

## Identification of geodesic chirping Alfvén modes and q-factor estimation in hot core tokamak plasmas in ASDEX Upgrade

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Series of low frequency Alfvén eigenmodes (AE) [1,2] driven by ICRH were regularly observed in ASDEX Upgrade discharges with long sawtooth period. One of them (dubbed as *sierpes* [1]) with poloidal/toroidal mode numbers  $M/N=1$  is excited at the  $q=1$  surface, which frequency of  $\approx 80$  kHz, defined by a geodesic continuum in the hot plasma core [2,3]. The *sierpes* frequency increases slightly during a sawtooth period in this shot. Other modes have a chirping frequency spectrum, which varies strongly in the band of 50-170 kHz during one sawtooth. This behavior is very surprising and differs strongly from Alfvén cascades [4], which are also observed during the initial inversed shear stage of the ASDEX Upgrade discharges [2]. These chirping Alfvén modes are detected by core soft X ray (SXR) diagnostics but magnetic probes do not detect them. The chirping spectrum is anticipated by decreasing frequency modes and both behaviors may be presented by the geodesic Alfvén continuum (GAC) spectrum

$$\omega \approx \frac{\omega_i^*}{2} + \frac{NV}{R_0} + \sqrt{c_A^2 k_{\parallel}^2 + \omega_{\text{geo}}^2}, \omega_{\text{geo}}^2 \approx \left[ \frac{7}{2} + 2 \frac{T_e}{T_i} + \left( \frac{23}{8} + 2 \frac{T_e}{T_i} + \frac{T_e^2}{2T_i^2} \right) \frac{v_{Ti}^2}{q^2 R_0^2 \omega^2} \right] \frac{v_{Ti}^2}{R_0^2} \quad (1)$$

where  $\omega_{\alpha}^* = \frac{k_b}{\omega_{c\alpha} n_{\alpha}} \frac{\partial}{\partial r} (v_{T\alpha}^2 n_{\alpha})$  is drift frequency,  $c_A = \frac{B}{\sqrt{4\pi n_i m_i}}$  is the Alfvén speed,

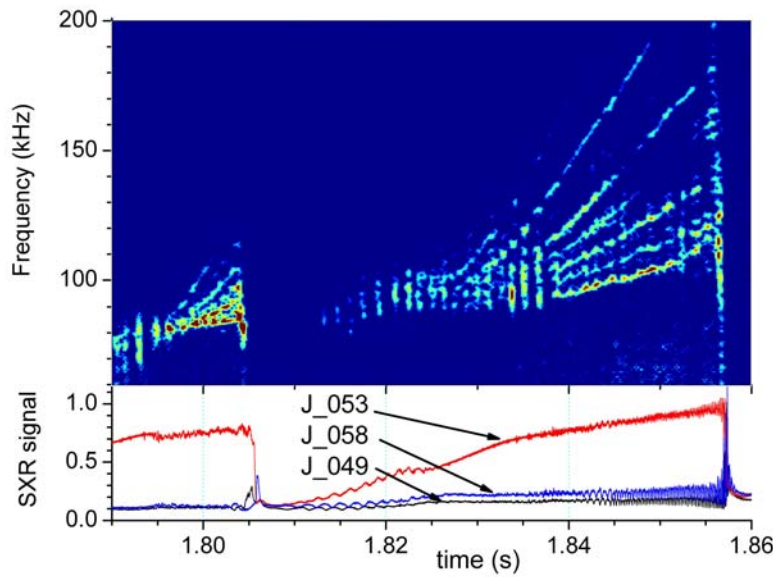
$$k_{\parallel} = \frac{B_{\zeta}}{BR_0} \left( N + \frac{M}{q} \right), k_b \approx \frac{MB_{\zeta}}{rB}, v_{Te,i} = \sqrt{\frac{T_{e,i}}{m_{e,i}}} \text{ is the electron or ion thermal}$$

speed,  $V$  is toroidal rotation velocity,  $M$  and  $N$  are poloidal and toroidal mode numbers, respectively,  $\mathbf{B}$  is magnetic field,  $R_0$  is major radius, and  $q$  is safety factor. We note that the geodesic continuum frequency has two branches [3,5]. The upper branch  $\omega_{\text{geo}}$  was named as beta induced AE [2] (or geodesic ion induced Alfvén mode (GIAM) [3]).

Here, we analyze the experimental conditions for the chirping AE excitation in the 50-180 kHz frequency band that appears during a monster sawtooth in discharges No 22325, and No 23828. An interpretation of the chirping Alfvén modes involves the theory of modes [5] excited at maximum of the geodesic Alfvén continuum in Eq. (1), which is modified by the geodesic effect [2,3]. The AE propagation at the GAC

extremum [5] depends on the relation between logarithmic gradients of plasma pressure and the magnetic shear. When the pressure gradients are strong, the AE may propagate at the maximum of the GAC; however, if these gradients are weak, especially after a sawtooth, the modes may appear at the GAC minimum. Finally, we are going to use these modes to estimate the central q-value and the geodesic frequency.

We start by analyzing the discharge No 22325, whose parameters were  $R_0 = 1.7\text{m}$ , minor radius  $a=0.5\text{ m}$ , magnetic field 2 T, plasma current 0.8 MA, ICRH power 4.5 MW, density  $4 \times 10^{19}\text{ m}^3$  of rather flat profile, and sharp electron temperature with small variation of maximum of 3 keV during the most part of the sawtooth period  $t=1.81\text{-}1.86\text{s}$ . The ion temperature with maximum of 2.5keV is measured at  $t=1.85\text{s}$  by the neutral beam diagnostic that gives the fundamental drift frequency  $f_1^* \approx 2.5\text{ kHz}$  in the plasma core. At  $t=1.848\text{s}$ , the frequencies  $f_{\text{GA}}=103, 112.1, 122, 134.5, \text{ and } 151.3\text{ kHz}$  are found for the respective lowest toroidal mode numbers  $N=3, 4, 5, 6, \text{ and } 7$  in the



spectrogram

presented in Fig.1.

*Fig.1. Spectrogram of J\_053, and amplitudes of J\_049, J\_053, and J\_058 signals in #22325.*

The  $q=1$  position is defined by inversion radius  $r_{\text{in}}=R_{\text{in}}-R_0 \approx 0.14\text{m}$  from the SXR system. These

important details suggest finding the  $q_0$ -value at the AWC maximum,  $r=0$ . To confirm the existence of AE, we use the quasi-cylindrical tokamak model [3,5] with geodesic effect taken into account for plasmas with hot electrons and cold ions,

$v_{Te} \gg \omega R_0 \gg v_{Ti}$ . The relevant equation for AE is represented in the Hain-Lust form:

$$\frac{1}{r} \frac{d}{dr} \left( r D \frac{dF}{dr} \right) + \left[ Q - \frac{M^2 D}{r^2} \right] F = 0, \quad D = \left( \frac{\omega}{c_A} - \frac{NV}{c_A R} \right)^2 - \frac{\omega_i^* \omega + \omega_{geo}^2}{c_A^2} - k_N^2 \quad (2)$$

where,  $Q = \frac{M}{r} \frac{d}{dr} \left[ \frac{2k_N}{R_0 q} + (\omega_i^* - \omega_e^*) \frac{\omega_{ci}}{c_A^2} \right]$ , and  $F = rE_b$  is binormal component of the

electric field. The equation  $D=0$  describes the geodesic Alfvén wave continuum shown in Eq. (1). After the saw-tooth crash, the plasma pressure profile is flat, as well as the q-profile,  $Q \approx 0$ , and eq. (2) has no eigenmode solutions. Further, the electron temperature is increasing and it begins to peak. In this case, the functions  $D$  and  $Q$  have maximum at  $r=0$  and they begin to be positive due to the pressure term, as well for the frequency above the geodesic Alfvén continuum. The eikonal solution of Eq. (2) is taken in Bessel

form  $F = F_0 J_M \left( \int_0^r \kappa dr \right)$  for large  $\kappa^2 = Q/D$ , where  $D$  has to be very small at  $r \approx 0$ . It

means that the mode frequency is very near to the GAC maximum one. The  $Q$ -function decreases with radius and it changes sign giving a reflection point for AE at  $r=r_f$  defined by the condition  $Q=0$ , which may be assumed at  $q \approx 1$  surface.

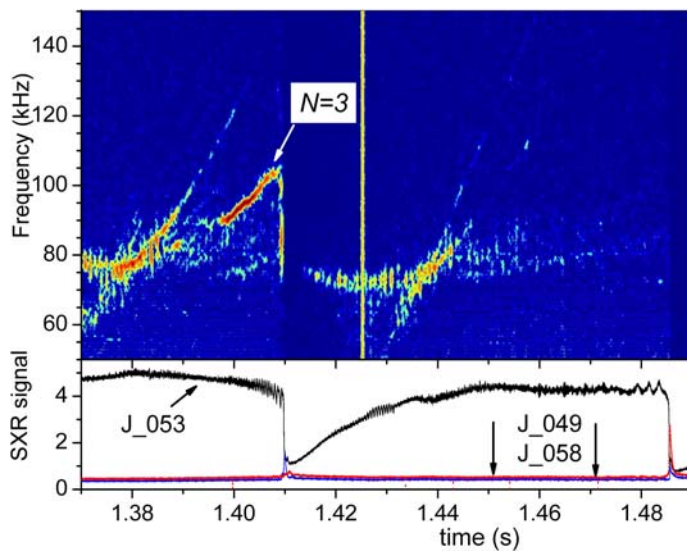
Employing the idea of AC excitation at the maximum of AWC where  $k_N = N\delta q / R_0 q_0$  for  $M=N$ , we exclude the combined drift and rotation frequency  $f_{rot} = f_i^* / 2M + V / 2\pi R_0$  from the system (1) through the frequency difference between the  $N$  and  $N_1$  AC modes

$$\frac{\omega_{N1}}{N_1} - \frac{\omega_N}{N} \approx \sqrt{\left( \frac{\omega_{geo}}{N_1} \right)^2 + \left( \frac{c_A \delta q}{R_0 q_0} \right)^2} - \sqrt{\left( \frac{\omega_{geo}}{N} \right)^2 + \left( \frac{c_A \delta q}{R_0 q_0} \right)^2} \quad (3)$$

where drift term  $(\omega_i^*)^2$  is disregarded under the square root as small as in Eq. (1).

Assuming six combination between the  $N=3-7$  AE modes, we found  $f_{geo} = 89 \pm 1$  kHz, which yields  $q_0 \approx 0.965 \pm 0.001$  at  $t=1.848$ s. At  $t=1.856$ s, the same procedure gives  $f_{geo} = 95.6 \pm 1$  kHz,  $q_0 \approx 0.955 \pm 0.001$  and  $f_{rot} = 0.7$  kHz. We note that the general accuracy of the  $\delta q$  estimation appears as 5%, which is defined by the central density measured by Thomson scattering and drift and flow corrections is smaller than 1 kHz and they may be ignored in our analysis. The geodesic frequency  $f_{geo} \approx 86.5 \pm 1.5$  kHz is independently calculated from Eq.(1) at  $t=1.848$ s that satisfactory coincidence gives support to our approach. Next, we propose that the position of the AE reflection point is at the  $q=1$  rational surface  $r_{in}=0.14$ m due to strong q-profile variation. Then, using the proposed plasma profiles at  $t=1.85$ s, we solve Eq.(2) for  $N=3$ , and find that the  $N=3$  eigenfrequency is  $\omega = \omega_{GA} + \delta\omega$  where  $\delta\omega / \omega \approx 0.01$ . The radial form of the eigenfunction is very similar to the  $M=3$  asymptotic solution, which is presented in the form of Bessel

function. The same procedure is applied to the H mode discharge No 23828, whose spectrogram of the central SXR channel (J\_053) for the first sawtooth period is shown in Fig.2. The parameters of this discharge are similar to those given above with  $T_e = 2.9$  keV and a similar electron temperature profile before saw tooth crash, however, it has higher central density  $5.2 \times 10^{19} \text{ m}^{-3}$ . Unfortunately, the toroidal mode numbers were not directly identified for this discharge due to weak magnetic probe signals but we may calculate  $\delta q$  through the difference between three neighbor modes at  $t = 1.398$  s using Eq (3). From the calculations we found  $\delta q = 0.042$ , and  $f_{\text{geo}} \approx 74.5$  kHz, and  $N=3$  for the lowers branch that gives a small value of the rotation frequency ( $< 1$  kHz). Then, assuming that the ion temperature is not changed and the geodesic frequency is correctly defined by Eq. (1), and using the frequency  $\approx 103.6$  kHz of the  $N=3$  Alfvén mode in Fig.2 before the sawtooth crash, we get  $\delta q \approx 0.06$ ,  $q_0 \approx 0.94$ . We also find  $N=5$  for



the highest visible AE mode using Eq (1).

*Fig.2. Spectrogram of J\_053, and amplitudes of J\_049, J\_053, and J\_058 signals in #23828 showing the inversion radius  $R_{in}-R_0 \approx 0.14$  m is calculated from SXR channels.*

Finally, we conclude that the low frequency

modes, which appear in the ASDEX Upgrade discharges heated by ICRH, are identified as Alfvén eigenmodes excited at the geodesic Alfvén continuum maximum. Based on the simplified equations for this continuum, analyses of spectrograms of SXR, and magnetic probe channels for these modes, we calculate of the deviation  $\delta q$  of q-factor from one and geodesic frequency during sawtooth period that can serve as indirect experimental confirmation of the geodesic effect in the hot plasma core.

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