Transport of Energetic Particles in STs due to Non-Conservation of the Magnetic Moment

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TIME VARIATIONS OF MAGNETIC MOMENT

$$\dot{\mu} = v_\perp \left(v_\perp^2 + v_\parallel^2\right)/(B\rho)\sin\alpha, \quad \dot{\alpha} = -\omega_{Bi},$$

$\mu = v_\perp^2/B$ **- magnetic moment,**

α **- gyro-phase,**

$v_\perp$ **- perpendicular component of particle velocity,**

ω_{Bi} **- cyclotron frequency and**

ρ **- curvature radius of magnetic field line**

For $\rho_L/\rho << 1$ **magnetic moment** $\mu = \bar{\mu} + \delta\mu$

$\bar{\mu}$ **- gyro-averaged magnetic moment**

$\delta\mu/\mu = W/(\mu\omega_B)\cos\alpha \quad (\rho_L/\rho)(v_\parallel/v_\perp)\cos\alpha$ **- gyro oscillations**

$d\bar{\mu}/dt \neq 0$ **due to resonant interaction of ion gyration and bounce oscillations of guiding center**

RESONANCE CONDITION

$$\omega_{Bi} = l\omega_b, \quad l = 1,2, \ldots$$

ω_{Bi}, ω_b – gyro and bounce frequencies,

$l = \omega_B/\omega_b \propto (R/\rho_L)(qA^{0.5}) \sim 10^2\text{-}10^3$ for fast ions in conventional tokamak

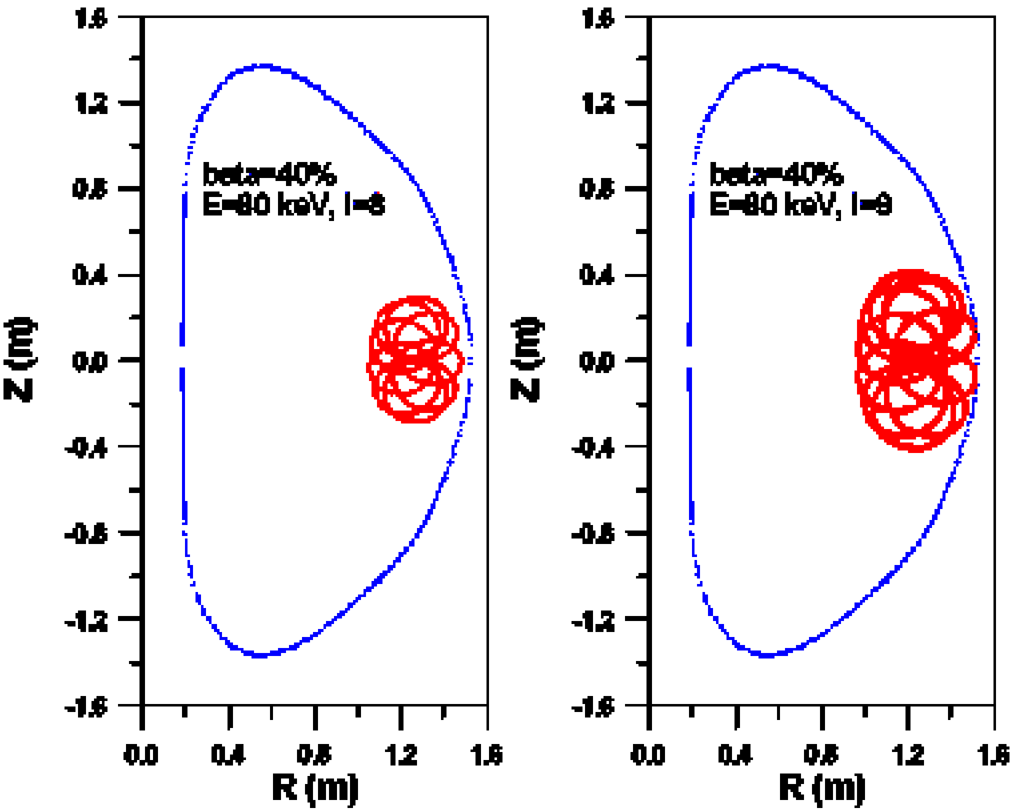
$l = \omega_B/\omega_b \sim$ 10-30 for NBI ions in NSTX

low l essentially enhances efficiency of resonant interaction

GYRO-ORBITS 0F NBI IONS IN NSTX

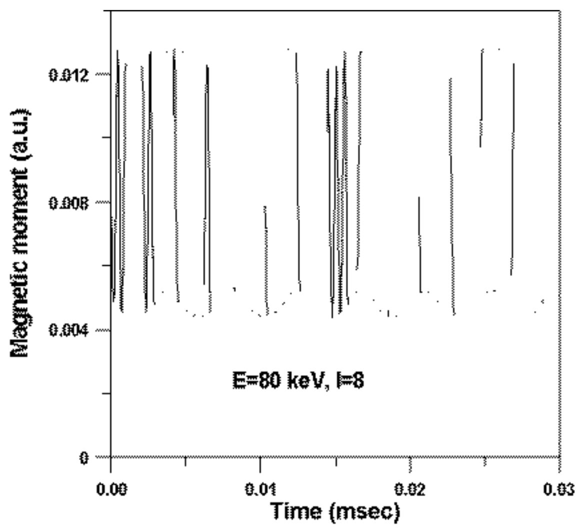
1. Quasi-adiabatic orbits (deeply trapped fast ions)

Variation of gyro-averaged μ is superposition of regular oscillations $\Delta\bar{\mu}_{b} + \Delta\bar{\mu}_{sb}$ with bounce (ω_b) and "superbanana" (ω_{sb}) frequencies correspondingly; ($\omega_{sb} << \omega_b$)

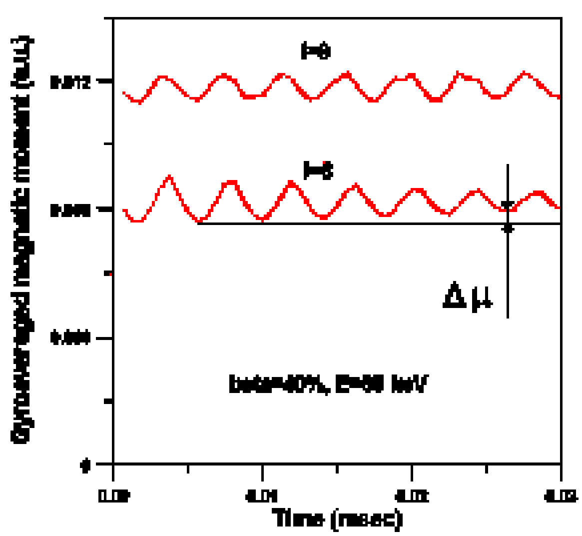


Time variations of magnetic moment

a) time variations including gyro-oscillations



b) gyro-averaged oscillations of μ

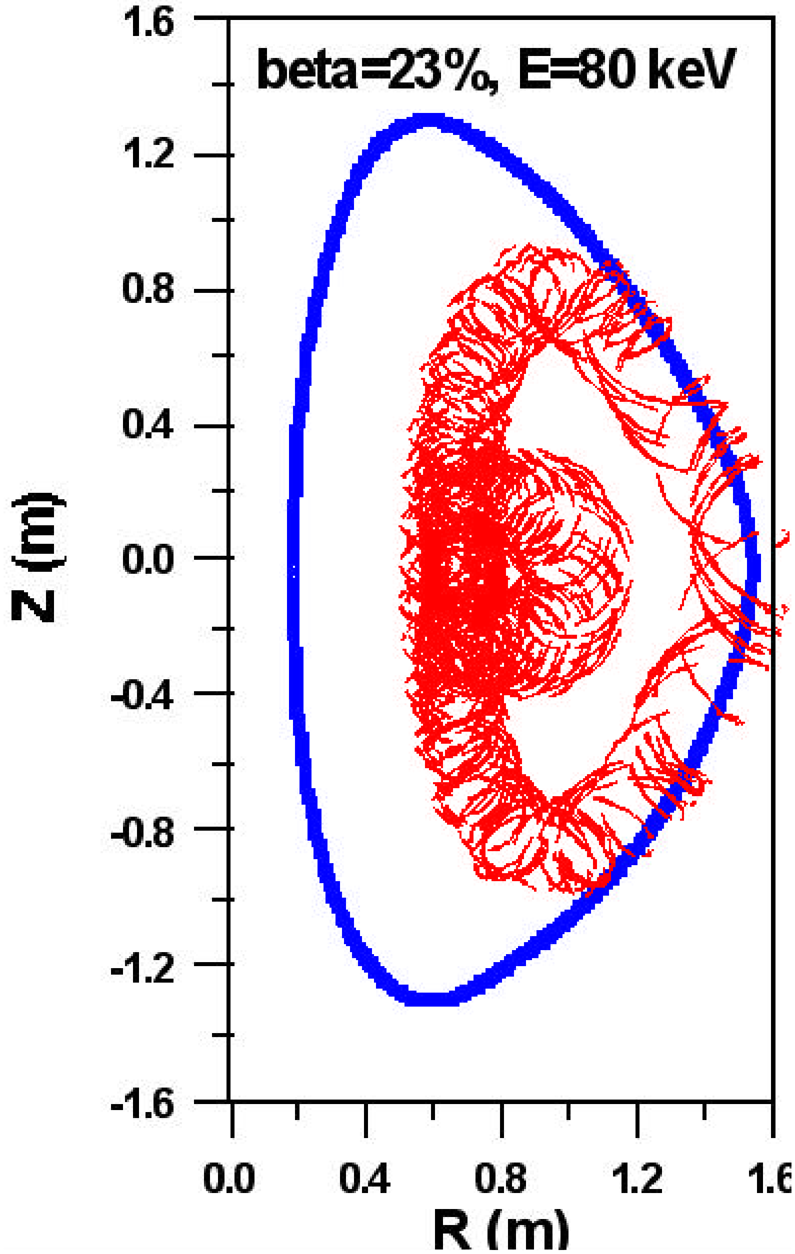


$\Delta\mu_{sb} << \mu_{l+1} - \mu_l$

$\mu_{l+1} - \mu_l$ - distance between two neighbouring resonances

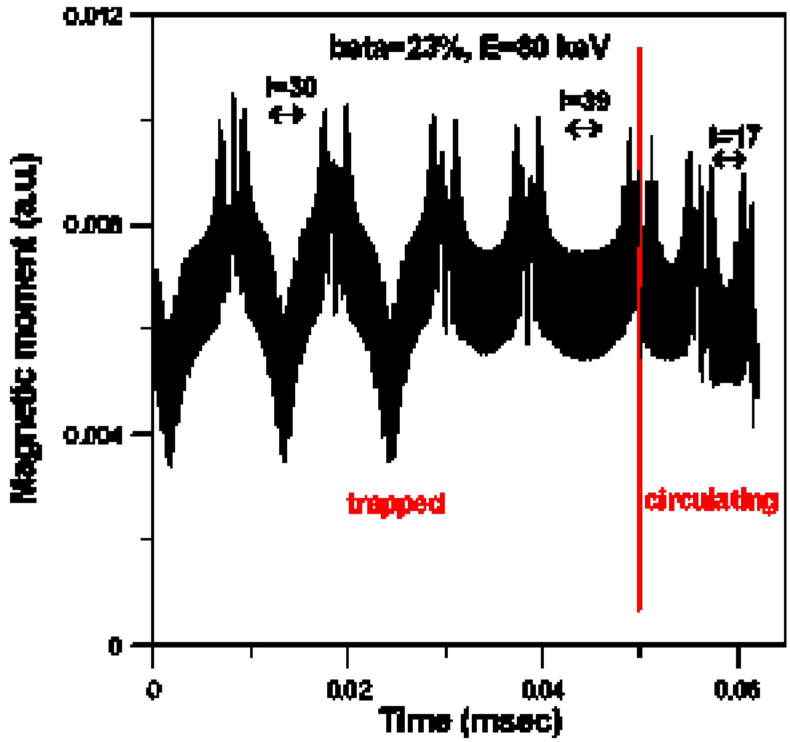
Variations of μ are adiabatic – no stochasticity

2. Stochastic behaviour of circulating and barely trapped ions



Barely trapped orbit transforming into circulating one due to the nonconservation of magnetic moment ($\Delta E/E < 10^{-5}$, $\Delta P_{\varphi}/P_{\varphi} < 10^{-6}$)

time variations of magnetic moment



$\Delta\mu_{sb} >> \mu_{l+1} - \mu_l$

For above Fig. distance between two neighbouring resonances, $\mu_{l+1} - \mu_l \sim 10^{-2}\mu$, **while** $\Delta\mu_{sb} > 10^{-1}\mu$

Circulating and barely trapped NBI ions in NSTX possess stochastic behaviour due to non-conservation of magnetic moment

For typical variation of magnetic moment per bounce period, $\Delta\mu_b \sim 10^{-2}\mu$, **we obtain the following estimation of stochastic diffusion rate in magnetic moment**

$$D_{st}/\mu^2 \approx \frac{(\Delta\mu_b)^2 \omega_b}{\mu^2} \lesssim 10\,s^{-1} << \nu$$

CONCLUSION

nonconservation of magnetic moment of fast particles in NSTX shown to result in stochastic behaviour of circulating and barely trapped NBI ions and rather strong diffusion of them in radial coordinate and pitch-angle