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SOURCES OF HIGHLY STRIPPED IONS

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ABSTRACT

The condition that $n\tau$, the product of density and containment time, is sufficiently high to strip ions almost to their 'steady-state' degree of ionization can be achieved in certain high density pulsed devices of thermonuclear interest. One such plasma, that produced when a solid pellet is irradiated by a Q-spoiled laser beam, looks promising as a source of highly-stripped ions. Present calculations show that the ions could be extracted for acceleration experiments with a mean charge exceeding ten.

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CONTENTS

1 INTRODUCTION

The use of heavy ions as projectiles for biological materials and nuclear physics research has become increasingly exploited in recent years and there are a number of devices and processes for accelerating them to high energy. One possible investigation requiring a higher energy than hitherto achieved is the creation of superheavy nuclei. Possible reactions (Ghiorso, 1967) are shown in Table 1.

TABLE 1

Reaction	Spallation product	Peak cross section (mb)	ion energy MeV	MeV/ nucleon
$Cf^{252}_{98} + Ni^{60}_{28}$	126^{311}	0·002	344	5·7
	126^{310}	1	346	5·8
	126^{309}	22	350	5·8
	126^{308}	65	366	6·1
$Hf^{180}_{72} + Xe^{132}_{54}$	126^{310}	64	754	5·7
$Th^{232}_{90} + Kr^{80}_{36}$	126^{310}	19	441	5·5

For such reactions, energies in the range 5 - 7 MeV per nucleon are required. To detect the product (if any), currents of 10^6 - 10^{13} ions/sec are estimated to be desirable (Ghiorso, 1967); the wide range of possibilities arises from the uncertainty of the lifetime of the product nucleus, and the detection methods possible.

In the detailed studies of the possible ways of producing such accelerated heavy ions, much stress is rightly laid on the need to produce ions of a high charge to mass ratio $Z/A \equiv \varepsilon$. Methods used hitherto and adopted in current proposals (e.g. Ghiorso, 1966 and 1967) depend on accelerating ions of low ($\varepsilon < 0{\cdot}08$) charge produced in a conventional r.f. or calutron-type ion source, and then accelerating them to sufficient energy ($\gtrsim$ 10 MeV) to strip further electrons by passing them through stripping foils. The consequences appear to be a massive acceleration device and an uneasy compromise between efficiency of acceleration on the one hand and scattering and foil degradation on the other.

Recently quite a new source of highly-stripped ions has been proposed (Daugherty et al., 1968) in which the ions can be created and held in the potential well formed by an electron cloud circulating in a torus and the positively charged torus wall. Experimental evidence for the highly stripped stages is not however available at present.

It is the purpose of this paper to point out that highly-stripped heavy ions are comparatively easily achieved in plasmas studied in connexion with thermonuclear fusion and that there may be the possibility of developing new types of ion sources which will ease the problem of achieving substantial currents of highly stripped ions for acceleration to the energies required by the reactions in Table 1.

2. HIGHLY-STRIPPED IONS IN PLASMAS

Plasma spectroscopists have long known that highly ionized species occur in the solar corona and in certain types of spark sources (Édlen 1942 , 1947). Such species have also been observed in thermonuclear devices (e.g. Peacock et al. 1966). At present, the ion species with the highest ionization energy observed in the laboratory is A XVIII [ψ_i(A XVII) = 4·1 keV] and has been produced in the 'plasma focus' - a high-density pinch experiment (Peacock et al., 1969).

The conditions required to produce highly stripped ions are (i) the electron temperature must be at least of the order of one-tenth (assuming a Saha ionization balance, or about one-fifth on a coronal balance) of the ionization potential required to remove the final electron; (ii) the confinement time of the ions must be sufficient to allow the ionization to take place.

As far as the temperature is concerned, a number of laboratory devices produce plasma with electron temperature in the range 100 eV - 1 keV, so that the temperature requirement for producing sufficient highly-stripped ions can be met. In general there is no local thermodynamic equilibrium, and the steady state degree of ionization is calculated by equating the rate of electron-impact ionization to the rate of recombination. Detailed claculations of this type have been carried out by McWhirter (1965) and House (1964).

The time τ required to reach a steady-state ion population depends on the electron number density n_e. The general value for the rate coefficient $\langle \sigma v_e \rangle$ at which there is ionization and recombination balance is 10^{-12} cm^3 sec^{-1} for H-like ions irrespective of their charge (McWhirter, 1965), so that the containment criterion for producing highly stripped ions is

$$\tau \simeq 10^{12}/n_e \text{ secs.} \qquad \ldots (1)$$

This criterion is about 100 times less severe than that ($n\tau \gtrsim 10^{14}$cm^{-3} sec) required for power-producing thermonuclear reactors (Lawson, 1957). and is now achieved in a number of devices generating high density plasma.

3. LASER-PRODUCED PLASMAS

From the point of view of application to ion sources, an attractive system is to produce plasma by irradiating a solid particle with the light pulse from a Q-spoiled laser. Because of the high value of the initial number density in this plasma, criterion (1) can be met without recourse to magnetic confinement. The plasma can be produced at a fixed point inside a hard vacuum system. There are no complications due to differential pumping, as in conventional ion sources. The energy source is modest (10 kjoules electrical energy) and can be several metres removed from the ion chamber.

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 nsec ½ width) focused with a 10 cm lens onto a solid surface produces 10^{15} ions of target material in a terminal ion stage with $\psi_i \gtrsim 400$ eV. A spectrum is shown in Fig.1 of the laser plasma produced when a 450 MW, Q-spoiled ruby laser is focused on an iron target 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 (stigmatic to ±0·5 mm) on the photographic plate. It is seen that ion stages of Fe XVI, Fe XV emit the strongest lines in the spectrum. They extend at least 2 mm from the target surface. Most of the ions initially may be in the ground level of the Ne-like, Fe XVII. Analysis of a similar potassium oxide plasma, Burgess et al (1967), yields electron densities close to 5×10^{20} cm^{-3} within 0·5 mm of the target surface. The peak electron temperature is of the order 100 to 120 eV. Basov et al.(1966), using non-spectroscopic diagnostic techniques measure similar values for the plasma parameters.

These experimental results were obtained with solid surfaces irradiated by laser light. To control the number of ions and to avoid production of relatively large quantities of cold, partially-ionized plasma, the use of isolated particles is probably desirable. Techniques for striking such isolated particles with laser light are developed (Francis et al., 1967 and Sucov et al., 1967) and do not appear to present formidable difficulties. There are as yet no spectroscopic analyses of the plasmas formed by irradiating isolated particles of high-Z material.

Haught et al.(1967) calculate that the use of shorter irradiation pulses on an isolated particle at high peak power (than that used to generate the spectrum of Fig.1) will result in higher plasma temperatures. Several gigawatts of laser power for a duration 0·1 to 1 nanosecond is about ideal and is currently practicable. Burgess et al. (1967) show experimentally that, at a massive target surface, the degree of ionization and the plasma temperature generated increases with incident laser power.

4. ION STAGES PRODUCED AFTER EXPANSION

An important consideration is the recombination of the highly-ionized species as the plasma expands in space. Dawson (1964) has formulated a spherically symmetrical model for the plasma formation and expansion which is used here to estimate the ion species available for acceleration after the expansion phase is over. The laser radiation is assumed to be absorbed by electron-ion collisions in that part of the plasma which has a density, n_e, $2{\cdot}4 \times 10^{21}\,\mathrm{cm}^{-3}$. The absorption is confined to a thin layer. Expansion of the plasma in front of this layer causes the plasma frequency to fall below the laser frequency and in this region absorption is neglected.

Figs.2 and 3 illustrate the change in temperature and radius of an iron plasma under two sets of conditions. In Fig.2 the energy input is 10 gigawatts, while in Fig.3 the energy input is at the rate of 500 MW. In practice 500 MW gives a terminal radial expansion velocity nearer 10^7 cm/sec and a temperature of about 100 eV (Burgess et al., 1967).

The density and temperature at time $t > \tau$ (laser pulse) is assumed uniform, and given by the adiabatic expansion of the plasma:

$$n_i = n_{oi} \left(\frac{r_o}{r}\right)^3 \qquad T = T_o \left(\frac{r_o}{r}\right)^2 ; \qquad \ldots (2)$$

where $r = r_o + \int v\,dt$, r_o is the initial radius, n_{oi} and T_o the initial density and temperature and v is the expansion velocity.

The calculated expansion phase is illustrated in Fig.4. During this short time-scale, cooling by radiation losses and, in the case of a massive target, thermal conduction will not materially affect the results. A rough value of the charge of the final ionization stage can be obtained from quite simple considerations in which standard recombination formulae are combined with equations (2).

Allen (1955) gives the generalized radiative recombination coefficient α defined as

$$-\alpha\, n_e n_i = \left(\partial n_e / \partial t\right)_{recomb} , \qquad \ldots (3)$$

to be

$$\alpha = 2{\cdot}7 \times 10^{-13}\, Z^2\, T_e^{-3/4}\ \mathrm{cm}^3\ \mathrm{sec}^{-1} . \quad (T_e \text{ in eV}). \qquad \ldots (4)$$

The mean ion charge on expansion can then be estimated by supposing that all the ions have the same charge Z which therefore is subject to recombination at the rate

$$\dot{Z} = -\,2{\cdot}7 \times 10^{-13}\, Z^3\, T_e^{-3/4}\, n_i \qquad \ldots (5)$$

where we have $n_e = Z n_i$. Combining this with equation (2) and integrating yields the mean charge Z as a function of the radius of the expanding plasma blob:

$$Z^{-2} - Z^{-2} = 5{\cdot}4 \times 10^{-13}\, T_{eo}^{-3/4}\, n_{io} \int_{r_o}^{r} \left(\frac{r_o}{r}\right)^{3/2} dt , \qquad \ldots (6)$$

where Z_o is the charge state, r_o the radius and n_{io} the ion density when the energy input to electrons ceases. As a simplifying assumption the radial expansion velocity $v = v_o$ is taken to be constant, then

$$Z^{-2} - Z_o^{-2} = 1{\cdot}08 \times 10^{-12}\, T_{eo}^{-\frac{3}{4}}\, n_{io}\, \frac{r_o}{v_o}\left[1 - \left(\frac{r_o}{r}\right)^{\frac{1}{2}}\right]. \qquad \ldots (7)$$

Making two further simplifications, (1) that $Z_o^2 \gg Z^2$ and (2) that the expansion velocity v_o is given by

$$\tfrac{1}{2} M v_o^2 = (\tfrac{3}{2})\, Z_o\, kT_{eo} ,$$

where M is the ion mass, then the ultimate state reached is

$$Z(r \to \infty) \simeq 1{\cdot}3 \times 10^9\, T_{eo}^{\frac{5}{8}}\, (Z_o/A)^{\frac{1}{4}}\, (n_{io}\, r_o)^{-\frac{1}{2}}, \qquad \ldots (8)$$

where A is the atomic weight. Taking the figures $T_{eo} = 1000$ eV, $Z_o/A = \frac{1}{2}$, $n_{io} = 10^{21}$ cm^{-3} and $r_o = 10^{-2}$ cm, then $Z(r \to \infty) \simeq 20$ is the highest average charge state which can be expected to remain after the blob has expanded.

In more detail, the recombination in the expanding plasma has been computed for an iron plasma. Iron is chosen because the ionization potentials are documented (Moore, 1949). The expansion velocity $\frac{dr}{dt} = v$; the electron density is

$$n_e = n_{FeII} + 2n_{FeIII} + \ldots \quad 16n_{FeXVII} + \ldots ; \qquad \ldots (9)$$

but in the first place, the approximation $n_e\, r^3 = \text{const}(N_e)$ has been used, so that

$$\frac{dn_e}{dt} = -\,(3\dot{r}/r) \times n_e . \qquad \ldots (10)$$

Equation of motion :

$$\frac{d^2 r}{dt^2} = \frac{5(N_e + N_i)kT}{\bar{M} r} , \qquad \ldots (11)$$

where

$$\bar{M} = m_i\, N_i .$$

Equation of energy balance

$$\frac{dT}{dt} = -\frac{2Tv}{r} + \frac{2}{3}\,\frac{W}{N_e + N_i} \qquad \ldots (12)$$

where W is the laser input power. The ionization energy has been neglected.

The transient build-up in the ion population can be readily calculated by balancing the ionization, S_i, with the recombination, α^r, rates for each ion. The rate coefficients have been taken from Kolb and McWhirter (1964), McWhirter (1965).

$$S_i = \frac{9\times 10^{-6}\ \xi \cdot \sqrt{\frac{T_e}{\psi}} \cdot e^{-\psi/T_e}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}}{\left(4{\cdot}88 + \frac{T_e}{\psi}\right) \cdot \psi^{3/2}} \qquad \ldots (13)$$

ξ is the effective number of electrons with ionization potential ψ and T_e, the electron temperature, is in eV.

$$\alpha^r = 5{\cdot}2\times 10^{-14}\,\lambda^{\frac{1}{2}}\,Z\left\{0{\cdot}429 + \tfrac{1}{2}\,\ell n\lambda + \frac{0{\cdot}469}{\lambda^{\frac{1}{2}}}\right\}\mathrm{cm}^3\ \mathrm{sec}^{-1} \qquad \ldots (14)$$

where $\lambda = \psi/T_e$. Fig.5 shows that the steady-state ionization conditions are well established within the laser pulse time, as expected from equation (1). The steady-state, semi-coronal population is shown in Fig.6 as a function of temperature. For T_e greater than 100 eV the dominant ion charge is + 16 or higher.

At high densities, three-body recombination has also to be taken into account. The three-body recombination into the ground levels is computed using the formula obtained from equation (13) and from detailed balance considerations:

$$\alpha^{3b} = \frac{2{\cdot}97\times 10^{-27}\ \xi\ \sqrt{\frac{T_e}{\psi}}}{\left(4{\cdot}88 + \frac{T_e}{\psi}\right) \cdot T_e^{3/2}\ \psi^{3/2}}\ \mathrm{cm}^3\ \mathrm{sec}^{-1} \qquad \ldots (15)$$

Both recombination rates are compared in Fig.7 for a plasma with an electron density of 10^{21} cm^{-3}. For $n_e < 10^{20}$ cm^{-3} radiative recombination need only be considered (see also House, 1964).

For the k^th^ ionization stage, we have:

$$\frac{dn_k}{dt} = n_e n_{k-1} S_{k-1} + n_e n_{k+1} \alpha^{r}_{k+1} + n_e^2 n_{k+1} \alpha^{3b}_{k+1} \qquad \ldots (16)$$
$$- n_e n_k S_k - n_e n_k \alpha^{r}_{k} - n_e^2 n_k \alpha^{3b}_{k} - 3 n_k \frac{v}{r} .$$

The above equations (16) coupled with (11) and (12) have been solved using the Culham KDF9 computer for a few typical examples as in Figs. 8 and 9.

As can be seen, the predominant ions at the end of the expansion phase are Fe (VII) and Fe(VIII). Equation (7) predicts the average Z to be 6·5 in the same circumstance, in excellent agreement. The crude prediction of equation (8) gives a rather lower figure, Z = 5·2, because it neglects the term Z_o^{-2} of equation (7).

It is apparent that the important recombination phase is in the early expansion < 20 nsec, i.e. (< 1 mm from the target at an expansion velocity of 10^7 cm sec^{-1}). If the highest ion stages are sustained by some process for a few tens of nanoseconds, the charge of the final ionization stages can be higher.

There is experimental evidence that some such process for sustaining T_e during the expansion occurs, see Fig.1, where in contradiction to the above calculations, some of the strongest emission lines at 2 mm from the Fe target are Fe XVI. Relaxation of the ion-electron energies during the expansion has not been taken into account in the calculations because of the predominantly radial energies of the particles. However this effect will indeed transfer some energy from the ions to the electrons. Other possible explanations include, as mentioned, the identity of the 'initial' ion stage which may be Fe XVII. Also 3-body recombination in the early expansion sustains the electron temperature at a higher value than the simple adiabatic law equation (2) and this effect has not been included in the calculations. Finally, absorption of the ruby laser energy when $n_e < 2{\cdot}4 \times 10^{21}\,cm^{-3}$ in the expanding plasma ahead of the absorption layer may be significant.

One can conclude here by stating that there is experimental evidence that the predominant 'final' ion stage in the expanding blob somewhat exceeds the Fe VIII predicted by the simple model calculations.

With a laser pulse, similar to that used for Fig.1, irradiating a massive target of polyethylene about 3% (2×10^{14} ions) of the carbon ions released from the target were completely stripped (CVI, $\psi_i =$ 490 eV); Boland et al. (1968). The calculations of Haught et al. (1968) indicate that the target should be an isolated speck of material in order to optimise the mean energy of the ions (which may reach several keV with a laser pulse of 1 J in 10^{-1} nsec). In Section 7 therefore we consider 10^{15} highly-stripped ions with energies up to 10 keV as a reasonable plasma production using Q-spoiled lasers.

5. OTHER LABORATORY PLASMAS

Other heavy ion plasma sources, e.g. the 'Plasma Focus', have been shown to produce ions with $\psi \sim 4$ keV, Peacock et al. (1969); and this source is certainly energetic enough to produce Li-like Fe and Ni, (i.e. Ni XXVI). A low inductance vacuum spark has produced Sn XXIV (Édlen, 1947). Theta-pinches have produced Fe XVII on the addition of a few percent $Fe(CO)_5$ to the ambient gas filling, (Peacock et al. 1966). The presence of contaminants and relatively low ion stages, however, in the later stage of these magnetically confined plasma makes these sources less attractive for the present purpose.

6. UTILIZATION OF THE IONS

The somewhat explosive nature of the laser-produced plasma source presents a number of problems of handling the output. A plasma generated from a solid particle containing 10^{15} atoms, which are ionized to a mean value $Z = 10$, represents 10^{-3} c. To accelerate the ions to 350 MeV requires about 60 kJ of energy; and, if accelerated over a period of 1 μsec, would require beam currents greater than 10^3 A.

We have examined in outline the restrictions set by conventional beam theory (Pierce, 1954) of electrostatic acceleration, both with and without magnetic guiding. In fields typical of a Van de Graaf 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 msec. Such confinement times are within the capabilities 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, the rise δT of temperature of the target surface when energy J is released per unit area in time t is given by :

$$\delta T = 2J \Big/ \left[t^{\frac{1}{2}} (\pi \kappa C_p \rho)^{\frac{1}{2}} \right] \qquad \ldots (17)$$

where κ is the thermal conductivity, C_p the specific heat and ρ the density. For the most favourable metals $(\pi \kappa C_p \rho)^{\frac{1}{2}}$ has a value of about $2\ \mathrm{J\ cm^{-2}\ sec^{-\frac{1}{2}}}$, so that to keep the temperature rise within 10^3 deg.C, and $t \simeq 10^{-3}$ sec, the target area has to be about $10^3\ \mathrm{cm}^2$. For times shorter than about 100 μsec, equation (17) over-estimates the rise of surface temperature because the range of the particles becomes comparable with the thermal penetration depths.

Of course, if the super heavy nuclei outlined in Table 1 have very short lifetimes, the possibility of exploiting the pulsed nature of the ion source might be extremely valuable.

7. A TRAP SYSTEM FOR THE IONS

If we suppose 10^{15} ions with $Z = 20$ are produced, the first parameter of importance is the density needed to avoid recombination. From (3) the recombination time for ions with $Z = 20$ can be calculated for a trap in which the electron temperature is kept at about 10 eV (for instance by microwave heating) to be

$$\tau_{re} \simeq \frac{10^{11}}{n_i} \text{ sec} . \qquad \ldots (18)$$

For a 'hold-up' time of 10 msec, a trap volume of about 10^2cc for the 10^{15} ions is required. Considerations of particle leakage out of the trap (see later) may necessitate a somewhat larger volume.

The best form of magnetic trap must depend on a variety of factors. At the densities expected, the ions will form a plasma, and therefore 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 (Bernstein et al. 1965) where the present observed confinement times are about ¼ sec at a plasma density of 5×10^9 cm^{-3}. Haught et al. (1968) 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. The classical confinement time is the ion-ion collision time for scattering into the loss cone. From Spitzer (1961), equation 5.26

$$\tau_{\text{scatt}} = \frac{1{\cdot}4 \times 10^7 \cdot A^{\frac{1}{2}} \cdot T^{3/2}}{n_i \, Z^4 \, \ell n \, \Lambda} \, . \qquad \ldots (19)$$

Thus we obtain a leakage time τ_ℓ for the particle which is about $\tau_{\text{scatt}} \log R$, where R is the magnetic mirror ratio. For $Z = 20$, $A = 60$, $T_i = 10^4$ eV, $n_i = 10^{15}/V_0$ and $R = 4$, where V_0 is the trap volume in cc,

$$\tau_\ell = 2 \times 10^{-8} \, V_0 \qquad (V_0 \text{ in cc}). \qquad \ldots (20)$$

With $V_0 = 10^2$ cc, the short leakage time emerges as a telling restriction at high Z. Some compromise may be needed, for example 10^{14} ions in a volume of 10^4 cc. In addition, to keep the scattering time long, the ions must retain their energy of about $Z_0 \, kT_{io}$; to prevent cooling by electron collision, the electrons will have to be maintained at about 100 eV in the present example.

The expansion of the plasma to fill a volume of 10^4 cc may present difficulties, for the plasma expansion is likely to slow down after the plasma pressure is equal to the magnetic pressure. By allowing electron flow along the line of force, the ions will penetrate the field to the full depth of their Larmor diameter, as has been observed experimentally (Ashby, 1967). At a field of 5000 Oe the Larmor radius of a 10 keV, $Z = 20$, $A = 60$ ion is about 1 cm, so that the required volume can be approached with a plasma column metres or so long, at this field strength. Weaker fields would give a larger volume, but may lead to difficulty in keeping the magnetic moment of the ions an adiabatic invariant.

Closed-line traps have longer classical confinement times and could be used to avoid these difficulties. The toroidal multipole traps appear to be the most stable. If the current-carrying rings were superconducting and levitated, so that the losses were solely due to diffusion across the lines of force, then with currents of about 500 kA in the rings, the classical confinement time could exceed about 10 msec. Techniques for guiding the ions out of the trap into the accelerator would require development.

8. DISCUSSION

An outline arrangement of the proposed heavy ion source coupled to a van de Graaf or other electrostatic accelerator is shown in Fig.10. A 50 micron diameter particle falls through the focal volume of the 5 to 10 cm focusing lens and triggers the laser pulse at regular intervals, about every 10 seconds. 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 10^{13} ions sec^{-1}, which is at the upper limit of the ion flux needed for the experiments on the reactions shown in Table 1. 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 single-stage Van de Graaf 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. Using a pulsed magnetic mirror with an exit aperture of 4 cm, the emergent beam can be radially confined by a static axial magnetic field which is effectively an extension of the mirror field as in Fig.10.

An accelerating voltage of 1 MV/metre applied to the source and an axial magnetic field of 2×10^4 Oe will result in an expansion of the beam by a factor of 1·4. If the magnetic field is an order of magnitude less, 2×10^3 Oe, the maximum beam current available with a fixed aperture of 4 cm is reduced to 0·05 amps. This lower field however has a number of advantages. First, the beam diameter after acceleration is about equal to the input diameter. Secondly, the volume of the adiabatic trap and hence τ_ℓ is increased. Thirdly, it is technologically easier to extend this lower field along the whole accelerator column and lastly, the pulsed thermal loading on the target is reduced. High voltage failure of the accelerator electrodes due to the presence of even the lower magnetic field is an additional problem.

An alternative electrostatic accelerator which may be adopted for use with heavy ions and which makes use of the pulsed nature of the source is the low impedance, high peak-power generator (Graybill and Nablo, 1967; Brewster et al. 1965). Currently this type of machine is capable of accelerating electrons in pulses of tens of kiloamps (with relativistic focusing) to energies of over 10 MeV. In this case the ions need not be magnetically contained but the rapid, almost explosive nature of the device is more of a limiting factor.

Other possible types of accelerators are the Heavy Ion Linear accelerator (HILAC) such as is described by Rose (1967), and the variable Energy Cyclotron (Lawson, 1962). The Cyclotron has the advantage over LINAC and electrostatic acceleration in general in that the final ion energy scales as the square of the ion charge (Lawson,1962, 1965); typically $E_{(out)} = \frac{80 Z^2}{A}$ MeV. For $A = 60$, and $Z = 20$, ion energies of 533 MeV can be expected, certainly energetic enough for the reactions in Table 1. The problem of designing the source so as to channel the initially high thermal energy in the ions into a cone with an emittance acceptable to the accelerator is more critical in these devices. In the Variable Energy Cyclotron for example, a source emittance of 300 (mm × milliradians) is a reasonable figure with an accelerating potential of 20 kV. Simple geometrical occlusion of the expanding laser plasma blob to produce this emittance with a source aperture of 4 cm would cause a 2×10^{-2} reduction in the total number of ions accelerated while the duty cycle would be limited to the expansion time of untrapped ions, i.e. less than 1 μsec. Use of a magnetic trap is probably essential with a leakage time from 1 to 10^3 μsec. The total accommodation volume between the Dees is physically limited to about 1 litre so that the trap shown in Fig.10 would be modified somewhat. The population of ions simultaneously in different stages of ionization is also a problem with these accelerators.

In conclusion the generation of high-stripped ions and the advance in magnetic confinement systems in thermonuclear research may be exploited to develop an ion source giving a yield of 10^{13} ions per second. The ions can be produced in vacuo and are observed to have an initial charged state approaching +20. Calculations of the recombination rates suggest that the charge state available for acceleration can be at least +10 and perhaps up to +20. The injection of these ions into an accelerator presents some difficult problems which however look technically feasible. The source is of interest for heavy ion acceleration especially in those experiments aimed at synthesizing transuranic elements.

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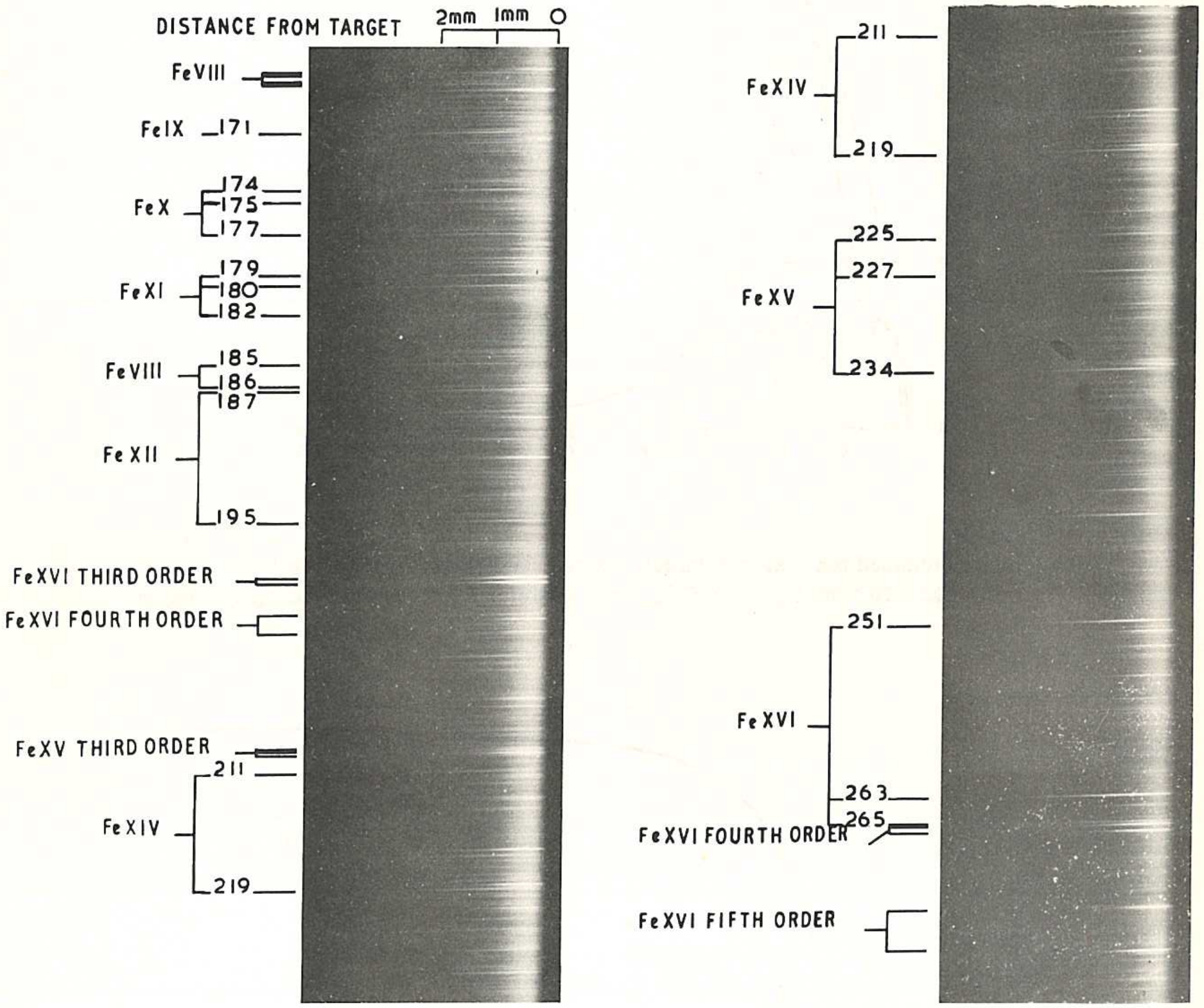

Fig. 1 (CLM-P196)
Space-resolved, laser produced spectra of iron. Incident ruby energy 10 joules within 20 nsec

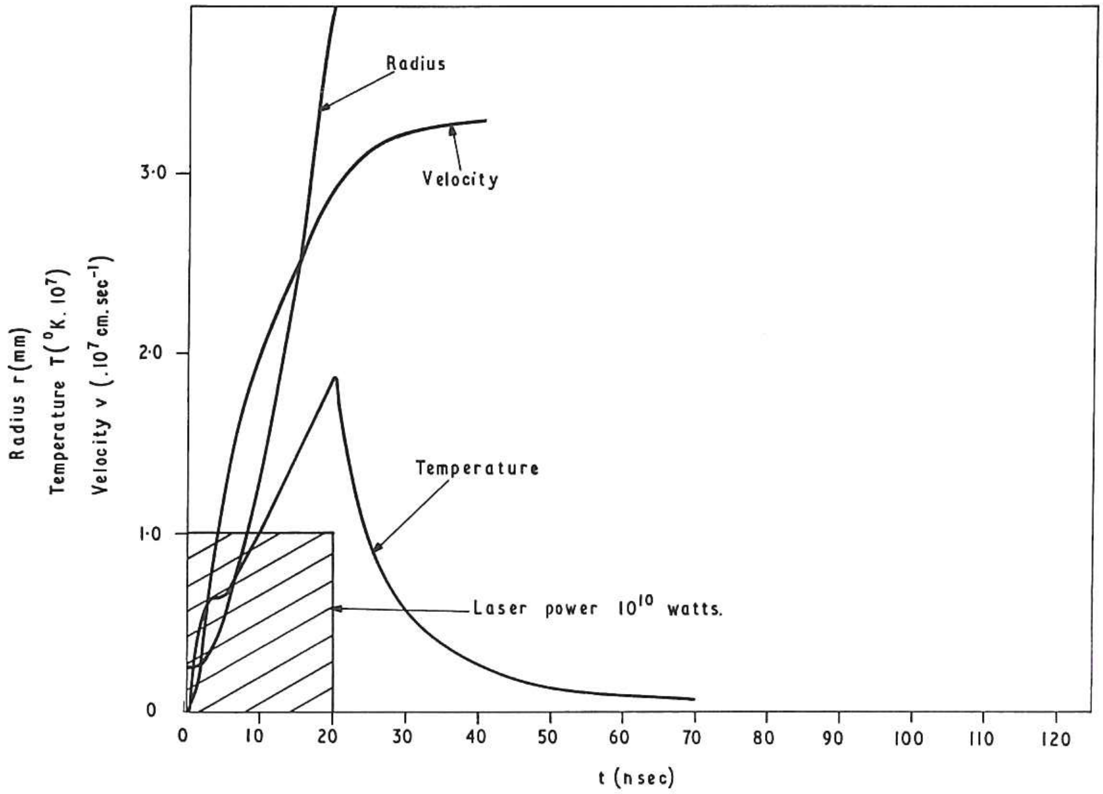

Fig. 2 (CLM-P 196)

Laser produced plasma, iron target. Initial conditions; W = 10^{10} watts for 20 nsec, $r_a = 2.5 \times 10^{-2}$ cm, $N_e = 6 \times 10^{17}$; total particles kept constant during expansion

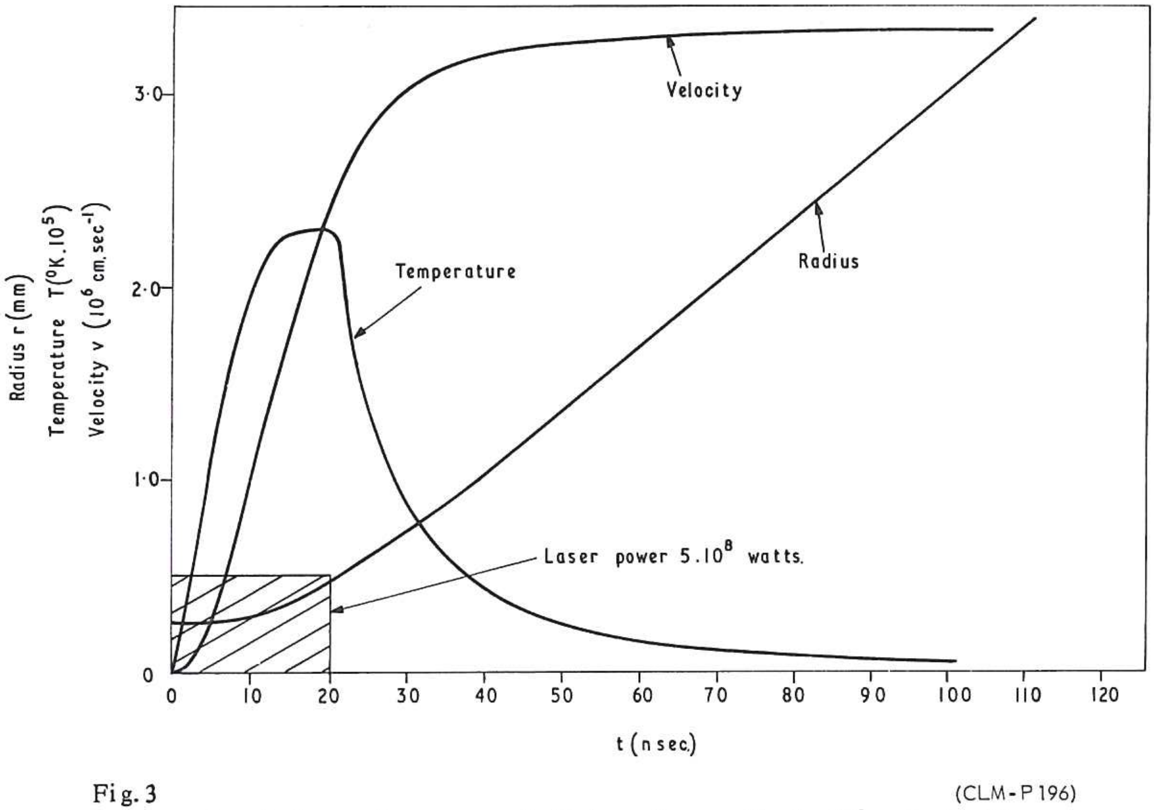

Fig. 3 (CLM-P 196)

Laser produced plasma, iron target. Initial conditions; W = 5×10^8 watts for 20 nsec, $r_0 = 2.5 \times 10^{-2}$ cm, $N_e = 6 \times 10^{17}$; total particles kept constant during expansion

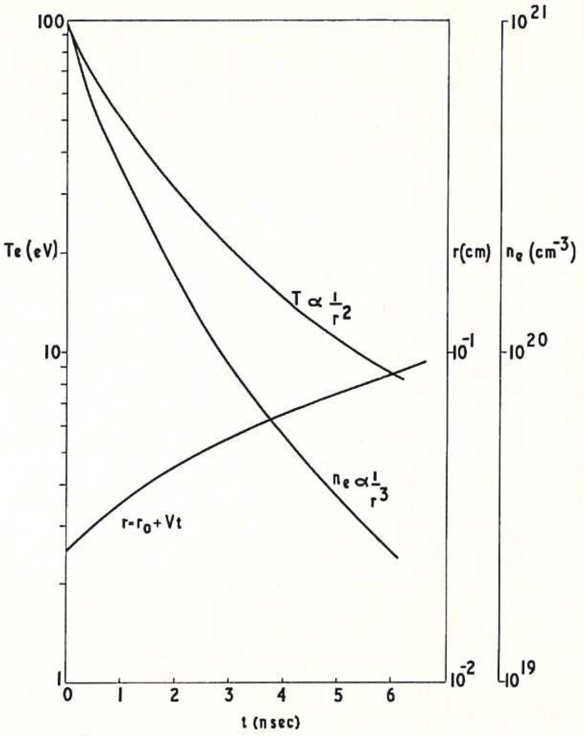

Fig.4 (CLM-P 196)

Expansion phase of laser produced plasma; $r_0=2.5\times10^{-2}$ cm, $v_0= 10^7$ cm sec^{-1}

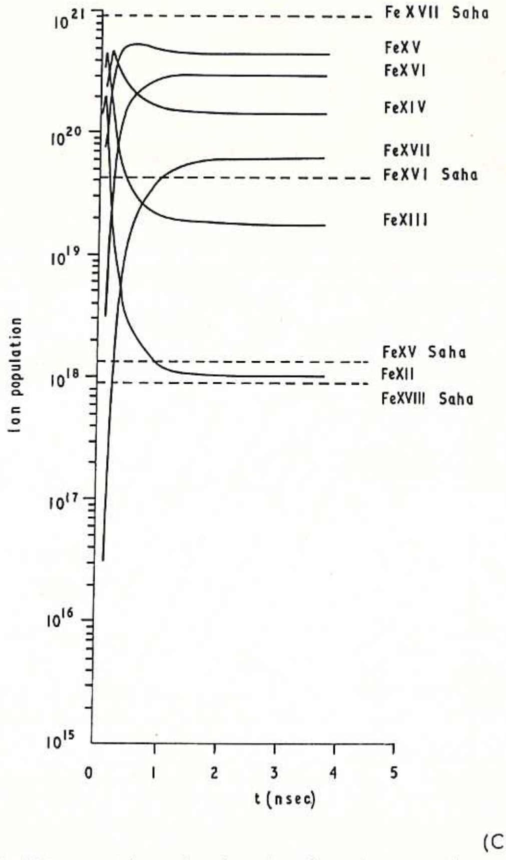

Fig. 5 (CLM-P 196)

Transient build-up of iron ionization in plasma with parameters

$T_e = 100$ eV, $n_e = 10^{21}$ cm^{-3}

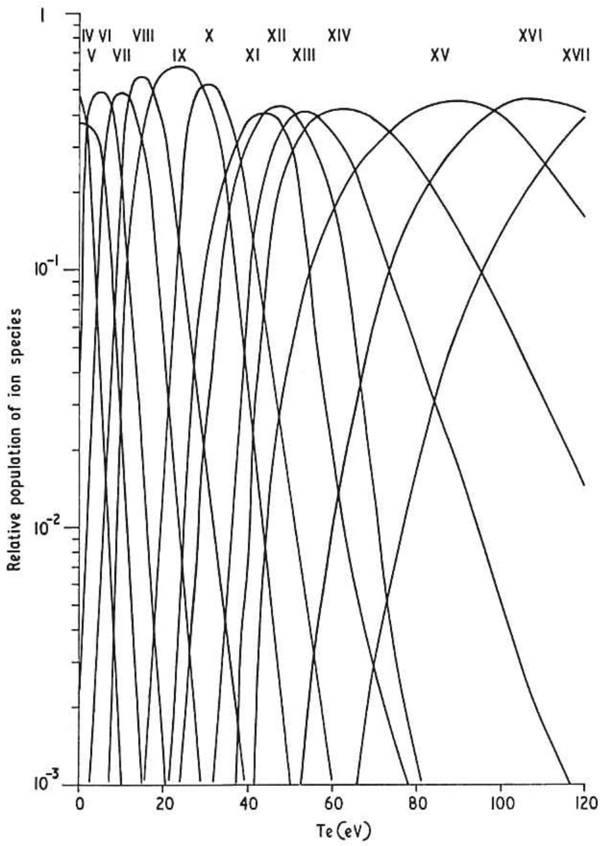

Fig. 6 (CLM-P 196)
Steady state, semi-coronal iron population as a function of plasma temperature

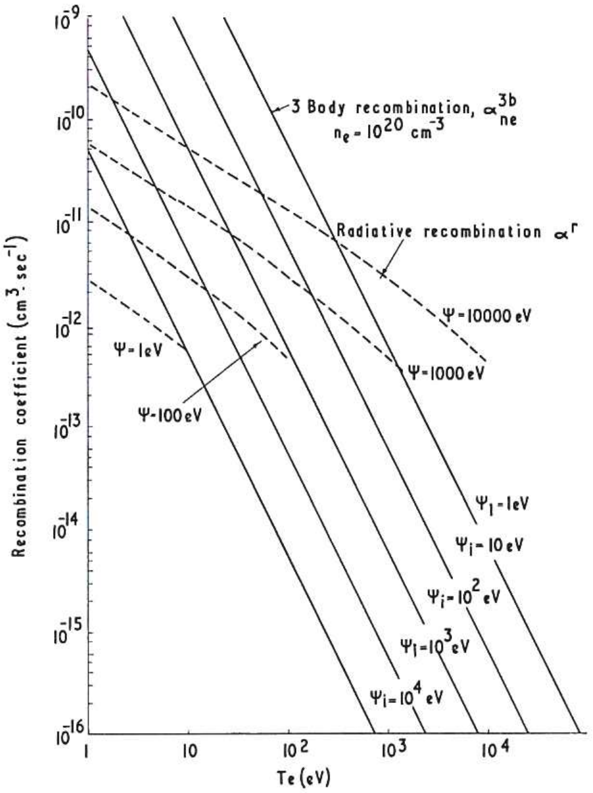

Fig. 7 (CLM-P 196)
Recombination coefficients (cm^3 sec^{-1}) as a function of ionization potential, ψ_1

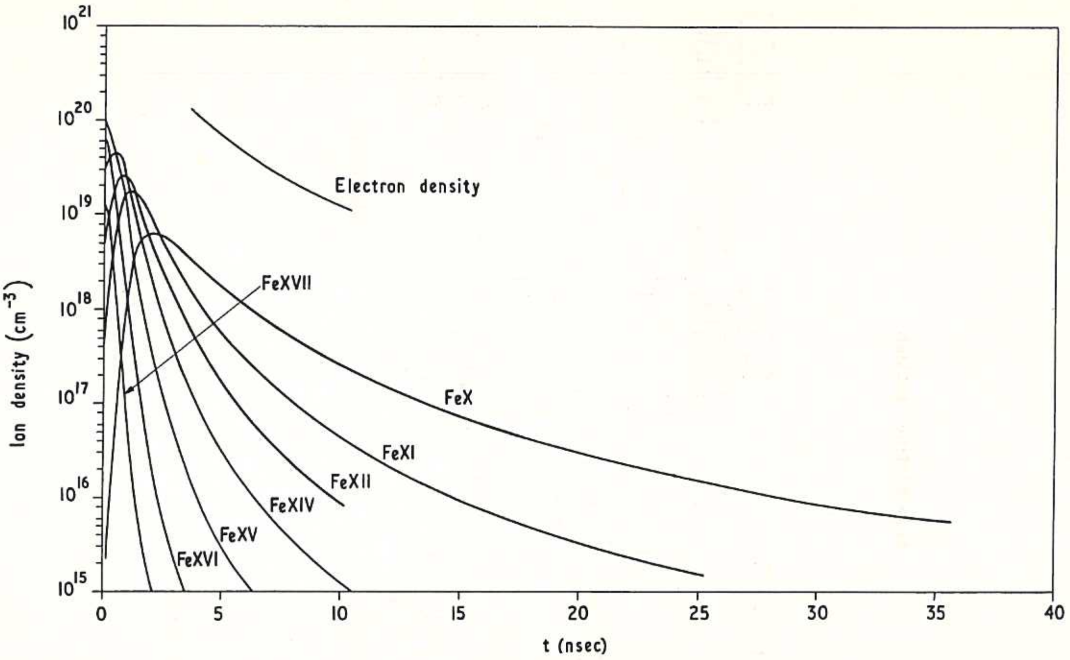

Fig. 8 (CLM-P 196)

Transient ion population in early phase of expanding iron plasma. Initial conditions;
$T_e = 100$ eV, $r_0 = 0.25$ mm, $v_0 = 10^7$ cm sec^{-1}, $N_e = 3 \times 10^{21}$ cm^{-3}

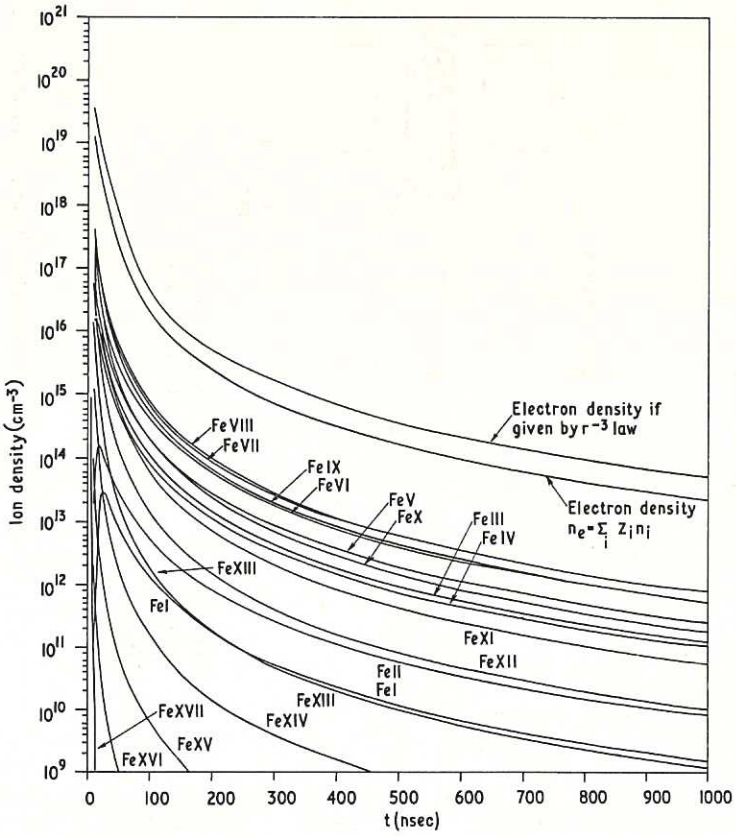

Fig. 9 (CLM-P 196)

Transient ion population in late phase of expanding iron plasma. Initial conditions
$T_e = 100$ eV, $r_0 = 0.25$ mm, $v_0 = 10^7$ cm sec^{-1}, $N_e = 3 \times 10^{21}$ cm^{-3}

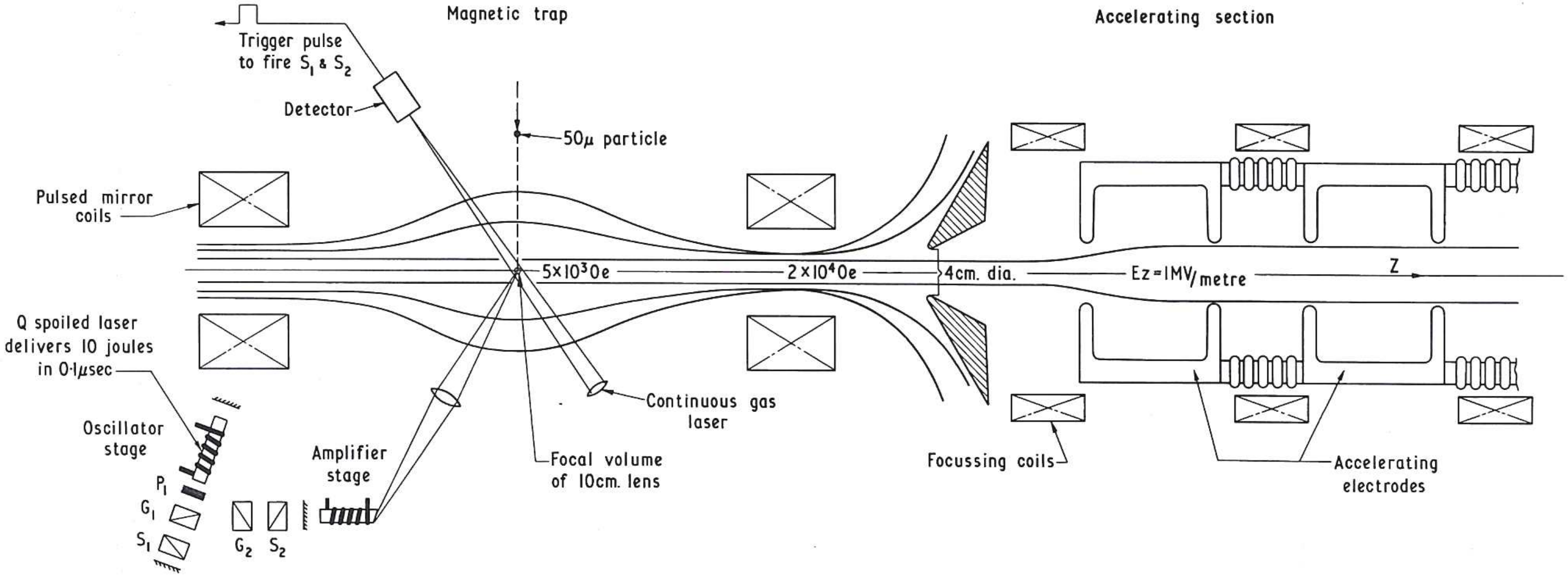

Fig. 10 Schematic diagram of heavy ion source (CLM-P196)