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NEUTRAL-BEAM INJECTION

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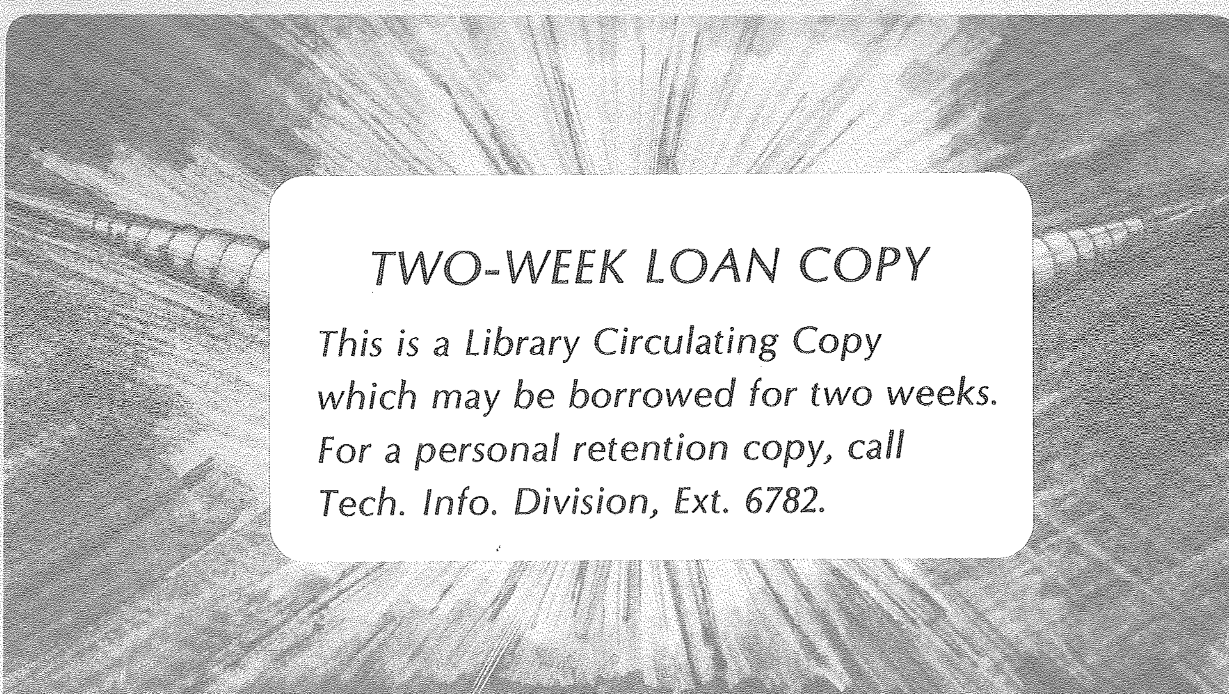

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NEUTRAL-BEAM INJECTION

Wulf B. Kunkel

I. Introduction

The emphasis in the preceding chapters has been on magnetic confinement of high temperature plasmas. The question of production and heating of such plasmas has been dealt with relatively more briefly. It should not be inferred, however, that these matters must therefore be either trivial or unimportant. A review of the history reveals that in the early days all these aspects of the controlled fusion problem were considered to be on a par, and were tackled simultaneously and with equal vigor. Only the confinement problem turned out to be much more complex than initially anticipated, and richer in challenge to the plasma physicist than the questions of plasma production and heating. On the other hand, the properties of high-temperature plasmas and plasma confinement can only be studied experimentally after the problems of production and of heating to adequate temperatures are solved.

It is the purpose of this and the next chapter to supplement the preceding discussions with more detail on two important subjects: neutral-beam injection and radio-frequency heating. These are the major contenders for heating in present and future tokamak and mirror fusion experiments, and even in several proposed reactors. For neutral beams we emphasize here the technology involved, which has undergone a rather remarkable development. The physics of particle and energy deposition in the plasma, and the discussion of the resulting effects on the confined plasma, have been included in previous chapters, and some experimental results are quoted there.

Other heating processes of relevance to fusion are mentioned elsewhere in this book, in connection with the experiments where they are used: i.e.

ohmic heating, adiabatic compression heating, and alpha-particle heating in Chapter 3 by H.P. Furth; more ohmic heating in Chapter 7, and shock-implosion heating, laser heating, and relativistic-electron beam heating in Chapter 8, both by W. E. Quinn. These methods are relatively straightforward in their physics and their technology, or in any case they are considered to be adequately covered by these other authors.

It is apparent from many of these discussions, and it will become obvious in the following chapters, that success in controlled fusion depends as much on advances in technology as it does on progress in plasma physics. A thorough treatment of many of the topics on the technology for fusion is beyond the scope of this text, however. The subject could easily fill an entire volume of its own. Moreover, these developments are currently proceeding at such a rapid pace that many sections of such a book would be obsolete before the latter could reach the market. Therefore, quite in general, for up-to-date briefings on matters of fusion technology we prefer to direct the reader to the appropriate literature where both surveys, or summaries, and specialized reports have been published in recent years, and where new findings presumably can be followed in the near future. The principal publications that come to mind are the proceedings of the various "Topical Meetings on Technology of Controlled Nuclear Fusion," "Symposia on Engineering Problems of Fusion Research," and (European) "Symposia on Fusion Technology," etc., (see Bibliography).

II. Neutral Injection Requirements

A. General Considerations

The most successful and hence the most popular technique of heating magnetically-confined plasma to thermonuclear temperatures today consists of the injection and capture of energetic neutral hydrogen isotopes. The injected particles traverse the vacuum and external magnetic field unhindered and become trapped in the confinement region by charge exchange and ionizing collisions, and their energy is then shared with the target plasma by coulomb collisions. The principle of the method is indicated schematically in Fig. 1.

There are two distinct operating modes as far as the resulting plasma is concerned. In ordinary mirror cells, in which the mean life time is a single ion scattering time, the process serves simultaneously as fuel injection. The injected particles do not have a chance to transfer much of their energy to other ions by direct interaction. The resulting plasma will have a somewhat lower average ion energy than that of the incoming ions because some of the latter must be shared with the electrons. In general, energy transfer from fast ions to less energetic electrons can be described as a form of friction between the species and is accompanied by very little ion scattering. Thus the energy decay time for the trapped ions may be of the same order as their mirror loss time.

When the ion lifetime is much longer than their scattering time, on the other hand, as is the case in tokamaks, and in the central cells of tandem mirrors, then fuel injection and energy injection can be separated, and neutral beams can be used primarily for plasma heating. The injection energy in that case can be much higher than the thermal ion energy within the plasma, and will be determined by different considerations.

It should be noted that the presence of injected suprathermal particles results in a bonus for fusion reactors if these particles are reactants, such as deuterons. They can substantially increase the fusion rate, or even dominate it, as in the so-called Two-Component Tokamak (TCT), and thereby reduce the value of $n\tau$ required for breakeven (Jassby, 1977).

B. Basic Requirements

There are essentially four requirements for the parameters of a neutral beam injection system: (1) The neutral-particle energy must be high enough to assure adequate penetration into the plasma before ionization and trapping occurs, but not so high that a substantial fraction traverses completely and is wasted or causes damage on the other side of the container. (2) The beam power deposited in the target must be high enough to provide the desired heating of the plasma. (3) The beam composition and energy spread must meet the specifications on which (1) and (2) are based. In general this also implies an upper limit on the allowable contamination by impurities. (4) The pulse length and repetition rate must be consistent with the goals of the application. In the experimental phase of confinement studies this means for example that the pulse length must exceed the expected energy confinement time if steady state conditions are to be produced.

Since confinement times generally scale favorably with increasing size, experiments have been getting progressively larger over the years, and the first reactors will probably be larger still. Consequently, the trend in neutral beam requirements has been towards higher energy and longer pulse length with each step forward (see Table 1), calling for hundreds of kilovolts and d.c. operation for some types of future power reactors.

C. Beam Energy

The energy of the neutral atoms is primarily determined by the need to deposit the particles well inside the plasma, preferably near the axis of of the column. After entering the plasma a beam of fast neutrals attenuates by charge exchange collisions and by ionizing collisions with plasma ions and electrons

$$dI = -\alpha I dx \qquad (1)$$

The probability α of electron loss per centimeter of propagation in the beam direction x, has been thoroughly discussed by Riviere (1971) and by Rome et al. (1974), and useful simplified expressions for design estimates have been given by Sweetman (1973). For hydrogen atoms with energies $E < 40$ keV (or deuterium atoms with $E < 80$ keV) the attenuation is primarily caused by charge exchange. At higher energies the dominant process is ionization by plasma ions (see Fig. 2).

According to Sweetman for $E > 40$ keV the rate can be approximated by

$$\alpha(\text{cm}^{-1}) \approx 1.8 \times 10^{-14} \; n\,(\text{cm}^{-3})/E(\text{keV}) \qquad (2)$$

where E is the energy per nucleon of the neutral particle in keV. The length $\lambda_i \equiv \alpha^{-1}$ can be looked upon as a mean-free-path for ionization and must be comparable to the desired depth of penetration. Impurities near the plasma boundaries are deleterious not only because of enhanced radiation losses but also because they capture electrons from the neutral beam and thus interfere with neutral-beam penetration. Obviously, impurities with large Z-values in the beam are particularly undesirable and generally the amount should not exceed a small fraction of one percent, unless they can be removed efficiently by a well-working diverter action in the outermost layer of the plasma.

D. Beam Power and "Current" (Flux)

The standard method of producing the required neutral beams consists of first generating and accelerating ions to the desired energy and then converting them (or a fraction of them) into neutral atoms by a charge-changing process. The latter is accomplished simply by passing the ion beam through a gas-containing "neutralizer" region. The beam flux is therefore usually expressed as a "current" in equivalent amperes, as if the particles were charged.

While the desired particle energy and beam purity are readily obtained with conventional ion sources in the milliampere range, the power levels required for meaningful fusion experiments call for new technological development. The power needed to sustain a plasma of volume V liters with a mean density of $\bar{n}$ ions/cm^3, ion and electron "temperatures" of T_i and T_e resp. (in keV/ particle) and energy confinement time τ expressed in milliseconds is given by

$$P(kW) \approx 2.4 \times 10^{-13}\, \bar{n}\, (cm^{-3})(T_i + T_e)(keV)V(\ell)/\tau(ms)\ (3) \qquad (3)$$

This translates into tens or hundreds of amperes for large fusion experiments, and perhaps over a thousand amperes for fusion reactors! Moreover, since this power must enter the confinement region in the form of energetic neutral atoms, the conversion from accelerated ions to neutrals (by electron capture for positive ions or by electron detachment for negative ions) is an essential step. As seen in Fig. 2, the electron capture cross section is a decreasing function of the particle velocity. The charge exchange target thickness therefore has to be larger for higher energy beams. Unfortunately, the probability of reionization decreases less rapidly with increasing energy than the probability of electron capture, so that the net conversion efficiency for positive ions into neutrals by thick neutralizer targets is still a rapidly decreasing function of energy (see Fig. 3), and at a given energy is lower for hydrogen than for deuterium (Berkner et al., 1975). At energies well above 100 keV for deuterium, therefore, the use of negative ions is preferred. But even then, the accelerated ion current must always be considerably larger than the specified neutral flux.

Of course, large fusion experiments (and reactors) can easily accommodate a number of neutral beam injectors operating simultaneously. In fact, it is generally advantageous, for a variety of reasons, to design the machine with several "beam lines" distributed around it. Nevertheless, tens of amperes per ion source are usually required (see Table I).

E. Beam Intensity and Divergence

Finally, low beam divergence is of crucial importance since the ions can no longer be focused after they have been converted into neutral atoms. The openings through which the particles must pass to enter the containment region tend to be literally "the bottle necks" for neutral beam heating. Since injector beam lines must usually be several meters long to pass through coils and shields and to allow for differential pumping and for deflection and removal of the residual ions, the maximum permissible beam divergence often is only of the order of one degree.

This latter rather stringent criterion calls for special attention to ion optics in the beam-forming region. It also explains why the ion source brightness (current density per unit solid angle) is more important here than the source intensity alone. A large ion current emission is useless for neutral beams if it cannot be confined to a small solid angle.

In the interest of compactness, on the other hand, the current density at the source should be as high as possible. Ion beam intensity is generally limited by the maximum space charge density that can be accommodated by the ion optics.

In Section IV it is shown that for practical reasons this current density is at most a few hundred milliamperes per square centimeter. As a final result, then, when realistic transparencies, like 50%, and the incomplete conversion to neutrals are considered, the power density of a neutral-beam source is limited to a few kilowatt/cm^2. It follows that megawatt beams must have cross sections measuring hundreds of square centimeters.

F. Beam Composition and Energy Mix

Electric discharges in hydrogen produce three species of positive ions: H^+, H_2^+ and H_3^+. Ion beams fed by such discharges then generally contain all three species, but the composition is unfortunately not readily predictable as a function of operating parameters. In general, the atomic fraction in the beam increases with power density (i.e. with ion current density) and, for low gas pressures, with the depth of the source chamber (Bromberg and Smullin, 1977). Atomic fractions in excess of 80% have been reported (Tsai *et al.*, 1977a).

The species mix in the beam is important for several reasons. First of all, there is an effect on the current. All hydrogen ions are singly charged so that they all have the same energy. But the large differences in mass mean large differences in velocity and hence large differences in their relative contribution to the space charge which limits the current density.

More significant is the effect on the resulting neutral beam. The cross section for dissociation processes in high-speed collisions between molecular ions and neutral gas particles is higher than any other. Thus most particles exiting from a neutralizer cell are atomic; and when the gas target is dense enough to maximize neutralization, all particles emanating from it are atomic. This means each H_2^+ ion or D_2^+ ion gives rise to two atoms, each carrying half the energy, while H_3^+ or D_3^+ ions split into three particles of 1/3 of the original energy. The scattering and energy spread produced in the dissociating and charge changing collisions at high speed tend to be minor and can be ignored in a first approximation.

The relevant cross sections for these hydrogen ion interactions with hydrogen gas target molecules are fairly well-known (Stearns, et al., 1976) (Barnett, et al., 1977). Hence neutralizer output yields have been calculated as a function of target thickness for low density beams (i.e. for beams that do not modify the target by their presence), for different input species and for a variety of beam energies (Berkner, et al., 1975) (Stearns, et al., 1976) (Kim and Haselton, 1978). Several graphs from Stearns et al. are shown in Fig. 4 and 5.

When the target is thick enough to ensure a perfect balance between the various electron capture and loss processes, we speak of the beam having reached its "equilibrium" composition. The power in neutral particles may reach a maximum before the equilibrium, at an optimum target thickness. The power flow distribution in beams that have passed through optimized neutralizers have also been calculated by the above authors. A few representative examples for several initial energies and for species mixes are shown in Fig. 6 and 7. The quantitative values in these examples have been normalized to a presumed goal, i.e. 1 MW of atomic neutrals at full energy since these penetrate most, according to Eq. (2). The poor neutral yield at high ion velocity is very apparent here. The importance of starting out with a large atomic ion fraction in the source is also well-demonstrated if the yield of full-energy atoms is to be maximized. Large amounts of power remaining in charged particles represent serious technological problems.

III. Neutral Beam Injection System

A. General Features

A typical neutral beam injector system based on positive ions consists of the following components (see Fig. 8, taken from Ehlers et al. (1975)):

1. Ion source (an electric gas discharge or plasma generator).
2. Accelerating structure (a set of grids).
3. Neutralizer (a beam-transport region containing low density gas).
4. Ion separator (a sweep magnet and divertor tube).
5. Ion dump (possibly an energy recovery system).
6. Neutral-beam transport tube.
7. Pumping system (possibly using cryogenic panels).
8. Source and beam power supplies.
9. Control system (computerized and fully automated).
10. Various automatic diagnostic devices (current and temperature sensors and spectroscopic monitors).

As a concrete example, Fig. 9 shows schematically the neutral beam line developed for the TFTR Experiment (see Chapter 3) by the Lawrence Livermore and Berkeley Laboratories (Pittenger, et al., 1977). Neutral injectors developed elsewhere are similar in their essential features although they may differ in detail, such as the type of ion source used or the method of control chosen (Coupland et al., 1976) (Dagenhart, et al., 1977) (Stirling et al., 1977).

The principal functions of the various components are obvious and need little explanation. The system operation is as follows: A deuterium plasma is created in the plasma generator by means of a high-current discharge. Ions from this plasma are accelerated in a carefully designed multi-electrode structure. The ions then pass through a neutralizer containing deuterium gas, and a fraction becomes neutralized by charge-exchange collisions. Remaining ions are removed from the beam by the sweep magnet; otherwise, the various reactor magnetic fields would bend the ions into surfaces near the entrance port, possibly releasing gas bursts or melting the surfaces. The considerable power in this ion beam must be handled by the ion-beam dump. The vacuum pumps distributed along the beam line remove most of the gas emerging from the neutralizer and the ion beam dump and must maintain the pressure between the sweep magnet and the entrance port at a sufficiently low value that very little of the neutral beam is reionized. Only an extremely small fraction of the beam particles can be allowed to strike any of the surfaces along the beam line and at the entrance port to the confinement region because gas evolution and reionization would otherwise lead to beam attenuation and to material damage. Well-regulated power supplies are required to assure good beam optics. To minimize accelerator damage when a spark occurs, the power supplies must also be capable of rapid turn-off with a minimum of stored energy (e.g. in cable capacitance). Optical, mechanical, and electrical sensors determine the condition and performance of the neutral beam system and permit the control system to adjust the power supply voltages and to shut down the system if a malfunction occurs.

B. Variations

Some possible variations should be mentioned at this point because they may represent improvements or even requirements for future systems:

1. The neutralizer shown here is closely coupled to the ion source and simply utilizes the residual gas coming from that source. This is most economical as far as gas utilization and pumping needs are concerned. However, this may not be the optimum configuration for the system as a whole, or it may not be adequate in the long run, particularly for future steady state

operation. Thus separate neutralizers, with independent gas supplies must be considered as an option.

2. The large amount of power delivered to the ion dump (e.g. see Fig. 6 and 7) poses a serious problem for long pulses, in addition to being extremely wasteful of energy. Hence efforts are under way to develop efficient energy recovery methods to take the place of, or at least to modify, the simple (thermal dissipation) beam dump. It is to be hoped that future neutral beam injectors will incorporate means for the direct electrical recovery of most of the unneutralized ion beam energy (Barr et al., 1977) (Fumelli and Raimbault, 1976), as explained in Section VI C.

3. Considerable simplification is possible, on the other hand, if only very short pulses, of a few milliseconds or less, are needed for the experiments. If, in addition, the particle energy is low enough so that, according to Fig. 6, over 80% of the beam is converted to neutrals, then no separately provided ion dump is needed. This has been the case in the studies of plasma build-up, stability and confinement in the 2XII mirror machine (Coensgen et al., 1975).

4. In Fig. 3 it is seen that for deuterium atom energies much above 100 keV it would be better to start out with negative ions, and at several hundred keV use of negative ions is the only choice. The search for multi-ampere negative ion sources is therefore being pursued vigorously, as demonstrated by the Conference on Negative Ion Sources (1977) (See Bibliography), and if successful, future high-energy neutral beam systems may operate with their voltage reversed from that shown in Fig. 8. The neutralizer in that case must be an electron detachment cell instead of an electron capture region (Hooper, 1978).

The following three sections discuss the major components in greater detail.

IV. Beam Forming Elements

The fact that the trajectories of neutral atoms cannot be bent or focused places a special burden on the ion-optical properties of the beam-forming system. The quality of the neutral beam, as far as divergence, intensity distribution and location of the focal spot is concerned, is determined by the conditions in the ion beam as it passes through the neutralizer. The science of ion optics is well-developed because charged-particle beams find many applications (Septier, 1967). However, the special requirements here, and particularly the large space charge effects encountered in our case, and the large total current to be handled make our beam-forming problem unique. The accelerating structures must meet the following requirements:

(a) They must be able to handle large total ion currents in the range of tens of amperes, i.e. much larger than had ever been considered before.

(b) They must be designed to maximize the current density (i.e. minimize the electrode spacing for the specified acceleration energy. This means they must operate close to the breakdown threshold.

(c) They must be designed to minimize the divergence of the accelerated beam, taking space charge into account. This means the ion optics demands close attention.

(d) They must not distort beyond specified tolerances in the presence of considerable heat loading from the ion source and from scattering processes within the gaps.

Requirements (a), (b) and (c) combined force us to resort to multiple-aperture beam-forming structures.

We start the discussion with a close look at ion optics of a single aperture because this crucial item deserves special attention.

A. Ion Optics

A simple ion-beam-forming arrangement consists of two metal electrodes, #1 and #2, with aligned apertures, as shown in Fig. 10(a). A flow of ions is supplied on one side, say on the left, coming from a suitable plasma generated by means of an electric discharge, for example. When an electric potential difference $\Delta\phi = \phi_1 - \phi_2$ is applied between the electrodes with $\phi_1 > \phi_2$, electrons are repelled from the gap and reflected back into the source while ions are accelerated upon leaving the source. To some extent the same is, of course, also true for the electrons and ions approaching the metal surface above and below our aperture if the latter is kept negative with respect to the plasma potential ϕ_p, e.g. if the wall collects no net current (i.e. is at floating potential with respect to the plasma potential on the left). Indeed, a field is needed to prevent an excess charge-deposition by the faster moving electrons. In that case the electric field at the wall facing the plasma is given by $E_W = a\sqrt{n_e kT_e}$ in esu where n_e and T_e describe the conditions inside the source plasma and a is a constant in the neighborhood of 5 if esu are used. Thus for an ion source with $n_e \approx 10^{12}$ cm^{-3} and $kT_e \approx 10$ eV we have typically $E_W \approx 5000$ V/cm.

To obtain perfect unidirectional ion motion, for simplicity, we could arrange our accelerator to meet this boundary condition on the flat surface inside the ion beam in the plane of electrode #1. This would require that the ion current density j leaving the plasma satisfies the so-called Child-Langmuir relationship for a plane parallel diode of infinite lateral extent with effective electrode spacing $d_1 = d + \delta$, where d denotes the electrode spacing and δ is the sheath width. The relevant potential difference here is $\Delta\phi_1 = \phi_p - \phi_2$; in other words, the current density must be (Kirstein et al. 1967)

$$j = \left(\frac{2q}{m}\right)^{1/2} \frac{(\Delta\phi_1)^{3/2}}{9\pi d_1^2} \quad (4)$$

where it is assumed that the electric field is negligible at the plasma edge, i.e., at the emitting surface that determines the values of d_1 and ϕ_p. Equation (4) is derived from conservation of energy and Poisson's equation assuming stationary charge flow of one sign without sources or sinks. In other words, for positive ion beam formation the presence of electrons in the sheath is neglected.

An exact match to equation (4) is essential because it should be understood that the presence of plasma electrons force the location and shape of the plasma edge (the "meniscus," or the boundary between the quasineutral plasma and the sheath) always to adjust itself automatically so that the net space charge density in the ion flow is just enough to reduce the electric field at the plasma edge to almost zero (i.e. to the value of the internal "ambipolar" field of the plasma). In other words: the space charge limited ion flow always exactly matches the total ion emission from a free plasma surface. For a given electrode spacing d and voltage $\Delta\Phi$ an increase in ion current density would make the meniscus bulge out to the right while a reduction of ion current density would cause the boundary to recede to the left, forming a concave emitting meniscus.

Suppose we have produced an exact match for a flat emitting surface as shown in Fig 10(a). If we then also control the field gradient at the beam boundary by means of a set of auxiliary electrodes to be the same as that called for in one-dimensional space charge flow, the situation is almost indistinguishable from the ideal infinite plane diode for which eq. (4) was derived. Only the plane equipotential that would be required in the aperture of electrode #2 cannot be simulated. On the contrary, in a plane diode the field would have a maximum at the location of electrode #2 whereas the longitudinal field within the beam must go to zero inside the hole, i.e. all field lines turn sideways to terminate on the solid metal electrodes. This does not cause a significant deflection, however, if the beam has been accelerated to high velocities, but it raises the potential on the beam axis well above the value of electrode #2. To the right of electrode #2 the beam will start spreading, of course, but this can be minimized by providing neutralizing electrons. These latter must be prevented from being accelerated backwards to the left. This can be accomplished by ensuring somehow that the plasma potential on the right is sufficiently positive with respect to electrode #2. The most common method, and the most effective one in the case of intense positive ion beams with large space charge density is the addition of a third electrode producing a small reverse field. The three-electrode structure is called an accel-decel system. A certain amount of defocusing cannot be avoided in any event.

The system described above can in practice only be approximated for relatively low current densities and for very high applied voltages, well above 100 kV, so that the spacing d can be large compared to the thickness of the electrodes and so that any intrinsic thermal spreading of the beam can be neglected. In general, however, both thermal spread and nonzero electrode thickness cause unavoidable deviations from the ideal unidirectional diode flow, even in the first aperture, that must be taken into consideration. It is virtually impossible to obtain a flat meniscus when electrode #1 is not infinitesimally thin. This is because the equipotential surfaces cannot be flat near electrodes of finite thickness. Figure 10(b) shows qualitatively the situation for a straight cylindrical bore hole when the meniscus is somewhere halfway between front and back surface of the first electrode. The central portion of the beam is compressed by the concave curvature of the meniscus and of the equipotentials near the meniscus. The edge of the beam is spread out, on the other hand, and in general, will have a poorly controlled distribution (a so-called "fringe" or "halo"). Some ions near the beam edge will strike the side walls of the #1 electrode and will be lost.

The effect of the beam compression has the advantage of counteracting the defocusing effect of the exit aperture and of reducing beam interception "downstream." On the other hand, it increases the angular divergence due to nonzero beam temperature, since compression always amplifies heat. It should also be noted that because of the aperture #2 and the "decel" potential the beam is accelerated through a reduced potential difference: $\Delta\phi_3 < \phi_p - \phi_2$. Finally, the effective spacing d_3 is always significantly larger than the electrode spacing d, since much of the electrode thickness must usually be included to describe the equivalent diode. For quantitative purposes, in practical units, the current is given by

$$jd_3^{\,2}(\text{amp}) = 1.8 \times 10^{-3}(Z/A)^{1/2}(\Delta\phi_3(\text{kV}))^{3/2} \qquad (5)$$

where we have substituted in (4) the charge $q = 4.8 \times 10^{-10} Z$ esu and the mass $m = 1.6 \times 10^{-24} A$ gm. Because of the above considerations, the value in (5) must be considered as an ideal upper bound.

The ion optics for finite thickness electrodes can be optimized by appropriate shaping of the hole edges. This is done by giving the aperture a suitable wedge-angle such that the equipotentials within the charge beam are flat, (Pierce, 1949), or slightly curved to match the concave plasma meniscus, as shown qualitatively in Fig. 10(c). This procedure should minimize the flux of ions in the fringes surrounding the main beam and thus prove to be advantageous for neutral beam operation. Unfortunately, this feature increases the minimum space between neighboring beams and it also must make the optics again more sensitive to current density than the straight holes. The effect of edge shaping on the beam quality for single apertures has been investigated recently experimentally as well as with a computer (Grisham, et al., 1977).

Most ion sources use apertures in the shape of circular holes and thus produce ion beams with axial symmetry. This symmetry not only affords the greatest ease of construction but it also minimizes the magnitude of space charge potentials within the beams and thus maximizes ion optical control by the electrodes. However, if multiple apertures have to be used consisting of a set of funnel-shaped holes the net transparency of the structure suffers as well as the symmetry. The transmission can be increased again if highly elongated slots are used instead of circular holes, i.e. if the accelerating structure is made of sets of parallel rails rather than of sheets perforated with circular holes. This is the topic of the next section.

B. Multiple Aperture Structures

According to eq. (4) and (5) the current density that can be handled in our electrostatic ion accelerators increases rapidly when the acceleration gap spacing d is decreased. It turns out, however, that d has a practical lower limit imposed by the threshold for electrical breakdown, i.e. the minimum value for d is a function of $\Delta\phi$. In the literature (Green, 1974) one finds $d_{min} \propto (\Delta\phi)^2$ but more recent experience with conditioned molybdenum electrodes indicates that in the presence of intense ion beams a good rule seems to be (Cooper, 1976)

$$d_{min}(cm) \approx 0.01\ \Delta\phi(kV). \tag{6}$$

It is not yet known what sets the limit, whether it is the surface condition or the bombardment by scattered stray particles, or photons, or a combination of several factors. Equation (6) is entirely empirical, and only approximate. Since $\Delta\phi_3/\Delta\phi < 1$ and, perhaps $d_3/d_{min} \approx 1.4$, we conclude that for deuterium

$$j(A/cm^2) < 7/(\Delta\phi(kV))^{1/2} \tag{7}$$

For voltages $\Delta\phi < 30$ kV d_{min} may be given by mechanical limitations, e.g. $d_{min} \approx 0.2$ cm, and $d_3 \approx 0.3$ or 0.4 cm may be more realistic. In any case, good ion optics is seen to be limited to deuteron current densities well below 1 A/cm^2. In other words, tens of amperes requires several tens of square centimeters ion beam cross section, much too large for a single orifice, and multiple-aperture beam-forming systems have to be used. Such systems have been developed before, as components in space technology, for electrostatic propulsion by means of so-called "ion motors" or "ion thrusters" (Brewer, 1970) (Kaufman, 1974). The "propellant" in these devices is usually mercury or cesium vapor instead of isotopes of hydrogen, and the current densities are very much smaller. On the other hand, very large structures with thousands of circular holes have been made and successfully operated. Perhaps the largest of these is a 1.5 m diameter thruster with a total mercury ion current of 15.7 A accelerated to 4000 volt (Nakanishi and Pawlik, 1968). The giant multiple-aperture electrodes had to be preformed into a spherical curvature of 5.75 m radius for mechanical stability and to prevent warping due to thermal effects. Very stable operation was obtained, continuous operations being limited by erosion of the second aperture in this case to between 500 and 800 hours.

The ion sources and beam forming structures for the fusion application are not and cannot be physically quite so large. However, the higher accelerating voltage and the much larger current density in our case give rise to a much larger thermal load on the beam forming elements. The first grid is a wall section of the ionizing discharge. If it is at floating potential, for example, it receives the power density

$$\begin{aligned} P_W &= j(\phi_i + \phi_p - \phi_1 + kT_e/e) \\ & \quad j[\phi_i + (1 + 0.5 \ \ell n \ m_i/m_e) \ kT_e/e] \end{aligned} \qquad (8)$$

where ϕ_i is the ionization potential and m_i is the mass of the ions. For $j = 0.5 \ A/cm^2$ of deuterons this turns out to be between 20 and 30 watt/cm^2, since the electron mean energy is $5 \ eV < kT_e < 10 \ eV$.

In addition, there is always a certain amount of bombardment by energetic particles from the acceleration gap. For grid #1 this may not be significant under good operating conditions, but the other electrodes invariably also must dissipate substantial amounts of power. The latter presumably is at least in part due to bombardment by ions originating from the neutralizer, since all ions coming from there end up on one of the electrodes.

Furthermore, a surprising number of charge-changing collisions can take place within the accelerating structure, between the fast ions and the residual gas that is passing through the orifices. Obviously, such events are likely to lead to electrode bombardment. The magnitude of this effect is difficult to predict with precision, but it is not hard to show that it can also readily exceed 10 W/cm^2:

If the gas density in the beam-forming structure is $n_g(cm^{-3})$ and the charge exchange cross-section is σ_x, the fraction of the ion current "scattered" in a distance dx is given by

$$dj = j\, n_g \sigma_x\, dx.$$

Since σ_x decreases with increasing energy (see Fig. 2) and n_g decreases with increasing distance x, the product $n_g\sigma_x$ is largest near the ion source and, unless special precautions are taken, the probability that both, or at least one, of the particles involved will strike one of the electrodes is also large because neither of these particles will be properly focused. Let the mean energy per "scattered" particle deposited on the electrodes be denoted by W_s; then the fraction of the total beam power density that is scattered in dx and intercepted by the electrodes is given by

$$\frac{W_s dj}{ej\Delta\phi_3} = n_g \sigma_x dx \tag{9}$$

where $W_s/e\Delta\phi_3$ may be of the order of 0.5. The gas density is likely to be $n_g > 10^{13}\text{cm}^{-3}$, and Fig. 2 shows $\sigma_x \approx 10^{-15}$ cm^2. It follows that the scattered fraction originating in a gap of a few millimeters is $\int n_g\sigma_x dx > 10^{-3}$. Thus, for a beam power density of $j\Delta\phi_3 = 3 \times 10^4 \text{W/cm}^2$, such as exists in the TFTR source, gas interaction can easily give rise to an intercepted power density in excess in 10 W/cm^2.

Finally, electrons released by ion bombardment, for example from the accelerating electrode, unless special precautions are taken have a fair probability of striking the beam-forming electrode with the full accelerating energy. This obviously can be a very substantial power deposition that must be dealt with somehow. It is usually not known with certainty which mechanism is responsible for what fraction of the accelerator dissipation. But it is known with certainty that cooling is required to keep the large multiple-aperture structures from overheating. It should be noted in passing that many, if not most, electrons liberated within the structure are accelerated back into the source and may cause problems there. At the very least, provisions must be made to dissipate the power deposited in this way, that can be quite substantial.

Most multiple-aperture systems are made out of precision-drilled metal sheets that are carefully spaced and aligned, and perhaps slightly dished into spherical surfaces to produce converging beamlets and enhanced mechanical stability. However, such plates need to be clamped at the edge, and even very modest temperature changes give rise to buckling which results in deterioration of the beam optics. Thus temperature control by efficient water cooling is required even for moderately short beam pulses. To prevent any distortion, the electrodes in the accelerator structure have to be webbed with cooling tubes in close thermal contact good enough for continuous dc operation even if they are only used for 100 ms pulses with a modest duty cycle. Such tubes reduce the net transparency of the accelerator.

The rail structure used for the rectangular beam-forming systems developed at the Lawrence Berkeley Laboratory has a number of advantages in this respect: (1) The transmission can be kept high, at about 60%, even though the first electrode rails are shaped as shown in Fig. 10 (c). (2) The rails can easily be kept from buckling as a result of temperature changes by permitting longitudinal expansion. (3) Beamlets formed in the shape of ribbons, by using apertures in the shape of long slots, are well-suited for neutral beam injection through rectangular orifices in the confinement device. (4) The effect of neighboring beamlets formed by parallel slots does not destory the symmetry of the space charge flow and can thus be included in the ion optical design with high accuracy. (5) Finally, rectangular-shaped ion sources can be stacked more compactly than cylindrical ones whenever more than one source has to be included in a single beam line.

A complication and potential source of trouble in slot extractors is the modified ion optics at the ends of the slots where some beam interception is more difficult to avoid.

For short pulses, up to about 1 second duration, one can let metal rails heat up during the pulse and cool down from the ends between pulses. A structure measuring 10 cm × 40 cm designed to accelerate 65A of deuterons to 120 keV for the TFTR experiment is shown in Fig. 11. For much longer pulses, and for dc operation, the grid has to be constructed of tubing for continuous water cooling. No loss of transparency is incurred, only an increase in complexity and cost. Rails have been bent into circular arcs to produce geometric focusing in the direction parallel to the slots. The grids have also been offset sideways so as to produce a convergence of the beamlets in the direction perpendicular to the slots (Baker, et al, 1975). [This technique has been studied more extensively for circular apertures by Stewart et al. (1975).] The beam dimensions at a predetermined "focal spot," e.g. at the entrance to the main vacuum chamber, can thus be made nearly independent of the physical size of the source. Thus, although rectangular sources and structures are undoubtedly more difficult and more costly to construct and to repair and to modify than cylindrical ones there are many features that may make this shape preferable.

C. Computer Aided Accelerator Design

The ion optics in general and the beam divergnce in particular, is sufficiently important for the neutral-beam injector performance that a special effort at optimization was initiated by Cooper and coworkers (1974). These authors developed a powerful computer program which calculates and optimizes ion extraction and ion trajectories with more realistic input data and more complete physics than had been attempted before. The program is called WOLF, which is the inverse of FLOW, indicating that an inversion is involved that finds the boundary conditions which result in beams with minimum divergence.

The program treats symmetric or asymmetric two-dimensional extractors (slots), with no magnetic field. Ion flow with space charge is calculated by solving the equations of motion and Poisson's equation iteratively on a flexible triangular mesh attached to the boundaries. The emitting surface is assumed to be a flexible surface at the position of the plasma sheath edge. Ions are assumed to arrive at this surface with a distribution in directed velocities to simulate an ion wind; a non-zero ion temperature and the effects of electrons in the sheath are included. The magnitude of the electric field E_0 on the surface must also be specified. The ion velocity distribution and E_0 must be calculated, assumed, or derived from measurements of the plasma properties. The ion current density j^+ can be specified or treated as a variable. WOLF then varies the shape of the emitting surface until the electric field at each mesh interval on the emitter equals E_0 in a least-squares sense; this is equivalent to specifying j^+ = constant on the surface, and determines the shape that the plasma sheath edge will assume in the vicinity of the extractor electrode. In addition, the program can vary the shape and potential of selected electrodes to minimize the beam divergence. This program is the first step toward a model containing enough physics of the plasma and of the extraction process to accurately predict the performance of a given extractor, and then to optimize the extractor design for a given task.

An optimized three-electrode accelerator structure with computed equipotentials and low divergence ion beam is seen in Fig. 12. The defocusing property of the second aperture and of the deceleration gap at the right are easily recognized. A single beam is shown but a periodic grid consisting of many identical beams is assumed. The effect of neighboring beams on the optics is found to be surprisingly small, however, and can generally be neglected. The simple accel-decel (three-electrode) structure shown here is adequate for voltages up to at least 40 kV. Observed beam divergences are in fairly good agreement with those calculated if it is assumed that the ions leave the plasma on the left with a transverse random energy (i.e. a "temperature") of approximately 1 eV (Baker, et al., 1975).

The WOLF code has been used to design the accelerating structure for the 120 keV injectors for TFTR and 80 keV injectors for Doublett III (see Fig. 13). In this case it was found necessary to add a fourth electrode, the so-called gradient grid, interposed between the beam-forming (first) grid and the main accelerating electrode. Its function is to adjust the electric field gradient in the neighborhood of the first aperture to match the conditions in unidirectional space charge limited flow, much as the gradient grids in Fig. 10(a). It turns out, surprisingly, that only one such grid is required to produce the desired effect (see Fig. 13).

The code has been enlarged to include the few disturbing collisional (charge exchange, ionization and secondary electron) effects in the calculations (Cooper, 1979). The peculiar shape of the most negative electrode (the principal accelerating electrode) has been designed to minimize the flux of secondary electrons originating there and impinging on the gradient grid. Very few milliamperes of this current can easily overheat the gradient grid or could even cause spark breakdown. Most ions formed by collisions within the beam in this case are found to clear the electrodes, but they are not likely to be well enough collimated to reach the target plasma. Of course, we rely on the original ions which have not suffered strong collisions.

Experimentally observed beam divergences agree rather well with those calculated. It is, for example, straightforward to determine the half-width of a beam as a function of ion current density at the source, keeping all electrode potentials constant at optimized values for a certain given current density (see Fig. 14). The measured beam divergence is found to have a minimum at a current density that is generally within 10% of the design value. This figure also demonstrates the importance of a uniform source current density profile "illuminating" the multiple-aperture beam-forming structure. It is extremely difficult to match a large-area high-quality extraction and acceleration system to a plasma source with a nonuniform ion current density. The design of appropriate sources is the subject of the next section.

In closing this section it sould be noted, however, that low temperature and good ion optics at the accelerating structure are necessary but not sufficient to guarantee a low-divergence beam. It is also essential that the beam does not deteriorate during its passage through the neutralizer. The latter contains a partially ionized gas and thus can affect the ion trajectories through collective effects such as nonuniform or fluctuating plasma potentials as well as through ordinary binary scattering. Recent observation of disappointing beam quality in large high-energy injectors have raised the suspicion that beam-plasma instabilities can come into play under certain conditions (D'Angelo, 1979). The matter has not yet been resolved, however, and the physics of collective effects in neutralizers is still under study.

V. High-Performance Ion Sources

A. Large Area Sources

The principal creation process utilized in the sources described here consists of ionizing collisions between electrons and atoms or molecules. Crudely speaking such collisional ionizers could be divided into two classes: electron bombardment chambers and active electric discharges.

(1) In an electron bombardment source electrons of sufficient energy, coming from an electron source, are injected into the gas, and only these "primaries" are responsible for the ionization process. The liberated electrons are partly lost and partly accumulated, neutralizing the ion space charge, but they do not gain enough energy to participate in the ionization process.

(2) If the secondary electrons are heated up, by electric fields or by collisions, so that they can materially contribute to the ionization rate, we call the process an active electric discharge. With a suitable power input these latter can give rise to highly ionized dense plasmas.

Over the years many different types of discharges have been developed, and descriptions of those suitable for ion sources can be found in the literature (Green, 1974) (Vâlyi, 1977). The special requirements for the neutral beam sources under discussion here cannot be met by any of the standard discharges, however. The major problem is the large area of uniform ion current density needed to match the extended multiple-aperture beam-forming structures described in the preceding section. In electric discharge plasmas the ion density usually is quite nonuniform, with a pronounced maximum in the center, because both ions and electrons are lost on the walls. In addition, such plasmas frequently tend to be not completely steady but exhibit fluctuations of unacceptable amplitude. The resulting imperfections in ion optics have a detrimental effect on the quality of the neutral beams produced. The problem is much more serious in our intense deuteron sources than in the large ion thrusters because of the higher power level and because of the more stringent requirement for the maximum allowable beam divergence. Also, discharges in hydrogen, because of the smaller ion inertia, tend to be much more "temperamental" than those in the heavier gases.

Special large-area high-current ion sources are therefore under development for the specific purpose of supplying the appropriate ion fluxes for the multiple-aperture accelerating structures of neutral-beam injector systems (Green, 1978). Electron bombardment ionizers in which all or most of the ionization is produced by a diffuse distribution of energetic primary electrons have a better chance of operating with a low fluctuation level and yielding more uniform ion densities than the active discharges described before. On the other hand, such schemes need very large primary electron currents to yield adequate ion fluxes in tenuous hydrogen unless the primaries are magnetically confined. These matters, which are still the subject of active research, are discussed further in Sections C, D and E.

B. Requirements

In general we must expect that an ion source will have to meet a set of specifications that will depend on the particular application. For example, the ion optics and acceptable tolerances in the neutral beam may call for uniformity of the ion current density over the entire extraction area such that the maximum deviations from the mean value may not exceed 5%. Simiarly, the fluctuation level typically must then not exceed 5%.

Other requirements could address the ion species mix as discussed in Section IIF. For example, an atomic ion fraction of at least 75% may be specified for a particular application to ensure adequate penetration into the target. Similarly, the gas utilization is a matter of interest, in connection with the required pumping speed and the design of the neutralizer, but most importantly, because residual gas affects the always detrimental scattering rate within the accelerator structure.

The energy in random motion of the ions (ion temperature) is also a significant variable since it determines the irreducible divergence of the extracted ion beams. Ideally, one would like to have zero ion temperature, but the nonuniformity of the plasma potential within the source always give rise to some random ion energy that is rarely much less than 1 eV, even in the absence of fluctuations and collisions.

Electron-ion recombination is never significant in these low-density discharges or bombardment sources. The probability and hence the rate coefficient for this process is much too low, even at electron thermal energies as low as 1 eV. Charge exchange processes may occur, but for every ionization event in the volume exactly one ion and one electron are delivered to the boundary of the chamber somewhere. The ideal ion source would deliver all ions to the accelerator and none to any other surface. One could thus define the source efficiency by dividing the accelerated ion current by the total ionization rate in the source. The latter is, however, not directly observable. It is therefore customary, and indeed more meaningful, to express the efficiency by giving the energy expended in the source, in eV per ion in the extracted beam. High-intensity low-divergence hydrogen ion sources tend to operate with disappointingly poor electrical efficiencies. Values below 1 keV per beam ion are considered good. (This is high compared to ionization energies, but acceptable, since it is low compared to final ion energies.)

Finally, dependability and durability are important considerations also. Ruggedness and simplicity, and ease of operation, are obviously desirable. To the extent that these requirement are not necessarily compatible with all the essential features discussed before, high performance source design and choices are always based on compromise.

C. Field Free Sources

The best controlled and conceptually the simplest large area ion sources are derived from the multifilament quiescent plasma generators pioneered by MacKenzie and coworkers at the University of California at Los Angeles (Taylor, et al., 1972). These consist of metal vacuum chambers which are lined on the inside with a large number of independently heated electron emitting tungsten filaments (see Fig. 15). The latter are held at a modest negative potential, e.g. -50 volt, with respect to the wall or with respect to a portion of the wall (the "anode"), in the presence of a very low density gas. Ionization by electron bombardment then converts a fraction of the gas into a plasma which, if it is sufficiently dense, modifies in turn the electric field distribution inside the chamber until almost the entire applied potential difference appears across very thin sheaths surrounding the filaments.

Each filament thus becomes a cylindrical source of almost monoenergetic electrons (the primaries) that cross the chamber in random directions. For gas densities low enough so that all mean free paths are larger than the chamber dimension, this arrangement yields a diffuse, beautifully stable plasma that can have a reasonably uniform density distribution over most of the enclosed space. Fig. 16 shows representative probe traces and measured density profiles in the large rectangular source (Ehlers, 1977) that is used to supply the ions for the accelerator photographed in Fig. 11. The currents and power density here are much larger than in the plasma chambers used for basic studies if ion current densities in excess of 0.1A/cm^2 are to be generated. In that case the term "arc discharge" becomes more appropriate also because the plasma electrons appear to get heated enough to participate in the ionization (Schoenberg and Kunkel, 1979).

This type of plasma generator is called field-free because no magnetic field is present except the one produced by the filaments and by the discharge current itself. The absence of a superimposed field is important in these sources because such fields interfere with the ion optics in the beam forming structure, and in addition they tend to give rise to fluctuations in the plasma. Magnetic fields are usually added to electrical discharges in order to confine the ionizing electrons, or at least to increase their path length, and thereby gain in efficiency. The field-free multifilament plasma generator described here is therefore electrically rather inefficient, in the interest of simplicity and quiescence. Very large discharge current (2000A) and power (80 kW) are required to deliver the 65A ion flux to the beam forming structure, i.e. 1.2 keV per beam ion. While this represents only 1% of the total power of 120 keV per ion it places a heavy dissipation burden on the structure and leads to heating and erosion.

This design is therefore only suitable for pulsed operation with modest duty cycles. The first phase of TFTR operation, for example, calls for injection pulses of 0.5 sec duration at 5 min intervals, which can be handled in this manner. It should be noted at this point that the term "field-free" must not be taken to exclude all magnetic insulation. As a matter of fact the filaments as shown in Fig. 15 are so arranged that the magnetic field due to the heater current impedes the electron flow to the side walls. In addition, the magnetic field accompanying the discharge current is not negligible and the electron trajectories are strongly affected. It is even necessary to distribute the cables that feed the arc current very symmetrically lest the stray fields cause a nonuniform plasma distribution in the source (Ehlers, 1977).

D. Magnetic Buckets

The efficiency of the field-free source could be much improved if the magnetic surface barrier produced by the filaments in Fig. 15 could be made five times stronger and could be spread over all surfaces except the extraction window. Such a design has not yet been produced, however, and may never be realized for ion sources. On a large scale this system is under study as a magnetic confinement scheme for advanced fuel fusion reactors and has been given the name Multipole (see Chapter 16). Closely related is the so-called "picket fence" arrangement consisting of multiple magnetic line-cusps (Tuck, 1958). The development of small-sized very strong permanent magnets has made it possible to surround field-free plasma generators with closely-spaced magnetic pole faces of alternating polarity, thereby creating a multipolar magnetic surface barrier.

This system has first been successfully applied to ion-propulsion engines (Ramsey, 1972) and to large quiescent plasma generators (Limpaecher and and MacKenzie, 1973) and both impressive efficiency and remarkable plasma uniformity have been achieved. More recently such "magnetic buckets" have been incorporated independently by several neutral injection development groups into their newest versions of large ion sources (Stirling, et al., (Tsai et al., 1977a), (Green, 1978) (Ehlers and Leung, 1979). For example, Fig. 17 shows the cross section of a 65A, 120kV (TFTR) field free plasma generator modified to operate with surface magnets and fewer filaments (Biagi, et al., 1979). Higher efficiency and also an increased atomic ion fraction are obtained in this version.

There is little doubt that field-free sources for pulses of more than 1 sec pulse length, and certainly for dc operation, will have to have surface magnetic fields in order to have acceptable efficiency. But even then it does not seem likely that sufficient electrons for continuous operation can be provided by heated filaments. The latest developmental efforts therefore are directed towards the cathode problem.

Ion propulsion engines using hollow cathodes and mercury vapor as propellant have been demonstrated to work continuously and reliably for about 10,000 hours (Nakanishi and Finke, 1974). No such feat has yet been accomplished with a large hydrogen ion source. But there is hope that this will be solved before long as new materials such as LaB_6 and self-replenishing oxide cathodes show promise. One advantage of plasma generators with magnetic buckets is that it makes little difference by what means the electrons are supplied. It could, for example, be another discharge plasma. This is the basic idea underlying the discharge systems having a second electron accelerating sheath. We shall call them "tandem discharges."

E. Tandem Discharges

The idea of dividing the discharge for steady state ion sources into two regions, the "cathode region" and the "anode region" was introduced by Von Ardenne quite a long time ago, in his so-called "duoplasmatron" (Von Ardenne, 1956). The latter is a highly successful and popular small sized very intense ion generator with excellent gas utilization. The design is fairly complex involving an independently heated cathode filament, a magnetic field funnel and a constriction forming a small region of extremely high current density that is responsible for most of the ionization.

On a very different scale, it turns out that the large ion "motors" for electrostatic propulsion also use often such tandem discharges, although frequently they are simply called electron bombardment sources (Kaufman, 1974). In this case separately heated hollow cathodes are used and the cathode region is usually separated from the main ionization chamber by a baffle arrangement.

In either of these two examples a sheath establishes itself at the boundary between the two discharge regions accelerating electrons from the cathode plasma into the anode region which forms the main body of the ion source. The principal virtue of this arrangement, as far as we are concerned in the present context, is the fact that the cathode plasma here acts as an electron emitter that does not erode as a result of ion bombardment, and does not wear out due to gradual evaporation. The cathode plasma acts as a sort of buffer zone between the main body of the discharge and the real cathode. Moreover, the gas density can be higher near the cathode than in the main chamber, giving shorter free paths and easier ionization conditions, so that the demands on the cathode itself are much less severe than they would be without the buffer zone. Because of the presence of the double sheath the voltage across these tandem discharges are higher than in simple plasma generators. Thus for operation at the same power the current is lower, which again is easier on the cathodes and on the entire discharge circuit. It seems likely that ion sources for continuously operating neutral beam injectors will be operating on the tandem-discharge principle.

A well-tested plasma generator in tandem discharge form that is widely used in the production of neutral beams is the "DuoPIGatron" developed by the Oak Ridge National Laboratory (Davis et al., 1975) (Tsai, et al., (1977b). It consists of a husky duoplasmatron in which the anode discharge is operated in the manner of a so-called "Penning Ionization Gauge" (PIG) discharge. A PIG discharge is a clever arrangement in which the ionizing electrons are trapped on magnetic field lines in a potential well between two negative electrodes, e.g. a cathode (or virtual cathode) and a reflector electrode. In order to get out, i.e. move toward the wall or the anode the electrons have to collide with the gas atoms. At very low gas density and electron density the current is thus proportional to the gas pressure; hence the application as a pressure gauge. For higher power levels the device is sometimes called "reflex discharge" and has become a popular ion source because of its good utilization of primary electrons at low gas density. The Duo-PIGatron is thus a reflex discharge ion source using a Von Ardenne arrangement as electron supply. It is suitable for long pulses and presumably even for continuous operation.

Unfortunately, duoplasmatrons and reflex discharges, and in fact all arrangements where current carriers have to cross magnetic field lines, are characterized by sizeable fluctuations. This is not surprising inasmuch as it is well-known that transport across a magnetic field is aided by flute-like instabilities which are undoubtedly present in these discharges (Cap, 1976). But density fluctuations produce time-varying mismatches in the ion optics and therefore degrade the quality of the beams.

In addition, the plasma that is formed in the reflex discharge region tends to be nonuniform in space, with the time-averaged density being highest near the axis. This has been remedied by replacing the solenoid magnet of the reflex chamber by multipoles (Tsai, et al., 1977a). The device could thus be described as a magnetic bucket operated in a reflex mode with the electrons supplied by a large Von Ardenne source. Both fluctuation level and uniformity are vastly improved in this way. A sketch of such a modified Duo-PIGatron, good for an ion current of 60A, as used in the Princeton Large

Torus (PLT) experiment, is shown in Fig. 18. Larger versions yet are to be installed at the Poloidal Diverter Experiment (PDX) at Princeton.

Another scheme for illuminating large multiple-aperture beam forming structures with a uniform intense ion flux is the Periplasmatron developed in France (Fumelli and Valckx, 1976)(Becherer et al, 1977). In this device, as the name suggests, the body of the plasma generator is surrounded by duoplasmatrons all along the perimeter, so that no additional magnetic field is needed to contain the plasma radially. Of course, great care must be taken to ensure uniform operation along the perimeter. The complexity and the extra space that is needed are disadvantages, but presumably high ion densities can be obtained without placing heavy demands on the cathodes, and arbitrary shapes of extraction areas can be accommodated.

The development of high-performance ion sources for neutral-beam injectors is a continuing effort that presents considerable challenge. It will be interesting to see what improvements will evolve in the future.

VI. Efficiency Enhancement

In Fig. 3 it is seen that the efficiency with which neutral beams are formed from positive ions decreased rapidly with increasing particle energy, and at proton energies above 75 keV (or deuteron energies above 150 keV) drops to below 30%. Since future beam-driven systems are likely to require energies well above 150 keV it is essential that means be developed for the improvement of neutral-beam production efficiency. There are two possibilities that suggest themselves:

1. The use of negative ions would be much more desirable because the efficiency of conversion of these to neutrals is much higher, as indicated in Fig. 3. The latter is not surprising since it must be much easier to detach the extra electron from the hydrogen atom than to strip the atom completely. The efficiency here is given simply by the ratio of the probabilities for those two processes.

2. All or most of the energy of the portion of the ion beam that is not converted to neutral atoms should be recoverable directly, in the form of electrical energy.

At the time of this writing neither one of these methods is well-developed, but brief discussions of the ideas and the problems are included here.

A. Negative Hydrogen Ion Sources

Hydrogen atoms can attach a second electron filling the 1s shell to form stable negative ions with binding energies of 0.75 eV. Radiative attachment, for example,

$$H + e \rightarrow H^{-} + h\nu \tag{10}$$

is responsible for a substantial portion of the continuum emitted by partially ionized hydrogen gas at high pressure. This process is not suitable for H^- production in our ion sources, however, because the cross section is too small, i.e. it requires unacceptably high neutral gas densities. Quite in general, the attachment energy is too low, in comparison with any ionization energy for positive ions, to allow a large fraction of negative ions to exist in any equilibrium or near-equilibrium situation. The negative ion production we are looking for is thus strictly a nonequilibrium process.

Under suitable conditions electric discharges in hydrogen yield surprising amounts of negative ions. The physical processes involved have not yet been completely ascertained, and quantitative predictions are not yet possible. But sources of negative hydrogen ions exist, yielding several milliamperes in the steady state and amperes under pulsed conditions with pulse lengths in the msec range (Prelec, 1977).

The most important negative-ion formation processes in electric discharges are probably the following.

1. Volume production

$$H_2 + e \rightarrow H + H^- \tag{11}$$

This process seems to have a substantial cross section if the molecule is in a highly excited vibrational state and if the electron has a few eV energy. Such states and such energies must naturally exist in active discharges, and thus one would expect reaction (11) to be responsible for a certain H^- content in discharge plasmas, depending on conditions.

2. Surface production.

Solid surfaces are likely candidates for supplying electrons. When hydrogen ions or atoms impinge on surfaces with an energy in the hundred eV range they have a certain quite substantial probability of getting specularly reflected back with little energy loss. It turns out that these atoms, in turn, have a nonzero probability of carrying away an extra electron, i.e. are in the form of a negative ion.

$$H^+ + \text{surface} \rightarrow H^- \tag{12a}$$

$$H^0 + \text{surface} \rightarrow H^- \tag{12b}$$

This is thus a likely effect to occur at discharge cathodes. The probability for this process naturally depends on the state of the surface as well as on the energy of the impinging particles. The yield seems to be particularly high when the surface is coated with a monolayer of cesium (Bibliography No. 12, 1977) (Hiskes et al, 1976). The matter of bombardment is being investigated both experimentally and in theory, with the goal of determining the optimum conditions for our ion source application.

There are two problems in the utilization of these phenomena for the purpose of negative-ion sources. First of all, the negative ions formed in the volume or on the surface are readily destroyed again in the discharge itself. Secondly, those that survive and reach an acceleration structure must be separated in some way from the free electrons. The latter is usually accomplished by interposing a transverse magnetic field and somehow collecting the deflected electrons while accelerating the ions which have a much larger gyroradius. The net yield of negative ions is limited by the destruction processes and by the interference of the electron separation process with the ion optics. But as mentioned before, sizable negative ion currents have been reported (Ehlers and Leung, 1980), and there is hope that some day neutral beams of interesting intensity will be generated from negative ions produced by direct extraction from a discharge.

B. Double Electron Capture

Neutral hydrogen atoms in flight through a vapor of an easily ionized metal that is capable of forming a hydride molecule have a fair probability of capturing an electron, leaving a metal ion behind.

$$H^0 + M^0 \rightarrow H^- + M^+ \qquad (13)$$

Since it is easiest to produce the fast atom starting from a positive ion undergoing electron capture

$$H^+ + M^0 \rightarrow H^0 + M^+ \qquad (14)$$

the two-step process has become known as double-capture. Negative ion yields for protons and deuterons of various energies passing through alkali and some alkaline earth metal vapors have been measured recently (Schlachter, et al., 1979), and the results are plotted in Fig. 19. It is seen that the yield increases with decreasing velocity of the hydrogen projectile and can reach 30% for low energy deuterons in cesium vapor. Research is underway to increase the yield further, for example with the help of laser photons by pumping the target in such a way that the probability of charge transfer is increased.

This then suggests another method of generating intense negative ion beams: We start by creating first a very intense low energy positive ion beam in a standard positive ion source described before. We pass this beam through a cell containing an appropriate vapor, such as cesium or sodium, and separate out the emerging negative ions for further acceleration to high energy. This double capture method is also under development at various laboratories, and moderately encouraging results have been obtained (Bibliography No. 12, 1977) (Hooper, 1978).

It is readily understood that this method has its own problems: low energy beams are limited to low current densities by the Child-Langmuir relation, Eq. (4). Moreover, low-energy beams cannot easily be transported over distances, they tend to spread very quickly, in addition to suffering noticeable scattering in the vapor target. Finally, the vapor target itself may pose a problem; it must not contaminate the ion source and it must not be allowed to accumulate too many positive ions. Remedies are being tried out: the vapors are introduced as supersonic jets at right angles to the ion beam lines. This minimizes the transfer of vapor into the source. The current density in low energy ion beams can be increased by using an exaggerated "accel-decel" system, i.e., by accelerating ions first to 10 or 20 keV and then decelerating them again down to 1 or 2 keV. The unavoidable penalty in this case is a rather large beam divergence since the deceleration process is always defocusing (see Fig. 12, for example). Since low beam divergence is crucial, as we have seen before, a compromise will be required, and it will take some time and effort to find the optimum conditions.

It also seems possible that positive ion beams of usable low energies could be formed by direct acceleration from the source plasma in the first sheath. This would require an enhanced sheath, such as exists around a very negative probe or in front of a cold cathode. If beams of sufficiently low divergence could be formed in this way and passed through a nearby charge exchange cell without contaminating the source, interesting negative ion beams of perhaps 50 mA/cm^2 could be generated. The problem of accelerating 1 or

2A in such a beam to, say, 200 kV or more remains to be solved also, of course, but that is generally being considered only a minor hurdle.

C. Direct Energy Recovery

In principle, the electrostatic acceleration of ions is a reversible process. It should therefore be possible to reconvert into electrical power nearly all the energy of the ions that have not been transformed into neutral atoms by electron capture. In reality, most or many of the ions that are leaving the neutralizer have suffered some interaction on the way, i.e., the reversibility argument is not strictly applicable and it is not obvious what fraction is recoverable. Only if the original ion beam is 100% atomic, or if the neutralizer target is "thin" in the sense of providing negligible probability for more than a single charge exchange event for any beam particle, can the reversibility argument be considered valid. In general we deal with mixed species and usually with multiple transfer events so that the ion beams exiting from the neutralizing region are not only less intense but also distributed in energy. This aspect is very clearly illustrated in Figs. 6 and 7, where the composition of the emanating ion beams has been computed for a number of representative cases. Even so, the idea of recovering a substantial fraction of the otherwise wasted power is intriguing and merits serious consideration.

The possibility of direct conversion of the energy of ions escaping from magnetic confinement nuclear fusion devices has been considered in connection with mirror machines (Barr and Moir, 1976) (see Chapter 6 by R. F. Post). The problem of direct recovery of the unneutralized ion beam energy is closely related, and in several ways should be simpler because of the good initial beam collimation and because of the discrete particle energy distribution. Only the rather high power density in the ion beams tends to make direct conversion here more difficult than on the particle flux escaping from mirror machines.

The central problem of all schemes for the direct recovery of the positive-ion-beam energy is the suppression of the electron flow. The same electric potential gradient that slows down the ions accelerates electrons. It is thus imperative that the electrons, which are necessarily present in the neutralizer region, must be prevented from reaching the ion retardation region. Electron suppression can be accomplished either electrostatically or magnetically. Both schemes are being tried out, with variable success, by several injector development groups, but much work remains to be done. Fig. 20 shows schematically the essential elements of a direct-recovery system in which the electron current is suppressed electrostatically (Barr et al. 1979).

In the system shown the neutralizer is at ground potential. Therefore the ion collector must be operated at positive high voltage to slow down the ions. If the ion energies are distributed, for example, as indicated in Fig. 6 or 7, the collector must be more complex if it is not to reflect ions back into the neutralizer. In order to be effective as an efficient recovery system it would have to be subdivided somewhat like the direct convertor described by Post in Chapter 6, and by Barr and Moir (1976).

It is also possible to operate an injector system with the neutralizer at high negative potential and the source only slightly positive, so that the residual full energy ions can be collected at ground potential. This is a very attractive option since the currents that need to be handled at full voltage are smaller. The problem in this case has to do with insulation of the neutralizer, and with preventing electrons from leaving the neutralizer region in lage quantities. Work on this variant is also in progress and results so far seem promising (Fumelli et al., 1978). Direct energy recovery is not yet in a state where it can be considered as a developed technique.

Acknowledgments

Much of the material in this chapter is based on the untiring efforts of my associates in the Neutral Beam Development Group at the Lawrence Berkeley Laboratory. Their contributions are gratefully acknowledged.

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Figure Captions

Fig. 1 Principle of neutral-beam injection. Note that for injection perpendicular to B trapped ions and electrons get separated by one ion-gyroradius, i.e. the process is accompanied by a current which transmits the beam momentum to the fields and thereby to the target plasma.

Fig. 2 The cross sections for ionization of the injected neutral beam versus energy, (after Sweetman, 1973). Cross sections for ionization by electrons are given for electron temperatures in the plasma $T_e < 5$ eV, $T_e = 100$ eV, 1 keV and 10 keV.

Fig. 3 Neutralization efficiency as function of particle energy, where η = power in neutral atoms out/power in ion beam entering neutralizer.

Fig. 4 Neutralization efficiency, η' vs. D_2-neutralizer thickness for each of the four beams; D^+, D_2^+, D_3^+, and D^- at injection energies E, 2E, 3E and E, respectively, for atomic neutrals at energy E = 40 keV. (Equivalent hydrogen energy shown in parentheses.)

Fig. 5 Neutralization efficiency η' vs. D_2-neutralizer thickness (see Fig. 4) for E = 160 keV. Efficiency $\eta' \equiv$ power in neutrals of energy E/total power in incident ion beam.

Fig. 6 Power flow diagrams for 1 MW 20-, 40-, 80-, and 160-kV atomic hydrogen and deuterium injection systems. Total power in ion beam incident on neutralizer is shown, assuming a typical species mix.

Fig. 7 Power-flow diagrams for 1 MW, 120 keV D^0 and H^0 injection systems, for three initial deuterium-ion-species compositions and three equivalent hydrogen-ion-species compositions at "optimum" neutralizer target-thicknesses.

Fig. 8 Neutral-Beam Injection System (Schematic).

Fig. 9 Design drawing for TFTR beamline.

Fig. 10 Formation of ion beams: (a) schematic and idealized, for rectilinear flow; (b) effect of finite electrode thickness; (c) Pierce geometry and decel gap.

Fig. 11 120 kV 65A Accelerator for TFTR

Fig. 12 Computer-optimized ion beam showing equipotentials, for a three-electrode structure

Fig. 13 80 kV computer optimized ion beam for Doublet III, with four grids.

Fig. 14 Beam divergence, (1/e Gaussian half-width) determined optically from Doppler profile of Balmer lines in neutralizer, as function of ion-current at emitter for 110 keV deuterium beams with all electrode potentials kept constant.

Fig. 15 Design drawing of "fractional area" (10 cm x 10 cm) 120 kV 15A deuterium ion source with four-electrode accelerating structure.

Fig. 16 Current density profiles and oscilloscope traces of probe currents and arc voltage and current for large rectangular field-free multifilament source.

Fig. 17 Design drawing of 120 kV 65A deuterium ion accelerating structure and source with multipole magnets (bucket source). These sources are good for pulses up to 1.5 seconds long.

Fig. 18 The modified 22-cm diameter duoPIGatron ion source with magnetic bucket developed at the Oak Ridge National Laboratory.

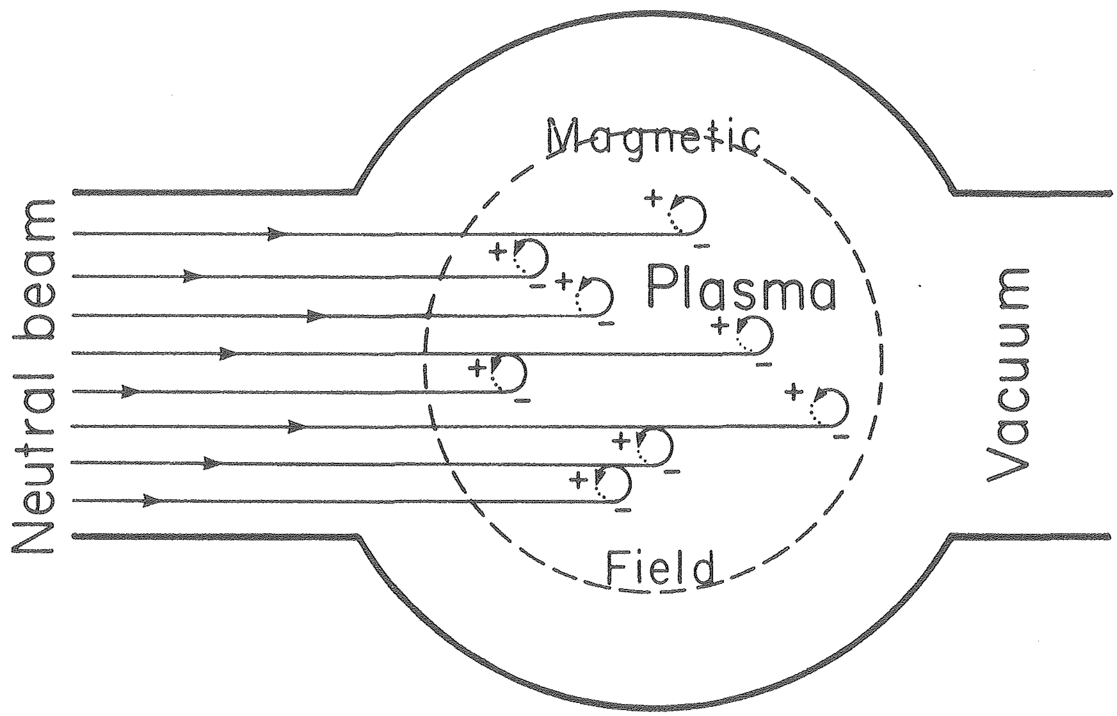
Fig. 19 Negative deuterium ion yield in thick metal vapor targets via double electron capture as function of incident deuteron energy.

Fig. 20 In-line direct energy recovery system for unneutralized positive ions in neutral beam (idealized).

NEUTRAL BEAM SOURCE REQUIREMENTS

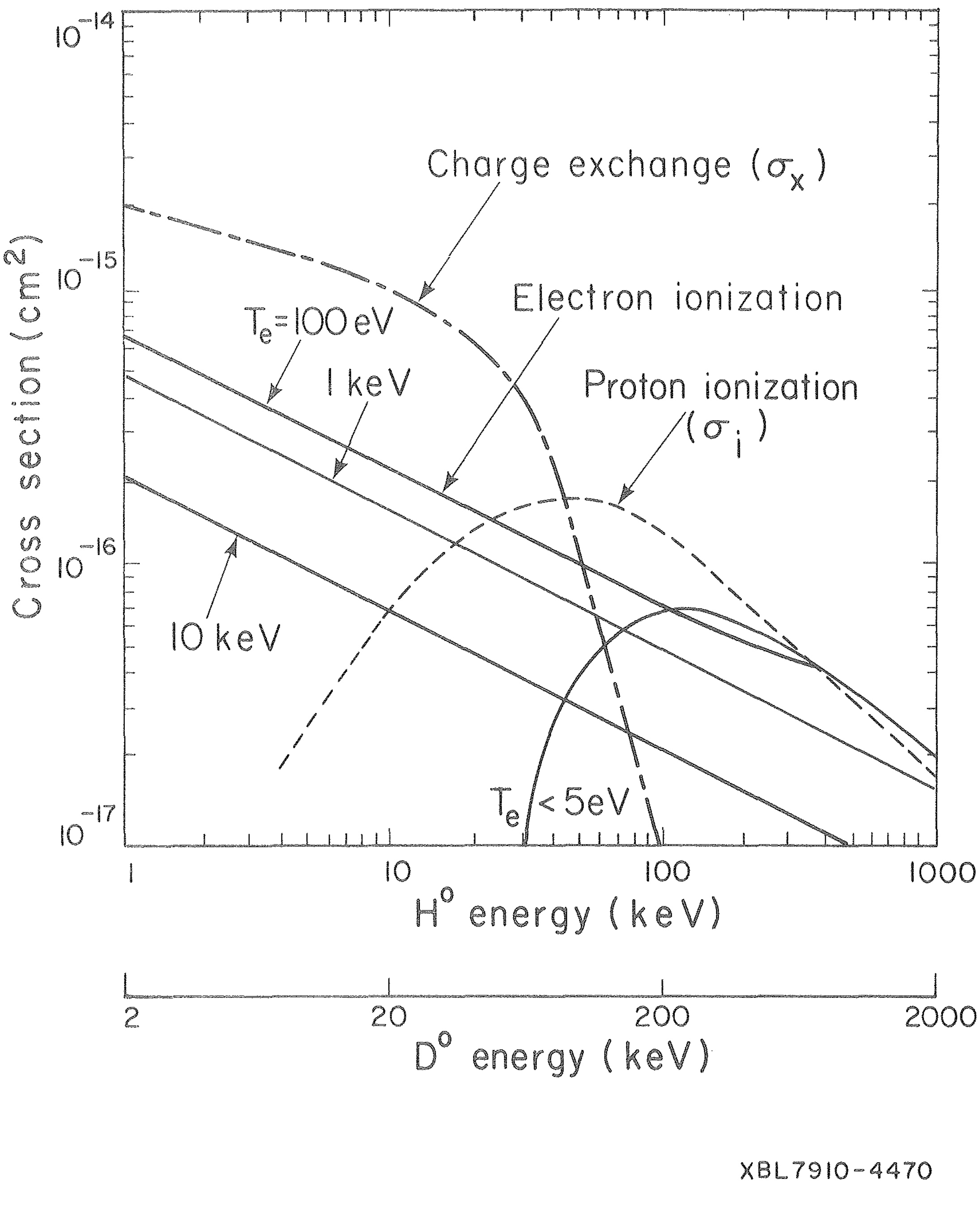
		Energy (keV)	Current (Amperes)	Pulse Length (Seconds)	Number Sources	Year
Princeton Large Torus	(PLT)	40	60	0.3	4	1978
Impurity Study Experiment	(ISX-B)	40	100	0.1	4	1979
Poloidal Diverter Experiment	(PDX)	50	100	0.5	4	1979
Noncircular Cross Section Tokomak	(Doublet III)	80	80	0.5	4	1979
Tandem Mirror Experiment	(TMX)	20 40	80 65	0.025 0.025	16 8	1979
Tokomak Fusion Test Reactor	(TFTR)	120	60	0.5	9-12	1981
Tandem Mirror Fusion Test Facility	(MFTF-B)	80 80 20	60 80 100	30 0.5 0.01	7 16 20	1984
Engineering Test Facility	(ETF)	150	100	6	20	1990

TABLE I



XBL 7910-4468

Fig. 1



Charge exchange (σ_x)
Electron ionization
Proton ionization
(σ_i)
T_e=100 eV
1 keV
10 keV
T_e < 5eV
Cross section (cm^2)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
1
10
100
1000
H^o energy (keV)
2
20
200
2000
D^o energy (keV)
XBL7910-4470

Fig. 2

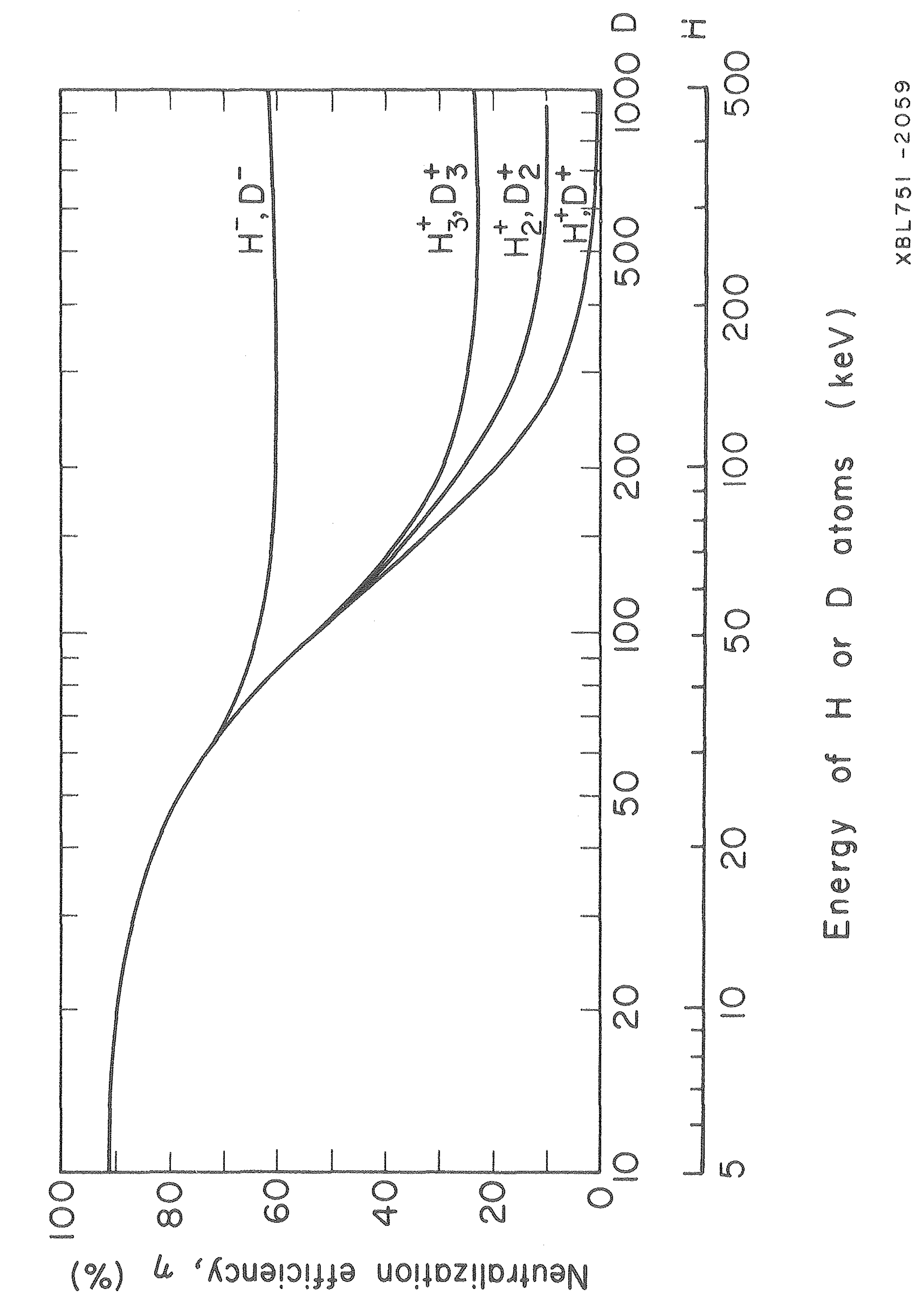
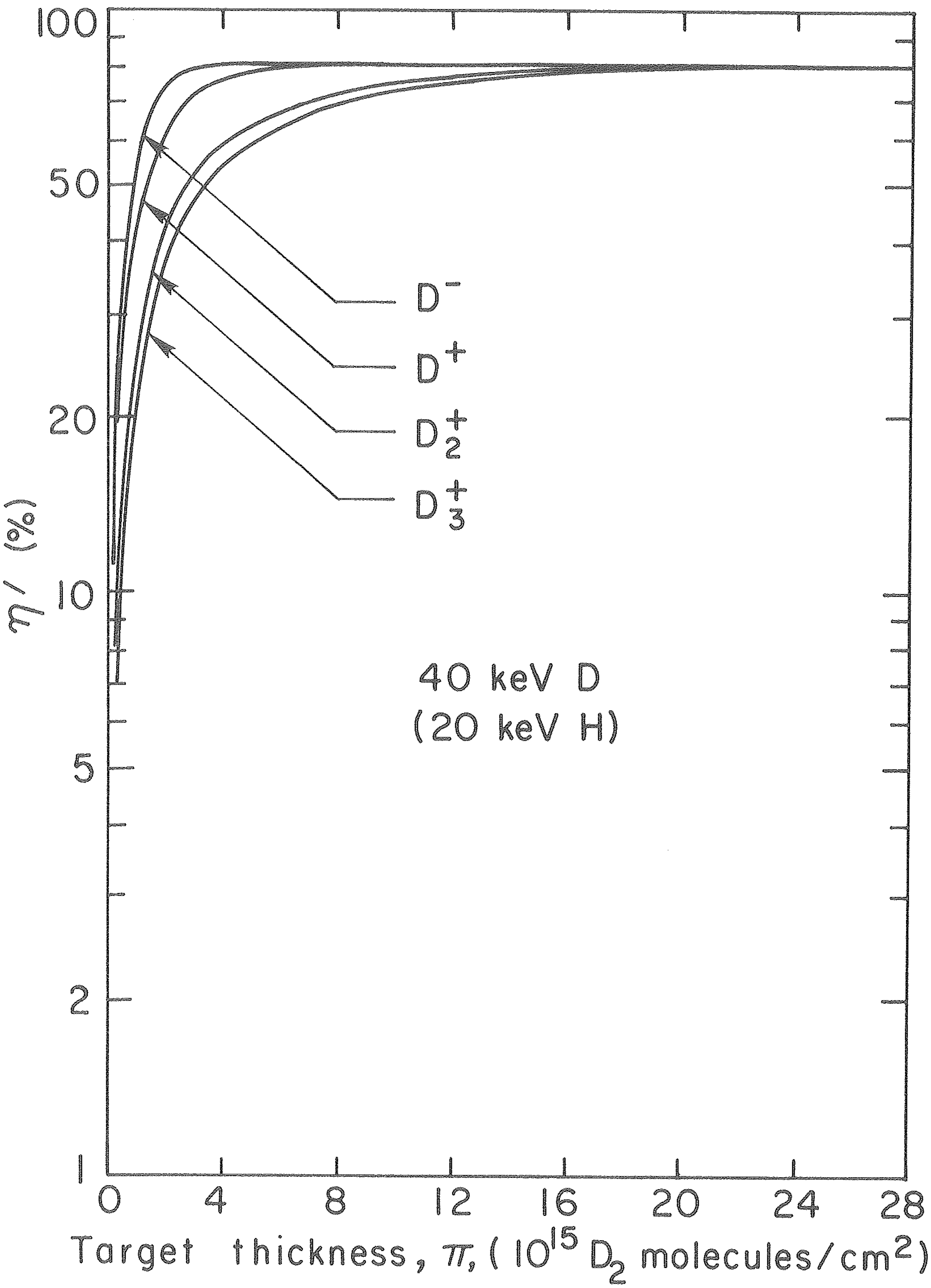

Neutralization efficiency, η (%)
100
80
60
40
20
0
Energy of H or D atoms (keV)
10
20
50
100
200
500
1000 D
5
10
20
50
100
200
500 H
H⁻, D⁻
H3+, D3+
H2+, D2+
H+, D+
XBL751-2059

Fig. 3



XBL769-3979

Fig. 4

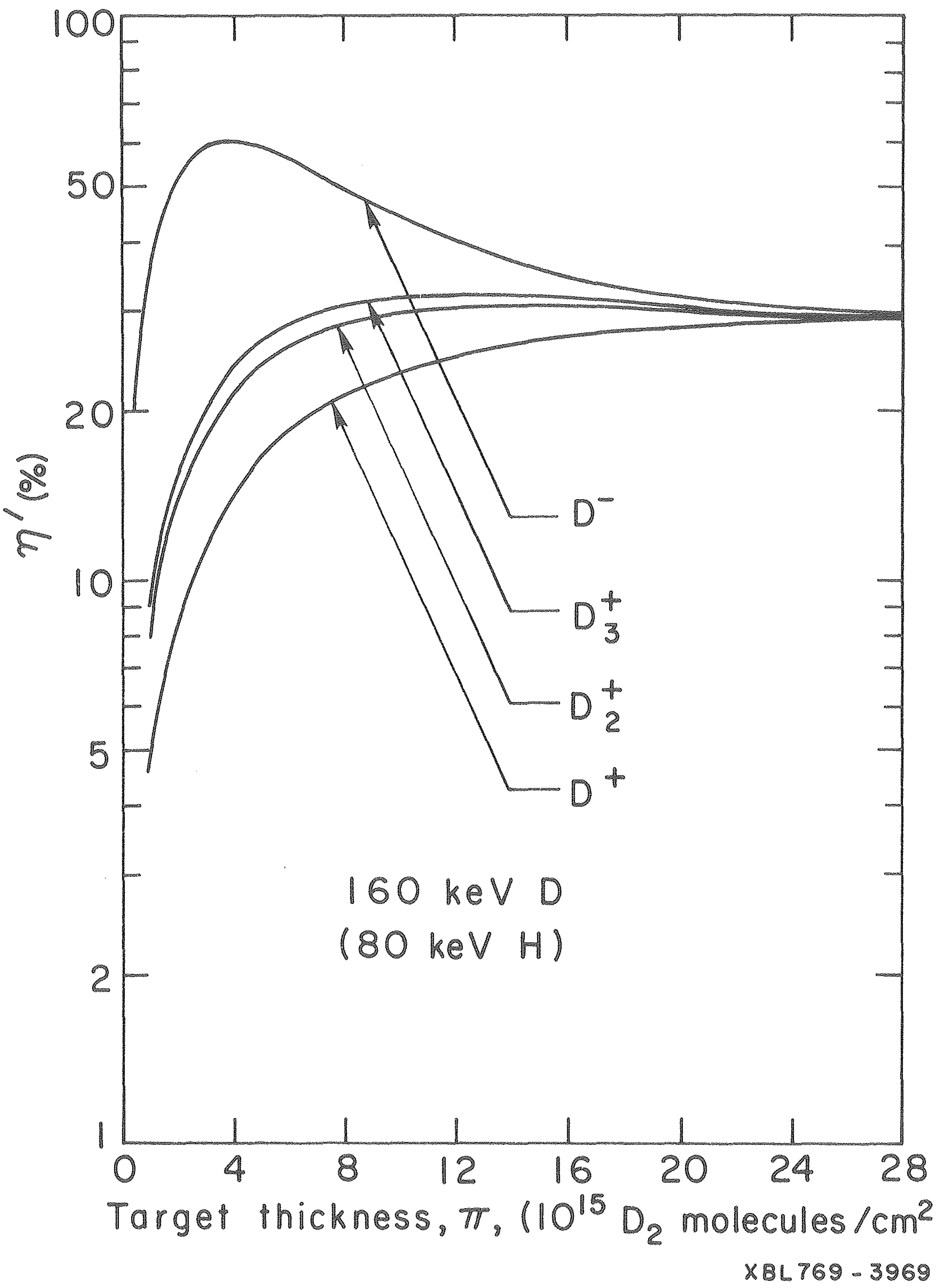
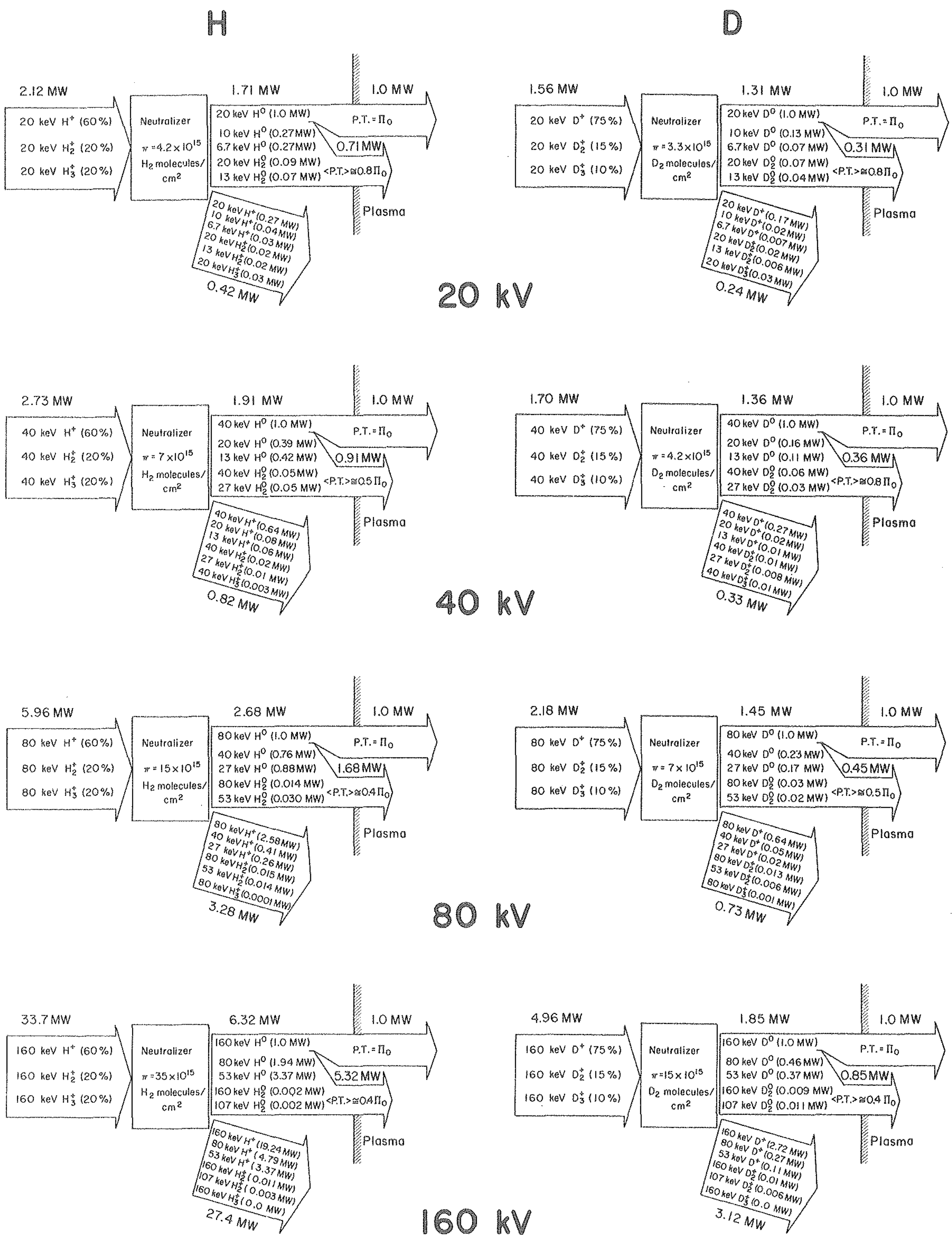
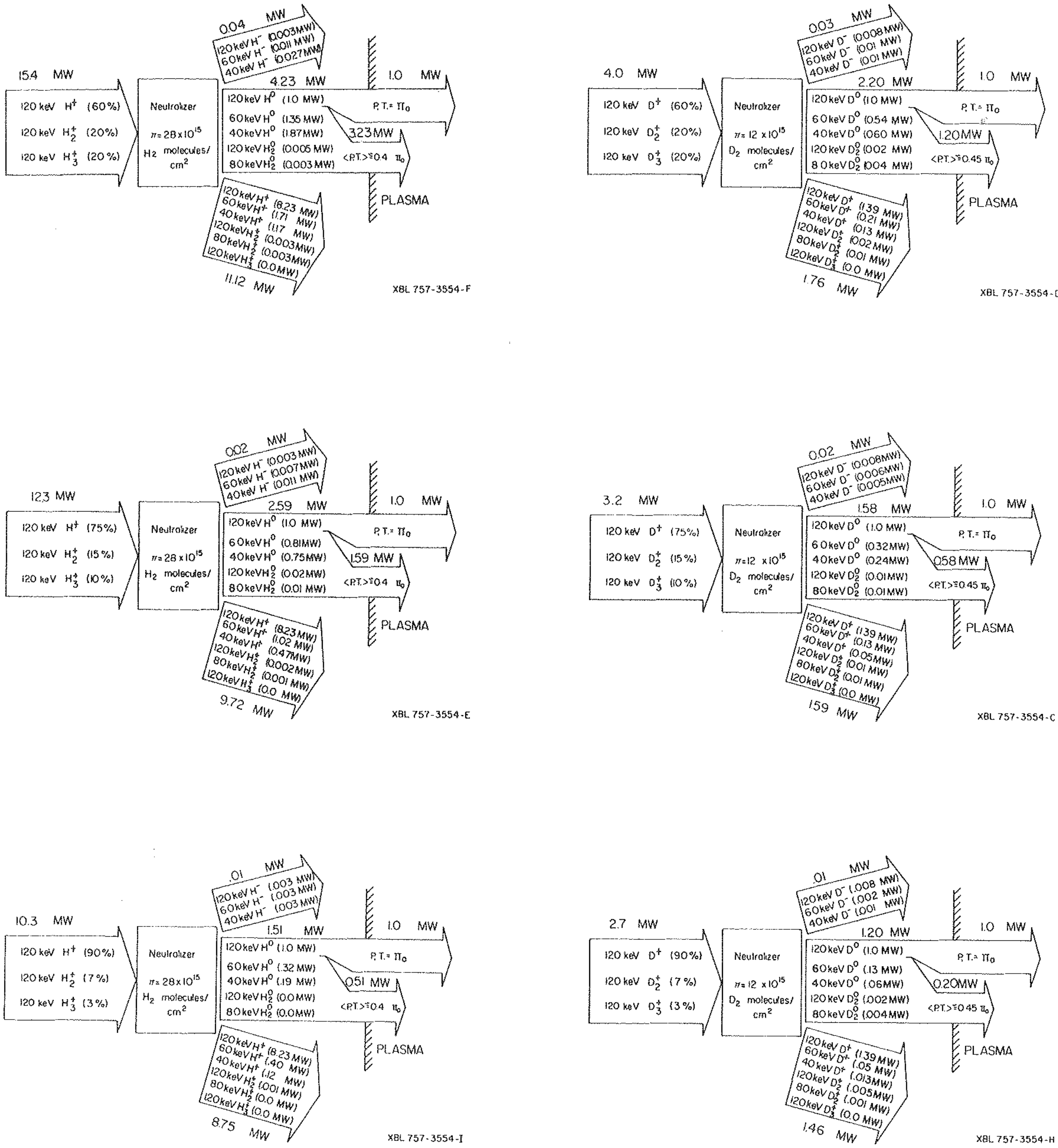

100
50
20
10
5
2
1
η′ (%)
D⁻
D3+
D2+
D+
160 keV D
(80 keV H)
0
4
8
12
16
20
24
28
Target thickness, π, (10^15 D2 molecules/cm²)
XBL769-3969

Fig. 5



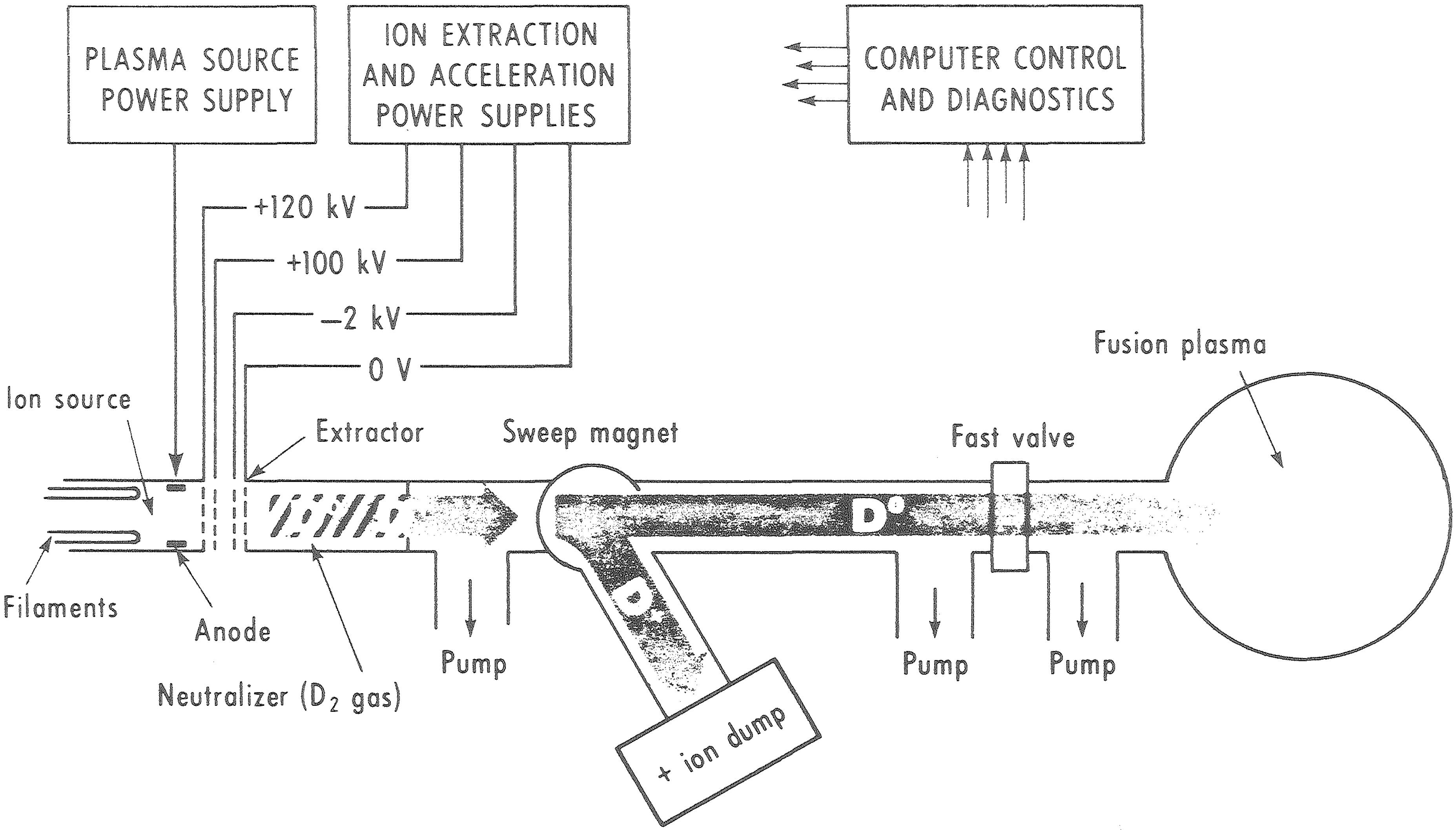
XBL 746-3550

Fig. 6



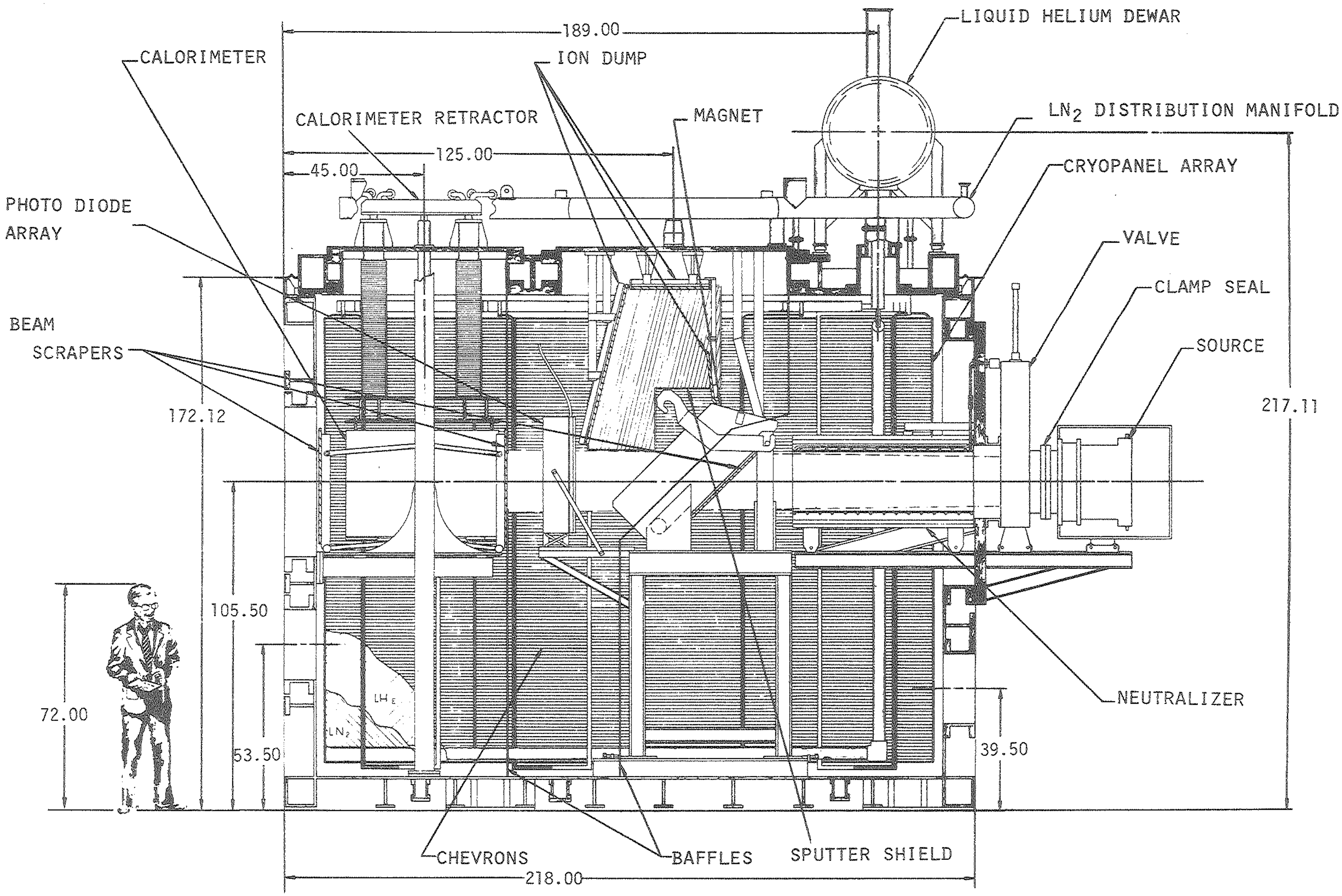
XBL 757-3554-J

Fig. 7



CBB751 8168

Fig. 8



NOTE: DIMENSIONS IN INCHES

XBL 788-10014

Fig. 9

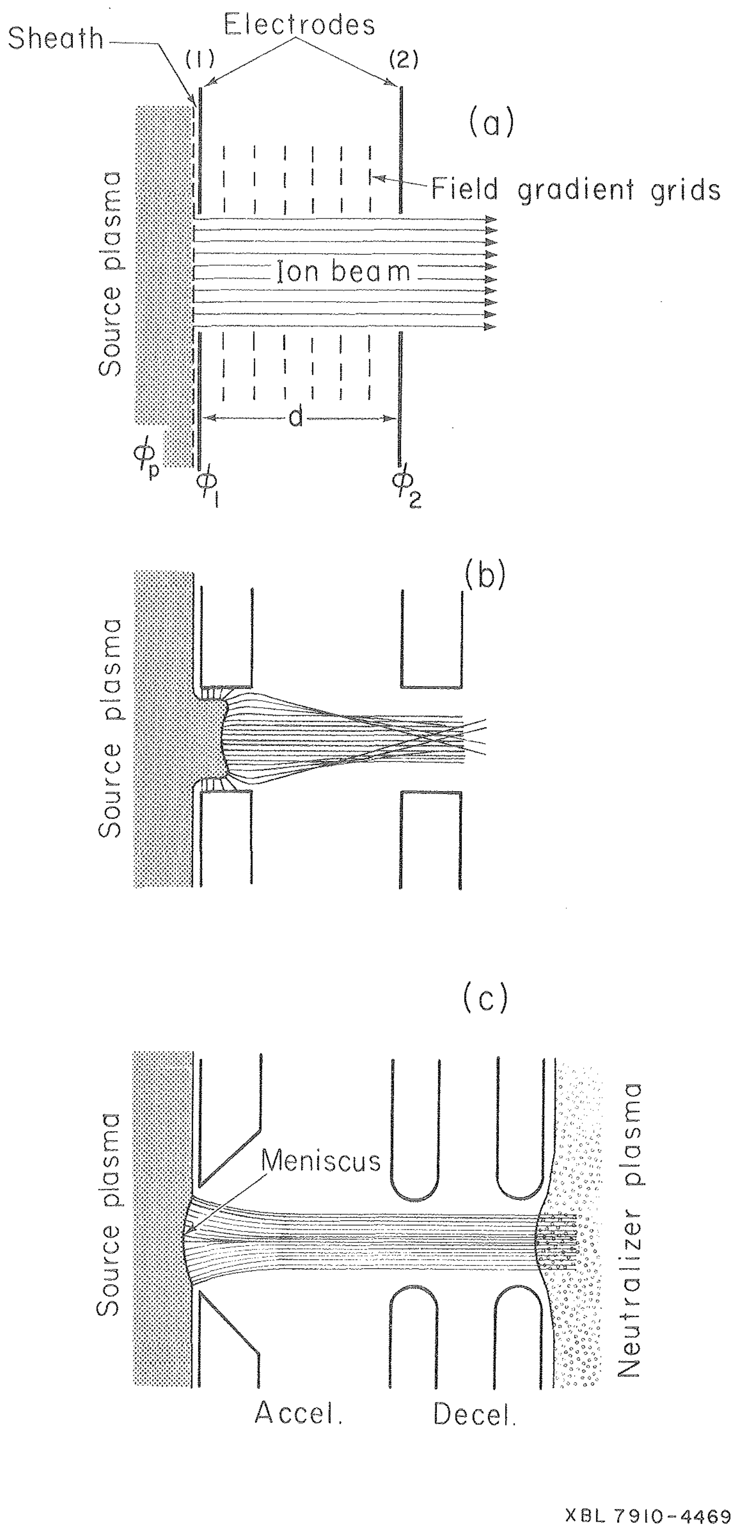

Sheath
Electrodes
(1)
(2)
(a)
Field gradient grids
Source plasma
Ion beam
d
ϕ_p
ϕ_1
ϕ_2
(b)
Source plasma
(c)
Meniscus
Source plasma
Neutralizer plasma
Accel.
Decel.
XBL 7910-4469

Fig. 10

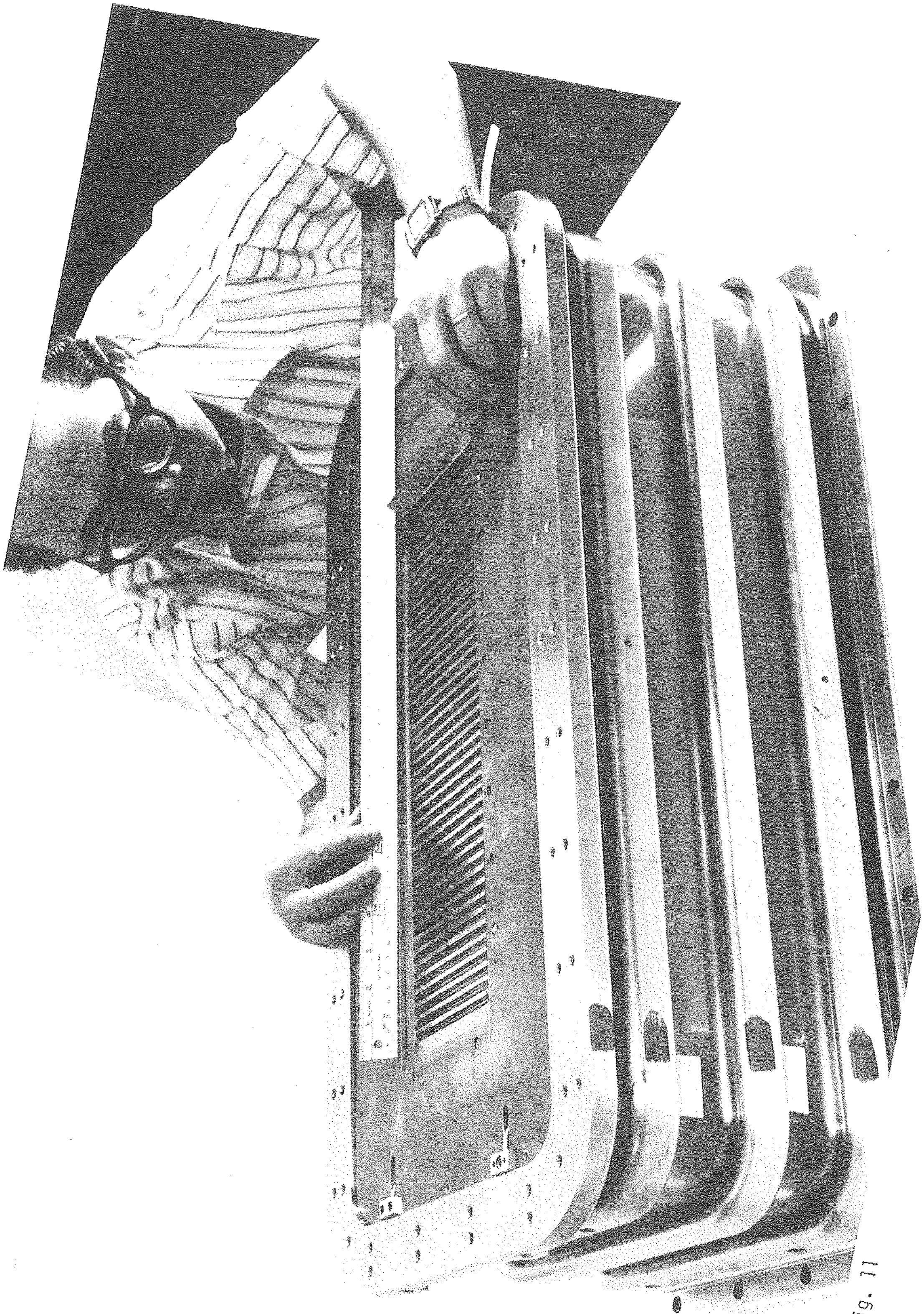
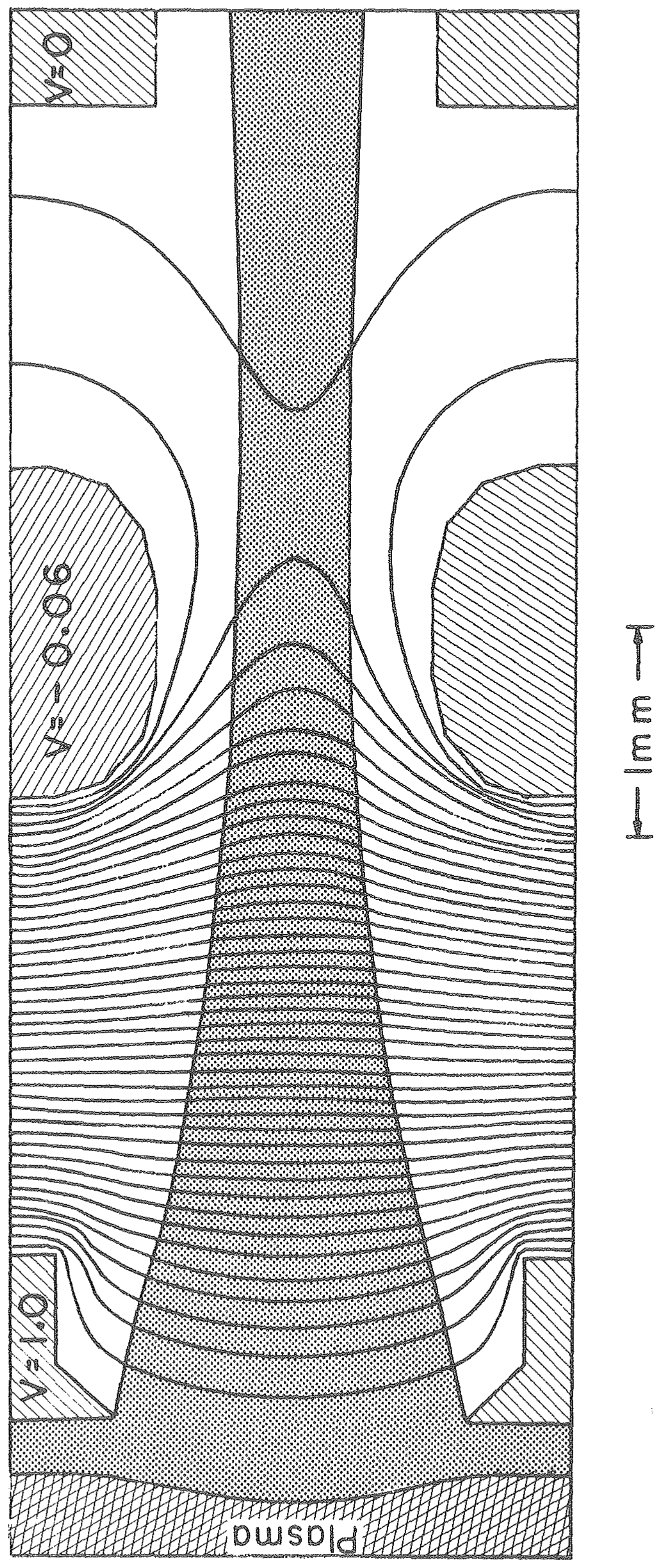


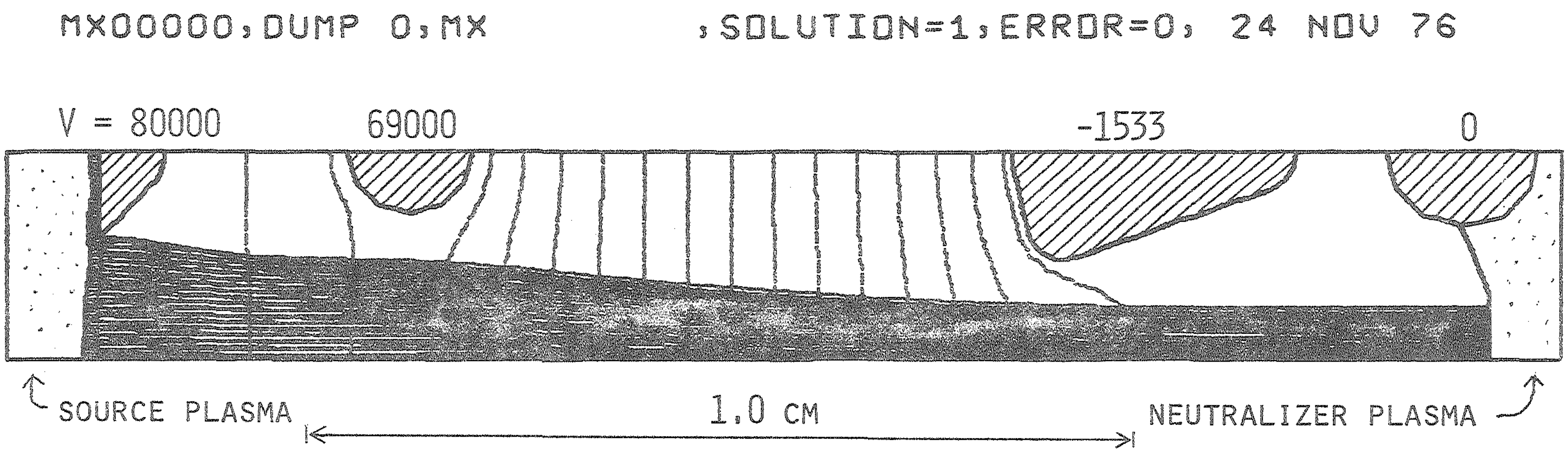
Fig. 11



XBL 748-4095

Fig. 12

Fig. 13



ION CURRENT DENSITY = 0.43 A/CM^2 (D^+)

TRANSPARENCY = 0.6

BEAM DIVERGENCE ($\sqrt{2}\ \theta_{RMS}$) = 0.55 DEGREES

XBL 7612-10931

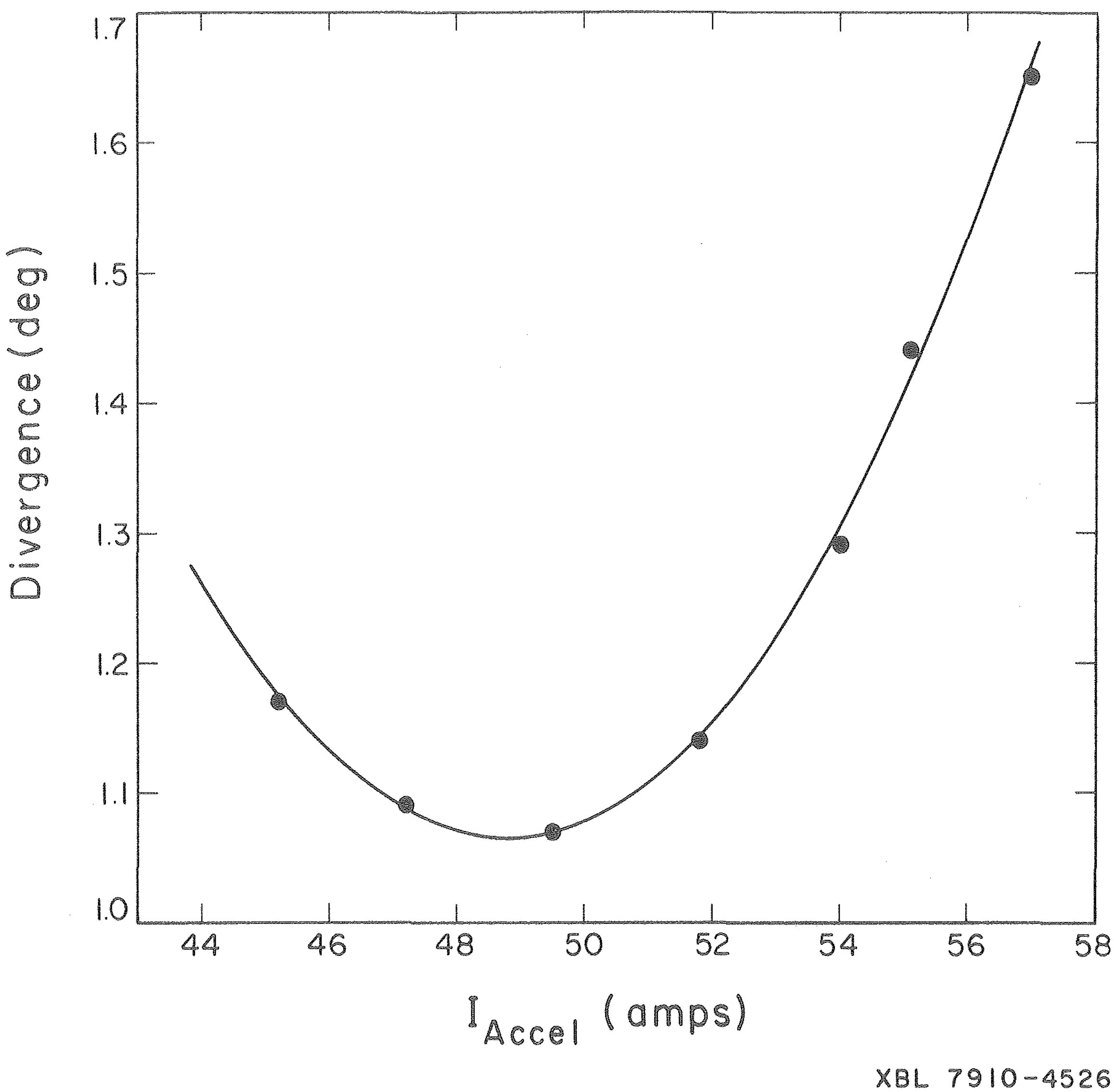

1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
Divergence (deg)
44
46
48
50
52
54
56
58
I_Accel (amps)
XBL 7910-4526

Fig. 14

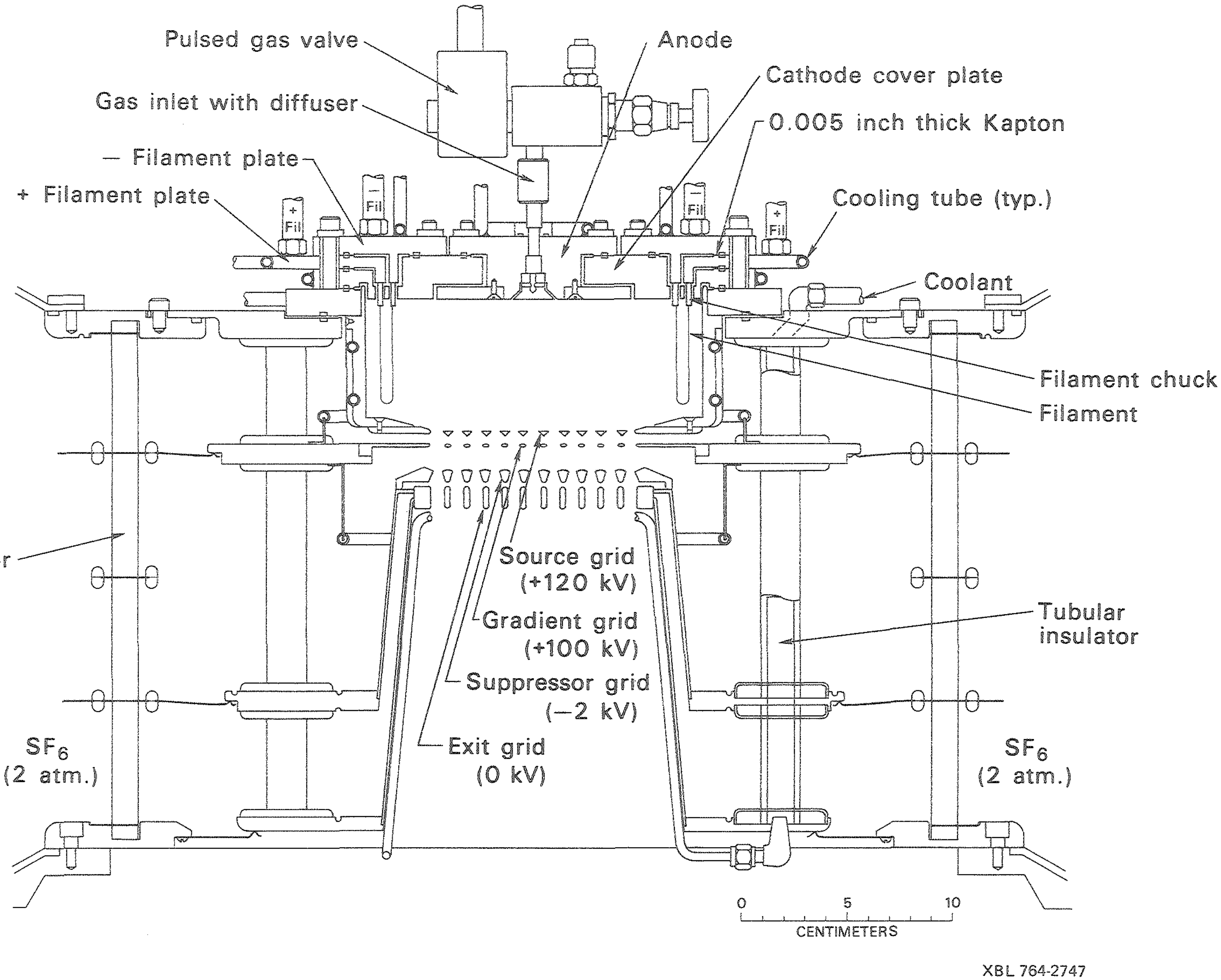
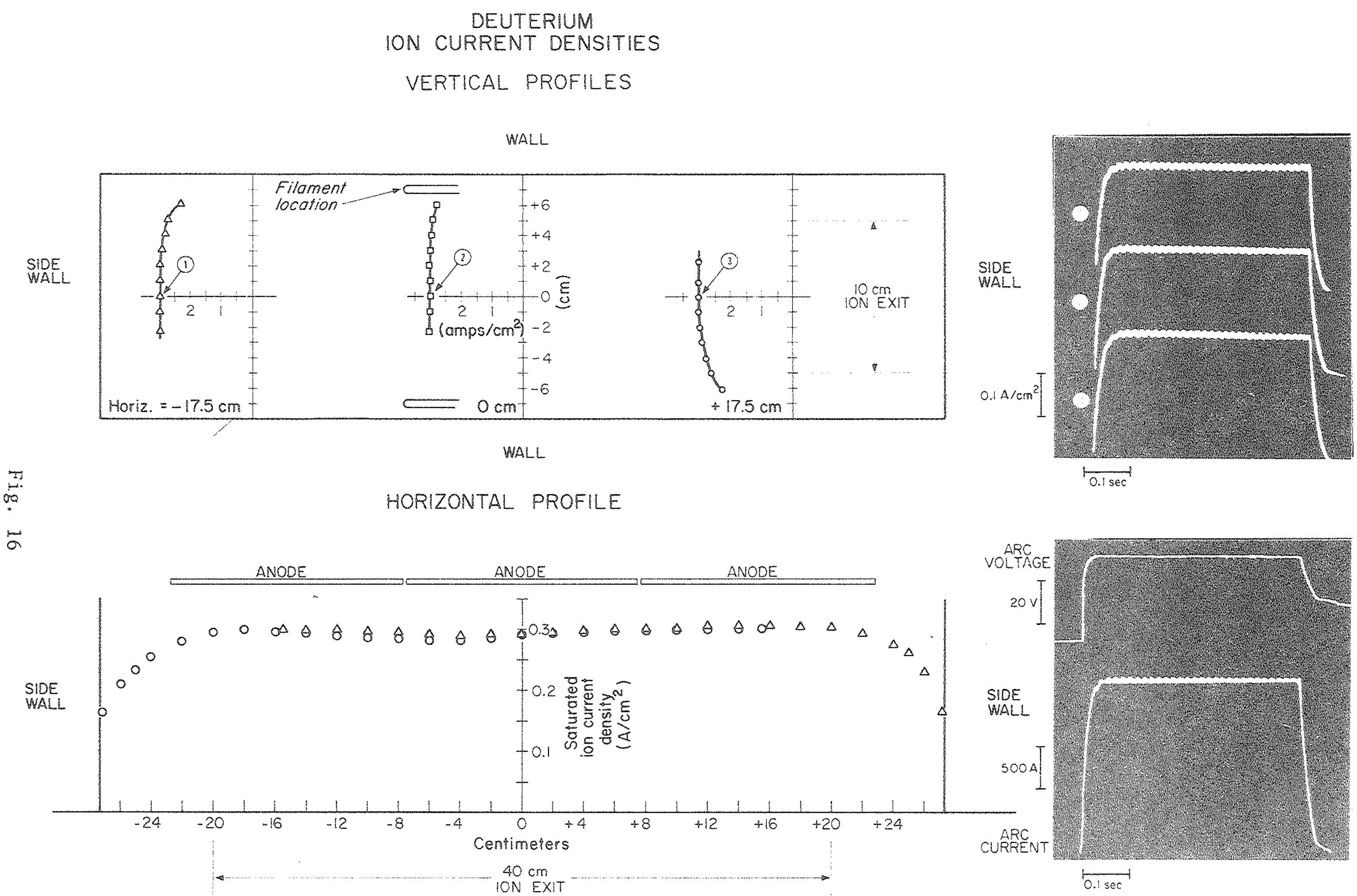
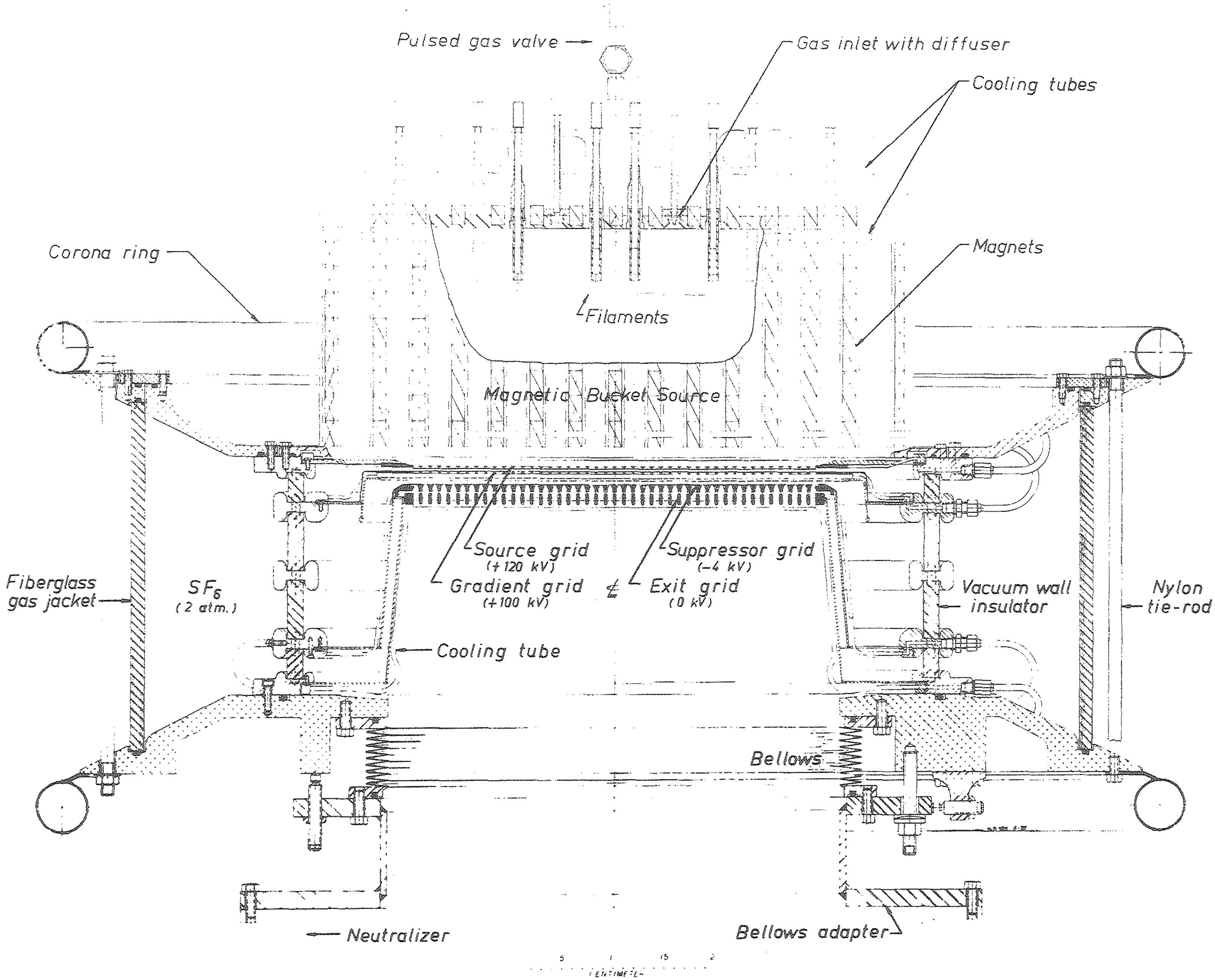

Pulsed gas valve
Anode
Cathode cover plate
Gas inlet with diffuser
0.005 inch thick Kapton
— Filament plate
+ Filament plate
Cooling tube (typ.)
Coolant
Filament chuck
Filament
Vacuum wall insulator
Source grid (+120 kV)
Gradient grid (+100 kV)
Suppressor grid (−2 kV)
Exit grid (0 kV)
Tubular insulator
SF_6 (2 atm.)
SF_6 (2 atm.)
0 5 10
CENTIMETERS
XBL 764-2747

Fig. 15



XBL 779-1928

Fig. 16



LBL "65-AMP." NEUTRAL BEAM SOURCE MODULE
(65-Amp, 120-keV, 0.5-sec.)

Fig. 17

CBB787 8075

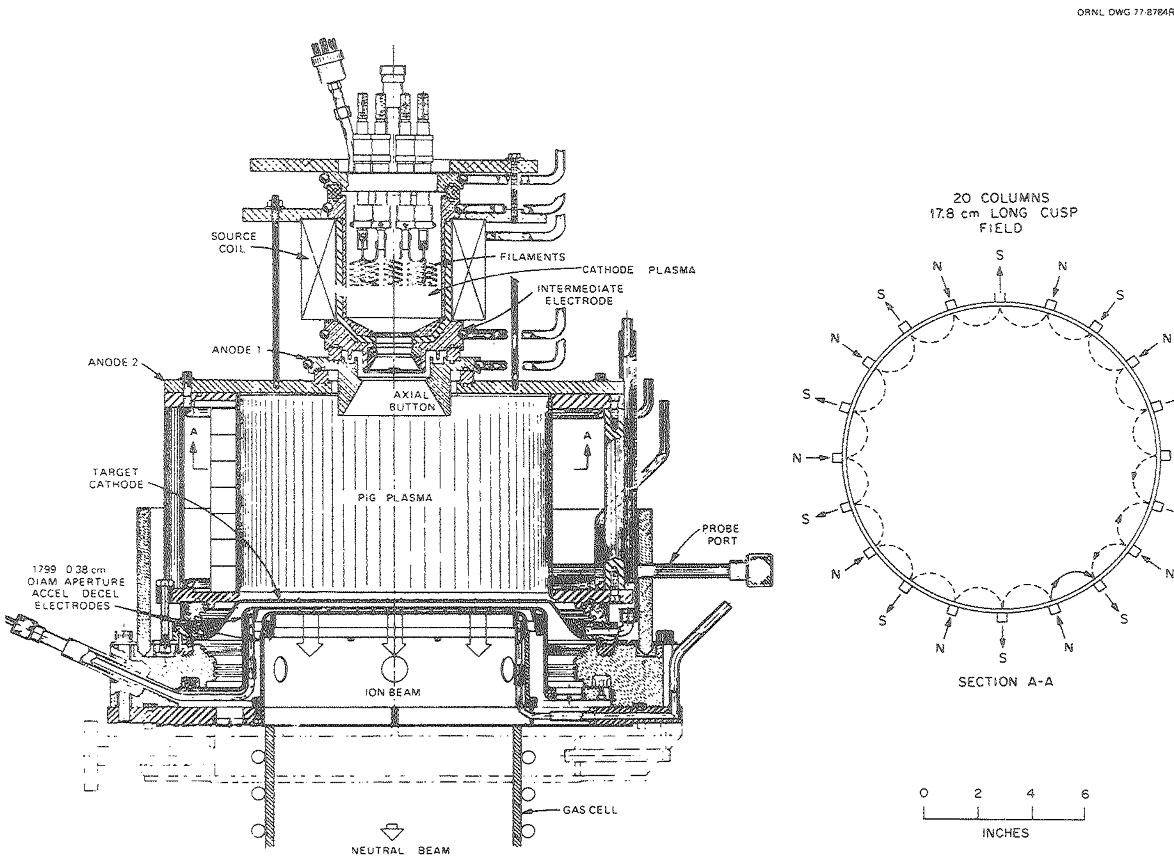
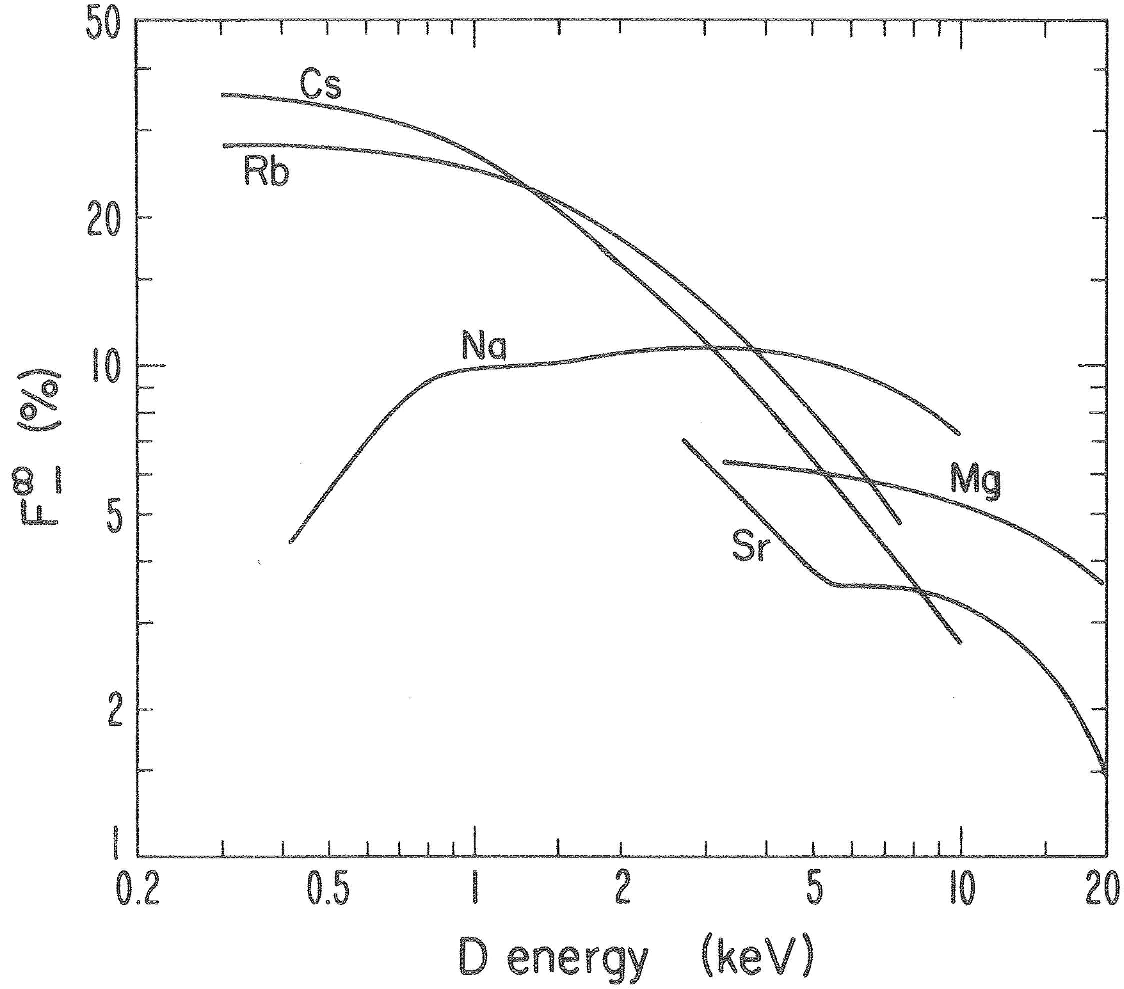


Fig. 18

XBL 806-10342



XBL 794-1085B

Fig. 19

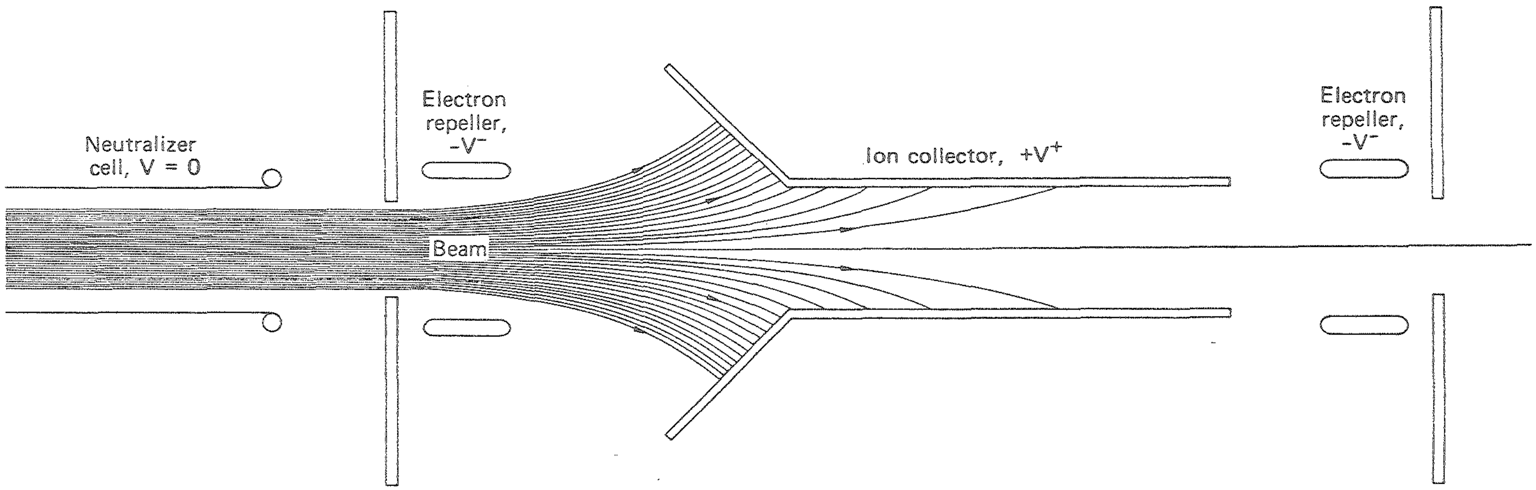


Fig. 20

XBL 789-10843