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LASER INDUCED ACCELERATION OF METAL FOILS

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ABSTRACT

Small metal foils have been accelerated to velocities of about 10^4 cm sec^{-1} by the action of ruby and CO_2 laser irradiation. The plasma pressures deduced from velocity measurements scale closely with those expected theoretically.

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High speed ballistic injection of D T pellets has been suggested as a possible method of fueling a controlled thermonuclear reactor. Gralnick [1] has shown that a 5000 MW(T) reactor would require 1 mm radius pellets injected at the rate of 85 per second. Velocities of about 10^6 cm sec^{-1} are necessary so that the penetration time is considerably less than the pellet disassembly time. A possible way of achieving such velocities is by laser induced ablation pressure.

Cooper [2] has treated the problem of a slab of D_2 under constant laser irradiation and has derived analytic expressions for the surface mass evaporation rate and the pressure acting on the target due to the hot plasma created. He deduces that the pressure obeys the following scaling, (neglecting a very weak time dependence).

$$P \propto I^{0.75} \lambda^{-0.25} , \qquad \ldots (1)$$

where I is the laser intensity and λ is the radiation wavelength.

On the other hand Puell [3] has produced a one-dimensional model describing the plasma production due to laser irradiation of any solid material. Using his analytic expressions for the plasma density and temperature we deduce that the plasma pressure follows the scaling given by

$$P \propto I^{0.77} \lambda^{-0.22} M^{0.39} Z^{-0.5} \qquad \ldots (2)$$

where M is the atomic weight of the target material and Z is the average charge state of the plasma created. It can be seen that both models predict very similar scalings of pressure with intensity and wavelength.

In this paper we wish to present preliminary measurements of the laser induced acceleration of small metal foils in order to check the above scalings.

The experimental arrangement is shown in Figs.1 and 2. A small piece of metal foil (typically 0.75 mm × 0.75 mm × 25 μm thick) is suspended between two parallel silica fibres mounted on a target holder situated at the centre of a vacuum chamber. The beams from either a 25 MW, 45 ns pulsed TEA CO_2 laser or a 500 MW, 18 ns pulsed ruby laser are focused onto one side of the foil to form a plasma. The plasma ablation pressure causes the foil to detach itself from the mounting fibres and travel in the direction normal to its surface. Foil velocities are determined using a shadowgraph system aligned normally to the foil direction of travel. A 40 MW, 20 ns pulsed ruby laser is used to illuminate the system. By exposing shadowgrams both before and after irradiation of the foil, the final velocity achieved by the foil can be measured. Typical shadowgrams taken before and 24 μs after irradiation of a foil with the ruby laser are shown in Fig.3.

Using 150 μg (25 μm thick) molybdenum foil targets, velocity measurements were made over a large range of laser intensities for both ruby and CO_2 laser irradiation. The velocity measurements (and corresponding momenta) are displayed in Fig.4. For ruby laser irradiation the focal spot diameter was adjusted to be $500\,\mu m$ as it was found that for smaller spot sizes the foils were ruptured by the laser pulse at the highest intensities. No rupturing of the foils occurred under CO_2 laser irradiation (focal spot diameter $275\,\mu m$).

In order to use the velocity measurements shown in Fig.4 to check the theoretical scalings given above, we need to relate the final foil velocity to the plasma pressure. If the target mass evaporated during the laser pulse is small compared to the original target mass then the final foil velocity is given by

$$\frac{vm}{tA} \propto P(\lambda\,,\,I) \qquad \ldots (3)$$

where m is the target mass, A the laser focal spot area and t the time of laser irradiation. For the highest ruby laser intensities used, where the mass evaporation rate is highest, Cooper's theory predicts a mass loss of only $10\,\mu g$. This is small compared to the original mass of $150\,\mu g$ so that the assumption of negligible mass loss is always valid for the results presented here. Hence for irradiation with either laser

$$P(I) \propto v\,. \qquad \ldots (4)$$

The experimental points in Fig.4 can be seen to obey closely a $v \propto P \propto I^{0.75}$ dependence for both ruby and CO_2 laser irradiation as predicted theoretically.

Gregg and Thomas [4] have carried out experiments which agree well with the above results. They have measured the momentum transferred to various target pendula irradiated in vacuum with a ruby laser giving a pulse of length 7.5 ns. For intensities between 10^9 and 3×10^{10} watts cm^{-2} their results show a pressure to intensity scaling of $P \propto I^n$ where n lines between 0.8 and 0.65 depending on the target material.

On the other hand Metz [5], using a Nd glass laser giving a pulse length of 250 psec, has made measurements of the momentum transferred to pendula of graphite and aluminium in vacuum. For intensities between 4×10^9 and 1.2×10^{10} watts cm^{-2} his results indicate $P \propto I^n$ where n lies between 3 and 4. These results are in conflict with those presented in this paper. Hora [6] has attempted to explain Metz's high value of index n in terms of the generation of strong ponderomotive force effects, leading to enhanced momentum transfer, at high laser intensities (> 10^{14} watts cm^{-2}). Unfortunately Hora has misquoted the laser intensities involved which are in fact far too low for such nonlinear effects to be important.

The scaling of the plasma pressure with laser wavelength can be checked by calculating the ratio $(v/tA)_{Ruby} / (v/tA)_{CO_2} \propto \frac{P(ruby)}{P_{(CO_2)}}$ for identical laser intensities. This gives a wavelength scaling of $P \propto \lambda^{-0.2}$, close to the theoretical $P \propto \lambda^{-0.25}$ or $\lambda^{-0.22}$.

For a ruby laser intensity of 10^{11} watts cm^{-2}, Cooper's theory predicts a pressure acting on the focal spot area of 6×10^{10} dynes cm^{-2} (~ 60 kbar) leading to a final foil velocity of 1.44×10^4 cm s^{-1}. At the same intensity Puell's theory gives a pressure of 5×10^{10} dynes cm^{-2} (assuming the plasma effective Z is 10) and corresponding foil velocity of 1.2×10^4 cm s^{-1}. These calculated values compare remarkably well with the measured foil velocity at this laser intensity of 1.4×10^4 cm s^{-1}.

To check the pressure scaling with M and Z velocity measurements were made using different foil materials irradiated with the ruby laser at an intensity of 1.45×10^{11} watts cm^{-2}. Fig.5 shows the results in terms of momentum acquired by each foil ($mv \propto P$) plotted against atomic weight. To compare these results with theory we need some relationship between M and Z since Z will increase as M is increased.

We assume that the plasma electron temperature occurring is independent of target material. This has been shown [7] to be a reasonable assumption for elements heavier than fluorine if the energy needed for ionization is taken into account. Puell's theory enables us to calculate an electron temperature of about 130 eV at the laser intensity used. From the results of House [8], who has calculated the ionization equilibrium of various elements, we find that at a constant temperature of 130 eV the average charge states occurring obeys reasonably well a $Z \propto M^{0.75}$ dependence between carbon ($M = 12$) and iron ($M = 56$). We assume that this dependence holds up to the heaviest elements used here and substitute it into the scaling given by Puell in equation (2) to find a pressure dependence on atomic weight given by

$$P \propto M^{0.015} .$$

Thus the pressure is virtually independent of the atomic weight. The roughly flat momentum against atomic weight results, shown in Fig.5, agree well with this theoretical scaling.

Finally we have noted that for laser shots where the foil and laser beam were incorrectly aligned very large rotational velocities were imparted to the foil. The highest observed was over 5 million revolutions per minute.

In conclusion, we have shown that the pressure exerted on a target surface due to laser induced ablation of material scales as predicted theoretically. The very weak wavelength dependence has been demonstrated experimentally.

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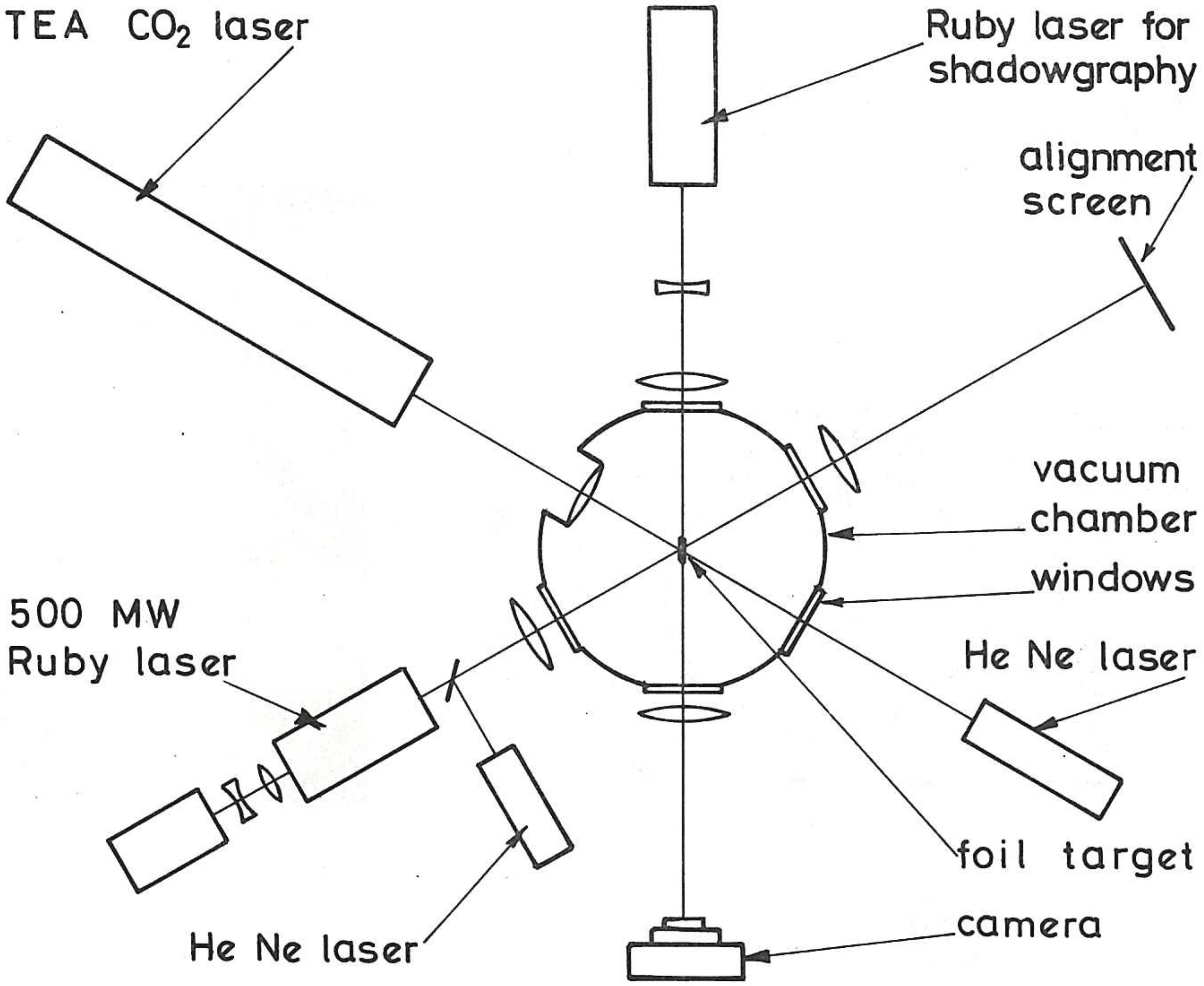

Fig.1 Experimental arrangement

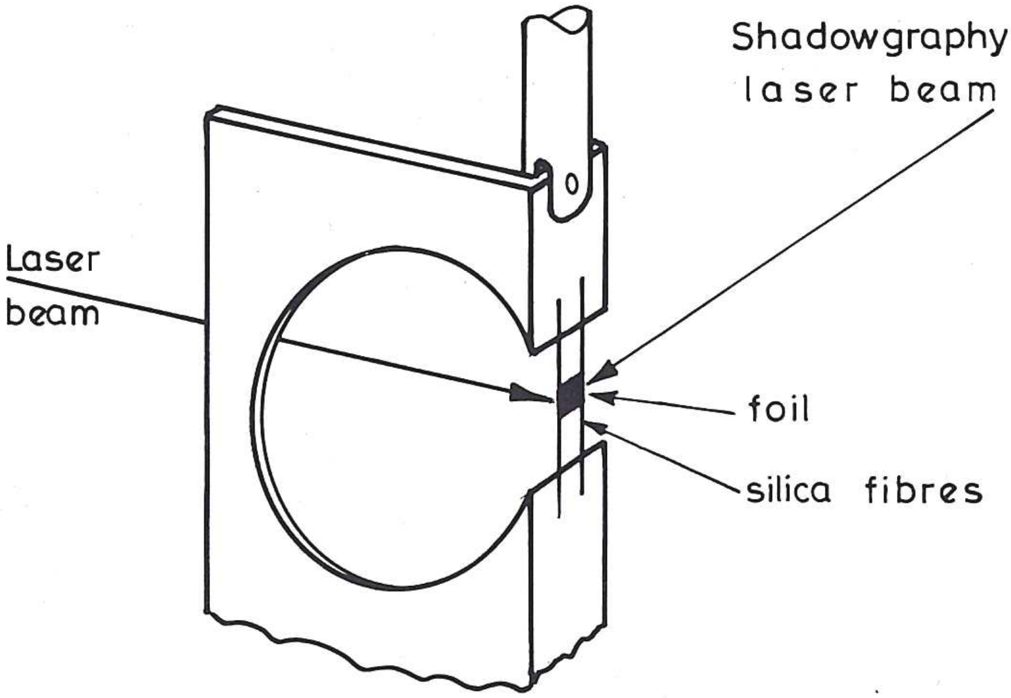

Fig.2 Target foil holder

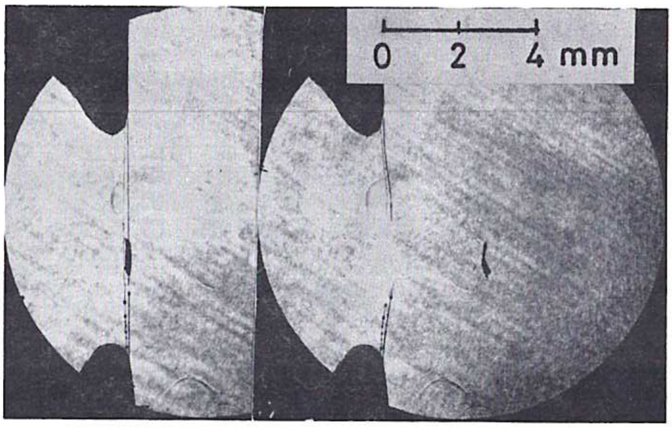

Fig.3 Shadowgrams taken before and 24μs after laser irradiation. Laser beam comes from left.

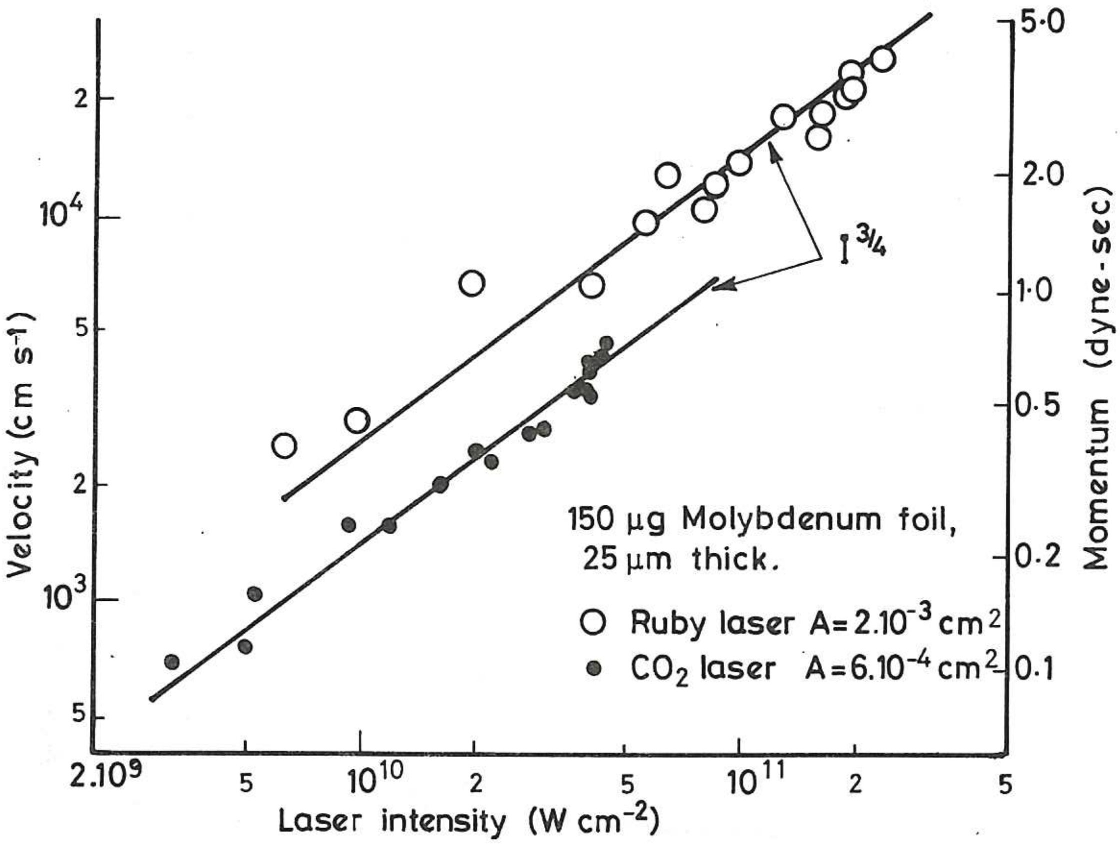

Fig.4 Foil velocity (and momentum) measurements for different ruby and CO_2 laser intenisities

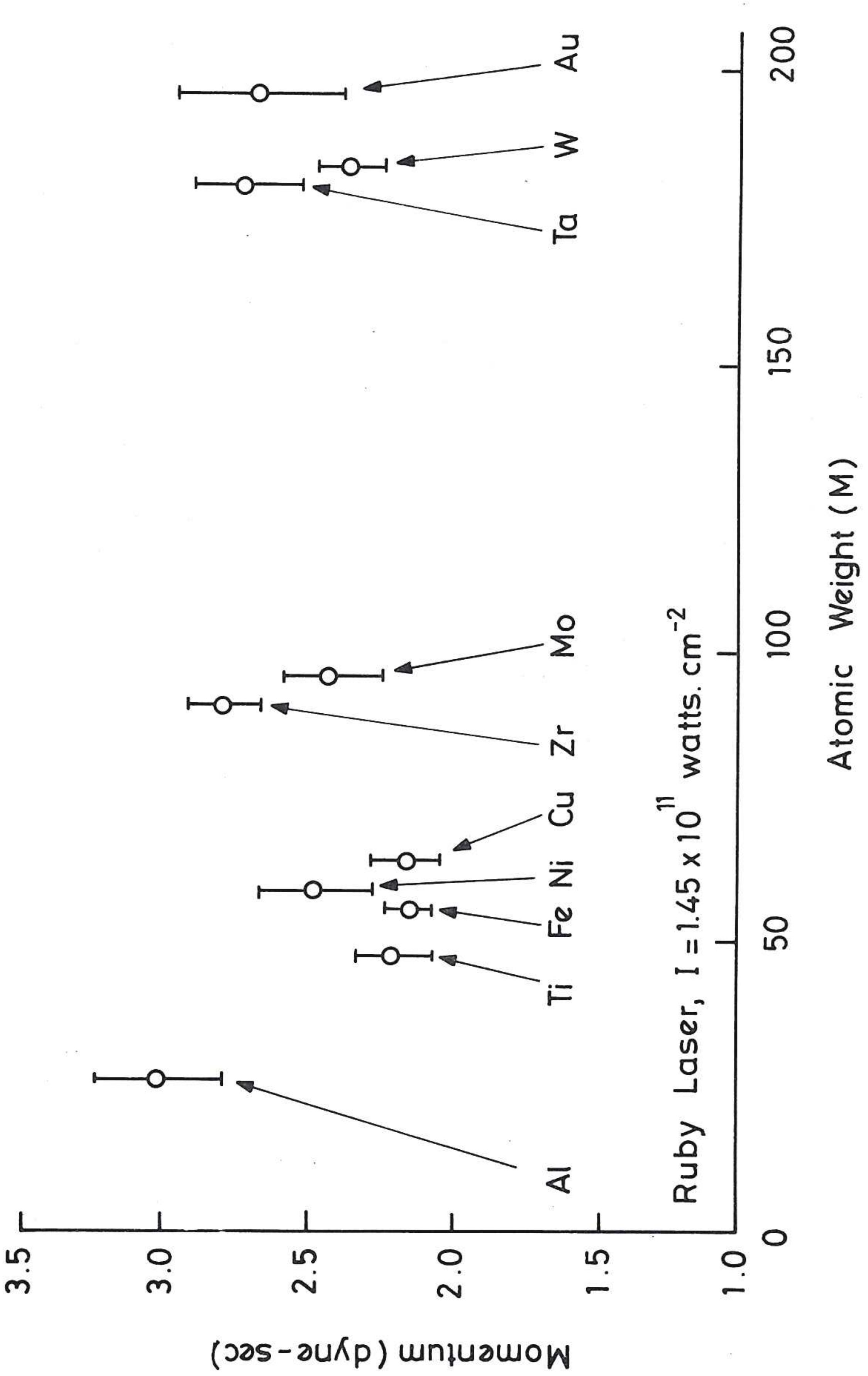

Fig.5 Foil momentum measurements for different target materials.