Analysis of retarding field energy analyzer transmission by simulation of ion trajectories

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Analysis of retarding field energy analyzer transmission by simulation of ion trajectories

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Retarding field energy analyzers (RFEAs) are used routinely for the measurement of ion energy distribution functions. By contrast, their ability to measure ion flux densities has been considered unreliable because of lack of knowledge about the effective transmission of the RFEA grids. In this work, we simulate the ion trajectories through a three-gridded RFEA using the simulation software SIMION. Using idealized test cases, it is shown that at high ion energy (i.e., >100 eV) the transmission is equal to the optical transmission rather than the product of the individual grid transparencies. Below 20 eV, ion trajectories are strongly influenced by the electric fields in between the grids. In this region, grid alignment and ion focusing effects contribute to fluctuations in transmission with ion energy. Subsequently the model has been used to simulate the transmission and energy resolution of an experimental RFEA probe. Grid misalignments reduce the transmission fluctuations at low energy. The model predicts the minimum energy resolution, which has been confirmed experimentally by irradiating the probe with a beam of ions with a small energy bandwidth. *Published by AIP Publishing.*
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I. INTRODUCTION

Many research and industrial plasma applications depend on accurate knowledge of the ion energy distribution function (IEDF) and ion flux densities. For example, surface modification processes in the semiconductor industries, such as reactive ion etching,^{1,2} atomic layer deposition,³ and etching,⁴ depend on both the flux density and the IEDF. In fusion experiments, the ion temperature in the plasma scrape-off layer and edge regions is an important parameter for the understanding of edge plasma physics.^{5,6} An emerging research field is the field studying plasmas driven by radiation in the next generation lithography tools. The used extreme ultraviolet radiation ionizes background gases in the tool, resulting in plasma generation near delicate surfaces such as multilayer mirrors. Ion fluxes induced by this plasma are believed to influence the lifetime of optical components,^{7,8} raising the need for accurate IEDF and ion flux density measurements.

Retarding field energy analyzers (RFEA), also called retarding potential analyzers, are relatively simple, compact, and affordable devices that can be used to measure both the IEDF and absolute ion flux densities. In contrast to the much more expensive and complex to operate ion mass spectrometers, they lack mass separation, which is often not required. They are commonly used to measure the IEDF in commercial and scientific applications.^{3,5,6,9,10} However, in most cases, the measured ion flux density is considered unreliable and therefore not usable due to the unknown transmission of ions through the device.^{9,11} Understanding this transmission could greatly enhance the usability of the RFEA as it could be used simultaneously for IEDF and ion flux density measurements.

This work describes the analysis of the effective transmission by simulating ion trajectories through an RFEA using the commercially available charged particle optics simulation software SIMION.^{12,13} Focus is on the effects of grid alignment because poor alignment impacts the transmission^{11,14,15} and energy resolution¹⁶ significantly.

The RFEA operating principles have been described extensively in the literature^{3,9,11,14} and are therefore only summarized here. Figure 1 shows a schematic of a three-gridded RFEA consisting of a stack of electrically insulated grids, G_0 through G_2 , and an ion collecting electrode C. The potential distribution inside the device is also shown. The first grid G_0 is facing the plasma and is at the same electric potential as the surface on which the RFEA is mounted. G_1 is at a negative potential compared to G_0 to repel plasma electrons. An ion retarding potential (V_R) is applied to G_2 . Only ions that have an initial kinetic energy at the entrance of the RFEA that is larger than qV_R , with q the ion's charge, will overcome this field and reach the collector. It therefore acts as a high pass filter for the ion energy. Extra grids are optional, for example, for the suppression of secondary electrons emitted by the collector. To measure the IEDF, V_R is swept while measuring the collector current. The IEDF is calculated by differentiating the collector current with respect to the retarding potential.

To determine the total ion flux density, it is sufficient to measure the collector current at $V_R < 0$ V and at V_R higher than the highest ion energy divided by the ion charge ($V_R > E_{ion}^{max}/q$). At $V_R < 0$ V, the potential does not provide a barrier and all ions are collected. At $V_R > E_{ion}^{max}/q$, all ions are stopped and there is no ion current to the collector which allows for the determination of any offsets and leak currents. The ion flux density incident on the surface is calculated by dividing the measured ion current by the effective sample area and the ion charge

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FIG. 1. Sketch of the potential distributions (top) and working principle (bottom) of the RFEA. G_0 is at wall potential, G_1 is biased negatively to repel electrons, the positive bias on G_2 can be scanned to select which ions can pass through to the collector C.

(we assume only singly charged ions). The effective sampling area is determined by the probe area and the effective transmission of the grid stack T_T , of which the latter is defined as the ion flux density at the collector relative to the flux incident on G_0 . In the literature, it has often been proposed that, when the pressure is sufficiently low to avoid ion collisions with background gas particles inside the device (typically below 10 Pa for 1 mm thick devices) and the spacing between the grids is sufficient [(much) larger than the grid hole separation], T_T is equal to the product of the individual grid transmissions T_i .^{14,17}

$$T_T = T_1 \times T_2 \cdots T_n, \quad (1)$$

with n being the number of applied grids. In the case of equal grids, $T_T = T_i^n$. The important assumption made here is that the individual beamlets passing through the grid apertures diverge sufficiently (due to ion lensing effects) so that a uniform flux is incident on each grid.^{11,14} This is illustrated in Fig. 2. One of the implications is that the alignment of the grids is not of importance for the effective transmission.

There have been attempts to experimentally verify the T_i^n transmission with varying results. By comparing Langmuir probe and RFEA measurements, Gahan *et al.* showed an agreement within 22%.¹⁷

Baloniak *et al.* also used a Langmuir probe, but did an additional experiment in which the collector was biased to a negative DC voltage while all other grids were biased to 0 V. T_T was determined by comparing the current to the top surface of the RFEA to the collector current. The T_T found was 3–4 times less than T_i^n . Their suggestion was that this was caused by the alignment of the grids, implicitly disregarding the assumptions leading to Eq. (1). Instead, the effective transmission was suspected to be equal to the optical transmission, T_o , which is defined as the open area set by the grids.

Denieffe *et al.* recorded the current to each of the grids to determine the effective transmission of all the individual grids.¹¹ The used RFEA had a metallic plate with holes in front

FIG. 2. Illustration of the T^n transmission rule. Ions passing through the grids become divergent due to electrostatic lens effects.

of G_0 . Their conclusion was that the effective transmission of G_0 was reduced by pressure-dependent ion angular distribution in combination with the angular acceptance of the RFEA. The beamlet spreading was sufficient to provide a uniform flux to subsequent grids.

When stacking grids with random displacements in the horizontal plane, the expectation value of the optical transmission corresponds to T_i^n .¹⁵ Baloniak *et al.* used the Monte Carlo simulation of the optical transmission with $n = 4$ grids with $T_i = 55\%$. He found an expectation value of $\langle T_T \rangle = 9.4\%$, which corresponds to T_i^4 . However, the standard deviation was 5.3% and the most probable transmission was 6.6%. The experimentally found T_T was 3–4 times lower than $\langle T_T \rangle$ but still within the standard deviation. Unfortunately they did not determine the optical transmission of their RFEA.

In summary, the discussion about T_T has been going on for decades and is ongoing. Experimental work had not yet brought a consensus on how the transmission of the individual grids combines to the effective transmission of the grid stack.

Section II presents the SIMION model that we used to investigate how ions are transported through an RFEA in a collisionless regime in the absence of magnetic fields. The influence of ion energy, grid alignment, and ion incident angle will be analyzed using three test cases that increase in complexity. This allow us to make a clear distinction between T_i^n and T_o . Subsequently the model will be applied to an experimental probe. We will focus on relatively low energy ions (i.e., below 20 eV) which occur in low temperature plasma applications without surface biasing.

II. MODEL

SIMION is a software package for the simulation of charged particle optics.^{12,13} It calculates the electrostatic fields in 2D or 3D geometries and the trajectories of charged particles moving through those field.

The models consist of a stack of three grids (G_0 – G_2) and a solid electrode (C) (see Fig. 3). The front of the grids is spaced 200 μm apart, and the distance between G_2 and C is also 200 μm .

FIG. 3. The 3D model as put into SIMION.

The square grid apertures are required for a Cartesian coordinate system. The thickness of the grids d is $25\ \mu\text{m}$. The width of the wires w is $10\ \mu\text{m}$ and the aperture width l is $50\ \mu\text{m}$. The resulting grid transparency $T_i = \frac{l^2}{(l+w)^2} = 69.4\%$. Because $n = 3$ and equivalent grids are used with transmission $T_i = T$, the transmission according to Eq. (1) is $T_i^n = T^3 = 33.4\%$.

Grids measuring $2 \times 2\ \text{mm}$ were simulated to reduce computational costs. The space in front of the RFEA is limited by a grounded electrode placed $2.5\ \text{mm}$ in front of G_0 . This results in a simulation domain of $2.0\ \text{mm} \times 2.0\ \text{mm} \times 3.1\ \text{mm}$.

The simulation mesh is set to $5\ \mu\text{m}/\text{gu}$ (grid unit), resulting in a domain of $401\ \text{gu} \times 401\ \text{gu}$ by $643\ \text{gu}$. This is sufficient to resolve the $10\ \mu\text{m}$ thick RFEA grid lines. The resulting geometry is shown in Fig. 3. Trajectory calculations include velocity reversal checks and a binary boundary approach method to adjust the simulation time step size for ions near boundaries, sharp gradients, and high field curvature areas.

TABLE I. Grid functions and applied potentials.

Grid	Function	Applied potential (V)
G_0	Ground	0
G_1	Electron repeller	-60
G_2	Retarding grid	Variable/-5
C	Collector	-10

The potentials on the grids are given in Table I. The potential on G_2 can be scanned to measure the energy distribution. In the following simulations, it is fixed at $-5\ \text{V}$, which is a typical potential when measuring the total ion flux.

An ion beam can be specified by the number of ions, ion energy, direction, origin, and beam diameter. Because the origin is placed in the field-free region in front of G_0 , the ions are not accelerated before they reach the RFEA. Hence, the energy at the entrance of the RFEA is equal to the beam energy. Transmission is defined as the number of ions that reach the collector divided by the number of injected ions.

The simulations are limited to a collisionless regime in the absence of magnetic fields. Magnetic fields could affect the ion trajectories and hence the transmission.¹⁴ The absence of collisions of ions with background gas particles is often a valid assumption due to the limited size and the low pressure environments in which RFEAs are usually operated. However, one should carefully assess that these effects are indeed negligible under their specific experimental conditions because in a collisional regime, charge exchange can create ions at rest inside the RFEA¹⁵ which can introduce a pressure dependent factor in the effective transmission.

Space charge effects have not been taken into account in the model. However, in Sec. IV D, it will be shown that there is little impact to be expected on the ion trajectories when the RFEA is operated well below the space charge limited current density.

A. Test cases

We consider three test cases which are illustrated in Fig. 4. Case 1 represents the idealized case, while cases 2 and 3 are inspired by features of the experimental probe that is investigated later on. The cases are as follows:

FIG. 4. The head-on view of the grids used in the three cases under investigation. Each color (black, yellow, red) represents a subsequent grid. (a) Case 1, (b) case 2, (c) case 3.

TABLE II. Summary of the test cases.

Test case	Summary	T_o (%)
Case 1	Aligned grids	69.44
Case 2	G_0 rotated 45°	48.15
Case 3	G_1 and G_2 displaced $20\ \mu\text{m}$	24.96

Case 1: Idealized case in which the grid apertures are perfectly aligned. The optical transmission is therefore equal to that of a single grid. The potential distributions and basic ion trajectories at normal incidence are investigated.

Case 2: One grid is rotated over 45° . The optical transmission is reduced but is still larger than T^3 . Also the symmetry of the repeating grids is broken as the rotated grid has a repetition length in the horizontal and vertical direction of $\sqrt{2}$ times the mesh repetition length. This case will be used to investigate the trajectories at incident angles larger than normal.

Case 3: G_1 is displaced $20\ \mu\text{m}$ in positive horizontal and vertical directions, while G_2 is displaced $20\ \mu\text{m}$ in the opposite directions. The resulting optical transmission is 24.96%, which is significantly less than the T^3 transmission of 33.4%. The transmission at normal incidence as a function of ion energy will be investigated and compared to that of the first two cases.

All cases have an equal T^3 transmission of 33.4%, but the optical transmission decreases by the displacement of the grids. The optical transmissions are given in Table II.

III. RESULTS

A. Potential distribution

Using case 1, the potential distributions inside the RFEA are investigated. Figure 5 shows the equipotential lines along the yz -plane for the potentials given in Table I. The cutout shows the grid lines and the curvature of the potential lines. The blue lines are spaced 1 V apart and run from 0 to -9 V. Yellow lines are spaced 10 V apart and start from -10 V. Some electric field lines are illustrated with red arrows.

In front of the grounded grid, there are no gradients in the potential and thus this region is field free. This ensures that ions that are injected in this region are not accelerated before they enter the RFEA and thus maintain their initial energy.

FIG. 5. The equipotential lines inside the RFEA along the yz -plane. The applied potentials are given in Table I. Blue lines are spaced at 1 V, yellow lines at 10 V. The electric field lines are illustrated with red arrows.

FIG. 6. Trajectories of 1000 ions with 1 eV energy in the case 1 geometry.

In between the grids, the potential curves are spaced evenly and symmetric, representing a homogeneous and constant electric field.

The equipotential lines curve around the grid wires. Ion lensing is expected in these areas. Just after G_0 , the electric field lines will point toward the normal, resulting in ion focusing. At G_2 , they will point away from the normal and therefore the ion beam is dispersed. At G_1 , focusing effects are expected to be less pronounced as the ions have a much higher velocity due to the large negative potential.

B. Ion trajectories at normal incidence

Ions trajectories are investigated in the model by injecting a mono-energetic beam of ions with a width equal to the grid repetition length $l + w$. The beam will therefore pass through one single grid opening. A 3D example is shown in Fig. 6. The beam energy was 1 eV.

Figure 7 shows the cutout in the yz -plane through the center of the ion beam for 1 eV, 4 eV, 10 eV, and 10 000 eV ions. Due to the Cartesian grids, the cutout is symmetric under rotation over 90° along the z -axis. Figure 7(a) shows the cutout of the 3D example in Fig. 6. Ions with an initial energy of 1 eV are strongly focused just behind the first grid. The negative potential at the electron repeller accelerates the ions into the RFEA. They pass the second and third grid in a broad

FIG. 7. Case 1 ion trajectories at 1, 4, and 10 eV and 10 keV. Ions are injected from the left in a beam with a radius equal to the grid's aperture spacing. (a) 1 eV, (b) 4 eV, (c) 10 eV, (d) 10 keV.

beam. Both grids obstruct a part of the ion beam. This situation closely resembles the picture sketched to support the T^3 transmission calculation.

The focus position depends on the initial energy. When the ion energy is increased, the focus point shifts further into the RFEA. Starting from approximately 3 eV, the beam is focused such that it passes the second grid without colliding with the

grid. Ions still hit the third grid, and thus the transmission is determined by the first and third grid, which is substantially higher than T^3 .

When the energy is increased substantially, the ions keep most of their initial velocity and focus effects become negligible. The beam also passes the third grid without collisions, and thus the effective transmission is equal to that of the single grid.

This test case shows that the grid alignment can have a major influence on the total transmission at high ion energies. Below a few eV, the ion lensing effect produce very broad beams so that T^3 will be a good approximation for the total transmission. At very high ion energies, the optical transmission becomes important which is determined by the grid alignment. Further on, we will compare the transmission as a function of energy for all three test cases.

C. Influence of ion incident angle

Test case 2 is used to investigate the influence of the ion incident angle α . This exercise demonstrates the maximum angle under which ions can be detected. Furthermore, it shows whether or not the azimuth θ , the angle between the incident ions and grid wires, influences the transmission. α and θ are illustrated in Fig. 8.

The rotation over 45° of G_0 is inspired by the experimental RFEA that will be investigated later on. T_o is greatly reduced and now measures 48.15%. The discretization by SIMION does not perfectly render the slanting lines of the rotated grid. This results in a grid transmission that is a bit higher. A higher resolution SIMION render was made ($2 \mu\text{m}/\text{gu}$), which has a lower optical transmission, which will be used when investigating the transmission at normal incidence later on. This model is too extensive to use for the analysis of the angular response.

Ion beams formed as shown in Figs. 7(c) and 7(d) will not pass through the second and third grid undisturbed, as was the case in the previous exercise. Aperture repetitions of the combined grid stack will no longer take place. The optical transmission now shows a slight variation with location. Therefore a much broader ion beam is used to average out

FIG. 8. Illustration of the incident angle α and the azimuth θ .

FIG. 9. Case 2 transmission as a function of the azimuth for 1 and 10 eV for multiple incident angles. At $\pm 90^\circ$ and 0° , the beam is parallel to the grid lines of G_0 , while at $\pm 45^\circ$ they are parallel to G_1 and G_2 . (a) 1 eV and (b) 10 eV.

these variations. The diameter is set to $500\ \mu\text{m}$, which spans over 8 aperture distances of a single grid.

This geometry is used to investigate how ions pass through the grids when arriving under an angle. This introduces a second velocity component, next to the velocity normal to the grid surface. We still set the ion energy and thus the speed, which will result in a smaller velocity normal to the RFEA at increasing incident angles.

The ions are injected close to G_0 in a circular distribution in the field free region in front of the RFEA. The ion energy and α are set, while θ is varied from -90 to 90° . The acceleration due to the negative potential on G_1 bends the ion trajectories toward the surface normal, especially when the ion energy is low. Therefore all ions with initial energies of $<2\ \text{eV}$ will remain within the simulation domain even at large α . At higher energies, ions can leave the volume via sidewalls of the simulated geometry, in which case the resulting transmission is not valid. This limits the validity of this method to α of 75° and 45° for, respectively, 10 and 100 eV ions.

Figures 9(a) and 9(b) show the transmission for a number of α 's as a function of θ . In general, the transmission decreases with increasing α . This is mainly due to the aspect ratio of the grid apertures ($d/l = \frac{1}{2}$). Ions hit the sides of the grids inside the apertures when they have a large incident angle. This effect becomes smaller with decreased ion energy. Trajectories of

1 eV are bent toward the normal due to the potential on G_1 , resulting in higher transmission at larger α .

A preference for certain θ occurs at α larger than 60° . At shearing incidence, ions have a higher chance of transmission when they arrive parallel to the grid lines of the top grid. Peculiar geometric effects cause small transmission peaks at the largest impact angles investigated here. In practice, these effects will most often not play a role because in plasmas the ions are highly directional due to the acceleration in the sheath.

D. Transmission at normal incidence

Case 3 distinguishes itself from the previous two in that T_o is significantly less than T^3 . This will allow for a clear distinction between T_o and T^3 in the effective transmission simulations that will follow in this section.

The transmission at normal incidence is determined by injecting an ion beam and registering how many of those arrive at the collector electrode. The ions are again released in a broad beam with a diameter of $500\ \mu\text{m}$. 10 000 ions are injected for each simulated energy.

The result for all three test cases is plotted in Fig. 10. Figure 10(a) shows the transmission for low ion energies, while the range is much larger in 10(b). The optical transmission for each model is indicated with a horizontal dashed line. Also displayed is T^3 , which is identical for all cases.

FIG. 10. Transmission at normal incidence for the three test cases using 10 000 ions per simulation. T_o and T^3 are indicated. For case 2, the high resolution model was used.

FIG. 11. Ion beam profile of 4 eV ions at G_2 .

Case 1 was used to study the RFEA made of aligned grids. This case shows distinctive features below 20 eV. Above 10 eV, the transmission is equal to the optical transmission. After passing through the first grid, ion beams are formed which pass through the second and third grid without colliding, as shown in Figs. 7(c) and 7(d). Beams with energies lower than 1.5 eV collide with all three grids. The resulting transmission is a bit higher than T^3 . A closer look reveals that T_T is close to $T^{5/2}$. The transmission increases with energy as G_1 captures less and less ions. Between 3 eV and 6 eV, a plateau is reached with a transmission of $T^{3/2}$. There the ions encounter only the first and last grid.

The $T^{5/2}$ and $T^{3/2}$ transmissions suggest that the transmission through one of the grids is set by $\sqrt{T}$, which can be defined as $\sqrt{T} = \frac{l}{l+w}$. Figure 11 shows the beam profile of 4 eV ions passing through the third grid. The profile is not circular, or square, but is shaped as a star. The grid blocks only a part of each of the arms of the star. Hence the transmission of a grating with parallel bars should be considered, which is defined as $\frac{l}{l+w}$.

In the other cases, the effective transmission converges to T_o at high ion energy, but at low energy the behavior is more complex.

Between the first and second grid, the beam will look similar in all cases, as the rotation of the first grid does not influence the potential distribution. In Fig. 7, it was shown that between 5 and 10 eV the ion beam is very narrow at the second grid. In case 3, the G_1 and G_2 are open at the center of the first grid. The focusing of the ion beam results in the increased transmission as seen in case 3. The transmission peaks again around 20 eV where the ions that are transmitted through G_1 are focused on an aperture in G_2 . The dip around 50 eV is caused by the beam being focused on a grid node of G_2 .

The rotation of the first grid breaks the periodicity of the grid stack. This decreases the transmission at low ion energies and also eliminates the high transmission between 5 and 10 eV. This results in T_T being equal to T^3 .

These exercises show that the transmission can be a function of ion energy. Due to the specific alignment of the grids, peaks and dips in the transmission occur, which can be hard to predict beforehand. It is expected that these features are smoothed out in an actual experiment due to imperfections in the RFEA construction and ion fluxes that have a spread in incident angle.

With a perfectly aligned grid, high effective transmissions are possible due to beamlet formation. Misalignment of the grids reduces the optical transmission and can therefore bring T_o close to T^3 .

IV. APPLICATION TO EXPERIMENTAL PROBE

In our experiments, a commercially available RFEA system is used (Semion Single Sensor, Impedans Ltd.¹⁸) with three grids. The button probe has been studied under a microscope [Fig. 12(a)] to determine the single grid transmission and the grid alignment. The image is created from a stack of three pictures, each focused at a different grid. The background in the pictures of the upper and middle grid has been removed so that only the grids themselves remain.

The single grid transmission is 75%, which is slightly larger than specified by the supplier (70%). T^3 is therefore

FIG. 12. The grids of the Impedans RFEA button probe [(a) and (b)] and the head on view of the simulated grid stack (c). (a) Microscope image, (b) the extracted grid structure, (c) SIMION grid structure.

42%. G_0 is rotated over 45° relative to G_1 and G_2 . During the production of the button probe, there is no effort put into the alignment of the grids.¹⁹ The resulting grid structure can therefore differ per probe. The bottom two grids are parallel, but there is a displacement of about $20\text{ }\mu\text{m}$ in the horizontal direction and $5\text{ }\mu\text{m}$ in the vertical directions. The grid structure has been extracted as shown in Fig. 12(c). T_o is 43.5%, which is close to T^3 .

A model is constructed that closely resembles the experimental button probe. The alignment of the grids is matched to the alignment from the microscope images. The limited mesh size of the SIMION simulation ($5\text{ }\mu\text{m/gu}$) does not allow for an exact replica of the grids. The aperture and grid wire width remain 50 and $10\text{ }\mu\text{m}$, respectively. The resulting T_o is 34.5%. The spacing between the grids and between G_2 and C is again set to $200\text{ }\mu\text{m}$ and the thickness of the grids is set to $25\text{ }\mu\text{m}$.¹⁹

We will now first determine the transmission as a function of ion energy and as a function of incident angle. Thereafter the energy resolution is investigated, followed by a comparison to experimental data.

A. Transmission at normal incidence

The transmission at normal incidence is shown in Fig. 13. The transmission is much less dependent on the ion energy than the three test cases. The rotation and displacement of the grids introduce a randomization that smoothes out focusing effects. Above 100 eV, the transmission is higher than the optical transmission which is again caused by the discretization of the diagonal grid lines. Although again a high resolution model was used (2 mm/gu), the optical transmission of the discretized SIMION grids is still slightly higher than originally designed.

B. Angular transmission

The angular transmission has been investigated in the same way as test case 2. The transmission has been averaged over θ . The standard deviation is used as error bars. The

FIG. 13. Transmission at normal incidence for the simulation of the experimental probe. The inset shows the transmission up to 500 eV. T_o is indicated.

FIG. 14. The RFEA transmission as a function of ion incident angle for ion energies 1 eV, 5 eV, 10 eV, and 100 eV. The error bars show the effect of the preferred transmission directions at certain energies.

resulting transmission has been plotted versus incident angle in Fig. 14.

The incident angle reduces the transmission substantially, especially at high ion energy.

The larger error bars for 1 eV above 60° are caused by the peaks in transmission at certain θ as was shown in Fig. 9(a).

Generally speaking the influence on plasma measurement will be limited, as high energy ions usually have small impact angles.

C. Energy resolution

The resolution is determined by simulating the IEDF measurement of a mono-energetic ion beam. The beam is injected at normal incidence. V_R is scanned with 0.25 eV steps, which is similar to the step size in an actual measurement. An I-V curve now corresponds to a transmission- V curve. The IEDF is determined by differentiating the transmission to V_R . The results for a 5 eV and 100 eV beam are shown in Fig. 15. The 100 eV beam is going to be used in Sec. IV E where it is compared to experimental data.

The roughness of the IEDF is the result of the numerical differentiation which causes small differences in the transmission to be amplified. In practice, these fluctuations will be smoothed out due to imperfections in the grids and the ion sources not being mono-energetic.

The width of the flank on the high energy side is caused by potential depression in the retarding grid.²⁰ The grids do not provide an ideal equipotential surface, as was shown in Fig. 5. Here, test case 1 is used to investigate the potential depression at the center of the apertures. In this simplified case, the apertures all line up and therefore the potential at the center of the apertures is represented by the potential on the straight line along the grid normal. The potential is plotted in Fig. 16 for V_R of 5 V. The grids are indicated and the grid potentials are displayed in red. The inset shows an enlarged view of the potential at the retarding grid.

FIG. 15. Simulations of an IEDF measurement with a mono-energetic ion beam. The IEDF is calculated by differentiating the transmission to V_R . (a) 5 eV and (b) 100 eV.

The potential applied on the grids is not reached inside the grid apertures. At the center of the retarding grid, a maximum of 3.9 V is reached, which is 1.1 V lower than the potential on the grid. With V_R set to 5 V, all ions with energy below 3.9 eV will be stopped, above 5 eV all ions will be transmitted, and between 3.9 eV and 5 eV a part will be transmitted.

The flank on the low energy side is broader. First, while V_R is still much lower than the ion energy, ions keep most of their initial velocity and are transmitted with the optical transmission. When V_R approaches the ion energy, part of the ions that pass a grid hole at short distance to a grid wire are deflected. The radius at which ions can pass through the grid apertures decreases with increasing V_R resulting in a steep decrease in transmission. Such behavior has been predicted by Sakai²¹ who considered the transmission of a single grid.

D. Space charge effects

The effect of space charge on the ion trajectories can now be estimated by comparing the electric fields inside the apertures due to the potential depression with the electric fields induced by space charge. The potential depression creates

FIG. 16. The potential distribution along the z -axis at the center of the simulation domain. The grids are indicated together with the set potentials in red. The inset shows the potential at the retarding grid. Here, the potential depression determines the resolution on the high energy side.

electric fields perpendicular to the direction of the ions that causes the focusing of the ion beamlets. The 1 V potential difference over half the aperture width of 25 μm creates electric fields in the order of 40 kV/m.

The radial electric fields, perpendicular to the ion velocity, due to space charge can be estimated using Gauss's law inside the apertures. The space-charge density is calculated by dividing the current density by the ion velocity: $\rho = J/v$. The maximum density is found for the Child-Langmuir space charge limited current and slow (thermal) ions, which is independent of the ion mass,

$$J = \frac{4}{9} \epsilon_0 \sqrt{\frac{2q}{m_i}} \frac{V^{\frac{3}{2}}}{d^2}, \quad (2)$$

$$v = \sqrt{\frac{8k_B T}{\pi m_i}}, \quad (3)$$

$$\rho = \frac{J}{v} = \frac{4}{9} \epsilon_0 \sqrt{\frac{\pi q}{4k_B T}} \frac{V^{\frac{3}{2}}}{d^2}, \quad (4)$$

where q and m_i are the ion's charge and mass, V and d are the potential difference (5 V), respectively, the distance (200 μm) between G_2 and C , T is the room temperature, and k_B and ϵ_0 are the Boltzmann constant and the permittivity of free space.

The resulting radial electric field at a distance r from the center of the aperture is

$$E_r = \frac{\rho r}{2\epsilon_0} < 10 \text{ kV/m}. \quad (5)$$

Therefore, even when the RFEA is operated near the space charge limited current density, the ion lensing will dominate over space charge effects. Hence, the exclusion of space charge from the simulations is justified.

E. Comparison to experiment

The SIMION results are compared to measurements of an ion beam with a narrow energy distribution. An ion gun (Oxford Applied Research, DC25s) is used to create a highly directional 100 eV beam of hydrogen ions incident on the

FIG. 17. Comparison between EQP and RFEA measurements of the ion gun IEDF and simulation of RFEA response with SIMION.

RFEA probe. The background pressure was lower than 0.1 Pa, ensuring that no collisions of ions with background gas take place inside the RFEA.

To determine the actual IEDF, the beam was also measured with an Electrostatic Quadrupole Plasma analyzer (EQP, Hidden Analytical) ion mass spectrometer, which has a much smaller energy bandwidth [0.5 eV full width at half maximum (FWHM)] than the RFEA.

The RFEA and EQP measured IEDFs are shown in Fig. 17. The RFEA measured IEDF was smoothed using a simple central moving average filter with a span of 3 data points. Broadening due to this smoothing is negligible.

The EQP measures a distribution centered at a slightly higher energy of 103.2 eV than set on the ion gun. The FWHM of the RFEA measured distribution is approximately 10 eV. The curves are almost symmetric around the central energy. At the low energy side, the RFEA IEDF does not go completely to zero.

The FWHM measured with the EQP is 3.2 eV, which is not limited by the EQP energy bandwidth and therefore represents the ion beam bandwidth. Because the beam is not mono-energetic, it is not possible to directly compare the result to the simulated IEDF from Fig. 15(b). Instead the simulation is taken as the RFEA instrument response curve. The convolution with the EQP measured IEDF yields the predicted outcome of the RFEA measurement. The result is also shown in Fig. 17. The resulting IEDF agrees fairly well with the RFEA measured IEDF. The FWHM is approximately 7.5 eV. Compared to the measurement, the IEDF is slightly shifted by 1 eV, but this shift is much less than the width of the distribution.

The FWHM is slightly underestimated. Grid imperfections and grid spacings being not fully homogeneous over the total RFEA surface could attribute to additional broadening of the IEDF. Therefore the width of the simulated IEDF should be treated as the minimum experimental width.

V. CONCLUSION

The transmission of RFEAs has been investigated by simulating ion trajectories through a stack of grids in the absence of magnetic fields in a collisionless regime.

In the first part, the focus was on the effective transmission during ion flux density measurements, with $V_R = -5$ V. The test cases showed that for high ion energy (>few hundred eV) at normal incidence, T_o is the effective transmission. The RFEA potentials are small compared to the ion energy, and therefore the ion trajectories are straight lines.

At low energies, the ion trajectories are strongly influenced by the electric fields between the grids. Beamlets are focused in the curved potential distributions around G_0 . The focus distance and the grid alignment determine whether there is a high or a low transmission, leading to fluctuations in the transmission as a function of ion energy. Rotation of the first grid effectively reduces these fluctuations by breaking the periodicity of the grid stack. Transmission decreases with the incident angle of ions on the first grid. There is a preference for certain values of θ at high impact angles, but in plasmas this effect will not be noticeable due to the absence of ions with a large impact angle.

The method demonstrated here allows for a relatively straightforward determination of the effective transmission of a RFEA probe with known grid alignment. When there is sufficient randomization in the grid placement, the effective transmission at normal incidence is equal to T_o over a wide range, which in our case is close to T_i^n . Furthermore, energy dependent transmission effects due to grid alignment can also be predicted. The application to the experimental probe and the comparison to the ion gun measurements showed that the model can also be used to predict the minimum experimental energy resolution.

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