A PROPOSED METHOD FOR REDUCING THE
STICKING CONSTANT IN MUON CATALYZED FUSION

DE88 015822

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ABSTRACT

We present a method of reducing the effective sticking coefficient involving reacceleration of the Heu ion-by-ion cyclotron resonance. It is necessary to work with the target D-T in solid or liquid form, and the target has to be divided into many thin rods or pellets of order 100 microns in radius. The idea is to impose a magnetic field and a rotating electric field. A balance is achieved between drag in the rods or pellets and acceleration in the region between, so that the Heu ion is held at a constant velocity until stripping occurs. Although stripping is greatly reduced, the idea is not practical as it stands because of the large alpha particle heat produced in the target.

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A liberal estimate of the minimum numbers for χ , the fusions per muon necessary for pure fusion in D-T muon catalyzed fusion (MCF), is obtained by taking 20 MeV/fusion, an efficiency of conversion of neutron heat to electricity of 40%, an accelerator efficiency of 80%, a beam cost of 2.5 GeV/muon, and a recycling of power for production of the muon of 50%. These numbers lead to a requirement that $\chi > 780$. It is clear that this is a very generous lower limit.

On the other hand, the standard formula for χ is

$$\chi = \frac{1}{\lambda_0/\lambda_c + \omega_S} < \frac{1}{\omega_S} , \quad (1)$$

where $\lambda_0 = 0.455 \times 10^{-6} \text{s}^{-1}$ is the decay rate of the muon, λ_c is the cycling rate, and ω_S^{eff} is the effective sticking parameter allowing for reactivation. Experimental and theoretical values are converging on a sticking value that is, with certain exceptions, greater than 0.3%.¹ The upper limit on χ is 333, at least a factor of two below the limit indicated above.

Thus, to make MCF practical it seems necessary to either reduce the cost of the muon or to reduce the effective sticking coefficient ω_S^{eff} . A possible method to accomplish the latter involves enhancing the reactivation coefficient R:

$$\omega_S^{\text{eff}} = \omega_S^0 \exp(-R) , \quad (2)$$

where ω_S^0 is the initial sticking probability and R is the accumulated probability for stripping, or reactivation of the muon from the $\text{He}\mu^+$, muonic ion. The $\text{He}\mu^+$ ion resulting from a sticking event initially moves rapidly

with an energy of $\epsilon_0 = 3.5$ MeV and velocity $v_0 = 1.3 \times 10^9$ cm/s. There is, consequently, a finite probability of either ionization by collision with target molecules or of charge transfer, thus freeing the muon for more fusions. The probability of this happening by the time that the Heu ion slows down to zero is between 30 and 40 percent depending on density.¹ By an inspection of Ref. 2, one finds that

$$\frac{dR}{d\epsilon} \approx 0.1/\text{MeV} \quad , \quad (3)$$

where the derivative is with respect to the drag energy lost in slowing down.

The idea described in this paper is to compensate the drag by an accelerating electric field so that the Heu is made to move at 3.5 MeV until stripping occurs. The stopping power in a D-T target at liquid hydrogen densities (LHD) is

$$\left(\frac{d\epsilon}{dx}\right)_{\text{drag}} \approx 45 \text{ MeV/cm} \frac{\epsilon_0}{\epsilon} \quad . \quad (4)$$

Consequently, this method is impractical in a high density target because an electric field of the same magnitude is needed. However, if the target is filamented into many fine rods of radius a (see Fig. 1) with a small filling factor f , then it is possible to extract the Heu ion from these target rods, accelerate it in a vacuum region between the rods, making up for any energy lost in the rods, and to keep the Heu ion at a constant velocity. Thus, a Heu ion passes through many filaments so that a balance between acceleration and drag is achieved.

For this purpose there are two requirements:

First, the rods of target material cannot be gaseous D-T since the very

high densities needed for rapid recycling would have to be at high pressure and have to be confined by a thick wall. This wall would necessarily stop the Heu ion before it could reach the vacuum region to be reaccelerated. This means the target D-T material must be in liquid or solid form and thus at a low temperature $\leq 25^\circ\text{K}$. It must be quite thin since the average path length for a Heu to leave the rod starting at a random position and moving in a random direction is approximately a . Combining this with Eq. (4) we see that for $a \approx 100$ microns the mean loss is $1/2$ MeV.

The second requirement is a strong magnetic field B parallel to the rod axes and of order 5-10 tesla to keep the Heu ion in the target area. Further, the accelerating electric field E is required to rotate at the gyration frequency of the Heu ion to keep the ion energized against the drag. If we treat the loss per passage through a single rod as small, the perpendicular motion of the Heu ion is approximated by

$$\frac{d\mathbf{v}}{dt} = \frac{e}{m_{\text{He}}} \mathbf{E}(t) + \mathbf{v} \times \mathbf{\Omega} - \alpha \mathbf{v} \quad , \quad (5)$$

where α is the mean drag coefficient, $\mathbf{\Omega} = eB/m_{\text{Heu}}c$, and

$$\mathbf{E}(t) = E_0 [\cos(\Omega t + \phi) \hat{x} + \sin(\Omega t + \phi) \hat{y}] \quad (6)$$

with $\hat{x}$ and $\hat{y}$ the cartesian unit vectors perpendicular to the cylinder axes. Since the fractional change in energy going through a rod is small, we approximate the discontinuous drag of the discrete rod by a smoothed out average drag force.

The initial velocity in the x,y plane ranges between 0 and v_0 , depending on the initial direction of motion relative to the cylinder axes. For

illustration purposes we consider only the case that $v = v_0$. By axisymmetry we may assume $\underline{v} = v_0 \hat{x}$ initially.

Orbits are shown in Figs. 2a - 2d for various choices of α and ϕ . If $\phi < 90^\circ$, the acceleration of the ion by the electric field is clear. The case $\phi > 90^\circ$ would seem to lead to deceleration. However for all except $\phi \approx 180^\circ$, phase stabilization rapidly occurs and v remains near v_0 after several gyrations. Phase stabilization is discussed in the appendix.

The velocity dependent drag coefficient α is given by

$$\frac{dv}{dt} = -\alpha v = \frac{1}{m_+ v_0} \left(\frac{d\epsilon}{dx} \right)_0 \left(\frac{v_0}{v} \right)^3 v, \quad (7)$$

where m_+ is the mass of the Heu ion, and $(d\epsilon/dx)_0$ is the stopping power at the velocity v_0 .

Because of the randomness of the phases at the time of emissions and the distribution of initial velocities of the Heu ion perpendicular to the rod axes, the ions should be treated by a kinetic theory that also includes the distribution of R values. However, as a much simplified theory seems to represent the situation fairly well, we restrict ourselves to this simplified theory. This enables us to make estimates of the field strengths and filling factors necessary for an effective reduction of the sticking process.

We assume that ϕ , the initial phase, is zero and estimate the velocity necessary to keep the Heu ion at v_0 . We ignore any ions with velocity components along the rod. If the phase is different, a somewhat larger electric field is necessary. The size of this field relative to the zero phase field is given in Table 1. An additional complication is the velocity dependence of the drag. If the electric field is slightly too large for balance, the ion will accelerate and the drag will decrease leading to a

greater imbalance and further acceleration. Similarly, for a slightly weaker field the particle will systematically decrease. Fortunately, this instability is not very fast and the ion can be kept near its initial velocity until stripping occurs. This effect is of substantial importance if one includes the variation possible in the initial perpendicular velocity. Only an accurate kinetic treatment of this problem will establish the viability of the stripping theory, but a rough treatment seems to show that this effect is not really serious. For this note we ignore these important complications.

Let us assume that we keep the Heu ion at a constant velocity v_0 . Then from Eq. (3) R will increase with time. Combining with the probability that the particle remains unstripped, $\exp -R$, we conclude that the mean time for stripping is that time when the Heu⁺ has suffered a drag energy of 10 MeV. During the same time the ion has gained an energy 10 MeV from the electric field. Hence,

$$eE_+ = \frac{10 \text{ MeV}}{(v_0 t_+)} = \frac{7.7 \text{ V/cm}}{t_+ (\mu\text{s})} \quad , \quad (8)$$

where t_+ is the mean stripping time in microseconds.

In the proposed scheme there will be several large cycles for the muon. First, it will generate an average of $x_0 = (\omega_s^0)^{-1}$ fusions before sticking. This will take a time of $1/(\omega_s^0 \lambda_0)$. Next it will enter the acceleration phase and spend a time t_+ as a Heu ion before being stripped. The large cycle will be repeated a number of times and the mean big cycling rate is thus

$$A_c = \frac{1}{t_+ + 1/\omega_s^0 \lambda_0} \quad .$$

There is a finite probability W that the Heu will slow to zero or escape to

the outer wall and avoid stripping during the acceleration phase. (This loss arises from particles with initial $\phi \approx 180$ and we estimate W as 10%.) Thus, the total number of fusions becomes

$$\Xi = \frac{1}{\omega_s^0} \left(\frac{1}{W + \lambda_o/\lambda_c} \right) = \frac{1}{\omega_s^0 (W + \lambda_o t_+) + \lambda_o/\lambda_c} .$$

On comparison with Eq. (1) we see the effective sticking probability is reduced to

$$\eta_s^{eff} = \omega_s^0 (W + \lambda_o t_+) .$$

Note that the initial sticking enters so to improve on the ω_s^{eff} in ordinary targets, needing $W + \lambda_o t_+ < (1-R) \approx 0.7$.

The filling factor is determined by t_+ since the Heu ion goes a distance $v_o t_+$. The stopping power at 3.5 MeV is about 45 MeV/cm in the rods so an average thickness of $10/45 = 0.22$ cm of rod material must be transversed. Thus,

$$f = \frac{\pi a^2}{D^2} = \frac{0.22}{v_o t_+} = \frac{1}{5900 t_+ (\mu s)}$$

and the rod spacing D is

$$D = 136 \sqrt{t_+ (\mu s)} a \approx 1.4 \sqrt{t_+ (\mu s)} \text{ cm} ,$$

with the last figure corresponding to $a \approx 0.01$ cm.

By way of illustration we assume $\omega_s^0 = 0.5\%$, $\lambda_o = 500 \times 10^6/\text{sec}$, $W = 0.1$ and list in Table 2 the values of the effective study coefficient η_s^{eff} , the

number of fusions Ξ , the necessary electric field E_+ , the reciprocal filling factor $1/f$, and the interrod spacing for various values of t_+ . The last column, for B_{++} , will be discussed presently.

It is seen that rather large but still achievable electric fields can lead to a substantial reduction of ω_{eff} . For the cycling rate chosen in this illustration $\lambda_0 = 500/\mu\text{sec}$, the number of fusions per muon can approach 1000.

The magnetic field B has not yet been determined. The electric field is independent of it provided that several gyrations of the Heu ion occur during the stripping time. However, B does set a lower limit of the total target area. Clearly, its diameter must be considerably bigger than twice the gyration radius of the Heu ion, ρ_+ , which is given by

$$2\rho_+ = \frac{52}{B_{\text{Tesla}}} .$$

This in turn sets the total voltage V_+ in the rotating electric field equal to $2\rho_+ E_+$.

There is a very important drawback to this scheme and any other scheme of power production at very low temperatures. This is presented by the He^{++} 3.5 MeV/fusion energy Q_1 delivered to the target. The minimum work per fusion w_1 to remove this energy is given by Carnot efficiency. That is,

$$w_1 = \frac{T_0 - T_1}{T_1} Q_1 ,$$

where T_1 is the temperature of the target and T_0 is the room temperature to which this energy must be removed. Taking $T_1 = 25^\circ\text{K}$ and $T_0 = 280^\circ\text{K}$, we get

$$w_1 = 35.7 \text{ MeV/fusion}$$

Clearly, this exceeds the 14.6 MeV fusion energy of the neutrons.

There are several schemes to overcome this difficulty. One such scheme has been suggested by E. Valeo and P. Kaw. It involves choosing the rod radii so small that the He^{++} ion can leave the rod without appreciable loss of fusion energy, and filling the interrod region with gas. If $a \approx 0.006 \text{ cm}$, the mean loss is 1 MeV/ He^{++} . Second, choose the magnetic field $B_{\perp}$ large enough so that the He^{++} gyro-orbit is smaller than $D/2$ so that the He^{++} ion cannot reach the neighboring rod. As a result the residual He^{++} energy is lost to the gas and can be removed at a reasonable temperature. Unfortunately, the magnetic fields required to satisfy this condition are very large. They are given in the last column of Table 2.

In conclusion, it appears technically possible to reduce the effective sticking coefficient by an arbitrarily large factor by working with a filamented solid or liquid D-T target. However, associated with this method is the serious problem of the removal of the 3.5 MeV He^{++} fusion energy at very low temperatures. This problem must somehow be resolved to make the scheme viable.

I should like to acknowledge useful discussions with a large number of people who have been very helpful with criticisms and helpful suggestions. Particularly important have been those with M. Rosenbluth, H. Furth, S. Cowley, S. Jones, T. Tajira, S. Eliezer, D. Jassby, and S. Cohen. Y.C. Sun has participated fully over several years in resolving the numerical situation and carrying out calculations. This work was performed under the auspices of U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

Appendix - Phase Stabilization

The equation of motion Eq. (5) of the Heu ion in the frame rotating at the gyration frequency is

$$\frac{d\mathbf{v}}{dt} = \frac{e}{m_{\text{Heu}}} \mathbf{E} - \alpha \frac{v_0^2}{v^3} \mathbf{v}, \quad (\text{A-1})$$

where $\mathbf{E}$ is a constant vector. The initial angle between $\mathbf{v}$ and $\mathbf{E}$ is ϕ . If $\phi < 90^\circ$ (Fig. 3a), $\mathbf{v}$ will be accelerated along $\mathbf{E}$. For $\alpha = 0$ one gets the dashed line. With drag it becomes the dotted line and converges towards the mean velocity discussed in the text. If $\phi > 90^\circ$ (Fig. 3b), the ion is again accelerated along $\mathbf{E}$. At first deceleration occurs and then reacceleration occurs with convergence towards the same mean velocity.

Because the mean balance point P_0 at $v = v_0 (\alpha m/eE)^{1/2}$ is an unstable point of Eq. (A-1), it is impossible to converge exactly to this point for all ϕ and fixed E . Those with ϕ near 180° approach P_0 and then decrease to the origin. Those ϕ near 0° pass P_0 and accelerate to infinite velocity. However, if the times are longer than the normal slowing down time, nearly complete stripping is possible. These details are not included in the simple treatment in the text, which merely presents the idea and rough estimate for the mean stripping of the required electric field. A more complete kinetic treatment will be presented in another paper.

References

- ¹ S.E. Jones, Nature 321, 127 (1986).
- ² J.S. Cohen, Phys. Rev. Lett. 58, 1407 (1987).

Table 1

<u>ϕ</u>	<u>$E/E(\phi=0)$</u>
0°	1
30°	1.1
45°	1.2
60°	1.34
90°	2.0
120°	4.0
135°	6.8

Table 2

$t_+(\mu s)$	α_s^{eff}	Ξ	$E_+(V/cm)$	$1/f$	$D(cm)$	$B_{++}(tesla)$
0.5	0.16	398	15.4	2950	1.0	160
0.4	0.14	432	19.2	2360	0.88	178
0.3	0.12	474	25.7	1770	0.77	206
0.2	0.10	534	38.5	1180	0.63	252
0.1	0.07	621	77.0	590	0.44	357

Figure Captions

Fig. 1 The D-T target is filamented into many fine rods. A B field is imposed parallel to the rod axes. There is an electric field rotating at the gyroperiod of the Heu ion perpendicular to B . A Heu ion is shown leaving one rod and passing through another rod.

Fig. 2a-2d Orbits of the Heu ion in velocity space. (2a) $\phi=45^\circ$ and the electric field is such that deceleration occurs. (2b) $\phi=45^\circ$ and acceleration occurs. (2c) $\phi=120^\circ$ and deceleration occurs. (2d) $\phi=120^\circ$ and acceleration occurs.

Fig. 3 Velocity orbits in the rotating frame.

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DT TARGET RODS

Fig. 1

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2

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ROTATING FRAME

(a)

(b)

Fig. 3

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