COMPUTATIONAL DESIGN STUDIES FOR AN ION EXTRACTION SYSTEM FOR THE OAK RIDGE NATIONAL LABORATORY ECR ION SOURCE

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Abstract

A three-electrode system for optimally extracting, high-intensity, multi-charged ion beams from an all-permanent-magnet, "volume"-type, ECR ion source, has been computationally designed. Beams of highest quality and transportability are extracted whenever the angular divergence is minimum. Under this condition, the plasma boundary has an optimum curvature, the angular divergence is consequently minimum; the perveance, the extraction gap, and the current density each have optimum values. Results obtained from computational simulation studies of the extraction optics are found to closely agree with those derived from elementary analytical theory for extraction of space-charge-dominated beams.

1 INTRODUCTION

Sophisticated techniques for simulating the actions of electric and magnetic fields on the motion of charged particle beams under their influence have greatly facilitated the design of beam transport components (lenses, magnets, steerers, deceleration/acceleration electrode systems, etc.) with low-aberration effects. Refs. 1-5 constitute a list of computer codes for simulating the extraction of space-charge-dominated ion beams from plasma ion sources. PBGUNS [3] was used in the present study to simulate extraction of mA intensity levels of multi-charged ion beams from a new concept [6] all-permanent-magnet ECR ion source under development at the Oak Ridge National Laboratory [7]. PBGUNS simulates the actions of electric and magnetic fields on positively and negatively charged ions moving through or accelerated by such fields. Poisson's equation

$$\nabla^2\phi = -\rho/\varepsilon_0 \qquad (1)$$

is solved at each point within the configuration using space-charge densities computed from the collective influence on the particle trajectories within the beam. In Eq. (1), ϕ is the electrical potential, ρ is the charge density, and ε_0 is the permittivity of free space.

2 THE REMOTELY POSITIONAL EXTRACTION ELECTRODE SYSTEM

A close-up of the three-electrode extraction system, equipped with provisions for remotely varying the extraction gap, *d*, is illustrated in Fig. 1. The electrode system consists of a focus (plasma) electrode at potential, ϕ_s, machined into the ion extraction region of the source, an extraction (accelerating) electrode at potential, ϕ_{ex}, and a ground-potential electrode at potential, $\phi_g = 0$. The spacing between the extraction and the ground electrode

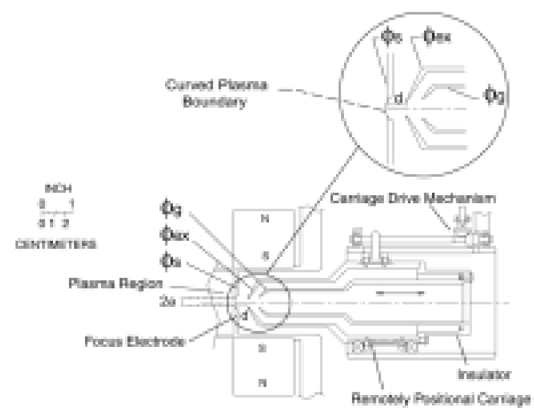

Fig. 1. Moveable electrode extraction system.

is fixed (gap: 10 mm). These electrodes are mechanically attached to each other by means of a ceramic insulator and are mounted, as an assembly, on a remotely positional miter-gear-driven carriage. The extraction gap, *d*, can be varied between 0.0 and 25.0 mm along the extraction axis by moving the assembly relative to the plasma electrode to optimize the electric field strength, E_{ex}, during ion extraction.

3 ELEMENTARY EXTRACTION OPTICS: ANALYTICAL THEORY

3.1 Langmuir-Blodgett formalism

Solutions to Poisson's equation (1) for space-charge-limited flow between concentric spherical electrodes can be represented by the Langmuir-Blodgett

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approximation [8]. Fig. 2 illustrates a simplified two-electrode system for the extraction of convergent positive-ion beams from a concave plasma emission boundary (sector angle: θ, spherical radius: r_s, and circular emission aperture: *a*), to a spherical geometry extraction electrode (spherical radius: r_{ex}, and aperture radius: *b*). Extraction is effected between the source at potential, ϕ_s, and the extraction electrode, at potential, ϕ_{ex}, separated by a distance $z = d = r_s - r_{ex}$.

The appropriate equation for space-charge-limited flow of electrical current, I, of a beam of particles of charge-state q and mass M, in a spherical sector electrode system, maintained at a potential difference, Δϕex, is given by:

$$I \cong (8\pi\varepsilon_0/9)(2q/M)^{1/2}\, \Delta\phi_{ex}^{\;3/2}\, (1 - \cos\theta)/(-\alpha)^2 \qquad (2)$$

where ε_0 is the permittivity of free space and α is a dimensionless parameter. α can be shown to be a solution to a non-linear differential equation expressed in series solution by:

$$-\alpha = -\mu + 0.3\mu^2 - 0.075\mu^3 + 0.00143\mu^4 - ... \qquad (3)$$

where $\mu = \ln (r_s/r_{ex})$. The series is valid for $r_s/r_{ex} > 1$. Tabulations of the function α can be found in several references, including Ref. [8].

The perveance, *P*, for the system is defined as:

$$P = I / \Delta\phi_{ex}^{\;3/2}$$
$$\cong [\{4\varepsilon_0/9\}(2e/M)^{1/2}\, \pi a^2/d^2][2\,(1 - \cos\theta)d^2/a^2(-\alpha)^2]$$
$$= 2P_{pp}\, [(1 - \cos\theta)\, d^2/a2\, (-\alpha)2] \qquad (4)$$

where P_{pp} is the perveance for extraction of space-charge-limited ion beams in a planar geometry electrode system, as first derived by Child [9], and independently by Langmuir [10]. After expansion of Eq. (4), to order d/rs for d<< rs, the following approximation is obtained:

$$P = I / \Delta\phi ex3/2 \cong Ppp\, (1 - 1.6d/rs) \qquad (5)$$

3.2 Minimum half-angular divergence

The beam, of convergence angle, θ, arrives on the other side of the aperture in the second electrode with final angular divergence, ω, after having been transmitted through the aperture of the extraction electrode. The aperture effect is illustrated by changes in angular divergence of the beam, ψ, so that the final angular divergence is ω = θ − ψ .

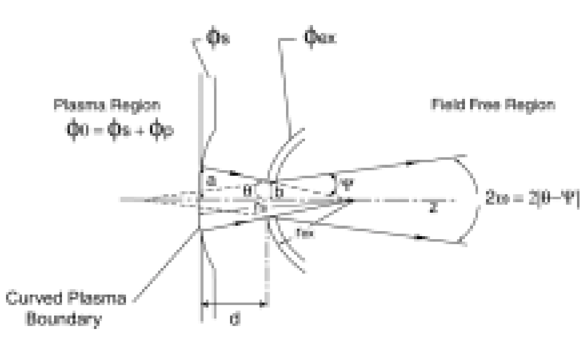

Fig. 2. Simplified spherical geometry, two-electrode for ion extraction from a concave spherical plasma boundary.

The respective half-angular divergences for the electrode system, displayed in Fig. 2, are:

$$\psi \cong b/3d \cong (a/d - \theta)/3 \qquad (6)$$

$$\theta \cong 0.625\,(1 - P/P_{pp})\, a/d \qquad (7)$$

$$\omega = \theta - \psi \cong (1 - 1.67P/P_{pp})\, a/d \qquad (8)$$

These expressions serve to illustrate how the final angular divergence, ω, is affected through changes in emission aperture, *a*, and plasma boundary, r_s, which are in turn affected by changes in plasma density, n_{e0}, and magnitude of the electric field, E_{ex}, used for ion extraction.

3.3 Optimum perveance

From Eq. 8, it is evident that ω versus *P* should reach a minimum whenever the perveance P_{opt} has the optimum value P_{popt} given by:

$$P_{popt} \cong P_{pp}\, / \,1.67 \cong 0.6\, P_{pp} \qquad (9)$$

for a planar geometry electrode system. Thus, the optimum current density, j_{+opt}, can be written:

$$j_{+opt} = P_{opt}\Delta\phi_{ex}^{\;3/2}/A_s = 0.6\, P_{pp}\Delta\phi_{ex}^{\;3/2}/A_s \qquad (10)$$

where A_s is the area of the emission aperture.

4 SIMULATION STUDIES

The objective of the simulation studies was to design a low-aberration, extraction electrode system for optimum extraction of space-charge-dominated ion beams. The magnetic field distribution described in Ref. [7] was used in all simulation studies, to account for magnetic field effects on the beams during extraction.

In Fig. 3, the ω versus *d* curves have minima, each corresponding to an optimum extraction electrode gap, d_{opt}. For fixed perveance, $d_{opt} \propto q^{1/4}$.

Fig. 4 displays optimum extraction gap versus charge- state. The optimum extraction gap, d_{opt}, increases with charge state, *q*, or average charge state $\langle q \rangle$ according to theory ($d_{opt} \propto q^{1/4}$).

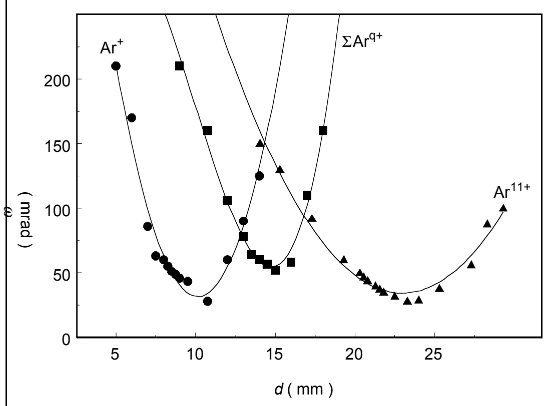

Fig. 3: Half-angular divergence, ω, versus extraction gap, *d*, for beams of Ar^+, ΣAr^{q+} and Ar^{11+}. Beam Intensity: 2.2 mA; $\Delta\phi_{ex}$: 13.1 kV; Beam Energy: 20 <q>keV.

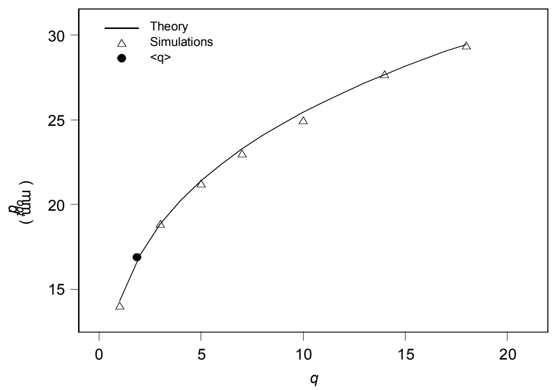

Fig. 4: Optimum extraction gap, d_{opt}, versus charge state,*q*. The solid symbol represents the average charge state <*q*>, as reported in Ref. [11]. Beam intensity: 1.45 mA; $\Delta\phi_{ex}$: 13.1 kV; Beam Energy: 20 <*q*> keV.

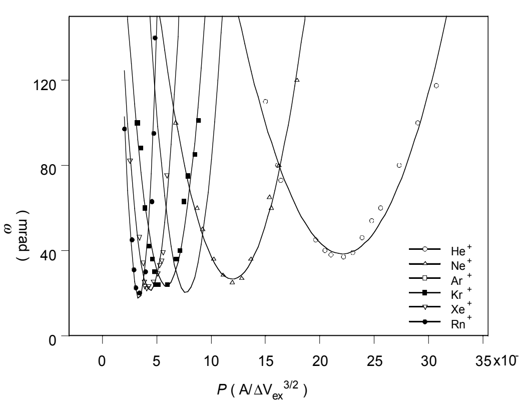

Fig. 5: Half-angular divergence, ω, versus extraction gap, *d*, for beams of He^+ (4.5 mA), Ne^+ (2.0 mA), Ar^+ (1.45 mA), Kr^+ (1.0 mA), Xe^+ (0.8 mA) and Rn^+ (0.6 mA).

The mass effect is clearly apparent in Fig. 5, which shows separate and distinct values for the perveance, $P \propto (1/M)^{1/2}$ as predicted from theory.

The current density, j_+, at the plasma-sheath interface must be equal to or exceed the space-charge-limited extraction current. As noted in Fig. 6, the optimum current density, j_{+opt}, occur at almost the same values predicted by Eq. 10.

5 CONCLUSIONS

These studies clearly demonstrate the necessity of providing means for varying the extraction gap for assuring high quality space-charge-dominated beams. The results derived from the simulations of the extraction optics agree closely with those predicted from elementary extraction theory. A remotely positional electrode system, such as described on this article, provides a preferred means for extracting high quality beams of a broad spectrum of species, multi-charged ions over a wide range and plasma densities.

REFERENCES

[1] J. C. Whitson, J. Smith and J. H. Whealton, J. Comp. Phys. **28** (1978) 408.

[2] J. H. Whealton, M. A. Bell, R. J. Raridon, K. E. Rothe and P. M. Ryan, *J. App Phys.* **64** (1988) 6210.

[3] J. E. Boers, *A digital computer code for the simulation of electron and ion beams on a PC,* IEEE Cat. No. 93CH3334-0 (1993) 213. (*PBGUNS* is an electron/ion optics simulation code, developed by *Thunderbird Simulations*, Garland, TX, USA).

[4] P. Spädtke, AXCEL-GSI, *Interaktives Simulations programm zur Berechnung von zwiedimensionalen*

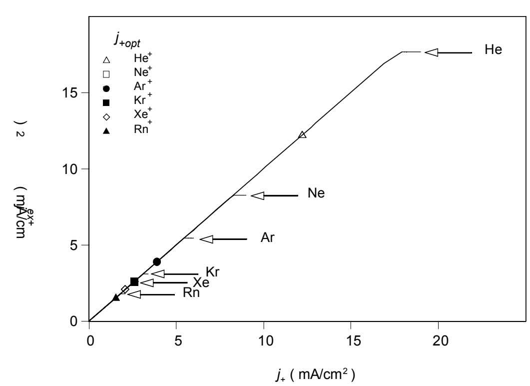

Fig. 6: Extracted ion current density, j_{ex+}, versus injected current density, j_+, for beams of He^+ (4.5 mA), Ne^+ (2.0 mA), Ar^+ (1.45 mA), Kr^+ (1.0 mA), Xe^+ (0.8 mA) and Rn^+ (0.6 mA). The space-charge-limited current densities for the parallel plate electrode system are indicated by arrows, while the respective optimum current density, j_{+opt}, as given by Eq. 11, for each specie is represented by a symbol.

Potentialverteilungen electrostatischer Anordnungen sowie von Ionbahnen in electrostatischen Feldern unter Berncksichtigung der Raumladung, GSI-Report 9 (1983).
[5] R. Becker and W. B. Herrmannsfeldt, *IGUN-A program for the simulation of ion extraction, including magnetic fields*, Rev. Sci. Instrum. **63** (1992) 2756.
[6] G. D. Alton and D. N. Smithe, *Rev. Sci. Instrum*. **65** (1994) 775.
[7] Y. Liu, G. D. Alton, C. A. Reed and D. L. Haynes, *Rev. Sci. Instrum*. **69** (1998) 1311.
[8] I. Langmuir and K. R. Blodgett, *Phys. Rev*. **24** (1924) 49.
[9] C. Child, *Phys. Rev*. **31** (1911) 492.
[10] I. Langmuir, *Phys. Rev*. **2** (1913) 450.
[11] A. Heinen, et al., Rev. Sci. Instrum. **69** (1998) 729.