# A PENNING DISCHARGE ION SOURCE FOR HIGH BRIGHTNESS *

G.W. Bennett and C.M. Turner
Brookhaven National Laboratory
Upton, L.I., New York

## Summary

The development, characteristics and emittance of the Penning discharge ion source used in the Cosmotron injector are described. The maximum value of brightness reported is 3 x $10^{12}$ mA $cm^{-2}$ $rad^{-2}$ at 78 mA total current, 23 keV beam energy. The results are superior to recent values for duoplasmatrons from various laboratories, except for total current.

## Introduction

### Historical Background

The first pulsed proton source to achieve currents greater than 1 mA for injection into an accelerator was the Penning cold cathode source (or Phillips ion gauge source). It was developed by Gow and Foster[1] in 1948 for use in the Van de Graaff injector for the Berkeley 30 MeV proton linear accelerator. Figure 1 shows the essential features. A Penning discharge is established in the volume defined by the soft aluminum cathodes and anode, in the presence of an axial magnetic field produced by a solenoid. They concluded that this type of source was limited to output currents of the order of a few mA.

This source was adopted virtually unchanged for incorporation into the Van de Graaff injector for the Cosmotron, when it was fabricated in 1949 and 1950. Initially it was capable of injecting about 0.75 mA of protons. After a long series of modifications over the years this source has been developed to the point where the Van de Graaff was routinely injecting 18 - 20 mA of protons at 3.6 MeV when Cosmotron operations were terminated on 31 December 1966. This intensity was determined more by practical considerations of reliability and gas flow through the 12 ft. acceleration tube than more fundamental factors. Test stand outputs of up to 500 mA total ion current were demonstrated over 10 years ago. Reliability of the source is indicated by uninterrupted service lifetimes of 1500 to 3000 hours.

### Details of the Source

Figure 2 shows the source geometry in use when operation of the Cosmotron was terminated. The following changes are to be noted: 1. A much more generous probe insulator permits the use of extraction voltage of at least 30 kV without breakdown. 2. Tantalum has been substituted for aluminum in the front cathode, allowing the cathode to be much thinner. This permits the introduction of "close coupled" extraction geometry, where the emphasis is on getting the extraction field as close as possible to the plasma in which the ions are generated. 3. Recently the plasma density at the orifice, and cathode life, were increased substantially by making the rear cathode reentrant into the anode. 4. The probe tip is made of platinum for longer life.

### Extraction

The close coupled extraction geometry has been in routine use for the last four years. With this geometry extraction takes place from the unperturbed primary plasma. With the duoplasmatron the plasma is first compressed magnetically to increase its density at a small orifice (small so as to reduce the transport of neutral gas). After passing this orifice the plasma is expanded to avoid the excessively high fields that would be required for extraction at the orifice.

The probable causes of reduction in brightness in a source are: 1. Non-uniform curvature of the plasma boundary from which extraction occurs, and 2. Departure from uniform radial charge density in the extracted beam. The close coupling scheme minimizes the space charge effects by rapid acceleration-with consequent reduction in charge density - and by allowing the beam to expand after extraction. It also minimizes non-uniform curvature of the plasma boundary by using the thinnest orifice diaphragm consistent with stability and durability requirements, thus eliminating edge effects at the orifice.

## Instrumentation

### Technique

Following incorporation of the close coupled extraction geometry it was observed that surprisingly sharp shadows, of 4 mil diameter grid wires in a focussing element, were cast by the ions. An estimate of the emittance gave a value substantially less than that being reported at that time for duoplasmatrons. While the standard technique for measuring emittance has been to observe the divergence of a thin segment of beam, this observation suggested the alternative procedure of observing the divergence of the shadow cast by a thin object occulting the beam. Analysis shows that space charge errors are virtually eliminated with the latter technique whereas such errors are often a dominant factor with the former.

### Test Stand

The emittance characteristics of the Cosmotron source were studied using the test stand depicted in Figure 3. An ion source assembly is mounted on the end of a vacuum chamber 8 inches ID, 4 feet long. The chamber is fitted with various ports for scanning wires, Faraday cups, fluorescent screen, etc. For the original measurements a sheet of Tantalum 2 mils thick, which had 10 mil square holes machined in it by an Electric Discharge Machine, was placed about 6 cm from the probe orifice. An image of these apertures was cast by the transmitted beam on a mylar film 9 cm downstream. Microscopic examination of the aperture plate and its image showed that details of the rather jagged apertures, with dimensions less than one mil, were faithfully reproduced, and there was no measurable penumbra. This gave an upper limit of 200 mm-mrad for the emittance area. The need for much higher magnification instrumentation was also apparent. The final measurements were made using an aperture of 0.010 inches by 0.70 inches using stainless steel razor blades. This aperture was crossed by 2 mil Nichrome wires spaced 10 mils apart. The aperture plate was "mapped" with a travelling microscope before it was positioned inside the probe electrode housing. The transmitted beam was scanned by a 3 mil wire electrode located 41.5 in downstream. The wire electrode was mounted on a threaded shaft allowing it to be positioned to better than 1 mil. The intensity of the beam impinging on the wire was measured by connecting it to an operational amplifier, the output of which was viewed on an oscilloscope. This arrangement kept the potential of the scanning wire at the virtual ground of the amplifier input to minimize perturbation of the beam. Collimating apertures were fitted in the vacuum chamber to prevent any beam from hitting the chamber walls in the vicinity of the scanning wire. The fluorescent screen allowed a visual check on the parallelism of the aperture grid wires and the scanning wire, as well as the location of the scanning wire relative to the beam shadows. With no focusing fields after the extraction electrode, the unoccluded beam at the location of the scanning wire would be 12 - 15 inches in diameter, larger than the ID of the vacuum chamber. For this reason the outer radial half of the beam was studied after mounting the source on a 5° wedge shaped shim. Axial symmetry of the beam was assumed.

A portion of a typical beam scan is shown in Figure 4, and the emittance diagram for the complete scan is shown in Figure 5. The angular dispersion (difference in $\alpha_r$) at each wire is the average 10% to 90% width of the shadow of each side of the wire, divided by the distance from aperture to scanning electrode. The relative radial location of each wire was determined from the observations with the travelling microscope, absolute radial location was measured with respect to the center of the beam.

## Total Current Measurement

Total ion current from the source was determined by measuring the pulsed probe current. The probe electrode, with aperture plate inserted, serves as a good geometry Faraday cup, because of the location and opacity of the plate. Secondary electron emission was negligible as long as the probe voltage was higher than about 15 kV so that the ions did not strike the probe electrode entrance canal.

## Beam Composition

The composition of the beam was studied by putting a plate with a single small aperture inside the probe housing, followed by a magnet to disperse components with differing charge to mass ratio. Protons typically represented approximately 75% of the total charged beam.

## Arc Pressure

A thermocouple gauge, corrected for hydrogen and mounted on the gas feed line close to the source, was used to measure the arc pressure. No correction was made for the impedance of the connecting tubing.

## Results

The apparatus allowed the probe voltage, arc current and pressure to be varied readily. Emittance measurements for various values of these parameters are tabulated in Figure 6. All measurements were made using the standard, high reliability Cosmotron source then in use, i.e., as shown in Figure 2 but without the reentrant rear cathode. The range of the variable parameters was restricted to be near normal injection values, those of Column A, Figure 6. The emittance results imply that the particles originate from a virtual source less than 1 mil in diameter located just inside the anode.

## Comparison with Duoplasmatron

Recent experience has shown [2,3] that emittance area of an accelerated beam does not scale with its axial momentum; the transverse phase space occupied by the beam is generally diluted with acceleration. For this reason it is not instructive to compare beam emittances if the axial momenta differ significantly. Duoplasmatron brightness values, reported for beam energies less than 50 keV are compared in Figure 7 with the results reported here. It is to be noted that the average of the results for the "close coupled" Penning source are brighter by a factor of 10 over the highest figure noted for a duoplasmatron.

## Conclusion

The Penning discharge ion source reported here has superior qualities of emittance, brightness and reliability. It is shown to be competitive with duoplasmatrons and warrants further development and application. Tests are in progress with this source in a modification of the Cosmotron injector to determine its emittance at 750 keV.

## Acknowledgement

This work reflects the skill, patience and cooperation of W. French, E. Lange, W. Jordan and P. Hichborn. We acknowledge their efforts with gratitude.

References

1. J. Gow and S. Foster, R.S.I. 24, 606 (53)
2. H. Wroe, Proc. of Lin. Acc. Conf., 1966, LA 3609, P. 394.
3. Brookhaven National Laboratory Accel. Dept. Internal Rept. GWB-6, by G. Bennett, Mar. '66.
4. J. Faure, Internal Rept., SEFS TD 64/3, "Source a Grande Brillance".
5. Brookhaven National Laboratory Accel. Dept. Internal Rept. HW-2, by H. Wroe, Feb. '66.
6. Th. Sluyters, Proc. of Lin. Acc. Conf., 1966, LA 3609, P.383.

* Work carried out under contract with the U.S. Atomic Energy Commission.

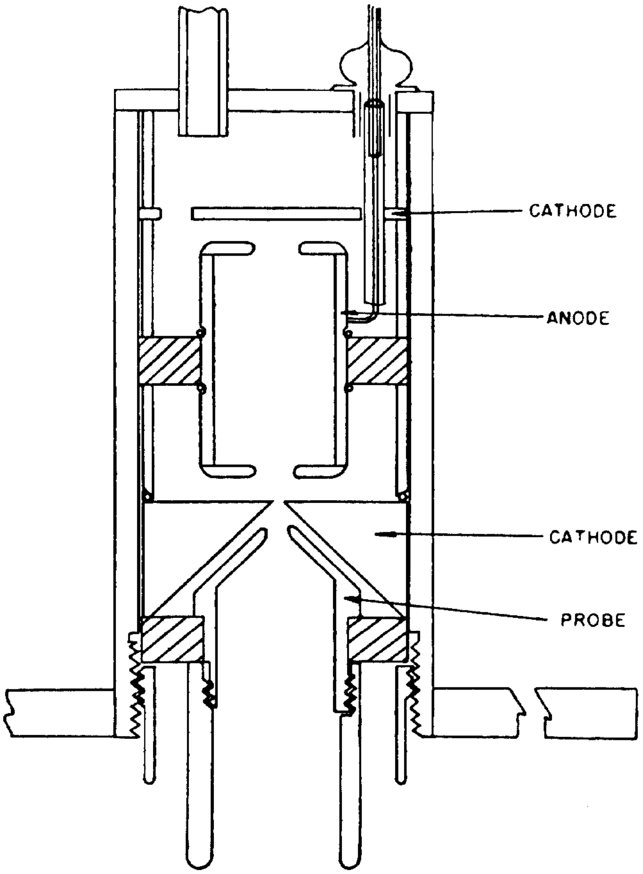

Fig. 1. Penning source developed by Gow and Foster (Ref. 1).

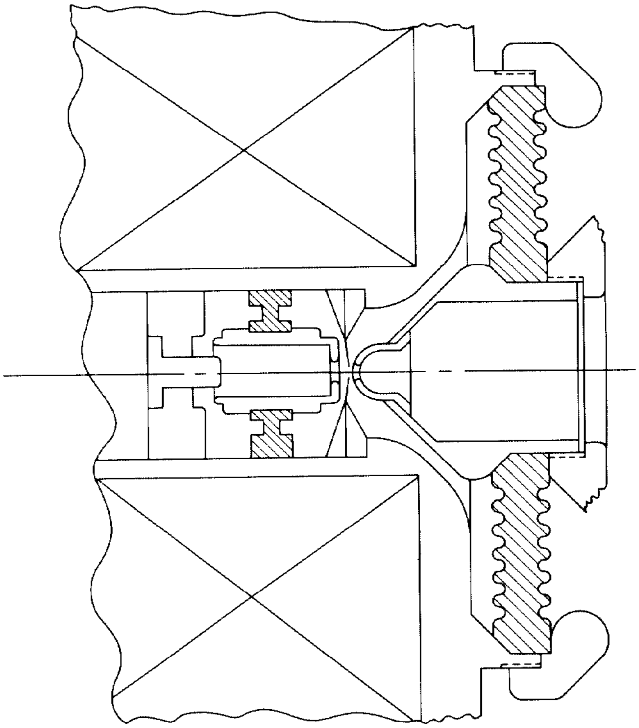

Fig. 2. Penning source developed for Cosmotron Injector.

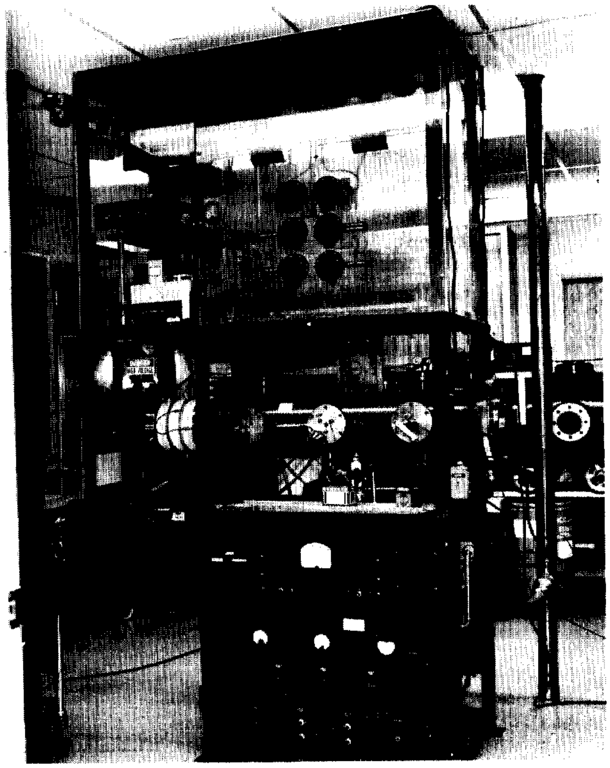

Fig. 3. Ion source test stand.

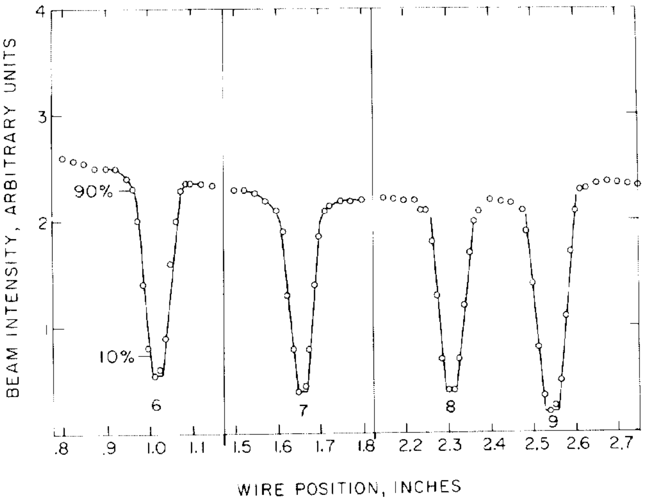

Fig. 4. Profile of a portion of beam transmitted by aperture plate, showing wire shadows. Wire 9 is 3 mils diameter, others are 2 mils. Conditions are those of column E, Fig. 6.

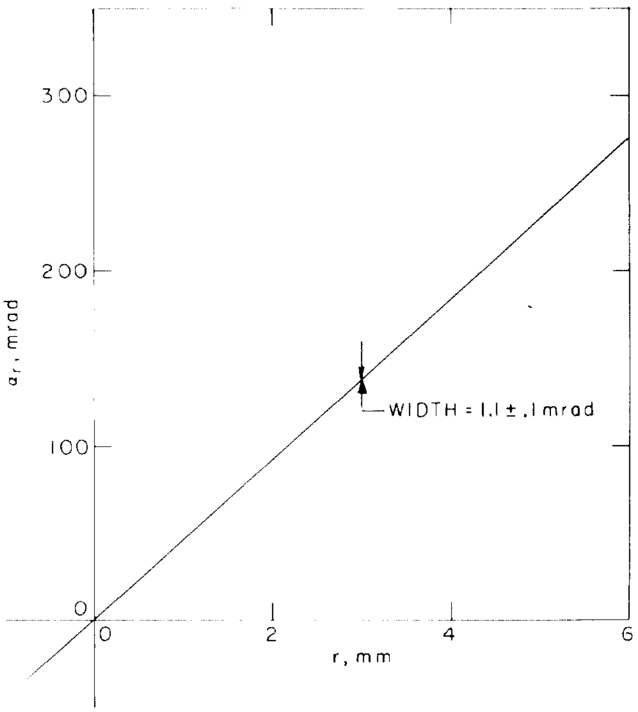

Fig. 5. Emittance diagram for conditions of column E, Fig. 6.

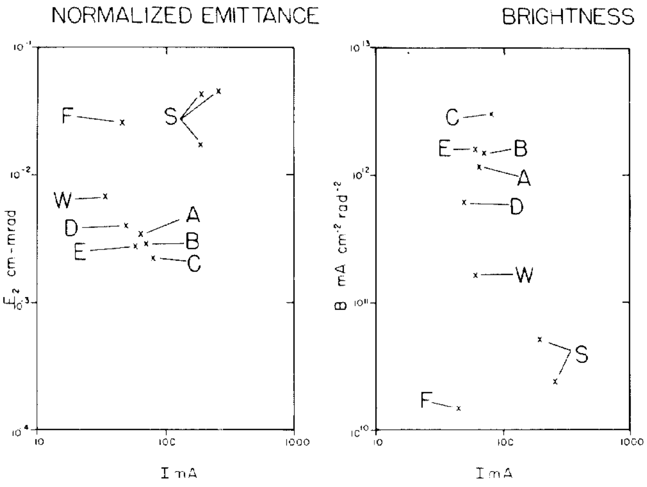

Fig. 7. Plot of Normalized Emittance and Brightness vs. Current for Cosmotron Source (Points A-E) and Duoplasmatron sources, with beam energy less than 50 keV. Point F, Faure-Ref. 4; Point S, Sluyters-Ref. 5; Point W, Wroe-Ref. 6.

| Column | | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Ion Current | mA | 65 | 67 | 78 | 50 | 60 |
| Probe Voltage | kV | 20.5 | 20.5 | 23 | 18 | 21 |
| Arc Pressure | μ | 320 | 315 | 300 | 320 | 170 |
| Arc Current | A | 2 | 3 | 2 | 2 | 2 |
| A = Emittance Area cm-mrad | | 1.60 | 1.44 | 1.02 | 2.01 | 1.30 |
| $E_2$ = Norm. Emittance cm-mrad, ($E_2 - A\beta\gamma/\pi$) | | $3.36\text{x}10^{-3}$ | $3.03\text{x}10^{-3}$ | $2.27\text{x}10^{-3}$ | $3.95\text{x}10^{-3}$ | $2.77\text{x}10^{-3}$ |
| B = Brightness $\frac{\text{mA}}{\text{cm}^2\ \text{rad}^2}$, ($B = \frac{2I}{\pi^2 E_2^2}$) | | $1.17\text{x}10^{12}$ | $1.49\text{x}10^{12}$ | $3.04\text{x}10^{12}$ | $6.5\text{x}10^{11}$ | $1.58\text{x}10^{12}$ |

Fig. 6. Table of Emittance and Brightness for various conditions of the Cosmotron Source.