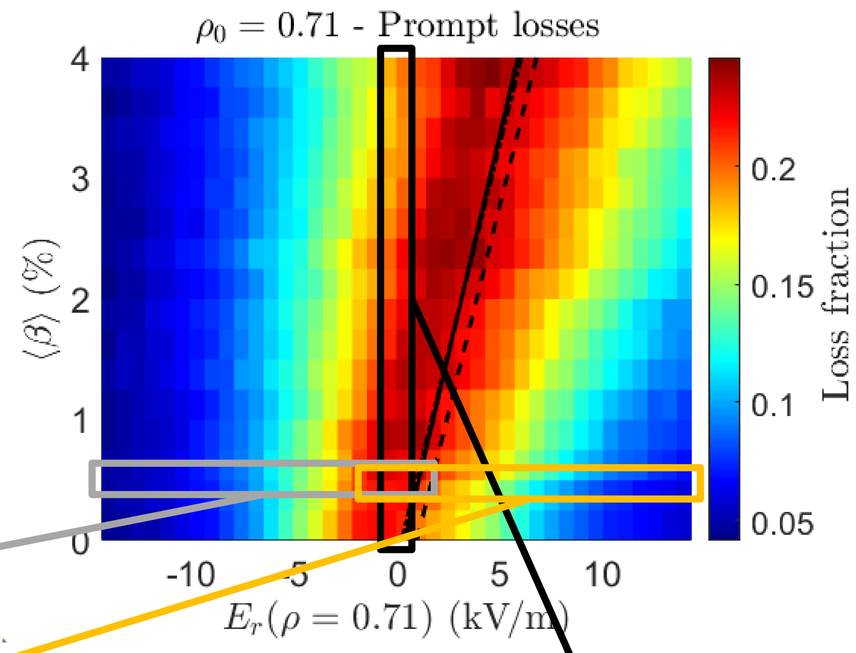
Equation (1) predicts $\overline{\mathbf{v}_d \cdot \nabla\alpha} = 0$ for the linear relation $E_r = (2\rho/a)\Psi_{LCFS}\left(I_0 + I_{\langle\beta\rangle}\langle\beta\rangle\right)$.

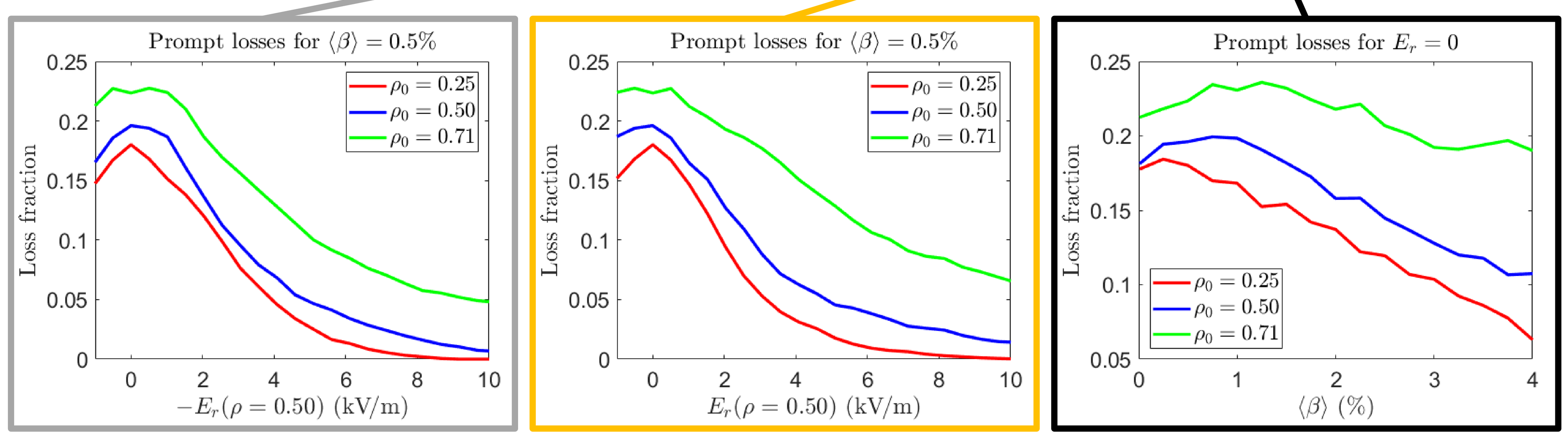
We compute I_0 and $I_{\langle\beta\rangle}$ for an exactly QI field that resembles W7-X, following [6].

Simulations with ASCOT show maximal losses in the expected region of the parameter space.

Small discrepancy in $E_{r,max\ losses}$ for $\langle\beta\rangle = 0$, probably due to W7-X not being exactly QI.

Good agreement on the slope of the region of maximal losses.





The effect of the radial electric field on the losses is comparable to the effect of $\langle\beta\rangle$. Hence, we see that **the ideal scan on $\langle\beta\rangle$ could be replaced with an ideal scan on E_r.**

5. Experimentally-based scan

Experimentally-based profiles (for density and temperature) from discharge #20181009.034 are employed [7].

In #20181009.034, density peaking caused by NBI permits an increase in temperature when additional ECRH is employed → Scan on n and T during the discharge → (Via ambipolarity of neoclassical fluxes) → Scan on E_r

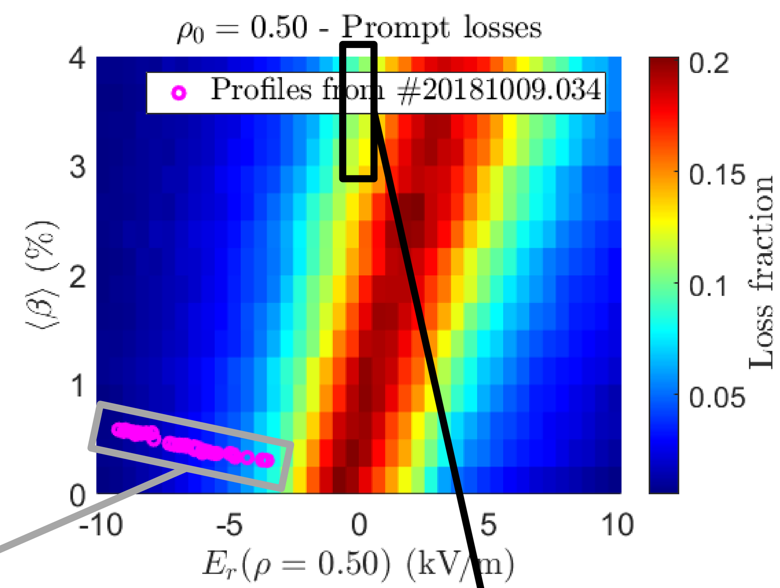
For each case, the magnetic equilibrium is computed with VMEC and the radial electric field is computed with SFINCS. The value $E_r(\rho = 0.45)$ is representative of the E_r profile size.

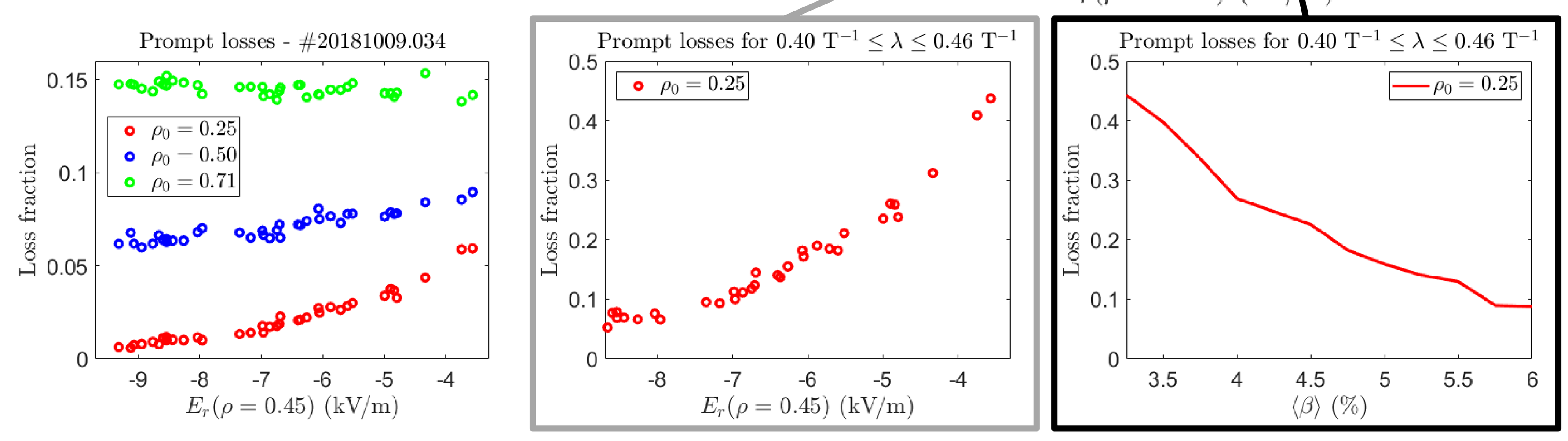
Plasmas of #20181009.034 are located at the bottom left part of the previous 2D plots.

For inner surfaces, $\rho_0 = 0.25$ and $\rho_0 = 0.50$, the losses decrease as $|E_r|$ increases.

For the outer surface, $\rho_0 = 0.71$, there is no clear dependence. Probably because E_r profiles do not vary appreciably for $\rho > 0.7$ between the time slices (not shown).

Afterwards, we focus on deeply-trapped (high λ) particles.





For deeply-trapped ions and close to the axis, and with the proper ranges for E_r and $\langle\beta\rangle$, the scan on E_r during the discharge #20181009.034 has the same effect as an ideal scan on $\langle\beta\rangle$.

This scenario could be used for the validation of W7-X optimization strategy.

6. Conclusions and future work

Conclusions:
- The radial electric field effect on fast-ion confinement has been confirmed to be equivalent to the effect of $\langle\beta\rangle$.
- As a consequence, one could propose a scan on the radial electric field for a (partial) experimental validation of W7-X magnetic field optimization strategy.
- Through a preliminary scan on realistic profiles of W7-X, a possible scenario for such validation has been discussed.

To be done:
- Analyze the possibility of generating and measuring fast ions in the phase space region where this effect is observed: deeply-trapped fast ions born close to the axis.

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[6] J.L. Velasco et al., *Nuclear Fusion* **63**(12), p. 126038 (2023).
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