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 $A(r) = \exp(-\sigma(s-a \phi)^2)$ with complex parameters $a$ and $s$ are used [4].

<table>
<thead>
<tr>
<th>Mode</th>
<th>$a (n=2)$</th>
<th>$s (n=2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>B</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>C</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>D</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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

Linear resonance

HAGIS result: linear resonances $\nu(\omega_c) - \nu(\omega) = \omega_c$, 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 $|\nu(\omega_c) - \nu(\omega)|$. $s$ is $\sqrt{2}$, $\nu_s$ is parallel velocity, $v_θ$ is Alfvén velocity. Particle initial $v_\parallel = 0, v_\perp = 1$, initial $\phi = 0, \zeta = 0$.

- $v_\parallel/v_\perp = 0.15$ corresponds to E=16 keV.
- $v_\parallel/v_\perp = 0.2$ 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 $v_\parallel$ can change significantly, $v_\perp$ reversal in the inner region is observed when varying the mode structure.

Test particle studies

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

- As predicted, particle energy changes significantly at p=2 resonance and $\delta < 0.4$.
- 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

- Radial distribution
  \[ f(\phi) = \frac{1}{\sqrt{1 + \exp(\frac{\phi - \phi_0}{\delta_0})}} \]
  with $\phi_0 = 0.16, \delta_0 = 0.2$.
- EP density at magnetic axis $(n=0) = 9.16E17 [1m^3]$

Mode saturation and linear growth rate

Linear growth rate $\gamma_f$ 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: $\gamma_f = 0.98\%, A_{sat} = 4.2\times 10^{-3}$.
- 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 $\gamma_f$ is similar to A. Synergistic effect of $im(\sigma) & lm(\omega_f)$?
- Case C: $\gamma_f$ & $A_{sat}$ slightly change.

$\delta$ & particle redistribution

- Alfven mode leads to the flattening of density and energy profiles ($\delta m, \delta E < 0$ for $\zeta < 0.5$).
- Perturbative mode structures (B,C,D) lead to changes in particle and energy transport with $\delta m, \delta E$ deviating by ~10%.
- Parallel velocity profile changes significantly due to the non-perturbative mode structure symmetry breaking. In the inner region ($\zeta < 0.5$), $u_\parallel$ 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 $\sigma = 40, s = 0.4 + 0.02i$. Vary imaginary part of $\sigma$.
- $u_\parallel$ reversed with $lm(\omega_f)$.

<table>
<thead>
<tr>
<th>$\delta E/B$</th>
<th>$\sigma$</th>
<th>$s$</th>
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<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
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\[ E + \int \int \frac{\partial}{\partial E} \frac{\partial}{\partial E} \delta F \delta F \delta E \delta E \]

\[ \nu_{\perp}(\omega_c) - \nu(\omega) = \omega_c \]

\[ \nu(\omega_c) - \nu(\omega) = \omega_c \]

\[ f(\phi) = \frac{1}{\sqrt{1 + \exp(\frac{\phi - \phi_0}{\delta_0})}} \]

\[ A_{sat} = 4.2\times 10^{-3} \]

\[ \delta m, \delta E < 0 \]

\[ \delta m, \delta E \]

\[ \delta m, \delta E \]

\[ \delta m, \delta E \]

\[ \delta m, \delta E \]

\[ \delta m, \delta E \]

\[ \delta m, \delta E \]