Bounce Frequency Fishbones

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September 2002

Supported by US DoE, NSF

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NSTX

PPPL
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• Large amplitude bursting modes are observed on NSTX, which are identified as bounce frequency fishbone modes.

• They are predicted to be important in discharges with a significant population of trapped particles with a large mean bounce angle, such as produced by near tangential beam injection into a small aspect ratio device.

• Such a distribution is often stable to the usual precession-resonance fishbone mode.

•These modes could be important in ignited plasmas, driven by the trapped alpha particle population.

PACS numbers: 52.35.Py 52.40.Mj

• Resonant interaction of high energy particles with magnetic perturbations in toroidal devices can produce large scale modification of the particle distribution, sometimes leading to particle loss.

• A well known example of this is the fishbone mode, first observed as a resonance with the mean particle toroidal precession.

PDX Group, PPPL, *PRL* **50**, 891 (1983).
White, Goldston, McGuire, Boozer, Monticello, Park *Phys Fluids* **26**, 2958 (1983).
Chen, White, and Rosenbluth *PRL* **52**, 1122 (1984).

Coppi and Porcelli *PRL* **57**, 2272 (1986).

• Later the fishbone was found to be possible also as a resonance with passing particles at the transit frequency.

Heidbrink et al *PRL* **57**, 835 (1986).
Betti and Freidberg *PRL* **70**, 3428 (1993).

Kolesnichenko, Marchenko, White *Phys Plasmas* **8**, 3143 (2001).

MODE-PARTICLE INTERACTION

•The analysis of the resonant interaction of high energy particles with magnetohydrodynamic (MHD) modes is well known.

• Perturb the equilibrium field $\vec{B}$ with $\delta\vec{B} = \nabla \times \alpha\vec{B}$ and also introduce an electric perturbation Φ.

$$\alpha = \alpha_{mn} e^{i(n\zeta - m\theta - \omega t)} \qquad \Phi = \Phi_{mn} e^{i(n\zeta - m\theta - \omega t)}.$$

•MHD mode, α_{mn} and Φ_{mn} related. $\nabla \times \vec{E} = -\partial_t \vec{B}$

$$\vec{E} = -\partial_t \alpha\vec{B} - \nabla\Phi = \omega\alpha_{mn} cos(n\zeta - m\theta - \omega t)\vec{B} - \nabla\Phi.$$
$$E_{\|} = \omega B \alpha_{mn} cos(n\zeta - m\theta - \omega t) - \vec{B} \cdot \nabla\Phi/B = 0.$$

• Using $\vec{\mathbf{B}} = \mathbf{g}(\psi)\nabla\zeta + \mathbf{I}(\psi)\nabla\theta + \delta\nabla\psi$
$\omega\alpha_{mn} = (nq - m)\Phi_{mn}/(gq + I)$

$$\frac{dE}{dt} = i\left[-n\dot{\zeta}_d + m\dot{\theta}_d\right]\Phi_{mn} e^{i(n\zeta - m\theta - \omega t)} - \Phi'_{mn}\dot{r} e^{i(m\theta - n\zeta - \omega t)}$$

$\dot{\zeta}_d$, $\dot{\theta}_d$, $\dot{r}$ the drifts

• Pendulum dominated by fundamental even for large bounce angle $\theta = (\theta_b + \delta) sin\omega_b t + \delta sin 3\omega_b t$ with $\delta = \theta_b^3/192$
$\omega_b = 1 - \theta_b^2/16$.

•An analysis was made of beam particles for NSTX shot 106218 at t = .13 sec

TRANSP to produce the equilibrium and the distribution of beam particles

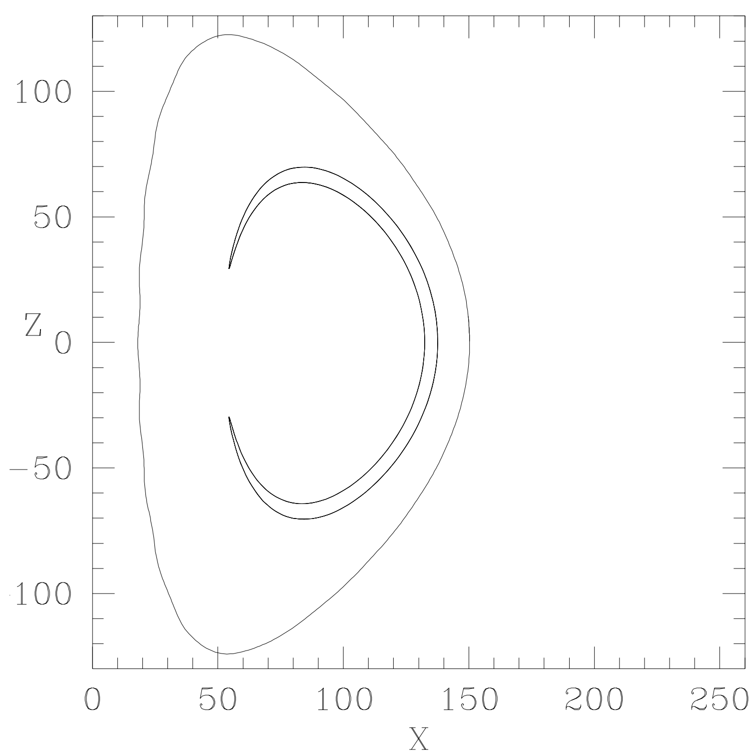
R. V. Budny, M. G. Bell A. C. Janos *et al*, Nucl Fusion **35**, 1497 (1995)

ORBIT to follow beam particle trajectories.

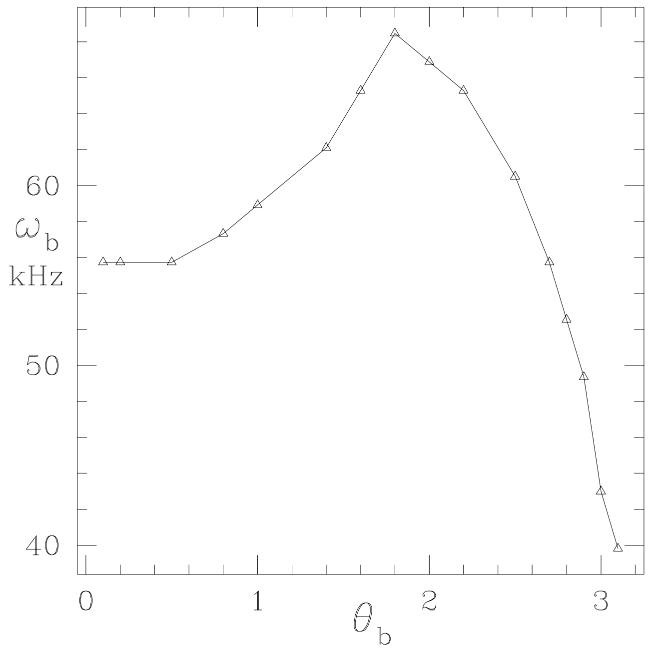
R.B. White, "The theory of toroidally confined plasmas", Imperial College Press, 2001.

R.B. White and M. S. Chance, Phys. Fluids **27** 2455 (1984)

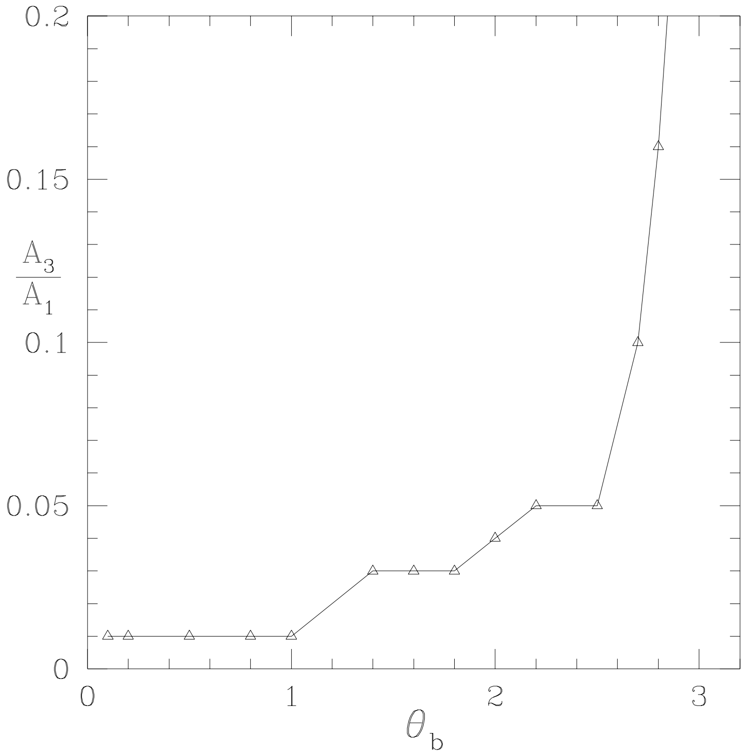
R.B. White, Phys. Fluids B **2**(4), 845 (1990)



•A banana orbit in NSTX behaves much like a pendulum



Bounce frequency vs bounce angle for 80 keV beam ion



Fundamental dominates for bounce angle less than 2.5

• Bounce motion dominated by the fundamental harmonic $\theta = \theta_b sin\omega_b t$.

•Trapped particles
$\theta = \theta_b sin\omega_b t, \quad \zeta = q\theta_b sin(\omega_b t), \quad r = r_0 + \rho_b e^{i\omega_b t}$
with r_0 the banana center, ρ_b the banana width

Bessel expansion $e^{ia\theta} = \sum_l J_l(a\theta_b)e^{il\omega_b t}$

$$\frac{dE}{dt} = i\left[-n\dot{\zeta}_d + m\dot{\theta}_d\right]\Phi_{mn}e^{i(n\zeta - m\theta - \omega t)} - \Phi'_{mn}\dot{r}e^{i(m\theta - n\zeta - \omega t)}$$

$$\frac{dE}{dt} \simeq -i\omega_d\Phi_{mn}\sum_l J_l((nq-m)\theta_b)e^{iQ_l}$$
$$-i\omega_b\rho_b\Phi'_{mn}\sum_l J_l((nq-m)\theta_b)e^{Q_{l+1}}$$

where $Q_l = n\omega_d t + l\omega_b t - \omega t$

• Resonance $Q \simeq constant.$
$\omega_d\Phi_{mn}$ resonant at $\omega = n\omega_d$ for $l = 0$
Also resonant at $\omega = n\omega_d \pm \omega_b$ for $l = \pm 1$
$\omega_b\rho_b\Phi'_{mn}$ resonant at $\omega = n\omega_d + \omega_b$ for $l = 0$

•Dominant resonant frequency determined by the particle distribution, the radial dependencies of Φ_{mn}, q and the bounce and precession frequencies.

Can have a whole zoo of fishbone frequencies, depending on particle distribution

•Usual fishbone is global mode so $\rho_b \Phi'_{mn} \ll \Phi_{mn}$ and deeply trapped particles, $\theta_b \ll 1$ so only $l = 0$ and $\omega = \omega_d$ is possible.

•For localized mode and or large θ_b resonance at $\omega \simeq \omega_b$ is also possible

$$\frac{dE}{dt} = K sin(Q) \qquad\qquad \frac{dQ}{dt} = n\omega_d + \omega_b - \omega$$

with $K \simeq \omega_d \Phi_{mn} J_1((m - nq)\theta_b) + \rho_b \omega_b \Phi'_{mn} J_0((m - nq)\theta_b)$.

•Expand $dQ = \partial_E Q(E - E_0)dt$ about $n\omega_d + \omega_b = \omega$

Use $\partial_E \omega_d = \omega_d/E$, $\partial_E \omega_b = \omega_b/2E$.

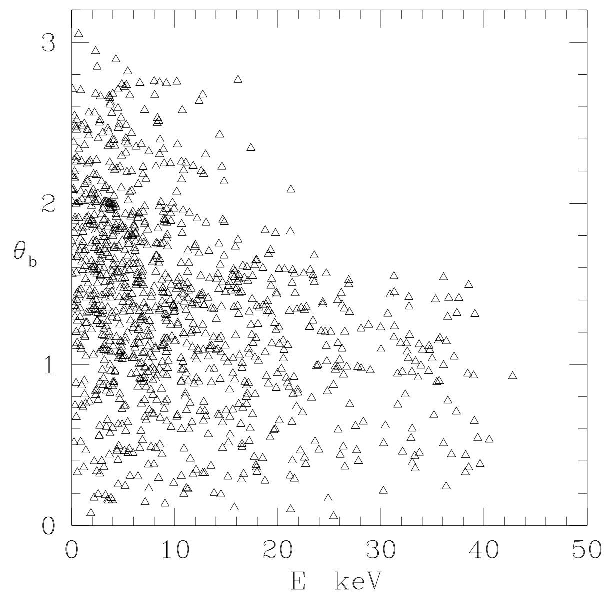
•Island in energy, minor radius, and frequency of the form

$(E - E_0)^2/2 = c - 2kcosQ$

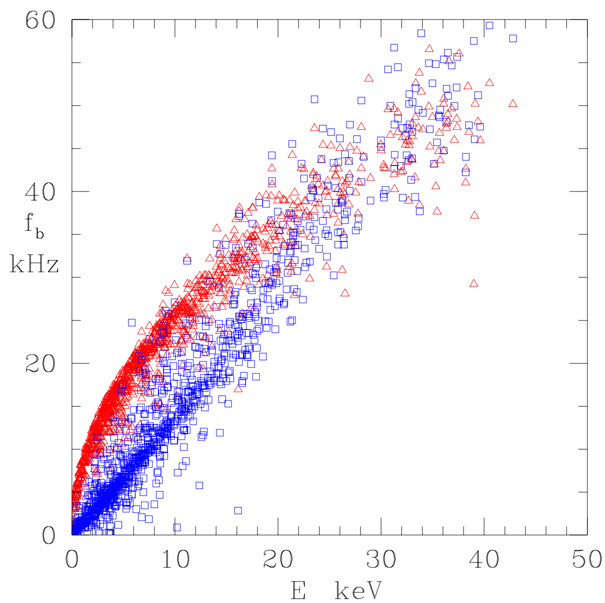
with $k = EK/\omega_b$

NSTX shot 106218 at t = .132 sec

- Beam is 24 percent trapped
- Trapped component has a very large mean bounce angle



Distribution of bounce angle vs energy. Mean = 1.6



Bounce and Precession can be comparable

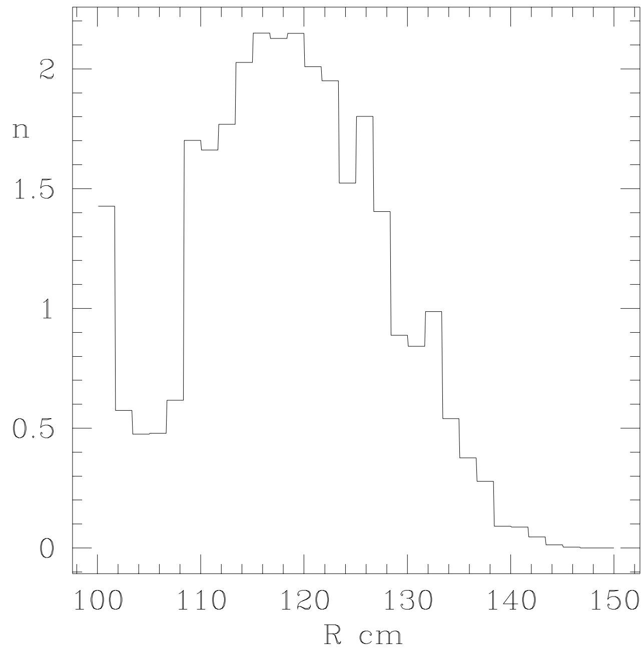
Distribution of bounce frequency vs energy.

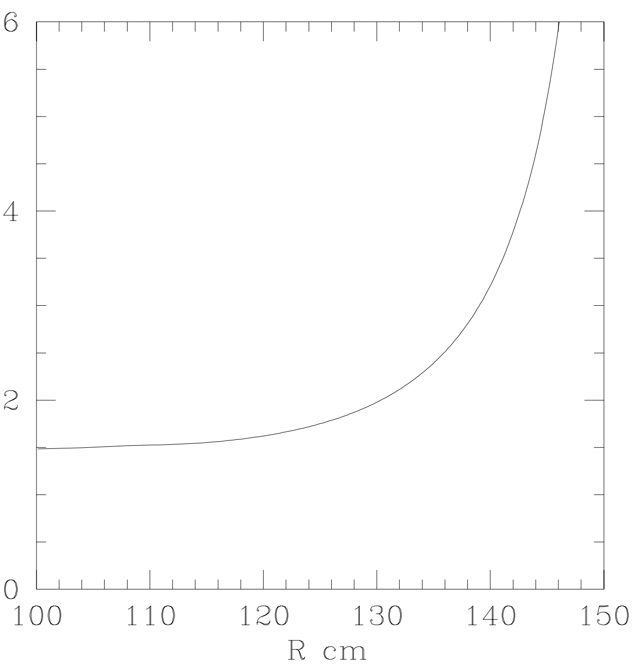
Red = bounce freq, Blue = precession

Mode Identification

Pressure profile has maximum gradient near the q=2 surface

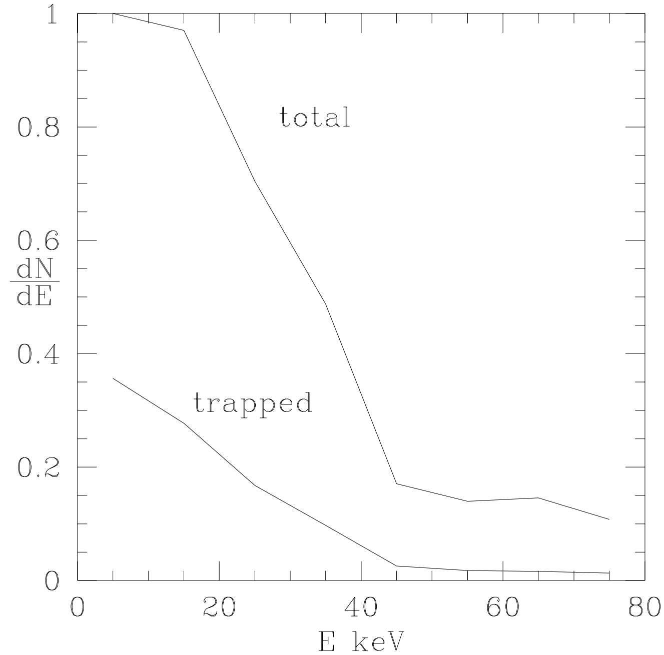
Shear is small





Why no drop in the neutron flux?

Examine the beam content vs energy



The mode is driven by the low energy beam particles

The expected loss of beam particles should be $\sim 20keV$

This would not cause a loss in neutron flux.

Simulate effect of modes on beam using 30 kHz rotating modes

Mode content m/n = 1/1, 2/1

No induced loss observed with modes of amplitude 10^{-3}

In an ignited plasma, with the alpha particles isotropic at birth, the mode could act on the high energy alphas. Losses?

Simulations to be carried out for ITER