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Construction of High-Aperture Optical System for Imaging Diagnostics of Pure Electron Plasma in Tesla-Range of Magnetic Field and Its Application

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Abstract

We have examined two candidates of the lens system for the high fidelity imaging diagnostics of a strongly magnetized pure electron plasma. Combining ray-tracing calculations and crosschecking experiments, we have come up to a zoom-type lens system and it shows a sufficient performance on an experiment under the high magnetic field. Here we report some examples of analyses of the experimental data obtained with the new imaging system.

Keywords:

imaging diagnostics, optical image transfer, electron plasma, vortex dynamics, two-dimensional density distribution, energy spectra

1. Introduction

Exact and sensitive observation of two-dimensional (2D) density distribution of electrons is an essential part of experimental studies of vortex dynamics of electrons as a fluid trapped uniformly between potential hills along the magnetic field, i.e. in a Malmberg trap [1,2]. An optical imaging system combined with a charge-coupled-device (CCD) camera and a phosphor plate is constructed for the observation of the density distributions with a wide dynamic range of 10 to 60000 and a high spatial resolution of 512×512 pixels [3]. As one increasingly recognizes strong influences of low-density background electrons to self-organization of ordered structures of high-density part of electrons (*e.g.* clumps), the requirements have also increased to the spatial resolution in observing extended distributions of electrons at further lower densities [1,4,5].

Because the isomorphic correspondence of magnetized pure electron plasmas to the Euler fluid critically depends on the smallness of gyro-radii compared to the length-scales of the density distribution, experiments under stronger magnetic field need to be carried out with improved spatial resolution [6,7]. We have started a new experimental program which includes the magnetic field variable up to 2.2 T from the maximum of 0.048 T for previous experiments. The increase in the magnetic field strength, however, causes difficulties in the normal operation of a CCD camera, and it has to be moved away from the viewing port of the vacuum vessel placed in the strong field. The requirement for displacement is to reduce the local magnetic field from 0.3 T down to below 0.01 T.

However, the reduction of the brightness and spatial resolution as seen from the removed camera must be compensated by inserting an optical transmission system between the port and the camera.

2. Examination of the lens systems

2.1 Design of the lens systems

We examine two candidates for the lens system. One is the relay lens system as used in periscopes [8,9]. Three lenses are placed as shown in Fig. 1(a). The lens with focal length

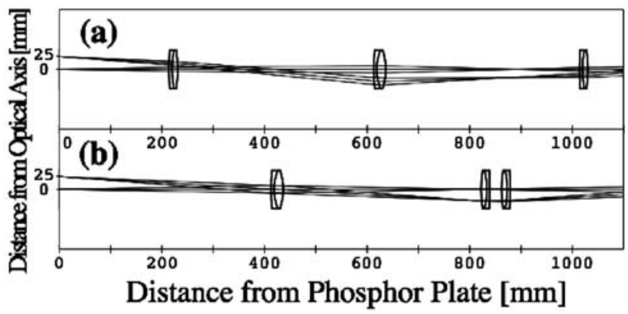

Fig. 1 Arrangements of achromatic lenses for (a) relay-lens system, and (b) zoom-type lens system. The phosphor plate as an image source is placed at $z = 0$.

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f = 200 mm is placed at the center between two f = 400 mm lenses with an equal separation of about 400 mm. A naive consideration predicts that the relay lens system optically shortens the distance between the first and the third lens by $2f = 2 \times 400$ mm with unit magnification.

Another candidate may be called a zoom-type lens system with configuration as shown in Fig. 1(b). The characteristic feature of this lens system is that magnification is varied by adjusting the positions of the second and the third lens.

2.2 Characterization of the lens systems

We have employed a ray-tracing technique for designing the actual system. The light rays emanating from different positions of the phosphor surface are numerically traced by applying Snell's law at every surface and interface of the doublets. Characteristics of the two lens systems are tested experimentally and evaluated relative to the standard configuration such that CCD camera is placed at the view port, i.e. at the position before the removal by 1 m.

The first test is made on the distortion of the image by comparing an original grid pattern with images recorded on the CCD camera. The distortion of the observed image from the original grid pattern is plotted in Fig. 2 as a function of the radial distance from the optical axis at the object plane. The triangles (△) stand for the deviations observed in the standard configuration.

The relay lens system, as represented by the open circles (○), shows unnegligible amount of deformations as the distance from the optical axis increases.

The zoom-type lens system shows the characteristic as plotted with solid circles (●). The contraction remains less than 1 % up to the radius of 30 mm, and we evaluate that the distortion is small enough to be corrected in the stage of data analysis.

In addition to the barrel distortion, coma aberrations appear. Results of experimental observation and numerical analyses with the ray-trace calculation are given in Fig. 3 for the two types of lens system.

The upper array in Fig. 3(a) shows images of the relay lens system predicted by the ray-trace code. The images experimentally obtained with the relay lens system are shown in the lower array in Fig. 3(a). Though an undistorted image is obtained near the optical axis, the focal spot spreads inward as the distance from the optical axis increases. This deterioration of the image quality with coma aberration is hardly correctable by posterior numerical calculations.

The corresponding features with the zoom-type lens system are depicted in Fig. 3(b). In terms of coma aberration, the zoom-type lens system is found to be superior to the relay lens system again.

By integrating the evaluations on the basis of Figs. 2 and 3, we have selected the zoom-type lens system as best suited to the imaging diagnostics for the pure electron plasma experiments with strong magnetic field.

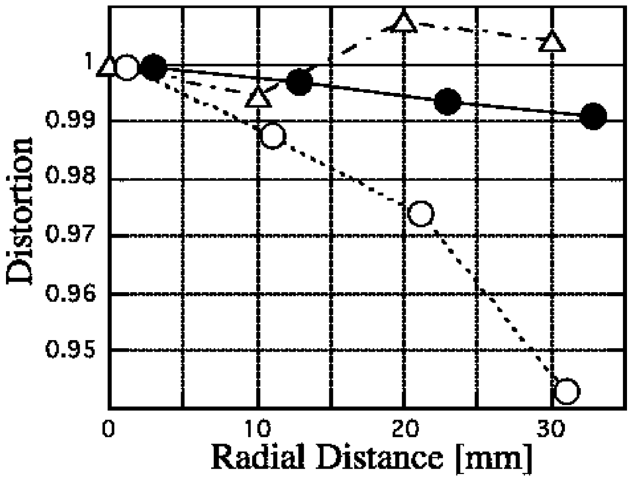

Fig. 2 Displacement of the image from the original point is plotted as a function of the distance from the optical axis. The relay-lens (○) shows larger displacement than the zoom-type (●) which is close to the standard case taken without the lens system (△).

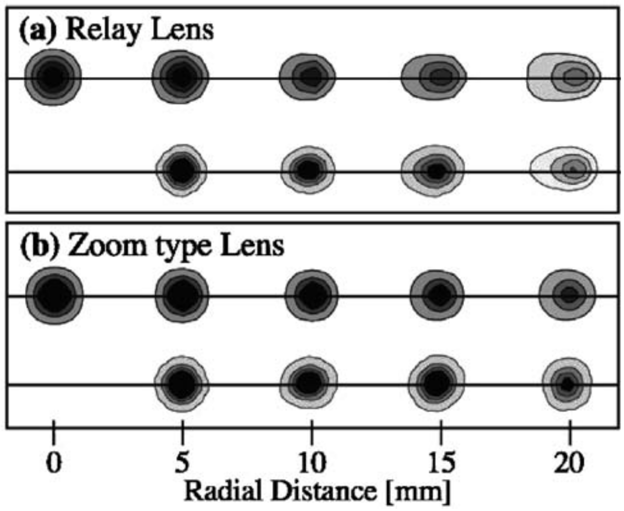

Fig. 3 Images of focal spots are depicted with contours for (a) relay-lens system and (b) zoom-type lens system. The upper arrays shows results with ray-trace calculation and the lower arrays are experimentally observed images. The relay-lens suffers severely from coma aberrations.

3. Sensitivity correction using electron plasma

For quantitative utilization of the phosphor images as recorded on the CCD camera, the establishment of a simple relationship is required between the count on each pixel of CCD and the electron number flowing into the phosphor spot corresponding to the pixel. The linearity observed up to the maximum count of 60000 allotted to each pixel is shown in Fig. 4 (a).

The efficiency of collecting photons depends on the distance from the optical axis at the light emitting surface.

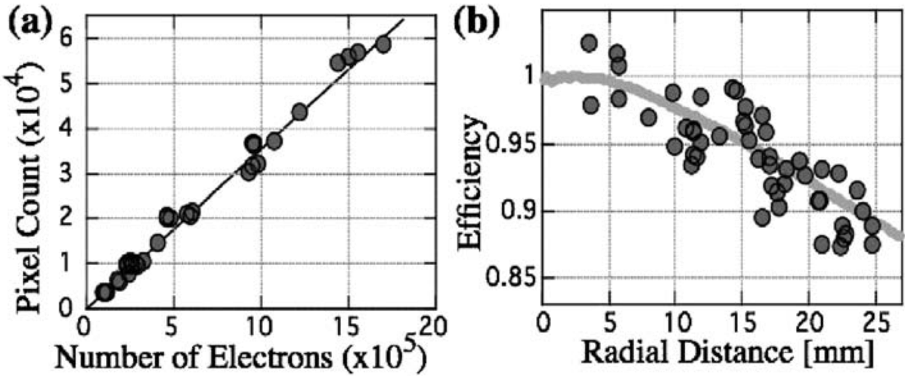

Fig. 4 (a) A linear relation is experimentally confirmed at each pixel of the CCD camera between the pixel count and the number of electrons collected at the associated location in the phosphor plate. (b) The light-collection efficiency of the total optical system is plotted as a function of the distance from the optical axis.

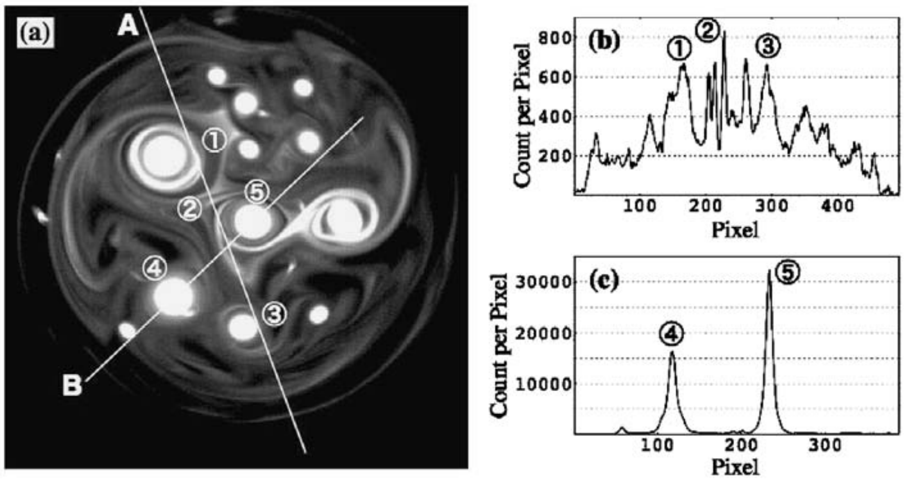

Fig. 5 (a) An image of the electron density distribution under 1 T magnetic field. (b) Fine structures can be observed along the line A in the low-level density distribution. (c) High level distribution of the clump electrons is recorded along the line B.

The dots are obtained from the observed images of the electron clumps. The integrated count over the well localized image of a clump is divided by the number of the constituting electrons. The linear relation obtained in Fig. 4(a) assures this procedure. The solid curve in Fig. 4(b) represents observed luminosity of a uniform light source. Both values are normalized by the on-axis value.

The two independent tests show a consistent result quantitatively indicating the light collecting efficiency as a function of the off-axial distance. The correction for the space dependent efficiency is included in the numerical analyses of the image data.

4. Application to non-neutral plasma vortex experiment

The electron density distribution observed in a vortex experiment under the 1 T magnetic field is shown in Fig. 5(a) as an example of the application of the newly developed optical system. The 512 × 512 mm pixels provide the view over the area of 45.5 × 45.4 mm at the mid-plane of the trap. The image is corrected numerically for position-dependent sensitivity by using Fig. 4(b).

The image data represents the distribution at 50 μs after the generation of 31 clumps. One can observe filamentary structures extending from the clumps that remain after the merger process in the initial phase. The brightness in the image Fig. 5(a) is enhanced to explicitly demonstrate the structures generated in the low-level distribution outside the clumps.

A wide dynamic range of the imaging observation is demonstrated in Figs. 5(b) and 5(c). Some points of characteristic structure, i.e. peaks of clumps and filaments, are numbered along the lines. The profile along the line A clearly shows the high capability of observing fine structures in the electron density distribution. A difference of 20 counts is sufficient to discern the low-level structures. The profile along the line B demonstrates a high dynamic range required for the observation of the clumps' profiles. The measured distribution shows a continuous profile of a high density clump peaking around 32000 (i.e. upper limit is 60000).

5. Conclusion

We have developed an achromatic lens system to transfer an optical image to a CCD camera removed by about 1m from the original location without losing brightness and without noticeable deformations. Experimental tests have revealed that the zoom-type lens system compares favorably with the relay lens system.

With the installation of the zoom-type lens system, the density distribution appearing in the vortex interactions of a pure electron plasma magnetized under 2 T has been recorded successfully on the CCD camera placed in a weak magnetic field of 0.007 T.

For quantitative analyses of the image data, we have established the linear relation between the electron number and the number counted at each pixel, and the correction factor for the position-dependent sensitivity of the whole imaging system.

By combining these results we have shown some examples of numerical analyses of the image data acquired in a vortex dynamics experiment carried out in a strong magnetic field of 1 T.

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