Heavy-Atom Neutral Beams for Tandem-Mirror End Plugs

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ABSTRACT

The advantages of neutral beams with $Z \geq 3$ formed from negative ions, accelerated to 0.5-1.0 MeV/amu, and neutralized with high efficiency, are investigated for use in tandem mirror reactor end plugs. These beams can produce Q's of 20-30, and thus can replace the currently proposed 200-500 keV neutral proton beams presently planned for tandem mirror reactors. Thus, these $Z \geq 3$ neutral beams increase the potential attractiveness of tandem mirror reactors by offering a substitute for difficult high energy neutral hydrogen end plug beams.

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Present designs for tandem mirror reactor systems rely on 200-500 keV neutral hydrogen beams and ECRH heating to maintain the electrostatic potential in the end cell [1,2]. The necessity of the use of such high energy beams and the difficulty of producing such beams has been a weakness of proposed tandem mirror reactors.

Neutral beams used on present mirror experiments are made by forming protons in a positive ion source, accelerating the protons electrostatically, and neutralizing the protons by charge exchange in a gas cell [3]. The neutralization efficiency of such beams becomes unacceptable at ~ 100 keV/amu because the charge exchange cross section for $H^+ + H_2 \rightarrow H^0 + H_2^+$ decreases rapidly with increasing energy above ~ 40 keV. Neutral beams formed by acceleration of H^- should be more efficient than H^+ ion source neutral beams since H^- at energies of 50-1000 keV can be neutralized with 40-95% efficiency by gas cells or laser photodetachment. However, it has proved difficult to make high current H^- sources, and no clearly acceptable H^- ion source now exists, although there are several promising candidates [4].

An alternative approach to hydrogen beams in the end plug might be the use of beams of neutral lithium, carbon, or oxygen ($Z \geq 3$) at energies of 0.5-1 MeV/amu. Such beams would be produced by the formation of negative ions of lithium, carbon, or oxygen, acceleration of the negative ions using an RF accelerator, neutralization of the negative ions by one electron loss impact collisions in a thin gas cell or by laser photodetachment, and injection into the end plug plasma (Fig. 1). The neutral atoms will be singly ionized and trapped in the plasma, and then will quickly reach the fully ionized state by electron and ion impact. They fuel and heat the end plug plasma via coulomb collisions. The end plug plasma will then primarily consist of fully ionized beam ions (Li^{+3} , C^{+6} , O^{+8} , etc.). Upon scattering into the end plug loss

cone, the $Z \geq 3$ ions escape through the end opposite the solenoid because the electric field pulling ions through the mirror is higher on that end. Furthermore, any ions escaping into the solenoid will not be confined in the solenoid and will escape through the opposite end plug because of their low collisionality.

In any event, impurity radiation from beam ions should not be a problem. At electron temperatures of 10-20 keV, low Z impurities such as Li, C, and O will be completely ionized and will radiate very little energy. Detailed calculations including line radiation show that a driven $Q = 20$ reactor can tolerate $n_c/n_e \sim 11\%$ if impurity radiation losses are the dominant energy losses [5].

Heavy charged beams have been proposed for mirror machines by Grand [6] and for tokamaks by Dawson and MacKenzie [7]. One disadvantage of charged beams is that they must be transported through the confining magnetic fields to the edge of the plasma. Neutral beams can easily penetrate the fields. E. Thompson [8] and T. Okawa [9] have proposed using neutral helium beams for injection into plasmas. Helium neutral beams are only possible for positive ion sources, since He^- is extremely difficult to make [10]. As such they are limited to ~ 150 keV/amu due to the difficulty of neutralizing He^+ by charge exchange with He^0 . The fact that helium cannot be pumped by conventional 4.2°K cryocondensation makes the construction of helium charge exchange cells extremely difficult.

The basic tandem mirror consists of a central solenoid whose ends are electrostatically plugged in separate cells where the density is kept high by neutral beam injection [11,12]. Since high electron collisionality leads to Boltzmann electrons, the potential and density satisfy the relation

$$e\phi = T_e \ln \frac{n}{n_c} \quad (3-1)$$

where e is the electronic charge, ϕ is the electrostatic potential, T_e is the electron temperature, n is the electron density at the point of interest, and n_c is a reference electron density, taken here to be the central cell electron density. Consequently, a high plug electron density is required to generate the potential which "plugs" the solenoid. The plug plasma is sustained by neutral beam injection; because of the high density, the mean ion energy in the plug has to be made large to reduce the collisionality and achieve adequate plug confinement. Consequently, the neutral beam sustaining the plug plasma has to be high energy. The high technology requirements for the end plug (high energy, high power neutral beam injection, and high magnetic field) led Baldwin and Logan [13] to invent the thermal barrier, which is a potential dip between the plug and central cell. This potential dip thermally insulates the plug electrons from central cell electrons, and thereby allows the plug electrons to be heated to a higher temperature. This increases the confining potential ϕ_c (see Fig. 2) for a given plug electron density. Because of the reduced density in the barrier, the plug density can be reduced below the central cell density and still maintain an adequate confining potential ϕ_c . Consequently, the thermal barrier has reduced the technology requirements in the plug — lower neutral beam power and energy, lower magnetic field. For a reactor, however, the plug neutral beam energy is still in the range 200-500 keV for hydrogen beams, which requires negative ion sources. There is also a distinct advantage to choosing the beam composition so that fusion reactions do not occur in the plug plasma. This greatly reduces the neutron shielding requirements for the yin-yang magnets. For this reason, the WITAMIR-I design uses protons in the end plugs.

High plug electron density and electron temperature plus low barrier electron density leads to profiles similar to that shown in Fig. 2, which was used for the recent WITAMIR-I design study [1]. The large mirror ratio from point (c) to point (b) in the barrier takes advantage of the decreasing density of screaming ions in an expanding magnetic flux tube. Neutral beams injected into the barrier loss cone are used to charge exchange away ions which scatter into the barrier and would otherwise fill the potential well. The resultant neutrals quickly leave the system. Electron cyclotron resonance heating (ECRH) is also used at the barrier minimum to create a hot, magnetically trapped electron population which decreases the passing electron density by charge conservation, and thus increases the barrier potential. Neutral beams are used in the plugs to maintain the ion density there, and plug ECRH is used to maintain the electron temperature. A more detailed analysis of the physics is given in Refs. 1 and 2.

The performance of the WITAMIR-I reactor design has been calculated using a code [14] which uses a zero-dimensional model to analyze power flows in the three regions — central cell, barrier, and end plug. Numerous physical processes are modeled, including collisional energy and particle transfer, neutral beam interactions with the plasma, electron cyclotron heating, particle losses out the ends, and radiation losses. Tables I and II show various important parameters for the WITAMIR-I reactor design. The values differ only slightly from those given in Ref. 1 because only ion impact ionization of the plug neutral beam is considered here, and a different subroutine for this cross section is used. Electron impact ionization is negligible. Note that folding the trapping fraction into the absorbed plug neutral beam power gives 18.3 MW of neutral hydrogen beam power incident on the plug plasma. Note also that 16 MW of 500 keV hydrogen atoms are not

absorbed in the plug plasma and must be handled in a beam dump. Further details of the WITAMIR-I design are given in Ref. 1.

For $Z \neq 1$ beams, the chain of events in the life of a neutral particle injected into the plug is: (1) the particle ionizes to $Z = 1$ and becomes magnetically trapped, (2) it reaches a fully ionized state which, in the high plug temperatures, will occur almost instantaneously, and (3) the fully ionized ion scatters out of the plug on the high potential side and is lost from the machine. Step 2 should occur so quickly that it will be neglected here.

Various pieces in the physics of the problem must be modified to include $Z \neq 1$ effects in the end plugs. Two obvious changes are that quasineutrality is now $n_{ep} = Zn_{ip}$ and that the potential attempting to thrust ions from the plug is now $Z(\phi_c + \phi_e)$. To find the plug ion loss rate, the Logan-Rensink plug model [15] is suitably modified as follows: (1) the ion-ion scattering ν_i is divided by Z^4 , one Z^2 for each ion as is obvious from the Rutherford cross section, and (2) the ion-electron drag ν_i is divided by Z^3 , one Z^2 for the ion and one Z for $n_{ep} = Zn_{ip}$. The two adjustable constants in the Logan-Rensink model are assumed to remain approximately the same. This approach seems reasonable since a perusal of Table I of Ref. 16 shows that the adjustable constants did not vary greatly as parameters varied in the Fokker-Planck studies.

For self ion impact ionization rates, we start with proton ionization cross sections, σ_{ion} , scaled from standard sources [16] for the desired species injected into hydrogen ions. The rate is then taken to be

$$\langle \sigma v \rangle_{ion} = Z^2 \sigma_{ionp} v_{inj}$$

where v_{inj} is the injection velocity.

The trapping fraction may be found from

$$f_{trap} = 1 - e^{-\lambda}$$

where

$$\lambda \equiv 1.43 \times 10^{-6} \frac{n_p r_p \langle \sigma v \rangle_{ion}}{E_{inj}^{1/2}}$$

is the ratio of beam path length in the plasma to mean free path. E_{inj} is the injection energy in eV, n_p is the plug density in cm^{-3} , and r_p is the plug radius in cm.

To assess the usefulness of $Z \geq 3$ neutral beams, lithium, carbon, and oxygen were chosen as representative beams, parametric studies near the WITAMIR-I reference case given in Tables I and II were performed. Although cases far from WITAMIR-I are not considered here, the present results are a good measure of the usefulness of $Z \neq 1$ beams since WITAMIR-I was well-optimized and Li, C, and O all give somewhat better results.

Approximately, the required plug power and electron density are independent of the rest of the tandem mirror. Differences in mass, charge, and injection energy give different plug temperatures and ion densities, leading to different distributions of needed plug input power between neutral beams and ECRH. In general, the total absorbed plug power decreases as E_{inj} increases. The equations involved are nonlinear, so the exact physical mechanism giving the effect of interest is not always clear, but the power decrease, as E_{inj} increases, seems to come from the lower density as temperatures increase for finite plug beta. However, the plug trapping rate

decreases as injection energy increases (shown in Fig. 3), decreasing the power absorbed by the plasma for a given beam power. When this effect is taken into account, we obtain the dependence of Q , defined here as the ratio of fusion power to injected power, on E_{inj} shown in Fig. 4.

Parameter lists for three representative $Z \neq 1$ cases are exhibited in Tables III and IV. Chosen were the maximum Q case for Li, the minimum E_{inj} case for C, and the maximum E_{inj} case for O. The Li and C cases are both at $E_{inj} = 5$ MeV, which further facilitates comparison. Note that most changes occur in plug parameters, but the central cell magnetic field has been adjusted to give the optimum plug-to-central-cell density ratio, and related parameters also vary significantly.

When H beams are used in the plugs, as in WITAMIR-I, the same dependence appears, as shown in Fig. 4, but the Q 's are approximately 10% lower. In view of the necessary approximations in a calculation of this scope and the difficulties of optimization, the slightly higher Q 's must be viewed as indicative rather than definite. However, they certainly show that C, Li, and O beams should be given careful consideration, particularly if they can be constructed more easily or cheaply than H beams.

The WITAMIR-I design is based on an inboard thermal barrier, and the calculations for heavy atom beams have used this configuration to facilitate comparison. One can expect similar results, however, with the use of heavy atom beams to sustain the sloshing ion plasma in the outboard A-cell and TMX upgrade configurations.

The use of heavy atom beams to fuel the end plugs requires a neutral beam system capable of CW operation with a high neutralization efficiency. The need to accelerate large currents to very high voltages (several MeV) renders RF acceleration more attractive than electrostatic acceleration. An RF

accelerator requires lower potentials (only ~ 200 keV instead of several MeV), which mitigates the voltage isolation problems. Unlike an electrostatic accelerator, it transmits only particles with the chosen q/m and acts as a filter of ionic impurities and electrons. In addition, since both ends of the RF accelerator can be relatively near ground potential, the neutralizer can be located after a magnet so that the accelerator does not necessarily require a sight-line to the plug cell. Conventional magnetically focused RF accelerators do not operate well with low velocity beams, but the recent advent of RF accelerators with electric quadrupole focusing, which is velocity-independent, circumvents this problem. Because of their strong focusing, the RF Quadrupole (RFQ) [17] and the Meqalac [18] accelerators can accept low energy input beams (50 keV Li^-) with a relatively high space charge density. For example, an RFQ to accelerate Li^- to 6 MeV should be able to capture and transmit 85-90% of the CW beam from the source [19], and have a gross electrical efficiency of $\sim 34\%$ [20]. Such an accelerator could be 10-11 meters long for Li^- and accelerate ~ 100 mA through a channel with an entrance aperture 6-7 cm in diameter, giving a final beam diameter of 1-2 cm [19]. The large input aperture is attractive because negative ion sources tend to operate at lower current densities than positive ion sources. Each beam channel would consist of a negative ion source module followed by a magnet (to limit alkali migration), a focusing lens, a preacceleration stage, and a RFQ accelerator. Accordingly, as shown in Fig. 5, a beam system would be comprised of a number of RFQ channels, with the beams being merged after the accelerator and aimed through a neutralizer into the end plug. Only a few channels would be needed in a system, due to the large amount of power per channel (1.6 MW for O^- at 16 MeV).

This approach requires negative ion source modules producing ~ 100 mA (or somewhat more to allow for losses). While such sources do not presently exist, there are relatively straightforward approaches to producing the requisite currents for at least three elements. These involve extracting positive ions from an arc and converting a portion of them to negative ions during passage through a transverse jet of alkali metal vapor. Approximately 50% conversion of O^+ to O^- has been measured in small scale experiments for 14 keV O^+ passed through a magnesium cell [21]. Hence, only 200-300 mA of O^+ should suffice to produce ~ 100 mA of O^- . Currents of this magnitude should be easily obtainable using a multiaperture duopigatron ion source with extraction grids a few cm across, which is much smaller than existing sources for hydrogen neutral injection [3]. Conversion of C^+ to C^- with $\sim 50\%$ efficiency has been demonstrated for low currents at 5 keV [21]. Calutron sources fed by CO_2 have produced C^+ beams with current densities of 11.4 mA/cm² [22], necessitating only ~ 20 cm² of C^+ emitting area for a 100 mA C^- module.

Li^- is more difficult to produce, but a conversion efficiency of $\sim 9\%$ has been observed at low current for 5 keV Li^+ traversing a cesium cell [21]. Thus, one needs $\sim 1-2$ A of Li^+ to produce an adequate Li^- beam. Fortunately, there is a well developed ion source for producing large Li^+ currents. Calutron sources operating CW for days have yielded ~ 1.2 A of Li^+ at a density of ~ 30 mA/cm² [23]. Accordingly, it appears feasible to build modules with the required negative ion current of ~ 100 mA for at least three elements, oxygen, carbon, or lithium, using only modifications of existing technology.

There are also other approaches which might lead to simpler high current sources, but these are at present more speculative than the two stage sources

discussed above. One possibility is to sputter negative ions from a surface, cesiated to lower the work function. The sputtering agent could be a cesium beam at a few keV [24], similar in principle to a system that has been used for H^- production. Alternatively, the sputtering agent might be plasma ions accelerated across a sheath of several hundred volts in front of the sputtering surface, a technique which has been successfully applied in an H^- source [25]. Carbon is a good candidate for negative ion production by sputtering, since it has a high electron affinity (1.27 eV) [26] and sputters well. In small sputter sources for nuclear physics applications, C^- is usually one of the most prolific negative ions [27,28]. Extracting Li^- from a plasma of Li^- and Na^+ created by photodissociating NaLi in a molecular beam with laser irradiation at 2350-2400 Å has also been proposed [29].

The neutralizer can be quite straightforward, the simplest version being a cell of a gas, such as CO_2 , which is easily pumped by cryocondensation. With a cell optimized in thickness, 50% or more of the beam might be neutralized. It might be feasible to use photodetachment by Ga As lasers [30] to neutralize 90% or more of a Li^- beam, depending upon how small the cross section of the merged beam can be. The economics of Li^- photodetachment neutralization (greater neutral fraction at the expense of laser exciting energy) are similar in kind to those for H^- [29], since the photodetachment cross sections are similar [31], but are potentially more favorable for Li^- because of the much higher beam energy density in the multi-MeV Li^- beam.

The power handling problems with these heavy beams are similar to those with conventional negative hydrogen-ion-based systems. The ions remaining after the neutralizer must be deflected and decelerated onto cooled dumps, and dumps are also required on the far side of the plug cell for the untrapped remnant of the beam.

Relative to hydrogen neutral beams, heavy neutral beams have a number of technical advantages. They afford higher power densities, permitting smaller access cross sections to the plugging cell, and they require less liquid helium cryocondensation pumping. In the case of a Li beam, the only significant gas load is the neutralizer gas, which can be selected for easy pumping. Even C^- or O^- sources running on gaseous feedstocks would enjoy a substantial advantage over hydrogen beam systems with regards to pumping. Because of the greater energy per atom, much less heavy ion current is required than in the H^- case, so the gas efflux from the source is greatly reduced. Moreover, CO_2 , CO , and O_2 can all be pumped adequately by 30°K cryocondensation, without resorting to 4.2°K liquid helium-cooled cryocondensation, as would be required for a H^- beam. The gross accelerator efficiency (the ratio of line power to accelerated beam power) for an RFQ should be ~ 34%, which might be further improved [20]. This is, of course, less efficient than an electrostatic accelerator for 500 keV hydrogen could be, but accelerating many amps of hydrogen to 500 keV electrostatically would prove very difficult, and might well require an RF accelerator for reliability. Moreover, the lower efficiency of the RF accelerator is somewhat offset by the higher capture fraction of the heavy neutral atoms in the plug, relative to hydrogen. This not only results in less accelerated beam being required, but also decreases the power loading on the far side beam dump of the plug cell. In any event, the power in the plug beam represents such a small portion of the steady-state power requirements of the tandem mirror with a thermal barrier that factors of 2-3 in its efficiency are relatively insignificant. H^+ ion sources are easier to make than the ones we discuss, but H^+ is precluded as a possible beam because of its extremely low (< 1%) neutralization efficiency at 500 keV. H^- can be made in significant

quantities, but because of the lower energy, more current is required than for the heavy beams at ~ 1 MeV/amu. Furthermore, at energies of a few keV in an alkali cell, O^- and C^- can more easily be made from positive ions than can H^- .

Another advantage of heavy atom beams, pointed out by Paul Drake [23], is that the usual pumping requirements for the end plugs would be reduced. Minimizing losses of hydrogen beam ions in the end plug due to charge exchange with background neutral gas (from both the neutral beam systems and neutralized and recycling plasma) requires high pumping speeds in the end plug. Relatively high H^0 densities would not lead to losses of Li^{+3} , C^{+6} , or O^{+8} since $H^0 + Li^{+3} \rightarrow Li^{+2} + p$, for example, and the Li^{+2} is still well confined.

Thus, heavy neutral beams offer the promise of easing the high energy injection problems with tandem mirrors. The Q's obtainable with heavy neutral beams are comparable to or better than the Q's obtainable with high energy hydrogen beams, and offer the promise of significant technical advantages. Furthermore, the cases presented here were run for comparison with a specific design, WITAMIR-I, and progress in as yet unexplored directions is likely.

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TABLE I. WITAMIR-I Power and Machine Parameters

Powers are given as absorbed plasma power. Q is defined as the ratio of the fusion power to the injected power.

<u>Parameter</u>	<u>Value</u>
Q	25.9
Fusion power	3000. MW
Neutron Wall Loading	2.5 MW/m ²
Plug ECRF power	15.0 MW
Plug neutral hydrogen beam power	
at 500 keV injection	1.7 MW
Plug trapping fraction	0.13
Barrier ECRF power	33.3 MW
Barrier neutral hydrogen beam power	
at 9.7 keV injection	12.8 MW
at 190 keV injection	42.2 MW
Central cell wall radius	0.93 m
Central cell length	165. m
Barrier length	10. m
Plug length	5.5 m
Central cell magnetic field	3.6 T
Barrier maximum field	14. T
Barrier minimum field	1.4 T
Plug maximum field	6.0 T
Plug minimum field	4.0 T

TABLE II. WITAMIR-I Plasma ParametersCentral Cell

Electron Density	$1.51 \times 10^{14} \text{ cm}^{-3}$
Ion temperature	32.5 keV
Electron temperature	32.7 keV
Potential, ϕ_c	102. keV
Beta, β_c	0.40
Plasma radius	0.72 m

Barrier

Minimum Electron Density	$6.9 \times 10^{12} \text{ cm}^{-3}$
Mean hot electron energy, E_{eH}	269 keV
Passing electron fraction, F_{ec}	0.27
Pumping parameter, g_b	2.0
Pumping fraction at low energy	0.95
Pumping fraction at high energy	0.05
Potential, ϕ_b	141. keV
Beta, β_b	0.235
Plasma radius average	0.59 m

Plug

Electron Density average	$2.4 \times 10^{13} \text{ cm}^{-3}$
Mean ion energy	1040 keV
Electron temperature	135 keV
Potential, $\phi_c + \phi_e$	326. keV
Cohen parameter, v_c	0.5
Beta, β_p	0.64
Plasma radius	0.77 m

TABLE III. Representative Power and Machine Parameters

Lithium at 5 MeV, Carbon at 5 MeV, and Oxygen at 16 MeV

<u>Parameter</u>	<u>Li</u>	<u>C</u>	<u>O</u>
Q	33.8	31.0	32.8
Fusion Power (MW)	3000	3000	3000
Neutron Wall Loading (MW/m ²)	1.83	2.27	2.05
Plug ECRF Power (MW)	4.4	5.1	1.8
Plug NB ($Z \geq 3$) Power (MW)	0.48	4.4	2.7
Plug NB ($Z \geq 3$) Energy (MeV)	5.	5.	16.
Plug Trapping Fraction	0.16	0.62	0.38
Barrier ECRF Power (MW)	34.6	32.8	33.0
Barrier hydrogen NB Power (MW)	10.6	12.1	11.3
at energy (keV)	9.9	9.7	9.8
Barrier hydrogen NB Power (MW)	36.2	40.0	38.1
at energy (keV)	194.	190.	192
CC Wall Radius (m)	1.26	1.02	1.13
CC Length (m)	165.	165.	165.
Barrier Length (m)	10.	10.	10.
Plug Length (m)	5.5	5.5	5.5
CC B Field (T)	3.0	3.4	3.2
Barrier Maximum Field (T)	14	14	14
Barrier Minimum Field (T)	1.4	1.4	1.4
Plug Maximum Field (T)	6	6	6
Plug Minimum Field (T)	4	4	4

TABLE IV. Representative Plasma Parameters
Lithium at 5 MeV, Carbon at 5 MeV, and Oxygen at 16 MeV

<u>Parameter</u>	<u>Li</u>	<u>C</u>	<u>O</u>
<u>Central Cell</u>			
Density (cm^{-3})	1.07×10^{14}	1.36×10^{14}	1.21×10^{14}
Ion Temp (keV)	32.5	32.5	32.5
Electron Temp (keV)	31.5	32.2	31.9
Potential, d_c (keV)	104	103	103
Beta, b_c	0.4	0.4	0.4
Plasma Radius (m)	1.01	0.80	0.89
<u>Barrier</u>			
Minimum Density (cm^{-3})	4.9×10^{12}	6.2×10^{12}	5.5×10^{12}
Hot Electron Energy (keV)	352	291	319
Passing Electron Fraction	0.20	0.25	0.23
Pumping Parameters, g_b	2	2	2
Low Energy Pump Frac.	0.95	0.95	0.95
High Energy Pump Frac.	0.05	0.05	0.05
Potential, d_b (keV)	144	141	143
Average Plasma Radius (m)	0.75	0.63	0.69
<u>Plug</u>			
Average Ion Density (cm^{-3})	3.1×10^{12}	3.5×10^{12}	1.74×10^{12}
Mean Ion Energy (MeV)	8.7	7.2	14.9
Electron Temp (keV)	194	153	170
Potential, $d_c + d_e$ (keV)	319	323	321
Beta, b_p	0.64	0.64	0.64
Plasma Radius (m)	0.99	0.83	0.91
Ion Charge, Z	3	6	8
Ion Mass (amu)	7	12	16

FIGURE CAPTIONS

- Fig. 1. Schematic design of negative carbon neutral injection systems for a tandem mirror reactor. The 5 MeV neutral C^0 atoms are injected perpendicularly into the end plug.
- Fig. 2. Density, temperature, electrostatic potential, and axial magnetic field profile for the Witamir-I design study tandem mirror reactor design study [1].
- Fig. 3. Trapping fractions for H, Li, C, and O beams as a function of energy.
- Fig. 4. Q for H, Li, C, and O beams as a function of the injection energy.
- Fig. 5. Schematic diagram of a modular heavy atom injection system.

C⁰ INJECTION

Fig. 2

Fig. 3

Fig. 4

A MODULAR HEAVY NEUTRAL BEAM SYSTEM

Fig. 5