EXPECTATIONS AND POSSIBLE INTERPRETATION OF ION SOURCE BEHAVIOR

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In the last few years there has been considerable progress in the development of ion sources and high gradient accelerator columns to yield high proton currents of good quality or low emittance. Most of the ion source work, but not all, has been concentrated on the duoplasmatron,[1] in many cases with an expansion cup. One recalls the work at Leningrad,[2] which stimulated new interest, the high current work at ORNL[3] in progress for several years, the significant improvement in beam brightness for high currents at CERN,[4] BNL,[5] and ANL.[6] At this conference further progress on beams of high brightness is reported from Saclay,[7] BNL,[8] CERN,[9] and MURA.[10]

It is now evident from the fine operational experience at CERN[9] and from measurements on accelerated beams at the other laboratories that high gradient columns are going to work, without serious deterioration in beam quality whenever the ion source is properly matched to the column.

If one defines a normalized emittance as

$$\mathcal{E}_n = \left(\frac{\text{phase space area}}{\pi}\right)\beta\gamma \qquad (1)$$

and calls δ the current density in the two-dimensional normalized phase space area, then

$$\pi\delta = \frac{I}{\mathcal{E}_n} \ . \qquad (2)$$

Typical values of $\pi\delta$ for operating preinjectors in the past have been 0.1-0.2 amperes per mrad-cm. Recently the value has been increased at CERN to approximately 1 A/mrad-cm for accelerated beams of several hundred mA. Meanwhile bench tests of ion sources at several other laboratories including Saclay and MURA in the current range below 200 mA and BNL up to 700 mA have yielded current densities of $\pi\delta \simeq 1.5$-10 A/cm-mrad. Furthermore the recent column tests show rather good preservation of this beam quality.[7-11]

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With the recent progress in ion source performance, it is natural to ask whether one is approaching an ultimate emittance or phase space density for some given beam current. A related question is, what change in emittance should one expect from a well-behaved source when its beam current is increased. One knows that the emission surface of the plasma must have a proper shape to avoid aberrations in the emittance pattern. The temperature of the plasma at this surface and the dimensions of the surface then determine the normalized emittance which takes the form of

$$\mathcal{E}_n = \left(\frac{\text{area}}{\pi}\right)\beta\gamma = \frac{a\,v_\perp}{c} \qquad (3)$$

where a is the half aperture of the plasma surface, $v_\perp$ is the transverse component of ion velocity and c is the velocity of light. The temperature, and hence $v_\perp$, is seldom known because the difficult measurements are usually not attempted. As a consequence there is divided opinion on what the temperature really is for a particular case. One might expect the acceleration of ions to velocities comparable with the electron temperature by an electric field within the plasma near the plasma sheath[12] to contribute to the ion temperature only as collisions are experienced in this region. When there is plasma expansion beyond the source anode aperture, the temperature at the surface is reduced from that at the anode aperture. This reduction is simply calculated if one can neglect collisions of the accelerated ions near the surface and significant heating due to arc current or ion recombination within the expansion region.

Despite the lack of knowledge of plasma temperatures, it may be interesting to assume a value and compare calculated emittances with certain measured values for undistorted beams. Suppose one assumes a temperature of kT = 1 eV at the plasma surface for a Maxwellian velocity distribution and a cutoff velocity corresponding to 2 kT. This gives a value of $v_\perp/c = 0.066$ mrad. For a plasma surface radius of a = 0.075 cm, one gets $\mathcal{E}_n = 0.0050$ mrad-cm. Wroe[13] has measured at BNL for a 0.075 cm radius plasma cup and a beam current of 60 mA an emittance of $\mathcal{E}_n = 0.006$ cm-mrad. For a radius of a = 0.6 cm, one obtains, for the same temperature, $\mathcal{E}_n = 0.040$ cm-mrad. At MURA[10,14] for a source with this radius and beam currents of 100 to 200 mA, values of $\mathcal{E}_n$ falling between 0.02 and 0.05 cm-mrad have been obtained for most of the measurements. Other measurements have given values near zero, indicating the need for a more precise technique of emittance measurements. Work at Saclay[7,15] with source expansion cups having radii of a = 0.35 cm and 0.5 cm gives emittances of $\mathcal{E}_n = 0.013 - 0.067$ cm-mrad for currents ranging from 23 mA to 100 mA. These values would indicate an effective ion temperature on the basis used here of kT near 1/3 eV at the lowest current (and smaller cup) but about 4 eV for the maximum current (and larger cup).

One might in general expect plasma temperature to increase with increasing beam current and thereby give an increase in emittance unless other factors are dominant in determining emittance. The actual variation of temperature moreover will depend on variation in such quantities as source magnet current, arc current and gas pressure. A prediction of change in emittance with beam current would thus appear difficult unless one understands well the operation of his source and varies the source parameters in a controlled, systematic fashion. Van Steenbergen[16] in a review paper two years ago on ion source and column performance discussed various factors affecting the emittance of a beam. He showed that, for some operating systems at least, the beam emittance is proportional to the beam current, and, hence that the brightness, $\mathcal{B} = \frac{1}{\frac{\pi^2}{2}\mathcal{E}_n^2}$, varies inversely as the current.

There are exceptions to this proportional behavior of emittance. For example, the Leningrad group[2] has obtained beams with emittance varying as $I^{1/2}$ and brightness constant up to approximately 300 mA, beyond which current the emittance increase is faster. Other results giving a slow variation of $\mathcal{E}_n$ with I at MURA and BNL will be discussed later.

Following a suggestion[17] that a laser initiated plasma might offer a beam of high brightness, the question of ultimate brightness arose. A laser beam can be focused to a very small diameter. The resulting high density plasma from evaporation of the solid or liquid target will quickly expand so that the effective size for ion emission will be much larger than the focal spot size of the laser beam. Suppose we look qualitatively at an idealized situation in which a spherical plasma ball expands uniformly with particles supplied at a constant rate of N per second from a source at the center. Such a spherical plasma with a continuous source would be difficult to achieve in practice. Nevertheless, under such equilibrium conditions, one would expect the density of the expanding plasma to decrease with radius so that beyond some radius R_o there would be little Coulomb scattering between individual ions.

With reference to Fig. 1 we may estimate an emittance for a flow of ions through an aperture a distance d from the ball to be

$$\mathcal{E}_n \simeq (d \tan\theta)\frac{p_\perp}{p}\beta\gamma = R_o \sin\theta\,\beta\gamma. \quad (4)$$

The current through the aperture will be $I = \frac{Ne}{2}(1 - \cos\theta)$, so the brightness is given approximately by

$$\mathcal{B} = \frac{I}{\frac{\pi^2}{2}\mathcal{E}_n^2} \simeq \frac{Ne}{\pi^2 R_o^2 (1 + \cos\theta)(\beta\gamma)^2}$$

$$\approx \frac{Ne}{2\pi^2 R_o^2 (\beta\gamma)^2} \quad (5)$$

where θ is assumed small.

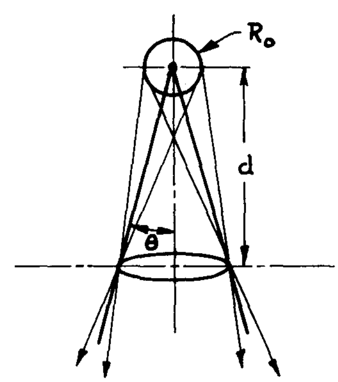

Fig. 1

Since the radius of no collisions is rather indefinite, we need some definition. Suppose we call σ the effective cross section for scattering through some angle, such as 90°, where multiple Coulomb scattering is involved. We can then require that R_o be that radius beyond which not more than a fraction F (10 per cent for example) of the ions scatter. One then has

$$F = \frac{1}{N} \int_{R_o}^{R} n \sigma n v_t \, 4 \pi r^2 \, dr \qquad (6)$$

for the fraction scattered between radial distances R_o and R. The density of ions is n and their relative velocity is v_t. With increasing radius the energy goes predominantly into energy of radial expansion with the temperature decreasing. If v is this radial velocity, then approximately $n = N/4 \pi r^2 v$. Substitution into (6) and solving for R_o gives, for R becoming very large,

$$R_o = \frac{N \sigma}{4 \pi v F} \frac{v_t}{v} \, . \qquad (7)$$

Substitution for R_o from (7) into (5) yields an expression for brightness as

$$\mathcal{B} = \frac{16 e c^2 F^2}{N \sigma^2 \gamma^2} \left(\frac{v}{v_t}\right)^2 . \qquad (8)$$

Before saying what may be wrong with this, one notes that those quantities dependent on the initial plasma temperature near the source are v, v_t, and σ ($\gamma = 1$ can be assumed). By setting F equal to some number and keeping temperature constant, one sees that the average brightness is inversely proportional to N and thus to the ion current. This situation prevails only if the radius R_o is larger than the source size. On the other hand, with N held constant as temperature is increased (and v/v_t remaining approximately constant), the brightness increases strongly because of decrease of σ with increasing energy approximately as $1/E^2$.

The above argument has neglected any recombination of ions during expansion and cooling of the plasma. Dawson[18] has discussed the effect of recombination and radiation on the temperature of an expanding plasma ball as well as production[19] of the plasma by a short laser pulse. To the extent that recombination takes place not only are ions reduced to neutrals but the temperature of the plasma is affected. Three-body recombination returns the ionization energy to the plasma and tends to keep the temperature up at larger radii, increasing the emittance. Taking this into account would modify the brightness expression (8). Because of the strong temperature dependence,[20] $(kT)^{-9/2}$, of the recombination rate, one would expect, however, a similar qualitative improvement of brightness with increasing initial temperature as in the case of Coulomb scattering. Because the recombination coefficient is proportional to the electron density,[20] one obtains a less strong dependence on N for R_o and $\mathcal{B}$.

From the foregoing discussion about existing and potential sources, one may not be surprised that change of emittance, or brightness, with beam current can have a varied behavior even if the ultimate emittance of the source is achieved. Detailed and systematic measurements on sources with variation of parameters should prove rewarding in terms of understanding these emittance variations and any limitation to ultimate emittance.

As an example of this approach we may cite two constant perveance experiments which have been performed, one at BNL by Wroe[13] and one at MURA by Fasolo.[10] In these measurements an effort was made to hold the plasma surface and particle trajectories constant as beam current was increased.

Measurements were made on an essentially distortion-free beam for maximum currents exceeding 100 mA. The emittance in both cases was approximately constant with increasing extraction voltage while the beam current changed by a factor of approximately 2.5. The diameter of the plasma expansion cup for the BNL source was 0.4 cm and approximately 1.2 cm for the MURA source. Since the MURA data are known better to the author, the procedure and results for that measurement are outlined in the following.

Operating Conditions:

Source pressure held constant.

Arc current approximately constant.

Source magnet field increased as extraction voltage increased so that particle trajectories and perveance were held constant.

$$I_b = k V^{3/2}$$

Experimental Results:

Measured emittance $\mathcal{E}$ constant with increasing voltage and beam current. Therefore,

$$\mathcal{E}_n = \frac{\mathcal{E}}{\pi}\beta\gamma \sim V^{1/2}$$

Magnet current varied linearly with and was nearly proportional to extraction voltage.

$$I_{mag} \sim B \sim V .$$

Deductions:

1. $\mathcal{E}_n \sim I_b^{1/3}$; $\mathcal{B} \sim I_b^{1/3}$
2. $\mathcal{E} = \pi\, ab \sim \frac{v_\perp}{v} \sim \frac{(kT)^{1/2}}{V^{1/2}}$ = constant

   $\therefore\ T \sim V \sim B$

   where T is plasma ion temperature.
3. $I_b \sim V^{3/2} \sim B^{3/2}$.

   Also $I_b = \pi a^2 n e v_z \sim n \sqrt{T} \sim n \sqrt{B}$ where n is ion plasma density.

   $\therefore\ n \sim B$.
4. From (2) and (3),

   $$n\,(kT) \sim B^2 .$$

In item 4 a relation between plasma density and temperature is reached which appears consistent if we believe an approximate balance between plasma pressure and magnetic field pressure should exist within the source. A direct measure of n or T was not made to check on their variation with B. The example is given, however, to point out the possible usefulness of well controlled experiments of this type in helping to understand source performance.

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