Determination of the effective secondary electron emission coefficient for low-pressure RF discharges based on pixel-based similarity of spatio-temporal excitation map images

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The heavy-particle induced secondary electron emission coefficient (γ) is a crucial parameter in the modeling of low pressure RF plasmas. As shown by numerous Particle-in-Cell/Monte Carlo Collision (PIC/MCC) simulation studies for diverse discharge conditions, the value of γ can have very strong effects on the electron power absorption, excitation/ionization dynamics and the plasma parameters. Unfortunately, experimental data for γ under plasma exposure are very difficult to obtain.

To overcome the lack of data for γ, different approaches are used in the simulations, such as self-consistent determination of the effective γ (which is the ratio of the emitted secondary electron and the incident ion fluxes at the surface, implicitly including the contributions of the other species to the secondary electron emission) [1], theoretical models [2], or computationally assisted spectroscopic techniques [3]. This latter method (known as *γ*-CAST) is based on phase resolved optical emission spectroscopy (PROES) measurements of the electron impact excitation rate from the ground state into a specific level of neutral gas atoms. For electropositive gases at high pressures, these measurements typically exhibit two distinct maxima adjacent to each electrode at different times within the RF period, one caused by electrons accelerated by sheath expansion (α-peak) while the other is due to secondary electrons accelerated towards the bulk by the sheath electric field (*γ*-peak). Contrasting the intensity ratios of these two maxima with results of PIC/MCC simulations performed for a sequence of *γ* coefficients under conditions identical to the experiments, could yield an effective secondary electron emission coefficient, ensuring a reasonable agreement between the experimental and simulation results for several discharge characteristics [4].

Here, we introduce an alternative of the *γ*-CAST method that combines PROES measurements with PIC/MCC simulations for the determination of the γ coefficient. In contrast to *γ*-CAST, this approach does not necessitate the simultaneous presence of both the α-peak and *γ*-peak in the excitation rate, making it applicable across a wider range of discharge conditions. The method relies on the similarity of images, specifically the pixel-based similarity of the maps of the spatio-temporal distribution of the electron impact excitation rate from the ground state into a specific level, obtained from measurement and simulations. The method is illustrated below by using PROES data obtained from a geometrically symmetric capacitively coupled plasma reactor operated with Ar gas (with a 10% Ne admixture for the PROES) and Cu electrodes located at a distance of 4 cm, at 100 Pa pressure, 700 V peak-to-peak voltage and 13.56 MHz driving frequency. The simulations are performed using a 1d PIC/MCC code, with different *γ* coefficients set as input values.

For the comparison of the spatio-temporal maps of the electron impact excitation rate obtained from PROES and PIC/MCC simulations (see Fig. 1), the PROES data are initially processed to remove the background noise and the simulation data matrices are reshaped to match the size of the PROES data matrix. In the comparison, only the regions close to the powered electrode (highlighted by dashed rectangles in Fig. 1) are used. Within this specified region, a “scan area” is defined in the grayscale

PROES image (see Fig. 2), capturing the dominant excitation pattern at the powered electrode. This area (image) is then compared to rectangles (images) of the same size extracted from the simulation data for a given *γ*. The sum of squared differences (SSD), a measure of match based on pixel-by-pixel intensity differences, is calculated for all possible image pairs. This involves the summation of squares for the product of pixel subtraction between the two images. These steps are then performed iteratively for all simulations with different *γ* coefficients (see the minimum SSD values obtained for different *γ* in panels of Fig. 2). Overall, the best match between PROES and PIC/MCC results is indicated by the minimum of all SSD values. In order to eliminate slight shifts in time and space between the experimental and computed images a shift is allowed along both *x* and *t* during the fitting process.

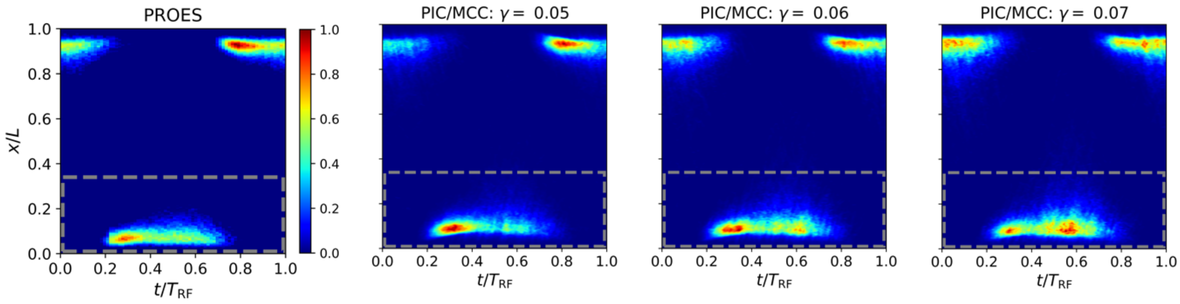

Fig. 1: Spatio-temporal plots of the electron impact excitation rate from the ground state into the Ar2p$_1$ level obtained by PROES and from PIC/MCC simulations for different values of the secondary electron emission coefficient, γ. The horizontal axes correspond to one RF period, the vertical axes show the distance from the powered electrode. The color scales of the plots are individually normalized to a maximum of 1. Discharge conditions: L = 2.5 cm, p = 100 Pa, f = 13.56 MHz, V_{pp} = 700 V. The grey dashed rectangles show the regions which are considered in the pixel-based comparison of the images.

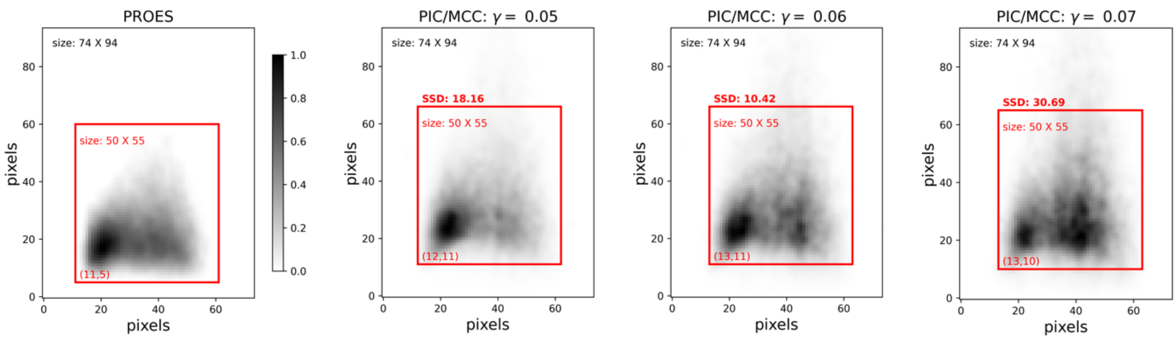

Fig. 2: Grayscale plots of the image regions marked by dashed gray rectangles in Fig. 1. The red rectangles indicate the "scan area" defined in the PROES image along with corresponding regions of the same size in the PIC/MCC images for which the best match (minimum SSD value) was obtained for the different γ coefficients. The SSD values for these cases are shown in the panels. Overall, γ = 0.06 results in the best agreement between PROES and PIC/MCC results.

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