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THEORY AND MODELLING
OF HELIUM ENRICHMENT IN PLASMA EXPERIMENTS
WITH PUMP LIMITERS

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Abstract

Helium enrichment in the exhaust gas stream flowing from a hydrogen-helium plasma is studied using an analytical theory and Monte Carlo simulations. To provide a sensitive experimental test in a tokamak, an unusual configuration, inverted from traditional designs, is proposed for a pump limiter. The principle can be tested in other plasma devices as well. The theory suggests that for typical plasma edge conditions in a confinement device, namely, $n = 10^{13} \text{ cm}^{-3}$ and $T_i = T_e = 5\text{-}30 \text{ eV}$, helium enrichment in the neutral gas exhaust stream can be very high, in the range 5 to 7, relative to the helium-hydrogen ratio in the plasma. Such high enrichment factors are achieved by exploiting the difference between the ionization rates of hydrogen and helium and the negligible helium charge exchange rate at these plasma conditions. A limiter arrangement is proposed in which the natural curvature of the toroidal magnetic field is used to isolate, using the plasma itself, the point of plasma neutralization from the location of the gas exhaust. The plasma region then acts to preferentially screen the recycling hydrogen by the processes of ionization and of charge-exchange-induced losses at open boundaries. The theory and analysis suggests that an experiment can provide a sensitive test of modules used to describe the plasma edge and of atomic and surface physics data used in these models.

I. Introduction

Considerable progress has been made in tokamak plasma experiments to develop particle exhaust schemes that successfully remove 5 to 10% of the edge plasma efflux. Two candidates receiving greatest attention are the magnetic divertor (1,2) and pump limiter (3,4). Both concepts have been extensively investigated experimentally in confinement devices, e.g., in MACROTOR (5), PDX (6), ASDEX (7), ALCATOR (8), D-III (9,10), ISX-B (11), and TEXTOR (12). Furthermore, sophisticated theoretical and computational models for design and analysis of these experiments have either been developed or are evolving (13,14,15).

The need for particle exhaust in fusion devices stems from the requirements of (i) impurity control, (ii) density control, and (iii) fusion product ash removal (i.e., helium exhaust). Whereas magnetic divertors are promising for suppression and exhaust of wall generated impurities, pump limiters are generally regarded as less suitable for this function unless the edge temperature is sufficiently low ($<50\text{eV}$). Density control appears to be feasible with both configurations (16,17). For ash removal in burning plasmas, on the other hand, the situation is only speculative. No particle removal experiments have been reported for a $\text{H}^{\circ}/\text{He}^{\circ}$ plasma with pump limiters, although there is no apparent difficulty in conducting such an experiment, while only one such experiment has been conducted in the divertor configuration (10). However, if one assumes that helium transport is not radically different from that of the background plasma, then computational models can be adopted to assess the effectiveness of various schemes for helium exhaust. In particular, the question of helium enrichment can be addressed, that is, is it possible, by virtue of either physical processes or of design to preferentially remove helium relative to the deuterium and tritium? An affirmative response would be highly desirable because the tritium inventory in the vacuum system could then be minimized, leading to more efficient utilization of fuel and generally greater economy of operation.

In this paper we demonstrate that helium enrichment in pump limiters is possible in principle. A simple theoretical model is used to display the underlying physics responsible for preferential helium exhaust. This is followed by rigorous Monte Carlo simulation of a proposed experiment, based on the simple theory, to test predictions brought out in this paper. In section II we elaborate on the distinguishing physical processes important for the

problem and, in section III, develop a theoretical model that quantifies the relationship between enrichment and the system parameters (line density, electron temperature, etc.) In section IV a pump limiter configuration is suggested which embodies these ideas and which could be used as a sensitive experimental test of the physical principles. In that section, the proposed experimental arrangement is analysed using a Monte Carlo code.

II. Helium Enrichment Modelling and Experiments

Early work on modelling neutral transport in divertors [18] indicated that greater neutral helium compression was possible than the fractional He^{++} concentration in the plasma, i.e., under identical conditions, more neutral He could be removed than D^0/T^0 , but the effect was not significant ($\leq 10\%$). Later more refined calculations [19] showed no enrichment under similar conditions, indeed, some de-enrichment was predicted (i.e., preferential removal of D^0/T^0 relative to He^0). The discrepancy in the results could be traced to differences in the atomic and molecular reaction rate data used for the plasma-neutral interaction in the codes. Prinja and Conn [20] showed that by optimizing the pump limiter configuration, helium enrichment is possible. Specifically, for a large enough exhaust duct aspect ratio (length to diameter), recombination of the atomic hydrogen to molecules and the resulting difference in wall interaction models can lead to a consistent enrichment factor of about 20%.

The only experiment addressing this issue is that of Shiwada, et al. [10] on the D-III tokamak. In the single null poloidal divertor configuration of D-III, they demonstrated that "no strong enrichment or impoverishment of helium was found in the divertor chamber," but they showed that enough compression was possible to make ash exhaust practical in burning plasmas.

The conclusion is evidently that for conventional divertor and pump limiter designs, significant helium enrichment is not possible because, from a particle-wall interaction point of view, the differences are negligible, while the plasma-neutral interactions confine the recycling He^0 and D^0/T^0 neutrals equally effectively.

We find that by adopting a more flexible design, the very significant differences in atomic processes between He^0 and D^0/T^0 can be judiciously exploited to yield non-trivial enrichment factors. Furthermore, since divertors have restricted flexibility, we find the ideas are most readily

incorporated into a pump limiter. In what follows, we shall consistently deal with the hydrogen-helium system because the differences in atomic physics between the hydrogen isotopes are largely negligible for the problem at hand. However, where these differences could make an impact, the affect of replacing H^0 by D^0/T^0 will be explicitly assessed.

It is well known [21] that hydrogen has a large resonant charge-exchange reaction rate, $\langle\sigma v\rangle_{cx}$, relative to helium at typical edge plasma temperatures. Thus for $T_e < 100\text{eV}$, $\langle\sigma v\rangle_{cx}$ for H^0 is about 20 times larger than that for He^0 . Furthermore, since in steady state the He^{++} density is approximately 10% of the proton density, we see that the mean free path (mfp) for He^0 charge exchange is about two orders of magnitude larger than that of hydrogen. On the other hand, the ratio of the electron impact ionization rate for hydrogen ($\langle\sigma v\rangle_e$) to that for helium ($\langle\sigma v\rangle_{e,He}$) decreases sharply with increasing temperature, going from about 10 at $T_e = 5\text{eV}$ to about 2 at 50eV, and is approximately unity at 100eV. Now, whereas charge exchange does not lead to a local loss of neutral atoms, the randomization of the orientation of neutrals following charge exchange reactions can eventually lead to losses at the boundary. Further, since the dominant reaction for hydrogen is charge exchange, this effect is likely to be significant. Helium, on the other hand, is largely unaffected by randomization associated with charge exchange and is only attenuated in magnitude by ionization (the effects of wall collisions is a separate issue and will be discussed later).

The larger hydrogen ionization rate also enhances the relative penetration depth of helium in a plasma. The plasma basically acts to preferentially "screen" out the hydrogen, allowing more helium to get through. In fact, it is precisely this effect which causes the de-enrichment observed in simulations [19] of standard divertor and pump limiter designs.

The essence of our approach is to utilize this phenomena (preferential screening of hydrogen) to advantage in a modified pump limiter design to provide a very sensitive experimental test. This will be described in section IV. In the next section, an idealized model is developed and solved analytically to make more quantitative the physical phenomena described here. The model also proves exceedingly useful in interpreting the subsequent Monte Carlo simulations.

III. Analytical Theory of Helium Enrichment

A. Model

Consider a one-dimensional slab plasma with prescribed line density n_a and temperature where a is the slab thickness. Consider a beam of neutral hydrogen and helium atoms incident from the left. We are interested in the fluxes of hydrogen and helium that emerge from the right face. If these are respectively designated by Γ_H and Γ_{He} , and the corresponding incident fluxes are Γ_H^+ and Γ_{He}^+ , then we define the enrichment factor, η , as

$$\eta = \frac{\Gamma_{He}/\Gamma_H}{\Gamma_{He}^+/\Gamma_H^+} . \quad (1)$$

We now develop approximate solutions for these fluxes. Ultimately we are interested in establishing the possibility of enrichment in a fully three dimensional system, complete with wall effects, for which analytic solutions are impossible. Thus, as an illustration, it is sufficient to develop only an approximate solution to the slab problem, but one that adequately describes how the differential atomic physics processes are manifest in yielding helium enrichment. We note here that simple, analytic neutral atom transport models have also been used to investigate the feasibility of the cool plasma mantle concept [26].

The Boltzmann equation for the neutral hydrogen atom distribution function f_0 may be written

$$\mu v \frac{\partial f_0}{\partial x} + f_0(x, v, \mu) = c f_m(v) n_0(x) \quad (2)$$

where v is the speed of the neutral atom normalized to the ion thermal speed, μ

is the particle direction cosine, i.e., $\mu = \underline{v} \cdot \underline{x} / v$, x is the distance into the slab normalized to the total mean free path (including charge exchange and ionization), $f_m(v)$ is the Maxwellian ion distribution and the parameter c is

$$c = \frac{\langle \sigma v \rangle_{cx}}{\langle \sigma v \rangle_{cx} + \langle \sigma v \rangle_e} = \frac{\langle \sigma v \rangle_{cx}}{\langle \sigma v \rangle_t} . \quad (3)$$

The parameter c is a measure of the relative strength of scattering (charge exchange). Since $\langle \sigma v \rangle_e / \langle \sigma v \rangle_{cx} < 1$ for hydrogen [21], clearly, c is in the range, $1/2 < c < 1$. The neutral density is n_0 and is given by

$$n_0(x) = \int dv f_0 = 2\pi \int_{-1}^1 du \int_0^{\infty} dv v^2 f_0(x, v, u) \quad (4)$$

Before proceeding with the solution, two further simplifying assumptions are made:

- i) We consider a semi-infinite plasma with vacuum boundary and a prescribed incident neutral flux at that boundary.
- ii) We approximate the ion distribution function by

$$f_m(v) = \frac{\delta(v_1 - v)}{4\pi v_1^2} \quad (5)$$

The ramifications of the first approximation will shortly be discussed. For now suffice it to say that this assumption makes the solution considerably simpler but does not alter our conclusions.

The second assumption is crucial for obtaining a simple closed-form solution. It has been extensively employed in previous neutral transport calculations [22,23] where it was shown to yield acceptable accuracy for the neutral density. (Naturally, the energy spectrum is totally unrealistic, but the neutral density does not depend sensitively on the energy spectrum).

The exact solution is readily obtained using the powerful techniques developed in neutron transport theory [24,25] for solving one-speed transport equations. The general solution can be written as a sum of two terms corresponding to the discrete and continuous (singular) components of the spectrum of the Boltzmann operator. However, physically, the continuous eigenfunction represents the effect of boundaries and sources, and decays very rapidly into the medium. We thus retain only the discrete, asymptotic solution that is dominant in the interior. Note that the second boundary of the slab is neglected but in the absence of any sources there, this is a good approximation. Thus we obtain:

$$n_H(z) = \frac{\Gamma_H^+}{v_1} f(c, v) e^{-vz/\lambda_t} \quad (6)$$

where $\lambda_t = v_1 / (n_e \langle \sigma v \rangle_t)$ is the total mean free path and v is the discrete eigenvalue obtained as the positive solution of the transcendental equation

$$1 - \frac{c}{2\pi} \ln \frac{1+s}{1-s} = 0 \quad (7)$$

This equation has roots, $s = \pm v$ with $0 < v < 1$. For $c=0$, $v=1$, while for $c=1$, $v=0$. For intermediate values of c , v is monotonic and can be readily computed from eqn. (7). The quantity $f(c,v)$ is a complicated function of c and v but is readily evaluated and not crucial for our discussion.

The corresponding solution for helium is trivial. As mentioned earlier, helium resonant charge exchange can be neglected and the result for the He^0 neutral density is quite simple

$$n_{\text{He}}(z) = \frac{\Gamma_{\text{He}}^+}{v_a} e^{-z/\lambda_a} \quad (8)$$

where $\lambda_a = v_a / (n_e \langle \sigma v \rangle_{ae})$ is the helium ionization mean free path.

Now consider a plasma slab of arbitrary thickness, a . From equations (1), (6) and (8), we find the enrichment factor is

$$\eta = \frac{1}{f(c,v)} \exp [a(v/\lambda_t - 1/\lambda_{ae})] \quad (9)$$

or, more explicitly,

$$\eta = \frac{1}{f(c,v)} \exp \left[a n_e \left(\frac{v}{v_1} (\langle \sigma v \rangle_e + \langle \sigma v \rangle_{cx}) - \frac{\langle \sigma v \rangle_{ae}}{v_a} \right) \right] \quad (10)$$

If further we use the thermal speeds for v_1 and v_a , eqn. (10) becomes

$$\eta = \frac{1}{f(c,v)} \exp \left[\frac{a n_e}{v_1} (v (\langle \sigma v \rangle_e + \langle \sigma v \rangle_{cx}) - 2 \langle \sigma v \rangle_{ae}) \right] \quad (11)$$

where the factor 2 in the exponent arises from $(m_a/m_H)^{1/2}$. Note that for D^0/T^0 this factor is smaller and will lead to an even higher value of helium enrichment factor.

B. Discussion

The interesting feature of eqn. (11) is that in the temperature range where the total hydrogen reaction rate is larger than the helium electron impact ionization rate, the enrichment increases exponentially with line density, $\overline{n_e a}$. However, it is the differential atomic physics which we alluded to earlier that makes possible enrichment factors greater than 1. We now consider this more quantitatively.

Numerical values for η as a function of temperature for $\overline{n_e a} =$

$2 \times 10^{14} \text{ cm}^{-2}$ are presented in Table 1. The corresponding ionization charge, exchange and total mean free paths are also displayed. Moderate enrichment is evident at low temperature ($T_e \approx 5 \text{ eV}$) but η increases sharply with increasing temperature thereafter. A maximum η value of about 7 occurs at $T_e \approx 25 \text{ eV}$, and is followed by a gradual decline in η as the plasma temperature increases further. These features can be explained by referring to the mean free paths. At low temperature ($T_e \approx 5 \text{ eV}$), the hydrogen and helium ionization mean free paths result in efficient penetration of both species. However, the dominant charge exchange reactions introduce "backscattering" of H^0 atoms that results in a finite H^0 albedo, i.e., reflection (and hence loss) of H^0 across the vacuum boundary. This results in slight enrichment as is evident in Table 1. With increasing temperature (5-20 eV), the ionization mean free path of H^0 decreases sharply, more rapidly than that of He^0 . With the resulting reduced penetration of hydrogen atoms, one witnesses a substantial growth in the enrichment factor. At higher temperatures still, the helium ionization mean free path begins to compete and the now increasing helium attenuation causes a turnover in enrichment at $T \approx 25 \text{ eV}$. Note that at this temperature, $\lambda/a \approx 1$. For T_e between 25 eV and 100 eV, helium and hydrogen ionization mean free paths are comparable and the enrichment is increasingly sustained by charge exchange losses of H^0 atoms at the left face.

The smaller value of λ_{ge} compared to λ_e at the highest temperature is the result of the larger mass for helium and the use of the thermal speed for the velocity of helium atoms. As mentioned earlier, the mass effect is conservative (for D^0/T^0 the mean free path would be shorter still) but use of the thermal speed for helium may not be appropriate. Although it is quite reasonable to assume this for H atoms because multiple charge exchange reactions insure destruction of all memory effects, a spread of energy of He^0 atoms at the source will be reflected in the enrichment - higher energy particles will penetrate deeper and thus enhance η but lower energy, wall temperature atoms will have the contrary effect. These effects can realistically be included only in more sophisticated numerical simulations, of the type discussed in the next section.

In sum, the simplified analytical model shows that the plasma acts as an effective screen for hydrogen atoms, and that if exploited in this manner in pump limiters, this plasma effect will lead to significant enrichment factors ($\eta \sim 5$). A question that arises is whether the excessive ionization of

helium might prove detrimental to the absolute exhaust rate for helium. We defer comment on this to the next section as it is best addressed within the context of a specific design configuration.

IV. Helium Enrichment in a Pump Limiter

A. Inverted Limiter and Monte Carlo Simulation

For a review of the numerous experimental tests of the pump limiter concept, we refer the reader to the review by Conn [4] (and references therein) which also contains an exposition on pump limiter analysis and design. For the purposes here, we consider a specific design, namely the early experiment conducted in the MACROTOR tokamak [5] and shown in fig. (1). Except for the throat entrance, which in this case is on the front face of the limiter, this design embodies all the characteristics of an optimized, standard pump limiter, i.e., it has a long throat filled with plasma, and an angled neutralizer plate with an adjacent pumping duct. The long throat prevents neutrals by reionization and charge exchange from escaping back into the plasma while the localized pump duct takes advantage of the enhanced conductance of the energetic neutrals leaving the plate.

As mentioned before, computations indicated that no helium enrichment is possible with these conventional designs. By referring to our arguments of the previous section, this is not surprising. In traversing the distance between the plate and duct opening, neutral atoms are not subjected to sufficient plasma screening. On the contrary, it is most likely the helium preferentially escapes back through the entrance of the limiter leading to the de-enrichment that is occasionally seen in simulations.

One very simple solution to this dilemma is to shift the pump duct to the opposite end of the limiter and collect there, but keeping the neutralization site at its original location. The resulting "inverted" limiter configuration is shown in fig. (2), a design which clearly utilizes the curvature of the toroidal magnetic field to achieve isolation of the neutralization and collection sites. The plasma between these two sites can now be used to screen the hydrogen in the manner that has already been discussed. Depending on the line density and electron temperature, one can expect significant helium enrichment.

The neutralizing plate on the right in fig. (2) has been straightened to direct reflecting neutrals to the opposite end, although the angular spread

will cause neutral collisions with the wall. Although this is inevitable (and even desirable) for hydrogen (because of randomization of direction by charge exchange), one would like the effect to be minimized for helium. At the left receiving end in fig. (2), the angled design for the deflection plate is retained in order to scatter particles (dominantly helium) preferentially into the duct opening. The entrance is now roughly in the mid-section of the limiter which, as we shall see below, proves critical for enrichment because it provides a lateral loss channel for hydrogen atoms.

In an attempt to quantify the merits of the inverted limiter concept for helium enrichment, we have carried out neutral transport simulations using the two-dimensional (2-D) Degas Monte Carlo code [13]. The code physics and particle tracking algorithm are described in detail in ref. [13] and are therefore not reproduced here. The essential features of the code are: tracking four neutral species, H^0 , D^0 , T^0 , He^0 (although we work with H^0 and He^0 ; a host of atomic and molecular processes to describe interactions of these neutrals with the plasma; a wall reflection model from which the neutral energy and angles are sampled, and a sheath at the right deflector plate that accelerates ions before reflecting them as neutrals. No approximation of the ion distribution function is, of course, necessary for the Monte Carlo simulation.

Neutral particles are tracked until they return to the scrape-off plasma through the entrance or transport down the duct and are pumped. An infinite pumping speed is assumed in these calculations, but this should not affect the enrichment. Ionization losses in the plasma are accounted for by weight reduction [13] during the particle history. The plasma is assumed static with a prescribed density and temperature, that is, reionized particles are not allowed to recycle. The code provides the throughput of each species, which in earlier notation is

$$Q_H = \Gamma_H(\text{pump})/\Gamma_H^+ \quad (12)$$

$$Q_{He} = \Gamma_{He}(\text{pump})/\Gamma_{He}^+ \quad (13)$$

and eqn. (1) gives the enrichment as

$$\eta = Q_{He}/Q_H \quad (14)$$

B. Results and Discussion

In Table 2 we compare the enrichment obtained from the Monte Carlo (MC) simulations (η_{MC}) and the theoretical results of the previous calculations (η_a). In the simulation, a constant density of $n_e = 10^{13} \text{ cm}^{-3}$ was used and the dimensions were such that $an_e = 2 \times 10^{14} \text{ cm}^{-2}$.

Except for the low temperature end ($T_e = 5\text{--}10\text{eV}$), the agreement between the Monte Carlo and analytical results is exceptionally good, both in magnitude and trend. The discrepancy can be explained by reference to the ionization (I_H and I_{He}) fractions and the lateral escape ratio, $L (L = I_H/I_\alpha)$, also displayed in Table 2. By lateral escape we refer to losses of neutrals through the entrance. At low temperatures, I_H is about 60% while I_{He} is only 10%.

Although large lateral losses are apparent for both species in the simulations, the relative loss is $L \approx 4$; i.e., significantly more hydrogen escapes through the entrance while more helium goes to the pump duct. As indicated earlier, enhanced lateral loss of hydrogen atoms results from charge exchange of hydrogen, a mechanism that is orders of magnitude less effective for helium. Since such losses cannot be included in a 1-D model, the underestimate of enrichment by the analytical model is not surprising. Note that the use of a vacuum boundary condition in the theoretical model partially simulates the lateral loss effect, but not to the same magnitude.

At higher temperature, the ionization fraction dominates over the lateral loss, and although the latter is still relatively large for hydrogen ($L \sim 3$), it is the large difference in ionization rates that is responsible for the high enrichment for $T_e = 15\text{--}30\text{eV}$. This is entirely consistent with the predictions of the analytical model. For $T_e > 30\text{eV}$ the helium ionization rate becomes comparable to the hydrogen rate and once again, it is the large lateral loss of hydrogen atoms that sustains the enrichment at $\eta \approx 3\text{--}4$, also predicted by theory.

These values of enrichment, ($\eta \approx 3\text{--}7$) are to be compared with $\eta < 1$ to $\eta \sim 1.2$ obtained for conventional designs. Furthermore, the inverted limiter results scale exponentially with density (verified by Monte Carlo simulations to $n_e = 5 \times 10^{13} \text{ cm}^{-3}$) and there is clearly room for optimization. For instance, lateral losses of helium can be reduced by increasing the thickness of the limiter so as to minimize neutral wall intersections. Charge exchange will continue to sustain large H^0 lateral losses.

One apparent shortcoming of this approach is the low throughput for the helium species. As mentioned earlier, the general objective in a burning plasma is to extract about 10% of the particle flux to the edge. The entrance width of the limiter is determined to satisfy this plasma intake requirement. However, once neutralized, significant ionization losses occur except at very low temperatures. Fig. (3) shows the variation in throughput for each specie as a function of electron temperature. The hydrogen throughput, Γ_H (pump) is consistently low (<10%) but Γ_{He} (pump) varies sharply from 40% at $T_e = 5\text{eV}$ to about 10% at $T_e = 30\text{eV}$. Thus, less than half the desired helium exhaust is achieved. The situation may be remedied, however, if we note the following:

- (i) The plasma intake is variable by adjusting the entrance width.
- (ii) The reionized neutrals will recycle from the plate and thus have multiple attempts at being pumped (or lost laterally). If γ is the probability that an ionized neutral returns to the plate rather than to the main plasma, then, very approximately, one can expect the throughput to go up to $Q/(1-\gamma)$. If the γ values are approximately the same for both species, the enrichment will not be affected.
- (iii) Neutral recycling will cool the edge plasma significantly and raise the density. Thus, it is conceivable that operating conditions of $T_e = 5-10\text{eV}$ and $n_e \gtrsim 10^{13}\text{ cm}^{-3}$ are achievable.

Finally we note by virtue of its simplicity that the scheme lends itself readily to experimental testing on existing tokamaks. Indeed, given the central role of helium enrichment in particle removal experiments such a test is clearly vital. Perhaps the most substantial gain from this experiment would be a much needed normalization of the theoretical and computational models used for predicting edge plasma conditions. This includes assessing the accuracy of atomic and surface physics data contained in the codes. The magnitude of the effect is large enough to clearly fall outside the range of experimental error.

V. Conclusions

In conclusion, we have demonstrated that inverting or rotating by 180° a conventional pumped limiter [5], a new design yielding enrichment factors of 5-7 under reasonable edge conditions ($T_e = 5-30\text{eV}$, $n_e = 10^{13}\text{cm}^{-3}$) is realized.

The substantial He^0 compression is possible because the neutralized H^0 and He^0 neutrals are made to traverse a thickness of plasma before collection. In the process, the H^0 atoms are preferentially screened out. The essential physics responsible for this effect lies in the difference in electron impact ionization rates between H^0 and He^0 and in the charge exchange cross section of H^0 . The latter process tends to randomize the H^0 atoms which eventually enhances losses to the main plasma at open boundaries.

Although the absolute throughput of H^0 is curtailed, the flexibility offered by the limiter design may permit one to compensate by increasing the plasma intake. In any case, an experiment based upon the theory and design suggested here will provide a sensitive test of plasma edge models and of the atomic and surface physics data used in these models.

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T(ev)	λ_{ai} (cm)	λ_{cx} (cm)	λ_e (cm)	λ_t (cm)	η
5	1736	10 229	9.6	1.6	
10	136	11.3	53	9.3	4.3
15	54	11.9	32	8.7	6.01
20	41	12.7	29	8.8	6.32
25	32	13.1	26	8.7	6.78
30	26	13.6	24	8.7	6.56
50	21	15.2	25.5	9.5	4.68
100	20	17.6	31	11.2	3.07

Table 1: Enrichment factor (η) and hydrogen and helium mean free paths (λ_{cx} , λ_e and λ_t are, respectively, the charge exchange, ionization and total mean free paths of hydrogen, and λ_{ae} the helium ionization mean free path) as a function of temperature.

T(ev)	$Q_H(\%)$		$I_H(\%)$	$Q_{He}(\%)$		$I_{He}(\%)$	$L = L_H/L_{He}$	η_{MC}	η_a
5	8.0	55.0	40.0		8.2	3.6	5.1	1.6	
10	3.6		22.3			6.3	4.3		
15	2.3	87.5	15.0		66.3	3.5	6.5	6.01	
20	1.9	90.0	12.2		72.6	3.45	6.42	6.32	
30	1.7		9.4			3.5	6.56		
50	1.5	92.7	7.0		83.7	2.8	4.4	4.68	
100	1.7	92.8	5.0		87.7	2.2	2.9	3.07	

Table 2: Hydrogen and helium throughputs (Q), ionization fractions (I), lateral loss ratio (L) and the Monte Carlo (η_{MC}) and analytic (η_a) enrichment factors, as a function of temperature.

FIGURE CAPTIONS

Figure 1: Geometry for Monte Carlo simulation of conventional pump limiter.

Figure 2: Geometry for inverted pump limiter used in Monte Carlo simulation.

Figure 3: Enrichment factor and hydrogen and helium through-puts versus temperature from Monte Carlo simulation of inverted pump limiter.