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IMPROVED BEAM CURRENT DENSITIES AT HIGH VOLTAGES

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INTRODUCTION

It is well known that the maximum, beam current density that can be obtained from a high-voltage ion source is limited by the voltage holding capability of the extraction grids.¹ To improve performance, postacceleration in the form of a double gap extractor has been proposed.² But this can incur a higher probability of breakdown in the second acceleration gap than it can in the first.

By modifying the shape of the cross section of the first acceleration grid laterals, however, a reduced and more equal probability of breakdown can be obtained in both the first and second gaps. The result is a major improvement in high voltage stability, permitting a higher maximum current density.

In the remaining sections, the performance of ion extractors is analyzed with crude approximations that show improved performance to be possible with the modifications mentioned above. However, additional studies are required to evaluate the beam optics in the presence of the deformed grids.

ION EXTRACTION AND ACCELERATION

The smooth operation of an ion source depends upon a good match between the source plasma, however generated, and the ion extractor. Initially, the beam is formed by an electric field that holds back the plasma electrons while drawing out the positive ions. As a result, the ions enter the beam with an energy approximately equal to that of the electrons, and with an extracted current density equal to

$$J = 0.4 n_+ e \left(\frac{kT_-}{M_+} \right)^{1/2} \quad (1)$$

In this expression, n_+ represents the ion density in the plasma, M_+ the ion mass, and T_- the electron temperature. Therefore, the initial beam current density is primarily a function of plasma parameters.

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Subsequently, the ions are accelerated through a grid structure by the acceleration grid potential V across an effective grid spacing x which, in accordance with Child's law, restricts the beam current density to

$$J = q \frac{V^{3/2}}{x^2} \quad , \quad (2)$$

where q is the perveance of the extractor.

For a planar structure:

$$q = \left(\frac{4}{9} \epsilon_0 \right) \left(\frac{2e}{M_+} \right)^{1/2} \quad , \quad (3)$$

with a value of $3.9 \times 10^{-8} \text{ A V}^{-3/2}$ for atomic deuterium.

However, in practice, q is somewhat smaller, because the extraction geometry is not planar and the extracted ion beam is not purely atomic. For instance, an operating LBL/LLL* ion source³ delivering a beam of 75% atomic, 15% diatomic, and 10% triatomic ions of deuterium has a perveance of

$$q = 2.68 \times 10^{-8} \text{ AV}^{-3/2} \quad . \quad (4)$$

Obviously, satisfactory performance of an ion source depends upon an extracted ion current density that equals the current density accelerated by the grids. As a result, a given set of source discharge conditions best supports an ion beam of a particular energy. Any desired change in beam characteristics must be accompanied by a corresponding change in the source discharge.

HIGH-VOLTAGE STANDOFF

Despite numerous investigations, there are no established values for high-voltage standoff across low-pressure gaps. This is because of the many variables that are involved. These include the electrode shape, surface condition, material, temperature and radiation environment, the background gas (its density and purity), as well as the previous history of high-voltage seasoning. However,⁴ for a given set of conditions, the breakdown voltage across a low-pressure gap of less than 1 cm is proportional to the gap length. Across a larger gap, in excess of 1 cm, it is roughly proportional to the square root of the gap length.

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At first glance, these relationships appear to be applicable to the spacing between adjacent grids in the extractor. But this may not be the case. As the beam current density varies with the spacing, so does the density of the background neutrals, ions, and electrons, along with the electrode temperature and the intensity of radiation from the plasma source; and their effect on the voltage holding properties of the grids is not known.

Nevertheless, we use the above relationships, not so much because they are correct or that they approximate the truth, but for the sake of convenience. Thus, if x is the effective grid-to-grid spacing as used in Child's law and $(x - \Delta)$ is the smallest physical spacing between grids (as shown in Fig. 1), a safe operating voltage for a source with $(x - \Delta)$ less than 1 cm is

$$V = C_1 (x - \Delta) \quad , \quad (5)$$

where C_1 is a proportionality constant, peculiar to the source design, that assures a low probability of high-voltage breakdown.

Similarly, for spacing greater than 1 cm,

$$V = C_2 (x - \Delta)^{1/2} \quad . \quad (6)$$

For a lack of better information, we make the convenient but unlikely assumption that the transition from one breakdown mode to another occurs abruptly at 1 cm. Thus, the proportionality constants in (5) and (6) are equal.

A suitable value for these constants can be obtained from³ an LBL/LLL ion source design that operates reliably at 20 kV. With $x = 0.39$ cm and $\Delta = 0.15$ cm,

$$C = 8.33 \times 10^4 \quad . \quad (7)$$

As more information about high-voltage source performance becomes available, the acceptable value of C may change, along with the assumed voltage-spacing relationships. Since we are not defining conditions for breakdown, but merely establishing a criterion for conservative operation, a wide range of values is acceptable.

Fig. 1. Single gap extractor [x = effective grid-to-grid spacing;
 $(x - \Delta)$ = smallest physical spacing between grids].

SINGLE GAP EXTRACTION

The assumed relationships for interelectrode spacing (Eqs. 5 and 6), when introduced into Child's law, result in

$$J = q C^2 \frac{V^{3/2}}{(V + \Delta C)^2} \quad (8)$$

for $(x - \Delta)$ less than 1 cm, and

$$J = q C^4 \frac{V^{3/2}}{(V^2 + \Delta C^2)^2} \quad (9)$$

for $(x - \Delta)$ greater than 1 cm.

Thus, from the data previously presented, the LBL/LLL type of ion source should be capable of delivering beams of current density

$$J = \frac{V^{3/2}}{(0.073 V + 920)^2} \quad (10)$$

for $V < 83.3$ kV, and

$$J = \frac{V^{3/2}}{[(0.88 \times 10^{-6})V^2 + 920]^2} \quad (11)$$

for $V > 83.3$ kV.

Ion current densities from (10) and (11) are plotted in Fig. 2. Equation (10) should be fairly representative of source behavior, because it is scaled from the performance of an actual 20-kV source. However, (11) is more questionable, since it depends upon the proportionality constant at large spacings for which there are no data.

DOUBLE GAP EXTRACTION

For better performance at high energy, a second acceleration gap can be added in series with the first, to accelerate the beam from the V_1 potential of grid 1 to the desired potential V_2 at grid 2. The beam behavior in the second gap can be analyzed with Poisson's equation. Boundary conditions are taken as V_1 , the initial beam energy, and $(\partial v / \partial x)_0$, the field that the beam encounters as it enters the second gap.

Fig. 2. Deuterium ion current density (extracted from the plasma) as a function of the final beam energy.

Thus:

$$\frac{\partial^2 v}{\partial x^2} = \left(\frac{J}{\epsilon_0} \right) \left(\frac{M_+}{2e} \right)^{1/2} v^{-1/2} \quad (12)$$

And

$$\int_{\left(\frac{\partial v}{\partial x} \right)_0^2}^{\left(\frac{\partial v}{\partial x} \right)^2} \frac{\partial}{\partial x} \left(\frac{\partial v}{\partial x} \right)^2 \partial x = \left(\frac{2J}{\epsilon_0} \right) \left(\frac{M_+}{2e} \right)^{1/2} \int_{v_1}^v v^{-1/2} \partial v. \quad (13)$$

If the potential profile in the second gap were a continuation of that of the first gap, the initial field would be:

$$\left(\frac{\partial v}{\partial x} \right)_0 = 4/3 (v_1/x_1), \quad (14)$$

and there would be little improvement over a large single gap (see Fig. 3a). However, to get more reliable high-voltage holding, the second gap must be as wide as possible. Thus, it is preferable to make the field in the second gap initially zero, causing the ion beam to travel farther before it attains the desired energy v_2 .⁵

This can be achieved by elongating the cross section of the grid 1 laterals as shown in Fig. 3b. Because the field in the second gap cannot penetrate deeply into the space between the laterals of grid 1, the ion beam enters the gap between grids 1 and 2 in the presence of a zero field.

Under these conditions, the solution of Poisson's equation⁵ is

$$J_2 = q \left[\frac{v_2^{3/2} + 3 v_1^{1/2} v_2 - 4 v_1^{3/2}}{(x_2)^2} \right], \quad (15)$$

or for:

$$\zeta = v_2/v_1, \quad (16)$$

$$J_2 = J_1 \left[\frac{\zeta^{3/2} + 3 \zeta - 4}{(x_2/x_1)^2} \right]. \quad (17)$$

(a)

(b)

Fig. 3. Double gap extractor. (a) potential diagram (b) schematic.

While the ion beam accelerates through the first gap, it converges, causing the average current density entering the second gap to be larger than that of the first gap. Assume that it is twice as large. Then, the ratio of gap lengths of a double gap extractor, which draws a beam from the plasma and accelerates it to a potential V_1 (and subsequently to V_2), must be:

$$(x_2/x_1) = \left(\frac{\zeta^{3/2} + 3\zeta - 4}{2} \right)^{1/2} \quad (18)$$

GAP SIZES

When considering the dimensions and voltage holding capabilities of a double gap, there are three possibilities: both gaps are less than 1 cm, one or the other is larger than 1 cm, or both gaps exceed 1 cm.

Possibility 1

When both gaps are less than 1 cm:

$$V_1 = C (x_1 - \Delta) \quad (19)$$

$$V_2 - V_1 = C (x_2 - \Delta) , \quad (20)$$

which, with (18), can be solved to give

$$x_1 = \frac{\Delta (2 - \zeta)}{\left[\left(\frac{\zeta^{3/2} + 3\zeta - 4}{2} \right)^{1/2} + (1 - \zeta) \right]} \quad (21)$$

Possibility 2

When the first gap is larger and the second gap is smaller than 1 cm, there is no advantage. However, when the first gap is smaller and the second gap is larger than 1 cm,

$$V_1 = C (x_1 - \Delta) \quad (22)$$

$$V_2 - V_1 = C (x_2 - \Delta)^{1/2} , \quad (23)$$

which results in a quadratic equation:

$$x_1^2 (\zeta - 1)^2 - \left[2\Delta (\zeta - 1)^2 + \left(\frac{\zeta^{3/2} + 3\zeta - 4}{2} \right)^{1/2} \right] x_1 + \left[\Delta^2 (\zeta - 1)^2 + \Delta \right] = 0, \quad (24)$$

of which only one root is meaningful.

Possibility 3

Finally, when both gaps are larger than 1 cm,

$$V_1 = C (x_1 - \Delta)^{1/2} \quad (25)$$

$$V_2 - V_1 = C (x_2 - \Delta)^{1/2}, \quad (26)$$

from which we obtain:

$$x_1 = \frac{\Delta [1 - (\zeta - 1)^2]}{\left[\left(\frac{\zeta^{3/2} + 3\zeta - 4}{2} \right)^{1/2} - (\zeta - 1)^2 \right]}. \quad (27)$$

The solutions to these equations are presented in Table 1, along with the values of x_2 , V_1 , and V_2 as determined from (16), (19), and (20). The ion current density J_1 came from (2). The value of J_0 , the equivalent neutral current per-unit-area of emitting plasma, is 95% of the maximum neutral current obtained when the positive ions pass through a gas neutralizer cell of optimum thickness.⁶

CONCLUSION

Figure 2 shows, within the accuracy of our assumptions, that a modified, double gap extractor will deliver a high-energy beam of significantly greater current density than that from an equivalent, single gap extractor. It is unfortunate that we are forced to use questionable assumptions to anticipate performance at high voltage; nevertheless, the same concept, which expands the allowable length of the gap 2 is applicable to any voltage-spacing relationship.

In general, the proportionality constant between the high-voltage breakdown and the gap length, or between the high-voltage breakdown and the square root of the gap length, or between the high-voltage breakdown and whatever function of the gap length that gives a reasonable approximation, is a measure of the source reliability. If this constant is low in value, breakdown is unlikely; if it is high, breakdown is continuous. Consequently,

Table 1. Double gap parameters

ζ	X_1 cm	X_2 cm	V_1 kV	V_2 kV	J_1 Acm^{-2}	J_0 Acm^{-2}	Possibility
1.20	0.25	0.17	9	10	0.33	0.28	
1.10	0.36	0.17	17	19	0.48	0.41	
1.05	0.50	0.17	29	30	0.53	0.44	Both gaps
1.02	0.76	0.16	51	52	0.53	0.40	< 1 cm
1.01	1.06	0.16	76	77	0.50	0.32	
1.0085	1.15	0.16	83	84	0.49	0.29	
1.0080	1.18	0.16	86	86	0.48	0.27	
8.0	0.31	1.44	14	108	0.43	0.20	
5.0	0.43	1.45	24	119	0.52	0.22	
4.0	0.54	1.53	33	131	0.54	0.20	
3.6	0.61	1.60	39	139	0.54	0.19	Second gap
3.2	0.72	1.71	47	151	0.54	0.17	> 1 cm
2.8	0.88	1.87	61	170	0.51	0.13	
2.6	1.00	2.00	71	184	0.51	0.11	
2.4	1.16	2.16	85	203	0.49	0.09	
2.415	1.14	2.14	83	200	0.49	0.09	
2.40	1.44	2.67	95	227	0.38	0.05	
2.38	2.30	4.25	122	291	0.22	0.02	Both gaps
2.37	3.41	6.26	150	356	0.14	--	> 1 cm
2.365	4.53	8.32	174	412	0.10	--	
2.36	6.87	12.58	216	510	0.06	--	

X_1, X_2, V_1, V_2 = gap spacing and voltages, respectively.

$\zeta = V_2/V_1$, the ratio of gap voltages.

J_1 = emitted ion current density.

J_0 = neutral current per-unit-area of emitting plasma.

good design calls for equal reliability in each gap. The result, as indicated in Fig. 2, can be a beam current density of higher output with improved reliability.

As might be expected, the neutral current obtainable from the positive ion beams is sharply reduced at high-beam energies. This is presented in Fig. 4, along with the anticipated output of two negative ion sources of neutrals. One uses photodetachment to strip electrons from the high-energy negative ions. The other uses a cesium metal vapor cell for the same purpose. It is evident, under the most favorable circumstances, that positive ion sources of very high energy neutrals cannot compete with negative ions sources.

Fig. 4. Equivalent current of neutral deuterium, per-unit-area of emitting plasma, as a function of the final beam energy.

REFERENCES

1. D. R. Sweetman, "Neutral Injection Heating", in *Symp. Plasma Heating and Injection* (Varennna, Italy, 1972), 117.
2. E. Thompson, "The Ion Optics of a Single Stage Post-Acceleration System", in *Proc. 2nd Symp. Ion Sources and Formation of Ion Beams* (Berkeley, California, 1974), II-7-1.
3. K. W. Ehlers, W. R. Baker, K. H. Berkner, W. S. Cooper, W. B. Kunkel, R. V. Pyle, and J. W. Stearns, "Large Area Plasma Sources", *Proc. 2nd Symp. Ion Sources and Formation of Ion Beams* (Berkeley, California, 1974) I-5-1.
4. R. Hackam, "Effects of Voltage Polarity, Electric Current, External Resistance, Number of Sparkings, Supply Frequency, and Addition of Hydrogen and Air on the Electric Breakdown in Vacuum", *J. Appl. Phys.* 46, 3789 (1975).
5. J. H. Fink, W. L. Barr, and G. W. Hamilton, "A 225 MW Neutral Injection System for a Mirror Fusion-Fission Hybrid Reactor", *Nucl. Fusion* 15, 1067 (1975).
6. K. H. Berkner, R. V. Pyle, and J. W. Stearns, "Intense Mixed-Energy Hydrogen Beams for CTR Injection". *Nucl. Fusion* 15, 249 (1975).

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