Sources of highly-stripped ions for ion accelerators

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ABSTRACT

Ions with ionisation potentials up to 4 keV are now produced in some high-temperature pulsed-plasma devices. This paper considers in particular the plasma produced by irradiation of any arbitrary target element by a pulsed, high intensity laser beam. The degree of ionisation and the absolute number of ions produced have been studied spectroscopically and it is evident that stripping of the ions to charge states of up to +20 can be achieved. This agrees with the calculations of the laser absorption and the plasma dynamic processes in the expanding plasma blob. The effective production rate for the highly stripped ions is $10^{14}\ s^{-1}$. Although extraction of these ions for accelerator purposes is technically difficult, calculations show that currents of 10^{13} ions s^{-1} with charge states between +10 and +20 can be expected from the laser plasma source.

1. INTRODUCTION

In recent years there has been an increasing use of energetic heavy ions as projectiles in the fields of biology and nuclear physics. Future developments, such as the production of super heavy nuclei, require heavy ions which are more energetic ($\gtrsim$ 350 MeV) than those now available. In the detailed studies which have been made of the possible ways of accelerating heavy ions to high energy, stress is rightly laid on the need to produce ions of a high charge to mass ratio. Methods used hitherto and adopted in current proposals (e.g. Ghiorso[1,2]) depend on accelerating ions of low charge produced in a conventional rf or calutron-type ion source to sufficient energy (>10 MeV) to strip further electrons by passing them through stripping foils. This technique is not entirely satisfactory since it produces a multiplicity of charge states, it suffers from beam loss by scattering, and also since the associated accelerator tends to be both massive and inaccessible, the latter making foil replacement difficult.

Attention is drawn to the fact that some of the most highly charged ions to be found in the laboratory are contained in the plasmas encountered in thermonuclear fusion research. One possibility is the plasma produced by the

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irradiation of a solid material by the focused beam from a high power laser. The simplicity of the plasma production makes it a potentially useful source of highly charged ions. This paper contains a description of the properties of this plasma and of its utilisation as an ion source. A more detailed account is to be found elsewhere.[3]

2. PROPERTIES OF A LASER-PRODUCED PLASMA

2.1. *Plasma production*

The material to be irradiated is placed at a fixed point inside a hard vacuum system. The laser pulse is focused by a lens, through a window in the vacuum system onto the material surface. The material within the focal region is raised to the vapour state and the dense vapour then strongly absorbs the laser energy, becoming heated and highly ionised. There are no complications due to differential pumping as in conventional ion sources. The energy source is modest (~10 kJ electrical energy) and can be located, with the laser, several metres from the vacuum chamber.

Studies have been made on a variety of solid elements (including solidified gases),[4,5] in the form of small isolated particles[6,7] and extended surfaces.[8,9] To control the number of ions and to avoid production of relatively large quantities of cold, partially ionised plasma, the use of isolated particles is probably desirable. Techniques for striking such isolated particles with laser light are developed[4,6] and do not appear to present formidable difficulties.

The two properties of the laser produced plasma which make it attractive as an ion source are that it contains high ion states and that recombination proceeds sufficiently slowly for these ion states to persist for usefully long times.

2.2. *High ion states*

Being formed from solid material the plasma has initially a very high density. It strongly absorbs the laser energy and is thereby raised to a high temperature. Concurrent with a high density and temperature is a high rate of ionisation, which if maintained for a sufficiently long time will lead to high ion states. In experiments to date typically 10 joules of energy in a *Q*-spoiled pulse of a ruby laser (500 MW with a Gaussian pulse shape, 20 ns half-width), focused with a 10 cm focal length lens onto a solid surface, produces a plasma of peak density $\sim 10^{20}\,cm^{-3}$, peak temperature ~100 eV, with $\sim 10^{15}$ ions in a terminal ion stage of potential ~400 eV.[9]

Detection of highly charged ions has been, in some cases, by particle charge analysis, but principally from the characteristic line radiation in the region 10-1000 Å, recorded by a grazing incidence vacuum spectrograph. The highest ion states detected include Co XIX (i.e. ^{18+}Co), Fe XVIII, Ni XVIII, and Mn XVII.[10,11] A spectrum is shown in Fig. 1 of the laser plasma produced when a 450 MW *Q*-spoiled ruby laser is focused onto a target of iron, with a 10 cm focal length lens. The emission close to the target was recorded with a grazing incidence spectrograph modified to produce a space-resolved image on the photographic plate. Ion states up to Fe XVI are seen. They extend at least 2 mm from the target surface.

The lasers described above, although most frequently used, do not represent the optimum for the production of high ion states. Haught *et al*[12] calculate that the use of shorter radiation pulses on an isolated particle at high peak power (higher than that used to generate the spectrum of Fig. 1) will result in higher plasma temperatures. Several gigawatts of laser power for a duration of 0·1–1 ns is about ideal and is currently available.

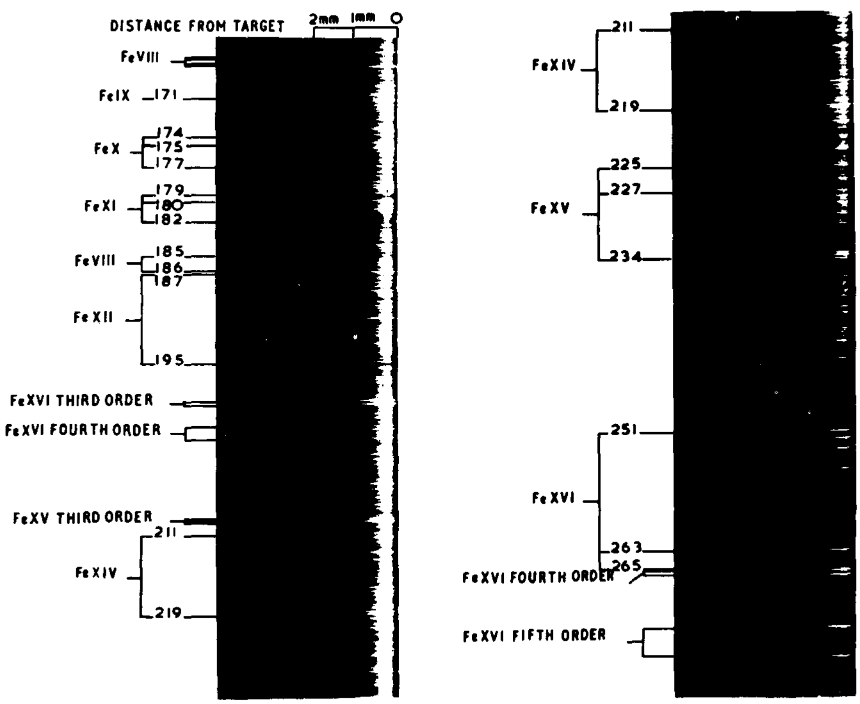

Fig. 1. Space resolved, laser produced spectra of iron. Incident ruby energy 10 J within 20 ns

2.3. *Recombination*

While the laser energy input to the plasma continues there will be net ionisation, up to the point where a balance is reached between the rates of ionisation and recombination. Peacock and Pease[3] have calculated that for the plasma conditions cited above, the balance is reached within the period of the laser pulse (in fact, within a few ns). In the case of an iron target, the ion species should be Fe XV–XVI, which is in good agreement with experiment.

After the termination of the laser pulse, as the plasma expands into the space around the target surface, the density and temperature decrease and there is net recombination. Calculations of these effects have been carried out, based on a model due to Dawson,[13] which predicts the development of the electron density and temperature with time, given the initial (measured) values. A set of rate equations was set up, one for each ion, which related the rate of change of ion density to the rates of ionisation and recombination. The solution of these equations gave the development with time of the state of ionisation of the plasma. This is shown in Fig. 2.

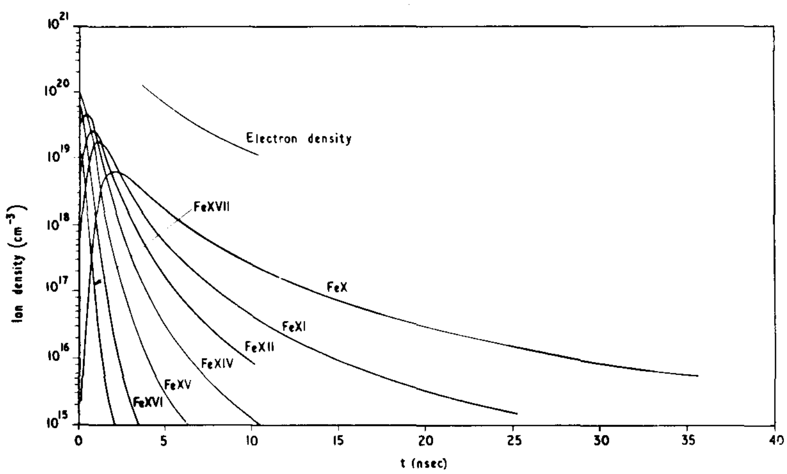

Fig. 2. Transient ion population in early phase of expanding iron plasma. Initial conditions $T_e = 100\ eV$, $n_e = 3 \times 10^{21} cm^{-3}$, *velocity* = $10^7 cm\ s^{-1}$, *particle radius* = 0·25 *mm*

It is apparent from Fig. 2 that the important recombination phase is in the early expansion <10 ns (i.e. <1 mm from the target at an expansion velocity of 10^7 cm s^{-1}). During this time the dominant ion species decreases from Fe XV to Fe X. A further decrease to Fe VII occurs only after a period of 10^{-5} s. The reason for this is as follows. Recombination can be shown to be radiative rather than three-body, and the rate of recombination can be shown to decrease rapidly with time, due to the rapidly decreasing density. When it becomes diminishingly small the ion then present, Fe X, is effectively 'frozen' into the expanding plasma. This situation is one of gross non-thermal equilibrium.

A terminal stage of ionisation higher than Fe X could be achieved if recombination during the first few nanoseconds could be at least partially arrested, perhaps by heating the plasma. Any three-body recombination which occurs during the early expansion will have a heating effect. In this connection Fig. 1 gives some grounds for optimism since it shows emission from Fe XVI somewhat further from the target surface (>2 mm) than predicted by this calculation (<1 mm). Note that beyond several millimetres the plasma conditions are such that all lines are too weak to be seen.

3. UTILISATION OF THE IONS

3.1. *General considerations*

The somewhat explosive nature of the laser-produced plasma source presents a number of problems of handling the output. We take as typical a plasma generated from a solid particle containing 10^{15} atoms, ionised to a mean value $Z = 10$. This represents a total charge of 10^{-3} coulombs. To accelerate the ions to 350 MeV requires ~60 kJ of energy, and if accelerated over a period of 1 μs would require beam currents greater than 10^3 A. In fields typical of a Van de Graaff accelerator beam, currents of 1–10 A can be envisaged, with beam radii in the range 1–10 cm. This means that the plasma produced by the source has to be confined (at low densities) and released slowly for acceleration over a period of about 1 ms. Such confinement times are within the capabilities of the magnetic trap systems of current thermonuclear research devices.

A further reason for this slow release of the plasma into the accelerator is the energy loading of the target. With a thick target of the most favourable metals the target area has to be about $10^3 cm^2$ to keep the temperature rise within 10^{3}°C in 1 ms. Of course, if the reaction products have very short lifetimes the possibility of exploiting the pulsed nature of the source might be extremely valuable.

3.2. *A trap system for the ions*

The best form of magnetic trap must depend on a variety of factors. At the densities expected the ions will form a plasma and the trap must be at least magnetohydrodynamically stable. An attractive form of trap would be a magnetic mirror of the well-type used, for instance, in the Phoenix II experiment,[14] where the present observed confinement times are about ¼ s at a plasma density of $5 \times 10^9 cm^{-3}$. Haught *et al*[7] report that the confinement of ions from a laser-produced plasma in a magnetic well is limited only by coulomb scattering into the loss cone. The ions would stream out of the trap along the lines of force which could be used to guide them into the accelerator. Calculations[3] show that both the recombination and the scattering times get bigger, the smaller the electron density. The latter is achieved by reducing the total number of particles, and also by increasing the volume (but not so that it becomes too large for the plasma to fill in the time available). About 10^{14} ions in a volume of $10^4 cm^3$ seems a reasonable compromise.

3.3. *A proposed ion source*

An outline arrangement of the proposed heavy ion source coupled to an electrostatic accelerator is shown in Fig. 3. A 50μ diam. particle falls through the focal volume of the 5-10 cm focusing lens and triggers the laser pulse at regular intervals, about every 10 s. The frequency of pulsing is determined by the problems of cooling the *Q*-spoiled laser and of recharging the high-voltage accelerator. With 10^{14} total ions per pulse, the equivalent beam current is of the order of 10^{13} ions s^{-1}, which is at the upper limit of the ion flux needed for the production of super heavy nuclei. An ion charge of +20 necessitates an accelerator potential of 20 MV to create ion energies of interest and this is rather high for existing Van de Graaff devices. An advantage of this type of accelerator, however, is that there should be little difficulty in physically accommodating a magnetic trap for the ions.

Other possible types of accelerators are the Heavy Ion Linear Accelerator (HILAC) such as is described by Rose,[15] and the Variable Energy Cyclotron (Lawson).[16] The cyclotron has the advantage over electrostatic accelerators in that the final ion energy scales as the square of the ion charge. Ion energies $\gtrsim$500 MeV can be expected. However, the problem of designing the source so as to channel the initially high thermal energy of the ions into a cone with an emittance acceptable to the accelerator is more critical in these devices.

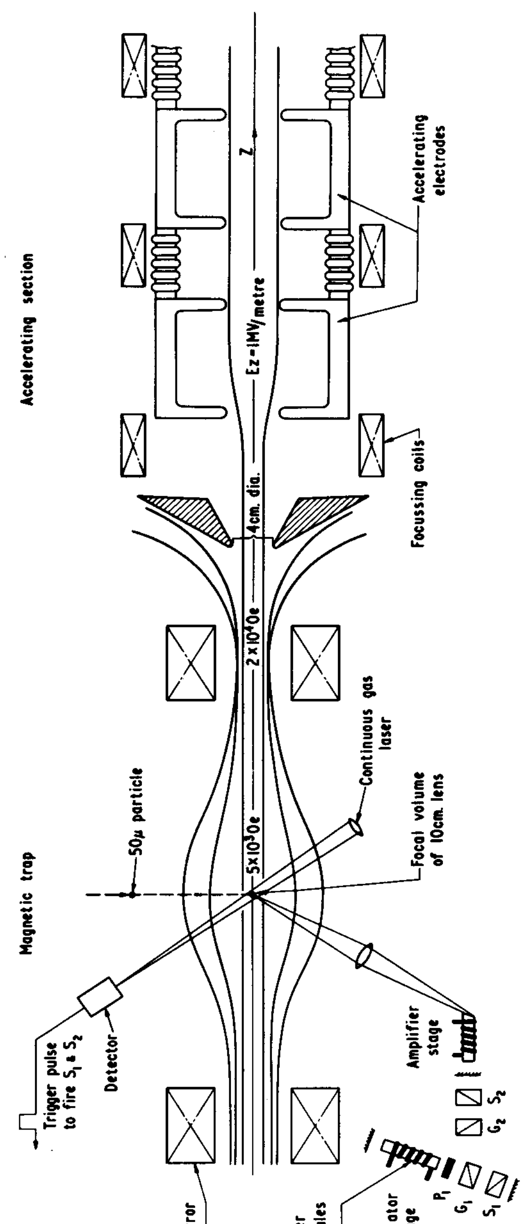

Fig. 3. Schematic diagram of heavy ion source

3.4. *Conclusion*

The generation of high ion states and the advance in magnetic confinement systems in thermonuclear research might be exploited to develop an ion source giving a yield of 10^{13} ions s^{-1}, with a charge state available for acceleration of at least +10 and perhaps up to +20.

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