Electron Fishbones: theory and experimental evidence

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Outline

- Experimental observations of electron fishbones: some historic background
- Experimental measurements on FTU and HL-1M: possibility of exciting electron fishbones in extremely different conditions
- Analytic theory of electron fishbones
  - Classic fishbone theory: drive mechanism
  - Kinetic layer equations: importance of ion compressibility
  - Optimal conditions for high-frequency e-fishbones
- Relevance for burning plasmas: nonlinear evolution equations for the fishbone cycle
- Discussions and Conclusions

Experimental Observations I: historic background

- Fishbone - like internal kink instabilities have been observed on DIII-D in conjunction with ECRH on the high field side. (Wong et al, PRL **85**, 996, 2000). Excitation by barely trapped suprathermal electrons, characterized by drift-reversal and destabilizing a mode propagating in the ion diamagnetic direction for inverted tail spatial gradient.
- Similar but higher frequency modes were observed in Compass-D (Valovic et al, NF **40**, 1569, 2000). There $\omega \lesssim \omega_{TAE}$ and the mode characterized by chirping frequency was observed with ECRH and LH.
- Observations of electron fishbones with ECRH only HL-1M; (J. Li et al., IAEA 2002; Ding, et al., NF **42**, 1, 2002) and LH only FTU; (F. Romanelli et al., IAEA 2002; P.Smeulders, et al., ECA **26B**, D-5.016, 2002)
- Recent observations of electron fishbone activity on Tore Supra with inverted q profiles $q_{min} \gtrsim 2$ (P. Maget, et al., NF **46**, 797, 2006).

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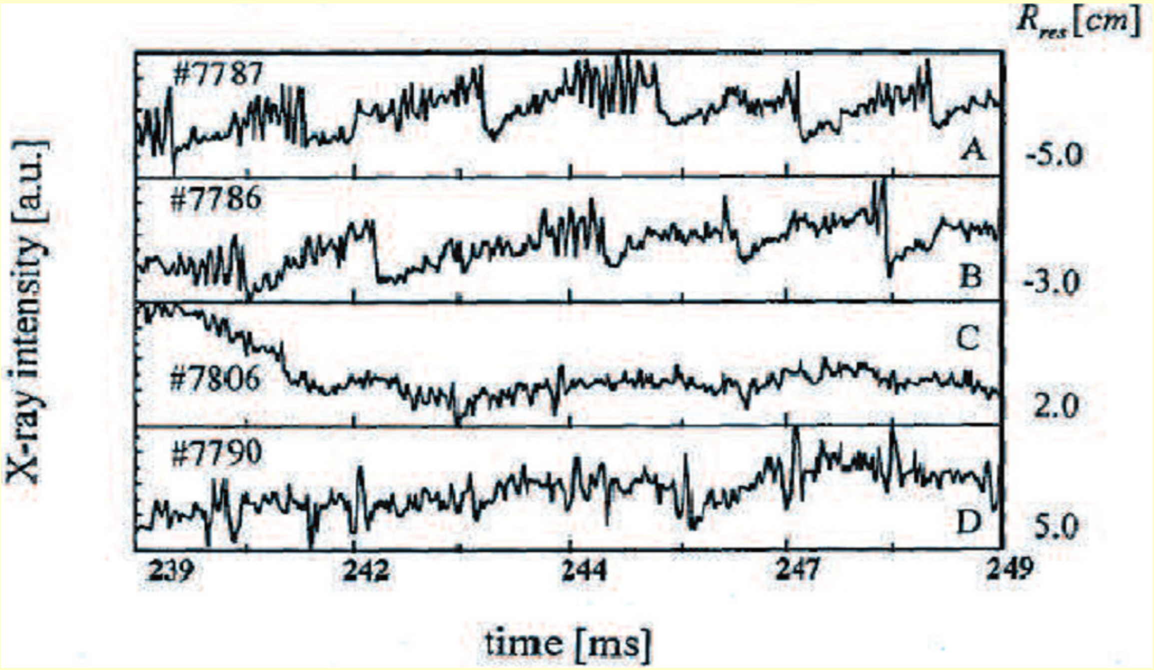
Experimental Observations II: HL-1M with ECRH only

Ding, et al., NF **42**, 1, 2002

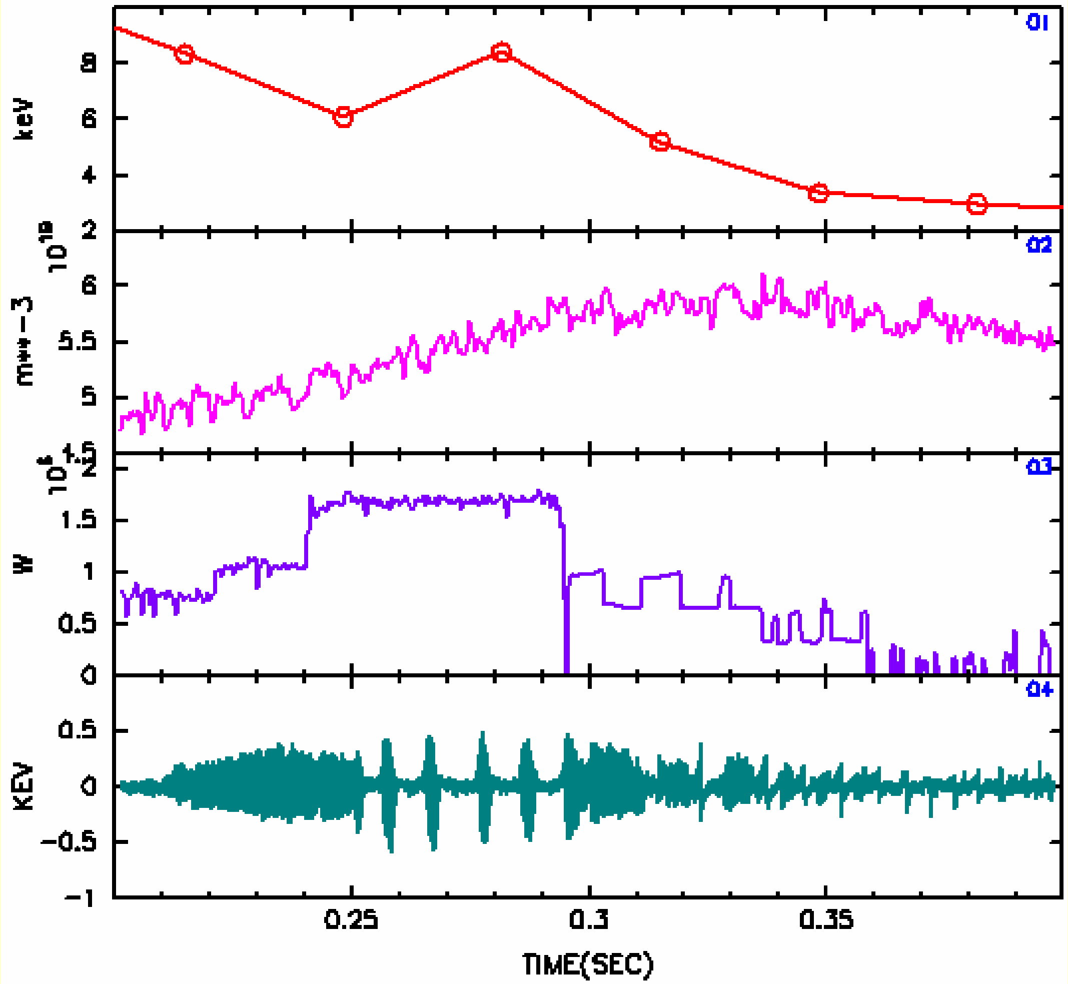


Courtesy of SWIP

- Excitation of the (1,1) mode was observed only when the ECR location is on the high field side near the q = 1 surface.
- This feature is similar to the previous result from the DIII-D tokamak.

Experimental Observations III: FTU with LH only

P.Smeulders, et al., ECA **26B**, D-5.016, 2002



- Fishbones are visible with only when LH power is on.
- Clear transition in nonlinear behavior as LH power is increased.

Analytic theory of electron fishbones I

Generalized fishbone-like dispersion relation (L. Chen, et al., PRL **52**, 1122, 1984)

$$\mathrm{i}\Lambda|s| = \delta\hat{W} = \delta\hat{W}_f + \delta\hat{W}_k$$

$$\delta\hat{W}_f = 3\pi\Delta q_0 \left(13/144 - \beta_{ps}^2\right)\left(r_s^2/R_0^2\right)$$

Ideal MHD response (M.N. Bussac, et al., PRL **35**, 1638, 1975)

$$\delta\hat{W}_k = 4\frac{\pi^2}{B_0^2} m\omega_c^2 \frac{R_0}{r_s^2}\int_0^{r_s}\frac{r^3}{q}dr\int \mathcal{E}d\mathcal{E}d\lambda \sum_{v_\parallel/|v_\parallel|=\pm 1}\tau_b\bar{\omega}_d^2\frac{QF_0}{\bar{\omega}_d-\omega}$$

Fast electron kinetic response (L. Chen, et al., PRL **52**, 1122, 1984)

Analytic theory of electron fishbones II

Generalized fishbone-like dispersion relation (L. Chen, et al., PRL **52**, 1122, 1984)

$$i\Lambda|s| = \delta\hat{W} = \delta\hat{W}_f + \delta\hat{W}_k$$

Banana regime

$$|\omega| \ll \omega_{bi} \ll \omega_{ti}$$

$$\Lambda^2 = \left(\omega^2/\omega_A^2\right)\left(1-\omega_{*pi}/\omega\right)\left[1+\left(1.6(R_0/r)^{1/2}+0.5\right)q^2\right]$$

Inertial layer response (J.P. Graves, et al., PPCF **42**, 1049, 2000) is asymmetric

High frequency regime

$$|\omega| \gg \omega_{ti}$$

$$\Lambda^2 = \frac{\omega^2}{\omega_A^2} - \frac{\omega_{BAE}^2}{\omega_A^2}\left[1+\frac{\omega_{BAE}^2}{q^2\omega^2}\frac{(46/49)+(32/49)(T_e/T_i)+(8/49)(T_e/T_i)^2}{\left(1+(4/7)(T_e/T_i)\right)^2}\right]$$

Inertial layer response (F. Zonca, et al., PPCF **38**, 2011, 1996) is symmetric

$$\omega_{BAE} = q\omega_{ti}(7/4+T_e/T_i)^{1/2}$$

IAEA FEC 2006 F. Zonca et al.

Analytic theory of electron fishbones III: ECRH

- Asymmetry of Alfvén continuum favors the excitation of modes propagating in the ion diamagnetic direction.
- High field side ECRH fulfills this requirement and guarantees both drift-reversal of the barely trapped supra-thermal electrons as well as the inverted spatial gradient of the supra-thermal tail (K.L. Wong, et al., PRL **85**, 996, 2000).
- Consistent with experimental observations (DIII-D, HL-1M).

Analytic theory of electron fishbones IV: LH

- Asymmetry of Alfvén continuum favors the excitation of modes propagating in the ion diamagnetic direction.
- Trapped and barely circulating supra-thermal electrons produced by LH give less selective mode drive than ECRH.
- Well circulating supra-thermal electrons modify the current profile, eventually reversing the magnetic shear and broadening the fraction of trapped particles characterized by drift reversal.

$$\bar{\omega}_d = \frac{\mathcal{E}}{\omega_c R_0}\frac{q}{r}\left[\frac{2\mathbb{E}(1/\kappa)}{\mathbb{K}(1/\kappa)} - 1 + 4s\left(\frac{\mathbb{E}(1/\kappa)}{\mathbb{K}(1/\kappa)} + \frac{1}{\kappa^2} - 1\right) - \frac{\alpha}{2q^2} - \frac{4\alpha}{3}\left(1 - 1/\kappa^2 + (2/\kappa^2 - 1)\frac{\mathbb{E}(1/\kappa)}{\mathbb{K}(1/\kappa)}\right)\right]$$

- With s=0 but S=(r/q)√q”>0, fishbone dispersion relation is modified (R.J. Hastie, et al., PF **30**, 1756, 1987). Δq=q-1

$$-S\left(\Delta q^2 - \Lambda^2\right)^{3/4}\left[1 + \Delta q/\sqrt{\Delta q^2 - \Lambda^2}\right]^{1/2} = \delta\hat{W}_f + \delta\hat{W}_k$$

Critical threshold for electron fishbones on FTU with LH

Real frequency

$$\delta \hat{W}_f + \mathbb{R}\mathrm{e}\delta \hat{W}_k = (S/\sqrt{2})\Lambda^{3/2} \simeq 0$$

Growth rate

$$\gamma = \Gamma \left[\int_0^{r_s} (r/r_s)\left(\partial \beta_{h,res}/\partial r\right) dr - \beta_{h,c} \right]$$

$$\Gamma = -(R_0/r_s)(\partial \mathbb{R}\mathrm{e}\delta \hat{W}_k/\partial \omega)^{-1}$$

$$\mathbb{I}\mathrm{m}\delta \hat{W}_k \equiv (R_0/r_s^2)\int_0^{r_s} r dr \partial_r \beta_{h,res}$$

- Critical threshold for electron fishbones on FTU with LH only

$$\beta_{h,c} = (r_s/R_0)(S/2^{1/2})\Lambda^{3/2} \simeq 1.43 (r_s/R_0)^{1/4} S (\omega/\omega_A)^{3/2}(1-\omega_{*pi}/\omega)^{3/4}$$

- Typical values: $\beta_{h,c}/S \approx 3 \times 10^{-4}$

- Consistent with FTU observations: $\beta_{h,res} \gtrsim 0.7 \times 10^{-4}$ for 1MW and $\beta_{h,res} \gtrsim 1.2 \times 10^{-4}$ for 1.7MW, with S=0.1÷0.2.

Optimal condition for high frequency (electron) fishbones

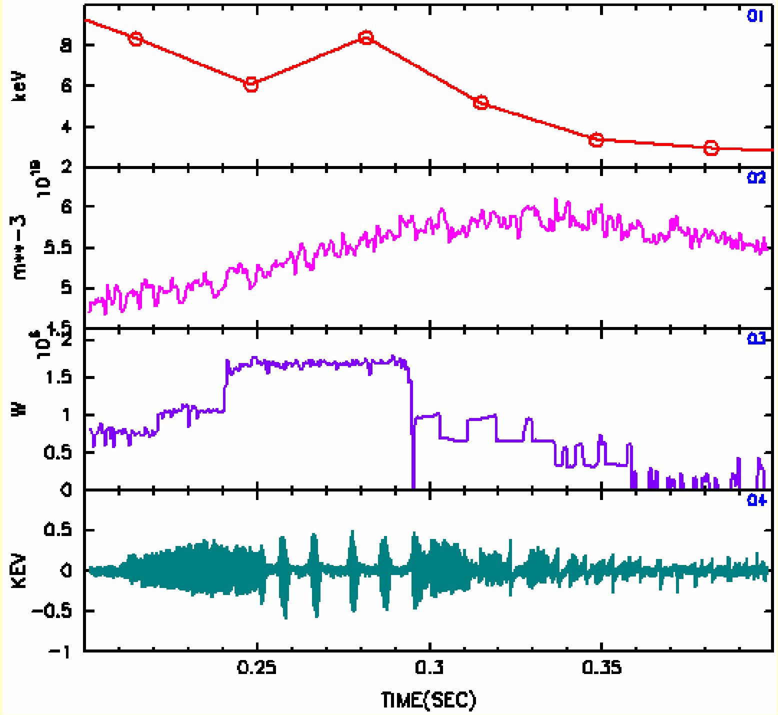
- Symmetry of Alfvén continuum favors the excitation of modes propagating in both ion and electron diamagnetic direction.

$$\Lambda^2 = \frac{\omega^2}{\omega_A^2} - \frac{\omega_{BAE}^2}{\omega_A^2}\left[1 + \frac{\omega_{BAE}^2}{q^2\omega^2}\frac{(46/49) + (32/49)(T_e/T_i) + (8/49)(T_e/T_i)^2}{(1 + (4/7)(T_e/T_i))^2}\right] \qquad |\omega| \gg \omega_{ti}$$

- Formation of the Beta induced Alfvén Eigenmode gap (W.W. Heidbrink, et al., PRL **71**, 855, 1993) at frequencies degenerate with Geodesic Acoustic Modes (GAM).
- Effective mode excitation would require high power ECRH (ICRH) on axis and $T_h \gtrsim 200keV$ on FTU (typical $T_h \simeq 30keV$)
- For consistency requirements $T_e \gg T_i$ and/or $q \gtrsim 2$
- Theory predicts possible observation of fishbone-like MHD modes near (below) the GAM frequency.

Relevance for burning plasmas

- The bounce averaged dynamics of both trapped as well as barely circulating electrons depends on energy (not mass).
- Their effect on low frequency MHD modes can be used to simulate/analyze the analogous effect of charged fusion products in the small dimensionless orbit limit (unlike fast ions in present EXP).
- The combined use of ECRH and LH provide extremely flexible tools to investigate various nonlinear behaviors, of which FTU experimental results provide a clear example.
- Possibility of validating models for Integrated Modeling of fishbone NL dynamics and induced transports.



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Nonlinear evolution equations for the fishbone cycle (i)

- Nonlinear suprathermal response due to wave-particle resonances is computed from nonlinear GKE $\delta\xi_0 = \delta\xi_{r0}/r_s$

$$\frac{\partial}{\partial t}\delta H_{NL} = -\frac{2}{r}\omega_c\omega^2\frac{\partial}{\partial r}\left[\left(1-\frac{(q-1)\bar{v}_\parallel}{\omega q R_0}\right)\mathbb{Im}\left(\frac{\bar{\omega}_d}{\bar{\omega}_d-\omega}\right)\left(\frac{QF_0}{\omega}\right)r^2r_s^2\left|\delta\xi_0\right|^2\right]$$

- Fast electron density relaxes according to diffusion processes due to fisbone fluctuations.

$$\frac{\partial}{\partial t}n_h = \dot{N}_h - \frac{2}{r}\omega_c\omega^2\frac{\partial}{\partial r}\left[r^2r_s^2\left|\delta\xi_0\right|^2 f_{eff,h}\left(\frac{Q_{res}n_h}{\omega}\right)\right]$$

- Same spirit of B.N. Breizman, et al., POP **5**, 2326, 1998 and J. Candy, et al., POP **6**, 1822, 1999. Here, nonlinear equations are derived in explicit form.

Nonlinear evolution equations for the fishbone cycle (ii)

- Mode frequency chirps downward according to

$$\delta\hat{W}_f + \mathbb{R}\mathrm{e}\delta\hat{W}_k + \mathbb{R}\mathrm{e}\delta\hat{W}_{k,NL} = (S/\sqrt{2})\Lambda^{3/2} \simeq 0$$

$$\frac{\partial}{\partial t}\delta\mathbb{R}\mathrm{e}\hat{W}_{k,NL} \simeq -2\frac{\pi^2}{B_0^2}m\omega_c^3\frac{R_0}{r_s^2}\int_0^{r_s}\frac{r^2}{q}dr\int d\mathcal{E}d\lambda \sum_{v_\parallel/|v_\parallel|=\pm 1}\bar{\omega}_d^2\,\mathbb{I}\mathrm{m}\left(\frac{Q}{\bar{\omega}_d-\omega}\right)\frac{1}{\mathcal{E}}\frac{\partial}{\partial\mathcal{E}}\left\{\tau_b\bar{\omega}_d\mathcal{E}^3\frac{\partial}{\partial r}\left[r^2r_s^2QF_0\left(1-\frac{(q-1)\bar{v}_\parallel}{\omega q R_0}\right)|\delta\xi_0|^2\right]\right\}$$

- Characteristic time scale for frequency chirping $\propto |\delta\xi_0|^{-2}$

- Nonlinear evolution equations for fishbone amplitude and resonant particles

$$(d/dt)\,|\delta\xi_0|^2 = 2\Gamma\left[\int_0^{r_s}(r/r_s)\left(\partial\beta_{h,res}/\partial r\right)dr - \beta_{h,c}\right]|\delta\xi_0|^2$$

$$\frac{\partial}{\partial t}\left[|\delta\xi_0|^2\left(\frac{\partial}{\partial t}-\nu_{ext}\right)\frac{\partial}{\partial r}\beta_{h,res}\right] = 2C\omega^2\frac{r_s^2}{r^2}|\delta\xi_0|^4\frac{\partial^2}{\partial r^2}\left(r^2\frac{\partial}{\partial r}\beta_{h,res}\right)$$

- Fishbone amplitude and resonant electron transport time scale $\approx |\delta\xi_0|^{-1}$

Discussions and Conclusions

- Fishbone – like mode excitations by suprathermal electrons is possible in extremely different conditions: ECRH, LH, combinations.
- Analytic theory is succesful in explaining these behaviors: theory also predicts optimal conditions for (electron/ion) fishbones at frequencies comparable with GAM/BAE.
- Relevance of these studies for burning plasmas stability and transport of both fast electrons and fusion products.
- ECRH+LH (as in FTU) provide very flexible tools for these studies and a testbed for verifying prediction of nonlinear theories.
- Presented a simple (yet relevant) nonlinear first-principle based model for the fishbone cycle and fast particle transport.
- NEXT: integrated modeling of the fishbone cycle and induced transport