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Moderate Energy Ions for High Energy Density Physics Experiments

by

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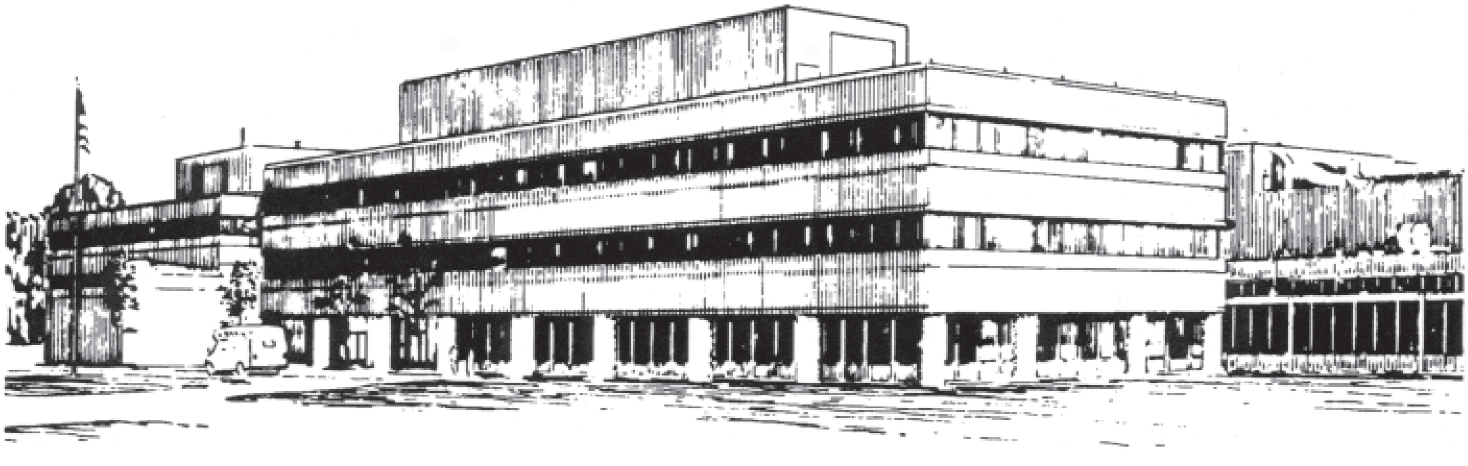

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Moderate energy ions for high energy density physics experiments

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Abstract

This research note gives the results of a preliminary exploration of whether moderate energy ions (approximately 0.3 – 3 MeV/amu) could be useful as modest-cost drivers for high energy density physics experiments. It is found that, if the target thickness is chosen so that the ion beam enters and then leaves the target in the vicinity of the peak of the dE/dX (stopping power) curve, high uniformity of energy deposition may be achievable while also maximizing the amount of energy per beam particle deposited within the target.

High energy density physics (HEDP) studies require deposition of large amounts of energy into a small target volume over an interval shorter than the disassembly time, while maintaining as much uniformity as possible across the full thickness of the target.[1] Compact and modestly priced lasers can supply high power densities[1] to thin targets, but with poor uniformity across the target thickness. Alternatively, large particle accelerators such as those at Gesellschaft fur Schwer Ionenforschung (Heavy Ion Research Group, Darmstadt) or the Relativistic Heavy Ion Collider[1] can provide much more uniform heating across targets of a wide range of thickness using their available beams with energies of hundreds of MeVto many GeV per amu.

This research note describes a scoping study to evaluate what range of parameters might be achievable using ion beams in a moderate cost (and therefore moderate acceleration velocity) facility, such as might be consistent with near-term goals of the heavy ion Fusion program.[2]

Figure 1 (from Ref. 3) shows typical stopping power curves for a wide range of beam ions in aluminum. The general characteristics of the curves are similar to those for a broad range of target elements.[3-6] At high energies dE/dX, the rate of ion energy loss in the target, is slowly varying with energy, but at low energies it rises to much larger values, peaking at progressively lower beam energies and at lower stopping powers as the atomic number of the projectile drops. Throughout most of this range, the stopping power is transferred almost entirely to target electrons. Only at very low energies (typically an order-of-magnitude lower than the peak of the dE/dX curve) does stopping by target nuclei become significant.

The traditional approach to achieving uniformity of energy deposition across the target thickness is to use ions that enter and exit the target with energies much greater than the energy of the dE/dX peak, thereby entirely avoiding the region over which dE/dX changes rapidly with ion energy.

The study described here explores an alternative strategy, which is to pick the target thickness and beam energy such that the ion beam enters the target at an energy near or a little above the dE/dX peak, and leaves the target at an energy which is still within the peak. Since dE^2/dX^2 goes to zero at the peak, this strategy gives the conditions under which both the energy deposited per unit volume by each beam ion and the uniformity of deposition through the target thickness are simultaneously maximized.

The facility assumed for the first iteration of this study is constrained to have a maximum acceleration capability of a megavolt in the extractor/accelerator stage, followed by a compression region with up to an additional megavolt of acceleration to compress a 200 nanosecond pulse to 1 nanosecond. It is also assumed that a plasma lens focuses the beam to a 1 mm radius uniform spot on the target.

The ion source assumptions for proton beams use the current density achieved in the ion sources that operated on the Poloidal Divertor Experiment (PDX) tokamak[7-10] (280 mA/cm^2) multiplied by the grid transparency of 50% and an 85% atomic ion fraction. The slower diatomic and triatomic molecular ions would arrive at the target after the experiment was over. The extractor/accelerator grids are assumed to have a radius of 5 cm (much smaller than the PDX ion sources). For He^{+1} the assumptions are the same, except that the current density is reduced a factor of 2 to approximately adjust for the reduction in perveance due to the larger mass/charge ratio.

For ions heavier than helium, it is assumed that helium-like ions (ions from which all the electrons had been removed except for the last two) are produced in a pulsed ECR source from which, after time-of-flight charge state selection[11], the ions are extracted from a 5 cm radius grid with 50% transparency in pulses of 2.5 x 10^{11} ions.

The results in Tables 1 and 2 use the dE/dX values tabulated in ref. 3. These, along with the other tabulations and measurements[3-6] do not mention the charge state of the incident ion since, even though the stopping power varies with the effective charge state of the ion in the target, charge state equilibrium is rapidly achieved once an ion enters a solid target. Estimates by Kaganovich[12] are that, for example, in aluminum or silver, 1 MeV/amu Ne^{+1} would require about 0.5 micron to reach equilibrium at Ne^{+7}. The tables below do not take account of the initial variation in power deposition while charge state equilibrium is being established, but since the examples considered here are all entering the target at charge states near what their equilibrium is likely to be, the distance to achieve equilibrium is probably shorter than the 0.5 micron estimate. In any event, if an ECR source, which produces a wide range of charge states, were used, the charge state could be selected to be at or near the equilibrium for the target, reducing the equilibration distance to near zero.

The target example used for Tables 1 and 2 is solid titanium, which was chosen as an intermediate mass that would be reasonably typical of a wide range of solid metal targets. Table 1 displays the parameters for a 1 micron thick titanium target, using beams in a facility limited to a maximum acceleration of 2 megavolts (allowing for instance 104 MeV Xe^{+52}). Although the 1 micron thickness represents a relatively small portion of the range for each of these ions, the overall usage of pulse energy is still reasonably efficient because the portion of the range within the target is near the dE/dX peak for several of these examples. The uniformity is tabulated as the difference between the maximum and minimum dE/dX across the target, divided by the minimum. The uniformity is best in a case such as the 16 MeV Ne^{+8} example, where the ion enters the target at an energy just above the dE/dX peak, and leaves with a substantial amount of its potential range still remaining. The helium-like ions heavier than neon need more than 2 megavolts of acceleration capability to reach their dE/dX peaks, and thus their uniformity is degraded. The H^{+} beams achieve uniformity through the conventional approach of entering the target at an energy many times the energy of the dE/dX peak, and exiting the target after traveling a small portion of their potential range and depositing only a small portion of their total energy. The 1 MeV He^{+} beam, which enters the target a little above the dE/dX peak, appears well matched to this 1 micron target example in terms of uniformity and intensity of energy deposition. The accelerated power is listed for these examples, although, since the beam pulses are very short and don’t required significant repetition rates, the cost of an experimental facility would probably scale considerably weaker than linear with the accelerated power.

The energy deposition magnitudes shown for the examples of Table 1 lie within the range of interest for HEDP studies, principally in the region known as warm dense matter[1]. These would produce electron temperatures ranging from about 0.8 – 4.5 x 10^4 K for the examples shown, and hydrodynamic velocities of about 1 – 4 x 10^3 m/s according to estimates by Kaganovich[12]. In these estimates, Kaganovich assumes that all the deposited energy goes into electron kinetic energy, and that the ions are accelerated to the ion sound velocity corresponding to that electron temperature. Since excitation and ionization energies are not included, these are upper limit estimates. These estimates imply that the shock waves could pass through a 1 micron target on timescales of order 0.25 to 0.75 nsec for the examples given, which suggests that the target would begin to disassemble during the 1 nsec pulse assumed for this example. In actuality, the disassembly time for these examples would be considerably longer than these estimates, since the estimated temperatures and hydrodynamic velocities would not be reached until the end of the beam pulse. Nonetheless, since there is a strong advantage in HEDP experiments to having the energy deposited on a timescale shorter than the disassembly time, it appears that either the beam pulse would need to be compressed by an even larger factor to a duration shorter than the 1 nanosecond assumed for this study, or that the target would need to be thicker.

Table 2 shows some sample parameters for thicker solid titanium targets, using the same assumptions as for Table 1, but with the constraint of no more than 2 megavolts of acceleration potential relaxed for neon and krypton (so that, for instance, 7.91 MV of acceleration potential yields 269 MeV Kr^{+34}. This allows reasonable uniformity and deposition intensity for significantly thicker solid targets, which would have proportionally longer hydrodynamic disassembly times.

In an HEDP experiment operating in the regime explored by this study, range-shortening effects as the target became a plasma would modify the values presented in these tables. These effects were not included because there was no way to include them in these simple estimates; much more elaborate calculations with inertial confinement target codes would be required. However, to the extent to which plasma range-shortening effects would occur in an actual experiment, their dominant effect would presumably be to increase the rate of energy transfer while extending the dE/dX peak towards lower beam energies. This could be expected to increase the attainable energy density deposited per unit volume to values somewhat greater than those predicted in this study, while also perhaps making the deposition uniformity even more homogenous than shown in the tables.

The examples in this study all assumed monoenergetic beams. However, since the magnitude of dE/dX is slowly varying with beam energy in the vicinity of the dE/dX peak, moderate amounts of beam energy spread (10 – 15%) would have little affect upon the achievable parameters, so long as the spread did not lengthen the duration of the pulse striking the target.

Under the assumptions used in this study, it appears that a facility using thin targets sized to exploit the peak of the stopping power curve might allow very uniform deposition of energy at intensities useful for HEDP experiments with facilities much smaller in scale than the existing facilities which do HEDP experiments with beams of much higher energies per amu, operating far above the dE/dX peak. Of the examples considered, the ion source technology assumed for the H^+ and He^+ examples is well established, while the ECR source parameters for the other ions have not yet been demonstrated and would require development. Thus, it would appear easier to first try using He^+, and then if that appeared promising, to perhaps attempt the more challenging heavier ions. Developing the degree of pulse compression and focusing assumed for this study would be challenging, but finding the practical limits would benefit technologies suitable for the heavy ion fusion program as well as HEDP research. In any event, it appears that more detailed modeling of this approach would be merited, including exploring other sorts of targets than the simple solids assumed here.

Acknowledgements

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References

[1] R. C. Davidson, D. Arnett, J. Dahlbburg *et al.*, Frontiers in High Energy Density Physics, (The National Academies Press, Washington, D. C., 2003), p. 13-77 .

[2] B. G. Logan, F. Bieniosek, C. M. Celata *et al.*, to be pub. in Proc. of the Int. Conf. On Heavy Ion Fusion, Princeton, 2004, edited by E. P. Lee, H. Qin, A. Molvik (Nucl. Instru. & Methods in Phys. Res. A).

[3] L. C. Northcliffe and R. F. Schilling, Nuclear Data Tables **A7**, 233 (1970).

[4] L. Winsberg, Atomic Data and Nuclear Data Tables **20**, 389 (1977).

[5] J. S. Forster, D. Ward, H. R. Andrews, G. C. Ball, G. Costa, W. Davies, and I. Mitchell, Nuclear Inst. And Methods **136**, 349 (1976).

[6] J. F. Janni, Atomic Data and Nuclear Data Tables **27**, 341 (1982).

[7] M. M. Menon, C. C. Tsai, W. L. Gardner, *et al.*, Proc. of the 8th Symp on Eng. Problems of Fus. Res.,San Francisco, 1979, edited by C. K. McGregor, T. H. Batzer (IEEE Pub. No. 79CH1441-5 NPS, 1979), Vol. 1, p. 656.

[8] Ibid., W. L. Gardner, G. C. Barber, C. W. Blue *et al.*, p. 972.

[9] Ibid., D. A. Everitt, T. J. Huxford, C. C. Tsai, p. 1051.

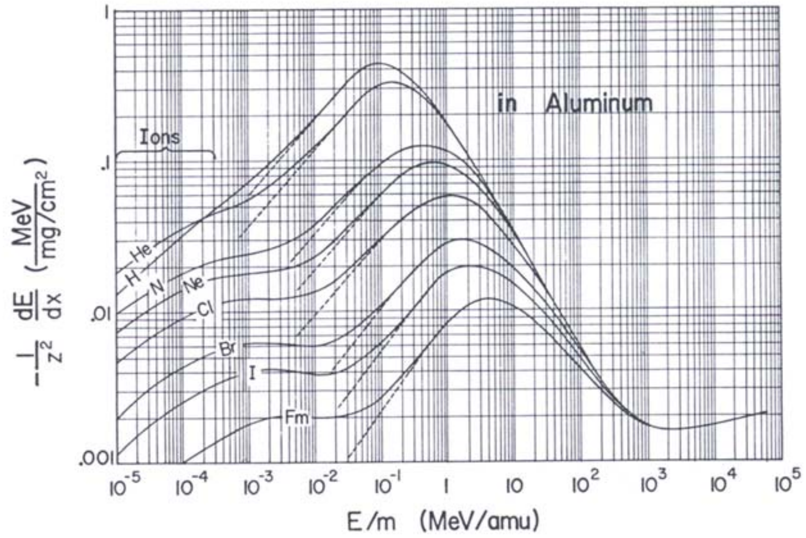
[10] M. M. Menon, Proc. of the IEEE **69,** No. 8, 1012 (1981).

[11] B. G. Logan, private communication (2003).

[12] I. Kaganovich, private communication (2003).

Figure captions

[1] Stopping-power curves for heavy ions in aluminum from Ref. 3. The solid curves are a semiempirical fit to available data. The dashed curves are the electronic contribution at low energies (semitheoretical).


in Aluminum
Ions
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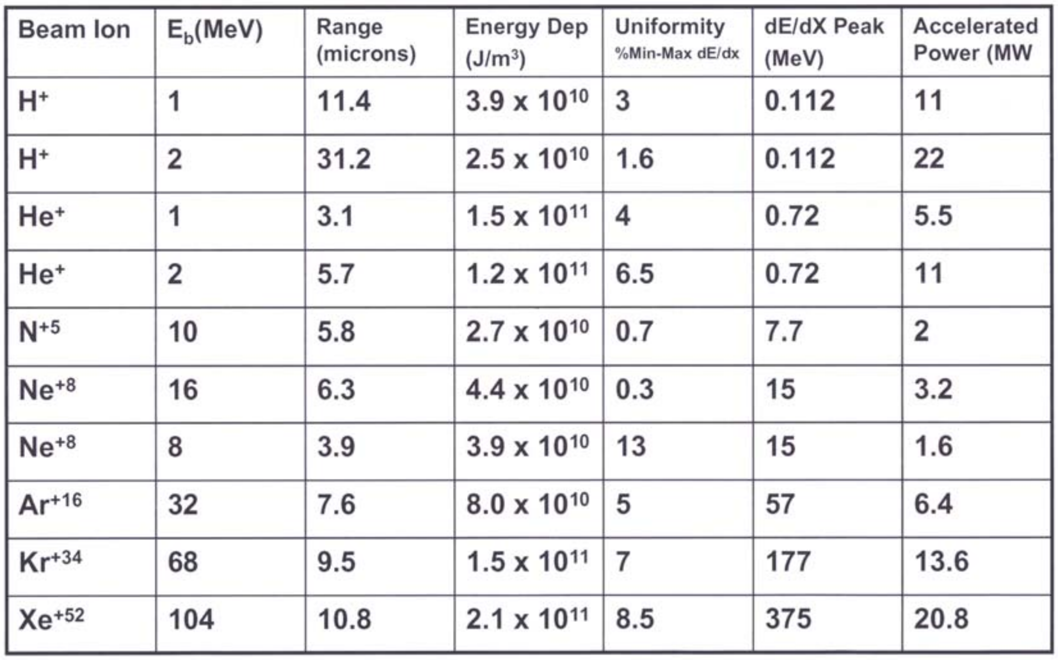
$-\frac{1}{z^2}\frac{dE}{dx}$ ($\frac{MeV}{mg/cm^2}$)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5
E/m (MeV/amu)

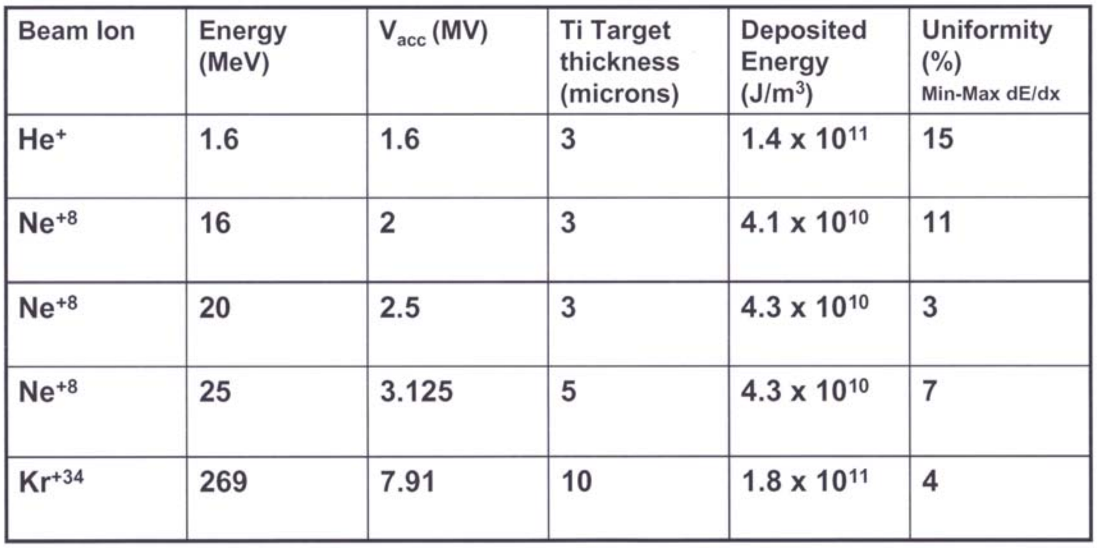
Figure 1

Table I. Energy deposition characteristics for sample beams in a 1 micron thick solid titanium target, for a facility with a maximum acceleration potential of 2 megavolts.



Beam Ion	E_b(MeV)	Range (microns)	Energy Dep (J/m^3)	Uniformity %Min-Max dE/dx	dE/dX Peak (MeV)	Accelerated Power (MW
H^+	1	11.4	3.9×10^{10}	3	0.112	11
H^+	2	31.2	2.5×10^{10}	1.6	0.112	22
He^+	1	3.1	1.5×10^{11}	4	0.72	5.5
He^+	2	5.7	1.2×10^{11}	6.5	0.72	11
N^{+5}	10	5.8	2.7×10^{10}	0.7	7.7	2
Ne^{+8}	16	6.3	4.4×10^{10}	0.3	15	3.2
Ne^{+8}	8	3.9	3.9×10^{10}	13	15	1.6
Ar^{+16}	32	7.6	8.0×10^{10}	5	57	6.4
Kr^{+34}	68	9.5	1.5×10^{11}	7	177	13.6
Xe^{+52}	104	10.8	2.1×10^{11}	8.5	375	20.8

Table II. Energy deposition characteristics for sample beams in thicker solid targets, and with relaxed constraints on the maximum acceleration potential.



Beam Ion	Energy (MeV)	V_{acc} (MV)	Ti Target thickness (microns)	Deposited Energy (J/m^3)	Uniformity (%) Min-Max dE/dx
He^+	1.6	1.6	3	1.4×10^{11}	15
Ne^{+8}	16	2	3	4.1×10^{10}	11
Ne^{+8}	20	2.5	3	4.3×10^{10}	3
Ne^{+8}	25	3.125	5	4.3×10^{10}	7
Kr^{+34}	269	7.91	10	1.8×10^{11}	4

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