HIGH CURRENT DC ION BEAMS*

George G. Kelley
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Summary

The beam systems which have been developed for use in high energy injection experiments in thermonuclear research are described. An attempt is made to compare the quality of these beams (not the relative merit of the injection systems). Problems peculiar to the production of intense dc beams are discussed.

Introduction

At the present time intense dc ion beams are used both in isotope separation and in experiments leading to controlled thermonuclear power. This paper will deal only with the latter application. In one kind of experiment a plasma containing very energetic ions is built up by trapping previously accelerated particles in a suitably shaped magnetic field. The major devices of this kind are the OGRA's at the Kirchatov Institute in Moscow, the PHOENIX experiments at the Culham Laboratory in England, the MMII device at Fontenay-aux-Roses, France, the ALICE experiments at Lawrence Radiation Laboratory in Livermore, California, and the DCX experiments at the Oak Ridge National Laboratory in Oak Ridge, Tennessee.[1,2] The injectors used in these experiments will be described briefly, and problems peculiar to the production and handling of dc beams will be discussed.

The interaction between this work and the development of preinjectors for high energy accelerators has been considerably less than might be expected at first thought. Several factors have been responsible for the separation of these two fields. In the first place, there has been a different point of view. A preinjector must be tailored to a device whose ion optical properties have been carefully worked out. The preinjector must produce the maximum possible beam in a particular region of phase space. On the other hand, the thermonuclear devices have requirements which depend primarily on a particular spatial limitation of the beam. Usually all of the current entering the magnetic trap is useful. In the second place, preinjectors work with short pulses of current reducing the problems of heat dissipation but preventing the buildup of an electron population to reduce the dispersive force of space charge. The emittance figure found using short beam pulses does not apply when the beam remains on long enough to become neutralized (several hundred μs at typical pressures). Detailed measurements are difficult on intense dc beams. In view of the difference in both the nature of the problems to be solved and in the methods used for evaluating performance, the amount of interaction is understandable. Some very important problems, such as column design, and the control of the shape of the ion emission surface at the source, are common to both fields, however.

Evaluation of Performance

The true emittance and brightness of a beam depend only on random motions of the particles. Wroe has shown that when the brightness is measured properly directly after extraction, it has the value expected from the temperature of the ions in the source--much higher than would be inferred from previous measurements.[3] Since this quantity is invariant in a steady beam for rays at small angles to the axis (so that the axial and transverse motions are uncoupled) any decrease in measured brightness must be due to time dependent effects. These effects are likely to be important, if at all only in space charge-neutralized beams. Improvements in performance must come then from improved beam optics.

In order to make a rough comparison of the performance of the various systems to be described in this paper, we shall use an effective brightness which is the ratio of current density to the maximum possible angular spread of the particles, normalized to a constant accelerating voltage and constant mass. It is defined as follows:

$$B = \frac{720\ AI}{V\ h_2\ w_2\ h_1\ w_1/L^2} \tag{1}$$

for ribbon beams and

$$B = \frac{900\ AI}{V\ d_2^2\ d_1^2/L^2} \tag{2}$$

for beams of circular cross section where A is the mass in amu, I is the current in mA, V is the accelerating voltage in MeV, h_1 and w_1 are the height and width of a defining aperture, a distance L from the exit aperture, which has a height and width h_2 and w_2. For circular beams d_1 and d_2 are the corresponding diameters. Dimensions are in cm. This quantity differs from the true brightness as defined by van Steenbergen[4] by the assumption that the rays at all points of the exit aperture diverge at the maximum angle defined by the presence of another limiting aperture. The number grossly underestimates the true brightness since there is evidence that beams are in general much more highly organized. The values obtained should not be taken too seriously since they depend sensitively on the convergence angle which is not well known and which should really be a

*Research sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

weighted average across the exit apertures. Also they do not measure the relative merits of the systems as injectors because other factors are involved.

Crossed Field Extraction

General

The injectors used in the OGRA and ALICE experiments obtain ions from the source plasma by diffusion across a strong magnetic field. In the source itself, an arc runs along magnetic field lines from a heated filament. There are apertures defining the electron stream to produce a ribbon of plasma which is located very close to the exit aperture. The plasma density in these crossed-field sources is insufficient to prevent the passage of neutral gas in the source through it, and the resulting gas efficiency is rather low (approximately 20% or less). Large pumps and long beam paths with differential pumping are required to prevent excessive pressure in the beam region.

The OGRA's

The injectors for the OGRA devices are alike except for the addition of a neutralizing cell and analyzing magnet in OGRA-II to provide a beam of neutral atomic hydrogen.[5,6,7] Figure 1 shows the essential features of these injectors. Some spreading of the beams is believed due to fluctuations arising from instabilities in the ion source. This difficulty is common to all of the ion sources used. It is dealt with at some length by Artemenkov et al.,[7] and by Kistemaker et al.[8] The Russian workers state that by proper adjustment of the gas flow to the source, the modulation of the beam can be reduced to 15 to 20%.

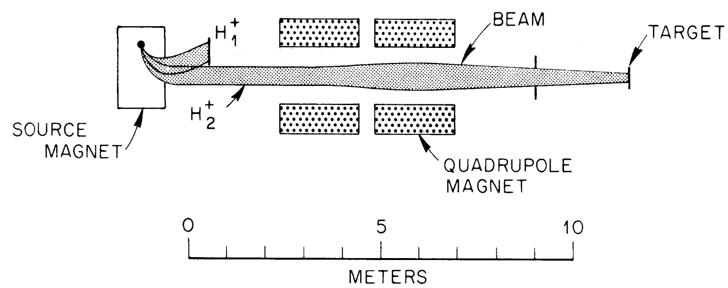
The value of the effective brightness of the OGRA-I beam was calculated using reported values of 155 mA of molecular ions at 160 kV through a 36 cm^2 aperture at a reported convergence angle of 5°. It is

$$B = \frac{720 \times 155 \times 2}{0.16 \times 36 \times 7.9 \times 10^{-3}} = 4.9 \times 10^{6}$$

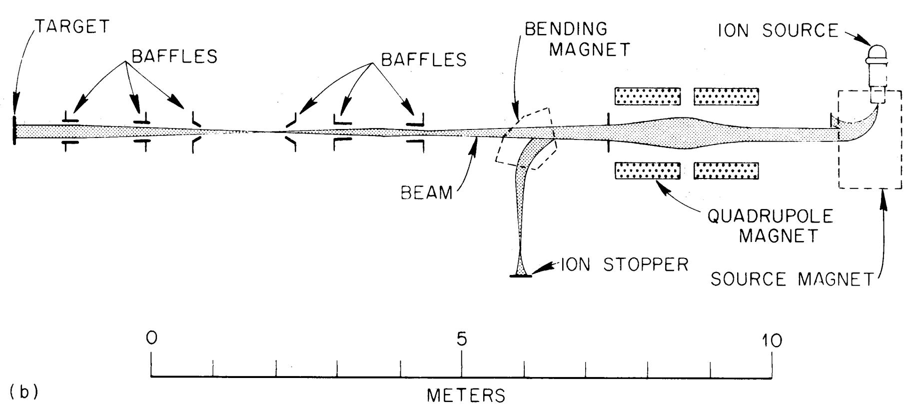
The size of the limiting aperture has not been reported.

ALICE

The crossed field sources at LRL are used to produce neutral beams at considerably lower energy.[9] A typical arrangement is shown in



(a)



(b)

Fig. 1 - The OGRA Injectors. (a) OGRA-I. The beam is limited by a 6 x 6 cm aperture at the target, which is actually the point of entry into the magnetic trap. (b) OGRA-II. The smallest aperture, where the beam is smallest, is 4.5 x 10 cm. The maximum H_o current through this aperture is 26 ma. The scales shown are approximate.

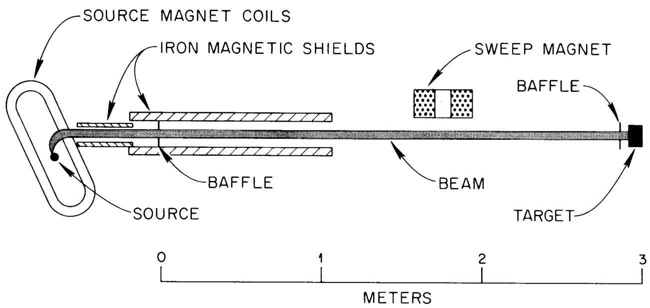


Fig. 2 - The ALICE Injector.

Figure 2. The source has an arc cross section of 0.125 in x 0.3 in and an exit slit of 0.102 in x 3 in. A typical extraction gap is 0.06 in. More recent design uses an ion source slit of 0.170 in x 2.5 in. This source produces 50 mA equivalent current of 20 keV H_0 through a 2.0 x 5.1 cm baffle $11\frac{3}{4}$ ft from the source. The effective brightness calculated from this information and the assumption that the beam width remains constant is

$$B = \frac{720 \times 74}{0.02 \times 2 \times 5.1 \times 2 \times 5.1/360^2}$$

$$= 3.3 \times 10^9$$

Extraction in Axial Magnetic Fields

General

The PHOENIX experiments at Culham and the DCX's at Oak Ridge use a beam derived from ions from a duoplasmatron source.[10] This type of source has the advantage of considerably greater gas efficiency because of the high density and high degree of ionization of its plasma, but it is at some disadvantage at low extraction voltages because it is adapted only to the production of axisymmetric beams. The crossed field sources produce ribbon beams whose total output can be increased by increasing the length of the extraction slit. There is a fundamental limitation, however, with axisymmetric beams. The current density in a beam due to space charge limitation of the current at the surface of the plasma is given by

$$j = \frac{5.44 \times 10^{-8}\, V^{3/2}}{A^{1/2}\, z^2} \qquad (3)$$

where j is the current density in amperes/cm^2, V is the extraction voltage, A is the mass number in amu, and z is the spacing between electrodes in cm. This formula applies in the case of a beam of infinite cross section or in Pierce geometry.[11] It is a good approximation in general if the beam diameter is comparable to the length of the extraction gap. The ions are assumed to be emitted at zero velocity. The total current then in a beam is

$$I = \pi r^2 j = \frac{5.44 \times 10^{-8}\, \pi\, V^{3/2}}{z^2/r^2} \qquad (4)$$

The denominator is seen to be a factor depending on the geometry of the extraction gap. If the gap is much smaller than the diameter of the beam, the extraction field is very nonuniform with respect to radius and the beam is badly distorted. Thus for a given degree of distortion, the total current depends only on $V^{3/2}$. In other words the perveance is fixed. A ribbon beam suffers this same restriction across its width, but its area can be much greater. The above formula can be used to predict the maximum current of ions from the source that can be handled at a given extraction voltage without beam loss to the extractor. A correction must be made for the presence of the extractor hole, however. It has been found empirically that the formula

$$I = \frac{5.44 \times 10^{-8}\, \pi\, V^{3/2}}{A^{1/2}\, (z + r)^2/r^2} \qquad (5)$$

predicts the maximum current usually to better than 5%.[12] The graph shown in Figure 4 is simply a plot of the predicted current for a beam in which the extraction gap length is equal to the diameter of the extraction aperture.

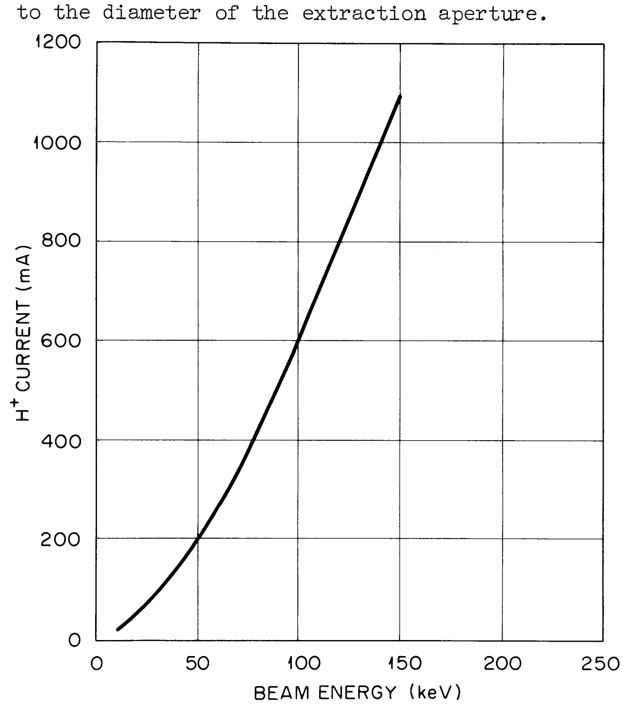


Fig. 3 - Maximum Current Expected from an Axial Field Source without Gridded Apertures.

Somewhat more current than indicated can be obtained, but the quality of the beam deteriorates rapidly with increased current. Grids at the source aperture and the extraction electrode can eliminate this restriction, but heat dissipation problems make their use difficult at low extraction voltage and impossible above about 20 kV. The source gas efficiency is impaired by the use of grids because of recombination of the source plasma on the grid structure.

When a duoplasmatron is operated at high gas efficiency, the plasma density at the source anode aperture is about 10^{14} ions/cm^3 and the ions have an outward directed velocity of greater than 10 eV. The result is a plasma flow equivalent to a current density of up to 100 A/cm^2. At the same time, the extraction current density is determined by space charge (Equations 1 and 2), and in most cases, is less than about 3 A/cm^2. The plasma then must expand as it leaves the aperture until it has formed itself into a configuration in which the current is space-charge limited at all points on its surface. In order to prevent ion emission from the sides of the resulting bubble, a cup is provided to expose only the expanded front surface of the plasma to the extraction field. The control of the shape of this surface probably is the biggest problem in beam technology. The amount of expansion allowed and the strength of the extraction field which is most desirable, depends on the relative importance of the initial diameter of the beam and the effect of space charge forces in it. When the beam is accelerated to very high energy as rapidly as possible, it usually is best to use the maximum possible electric field consistent with high voltage technology and the smallest possible initial beam diameter. At low energies a larger initial beam may produce a greater intensity at a distance from the source.

For values of perveance up to about 2×10^{-10} A/V$^{3/2}$, corresponding to a current of 100 mA at 80 kV, electrostatic focusing by means of a unipotential lens can be used. Higher perveance beams require the use of magnetic lenses. The dependence of the focal length on mass in these lenses permits separation of mass species by apertures. In all cases when it is desired to obtain a beam of the highest possible current density, the lens should be as close to the source as possible. Both the PHOENIX injectors and the DCX injectors use solenoidal magnetic lenses. In every case the ion source is in the stray field of this lens, and special attention must be paid to the field which exists at the plasma emission surface. Compensating coils are required to optimize performance. This subject will be discussed in more detail below.

Fluctuations in the current from these sources usually can be held below 10% peak to peak by proper adjustment of gas flow and magnetic field.

PHOENIX

The PHOENIX-II injector[13] has a beam path shown in Figure 4. It can pass 50 mA of H_2^+ at 40 keV through a 4.6 cm diameter aperture 300 cm from the source exit. The convergence angle is 0.02 radians. When the source is adjusted to produce an H_1^+ beam, 200 mA at 56 kV can be passed through the system. In actual use the H_2^+ beam is neutralized in a vapor cell to produce 20 keV H_o particles. The H_2^+ beam and the H_1^+ beam require 200 mA and 800 mA respectively of total power supply drain, and source arc currents of 10 A and 24 A respectively. The effective brightness for the molecular ion beam is

$$B = \frac{900 \times 50 \times 2}{.04 \times 4.6^2 \times 8^2/185^2} = 5.7 \times 10^7$$

The Oak Ridge Beams

The beam path for the DCX-1.5, DCX-3, and INTEREM experiments at Oak Ridge is shown in Figure 5.[15] The beam at 240 cm corresponds to an effective brightness of

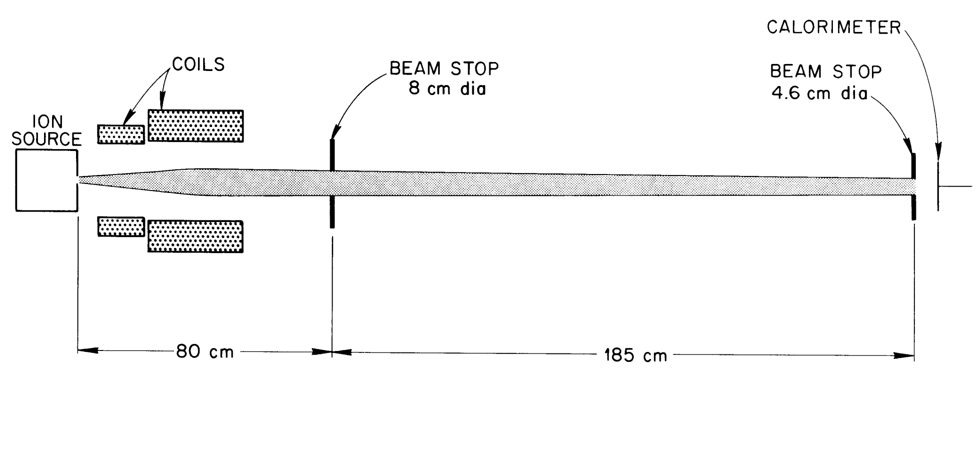


Fig. 4 - The PHOENIX Injector.

$$B = \frac{900 \times 66 \times 2}{0.04 \times 3.8^2 \times 3.8^2/184^2} = 4.8 \times 10^8$$

for molecular ions at 40 keV. These ions are dissociated in a magnesium vapor cell to produce a beam of 20 keV neutral hydrogen.

Other experiments at Oak Ridge (DCX-2) use hydrogen ion beams at 600 keV.[15] The power supply for accelerating these beams has taps at 150 kV, 300 kV, and 450 kV. The first 150 kV is supplied directly to the extraction gap. The gap spacing is about 8 mm. Acceleration is done as quickly as possible and the beam enters a solenoidal magnetic lens directly below the column. Figure 6 shows the arrangement. This system has produced a beam of 350 mA total hydrogen ion current and has produced 100 mA of H_2^+ ions through the duct shown. It has been in operation since 1960.[16]

Problems of Power Dissipation

Ion sources for the production of continuous currents of large fractions of 1 ampere require source arc currents of many amperes. As an example, 40 A of arc current were needed in a particular rather efficient duoplasmatron to produce 1 A of proton output. Cooling of the source then is a major problem, particularly in the axial field case, since most of the power is produced on an extremely small area at the emission aperture of the anode. The original duoplasmatron of von Ardenne could not be operated continuously at arc currents of greater than about 5 A. The power was dissipated on a tungsten insert and the heat was conducted from this insert to an iron anode. At Oak Ridge we found that most of the temperature drop was across the joint between the insert and the main body of the anode. In fact, it turned out that ferromagnetic material was not needed in the anode[17] and that solid copper could withstand at least 50 A of arc--the improved heat conductivity more than offsetting the differences in melting temperature. Improved cooling was needed also in the intermediate electrode. Sources of this type are described elsewhere.

Dissipation of the energy of the beam itself also presents a problem. Power densities can easily be pushed beyond the capabilities of the best available heat transfer techniques. The greatest power density can be handled by the technique shown in Figure 7.[18] The beam terminates on copper tubes in which are swaged spiral ribbons of inconel. Centrifugal force

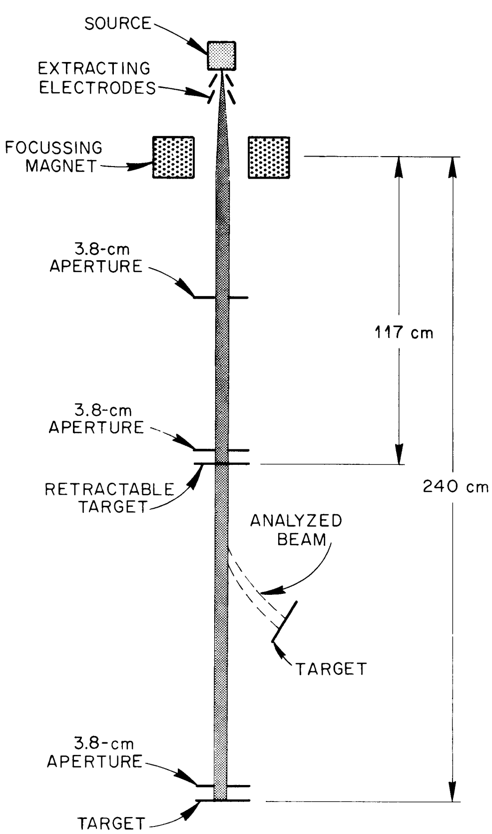


Fig. 5 - Injectors Simulating the INTEREM and DCX-3 Geometries. 140 mA and 82 mA of 40 keV H_2^+ ions are delivered to the targets at 117 cm and 240 cm respectively.

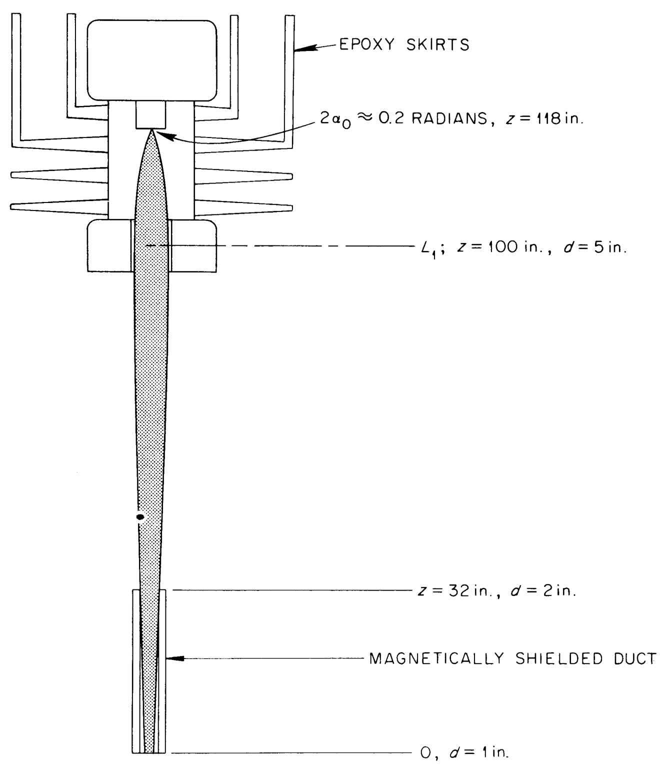


Fig. 6 - The DCX-2 Injector. The maximum beam through the duct is 100 mA of H_2^+ ions at 600 keV.

causes the water to flow in a thin film on the inner surface of the tubes at very high velocity. When the target is placed so that the beam strikes the tubes at a grazing angle, power densities of more than 6 kW/cm^2 can be sustained.

In spite of the very large amount of power carried by these dc beams, in many cases the loss to the accelerating electrodes is so small that they require no deliberate cooling. The electrodes usually are of stainless steel.

Problems of Voltage Breakdown

In all of the systems used for producing intense dc beams, there are both electric and magnetic fields within the vacuum system. Many of the problems of voltage standoff are caused by the presence of the magnetic field. In the crossed field sources, electrons formed in the extraction gap follow a trochoidal path in the fields and are intensified by cascading. These electrons cause damage to the source supports unless some means are provided to get rid of them. The axisymmetric sources can have problems too, but of a different kind. Unless great care is taken in design, there will be electrostatic potential wells for electrons constrained to follow magnetic lines of force. In such a situation the electrons drift around the axis of symmetry, under the influence of the forces due to the crossed fields. A cascading process occurs until there is sufficient plasma to cause breakdown. Figure 8 shows a design in which electron trapping regions are avoided.[19] The prototype of the source itself is due to the Sukumi group under Demirkhanov.[20] This group has done other excellent work with dc beams.[21] It is especially suited to the production of large currents (hundreds of ma) of molecular ions. This source and accelerator are used with the system of Figure 5.

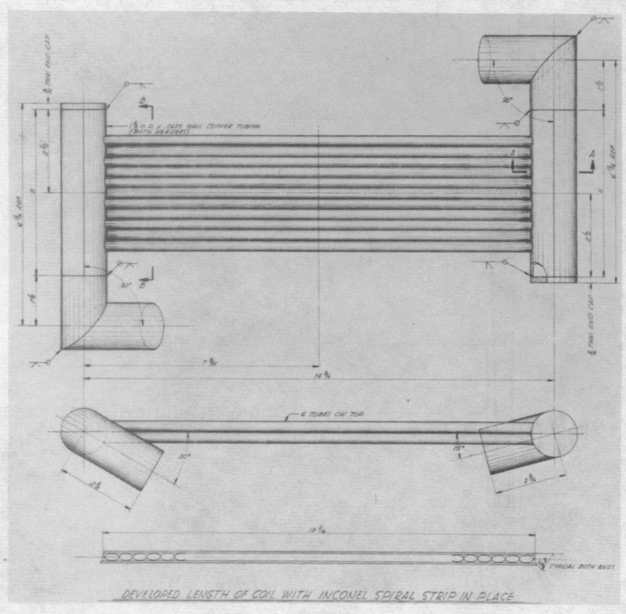


Fig. 7 - Target used for High Intensity DC Beams.

Voltage cleanup time is reduced by designing the electrodes to have a minimum amount of surface at a high electric field. It also seems to help to avoid situations where particle flight paths coincide with electric field lines. In other words, plain parallel surfaces, coaxial cylinders, and concentric spheres should be avoided. When the surface area is small, we have found that many materials, among them copper, stainless steel, nickel, and platinum, but not aluminum, will withstand at least 2 MV/cm at voltages up to 80 kV after cleanup. At higher total voltage, the CERN group has found titanium to be particularly good.[14]

The terminal equipment for the production of high current dc beams is considerably larger than that required for beams of low average power. In some cases voltages are supplied through long transmission cables. As a result, transient currents during a discharge can be much greater and may have more serious effect. These problems and some solutions are described elsewhere.[15] It is interesting and perhaps surprising that damage to source and electrodes is not a serious problem in most cases. In the Oak Ridge work breakdowns are detected electronically, but power is removed through standard commercial quick-acting disconnects, or in the case of the 600 kV (1A) supply, by means of vacuum switches in the primary. Damage is done only when there is an abnormal flood of backstreaming electrons such as produced by a vacuum failure or in the absence of an electron suppressor, to be discussed below.

Space Charge Neutralization

If the positive ion beam is allowed to be a trap for electrons, or in other words, if the electrons formed in the beam and by secondary emission from a target are kept out of regions where they can be pulled from the beam by electric fields, the beam charge will be neutralized.[15,22] The degree of neutralization will depend on how effectively the electrons are contained. It is easy to calculate the time required

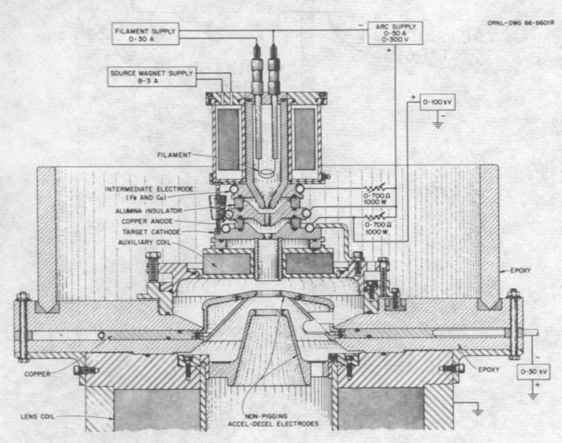


Fig. 8 - Beam Accelerating System in which Electron Trapping Regions have been avoided.

for this neutralization process assuming that electrons come from collisions with the background gas. It is simply the beam density divided by the rate of electron production per unit volume, or

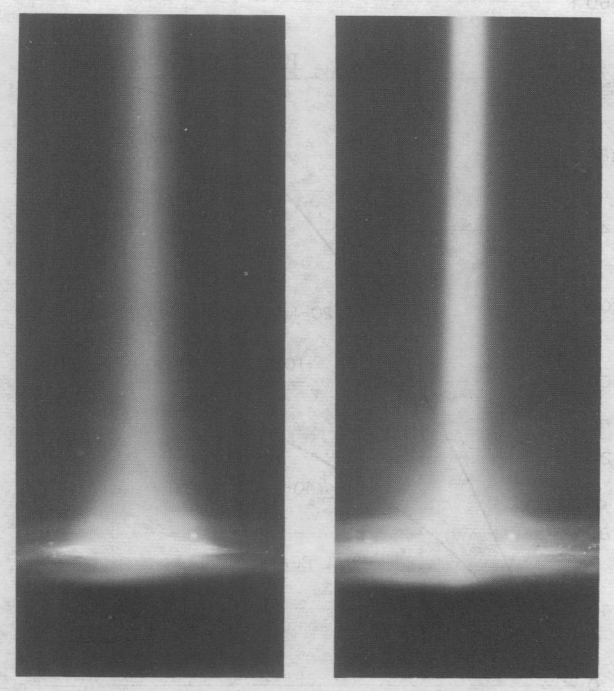
$$\tau = \frac{n_b}{n_o \sigma_i v_b \quad v_b n_b} = \frac{1}{n_o \sigma_i v_b} \qquad (6)$$

where n_b is the beam particle density, n_o is the background density, σ_i is the ionization cross section of the background gas, and v_b is the beam velocity. This time constant is about 240 μs for a 100 kV proton beam passing through hydrogen at a pressure of 2×10^{-6} torr. It depends only very weakly on energy, being about 340 μs at 20 keV.

Electrons are lost most readily in the accelerating gaps. This loss is avoided automatically by the use of a solenoidal magnetic lens for focusing. It also can be avoided by deaccelerating the ion beam before it enters the field free region. The accel-decel arrangement also is used in the OGRA and ALICE crossed-field sources, but in this case only electrons formed in the vicinity of the extraction gap are affected. The transverse magnetic field prevents migration of electrons from the drift space into the vicinity of the source.

The effect of neutralization is shown in Figure 9.[23] These beams both are 50 mA at 60 keV of total hydrogen ion current. They have been focused by a unipotential lens operated at a negative voltage with respect to the beam drift chamber so that electrons are confined to the beam drift region. In the picture on the left, electrons are being drained from the beam by a positive target bias. The beam on the right is space-charge neutralized.

When there is a beam cross-over, the neutralization fails to allow the ions to follow straight flight paths for reasons not completely understood. Figure 10 is a photograph made at Oak Ridge of a helium ion beam focused by a solenoidal magnetic lens in the region of a cross-over and beyond. The radial current distribution in this beam was studied by means of a differential calorimeter probe. We found that beyond the cross-over, most of the beam current was flowing in a hollow cone having a divergence angle about twice the convergence angle of the incoming beam. There was also an intense component in the form of a collimated rod on axis. We believe that the central rod is caused by the trapping of ions in the potential well of a virtual cathode formed by the electrons oscillating radially in the symmetrical space charge field. A 15 V potential difference can trap 30 keV ions which would otherwise be diverging at an angle of less than $1\frac{1}{4}°$. This phenomenon is particularly unfortunate since, if the ions formed the kind of cross-over expected from geometrical optics, the current density of a beam could be increased by collimating it just beyond the cross-over.



(a) (b)

Fig. 9 - A 50 mA 60 keV H_2^+ Beam; (a) without Space Charge Neutralization, (b) with Space Charge Neutralization.

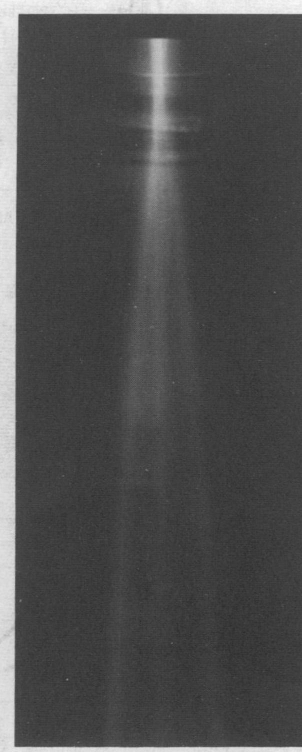


Fig. 10 - Behavior of an Intense Beam beyond a Cross-Over. The beam is composed of helium ions at 30 keV.

Control of the Emission Surface

The exceptionally high value of effective brightness for the Livermore crossed-field source may be due to the fact that the ion emission surface is controlled by the electron beam in the source and the parallel magnetic field, and is flat. The axisymmetric sources do not permit a direct control of the plasma emission surface. The problem was reviewed by Gabovich.[24] Later Gabovich et al. allowed a considerable expansion of the source plasma before extraction.[25] Books et al.[22] found that the resulting plasma surface had a central convex bulge, and that this bulge could be eliminated by making the walls of the expansion chamber conical.[26] When a strong magnetic field is present, however, the situation again is difficult. Experiments made using a small auxiliary coil around the expansion chamber to control the magnetic field at its surface yielded greatest beam intensity when the coil was adjusted to produce zero field at the surface. Another smaller optimum was found when the sense of the auxiliary coil was reversed at a value which produced a parallel magnetic field at the surface. In the null field case the symmetry of the extracted beam is disturbed easily by the effect of small assymmetries in the coils or by small stray magnetic fields.

Evidence of difficulties at the plasma surface is found in the fact that in axisymmetric systems whenever the current is maximized through an aperture, the current density is sharply peaked on axis. Figure 11 shows an example of this effect. These scans were made using the differential calorimeter probe shown in Figure 12.[27] New equipment recently designed will make it possible to study the angular distribution of the beam rays as well as the intensity distribution. It will be possible then to tell whether the fault is nonuniform emission at the plasma surface, variations in the radius of curvature of the plasma surface, or a combination of both.

Conclusion

The performance of some ion beam systems used in thermonuclear research has been described. In all cases average current densities obtained normalized to constant convergence angle have been less by more than two orders of magnitude than should be obtainable with perfect optics.

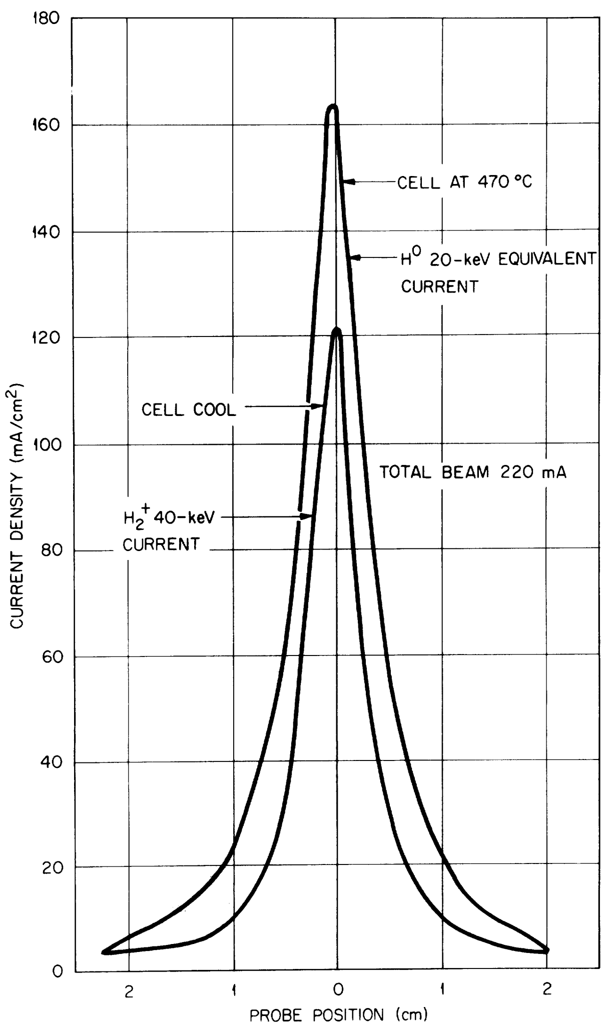


Fig. 11 - Radial Current Distribution in a Beam with Parameters adjusted to Maximize Current through a 4.2 cm Diameter Aperture.

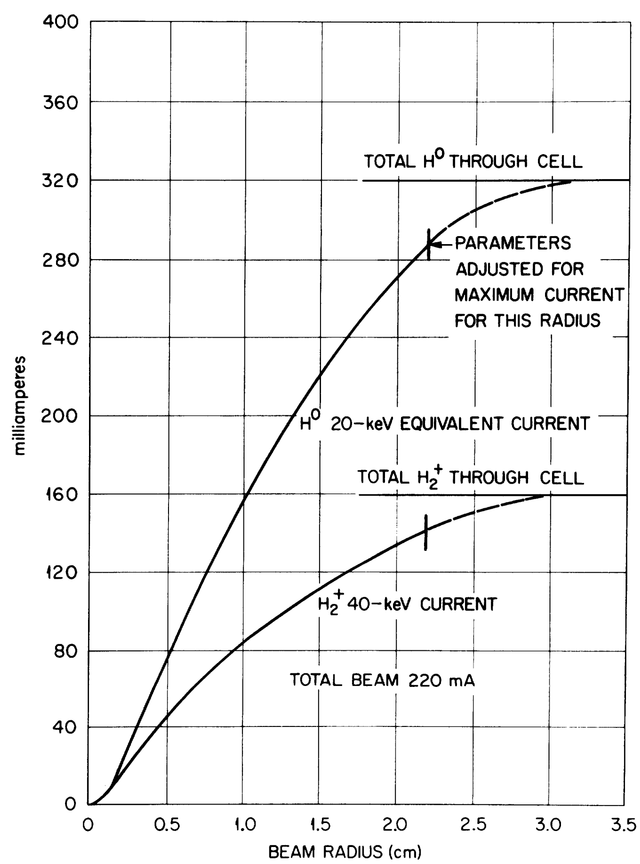


Fig. 12 - Total Current as a Function of Radius for the Current Distribution in Fig. 11.

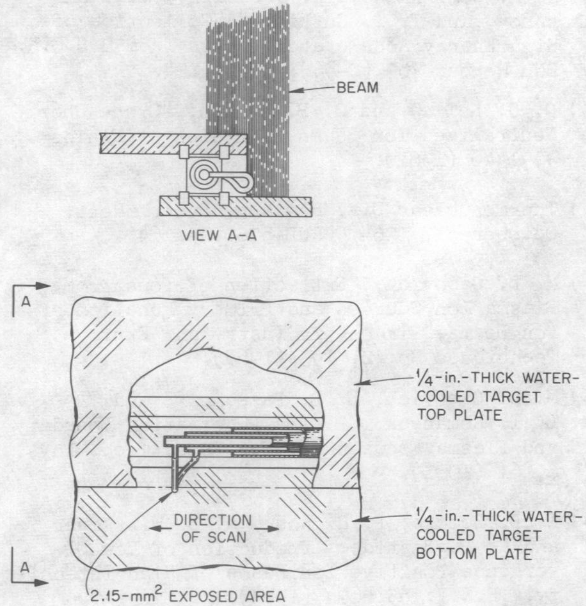


Fig. 13 - Differential Calorimetric Probe used for Obtaining Results shown in Fig. 11.

This effect can be seen by substituting kT/V for $(d_1 + d_2)^2/L^2$, the square of the convergence angle, into the formula for effective brightness. Here kT is the ion temperature in eV at the emission surface, which is probably less than 1 eV. The conclusion is also born out by the experiments of Wroe and others.[3,28] Fluctuations in the ion current emitted from the source affect intensity since they prevent the beam from being space-charge neutralized at all times, but in most cases the shape of the plasma emission surface and spatial nonuniformity are probably more important factors.

The presence of electron trapping regions when there is a magnetic field in an accelerating column has a marked effect on the voltage holding capability of the column. These regions can be eliminated by careful design.

The MMII injector has not been discussed since it produces an inward-directed flow of ions from an annular source. It does not produce an ion beam.

References

(1) Proceedings of the IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Salzburg, 1961, J. Plasma Phys. and Thermonuclear Fusion, Part 1, 1962 Supplement.

(2) Proceedings of the Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, CN-21/112 (1965).

(3) H. Wroe, Brookhaven National Laboratory Accelerator Dept. AGS Internal Repts. HW-1, HW-2, and HW-3, (1965-66).

(4) A. van Steenbergen, "Recent Developments in High Intensity Ion Beam Production and Preacceleration," IEEE Transactions on Nuc. Science, NS-12, No. 3, June, 1965.

(5) P. M. Morozov and L. N. Pilgunov, "A Source of Molecular Hydrogen Ions for the 'OGRA' Apparatus," Sov. Phys. Tech. Phys. 8, 347 (1963).

(6) A. L. Bezbatchenko, V. V. Kuznetsov, N. P. Malakhov, and N. N. Semashko, "Injection of an Ion Beam into the Magnetic Mirror Machine OGRA," Plasma Phys. (J. of Nuc. Energy Part C) 6, 301 (1964).

(7) L. I. Artemenkov, N. I. Klochkov, V. V. Kuznetzov, V. M. Kulygin, N. P. Malakhov, P. A. Mukhin, D. A. Panov, V. S. Svishchev, and N. N. Semashko, "An Injector of Fast Hydrogen Atoms," Proc. VII Int. Conf. on Ionization Phenomena in Gases, Belgrade, 1965.

(8) J. Kistemaker, P. K. Rol, and J. Politiek, "Some Plasma-Physical Aspects of Mono- and Duo-Plasmatron Ion Sources," Nuc. Instr. and Methods 38, 1 (1965).

(9) F. J. Gordon and C. C. Damm, "High Intensity Source of 20-KeV Hydrogen Atoms," R.S.I. 34, 963 (1963). See also Lawrence Radiation Laboratory Progress Repts. UCRL-14285 and UCRL-50002.

(10) M. von Ardenne, Tabellen der Electronenphysik, Ionenphysik, and Übermikroskopie, VEB Deutscher Verlag der Wissenschaften, Berlin (1956).

(11) J. R. Pierce, Theory and Design of Electron Beams (D. Van Nostrand Company, Inc., New York, 1954), 2nd edition.

(12) G. G. Kelley, N. H. Lazar, and O. B. Morgan, "A Source for the Production of Large DC Ion Currents," Nuc. Instr. and Methods 10, 263 (1961).

(13) D. P. Hammond and D. R. Sweetman, "The Phoenix-II Injector and Burial Lime Commissioning," Proc. 4th Symposium on Engineering Problems in Thermonuclear Research, Frascatti, 1966.

(14) J. Haguenin and R. Dubois, "Measurement of a High Gradient Accelerator Tube Model-Investigation of the Properties of Titanium Electrodes," CERN, 65-23.

(15) O. B. Morgan, G. G. Kelley, and R. C. Davis, "The Technology of Intense DC Ion Beams," R.S.I. (to be published).

(16) Thermonuclear Div. Semiann. Progr. Rept. July 31, 1959, ORNL-2802. See also Thermonuclear Div. Progr. Rept. February 1, 1961-October 31, 1961, ORNL-3239, p. 67.

(17) Thermonuclear Proj. Semiann. Rept. January 31, 1960, ORNL-2926, p. 60.

(18) W. R. Gambill, R. D. Bundy and R. W. Wansbrough, "Heat Transfer, Burnout and Pressure Drop for Water in Swirl Flow Tubes with Internal Twisted Tapes," Chem. Eng. Symp. Series 57, 32 (1961).

(19) Thermonuclear Div. Semiann. Progr. Rept. April 30, 1966, ORNL-3989, p. 89.

(20) O. F. Poroshin and J. Coutant (unpublished).

(21) R. A. Demirkhanov, H. Freulich, U. V. Kursanov, and T. I. Gutkin, "A Collection of High Energy Accelerator Papers from U.S.S.R.," BNL Report 767 (C-36), 1962, 224.

(22) G. G. Kelley and O. B. Morgan, "Space Charge Neutralized Ion Beams," Physics of Fluids 4, 1446 (1961).

(23) Thermonuclear Div. Semiann. Progr. Rept. October 31, 1964, ORNL-3760, p. 64.

(24) M. D. Gabovich, "Extraction of Ions from Plasma Ion Sources and Primary Function of Ion Beams," Trans. in Instr. and Exp. Techniques No. 2, 195 (1963).

(25) M. D. Gabovich, L. L. Pasechnik, and L. I. Romanyuk, "Plasma Penetration Boundary and Plasma Focusing," Sov. Phys. Tech. Phys. 6, 61 (1961).

(26) N. B. Brooks, P. H. Rose, A. B. Wittkower and R. P. Bastide, "Production of Low Divergence Positive Ion Beams of High Intensity," R.S.I. 35, 894 (1964).

(27) Thermonuclear Div. Semiann. Progr. Rept. October 31, 1966, p. 88.

(28) See papers presented at the 1966 Linear Accelerator Conference by Sluyters (Brookhaven), Vosicki et al. (CERN), and Faure et al. (Saclay).