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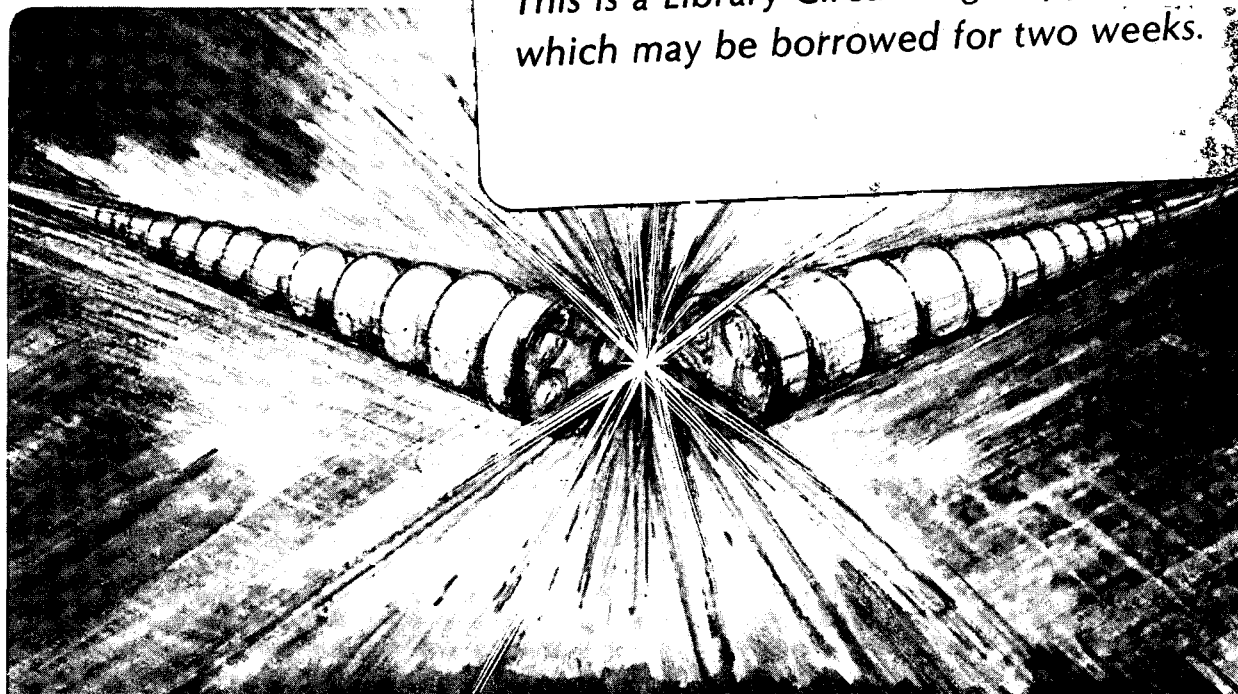
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A.S. Schlachter and W.S. Cooper

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CONFINED ALPHA PARTICLES IN A BURNING PLASMA*

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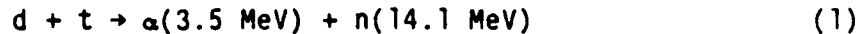
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ABSTRACT

Diagnostic methods for fast confined alpha particles are essential for a burning plasma experiment. Several methods which use energetic neutral beams have been proposed. We review these methods and discuss system considerations for their implementation.

INTRODUCTION

Alpha particles (He^{2+} ions) produced in the d-t fusion reaction



are born at an energy of 3.5 MeV, or 880 keV/u. Most are trapped in the magnetic field confining the plasma and slow down by interaction with plasma ions and electrons, thereby heating the plasma. The plasma is called "ignited" when the alpha particles produced by the d-t fusion reaction provide sufficient heat to the plasma to sustain the reaction, i.e., a "burning" plasma.

A new generation of tokamaks is being planned in which a primary objective is to achieve ignition. An essential diagnostic is measurement of the spatial, temporal, and velocity distribution of the fast alpha particles as they slow down, to ascertain whether they slow down classically or by some other energy-loss mechanism, and to answer questions concerning alpha-particle confinement and efficiency of alpha-particle heating.

Alpha particles will have a distribution of velocities as they slow down. Most alpha particles will be confined by the magnetic field of the tokamak; some fraction will escape. Measurements can be made relatively easily of the escaping alpha particles; their distribution, however, might not be characteristic of the confined alpha particles. Neutrons from the d-t reaction (1) will certainly escape the plasma, and measurements can be made of their distribution. Alpha particles which are confined will become thermalized. This paper addresses methods of detecting fast confined alpha particles.

Development of a diagnostic method for fast confined alpha particles is difficult because of the high energy of the alpha

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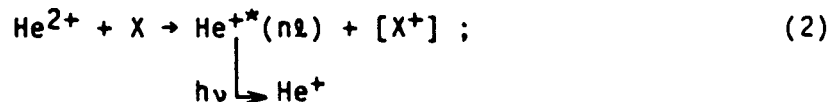
particles and because of the minimal access to and large background emission from a burning-plasma reactor. Parameters for the current in the United-States project, CIT (Compact Ignition Tokamak), include electron and ion densities of the order of $5 \times 10^{14} \text{ cm}^{-3}$, electron and ion temperatures of 10 keV, alpha-particle density of $3 \times 10^{13} \text{ cm}^{-3}$, and minor radius of less than 50 cm. CIT will be small and compact, with limited access for diagnostics. The burning plasma will generate a considerable flux of neutrons and photons, and activation will require remote-handling capability for equipment exposed to the plasma.

The topic of alpha-particle diagnostics and related atomic-physics issues has been recently reviewed by members of the Princeton Plasma Physics group (Post, Zweben, Grisham, and Fonck)¹⁻³ and by Schumacher,⁴ while alpha-particle effects were the topic by a recent workshop.⁵ The purpose of this paper is to review proposed methods for fast confined alpha-particle diagnostics in a burning-plasma reactor which are based upon energetic atomic beams, including discussion of accelerator requirements to implement a diagnostic. Much of what is presented here has been proposed and discussed in important articles by Post, Grisham, and co-workers at PPPL,^{6,7} by participants in the NYU workshop,⁵ and in reports from Nagoya.^{8,9}

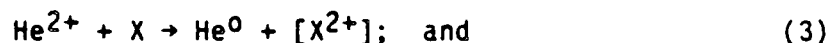
A variety of methods has been proposed⁵ for a diagnostic for fast confined alpha particles. These methods include laser techniques (small-angle infra-red Thomson scattering), microwave techniques (lower-hybrid-wave damping, ion-cyclotron emission), nuclear-reaction methods (gamma-ray emission), and charge-transfer methods. The charge-transfer methods use an energetic beam of atoms injected into the plasma as a target for charge transfer by the alpha particles. This method is described in the following paragraphs.

The major neutral-beam-based methods considered for a diagnostic for fast confined alpha particles are

a) single-electron capture by He^{2+} from an energetic neutral atom beam injected into the plasma to serve as a charge-transfer target (charge-exchange recombination spectroscopy), leading to emission of a photon from excited states of He^+ :



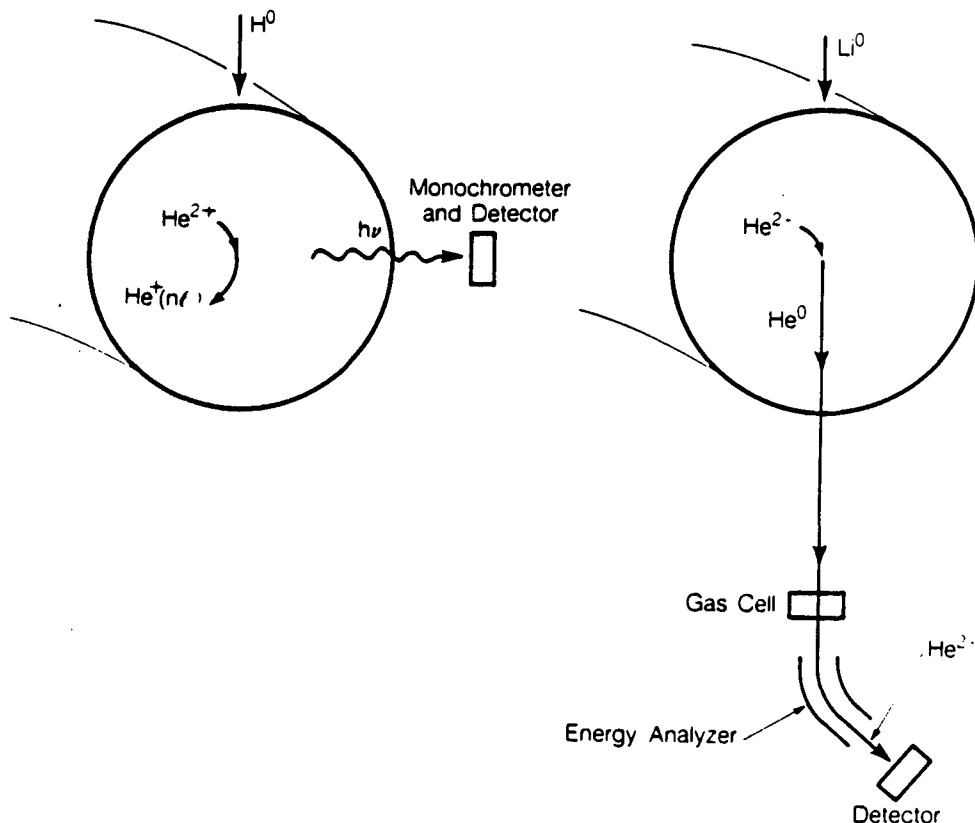
(b) two-electron capture by He^{2+} from an energetic neutral atom beam injected into the plasma, creating a fast He atom which, being neutral, can escape the confining magnetic field:



(c) nuclear methods, in which the alpha particle interacts with target nuclei which are introduced into the plasma, resulting

in emission of a gamma ray.¹⁰ This latter method seems especially difficult, or requires an appreciable admixture of the target specie in the plasma, and will not be discussed in this paper. Non-beam-based methods for alpha-particle diagnostics have also been proposed, as well as diagnostics on the neutrons which are also emitted in the d-t reaction. Methods (a) and (b) have been discussed by Post et al.,⁷ while an implementation of method (b) using a Li^0 beam has been discussed by Grisham et al.⁶ and, using a He^0 beam, by Sasao and Sato.⁸

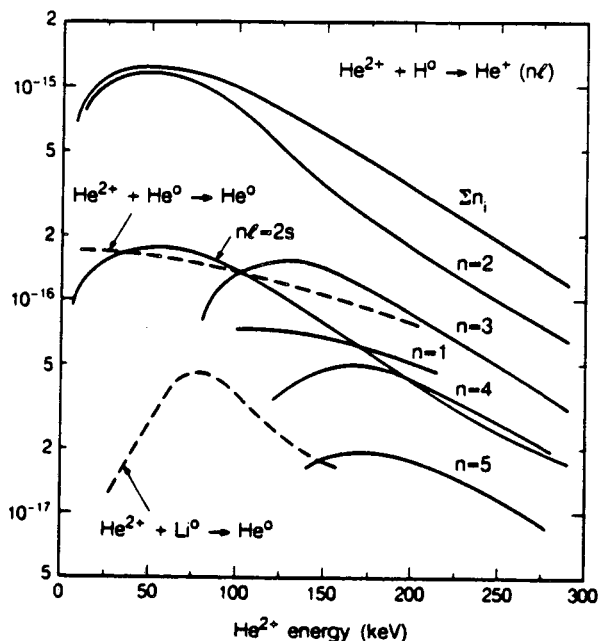
Methods (a) and (b) are shown schematically in Fig. 1 for the most likely candidates for the target beam: H^0 for reaction (2)



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Fig. 1 Schematic diagram of neutral-beam methods for fast confined alpha-particle diagnostics, showing likely candidates for injected beams.

and He^0 or Li^0 for reaction (3); these choices are explained in more detail in the following sections. The corresponding cross sections for reactions (2) and (3) are shown in Fig. 2. As Post et al. have discussed,⁷ the cross sections for the



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Fig. 2 Cross sections in units of cm^2 relevant to fast alpha-particle diagnostics. The cross sections for formation of He^+ (Σn_i) and $\text{He}^+(2s)$ are measured, as are the cross sections for formation of He^0 . The cross sections for formation of $\text{He}^+(n=2,3,4,5,)$ are estimated only (see text).

He^+ formed by electron capture will be in an excited state, $\text{He}^+(n\ell)$, where $n\ell$ refers to the quantum numbers of the state ($n > 1$), and will therefore decay radiatively with emission of a photon from the He^+ spectrum, which can be detected outside the plasma. This approach has been described by Post et al.⁷

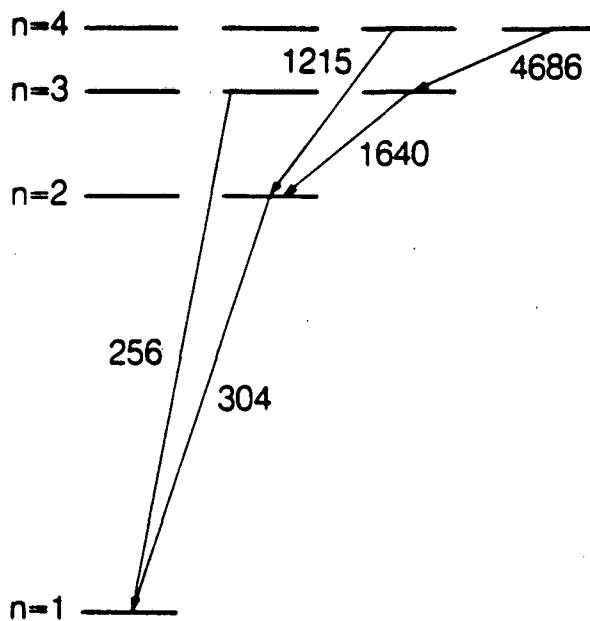
The neutral beam serving as a charge-transfer target must have a velocity of the order of the alpha particles to be useful, because the cross section for electron capture is appreciable only at small relative energies. For example, Fig. 2 shows estimated cross sections for reaction 2 with X being an atomic hydrogen beam. This is a logical candidate, because intense H^0 beams are presently being developed at LBL and elsewhere. The cross sections for $\text{He}^{2+} + \text{H}^0 \rightarrow \text{He}^+(n\ell)$ were estimated by comparing calculations by R. E. Olson¹² with measured cross sections for electron capture into all states of He^+ and into the $\text{He}^+(2s)$ state.¹³ The accuracy of these estimated cross sections is, at best, a factor of 2, and could be considerably worse. Electron capture into the $n=2$ state predominates because

reactions shown in Fig. 2 are small for high velocities, and thus the diagnostic method has velocity selectivity, i.e., fast alpha particles interact essentially only with injected target atoms of the same velocity (magnitude and direction). Varying the velocity of the injected target beam and varying its direction, if possible (given limited access), will allow measurement of the velocity distribution of the fast alpha particles.

SINGLE-ELECTRON CAPTURE TO $\text{He}^+(n\ell)$ FOLLOWED BY PHOTON EMISSION

The method of single-electron capture by a fast confined alpha particle from a neutral atomic beam injected to serve as a charge-transfer target is a form of charge-exchange recombination spectroscopy.¹¹ Most of the

the reaction is accidentally resonant for collision with a ground-state H^0 atom. The $He^+(n=2)$ state decays radiatively with the emission of a photon at 304 Å, well into the vacuum ultraviolet spectral region. The estimated cross section for formation of $He^+(n=3)$ shows a broad peak at higher energy than the cross section for formation of $He^+(n=2)$, and down in magnitude by approximately a factor of ten. The estimated cross sections for formation of $He^+(n=4)$ and $He^+(n=5)$ are down by approximately a factor of 2 and 4 from the $He^+(n=3)$ cross section. The $He^+(n=3)$ level decays radiatively with the emission of a photon at 1640 Å, which is in the vacuum ultraviolet, and where refractive optics are useable; the $He^+(n=4 \rightarrow 3)$ transition is in the visible (blue) spectral range at 4686 Å. These transitions are shown in Fig. 3. Note that the He^+ spectrum is the same as the H^0 spectrum, but with the energies multiplied by a factor of 4; e.g., $He^+(4 \rightarrow 2)$ radiates at the same energy as $H^0(2 \rightarrow 1)$, which is Lyman-alpha for H atoms.



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Fig. 3 Levels of $He^+(n \leq 4)$ shown schematically. The numbers are transition wavelengths in Angstrom units.

The photons radiated by $He^+(n \leq 4)$ will be Doppler-shifted because the ions are moving, and the photons can thus be distinguished from radiation from any slow He^+ ions which might be in the plasma or along the line of sight. The photons are, however, emitted into 4π solid angle, and only a small fraction will be detected, depending primarily upon constraints imposed by limited access. Mirror and refractive optics can be used for $He^+(n=3 \rightarrow 2)$ radiation at 1640 Å; a high-reflectivity multi-layer mirror will be used for $He^+(n=2 \rightarrow 1)$ radiation at 304 Å.

Estimated signal level for reasonable target-beam parameters in either case is estimated to be smaller than the bremsstrahlung

background from the plasma, so that some signal-processing techniques will be needed.¹⁵ The collecting mirror or lens will be exposed to an intense x-ray and neutron flux, so that radiation hardening will be a consideration in the design of a diagnostic system.

There are additional considerations. One is that a Li^0 beam could be used as a charge-transfer target; this would give a greater yield of $\text{He}^+(n=3)$. However, intense Li^0 beams are not presently under development, while intense H^0 beams are being actively developed. Another consideration is that $\text{He}^+(n \geq 2)$ must radiate before being collisionally ionized to produce a photon; this limits the usefulness of He^+ states with large values on n . Finally, the intense magnetic field of the tokamak (10 Tesla) will cause changes in state lifetimes, state populations, and decay rates.

TWO-ELECTRON CAPTURE TO He^0

A fast alpha particle which captures 2 electrons from a target atom will become a fast neutral He atom, which has some likelihood of traversing the plasma and, being neutral, will escape the confining magnetic field, where it can be reionized and energy analyzed, or otherwise detected. This approach has been described by Grisham et al.,⁶ who proposed the use of a fast Li^0 beam as the injected charge-transfer target. The cross section for 2-electron transfer¹⁴ from Li^0 to He^{++} is shown in Fig. 2; it is appreciable only at small relative velocities, hence the injected Li^0 beam must have an energy in the 5-6 MeV range to interact with alpha particles at their birth velocity.

Beam penetration through the plasma must be considered both for the Li^0 beam injected to serve as a charge-transfer target and for the He^0 beam produced when the alpha particles capture 2 electrons. The latter depends upon the state of the He^0 atoms; any state other than the ground $1s^2 \ ^1S$ state is likely to be reionized in traversing the remaining plasma. However, it is likely that most of the He^0 beam will be in the ground state.¹²

The choice of a target beam for 2-electron transfer is dictated primarily by the requirement that the beam velocity be approximately equal to the birth velocity of the alpha particles, thus use of a heavy specie would require a high energy to achieve the necessary velocity. Atomic hydrogen only has one electron, and is thus not a candidate. Neutral He would be an excellent choice, because the 2-electron-transfer cross section,¹⁶ $\text{He}^2 + \text{He}^0 \rightarrow \text{He}^0 + \text{He}^{2+}$ is larger than 10^{-16} cm^2 , i.e., at least a factor of 3 larger than for a Li^0 target beam. However, fast He^0 in the ground state is not the predominant product of neutralization of energetic He^- in a gas target,¹⁷ rather the $1s2s \ ^3S$ metastable state is formed. Options could include neutralization and dissociation of a positive molecular ion, e.g., HeH^+ or He_2^+ , or of the negative ion He_2^- , which could result in fast ground-state He^0 , or decay of metastable He^- in a long drift space, as proposed by Sasso and Sato.⁸ These ideas notwithstanding, Li^0 is the likely candidate for a target beam. However, a fast beam of ground-state He^0 would be very desirable.

The fast He⁰ beam that exits the plasma can be reionized and energy analyzed, to distinguish fast He⁰ from other ions and atoms emitted by the plasma. Although the cross section for 2-electron transfer is 1 to 2 orders of magnitude smaller than that for 1-electron transfer to He⁺⁽ⁿ⁼²⁾, essentially all the He⁰ will exit the plasma (excepting those which are collisionally ionized) in the direction of the incident target beam, and can thus be detected.

SYSTEM CONSIDERATIONS

The successful development of atomic-beam-based alpha-particle diagnostic schemes will pose challenges in the area of ion source and accelerator development. Since only hydrogen or deuterium beams are presently under development, we shall confine our discussion to accelerators for these species. In addition, for reasons of economy of power and space utilization, we consider only systems capable of dc operation in a multiple-aperture configuration.

The confined alpha-particle diagnostic requires beam energies up to 1 MeV, thus H⁻ ions must be accelerated, as only negative ions can be converted to neutral atoms at these energies with high efficiencies. The beam energy must also be variable, from a few hundred keV up to approximately 1 MeV; it would be desirable for beam current to be approximately constant, i.e., independent of the beam energy.

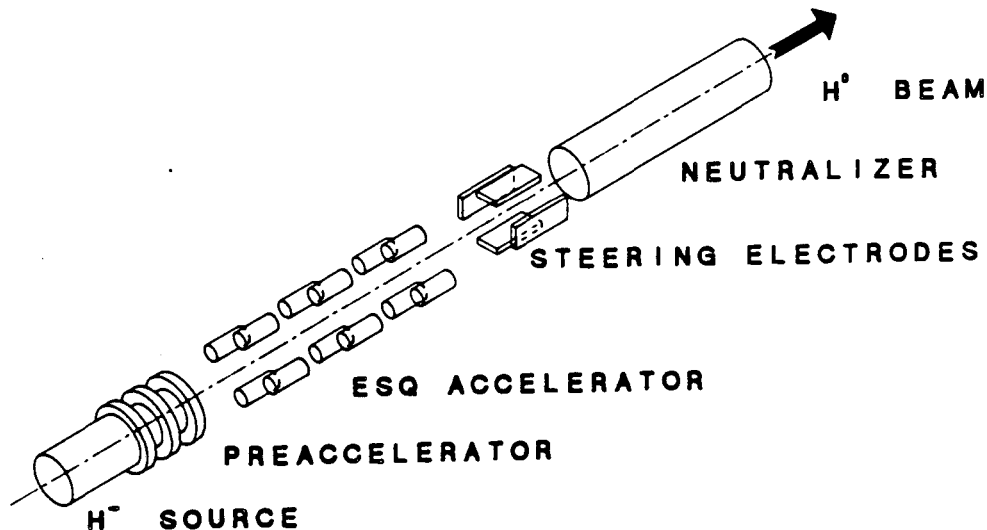
Although a conventional Pierce column has reached 350 mA of H⁺ at 600 keV dc operation,¹⁸ another approach must be followed to allow variation of the beam energy with minimal change of current. The Pierce type of accelerator achieves control of the beam space charge by a suitable choice of axial gradient in the accelerating electric field, which, through Maxwell's equations, introduces a radial component of field that just balances the repulsive force due to the beam's space charge. This balance of forces is achieved if the beam current is proportional to the three-halves power of the accelerating voltage:

$$I = p v^{3/2} \quad (4)$$

where P is the perveance of the beam. This is the familiar Child-Langmuir formulation for space-charge limited flow. It is clear from this expression that a reduction of voltage in a straight-forward electrostatic accelerator will necessarily be accompanied by a substantial reduction in current.

The function of controlling the beam's space charge must be separated from that of acceleration in order to achieve variable beam energy at constant current. This can be done by devising a series of focussing elements such as electrostatic quadrupoles (ESQ)¹⁹ or curved plates employing transverse-field focussing (TFF),²⁰ with a potential difference applied between successive sets of focussing elements, to accelerate a beam from a modest

energy, of the order of 100 keV, to the final desired energy. Both concepts have been tested and shown to work.^{21,22} A highly schematic drawing of an ESQ accelerator and beamline is shown in Fig. 4.



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Fig. 4 Schematic diagram of an ESQ accelerator for producing a high-current H^- beam, and an H^0 beam following neutralization.

This approach also promises a certain resistance to electrical breakdown, as the electrostatic fields required for focussing and acceleration can be kept modest, probably 50 kV/cm or less, and there are transverse fields everywhere to impede the motion of newly formed electrons and ions in the axial direction.

Beam intensities of up to 1 A will probably be required. Small volume-production sources of H^- ions have recently achieved high current densities, in excess of 250 mA/cm² for 5 msec pulses,²³ and it is not unreasonable to expect that, with continued development, current densities of 30-50 mA/cm² will be achieved in dc operation. It may be possible to make the sources so small that one could use one "sourcelet" per beamlet, with an ESQ accelerator, thus providing a relatively inexpensive approach to developing a system to meet the design requirements. A module of this type might accelerate 0.2 A of H^- to 1 MeV in dc operation, and deliver 0.1 A of H^0 to the plasma as a diagnostic beam. Higher total currents would be achieved by stacking of modules. In principle, individual sourcelets could be switched on and off to provide signal coding of the beam as an aid in detection of a weak signal from the alpha particles, and individual beamlets could be steered electrostatically to move the beam to different positions within the target plasma.

An energetic H^- beam can be neutralized in a gas or vapor cell or jet with an efficiency of 50-60%. Higher neutralization

efficiency could be achieved with a plasma (85%) or with a photo-neutralizer (which could, in principle, approach 100% neutral fraction).

A high-current ion source and accelerator for Li^- would be required to implement a diagnostic method using Li^0 . Although Li^- production has been discussed,²⁴ we are not aware of any work in progress on a Li^- ion source and accelerator capable of the performance required for use of a Li^0 beam for an alpha-particle diagnostic. Neutralization of Li^- has, however, been measured.²⁵

A high-current He^0 beam poses atomic-physics questions, as production of He^- in a neutralizer will not provide a beam of He^0 primarily in the ground state. Furthermore, He^- is generally more difficult to produce than H^- or Li^- , although high currents have been produced.²⁶ Alternative methods of producing high-energy ground-state He^0 should be sought. The method⁸ of neutralization by spontaneous decay of metastable He^- would require a drift space of the order of 100 m. A speculative method would be acceleration of a molecular ion containing He, resulting in energetic He^0 after neutralization and dissociation; it is not known if this method would produce an appreciable yield of ground-state He atoms.

We are presently beginning to consider questions of beam penetration into the plasma for H^0 , He^0 , and Li^0 , and penetration for He^0 (neutralized alpha particles) to escape the plasma. These considerations will include the enhancement of cross sections due to multistep collision processes.²⁷

A substantial development program will be required to demonstrate that these concepts can be developed into a working alpha-particle diagnostic system.

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