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*Princeton Plasma Physics Laboratory, Princeton, New Jersey.
†University of California-Irvine, Irvine, California.
‡FAR-TECH, Inc., San Diego, California.
¶Euratom/CCFE Fusion Association, Abingdon, United Kingdom.
§Japan Atomic Energy Agency, Ibaraki, Japan.
#CRPP-EPFL, Lausanne, Switzerland.
$^{\infty}$Lawrence Livermore National Laboratory, Livermore, California.

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# Off-axis Fishbone Modes and Excitation of RWM in DIII-D

M. Okabayashi[1], J.S. deGrassie[2], W.W. Heidbrink[3], Y. In[4], Y.Q. Liu[5], G. Matsunaga[6], H. Reimerdes[7], E.J. Strait[2], M. Takechi[6], G.L. Jackson[2], J.M. Hanson[8], R.J. La Haye[2], M.J. Lanctot[9], and P.E. Sieck[2]

[1]*Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543-0451, USA*
[2]*General Atomics, PO Box 85608, San Diego, California 92186-5608, USA*
[3]*University of California-Irvine, Irvine, California 92697, USA*
[4]*FAR-TECH, Inc., 10350 Science Center Drive, San Diego, California 92121, USA*
[5]*Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[6]*Japan Atomic Energy Agency, 801-1, Mukouyama, Naka, Ibaraki 311-0193, Japan*
[7]*CRPP-EPFL, CH-1015 Lausanne, Switzerland*
[8]*Columbia University, 2960 Broadway, New York, NY 10027-6900, USA*
[9]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

In neutral beam injection (NBI) heated plasmas above the no-wall limit of the external kink and central safety factor $q(0)>1$, bursting MHD modes often trigger the resistive wall mode (RWM) in JT-60U and DIII-D [1–3]. The RWM is considered a potentially-disruptive global MHD that would be unstable even in the presence of a conducting wall. Present theoretical understanding is that the stabilization above the no-wall kink-limit is sensitive to the plasma rotation and kinetic effects, in particular to a significant contribution of precession drift of trapped energetic particles (EPs). Significant losses of trapped EP reduce the population of precession-drifting particles, possibly leading to the RWM onset. Accompanying EP losses, the non-ambipolar radial electric field causes a sudden reduction in toroidal plasma rotation, reducing the stabilizing effect. Thus, the bursting modes are thought to impact the stability in two serious ways. There arise several issues in the process of bursting modes triggering RWM. One of them is the mode character of bursting mode and another is the transient process of RWM onset. This paper will briefly describe the bursting mode and one aspect of nonlinear behavior by discussing the relationship of poloidal/toroidal components of magnetic perturbations. The toroidal component is useful to identify the characteristics of EP-driven bursting mode.

An example of a classical fishbone in comparison with an off-axis-fishbone is shown in Fig. 1.

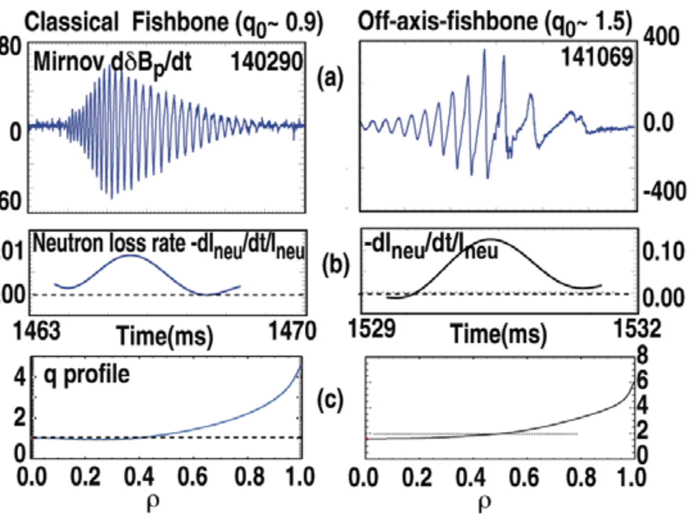



Fig. 1. The comparison of classical fishbone mode with $q(0)\sim1$ (#140290) (left) and off-axis fishbone (#141069) (right). (a) Poloidal magnetic pickup loop, (b) neutron emission rate ($-dI_{neu}/dt/I_{neu}$), and (c) $q$-profile vs $\rho$.

The bursting modes are named the off-axis fishbone mode (OFM) since many commonalities exist between classical fishbone [with $q(0)$~1] [4] and the bursting mode. As reported in detail in Ref. [3], the growth is well fitted with an exponential increase. The bursting modes appear in a repetitive manner. The modes cause losses of fast ions that peak near the time of maximum mode amplitude. Fast ions are expelled to the outside of the plasma with a fixed phase relative to the mode (known as a "beacon"). Frequency chirping always occurs near maximum amplitude. During a burst, the frequency chirps most rapidly as the mode reaches its maximum amplitude. Larger amplitude bursts have larger growth rates and the initial mode frequency is near the EP precession drift frequency.

Distinct differences exist between the classical fishbone and the off-axis-fishbone. The amplitude of the OFM peaks near $q$=2 surface. (Thus, this oscillatory mode has been named as OFF-AXIS fishbone.) In the decay phase, the mode amplitude is non-reproducible and the decay rate is no longer fitted with simple exponential decay (Fig. 1). Typically, the decay time of the OFM is much shorter than the buildup time period. Sometimes the burst decays in a few cycles with large amplitude. Often the mode distortion remains large but, with lower amplitude cases, sometimes nearly sinusoidal oscillations persist. This distortion seems quite universal, independent from the neutral beam injection (NBI) energy and geometrical factors, since very similar distortions were routinely observed in JT-60U, where the injection energy and NBI arrangement were quite different. Thus, the mode distortion is not sensitive to the details of EP distribution functions.

A question arises of what is the relationship between the classical fishbone and off-axis-fishbone with so many commonalities. Taking into account the excitation of the RWM, namely, an external kink with resistive wall, its relation to the EP branch can be compared to that of the relation of the internal kink branch to the classical fishbone. This hypothesis implies that the EP-driven branch should behave as a classical fishbone, but with external kink character. With the EP losses due to the OFM, the RWM becomes less stable. Furthermore, the rotation drop resulting from the EP transport losses can also decrease the RWM stability (Fig. 2). For RWM stability, the expulsion of trapped EP causes the reduction of precession drift population, leading to loss of RWM stabilization by kinetic effect.

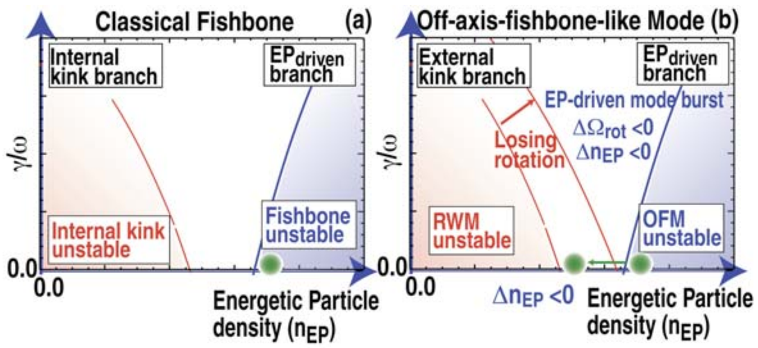



Fig.2. A paradigm of classical fishbone mode and off-axis-fishbone mode.

High $\beta_N$ (defined as plasma pressure normalized by $(I_p/aB_T)$ where $I_p$ is the plasma current, $a$ is the plasma minor radius, and $B_T$ is the toroidal field strength) above no-wall limit was explored with weakly-shaped configuration with $I_p$ = 1.1 MA and toroidal field $B_T$ = 1.7 T. A modest no-wall limit in this plasma ($\beta_N$=1.9) allowed achieving low plasma rotation regime and challenging the RWM kinetic stabilization by minimum NBI torque with balanced NBI injection. An example of the RWM excitation is shown in Fig. 3. The distortion of busting modes is observed in a repetitive manner by magnetic pickup probes as well as ECE radial profiles [1]. Thus, the nonlinear behavior is global.

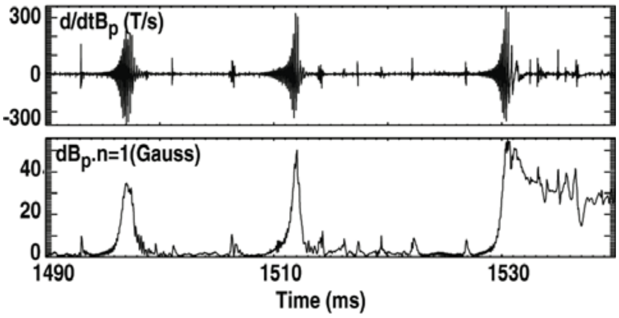
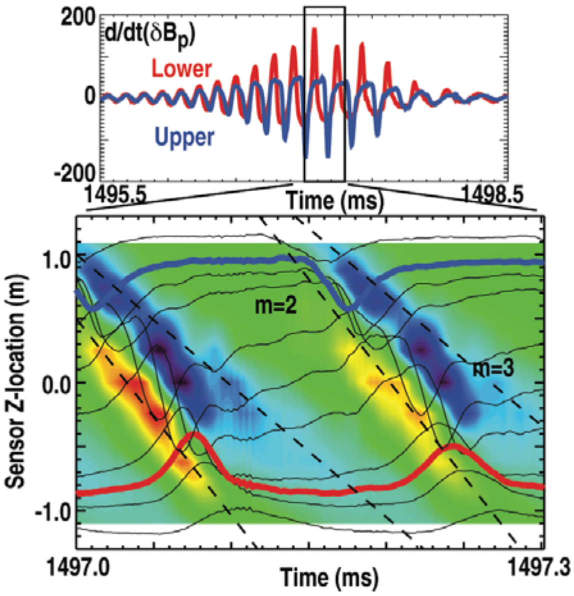



Fig. 3. The off-axis fishbone bursting and the onset of RWM. (a) Poloidal magnetic pickup loop, and (b) the $n$=1 $B_p$ amplitude.

Poloidal magnetic sensor arrays and a toroidal magnetic sensor array at the mid-plane provide the mode structure and illustrate a possible process of mode distortion. Nonlinear behavior observed in the poloidal magnetic sensors was identified as a combination of $m$=2,3 components, using the poloidal magnetic sensor array located vertically at the outboard side midplane (Fig. 4). The $m$=2 component was the major contributor to the mode distortion [1,3]. The relation of $m$=2,3 components was not clarifiable from poloidal sensors only. Figure 5 shows the magnetic pickup loop signals of the toroidal and poloidal component at the midplane, in the expanded time period ($t$ = 1495.5–1498.5 ms) for the shot shown in Fig. 3. These two loops are located closely each other in the toroidal angle, separated by 10 degrees. If the mode is a single rotating mode, the toroidal and poloidal sensor signals are different only as sine and cosine components.




Fig, 4. Poloidal mode identification with poloidal array of $d/dt$( $B_p$) sensors covering almost over the one poloidal wavelength of $m$=3. The mode distortion component is $m$=2 and the sinusoidal oscillatory component with $m$=3.

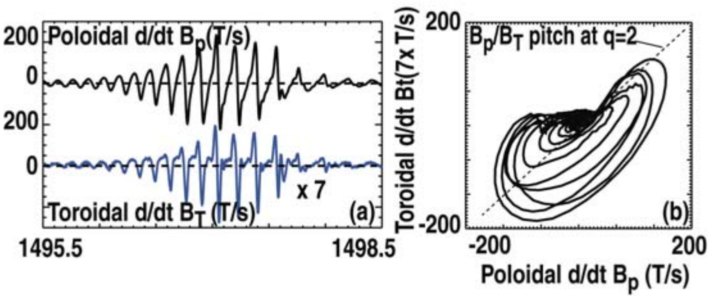



Fig. 5. The mode distortion observed (a) toroidal/poloidal components vs time and (b) the trajectory of $d/dt$( $B_p$) and $d/dt$( $B_p$).

For the case of an EP-driven mode, the relation of two sensor signals shows complex nonlinearity in time evolution. The large amplitude of $d/dt(\delta B_T)$ occurred at narrowly limited time period of about less than a quarter of each oscillation period. As shown in the domain of $[d/dt(\delta B_T), d/dt(\delta B_p)]$ [Fig. 5(b)] the magnetic sensor signals increased with the ratio constant. The distortion grew with nearly fixed mode structure $\delta B_T/\delta B_p$ incrementally-constant at least for this period. The ratio of $(d/dt\delta B_T)$ and $(d/dt\delta B_p) = 0.17$, which is close to the inverse of the magnetic pitch at $q$=2 surface. The magnetic perturbation remained perpendicular to the magnetic field line around $q$~2 in spite of nonlinear behavior. Then, later, the mode becomes rotating again, recovering a part of an elliptic trace as was shown in the domain $[(d/dt\delta B_p), (d/dt\delta B_T)]$ plot. During the time period where $d/dt(\delta B_T)$~0, it is hard to interpret the mode behavior.

This observation suggests that these two sensor signals are a consequence of the combination of at least two different modes rather than simply due to two components of one mode. This leads to a speculation that these two modes may belong to the branches discussed in Fig. 1: one with the oscillatory branch is related to the EP branch and the other with the external kink branch related to the mode distortion. One possible cause is the nonlinear process due to the increase of pressure gradient proposed by W. Park [5], but, in the present OFM case, the mode distortion approaches to plasma center [1]. Thus, the cause must be radially broader than simple local pressure gradient. Still, further analysis and theoretical studies are needed to clarify the process of onset of nearly-zero frequency RWM.

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