A SUMMARY OF LASER ION SOURCE WORK WITH DIFFERENT LASER WAVELENGTHS

R. Scrivens

Work with laser-plasma and laser-target interactions are widespread, but in general they concentrate on the use of high power lasers for Inertial Confinement Fusion (ICF), X-ray generation and material processing. The use of laser-plasma as a source of highly-charged medium or heavy mass ions is only studied at a few institutes. Furthermore, most of the results have been obtained using CO_2 lasers (which can provide high energy pulses at reasonable rep-rates of at least a few shots per minute) or neodymium lasers (Nd:YAG or Nd:Glass). Of other laser types, Excimer, Iodine, Ruby and Titanium Sapphire (among others) can give high peak power pulses which may be of interest for Laser Ion Sources (LIS).

This short note will not discuss the physics of operating a LIS at different wavelengths, but summarizes the known work at different institutes where charge-state distributions and ion particle numbers have been measured. Other CO_2 laser sources are not discussed.

The most important parameters of the experimental set-ups are shown with some results in Table 1. Surprisingly, many papers still fail to detail some of the most basic parameters of the laser (e.g. pulse length). For ion yield, most papers give the highest charge-state seen, but few give any indication of the number of ions obtained from either from the total or in particular from one charge-state.

The following symbols are used to describe the experimental geometries: α_t is the target illumination angle and L_{te} is the target to extraction distance.

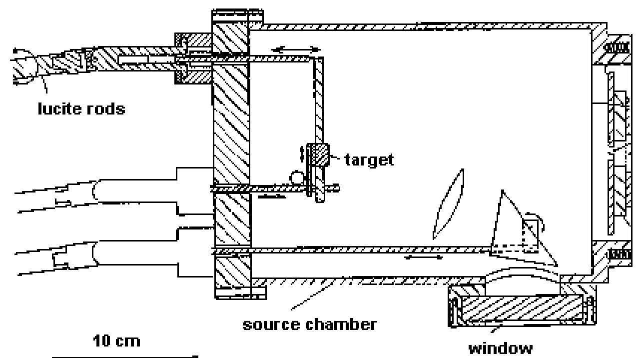
U. Herleb - CERN [[1]]

Primarily this source was used for studies of space-charge compensation with a ferroelectric cathode. The source (using an Nd:YAG laser) had an isolated target chamber allowing beam extraction. An Electrostatic Ion Analyzer (EIA) was used to measure charge-states. Al^{7+} was the highest charge-state seen with Al^{5+} at the distribution peak. The distance from target to extraction is unknown. The target illumination angle is estimated to be α_t ~20^o from the experimental schema.

The Munich Source [[2]]

Used as a source on a Van de Graaff generator. Charge-states up to Au^{15+} were seen, with a high charge-state peak at 11+. It is not easy to find a consistent set of values for ion currents. With a Ta target, 500 mA peak current (total) was seen with a 40 mm extraction aperture, but it appears without extraction voltage. The ion collector was a biased metal plate. The target to extraction distance is not explicitly given, but can be estimated as L_{te}~200 mm and the α_t~20^o from the experimental schema. With a 5 mm extraction aperture, and a ramped extraction voltage from 3 to 6 kV, ~11 mA (total) was measured 2.26 m downstream of extraction.

The experimental schema and a TOF current distribution for gold ion beam measured 2.26 m after extraction (including and Einzel lens in the beam transport) are shown in Figure 1.



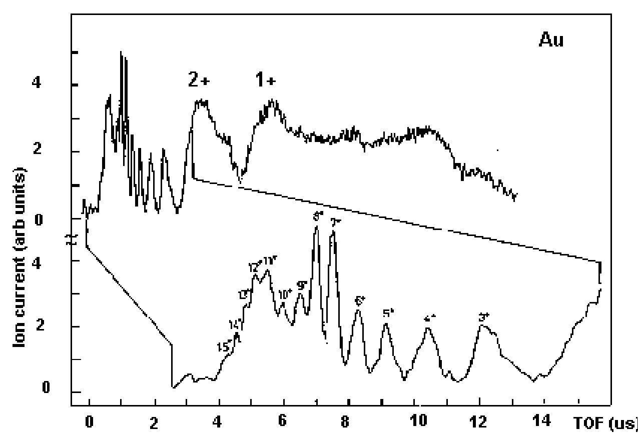


Figure 1. Experimental schema of the Munich laser ion source, with a TOF measurement of the Au beam, after [[2]].

The Kaiserslauten source [[3]]

Principal application of this source (with α_t =45^o) was to test the recombination of Ta ions in a plasma, so no high voltage extraction system was available. A 180^o multi-channel analyzer was used for charge-state distributions. Results were published for up to Ta^{6+}, but it is not clear whether higher charge-states were seen, but were not interesting for the application.

PERUN - Prague [[4],[5],[6]]

Using the PERUN Iodine laser system many experiments have been performed for ion generation, in particular for different harmonics of the laser light.

For the first harmonic (1.315 μm) charge-states as high as Ta^{53+} have been seen, with energies above 4.8 MeV (90 keV/charge) where α_t=30°, L_{te}=94 cm and the EIA detection angle was 10° from the target normal and a charge-collector 40° below the EIA. The abundance of all charge-states from Ta^{1+} to Ta^{45+} was found to be comparable and in the range of (2.0±1.5)%. Current densities were 22.8 mAcm^{-2} (assumed total), but the lack of an isolated target chamber makes extraction and therefore reliable current measurements difficult.

For the 2nd and 3rd harmonics (657 nm and 438 nm - E=17.8 and 17.6 J laser energy respectively) a similar high charge-state feature is seen, and ~10^8 Ta^{40+} ions are reported for the 3f case.

IPPLM - Warsaw [[6]]

Two different focusing-target set-ups are described for this Nd:Glass laser system. With the laser normal to the target and a EIA at 45°, charge-states up to Ta^{27+} were seen with an energy of ~650 keV (~24 keV/charge) with very small abundance, while Ta $^{20+}$ is seen with to provide ~0.1% of the total ion number. A full charge-state distribution is shown for this case, with arbitrary units.

When the laser target illumination angle was changed to 45° and the EIA put on the target normal, up to Ta^{42+} (E>1 MeV) and Pb^{34+} (E~1.1 MeV) were registered, but no complete charge-state distribution is shown in this case. It is not clear why it is possible to ionize Ta_{181} more highly than Pb_{208} in this case. No absolute ion numbers or ion currents are given.

Alberta - KrF and Ruby [[7]]

Investigation of the charge-states and velocity distributions for both KrF (248 nm - τ=20 ns) and Ruby (694 nm - τ =25 ns) lasers, including similar power density measurements are reported. Furthermore, the KrF could be operated with 2 ns pulses with the same total energy. The experimental set-up included a novel spectrometer with a time dependent electric field and 12 charge collectors to measure charge-state distributions in a single shot (although not for many charge-states).

α_t is not given, but a quartz focusing lens was used, excluding the possibility of near normal illumination. The target to detector distance was 800 mm. The distributions were also measured as a function of angle from the surface normal.

With the 2 ns KrF pulse up to 20 A/St was measured (equivalent to ~20 mA in a 3 cm diameter aperture) for Al^{7+} was measured with the 2 ns pulses, with a corresponding value of 0.4 A/St for Al^{4+} for the 20 ns pulses. In both cases the charge-state is the highest detailed in the results.

When the Ruby and KrF laser induced pulses are compared under similar power density regimes (i.e. 25 ns and 20 ns pulses respectively), the 694 nm Ruby laser induces slightly higher charge-states. A current density of 20 A/St is shown for Al^{4+} (at 694 nm) in comparison with 0.4 A/St (at 248 nm).

A summary of the average charge-state as a function of velocity for different laser pulses is shown in Figure 1.

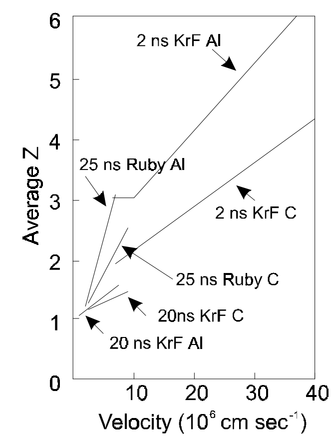


Figure 2. Average charge-state as a function of velocity for different experimental conditions. Each line is labeled with the laser pulse length, laser type and target element. After [[7]].

Atomic Clusters [[8],[9]]

A Ti:Sapphire laser (E<20 mJ) with 150 fs pulse width was focused into a jet of atomic clusters of xenon. The clusters explode after being super-heated with highly ionised ions being emitted (with spherical symmetry).

Using a multi-channel plate as a detector, ions up to Xe^{50+} are seen with energies as high as 1 MeV. The average ion velocity is ~45 keV, averaged over all states, with the highest intensity charge-states apparently equally distributed from 1+ to >20+.

The process is highly efficient from the conversion of laser energy into the total number of ions and their kinetic energy, with most of the laser light being absorbed by the gas, then most of the energy in each cluster being transferred to the ions. This is in contrast to a solid target source, where most of the energy is conducted into the target.

Other Experiments

Two further experiments for ion generation with a laser - solid target interaction are given in [[10],[11]], where the basic properties of the source are not given, but some idea of the charge-states obtained are.

In [[10]] a Nd:YAG (0.8 J) laser source was used and the charge-states of ions reflected off a gold surface was studied. It appears that Al^{7+} was seen from the source, but no quantities are given.

A milliJoule laser (type unknown) at 400 nm with a 140 fs pulse was investigated in [[11]], where a magnetic analyzer and streak camera were used to study the resulting charge-states. Surprisingly with an aluminum target, only charge-states up to Al^{3+} was observed with fully stripped carbon, and small numbers of oxygen ions up to 3+. No ion abundances are given.

References

[1] U. Herleb, H. Riege, *Experiments on ion space-charge neutralization with pulsed electron beams*, Beams 96 conf. Prague, 1996.

[2] J. Sellmair, G. Korschinek, *The Munich Laser Ion Source*, Nucl. Instrum. Meth. A286, p473-477, (1988).

[3] A. Rupp , K Rohr, *Velocity-resolved recombination dynamics in a laser-produced Ta plasma*, J. Phys. D: Appl. Phys. 28 p468-472, (1995).

[4] K. Rohlena, B. Kralikova, L. Laska, K. Masek, M. Pfeifer, J. Skala, P. Straka, J. Farny, J. Wolowski, E. Woryna, W. Mroz, A. Golubev, B. Sharkov, A. Shumshurov, H. Haseroth, H. Kugler, K. Langbein, J. Tambini, *Ion Emission from high Z laser plasmas*, Proc. Int. Conf. on Linear Accelerators 1996, Geneva, Switzerland.

[5] L. Láska, J. Krása, K. Masek, M. Pfeifer, P. Trenda, B. Bralikova, J. Skala, K. Rohlena, E. Woryna, J. Farny, P. Parys, J. Wolowski, W. Mróz, A. Shumshurov, B. Sharkov, J. Collier, K. Langbein, H. Haseroth, *Multiply charged ion generation from NIR and visible laser- produced plasma*, Rev. Sci. Instrum. 67 (3) March (1996).

[6] W. Mróz, P. Parys, J. Wolowski, E. Woryna, L. Láska, K. Masek., K. Rohlena, J. Collier, H. Haseroth, H. Lugler, K.L. Langbein, O.B. Shamaev, B.Y. Sharkov, A. V. Shumshurov, *Experimental investigations of multicharged ion fluxes from laser-produced plasmas*, Int. Symposium on Heavy Ion Inertial Fusion, Princeton, (1995) and Fusion Engineering Design, May 1996.

[7] YY. Tsui, R. Fedosejevs, AA. Offenberger, *Experimental study of charge state distribution from KrF and ruby laser-produced plasmas*, Phys. Fluids B, 5 (9), p3357-3368, (1993).

[8] T. Ditmire, JWG. Tisch, E. Springate, MB. Mason, N. Hay, RA. Smith, J. Marangos, MHR. Hutchinson, *High-energy ions produced in explosions of superheated atomic clusters*, Nature, vol. 386 (6), p54-56, (1997).

[9] T. Ditmire, T. Donnelly, RW. Falcone, MD. Perry, *Strong X-ray Emission from High-Temperature Plasmas Produced by Intense Irradiation of Clusters*, Phys. Rev. Lett. 75 (17), p3122-3125, (1995).

[10] RH. Hughes, DO. Pederson, XM. Ye, *Observation of fractional neutralization of slow multicharged ions by impact on a metal surface*, Appl. Phys. Lett vol. 47 (12), p 1282-1284, (1985).

[11] G. Guethlein, J. Bonlie, D. Price, R. Sheperd, B. Young, R. Stewart, *Charge and mass resolved time of flight observations of 140 fs laser produced ions*, Rev. Sci. Instrum. vol. 66 (1), p333-335, (1995).

Experiment	ref	Laser (λ/µm)	E (J)	τ (ns)	P_t (W/cm^2)	element + charge-state	Ion current
U.Herleb - CERN	[[1]]	Nd:YAG (1.06)	0.8	5	$3x10^{10}$	Al^{7+}	Al - 20 mA / 4 µs / 12 mm
Munich	[[2]]	Nd:YAG (1.06)	0.3		10^{12}	Au^{15+}	Ta - 500 mA / 5 µs / 40 mm
Kaiserslauten	[[3]]	Nd:YAG (1.06)	0.21	20	10^{11}	Ta^{6+}	
PERUN - Prague	[[4]-[6]]	Iodine (1.315)	50	>0.35	10^{15}	Ta^{42+}	Ta - 22.8 mAcm^{-2} @ 94 cm
IPPLM - Warsaw	[[6]]	Nd:Glass (1.06)	<20	1	10^{14}	Ta^{27+} + Ta^{42+}	
Alberta, Canada	[[7]]	KrF (0.248)	1	2-20	1-$80x10^{11}$	Al^{7+}	See text
Alberta, Canada	[[7]]	Ruby (0.694)	1	25	10^{11}	Al^{4+}	See text
Imperial, London	[[8],[9]]	Ti:Saph (0.780)	<0.02	150 fs	$>10^{16}$	~Xe^{50+}	
Arkansas	[[10]]	Nd:YAG	0.8			Al^{7+}	
LLNL	[[11]]	? (400 nm)	mJ	140 fs		C^{6+}	
CERN LIS		CO_2 (10.6)	29	70	10^{12}	Ta^{24+}	Ta - 60 mA / 5 µs / 30 mm

Table 1. Some important parameter from laser ion source operating with differing laser systems, taken from the quoted references. The power densities are usually estimated values, and should be taken with some caution. The charge-state indicated is normally the highest seen (not the most abundant).