Ion Beam Extraction Optics Study for KAIMIR Neutral Beam Injector

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1. Introduction

The KAIMIR machine [1] requires high-current neutral beam injection for plasma heating. This study presents the design of a three-electrode multi-hole beam extraction and acceleration system consisting of a Plasma Grid (G1), a Suppressor Grid (G2), and a Ground Grid (G3). The primary objective was to achieve a 25 keV beam with a total current of 4 A, distributed across approximately 100 extraction apertures (40 mA per hole). Considering the beam transport efficiency of 60–70% through the beamline, including the neutralization efficiency, the required extraction current of 4 A ensures sufficient power delivery to the plasma.

2. Design Methodology and Results

2.1 Analytical Estimation of Grid Geometry

Prior to numerical simulation, the initial grid geometry was determined analytically using the Child-Langmuir law:

$$J = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\, V^{\frac{3}{2}}/d^2 \qquad (1)$$

Following Uhlemann and Wang [2], the gap distance d was replaced by an effective gap deff that accounts for the electric field distortion at the grid apertures:

$$d_{eff} = d1 + D1 + 0.8r_2 \qquad (2)$$

d1 is the G1-G2 gap, D1 is the G1 thickness, and r_2 is the G2 aperture radius. At perveance-matched conditions, the achievable current density is typically ~60% of the Child-Langmuir limit [5].

Starting from a preliminary geometry (G1 aperture: 7.5 mm, G1 thickness: 1.5 mm, G2 thickness: 1.8 mm, G2 aperture: 4 mm), the required G1–G2 gap to deliver 4 A across 100 apertures was calculated. With these initial values, the effective gap for a 7.5 mm metal-to-metal gap is $d_{eff} = 7.5 + 1.5 + 0.8 \times 2.0 = 10.6$ mm, yielding a Child-Langmuir limit of ~192 mA/cm^2 and an expected ~115 mA/cm^2 at 60% perveance matching, corresponding to ~3.3 A. Reducing the gap to 6.5 mm gives deff = 9.6 mm, raising the estimated current to ~4 A at ~145 mA/cm^2. These analytical estimates established the gap range of 6–8 mm as the starting point for IGUN [3] simulations.

2.2 IGUN Optimization Results

Using the analytically determined gap range as input, IGUN simulations were performed to refine the grid geometry. Perveance scans, plotting total beam current versus RMS beam divergence, confirmed the analytical predictions and identified the minimum divergence condition at each geometry. During the optimization, the following modifications were made to address structural, thermal, and fabrication requirements.

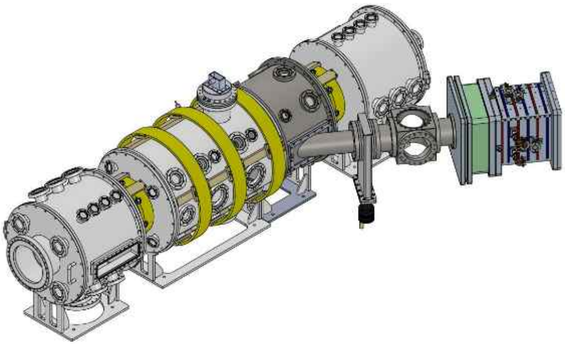

Fig. 1. Scematic diagram of the KAIMIR chamber and neutral beam injection (NBI) system.

The G2 and G3 thicknesses were increased from 1.8 mm to 3.0 mm for structural integrity and voltage holding, and the G1 thickness was increased from 1.5mm to 2.0 mm for fabrication feasibility. The G2 and G3 aperture diameters were enlarged from 4.0 mm to 5.0 mm to accommodate the thicker grids without excessive beam loss. A two-stage G1 structure was adopted for lower beam divergence instead of Pierce angle. The suppression voltage was optimized through simulations varying from -1.0 kV to -3.0 kV with concurrent grid structure adjustments, establishing -2.0 kV as the minimum required for effective backstreaming electron suppression.

These geometric changes increased the effective gap (Eq. 2), reducing the optimal current below the 4 A target. To recover the target current, the G1–G2 gap was reduced from 7.5 mm to 5.5 mm.

$$deff = 5.5 + 2.0 + 0.8 \times 2.5 = 9.5 \text{ mm}$$

The corresponding Child-Langmuir current density is ~239 mA/cm^2, giving ~143 mA/cm^2 at 60% perveance matching, or ~4.0 A total across 100 apertures. The minimum beam divergence at this optimum is approximately 1.0°. The total voltage across the G1–G2 gap is 27 kV (25 kV acceleration + 2 kV suppression), yielding an average electric field of ~49 kV/cm. IGUN simulations show the peak field at the aperture edge reaches approximately 100 kV/cm due to field enhancement, imposing strict requirements on voltage holding and surface conditioning.

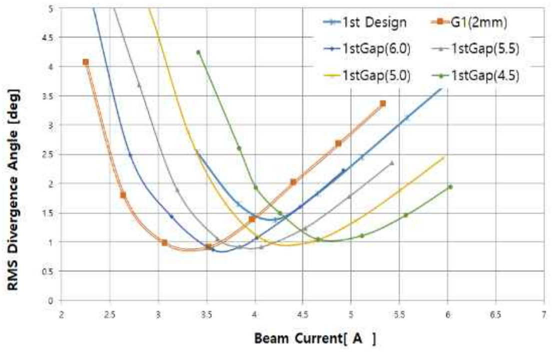

Fig. 2. Beam optics simulation results as a function of the G1-G2 gap distance (1st Gap)

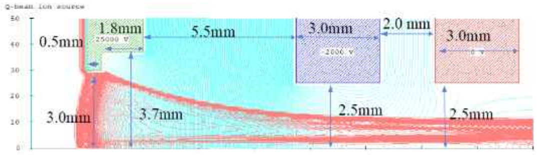

Fig. 3. Final grid geometry proposed from simulation and the corresponding beam space charge distribution.

2.3 Beam Steering and Focusing

Beam focusing toward a common focal point is achieved by controlled displacement of the G1 apertures. Stewart et al. [6] first demonstrated this aperture displacement technique, and Whealton [7] developed the corresponding linear optics theory. The deflection angle θ for a beamlet at displacement δ from the aperture axis is:

$$\tan(\theta) = \delta(E2 - E1) / (4V) \qquad (3)$$

where E1 and E2 are the electric fields on either side of the aperture and V is the beam potential [7]. For the finalized geometry, with E1 ≈ 49 kV/cm (G1–G2) and the beam potential of 25 keV, this yields a deflection sensitivity of ~4.9°/mm.

KOBRA-3INP [4] simulations confirmed a linear relationship:

$$\text{Focusing Angle (deg)} \approx 5 \times \text{G1 displacement (mm)} \qquad (4)$$

The agreement between the analytical estimate (~4.9°/mm) and the simulation (~5°/mm) validates the thin-lens approximation for the present geometry. However, a displacement exceeding 0.4 mm leads to direct beam interception on the grids, consistent with observations by Tarz et al. [8]. A focusing angle of 3° entails 2–3% beam loss on the grid structures.

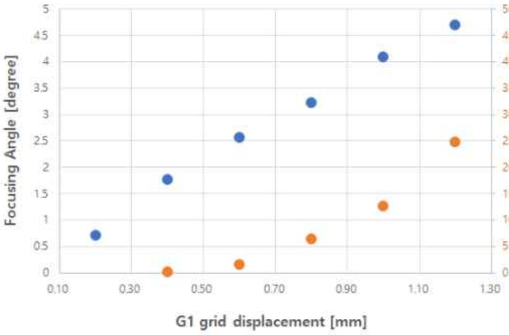

Fig. 4. Ion beam tilting angle and beam loss fraction at the G2 and G3 grids as a function of G1 displacement.

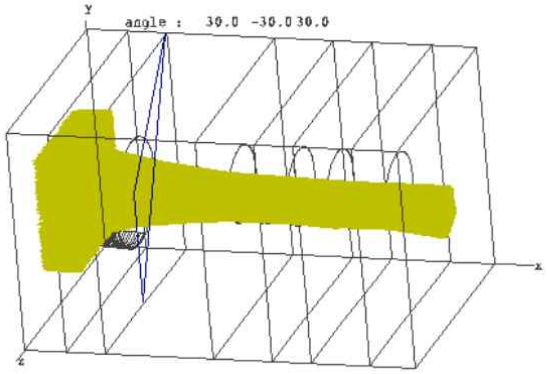

Fig. 5. Example of beam optics simulation using KOBRA-3INP.

3. Conclusions

The beam extraction accelerator design for the KAIMIR machine has been completed. The grid geometry was first determined analytically using the modified perveance law [2], then refined through iterative IGUN and KOBRA-3INP simulations. The final design parameters are shown in Fig. 3.

The finalized configuration consists of a G1–G2 gap of 5.5 mm (deff = 9.5 mm), a G1 thickness of 2.0 mm with a two-stage Pierce structure, G2 and G3 thicknesses of 3.0 mm with 5.0 mm aperture diameters, a G1 aperture diameter of 6.0 mm, and a suppression voltage of -2.0 kV. The design delivers 25 keV / 4 A with a minimum divergence of ~1° at the perveance-matched condition. The peak electric field at the aperture edge is approximately 100 kV/cm. Beam steering via aperture displacement provides ~5°/mm sensitivity, in agreement with both the linear optics theory and numerical simulation.

Future work will focus on the engineering design of the grid assembly, thermal analysis under beam loading, and experimental validation through beam extraction tests.

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