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INFLUENCE OF RADIAL ELECTRIC FIELD ON STOCHASTIC DIFFUSION IN WENDELSTEIN-TYPE STELLARATORS

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Motivation: delayed collisionless losses of fast ions

• Confinement of fast ions in optimized Wendelstein-line stellarators is improved due to high β: diamagnetic drift tends to cancel ∇*B* drift so that average radial magnetic drift vanishes, minimizing prompt losses

• **However**, high β does not prevent delayed losses of 3.5 MeV alpha particles, as shown numerically in [W. Lotz, P. Merkel, J. Nuhrenberg, E. Strumberger, *Plasma Phys. Contr. Fusion* **34** (1992) 1037].

• Suggested loss mechanism: stochastic diffusion due to repeated particle trapping and de-trapping in local magnetic wells: [C.D. Beidler, Ya.I. Kolesnichenko, V.S. Marchenko, I.N. Sidorenko, H. Wobig, *Phys. Plasmas* **8** (2001) 2731].

• Trapping/de-trapping probability and nonadiabatic jumps of $J_{||}$ consistently described in theory of stochastic diffusion developed in [A.V. Tykhyy, *Ukr. J. Phys.* **63**(6) (2018) 495].

Does radial electric field affect stochastic diffusion?

• Radial electric field (E_r) is always present in stellarators.

• E_r creates additional ***E*** x ***B*** drift. $E_r < 0$ adds to diamagnetic drift, $E_r > 0$ reduces it.

• E_r affects orbits of particles trapped in local magnetic wells by modifying the contours of the longitudinal adiabatic invariant of bounce motion, $J_{||}$: $E_r < 0$ improves their confinement, $E_r > 0$ degrades it [1, 2].

[1] Ya.I. Kolesnichenko, V.V. Lutsenko, A.V. Tykhyy, A. Weller, A. Werner, H. Wobig, J. Geiger, *Phys. Plasmas* 13 (2006) 072504

[2] J.M. Faustin, W.A. Cooper, J.P. Graves, D. Pfeerle, J. Geiger, *Nucl. Fusion* 56 (2016) 092006

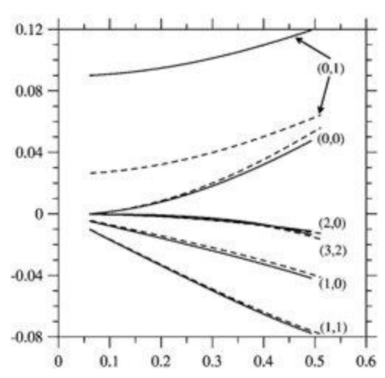
• Effect of E_r on stochastic diffusion has not yet been studied, motivating the present work.

Magnetic field in Wendelstein-line stellarators

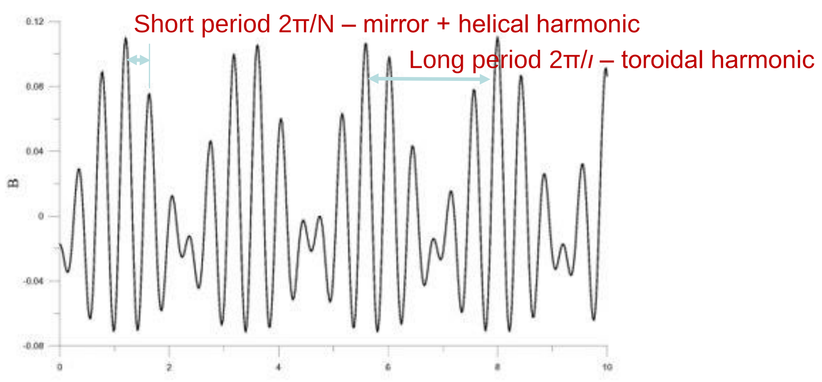
- Magnetic field strength |*B*| in Wendelstein-line stellarators has multiple harmonics, with mirror, helical, toroidal and diamagnetic being the largest by magnitude
- Model magnetic field includes only these four harmonics:

$$B/\bar{B} = 1 + \epsilon_0 - \epsilon_t \cos\vartheta + \epsilon_m \cos N\varphi - \epsilon_h \cos(N\varphi - \vartheta)$$

$$B/\bar{B} = 1 + \epsilon_0 - \epsilon_t \cos\vartheta + \epsilon_{hm} \cos N(\varphi - \varphi_t)$$



- Number of magnetic field periods $N >> 1$, rotational transform ɩ 1
- Resulting |*B*| variation along a field line has two periods:



• Two periods of |*B*| variation create two types of trapped particles

• Locations of |*B*| wells not aligned on neighboring field lines due to ɩ

• As particles drift between field lines, they may become trapped in or de-trap from short-period (mirror/helical) |*B*| wells

Trapped particles in stellarators

To characterize the type of particle orbits, we introduce the trapping parameter *κ* and particle pitch parameter *α*:

$$\kappa^2 = \frac{\alpha - \epsilon_E - \epsilon_0 + \epsilon_t \cos\vartheta + \epsilon_{hm}}{2\epsilon_{hm}}$$

$$\frac{m{v_{||}}^2}{2} = 2\mu\bar{B}\epsilon_{hm}\left[\kappa^2 - \cos^2\frac{N(\varphi-\varphi_t)}{2}\right]$$

$$\alpha = \frac{W}{\mu\bar{B}} - 1 \qquad \epsilon_E = -\frac{e}{\mu\bar{B}}\int^r E_r(r')dr'$$

$\kappa^2 < 1$ - particle trapped in mirror/helical well, "locally trapped"

$\kappa^2 > 1$ - "locally passing" but may be trapped in toroidal well

κ changes as particle drifts between field lines

• Localized particles always have $\kappa^2 < 1$

• Passing particles always have $\kappa^2 > 1$

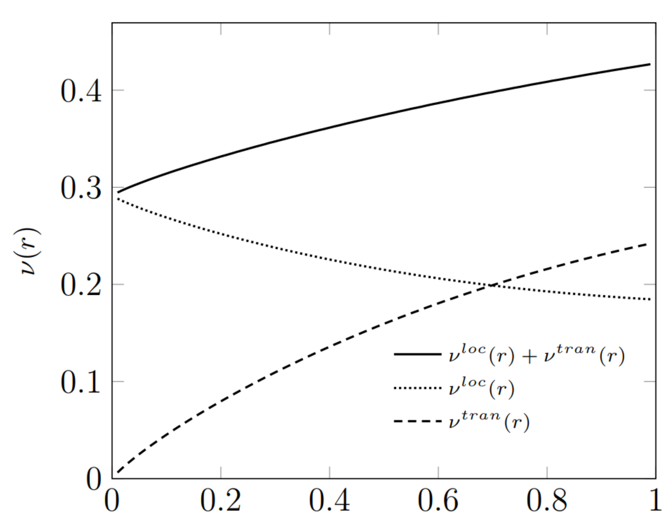
• Transitioning particles switch locally trapped locally passing

α for localized, transitioning, and passing particles lies in ranges (in narrow orbit approximation):

$$\epsilon_0 - \epsilon_m + \epsilon_h - \epsilon_t < (\alpha^{loc} - \epsilon_E) < \epsilon_0 + \epsilon_m - \epsilon_h - \epsilon_t$$

$$\epsilon_0 + \epsilon_m - \epsilon_h - \epsilon_t < (\alpha^{tran} - \epsilon_E) < \epsilon_0 + \epsilon_m + \epsilon_h + \epsilon_t$$

$$\epsilon_0 + \epsilon_m + \epsilon_h + \epsilon_t < (\alpha^{pass} - \epsilon_E)$$



Radial dependence of fraction of trapped alpha particles born in a Helias reactor. Fraction of born trapped particles is **30-40%.**

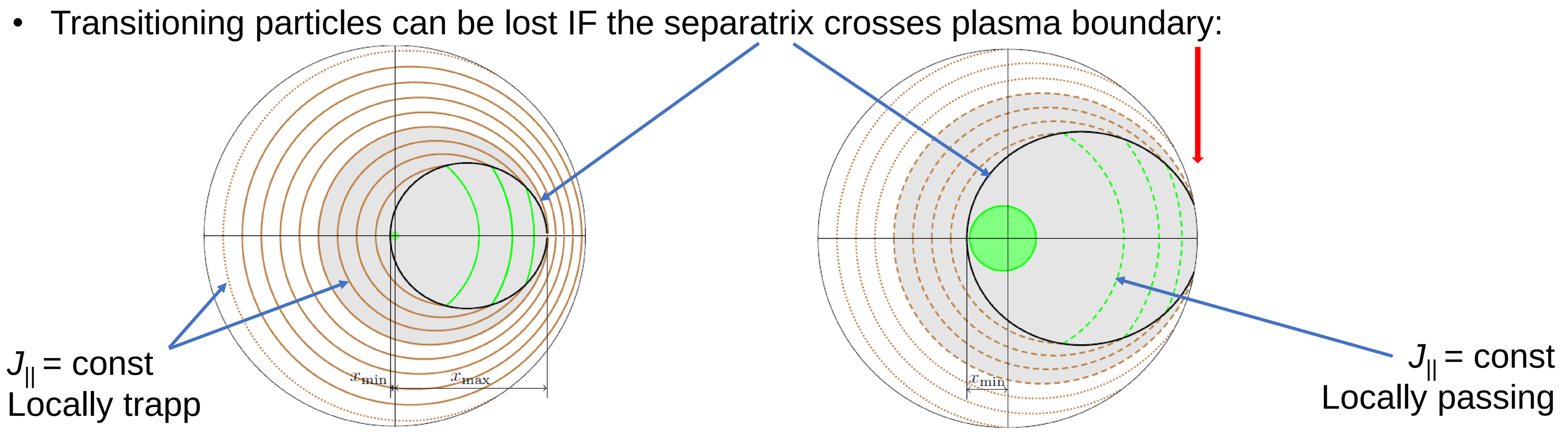
• Stochastic diffusion affects transitioning particles

• Transitioning particles constitute a considerable amount of fast ion population

• Fraction of transitioning particles depends on radial profiles of plasma parameters

Stochastic diffusion of transitioning particles

- Drift causes transitions between locally trapped and locally passing states
- Bounce period becomes very large close to transition point $v_{||} = 0$, **therefore**
- Longitudinal adiabatic invariant $J_{||}$ of bounce motion not conserved during transition
- Random jumps of $J_{||}$ lead to diffusion of transition point along the separatrix, $\kappa^2 = 1$, where particles transition between locally trapped and locally passing states [6]
- Transitioning particles can be lost IF the separatrix crosses plasma boundary:

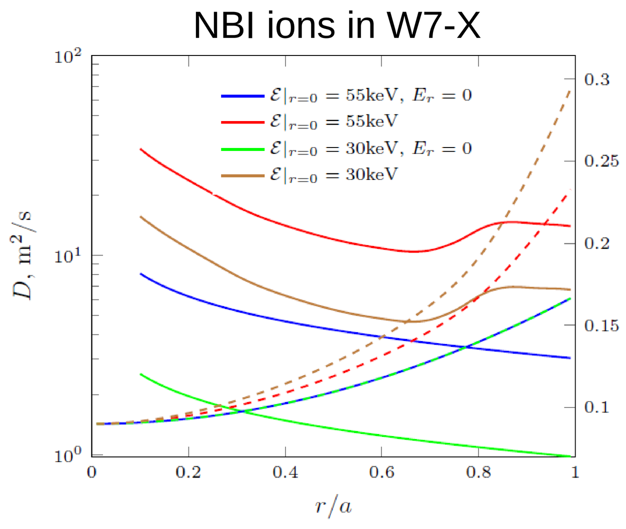


Bounce-averaged drift orbits (contours of $J_{||}$) for locally trapped (brown) and locally passing (green) 3.5 MeV alpha particles in the intermediate Helias reactor (option "A") in the poloidal plane in flux coordinates. Left: α = 0.12, right: α = 0.15

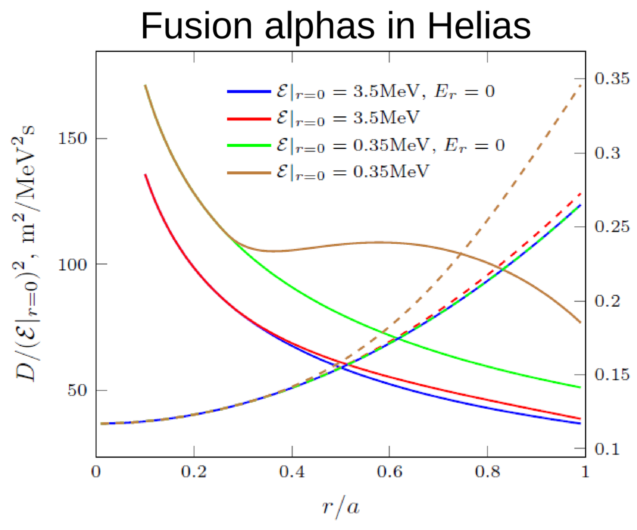
Effect of E_r on stochastic diffusion coefficient

- SD coefficient **strongly depends on particle energy (~$\mathcal{E}^2$)**
- $E_r < 0$ **increases** diffusion coefficient up to 2x
- Is $E_r < 0$ bad for confinement of transitioning particles?

NBI ions in W7-X



Fusion alphas in Helias



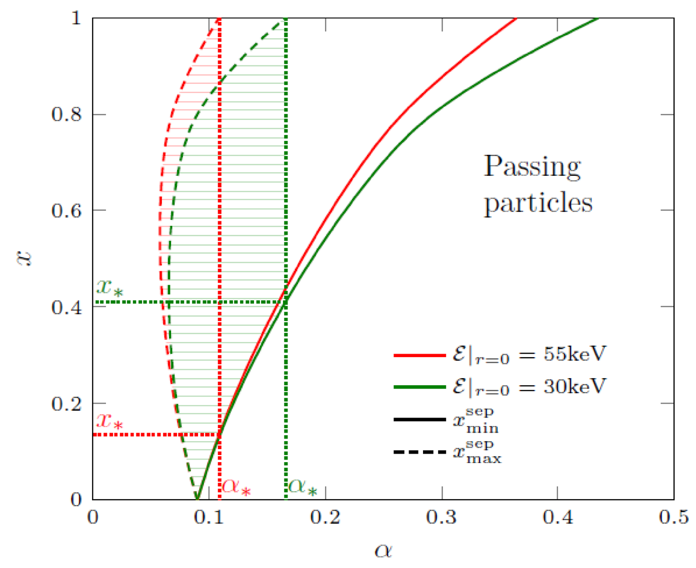
"intermediate" Helias, option A: R = 14m, $n_e = 2\cdot10^{20}$ m^{-3}, $T_e \approx T_i$ = 10 keV
max E_r ~ -25 kV/m, potential difference center to edge ~ 10 kV
Warmer et al. *Plasma Phys. Control. Fusion* **58**(7) 074006 (2016)

NBI ions in Wendelstein 7-X

• **For $E_r = 0$, all NBI ions can be lost to SD** but diffusion time τ_D ~ 25ms is close to or larger than slowing down time

• Relatively low plasma β makes it possible for most transitioning NBI ions with $\mathcal{E}$ = 55 keV to be lost even in presence of $E_r < 0$

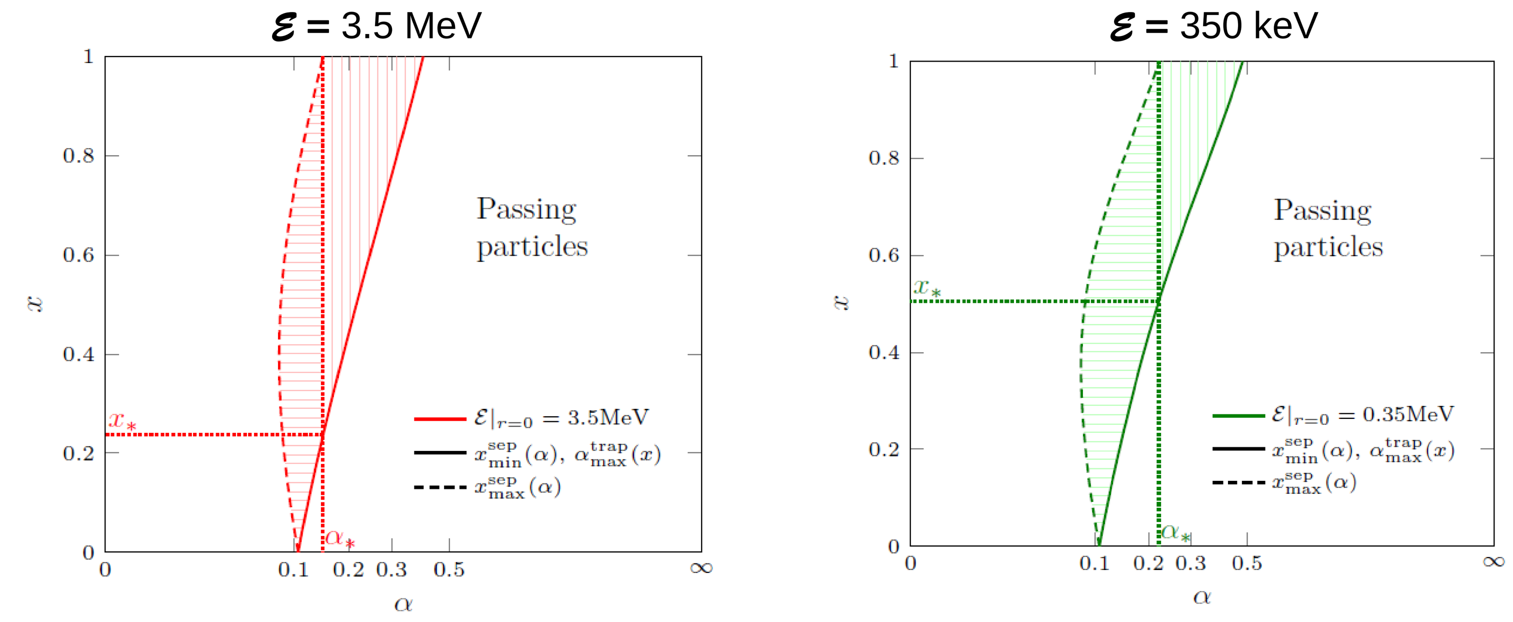
• Larger effect of E_r at $\mathcal{E}$ = 30 keV significantly improves confinement of transitioning ions



W7-X: R = 5.5m, B = 3 T, $n_e = 7\cdot10^{19}$ m^{-3}, $T_e \approx T_i$ = 3 keV
max E_r ~ -10 kV/m, potential difference center to edge ~ 1 kV
$E_r > 0$ (electron root) also observed
Pablant et al. *Phys. Plasmas* **25** 022508 (2018)

Alphas in the Helias reactor

$\mathcal{E}$ = 3.5 MeV $\mathcal{E}$ = 350 keV



• E_r is too weak to affect 3.5 MeV particles; about 50% transitioning particles are lost

• Characteristic diffusion time τ_D ~ 2.5ms << slowing down time (85ms in "Option A")

• Enough transitioning particles are retained and slowed down

• Slowed-down transitioning particles have better confinement and much larger τ_D ~ 150ms (180ms without the effect of E_r on diffusion coefficient)

Summary and conclusions

- Transitioning fast ions are subject to stochastic diffusion (SD) in Wendelstein-line stellarators. The fraction of transitioning ions is considerable.
- SD leads to loss / redistribution of fast ions when the separatrix (κ^2 = 1) intersects / stays within the plasma boundary.
- Because the separatrix location depends on particle pitch, a part of 3.5 MeV alpha particles in a Helias reactor is lost because of SD, another part is confined.
- Radial electric field (E_r) affects both SD coefficient and separatrix location. $E_r < 0$ increases SD coefficient, but shifts the separatrix in such a way that fast ion confinement improves. $E_r > 0$ degrades fast ion confinement.
- 3.5 MeV alpha particles in HELIAS reactor are weakly sensitive to the electric field, but partly thermalized alphas are affected. Due to this, SD may contribute to ash removal when $E_r > 0$.
- Confinement of 55 keV NBI ions in W7-X high-mirror configuration is improved significantly due to $E_r < 0$.
- In general, E_r can be used for both loss mitigation and energy deposition profile optimization.

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