PROGRESS IN HIGH INTENSITY ION SOURCE AND ACCELERATOR COLUMN DEVELOPMENT

A. van Steenbergen
Brookhaven National Laboratory

Recent work on ion sources has shown a gradual increase of proton beam intensities obtainable from preinjector systems. In general, together with an increase in beam intensity an increase of the beam emittance was observed. Up to the space-charge limit in the BNL AGS, this will become most likely the determining factor in AGS beam intensity. This will be especially so when multiple turn injection will be used at the AGS, which is scheduled to be completed during the next month.

Further, preinjector intensities for the proposed BNL 500 MeV linac injector will be of the order of 500 mA in order to obtain linac beam intensities of at least 100 mA.

Only recently have ion sources been developed capable of total beam outputs of this order of magnitude and being suitable at the same time for use in conjunction with particle accelerators because of emittance characteristics. For completeness sake a short enumeration of these sources follows:

1) PIG Ion Source. Here a plasma is obtained by means of a gas discharge in a simple two electrode structure. Secondary electron emission to sustain the discharge is obtained by means of ion impact on the cold cathodes. Electron oscillation between the two cathodes is maintained for high ionization efficiency by means of the anode-cathode electrical field and an axial magnetic field.

2) Rf Ion Source. An electrodeless ("magnetically" excited) discharge, by means of a radio-frequency field is obtained in a ceramic or pyrex source "pot." An extra electrode in the plasma chamber is used to establish a field in a ceramic channel for ion extraction from the plasma boundary located within the source pot.

3) Duoplasmatron Source. A hot cathode (emission layer coated cathode or a tungsten cathode) is used for the production of electrons for gas ionization in a three-electrode structure. With a conical geometry of the extra electrode between cathode and anode some plasma compression is obtained. Further compaction, between the extra electrode and the anode is accomplished by means of magnetic mirror fields around the

interspace of these electrodes. For higher output currents, a specially shaped aperture button makes it possible to obtain ion emission from a larger area than the source aperture opening (small plasma cup).

4) Lamb-Lofgren Source.* This source is a version of the "magnetic" ion source, i.e., a hot cathode discharge type source with plasma concentration by means of an axial magnetic field. Here, instead of a single aperture hole, a multiple of apertures is used to let the plasma expand in a large cylindrical plasma expansion cup. With the extraction field a concave plasma sheath is formed within the relatively large plasma expansion cup.

5) "Modified" Duoplasmatron Ion Source (Solnyshkov, et al). A large plasma expansion cup is attached to the basic duoplasmatron source and ion extraction takes place from a shaped plasma boundary sheath.

6) "Modified" PIG Source (Gabovich, et al). This is the basic PIG source with hot cathode and large plasma expansion cup.

In order to establish some criteria by which to compare these various ion sources, it is useful to define source brightness and related beam emittance again. The momentum normalized beam emittance, as related to the two-dimensional phase space projection is given by,

$$v = \beta\gamma \frac{\iint F(x, \alpha_x)\, dx\, d\alpha_x}{\pi} = \beta\gamma\, E$$

where v is the emittance invariant and $F(x, \alpha_x)$ represents the two-dimensional transverse phase space boundary for a proton beam, determined at a particular energy.

The source "brightness" may now be defined as:

$$B = \frac{I}{\pi^2 v^2},$$

*Ion extraction from a large plasma boundary and plasma boundary shaping ("plasma boundary focusing") by means of grids or extraction fields, as applied in the "modified" duoplasmatron source and "modified" PIG source were first incorporated in this particular ion source design.

which specifies the particles per unit time density in four-dimensional phase space, assuming a simplified E, t distribution.[1,2] This definition is identical to the statement that the source brightness is the particle flux (current density) per unit solid angle.

Referring now to the conventional duoplasmatron source, the rf source and the PIG source, these sources showed generally the behavior that the emittance increased linearly with the output beam current. This was observed at BNL for the PIG source and conventional duoplasmatron source and similarly at CERN for the rf source. This behavior is expressed as:

$$v = \frac{I}{\pi \delta}$$

and consequently,

$$B = \frac{\delta^2}{I} ,$$

with δ a constant.*

It was rather disturbing to observe that the four-dimensional phase space density decreased with extraction of higher beam intensities from the ion source. Regarding this, it is useful to consider the optimum expected ion source emittance versus output beam intensity.

The minimum emittance is determined by the transverse velocity components existing at the plasma boundary from which beam extraction takes place. The magnitude of the transverse components is determined by the plasma temperature.

Taking the simplest case of a plane plasma boundary and homogeneous particle density filling of the plasma of N ions per unit volume, then for ion extraction from an area a^2 one finds for the emittance

$$v = \frac{2}{\pi} \beta \gamma \, a \, p_x / p_z = \frac{2 \beta \gamma \, a \, m_o \, \bar{\bar{\nu}}_x}{\pi \beta \gamma \, m_o \, c} = \frac{2 \, a \, \bar{\bar{\nu}}_x}{\pi c} .$$

Using a simple cut-off of the Maxwell-Boltzmann momentum distribution and assuming plasma equilibrium, i.e., $T_i \cong T_e$, one finds[3]

---

*The brightness as defined here refers to four-dimensional phase space only, the time structure of the beam may change the δ and B values.

$$\bar{\nu}_x \leq \left(\frac{k\, T_i}{m_o} \right)^{1/2} .$$

Here $\bar{\nu}_x$ is the x component of the mean velocity of the ions near the plasma boundary.

Further, the total beam extracted from the plasma boundary for a space-charge limited beam may be obtained from the diffusion equation:

$$I = a^2 \, Ne \, \bar{\nu}_z$$

or similarly

$$a = I^{1/2} \left[N^{1/2} \, e^{1/2} \left(\frac{k\, T_i}{m_o} \right)^{1/4} \right]^{-1} .$$

Actually, because of limitations in beam extraction due to space-charge effects, a more practical expression for a would be given by Langmuir's equation:

$$a = I^{1/2} \left[\frac{4\,\epsilon_o}{9} \; \frac{2\,e}{m_o} \; \frac{V_{extr.}^{\;3/2}}{g^2} \right]^{-1/2} .$$

Comparison of the two expressions indicates that a practical upper limit exists for N. For higher values of N and a given extraction field and geometry the plasma boundary takes on such a shape that unacceptable optical conditions result. Therefore, for any practical system, the maximum value of N may not be determined by the ion source capabilities only, but, especially with recent ion source developments, by limitations in ($V_{extr.}^{\;3/2}/g^2$).

For the present argument the first expression for a will be used. Substitution of a and $\bar{\nu}_x$ yields:

$$v = \left(\frac{1}{\pi \, B_o^{\;1/2}} \right) I^{1/2}$$

with B_o a constant,

$$\left[\text{or } v = \frac{2\,a}{\pi} \left(\frac{k\, T_i}{m_o c^2} \right)^{1/2} \right]$$

and by definition $B = \frac{I}{\pi^2 v^2}$, therefore

$$B = B_o = \frac{N e c}{4 \left(\frac{k T_i}{m_o c^2} \right)^{1/2}} .$$

Contrary to experimentally observed behavior, theoretically the source brightness would be independent of output current, as it should be.

The foregoing approach may be enforced by substituting some practical values for T and N in the expression for B_o. An expanded plasma from a pulsed high-intensity PIG source with hot cathode was studied by Gabovich et al.[4] Here, a plasma expansion system, similar to that used by A. I. Solnyshkov[5] for the duoplasmatron ion source, was used. Typical values for N and T in the expanded plasma are $10^{12}/cm^3$ and 10^5 °K, respectively. This substituted yiel ds for B_o:

$$B_o = 1.2 \times 10^{10} \frac{ma}{cm^2\text{-}rad^2} .$$

This value is indicat ed in Fig. 1. Also given here are values for B and v derived from Solnyshkov's results obtained with a modified duoplasmatron source. Through these points lines have been drawn in the log-log emittance current plot of "suggested" output current dependence of the modified duoplasmatron source. At the present time this is only supported by the assumption that with extraction from a relatively large plasma boundary area the theoretical expected current dependence of v and B may be approached.

The B_o value as calculated is of the same order of magnitude as the approximate B value obtained from Solnyshkov's experimental results.

The experimental observed behavior of v and B as a function of I for the conventional duoplasmatron source, rf source and PIG source is also given in this figure. Further the range of some recent results for v and B with the modified duoplasmatron source as obtained by B. Vosicki at CERN and L. Oleksiuk at BNL are also indicated. These results will be discussed in detail by L. Oleksiuk.

The foregoing approach suggests immediately that it is desirable to keep the plasma temperature low in order to obtain high B_o values and low v values. It also explains the reason for the encouraging results obtained with the sources with large plasma expansion.

$$V = \beta\gamma \frac{\text{Area } F(x, \alpha_x)}{\pi} = \beta\gamma E\,; \quad B = \frac{B(p_z^{\,2})}{\beta^2\gamma^2}\,; \text{ for } \delta \text{ definition, see text.}$$

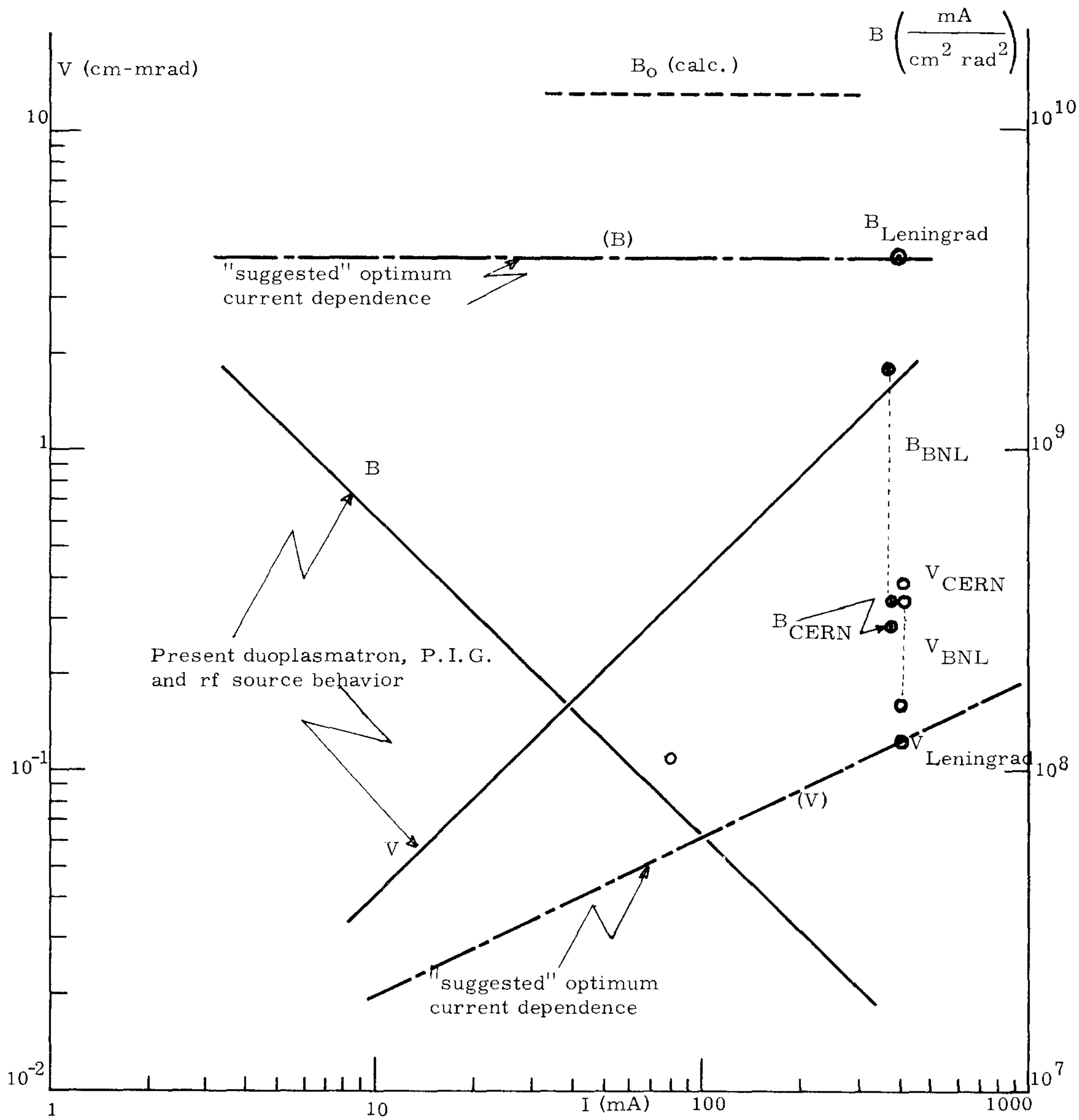

Fig. 1. ION SOURCE CHARACTERISTICS

It is evident that the ion sources using plasma expansion and plasma boundary focusing may substantially improve present ion source (PIG, rf and duoplasmatron) brightness figures. With these sources, beam intensities of the order of 500 mA are readily obtained. It is in a sense secondary how the expanded plasma is established, as long as the appropriate plasma temperature and density may be obtained. Therefore, in a first approach several of the above mentioned ion sources will be suitable. Some pertinent parameters of these sources have been collected from the literature and from BNL experience. These are given in Table I. The figures given are meant for comparison only and all values given should be considered to be approximate only. There should be no clear cut choice between the modified PIG souce, the Lamb-Lofgren "magnetic" source and the modified duoplasmatron source. However, with the duoplasmatron a high density primary plasma is obtained in a rather efficient way. This source is therefore more suitable to produce an expanded plasma without actually enlarging the ion source aperture to any appreciable extent, which should be avoided to the extent possible because of neutral gas flow into the acceleration column.

Some thought has been given to the most desirable shape of the plasma boundary in the modified duoplasmatron source. This is illustrated in an oversimplified way in Fig. 2. The possibility of positive aberration and also space-charge blow-up with a consequent equivalent negative aberration in the proton beam should be avoided to reduce effective phase space dilution. Presently, the first case illustrated, i.e., that of an essentially flat boundary is being considered as a desirable configuration together with a high gradient column approach as will be further detailed below.

In Fig. 2 is also indicated the possible reason for the experimentally observed emittance-current behavior in the conventional duoplasmatron source ($v = C_1 I$ instead of $v = C_2 I^{1/2}$ as expected). As illustrated the measured emittance would be

$$v \cong \beta\gamma a \alpha .$$

From elementary electron optics $\alpha = C_3 I^{1/2}$, further, Langmuir's equation gives $a = C_4 I^{1/2}$, consequently $v = I/\pi\delta$.

Even though the source brightness values obtained with the Solnyshkov source are promising one might say that developments are not so far advanced yet that one could speak of an operational source at present. Some problems are mentioned:

TABLE I

Evaluation of High Intensity Ion Sources		P.I.G. Source	RF Source	Duo-plasma-tron Source	With large plasma expansion and plasma boundary focusing: Lamb-Lofgren "Magnetic" Source	P.I.G Source With Hot Cathode	Modified Duoplasmatron Source
Reported maximum	units						
Ion currents: after single electrode acceleration	mA	150	350	1000	1000	1000	800
after C-W acceleration	mA	90	250	150	-	-	400
Ion source brightness: B* (for definition see text)	$\frac{A}{(m.\ rad)^2}$	5.10^8	5.10^8	5.10^8	$\geq 5.10^7$	-	5.10^{10}
Expectation of approaching $B = B_o$ instead of $B = \delta^2/I$		neg.	neg.	neg.	pos.	pos.	pos.
Physical characteristics: beam energy spread	eV	< 10	10	< 1	-	-	-
typical maximum proton percent	%	50-80	60-90	60-90	95	-	-
Characteristics related to complexity of auxiliary equipment: gas consumption	Ncm^3/h	10-100	10-100	50	2000	1000	100-200
power input / duty factor**	kW	0.5-5	1-10	0.5-2	5-10	5	1-5
power for solenoids etc.	kW	1	0.5	0.5	10	1	0.5
cathode heating	kW	-	-	0.1-0.5	1	0.1-0.5	0.1-0.5
discharge current	A	1-5	-	10-40	100	40	20-100

*Because of the measured current dependence (or possible current dependence), the value given refers to the cited current after C-W acceleration.

**Related to source discharge current only.

a. With the large plasma boundary extraction use is made of plasma boundary focusing, i. e., the beam optics will depend on the boundary shape. This in turn depends sensitively on extraction field, its distribution and plasma density. Slight variations in source parameters are expected to affect beam optics substantially. In this connection also the nonuniform plasma density is a problem resulting in complex emittance patterns. For plasma boundary shaping a shaped grid might be used. This is shown in Fig. 3 together with a version of the modified duoplasmatron source. If a grid is used on the extraction electrode scattering of protons due to the fine structure of the local fields might prove to be causing effective dilution of phase space. This is presently being studied at BNL.

b. Plasma oscillations and boundary instabilities. With the conventional duoplasmatron source, beam intensity modulations with frequencies up to 30 Mc/s and even higher have been observed with the wide band frequency system of the AGS. At times, beam intensity modulations of nearly 75% have been observed, while under optimum conditions this was still of the order of 5% to 10%.

c. Further measurements are needed on proton percentage from an expanded, lower temperature, plasma with the Solnyshkov source.

With conventional Cockcroft-Walton acceleration columns the voltage gradients are such that a relatively large diameter column aperture is needed in order to be able to transfer of the order of 400 mA total beam. Also, with a larger diameter beam, problems connected with aberrations would be more serious.

An alternative is to try to improve the accelerator column gradient. Further, with the possibility of extracting beams from large plasma boundary diameters and actually also the desirability of doing so in connection with beam emittance and source brightness, it becomes attractive to consider again the "Pierce" approach of beam formation. In the small beam diameter case, an unpractical high voltage gradient is required to support the "rectilinear: beams; this because of the higher current densities involved, i. e., $\cong 1\ A/cm^2$. With current densities of the order of $0.1\ A/cm^2$ the required fields approach practical values again. Various text books on electron optics detail the "Pierce" approach. Here only the resulting formulas will be given.

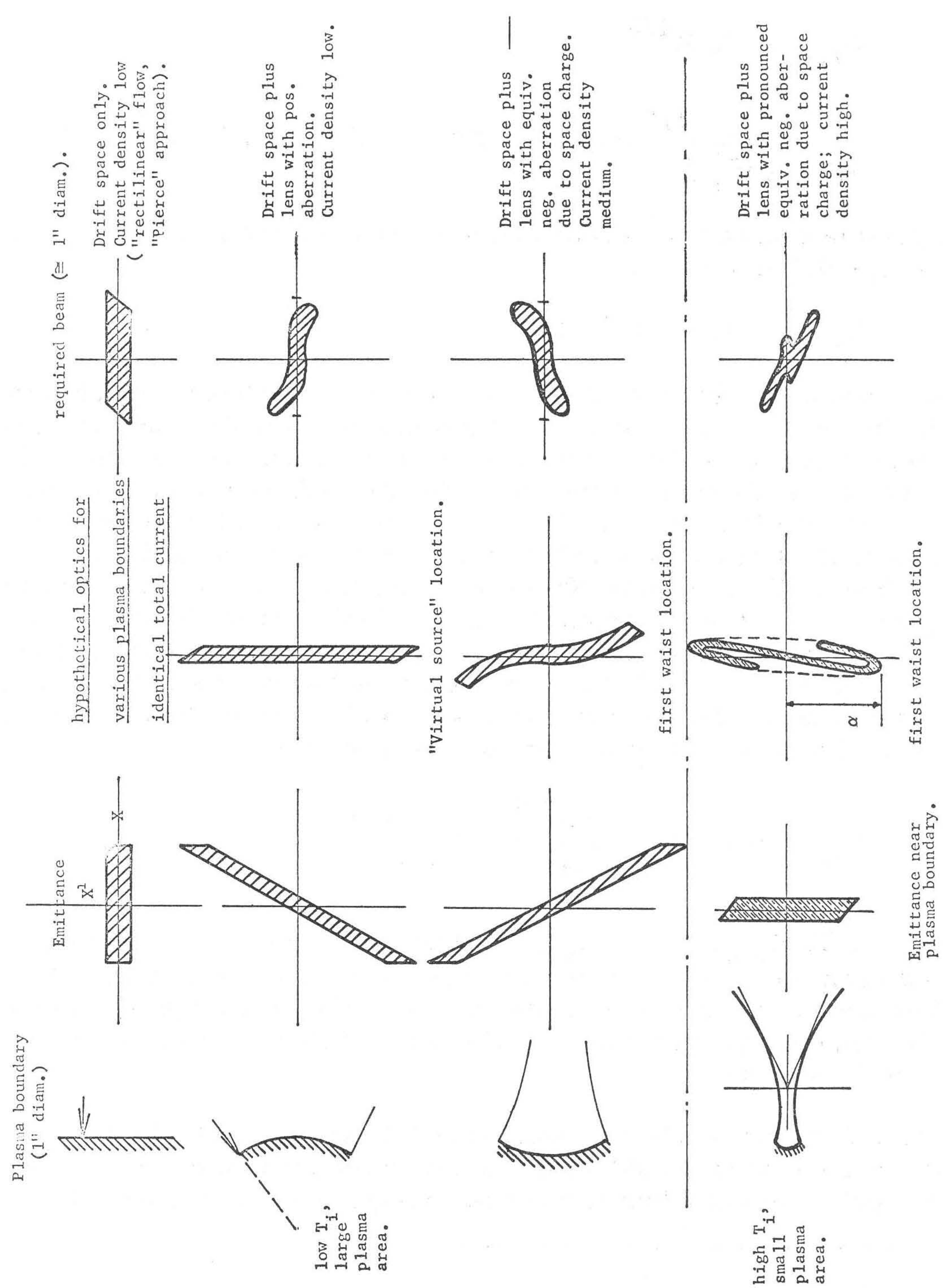
Plasma boundary (1" diam.)
Emittance
X'
X
hypothetical optics for
various plasma boundaries
identical total current
required beam (≅ 1" diam.).
Drift space only. Current density low ("rectilinear" flow, "pierce" approach).
Drift space plus lens with pos. aberration. Current density low.
Drift space plus lens with equiv. neg. aberration due to space charge. Current density medium.
Drift space plus lens with pronounced equiv. neg. aberration due to space charge; current density high.
"Virtual source" location.
first waist location.
first waist location.
α
low T_i, large plasma area.
high T_i, small plasma area.
Emittance near plasma boundary.

Fig. 2

For a "rectilinear"* flow with cylindrical boundaries the axial potential distribution is given by

$$U_{z,o} = A_i \, Z^{4/3}$$

with

$$A_i = \left(\frac{m_p}{m_e}\right)^{1/3} A_e \qquad \text{and} \qquad A_e = 5.7 \quad 10^3 \quad j^{2/3} .$$

For a plasma boundary of 1 inch diameter and 500 mA total current one obtains $j_o = 0.1 \ A/cm^2$ and

$$U_{z,o} = 1.5 \quad 10^4 \quad Z^{4/3} .$$

The potential distribution outside the beam boundary has to match this distribution at the beam boundary. This has been obtained analytically and can be approached for practical electrode shapes with an electrolytic tank. The axial distribution together with the required fields as a function of axial location are given in Fig. 4. In this case the extraction electrode held at 50 kV is matched at the proper location and given the proper shape. Consequently 700 kV will be held across a gap of approximately 16.5 cm. The maximum axial field indicated is ≅ 50 kV/cm. Similarly some parameters for the spherical case, i.e., a beam cone cut out of the inner space between two spheres has been explored. Again a plasma boundary diameter of 1 inch and total beam of 500 mA have been assumed. The axial potential distribution is given by

$$I_{op} = 2.4 \quad 10^{-6} \ \frac{\sin^2 \frac{\theta}{2}}{\alpha^2} \ U_{z,o}^{3/2}$$

with $\alpha^2 = f\,(R/R_{plasma\ boundary})$, a known function. The results, matched again to the extraction electrode, are also shown in Fig. 4. The field has been limited to 10 MV/m, resulting in a slight deviation from the required potential distribution above 650 kV. This is not thought to be serious.

As a first approach the "rectilinear" beam with cylindrical beam boundaries have been considered. An electrode system enforcing the required potential distribution has been designed and at present, first

---

*This would constitute a beam emittance of zero value, which does not occur in practice. Nevertheless the approach is useful.

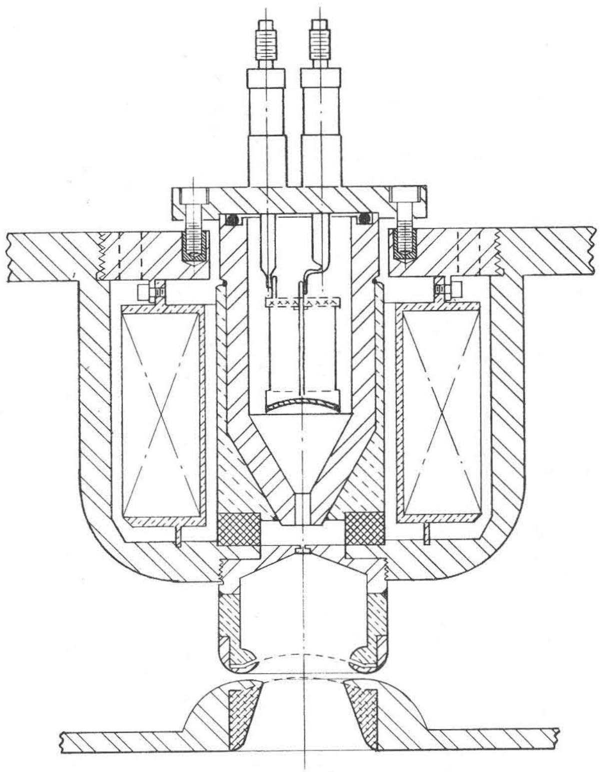

Fig. 3 Modified Duoplasmatron

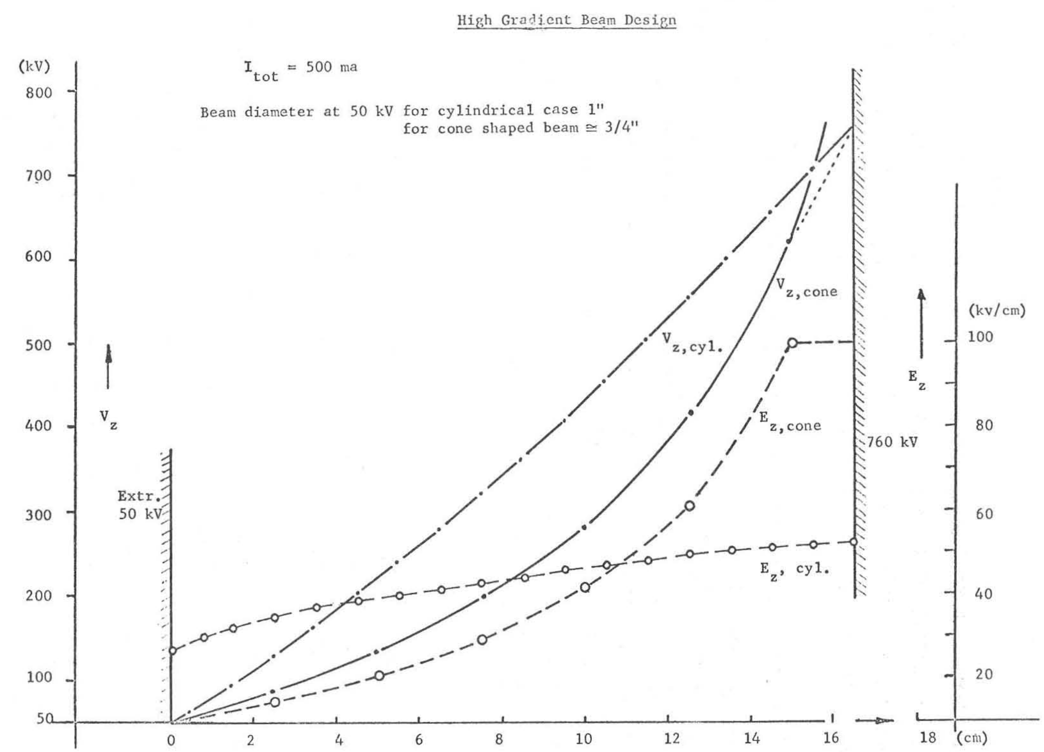

Fig. 4

approach equipotential measurements have been done with a semi-automatic equipotential plotter. An electrolytic tank of 30" x 24" and the plotter have been built by Mr. A. Soukas, who also did some of the measurements, an example of which is given in Fig. 5.

The finally synthesized electrode structure will be mounted in a high gradient large diameter column structure, as shown in Fig. 6. This is a double walled structure with the possibility of conditioned and cooled gas mixture flow in the interspace for cooling of the voltage dividing resistors and improved voltage rating. The total length of the column is about 40 inches for 750 kV. A test section is presently being built up to evaluate some of the design approaches in more detail. The over-all preinjector arrangement as envisaged at present is shown in Fig. 7.

LAPOSTOLLE: I would like to ask you two questions. First, what type of aberration do you consider due to space charge? Is that due to non-uniform density or to the potential drop inside the beam?

VAN STEENBERGEN: I have talked in terms of equivalent negative aberration, because the space-charge effects, even in a homogeneous beam with potential drop inside the beam, tend to distort the two-dimensional phase-space boundary in a sense opposite to that due to spherical aberration. I assume that boundary distortion due to space-charge in a nonhomogeneous beam would tend to be more serious and lead to more equivalent negative aberration.

LAPOSTOLLE: Now, I have the second question, which was about your high gradient column design where you try to have a field distribution which fits the space-charge law in some way. That of course only applies for a given current density.

VAN STEENBERGEN: The equipotential distribution at the boundary is correct for one value of current density only. Therefore, at present the preliminary design is for a particular total current, i.e., 500 mA only; it is not expected to suit typically a 50 mA total beam.

MORGAN: In your high gradient column design, did you worry about regions of electron oscillation in the stray field of the solenoid lens which is right beneath the column? We found this to be real critical in the design of our column.

VAN STEENBERGEN: We did not consider this yet.

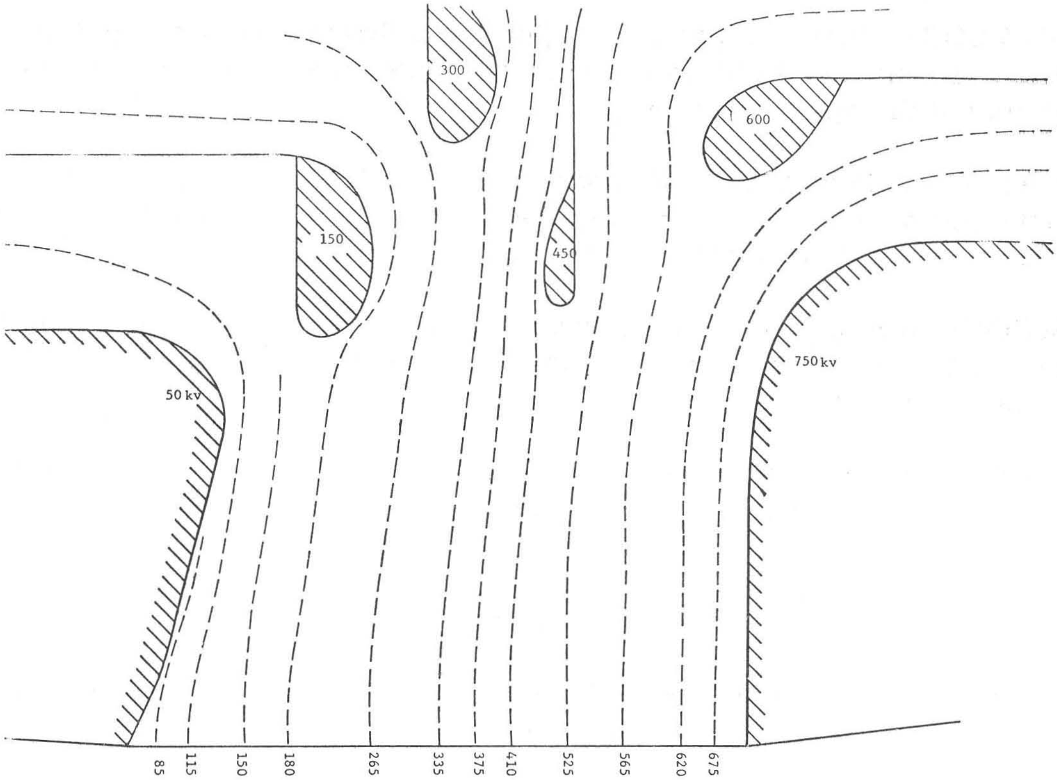

Fig. 5

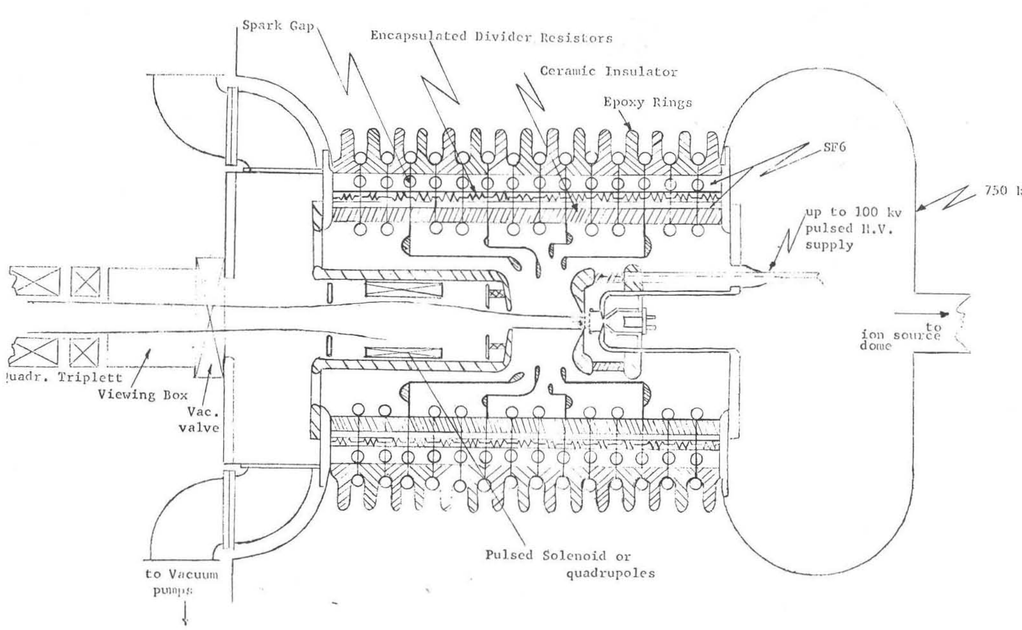

Fig. 7 High Gradient Accelerator Column Arrangement

TAYLOR: Have you plotted trajectories through on a computer? And if so, I want to ask you what sort of program you use and how you included the space charge?

VAN STEENBERGEN: We hope to start using the Kirstein program but have not done so yet. I recognize completely that the equipotential tank leads to a first approximation only.

WROE: Would you say a bit more about those ion temperatures you quoted? I notice you wrote down 10^5 °K and 10^{12} ions per cm^3. Is this a measured value?

VAN STEENBERGEN: This was a measured value by Gabovich with an expansion cup attached to a hot cathode P.I.G. source.

REFERENCES

1. A. van Steenbergen *et al.* Proceedings of the International Conference on High Energy Accelerators, Dubna, August 1963.

2. A. van Steenbergen, BNL Internal Report, AADD-29, March 1964.

3. A. Guthrie and R. W. Wakerling, "The Characteristics of Electrical Discharges in Magnetic Fields", McGraw-Hill, May 1949.

4. M. D. Gabovich *et al.* Soviet Physics-Technical Physics, Vol. 6, March 1, 1961, p. 766.

5. A. I. Solnyshkov *et al.*, Proceedings of the Conference on High Energy Accelerators, Dubna, August 1963.

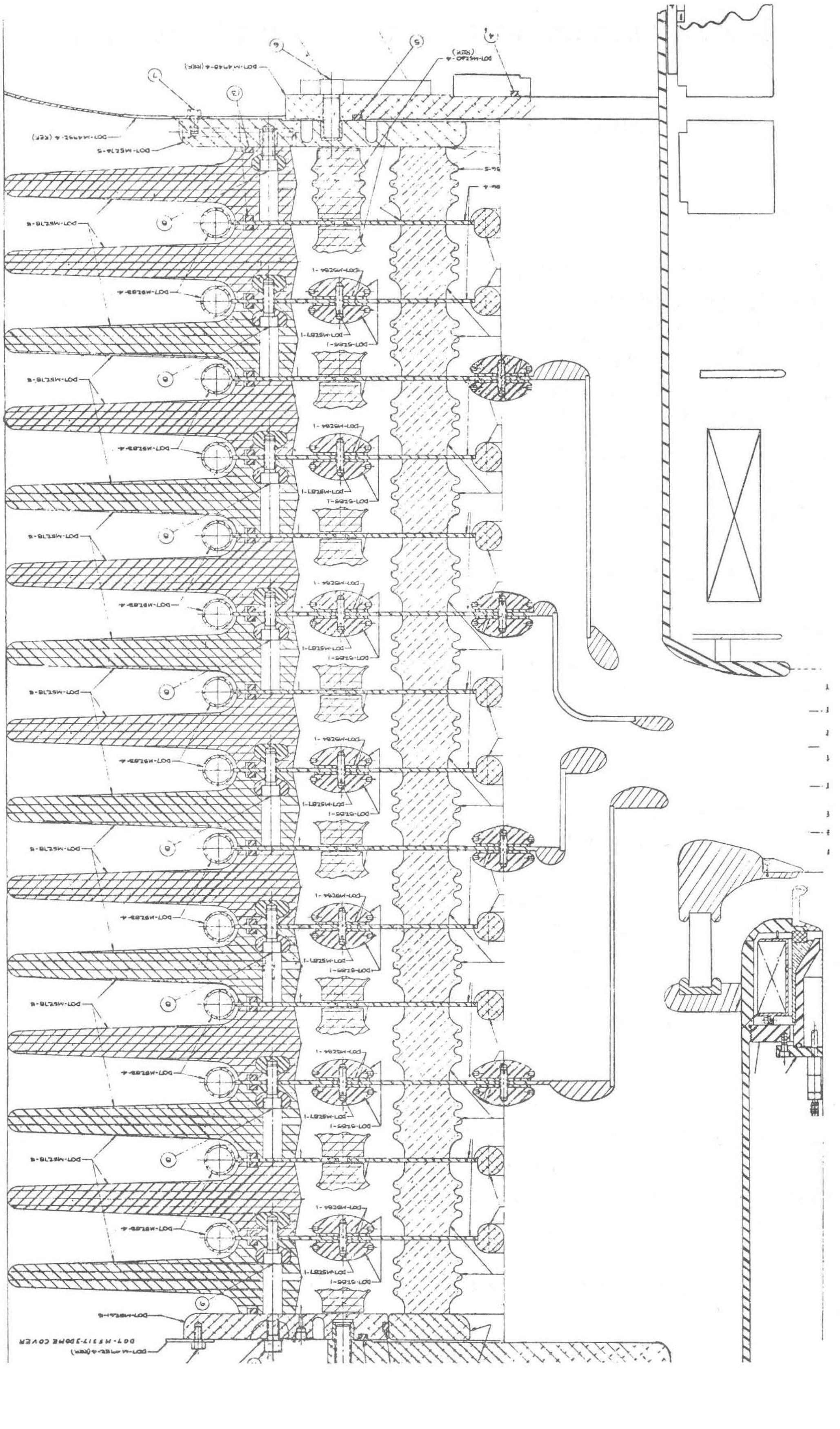

Fig. 6