Review of Laser Driven Sources for Multi-Charged Ions

M. Okamura (BNL)
S. Kondrashev (ANL)
High current multi charged heavy ion sources

- **Electron cyclotron resonance ion source (ECR)**
  - CW operation
  - Well established
- **Electron beam ion source (EBIS)**
  - Flexible operation
  - High charge states from very heavy species
- **Laser ion source (LIS)**
  - Powerful pulse current
  - Simple structure
High current multi charged heavy ion sources

- Laser ion source (LIS)
  - Backward ablation
- Forward emission
- Selective ionization
High current multi charged heavy ion sources

- Laser ion source (LIS)

1969 First idea was proposed by Byckovsky, Peacock and Pease.
1977 JINR Dubna Cr\textsuperscript{13+} (Synchrophasotron)
1988 Technical University of Munich, ITEP (Van de Graaff)
1994 GSI, ITEP Ta\textsuperscript{10+} (RFQ)
2000 ITEP C\textsuperscript{4+} (Synchrotron)
Production of laser plasma

Expanding plasma
Laser light
Features of laser plasma

- Very high density plasma induced from a SOLID target.

- Plasma expands from the target.

- Initial velocity of the plasma expansion depends on laser power density. (Ions have initial velocity, about 100 eV/u)

- Total amount of ions depends on laser power.

- Charge state distribution depends on laser power density.
  (High power density $\rightarrow$ Highly charged states)
Solid targets
Solid targets
Solid targets
Solid targets

0.2 mm
Solid targets
Solid targets

The volume is:

$$\frac{1}{3} \pi r^2 d = 3.33 \times 10^{-13} \text{ m}^3$$

$r = 0.1 \text{ mm}$
The volume is:

\[ \frac{1}{3} \pi r^2 h = 3.33 \times 10^{-13} \text{ m}^3 \]

Assuming an Alminum target, the density is about 2.7 g/cm³, and the volume contains:

\[ 2.0 \times 10^{16} \text{ ions.} \]
Solid targets

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\]

If we get 1 μs pulse with charge state 10+ beam,
\[
6.02 \times 10^{23} \times \frac{2700}{27/1000} \times \frac{1}{\left(\frac{r^2 d}{10^{-6}}\right)} = 32200 \text{ A}
\]
Probably only 1% are ionized.
Roughly 320 A beam is produced.
Solid targets

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Probably only 1% are ionized. Roughly 320 A beam is produced.
Beam current and Pulse length

$^{27}\text{Al}^{10+}$ and $^{181}\text{Ta}^{1+}$ ion currents (into 1 cm$^2$ aperture) and pulse lengths dependences on distance from targets.

\[ \tau \propto L \]
\[ I \propto L^{-3} \]

$L$ : Distance from target to extraction point

Al - 3 J/30 ns Nd-glass 1062 nm laser ($10^{11}$ W/cm$^2$)
Ta - 1 J/5 ns Nd-YAG 532 nm laser ($10^{9}$ W/cm$^2$)
LIS development for LHC

Requirements
- Ion species – Pb\textsuperscript{25+}
- Current – 8 mA
- Pulse length – 5.5 $\mu$s
- Rep-rate – 1 Hz

100 J/1 Hz MO-PA CO\textsubscript{2}-laser system
LIS development for LHC
Laser pulse statistics (generator mode)

Pulse power spectra
- Number of shots
- Pulse power, GW

Pulse width spectra
- Number of shots
- Pulse width [ns]

Laser pulse power
- Pulse power, GW
- <P> = 0.96 GW
  Sigma = 0.05 GW

Pulse duration
- PWHM, ns
- <FWHM> = 88 ns
  Sigma = 5.3 ns
LIS development for LHC
Laser pulse statistics (MO–PA mode)

MO&PA  90 J operation of 1 hr 15 min at 1 Hz

1 hr  0.25 Hz
LIS development for LHC
Lead ion generation

First results from LIS - December 2002

Preliminary

This charge-state distribution, combined with an average current of 0.363 mA over 4 microseconds, 1750 mm from the target, leads to $2.3 \times 10^{10}$ Pb$^{27+}$ ions at a pulselength of 3.6 microseconds for the standard extraction geometry (aperture 34 mm)

The project was unfortunately stopped in 2003.
Need a powerful laser??

Glass-laser

<table>
<thead>
<tr>
<th>Nd-Glass-Laser</th>
<th>B.M.industries SERIE 5000</th>
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<tbody>
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</tr>
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<td>Divergence</td>
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<tr>
<td>Repetition rate</td>
<td>45 second cooling time needed per shot</td>
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YAG-laser

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<td>Repetition rate</td>
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$\sim 10^{11} \text{ W/cm}^2$  $\sim 10^{12} \text{ W/cm}^2$
Need a powerful laser??

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$\sim 10^{11}$ W/cm$^2$  $\sim 10^{12}$ W/cm$^2$
Plasmas using conventional lasers in RIKEN

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$\sim 10^{11}$ W/cm$^2$  \hspace{2cm}  $\sim 10^{12}$ W/cm$^2$
Charge states distribution using small lasers

AI : Glass

AI : YAG

Iron : Glass

Iron : YAG

$\sim 10^{11}$ W/cm$^2$

$\sim 10^{12}$ W/cm$^2$
Charge states distribution using small lasers

Silver : Glass

7+ 9+ 11+

Silver : YAG

7+ 15+ 16+ 20+

Ta : Glass

3+ 4+ 5+ 6+

Ta : YAG

7+ 8+ 9+

$\sim 10^{11}$ W/cm$^2$

$\sim 10^{12}$ W/cm$^2$
Charge states using small lasers

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
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Glass–laser $10^{11}$ W/cm$^2$

YAG–laser $10^{12}$ W/cm$^2$

Glass laser: Fe$^{17+}$

YAG laser: Ag$^{20+}$

The heavier species need the higher laser power density.

$\rightarrow$ High power laser

or

$\rightarrow$ Short pulse laser
Need really high charge states??

Iodine laser at the PALS Research Center in Prague
\[ \lambda = 1.315 \, \mu \text{m}, \ E \leq 1 \, \text{KJ}, \ 8 \times 10^{16} \, \text{W/cm}^2 \]

Obtained maximum charge states from Ta.

<table>
<thead>
<tr>
<th>Element</th>
<th>56Co$^{56}$</th>
<th>58Ni$^{58}$</th>
<th>103Ag$^{103}$</th>
<th>113Sn$^{113}$</th>
<th>181Ta$^{181}$</th>
<th>191W$^{191}$</th>
<th>197Pt$^{197}$</th>
<th>198Au$^{198}$</th>
<th>206Pb$^{206}$</th>
<th>209Bi$^{209}$</th>
</tr>
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<tbody>
<tr>
<td>( z_{\text{max}} )</td>
<td>25</td>
<td>26</td>
<td>38</td>
<td>38</td>
<td>55</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>( E_{\text{max}} ) (MeV)</td>
<td>2.6</td>
<td>2.5</td>
<td>3.6</td>
<td>3.5</td>
<td>34</td>
<td>4.9</td>
<td>8.5</td>
<td>4.8</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>( j^* ) (mA/cm$^2$)</td>
<td>32.4</td>
<td>24.2</td>
<td>27.5</td>
<td>22.3</td>
<td>49.0</td>
<td>24.2</td>
<td>19.2</td>
<td>21.9</td>
<td>19.8</td>
<td>13.0</td>
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*Recalculated to the distance of 100 cm \( (j \sim 1/ L^3) \)

A short pulse laser is good for accelerator application. (We plan to verify this in next step)

Courtesy of Dr. L. L’aska
Plasmas with a high power laser density

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<th>$^{68}$Ni</th>
<th>$^{109}$Ag</th>
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<th>$^{101}$Ta</th>
<th>$^{104}$W</th>
<th>$^{195}$Pt</th>
<th>$^{197}$Au</th>
<th>$^{207}$Pb</th>
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A short pulse laser is good for accelerator application. (We plan to verify this in next step)

*Recalculated to the distance of 100 cm ($j \sim 1/L^3$)

Courtesy of Dr. L. L'aska
We can provide ultra high current, but,,

It’s not so easy to put it into an RFQ!!

Traditional injection scheme
Direct Plasma Injection Scheme (DPIS)
Direct Plasma Injection Scheme (DPIS)
Direct Plasma Injection Scheme (DPIS)

- Dense expanding plasma from solid targets.
- Retaining high brightness, heavy ions can be delivered to RFQ.
- Since ions in plasma, space charge effect can be neglected.
- No focusing lenses.
- No high voltage cage, no isolating transformer.
- Low construction cost.
- Low operation cost.
First DPIS (2001) at TITech (Tokyo)

9 mA (peak total) Carbon was obtained.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge to mass ratio</td>
<td>≥1/16</td>
</tr>
<tr>
<td>Operating frequency (MHz)</td>
<td>80</td>
</tr>
<tr>
<td>Input energy (keV/amu)</td>
<td>5</td>
</tr>
<tr>
<td>Output energy (keV/amu)</td>
<td>214</td>
</tr>
<tr>
<td>Normalized emittance (100%) (cm-mrad)</td>
<td>0.05μ</td>
</tr>
<tr>
<td>Vane length (cm)</td>
<td>422</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>273</td>
</tr>
<tr>
<td>Characteristic bore radius, (r_0) (cm)</td>
<td>0.465</td>
</tr>
<tr>
<td>Synchronous phase, (\phi_s)</td>
<td>-90° to -20°</td>
</tr>
<tr>
<td>Transmission</td>
<td>6.84 mA</td>
</tr>
</tbody>
</table>

for \(q/A=1/16\) beam 10 mA input
Newly designed RFQ for DPIS

<table>
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<th>Parameter</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Length of Varie Modulated portion</td>
<td>1.42 m</td>
</tr>
<tr>
<td>Frequency</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Radius of Aperture</td>
<td>6.55 mm</td>
</tr>
<tr>
<td>Nominal RF Voltage</td>
<td>120 kV</td>
</tr>
<tr>
<td>Nominal RF Power</td>
<td>200 kW</td>
</tr>
<tr>
<td>Ion Charge State-to-Mass Ratio (Z/A)</td>
<td>≥ 1/3</td>
</tr>
<tr>
<td>Input Energy</td>
<td>20 keV/u</td>
</tr>
<tr>
<td>Output Energy</td>
<td>100 keV/u</td>
</tr>
<tr>
<td>Output Current for 100 mA $^{12}$C $^+$ Ion Injection (Result of Simulations)</td>
<td>76 mA</td>
</tr>
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</table>

The RFQ was dedicatedly designed and fabricated for DPIS collaborating with A. Schempp and R. A. Jameson.
Ion source box

Source box

Accelerated total peak current after the RFQ, 100 keV/u

2004 Carbon beam with 4 J CO₂ laser, 60 mA
2005 Bare carbon beam with 300 mJ YAG laser, 17 mA
2006 Al beam with 2.3 J YAG laser, 70 mA
Ion source box

Source box

Accelerated total peak current after the RFQ, 100 keV/u

- 2004 Carbon beam with 4 J CO₂ laser. 60 mA
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- 2006 Al beam with 2.3 J YAG laser, 70 mA
Carbon with 4 J CO\textsubscript{2} laser

Total current after RFQ

60mA at peak!

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<tr>
<th></th>
<th>Peak</th>
<th>Integral</th>
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<tbody>
<tr>
<td>C^{5+}</td>
<td>26%</td>
<td>24%</td>
</tr>
<tr>
<td>C^{4+}</td>
<td>64%</td>
<td>60%</td>
</tr>
<tr>
<td>C^{3+}</td>
<td>10%</td>
<td>16%</td>
</tr>
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Analyzed signals

35mA at peak C^{4+}
6.3 \times 10^{10} C^{4+} particles

Un-accelerated
Carbon with 300 mJ YAG laser
RFQ voltage : 100 %

Extraction voltage 40 kV

11 kV
13 kV
15.7 kV
Carbon with 300 mJ YAG laser
RFQ voltage : 75 %

[Graph showing analysis of carbon signals with peaks at different voltages: 10.9 kV and 15.7 kV, labeled as C6+ and C5+]

Extraction voltage 40 kV
Carbon with 300 mJ YAG laser
RFQ voltage : 61 %

Pure 6+ beam can be delivered by adjusting operating condition of the RFQ.
Carbon with 300 mJ YAG laser
RFQ voltage: 61%

Current [mA]

C6+
non accelerated particles

17mA C6+ peak current

Number of particles: 6.0 \times 10^9
Aluminum with 2.3 J YAG laser

(I) Amplitude of RF voltage - 120 kV

Extraction voltage scan

(II) Extraction potential - 60 kV

RFQ voltage scan

Laser spot size setting was optimized to get Al\(^{9+}\).
Aluminum with 2.3 J YAG laser
Charge state distribution

Extraction potential – 60 kV, Amplitude of RF voltage – 120 kV

- $^{27}\text{Al}$ ion beam with total current up to 70 mA, 0.65 $\mu$s
- $^{27}\text{Al}^{9+}$ ions occupy about 65%.
Iron with 2.3 J YAG laser

Mar 14, 2006 Fe acceleration

Mainly Fe^{16+} injected
Shot-to-shot stability

- A 3D manipulator provides every new surface.
- The target position controlled within 0.1 mm accuracy.
Shot-to-shot stability

Extraction potential - 60 kV, Amplitude of RF voltage - 120 kV

\[ \langle I \rangle = 49 \text{ mA} \pm 6\% \]

\[ \langle \tau \rangle = 0.56 \mu \text{s} \pm 11\% \]

Can be improved more.

Easy to get more stability on lower mass element like Carbon.
Hybrid (LIS for ECR)

**TABLE III.** The best current for Ta and Au beams (** indicates the presence of the collimator above the extractor and a reduction of a factor 3 in current.**)

<table>
<thead>
<tr>
<th>Charge state</th>
<th>Ta current (e µA)</th>
<th>Au current (e µA)</th>
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<td>22</td>
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YAG laser (0.9 J/µs, 5x10⁹ W/cm²)
SERSE superconducting ECRIS (18 GHz)

- Initial ions seeded by a LIS for 18 GHz ECR.
- Plasma produced inside of the ECR chamber.

INFN—Laboratori Nazionali del Sud.
Hybrid (LIS for EBIS)

C, Mg, Si, S, Ca, Ti, Cr, Mn, Fe, Au, U
$10^{10}$ particles

Ta (1m, 1cm$^2$)

BNL EBIS project

LIS for 1+ ion injection to EBIS

- mA class low charge state ion.
- 30 to 50 $\mu$s
- Multiple targets (species switching pulse to pulse)
- Targets last very long time. (no crater)
LIS for Electrostatic accelerator

RARAF, Columbia University
Micro-beam for the Biology

- Laser provides ionization energy to a high voltage terminal.
- 100 Hz operation was verified.

Quanta-Ray LAB-190-100
Nd:YAG
(100 Hz–325 mJ/pulse, 10 ns)

At Columbia University's Radiological Research Accelerator Facility (RARAF), a single-particle single-cell microbeam is used to study fundamental cellular response to irradiation.

NIM B 241 (2005) 874-879
Courtesy of Dr. A. Bigelow
Cryo target for LIS

Frozen Ne as a laser target
All gases except He applicable.
Summary

- LIS can provide pulsed highly charged intense heavy ions.
- Commercially available lasers provide high charge and high current up to Ag.
- Short pulse laser? Possibilities of high charge ions from heavy species.
- DPIS is effective to provide intense current and is simple.
  
  Carbon: 60 mA (peak, C^{4+} 60 %)

  C^{6+}: 17 mA

  Aluminium: 70 mA (peak, Al^{9+} 65 %)

- Good stability can be achieved.
- LIS could provide primary beams for ECR and EBIS.
- LIS is also good for low charge, heavy mass and long pulse beam.
- High repetition rate matches future accelerators.
- Gas species can be used as targets.
The authors thank to colleagues at:

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Kyusyu U.
AEC
NIRS
ITEP
IMP
Frankfurt U.
CERN
PALS
INFN
BNL
Columbia U.

Thank you for your attention.