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THE BEAM-TARGET INTERACTION IN HEAVY ION FUSION*

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Abstract

The beam-target interaction in heavy ion fusion is theoretically understood, but experimental verification at appropriate beam intensities is not possible using existing accelerators. If fusion-intensity ion beams were to lose significantly less energy in passing through matter than calculated it would increase the cost of heavy ion fusion. In the worst case the cost scaling is such that a 25% decrease in energy loss would increase the cost of the accelerator by roughly 10%. In this paper we show that fundamental considerations place a lower bound on ion energy loss. The lower bound is not significantly less than the expected energy loss obtained from detailed calculations.

The beam-target interaction in laser fusion has proved to be a very challenging problem. It is therefore natural to be concerned about the beam-target interaction in heavy ion fusion. Much of this concern seems to arise from the feeling that a beam capable of target ignition is in some sense "intense" and thus qualitatively different than the low-intensity beams with which we are familiar in nuclear science. Intensity must of course be quantified and by several measures heavy ion fusion beams are not truly intense. For example, we will show that for typical target and beam parameters the electron density in the target is roughly nine orders of magnitude larger than the density of beam ions. Furthermore there are about 1000 Debye lengths between beam ions in the target so that one might expect the beam ions to behave independently. These statements are simply a manifestation of the fact that for heavy ion fusion each beam particle carries a large energy (~ 10 GeV). This can be contrasted with light ion (proton) or electron beam fusion where the expected particle energy is 1 - 10 MeV or with laser fusion where each photon carries an energy of about 1 eV.

However, there are some ways in which heavy ion beams must be considered intense. Collective effects are important in the propagation of the beam in

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the accelerator and through the combustion chamber to the target. This is discussed extensively in other sections of this workshop report.

There are two classes of ion beam physics that must be considered: nuclear and electromagnetic. Recent accelerator design effort has been directed toward accelerating heavy ions to a maximum energy of about 20 GeV. At this energy the calculated range of a heavy ion is much less than a nuclear collision length so that only a small fraction of the incident ions will produce nuclear reactions.[1] Furthermore, nuclear processes are unaffected by the state of matter in the target so that measurements of cross sections with low intensity beams are directly applicable. The only area of conceivable uncertainty involves electromagnetic phenomena.

The electromagnetic interaction of low intensity ion beams with ordinary matter has been reasonably well understood for about 60 years. The calculated energy loss of heavy ions in matter (or range) is in excellent agreement with experiments.[2,3] However, experiments with heavy ion beams at the appropriate energies, intensities and matter temperatures have never been performed. Some additional relevant experiments might be performed at existing heavy ion accelerators, but it has not yet been possible to attain fusion-intensity beams. The continuing experiments in light ion fusion are also relevant to heavy ion energy deposition and may provide early verification of ion stopping predictions in hot matter.

In order to achieve fusion conditions, it is necessary to deposit $\gtrsim 2 \times 10^7$ J/g in the target.[4] Thus for a given target size, less total energy is required if the range of the incident ions is short. On the other hand, there are significant accelerator design considerations that push one in the direction of high ion kinetic energy and therefore long range. Any anomalous effect that shortened the range of the ion would be welcome. Conversely, if the range of the ions were significantly larger than calculated it would increase the cost of the heavy ion accelerator. The estimates presented at this workshop show accelerator costs increasing as (output energy)$^{\sim 0.4}$. Thus if the range were 25% too long, one could compensate by increasing the output energy by 25% to achieve $\gtrsim 2 \times 10^7$ J/g. This would increase the cost of the accelerator by about 10%. This represents the worst case since it might be possible to redesign the target or accelerator to reduce the cost penalty. Fortunately, fundamental physical arguments indicate that the range will not be significantly larger than calculated.

As an ion passes through matter, it transfers energy to the ions and electrons in the matter through binary Coulomb collisions. It may also lose energy through excitation of plasma waves or other collective processes.[5] In the following considerations, we will place an upper limit on the range of ions by making the pessimistic assumption that only binary Coulomb collisions with electrons contribute to the energy loss. As a by-product we will also obtain an expression for the spectrum of the energetic electrons produced by an ion beam and discuss preheat.

The cross section for scattering of electrons by ions with charge Z_e is given by the well-known Mott cross section

$$\frac{d\sigma}{d\Omega} = \frac{Z^2e^4}{4p^2v^2\sin^4\left(\frac{\theta}{2}\right)}\left[1 - \frac{v^2}{c^2}\sin^2\frac{\theta}{2}\right] ,$$

where p is the three-momentum of the incident particle, v is its velocity, θ is the scattering angle, and c is the speed of light. Assuming that the electron is initially at rest (or moving slowly), it is convenient to express this cross section in terms of the final kinetic energy of the electron in the laboratory, $T = mc^2\beta^2\gamma^2(1 - \cos\theta)$ where m is the electron mass, βc is the ion velocity, and, as usual, $\gamma = (1 - \beta^2)^{-1/2}$. Making the transformation of variables, we obtain

$$\frac{d\sigma}{dT} = \frac{2\pi Z^2e^4}{mc^2\beta^2} \quad \frac{1}{T^2} - \left[\frac{1}{2mc^2\gamma^2T}\right] .$$

Note that the maximum electron kinetic energy, T_{max}, is given by setting $\cos\theta = -1$ so that $T_{max} = 2mc^2\beta^2\gamma^2$. For nonrelativistic ions, $2mc^2\gamma^2T \gg T^2$ so that the electron spectrum produced by nonrelativistic ions is given by $d\sigma/dT \propto 1/T^2$. As usual, this diverges as $T \to 0$, corresponding to an infinite impact parameter, and it is necessary to impose some T_{min}. Physically, T_{min} is determined by atomic binding energies or Debye screening, depending on the state of the stopping medium. In addition to the electrons having the $1/T^2$ spectrum, there can also be a component associated with the incident ion if it is not fully stripped when it hits the targets. Since these electrons have about the same velocity as the incident ion, their kinetic energy is down by the ratio of the sum of their masses to the ion mass. Thus they contain only a negligible fraction of the beam energy and can be ignored.

Using the electron spectrum we have performed detailed Monte Carlo calculations of target preheat. These calculations are somewhat dependent on specific target designs and beam energies, but indicate that electron preheat is not a problem.

We now return to the question of energy loss. The energy loss of an ion per unit length is calculated by integrating $d\sigma/dT$ between T_{min} and T_{max} yielding,

$$dE/dx \propto \frac{Z_{eff}^2}{\beta^2}\left[\ln(T_{max}/T_{min})-\beta^2\right] .$$

Note that we have replaced Z^2 by Z_{eff}^2 since the ion may not be fully stripped.

In order to obtain values for the parameters in this expression, we consider typical beam and target conditions. In particular, we will assume that a 10^{14} watt, 20 GeV heavy ion beam ($A \sim 200$) is incident on a target having an electron density of $n_e \sim 10^{23}/cm^3$ ($\sim$ solid density) at a temperature of 200 eV. The beam radius is assumed to be $\gtrsim 1$ mm. With these values, the ion density in the beam is given by $n_b \lesssim 2 \times 10^{14}/cm^3$. The

Debye length is $\lambda_D \sim 3 \times 10^{-8}$ cm and the thermal speed of the target electrons is $\beta_e \sim 0.03$. For the typical speed of an incident ion, we take the value after it has lost one half of its initial energy, obtaining $\beta \sim 0.3$.

It has been experimentally established that Z_{eff} is a function of ion velocity.[6,7] As one might expect, an ion is stripped to the point that the orbital velocities of the remaining electrons are greater than or equal to the velocity of the ion. Brown and Moak[7] find that the experimental data for a variety of projectiles and targets are well approximated by $Z_{eff}/Z = 1 - 1.034 \exp(-137\beta/Z^{0.69})$. Thus for $\beta \geqslant 0.3$ even heavy ions are more than 80% ionized and the dependence of Z_{eff} on β has become quite weak. Although the experiments have been performed in cold matter, the fact that Z_{eff} depends only on β and not on other target characteristics implies that in the plasma case Z_{eff} will depend on the relative velocity of the ion with respect to the target particles. In our case β is an order of magnitude larger than β_e which is in turn 2 or 3 orders of magnitude larger than the thermal velocity of the target ions so that temperature effects on Z_{eff} should be small. In fact, in the limiting case where $\beta \ll \beta_e$, Z_{eff} is increased relative to cold matter by thermal ionization.

In obtaining dE/dx, we should also integrate over the appropriate thermal electron distribution. It can be shown that this is important only for $\beta \lesssim \beta_e$.[8]

For $\beta = 0.3$, T_{max} is about 100 keV. In a plasma the electric field of the incident ion is expected to be screened at distances larger than λ_D. Thus, for free electrons, T_{min} is determined by setting the impact parameter equal to a Debye length. In this case,[5]

$$T_{min} = \frac{2Z_{eff}^2 e^4}{mc^2 \beta^2 \lambda_D^2} \lesssim 10^{-2} \text{ kev} .$$

Since $n_e \sim 10^{23}/\text{cm}^3$ and $\lambda_D \sim 3 \times 10^{-8}$ cm there are only a few electrons in λ_D^3. For this reason collisions with impact parameters less than λ_D must be unscreened binary collisions. We can ignore β^2 compared to $\ell n(T_{max}/T_{min})$ since $T_{max}/T_{min} \gtrsim 10^4$. The energy loss due to plasma excitation at impact parameters larger than λ_D has been calculated by Jackson.[5] The net effect of this additional loss is equivalent to multiplying T_{max}/T_{min} by $[1.123\beta c/\omega_p\lambda_D]^2$ where ω_p is the plasma frequency. For our assumed conditions this increases the value of T_{max}/T_{min} by a factor of 290. Thus even in the worst case where $T_{max} = 10^4$, binary collisions alone account for $\ell n(10^4)/\ell n(290 \times 10^4) = 62\%$ of the total dE/dx. This represents a minimum energy loss rate that is independent of a detailed understanding of plasma physics.

Our ability to calculate this minimum energy loss rate depends on only three obvious or well-tested assumptions:

1. Validity of the Mott cross section.

2. Weak dependence of Z_{eff} on target conditions for relevant beam and target parameters.
3. Binary nature of collisions for impact parameters less than a Debye length (especially since there are only a few electrons per λ_D^3.).

Since the ions must lose energy through binary collisions that account for most of the energy loss, the only way the range can be significantly longer than calculated is for some mechanism to exist that accelerates the ions. To compete with the binary collisions, the accelerating field would have to add $\sim$ 20 GeV to a heavy ion in about 1 cm (range $\sim$ 1 g/cm^2 $\Rightarrow$1 cm at density = 1 g/cm^3). Assuming $Z_{eff} \lesssim 100$, this would require a minimum electric field of 2×10^8 V/cm over a distance of about 1 cm.

Since the only source of energy is the ion beam this would require a chain of events whereby the ion beam could accelerate itself. In any case 2×10^8 V/cm fields are rather inconceivable. Joule heating results in a power dissipation per unit volume given by E^2/η where E is the electric field and η is the resistivity of the plasma. Following Spitzer[8] we calculate $\eta \sim 10^{-3}$ ohm cm for a high Z plasma and $\eta \sim 10^{-5}$ ohm cm for a low Z plasma. Thus a 2×10^8 V/cm field produces $\gtrsim 10^{19}$ W/cm^3 in a high Z plasma and $\gtrsim 10^{21}$ W/cm^3 in a low Z plasma. Since the total power deposited by the beam is only about 3×10^{15} W/cm^3 the Spitzer resistivity would have to be wrong by more than 3 to 5 orders of magnitude before such fields become energetically possible.

In order to simplify the analysis we have considered only free electrons. For typical conditions high Z targets are only about 40% ionized so that there is also a contribution to dE/dx from bound electrons. Energy transfer to bound electrons is well understood from our experience with ordinary matter,[2,3,5] but two modifications are required in the partially-ionized case. The average binding energy of the electrons is increased and impact parameters greater than λ_D are excluded. Neither of these modifications fundamentally alters the physics of the situation.

If the beam strikes matter at all, it appears that it will stop as predicted. If the beam carried a large amount of momentum, it is conceivable that it could sweep the target material out of its way. Very simple calculations show that the effects of momentum deposition by a heavy ion beam are negligible compared to the thermal pressure developed by energy deposition.

In conclusion, it seems unlikely that fusion-intensity ion beams will have significantly less energy loss than predicted.

Acknowledgments

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References

1. R. Silberberg and C. H. Tsao, Proceedings of the Heavy Ion Fusion Workshop, Brookhaven National Laboratory Report BNL 50769, p. 76

(1977). The calculations in this paper are for 63 GeV bismuth. The formulas can be used with range-energy information to obtain results at 20 GeV. Range-energy information for ions incident on lead is given in reference 4. For low Z targets the range is nearly a factor of two less.

2. G. Tarlé and M. Solarz, Phys. Rev. Lett. 41, 483(1978). This paper reports very small discrepancies between theory and experiment. For the purposes of heavy ion fusion the agreement is excellent.
3. For a review article see L. C. Northcliffe Ann. Rev. Nucl. Sci. 13, 67(1963).
4. R. O. Bangerter, see reference 1, p. 78.
5. J. D. Jackson, Classical Electrodynamics, Chapter 13 (John Wiley and Sons 1962).
6. H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).
7. M. D. Brown and C. D. Moak, Phys. Rev. B 6, 90 (1972).
8. L. Spitzer, Physics of Fully Ionized Gases, Chapter 5 (John Wiley and Sons 1962).