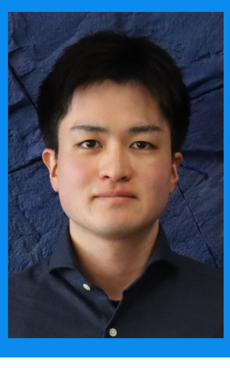
Experimental observation of stabilization effect of AE bursts due to resonant interaction with fast ions in LHD plasmas



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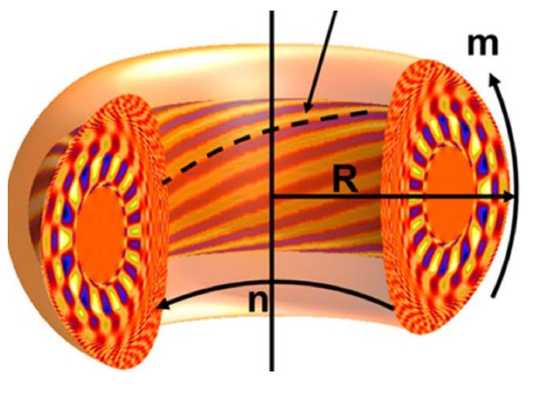
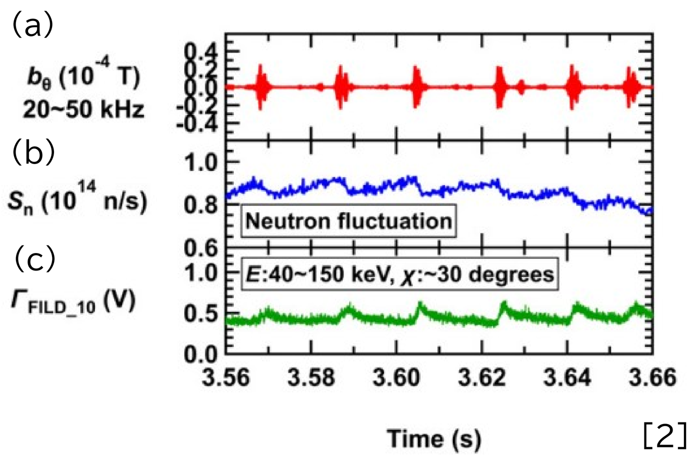
Importance of wave-particle interactions

- Fast ions play a crucial role in plasma heating
- Fast ions are anomalously transported due to resonant interaction with Alfvén Eigenmodes (AEs), resulting in degradation of heating efficiency
- Understanding wave-particle interaction is essential
- The phase-space dynamics of fast ions is the key to understanding wave-particle interaction



Schematic structure of Toroidal Alfven Eigenmode (TAE) [1]

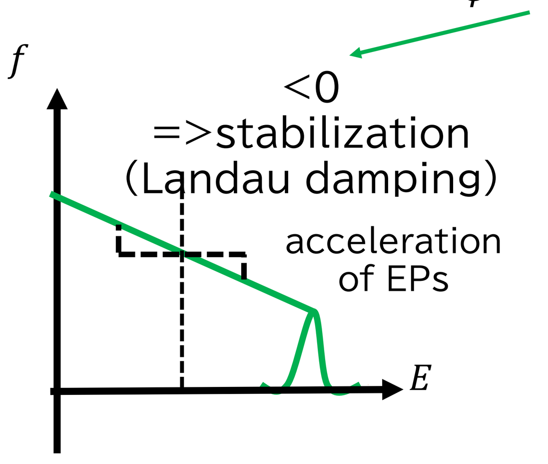


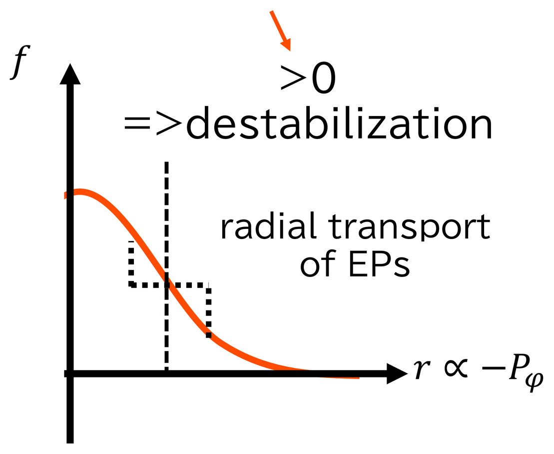
[2]

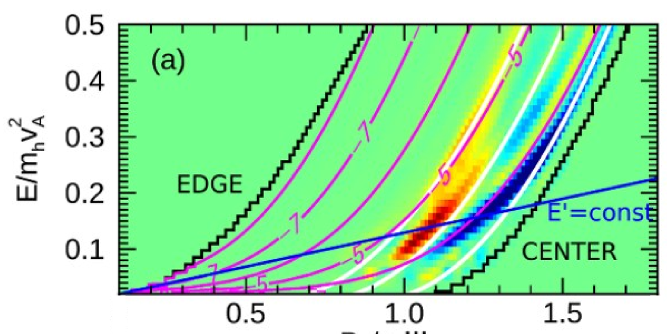
(a)Bursting activities of AEs
(b)Drop of indicator of fast ions in plasmas
(c)Increase of loss of fast ions

Contribution of Fast ions to AEs

- Fast ions interact with AEs while conserving $E' = E - \omega P_\varphi/n$ [3]
  - E : **energy**, ω :angular frequency n : toroidal mode number, P_φ : toroidal canonical momentum($\approx -e_h\Psi, \Psi \propto r$), Ψ : poloidal magnetic flux, r : **radial position**
- Free energy has components of energy and radial gradient
- $\frac{\partial f}{\partial E}\Big|_{E'} = \frac{\partial f}{\partial E} + \frac{n}{\omega}\frac{\partial f}{\partial P_\varphi} \approx \frac{\partial f}{\partial E} - \frac{n}{\omega}\frac{\tau q}{e_h B r}\frac{\partial f}{\partial r}$





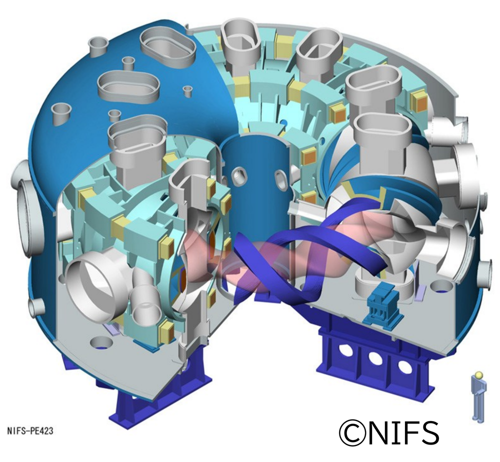


Simulated phase-space dynamics of fast ions interacting with TAE in a tokamak plasma [4]

Experimental study of wave-particle interaction

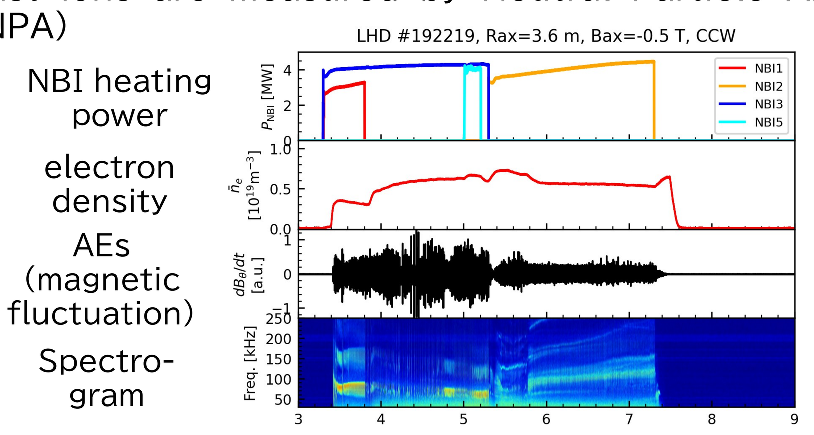
- Contribution of $\partial f/\partial r$ and resulting transport have been intensively investigated
- Experimental investigation of dynamics in energy space has been limited by insufficient time resolution of fast ion measurements
- **The objective of our research is to investigate the dynamics of fast ions in energy space, particularly by resolving the temporal evolution of AEs and analyzing the associated dynamics**

Experiment and measurement



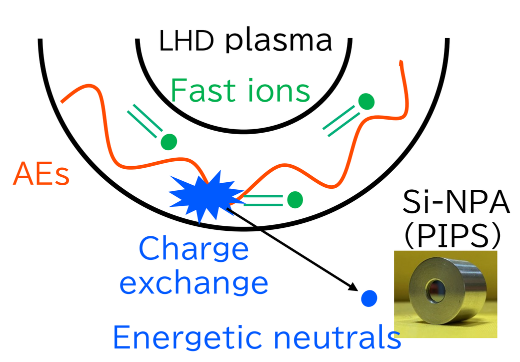
major radius	3.9m
minor radius	0.6m
plasma volume	30m³
magnetic field strength	~3T

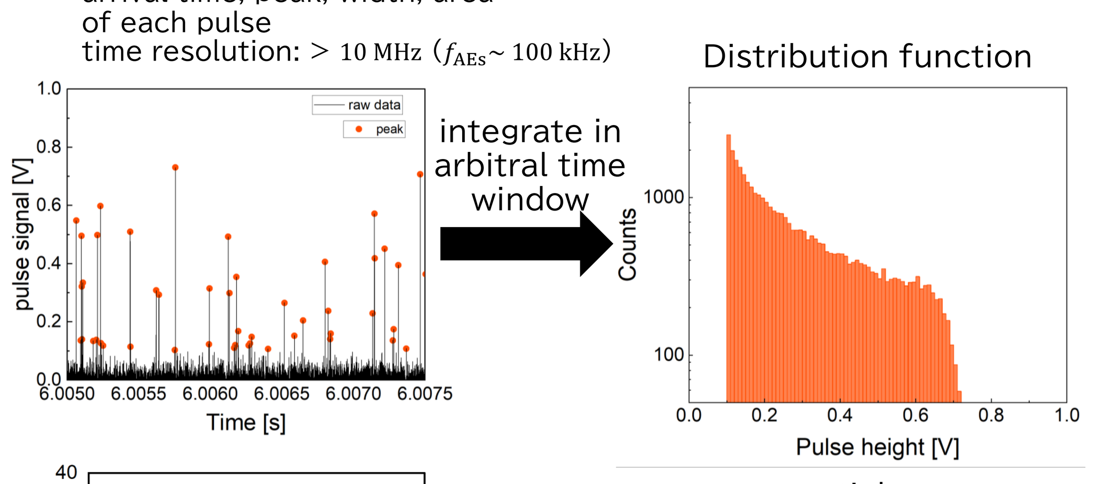
- Large Helical Device (LHD)
- Fast (super Alfvénic) ions are generated by Neutral Beam Injection (NBI)
- AEs are measured by magnetic probe
- Fast ions are measured by Neutral Particle Analyzer (NPA)



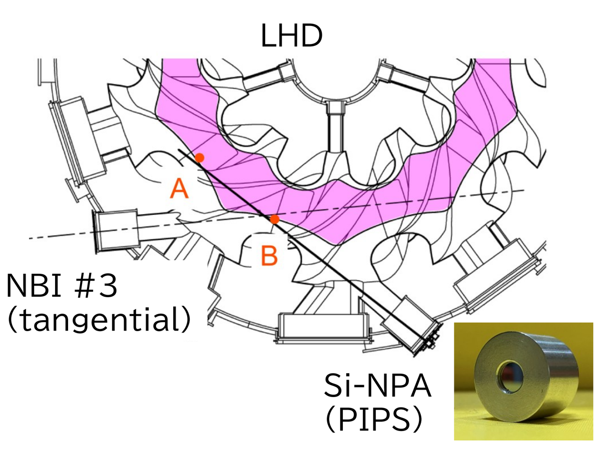
Typical discharge pattern

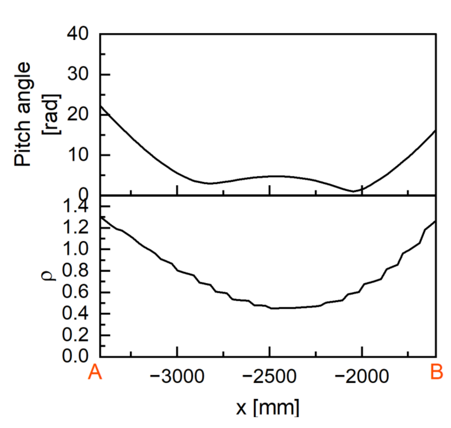
Direct observation of wave-particle interaction by Si-NPA with high-time resolution





∝ particle energy



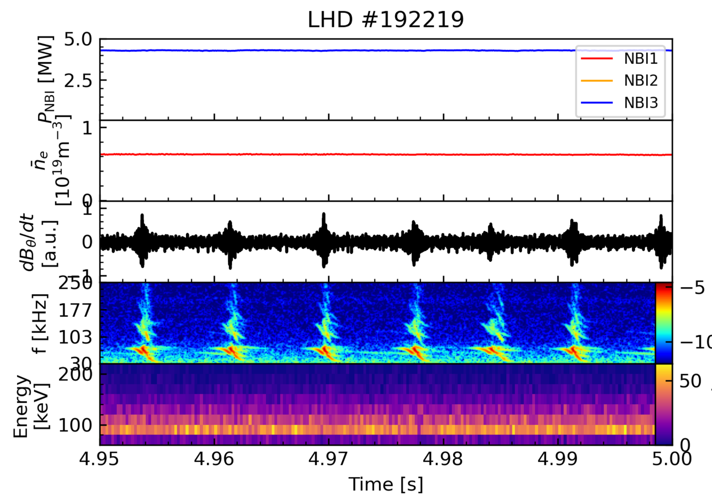


Localized measurement of fast ions injected by tangential NBI in the region where AEs are likely to be excited

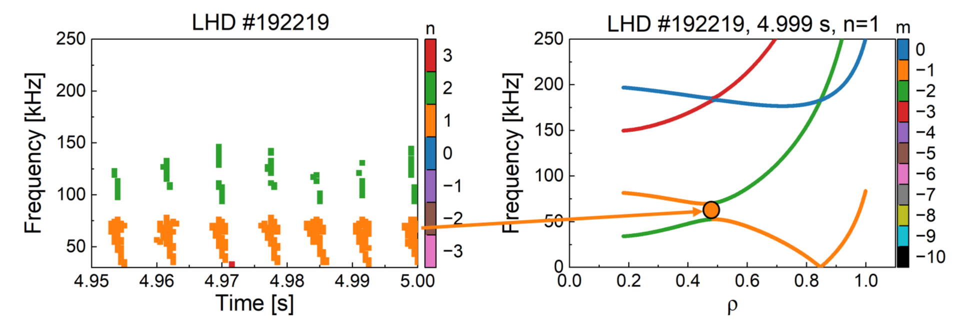
Summary

- We experimentally investigated interactions between fast ions and AEs through the dynamics of fast ions in energy space.
- In the LHD experiments, fast ions were measured by a Si-NPA with high-time resolution.
- Bursting AE activities were classified into growth/decay phases.
- The energy spectrum of fast ions in each phase was compared to that of the reference phase, where AE activity was negligible.
- Consequently, Landau damping of AEs by fast ions was observed in growth and decay phases.
- ➢ This suggests that fast ions simultaneously contribute to AEs in two competing ways: stabilization and destabilization.

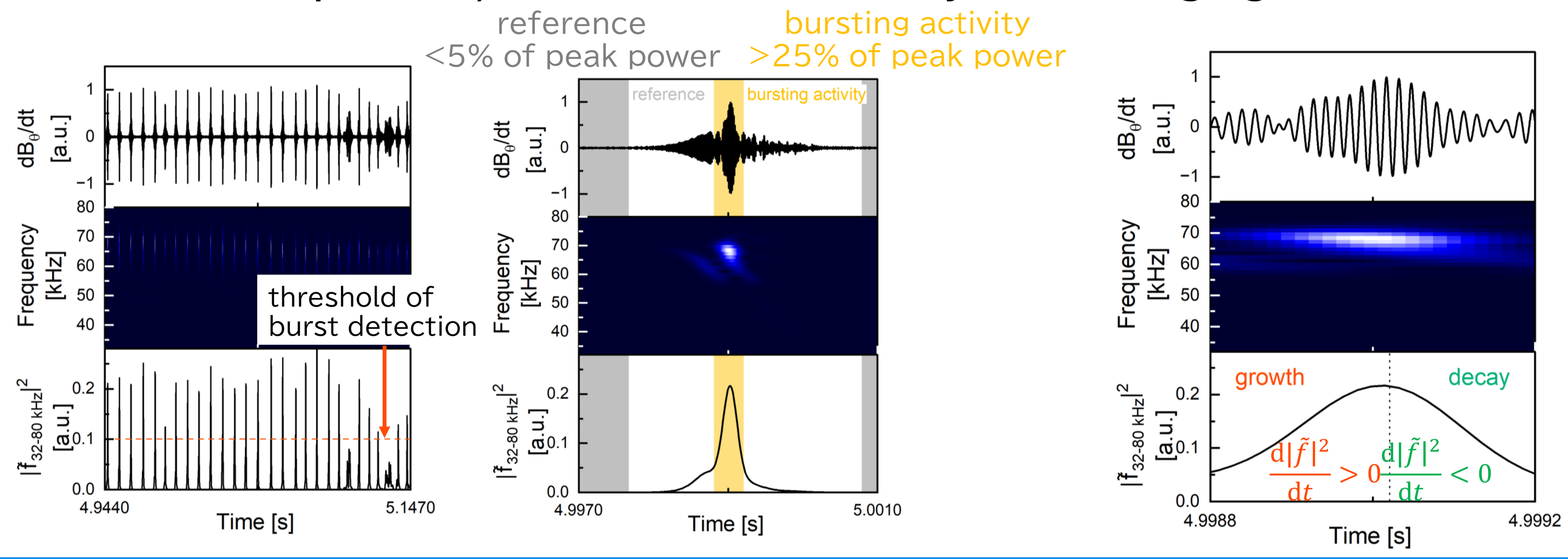
Typical discharge and Analysis of bursting activities



- TAE bursts were observed
  - $n = 1, |m|/|m+1| = 1/2$

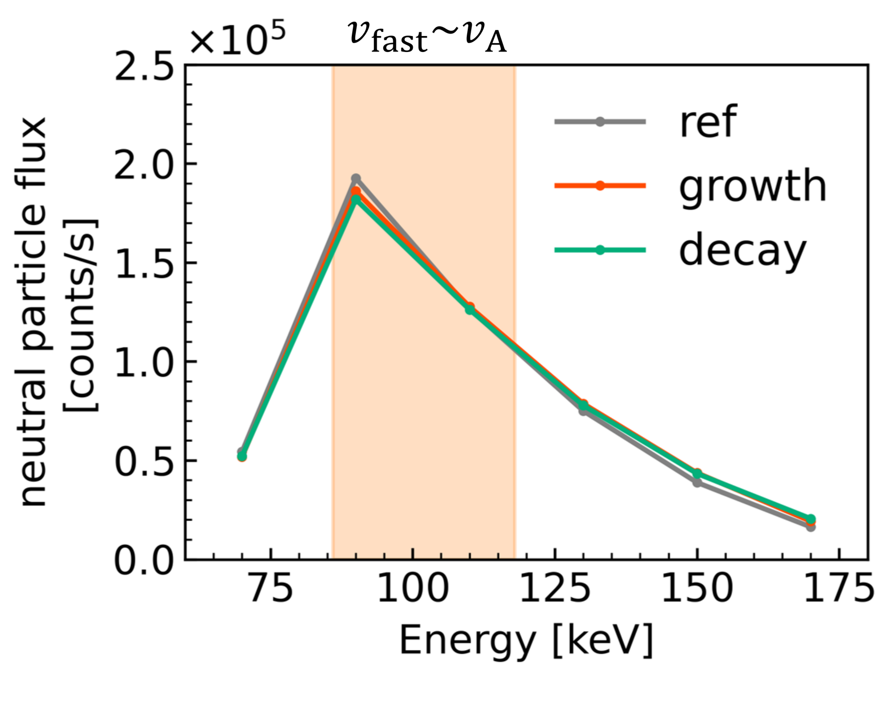


- The sign of the time derivative of the power spectrum was used to classify growth and decay phases of TAE bursts
- The energy spectrum of fast ions in each phase was conditionally averaged and compared to that of the reference phase, where AE activity was negligible

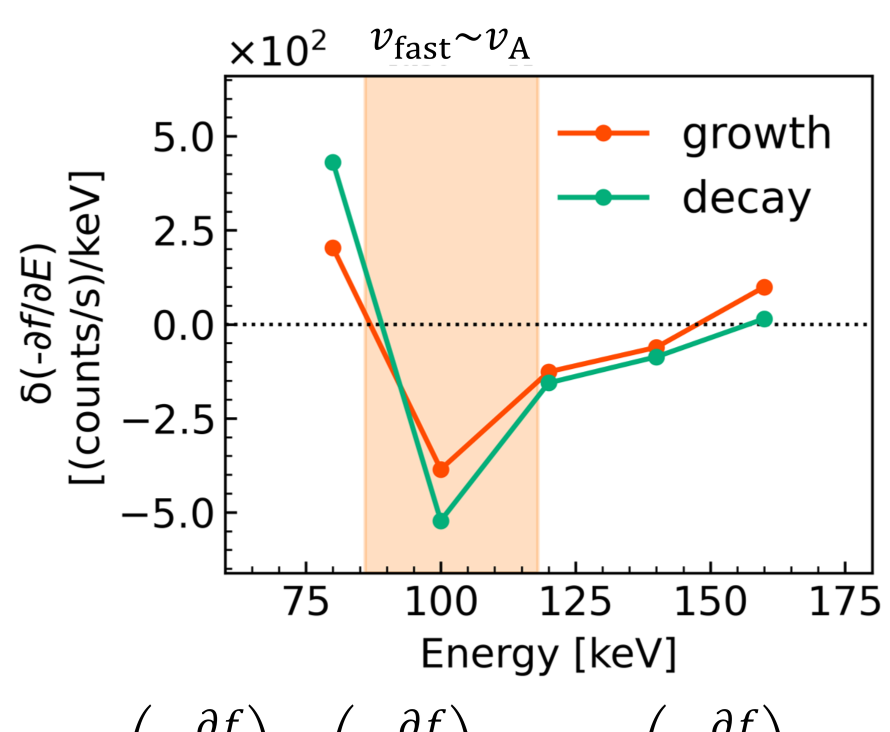


Stabilization of TAE bursts by fast ions

- Local reduction of the negative gradient
- ➢ Energy transfer from TAEs to fast ions
- Satisfies resonance condition ($v_{fast} \sim v_A$)
- ➢ **Landau damping of TAEs by fast ions**
- Landau damping was observed even in growth phases
- ➢ **This suggests that fast ions simultaneously contribute to AEs in two competing ways: stabilization and destabilization**



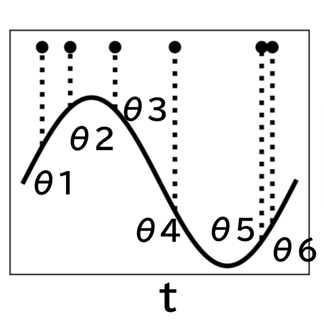
$f(E)$ =neutral particle flux



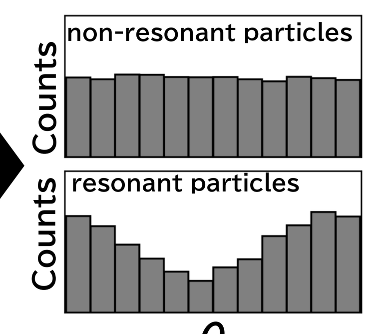
$$\delta\left(-\frac{\partial f}{\partial E}\right) = \left(-\frac{\partial f}{\partial E}\right)_{\substack{growth \\ decay}} - \left(-\frac{\partial f}{\partial E}\right)_{ref}$$

Future work

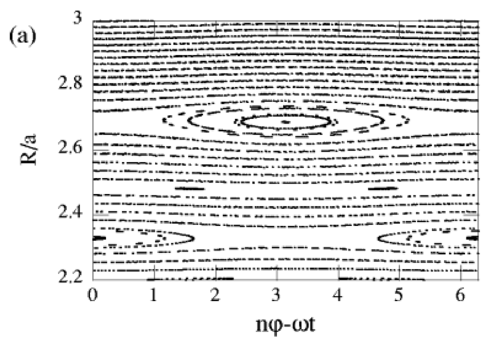
- Numerical validation using the FIDASIM code [5]
- Experimental observation and understanding of nonlinear processes, such as particle trapping



Phase relationship between fast ions and AEs



Distribution of fast ions in wave-rest frame



Phase-space structure due to particle trapping [3]

Reference: [1] Garcia-Munoz et. al, PPCF, 61, 054007 (2019) [2]Ogawa et al, Nucl. Fusion, 62, 11, 112001 (2022) [3] Todo, Rev. Mod. Plasma Phys. 3, 1 (2019) [4] Todo et. al, PPCF, 63, 075018 (2021) [5]Geiger et. al, PPCF, 62, 105008 (2020)

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