Max-Planck-Institut für Plasmaphysik

Effects of the non-perturbative mode structure on energetic particle transport

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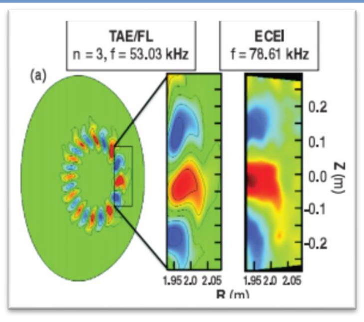
Motivation

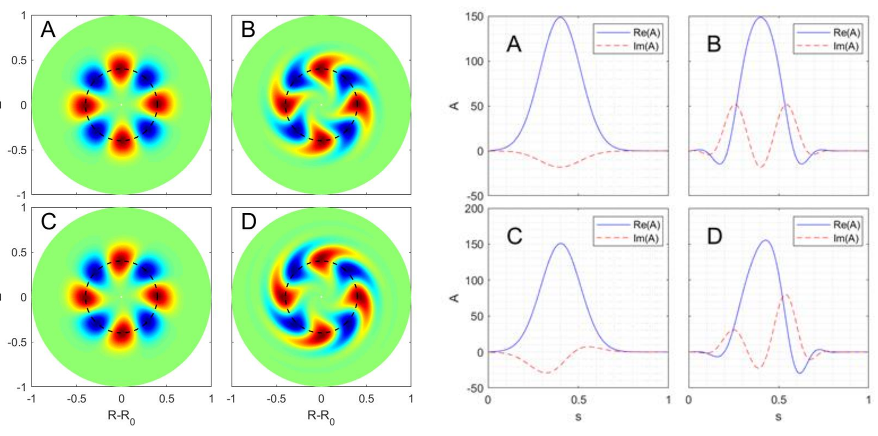


- The mode distortion can be induced by EP non-perturbative effects [1].
- The non-perturbative EP effects can change the wave-particle interaction, the mode growth rate, the saturation level, in turn, the EP transport changes [2, 3].
- The non-perturbative mode structure can be represented by the "symmetry breaking" in parallel and radial directions [4].
- While "symmetry breaking" has been intensively studied in micro-turbulence transport (w/o EPs) due to its effects on intrinsic toroidal rotation, its effects on EP transport are less well understood.

Mode structure with Symm. Breaking

➔ EPs induce radial & up-down mode structure symmetry breaking.
The radial mode structure $A(s) = \exp\{-\sigma(s-s_0)^2\}$ with complex parameters σ and s_0 are used [4]. s : radial coordinate

	A	B
σ	40	40-50i
s_0	0.4	0.4
	C	D
σ	40	40-50i
s_0	0.4+0.02i	0.4+0.02i

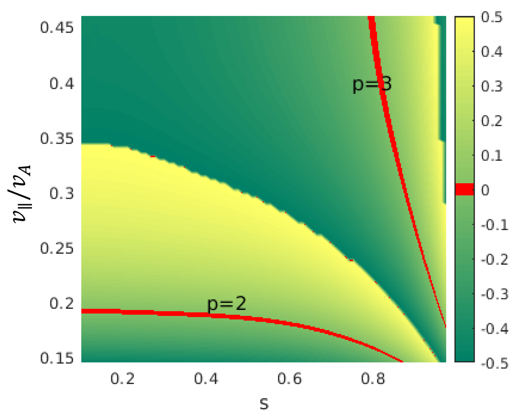


- RSAE mode for AUG #31213, f=133 kHz, n=2, m=4 (LIGKA results).
- Case A is fitted mode structure using LIGKA [6] results.
- Cases B, C, D mimic experiment and HMGC simulation results [7].
- Base case A, without symmetry breaking.

Linear resonance

- HAGIS result: linear resonances ($n\langle\omega_\zeta\rangle - p\langle\omega_\theta\rangle = \omega$, red lines, p= 2, 3) in phase space for a 133 kHz $n=2$ mode in the circular equilibrium matched to AUG #31213. Color bar represents $[n\langle\omega_\zeta\rangle - \omega]/\langle\omega_\theta\rangle - \mathrm{p}$. s is $\sqrt{\psi}$. $v_\parallel$ is parallel velocity; v_A is Alfvén velocity. Particle initial $v_\perp$=0, $v_\parallel/v = 1$, initial $\theta = 0$, $\zeta = 0$.

- $v_\parallel/v_A$=0.15 corresponds to E=16 keV
- $v_\parallel/v_A$=0.2 corresponds to E=28 keV.
- NBI birth energy: 93 keV.
- In this range, for co-passing particles p=2 resonance dominates.

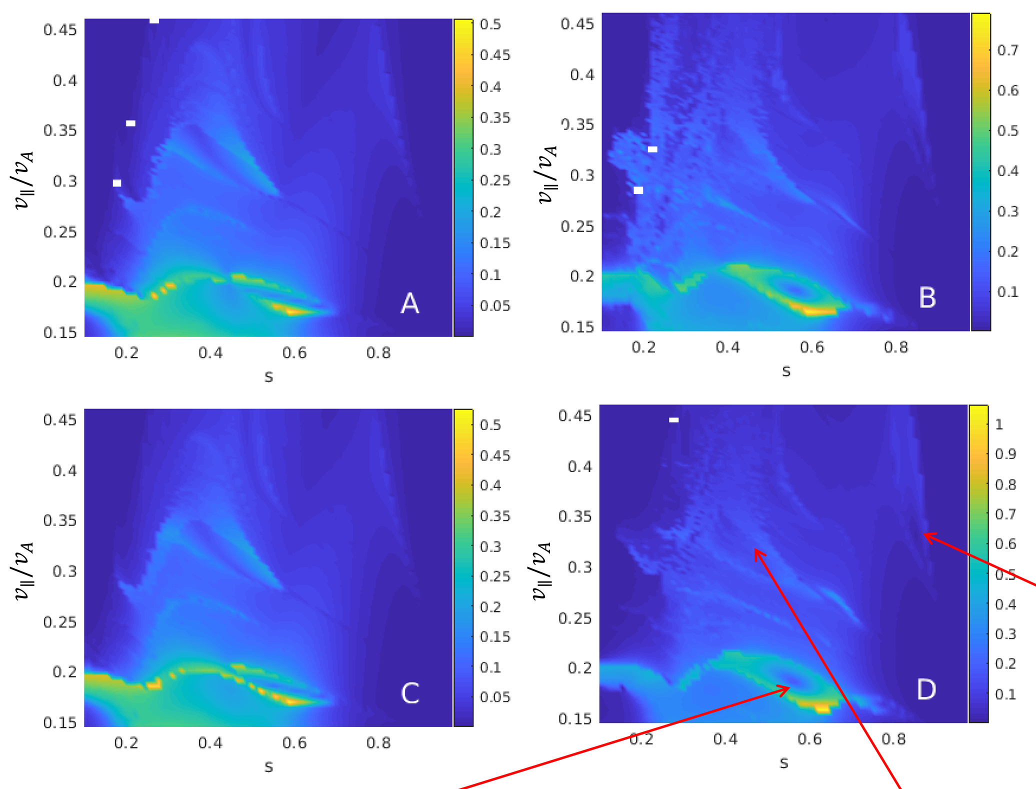


Conclusions

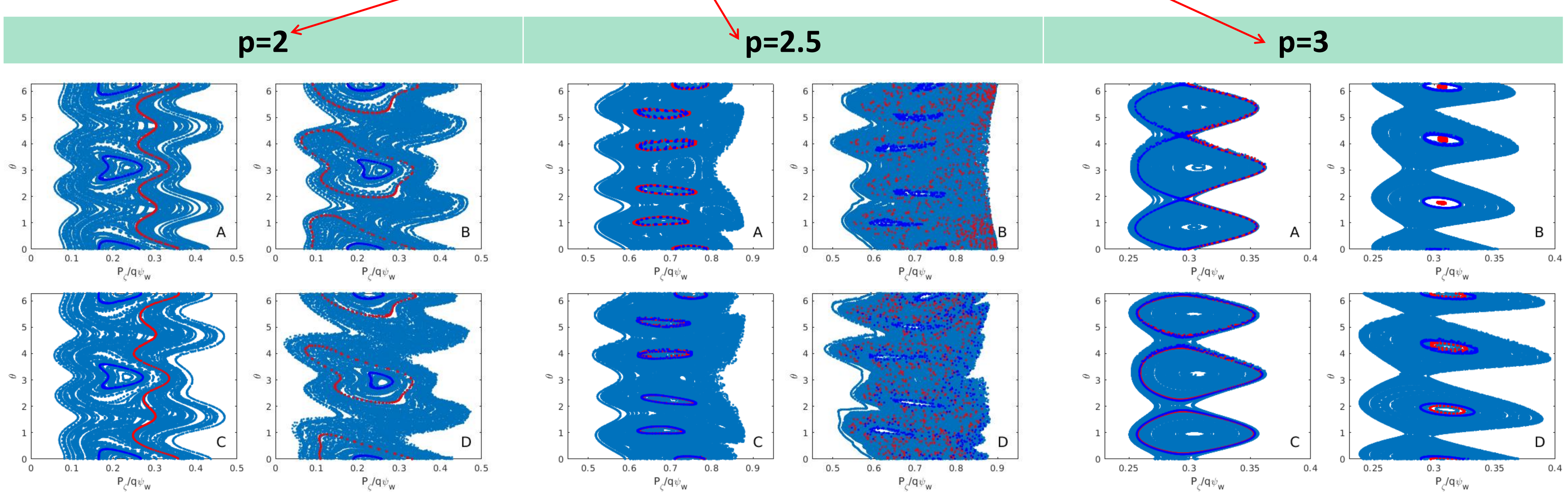
- LIGKA-HAGIS [5,6] coupling scheme has been applied to the studies of EP-wave interaction and transport analyses using the analytical mode structure with symmetry breaking properties [4] according to experimental and simulation observations [7,8].
- Analyses based on AUG parameters show that non-perturbative mode structure can be important for EP transport modelling.
- Particle resonance pattern changes due to the mode structure symmetry breaking
  - Mode structure symmetry breaking leads to distortion of wave-particle resonance island structures; the mode radial propagation plays an important role. This provides new features in addition to the analyses using perturbative mode structures [9].
- With mode symmetry breaking effects:
  - Mode linear growth rate can change by 10% and saturation level can change by 20%.
  - EP density and energy transport can change by 10%.
  - EP parallel velocity $u_\parallel$ can change significantly, $u_\parallel$ reversal in the inner region is observed when varying the mode structures.

Test particle studies

Particle energy change after 20 poloidal circles with a fixed mode amplitude $\delta B/B = 10^{-3}$ (≈ HAGIS saturation value).

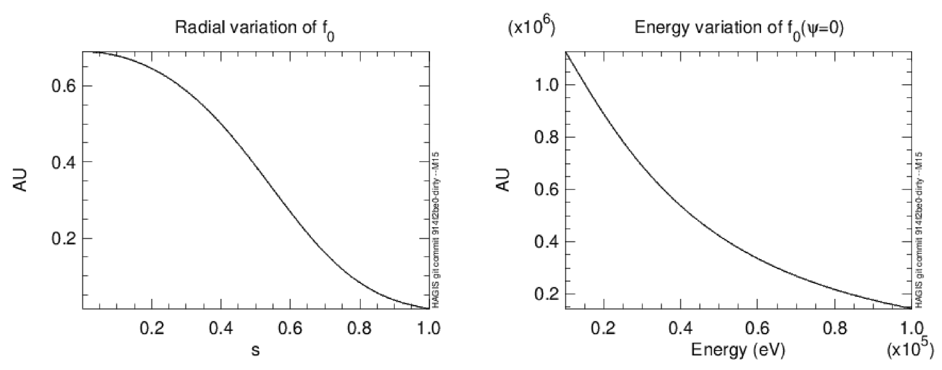


- As predicted, particle energy changes significantly at p=2 resonance and s around 0.4.
- Resonance lines are visible in A,B,C,D but can be distorted due to different mode structures.
- A and C are similar; B and D are similar (also see saturation level analyses following).
- B and D, featured with the significant radial propagation in mode structures, are distorted compared with A.
- For this case, the p=2.5 nonlinear resonance is also observed. At the p=2.5, the resonance structure is due to the coupling of the two primary resonance p=2 and p=3.
- Resonance islands are narrow at p=3.



Delta f studies

EP Initial distribution



- Energy distribution

$$f(E) = \frac{1}{E^{3/2} + E_c^{3/2}} \mathrm{erfc}\left(\frac{E - E_0}{\Delta E}\right)$$

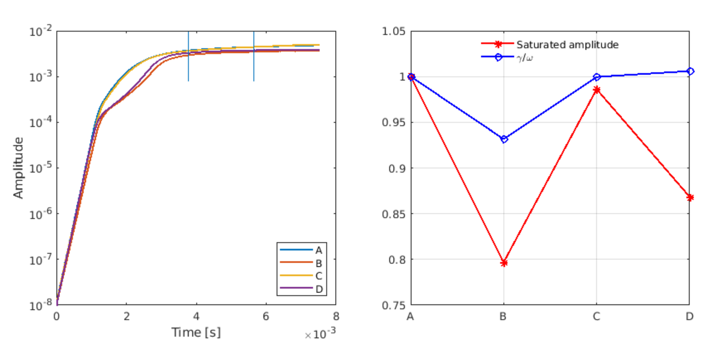
with $\mathrm{E_0} = 93$ keV, $\mathrm{E_c} = 37.21$ keV, $\Delta E = 149.9$ keV

- Pitch angle **isotropic** distribution.
- Radial distribution

$$f(\psi) = 1/[1 + exp\left(\frac{\psi - \psi_0}{\delta\psi}\right)], \text{ with } \psi_0 = 0.16, \delta\psi = 0.2.$$

- EP density at magnetic axis n(0) = 9.163E+17 [1/m^3]

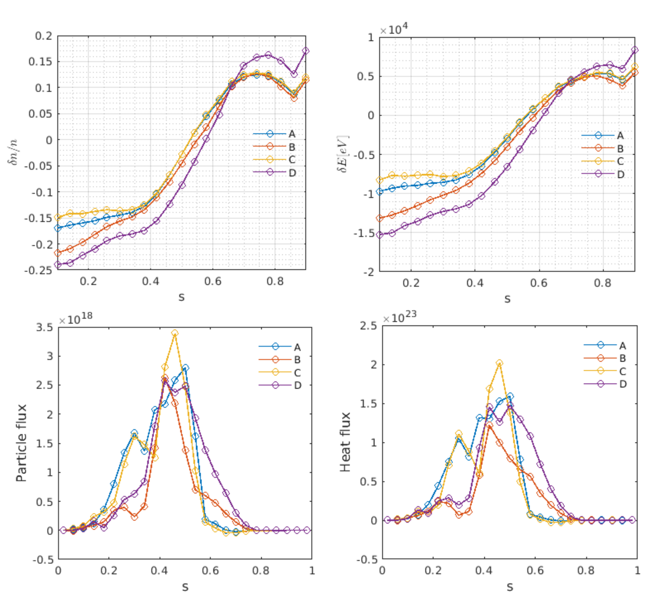
Mode saturation and linear growth rate

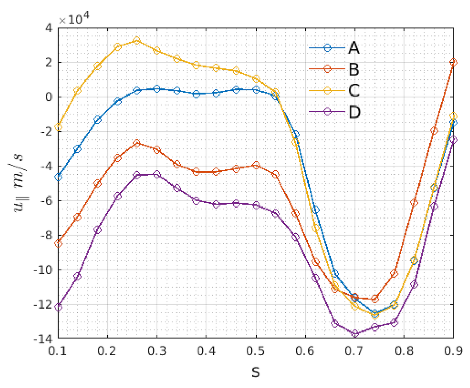


Linear growth rate γ_L is fitted during the first 1000 steps; averaged saturation level A_{sat} during 10000-15000 steps (t=3.77-5.65 ms)

- Base case A: $\gamma_L/\omega = 0.98\%$, A_{sat} is 4.2× 10^{-3}.
- Compare B with A: due to radial propagation, the linear growth rate & saturation of B decrease by ~5% & 20% respectively.
- Case D: A_{sat} decreases, but γ_L is similar to A. Synergistic effect of $\mathrm{Im}\{\sigma\}$ & $\mathrm{Im}\{s_0\}$?
- Case C: γ and A_{sat} slightly change.

δf and particle redistribution





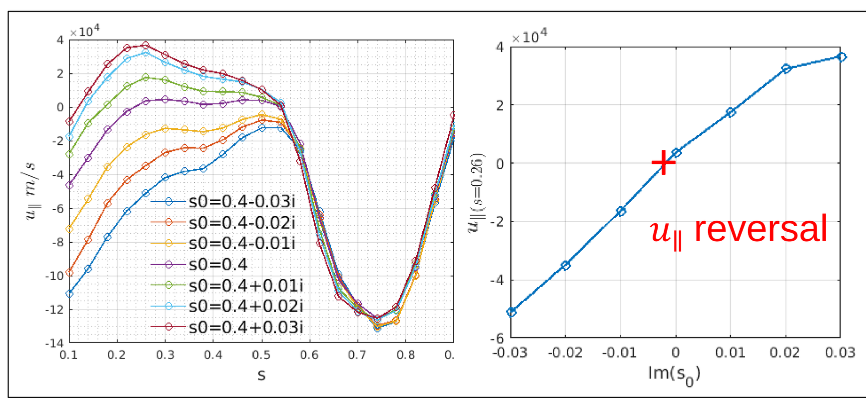
Parallel velocity radial distribution:

$$u_\parallel = \frac{\int \delta f \cdot v_\parallel \, dv^3}{\int f \, dv^3}$$

significantly different

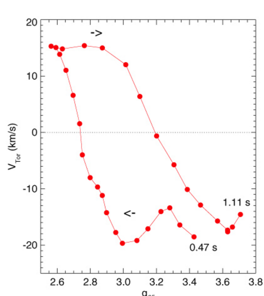
EP density radial distribution: $\delta n/n$ (left); Energy change: $\delta E = \frac{\int \delta f \cdot E \, dv^3}{\int f \, dv^3}$ (middle)

- Alfvén mode leads to the flattening of density and energy profiles ($\delta n, \delta E < 0$ for $s < 0.5$; $\delta n, \delta E > 0$ for $s > 0.5$)
- Perturbative mode structures (B,C,D) lead to changes in particle and energy transport with $\delta n, \delta E$ deviating by ~10%
- Parallel velocity profile changes significantly due to the non-perturbative mode structure symmetry breaking. In the inner region ($s < 0.5$), $u_\parallel$ can change its direction (rotation reversal)
- All figures are averaged over t=3.77-5.65 ms except particle and heat flux averaged over t=0-3.77 ms.



- Choose case C, with σ = 40, $s_0 = 0.4 + 0.02i$. Vary imaginary part of $\mathrm{s_0}$.
- $u_\parallel$ reversed with $\mathrm{Im}(s_0)$.

- Toroidal rotation reversal of thermal ions has been widely observed (w/o EP) [Rice et al, Nucl. Fusion, 51 (8), 083005 (2011)]
- EP effects on thermal ion rotation needs to be studied for burning plasmas



[1] Tobias PRL 2011 [2] Zonca, NF 2005 [3] Chen RMP 2016 [4] Lu NF 2018 [5] Pinches CPC 1998 [6] Lauber JCP 2007 [7] Briguglio POP 1995 [8] Z. Wang PRL 2013 [9] Meng NF 2018

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