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Reconstruction of three-dimensional structure of plasma emission using multi-directional imaging

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1. Introduction

In recent years, plasma-based processes have advanced in various application areas such as materials processing, thin-film deposition, and surface modification. These developments have brought increasing demands for improved spatial uniformity, process stability, and selectivity. Such performance is closely related to the three-dimensional (3D) spatial distribution of internal plasma properties, including electron density, optical emission, ion distribution, and sheath structure.

To analyze these properties, diagnostic methods capable of visualizing the internal structure of the plasma with high spatial resolution are becoming increasingly important. However, inserting probes into the plasma can disturb the discharge conditions or affect the process itself.

Therefore, the development of non-intrusive, high-resolution 3D diagnostic techniques that minimize disturbance to the plasma is strongly required. To address these challenges, we have been developing a diagnostic method based on tomographic reconstruction using multi-view plasma emission imaging [1].

2. Methodology and Experimental Conditions

The reconstruction 3D region is divided into voxels, with the emission intensity of each voxel represented as a vector $\boldsymbol{f}$, and the set of captured 2D images represented as a vector $\boldsymbol{g}$. These are related through a system matrix H, which contains the geometric characteristics of the imaging system, expressed as:

$$H\boldsymbol{f} = \boldsymbol{g} \qquad (1)$$

This inverse problem is solved using Tikhonov-Phillips regularization, with the solution given by:

$$\boldsymbol{f} = (H^{\mathrm{T}}H + \alpha C^{\mathrm{T}}C + \beta I^{\mathrm{T}}I)^{-1}\, H^{\mathrm{T}}\boldsymbol{g} \qquad (2)$$

Here, C is the Laplacian matrix, I is the identity matrix, and α and β are regularization parameters. The matrix H was constructed experimentally using checkerboard images to calibrate the camera parameters H.

For the evaluation experiment, we used cameras equipped with telecentric lenses and bandpass filters to capture optical emission images from two orthogonal directions (90° apart). The discharge gas was either Ar or a mixture of Ar and Ne, introduced into a capacitively coupled plasma (CCP) reactor with a diameter of 300 mm and electrode gap of 45 mm. The pressure was maintained at 6.7–13 Pa, and a VHF power (40.68 MHz) was applied to the powered RF electrode (diameter 110 mm). The chamber walls were black-coated to reduce light reflection.

Due to the limited number of observation windows, pseudo-four-directional image data were created by mirroring the acquired images, assuming axial symmetry. To reduce optical aberration caused by incident angle dependency of the bandpass filter, telecentric lenses were used.

For simplified emission analysis, we assumed that the emission intensity I is proportional to the electron-impact excitation rate $k_{\mathrm{ex}}n_{\mathrm{e}}n_{\mathrm{g}}$. Here, k_{ex} is defined as the integral of the excitation cross section and the electron velocity distribution function. The excitation threshold energies for Ne (580 nm) and Ar (750 nm) lines are 20.7 eV and 13.3 eV, respectively. From the intensity ratio $I_{\mathrm{Ne}}/I_{\mathrm{Ar}}$, we estimated the spatial variation in electron energy. The ratio was highest near the electrode and decreased with increasing distance, consistent with the expected behavior in a CCP, where electrons are typically accelerated near the sheath.

3. Asymmetric Plasma Reconstruction and System Improvement

To improve spatial resolution, increasing the number of observation directions is essential. However, due to structural constraints of the vacuum chamber, it is difficult to add additional ports. To investigate the feasibility of reconstructing a 3D structure from 2D images, we intentionally created an asymmetric plasma by covering half of the RF electrode surface with an insulating material. Instead of moving the cameras, we rotated the position of the insulator and used three fixed cameras to acquire pseudo multi-directional images. The reconstruction results reproduced the nonuniform emission intensity, demonstrating that the proposed technique can be applied to the diagnosis of asymmetric 3D plasma structures.

Furthermore, to improve the accuracy and reliability of the reconstruction, we developed a new apparatus equipped with a rotatable top flange that allows angular scanning while maintaining vacuum. The borescope camera, inserted from the top flange, can capture images at arbitrary angles and heights, and its optical axis is aligned with the central axis of the electrode. In addition, a cylindrical liner with a diameter of 180 mm and height of 40 mm was installed to spatially confine the plasma. Emission images were acquired at four heights and from eight directions at 45° intervals around the chamber, totaling 32 viewpoints. The reconstructed 3D emission distribution revealed detailed sheath structures near the RF electrode, confirming both the system's effectiveness and the high spatial resolution of the method.

References

[1] M. Kyuzo, et al., Jpn. J. Appl. Phys. 63, 056004 (2024).