Cyclotron Harmonic Lines in Magnetic Fluctuations of Spiralling Electrons in Plasmas

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The magnetic fluctuation spectrum in a magnetoplasma containing energetic electrons is observed to exhibit many lines at the cyclotron harmonics ($\omega = n\omega_{ce}$, $n = 1\ldots15$). It is shown that these fluctuations are neither due to cyclotron radiation nor due to velocity-space instabilities but due to coherent solenoidal fields produced by electron cyclotron orbits and excited by thermal fluctuations. Such line spectra, observed in discharges and beam-plasma systems, may be useful for precise magnetic field diagnostics in plasmas.

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Emissions of cyclotron radiation in plasmas is a topic of general interest. It is observed in laboratory plasmas [1], used for temperature diagnostics in tokamaks [2], and well known in space plasma physics [3]. Two mechanisms for generating cyclotron harmonic lines are generally discussed in the literature: (i) The accelerated motion of single, nonrelativistic charged particles in magnetic fields gives rise to electromagnetic radiation at $\omega = n\omega_{ce}$, $n = 1,2,\ldots$ [4,5]. (ii) Velocity space instabilities can excite longitudinal cyclotron harmonic waves which may convert into electromagnetic waves [6]. In this Letter we present new observations of electromagnetic fluctuations at $n\omega_{ce}$ which are neither due to cyclotron radiation nor due to plasma instabilities. When electrons with random fluctuations spiral in a plasma the ordered cyclotron motion forms solenoidal rf fields of high phase coherence along $\mathbf{B}_0$ whenever $\omega = kv_\perp = n\omega_{ce}$. It will be shown that out of the broad thermal noise spectrum of an injected electron beam a narrow-band line spectrum evolves by interference effects. These observations are not only of intrinsic interest as a new fluctuation process but may have importance to electron energy transport and can be useful for precise local magnetic field diagnostics in plasmas.

The experiments are performed in a large (1 m diam × 2 m length) pulsed discharge plasma ($n_e \lesssim 5\times10^{11}$ cm^{-3}, $kT_e \lesssim 1$ eV, $B_0 \simeq 10$ G, $p = 1.3\times10^{-4}$ Torr Ar) sketched in Fig. 1. During the discharge a tail of energetic ($\frac{1}{2}mv^2 \simeq 40$ eV), ionizing electrons is present while the afterglow is Maxwellian ($kT_e < 1$ eV) except during the controlled injection of a pulsed electron beam ($V_b < 100$ V, $I_b < 100$ mA, 8 mm diam, $0 < \theta_{\rm pitch} \leq 90°$, $t_{\rm pulse} \simeq 5$ μs). The beam current can be modulated with broad-band noise (0...300 MHz) or with a monochromatic rf source. Magnetic fluctuations are detected with two electrostatically shielded magnetic loop antennas ($r_{\rm major} \simeq 2.25$ cm, $r_{\rm minor} \simeq 1$ mm) connected via low-noise broad-band amplifiers (NF $\simeq$ 2 dB, 1-500 MHz) to a digital oscilloscope (LeCroy 7200, 400 MHz, 1 Gs/s). The latter is used to analyze fluctuations in time and frequency, perform ensemble and conditional averages with "smart" triggering [7]. Electron density and temperature are obtained from Langmuir probes, whistler wave interferometry, and beam diagnostics [8].

Figure 2 shows a typical fluctuation spectrum of $\tilde{B}_z(t)$ detected in the flux tube ($r = 0$, $\Delta z = 15$ cm) of a 100 eV, 50 mA, 8 mm diam unmodulated electron beam injected at high pitch angle ($\theta_b \gtrsim 80°$) into a dense afterglow plasma ($f_{pe}/f_{ce} \simeq 100$). Emissions are observed throughout the whistler wave band ($\omega_{ce}^{1/2}\omega_{ci}^{1/2} \lesssim \omega \lesssim \omega_{ce}$), and at

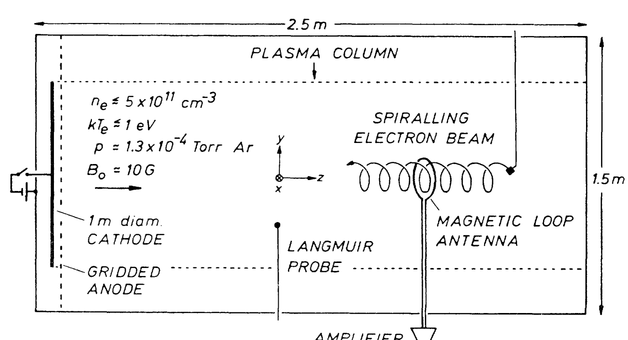

FIG. 1. Experimental setup for measuring magnetic fluctuations in the cyclotron frequency range due to spiralling electrons.

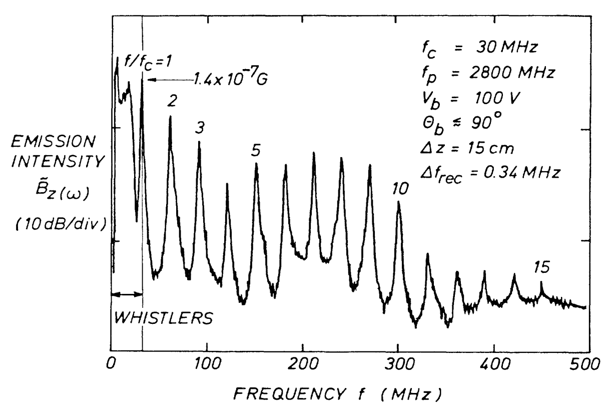

FIG. 2. Typical fluctuation spectrum of $\tilde{B}_z$ in the flux tube of a spiralling electron beam, exhibiting whistlers ($f < f_c$) and cyclotron harmonics ($f/f_c = 1\ldots15$).

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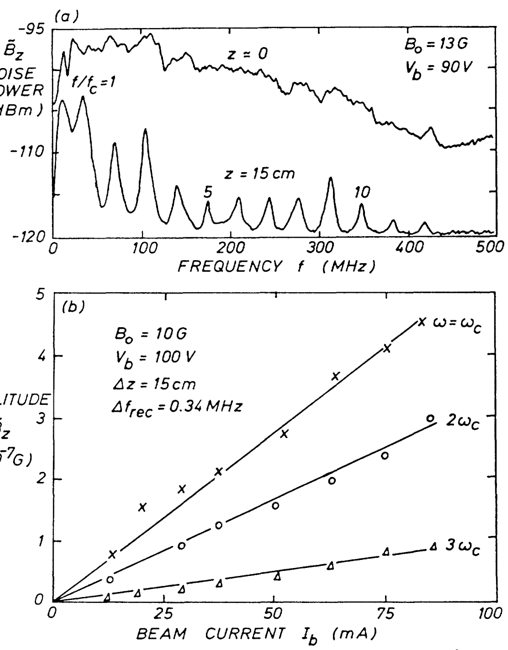

FIG. 3. (a) Comparison of fluctuation spectra $\tilde{B}_z(\omega)$ near the beam injection point ($z=0$) and after several cyclotron orbits ($z=15$ cm) which filter out the cyclotron harmonic lines. No convective instability is involved. (b) Linearity between fluctuation amplitude and dc beam current ($\tilde{B}_z \propto I_b$) indicates absence of an absolute instability.

the electron cyclotron frequency and its harmonics ($\omega = n\omega_{ce}, n=1\dots15$). The amplitude of the fluctuations is at the thermal level, i.e., the normalized fluctuation level of the beam-generated magnetic field, integrated over all lines, $\tilde{B}_b/B_{bo} \simeq \tilde{I}_b/I_{bo} \simeq 1.5\times10^{-3}$ is of the same order of magnitude as the thermal beam density fluctuations, $\tilde{n}_b/n_{bo} \simeq (n_b\lambda_{Db}^3)^{-1} \simeq 0.9\times10^{-3}$, where $n_b \simeq 1.1\times10^9$ cm^{-3}, $kT_b \simeq 0.1$ eV.

The line emissions, which are the focus of this work spatially evolve from a broad-band fluctuation spectrum near the beam injection point. Figure 3(a) shows a comparison of $\tilde{B}_z(\omega)$ at $\Delta z=0$ and $\Delta z=15$ cm from the source. The line spectrum appears to result from a filtering process involving the electron cyclotron motion as will be explained further below. It is evident that the lines are not spatially growing as in convective instabilities. Furthermore, Fig. 3(b) shows that the emission amplitude scales linearly with beam current, implying the absence of absolute instabilities with thresholds.

Figure 4 summarizes the spatial characteristics of the fluctuations. Typical radial amplitude distributions $|\tilde{B}_{z(x)}|$ shown in Fig. 4(a) indicate that the fundamental line ($\omega=\omega_{ce}$) maximizes in the flux tube of the spiralling beam resembling the field distribution of a solenoid. The second harmonic ($\omega=2\omega_{ce}$), however, exhibits a minimum on axis and two maxima near the particle orbit hence consists of two adjacent but opposing solenoidal fields (quadrupole). The phase fronts of the second har-

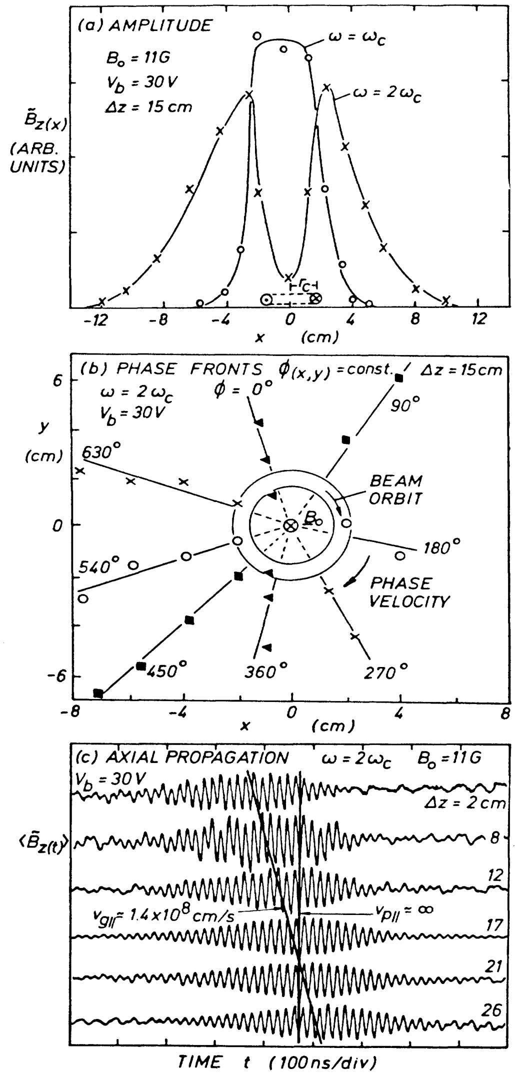

FIG. 4. Spatial characteristics of the line emissions. (a) Radial amplitude profile for the first two harmonics showing $|\tilde{B}_z|$ to peak near the beam of radius $r_c \simeq 1.7$ cm. (b) Phase fronts of the magnetic fluctuations at the second harmonic showing rigid co-rotation with the orbiting electron beam and $\omega/\omega_c=2$ azimuthal oscillations per orbit. (c) Axial propagation characteristics obtained by conditionally averaging [7] $\langle\tilde{B}_z(t)\rangle$ at different antenna positions Δz. While the phases remain constant ($v_{ph}=\omega/k_\parallel \simeq \infty$) the wave packets propagate at a group velocity corresponding to the axial beam velocity ($v_{g\parallel} \simeq v_{b\parallel}, \frac{1}{2}mv_\parallel^2 \simeq 5$ eV).

monic, $\phi_{(r,\theta)}=$const, displayed in Fig. 4(b), show that the magnetic fluctuations move with the electrons as a rigid rotor, $\omega=n\omega_{ce}=$const. For the fundamental ($n=1$), there is one azimuthal wavelength per rotation ($\Delta\phi=2\pi$), for the second harmonic, shown here, there are two periodic perturbations per orbit, etc. ($\Delta\phi=n2\pi$). Axially, along the guiding center of the beam the phases are found to be constant, $\phi(z)\simeq$const, and the amplitudes decay only slowly, $\tilde{B}/(d\tilde{B}/dz) \gtrsim 30$ cm. However, as shown in Fig. 4(c), the envelope of wave packets at $n\omega_{ce}$ propagates axially at a finite group velocity $v_g \simeq 1.4\times 10^8$ cm/s, approximately given by the axial beam velocity.

Based on these observations the following physical picture for the emission process emerges (see Fig. 5): The orbiting electron beam exhibits at the thermal level a broad spectrum of density fluctuations ($0 < \omega < \omega_{pb} \simeq 2\pi\times 500$ MHz) which give rise to free-streaming current perturbations of dispersion $\omega = kv_b$ (**k** along beam) [9,10]. For those frequencies which are synchronized with the cyclotron rotation ($\omega = n\omega_{ce}$), the current perturbations of the spiralling beam are all axially aligned resulting in a coherent solenoidal magnetic field perturbation $\tilde{B}_z$ observable with a magnetic loop antenna. When the frequency deviates from synchronism ($\omega - n\omega_{ce} = \Delta\omega$) the perturbation slips/advances from orbit to orbit resulting in a spiral-shaped perturbation. The axial amplitude $\tilde{B}_z$ is reduced explaining the abovementioned filtering effect. The axial phase velocity becomes finite ($v_{ph\parallel} = v_{b\parallel}\omega_c/\Delta\omega$) and changes direction with the sign of $\Delta\omega$. The latter has been experimentally verified by modulating the beam and measuring the axial phase velocity.

It is worth pointing out that the line spectrum does not involve any collective eigenmodes of the background plasma. For $\omega = n\omega_{ce} \ll \omega_{pe}$, the only relevant eigenmodes are the electromagnetic cyclotron harmonic waves propagating across $\mathbf{B}_0$, in particular the extraordinary mode ($\tilde{\mathbf{E}} \perp \mathbf{B}_0, \tilde{\mathbf{H}} \parallel \mathbf{B}_0$) which matches the observed polarization [6]. However, in the present low-β ($\sim 10^{-2}$) plasma these modes exist for $k\rho_e \ll 1$ only in extremely narrow bands below $n\omega_{ce}$ which is inconsistent with the observed linewidths. Additional discrepancies exist in the propagation characteristics: (i) theoretically $v_{g\parallel} = v_{ph\parallel} = \infty$ while observationally $v_{g\parallel} \simeq v_{b\parallel}$, (ii) absence of line emissions in the beam flux tube opposite to the beam propagation, and (iii) insensitivity of line emissions to plasma parameter variations ($n_e = 10^8 \ldots 10^{11}$ cm^{-3}, $kT_e = 0.2\ldots 2$ eV). Thus, the observed line emissions involve only ballistic modes of the electron beam.

Because of the small fluctuation level the cyclotron harmonics are not generated by nonlinear effects. Using tuned amplifiers and conditional averaging, it has been found that no correlations exist between different harmonics. When the beam is modulated with broad-band noise all lines are enhanced while a monochromatic modulation enhances $\tilde{B}_z$ only at the selected line.

Cyclotron harmonic lines are observed over a wide range of beam voltages ($13 < V_b < 100$ V) but not in the Maxwellian afterglow plasma. However, several lines ($n = 1\ldots 3$) are found in the active discharge where ionizing electrons (40 eV) are injected along **B** and pitch angle scattered by beam-plasma instabilities [11]. The spatially uniform fluctuations correlate only along flux tubes defined by the energetic electrons ($r_{ce} \simeq 2$ cm), indicating a multitude of independently fluctuating beamlets.

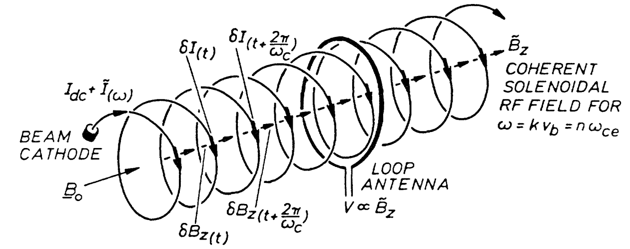

FIG. 5. A new physical model explains the generation of cyclotron harmonic lines by a spiralling electron beam. At the thermal level the injected beam current contains broad-band fluctuations $\tilde{I}_{(\omega)}$ ($0 < f < f_{pb} \simeq 500$ MHz). Those frequency components which rotate synchronously with the cyclotron motion ($\omega = n\omega_c$) produce identical magnetic perturbations for each orbit which add up to a coherent solenoidal rf field structure observable with a magnetic loop antenna. Off resonance, the perturbations $\delta I, \delta B$ slip from orbit to orbit and do not constructively interfere, which explains the observed filtering effect. No collective plasma mode or instability is required to explain the observed line spectrum.

The present work points out a new cyclotron emission process which may have interesting implications and applications. In underdense plasmas ($\omega_{pe} \lesssim n\omega_{ce}$), the solenoidal rf structures can radiate which could be mistaken as cyclotron radiation or instabilities [1]. In magnetic confinement devices the solenoidal rf fields may enhance cross-field electron heat transport. In high-beta plasmas ($\beta \gtrsim 1\%$) the line emissions at $n\omega_{ce}$ yield a precise ($\pm 0.5\%$) measure for the *in situ* magnetic field strength.

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