

Observation of Fast-Electron-Driven Alfvénic Modes in the HSX Stellarator

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Alfvén instabilities driven by energetic ions have been observed in several experiments on tokamaks [1,2] as well as stellarators [3]. These energetic ions are produced by neutral-beam injection or ion cyclotron resonance heating. In future reactor devices, these ions may also stem from the thermonuclear fusion D-T reaction. The effect of Alfvén eigenmodes (AE) on plasma confinement and machine operation are of great interest to the fusion community. The condition for resonance is met by particles with velocity *of order* or greater than the Alfvén velocity [$V_A = B / (4\pi n_i m_i)^{1/2}$, where $n_i m_i$ is the ion mass density] and the mode is driven unstable through the inverse Landau damping process when $\omega_p^* > \omega_A$, where ω_A is the Alfvén frequency and ω_p^* is the diamagnetic drift frequency of the energetic particle species. In addition, trapped energetic particles with a precessional drift frequency matching the mode frequency can also excite the instability. In both cases, a basic feature of these resonances is that they depend on the particle energy, not mass. Thus, energetic electrons are able to drive fast particle instabilities just as effectively as energetic ions.

The HSX device is the first of a new generation of stellarators that exploit the concept of quasi-symmetric magnetic fields. The plasma is both produced and heated by use of electron cyclotron resonance heating (ECRH) at the 2nd harmonic X-mode resonance. This heating configuration routinely generates a nonthermal energetic electron population. In this paper, we report on the first experimental evidence for fast-electron-driven Alfvénic modes in quasi-helically symmetric (QHS) HSX plasmas. Such modes have previously been observed in both tokamaks[2] and stellarator[3] but have always been driven by energetic ions, not electrons.[4] This instability is only observed for quasi-helically symmetric HSX plasmas. When a toroidal mirror term is introduced into the magnetic field spectrum, allowing HSX to operate as a conventional stellarator, the Alfvénic fluctuation is no longer observed. Measurements presented in this paper suggest two new results; (1) fast electrons can drive the Alfvénic instability, and (2) quasi-symmetry makes a difference, presumably

by better confining the particles that drive the instability as compared to the conventional stellarator configuration.

The observed fluctuation is a coherent, m -odd (1?) mode that is seen in the plasma core and edge. Magnetic field fluctuations are measured using external magnetic coils while interferometry and Langmuir probes diagnostics are employed to measure perturbations in the plasma electron density. These fluctuations are observed in the frequency range of 20-120 kHz and scale with ion mass density according to expectations for Alfvénic modes. Theory predicts a Global Alfvén Eigenmode (GAE) mode in the gap below the Alfvén continua can be excited in the frequency range of the measured fluctuations. Measurements show this mode can be quasi-continuous, bursting, and in some cases have fast frequency chirps. The presence of Alfvénic mode activity can lead to decreased stored energy in HSX.

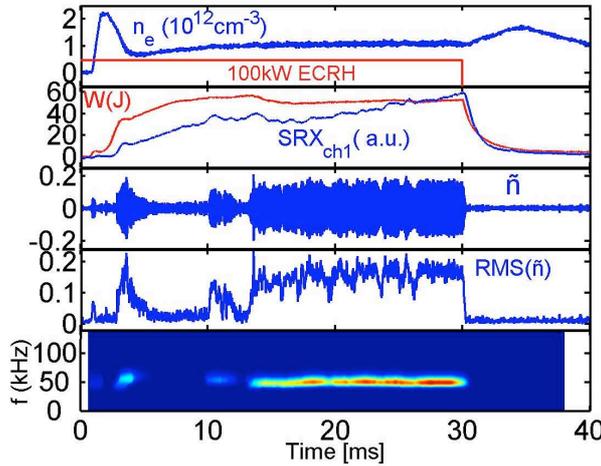


Fig. 1. Coherent fluctuation mode observed for QHS plasma in HSX stellarator.

Temporal evolution of a QHS discharge ($\bar{n}_e \approx 1 \times 10^{12} \text{ cm}^{-3}$) is shown in Fig. 1, where 100 kW of ECRH power terminates at ~ 30 ms. During the ECRH pulse, a single coherent mode is observed on the electron density trace (as measured by interferometry) at frequency ~ 50 kHz. After ECRH turn-off, the mode decays on a timescale (~ 0.2 ms) much faster than the energy confinement

time (~ 1 ms). This suggests the possibility that energetic particles (trapped or passing) generated by ECRH may be driving the mode. A characteristic feature of second harmonic X-mode heating (28 GHz, $B_T=0.5$ T) is the generation of hot electrons with high perpendicular velocities ($T_{e\perp} \gg T_{e\parallel}$) as evidenced by electron cyclotron emission (ECE) and x-ray measurements. HSX ions are cold (~ 20 eV).

Evidence for the mode is also observed on external magnetic coils as shown in Fig. 2(a) for a lower density ($\bar{n}_e \approx 0.8 \times 10^{12} \text{ cm}^{-3}$) QHS plasma. Here, in addition to the primary mode at 40 kHz, a satellite frequency at 60 kHz is also detected. These same spectral components are also measured by the interferometer. By examining the phase of the mode from the various chords of the 9-channel interferometer, it is determined that the mode has a

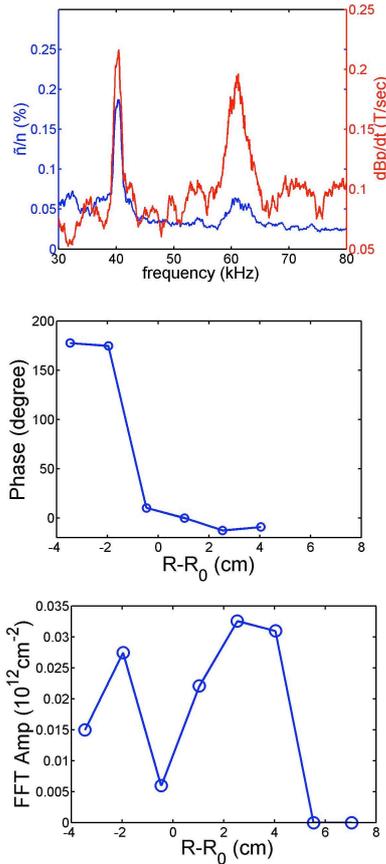


Fig. 2. Mode density (blue) and magnetic (red) signatures, (b) phase, and (c) line-averaged spatial distribution.

m =odd nature as a π -phase change is clearly seen for chords on opposite sides of the magnetic axis (see Fig. 2(b)). The spatial distribution of the density fluctuation can also be extracted from the interferometer data. As shown in Fig. 2(c), the mode has a relative minimum for the chord nearest the magnetic axis as expected for an $m=1$ perturbation. The radial mode structure is centered around $r/a=0.5$ in the steep density gradient region. The mode is also seen on the electron cyclotron emission measurements. This fluctuation is observed at all densities up to $\bar{n}_e \leq 2.3 \times 10^{12} \text{ cm}^{-3}$ on HSX with amplitude peaking at $\tilde{n}/\bar{n}_e \approx 0.005 - 0.01$ (for $\bar{n}_e \approx 1 \times 10^{12} \text{ cm}^{-3}$). The magnetic perturbation amplitude is $\sim 4 \times 10^{-5}$ at the wall.

Theoretical predictions obtained from the STELLGAP code [5] using the HSX quasi-helically symmetric equilibria show a gap for the $m=1, n=1$ GAE in the spectral region where the fluctuations are experimentally observed. The STELLGAP code calculates all of the eigenvalues of the Alfvén continuum equation on each flux surface and can take into account interactions between multiple toroidal modes while retaining an adequately resolved Fourier spectrum for the equilibrium quantities. GAE modes with discrete frequencies $\omega_{GAE} \leq k_{||} v_A \equiv \omega_A$ [parallel wave number $k_{||} = (m\ell - n)/R$] are predicted and found consistent with the measured fluctuations as shown in Fig. 3. The higher frequency satellite may have different mode number thereby appearing in a different gap. Frequency scaling with ion mass density is observed to be consistent with the expected $(m_i n_i)^{-1/2}$ scaling of V_A . Satellite frequencies are observed in H, D and He plasmas. Since ECRH is the only source for plasma

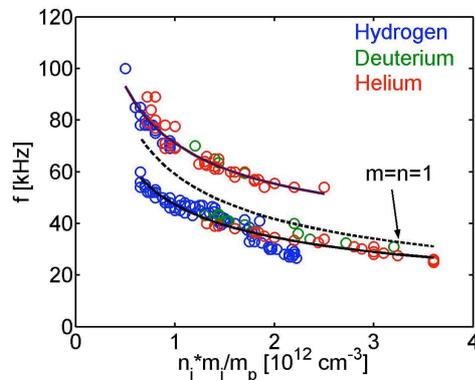


Fig. 3. Mode ion mass density scaling. Solid line represents Alfvénic scaling and dashed line the $m=n=1$ resonance.

production and heating, varying the toroidal field to identify B_T scaling is not feasible.

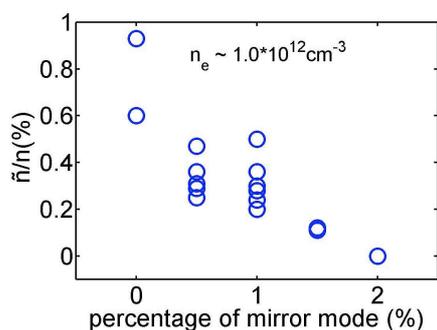


Fig. 4. Mode disappears with 2% mirror perturbation.

The mode amplitude is also observed to increase with heating power (P_{ECRH}) and degrades confinement for $P_{ECRH} \geq 100$ kW (see Fig. 1). A distinguishing feature of these fluctuations is that they are *only* observed for quasi-helically symmetric HSX plasmas. Introduction of a toroidal mirror term in the magnetic field spectrum, accomplished via the use of external windings, can serve to degrade the quasi-helical symmetry. A 10% toroidal mirror term

acts to make HSX operate as a conventional stellarator with increased loss of trapped particles. The measured mode amplitude is observed to be sensitive to this perturbation and rapidly decreases with the introduction of a toroidal mirror term as shown in Fig. 4. When the mirror perturbation reaches just 2%, the Alfvénic mode is no longer observed. The STELLGAP code predicts a gap for the mirror (standard stellarator) configuration on HSX, similar to that for the QHS configuration.

The observed difference between QHS and conventional stellarator plasmas can potentially be explained by direct orbit losses. For the conventional stellarator configuration, trapped particles generated by the 2nd harmonic ECRH can suffer direct orbit loss and are not available to drive the Alfvénic mode. However, for QHS operation, these energetic trapped particles are better confined and can act to drive the instability. Measurements indicate that the fast particle population is larger in the QHS configuration as compared to the conventional stellarator mode as evidenced by the soft (0.6-6 keV) and hard (>25 keV) x-ray fluxes. In addition, the decay in the hard x-ray flux after ECRH turnoff is 3 times longer in QHS plasmas. Experiments also show improved ECRH absorption and faster growth rate in plasma formation for the QHS configuration implying improved particle confinement. Since trapped particles are predicted to be confined to narrow banana orbits in QHS as opposed to the mirror configuration, this may be an indication that quasi-helically symmetry does indeed make a difference.

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[4] Fast-electron-driven instabilities have previously been observed in the COMPASS tokamak with ECRH but limited measurements prevented identification of the mode. M. Valovic et al., Nucl. Fusion **40**,1569(2000).

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