AN EXTENDED RF ION SOURCE WITH SMALL PHASE SPACE EMITTANCE AREA

Rolland Perry
Argonne National Laboratory

Several types of ion sources have been designed for use on particle accelerators, and considerable effort has been devoted to attaining large beam currents. Somewhat less work has been done in the direction of reducing the beam divergence or of minimizing the effects of space charge. Since the latter effects are greatest in the region of low beam velocity, and since the emittance properties are established at the source, the present work is aimed at making some improvements in these two respects, without sacrificing intensity.

Historically, the first concepts were stimulated by a discussion of an electron gun for an electron microscope by A. V. Crewe, and the results are applicable to electrons as well as ions, except in different methods of production. Moreover, while the present design is based on the use of an rf excitation of a plasma, one might possibly adapt other methods of plasma production and extraction to achieve similar results.

The general arrangement of the source is simply that of a hollow donut-shaped cavity excited by an rf power source as shown in Fig. 1. Ions are extracted from the cavity by means of a dc field applied across a diameter between A and C, and the ions must traverse a narrow channel or slit arrangement which restricts their divergence angle. Since the slit extends all the way around the circular length of the donut, the area of extraction may be large even though the width w is made small, thus permitting almost arbitrarily large beam extraction.

The beam exit direction may be oriented at any arbitrary angle , which may be chosen to be compatible with some focusing and accelerating system.

First we look at the case of $\varphi = \pi/2$ in which case the central rays from all points around the circumference of the circular slit are emitted parallel to the axis of symmetry. The noncentral rays will have maximum divergence angle

$$\Delta\varphi = \frac{w}{\ell}$$

where ℓ is the length of the extraction channel. The area in phase space is

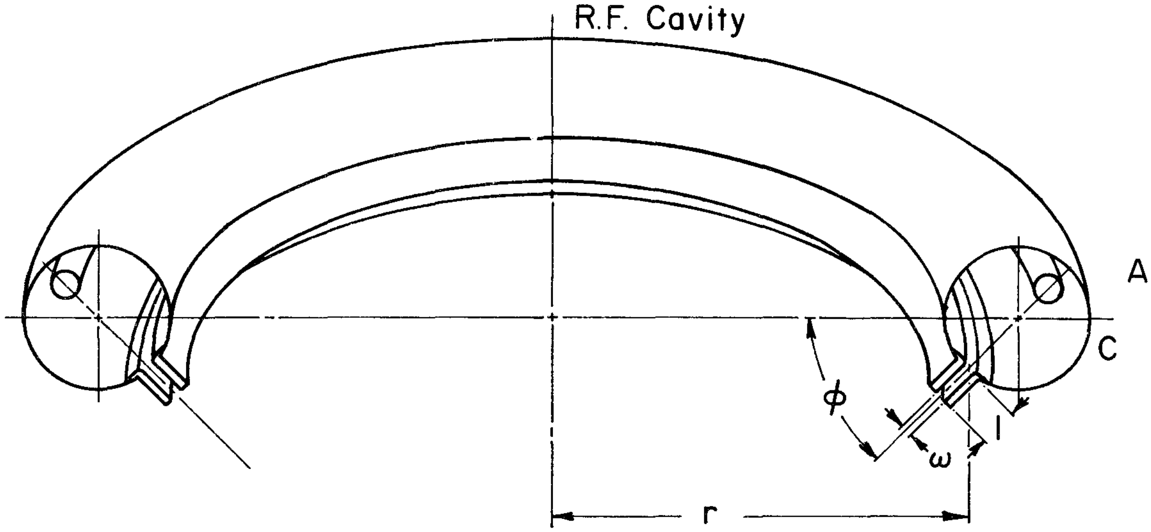

FIG. 1

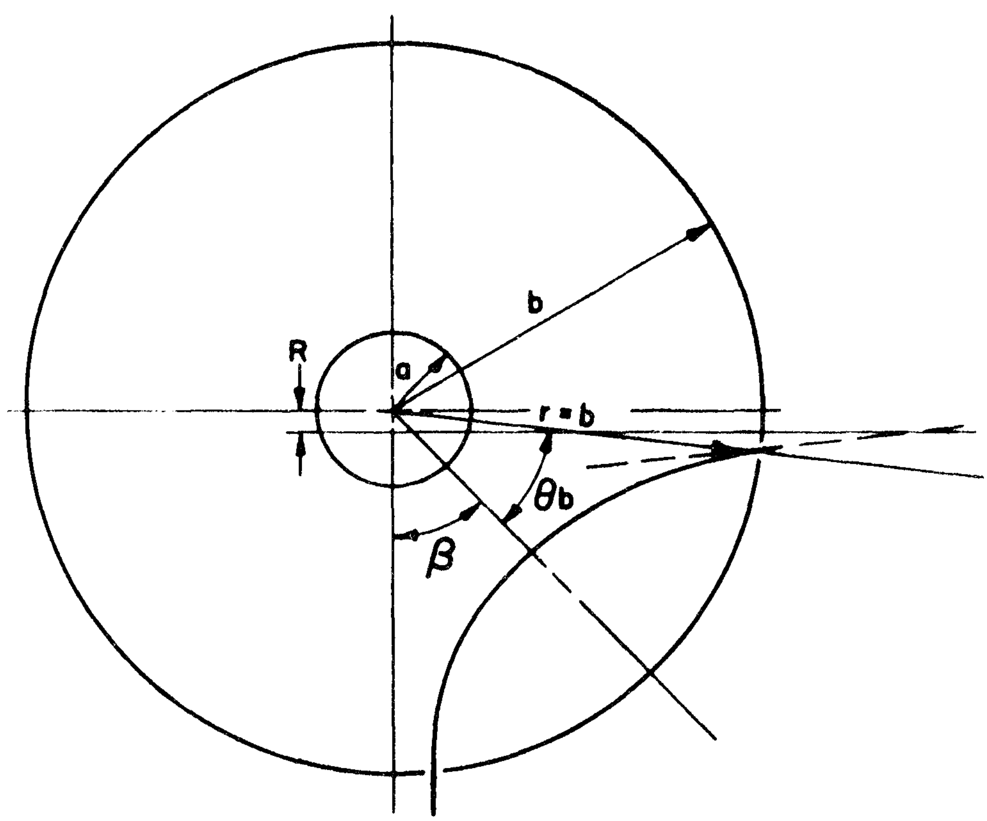

FIG. 2

$$A_x' \equiv r \alpha \pi = r \Delta\varphi \pi \quad .$$

Let w = 0.010'', ℓ = 1'', r = 7.5 cm. Then

$$A_x = r \Delta\varphi \pi = 7.5 \times 0.01 \pi = 75 \pi \text{ cm mrad}$$

at an extraction voltage of 20 or 30 kV which is typical for an rf source. This becomes about 12.5 π cm mrad at 750 keV or 15 π cm mrad at 500 keV. The extraction area for this condition is

$$\begin{aligned} S &= 2 \pi r w \\ &= 2 \pi \times 7.5 \times 0.025 \\ &= 1.18 \text{ cm}^2 . \end{aligned}$$

Compare these numbers with the corresponding values for rf sources of the CERN type, where

$$A_x \simeq 20 \pi \text{ cm mrad at } 500 \text{ keV}$$

$$S \simeq \pi (0.2)^2 = 0.125 \text{ cm}^2 .$$

Now the geometry of accelerating tubes may not be compatible with a beam diameter as large as 15 cm, so the diameter may be chosen to satisfy this limitation. Likewise one may wish to inject into the accelerating tube at some arbitrary focusing angle. This may be done either by choosing the angle to meet the requirements, or, if this is not otherwise compatible, by injecting into a spherical condenser cavity and deflecting it by means of the electrostatic field in the cavity to form a hollow beam of arbitrary diameter and convergence angle.

The requirements for accomplishing this are as follows: The central ray from the slit must enter the spherical cavity at $r = b$ tangent to a hyperbolic path shown in Fig. 2 and described by the relation

$$\frac{1}{r} = \frac{\sqrt{\left(V_a \frac{ab}{b-a}\right)^2 + 4 R^2 \quad V_e + \left(V_a \frac{a}{b-a}\right)^2} \cos \theta - V_a \frac{ab}{b-a}}{2 R^2 \left[V_e + V_a \frac{a}{b-a} \right]}$$

This is a solution of the equations of motion for a particle of mass m and charge e moving in a central force field:

$$m\left[\ddot{r} - r\,\dot{\theta}^2\right] = \frac{Q\,e}{r^2}$$

$$m\left[2\,\dot{r}\,\dot{\theta} + r\,\ddot{\theta}\right] = 0 \quad .$$

The quantities in the trajectory equation are as follows:

a = radius of inner sphere

b = radius of condenser cavity

R = distance from center of sphere to asymptotic line toward which the hyperbola tends at infinity

V_a = potential on inner sphere

V_e = extraction voltage which corresponds to the kinetic energy the particle must have as it enters the chamber, i.e.,

$$e\,V_e = \frac{1}{2}\,m\,U_i^2 + \int_{\infty}^{b} \frac{Q\,e}{r^2}\,dr = e\,V_i - e\,V_b; \qquad V_b \equiv V_a\,\frac{a}{b-a} \quad .$$

The asymptotes are defined by

$$\tan\beta = \frac{2\,R\left[V_e + V_a\,\frac{a}{b-a}\right]}{V_a\,\frac{ab}{b-a}} \quad .$$

There are two benefits to be expected from using a hollow cylindrical or conical beam, viz

1. Since space-charge effects are more nearly the same for all particles due to the $\frac{1}{r}$ dependence, the distortion of the phase space figure due to space charge will be minimized, and

2. Since all particles traversing an axially symmetric lens will see essentially the same field configuration, lens aberrations should be minimized, thus reducing growth of phase space area from this cause.

A number of problems need to be examined in connection with the rf source as described. Figure 3 shows a conceptual design for such a source together with a spherical condenser lens system. The rf cavity would be driven in the TM_{010} mode from a wave guide coupling through an iris into the cavity. For a cavity diameter of about 4 cm the frequency would be about 5000-6000 Mc/sec. Peak power requirements would be a few hundred watts.

CURTIS: With respect to your concern about violating Liouville's theorem, should I understand from your numbers that density in the region of phase space occupied by the particles has increased in the deflected beam over what it was in the converging ring of beam?

PERRY: One is concentrating the beam into a smaller diameter in the deflected beam. One might expect from Liouville's theorem that the divergence angle would actually go up in the process. The divergence angle does go up but it apparently does not increase in proportion to the reduction of beam radius according to my simple calculations which I am pretty sure are questionable.

LAPOSTOLLE: That worries me, and I also have some doubts about your estimated emittance. It is clear that, having a narrow slit, you can reduce very much the angle of divergence in the direction perpendicular to the slit. But in the direction parallel to the slit the emittance can be very large. The two directions cannot be considered independently in your bending system and I think that this could explain the apparent disagreement with Liouville's theorem.

PERRY: The extraction field has no component in the parallel direction, so the component of velocity in this direction is only the thermal component, which would be small in comparison.

LAPOSTOLLE: But there is no focusing in this direction from your deflecting system.

CURTIS: There would actually be divergence in this direction from the deflecting system.

PERRY: Yes, this is true. I cannot vouch for anything at present in terms of actual magnitude of emittance.

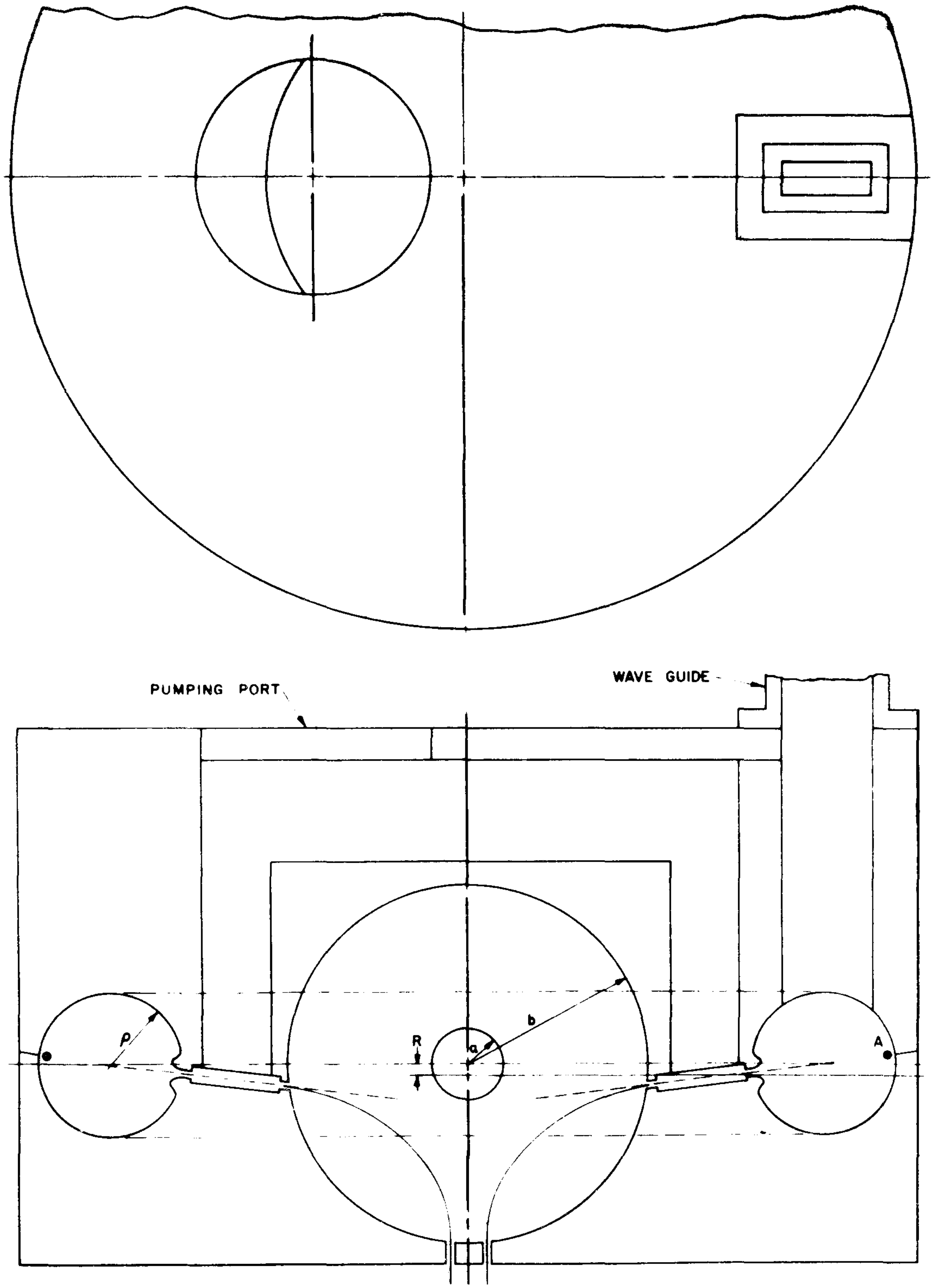

FIG. 3 EXTENDED RF ION SOURCE