Laser Ion Sources for Particle Accelerators

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Abstract.
There is an interest in accelerating atomic nuclei to produce particle beams for medical therapy, atomic and nuclear physics, inertial confinement fusion and particle physics. Laser Ion Sources, in which ions are extracted from plasma created when a high power density laser beam pulse strikes a solid surface in a vacuum, are not in common use. However, some new developments in which heavy ions have been accelerated show that such sources have the potential to provide the beams required for high-energy accelerator systems.

INTRODUCTION

In this paper I will discuss an application of laser produced plasma in which highly charged ions are created by focussing a high intensity laser beam onto a solid surface and are used as an ion source(LIS) for high-energy accelerator systems.
The ion pulse duration from a LIS is limited to several microseconds, but this is adequate when the ions acceleration is to be made in synchrotron rings. There have been proposals to increase the duty cycle(1,3), but these will not be covered here.
In order to illustrate the novel problems of a LIS, I will report on the work of the collaboration involving the Institute of Theoretical and Experimental Physics (ITEP), the Troitsk Branch of the Kurchatov Institute (TRINITI) and CERN.
With the advent of high power pulsed lasers in the late 1960s, it was realized that laser produced plasma is a copious source of ions (2,3).
The attraction of a LIS to the accelerator designer is that high-charge ions can be obtained and less

expensive accelerators are required to arrive at a given ion energy. At present, there are three types of sources for high-charge state ions used by high energy accelerators. Apart from the LIS these are electron cyclotron resonance(ECR) and electron beam ion sources(EBIS)(4). In all of these, the ions are formed by successive electron stripping by energetic electrons in the plasma. They differ in the balance between plasma density and the containment time of ions in the stripping volume. Electron energies, whether due to electron acceleration or heating through absorption of electromagnetic radiation, must be greater than the ionization energy of the highest charge state required.

A LASER ION SOURCE AT CERN.

At CERN, there has been a programme of ion acceleration which has culminated in the construction of a heavy ion acceleration facility for producing very high energy ion beams that interact with fixed targets(5). Now approval has been given for the Large Hadron Collider(LHC) which will use heavy ions as well as protons(6). The ion center-of-mass collision energy possible is 1200 TeV! However, the ECR source used in this facility is unable to provide the required ion beam intensity. It was decided to investigate whether a LIS could provide sufficient source brightness. The parameters in Table 1 are needed for LHC operation. The aim of the work at CERN(7,8) and TRINITI(9) is to determine the LIS parameters needed to meet these requirements. Because of reliability and repetition rate we use CO_2 gas lasers. Problems addressed are those of laser parameters, ion

TABLE 1. Ion Source Specification for LHC Operation.

Element, charge state	Pb^{25+}	Average current	10 mA
Current pulse duration	6 μs	Extraction voltage	80 kV
Ion beam emittance	$\leq 100\pi$ mm·mrad	Repetition frequency	1 Hz
Operating period	> 300 hr	Number of ions/pulse	$1.5 \cdot 10^{10}$

yields (including energy spread, transverse emittance, pulse duration and beam formation) and target surface deterioration. At CERN we work with a laser oscillator capable of delivering 50 J/pulse, and can extract and accelerate an ion beam while at TRINITI we have the much more powerful and versatile (but lower repetition rate) TIR-1 oscillator-amplifier system with which we can explore yields over a wider range of power density and pulse duration at the target.

Experimental Techniques

Ion Yields

The laser beam enters the vacuum chamber through a NaCl window, goes past the target and is focussed back onto it by the copper mirror, as shown in Fig.1.
The hot, dense plasma formed at the target expands, through the hole in the focussing mirror, towards the entrance slit of either an electrostatic or magnet analyzer where the ion paths are bent to an exit slit.
The analyzer accepts ions within a narrow range of either charge state/energy or charge state/momentum. If the production time and focussed beam diameter are small compared with the ion flight time and path length to the analyzer, the detector signal oscillograph record shows a number of peaks (time of flight(TOF) spectra), appearing at definite times, due to the different charge-states present (Fig.2).
Scanning the analyzer field over successive laser shots enables the velocity distributions, for each ion species, to be determined from the amplitudes and times of flight for each peak. A useful presentation, referred to as a velocity diagram(VD) and used in Figs. 3, 7 and 8, is obtained by locating each TOF spectrum at the analyzer magnet setting along the horizontal axis with the time axis parallel to the vertical axis. The third dimension can be color coded for intensity. Points for different charge states fall in separate areas.
The yield/sr is given by calculating the ion current waveform, from the velocity distributions, normalizing by comparing with ion currents measured at the analyzer entrance slit and integrating each velocity distribution(10,11).

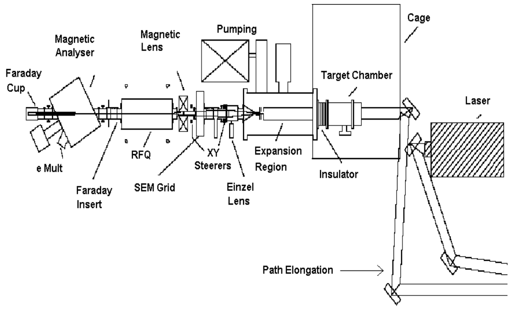

FIGURE 1. Layout of LIS test stand.

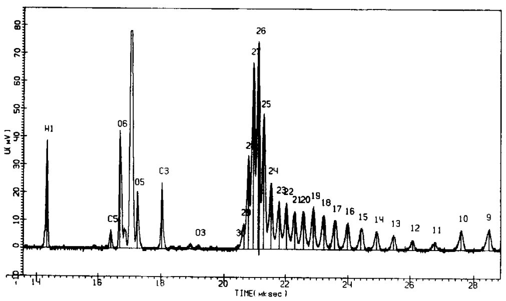

FIGURE 2. TOF spectrum.

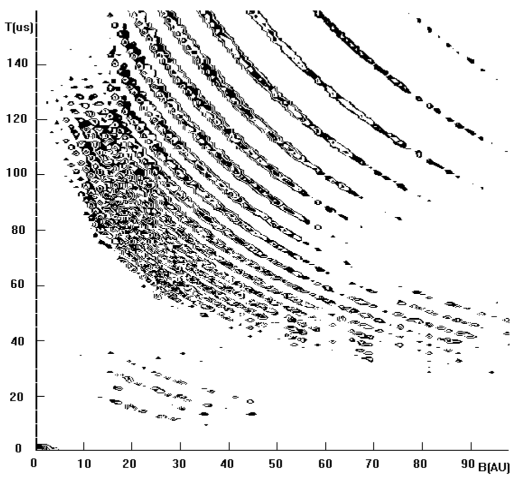

FIGURE 3. Velocity diagram
for

unaccelerated ions.

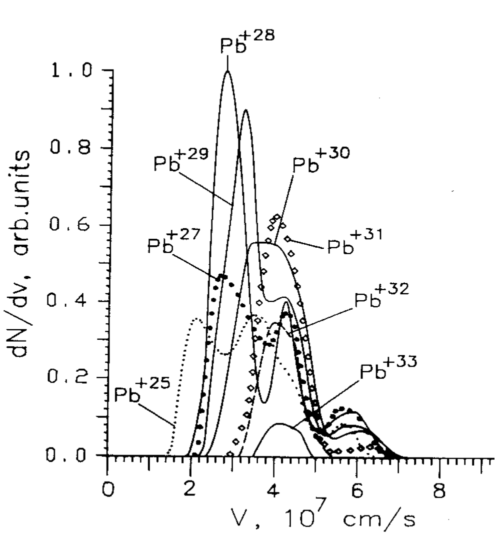

FIGURE 4. Velocity distributions

The pulse length of the ion beam is due to velocity spread and depends on the length between the target and the extraction electrodes. The initial experiments at CERN were encouraging, but a number of questions relating to an operating source could not be answered with the laser power available. We needed to know more concerning the minimum parameters of the laser system such as the energy/pulse, target power density and how changing focal spot diameter affects the ion energy spread as this in turn is important in determining the ion pulse duration and current density at the extraction system. Also we were concerned, at the higher power densities, about target surface deterioration due to cratering. The TIR-1 system was modified to investigate these problems. The lower repetition rate available makes it time-consuming to determine complete velocity distributions, but as can be seen in Fig.4, these are quite similar for the group of higher charge states and the analyzer can be used as a relative yield monitor at a single field setting. Two different laser configurations were employed: a) an oscillator with beam switching to control pulse length, followed by an amplifier, and b) a high power gain-switched oscillator.
A first set of measurements was made with a laser pulse duration of 25 ns and a pulse power of ≈ 100 J/pulse. The maximum power density was estimated to be $4 \cdot 10^{13}$ W.cm^{-2}, using a measured value of focal spot diameter of 65 μm at 40% maximum intensity. At TRINITI it was possible to control the pulse shape and it was observed that pulses with a fast rise-time were the most effective. Measurements were made with different pulse lengths; the highest power density of $6 \cdot 10^{14}$ W.cm^{-2} being achieved with a 2.5 ns pulse. A summary of all measurements is shown in Fig.5.

Beam Formation

The ions must be accepted into the accelerator chain. They are extracted from the expanding plasma by maintaining the target chamber, shown in Fig.1, at a positive potential. The drift must be sufficiently long to ensure a low plasma density and charge separation. Distances in our experiments range from ≈30–300 cm. Because of space-charge effects and ion momentum spread in the expanding plasma, the extraction potential is set to 80 kV.

Fig. 7 was obtained by using the same analyzing magnet as for Fig.3, but this time for an extracted beam. Only a few of the lines, for Ta^{17+} through Ta^{20+}, can be seen. We have been successful in reducing the ion energy spread by modulating the extraction voltage. The resulting reduction in momentum spread can be seen in Fig.8. The analyzer slits were opened to accept this corrected momentum spread and the current for Ta^{18+} ions is shown in Fig.6.

Transverse Emittance

Only ion trajectories in a fixed volume of phase-space can be injected into a subsequent component. In addition, the ion beam must be matched to the next accelerator by a beam transport line containing focussing elements. Space charge defocussing effects have to be included. We have made some emittance measurements in which the extracted beam impinges on a perforated obstacle. Ions pass through the holes and are detected by the multi-channel plate device(MCP). The image on the MCP output phosphor screen is recorded with a CCD camera, which enables the image to be digitized and the transverse emittance to be calculated. In early measurements, the MCP was gated with a pulse of width of $\approx 10\mu$s. Many different ion species are included and, as well, the emittance is a value integrated over the time duration of the gate. The maximum values of trajectory position and angle are directly related to the geometry of the target and extraction aperture, modified by the focussing action of the extraction field and defocussing by space charge fields. The value of the emittance was $\approx 60\pi$ mm.mrad for a current of 4 mA extracted with a voltage of 50 kV.

Acceleration of a LIS beam

We are primarily interested in accelerating heavy ions but we wished to demonstrate that we could accelerate ions from a LIS. A Radiofrequency Quadrupole(RFQ) linac was available but had been designed for medium mass ions. However, it was possible to accelerate ions from an aluminium plasma. The extraction voltage had to be set to $\approx$ 15KV which prevented an efficient ion beam transport through the two matching lenses between the extraction electrodes and the RFQ linac. Nevertheless, we succeeded in obtaining 2 to 3 mA of a mixture of Al^{9+} and $^{10+}$ ions analyzed at the exit of the linac.

Numerical Simulations

As well as experimental work, there have been two activities(12,13) in which the absorption of the laser energy, electron heat conduction, electron-ion temperature relaxation and the expansion of the plasma out to distances of some meters from the target have been simulated numerically. Clearly the entire simulation is extremely difficult so that a number of simplifications both in the atomic physics and the self-consistent kinetic equations have had to be made. In both cases, a single fluid with distinct temperatures for electrons and ions is described. Such a model is sufficient for an adequate description of inverse-bremsstrahlung absorption, but cannot treat specific features of laser-plasma interaction such as resonant effects, nonlinear forces (14). However, anomalous absorption effects are included using a semi-empirical model. Effects due to electrical fields created by charge separation cannot, of necessity, be modelled in these simulations. Although it is necessary to make adjustments of some model parameters such as the electron heat conduction limiting parameter, and considering the necessity to make some simplifications of the atomic physics models, these simulations can reproduce the observed ion yields and energy spectra over the range of laser parameters considered in our work and are extremely useful in arriving at general scaling laws.

SOME OPERATING ION SOURCES

The work towards a high charge state intense source for CERN has now

progressed to the stage that we can nearly complete the specification of the laser system. It will be a two-stage system, with a clean pulse of about 30 ns and a pulse energy of 80 J/pulse, operating at 1 Hz.
I wish now to mention three operational ion sources that use more modest lasers.
The first use of a LIS for a high energy accelerator was at the Joint Institute for Nuclear Research Synchrophasotron at Dubna. In 1976, a target chamber was mounted 150 cm away from the high voltage column of the linac, LU-20, and irradiated by a Nd-glass laser which was focussed through salt lenses producing a power density of $\approx 10^{13}$ W.cm^{-2} at the target. This was replaced in 1983 by a 10 J/pulse CO_2 laser operating at 1 Hz(15).
Table 2 lists some of the ions that have been accelerated.

TABLE 2. Number of Ions/pulse, N_{LU}, at exit of the Dubna Linac, LU-20.

Ion	Target Material	N_{LU}	Ion	Target Material	N_{LU}
$^{6}Li^{3+}$	LiF	$3.5 \cdot 10^{9}$	$^{19}F^{9+}$	Teflon	$2.5 \cdot 10^{9}$
$^{16}O^{8+}$	SiO_2	$3.0 \cdot 10^{9}$	$^{24}Mg^{12+}$	Mg	$1.0 \cdot 10^{9}$
$^{7}Li^{3+}$	LiF	$5.0 \cdot 10^{10}$	$^{28}Si^{14+}$	Si, SiO_2	$1.0 \cdot 10^{8}$
$^{12}C^{6+}$	Graphite	$1.5 \cdot 10^{10}$			

At ITEP, there is a special interest in producing medium mass ions for acceleration in the ITEP synchrotron to produce beams for medical therapy. The LIS turns out to be very successful for carbon ions which are of special interest for this application.
Recently, using a 1 Hz, 10J/pulse carbon-dioxide laser, currents of 30 mA of C^{4+} ions have been obtained.
Another collaboration involving the ITEP group is that with GSI, Darmstadt.
Here the interest has been in producing high-intensity high-mass ions beams in order to measure the absorption of ion beams in plasma. This data is required for investigations involving high-energy particle beams as drivers for Inertial Confinement Fusion (16).
The laser used in the ion source produces a 4J pulse lasting 40 ns at 1 Hz.

After passing through the beam transport line,
which has been specially designed to compensate for space-charge forces,
the Ta^{9+} ions are
accelerated to an energy of 8 MeV/ion by a
RFQ linac. The average current during the pulse was 4 mA.

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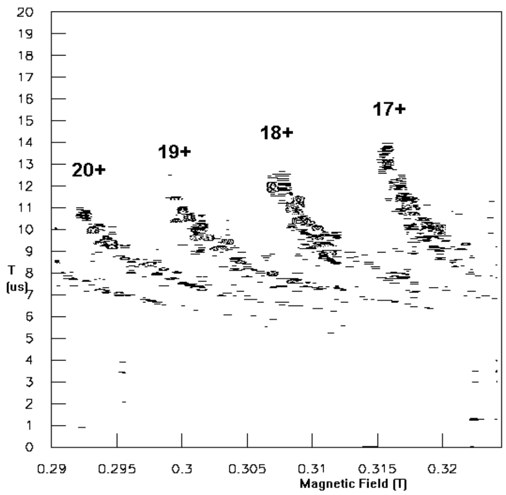

FIGURE 7. Velocity diagram for extracted ions

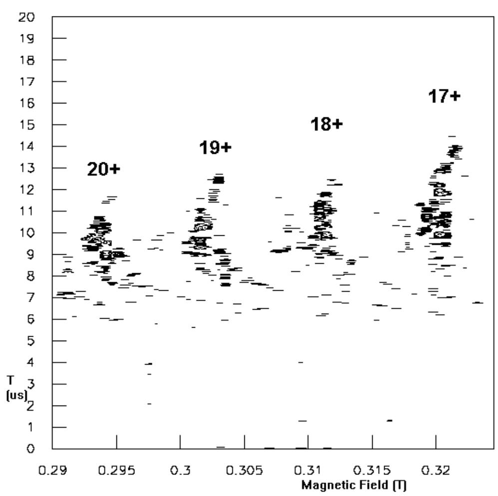

FIGURE 8. Velocity diagram with modulated
extraction voltage.