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Measurement of Magnetic Field in a Laboratory Plasma by Thomson Scattering of Laser Light

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(Received 5 October 1970)

A 2.7-Å band of the spectrum of ruby-laser light scattered by a plasma (20 eV, 10^{15} electrons/cm^3) in the presence of a magnetic field of about 15 kG has been isolated and passed through a 0.1-Å resolution interferometer. Magnetic modulation of the spectrum has been detected. There is reasonable agreement between the field strength calculated from the modulation and that measured by Faraday rotation.

Thomson scattering of laser light is favored as a diagnostic technique for laboratory plasmas because of its many desirable features which include high spatial and temporal resolution, freedom from serious perturbing influence on the plasma, and applicability to a wide range of plasma conditions. The motivation of the present work is to bring magnetic field into the set of plasma parameters which can be measured by laser-light scattering.

The scattered light spectrum for a Vlasov plasma in a magnetic field has been calculated by a number of authors.[1-4] It has been shown that the magnetic field influences the spectrum only when the differential wave vector $\vec{k}$ is nearly perpendicular to the magnetic field vector $\vec{B}$. When this condition is satisfied, the spectrum exhibits peaks at near-integer multiples of the electron gyrofrequency ω_{ce}. These peaks are a manifestation of the Bernstein modes,[5] and at frequencies characteristic of ion effects, like kv_i (v_i being the ion thermal speed), they show the interaction between these modes and the ion-electron collective modes. For wavelengths very short compared with the Larmor radius, however, the electrons behave independently and the magnetic structure of the spectrum can be understood in terms of the sinusoidally varying Doppler shift experienced by light waves scattered by electrons which are performing gyrations at the Larmor frequency about magnetic lines of force.[6]

If the $\vec{k}$ vector is not exactly perpendicular to $\vec{B}$, the component of the motion of the electrons along $\vec{B}$ introduces a Doppler broadening of the peaks proportional to the projection of the electron thermal velocity v_e along the $\vec{k}$ direction, namely, $v_e \cos\varphi$, where φ is the angle between $\vec{k}$ and $\vec{B}$. Should the resulting frequency line breadth $2kv_e\cos\varphi$ exceed the spacing between the lines, ω_{ce}, then smearing of the peaks will occur. Accordingly, a necessary condition for the appearance of magnetic fine structure is that $2kv_e \cos\varphi \leqslant \omega_{ce}$.

An experiment designed to detect this magnetic structure has been carried out in our laboratory. Figure 1 shows the experimental arrangement. A 3-kJ preionized θ-pinch discharge in 45 mTorr of hydrogen is the plasma source. It generates an axial magnetic field peaking in the neighborhood of 15 kG. Light from a 100-MW ruby laser is directed through the center of the θ coil at an angle of 15° to the coil axis. Provision is made to collect light scattered in the plane containing the incident beam and the coil axis, at an angle of 30° to the former and 15° to the latter. The scattering vector $\vec{k}$ is thus perpendicular to the coil axis, which is assumed to coincide with the direction of the magnetic field $\vec{B}$ at the center of the coil's midplane. This assumption depends upon the plasma exerting negligible influence upon the direction of $\vec{B}$, and is justified retrospectively by the very low value of the plasma diamagnetism. Measured by the parameter $\beta = 2n\kappa T/(B^2/8\pi)$, the latter was about 2% at peak field.

The axes of the incident- and scattered-light optical trains were aligned with respect to the coil axis with the help of accurately ground constant-deviation prisms of 90° and 105°. The essential elements in each optical train are two irises and a lens, one iris being imaged by the lens into the plasma to determine the scattering volume, and the other determining the solid angle illuminated or viewed. The scattering volume defined in this way is the space common to two interpenetrating cylinders 0.5 cm in diameter and intersecting at an angle of 30°. The solid-angle cone through which light illuminates a point in the scattering volume was made the same as that over which scattered light is detected, and each had a half-angle of 0.85°. This implies that each point in the scattering volume is characterized by the same set of $\vec{k}$ vectors occupying a cone of half-angle 0.85°, whose axis is perpendicular to the θ coil axis, or $\vec{B}$.

The apparatus designed to disperse the scattered light consists of a narrow-band (2.7 Å) dielectric interference filter and a Fabry-Perot interferometer capable of better than 0.1-Å resolution. The interference filter was mounted in such a way that it could be tilted with respect to the direction of the incident illumination so as to change the wavelength of the passband. This facility allows us to build up, over a sequence of machine discharges, the spectrum of scattered light at comparatively low resolution, from which the plasma electron temperature and density are deduced. It also serves to isolate a fraction of the spectrum which is further dispersed in the Fabry-Perot. The latter consists of an etalon with optically contacted spacers whose passband is altered by changing the index of refraction (pressure) of the gas between the plates. Light emerging from the etalon is focused onto a stop whose diameter was chosen to match the Fabry-Perot resolution. Behind this stop is the detector, a photomultiplier, RCA model C31000E, having a quantum efficiency of approximately 6% at 6943 Å. It is really this resolution stop, imaged onto the angle-selecting iris in the light-collection train, that determines the angular limits of the cone within which the $\vec{k}$ vectors lie.

The fine structure of the central part of the scattered-light spectrum was recorded under two different magnetic field conditions, and the results are displayed in Fig. 2. The first measurement [Fig. 2(a)] was carried out at the peak of the first half-cycle of the coil current; the second [Fig. 2(b)], at approximately the time when the current, and so the field, was half the peak value. An independent estimate of the magnetic field was made in an auxiliary experiment in which Faraday rotation in a small cylinder of dense glass placed at the coil's center was measured. This gave a value of 16 kG for the magnetic field at the current peak. The first scattered-light distribution was measured in the presence of a field of approximately 8 kG. Each spectrum is seen to be split into a sequence of regularly spaced peaks. In both spectra, four peaks are clearly resolved. The spacing between peaks in the first distribution is 0.62 Å, in the

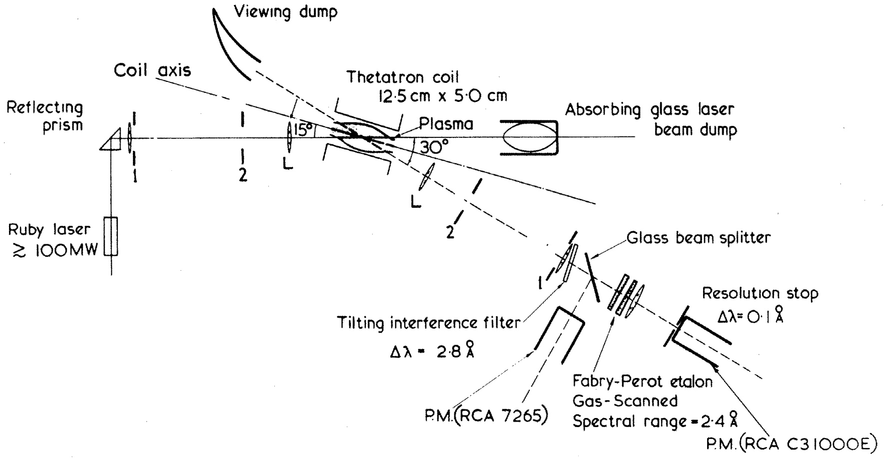

FIG. 1. Layout of the experimental apparatus. Irises labeled "1" are imaged into the plasma by the lenses L to define scattering volume. Solid angle illuminated is equal to solid angle viewed and is defined by the irises labeled "2."

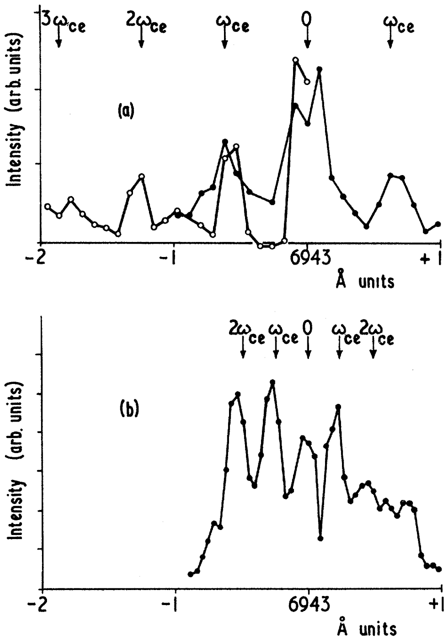

FIG. 2. (a) Scattered-light spectrum for $B = 14$ kG (16 kG by Faraday rotation). Two experimental runs are shown: closed circles, premonochromator centered at 6943.0 Å; open circles, premonochromator centered at 6941.6 Å. (b) Scattered-light spectrum for $B = 5.5$ kG (8 kG by Faraday rotation).

second, 0.24 Å. Assuming that the peaks stem from the expected magnetic field effect, their spacings correspond to fields of 14 and 5.5 kG, respectively. Thus there is reasonable agreement between the fields derived from the scattered-light spectra and those measured by Faraday rotation.

The individual peaks are narrower, hence the degree of modulation is greater than was anticipated. The spectrum measured with the tilting filter alone in the high-field case [Fig. 2(a)] was consistent with an electron temperature $T_e = 20$ eV and a density, confirmed by an independent Rayleigh-scattering measurement, of a few times 10^{15} electrons/cm^3. These numbers correspond to a correlation parameter α between 0.2 and 0.3. Assuming that the width of the peaks is given by $2kv_e \cos\varphi$, using the above value of T_e to determine v_e, and allowing for instrumental broadening, we find that the observed peak width in the 14-kG case corresponds to an effective angle between $\vec{k}$ and $\vec{B}$ of 89.7°. From the geometry of the experiment, however, it is clear that the observed frequency distribution is a composite one consisting of a weighted sum of spectra for the various angles φ included within the $\vec{k}$-vector cone, from 89.15° to 90.85°. Because $\vec{B}$ is an axis of symmetry for the problem, the composition of the observed distribution will be weighted towards spectra corresponding to φ near 90°. Thus composite peaks whose widths are consistent with an angle φ significantly nearer to 90° than the $\vec{k}$ vector cone angle are to be expected. This has the consequence that the perpendicularity condition between $\vec{k}$ and $\vec{B}$ for the appearance of magnetic structure is less stringent than has been assumed hitherto.

In neither of the two spectra presented in Fig. 2 are correlations negligible. This is especially true in the low-field example [Fig. 2(b)] where the narrower peak width is thought to be due, at least in part, to a lower electron temperature corresponding to a higher value of α. The general spectrum function for a plasma in a magnetic field [given by Hagfors,[3] Eqs. (45) and (50)] has been evaluated numerically to investigate the frequency distributions which are theoretically possible. A detailed discussion of the results of these computations will be presented elsewhere, but in particular it is found that the ion term is capable of exhibiting modulation near the electron gyrofrequency ω_{ce} when the latter is smaller than the characteristic ion frequency kv_i. It is conjectured that the spectrum shown in Fig. 2(b) is an example of this.

Our conclusions can be summarized as follows: In an experiment in which the differential-scattering vector $\vec{k}$ was almost perpendicular to the magnetic field $\vec{B}$, fine structure consisting of a sequence of regularly spaced peaks has been detected in the scattered-light spectrum. The intervals between the peaks are approximately equal to the electron gyrofrequency determined independently by a Faraday rotation measurement. Peaks have been resolved corresponding to magnetic fields of the order of 10 kG. This is an order of magnitude smaller than the field for which a similar observation has recently been reported[7]; indeed, our field strengths are typical of those encountered in laboratory controlled-fusion experiments. The individual peaks are narrower and the spectral modulation is greater than was anticipated, and this is attributed to the composition of the observed distributions being weighted towards values of φ, the angle between $\vec{k}$ and $\vec{B}$, approaching 90°. This has the consequence that the perpendicularity condition between $\vec{k}$ and $\vec{B}$ for the appearance of magnetic structure is less stringent than has been assumed hitherto. There is some evidence that the modulation of the ion feature at the electron gyrofrequency has been observed. Computation shows that this would not be inconsistent with theory.

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Influence of High-Frequency Electric Fields on Equilibrium and Stability of Toroidal Plasmas

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(Received 27 August 1970)

The effect of a high-frequency toroidal electric field on equilibrium and stability of a toroidal plasma is considered. It is shown that for some values of the electric field, one can change the particle orbits considerably with important consequences to diffusion and stability.

Several theoretical works in the past few years have pointed out the role of trapped particles for equilibrium diffusion and stability of plasma in toroidal magnetic fields.[1-4] Most recently, the first experimental evidence of a trapped-particle effect has also been reported.[5]

We start here an analysis of the possible effects of high-frequency (h.f.) electric fields parallel to magnetic field lines on equilibrium and stability in toroidal magnetic fields. (Such h.f. fields have already been proposed in the literature as a means of stabilizing low-frequency instabilities,[6,7] but the work done refers to the case of plane plasmas in uniform magnetic fields.) It will be found that h.f. electric fields can affect considerably the trapped particle orbits. In turn, trapping determines equilibrium and stability in a critical way as was first shown in Refs. 1 and 2. Owing to shielding of the time-varying electric fields from the plasma (except for the case where these are electrostatic fields of plasma eigenmodes), the considerations we will develop will be especially relevant for low-density toroidal plasmas (multipoles, stellarators). The analysis will indicate that h.f. electric fields could be proposed as a diagnostic tool for investigating physical effects related to particle trapping in toroidal plasmas. We refer to a collisionless low-β plasma in a magnetic field whose intensity varies sinusoidally along magnetic lines:

$$\vec{B} = B_0(1+\epsilon\cos kz)\hat{e}_z, \tag{1}$$

with $\epsilon \ll 1$. As is well known, such a model can represent the field of an axisymmetric toroidal plasma, periodicity being given by the rotational transform (it can possibly represent also a bumpy torus field where magnetic lines are closed). In the first case, which is the one on which we focus our attention, $\epsilon = r/R$, where r, R are the minor and major radii of the torus, respectively; $K = \iota/2\pi R$, where $\iota/2\pi = \Theta/\epsilon$ is the rotational transform ($\Theta = B_\theta/B_z \ll 1$ being the ratio between poloidal and toroidal field components). In the equilibrium we also introduce a h.f. electric field, uniform in space in the toroidal direction, which we take in the form (for simplicity we do not consider any static electric field)

$$\vec{E} = E_0 \cos\Omega t\hat{e}_z, \tag{2}$$

with frequency $\Omega \gg \omega_{bj}$, where

$$\omega_{bj} = (\oint dl/v_\parallel)^{-1} \sim \epsilon^{1/2} k V_{\mathrm{th}j}$$

is the frequency associated with the periodic trapped-particle motion ($V_{\mathrm{th}j}$ is the jth particle thermal velocity). The time-varying poloidal field $B_1(t) = B_1\cos\Omega t$, which is in general associated with (2) (except for the case where $\vec{E}$ is the field of an electrostatic wave), will not be included in the present analysis. This is justified for the discussion of the dynamical effects on the toroidal equilibrium if $B_1/B_0 < 1$ (in which case the magnitudes of the magnetic gradient drift and of the particle velocity parallel to the magnetic field are not affected by the oscillating B_1 field).[8] The influence of a poloidal oscillating magnetic field on trapped-particle instabilities on the other