STUDIES OF COLLECTIVE PROCESSES IN REB-PLASMA SYSTEMS

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Abstract

This paper reviews the following papers presented at this Conference: "Experimental study of collective processes in REB" by L. U. Bogdanov and G. G. Sominski [1], "Spectrum of plasma electrons observed in strong Langmuir turbulence driven by REB" by L. N. Vyacheslavov, V. F. Gurko, I. V. Kandaurov, E. P. Kruglyakov, O. I. Meshkov and A. L. Sanin [2], "Energy and angular spreads of beam electrons and microwave radiation" by H. Koguchi, M. Masuzaki, M. Yoshikawa, S. Takahata, K. Toda, R. Ando and K. Kamada [3], "Macroscopic symptoms of collapse in REB-plasma interaction experiments in strong magnetic field" by V. S. Burmasov, I. V. Kandaurov, E. P. Kruglyakov, O. I. Meshkov, A. L. Sanin and L. N. Vyacheslavov [4], "Broadband mm radiation from beam driven strong turbulence" by M. Masuzaki, H. Yoshida, R. Ando, K. Kamada, A. Ikeda, C. Y. Lee and M. Kawada [5], and "Spectroscopic measurements of turbulent Langmuir fields at the Prague relativistic electron beam experiment" by J. Ullschmied, M. Šimek, K. Koláček and M. Řípa [6].

INTRODUCTION

Recently the beam-driven strong Langmuir turbulence has attracted much attention theoretically, computationally and experimentally. At this Conference presented are five papers on the experimental study of the beam-driven strong Langmuir turbulence, which includes two papers from the Kanazawa University group, two papers from a group at Budker Institute of Nuclear Physics and one paper from a group at Institute of Plasma Physics, Czech Academy of Science. This paper reviews these papers as well as one paper on collective processes in REB.

WORKS AT KANAZAWA UNIVERSITY

Summary of Previous Results

1. Spectroscopic measurements of turbulent electric fields [7]

An intense relativistic electron beam (IREB) of 1.2 - 1.4 MeV, about 10 kA and 30 ns was injected into an unmagnetized plasma produced by a pair of rail-type plasma guns. The drift chamber, made of stainless-steel, 60 cm long and 16 cm in diameter, was filled with helium gas of 20 mTorr. The plasma density was varied with the delay time from the firing time of the guns. The ratio of the beam density to the plasma density was from 0.002 to 0.4. High frequency strong electric fields originating from interaction of the beam with the plasma were observed using two optical diagnostic techniques; the Stark shift measurement and the plasma satellite method. From the Stark shift measurement it was found that high frequency strong electric fields with Gaussian distribution existed in the plasma, and that the dimensionless electrostatic energy density $W\sim 1.1$. From this result it was concluded that the plasma was in a strong Langmuir turbulence state in which formation, collapse and burnout of cavitons are repeated. Here cavitons are spatially localized volumes with density depletion in which large amplitude electrostatic waves are trapped. From the plasma satellite method mean electric fields in the plasma was obtained. The strong field regions were found, from electric fields obtained by both measurements, to occupy a few percent of the beam volume. After a tentative analysis using simulation results [8] the final scale of caviton was estimated to be about 20 l_d.

2. Microwave measurements [9]

In the same experimental device strong microwave radiation into a observation window of 18 - 40 GHz was observed. The radiation was broadband above the plasma frequency. The radiation was found to be from beam electrons. There was optimal ratio of the beam density to the plasma density and it was about 0.01.

3. Correlation between microwave and strong Langmuir turbulence [10]

It was found that the strong Langmuir turbulence state was a necessary condition for the microwave radiation, but not sufficient one.

Energy and Angular Spreads of Beam Electrons and Microwave Radiation [3]

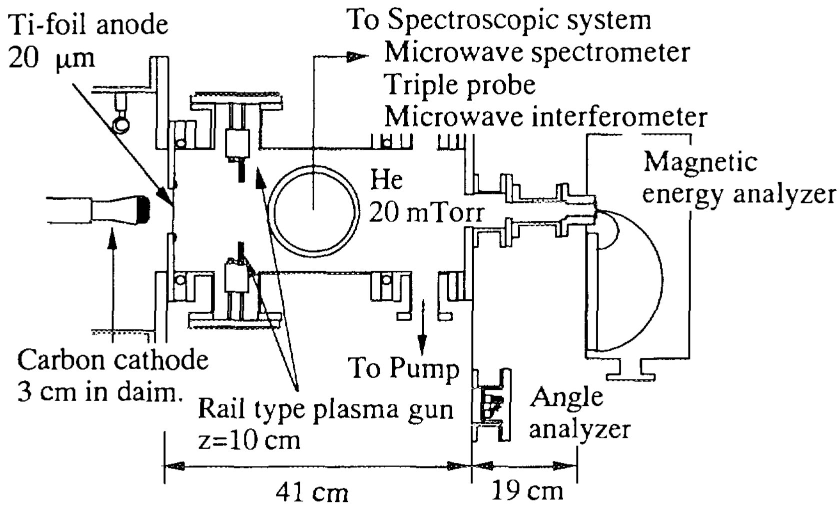


Fig. 1. The experimental setup

For deeper understanding of the strong Langmuir turbulence state investigation of the beam properties after passing the plasma is also important as well as the spectroscopic measurements. The energy distribution and the angular spread (perpendicular velocity scattering) of the beam electrons after passing the plasma were measured by means of a magnetic energy analyzer and an angle analyzer, respectively. The measured energy distribution and the angular spread were analyzed using the theory of transit-time interactions [11].

Figure 1 shows the experimental setup which was the same as described above. Figure 2 shows the plasma density as a function of the delay time τ after the firing time of the guns. The electron temperature without the IREB injection was 6 - 9 eV.

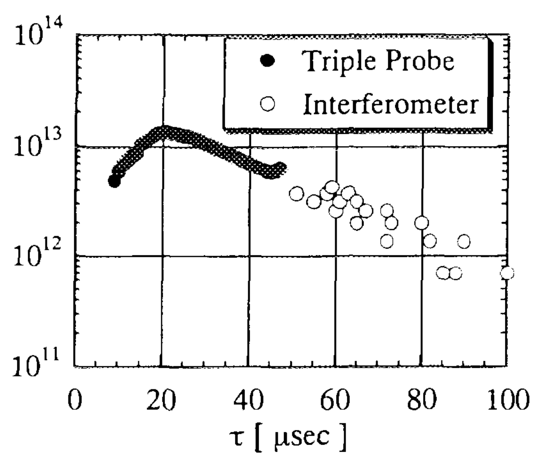


Fig. 2. The plasma density

The observable energy range of the magnetic energy analyzer in this experiment was 90 keV - 1.54 MeV. The energy resolution was 40 keV, and the time resolution was a few ns. During 15 - 30 ns into the beam pulse, the energy distribution showed Gaussian spectra. Fig. 3 a) shows the averaged standard deviation of the energy distribution as a function of τ, where the initial spread of 58 keV is taken into account.

The angle spread (perpendicular scattering) was measured by an angle analyzer. It consisted of a Faraday cup of 0.6 cm in outer diameter and three brass disks of 0.2 cm thick which were set coaxially. The center Faraday cup covered the sinusoidal

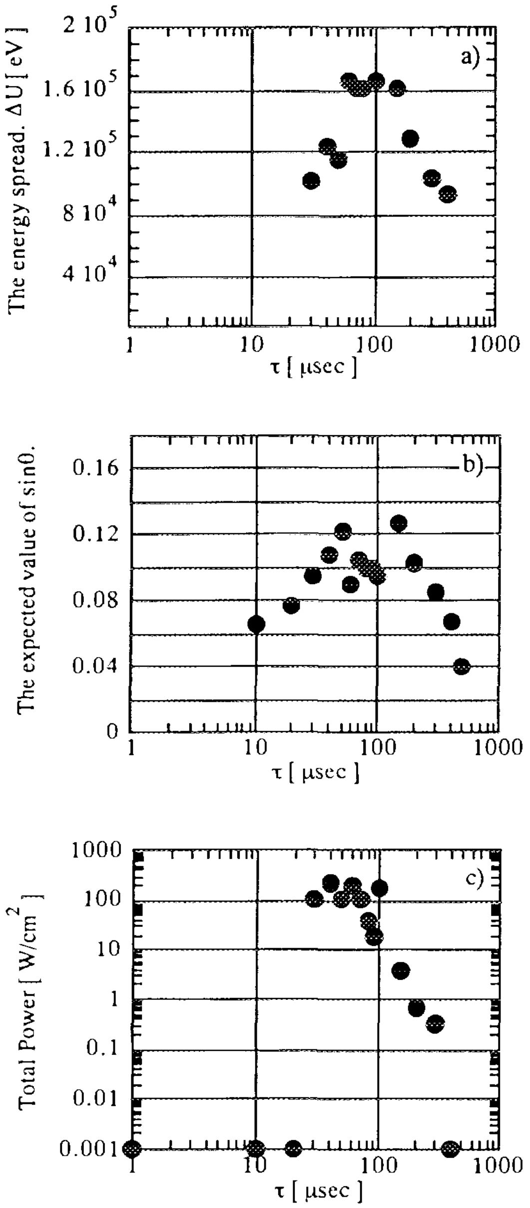


Fig. 3. The energy spread, the expected value of sin θ and the total power of the microwave radiation vs. τ.

range of the scattering angle of 0 - 0.1 and three disks covered 0.1 - 0.2, 0.2 - 0.3 and 0.3 - 0.4, respectively. The angle analyzer was set in the axis at the end of the chamber. The time-evolved expected values of the sine of the scattering angles were calculated from these output signals. Figure 3 b) shows the averaged expected values of the scattering angles as a function of τ. The initial spread is taken into account.

The high power broadband microwave radiation was measured at 17.5 cm downstream from the anode by a 5-channel microwave spectrometer of filter-bank type. The frequency range covered was 18 - 40 GHz. The total power of microwave radiation in this frequency range is shown in Fig. 3 c) as also a function of τ.

The electron temperature T_e after the IREB injection was estimated from the spectroscopic measurement of the intensity ratio of HeI 492.19 nm line to HeI 471.31 nm line by comparing the experimental results with the newly developed collisional radiative model [12]. The intensity of the high frequency turbulent electric field E_s was obtained measuring the Stark shift of HeI 501.57 nm line.

The energy and angular spreads of beam electrons are caused by scattering of beam electrons in energy and in perpendicular velocity during interaction with cavitons. The theory of multidimensional transit-time interactions was applied to analyze these spreads. The scatterings due to single interaction with a caviton was calculated, and then total energy spread ΔU and angular spread (perpendicular scattering) $\Delta v_\perp/v_b$ were estimated. Figure 4 shows ΔU and $\Delta v_\perp/v_b$ for the plasma density n_p = 1.6×10^{12} cm^{-3}. The dipole moments of all

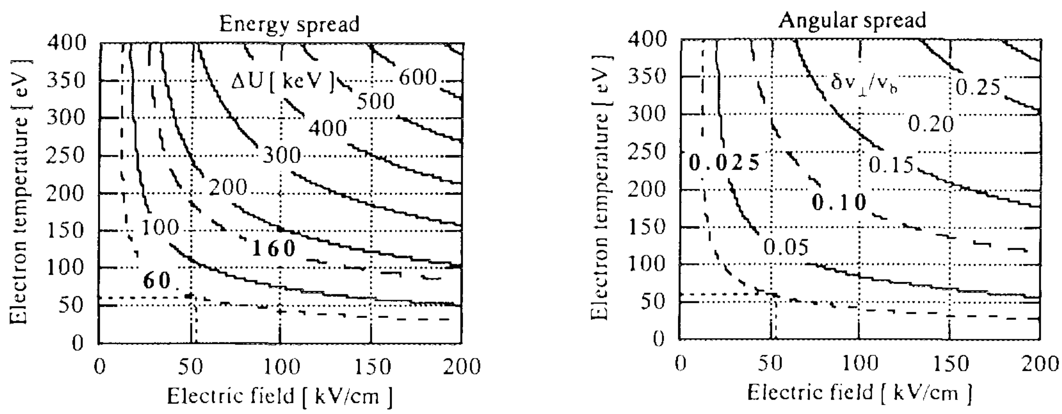


Fig. 4. The energy and angular spreads. The dipole moments of all cavitons are parallel to the beam direction.

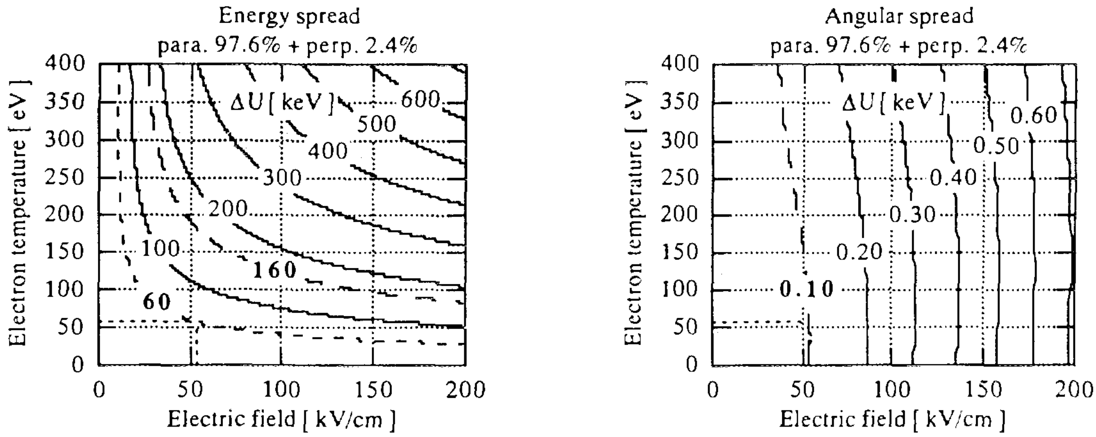


Fig. 5. The energy and angular spreads. Cavitons with perpendicular dipole moment are assumed to be 2.4 %.

cavitons are assumed to be parallel to the direction of the beam propagation. In this case T_e and E_s were 57 eV and 54 kV/cm, respectively. From the energy analyzer measurement ΔU = 160 keV and from the angle analyzer measurement $\Delta v_\perp/v_b$ = 0.10, while the measured values of T_e and E_s give ΔU =60 keV and $\Delta v_\perp/v_b$ = 0.025. If it is assumed that dipole moments of some cavitons are perpendicular to the direction of beam propagation, the angular spread obtained from the measured values of T_e and E_s can be made to coincide with that obtained from the angle analyzer measurement. Figure 5 shows ΔU and $\Delta v_\perp/v_b$ for the case in which cavitons with dipole moment perpendicular to the direction of the beam propagation is assumed to be 2.4 %. Both values of $\Delta v_\perp/v_b$ agree well and almost independent of T_e. However, difference between both values of ΔU remains almost the same. One reason of this disagreement may be inaccuracy of T_e measurement. The electron temperature in the IREB pulse duration could not be obtained because of limitation of the measuring system. If T_e is higher than 100 eV, ΔU determined from T_e and E_s will become close to that obtained from energy analyzer measurement.

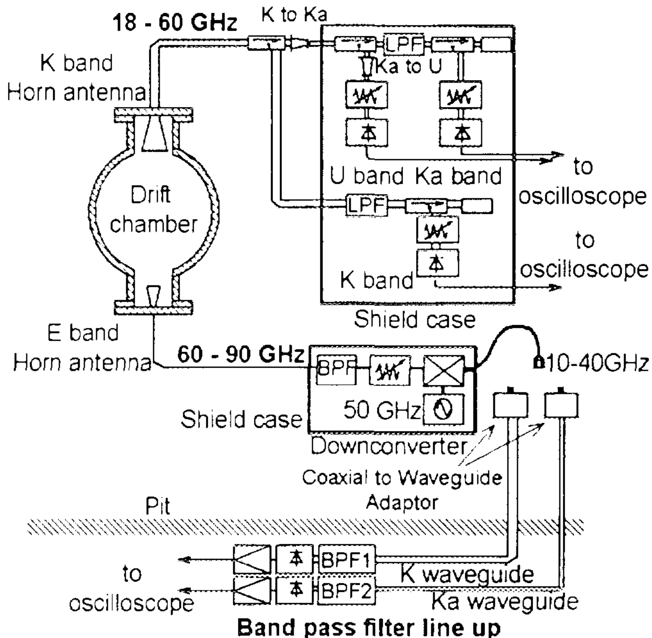
From Fig. 3 it can be seen that the dependence of the microwave radiation on τ is almost the same as dependences of the energy and the angular spreads on τ. The wider the energy and angular spreads, the higher the total power of the radiation.

Followings are summaries.

1. The energy spread ΔU and the angular spread $\Delta v_\perp/v_b$ of IREB electrons after passing the plasma were measured using a magnetic energy analyzer and an angle analyzer, respectively.
2. Theory of multidimensional transit-time interactions was applied to analyze the experimental data.
3. The energy and angular spreads were also estimated using the spectroscopically measured intensity of high frequency electric fields and the electron temperature.
4. The energy spread obtained using the energy analyzer was higher than that obtained using the spectroscopic data.
5. One reason of this discrepancy may be inaccuracy of the electron temperature measurement. The electron temperature in the IREB pulse duration could not be obtained because of limitation of the measuring system.
6. The angular spread obtained using the angle analyzer and that obtained using the spectroscopic data agreed when the percentage of the dipole moments perpendicular to the direction of the beam propagation was taken to be 2.4 %.
7. The above result seems to show that not all of the dipole moments were parallel to the direction of the beam propagation.
8. In connection with the microwave radiation, the wider the energy and angular spreads, the higher the total power of the microwave radiation.

As there was evidence of emission of radiation higher than 40 GHz, the observation window was widened up to F band using a heterodyne spectrometer covering E band (60 - 90 GHz) and a full band detector covering F band (90 - 140 GHz) in addition to the filter-bank type spectrometer covering K, Ka and U bands (18 - 60 GHz) used previously. The radiation was measured radially at 17.5 cm from the anode. Figure 6 shows a schematic diagram of the heterodyne spectrometer and its setup for the radial measurement. It consisted of a downconverter unit, an IF unit and a power unit. The downconverter consisted of a bandpass filter, a variable attenuator, a mixer and a local oscillator with frequency of 50 GHz. The IF unit consisted of bandpass filters, Schottky diodes and pulse amplifiers. It covered 10 - 40 GHz in 5 channels. Filters and detectors used were diverted ones from the filter-bank type spectrometer. Calibration was made at 60 GHz, In this setup full band K, Ka and U band detectors were prepared, and simultaneous measurements were carried out. Figure 7 shows a schematic diagram of the F band detector and its setup for the radial measurements. It consisted of a bandpass filter, an attenuator, a Schottky diode and a pulse amplifier. In this setup full band Ka, U and E band detectors were also prepared and simultaneous measurements were done.

Figure 8 shows a typical radiation spectrum observed when the plasma frequency was about 13 GHz at the measuring position. In this case helium gas was not introduced. Results from two experimental runs are compiled into one. In one of them the setup shown in Fig. 6 was used, and in the other the setup shown in Fig. 7 was used. It was ascertained that radiation was emitted to at least about 140 GHz.



BPF1	BPF2
18.0-22.2	26.5-31.0
22.2-26.5	30.7-35.7
-	35.5-40.0

Fig. 6. The setup of the E band heterodyne spectrometer.

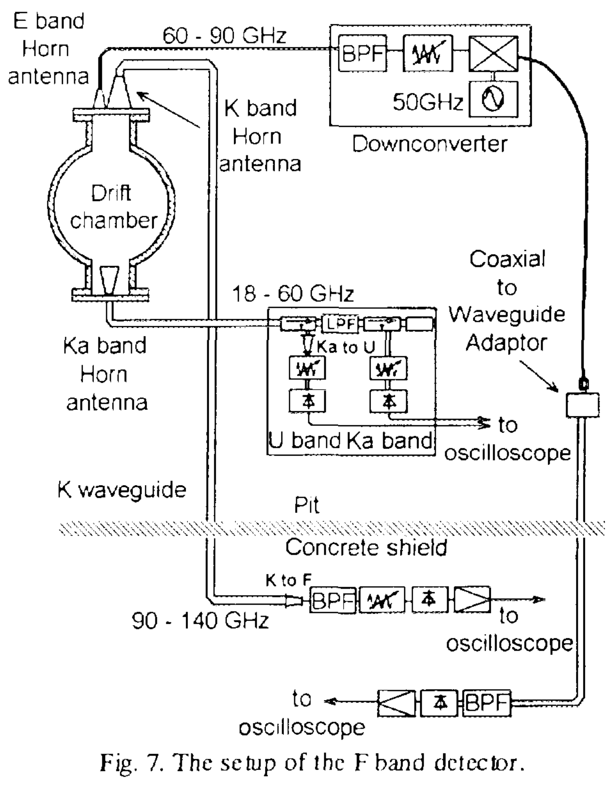


Fig. 7. The setup of the F band detector.

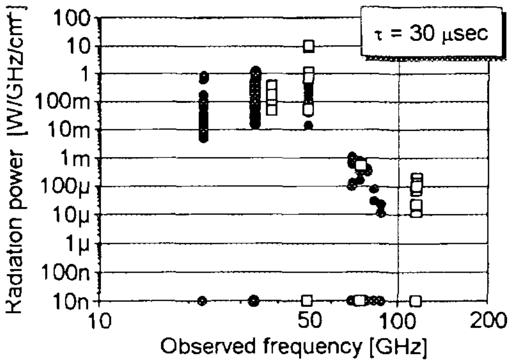


Fig. 8. An experimentally obtained spectrum.

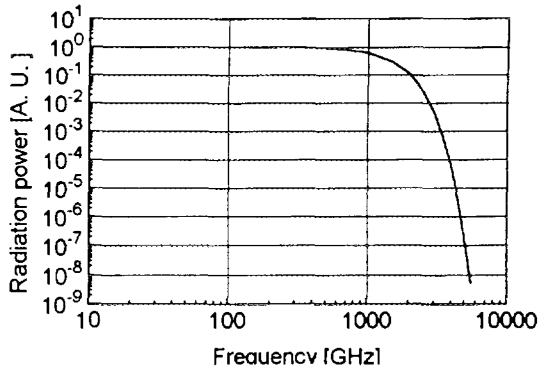


Fig. 9. An example of calculated spectrum.

The power level was high in K to U bands, but it decreased steeply in E and F bands.

Calculation of the radiation spectra was done according to the collective Compton boosting model. In this model the broadband intense radiation is due to the interaction of the density modulated beam electrons with intense high frequency electric fields in cavitons, their characteristic charge density oscillation being assumed to be dipolar. Several spectral density functions for the beam density modulation are assumed. Our calculation were done for each spectral density function and for each direction of the dipole moment. Figure 9 is an example for which Gaussian spectral density function and dipole moment perpendicular to the direction of the beam propagation are assumed. The experimental and calculated spectra resemble each other in shape qualitatively, although quantitatively they are very different.

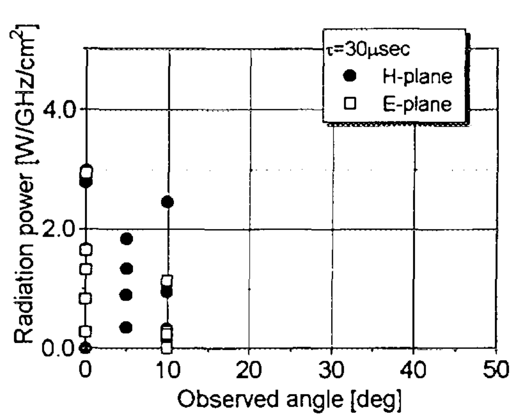


Fig. 10. Angular distribution of the radiation.

Angular distribution of the radiation in Ka band was measured at the end of the chamber varying the horn position. When the dipole moments of the cavitons are parallel to the beam direction, intensity in the axis will be null. On the other hand, when the dipole moments are perpendicular to the beam direction, the intensity in the axis will be maximum. It may be natural to think that the directions of all dipole moments are parallel to the direction of the beam direction, since the electrostatic fields are produced by the beam-plasma instability. Figure 10 shows the measured radiation power as a function of angle. The radiation power observed was almost the same when the horn was rotated 90° around its axis. The results suggests that not all of the dipole moments were aligned to the beam direction on the contrary to the expectation.

Followings are summaries.

1. Radiation was emitted to at least about 140 GHz.

2. The power level was high in K to U bands, but it decreased steeply in E and F bands.

3. At present the Compton boosting model seems to be not able to explain the experimentally obtained spectrum.

4. It is still thought that the radiation is due to beam electrons interacting with caviton fields. The reasons are: (1) The strong turbulence state was found to be a necessary condition for the radiation, and (2) it was found that the wider the energy and angular spreads of the beam electrons due to the interaction with the caviton

fields, the higher the total power of the radiation.

5. Angular distribution of the radiation was measured in Ka band, and the result suggests that not all of the dipole moments of the cavitons were aligned to the direction of the beam propagation.

Future plan includes (1) completion of the F band spectrometer which is a 3-channel Fabry-Perot interferometer type, (2) spectrum measurements in the axial direction and (3) measurement of the beam modulation.

WORKS AT BUDKER INSTITUTE OF NUCLEAR PHYSICS

Macroscopic Symptoms of Collapse in REB-Plasma Interaction Experiments in Strong Magnetic Field [4]

Up to now, as to the case of REB injection into a plasma in a strong magnetic field there is no experiment on the Langmuir waves collapse. This paper presents the first macroscopic manifestations of the Langmuir waves collapse for the case of strong REB-plasma interaction in a strong magnetic field.

The experiments were carried out on the GOL-M device. The parameters of target plasma were as follows: The plasma density was 1.5×10^{15} cm^{-3}, the initial electron temperature was 1 eV, the diameter was 6 cm and the length was 250 cm. A strong mirror magnetic field was applied. The field strengths were 2.5 T in the uniform section and 4.5 T at the mirrors. The injected beam parameters were as follows: The energy was 700 keV, the maximum current was 2 - 3 kA, the diameter was 2 cm and the duration was 200 ns. After 40 ns from the starting time of the beam the plasma temperature increased up to 30 - 50 eV, so the plasma became a nonisothermal state (the electron temperature much higher than the ion temperature).

Two macroscopic indications of the existence of collapsing cavitons in the plasma were found.

1. Appearance of energetic tails on the electron distribution function.

At the final stages of collapsing cavitons, the energy of Langmuir waves trapped in the cavitons are transferred to a small portion of electrons crossing the cavitons during the time less than the period of electric field oscillations in the cavitons, and energetic tails appear on the electron distribution function. Such tails have been observed in the experiments carried out by this group. Some detail is described in the other paper [2].

2. Existence of intense ion-sound turbulence.

At the final stage of caviton collapse the Langmuir waves inside the caviton decay due to the electron damping. Since the plasma densities inside cavitons are low, ion-sound waves are excited. When the electron temperature is much higher than the ion temperature, the damping of the ion-sound waves is weak. So the collapse process should create an intense ion-sound turbulence.

The spectra of low frequency fluctuation were studied by the collective laser scattering method using a pulsed CO_2 laser. The scattered radiation was detected at three angles, 6°, 11° and 16° to the direction of the laser beam propagation. The frequency and the space spectra of low frequency fluctuations were studied. The spectrum of the scattered radiation was studied with the aid of a grating monochromator with a 30 GHz resolution. To identify the exact value of the frequency of oscillations an absorption cell with ammonia was installed between the grating and detector. The frequency of the low frequency fluctuations was found to be 2 GHz, which agreed well with the frequency of the ion-sound oscillations for the experimental conditions. It was ascertained that the ion-sound fluctuation was not excited by the return current, but appeared as a consequence of the strong Langmuir turbulence. The level of the strong Langmuir turbulence, observed using an additional channel at small angle (0.5°) to the laser beam direction, correlated well with the level of the ion-sound fluctuation. In Fig. 11 curve 1 is their first result of the measurements of the k-spectrum of the ion-sound turbulence in a strong magnetic field. From the space spectrum of the

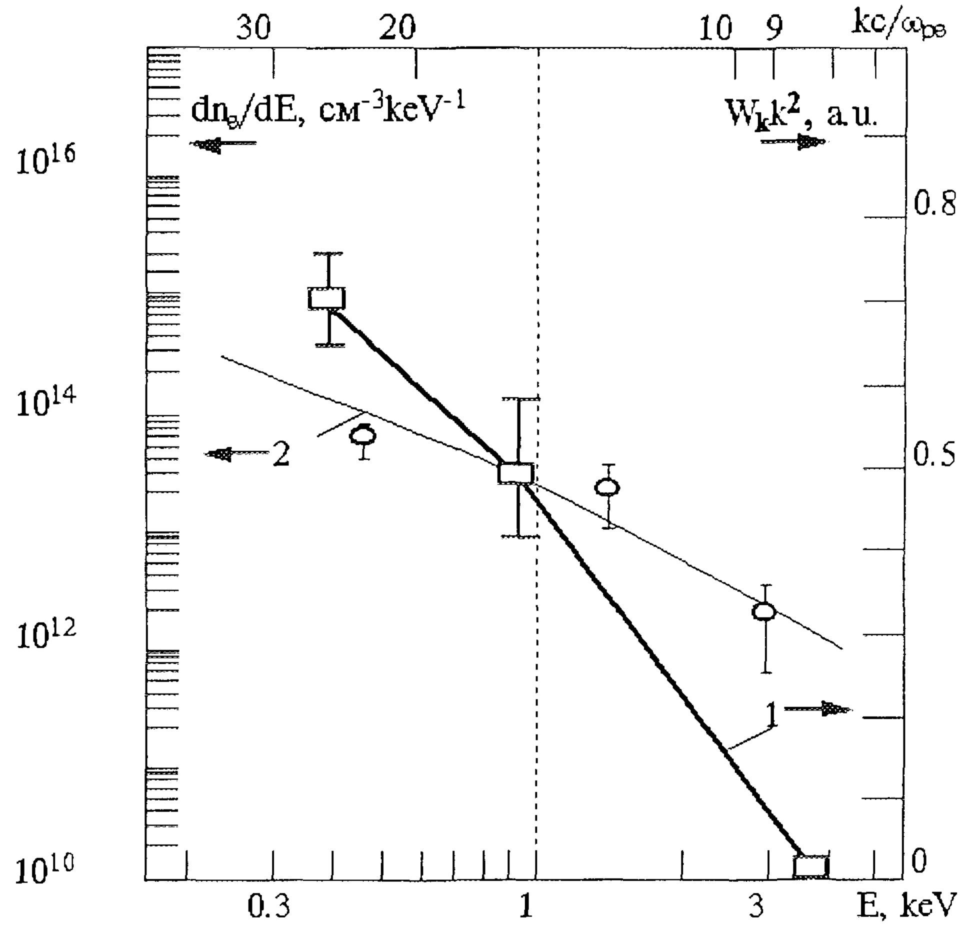


Fig. 11. k-spectrum of ion-sound turbulence (curve 1) and non-Maxwellian part of the electron distribution function of plasma electrons (curve 2) vs. electron energy E or vs. normalized wave number k. The scale of E and k correspond to each other through the ratio $k = \omega_{pe}/v_e$.

ion-sound turbulence the characteristic size of the cavitons at their final stage was estimated to be less than 30 λ_d. This Figure also shows the non-Maxwellian tail of the distribution function of the plasma electrons after heating (curve 2).

Spectrum of Plasma Electrons Observed in Strong Langmuir Turbulence Driven by REB [2]

This paper presents the experimental observation of the non-Maxwellian electron distribution of a plasma due to strong REB-plasma interaction and a discussion of the possible mechanism of plasma heating.

The experimental device was the same as described above. The Thomson scattering technique was used for studying of a non-Maxwellian electron distribution function. Two simultaneously operating systems were employed for observation of light scattered at the angles of 90° and 8°, respectively. The former system was used to measure the temperature and the density of the bulk of plasma electrons, and the latter system was used for studying of the superthermal tails of the electron distribution function. A Nd-glass laser was used as the light source. In the latter system the scattered light was received by a 6-channel polychromator.

The laser pulse was delayed by 50 - 100 ns from the beginning of the REB pulse.

Signals were obtained in four channels in the latter system. It was assumed that the distribution function has the power law: $f(E) \propto E_e^{-\alpha}$ for the energies above 300 eV (approximately 10 times the electron temperature), and $\alpha = 2.5$ was the best fit to the experimental signals.

It is claimed to be evident that the heating of non-Maxwellian part of the electron distribution function is connected with the Landau damping of slow Langmuir waves. A discussion is given on the main mechanism of transferring of the energy of turbulent oscillations towards the short wavelength side of the spectrum.

WORKS AT INSTITUTE OF PLASMA PHYSICS, CZECH ACADEMY OF SCIENCE

Spectroscopic Measurements of Turbulent Langmuir Fields at the Prague Relativistic Electron Beam Experiment [6]

In the Prague REB-plasma experiment REBEX a REB (500 kV, 80 kA, 100 ns) is injected into a hydrogen plasma column 1 m long and 7 cm in diameter bounded in longitudinal direction by thin Al foils. A magnetic field of 0.6 T is applied. The plasma density is 5×10^{14} - 10^{16} cm^{-3}. In order to estimate the intensity of turbulent Langmuir fields from the Stark component of Balmer emission lines three different spectroscopic apparatuses have been used. In this paper these three spectroscopic apparatuses are compared from the point of view of their suitability for measurements of emission line profiles in REB-plasma experiments.

The first apparatus was a 6-channel polychromator with a photomultiplier detection system. Its spectral and time resolution was 0.08 nm/channel and 20 ns, respectively. The time resolution of this system was sufficient for time-resolved measurements of the intensity and width of plasma emission lines, while its sensitivity and spectral resolution proved to be too low for performing any detailed studies of the line shape, and of the line wings in particular.

It should be noted that this group found the LF Stark effects of the intense ion-sound waves, remnants of the burned out Langmuir cavitons, using this spectrometer [13].

The second one was of the intracavity laser absorption spectrometer type, with a 256-pixel CCD camera detection system which made it possible to increase the spectral resolution up to 0.004 nm/pixel. The time resolution was 40 ns. The spectral resolution of this spectrometer was excellent, but the time dependences of the line shape could be constructed on the shot-to-shot basis only. A sufficient number of identical shots was to be collected.

Recently, a new spectroscopic system consisting of the 2-m spectrometer PGS2 Carl Zeiss Jena and of a 512-pixel detecting head (Jovin Yvon) with a computer controlling system has been introduced by this group. Preliminary test measurements suggest that both the sensitivity and the spectral and time resolutions of the system might be sufficient for studies of profiles of the most intense emission lines at the REBEX experiment, but we should wait for its full operation for a little while with expectation of excellent results.

OTHER WORK

Experimental Study of Collective Processes in REB [1]

This paper is not on the beam-plasma interaction, but on the space charge oscillation on a REB. A special low-disturbing technique was used for time and space resolved measurements of the space charge oscillation.

The experiments were done at the SER-1 setup at Saint-Petersburg Technical University. The beam voltage was 220 kV, the beam current was 0.7 - 1.1 kA and the pulse duration was 1 - 3 μs. A magnetic field of 1 T was applied. Two local magnetic field bumps were applied. Using two HF probes temporal and spatial variations of the oscillations were obtained. At the saturation level discrete peaks were discernible in spectra in the frequency range of 100 - 1500 GHz with the strongest in the 700 - 1200 GHz. The amplitude of the oscillations increased with distance from the cathode which indicates their convective nature. Application of the magnetic field bumps revealed the existence of electrons with relatively large transverse and small axial velocity components. It is thought that the space charge oscillations were mainly due to the double-stream instability caused by interaction of an electron flow emitted from the front surface of cathode plasma with maximum axial velocities with an electron flow from the outer generatrix of the plasma with maximum transverse velocity and so with minimum axial velocity. Other mechanisms are also discussed.

CONCLUDING REMARK

Strong Langmuir turbulence state due to the REB-plasma interaction is an interesting research field not only in itself as one theme of fundamental plasma physics, but also in connection with plasma heating, high power microwave devices using REB-plasma systems and space physics. I hope further development of researches in theory, simulation and experiment in this field.

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