ION SOURCE AND COLUMN PERFORMANCE AT ORNL*

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Most of the experimental work in controlled fusion in Oak Ridge is based on the trapping of high energy molecular ions in a magnetic "bottle" by dissociation of the ions in the bottle. For the past six years our group has been concerned with the development of injectors for these experiments. Large dc currents are needed and large current densities are desirable. Since we are not interested in short pulse performance and do not have to match emittance shape to an accelerator, our approach has been different from that of the people making preinjectors. We have not been measuring emittance but have concerned ourselves with passing a beam through the smallest possible channel in specific geometries. Our beams are pulsed on and off, but generally we are not concerned with the first 100 μsec after turn-on or turn-off. On the other hand, we have the problem of dissipation of very large amounts of power at high power densities.

Two power supplies and two test stands have been used for our studies. One test location is in a small laboratory. It has available up to 100 kV at 3 amp. Here we have made source studies and have done magnetic deflection beam analysis. The other test facility is in a large open area and is coupled to a 600 kV, 1 amp supply. At this site we have tested accelerator tubes and made studies of beam profile and of targets.

We have been using the duoplasmatron of von Ardenne. We started with what was practically a Chinese copy of a source described in his books, but we could not get sufficient heat transfer from the tungsten anode insert to the anode to permit operation at high dc arc currents. A current of about 5 amp was the most that could be maintained reliably for long periods. After we found that we could get good performance with nonmagnetic anodes, we changed to solid copper. A solid molybdenum should work somewhat better, but it is less convenient to use. One other change had to be made to permit operation at steady arc currents greater than 10 amp. The tip of the intermediate electrode needs to be cooled very well to prevent heating beyond the curie temperature. A water-cooled copper block is brazed to this electrode just beyond the tip. Figure 1 is

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a cross-sectional view of one of our present sources. We are using filaments of a type designed by C. D. Moak of the Physics Division of ORNL. They are made from 40 mil tantalum wire covered with a platinum gauze and wrapped in a bi-filar spiral. Care is taken to see that no part of the finished filament is directly on the axis of the assembly. The filaments are then dipped in a barium strontium carbonate solution, the standard cathode dip used in tube manufacture. They require no activation procedure but should be outgassed in a separate system to prevent dirtying the source. Operating current is about 20 amp. These filaments have a life in the hundreds of hours when they are kept away from the high energy electrons which stream back through the anode aperture from the accelerating gap.

The methods we have used for determining the mass ratios in the plasma from the source will be described later. Our main interest has been in the production of molecular ions. When a source is run with a small spacing between intermediate electrode and anode--about 1/16 of an inch--and if the source is run gas starved, i.e., at sufficient arc voltage and at low enough source pressure that the desired output current is insensitive to variations in arc voltage, then the H_2^+ ion component is at least 60% up to 100 mA and at least 95 mA of H_2^+ has been obtained at correspondingly higher total currents. The proton yield can be increased by increasing the intermediate electrode to anode spacing to at least 1/4 inch, and by the use of high electron densities--by reduced anode aperture size and increased arc current for a given output. A relative proton yield of 90% has been obtained at moderate current, and proton yield seems to be even more favored at higher currents. Triatomic ions are produced by operating at high gas pressures and low arc voltage. A maximum of 37 mA of H_3^+ has been produced.

The plasma streaming through the anode aperture in the source consists of rather energetic electrons--up to 100 eV--and considerably lower energy ions. The ions have a directed energy of the order of about typically 8 V. When a strong electric field is created in the region beyond the aperture, the electrons are repelled and the ions accelerated. There results a plasma-beam boundary which forms at such a place that the space charge of the ion beam shields the plasma surface from the extracting field. Since the current density of ions in the anode aperture may be as high as 100 amp/sq cm (it is kept high to make the gas efficiency of the source high--typically greater than 90%) and since the maximum current density that can be supported with physically realizable extracting fields is under about 2 amp/sq cm, the plasma will expand into the region below the aperture. For a long time we thought that the arrangement using the highest possible field and correspondingly the smallest amount of expansion was most desirable. Recently we have

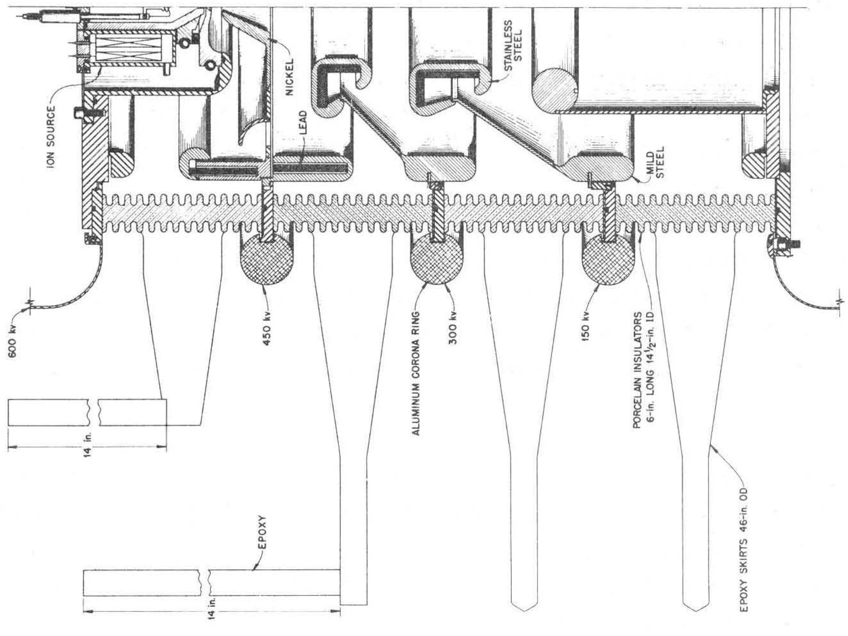

FIG. 2 600 KV ACCELERATOR TUBE

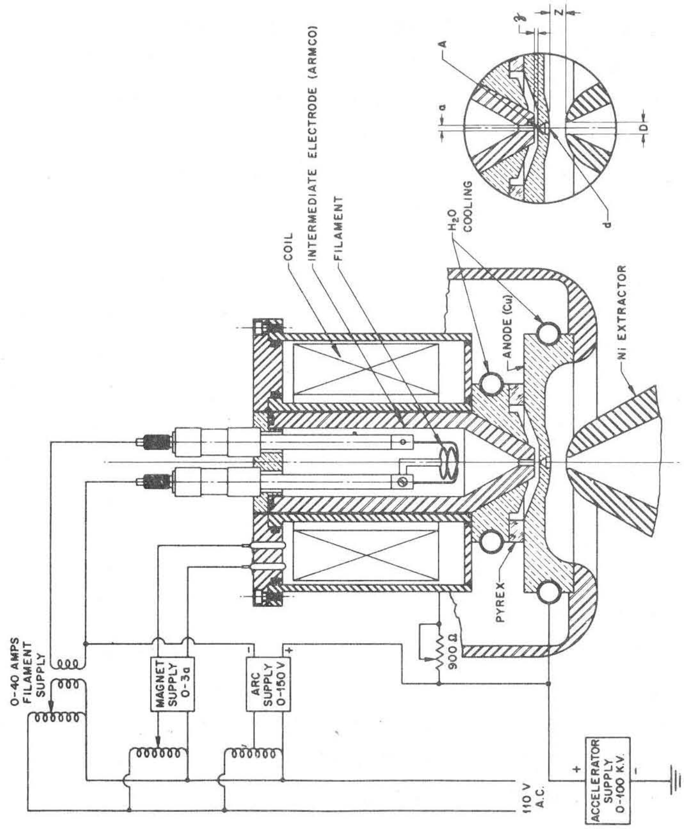

FIG. I MODIFIED DUOPLASMATRON ION SOURCE been experimenting with large cup arrangements found to give better beam quality by the Leningrad group and others.* This arrangement has the further advantage of more reliable voltage breakdown characteristics.

The maximum current that can be obtained with a given maximum allowable divergence of the beam after extracting depends only on the extraction voltage. Since the current density for space-charge limited current is given, for an infinite plane beam, and for a parallel cylindrical beam using Pierce geometry, by the expression

$$j = \frac{5.44 \times 10^{-8}\ \phi^{3/2}}{M^{1/2}\ Z^2}$$

where M is the mass number, j is in amp/sq cm, ϕ is in volts, and z is the electrode spacing in centimeters, the total current depends only on ϕ for a given ratio of spacing to beam diameter. We have found that this expression predicts the maximum current density even when the electrode shape is far from that which would be expected to produce a parallel beam according to the derivation of Pierce. (To get good agreement, however, it is necessary to make an empirical correction which consists of increasing the value of z by the radius of the aperture in the accelerating electrode.) For a spacing of twice the radius of the beam which seems to be a reasonable choice, the maximum current is given by $I = 19\ V^{3/2}$ where I is in mA and V is tens of kV for protons. The maximum current then which can be obtained in a beam of moderate divergence at 150 kV is slightly over 1 amp.

A current of 500 mA has been extracted from a source on the small test stand at 100 kV. A current of 400 mA was extracted from this source continuously for a period of four hours.

Our 600 kV supply has a 170 mA bleeder with taps at 150 kV, 300 kV, and 450 kV. We extract from the source plasma at 150 kV and accelerate the beam in three more 150 kV high-gradient, close-spaced steps. An ion from the source is accelerated to the full voltage in approximately 12 inches. Figure 2 is a cross-sectional view of the accelerator tube. There

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*A. I. Solnyshkov et al., "Current Injector for a Strong Focused Linac," Proceedings of the Dubna Conference (1963). See M. D. Gabovich, Review Article, "Extraction of Ions from Plasma Ion Sources and Primary Formation of Ion Beams," Instruments and Experimental Techniques, No. 2, pp. 195-206 (March-April, 1963). See also N. B. Brooks et al., "Production of Low Divergence Positive Ion Beams of High Intensity," Rev. Sci. Instr. 35, 894 (July 1964).

are four alumina insulators six inches high by fourteen inches ID. These are fastened to stainless steel rings by the vinyl seal technique. The rings provide electrical connection and alignment. Viton O-rings are used between the metal pieces. Skirts of unfilled epoxy molded to the insulator sections provide a large external breakdown path. Some of these skirts have been in use for over two years with no trouble due to breakdown through the interface between epoxy and ceramic. The electrodes are designed to keep the metal surface area having a strong field at a minimum. We made tests which showed that voltage cleanup problems become much greater when the linear dimension of the surface at high field is large compared to the electrode spacing. A solenoid focusing magnet is provided just below the accelerator tube to converge the beam. It is capable of operation at 2.4×10^5 amp turns and has six-inch diameter throat.

The site of the development of this tube is shown in Fig. 3 and Fig. 4. The beam is passed into a long cylindrical tank where probe studies and visual observation can be made. By means of an extension on the bottom of this tank the beam can be allowed to travel about 17 feet before striking a target. A profile measurement at a number of points along the beam gave an extrapolated value of 2.9 inches for the diameter of the beam in the lens at a total beam current of 180 mA. This measurement was made quite some time ago. We believe now that with large source cups we can make the beam considerably smaller. Large beam currents can be mass analyzed by this test facility by making use of the different focal lengths of the magnetic lens for the different mass components. These can be focused successively through a small aperture and the power on a target beyond measured calorimetrically. There is an essentially complete self-neutralization of the space charge of the beam by electron trapping. The beam profile shows no space charge spreading down to the lowest operating pressure which can be obtained in the system--2×10^{-6} mm Hg. We found, however, that the beam cannot be passed through a crossover in the region below the lens without being seriously disrupted. When a beam component is focused in the observation tank, it appears to get brighter as it gets smaller down to a diameter of about 1 cm and then becomes less bright but continues to converge to a sharp point. Nothing is seen of the beam below this point. When the beam is allowed to fall on a target and the lens strength is increased, the spot size becomes smaller and smaller and more and more intense down to no more than a pin point. With a further increase in lens strength, the spot disappears. We intend to study this phenomenon in greater detail.

We have operated this accelerator at a total power supply drain of 330 mA. At the same time we were able to account calorimetrically for about 300 mA. We do not know what became of the other 30 mA. It did not flow to any of the electrodes in the tube. These currents were

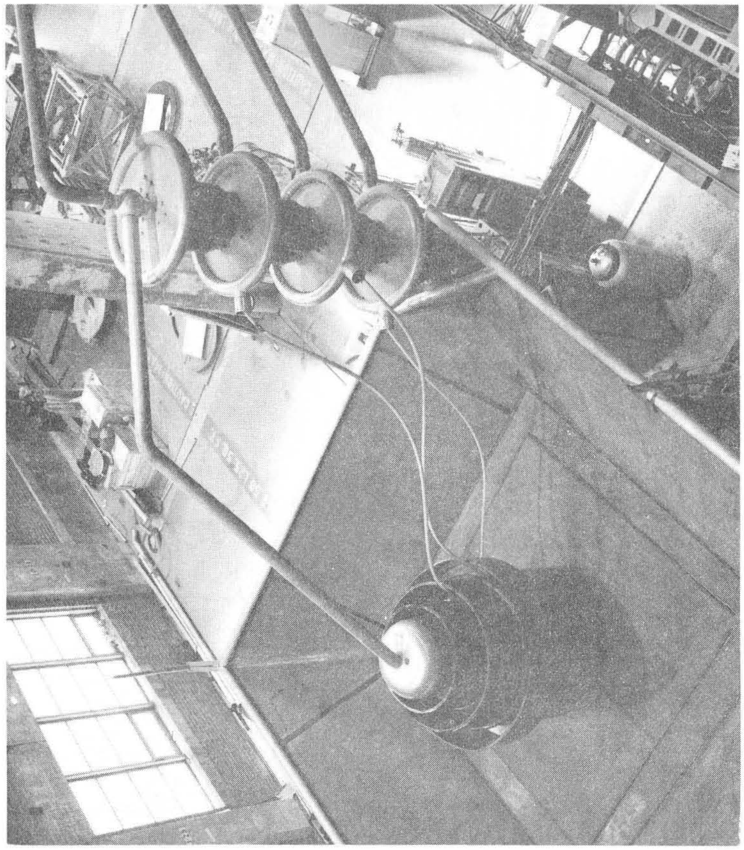

FIG. 4 TOP VIEW OF ACCELERATOR TEST STAND

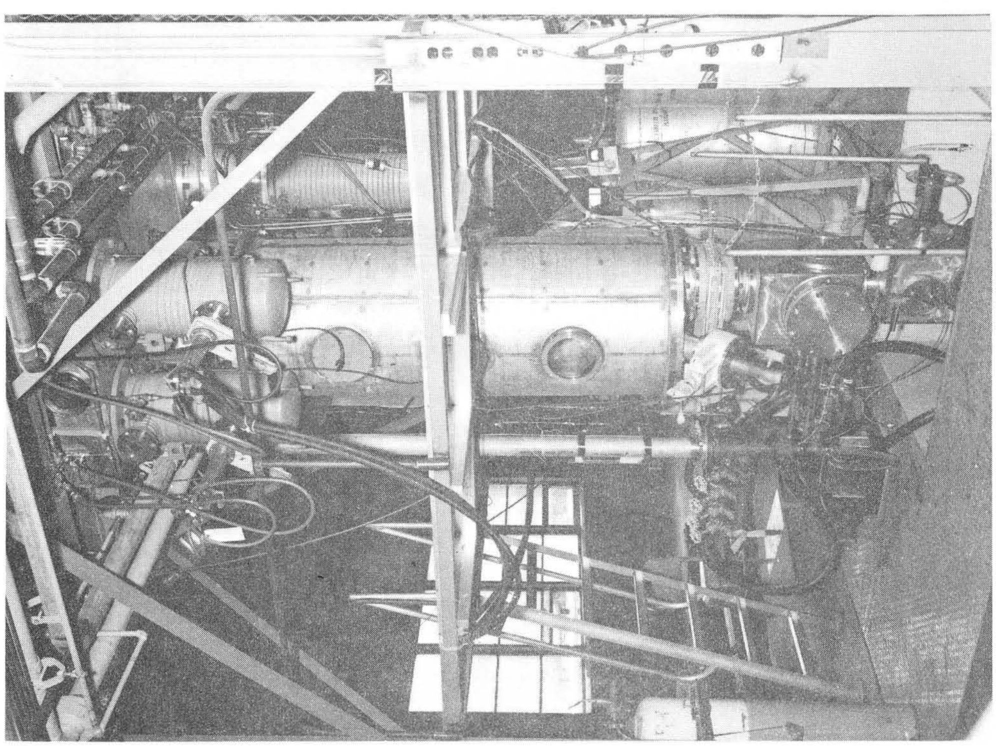

FIG. 3 VACUUM CHAMBER FOR ACCELERATOR TEST STAND

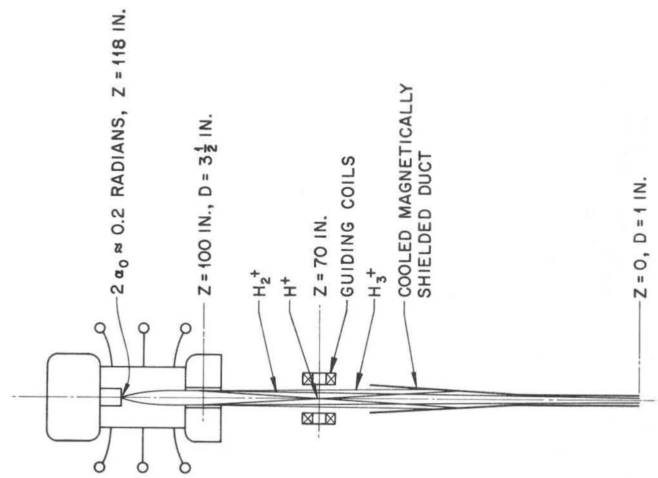

FIG. 6 DCX-2 INJECTION SYSTEM

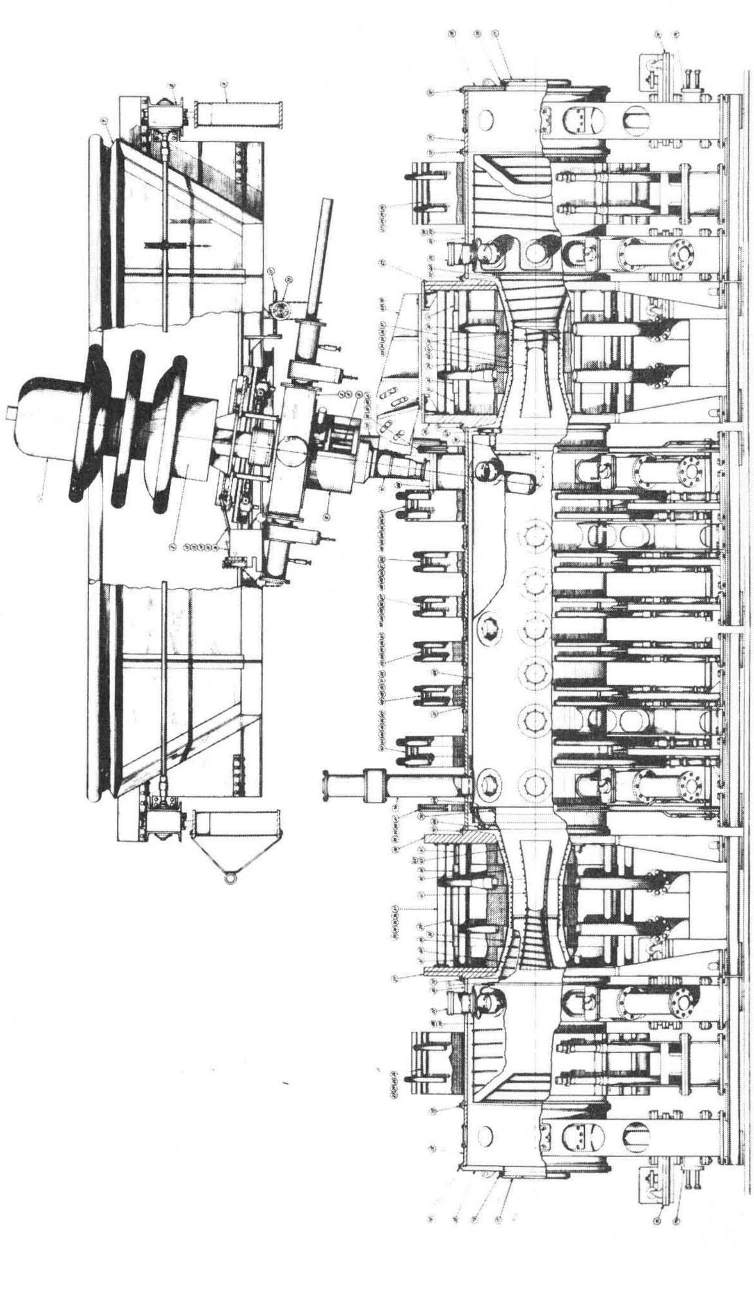

FIG. 5 CUTAWAY VIEW OF DCX-2

measured to be no larger than 1 mA. At the same time the power dissipated by the source anode was being monitored. An electron current of 0.5 mA at the full energy should have been detectable. No power difference was measured when the accelerating voltage was turned on or off.

The beam can be switched on and off by an electronic switching device in the source-arc supply. This switch is operated through a crater lamp-photomultiplier light beam link between ground and the 600 kV level. The beam can be turned on and off in less than 2 μsec.

The instantaneous beam current is transmitted from the 600 kV level to ground through a FM radio link. The system uses two commercial FM receivers having AFC, with slight modification. The arrangement has excellent linearity and low drift and has a time resolution of about 13 msec.

We have found, as have others, that an accel-decel arrangement can be used to permit neutralization of an ion beam. To be successful the arrangement must provide an electron-repelling field only in a small region around the beam. The exit electrode should be at ground potential and the beam beyond should not be able to "see" other potentials. We have neutralized a 50 mA, 70 kV beam after the beam had passed through an Einzel lens. A potential of - 3 kV, with aperture sizes of 1 to 1.5 inches, was enough to prevent electron loss from the beam.

Figure 5 shows a cutaway view of DCX-2, the largest of the experimental devices at Oak Ridge. In this device 600 keV H_2^+ ions are injected through a magnetically shielded channel into a uniform 12 kilogauss field. This field increases to 39 kilogauss at points 81 inches either side of the midplane. Ions enter the field 9 inches from the longitudinal axis at such an angle that they have a helical trajectory passing from a point near one magnetic mirror to slightly beyond a corresponding point near the other mirror. The orbit diameter is 10.3 inches. These ions reflect and return to the injector after having traveled a distance of the order of 100 meters. During their flight some of them are dissociated either by background gas and plasma or by a vacuum arc run between electrodes at opposite ends of the machine. The protons resulting circulate between reflection points and precess at each reflection, but some of them are deposited in the field in such a way that they do not return to the injector in spite of this precession. The mechanical and magnetic design of the injection channel is quite difficult. It consists of a hyperco cylinder with overlaid windings which compensate externally for the effect of the cylinder and also cancel the longitudinal component of magnetic field along the cylinder. The problems of design of the injection duct make a small channel very desirable. The value chosen was 1-5/8 inches. Figure 6 is a schematic view of the beam path. Steering magnetic fields are provided in the pumping chamber just below the lens to compensate for small misalignments and for the effect of the stray magnetic field. This field is reduced along the beam path by the use of ferromagnetic materials in the electrodes and in other hardware wherever possible. It probably is the effect of the small residual field which has prevented injection of more than 50 mA of H_2^+ into DCX-2 in spite of the fact that, as has been said above, 95 mA have been passed through an identical structure in the test stand. The losses probably will be reduced by repair of the 600 kV supply which has been producing an abnormally large voltage ripple.

WROE: Could you just say quickly what type of resistors you used for grading the column?

KELLEY: I don't know the brand. They are just very many wire-wound resistors in an oil-filled column.

FEATHERSTONE: I was interested in your 1 A continuous 600 kV supply. Is it possible to keep the stored energy in the capacities fairly low, or do you worry about damage to electrodes in the column when a spark occurs?

KELLEY: Well, we worried about it until we found in practice that it did not cause us trouble. We have a 0.0125 μf condenser and then a 14,000 Ω series resistor between the condenser and the output, which consists of the isolation transformer capacity which I think mounts up to about 700 $\mu\mu$f .