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Improvement Study on the Influence of Plasma Electrode Edge on Emittance in ECR Ion Sources

Authors: Deng, Dr. Qi, Xie, Dr. Xiu-Cui, liu, Prof. yonghao, Li, Prof. Deming, Deng, Dr. Qi

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Abstract

In the design of extraction systems for intense ion sources, particularly Electron Cyclotron Resonance (ECR) ion sources, overall configuration of electrodes is the main consideration. However, a detailed aspect has not received sufficient attention, that is, the influence of the front edge of plasma electrode. Near this edge, direction of electric field changes abruptly, causing ions subjected to these electric field forces to move aberrantly, which subsequently increases the emittance of ion beam. The extent of this phenomenon may be underestimated. By chamfering the front edge, emittance is significantly improved. Two types of chamfering have been investigated and both perform well. It is suggested that chamfering be a practical way in designing plasma electrode and improving emittance.

Full Text

Preamble

Improvement Study on the Influence of Plasma Electrode Edge on Emittance of ECR Ion Sources

Qi Deng,[1,2] Xiucui Xie,[1] Yonghao Liu,[1] and Deming Li[1,2,*]

[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: In the design of extraction systems for intense ion sources, particularly Electron Cyclotron Resonance (ECR) ion sources, the overall configuration of electrodes is the primary consideration. However, one detailed aspect has not received sufficient attention: the influence of the front edge of the plasma electrode. Near this edge, the direction of the electric field changes abruptly, causing

ions subjected to these field forces to move aberrantly, which subsequently increases the emittance of the ion beam. The extent of this phenomenon may be underestimated. By chamfering the front edge, the emittance can be significantly improved. Two types of chamfering have been investigated, and both perform well. It is suggested that chamfering represents a practical approach for designing plasma electrodes and improving emittance.

Keywords: ion sources; plasma electrode; emittance improvement; chamfering

INTRODUCTION

Studies on improving ion beam emittance are consistently important in ECR ion source research, with most investigations concentrating on the holistic configuration of electrodes and space charge compensation [1–3]. However, the influence of structural details of the plasma electrode may have been overlooked.

During ion extraction from plasma, the electric field penetrates into the aperture of the plasma electrode and interacts with the plasma to form an emitting sheath [4, 5]. When the electric field in the aperture exhibits a low degree of consistency, the plasma sheath deforms, thereby increasing the emittance. The front edge of the plasma electrode is the factor that causes this inconsistency in the electric field. The front angle of the extracting aperture is typically a right angle or a Pierce angle, which implies that at the front end, an edge exists where two faces of the electrode intersect, around which equipotential lines bend dramatically. The front edge, as part of the metal equipotential body, hinders the neighboring electric field from penetrating into the aperture, squeezing equipotential lines and causing distortion in the electric fields.

Ions in this region subjected to these electric field forces move toward the central axis at an abnormal angle, as shown in Fig. 1 Figure 1: see original paper. Regardless of whether the electrode aperture is thick or thin, this effect occurs as long as electric fields penetrate into it. For a thin aperture, electric fields penetrate into the backside and become even more distorted [6–8], as illustrated in Fig. 1(b). This effect has not been systematically discussed, perhaps because its impact is thought to be minimal. An ECR ion source typically uses a plasma electrode with an aperture several millimeters in diameter [9], which is large enough that the electric field penetrates directly into the aperture. The plasma boundary forms within the aperture, and this phenomenon indeed exists in intense ion sources. Sometimes researchers seek to obtain a sufficiently convergent ion beam to compensate for space charge effects by increasing the extraction voltage. In these cases, electric fields penetrate more deeply into the aperture, making this phenomenon even more prominent and potentially responsible for hollow beams.

II. PHYSICAL ANALYSIS

Formation of the plasma boundary, or the so-called meniscus, results from the interaction between plasma and electric field. The shape of the meniscus depends on plasma density and electric field strength. With a strong electric field and low plasma density, a more concave meniscus is obtained, and vice versa [10].

Around the rear side of the front edge, electrostatic shielding occurs near the inner wall, thereby weakening the electric field strength. With a weaker electric field, plasma diffuses forward along the inner wall of the aperture. Consequently, the periphery of the meniscus becomes elongated, meaning the curvature of the meniscus changes at an uneven slope near the front edge. Ions emitted from this part of the meniscus move in different directions and cannot be well focused, resulting in increased emittance. Another effect can further aggravate the situation. Examining the simulation result of electrostatic field distribution without plasma in the extraction system reveals that, as the plasma electrode is an equipotential body, electric field directions are perpendicular to the inner wall of the extracting channel, as shown in Fig. 2 [Figure 2: see original paper]. When plasma is present in the aperture and ions from the plasma approach the inner wall, the electric fields cause them to move toward the central axis of the system. At the periphery of the meniscus where plasma density is low, this effect plays a significant role and exacerbates meniscus aberration.

III. SIMULATION RESULTS

Based on the above analysis, we explored approaches to mitigate this effect using PBGUNS codes to simulate modified models. The aperture cannot be overly thin; in other words, it must maintain a certain thickness, as mentioned in Section I, to prevent the electric field from penetrating into the backside of the aperture and becoming more distorted. Here, we do not account for density variation of plasma with aperture depth, as we focus solely on the effect caused by the front edge. The front edge, as a point of mutation, should be weakened to reduce its interference with electric fields. To focus on this issue, we simulated an extraction system consisting of two electrodes to clarify the phenomena. The parameters of the extraction system are listed in Table 1 .

A direct approach involves trimming the front edge to create a chamfer. A 45-degree straight chamfer was implemented as an initial attempt. Emittance was measured at a target 83.7 mm from the extracting aperture with negative hydrogen ions extracted. Simulation results show that RMS emittance improved from $1.859 \times 10^{-1}\ \pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ to $5.709 \times 10^{-2}\ \pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. The initial beam exhibited a gap in the middle and scattered in the outer ring, as circled by the orange dashes in Fig. 3 Figure 3: see original paper. After chamfering, the beam distribution became more concentrated, as circled in Fig. 3(b).

Chamfering can be performed linearly or circularly, with different incline angles, lengths, and arc radii. The impacts of these parameters on emittance were

investigated. Straight chamfering was tested with various angles, including 10°, 20°, 30°, 35°, 40°, 42°, 45°, 50°, and 60°. The inner endpoint of the straight chamfer was fixed at 0.3 mm deeper than the original front point, while the outer endpoint moved as the angle changed. Fig. 4 [Figure 4: see original paper] shows the emittance variation with chamfering angles.

We observed that for most angles, emittance reduced to approximately one-third of the original value. The best emittance improvement was achieved around 40° chamfering. With the largest and smallest angles, emittance did not improve significantly. This occurs because when the chamfering angle is small, the front edge merely moves upward slightly, and its influence on the electric field has not been sufficiently reduced. When the chamfering angle is large, the electric field penetrates through the chamfer to the extracting aperture and interacts with plasma, causing the emitting surface to move inward. The inner endpoint then assumes the position of the former front edge as a new mutation point, distorting the electric field and making the situation similar to that without chamfering.

With circular chamfering, as radius varied from 0.3 mm to 2.2 mm, the best emittance improvement occurred at approximately 1.5 mm, as shown in Fig. 4. When the radius is small, the electric field distribution does not change significantly, similar to the case without chamfering. As the radius increases, the chamfering effect begins to work. However, the electric field near the surface, especially a bending surface of a conductor, is typically much stronger than at other locations in the field. Thus, in our case, the front edge exerts considerable influence on the moving directions of ions, and the emittance decreases. When the radius becomes too large, the circular front surface compresses electric fields, and the front edge effect begins to dominate, resulting in increased emittance.

Both straight and circular chamfering, with appropriate angles or radii, can mitigate the influence of the front edge. Straight chamfering can lower emittance significantly across a relatively wide range of angles. Circular chamfering lowers emittance within a narrow range of radii, but the most optimal emittance improvement is obtained with this approach. It is difficult to assert that circular chamfering is superior to straight chamfering, or vice versa, as this requires systematic investigation under more conditions.

When performing chamfering while fixing the inner endpoint 0.3 mm deeper than the original front point, the spacing between the inner endpoint and the puller electrode becomes 0.3 mm larger than the previous gap between the two electrodes. It cannot be excluded that this increased gap weakens the electric field and alters the emitting surface. Therefore, we moved the puller electrode 0.3 mm forward after chamfering at 30°, 40°, 50°, and 60° to offset the increased spacing. Results in Fig. 5 [Figure 5: see original paper] show that emittance still achieved obvious improvement compared to the original $1.859 \times 10^{-1}\ \pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$.

IV. DISCUSSION

Moving the puller electrode forward by the same distance as front point retraction actually shortens the overall spacing between the plasma electrode and puller electrode. Even so, the emittance decreases significantly after chamfering, demonstrating that chamfering is indeed an effective method for reducing emittance. The physical mechanism behind this is that the front edge exerts considerable influence on the moving directions of ions, emphasizing the importance of trimming the front point.

Other structures of plasma electrodes, such as stepped electrodes, can also be regarded as a type of chamfering and may play a role in reducing emittance. However, their front surfaces change more rapidly and bring about more severe mutation of the electric field. Backside chamfering is also not advisable for the same reason as thin electrodes. We will not extend this discussion further here, but simply illustrate that emittance can be improved through chamfering. Extraction voltage, ion current, and ion species were not, nor do they need to be, carefully selected and optimized in our model, but are sufficient to demonstrate the issue.

V. CONCLUSION

Studies regarding the effect of extraction systems on emittance of ECR ion sources have traditionally focused on the overall configuration of electrodes. However, we propose that the front edge of the electrode also significantly influences emittance. Based on physical analysis, chamfering the front edge can notably reduce emittance. The two types of chamfering we investigated both improve emittance, indicating that chamfering can be a useful approach in designing extraction electrodes. Future work should include conducting experiments for comparison with simulations, which requires emittance measurement equipment not currently available. The states of plasma and meniscus after chamfering are also important aspects to investigate.

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