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FOR

DEVELOPMENT OF HIGH CURRENT LOW ENERGY H^+ ION SOURCE

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Development of High Current Low Energy H^+ Ion Source

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I. Introduction: The Problem

The ultimate goal of this work is the development of an ion source suitable for double charge exchange of D^+ ions to D^- ions in cesium or other vapor. Since the fraction of the D^+ which changes to D^- may be as high as 0.35 in the energy below one keV, the process appears very favorable.¹

What is desired is a source of several hundred cm^2 area, with a D^+ current density greater than, say $0.2A/cm^2$. Small angular spread is essential with up to about 0.1 radian being acceptable.

II. Approach

A simple approach to this problem appears to be through the fine mesh extraction electrodes developed at this laboratory.²⁻⁴ In this system a single grid facing the ion source plasma constitutes the entire extraction electrode system, as shown in Fig. 1. If the potential difference between the grid and the source plasma is large compared to the ion energy at the plasma boundary, then the distance s_0 is just the Child-Langmuir distance corresponding to the ion current density J and the potential difference V_0 between the plasma and the grid.

Although we have run with negative grid potentials, the extraction grid is normally held at the same potential as the ion beam surroundings. In this case the ion beam will rise to a sufficiently positive potential to trap space charge neutralizing electrons. This is illustrated at the bottom of Fig. 1.

Space charge spreading at the beam edges in the accel gap can be corrected by Pierce electrodes but this is an unnecessary refinement if s_0 is much less than the lateral beam dimensions. Furthermore, the trajectories at the beam

II. Approach (continued)

boundaries are much more influenced by the shape of the plasma boundary than by space charge. If s_0 is increased over the value shown in Fig. 1, the plasma boundary will be concave at the place where the boundary approaches the defining aperture, and the beam edges converge. If s_0 is decreased the plasma bulges out toward the grid and the beam edges diverge.

There are limitations in the application of the fine mesh grid system to high current density beams. Let us consider these one at a time.

III. Planarity of Equipotentials

For a grid which is too coarse, a condition such as that shown in Fig. 2 might obtain. In this case the potential between grid wires is significantly positive with respect to the grid wires and the plasma surface has ripples reflecting the periodicity of the grid. This phenomenon causes, as illustrated, ion interception much larger than the geometric cross-section of the grid wires and a large angular spread in the emerging beam.

It is necessary to avoid this phenomenon by using grids whose wire to wire spacing is small compared to the spacing s_0 to the plasma. In this case the ripple in potential in the plane of the grid can be expected to be a small fraction of the grid to the plasma voltage. For square grid of spacing "a" in each direction the ripple in potential can be expected to fall off as $\exp - (2\sqrt{\pi}x/a)$, where x is distance from the grid. For $x/a=2$ this factor is 1.91×10^{-8} . It is likely that a grid spacing which is 1/2 the acceleration sheath thickness is ample to avoid the undesirable effects illustrated in Fig. 2.

It is easy to show that under this condition space charge effects in the

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III. Planarity of Equipotentials (continued)

vicinity of the grids which would increase the ripple in voltage in the grid plane are negligible. This can be done approximately as follows: The space charge density at the grid is given by

$$\rho = \frac{4\epsilon_0}{9} \frac{V_0}{s_0^2} \quad (1)$$

The potential variation from center to periphery of a cylinder of diameter of a containing that amount of charge is seen to be

$$\Delta V = \frac{V_0}{36} \frac{a^2}{s_0^2} \quad (2)$$

For $s_0 \approx 2a$ this gives

$$\Delta V = \frac{V_0}{144} \quad (3)$$

small enough to guarantee a negligible space charge effect.

The value of s_0 can be expected to be much larger than $2a$. For example for a 250 in.^{-1} mesh, which is a commercially available tungsten grid, $a = 0.004 \text{ in.} = 0.01 \text{ cm}$. A value of $s_0 = 2a$ would correspond to current of 0.77 A/cm^2 at 400 volts, far in excess of desired currents.

The assumption that the plasma boundary is planar and ion trajectories initially all parallel appears to be one that is reasonable.

IV. Grid Heating

With s/a sufficiently large, the trajectories can be expected to be essentially straight, with small deflections produced close to the grid plane,

IV. Grid Heating (continued)

as discussed later. In this case the power per unit area striking the grids is just the average power per unit area,

$$P = JV_0, \quad (4)$$

For a circular grid wire the radiating area per unit length of wire is πd , whereas the cross-section per unit length for ion beam interception is just d . The wire temperature will be determined by

$$e\sigma T^4 = P/\pi, \quad (5)$$

where e is the emissivity, σ the Stefan-Boltzmann constant and T the absolute temperature of the wire. Using tungsten emissivity values of Roessen and Wensel⁵, we obtain the curve shown in Fig. 3.

Ultimately the temperature limitation will be provided either by the thermionic electron emission from the grid or by the rate of evaporation of tungsten. Since the saturation electron current becomes ⁵ 0.1 A/cm^2 at about 2380°K this would appear to be an upper limit to the allowable grid temperature, depending somewhat on the grid to plasma potential difference. This would correspond to 170 watts/cm^2 of ion beam. At 2380°K the evaporation rate of tungsten, calculated from vapor pressure data,⁶ is $1.8 \times 10^{-11} \text{ cm/sec}$. At this rate it would take about 4-1/2 years to evaporate 0.001" of tungsten. A limit of 170 watts/cm^2 would seem to be a reasonable limit.

V. Sputtering Limit

For heavy ions, the rate at which the grid sputters severely limits operating time. For H⁺ or D⁺ this limitation is not severe. Since we are ultimately interested in D⁺ beams let us examine the sputtering limitation

V. Sputtering Limit (continued)

in the low energy range. The sputtering yield⁷ for D⁺ on tungsten is given by $\alpha = 7.2 \times 10^{-4}$ atoms/cm at 1 keV and dropping rapidly as the energy is decreased.

It is a simple matter to show that the rate of sputtering, in cm/sec, is given by

$$S = 9.9 \times 10^{-5} \alpha J \quad (6)$$

where J is the current density in A/cm². For example, if J = 0.2 A/cm² and α at the value given for 1 keV we obtain

$$\begin{aligned} S &= 1.43 \times 10^{-8} \text{ cm/sec} \\ &= 1.24 \times 10^{-3} \text{ cm/day} \end{aligned}$$

For a grid thickness of 2.5×10^{-3} cm this could be a serious limit. The sputtering isn't well known below 1 keV but is dropping off very rapidly in this region. For an $\alpha \approx 10^{-4}$ atoms/ion anticipated at 300-400 volts the sputtering limitation on lifetime would be satisfactory.

VI. Angular Divergence

An approximation to the divergence caused by fields near the grid can be obtained by considering each hole as acting independently and using the formula⁸

$$f = 4 \frac{V_0}{V_2' - V_1'} \quad (7)$$

for the focal length of an aperture. Take V_2' , the potential gradient on the downstream side of the grid to be negligible compared to the gradient $4V_0/s_0$ on the upstream side. We then obtain

$$f = 3s_0 \quad (8)$$

VI. Angular Divergence (continued)

As illustrated in Fig. 4 this yields an angular divergence

$$\theta = \pm a/6s_0 \quad (9)$$

The angular spread given by this equation, together with the Child-Langmuir equation relating s_0 to J and V_0 , and the material of the previous section relating the temperature to beam power density JV , has been put together in the curves of Fig. 4 for a 250 in⁻¹ grid. For example, suppose one could say that a grid running at 2300° K. and angular divergence of 4° from the mean path, were acceptable parameters. Fig. 4 shows that this could be obtained with a current density of 420 mA/cm² at a voltage of 350 volts.

VII. Initial Tests

The concept of fine mesh extraction of low energy high density ion beams was tested using two multipole containment ion sources.

Preliminary development of the fine mesh single grid system was done with the ion source described in reference 4. This ion source, approximately 14 x 14 x 18 cm in size, uses ceramic magnets and is capable of producing a quiet, highly uniform plasma in hydrogen (or other gases) of density approximately $n = 2 \times 10^{11}$ cm⁻³.

A woven tungsten grid of 0.03 mm wire of 55 lines/cm mesh was used for ion acceleration. The mesh was kept tightly stretched by stainless steel spring fingers. This assembly is shown schematically in Fig. 5.

Using this assembly, a 2cm x 2 cm hydrogen ion beam of 20 nV/cm² was accelerated to energies ranging from 1 keV to 3 keV. Maximum power dissipation of the grid was 60 W/cm². At this power level the grid was a bright orange color.

VII. Initial Test (continued)

The beam was collected at a target approximately 20 cm from the accel grid plane. Measurements of the angular divergence of the beam due to grid optics had been previously made ⁵ using a lower current argon ion beam and were found to correspond closely to values calculated using eq. 9. The 20 mA/cm^2 hydrogen beam was clearly visible, and appeared to be uniform and to have an angular divergence of less than two degrees. Examination of the grid after operation indicated no damage or distortion due to heating.

These preliminary tests indicated the feasibility of the fine mesh system for relatively high current density ion beams, but ion source limitations precluded extraction of current densities in excess of approximately 25 mA/cm^2 . An accelerator system was then designed and constructed for the IBIS source. ⁹

VIII. High Power Dissipation Grid Tests

A. Experimental Assembly

The grid assembly used for high power dissipation testing of the woven tungsten grids is shown schematically in Fig. 6. The boron nitride aperture limited ion extraction to a circular beam of area 2 cm^2 . The grid is woven tungsten, 71 lines/cm of 0.02mm wire, held in tension by four 0.25mm thick molybdenum sheets.

The ion source used (IBIS, ref. (9)) is capable of producing highly uniform quiescent plasmas with densities of a few times 10^{12} cm^{-3} , and so is able to supply more than enough current for testing of the fine mesh grids.

The experimental arrangement is shown schematically in Fig. 7. The

VIII. High Power Dissipation Grid Tests

A. Experimental Assembly (continued)

aperture plate has an area exposed to the source plasma of 240cm^2 , so that monitoring the ion current to this plate provides a measure of the ion current density actually arriving at the plane of the accel grid. This was taken as the primary measure of incident beam current density for calculations of grid power dissipation.

At high power densities, the grid emits an electron current approaching 100 mA/cm^2 , most of which falls into the ion source, although some of these electrons may contribute to space charge neutralization of the ion beam. This emission current appears as a current in the accel supply, added to the ion current extracted from the ion source. The grid is 73% transparent.

The ion beam propagates approximately 15 cm and is collected on a water cooled copper target. In operation the hydrogen chamber pressure is 2×10^{-3} torr to 5×10^{-3} torr, and so the charge exchange mean free path at 1keV ion energy is comparable to the beam propagation distance, so that approximately 1/2 the beam can be expected to strike the collector. The target is large, and many of the slow charge exchange ions will be collected by the target. The rest fall to the surrounding screen.

B. Measurements

This accel system has been operated at beam energies between 1keV and 2keV and extracted current densities from 70 to 140 mA/cm^2 . The maximum power dissipation of the grid in this series of tests was 160W/cm^2 .

The power dissipation of 160W/cm^2 was calculated from an accelerator voltage of 2000 volts and an incident current density of 80 mA/cm^2 , measured

VIII. High Power Dissipation Grid Tests

B. Measurements (continued)

at the aperture plate. Current in the accel high voltage supply was 200mA, so that 40mA must be attributed to electron emission from the grid or spurious discharge or leakage. The total beam current after acceleration was then $0.73 \times 2 \times 80 \text{ mA} = 116 \text{ mA}$. The current collected at the beam target was 98mA, indicating that most of the charge exchange ions are being collected by the large target. The beam was highly visible, and appeared to have less than 5° divergence.

The beam current density was increased to 110 mA/cm^2 (150 mA/cm^2 incident on the accel grid) at an accel voltage of 1kV to observe the effect of increased beam density on propagation. The increased source plasma density necessary for increased ion current required an increase in the chamber neutral gas pressure, and a corresponding increase in beam losses to charge exchange. The first eight centimeters appeared to have an angular divergence of less than 5° . Past 8cm, the beam rapidly became diffuse.

The attached photograph is of a beam of 60 mA/cm^2 at 1keV. The bright oval near the accel end of the beam is a reflection of the accel grid in one of the flat molybdenum grid tensioners. The beam can be seen to propagate with very low divergence.

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IX. Conclusions

These small scale tests have demonstrated the ability of the fine mesh tungsten accelerator grid system to produce low energy hydrogen ion beams of high current density. The current densities measured are within a factor of two of those required for a practical double charge exchange system. The 2cm^2 test beam area, while much smaller than that of an operating system, is large enough to demonstrate the magnitude of important space charge effects, and beam propagation over many centimeters was accomplished with divergences comparable to those expected from accel optics calculations.

The measurements indicate that the power dissipation capability of the woven mesh grid will probably not be a limiting factor. The $160\text{W}/\text{cm}^2$ achieved is not an ultimate limit, and would correspond to $320\text{mA}/\text{cm}^2$ at 500eV beam energy. Overall, the test results were very encouraging and indicate that a test of a full scale fine mesh accelerator would have a high probability of success.

NOTICE

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Hydrogen ion beam, 1 keV energy, 60 mA/cm^2 .

Figure 1

Schematic of single grid extraction system, with potential variation.

Figure 2

Difficulties associated with inadequate sheath to grid spacing ratio.

Figure 3

Theoretical temperature of a tungsten grid bombarded by an ion beam of power per unit area P .

Figure 4

Current density and voltage contours for a D^+ ion beam on a temperature, divergence angle plane, for 250 line per inch tungsten mesh.

FINE MESH EXTRACTOR

FIG 5

FINE MESH EXTRACTOR FOR IBIS

Fig 6

LOW ENERGY ION BEAM EXPERIMENT