MASTER TOBER 1981

PPPL-1839
UC-20D

PLASMA HEATING WITH MULTI-MeV NEUTRAL ATOM BEAMS

BY

L.R. GRISHAM, D.E. POST,
D.R. MIKKELSEN AND H.P. EUBANK

PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

Plasma Heating with Multi-MeV Neutral Atom Beams

L. R. Grisham, D. E. Post, D. R. Mikkelsen, and H. P. Eubank
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Abstract

We explore the utility and feasibility of neutral beams of $A \geq 6$ AMU formed from negative ions, and also of D^0 formed from D^-. The negative ions would be accelerated to ~ 1-2 MeV/AMU and neutralized, whereupon the neutral atoms would be used to heat and, perhaps, to drive current in magnetically confined plasmas. Such beams appear feasible and offer the promise of significant advantages relative to conventional neutral beams based on positive deuterium ions at ~ 150 keV.

I. Introduction

Almost all plans for magnetically confined fusion plasma devices require some form of supplemental heating. The most successful method used to heat plasmas in present day machines has been the injection of 20-60 keV beams of hydrogen or deuterium atoms. These beams are formed by electrostatically accelerating protons or deuterons and then neutralizing them by charge exchange with hydrogen. However, the charge-exchange cross section drops rapidly at energies above ~ 80 keV/AMU, so only a small fraction of a high energy ($\gtrsim$ 80 keV/AMU) beam is neutralized. Moreover, in addition to D^+, the ion sources make $D_2{}^+$ and $D_3{}^+$, which produce neutrals in the beam at one-half and one-third of the full energy. Because these undesirable fractional energy components are more easily neutralized than the full energy component, they carry a progressively larger share of the power in the neutral beam as the energy is increased. On the other hand, a restriction to energies below 80 keV/AMU limits the size and density of plasma that such a beam can penetrate and heat. Further, these beams result in high power densities on surfaces in the ion source and acceleration grids, and need massive liquid helium cryocondensation vacuum pumps. Negative deuterium ions can be neutralized efficiently at high energies, and they have previously been considered for applications at injection energies of a few hundred keV. Unfortunately, producing the large currents (many amps) required at such energies, so far, has proved to be an elusive goal.

II. The Proposed Approach

An alternative approach would be to accelerate the negative ions to much higher energies and, going a step further, to use more massive negative ions so that, for a given velocity, the energy per ion would be greater.

Incorporating these measures would greatly decrease the amount of current required to yield a particular neutral injection power. In this paper, we propose a novel heating method in which negative ions of atomic mass $A \geq 6$ AMU are accelerated to 1-2 MeV/AMU, neutralized, and injected into a plasma (Fig. 1). There they go through successive stages of ionization, heat the plasma as they slow down, and under appropriate conditions drive current. Negative deuterium beams might also be used for this scheme at energies of 1-2 MeV/AMU, although, as will be mentioned, using D^- would sacrifice some of the benefits associated with the heavier ions. These high energies were not a viable option for the electrostatic injectors conventionally used for neutral injection, where high energies required equally high voltages relative to ground. However, this connection between energy and operating voltage is severed if instead one uses a RF linear accelerator in which case one pays for greater energy by lengthening the accelerator rather than by a higher potential. Since length probably can be more easily achieved and tolerated near a reactor than can multimegavolt potentials, we propose to use a RF accelerator.

Dawson and McKenzie[1] and Grand[2] have proposed injection of positive ions (B^+, Ne^+, etc.) as an alternative to neutral hydrogen injection. Ohkawa[3] and Thompson[4] considered neutral helium beams for current drive and heating. The advantages of the positive ion injection schemes are that, in principle, there is no inefficiency due to incomplete beam neutralization, and that high current positive ion sources are straightforward to build for a number of elements. The ions are accelerated to $\sim$ 1 MeV/AMU, at which energy the completely ionized nuclei will be as well confined in the plasma as the alpha particles produced by D-T fusion. After reaching the edge of the tokamak, the ions drift into the plasma on unconfined orbits with $\rho_p \propto (A/q)$, where ρ_p is the poloidal gyroradius, A is the atomic mass in AMU, and q is the charge. In the plasma, the singly charged ion is further ionized until $q = Z$ (Z is the atomic number), while ρ_p shrinks by a factor of Z, so the fully ionized particle is on a confined orbit. The use of neutral light atom beams retains the advantage of conventional deuterium neutral injection (which allows easy transport through the tokamak's strong fringing magnetic fields and tangential aiming to achieve centrally peaked heating), while gaining enhanced penetration through the orbit compression associated with the drifting of the less-than-fully-stripped ions, and allowing injector currents much lower than those required with deuterium at 100-200 keV/AMU.

If one wishes to maximize the energy density in the beam and to minimize the current required to achieve a given beam power, then it is desirable to inject at the highest possible energy which still allows adequate confinement of the fully stripped ions and for which the plasma is opaque. Of these two constraints, the first is more restrictive, varying as the Z of the beam, while the second varies (relative to D^o) as $\sim Z^2$ for light atoms. This suggests that there are advantages to using the most massive element whose negative ions can be prolifically produced and efficiently neutralized. However, as will be mentioned later, there are also other considerations which tend to place upper limits on the mass of the beam. In particular, at a given energy/amu, the confinement of the beam particles in their initial stages of ionization degrades as the mass increases, and the amount of power which might be radiated by the thermalized beam ions becomes more significant compared to the power they bring into the plasma. All these constraints combine to define a mass range of roughly $6 \leq A \leq 30$ from which to select light atom beams. These limits are, of course, flexible, but we have taken them as an approximate guide in selecting candidate negative ions.

III. Computations

We have calculated the heating profiles and driven current to be expected from injection of deuterium and heavier atoms using Monte-Carlo tecnniques. We have used a particle simulation code which injects neutral atoms into an elliptical cross-section tokamak and calculates the ionization distribution resulting from electron impact, proton impact, and charge transfer, and ionization by impurity ions in the plasma. The ions then follow guiding center trajectories including finite gyroradius effects, undergoing successive single ionizations until they are fully stripped. These fully stripped ions follow guiding center orbits which are progressively modified by coulomb collisions with the background plasma. The plasma heating rate and the beam driven current are integrated over the history of each particle.

IV. Heating Discussion

Table I shows the plasma parameters used for our computations of injection into an INTOR-sized plasma. [The high T_e was chosen to give a good current drive efficiency; the beam penetration would be essentially unchanged if $T_e(r=0)$ were 20 keV.] Figure 2 shows initial drift orbits for the O^+ ions resulting from ionization of 32 MeV oxygen atoms injected either co- or counter to the plasma current and ionized at the x's. It is apparent that if counter-injection is required it must be done from the inboard side of the tokamak. Figure 3 shows a typical drift orbit of an oxygen ion, injected counter to the plasma current at 32 MeV, as it undergoes successive ionizations. The multiple stages of ionization allow inboard drifting which causes the final energy deposition profile to peak in the central plasma. This becomes more apparent in Fig. 4, where we see that although the initial deposition profile of O^+ resulting from ionization of 16 MeV co-injected O^0 is in the outer portion of the plasma, the final heating deposition profile (O^{+8}) is strongly peaked near the axis. The sharpness of the peaking arises because almost all of the energy transfer to the plasma occurs after the atom is totally ionized, and consequently has completed drifting inward. We show for comparison the heating deposition profile resulting from co-injection of a monoenergetic 2 MeV D^0 beam, which would have to be produced from D^- ions. Figure 4 also shows the heating deposition profile for co-injection of 150 keV D^0 made from positive ions. In this case, 60% of the power in the neutral beam is at the full accelerating energy, while 24% is at half energy and 16% is at one-third energy. For comparison, we also give the heating profile resulting from injection of 46 MeV Na^+. Note that good penetration can be achieved by injecting light positive ions, but a higher energy/amu is required than would be needed to achieve the same penetration with light atom beams. This might be viewed as an advantage for positive ion injection, since it permits smaller beam currents if the cross-field access problem can be solved. Figure 5 depicts the integrated power deposited inside a given radius for the same beams as in Fig. 4. It is clear that, while 2 MeV D^0 is similar to 16 MeV O^0 in its ability to deposit heat in the plasma core, 150 keV D^0 is much worse. The 16 MeV O^0 beam deposits about 85% of its energy inside the inner half of the minor radius, or inside the inner quarter of the plasma volume. Although not shown, the peaking of the heating profile is qualitatively similar for other possible beams, such as Li^0 or C^0 at 1 MeV/AMU. Such a peaked heating profile reduces the injected power required to achieve ignition. The reduction has been shown to be as much as a factor of two compared with positive ion-based deuterium neutral injection.[6]

In the MeV/amu energy range the ionization cross section is almost proportional to Z_{eff}. The exponential nature of the neutral beam attenuation produces a large reduction in the neutral beam penetration when Z_{eff} is raised to 2-3. This is compensated to some extent in the case of oxygen by the orbit penetration, which continues to higher charge states since the mean lifetime of each state is reduced but the orbit period is unchanged (penetration ceases when the mean lifetime is greater than half the orbit period). When Z_{eff} was raised to 3, the power deposited inside $r = a/2$ dropped from 0.81 to 0.80 of the input power, and the power inside $r = a/4$ dropped from 0.40 to 0.32. The oxygen beam is thus relatively insensitive to changes in Z_{eff}.

There is a small beam-driven counter-directed current of $\lesssim 0.02$ Amps/watt. This is much smaller than the result in the next section because the beam orientation used for heating produces very little $v_{\parallel}/v$ and hence very little current.

V. Current Drive Discussion

The total current, J_{BD}, driven by a beam is $J_{bd}(r) = J_{circ}(r)\ \{1 - Z_B/Z_{eff}[1 - G(r/R_o,\ Z_{eff})]\}$, where J_{circ} is the circulating beam current, Z_B is the atomic number of the beam, and G is the trapped-electron correction term from Start and Cordey.[7] We refer to the current given by the above equation as the "neoclassical" beam-driven current. The "classical" current is given by the same equation with the factor G left out. Table II gives the current driven by various beams at their optimum energies for current drive. The neoclassical currents use a value for "G" of $\approx 1/2$. We see that the attractiveness of the heavier atoms relative to D^o as a current drive mechanism depends upon how important the neoclassical correction to the current turns out to be. If the current behaves neoclassically, then D^o at 1.0-1.5 MeV offers the greatest efficiency in terms of the ratio of current driven divided by the injected power. On the other hand, if the current drive is classical (i.e., if the trapped electron correction is relatively small), then O^o and Si^o both afford greater efficiency in terms of the injected power than does D^o. At this time, the state of knowledge of tokamaks appears to be inadequate to say how significant the neoclassical effects will be. The total current drive efficiency would also depend, of course, upon the power efficiency of the injector system, which in turn depends upon the accelerator and neutralizer efficiencies. At 1.0-1.5 MeV the D^o might require an RF accelerator with an efficiency similar to that associated with acceleration of the heavier atoms. The neutralization efficiencies depend upon the type of neutralizer employed, but would probably not be greatly dissimilar if photodetachment neutralizers were used.

An additional consideration is that, while D^o can be co-injected for current drive, the heavier atoms must be counter-injected (and from the inboard side because of the orbits) if they are used for current drive instead of just for heating. This difference arises because the correct value of G, the neoclassical correction factor, lies somewhere between 0 and 1; consequently, $J_{bd} \propto J_{circ}$ for D^o, while $J_{bd} \propto -J_{circ}$ for $Z_b >> Z_{eff}$ (we assumed $Z_{eff} \sim 2$ for D^o current drive and 1.25 for current drive with the heavier atoms).

Since, for the heavier atoms, the optimum energies for current drive are much higher than those for D^o, the heavy atom beam current required is much less than would be required with D^o, whether the current drive behaves classically or neoclassically. This is advantageous, since it may allow smaller tokamak access ducts.

VI. Plasma Impurity Effects

The impurity buildup due to these beams should pose no major problems.

INTOR is expected to require 60 MW of conventional neutral beam heating. Assuming as a worst case that 60 MW of 12 MeV carbon is required, then the fueling rate for carbon is 0.3% per second, and the resulting increase in Z_{eff} is 0.09 per second. A driven Q = 20 reactor can tolerate $n_C/n_E \sim 11\%$ since fully stripped carbon does not radiate strongly.[8] In any event, the carbon ion accumulation rate is less than the helium ion accumulation rate, so the removal of the thermalized carbon is less of a problem than is helium ash removal. Figure 6 shows the allowed impurity concentration versus Z for several temperatures for an ignited plasma.

VII. Technological Base

The utility of this technique is contingent upon the development of a high current negative ion source of an appropriate element (a total current of ~ 100 mA-1A at a density of at least a few mA/cm^2), a tractable accelerator and an efficient neutralizer. None of these exist in a suitable form at this time, so it is necessary to establish that there is an adequate physics and technology base to allow development of the units required.

VIII. Ion Sources

In selecting negative ions for our feasibility study, we used a number of criteria: ease of production, ease of pumping, that the ion should not be too massive (for reasons which are discussed later), and that the feedstock should not be unduly corrosive. Many elements have electron affinities comparable to or larger than deuterium's (0.75 eV) and, consequently, are in one respect simpler to make. The actual ease of production depends, naturally, upon other factors as well: among them, the vapor pressure as a function of temperature and the sputtering yield. The three ions which best fit our criteria were Li^-

which is bound by 0.62 eV, C^-, which is bound by 1.27 eV, and O^-, which is bound by 1.46 eV. Fluorine is even more electronegative, with an electron affinity of 3.40 eV, and F^- can be produced easily, but the gas is so corrosive as to make it unattractive unless none of the other candidate ions could be produced in sufficient quantities. Silicon, with an electron affinity of 1.3[illegible] eV, is probably also a viable candidate, since [illegible] be produced relatively easily in sputtering sources.[9]

The most straightforward approach to developing a source is to use a two-stage system in which positive ions are extracted from an arc and sent through a transverse supersonic jet of metal vapor, where some portion of the beam is converted to negative ions. In low current experiments[10] at 5 keV, ~ 9% of a Li^+ and [illegible] of a C^+ beam have been converted to the negative ions in a cesium cell, while [illegible] conversion of O^+ to O^- was observed with 14 keV O^+ passing through a magnesium cell, and ~ 25% conversion (non-optimized) of Si^+ to Si^- at 20 keV in a magnesium cell. Thus, to produce a 100 mA O^- source module [illegible] only [illegible] 200 mA of O^+ (actually somewhat more to allow for losses due to [illegible] and scattering). Since oxygen is a gas at room temperature, [illegible] currents should be obtainable with a multiaperture duoplasmatron [illegible] source, smaller than the ones presently used for hydrogen neutral beam injection.[11] Further, it should be quite feasible to build a 2-4 amp O^+ source, and thus a 1-2 amp O^- source, if a RF accelerator can be developed which can handle that much current in a channel. Although producing large currents of Li^+ is more difficult, there is an established technology for doing so. Calutron sources used for isotope separation have produced ~ 1.2 A of Li^+ at ~ 30 mA/cm^2,[12] which should be sufficient for a 100 mA Li^- module. Figure 7 shows a schematic design of a Li^+ source based upon the Oak Ridge National Laboratory calutron technology. Calutron sources have also produced C^+ beams at average current densities of 11.4 mA/cm^2, using CO_2 or CO as a feedstock. Thus, at a negative ion conversion efficiency of 50%, only ~ 20 cm^2 of C^+ emitting area would be required for a 100 mA C^- module. Using Si S_2 or Si Cl_4 as a feedstock, calutron sources have produced as much as 45 mA of Si^- (and an average of 27 mA over many hours) at current densities of ~ 10 mA/cm^2.[13] Even with the quoted non-optimized conversion efficiency of 25%, this would give 2.5 mA/cm^2 Si^-, which would be an adequate current density, and this could probably be enhanced by optimizing the beam energy. These calutron sources, moreover, have operated continuously for many days. Accordingly, it appears that the technologies exist to produce, with development, sufficient positive ion currents for the two-stage source approach to be successful for at least four elements, and there is no reason why the conversion results at low currents should not scale up with size.

While the two-stage approach appears to have a high probability of yielding a source with adequate current, intensity, and divergence characteristics, such sources are relatively complicated to operate because of the supersonic metal vapor cells. If a great many such sources were required for a tokamak, simplicity would be a desirable characteristic. There are a number of other approaches which, while less proven than two-stage systems, might lead to simpler sources. Negative ions of the surface material might be sputtered by a cesium beam from plates of carbon, silicon, lithium, or an oxygenated substrate. This is done for small currents in accelerator applications,[3,14] and has been used for H^- production in the mA range,[15] but may face difficulties for production of larger currents of heavier ions because of high cesium beam power densities on the sputtering plate, prolific production of secondary electrons, and the difficulty of producing sufficiently intense Cs^+ sputtering beams by surface ionization.

Alternatively, and with a much greater chance of success, one may use a plasma as the source of the sputtering ions. This might be done in a surface-plasma source similar in type to the one developed by Ehlers and Leung for D^- production.[16] In such a source (Fig. 8), positive ions of cesium and the working gas are accelerated from the plasma across a thin sheath to strike a negatively biased converter plate which is cesiated to lower its work function. Negative ions are produced by sputtering or reflection processes, and are accelerated back across the sheath. Since the incident positive ions are supplied by the plasma, it is possible to have a high current density striking a large converter area, and thus to produce relatively large negative ion yields. A source of this type has produced as much as 480 mA of H^-. It appears likely that a surface plasma source could produce adequate quantities of O^-, C^-, or Si^-, and perhaps of Li^- as well. For O^- the feedstock gas could be oxygen; for the other ions an inert gas such as argon might be used with a converter plate made of the desired material. Alternatively, for C^- production a carbonaceous gas might be used as the feedstock, and for Si^- silene might be used. An additional possible production mechanism that has been proposed for Li^- is photodissociation of NaLi molecules into Na^+ and Li^-, using a laser at 2350-2400 Å.[17]

If one chooses to use D^- in the MeV range instead of a heavier ion, then the existing surface plasma source of Ehlers and Leung is already adequate to supply an RFQ accelerator channel carrying a few hundred mA, and promising D^- sources are also being developed at Oak Ridge National Laboratory[18,19] and at Brookhaven National Laboratory.[20]

IX. Accelerator

The second critical component is the accelerator. An electrostatic accelerator appears to be precluded by the combined requirements of very high voltage and high current, along with the constraints of having to operate near the tokamak while conventional magnetically focused RF accelerators do not perform well at low β. However, recent development of RF accelerators with electric quadrupole focusing is ideally suited for this application. These accelerators, the RF Quadrupole (RFQ)[21] and the Meqalac[22], because of their velocity-independent strong focusing, can accept input beams of low energy (50-200 keV), high space charge density, and high emittance. Aside from the very major advantages of having strong focusing and modest component voltages with respect to ground, these RF accelerators have a number of other desirable characteristics which are salient to their use for this application. The insulators are relatively well shielded from metal vapor deposition and, thus, are unlikely to undergo high voltage breakdown. Since both ends of the RF accelerator can be near ground potential, it does not necessarily require a direct line of sight to the plasma. (This would not be the case with an electrostatic accelerator if one wanted the ion source to be near ground; then a tandem arrangement would be required with the post-neutralizer side of the accelerator column looking directly at the plasma.) RF quadrupole accelerators are also less sensitive to parasitic processes than are multi-MeV electrostatic accelerators. They do not accelerate heavy impurities very effectively, and they quickly over-focus electrons, ejecting them from the beam. Consequently, any secondary electrons cannot propagate very far along the accelerator, and thus they give rise to little power drain. RF quadrupole accelerators can also have very high capture and transmission efficiencies (~ 85-90%), and their operation is simple because the focusing and bunching are determined by the machining of the vanes. Further, with a single channel resonator, the structure can be reasonably open for pumping which can be done through screened apertures in the cavity wall.

The Meqalac accelerator uses electrostatic quadrupoles and many small current carrying channels in parallel, while each RFQ has a single large channel delineated by four scalloped resonator vanes. Without the scalloping, the four vanes provide only radial focusing; as the scallops are introduced (180° out of phase in the two normal planes), they give rise to longitudinal components in the electric field which accelerate the beam. At present, the large input aperture (6-16 cm or more[23]) and high single channel current capability possible with a RFQ appear to be more compatible with the presently envisioned ion sources than does the Meqalac. Consequently our feasibility study has concentrated on use of the RFQ accelerator. As an example of a possible accelerator module,[23] a RFQ accelerating 100 mA of Li^- per channel to 6 MeV could be 10-11 meters long, while capturing and transmitting 85-90% of the CW input beam. For this example, the input normalized emittance acceptance (v/c x emittance) should be 0.25 cm mrad, and could be made even larger. This should be adequate for our applications. The emerging high energy beam diameter would be ~ 2 cm, giving an energy density of ~ 200 kW/cm^2. This would degrade unless the beams were either quickly neutralized or, at least, space charge neutralized by positive ions. The positive ions could either come from ionization of background gas, or they could be purposely injected at low energy from positive ion sources. Since the negative ions would be moving very fast, only comparatively few slow positive ions would be required to maintain space charge neutrality.[23] If space charge neutralization of a bunched beam proves difficult, it may be necessary to place quadrupoles around the neutralizer to control the beam until it is neutralized. The gross system electrical efficiency of a RFQ should be quite good. A detailed study done for a specific example (2-3 A of D^- accelerated to 1 MeV) indicated a gross electrical efficiency (wall-plug to transmitted beam) of 35-38%.[24] Since 100 mA per channel appears to be a convenient current for present RFQ accelerator designs, a beam assembly could be composed of a number of RFQ channels, each carrying ~ 100 mA and fed by a negative ion source module with a magnet, lens, and preacceleration stage. With present resonator designs, it would probably be necessary, for reasons of power efficiency, to have a separate resonator for each channel; this should not pose a major problem so long as the number of channels in a system is not excessive and so long as the accelerators can be well back from the tokamak, which should be feasible due to the small divergence to be expected in the high energy neutral beam. Figure 9 shows a schematic of how a single source-accelerator module might appear. This example is for Li^-, but the arrangement would be similar for other ions. After acceleration, the beams would be merged and aimed through a neutralizer into the torus. The power per channel would be very large, so only a few channels would be needed for each beam assembly. The achievable average beam power density in the duct will depend to some extent upon the aiming and merging of the beams. If there is space between individual beams as they pass through a common duct, then the effective average power density will necessarily be lower than the power density in a single beam. If, on the other hand, the beams are partially merged as they pass through the duct, the power density may be higher than for any of the individual constituent beams. The operational simplicity and reliability inherent to RF accelerators make them ideal for assembly into large heating systems. Figure 10 shows a layout of such a configuration. It should be stressed, however, that this is not the only possible arrangement of the beams. An alternative configuration would be to have each beam penetrate the blanket through its own individual duct, each of which could be much smaller than the duct required for the merged beams. The final choice of the aiming configuration will depend upon which allows blanket penetrations which give rise to the least neutron leakage and, if laser neutralizers are used, upon which configuration allows greater power efficiency in neutralization.

The simplest and most desirable arrangement would be to have a RFQ accelerator carrying ~ 1-3 amps of a heavy ion to 1-2 MeV/AMU. If the ion were O^-, for which a 1-3 amps source is probably not an unreasonable expectation, then the ion power in each channel could be 30-60 MW, and only 1-2 such modules might be required for an entire reactor. Present construction of RFQ accelerators is in the 100 mA range,[25] but designs are now being studied which could carry 1-3 amps in a single channel. The feasibility of this heating method is not, however, contingent upon the success of such high current accelerators; 100 mA/channel would be adequate.

X. Neutralizer

The simplest choice for a neutralizer is a thin cell of a condensable gas, such as N_2, which is easily pumped by cryocondensation. Recent measurements of neutralization efficiencies show that at 6-7 MeV, ~ 46% of Li^- can be neutralized using nitrogen,[26,27] and that as much as 54% can be neutralized[26] if one is willing to use hydrogen as a neutralizer. For heavier ions, however, the optimum measured neutral fractions are much lower[27]: ~ 27% for C^-, ~ 20% for O^-, and ~ 22% for Si^- using condensable gases such as argon, nitrogen, or carbon dioxide. This efficiency might be improved upon somewhat if one used hydrogen, but presumably it would not increase by as much as a factor of two. Since large amounts of energy will be involved if this is used on a reactor, it would be highly desirable to find a way to substantially increase the fraction of the beam neutralized, provided this can be done without expending even more energy on the neutralization process. A plasma neutralizer might offer an incremental gain in the neutralized fraction, but at the expense, in energy and difficulty, of maintaining the plasma. Lorentz neutralization by passage through an electric or magnetic field is probably not practical; unless all the ions became neutralized after traversing the same path length through a homogeneous field, the beam divergence would be greatly increased.

What does appear attractive is photodetachment neutralization with a laser. Neutralization of nearly all of the Li^- beam might be feasible by photodetachment with Ga As lasers (which can have efficiencies of 20-40%[28]), depending upon how small the final beam cross section can be made. Since the photodetachment cross-section of Li^- is similar to that of H^-.[29] the energy economies (increased neutralization efficiency versus laser exciting energy) are similar, but they are more favorable for Li^- because of the potentially much higher beam energy density.

For a particular ion beam of a given cross section and current, the photon line density required in the neutralizer cell increases proportionally to the beam ion velocity, V_I, because the ion dwell time within the cell varies as the inverse of the velocity. However, the energy carried per particle is increasing as $(V_I)^2$, so the neutralizer power efficiency ratio, E_N, of the amount of additional beam power neutralized (above what could be neutralized with a gas cell) divided by the required laser exciting power increases proportionally to V_I. In addition, if all other factors were constant, then, at a constant beam ion velocity, the power efficiency E_N would scale proportionally to the mass, so that laser neutralizers become more attractive as the mass increases. In practice, this favorable trend is offset by the fact that the photodetachment cross sections differ among ions (Li^- has the largest[28]: $\sigma \sim 0.9 \times 10^{-16} cm^2$ at 0.85μ, the Ga As laser wavelength, and rising to $\sim 1.3 \times 10^{-16} cm^3$ at wavelengths above 1.0μ), and by the fact that the thresholds for photodetachment vary with the electron affinity. Nonetheless, for small cross-section beams with very high energy densities, it will almost certainly be advantageous to use photodetachment neutralizers with any of these negative ions, most probably with an intracavity gas laser neutralizer (which allows one to use a lower efficiency laser), as suggested by McGeoch for D^- neutralization.[30] Two CW gas laser systems which operate at appropriate wavelengths for photodetachment of C^-, O^-, or Si^- are argon-ion lasers (at 4880 Å and 5145 Å) and krypton-ion lasers (at 6471 Å) [17].

XI. System

Once the individual components we have discussed are developed, they must be integrated into a practical beam system. As shown in Figs. 9 and 10, a beam system will consist of one or more negative ion sources, each followed by an analyzing magnet to allow metal vapors to deposit on cold plates, cryogenic pumping surfaces, lenses and an electrostatic preacceleration stage to tailor the beam emittance to the requirements of the RFQ, a RFQ accelerator, and a neutralizer sandwiched between cryogenic pumps (if gas were used). The neutral beam or beams would then, either individually or collectively, pass through a deflection magnet which would divert the remaining ions onto dumps, and the remaining neutrals would either pass into the plasma or strike a beam line calorimeter. There are a number of systems problems which deserve discussion.

XI.A. Gas Evolution and Handling

It is fundamentally more difficult to accelerate negative ions than positive ions over long distances because the negative ions are more easily prematurely neutralized by stripping on background gas. This dictates rather stringent vacuum constraints. For example, with a 10 meter accelerator length, the pressure should be kept below 10^{-6} torr to maintain negative ion stripping losses well below 3%. This should be a manageable problem with any of the heavy ($A \geq 6$) atoms we have discussed. The metal vapors can all be kept at very low pressures with refrigerated plates, and the possible feedstock or neutralizer gases can all be kept below 10^{-7} torr with cryogenic pumping at 28-30°k. It would also be possible, but more difficult, to maintain the accelerator pressure below 10^{-6} torr if a D^- beam were used. Even with the heavy atom beams some deuterium will invade the system from the duct to the torus. In addition, if the beams are used to drive current in an ignited plasma, then the helium ash might pose a problem if its partial pressure outside the plasma exceeds 10^{-6} torr. However, this can be dealt with by local cryocondensation pumping near the duct (4.2°k if only D_2 must be dealt with, and argon frost burial pumps[31] if helium ash must be pumped). This is simplified if the duct cross section and conductance can be kept reasonably small as a result of the high energy density in these beams. The pressure requirements in the duct itself are less stringent than in the accelerator, since the r uirement here is to keep the neutral beam from being ionized, and are similar to the requirements for other neutral beams.

One other possible source of gas bears mention. Particles which are lost from the beam within the accelerator will strike the resonator vanes or the inside of the resonator cavity and desorb gas. However, since the resonator structure is quite open, this gas can be pumped through the cavity ends, and if necessary through RF screened cryogenic pumps along the accelerator. The gas evolution per unit length should not be enormously more than will be encountered in the near term with the FMIT[25] accelerator, which will accelerate 100 mA of D^+ to 2 MeV. An associated problem is sputtering of, and the deposition of power on the resonator vanes by the lost beam particles. This should be somewhat more serious for the heavy beam accelerators than for the FMIT accelerator. The lost particles belong to three classes: (1) those lost through premature neutralization, (2) those lost at the beginning of the accelerator because they do not get bunched into the right part of the RF wave, and (3) those ejected from the beam by space charge effects. The first class of particles, as we discussed, will be minimized by keeping the pressure low. The second class is never effectively accelerated and, consequently, is lost at its relatively low injection energy. The third class does undergo some acceleration and is lost at progressively higher energies along the length of the accelerator. However, although the energy of the ejected particles increases as the beam is accelerated, the magnitude of the space charge forces ejecting the particles steadily decreases because the velocity is increasing. Moreover, although the total energy lost in this third class of particles will probably be higher for a multi-MeV heavy ion accelerator than for the FMIT accelerator, the heavy ion accelerator will be considerably longer, so the energy lost per unit length may not be greatly different. Consequently, heating of the RFQ vanes should not pose a serious problem to pulse length.

XI.B. Magnets

The fields required from the aiming magnets will probably be low enough that they can be constructed with iron cores, since the required angular diversions of the ion beams will be small. However, the deflection magnet for the unneutralized ions will probably be required to deflect the ions back from the torus where there is more space for ion dumps. This will require strong fields (as much as a few tesla, depending upon the ion and the energy), and so will probably need an air core magnet. The use of an air core magnet should not pose a problem to the beam since, due to its small diameter, all the ions can pass through the relatively flat central portion of the fringing field, and, in any event, good optics are neither required nor desirable for the dumped ions. The stray fields from an air core coil might pose more serious problems for the tokamak magnetics, so its design and location will have to be chosen so that this is minimized.

XI.C. Power Handling

Considering the very high energy densities possible with these beams (perhaps as much as several hundred kW per cm^2), handling the power on ion dumps and calorimeters appears, at first glance, to be a formidable problem. It appears even more intractable when one reflects that, because of the multi-MeV energies involved, direct recovery of the ion power by decelerating the ions as they approach the dumps is virtually impossible, since the dumps would then have to hold potentials in the megavolt range without being shorted out by electrons from the residual gas and plasma in the chamber. The saving factor, however, is that if the beams have very high power densities, they are at the same time not very large in diameter. Thus, the total power to be handled is no greater than would be the case with reactor-sized D^- beams (and is much less than would be encountered in the unneutralized ions if 150-200 keV D^+ were used), and it is, in fact, the total power in the beam, more than the power density, which determines how difficult the power handling problem is. This is because a small diameter beam can be spread out on a dump surface with a low beam intersection angle, and the resulting energy density on a given size of dump can be independent of the initial beam energy density. As an example, if the initial power density in a 2 cm diameter ion beam is 200 kW/cm^2, and if 50% of the ions are neutralized with a gas neutralizer, then a beam line calorimeter ~ 2 meters long (or one meter if it is folded) would reduce the power to 1 kW/cm^2. The power density can be somewhat further reduced, without increasing the calorimeter length, by also sloping the surface in the plane normal to the long dimension of the calorimeter, thus allowing the power to be spread in two dimensions. The beam line calorimeter would only be exposed to the beam for purposes of tuning, conditioning, or measuring the power of the beam.

The dumps for the unneutralized ions, on the other hand, would have to absorb power for long pulses, or even continuously, if the beam was used for current drive. However, the power handling problem is in some sense simpler for the ions. In the first place, the ions which emerge from the neutralizer cell will be both positive and negative, and so will be deflected onto opposing dumps at reduced power densities. Second, the magnetic field of the reflection coil can be tailored to defocus the ions in the plane transverse to the long dimension of the dump, enhancing the two-dimensional spreading of the power on the surface. Finally, the length of the ion dumps can be increased with less penalty than is the case with the beamline calorimeter.

Consequently, it should be possible to reduce the power density on the ion dumps to a few hundred W/cm^2. The task of handling the power in the unneutralized ions would, of course, essentially disappear if it proves feasible to use photodetachment to neutralize almost all of the beam. In this case, it may be possible to eliminate the deflection magnet altogether, or to at least reduce the required dispersion of the ion power to the point where an iron core magnet can be used to divert the ions through a small angle into small forward-lying dumps. A final point is that we have tacitly assumed that space for large ion dumps will be more readily available behind the neutralizer (away from the tokamak) than in front of it. If this should not be the case (for instance, if the beam is located a considerable distance from the tokamak), then it might be possible to locate the ion dumps forward of the neutralizer (towards the tokamak), and use a lower field in the deflection magnet so that an iron core might be feasible.

XI.D. Efficiencies

Naturally, it would be advantageous to improve the efficiency of the beam system. If the accelerator efficiency is ~ 35% (the best estimate we have at this time) and if the neutralization efficiency is ~ 48% with a condensable gas neutralizer for Li^-, then the overall efficiency will be ~ 17%, less the power consumed by the ion sources, the water pumps for the ion dumps and magnets, and the cryogenic refrigerators for the vacuum pumps. (The latter will be much less than it would be for 150-200 keV deuterium beams.) For the heavier ions, this system efficiency would be only ~ 9% using a condensable gas neutralizer. There are two principal ways in which the efficiency might be improved: by increasing the RF system efficiency, if this is feasible, or by using a higher efficiency neutralizer, as we discussed earlier. The beam efficiency is critical if it is used for current drive since its energy consumption affects the power gain of the reactor. The beam efficiency has much less effect on the energy gain if the beam is only used to ignite a plasma, but the capital and maintenance costs are increased if the efficiency is low.

Using a gas neutralizer, the system efficiency with Li^- would be only marginally acceptable, and the efficiency with the heavier ions appears to be unacceptably low. Accordingly, it appears that it will be necessary to develop a non-gaseous neutralizer (most probably a photodetachment neutralizer) to neutralize most of the beam and allow the system efficiency to more closely approach the accelerator efficiency. Two possible lasers for use in intracavity photodetachment of C^- or O^- are argon ion lasers (with strong lines at 4880 Å and 5145 Å) and krypton-ion lasers (with a strong line at 6471 Å), both of which are capable of CW operation. Producing a power-efficient photodetachment cavity neutralizer will, clearly, require a great deal of development, and at this point it is probably the most uncertain of the components required to implement the light atom injection scheme.

XI.E. Length

If 1-2 MeV/AMU Si^- were used as the beam, the accelerator might become quite long (~ 30-40 meters) and might require an extension of the building. However, provided the 14.5 MeV D-T neutrons were shielded from entering the accelerator cavity, any building extension would have a small volume and would only have to be capable of confining tritium and activation products that might be released in an accident; this requires considerably thinner walls than would be required to contain 14.5 MeV neutrons.

XII. Limits and Advantages

While this heating method, in principle, can be implemented with any negative ion, practical considerations may limit it to light ions ($A \lesssim 30$ AMU). Although the current required decreases as the chosen mass increases, the accelerator length required to achieve 1 MeV/AMU becomes excessive for heavier ions. Moreover, the energy per atom carried into the plasma is proportional to A, which means that it is approximately proportional to Z.

However, the energy radiated from the plasma core by the impurity varies as a function stronger than Z^2. Accordingly, for heavier atoms the ratio between energy carried in and energy radiated is less favorable than for lighter atoms. Most importantly, the confinement of the initial partially stripped ion deteriorates as the mass increases because the gyroradius of an ion of a given charge state is proportional to the mass f the energy/amu is kept constant.

Neutral light atom beams at 1-2 MeV/AMU afford easier and more certain plasma access than do beams of light positive ions, and they allow better penetration at lower energies/amu. The first point is a major advantage for light atom beams; the second might be an advantage for ion beams if RF accelerators are used. Relative to conventional hydrogen neutral beams formed from positive ions at 150-200 keV, light neutral atom beams can potentially afford higher neutralization efficiencies and lower injected power requirements due to greatly improved plasma penetration, resulting in more centralized power deposition. They require less ion current to produce the same injected power as a negative-ion based D^o beam. Because the limiting ion energy for confinement increases with mass, light neutral atom beams, in principle, can operate at higher power densities than D^o systems, which should allow smaller access ports through the tokamak blanket (leading to less neutron leakage). With some uncertainty as to the ion dumps, these systems, in principle, can operate CW due to relatively low power densities on source and accelerator surfaces. With photodetachment neutralization, the ion dumps could almost certainly take continuous operation.

A major advantage of these light atom beam systems is that they should require much less costly pumping per megawatt than does a deuterium beam. The neutralizer would probably use photodetachment, which produces no gas load, or if it did use a gas, it could be an easily pumped one, such as N_2, that could be cryopumped at ~ $25^{o}k$. The source loads are also easier to handle: Li vapor just requires cool plates; oxygen can be cryopumped using helium gas at $30^{o}k$, which is less costly and energy intensive than using liquid helium at $4.2^{o}k$, as would be required for a deuterium beam. Further, since the energy per atom is much higher than with conventional deuterium beams, the total beam current required to yield a given power is much lower, which means that the gas flow from the sources is also lower. These factors should yield significant savings in captial and operating costs for cryogenic pumping.

If carried to its logical conclusion, this light atom injection scheme offers the possibility of a simple heating system with very few components near the tokamak. An ideal beamline (Fig. 11) might consist of a single channel RFQ, fed by a single O^- source, accelerating 1-3 amps of O^- to 16-32 MeV. With > 95% neutralization by a photodetachment neutralizer, only 1-3 such systems might be required for a reactor. Since the source would necessarily be far from the tokamak, heavily shielded, and would feed the accelerator around an analyzing magnet, one could have two sources in place with analyzing magnets, such that one source could always be a spare available for maintenance. The simplicity of such an arrangement, if it can be developed, would appear to be a major attraction of the light atom heating method.

XIII. Conclusion

Heating with multi-MeV light atom beams has three major advantages: good central peaking of the heating profile, high beam power density, and greatly reduced pumping requirements. Deuterium beams in the 1-2 MeV range s. . the first advantage, and to a lesser extent the second, but put more severe and costly constraints on the cryogenic pumping to maintain a low enough pressure during acceleration. In addition, D^0 beams would require more accelerator channels to achieve a given total power. If used for current drive, the light atom beams may be more or less efficient than D^0 beams (in terms of the current driven per unit injected power), depending upon how important neoclassical effects are.

The principal disadvantage of these beams is that, in going to very high energies, and consequently to RF accelerators, the acceleration efficiency drops below what could be achieved with electrostatic acceleration at lower voltages ($\lesssim$ 400 keV). In addition, for negative ions heavier than Li^-, neutralization by a simple gas cell is relatively inefficient, and neutralization by other means, such as a photodetachment laser, is probably required. If light atom beams are used for current drive, the fact that they require inboard counter-injection is a disadvantage; it is, however, probably feasible since these high energy density beams could tolerate relatively small ducts. The fact that the light atom beams contribute impurities is undesirable, but deleterious effects due to thermalized beam ions are expected to be slight so long as the beam is not too massive ($A < 30$).

On balance, it appears that 1-2 MeV/AMU beams of light atoms ($A \gtrsim 6$), and perhaps of D^0, are quite attractive as a means of heating and igniting a reactor plasma, and they may be somewhat attractive for current drive. Equally important, it appears probably feasible to build and operate such beams. However, major development will be required of the components: the ion source, the accelerators, and especially of the neutralizer, and of the system embodying these components.

Acknowledgments

We especially thank J. M. Dawson for interesting conversations. In addition, it is a pleasure to acknowledge useful conversations with G. D. Alton, W. A. Bell, M. Bacall, K. Berkner, T. Boyd, J. Clarke, K. W. Ehlers, J. Hiskes, W. Graham, K. N. Leung, L. O. Love, J. A. Schmidt, L. D. Stewart, R. H. Stokes, D. A. Swensen, and T. P. Wangler.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

References

1. J. M. DAWSON and K. R. MACKENZIE, "Heating of Tokamak Plasmas by Means of Energetic Ion Beams with Z > 1," PPG-470, Plasma Physics Department, University of California, Los Angeles, California, March 1980.

2. PIERRE GRAND, private communication (1979).

3. J. OHKAWA, "New Methods of Driving Plasma Current in Fusion Devices," Nuclear Fusion 10, 185 (1970).

4. E. THOMPSON, "The Use of Energetic Helium Atoms for Heating Toroidal Systems," Nuclear Fusion 15, 347 (1975).

5. International Tokamak Reactor, Zero Phase, International Atomic Energy Agency, Vienna, Austria, 1980.

6. L. D. STEWART et al., "Merits of D^- Based Neutral Beam Injectors for Tokamaks," Th. Sluyters, Ed., Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven National Laboratory, Upton, New York (1980) p. 321.

7. D. T. H. START and J. H. CORDEY, "Beam-Induced Currents in Toroidal Plasmas of Arbitrary Aspect Ratio," Phys. Fluids 23, 1477 (1980).

8. R. V. JENSEN et al., "Critical Impurity Concentrations for Power Multiplication in Beam-Heated Toroidal Fusion Reactors," Nucl. Sci. and Eng. 65, 282 (1978).

9. CH. LUKNER, "Mechanisms for the Production of Negative Ions in Sputtering Sources," Nucl. Instr. and Math. 167, 249 (1979).

10. P. TYKESSON, "The Production of Negative Heavy Ion Beams through Charge-Exchange Process," Symposium of Northeastern Accelerator Personnel, Oak Ridge, Tennessee, October 23-25, 1978.

11. W. L. STIRLING, C. C. TSAI, and P. M. RYAN, "15 cm Duopigatron Source," Rev. Sci. Instrum. 48, 533 (1977).

12. L. O. LOVE, R. N. GOSLIN, W. A. BELL, H. B. GREENE, and W. K. PRATER, "Investigation of the Possibilities of Lithium Isotope Collection Using Alpha-2 Equipment," Oak Ridge National Laboratory Report ORNL-Y-728 (1951).

13. ORNL Electromagnetic Isotope Separation Manual, Oak Ridge National Laboratory.

14. R. MIDDLETON and C. J. ADAMS, "A Close to Universal Negative Ion Source," Nucl. Instrum. and Meth. 118, 329 (1979).

15. M. SEIDL, A. N. PARGELLIS, and J. GREER, "Emission of Negative Hydrogen Ions from Metal Hydrides Bombarded with Cesium Ions," Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL 51304, 111 (1981).

16. K. W. EHLERS, and K. N. LEUNG, "Multicusp Negative Ion Source " Rev. Sci. Instrum. 51, 721 (1980).

17. W. C. STWALLEY, University of Iowa, private communication (1980).

18. W. K. DAGENHART, W. L. STIRLING, H. H. HASELTON, G. G. KELLEY, J. KIM, C. C. TSAI, and J. H. WHEALTON, "Modified Calutron Negative Ion Source Operation and Future Plans," Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL 51304, 217 (1981).

19. C. C. TSAI, R. R. FEEZELL, H. H. HASELTON, D. E. SCHECTER, W. L. STIRLING, and J. H. WHEALTON, "Characteristics of a Modified Duopigatron Negative Ion Source," Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL 51304, 225 (1981).

20. K. PRELEC, "Progress in the Development of High Current Steady-State H^-/D^- Sources at BNL," Proceedings of the Second International Symposium on the

Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, ew York, October 1980, Th. Sluyters, Ed., BNL 51304, 145 (1981).

21. T. P. WANGLER and R. H. STOKES, "The Radio Frequency Quadrupole Linear Accelerator," to be published in Proceedings of the Sixth Conference on the Application of Accelerators in Research and Industry, November 3-5, 1980, North Texas State University, Denton, Texas.

22. A. W. MASCHKE, "Meqalac: A New Approach to Low Beta Acceleration," Brookhaven National Laboratory Report BNL 51029 (1979).

23. T. P. WANGLER, Los Alamos Scientific Laboratory, private communication (1980).

24. R. H. STOKES, Los Alamos Scientific Laboratory, private communication (1981).

25. R. H. STOKES et al., "The Radio-Frequency Quadrupole: General Properties and Specific Appications," to be published in Proceedings of the Eleventh International Conference on High Energy Accelerators, CERN, Geneva, July 7-11, 1980.

26. J. P. ALDRIDGE and J. D. King, "Charge-Exchange Cross-Sections for Li^- Ions at 6 MeV," Los Alamos Scientific Laboratory Report LA-8682-MS (1981).

27. B. M. JOHNSON, K. W. JONES, J. BARETTE, T. H. KRUSE, I. TSERRUYA, L. R. GRISHAM, and D. E. POST, "Neutralization Fractions for Li^-, C^-, O^-, and Si^- at Energies up to 7 MeV," to be published.

28. J. H. FINK and G. W. HAMILTON, "Efficient Production of Neutral Beams by Photodetachment of Negative Ions," Proceedings of the First International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams," Brookhaven, New York, September 1977, K. Prelec, Ed., Brookhaven National Laboratory Report BNL-50727, 129 (1978).

29. D. W. NORCROSS and D. L. MOORES, in Atomic Physics 3: Proceedings of

the Third International Conference on Atomic Physics, August 1972, Boulder, Colorado, S. J. Smith and G. K. Walter, Eds., Plenum Press, New York-London (1973).

30. M. W. MCGEOCH, "Laser Neutralization of Negative Ion Beams for Fusion," Proceedings of the Second Internationa Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL-512304, 304 (1981).

31. T. H. BATZER, R. E. PATRICK, and W. R. CALL, "A Neutral Beam Line Pump with Helium Cryotrapping Capability," Proceedings of t.e Tenth Symposium on Fusion Technology, Padova, Italy, September 4-9, 1978, Vol. 2, 745.

TABLE I

INTOR PARAMETERS

	I_p 6 MA
B_o	5.5T
R_o	5.3 m
a	1.2 m
b/a	1.6
Z_{eff}	(2.0 for D^o, 1.25 for O^o)
$n_e(r)$	1.1 $[1 - (r/a)^6]$ $10^{14} cm^3$
$T_e(r)$	50 $[1 - (r/a)^2]^2$ keV
$T_i(r)$	60 $[1 - (r/a)^2]^2$ keV
j(r)	α $[1 - (r/a)^2]$
$\bar{n}_e$	0.9 $10^{14} cm^{-3}$
$\langle n_e \rangle$	0.8 $10^{14} cm^{-3}$
$\langle \beta \rangle$	5 %
P_{fusion}	620 MW

TABLE II

Atom	Optimum Energy Energy (MeV)	Neoclassical Current Amps/watt	Classical Current Amps/watt
D^o	1.0 - 1.5	0.16	0.11
O^o	2.5 - 4.5	0.06	0.14
Si^o	60 - 75	0.10	0.20

Figure Captions

Fig. 1. Schematic of the light atom beam injection scheme.

Fig. 2. Initial drift orbits for O^+ born at the x's by ionization of 32 MeV oxygen atoms injected either parallel (co) or antiparallel (counter) to the plasma current.

Fig. 3. A typical drift orbit of an oxygen ion (born from an oxygen atom injected at 32 MeV counter to the plasma current) is shown as it undergoes successive ionizations as far as O^{+4}.

Fig. 4. Heating deposition profiles in an INTOR-sized plasma for 2 MeV D^o (made from D^-), 46 MeV Na^+, 150 keV D^o (made from D^+ yielding neutral power fractions of 60% at full energy, 24% at one-half energy, and 16% at one-third energy), 2 MeV D^o made from D^-, the initial birth profile of the 16 MeV O^+ resulting from the ionization co-injected O^o, and the final profile of the O^{+8} resulting from injection of the O^o.

Fig. 5. Integrated power deposited inside a given radius for the four beams of Fig. 4.

Fig. 6. Maximum allowed impurity concentration versus Z at three temperatures.

Fig. 7. A possible Li^+ source based upon the Oak Ridge National Laboratory calutron technology. The lithium vapor is ionized by electron bombardment.

Fig. 8. Conceptual design of an Ehlers-Leung type surface-plasma source which might be used for light negative ion production. For C^- production, the working gas would probably be an inert gas, such as argon. For O^- production, one might use a metallic converter

plate and oxygen as the working gas.

Fig. 9. Example of a possible light atom beam module. Negative ions are produced, deflected around an analyzing magnet to remove ionic and neutral impurities, preaccelerated, and focused into a Los Alamos RF quadrupole accelerator. The accelerated ions are aimed with a deflection magnet through a neutralizer. For any ions heavier than Li^-, a photodetachment neutralizer would probably be used, preceded by magnetic quadrupoles to focus the beam.

Fig. 10. A modular system for light atom beams, consisting of an array of sources and RF quadrupole accelerators of the Los Alamos type. The neutralizer pump, the ion dumps, and the associated magnet could probably be largely dispensed with if neutralization was done by photodetachment. Focusing magnetic quadrupoles would be located before the neutralizers.

Fig. 11. Conceptual design of a single channel high power system. One-to-several amps of O^- or another prolific light negative ion is extracted from one of the alternate sources (the other serving as a spare). The beam is accelerated to 16-32 MeV in a single RF quadrupole accelerator channel, and is subsequently aimed, focused by magnetic quadrupoles, and neutralized by photodetachment.

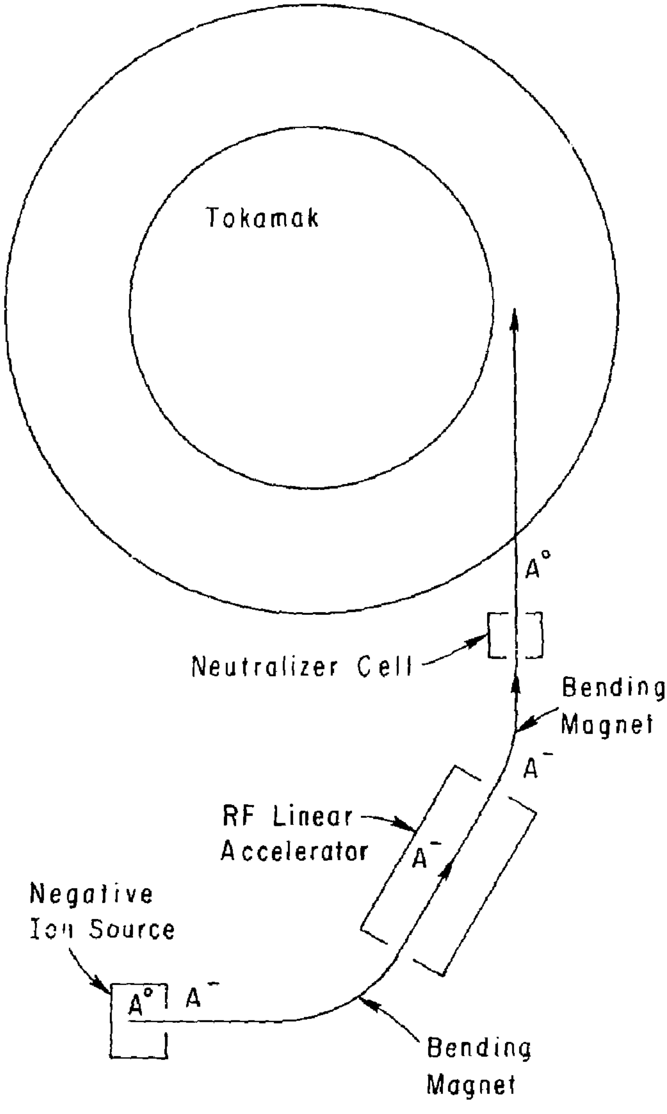

Tokamak
A°
Neutralizer Cell
Bending
Magnet
A⁻
RF Linear
Accelerator
A⁻
Negative
Ion Source
A°
A⁻
Bending
Magnet

Fig. 1 80298

#81X0684

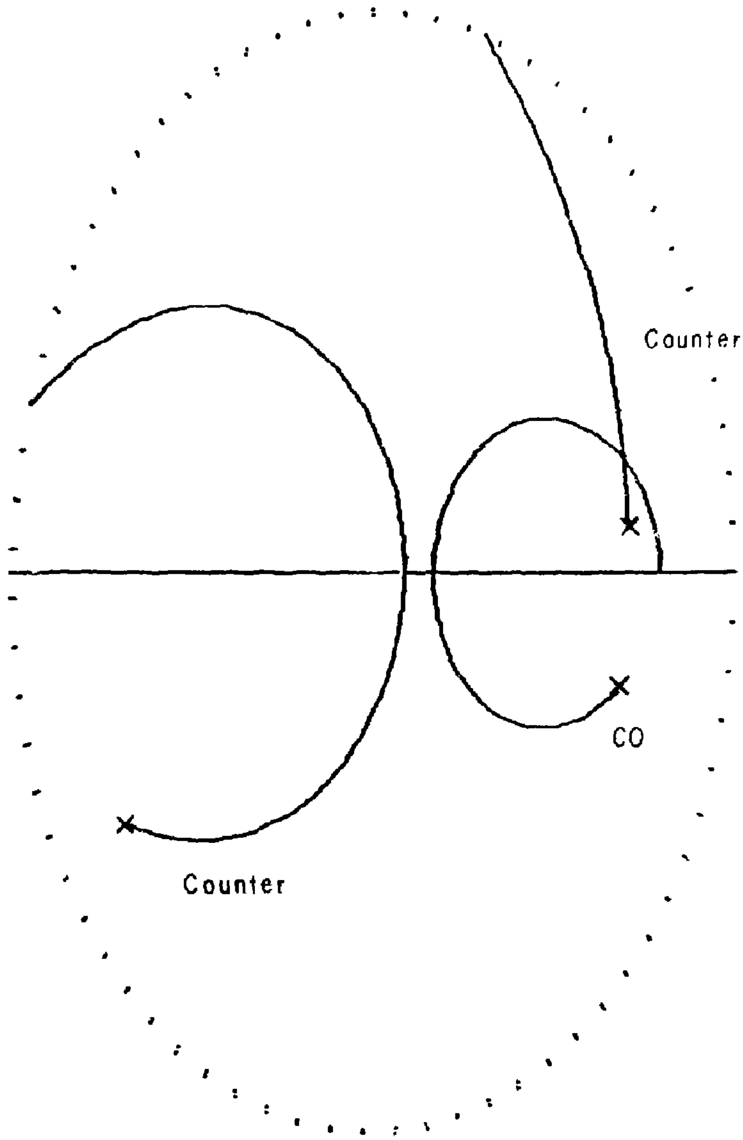


Fig. 2

#81X0685

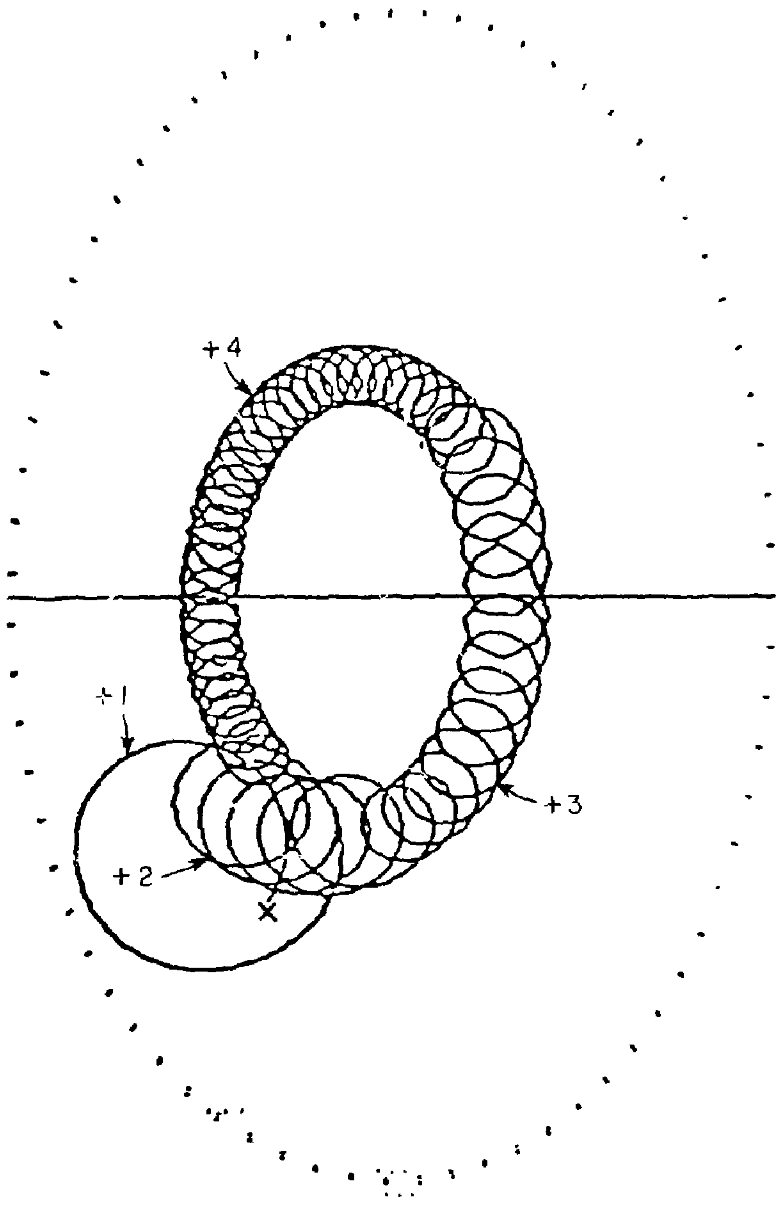


Fig. 3

81X0969

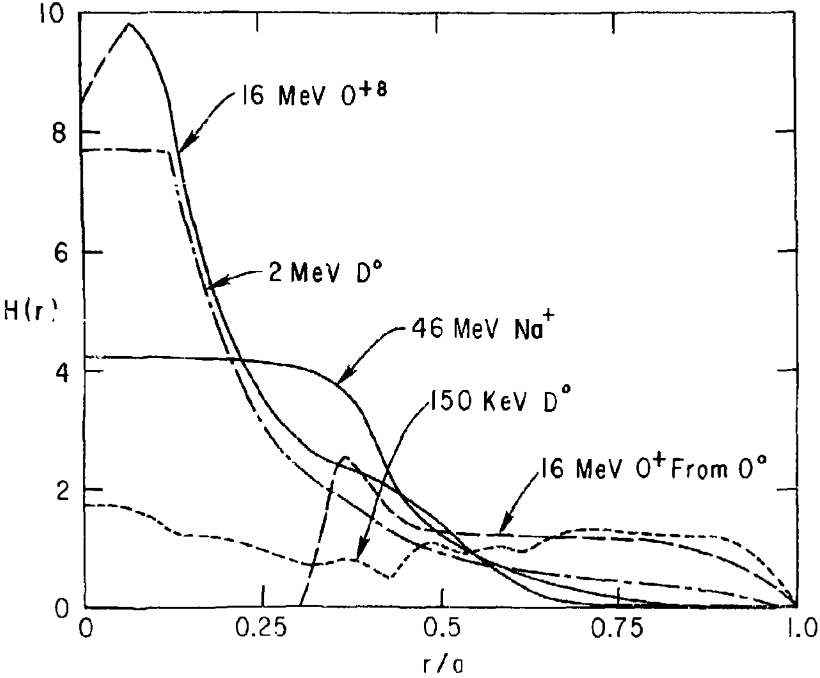
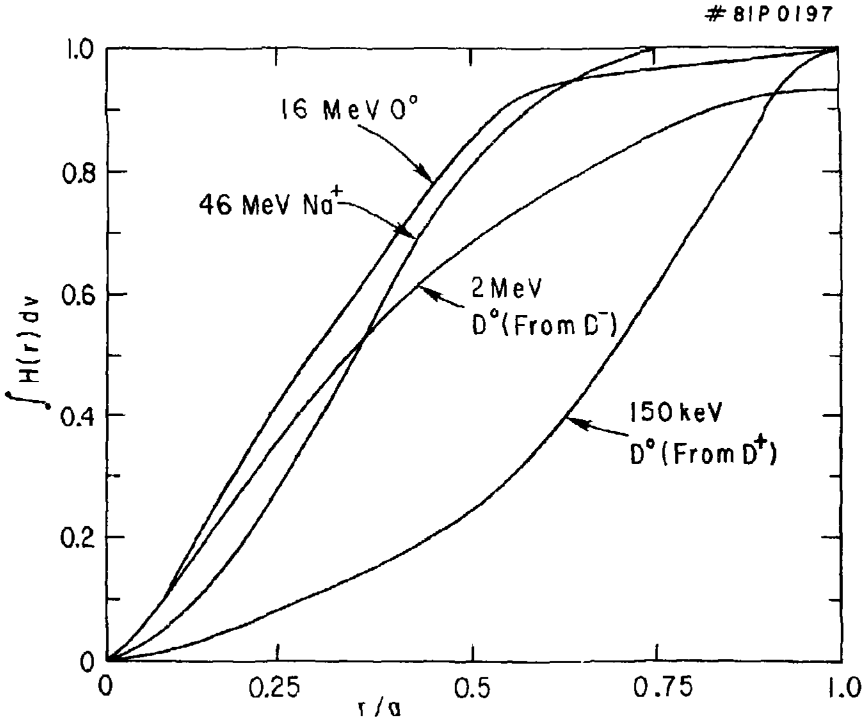


Fig. 4



81P 0197
16 MeV O°
46 MeV Na+
2 MeV
D°(From D⁻)
150 keV
D°(From D+)
∫ H(r) dv
r / a
0
0.2
0.4
0.6
0.8
1.0
0
0.25
0.5
0.75
1.0

Fig. 5

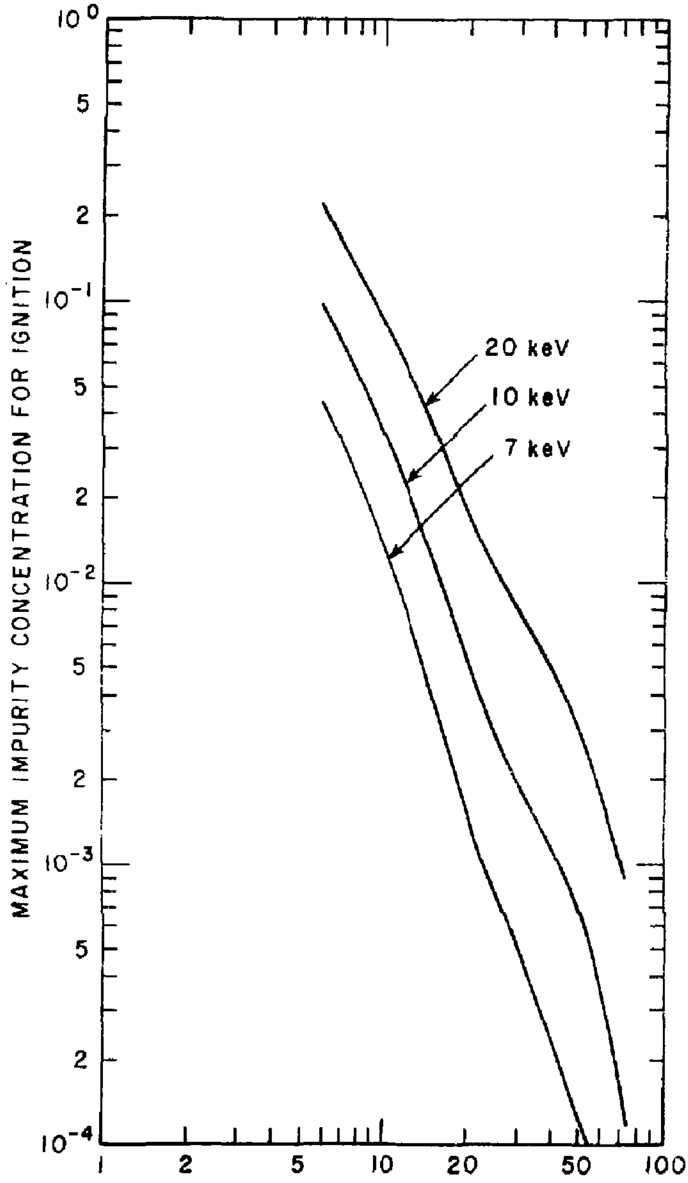

MAXIMUM IMPURITY CONCENTRATION FOR IGNITION
ATOMIC NUMBER
20 keV
10 keV
7 keV
10^0
5
2
10^{-1}
5
2
10^{-2}
5
2
10^{-3}
5
2
10^{-4}
1
2
5
10
20
50
100

Fig. 6

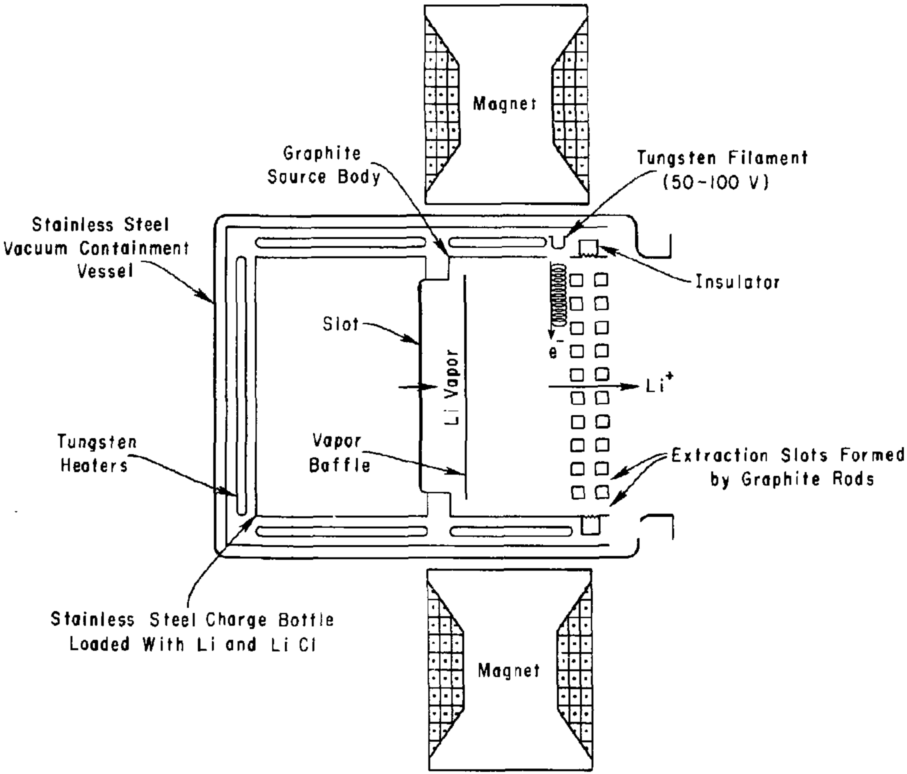
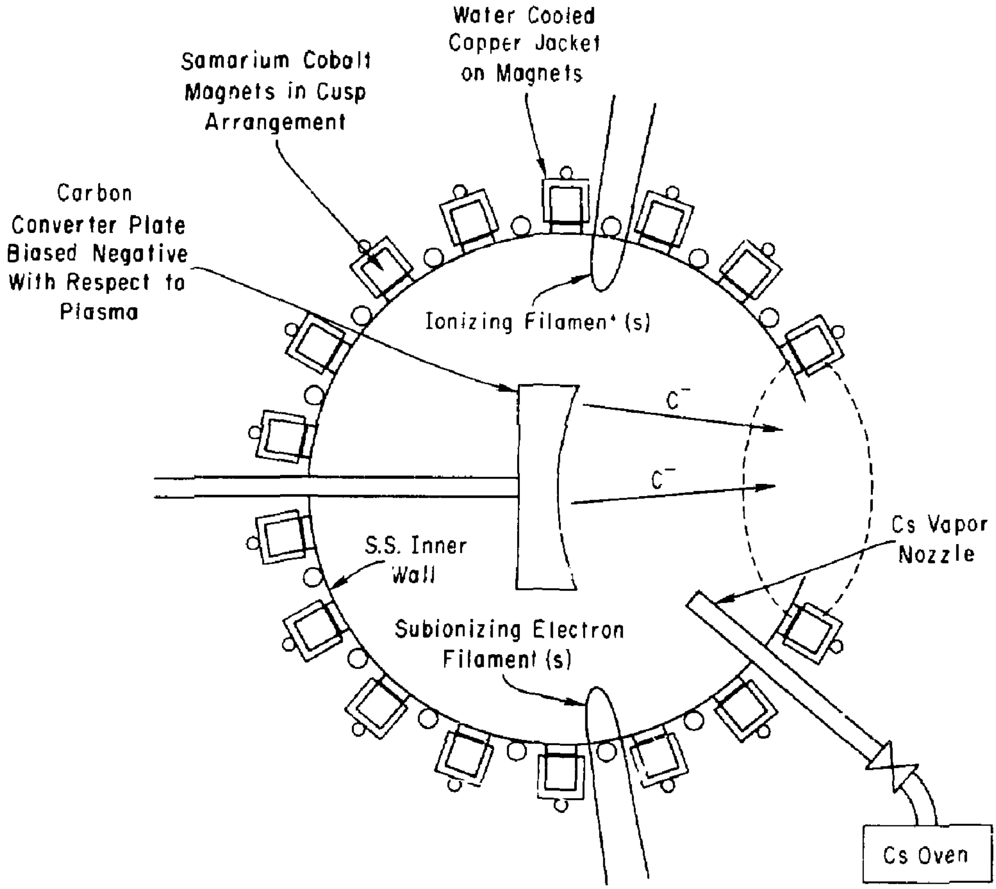

Magnet
Graphite
Source Body
Tungsten Filament
(50-100 V)
Stainless Steel
Vacuum Containment
Vessel
Insulator
Slot
Li Vapor
e⁻
Li⁺
Tungsten
Heaters
Vapor
Baffle
Extraction Slots Formed
by Graphite Rods
Stainless Steel Charge Bottle
Loaded With Li and Li Cl
Magnet

Fig. 7 806696



Water Cooled
Copper Jacket
on Magnets
Samarium Cobalt
Magnets in Cusp
Arrangement
Carbon
Converter Plate
Biased Negative
With Respect to
Plasma
Ionizing Filament (s)
C⁻
C⁻
Cs Vapor
Nozzle
S.S. Inner
Wall
Subionizing Electron
Filament (s)
Cs Oven

Fig. 8 806744

TWO STAGE Li^- MODULE USING AN ELECTRON BOMBARDMENT Li^- SOURCE

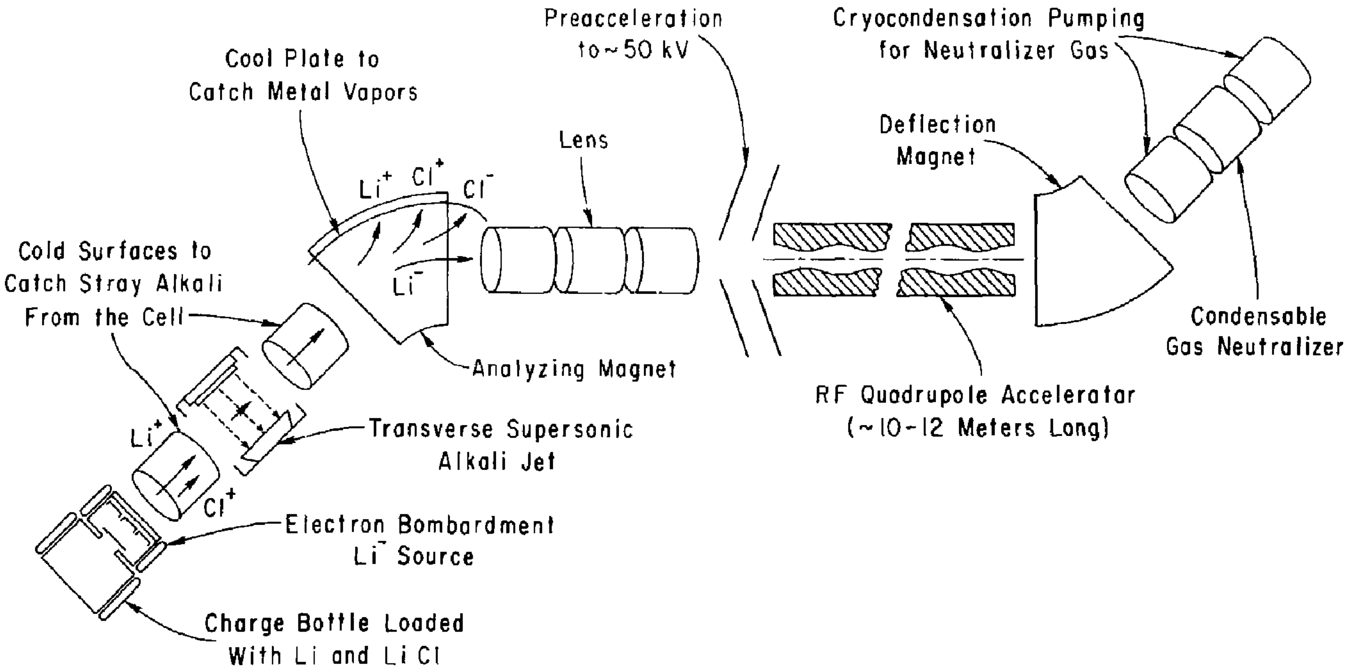


Fig. 9 806697

81X0477

A MODULAR HEAVY NEUTRAL BEAM SYSTEM

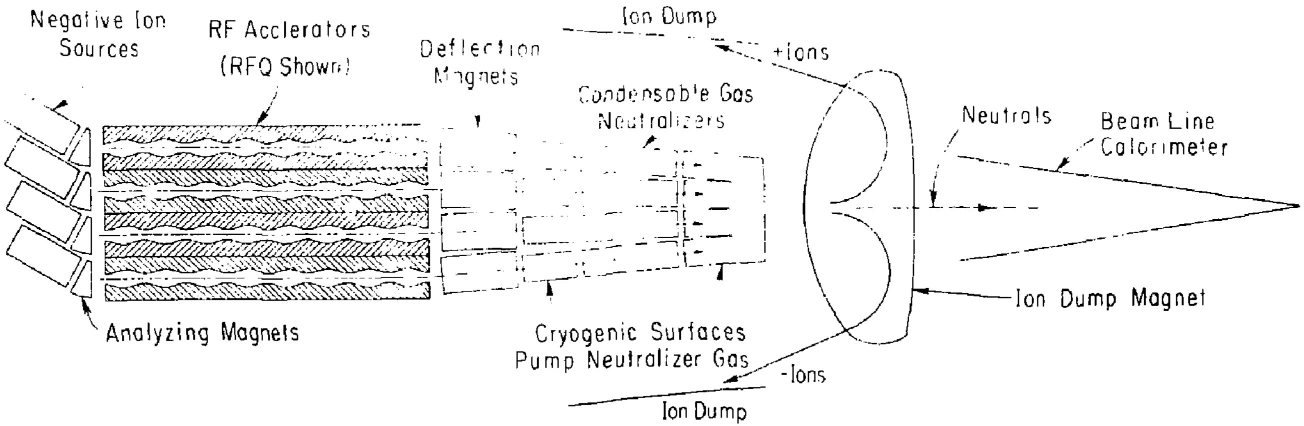


Fig. 10

81X0923

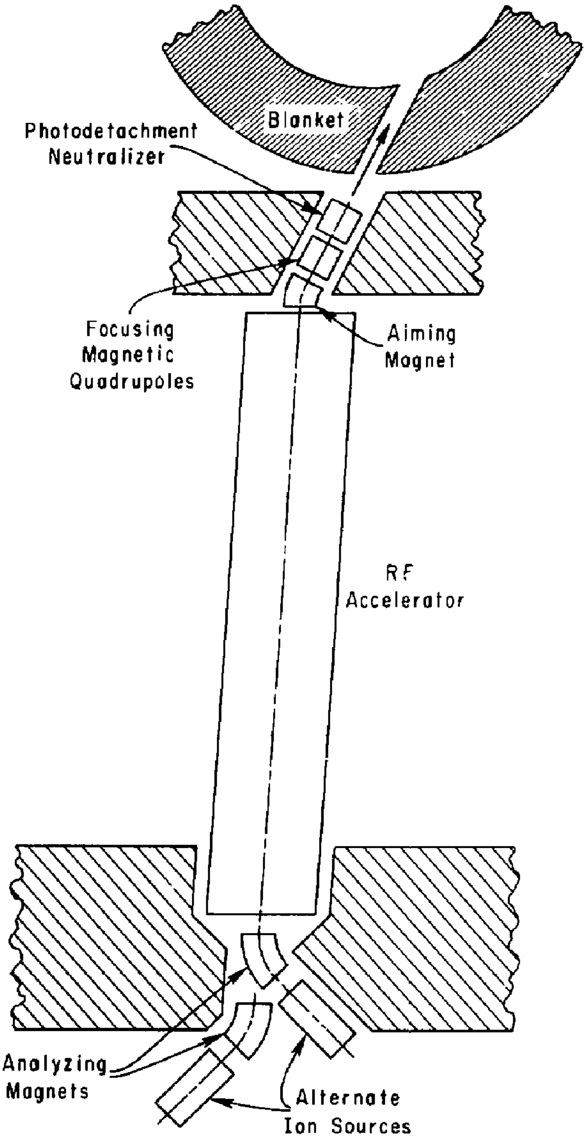


Fig. 11