Fast Particle Losses due to Toroidal Alfvén Modes in JET

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INTRODUCTION

- Toroidal Alfven Eigenmodes (TAEs) can be destabilized in JET by resonant interaction with high energy particles (e.g. α-particles, neutral beam particles, RF-heated ions).

- Resonant interaction leads to exchange of momentum and energy between particles and wave, which can cause:
  * 'anomalous' losses of fast particles due to TAEs [1, 2],
  * radial redistribution of fast particles and the plasma heating profiles.

- In hot ion JET discharges a spectrum of Kinetic TAE-modes [3] (KTAEs) can appear and be driven unstable, so fast particle particle transport due to KTAEs also has to be taken into account.

- An analysis of fast particle losses in the presence of finite-amplitude TAEs and KTAEs in JET (which are supposed to be driven unstable) is the aim of the present work.

TWO CODES ARE USED IN THIS ANALYSIS

- TAE-spectra and mode structure of TAEs are calculated by the toroidal linear spectral code CASTOR [4] (resistive MHD code for general geometry and finite-pressure plasma equilibrium). KTAE-spectra are calculated by CASTOR in the "complex resistivity" approximation [5].

- CASTOR eigenfunctions together with associated equilibrium provide the electromagnetic field input for a new guiding centre particle following code HAGIS [6].

JET TAE SPECTRA

- α-particle driven TAEs were analysed in a high-performance Deuterium JET discharge (#26087), assuming $n_D = n_T$.
- It was found that a modest decrease in density would destabilise TAEs, with the most likely candidates for TAE instability n = 3 modes.
- Three n = 3 TAE modes have been recognized for JET equilibrium.

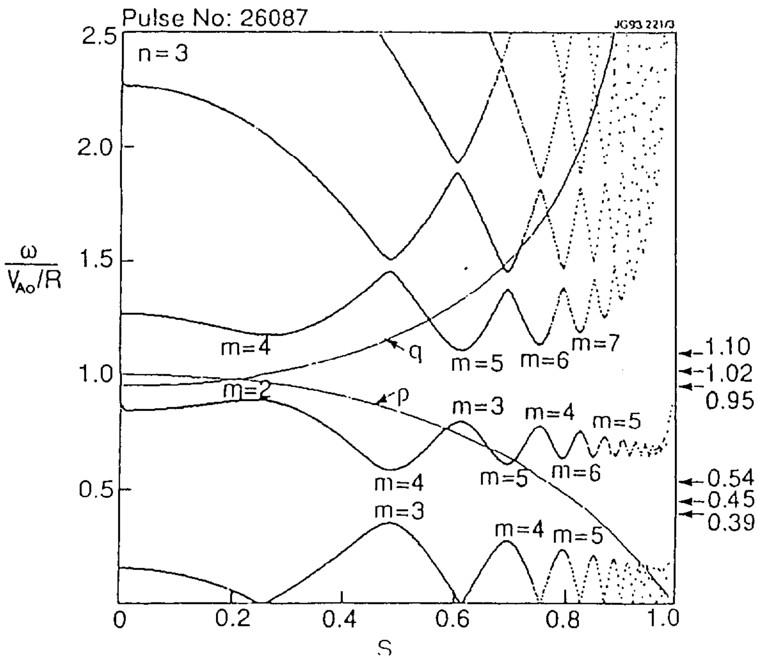


Fig. 1 Ideal MHD Spectrum for n = 3, s = $\psi^{1/2}$

Fig. 2 n = 3 TAE eigenfunction

COMPLEX RESISTIVITY APPROXIMATION FOR KTAE IN CASTOR CODE

- In hot-ion JET plasmas non-ideal effects due to Finite Larmor Radius of core ions become important to give the following corrections to the vorticity equation.

$$\underbrace{(\vec{b}\nabla)\left(\nabla_\perp^2(\vec{b}\nabla)\phi\right)+\nabla\left(\frac{\omega^2}{v_A^2}\nabla_\perp\phi\right)}_{\text{Ideal MHD Part}}+\underbrace{\frac{3}{4}\frac{\omega^2}{v_A^2}\rho_i^2\nabla_\perp^4\phi}_{\text{FLR}}+\underbrace{\left(1-i\delta(\nu_e)\right)\frac{\omega^2}{v_A^2}\rho_s^2\nabla_\perp^4\phi}_{E_\parallel\neq 0\ \text{Term}}=0$$

- In resistive MHD, analysed by CASTOR for $\left|\eta k_r^2/\omega\right| << 1$, the vorticity equation has a form

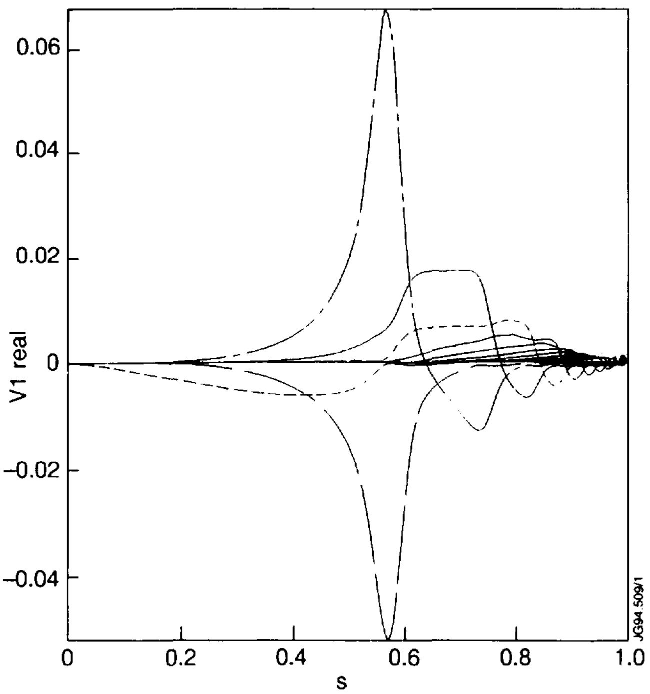
$$\underbrace{(\vec{b}\nabla)\left(\nabla_\perp^2(\vec{b}\nabla)\phi\right)+\nabla\left(\frac{\omega^2}{v_A^2}\nabla_\perp\phi\right)}_{\text{Ideal MHD Part}}+\underbrace{(\vec{b}\nabla)\left(\frac{i\eta}{4\pi\omega}\nabla_\perp^4(\vec{b}\nabla)\phi\right)}_{\text{Small resistivity}}=0$$

- In resistive term we put for KTAE $(\vec{b}\nabla)\approx\frac{i}{2qR}$ and introduce a "complex resistivity"

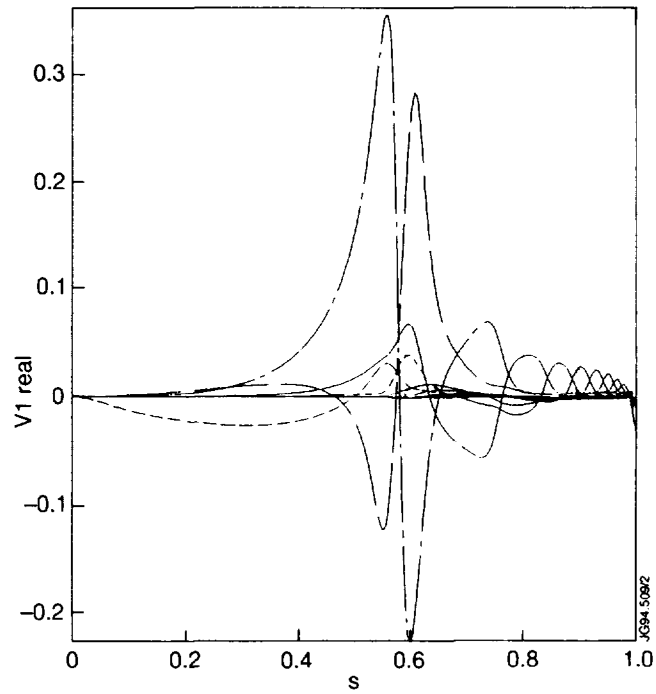
$$\eta = 4\pi\omega\rho_s^2\delta(\nu_e)+4\pi i\omega\left(\frac{3}{4}+\frac{T_e}{T_i}\right)\rho_s^2 .$$

This allows to analyse Kinetic TAE-spectrum with the aid of CASTOR.

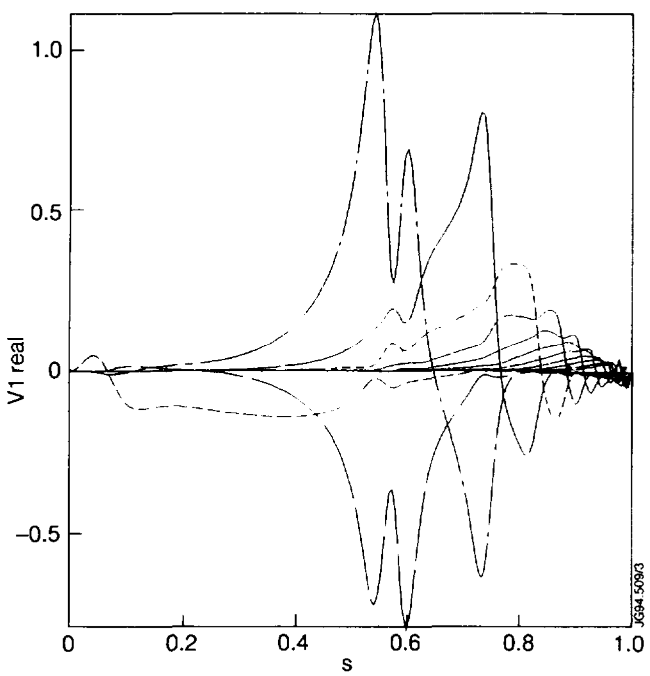
JET KTAE SPECTRA



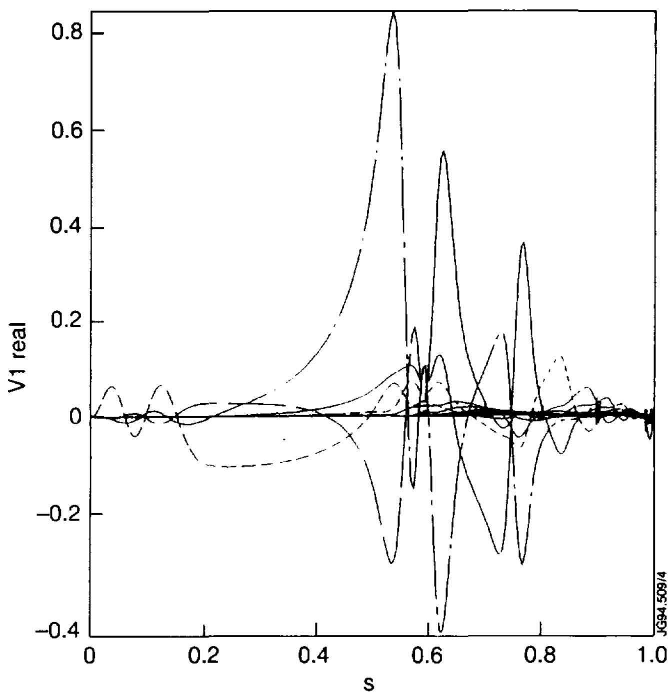
a) p = 0; ω/ω_A = 0.6768; γ/ω - 0.16%;



b) p = 1; ω/ω_A = 0.6901; γ/ω - 0.275%;



c) p = 2; ω/ω_A = 0.7170; γ/ω - 0.36%;



d) p = 3; ω/ω_A = 0.7365; γ/ω - 1.26%;

$\omega_A \equiv v_A(o)/R$.

Fig. 3 Kinetic TAE modes (n = 3) in JET: p is the quantum number of KTAE eigenvalue.

GUIDING CENTRE CODE HAGIS

(Hamiltonian Guiding Centre System)

Code follows particles within a plasma with general magnetic field under the influence of time-dependent electromagnetic perturbations.

- This code is based on a Hamiltonian formalism to enhance numerical accuracy.
- Without TAE perturbations for worst case (Pinch orbit) invariants of particle energy E and toroidal angular momentum P_φ conserved typically $0(10^{-10})$ over a poloidal transit.
- With TAE perturbation, the invariant $E-\omega P_\varphi/n$ is conserved $0(10^{-6})$ per transit.

FAST PARTICLE LOSS MECHANISIMS

- As in Ref. [1] two mechanisms for fast particle loss due to TAEs have been identified for JET cases studied:
- TAE-induced prompt losses near loss boundaries. These losses scale linearly with the applied TAE perturbation.
- Stochastic radial diffusion of fast particles occurs in the presence of finite-amplitude TAE when the particle excursions due to the primary and side-band TAE resonances overlap. For several excited TAEs global stochastic diffusion into loss cones may occur.

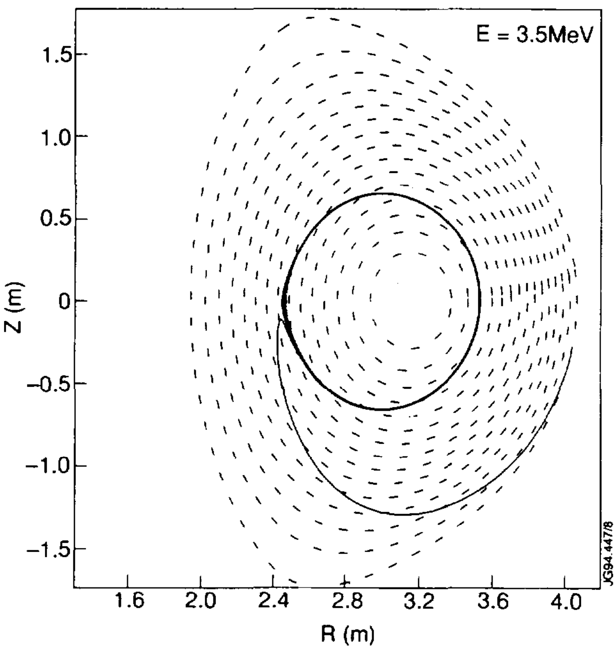


Fig. 4 Conversion of a barely passing particle into lost banana.

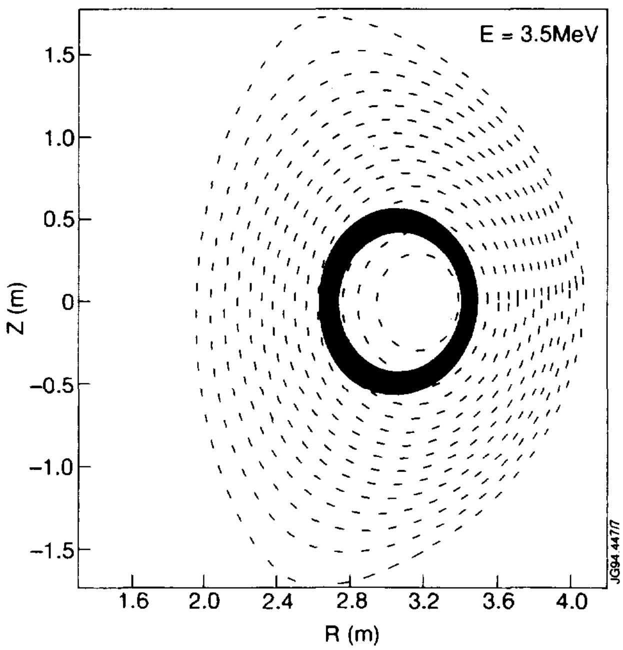


Fig. 5 Stochastic diffusion due to single n = 3 TAE.

TRANSITION FROM REGULAR TO STOCHASTIC PARTICLE MOTION DUE TO TAE

- For a single TAE mode the stochasticity threshold was analysed by examining the particle islands in a frame of reference which moves at the TAE frequency (i.e. $\zeta - \omega t/n$).
- Fairly high stochasticity threshold $\delta B_r / B \approx 3 \times 10^{-3}$ was found to be typical for single n = 3 mode, localised in the low shear region.

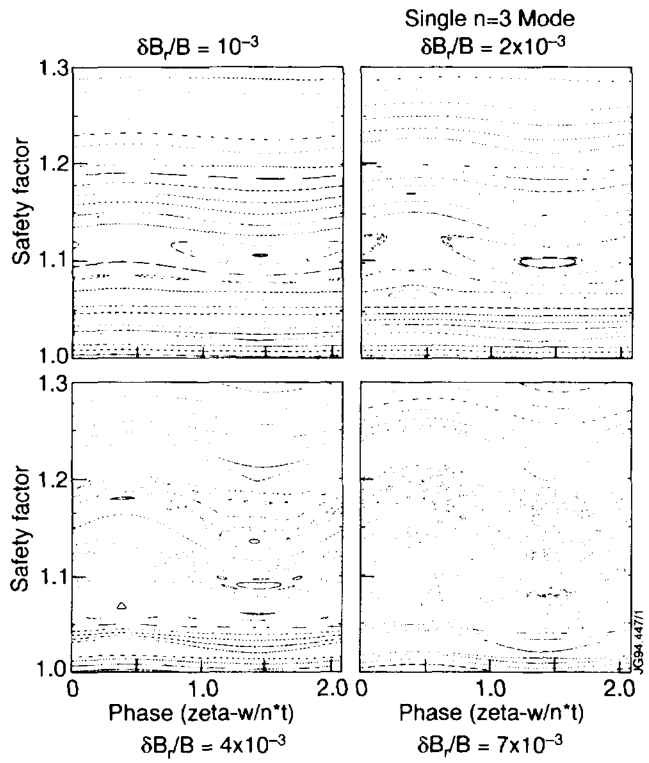


Fig. 6 Particle islands in the q = 0 plane plotted versus the phase (ζ–$\omega t/n$). The total (i.e. all poloidal harmonics) $\delta B_r/B_0$ values are: (a) 10^{-3}, (b) 2×10^{-3}, (c) 4×10^{-3} and (d) 7×10^{-3}.

- For multiple n = 3 TAE pertubations (of different frequency) the stochasticity threshold was found to be $\delta B_r / B \sim 10^{-3}$.

FAST PARTICLE LOSSES DUE TO TAE

- To study particle losses Monte-Carlo simulations of 50,000 α-particles have been made.
- α-particles have a slowing down distribution with 1.5 MeV ≤ E ≤ 3.5 MeV, a radial distribution α $(1-\Psi)^3$ and a random distribution in pitch angle, poloidal angle and toroidal angle.

- Three n = 3 TAE modes (ω/ω_A = 0.41, 0.51 and 0.58) have been used.

- These Monte-Carlo simulations show two distinct classes of lost α-particles with different time scales:
  * TAE-induced prompt losses (in ~20 μs) of particles born near a loss boundary.
  * Above a global stochasticity threshold continued long term loss of α-particles by stochastic diffusion into a loss boundary.

- Lost fast particle flux has a maximum at the outboard mid-plane, due to co-directed trapped and passing particle orbits intercepting the 'wall'.

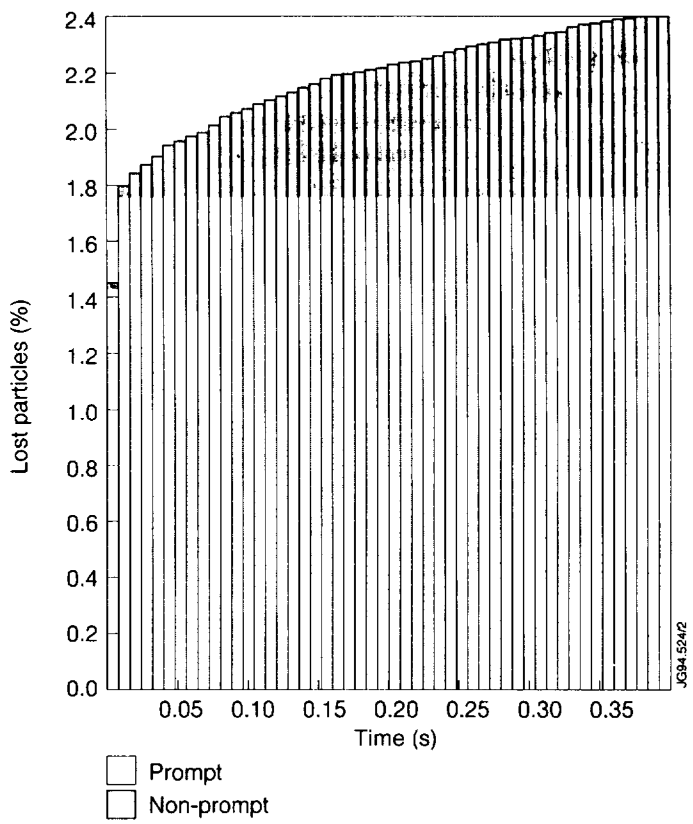


Fig. 7 Total number of lost particles versus time for $\delta B_r/B = 3\times10^{-3}$.

STOCHASTIC DIFFUSION DUE TO KTAE

- TAE- and Kinetic TAE-modes have different poloidal localization and eigenfrequency spectrum, so that fast particle transport due finite amplitude KTAEs has to be studied separately from TAE.

- A particle diffusion coefficient due to n = 3 KTAE-spectrum (p = 0, ..., 3-modes) and n = 3 TAE-spectrum was measured as a particle distribution spread $\langle \Delta P_\varphi^2 \rangle = \langle P_\varphi^2 \rangle - \langle P_\varphi \rangle^2$ in time ($\langle \quad \rangle$ = ensemble average).

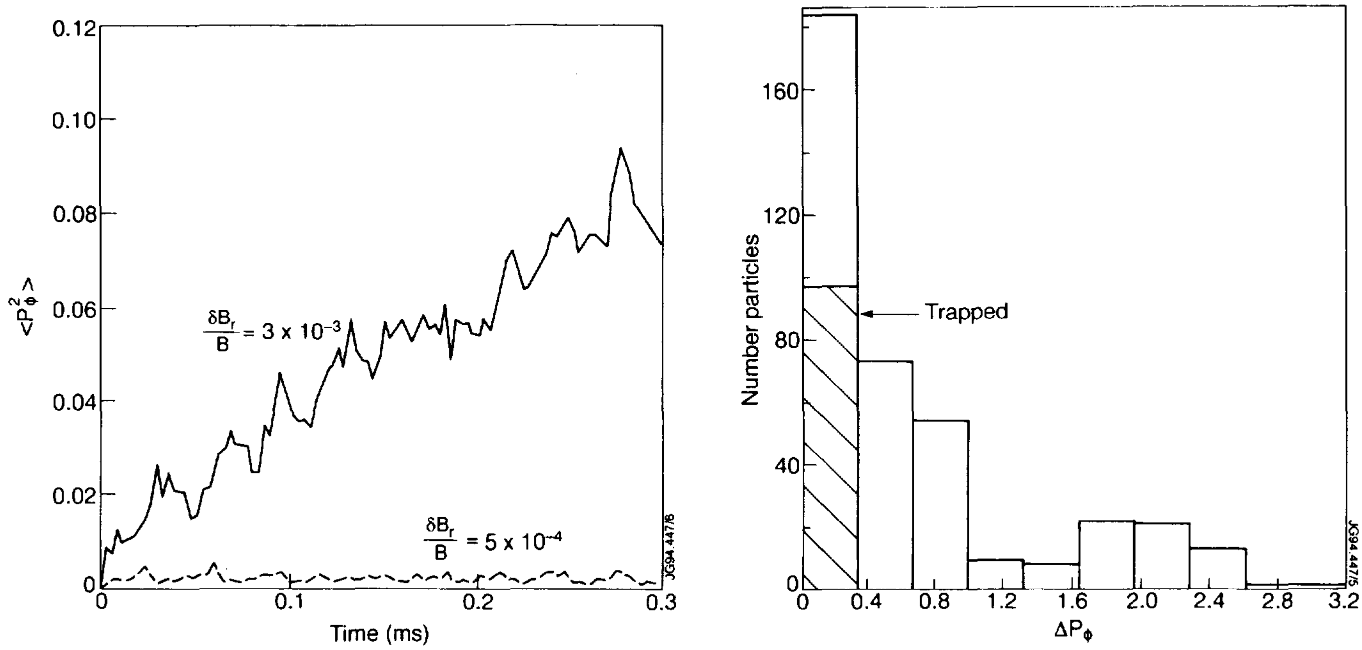


Fig. 8 (a) Variation of $\langle \Delta P_\varphi^2 \rangle \times 10^{40}$ with time for $\delta B_r/B = 3 \times 10^{-3}$ and 5×10^{-4} for TAE-case.
(b) Number of particles with given $\Delta P_\phi \times 10^{20}$ for $\Delta B_r/B = 3 \times 10^{-3}$, the shaded bars are trapped particles

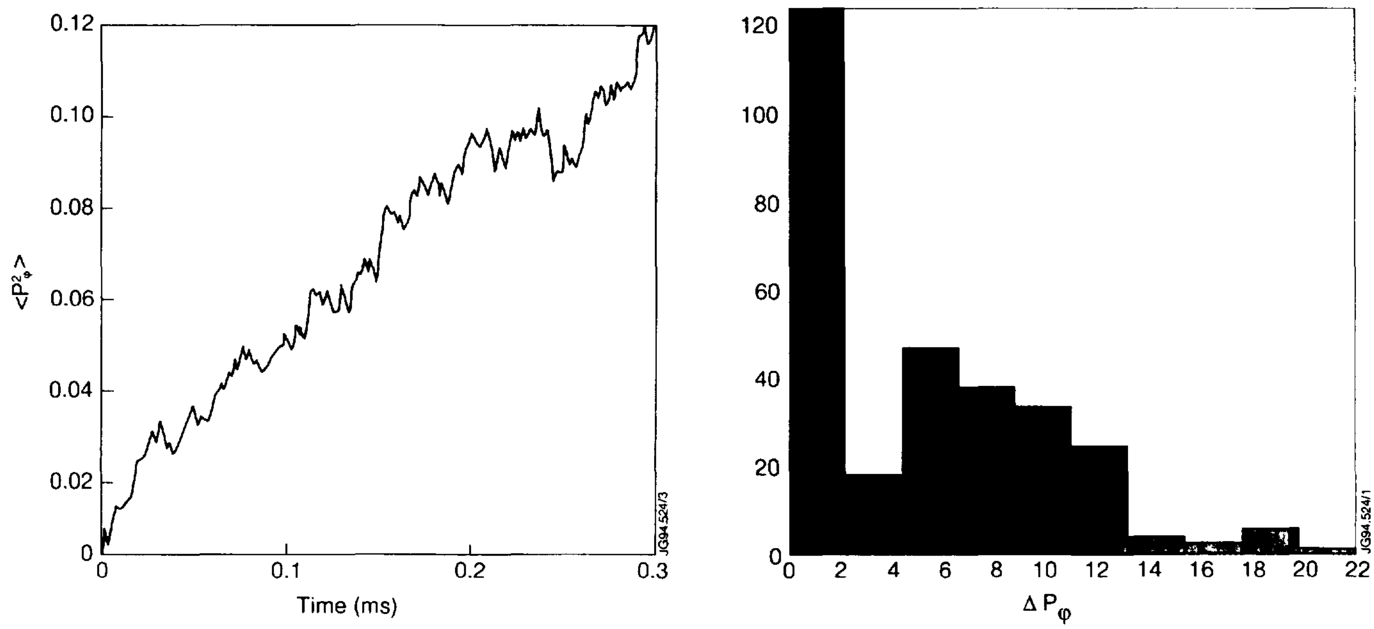


Fig. 9 (a) Variation of $\langle \Delta P_\varphi^2 \rangle \times 10^{40}$ with time for $\delta B_r/B = 4 \times 10^{-3}$ for KTAE-case.
(b) Number of particles with given $\Delta P_\phi \times 10^{20}$ for $\delta B_r/B = 4 \times 10^{-3}$.

- At the same amplitude per mode $\delta B_r/B = 10^{-3}$ KTAE-induced diffusion was found to be DKTAE ~ 1.5DTAE.

SUMMARY

- An extension of CASTOR code for the "complex resistivity" case has been developed to obtain the Kinetic TAE-spectrum in JET plasmas.

- A guiding centre particle following code HAGIS has been developed to study fast particle motion in the presence of unstable TAE and Kinetic TAE modes in JET.

- Additional 1% of α-particles are lost due to the studied n = 3 TAE-mode of $\delta B_r/B = 3 \times 10^{-3}$.

- KTAE-induced collisionnless fast particle diffusion was found to be DKTAE ~ 1.5DTAE at the same amplitude per mode $\delta B_r/B = 10^{-3}$.

- In cases studied alpha-particle losses due to TAE/KTAE cannot lead to the degradation of global confinement in JET, but can be unfavourable for first wall /divertor due to high localization of losses in poloidal direction.

- Possible anomalous radial redistribution of fast particle heating profile due to TAE/KTAE might be important and has to be studied in self-consistent approximation.

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