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PRODUCTION OF A HIGH-BRIGHTNESS BEAM USING AN OPTIMIZED EXTRACTION SYSTEM

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Ion beam lithography relies on high brightness beams in the micro-ampere range. For such intensities the saddle field ion source is a good choice as it offers high efficiency and easy operation. In our system, two screening electrodes are enclosed between two ground electrodes and an annular anode ensuring high operational reliability.

The optimization of the extraction system is performed both by experiments and by calculations according to the rules of the high current ion beam generation.

The top result for nitrogen at a 13.5 KeV beam energy is a 160 μA ion current with an emittance of 2.5 mm m rad. and an emittance-normalized brightness of 11.4 A/ /(mm m rad.)^2.

I. INTRODUCTION

For beams from plasma sources there exists a basic rule: the plasma density at the outlet plane must match the extraction conditions: the higher the extraction field is, the higher the density must be. In detail, the trajectories of the extracted ions are determined by the form of the equipotential surfaces; one surface however, namely the one at the source potential is not fixed in space but modelled by the force balance of the plasma pressure and the extraction field, thus influencing also the other equipotentials. The ions, because of their inertia, do not follow the field lines exactly and even distort by their own space charge the equiponential surface shapes. From the calculations [1], one can that generally only a part of the emitting are contributes to the actually transported beam, and the designer of an extraction system can almost try to increase this fraction.

For ion beam lithography and similar techniques, beams of medium currents but high optical quality are essential [2]. Therefore in the following some basic

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quantities which describe the most important parameters of ion beams will be defined and the ion optics of the extraction system is also given.

Our results are interested for ion thinning and machining applications and the choice of a saddle field ion source to produce the type of beams in question will appear quite convincing.

II. THEORETICAL CONSIDERATIONS

Before going into details, some formal definitions and laws regarding the beam quality will be given. More than the entire extracted beam current I, its transportable fraction I_{tr} is of importance. The value of I_{tr} is determined by the absolute beam emittance ε: $\varepsilon = A_E/\pi$, where A_E is the area of the beam trajectories within the two-dimensional phase space. Generally, two phasespace diagrams have to be considered, for two orthogonal transverse directions. In our case however, cylindrical symmetry can always be supposed and therefore, one emittance figure taken in one radial direction is sufficient.

In the plane of the beam waist, its emittance is calculated as the product of the waist radius r_0 and the divergence angle Θ_0 of those trajectories that cross the axis of symmetry: $\varepsilon = r_0 . \Theta_0$, at least if the emittance figure is an ellipse, which is normally fulfilled. Further, it has frequently been found [3] that for axially symmetric high brightness beams the waist is one-half of the extraction aperture width: $r_0 = r/2$.

The normalized emittance is defined as $\varepsilon_n = \beta . \gamma . \varepsilon$, where $\beta = v_i/c$, v_i is ion velocity, c is the vacuum light velocity, $\gamma = (1 - \beta^2)^{-1/2}$. ε_n is an invariant for beam energy changes. The quantity "brightness" relates the transported current to the beam emittance, here the emittance-normalized brightness will be used: $B_{\varepsilon n} = I_{tr}/\varepsilon_n^2$.

The formation of high brightness ion beams in a single-extraction aperture was extensively treated in the past [4, 5]. The developed theory combines the space charge limit for a stable ion flow (Child—Langmuir law) with the optical-lens action of the extraction apertures. As a result, the currents of extracted lowdivergence ion beams should scale as:

$$I^{theor.} \propto S^2 \cdot \frac{V^{3/2}}{(A/\xi)^{1/2}} \qquad (1)$$

while experimentally, the actually-transported high brightness beam currents are found scaling as:

$$I_{tr}^{exp} \propto \frac{S^2}{1 + aS^2} \cdot \frac{V^{3/2}}{(A/\xi)^{1/2}}, \qquad (2)$$

where S is the aspect ratio $S = r/d$, r is the outlet-aperture radius, d is the extraction gap width, V is extraction voltage, A is atomic mass number, ξ is ion charge stage, a is aberration factor "dimensionless parameter". Its exact value depends on the allowed beam divergence for a given extraction system (the chosen extraction electrode geometry). In our system the value of the parameter a amounts to 1.7.

In our study, we optimized such an extraction system, varying the outlet size as well as the extraction voltage and in all cases searching for the matching ion current density.

III. DESCRIPTION OF THE MODIFIED ION SOURCE

A schematic drawing of the modified ion source is shown in Fig. (1a). It consists mainly of a stainless steel annualar anode with a 4 mm hole diameter, two brass annular screens each with a 7 mm hole diameter and two brass disc cathodes. The two cathodes are earthed and placed symmetrically on both sides of the annular anode. One of the cathodes is used for gas inlet while the other serves as an extraction electrode. The cathode has a brass insert so that ion exit apertures of different sizes can be used. This also allows these inserts to be changed when they get damaged by continuous ion bombardment. The anode is isolated from the screens by ceramic isulators. All source parts are contained inside a stainless steel cylinder whose ends are the disc cathodes. Both anode and screens are 1.6 mm thick. Nitrogen gas is admitted into the source through the aperture of one insert, for the best interaction of the gas and the oscillating electrons, while the other is used for the ion beam extraction. The source is tested in a stainless steel chamber pumped by a conventional oil diffusion pump and a rotary pump. The pressure in the chamber is measured by an ionization gauge.

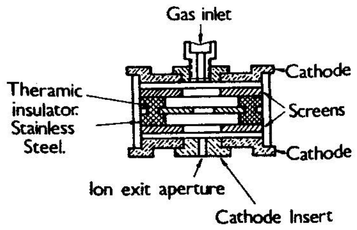

Fig. 1a. The modified source.

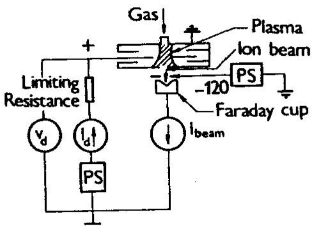

Fig. 1b. The electrical circuit.

Fig. (1b) shows the modified ion source with its associated electrical circuit. All the instruments are fed from a voltage stabilizer which is capable of maintaining its output voltage constant at 220 V, while the input ranges between 198 V and 242 V. The anode is connected to the positive high voltage terminal of the power supply via a milliameter and a limiting resistance. The discharge current I_d and the discharge voltage V_d are measured by means of the milliameter and an electrostatic kilovoltmeter, respecitvely. The ion beam current is measured by means of a conical Faraday cup connected to a microameter.

IV. EXPERIMENTAL RESULTS

All results shown here are measured by a Faraday cup. A scanning device with an x-y recorder is used to demonstrate the ion beam density profile. The scanner consists of a probe of 0.2 mm diameter and moves only in one direction by an electromechanical system. It is situated at a distance 75 cm from the ion exit aperture. A d.c. motor operates two wheels causing the probe to move along the horizontal direction as shown in Fig. (1c). The electrical circuit for operating the scanner is opened by microswitches and allows to reverse the direction of rotation of the motor. The probe is connected to a recording circuit and the amplitude of the beam profile is adjusted in addition to the adjustment of the x-y recorder.

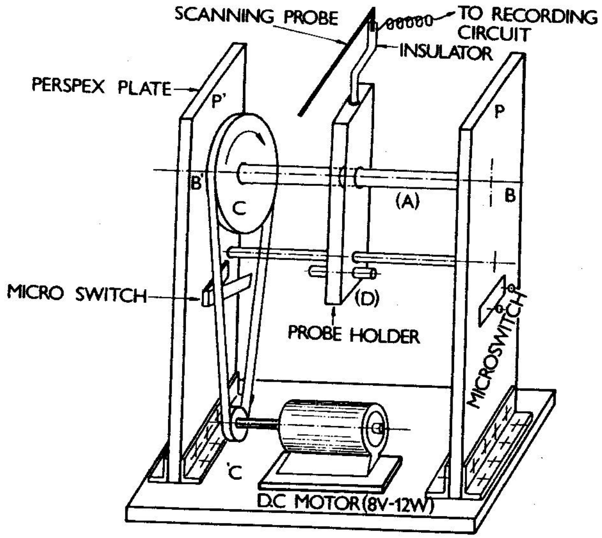

Fig. 1c. Mechanical motion of the beam scanner.

4.1 Analysis of the ion beam optics

The variations of angular divergence with perveance either by varying voltage or by current are illustrated in Fig. (2). The data show that the minimum divergence has the definite value. As the source conditions are varied to alter the extraction current for a given voltage ($V = 10$ kV) and source geometry (curve I), the divergence varies decreasing to a minimum at a perveance which is a fraction of that given by the Child-Langmuir relationship [6] for that geometry.

$$P_{min} = 1.03 \times 10^{-7}\left(\frac{r}{d}\right)^2 \quad \mathrm{A/V^{3/2}}. \tag{3}$$

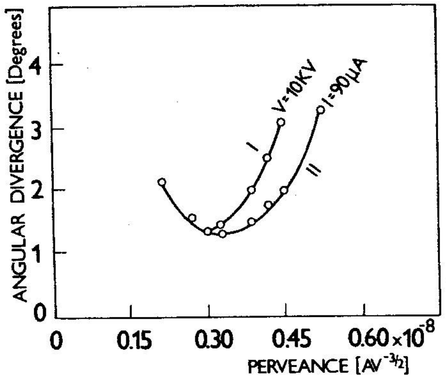

Fig. 2. Experimental data on beam divergence.

In the experiment in which the voltage is varied (curve II) but other parameters are kept constant, the extracted current is almost constant (90 μA) but the beam divergence varies. The change in divergence due to a change in perveance (either current or voltage) depends on the factor r/d.

4.2 Investigation of ion beam extraction geometries

The variation of perveance of the beam which can be extracted from the plasma through an aperture radius r_a and transmitted through an aperture in the extraction electrode of the radiius r_c (separation of electrode equal to d) is illustrated in Fig. (3).

Fig. (3) shows a comparison of the convergence as defined by the apertures for the measured perveance with the theoretical prediction given by Langmuir as:

$$\frac{I}{V^{3/2}} = \frac{1.467 \times 10^{-5}}{r_c \alpha^2} \quad \mathrm{A/V^{3/2}\,cm}, \tag{4}$$

where α is related to the radii of the electrodes by the equation

$$\alpha = Y + 0.1Y^2 + 0.017Y^3 \ldots$$

and $Y = \log(r_a/r_c)$, r_a being the anode radius & r_c the cathode radius. Here $r_a = 2$ mm, $d = 2.3$ mm.

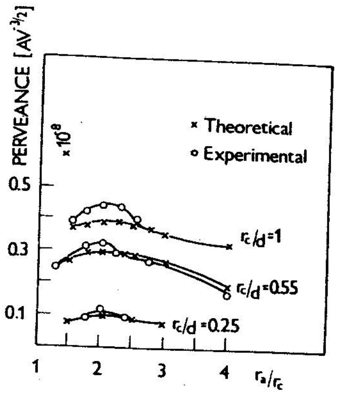

Fig. 3. Variation of perveance of beam with electrode geometries.

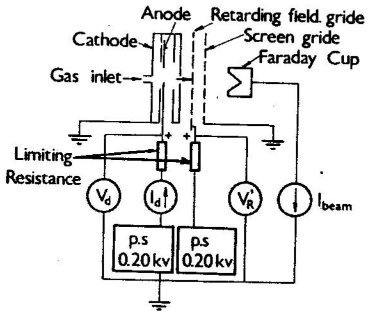

Fig. 4. Retarding field analyzer circuit.

It is seen from the figure that the deviation between the theory and the experiment is large for $r_c/d = 1$ in case of $r_a/r_c = 2$. Owing to the assumption involved in the derivation of equation (4), it is only valid for small (r_c/d). Using equation (2), the geometrical relations are best exploited when (r_c/d) is limited to $\lesssim 0.4$. At a high aspect ratio the electric field is diminished by the effect of the aperture. In a thorough experimental study, it is found that actually transported ion currents with a low divergence angle scale are as equation (2).

4.3 The ion beam energy distribution

The energy distribution of the nitrogen ion beam is measured using a retarding field energy analyser (which is) illustrated in Fig. (4). This energy analyser consists of two stainless steel meshes interposed between the source and a Faraday cup. A variable positive potential V_R' is applied to the retarding grid and the screening grid in front of the cup is earthed. The variation of the ion beam current with V_R' is studied at different pressures for different ion exit aperture diameters. The energy distribution curves are obtained from such a variation by subtracting the ion current at V_R' from that at $V_R' + \Delta V_R'$ and then the resultant ion current is plotted against $V_R' + \Delta V_R'/2 = V_R$. With a 1 mm diameter cathode aperture an intense peak with a half width of about 400 volt at 5 KV is observed as shown in Fig. (5) the energy of the peak is about 0.7 of the anode potential. Two peaks of lower energy are just visible in the tail. In order to obtain uniform ion etching or thinning, the ion beam should have a uniform current density and a small energy spread as much as possible. So the small ion exit aperture diameter, the good quality ion beam.

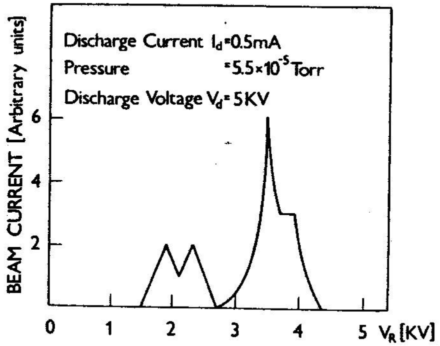

Fig. 5. Ion beam energy distribution.

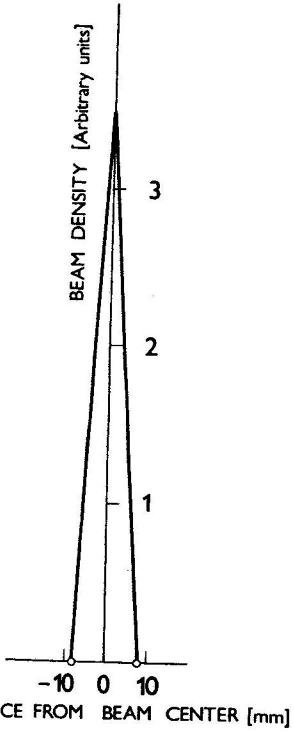

Fig. 6. Ion beam density profile.

4.4 The ion beam density profile

Fig. (6) shows the nitrogen ion beam density profile for the parameters: discharge current $I_d = 1.5$ mA, discharge voltage $V_d = 9.8$ kV, beam current = 93 μA and pressure = 4.2×10^{-5} torr. The profile is characterized by a sharp pencil head shape. The average current density is about 11.8 mA/cm². It is noticed that the profile becomes sharper with decreasing pressure.

4.5 Voltage dependence of beam parameters

The easy way to produce more ion current is to make use of the $I_{tr} \propto V^{3/2}$ law, by increasing the extraction voltage (see Fig. (7)). But this is possible only as long as the breakdown rate does not become prohibitive. The well-known limit [7] for frequent sparking:

$$V/\mathrm{KV} \leqslant 19\,(d/\mathrm{mm})^{1/2}$$

was superated in individual cases and linear dependence found:

$$V/\mathrm{KV} \leqslant 10\,d/\mathrm{mm}.$$

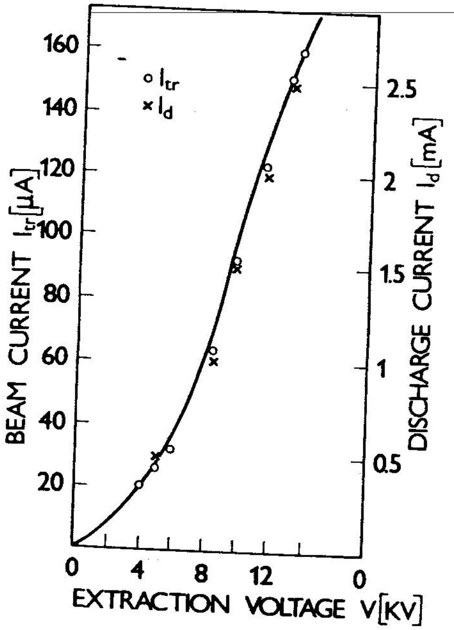

Fig. 7. Voltage dependence of measured transported current.

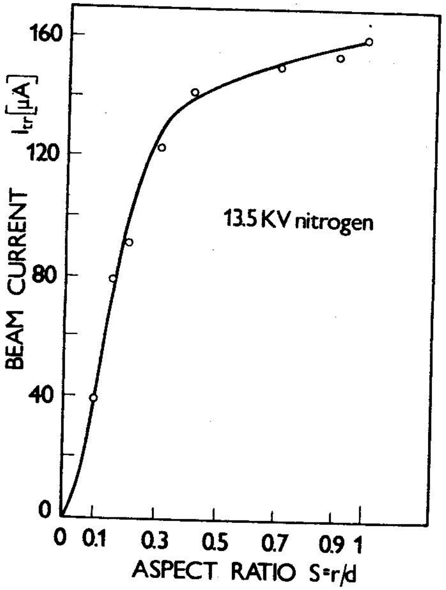

Fig. 8. Measured transported current at optimum extraction system parameters depending on the aspect ratio S.

Our experience definitely suggests that there might be no sharp limit referring to the voltage only, but that the minimum gap width also depends on the beam parameters.

Regarding the minimum d value, the collected data show that the implicit Kilpatrick law [8] marks a close lower limit for the gap widths in two decades of voltages and that a reasonably cautious empirical limit is given by the explicit formula.

Considering equation (2) there is under the restriction of the aspect ratio $S = r/d \leqslant 0.4$ always an absolute current limitation for a given system. The solid line in Fig. (7) shows the relation $I_{tr} \propto V^{3/2}$. The almost complete congruence of the ion current I_{tr} and the discharge current I_d, measured in different scales, indicates a linear dependence of the ion current upon the plasma density.

The dependence of the measured transported ion current I_{tr} on the aspect ratio S for the 13.5 KV nitrogen is shown in Fig. (8). The continuous curve is in terms of equation (2) a fit to all the experimental points together. It obeys the following relationship:

$$I_{tr}^{exp} = 5.65 \times 10^{-8} \frac{S^2 V^{3/2}}{(A/\xi)^{1/2}(1 + 1.7S^2)} \quad \mathrm{A/V^{3/2}}.$$

The variation of the minimum beam divergence with the extraction voltage is shown in Fig. (9). It is seen that at 13.5 KV, the divergence angle equals 0.6⁰.

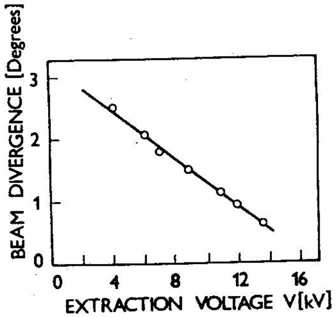

Fig. 9. Variation of minimum beam divergence with extraction voltage.

So the emittance normalized brightness $B_{\varepsilon n} = 11.4$ A/ (mm m rad)^2 with a 160 μA ion current and an absolute emittance of 2.5 mm m rad or the normalized emittance $\varepsilon_n = 3.75 \times 10^{-3}$ mm m rad.

V. CONCLUSION

The existence of a saturation limit for the transportable current with an increasing aspect ratio S strongly supports maintaining $S \lesssim 0.4$ when designing extraction systems, because the spilledbeam part extracted out of larger openings causes a quite unfavourable effect. If one needs to have a minimum dependence of divergence on the perveance, one needs a low perveance per aperture. At each extraction voltage the divergence can be reduced to a minimum by varying the source parameters.

The results quoted here do not always represent the best current values but rather the highest brightness obtained at a reasonable current. The brightness decreases with an increasing extraction voltage and appears to be well confirmed by the available experimental data.

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СОЗДАНИЕ ВЫСОКОИНТЕНСИВНОГО ПУЧКА С ИРИМЕНЕНИЕМ ОПТИМАЛИЗИРОВАННОЙ СИСТЕМЫ ВЫТЯГИВАНИЯ.

Ионная литография требует пучки высокой яркости в микроамперном диапазоне. Для таких интенсивностей хорошие свойства, высокую эффективность и простое управление имеет ионный источник с седловым полем. Расположением двух ограничивающих между двумя основными электродами анодом достигнута высокая устойчивость работы. Оптимализация системы вытягивания с целью достижения максимального тока проводилась также нумерически, как и на эксперименте. Максимальный ток 160 мкА ионов азота с энергией 13,5 кэВ получен с эмитанцией 2,5 мм.м.рад и эмитанцией приведенной к яркости 11,4 А/(мм.м.рад)^2.