LASER ION SOURCES FOR HIGHLY CHARGED IONS

T.R. Sherwood

ABSTRACT

The development of laser ion sources is reviewed in the light of possible future requirement for highly charged ions at CERN. After the advent of high power Q-switched pulsed lasers in the 1960’s, there was a number of proposals to use the laser produced plasma as sources of ions. Such ion sources have been constructed for a number of uses and, in particular, for injection of ions into particle accelerators. At CERN, a new test facility has recently started operation. Initial results indicate ion currents in excess of 5 mA for lead ions with charge state about 20.

Paper presented at the 4th International Conference on Ion Sources, Bensheim, Germany, September 30 - October 4, 1991

Geneva, Switzerland
March 1992
1. INTRODUCTION

At the European Centre for Nuclear Research (CERN), we are interested in sources of high charge state ions for our present and future heavy ion beam programs.

In recent years, particle physics experiments have been supplied with high energy beams (=150GeV/amu) of oxygen and sulphur ions\(^3\). This year, a project\(^2\), in collaboration with other laboratories, to accelerate lead ions to well above 100GeV/amu has been approved and is expected to be completed in 1994. For the oxygen and sulphur ions, we were able to use an existing linac injector.

An electron cyclotron resonance ion (ECR) source\(^3\) which produces nearly fully-stripped ions has been used to obtain these beams. It is operated with oxygen as an auxiliary gas and provides a mixed beam with 90% O\(^{6+}\) and 10% S\(^{12+}\) ions. The total current is 100\(\mu\)A at the entrance to the linac. A stripping stage is inserted between the linac and booster synchrotron, so that the circular machines accelerate fully stripped ions. Using multiple turn injection into the booster, a total of 2.10\(^9\) sulphur ions is finally accelerated in the CERN Super Proton Synchrotron.

It is not possible to accelerate heavy ions such as lead (even fully-stripped) in the existing linacs because of the excessive fields needed for the less favorable charge-to-mass ratios of these ions. The lead ion project (see Figure 1) calls for a new linac injector system which will consist of an ECR source, a radio-frequency quadrupole (RFQ) linac to accelerate the ions from 2.5 keV/amu to 250keV/amu and an interdigital 100/200MHz linac to produce 4.2MeV/amu ions. The ion source\(^4\) is to supply 80\(\mu\)A of ions with charge state \(\zeta>28\) for 600\(\mu\)s.

The interest in heavy ion beams at CERN is not limited to these projects. The proposal to construct a large hadron collider (LHC)\(^5\) in the 28km circumference electron-positron collider tunnel has provision for heavy ion-liquid collisions with a total centre of mass energy of \(= 1000\)TeV. We will not be able to reach the design luminosity of \(1.8 \times 10^{36}\)cm\(^{-2}\)s\(^{-1}\) with the lead ion facility mentioned above without further modifications. Various options for attaining the necessary beam brightness have been described\(^6\).

It became evident that the most straightforward way towards closing the gap was to upgrade the ion source.

There is always a compromise between obtaining a large number of ions and reaching a high charge state. At CERN, we must have a sufficiently high charge state before injection into the circular accelerators to obtain the required rate of acceleration and life-time due to charge exchange. This implies that using a low charge state ion source, even if of high intensity, requires a number of stripping stages with consequent loss of ions. The early stripping stages may in fact be impractical and the linac injector becomes long and expensive. In our present schemes, we compensate for low intensity by using multi-turn injection into the booster injection synchrotron. Unfortunately, this dilutes the horizontal transverse phase-space density. Beam-cooling schemes to counter this dilution are complicated and expensive but were considered because cooling rings already existed at CERN. However, in preparation for the future, it was felt that something should be done about the ion source itself.

Most sources of high-charge state ions involve successive ionization by electron impact in plasma-like environments. The charge state attained depends on the product of electron density and containment time. The electron energy must be sufficient to ionize the lowest level atomic electron to achieve the required charge state. Three types of sources come readily to mind. Detailed descriptions, recently published, may be found in the book edited by Brown\(^7\) and the proceedings of the last ICIS conference\(^8\).

1) The Electron Beam Ion Source (EBIS), in which ions are produced by electron impact and are trapped in the potential well of the electron beam. Limitations arise from the difficulty in obtaining high electron densities and the yield becomes limited as the electron beam is neutralized. Long containment times (tens of seconds) are possible giving rise to low yields of xenon ions with \(\zeta<50\).

2) The Electron Cyclotron Resonance Source (ECR) in which plasma electrons are heated by absorbing microwave (10 to 20 GHz) power to enable ionization. These sources are normally operated in nearly continuous mode and are the presently preferred type at CERN for heavy ions. Containment time is some tens of milliseconds. The electron density is limited, as increasing gas pressure leads to loss of high-charge state ions due to collisions with low-Z contaminants.

3) The Laser ion Source in which energy from a well-focused, short laser pulse creates a very dense plasma with kilovolt electron energies.

Over the last twenty years, the possibility of using laser ion sources has been considered a number of times. We had heard that there was some development of such sources in the USSR but, at CERN, detailed information was almost non-existent. During a visit to the Joint Institute for Nuclear research, Dubna, the author was impressed with
the possibilities. There they had mounted a target on the high-voltage platform; apart from a stepping motor to expose a fresh target surface, no power was required at the platform potential. The carbon dioxide pulsed laser consisted almost entirely of a pulsed power supply and was at ground potential. They claimed that they were producing reliable beams of nearly fully stripped medium-Z ions (up to silicon) that could be accelerated through their 20 MeV linac and 10 GeV Synchrophasotron with intensities comparable with those obtained for oxygen at CERN with an ECR source. This development was reported at Debrecen in 1987.

Since there were probably sufficient protagonists, in Europe and elsewhere, willing to develop ECR and EBIS sources, and because we wanted to engage in high-charge ion source work, we decided to follow the lead given by the Soviet Union and also, as we discovered, by the Technical University at Munich, where work was underway.

This talk is given from the perspective of one willing to try and exploit the possibilities of a using a laser produced plasma as a source of heavy ions for injection into an accelerator complex such as at CERN. Since Professor Bykovsky has covered many topics relating to laser ion sources, I will limit myself mainly to those features that pertain to producing ions in high-charge states.

2. HISTORICAL REVIEW

There is a good summary of the earliest laser produced plasma work before 1970 in the book by Ready. At this time the surprise of discovering high energy ions (several keV per ion) had been assimilated. This energy was found to correspond to the speed at which the plasma plume expanded into the vacuum away from the target. Laser irradiances were \(10^{10}\text{W.cm}^{-2}\). Another survey from this period is given by DeMichelli.

The first serious and detailed proposal to use a laser produced plasma as a source of ions for a particle accelerator was made in 1969 by Peacock and Pease. Observation of line spectra for iron showed the presence of charge states up to \(\zeta=15\) at distances 2mm from the target. Their analysis of recombination led them to predict that the average charge state after plasma expansion would be in the range 5 to 7.

By the time of the ion source conference in Gatlinburg in 1971, much more information on the production of high charge states was available as reported by Tonon, from the CEA laboratory at Limeil, Neodymium glass lasers with power densities in the \(10^{12}\text{W.cm}^{-2}\) range were available and charge states as high as 23+ were reached for cobalt. Furthermore, the ions with the higher charges were emitted into cones with quite narrow angles (10 to 20°).

Determination of energy spectra with both electrostatic and magnetic analyzers showed that although the highest charge state ions had the higher average energy, they tended to have the same maximum energy which increases with laser flux (e.g. 20keV for a flux of 2.10^{13}\text{W.cm}^{-2}).

Following this period, the activity at Limeil came to an end. The application of a laser produced plasma as a source of ions for injection into a high-energy particle accelerator took place at the 10GeV synchrophasotron at the Laboratory for Nuclear Reactions at the Joint Institute for Nuclear Research, Dubna. Most of this development concerns light or medium-mass ions (up to silicon). Just as at CERN, the linac injector cannot accelerate particles with values of \(\zeta/A\) much lower than 0.5 even in the 2\(\beta\) mode.

The advantage of using a gaseous (carbon dioxide molecular laser) became obvious in an operational system. The problems of target heating and vacuum degradation mentioned by earlier review authors are not a problem because of the low repetition rate of circular hadron accelerators.

Apart from the work at Dubna, there has been no major attempt, during the last 12 to 15 years, to develop laser ion sources for high-energy accelerators. There has been considerable interest in the observation of very high energy ions at the large laser laboratories around the world (see for example the summary by Horó), however, these systems are inappropriate in the context of injecting ions into conventional accelerator complexes.

Nevertheless, there are at least three laboratories at which this subject was pursued over this period, but with relatively low-energy laser pulses \((3 \text{ to } 11\text{J/pulse})\). Using neodymium-YAG lasers, an ion source for a Van de Graaff accelerator has been employed at the Technical University of Munich and a source has been constructed at the University of Arkansas. The work at Munich was continued using a neodymium glass laser at the Max Planck Institute for Quantum Optics nearby. The earlier work was extended to higher pulse power \((30\text{J})\). Different wavelengths \((\lambda=1.06, 0.53\mu\text{m})\) and pulse widths \((30\text{ps to } 10\text{ns})\) were used.
The group at the Institute for Theoretical and Experimental Physics, Moscow, have been studying ion production using carbon dioxide lasers\textsuperscript{23, 24}. Its interest ranges from sources of carbon ions for heavy ion inertial fusion research to sources as required at CERN.

3. THE SITUATION TODAY

Amongst the papers to be presented at this conference a five or six may be said to bear on the production of high charge ions from laser produced plasma. This is a considerable increase over the number presented at the last ICIS conference in Berkeley, in 1989, where nothing appeared on this subject. There will be reports by teams from JINR(Dubna) - Moscow Engineering Physics Institute, Munich Technical University - ITEP(Moscow) - GSI and CERN(Geneva) - ITEP(Moscow).

Perhaps the relative lack of interest in this field can be related to difficulties arising from obtaining lasers that can be operated at high repetition rates for long periods of time, the short duration of the ion pulse and pulse reproducibility. For injection into slow cycling circular accelerators repetition rates may be in the region of 1HZ, a value that should be possible with carbon dioxide lasers. In fact, at ITEP there is a system which can run for the order of 10\textsuperscript{6} pulses at this rate with a pulse energy about 1J. As mentioned earlier, the short pulse length may be used with advantage to conserve beam brightness. Since it is easy to operate the source at a high potential (very little power is needed on the high-voltage platform) and it is not necessary to work with very low ion velocities between the source and the beginning of the linac injector.

At CERN, in collaboration with ITEP, we are getting the first results from our test facility which is described\textsuperscript{25} in greater detail at this conference. However, some of the results concerning the observed average charge state are presented in this paper. These results are compared with calculations made by I. Rudskoy of ITEP using a simulation program for the expanding plasma. In this simulation, the plasma is represented as a series of discs travelling away from the target on the right of Figure 2.

In figures 3, 4 and 5, the average charge state is plotted as a function of ion velocity. The solid lines are calculated from the simulation program. Figure 3 is for a plasma that has expanded a distance 320cm from a lead target. The two sets of experimental points are for different laser focal spot diameters at the target. Figures 4 and 5 display data for constant laser parameters but with the ion analyser at different distances from the target. The curves marked 1 are the calculated results at the target just after the laser pulse and show the situation as the plasma is starting to expand. The results for distances away from the detector can interpreted as due to low velocity ions being more likely to suffer recombination.

Figure 4 shows data for a laser power density $= 1.5\text{GWcm}^{-2}$ and duration 200ns. The calculated temperature of the plasma at the end of laser pulse is 70eV. At higher initial temperatures the recombination is much less drastic as shown by the theoretical curves for a temperature of 340eV in Figure 5. It is planned, with the collaboration of the Troizk branch of the Kurchatov Institute, to use a more powerful laser and obtain this plasma temperature.

Estimates of the yields of ions of different charge states have been made by B. Sharkov. These are shown in Table 1. Yields into solid angles of $2.2.10^{-3}$ and $1.5.10^{-5}$ st. are given.
**Table 1. Lead ion yields for two different solid angles.**

<table>
<thead>
<tr>
<th>Charge State</th>
<th>Solid angle at Detector (Ω steradians)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω = 1.5×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Current (µA)</td>
</tr>
<tr>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>21</td>
<td>41</td>
</tr>
<tr>
<td>20</td>
<td>52</td>
</tr>
<tr>
<td>19</td>
<td>62</td>
</tr>
<tr>
<td>18</td>
<td>58</td>
</tr>
<tr>
<td>17</td>
<td>65</td>
</tr>
<tr>
<td>16</td>
<td>83</td>
</tr>
<tr>
<td>15</td>
<td>117</td>
</tr>
</tbody>
</table>

4. **RECOMBINATION**

The importance of the loss of high charge ions in the expanding and cooling plasma due to recombination was recognized in the early proposals for the design of laser ion sources. An experimental study of this subject, for carbon ions, was made by Tallents. As these authors note, simple considerations of the recombination processes predict a strong reduction in the number of highly charged ions. Experimental results show, however, a smaller effect than expected. One explanation is that a 'freezing' of the charge state distribution is produced due to energy fed to the free electrons in three-body recombination. Perhaps there are other techniques that could prevent the plasma cooling too rapidly. Further discussion of this subject will be given by the ITEP - GSI group later in the conference. As discussed above, the use of higher laser pulse energies also reduces the degree of recombination. This is associated with the higher maximum velocities associated with the highly charged ions.

There is an interplay between designing suitable extraction systems and recombination losses. If the plasma can be allowed to expand, ions and electrons can be more readily separated, but if the number of highly charged ions is severely reduced due to recombination, extraction closer to the target, at higher plasma density may be required, with increased problems due to space-charge in the extracted beam.

5. **EMITTANCE AND ENERGY SPREAD**

The emittance of beams from laser ion sources is generally considered to be low and there is no reason to challenge the earlier estimates of transverse emittance which are consistent with the normalized emittance, \( \varepsilon_n \), for a temperature \( T \) being given as \( \varepsilon_n = 2a\sqrt{kT/Mc^2} \), where \( a \) is the spot radius and \( M \) the ion mass. The effective values will be increased by extraction as well as due to space charge effects.

In the recent measurements at CERN the mean energy for the higher charge states is about 4keV/charge and the energy spread is comparable to this value. This range of ion velocity gives a variation in flight time, over a path of 3m. of \( \approx 6µs. \)
6. CONCLUSION

The latest results indicate, for the type of application needed at CERN, that a laser ion source might be competitive with other sources producing highly charged heavy ions. There are technical problems to overcome. A sufficiently powerful (= 100J/pulse) laser that can operate at a repetition rate of about 0.5 to 1 Hz continuously for some millions of pulses has to be developed. The inherent energy spread requires that the target is mounted at a potential of about 100kV or that a variable correcting voltage be applied. The preinjector voltage would be higher than is now used for ECR - RFQ combinations but, as practically no power is required on the platform, this gives the advantages of higher injection energy into a RFQ which may be designed to operate at a higher radio-frequency. Care must be taken in the linac design to ensure adequate cavity field stability in the presence of the short non-constant pulses supplied by the source. At CERN, it is proposed to continue studies in collaboration with ITEP and the Kurchatov Institute, to confirm our preliminary results, to increase ion yields and finally to specify a source able to meet the long term requirements for the future.
TO EXPERIMENTS  

$4 \times 10^8$ Pb IONS/SPS PULSE  
$50 - 160$ GeV/u

Figure 1. Schematic layout for the CERN lead ion project
Figure 2. Diagram for plasma simulation
Figure 3. Av. charge state (Lead ions) vs ion velocity at 3.2m from target.

- Triangle: focal spot position adjusted for max. ion charge state
- Circle: focal spot shifted by 1cm
Figure 4. Average charge state v ion velocity (Lead ions)
Figure 5. Average charge state v ion velocity (Lead ions)
Bibliography