PREACCELERATOR COLUMN DESIGN

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I. REQUIREMENTS

There are three principal requirements that we should like to meet in the design of a high current accelerating system. The first is that the undesirable effects of space-charge forces within the beam on beam emittance be removed or rendered insignificant. One practical approach to accomplish this is to use a beam from the source which is initially large in diameter to reduce the self-forces and which can be accelerated very quickly to reduce the time for the forces to act. Another approach is to use a Pierce-type field geometry to balance out the self-forces. Both approaches lead to a high field gradient in the accelerating gap or column. A second requirement is for reliability of operation against breakdown. Because of the premium placed on high field strength capability here, we wish, if possible, to design the overall system so that the chance of breakdown due to conditions external to the accelerating gap is small. Our principal concern then is the voltage-holding properties within the column. The third requirement is for ion source accessibility. Under the assumption that servicing of the ion source is a major cause of down time on a preaccelerator, it is important to provide for fast access and change capability. In particular, on an experimental facility where frequent changes may be needed, this is important. The use of two preinjectors with one on standby can be considered, of course, to give increased reliability in the case of accelerator operation.

II. ELECTRODE DESIGN

To provide for a large diameter beam we have chosen to use the scheme of a plasma expansion cup attached to a conventional duoplasmatron source, following the example of Solnyskov[1] and others. We propose that the extraction grid be the first electrode of the high gradient acceleration region. The beam will thus be accelerated quickly without the delay required in passing first through a focusing lens. The hope is that one can control the focal properties of the beam to some extent for any given current intensity by simultaneous adjustment of the plasma density and the extraction voltage. Use of a fine mesh grid to shape the boundary would be a welcome addition, if successful. A properly concave plasma surface will render the beam initially converging. The source position is shown in Fig. 1. The exact configuration of the source cup and extraction grid are subject to experimental change.

Unless one uses an accelerating field of the appropriate shape to counteract the space-charge forces, there will be some divergence of the beam. We can obtain some idea of the dependence on beam size and field gradient by assuming a uniform accelerating field. If one further assumes a cylindrical beam of radius R and of uniform charge density, which remains uniform across the beam diameter, one can derive an expression for the divergence of the ion beam after acceleration through some potential drop. This is given approximately for a particle at the edge of the beam by

$$\theta = \frac{I}{ER} \sqrt{\frac{m}{-2\,eV}} \ln \frac{V}{V_o}$$

for a long beam with neglect of end effects. The beam here is assumed parallel as it crosses the surface of potential V_o relative to the source. For a given final potential V one notes the divergence angle to be proportional to beam current I and inversely proportional to beam radius and to field strength E. For constant gradient and variable V there is a maximum θ for $\ln V/V_o = 2$. As an example we may consider a beam of 4 cm radius accelerated through a column or gap of 30 cm length. If the initial potential of the parallel beam is $V_o = -50$ kV and the final potential V is -500 kV, the angle θ becomes 6×10^{-3} radians. If V is changed to - 1000 kV, θ becomes 2.6×10^{-3} radians. This divergence is comparable with the spreading which results from thermal motion of the ions at the source but does not play the same role in determining beam emittance.

When a short high gradient accelerating column is considered, one is led to wonder if a single-gap two-electrode accelerator is feasible. If the field in such a gap were converging, it would tend to offset the beam divergence due to space-charge forces, to the diverging aperture lens at the gap exit and to the absence of focusing electrodes between source and gap entrance. A simple converging field geometry, not of the Pierce type, is given by concentric spherical electrodes as shown in Fig. 2.

The optics of the system is given by the formulas in the figure where f is the focal length of the exit aperture lens and F is the distance of focus from this aperture for a beam, which, starting from rest, is accelerated radially between the spheres. The drawing is for the special

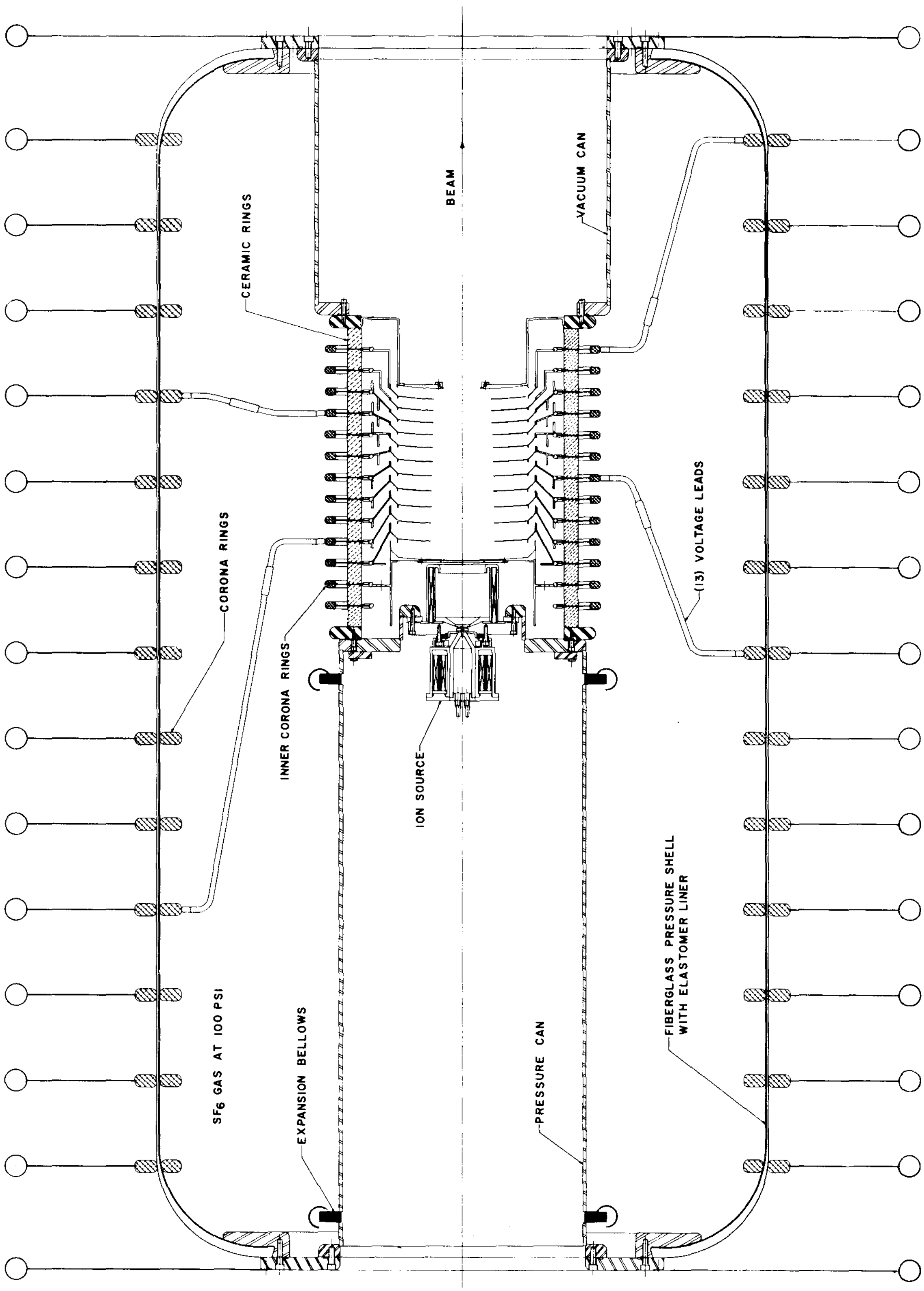

CERAMIC RINGS
BEAM
VACUUM CAN
CORONA RINGS
INNER CORONA RINGS
ION SOURCE
(13) VOLTAGE LEADS
SF6 GAS AT 100 PSI
EXPANSION BELLOWS
PRESSURE CAN
FIBERGLASS PRESSURE SHELL
WITH ELASTOMER LINER

FIG 1

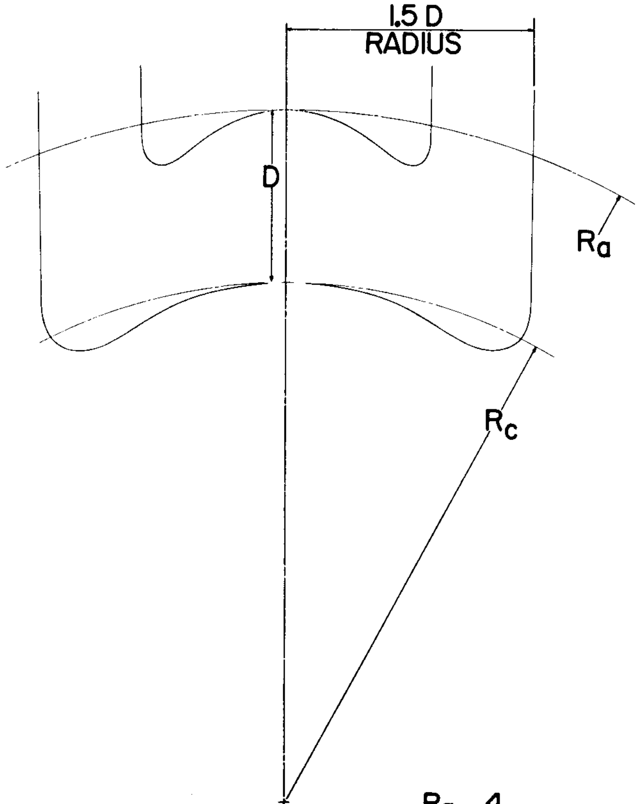
case of the sphere radii having the ratio of 4/3, which renders the beam parallel beyond the exit.

Aside from the question of adequate voltage insulation between the electrodes in vacuum, there is the problem of insulation at the boundary between vacuum and external pressure. One approach is to take the beam out through a grounded tube which passes through a high voltage bushing support for the high potential sphere. Another approach is to distort the electrode shapes to give a spherical field in the beam region when the grounded electrode is bent back to surround the high voltage electrode as shown in Fig. 2. The shapes given there were determined in an electrolytic tank and give closely the required field shape. A similar geometry, except for cylindrical electrodes, is used successfully as an electron gun[2] on the MURA 50 MeV accelerator. In this arrangement, the source leads enter through a high voltage bushing which supports the high voltage electrode.

Of prime concern in such a two-electrode system for the 500 to 1000 kV range is the large area of the electrodes in vacuum. Through the "area effect", one can expect to hold less voltage for large than for small area. For small gaps between stainless steel electrodes withstanding of the order of 100 kV, the breakdown voltage varies with area[3] approximately as $\frac{V}{V'} = \left(\frac{A'}{A}\right)^{0.15}$.

A way to reduce the electrode area required is to use a multi-electrode design, the usual practice, to aid in distributions of the potential across the gap. If one does this but keeps the re-entrant electrode shape suggested by Fig. 2, one obtains a design shown, in principle, in Fig. 3. The electrode area exposed to the total voltage difference is now greatly reduced, although the area of each electrode is still quite large. The "total voltage effect", however, whereby the breakdown voltage above 100 kV is approximately proportional to square root of electrode separation, is not now so severe. The voltage is divided across the several gaps of Fig. 3 by an external voltage divider (not shown). A further benefit resulting from use of the intermediate electrodes should be a reduction in x-ray intensity. It is clear that there exists good shielding of the ceramic rings from the beam.

There are certain problems of mechanical design associated with the sketch of Fig. 3. In addition, access to the ion source is limited, allowing removal of no more than the filament holder through the high voltage bushing. A large diameter access channel would be possible by this route only by use of ceramic rings of quite large diameter.



$$\frac{1}{F} = \frac{1}{R_c} + \frac{1}{f}$$

$$\frac{1}{f} = \frac{\Delta E}{4V} = -\frac{R_a/R_c}{4(R_a - R_c)}$$

$$\frac{1}{F} = \frac{3R_a/R_c - 4}{4(R_a - R_c)}$$

ELECTRODE DESIGN FOR $\frac{R_a}{R_c} = \frac{4}{3}$

FIG 2

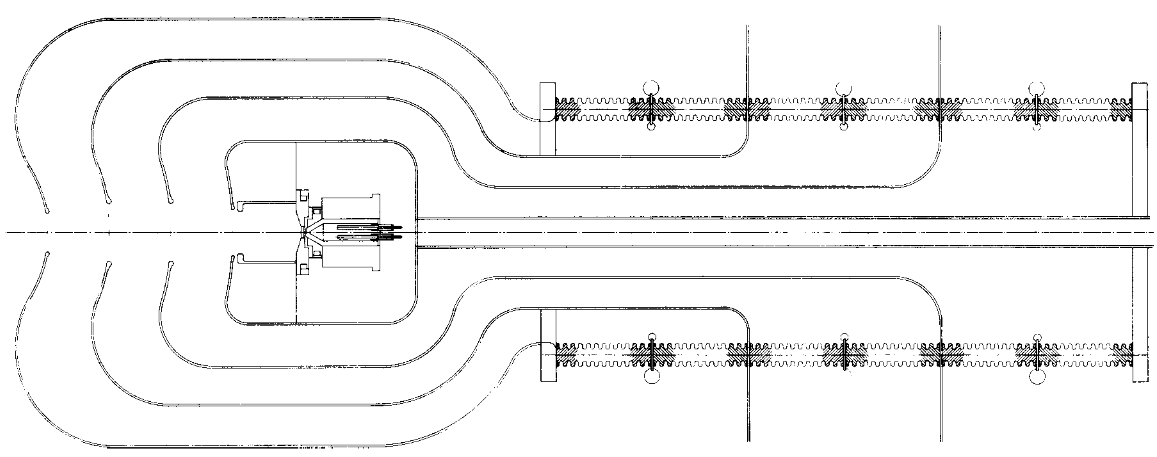


FIG 3

In the interest of achieving a high gradient column with good accessibility to the ion source as well as to the exit beam, we considered it prudent for the present to use a multi-electrode design with a more nearly conventional arrangement of the ceramic insulators. This is the design of Fig. 1, which still retains a converging field with the optics of Fig. 2. The accelerating gap is 30 cm long. The thin spherical electrodes have supports which flare out to a longer ceramic column of 21-inch length having 14 sections. A variable extraction voltage is applied across the first two sections while the other sections have an equal voltage difference across them.

The required field was achieved in an electrolytic tank by John Spooner with only the top and bottom spherical electrodes in place together with the z-shaped portions of the other eleven electrodes. This meant that the remaining electrodes of spherical shape could be placed along already existing equipotential surfaces. One can thereby hope that with accurate placement, the thin electrode edges will not be prone to voltage breakdown and will offer only a small perturbation in the field distribution due to finite electrode thickness. The thickness planned is 1/16 inch.

If the exit aperture in the last electrode is covered by a grid, the beam optics will, of course, be changed. The exit lens action is removed and an otherwise parallel beam will converge, except for space-charge effects, toward a minimum at the center of the spheres.

The electrode material having the best voltage holding properties in the 100 kV range that has come to our attention is a titanium alloy, Ti-7 Al-4 Mo. Furthermore, since it has a thermal coefficient of expansion which closely matches that of the ceramic rings, it becomes a good ring spacer material. Certain voltage tests which we have carried out on 304 stainless steel indicate that this also may be suitable. These included tests of a 0.9 cm gap between the end of a thin-walled right circular cylinder of 10-inch diameter and a plane. A cylinder of 1/16-inch wall held dc voltages well beyond 100 kV without breakdown when the gap was paralleled with a 0.02 μf capacitor. In the column a voltage gradient of 75 kV per gap, where the minimum spacing is 1 cm, would give over 900 kV for the total accelerating voltage.

The ceramic rings are 16 inches outer diameter. Each ring is 1-inch thick by 1-15/32 inches high and is recessed at the ends as may be seen in Fig. 1. This is to take advantage of any improvement in ability to hold voltage, as observed by others[4] when the cathode end is recessed. The rings will be vinyl sealed together.

In assembly the electrodes will be inserted into the column through the high voltage end. A jigging arrangement will permit accurate positioning of each spherical electrode with its attached z-shaped portion before it is connected to its conical support.

III. PRESSURIZED SHELL ASSEMBLY

In order to diminish the possibility of voltage breakdown outside the accelerator column, we decided to enclose the column in a pressurized atmosphere. A practical way to do this is to use a filament-wound fiberglass vessel as shown in Fig. 1. Such items are commercially made in a variety of sizes for rocket motor cases and chemical tanks. The vessel we plan to use is wound onto end flanges that were machined here at MURA. The wall thickness is 1/8 inch with an additional 1/16-inch butyl rubber liner to seal the fiberglass for SF_6 up to 100 lbs/in^2. The rubber can be made semiconductive to allow accumulated charge on the wall to drain off. The vessel is 42 inches inside diameter and 84 inches long.

There is a 17-inch diameter access channel to the source, which remains at atmospheric pressure. Bellows in this tube allow for some stretching of the pressurized tank. The column is under compression when evacuated and approximately neutral when up to air. Source changes are thus possible without the need to disturb tank pressure.

Each column electrode is connected to external corona rings on the fiberglass shell. A resistor string, not shown, divides the voltage here. The resistors can readily be changed if one should wish to alter the field distribution within the column. The position of the column within the tank can be changed, of course, from that shown by changing the electrode leads and the relative lengths of the source and beam exit channels.

Should one wish to test other electrode configurations, the tank should be capable of accommodating designs which vary greatly in electrode and insulator structure from that described here.

KELLEY: It looks as though there are several places in that design, first of all where electrons can be trapped from the magnetic field that you use for shaping the plasma surface. And I think you might get pigging trouble in those regions. Have you tested this?

CURTIS: No, this design has not been tested. The magnetic field indicated in the region of the cup may be undesirable and perhaps unnecessary.

KELLEY: We don't find it necessary to have a labyrinth sort of arrangement with a many bounce path between column and the beam. It seems that just barely shadowing is all that is necessary.

CURTIS: We wondered if this was really necessary and thought that the design might be a bit conservative in this respect.

KELLEY: Did I understand that your thin sheets now along equipotentials were there so that when you have the beam you will still force equipotentials at those places? Otherwise you don't need any electrode surface there.

CURTIS: One should not need any electrodes, except that they do reduce the area of the total gap and may therefore aid the voltage-holding ability. They also should reduce the x-ray level. We may actually remove them, depending on what experience tells us.

VAN STEENBERGEN: Does it make much difference in equipotential distribution outside, say, the beam region, if the high intensity beam is present or not? Are the electrodes at the correct place with beam?

CURTIS: They are in the correct place without beam as designed. It doesn't make a lot of difference whether the beam is present or not. This, of course, depends on the magnitude of beam current. For a 200 mA beam of 4 cm radius, the potential at the center of the beam increases by a few hundred volts. One can compare this with a voltage gradient of approximately 20 kV/cm for a total voltage of 600 kV to determine the displacement of the equipotential surfaces. Now it is possible, by varying the voltage on these electrodes to push the potential surfaces around quite freely. So I think it may be possible to adjust the voltage distribution externally and adequately correct any trouble resulting from displacement of the potential surfaces by the beam.

PRIEST: Lamb was saying that he had done exactly what you are saying and we have done it too. We vary the potential on these electrodes and get very good beam control and then having found out what the potential distribution is we then redesign the thing so that it doesn't need this variation. There is one comment I would like to make. It may be applicable in this case, I am not sure. In electron guns which are at all sophisticated where we really want to get a clean beam and the minimum amount of interception at the anode and so forth, we find we have to pay very special attention to the geometry at the edge of the cathode. And the thing we call the focus electrode, which is the element that does the field shaping, which surrounds the cathode and normally is at the same potential, has to be put in exactly the right place. I mean within a mil or so or you get into trouble. We found that we have to pay very good attention to this, and a trick we found we can play to overcome the effect of poor tolerances or misalignment is to insulate this electrode so that in the case of electrons we can put a little negative voltage on it, maybe 20 or 30 V. This does wonders to clean up the beam and I suppose if you put a positive voltage on this in your case it might do the same.

CURTIS: Is this again with a Pierce-type geometry?

PRIEST: Yes, I have seen several of these drawn here in the course of the day.

CURTIS: We also found that similar electrode biasing in a Pierce electron gun we once built was quite effective.

MARTIN, J. H.: In regard to breakdown, how much better is this titanium alloy than some good stainless steels?

CURTIS: Of course, different people who make measurements on the same materials do not always obtain the same results. Comparison measurements were made by Ion Physics Corporation people. At the same time that they reached 80 kV across a 1 mm gap for buff-polished Ti alloy electrodes of 20 cm^2 area, they could hold only 60 kV for 304 stainless steel. They achieved, I believe, 110 kV for optically polished Ti alloy.

WROE: I am thoroughly convinced that there is this difference between long and short gaps and I wouldn't consider extrapolating that result into a long gap for instance. I mean that this difference in materials may not apply either.

CURTIS: Yes, I am quite aware of that. We may be just as well off with stainless as with titanium alloy for long gaps. These short gap figures are just the only comparative information I have. There are, of course, several relatively high field short interelectrode gaps in the column design which I have described.

REFERENCES

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