A COMPARATIVE STUDY OF DRIFTING ARC AND EXTENDED STATIONARY ARC DUOPLASMATRONS*

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Abstract

A drifting arc duoplasmatron used in previous studies has been converted into an extended stationary arc duoplasmatron for use in a comparative study of these two basically different source types. To facilitate comparison, the Pierce extraction geometry of the drifting arc source has been retained. Some results of this study will be presented and discussed.

Introduction

The process of discovering and systematizing the representation of existing order among the complex relationships which characterize ion sources is largely one of classification. In a recent proposal for a study of plasma boundary and beam formation in a new class of ion sources,[1] several existing and proposed ion sources were considered from an analytical point of view in which an ion source is classified according to:

1. The nature of the plasma from which ions are extracted.
2. The nature and arrangement of the discharge electrodes.
3. The nature of the magnetic field distribution.
4. The nature of the electric field distribution in the extraction region.
5. The relationships between those elements obtained by disregarding the words "nature" and "arrangement" in the foregoing.

The present study of two existing source types is, at this time, concerned almost exclusively with items 1 and 2 above.

As in reference 1, an ion source in which a portion of the plasma is transported from the discharge chamber to a remote extraction region by mass motion in the general direction of the magnetic field will be called a "drifting arc" ion source. This term was first applied to the Lamb-Lofgren source[2] by those who participated in its development; it may also be applied to the von Ardenne duoplasmatron.[3]

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To emphasize a fundamental difference, an ion source in which ions are extracted directly from a portion of the plasma in the discharge chamber will be called a "stationary arc" ion source. We may differentiate further between a short stationary arc and an extended stationary arc. In the former, the discharge terminates on the cathode side of the anode, with the extraction voltage field penetrating through an aperture in the anode. In the latter, the discharge runs through an aperture or canal in the anode to a discharge electrode whose potential is less positive than that of the anode, and that of the local plasma, by an amount sufficient to repel electrons with enough energy to ionize one or more neutral atoms or molecules.

In a properly designed extended stationary arc ion source, these energetic electrons, after being repelled by the additional electrode, are trapped in the plasma until they can work their way across the magnetic field to the anode. While they are trapped, they are capable of undergoing one or more ionizing collisions with neutrals anywhere within the confines of the plasma. In particular, they are capable of reionizing recombination neutrals in the vicinity of the aperture or apertures (in the additional electrode) through which the beam ions are extracted. Since many of these recombination neutrals would otherwise escape from the source as neutrals, gas utilization efficiency is higher than it would be if there were no temporary trapping of energetic electrons.

The additional electrode which converts a drifting arc ion source, or a short stationary arc source, into an extended stationary arc ion source serves not only as a discharge electrode but also as the third component of the extraction geometry, the other two being the plasma boundary from which ions are extracted, and the extractor. To emphasize its role in the extraction process, we shall call this additional electrode the "grid". More generally, we shall apply this term to the third element in the extraction system even when this element is structurally or electrically a part of the anode, and we shall consider its role in beam formation[1,4] separately from its function as part of the discharge geometry.

When we wish to be explicit about the manner in which the grid functions as a discharge electrode, we shall differentiate between a floating grid, a grid that is connected directly to the cathode, and one which is connected to the anode through a resistor. It is consistent with the grid concept we have adopted to consider a drifting arc or short stationary arc as being obtained from an extended stationary arc by reducing the impedance of a grid-anode resistor to zero. It must be noted, however, that the optimum discharge geometry is not necessarily the same for a drifting arc as it is for an extended stationary arc.

In the present study we shall compare the characteristics of two drifting arc duoplasmatrons used in previous studies[5, 6] with those of two extended stationary arc duoplasmatrons (one of them rudimentary) obtained by modifying the source of reference 6. The information required for a meaningful comparison of these sources is essentially that required to design lens and column optics to obtain a proper match between an ion source and an accelerating column. Thus the present study has the further objective of gathering design data for source-column matching.

A Drifting Arc Duoplasmatron (Source I)

The drifting arc duoplasmatron of reference 5 is shown in Fig. 1. This source has been operated with the single 52-mil aperture shown in Fig. 1, and also with an anode insert with three 32-mil diameter holes on a 52-mil diameter circle.

Some results obtained with this insert are shown in Fig. 2, which illustrates the variation in beam quality as the beam current is increased by increasing the magnet current while keeping the source pressure, the arc current and the extraction voltage constant. Considering first the photographs of the fluorescent slit images produced by the beam impinging on the aluminized surface of a glass plate, we note: a rapid increase in beam diameter and divergence with increasing magnet and beam currents; beam aberrations at the lowest currents; the absence of measurable distortions at the higher currents. (The curvatures of the slit-edge images for the edges closest to the horizontal axis are caused by time-dependent variations in the shape and location of the plasma boundary and, thus, in the location of the virtual source point from which the beam appears to be diverging.) In the same figure, oscilloscope photographs show the variations of the beam current waveforms, and the effect of beam loading on the extraction voltage, as the magnet current is increased.

The large "hash" amplitudes at low magnet and beam current values, and the increasing departures of the beam current and extraction voltage waveforms from the ideal square wave as the beam current increases, are all undesirable. They represent large time-dependent variations in the shape and location of the plasma boundary, and in the energy of the beam, which make the task of getting the entire beam into the acceptance aperture of an accelerator, or a beam transport system, more difficult, if not impossible.

A very low gas utilization efficiency limited the beam currents that could be obtained in Source I, without exceeding the pumping capacity of the vacuum system, to several hundred milliamperes. At the higher currents, beam divergence was higher than desirable. A magnetic field shaping experiment[5] in which the aiding field of a solenoid mounted in the extractor was superimposed on the distribution produced by the source magnet demonstrated that the beam divergence could be reduced with this arrangement, but this approach to field shaping was not pursued far enough to determine its ultimate advantages and limitations.

A Shaped Field Drifting Arc Duoplasmatron (Source II)

The source of reference 6, shown in Fig. 3, was originally built as a replacement for Source I and was first operated as a duplicate, essentially, of the source geometry that gave the results shown in Fig. 2. It was then modified to accommodate the field shaping coils and iron geometry shown in Fig. 3. (Mild steel portions of the magnet circuits are shown cross-hatched in the drawing.)

The geometries of the extraction electrodes in Sources I and II are Pierce geometries designed to accelerate a 9/16-inch diameter beam acorss a 9/16-inch gap. Starting with the geometry of Fig. 3, and going through a number of modifications, efforts to obtain a magnetic field distribution that coincides, in the extraction region, with the correct electric field distribution (without at the same time increasing already large recombination losses) were unsuccessful. These efforts were hampered by a built-in obstacle in the form of iron in the magnetic circuits. To insure that an adequate amount of plasma reaches the extraction region, proper shaping of the magnetic field is required not only in the extraction region but also in the vicinity of the small aperture(s) used to impede the flow of gas into the extraction region, and in the intervening drift space as well. With possible but thus far undiscovered exceptions, changes that improve the distribution in one region have an adverse effect elsewhere when these changes are limited to those that may be made by reshaping iron or by superimposing additional distributions in the presence of iron.

With the larger expansion cup and modified iron geometry of the shaped field version of Source II, gas utilization efficiency is even lower than in Source I. Beam currents are limited to less than 200 mA, by pumping capacity, and the departures of the beam current waveforms from the ideal square wave are worse than in Source I.

With just the field of the source magnet, and for a given perveance, this source gives a beam of smaller radius and divergence than that obtained in Source I. Superposition of the fields produced by either or both of the field shaping magnets may, depending on polarities and magnitudes, either reduce or increase beam radius and divergence. If the effect is one of reduction, distortions are introduced; the larger the reduction the stronger the distortions. In some cases, the beam intensity close to the axis is so reduced that the beam appears to be hollow for short photographic exposures.

A Rudimentary Extended Stationary Arc Duoplasmatron (Source III)

It was stated above that a drifting arc or a short stationary arc ion source could be obtained from an extended stationary arc ion source by reducing the impedance of a grid-anode resistor to zero. To this statement was appended the admonition that the optimum discharge geometries are not necessarily the same for both modes of operation. This fact is illustrated by the results of two modifications of Source II, to be considered in this section and the next.

Figure 4 shows how a rudimentary extended stationary arc duoplasmatron was obtained from the drifting arc duoplasmatron of Fig. 3 by replacing the stainless steel grid insert at anode potential with a modified stainless steel insert insulated from the anode by a Teflon sleeve and Teflon rings, which are not shown.

Some results obtained with this geometry are also shown in Fig. 4. In this experiment, the cathode heat-shield assembly is connected (externally) to one lead of the oxide-coated cathode, which is similar in its bifilar spiral construction to one described by H. Wroe,[7] but differs in having a third lead to give additional structural support and, also, to carry the arc current.

A lead runs from the grid to a vacuum feed-thru which connects externally to a switch. The three-position switch permits operation with the grid floating or connected to the anode, directly or through a 1 k-Ω resistor. The data were taken with the resistor in the circuit.

In terms of beam current magnitudes and waveforms, the results shown here are not much different from those obtained with the direct grid-anode connection of Fig. 3. There is, however, a significant reduction in beam radius and divergence, for a given perveance, without the direct connection. This suggests that the plasma density distribution is somewhat better in this latter case.

The fact that there is no great improvement in gas utilization efficiency without the direct grid-anode connection is not unexpected. The significant difference between a drifting arc source and a properly designed extended stationary arc source is that in this latter source the combined effect of a potential well and a magnetic field is to impede the flow of electrons to the anode, so that these electrons are used more efficiently than they would otherwise be used. In the geometry of Fig. 4, the potential well and the magnetic field do not combine effectively to prevent the early loss of energetic electrons to the anode, and the discharge geometry falls far short of exploiting fully the advantages to be gained by using an extended stationary arc.

An Extended Stationary Arc Duoplasmatron (Source IV)

The simple modification of Source II shown in Fig. 4 was only a prelude to the drastic modification shown in Fig. 5. Cathode excepted, the discharge geometry in Source IV follows rather closely the design found to give the best results in the extended stationary arc duoplasmatron developed by Demirkhanov, Kursanov and Blagoveshchenskiy[8] for the production of 10 to 40 keV hydrogen ion beams with currents of the order of 2 A.

The Pierce extraction electrode geometry of Source II has been retained in Source IV. The grid-cup geometry represents a compromise between a desire to approximate, for the first try, the discharge geometry of Demirkhanov and his colleagues, and a desire to approximate the expansion cup geometry and cup magnetic field distribution of Source I (Fig. 1).

In considering some results obtained with this source we shall have occasion to stress the difference in cup magnetic field distributions in the two sources (I and IV).

As expected,[1] proper conversion of the drifting arc source into an extended stationary arc ion source has resulted in a substantially higher (four or five times higher) gas utilization efficiency. Where beam currents were limited to several hundred milliamperes, by vacuum pumping capacity, in drifting arc sources I and II, currents in excess of one ampere have been obtained with Source IV.

Of more immediate interest (since the present extraction geometry, and the extraction voltage supply, are neither designed nor suitable for currents of one ampere and more) is a notable improvement in beam current waveform for currents ranging from tens of milliamperes up to at least 500 mA.

Figure 6 shows the onset of damage to the aluminum coating on the glass plate due to a series of arc turn-off failures. Where the coating has been destroyed, light from the cathode and the plasma can be seen.

This figure also shows the results of a deliberate effort to obtain flat-topped beam pulses by tuning some of the parameters (cathode temperature, gas flow rate, magnet current, arc voltage, extraction supply voltage, pulse length and pulse repetition rate) which affect the waveforms and amplitudes of the beam current pulses, for a given geometry. Changes in one or more of the variables can, over limited ranges, be offset by changes in some or all of the other variables to give the same average amplitude, with the same or different energy, but the waveforms may be quite different for different sets of operating conditions.

Tuning for a flat-topped beam pulse, for a beam of given current and energy, can be a lengthy procedure. It is, however, a worthwhile effort if the beam is going to be injected into an accelerator or other device with a limited acceptance aperture. In this case, the rise and decay times of the leading and trailing edges of the beam pulse are also important.

If these times cannot be reduced to sufficiently small values, pulsing of the extraction voltage, with a pulse of shorter duration than that of the arc voltage, as is done at CERN,[9] is desirable. Pulsing of the extraction voltage would also permit extraction at higher voltage by eliminating the over-voltage required to compensate for beam loading.

In Fig. 6, it may be noted, the slit-image lines have, for the first time, distinct curvatures of the type associated with spherical abberation or pin-cushion distortion.[10] It is not likely that the extraction electrode geometry is the source of these distortions, since this geometry has not changed in the conversion from Source II to Source IV. What has changed, as noted above, is the magnetic field distribution in the grid-cup region. A portion of the field in the new geometry terminates on a conical surface which was not present in the other geometries. Off-axis, the effect of this conical surface is to produce a reversal in the direction of the axial component of the field. The distortion, not present with the field distributions of sources I and II, is probably related to this new distribution.

Some data obtained by holding source pressure, arc current and extraction voltage constant as the beam current is increased by increasing the magnet current are shown in Fig. 7. An emittance diagram for the 283 mA beam is also shown. For the normalized emittance and brightness we have used the notation and definitions of van Steenbergen.[11]

Quantitative Comparisons

Variations in beam radius and divergence with increasing magnet and beam currents as the source pressure, the arc current, and the extraction voltage are held constant are shown qualitatively in Figs. 2, 4 and 7 for Sources I, III and IV. The quantitative variations are shown in the beam characteristic curves of Fig. 8.

In every case, there is a transition region in which radius and divergence are multiple-valued functions of perveance. Below the transitions, multiple images of off-axis slits are obtained; above, multiple images are absent and, for Sources I and III, the beams are free of measurable aberrations. In the case of Source IV, we have seen that there are measurable aberrations above the transition region. The shift of the transition region to higher perveance in the case of Source III was also noted in the case of Source II and is evidently due to the smaller angle subtended at the 52-mil diameter anode aperture by the 9/16-inch diameter aperture in the grid and/or to the differences in cup magnetic field distributions.

Conclusions

Comparing qualitative and quantitative results obtained with these three sources, we find that with one exception the performance of Source IV is in all respects superior to those of the other two sources. The exception, beam distortion, should be amenable to correction by modification of the grid-cup magnetic field distribution.

Acknowledgments

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Addendum

In the Introduction, our preoccupation with axial extraction caused us to inadvertantly exclude from membership in the class of extended stationary arc ion sources, by the omission of a qualifying phrase, a well-known type of ion source which employs an extended stationary arc. In sources of this type, such as the cyclotron source of Livingston and Jones (Rev. Sci. Instr. 25, 552, 1954), the additional electrode of the extended stationary arc ion source is not a component of the extraction system, while the anode is.

This oversight should not go uncorrected. We choose to make the correction here, rather than in the Introduction, because this gives us the opportunity to stress, as we might not otherwise have done, that the anode can be the third component of the extraction system in an extended stationary arc ion source. Where a choice exists, as in a cyclotron source, it should be the third component, for reasons considered in reference 4.

DISCUSSION

(J. A. Fasolo)

LEFEBVRE, SACLAY: The influence of the coils in the plasma cup is not very clear to me. Did you find any improvement in the emittance, due to the action of these coils?

FASOLO, ANL: No. The only thing I did find, depending on the polarity and the magnitudes of the currents in the field shaping coils, was either an increase or decrease in the radius and divergence. In every case where there was a decrease, distortions were introduced into the beam; for the opposite case, there was no distortion and no improvement.

LEFEBVRE, SACLAY: If you have leakage field from the main magnet you can get rid of it with a coil in the plasma cup and then you will be faced with the fringing field from the coil.

FASOLO, ANL: Yes.

LEFEBVRE, SACLAY: So it is a never ending problem.

FASOLO, ANL: The whole problem is the iron. You can't get the distribution you want with iron in that region.

TENG, NAL: Does your study bear out the relationship that the emittance is proportional to the current? The last slide doesn't seem to show that.

FASOLO, ANL: I haven't looked at it for this source. For source No. 1, there was an experiment in which the perveance was kept constant; the emittance varied as the 1/3 power of beam current.

LEFEBVRE, SACLAY: We found that, for a certain geometry, the emittance is constant for a wide range of current. For example, the source in use now with the preinjector can deliver current between 20 and 100 milliamps and the emittance is constant over this range.

FASOLO, ANL: Do you mean normalized emittance, or the emittance diagram area?

LEFEBVRE, SACLAY: Normalized emittance.

MILLER, SLAC: I'd like to make a plea that when you give a normalized emittance, you use the units mc-cm. Then you don't have to say that it is normalized.

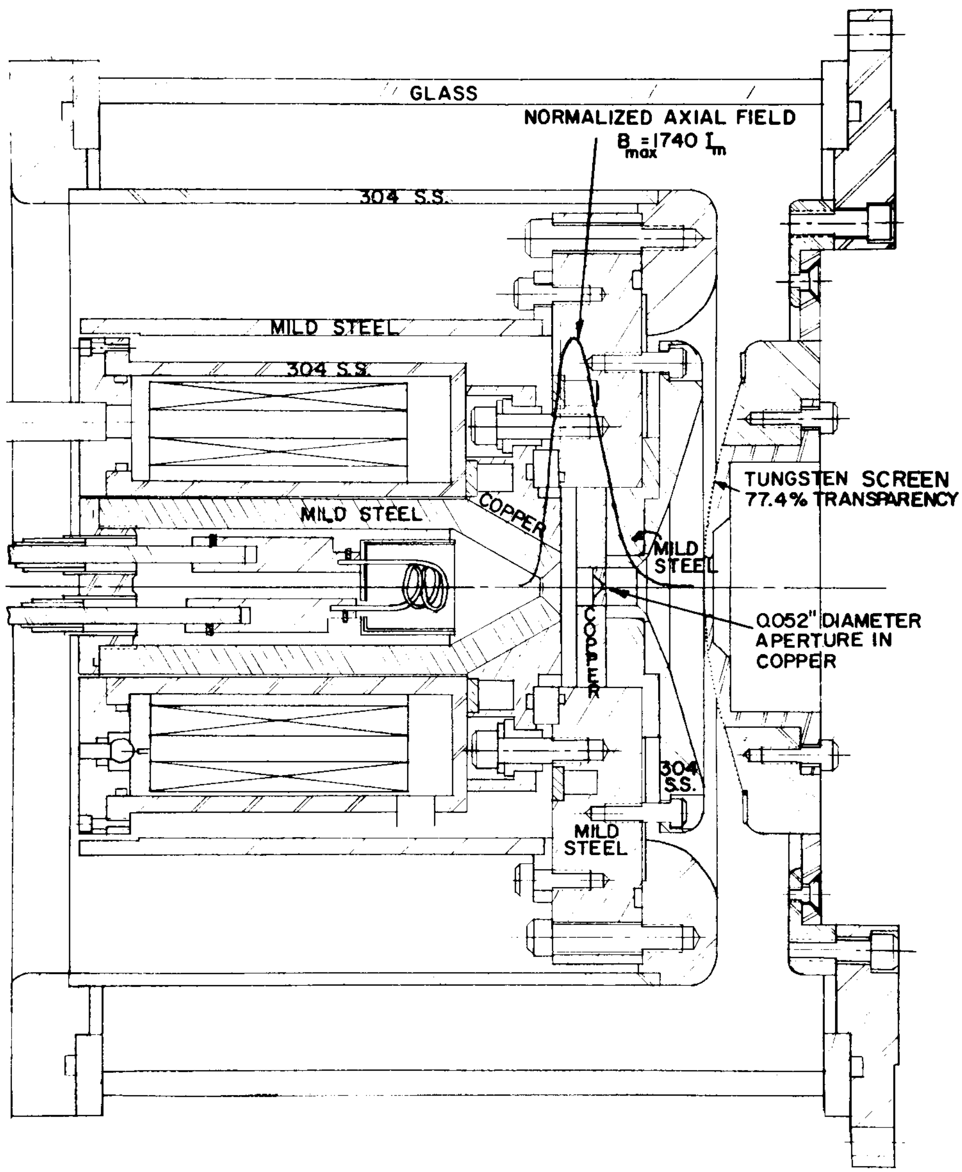

Fig. 1 The drifting arc duoplasmatron of reference 5. (Source I.)

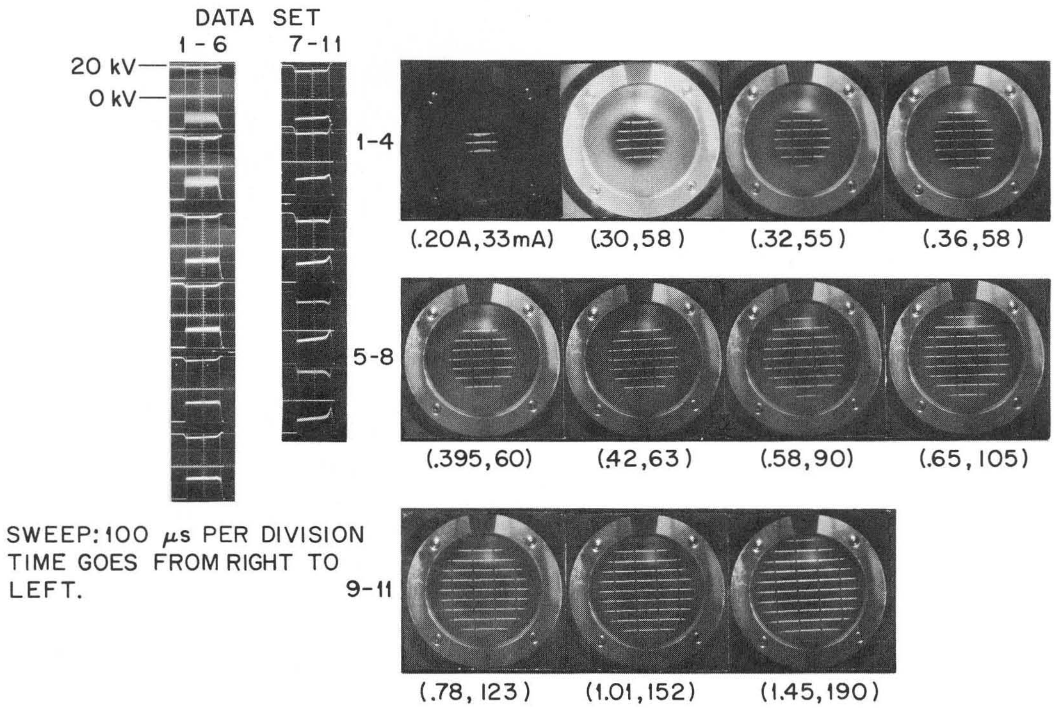

Fig. 2 Variations in beam current, etc., with increasing magnet current in Source I. Source pressure (uncorrected gauge reading): 200 μ. Arc current: 48 A. Extraction voltage: ~ 18kV. Magnet current (A) and Beam current (mA) are bracketed.

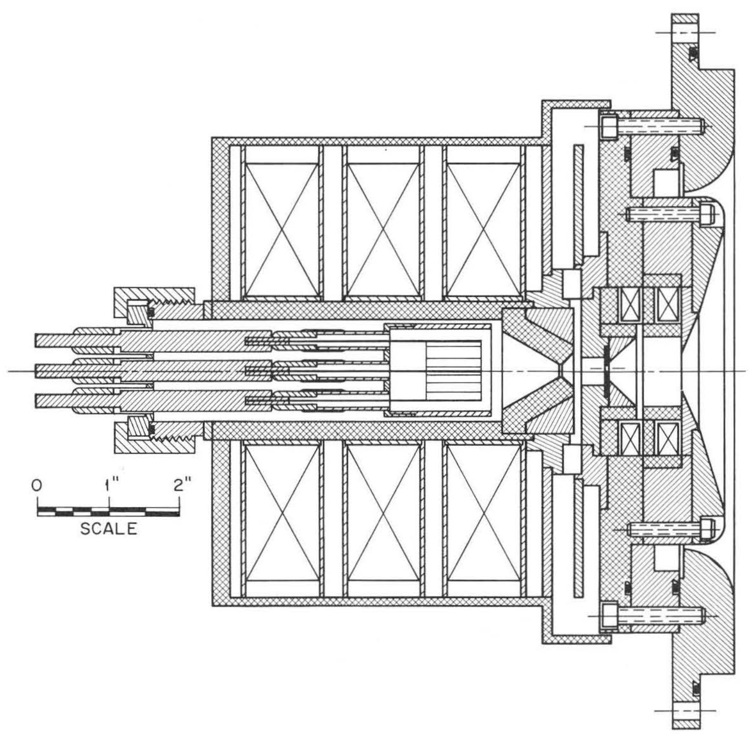

Fig. 3 The shaped field drifting arc duoplasmatron of reference 6. (Source II.)

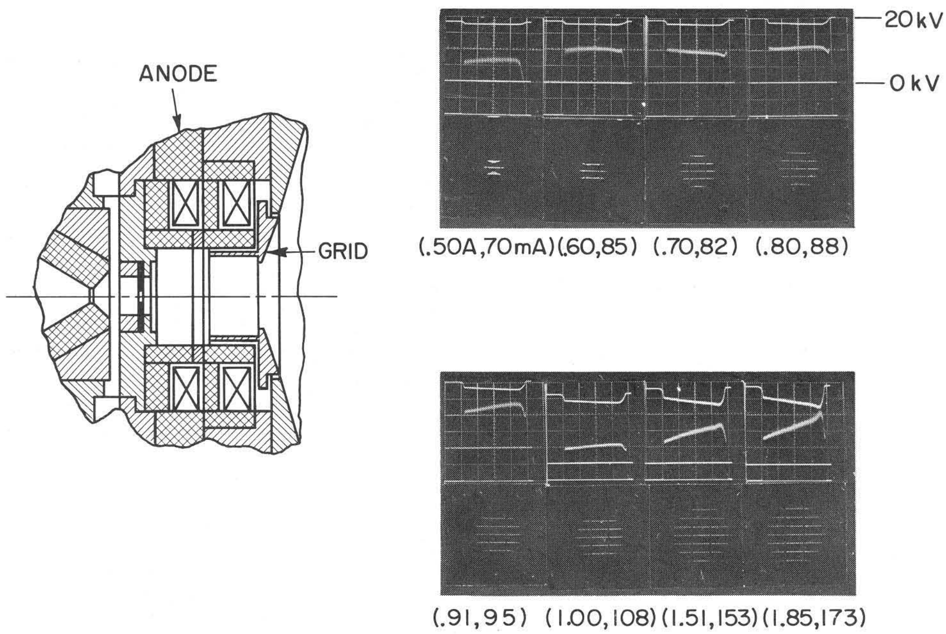

Fig. 4 Variations in beam current, etc., with increasing magnet current in a rudimentary extended stationary arc duoplasmatron. (Source III.) Grid insulation is not shown. Source pressure: 270 μ (typical for Source II, also). Arc current: 40A.

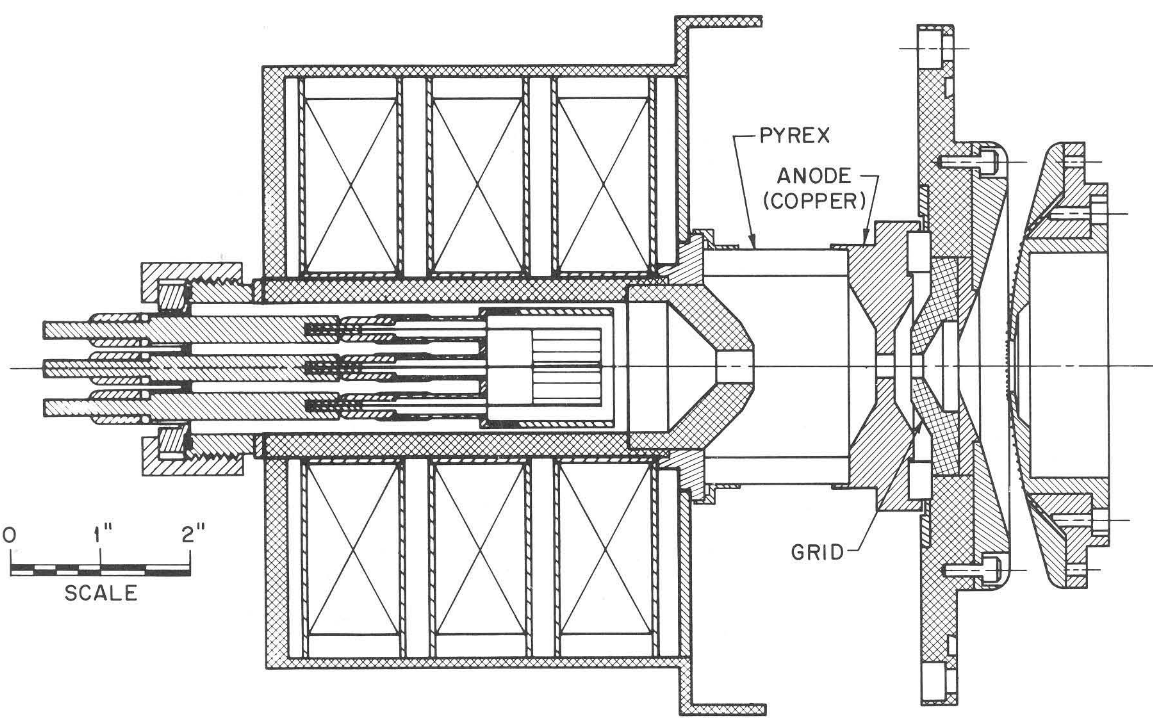

Fig. 5 An extended stationary arc duoplasmatron. (Source IV.)

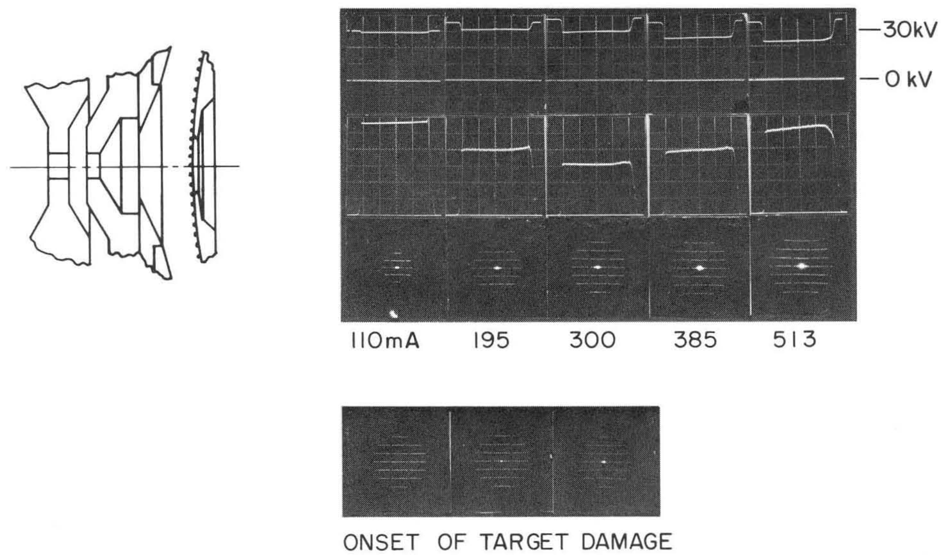

Fig. 6 Onset of damage to aluminized glass plate due to arc turn-off failures during bakeout run, and some results of tuning for flat-topped beam pulses in Source IV.

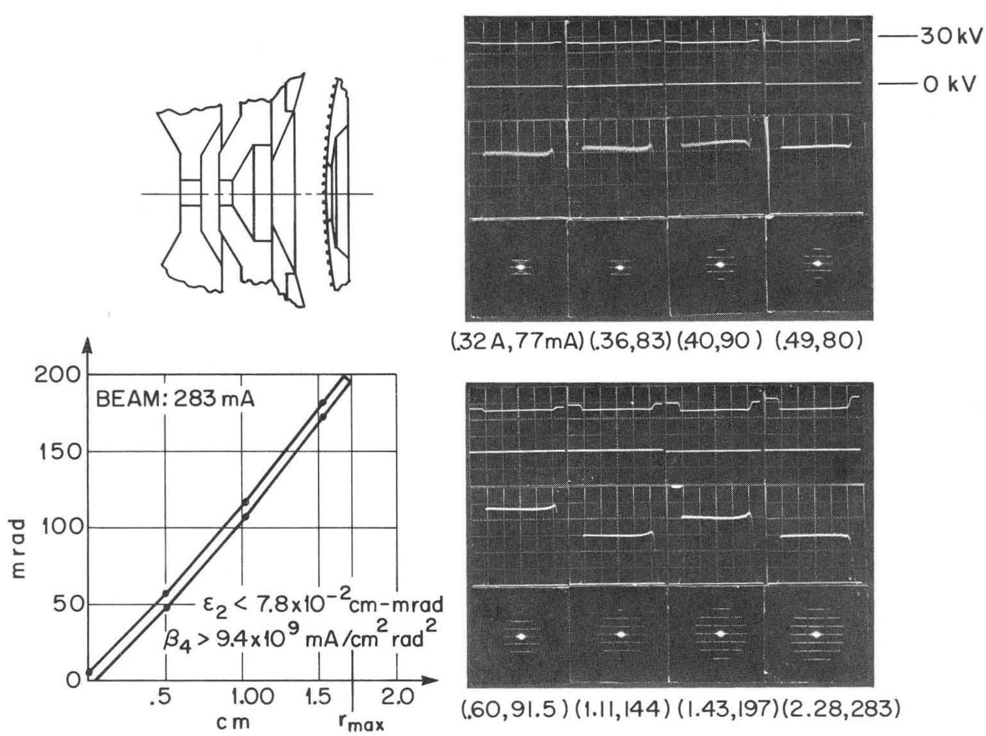

Fig. 7 Variations in beam current, etc., with increasing magnet current in Source IV. Source pressure: 83 μ. Arc current: 24A.

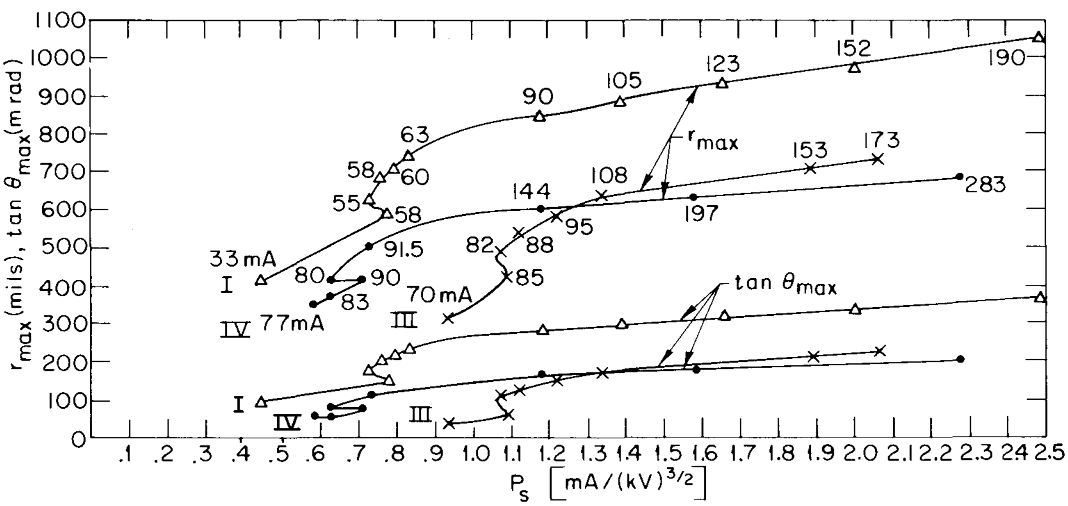

Fig. 8 Beam characteristic curves (beam radius and divergence vs. perveance) for Sources I, III and IV. Curves obtained from data shown in Figs. 2, 4 and 7. Source pressure, arc current and extraction voltage are constants in each experiment.