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HIGH BRIGHTNESS H^+ AND H^- SOURCES

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ABSTRACT

The brightness and emittance of a beam of ions can depend on the transverse ion temperature, lens aberrations, scattering collisions as well as other factors in the beam transport line. However it is the transverse ion temperature, which arises in the plasma source, which determines the minimum value of the emittance and hence the beam brightness as the other contributions can be eliminated by careful design. The plasma discharge both creates the positive and negative ions and then heats them to a temperature which is a function of the plasma molecular chemistry (for H^+) as well as the plasma density and electron temperature. We describe these processes and also methods whereby the discharge can be modified to reduce the effective ion temperature and hence raise the beam brightness.

INTRODUCTION

The beam brightness of a positive or negative ion beam is proportional to the beam current divided by the square of the beam emittance. This beam emittance is, in turn, proportional to the transverse ion velocity which depends on the aberrations of the accelerator which extracts ions from the plasma source, the transverse ion temperature in the plasma source and lastly stochastic scattering encountered by the beam ions in the drift region downstream of the accelerator. It is possible to virtually eliminate the first and third contributions to the transverse ion velocity by careful design which leaves the second contribution arising from the transverse ion temperature in the source as the sole determinant of the ultimate beam brightness.

The normalised beam brightness is defined by the expression:

$$B_n = 2I/\pi^2\varepsilon_{nx}\varepsilon_{ny}$$

where I is the beam current and ε_{nx} and ε_{ny} are root mean square normalised emittances in the x and y planes. Lapostolle[1] has created a definition for the r.m.s. beam emittance which is

$$\varepsilon_{nrms} = \beta\gamma\,(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)^{\frac{1}{2}}$$

This definition does not include the factor 4 derived by Lapostolle. Using this definition the non-relativistic emittance is:

$$\varepsilon_{nx} = \varepsilon_{ny} = \frac{r}{2}\left\{\frac{eT_i}{mc^2}\right\}^{\frac{1}{2}} \qquad (1)$$

for circular extraction apertures of radius r, and a maxwellian ion velocity distribution of temperature T_i. Hence

$$B_n = \frac{8mjc^2}{\pi eT_i} \qquad (2)$$

where j is the ion current density. This equation indicates that the sole determinants of beam brightness are the extracted current density and the ion temperature of the extracted particles.

In this paper we do not discuss in detail values of T_i existing in the various types of plasma sources that have been developed. Instead we describe plasma processes that can contribute to the ion temperature and the additional effects that exist when there is a substantial presence of negative ions. As an example we use the general model to derive the positive and negative ion temperature dependence on plasma parameters in a magnetic multipole source. These sources can produce positive ions in pulsed or dc operation and also negative ions are formed in the plasma without the use of cesium[2-4].

THE ION TEMPERATURE

We begin by making the general assumptions that the ion source is operating in a steady-state mode and that the ion distribution is sufficiently self-collisional for the ion temperature to be significantly different to the gas temperature. The latter requirement sets a minimum limit to the ion lifetime and plasma density as the ion-ion scattering time has to be shorter than the ion lifetime. This ion lifetime is normally determined by loss by charge-exchanging collisions (if it is a positive ion) as the new ion which emerges from such a collision has initially the same temperature as the gas molecules which set a lower limit to the ion temperature, T_i (in eV). Hence the model is valid if:

$$N_o(\sigma v)_{ce} < \tau_{ii}^{-1}$$

Hence $$N_o(\sigma v)_{ce} < 1.4\,10^{-13}\, n_i\lambda_{ii}T_i^{-3/2}A_i^{-1}\ [s^{-1}] \qquad (3)$$

where n_i is the ion density, N_o is the gas density, $(\sigma v)_{ce}$ is the charge exchange rate and A_i is the ion mass in units of the proton mass. λ_{ii} is the ion-ion coulomb logarithm which is typically 7 for plasmas in the density range of $10^{18}m^{-3}$. Applying Eq.3 to a hydrogen discharge sets a lower limit to the plasma density. This limit is:

$$\frac{n_i}{N_o} > 2.10^{-3}\ T_i^{3/2}$$

which permits low density plasmas ($n_i > 10^{10}$ cm^{-3}) to have thermal ion temperatures.

Positive Ion Energy Balance

The major heat source for positive ions is direct heating by the thermal electron distribution through coulomb collisions. Spitzer[3] has shown that this energy input, H_{e+} per ion, is:

$$H_{e+} = 1.36\,10^{-13}\frac{n_e(A_eA_+)^{\frac{1}{2}}\lambda_{ei}}{(A_eT_+ + A_+T_e)^{3/2}}\cdot(T_e - T_+)\ [eV.s^{-1}] \qquad (4)$$

where T_e is the electron temperature, A_e and A_+ is the electron and positive ion normalised masses and λ_{ei} is the electron-ion coulomb logarithm which is typically 9. As the electron mass is much smaller than the ion mass then

$$H_{e+} = 2.87\,10^{-14}\frac{n_e}{A_+\,T_e^{3/2}}(T_e - T_+)\ [eV.s^{-1}] \qquad (5)$$

Another energy input is due to the positive-negative ion coulomb collisions which yield a heating rate H_{-+} of:

$$H_{-+} = 9.56\,10^{-13}\,\frac{n_-\,(A_+A_-)^{\frac{1}{2}}}{(A_+T_- + A_-T_+)^{3/2}}\lambda_{ii}\cdot(T_- - T_+)[eV.s^{-1}] \qquad (6)$$

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where A_- is the normalised negative ion mass and n_- and T_- are its density and temperature. Lastly the creation and loss of positive ions via ionisation and charge exchange and recombination creates an effective energy input, H_{c+}. The value of H_{c+} is:

$$n_+H_{c+} = E_iN_0n_pS_i + E_+N_0n_+(\sigma v)_{ce} - T_+W_+n_+c_s - T_+(N_0n_+(\sigma v)_{ce} + n_+n_-(\sigma v)_{ii}) \quad (7)$$

where E_i is the energy gained in the ionisation event with a rate S_i, E_+ is the initial energy an ion has after charge exchange, $(\sigma v)_{ii}$ is the negative-positive ion recombination rate and n_p is the fast ionising electron density. The ion loss to the walls of the source is governed by the inverse scale length, W_+, and the ion sound speed c_s. Equation 7 can be simplified considerably as charge exchange rate is normally dominant over the other terms by at least an order of magnitude in the regime where we can use the concept of temperature[6]. Hence:

$$H_{c+} = N_0(\sigma v)_{ce}\,(E_+ - T_+) \quad (8)$$

We neglect the effects of elastic scattering of the ions on gas molecules as the rate coefficient derived from polarisation processes is very close to that of charge exchange (at least in H_2 and is much smaller for heavier elements). On equating the sum of H_c, H_{-+} and H_{e+} to zero for a steady state plasma we derive the positive ion energy balance equation which is:

$$H_c + H_{-+} + H_{e+} = 0 = N_0(\sigma v)_{ce}(E_+ - T_+) + 2.8710^{-14}\frac{n_e}{A_+T_e^{3/2}}(T_e - T_+) + 9.5210^{-13}\frac{n_-(A_+A_-)^{1/2}}{(A_+T_- + A_-T_+)^{3/2}}(T_- - T_+) \quad (9)$$

Negative Ion Energy Balance

Direct heating by electrons gives virtually identical expression to Eq.4, namely

$$H_{e-} = 2.8710^{-14}\frac{n_e}{A_-T_e^{3/2}}(T_e - T_-) \quad (10)$$

and a similar result is obtained for energy exchange between positive and negative ions yielding:

$$H_{+-} = 9.5210^{-13}\frac{n_+(A_+A_-)^{1/2}}{(A_+T_- + A_-T_+)^{3/2}}(T_+ - T_-) \quad (11)$$

The positive ion density is always larger than the negative ion density, hence H_{+-} has a larger effect on the negative ion temperature than the analogous term has on the positive ion temperature.

The creation and loss of negative ions also contributes to the energy balance. We only consider here the volumetric production and loss of negative ions which must be equal. The wall loss is neglected as negative ions are reflected by the plasma sheath. As the dominant loss is via ion-ion recombination for cold plasmas then we can write:

$$H_{c-} = n_+(\sigma v)_{ii}\,(E_- - T_-) \quad (12)$$

where E_- is the energy of formation via dissociative attachment. Wadehra[7] has described the derivation of E_- for hydrogen which is typically 0.3eV.

For a steady state plasma, we can equate the sum of H_{e-}, H_{+-} and H_{c-} to zero which yields:

$$n_+(\sigma v)_{ii}\,(E_- - T_-) + 9.5210^{-13}\frac{n_+(A_+A_-)^{1/2}(T_+ - T_-)}{(A_+T_- + A_-T_+)^{3/2}} + 2.8710^{-14}\frac{n_e(T_e - T_-)}{A_-T_e^{3/2}} = 0 \quad (13)$$

DERIVATION OF THE ION TEMPERATURES

The Positive Ion Temperature

The functional dependence of T_+ and T_- in Eqs.9 and 13 is complex. However a simpler expression can be derived by adding these two equations together after multiplying Eq.9 by n_+/n_-. This yields:

$$0 = 2.8710^{-14}\frac{n_e}{T_e^{3/2}}\left\{\frac{(T_e - T_-)}{A_-} + \frac{n_+}{n_-A_+}(T_e - T_+)\right\} + n_+(\sigma v)_{ii}\,(E_- - T_-) + N_0\frac{n_+}{n_-}(\sigma v)_{ce}\,(E_+ - T_-) \quad (14)$$

Equation 14 may be further simplified if the degree of ionisation is low so that the $(\sigma v)_{ii}$ term can be neglected. Hence:

$$N_0(T_+ - E_+) = \frac{2.8710^{-14}n_e}{T_e^{3/2}\,(\sigma v)_{ce}}\cdot\left[\frac{n_-}{A_-n_+}(T_e - T_-) + \frac{1}{A_+}(T_e - T_+)\right]$$

The above equation can be re-arranged to give:

$$T_+ = \frac{\left[E_+N_0 + \frac{2.8710^{-14}T_e^{-1}}{(\sigma v)_{ce}}\left(\frac{n_e}{A_+} + \frac{n_-n_e}{A_-n_+}\right) - \frac{2.8710^{-8}n_e\,n_-T_-}{(\sigma v)_{ce}A_-n_+T_e^{3/2}}\right]}{\left[N_0 + 2.810^{-14}n_e/T_e^{3/2}\,A_+(\sigma v)_{ce}\right]}$$

The same simplification relating to the probable degree of ionisation, indicates that the N_0 term is dominant in the denominator so that the final expression has the form:

$$T_+ = E_+ + \frac{2.8710^{-14}n_e}{N_0(\sigma v)_{ce}}\cdot\left\{T_e^{-1}\left(\frac{1}{A_+} + \frac{n_-}{A_-n_+}\right) - \frac{T_-^{1/2}}{T_e^{3/2}}\cdot\frac{n_-}{A_-n_+}\right\} \quad (15)$$

The above expression shows that we would expect the ion temperature to increase linearly with the electron density and to decrease down to the creation event energy with increasing gas pressure. This creation event energy is the kinetic energy of the gas molecules in the plasma chamber and hence represents the minimum ion temperature.

The contribution of negative ions to Eq.15 is more complicated. Providing T_- is less than T_e, which is usually the case then the presence of negative ions will slightly increase the positive ion temperature by an amount proportional to the fractional negative ion density, n_-/n_+. This effect can be increased in magnitude if the negative ions are formed by dissociative attachment which only occurs at low electron temperatures ($T_e \sim 1$ eV)[7]. The low electron temperature increases the coupling between the ions and electrons and causes the positive ion temperature to become close to that of the electrons.

The Negative Ion Temperature

Substitution of the likely values of $(\sigma v)_{ii}$ and the electron temperatures (and hence positive ion temperatures) into Eq.13 shows that the contribution made by electron heating is small compared with the other two terms providing T_+ is slightly larger than T_-. The elimination of this former term allows Eq.10 to be reduced to the approximate form:

$$T_- = T_+\frac{(E_-T_+^{1/2} + 9.5210^{-13}G/(\sigma v)_{ii})}{(T_+^{3/2} + 9.5210^{-13}G/(\sigma v)_{ii})} \quad (16)$$

where $$G = (A_+A_-)^{1/2}/(A_+ + A_-)^{3/2}$$

In the limit that $T_+^{3/2}$ is significantly smaller than the term containing G then we may expand Eq. 16 to obtain

$$T_- = T_+ - (\sigma v)_{ii} T_+^{1/2} (T_+ - E_-)/9.5210^{-13}G \qquad (17)$$

Both the above expressions indicate that T_- is always less than T_+ although the relative difference is very small at low values of T_+. This difference is independent of both plasma and gas density and only depends on the ion masses and the ion-ion recombination rate. As the positive ion temperature increases, the negative ion temperature decouples from the positive ion value and approaches a lower limit of E_- which is again the gas temperature. The electron heating term is never dominant as this term is smaller than the other by a factor $(m_e/m)^{1/2}$.

Emittance Growth on Extraction

Positive Ion Beams In the case of positive ions, the extraction process is simply to accelerate these ions across a sheath at the plasma edge so that their directed (drift) velocity is orthogonal to the plasma surface and parallel to the electric field (for thin sheaths). As a result the transverse velocity is conserved during extraction and we can substitute the ion temperature derived from Eq.15 into the expression for the normalised emittance for a circular aperture

$$\varepsilon_n = \frac{a}{2} \left\{ \frac{eT+}{m_+c^2} \right\}^{1/2} \qquad (18)$$

where this definition contains 39.3% of all beam particles if the transverse velocity distribution is gaussian and can be described by a temperature. The shape of the emittance diagram is elliptical.

Aberrations in the accelerator can cause the emittance diagram to develop fine structure, hence increasing the area of the ellipse which would contain this more complex diagram (Lawson[8]) and hence increasing the effective beam emittance. However, for a well designed accelerator this effect is usually small.

Negative Ion Beams The extraction of negative ion beams is more complex because of the presence of electrons in the plasma. In all sources where the negative ions are produced in the plasma this electron flux can be many times that of the negative ions due to the high electron thermal velocity and hence causes a severe problem in the accelerator unless the electron flux is suppressed. The simplest and commonest form of suppression is a transverse magnetic field which ranges from around 1 to 2 kilogauss in Penning type sources[9] to around 40 gauss in multipole filter sources[3]. This field reduces the electron flux to a small multiple of the negative ion flux.

This field has also weaker effect on the negative ions as it causes them to be slightly deflected, and gives a net transverse velocity, $v_\perp$, of:

$$v_\perp = \frac{e}{m} \int Bdl \qquad (19)$$

However as the negative ions do not originate at the same distance from the extraction plane then a spread in transverse velocity is obtained which is stochastic in nature. If the negative ions have a scattering mean path length, λ, then the mean square transverse velocity is:

$$\langle v_\perp{}^2 \rangle = \frac{e^2}{m^2} \int_0^\infty B^2 s^2 f(s)ds \Big/ \int_0^\infty f(s)ds$$

where $$f(s) = \exp(-S/\lambda)$$

$$\langle v_\perp{}^2 \rangle = 2e^2B^2\lambda^2/m_-{}^2 \qquad (20)$$

We have assumed that the magnetic field is uniform over one or two pathlengths. An effect of this type has been described by Smith et al[9].

This type of stochastic transverse velocity is not strictly maxwellian but can be used to gain an estimate of the effective transverse ion temperature by adding the two transverse velocities in quadrature. This yields:

$$T_- = \frac{m_-}{2e} \left(v_-^2 + \langle v_\perp{}^2 \rangle \right)$$
$$= T_{-0} + T_\perp \qquad (21)$$

where $$T_\perp = eB^2\lambda^2/m_- \qquad (22)$$

and T_{-0} is given by Eq.17.

The final step is to derive a value for λ, the mean path length. When the ion is on its last movement towards the plasma boundary, λ represents the distance between the plasma boundary and the last elastic scattering collision with either a gas molecule or ion causing re-randomization of the directed ion motion induced by the applied electric and magnetic fields. The limit derived in section 2 for the comparison of ion-ion and ion-molecule collisions shows that the former is usually dominant so that:

$$\lambda = \tau_{ii} v_d$$
$$\simeq 7.10^{13} v_d \, T_+^{1/2} A_+ T_e / n_+ \lambda_{ii}$$

The positive ion and negative ion drift velocities near the plasma edge are probably near the ion sound speed although no theory exists at present. However we will assume this to be the case and assume that both velocities are equal, yielding a final expression:

$$\lambda = 1.1 \times 10^4 . T_+^{1/2} T_e^2 / \lambda_{ii} j_+ \, [m] \qquad (23)$$

Equation 23 is interesting in that it indicates that λ is only likely to vary slowly with increasing values of j_+ as high ion fluxes are also associated with higher temperatures. Substitution of likely values to be encountered in ion sources where the negative ions are made in the plasma volume (ie T_e = 1eV so that dissociative attachment collisions occur and $T_+ \sim 0.5$eV) and using a positive ion current density of 500A/m^2 yields $\lambda = 2.210^{-2}$m. If the field at the extraction aperture is 50 gauss (a typical value) we find that $T_\perp$ becomes 1.2eV and is hence at least comparable with the intrinsic ion temperature derived from Eq.17.

The fundamental nature of both λ and $T_\perp$ indicate that they cannot be modified in a plasma of given ion flux except by either reducing T_e significantly (and hence T_+) or by reducing the applied magnetic field. A large reduction former is difficult to envisage as it will also cause a decrease in the negative ion flux as the peak of the dissociative attachment rate for H^- formation is between 0.5 and 1eV. It is easy to reduce B to a low value but this will probably cause a dramatic increase in the electron flux which is extracted in parallel with the negative ions.

MEASUREMENTS OF EMITTANCE AND BEAM BRIGHTNESS

Positive Ion Sources

In the literature a vast array of beam emittance measurements have been reported on a large variety of positive ion sources. Some of these measurements have been reported in review articles such as those by Green[10]. However the measurements made on positive ion beams extracted from magnetic multipole or "bucket" sources are perhaps of greatest interest as these sources approach most closely the idealized conditions described in the model reported in section 2. The reason for this lies in the fact that the plasma within the discharge is confined in a magnetic field well and hence is stable against most micro instabilities and at the same time it is also possible to achieve high plasma densities (and hence high ion current densities) in continuous operation.

This type of ion source has been mainly used in the controlled nuclear fusion area for the heating of confined plasmas by neutral beam (H°) injection but it has also more recently found some application as the pre-injector at S.I.N. (Olivo et al[11]). Holmes and Inman[12] have measured the ion temperature in source similar to that used at S.I.N. as a function of ion current density in both hydrogen and helium by extracting a beam and measuring its emittance. The results of this experiment are shown in Fig.1 where it can be seen that in helium the ion temperature rises slowly and linearly with ion current density while a more rapid increase is observed in a hydrogen discharge. The result for a helium discharge is consistent with Eq.15 which takes the form:

$$T_+ = E_+ + 10j_+/T_e^{3/2}N_0(\sigma v)_{ce}$$

The intercept at zero current density indicates that E_+ is of the order of 0.18eV.

The hydrogen results are rendered more complex to analyse because of the Frank-Condon energy release when H^+ ions are formed. This can be extremely large but the probable vibrational energy stored in the H_2^+ ion reduces it considerably. The proton fraction increases in the discharge with rising current density hence causing the average value of E_+ over all three hydrogen ion species to increase. Similar ion temperature measurements have been made using other multipole sources and accelerators including that at S.I.N.

We can use Eq.15 in the absence of negative ions to derive the ultimate beam brightness at very high ion current densities which is given by:

$$B_{n\infty} = \frac{8}{\pi}\frac{(em_p)^{1/2}c^2}{2.8710^{-14}} \cdot N_0(\sigma v)_{ce}\ (T_eA_+)^{3/2}\ [\mathrm{A.m^{-2}ster^{-1}}] \tag{24}$$

The source brightness only depends on the gas density, electron temperature and the type of ion (which fixes A_+ and $(\sigma v)_{ce}$). However it is not usually practical to raise N_0 beyond $10^{21}m^{-3}$ in these sources as it can effect the ion production by causing massive loss of ions from the discharge by cross-field diffusion (Green et al[13]).

Equation 24 is a good description for a helium discharge but is inaccurate for a hydrogen as E_+ is not conserved. The empirical upper limit for hydrogen appears to lie in the range of 5.10^{12} $A.m^{-2}.ster^{-1}$.

Negative Ion Sources

In this paper we limit the discussion of beam brightness to those sources where the negative ions are made within the plasma itself. The only sources where these ions are made definitively within the plasma are of the magnetic multipole type and have been described in detail by Bacal et al[14], Holmes et al[15] and Leung and Ehlers[16]. However, before going on to a more detailed discussion of beam emittance, there is some evidence that negative ions formed in Penning discharges catalysed by cesium may also be created by processes in the plasma volume. Although these sources have been principally operated in a pulsed mode, Smith et al[9] have reported beam emittances of 0.012πcm mrad for a 67mA beam extracted with a duration of 500μ seconds through a circular aperture of 5.4 mm in diameter.

Returning to the multipole negative ion sources, all reported work has centered on H^- beams which have been extracted from such sources which have been equipped with a transverse dipole field within the plasma chamber to cool the electrons in the plasma adjacent to the extraction aperture. As seen in the proceeding sections, the emittance of negative ion sources will be different (and probably higher) than an equivalent positive ion source operating at equal plasma density and temperature because of the contribution made by the magnetic field.

Baartman et al[17] have measured the emittance of an H^- beam from a multipole source, originally developed by Leung[16], as a function of the beam current and the result is shown is Fig.2. A quasi-linear increase in emittance is observed rising to 0.012π cm mrad for 36% of the beam (virtually the r.m.s. value) when j_- is $10mA/cm^2$ and the aperture radius is 3.3mm. At the highest current density ($12mA/cm^2$) an abrupt rise is seen which is probably due to the onset of plasma boundary operations caused by insufficiently large accelerator potentials.

A similar result of 0.006π cm mrad has been made by York et al[18] with a short pulse version of the same source but using a smaller 1.5mm radius aperture and a current density of $38mA/cm^2$. Emittance measurements have been made by McAdams and Holmes[19] on a source developed at Culham (Holmes et al[15,3]) with a larger aperture of 8mm radius and a current density of up to $7mA/cm^2$. These results also show that the r.m.s. emittance rises slowly to 0.017π cm mrad with increasing current density as shown in Fig.3 and this agrees with the other results described above. The emittance does obey a scaling law which is approximately porportional to λ^2 (ie T_e^5/j_+^2) as seen in Fig.4 although the data scatter is large. This lends support to the model described in section 3.

The value of emittance measured in all versions of the multipole source yields apparent ion temperature and which is larger that the probable/measured electron temperature. This ion temperature has a maximum value of 5eV for the source tested by Baartman[17], 6eV for the results obtained by York[18] and 2.3eV for the measurements made by McAdams and Holmes[19]. Hence it is probably the magnetic field effect which dominates the results and in these sources, the local field at the aperture is in the vicinity of 40 to 70 gaussian order to reduce the extracted electron flux and maximise the H^- flux.

Lower emittance beams could be obtained by reducing the magnetic field but alternative methods of coping with the increased electron flux must be developed which do not rely on strong magnetic fields at the extraction aperture. Equation 23 indicates that the field must be less than 20 gauss before the two contributions of the effective ion temperature approach equality.

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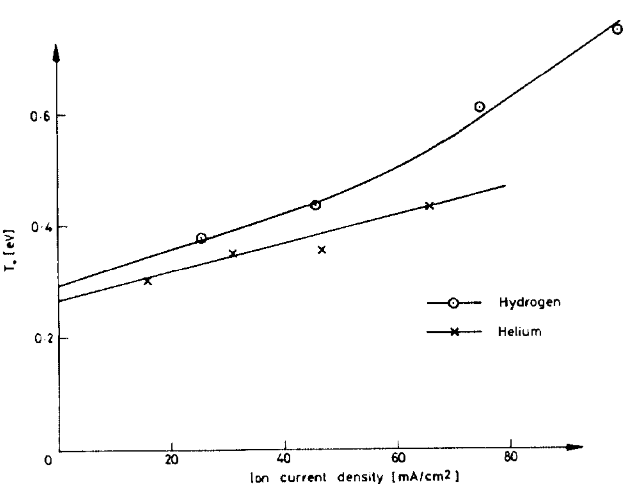

Fig.1 Variation of the ion temperature derived from the beam emittance with ion current density in an hydrogen and helium discharge.

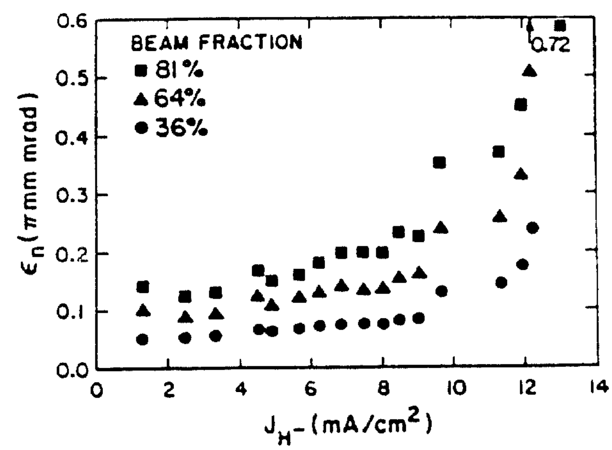

Fig.2 Beam emittance of an H^- beam measured by Baartman et al with H^- ion current density

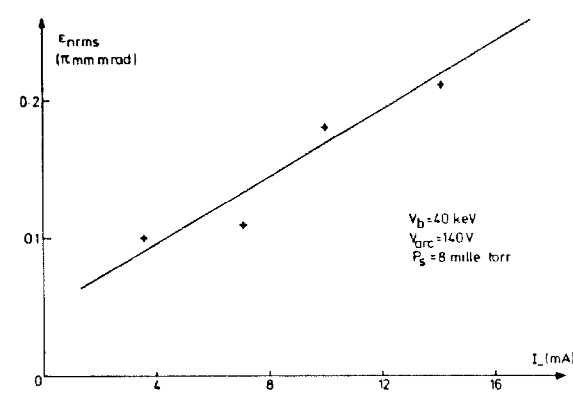

Fig.3 Beam emittance of an H^- beam measured by McAdams and Holmes as a function of the H^- beam current ($j_-=I/2mA/cm^2$).

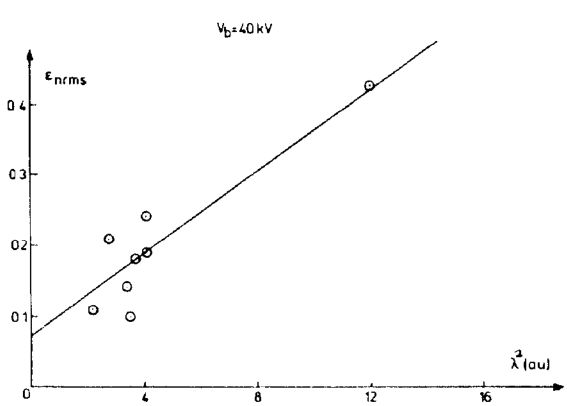

Fig.4 Beam emittance of an H^- beam measured by McAdams and Holmes as a function of the parameter λ^2.