FIZIKA 5 (1973) 131–138

LIGHT SCATTERING IN A DENSE COLD PLASMA

M. M. PLATIŠA*

Institute of Physics, Beograd

Received 17 March 1973

Abstract: Nearly all theories of light scattering from plasma, based on random-phase approximation, assume a large number of charged particles in a sphere of the Debye radius. This basic assumption was not valid for the dense cold theta pinch plasma used in this experiment. The cooperative domain was realized even at an observation angle of $\Theta = 90°$. The ion line was spectrally resolved and the scattering spectra were found to fit the theoretical profiles, within the limits of experimental error. It is shown that scattering theories can be applied even in the case of 0.7 particles per Debye sphere in accordance with Theimer's extended nonlinear correction theory.

1. Introduction

The spectrum of light incoherently scattered by free electrons from a plasma is determined by the spectral distribution of the electron density fluctuations. The theoretical aspect of calculation of these fluctuations has been considered by several authors, e. g. by Salpeter[1]. The shape of the scattered light spectrum is determined by the parameter

$$a = \frac{1}{K \cdot D} = \frac{\lambda}{4\pi D \sin\frac{\Theta}{2}}, \tag{1}$$

*) The author would like to express his appreciation for financial support received from the U.K.A.E.A. and to the University of Liverpool for the opportunity to carry out this work.

where K is the wave number, D is the Debye radius, λ is the wavelength of the incident light and Θ is the angle between the incident and scattered light. Assuming the mean thermal velocity of the electrons to be much higher than that of the ions, one can obtain the normalized scattering spectrum integrated over all frequencies[2] as

$$S(a) = S_e(a) + S_i(a). \tag{2}$$

Here

$$S_e(a) = \frac{1}{1 + a^2}, \text{ and} \tag{3}$$

$$S_i(a) = \frac{z\,a^4}{(1 + a^2)\left[1 + a^2\left(1 + z\frac{T_e}{T_i}\right)\right]}, \tag{4}$$

where z is the atomic number, T_e and T_i are the electron and ion temperatures, respectively. The first term of Equ. (2) represents the intensity of the scattering spectrum due to electrons, and the second that due to ions. The domain of light

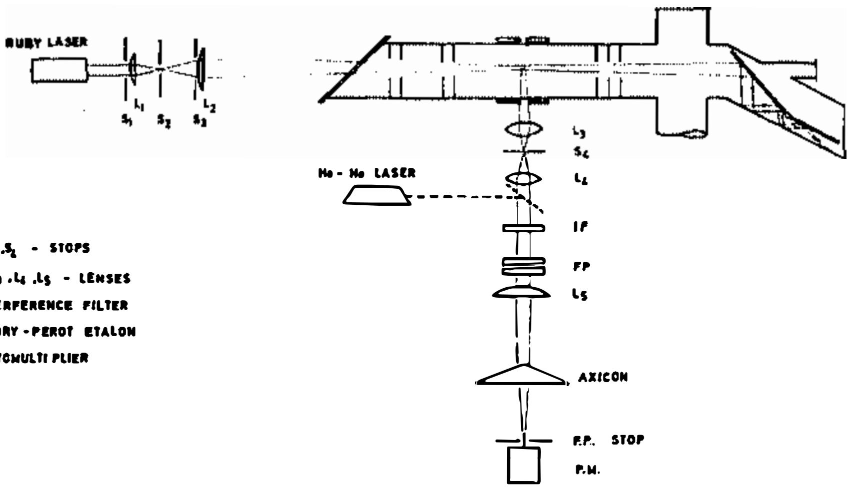

Fig. 1. Experimental arrangement.

scattering and the predominance of the electron or ion spectrum are determined only by the parameter a. For $a \ll 1$ the spectrum would be that appropriate to electrons performing their random thermal motion at the temperature of the temperature of the plasma. The ion spectrum is predominat when $a \gg 1$ and the width of the central or ion line is determined by the thermal motion of the ions[3]. The parameter β is defined in a similar way as a

$$\beta = \sqrt{\frac{a^2}{1 + a^2} \cdot \frac{z\,T_e}{T_i}}. \tag{5}$$

The parameter β determines the profile of the central ion line in a cooperative domain of light scattering.

Nearly all scattering theories based on random-phase approximation assume a large number of charged particles in a sphere of the Debye radius. This is an essential assumption for the application of the Debye-Hückel theory. For the case where this condition is not fulfilled Theimer[4] has derived an approximate correction for the application of the theories in this region. According to this theory the value of the scattering cross-section for $n_D < 0.5$ (n_D is the number of particles per Debye sphere) is found to differ significantly from that predicted by the linearized theory ($n_D \gg 1$). Recently Rohr[5] has found that the scattering theory[1] is in good agreement with experiment for only two particles per Debye sphere. The purpose of the present work is to prove the applicability of the scattering theories for plasmas where the number of particles in the Debye sphere is smaller than 1.

2. *Experimental set-up*

The plasma was produced in a theta-pinch consisting of four 100 kV, 0.5 μF coaxial capacitors which are discharged, at 55 kV, into a single-turn coil (8.5 cm in diameter and 22 cm in length) surrounding a Pyrex tube filled with H_2, at an initial pressure of 300 μTorr. The plasma created in this way was cold and dense

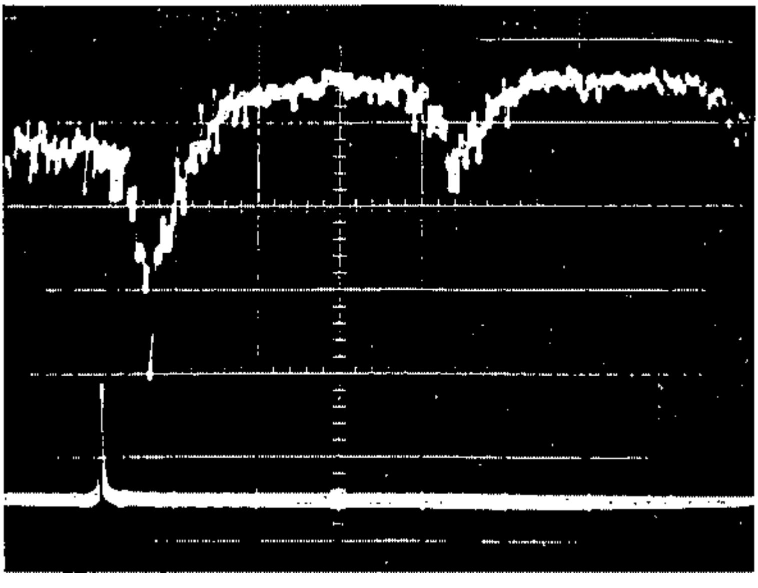

Fig. 2. Characteristical scattered signal,
Upper beam: plasma radiation plus scattered light signal,
Lower beam: monitor signal,
The time scale 0.5 μs/div.

with a small Debye length and therefore the co-operative domain of light scattering was expected, which made it necessary to use a spectral resolving instrument with a very high transmission and dispersion. For this purpose an Axicon-scanned Fabry-Perot spectrometer[6,7] was chosen. The final pressure in the vacuum system was $2 \cdot 10^{-6}$ Torr, with a leak rate in the system of $1.4 \cdot 10^{-5}$ l. Torr/s. In order to reduce a stray light, a system of stops was placed in the discharge tube, and a Brewster window was used as an entrance window. A laser beam dump was designed for the absorption of the laser light which passes through the plasma. The absorbers in the laser light dump were made of OB10 blue filter glass, which has a very low diffuse reflectivity. As a source of monochromatic light a giant ruby pulse laser of the type L.U.3 was used. The experimental set-up is given in Fig. 1. A Kerr cell and a Taylor-Archard calcite polarizing prism were used as an electrooptical shutter for Q-switching. The maximum output power of the ruby laser was 150 MW with a pulse width of 30 ns. The ruby rod (12" in diameter and 6" in length) and flash tube were placed in an elliptic cavity and were cooled by demineralized water. The circulating water was cooled at desired temperature by a refrigeration unit. The ruby rod temperature was controlled by a specially designed thermostat, to within $\pm$ 0.5°C at 6°C. Since the precise wavelength is determined by a particular order of the resonant reflector (an optically contacted Fabry-Perot etalon used as the front mirror), the laser wavelength varies with its temperature. In order to achieve the desired wavelength stability the resonant reflector temperature was thus controlled to within $\pm$0.1°C at 29.2°C. The laser light was focused into a 4 mm diameter cylinder along the axis of the theta coil, within which the plasma is formed, by usual arrangement of lenses and stops. The ruby laser was optimally adjusted and thermally tuned. Photomultipliers (RCA 7265) with a S-20 photocatode response, and a high speed silicon planar photodiode of the type 104 BPY (Mullard), were used as detectors. The time response of the detection system was limited only by the frequency band width of the used Tektronix oscilloscopes of the types 585 and 555 A.

3. Measurements and results

The light scattered from the center of the plasma cylinder was observed at an angle of $\Theta = 90°$. All measurements were performed without any bias magnetic field and preionization in the third half cycle or at the peak of the second compression of the plasma. At the peak of the second compression the trapped magnetic field was parallel to the driving field so that axial contraction or reversed field heating was absent. During the scanning of the ion line profile the output power from the ruby laser was kept below 15 MW, which was less than the perturbing level of the plasma heating by laser radiation[8], under the conditions of this experiment. The apparatus was calibrated by the Rayleigh scattering on filtered dry nitrogen. This nitrogen was dust free and a good linear dependence of the scattered signal on pressure was obtained. The ratio of the scattering signal to stray light signal at 750 Torr of nitrogen, during the Rayleigh scattering, was 5.3. Since the equivalent pressure for an electron density of $3 \cdot 10^{17}\,\mathrm{cm}^{-3}$ for light scattering in cooperative domain ($\alpha \gg 1$) corresponds to 1640 Torr, the ratio of the scattering signal to stray signal should be $\frac{1640}{750} \cdot 5.3 = 11.6$. Experimentally this ratio has been found to be about 12, which is in good agreement with the predicted value. The stray signal of the system was equivalent to 142 Torr of nitrogen. The ratio of the scattering signal to the plasma radiation was 0.83. A characteristic signal of scattered light is shown in Fig. 2. The plasma was optically thin over the passband of the interference filter (5Å) at the laser wavelength. The focused laser beam in the plasma observed was 4 mm in diameter. The flash duration and therefore the time interval from the start of the flash to the peak of the inversion population in the ruby crystal amounted to a few milliseconds. Thus it was necessary to trigger the flash tube in advance of the theta-capacitor bank by this amount. A delay was also necessary between the start of the theta-pinch discharge and the giant laser pulse which had to correspond to the desired compression peak of the plasma. In view of the short life of the plasma in this theta-pinch machine the most critical step in timing the system was the determination of the time interval from the start of the discharge to the laser pulse. Exact coincidence of the giant laser pulse with the peak plasma compression had to be achieved. The complete timing sequence is given in Fig. 3.

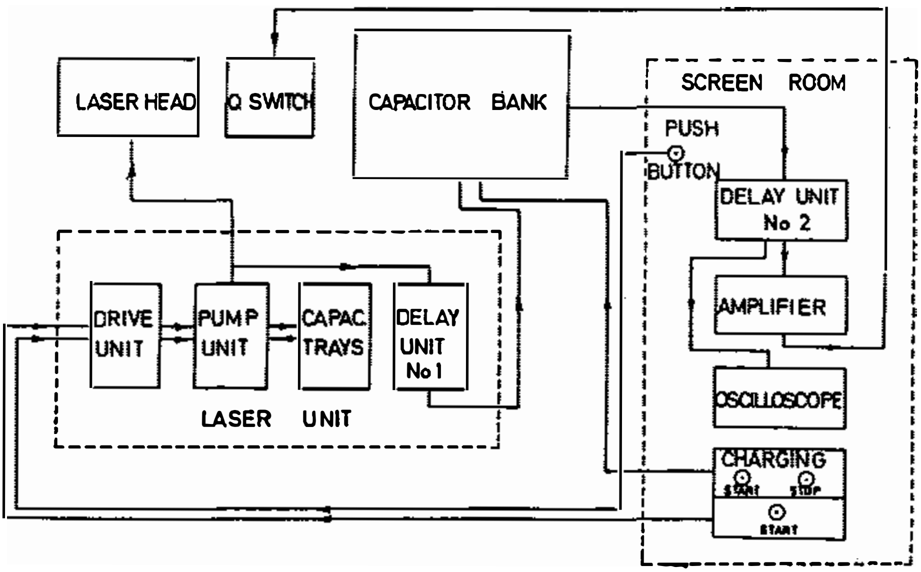

Fig. 3. The timing sequence.

For the scanning of the scattering spectra a shot by shot technique was used. Since the symmetry of the ion line was proved the scanning of the spectra was done only for the half line. The characteristic spectral distribution of the scattered light is presented in Fig. 4. The data for these spectra were obtained from a series of individual shots, approximately 80 shots being necessary to produce each spectrum. Each point represents the difference between the average of the set of shots with plasma and that without plasma for the same setting of the axicon. The errors bars on the points are experimental in that they are derived from the root mean square deviation from the mean of the sets of experimental readings. Variations in the intensity of the ruby laser output were detected by the photodiode monitor, and were normalized out of the scattered light signals. All the measurements were performed in a linear response range of the detectors.

The electron density was determined:

— from the shape of the scattering spectra,

— from the ratio of intensities of the Rayleigh scattered light from nitrogen and the plasma scattered light, and

— by spectroscopic method (H_β-line).

The discrepancy between these independently measured values was smaller than the experimental error.

The temperature was determined from the half width of the scattered spectra

4. Discussion and conclusion

The ion line was spectrally resolved and the structure of the spectra enabled the parameters β, α, n_e and T_i to be evaluated. The equipartition time was, under the conditions of the plasma, of the order of 10^{-10} seconds and therefore sufficiently short to establish immediately an isothermal plasma. This made it possible to determine the electron temperature from the spectra of the central line. In this case the relation between α and β is much simpler. For high values of α the parameter

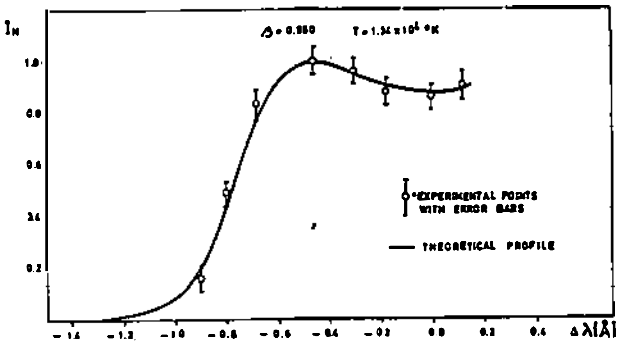

Fig. 4. Characteristical scattered light spectrum.

β is a very weak function of α. From the measured electron density and temperature the parameter α could be evaluated. Since $\alpha \gg 1$ the electron and ion distributions are strongly correlated and complete charge neutrality is achieved; the electron density then mainly follows that of the ions. The shape of the spectrum then differs considerably from the Gaussian shape obtained for noninteracting ions. For $z = T_e/T_i = 1$ the $\beta < 1$ domain was obtained and the ion spectra consist of two well developed peaks, on either side of the laser wavelength, which correspond to scattering by ion oscillations in the plasma. From Fig. 4. it can be seen that almost all the measured points are in agreement with the calculated profile within the error margins of about $\pm 10\%$. The effect of the Coulomb collisions causes the low frequency ion line to narrow considerably as the number of collisions increases and therefore the resonance peaks disappear since collisions damp out the positive ion oscillations. The effect of collisions, when normalized ion-ion collisional frequency is taken into consideration[9], is of the order of unity or greater, because ion thermal speed may then be reduced by collisions. Under the conditions of the plasma used in the present work, this frequency was calculated to be 0.4. Since the measured ion spectra display well defined undamped resonance ion peaks this suggests that the Coulomb collisional effects can practically be neglected, although the profiles are likely to be slightly affected. Under the conditions of this experiment the influence of the driving magnetic field on the scattered spectra was negligible. Since the temperature of the plasma was very low, relativistic effects were not to be expected.

The half-width of the central line is determined essentially by the ion temperature, while its shape depends on the ratio of the electron to ion temperature as well as on the value of α. According to relations (2), (3) and (4), this ratio, for an isothermal plasma, is given as a function of α as follows

$$R(\alpha) = \frac{S_i(\alpha)}{S_e(\alpha)} = \frac{\alpha^2}{1+\alpha^{-2}}. \tag{6}$$

Thus, using Salpeter's theory, one should expect, for a small number of particles in the Debye sphere, a change in the shape of the scattering spectrum. Since the intensity ratio is changed, the value of α and therefore the shape of the spectrum should also change. The smallest number of particles in the Debye sphere, in the plasma used, was $n_D = 0.7$ for $\alpha = 5.2$. This is the smallest number of particles in a Debye sphere attained in any scattering experiment so far. According to Theimer's correction theory the ratio of intensities in this case is less than 4% in comparison with Salpeter's ratio. The decrease in the intensity ratio given by Equ. (6) should lead to a decrease in the parameter α by less than 2%. For such small changes in α the change in β is, according to Equ. (5), practically negligible. Thus one cannot expect any change in the profile of the ion spectrum in accordance with the results. Since the experimental values of the scattering spectra fit the theoretical profiles, within the limits of experimental error, the scattering theory turns out to be a good approximation for the ion spectra even in the case of 0.7 particles per Debye sphere.

Acknowledgement

The author gratefully acknowledges the helpful discussions with Dr. M. Barrault.

References

1) E. E. Salpeter, Phys. Rev. **120** (1960 1528;
2) M. M. Platiša, Ph. D. Thesis, The University of Liverpool (1970);
3) M. M. Platiša, Fizika **2** Suppl. 1 (1970) 108;
4) O. Theimer, Phys. Letters **20** (1966) 639;
5) H. Röhr, Zeitschrift für Physik **209** (1968) 265;
6) J. Katzenstein, Appl. Optics **4** (1965) 761;
7) M. M. Platiša, Fizika, **5** (1973) 83;
8) M. M. Platiša Zbornik na trudovite Skopljc Volume II (1972) 409;
9) J. P. Dougherty J. Geophys. Res. **68** (1963) 5473.

RASEJANJE SVETLOSTI U GUSTOJ I HLADNOJ PLAZMI

M. M. PLATIŠA

Institut za fiziku, Beograd

Sadržaj

Salpeterova teorija o rasejanju svetlosti polazi, pored ostalih uslova i od toga, da u sferi Debyevog radiusa ima veliki broj čestica ($n_D \gg 1$). Ovo je suštinska pretpostavka za primenu Debye-Hückelove teorije. Taj uslov obično nije zadovoljen u hladnim gustim plazmama. Da bi se proverila primenljivost teorije o rasejanju svetlosti za dijagnostiku plazme, kad je broj čestica u Debyeovoj sfeıi malen, korišćena je hladna teta pinč plazma. U takvom izvoru plazme realizovan je kooperativni domen rasejanja svetlosti ($\alpha \gg 1$).

Jonska linija je spektralno razdvojena i iz njene strukture određena je elektronska koncentracija i jonska temperatura plazme. Eksperimentalne vrednosti spektra rasejane svetlosti centralne linije slažu se, u granicama greške, sa teorijskim profilom.

Na taj način je pokazano da se teorija o rasejanju svetlosti može koristiti za određivanje spektra jonske linije i za 0.7 čestica po Debyeovoj sferi u saglasnosti sa Theimerovom proširenom nelinearnom korekcionom teorijom.