Review of Laser Driven Sources for Multi-Charged Ions

M. Okamura (BNL)
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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^{13+} (Synchrophasotron)
1988 Technical University of Munich, ITEP (Van de Graaff)
1994 GSI, ITEP Ta^{10+} (RFQ)
2000 ITEP C^{4+} (Synchrotron)

Production of laser plasma

Sorry - animations cannot be displayed in PDF files

Expanding plasma

Laser light

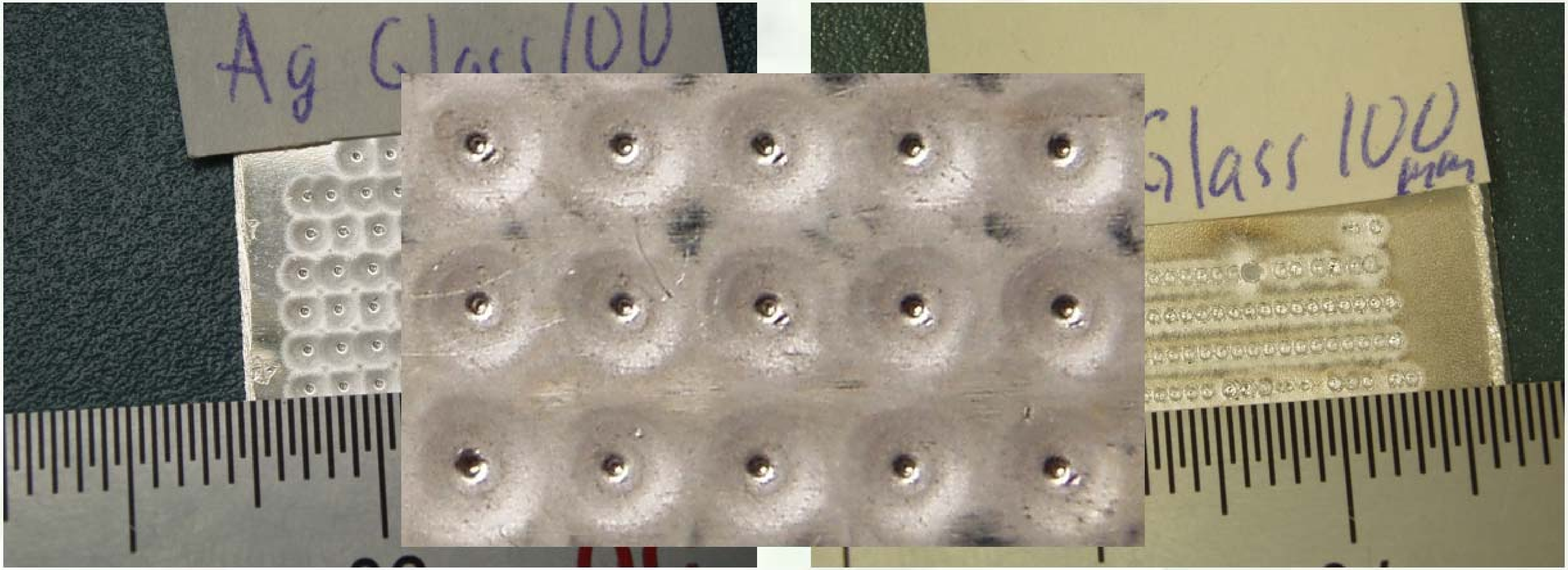
Features of laser plasma

- 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 ➞ Highly charged states)

Solid targets

Solid targets



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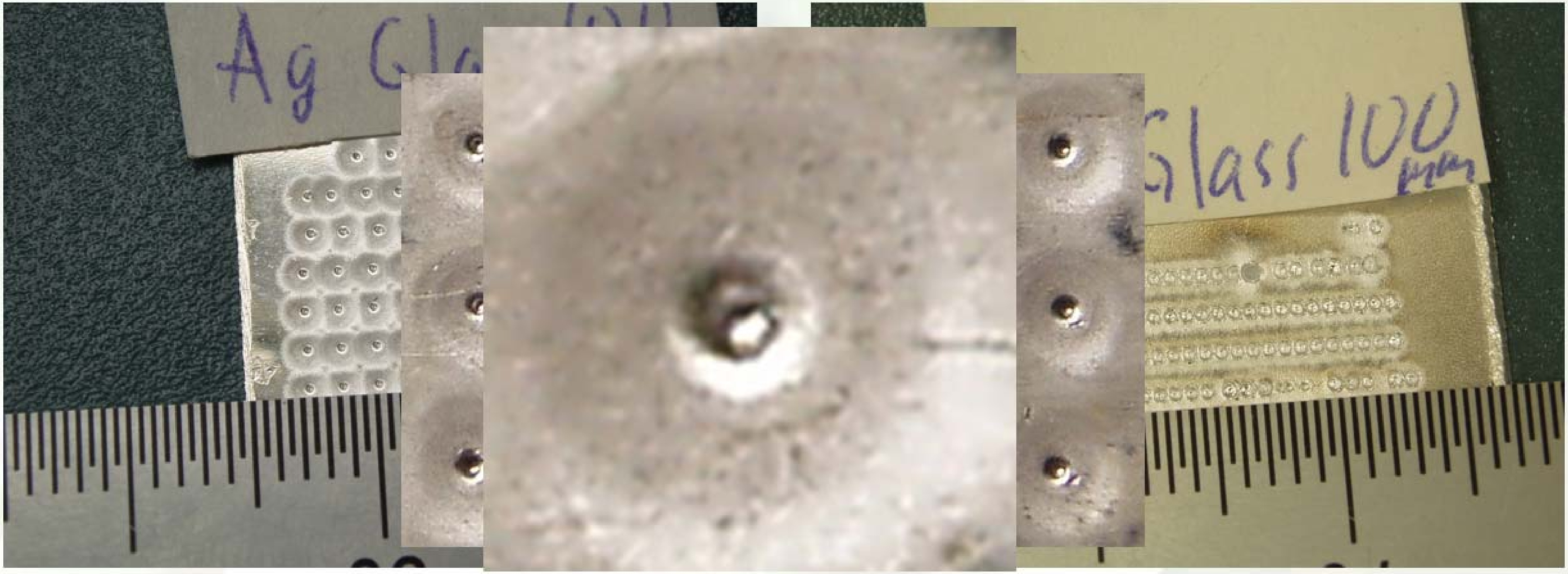

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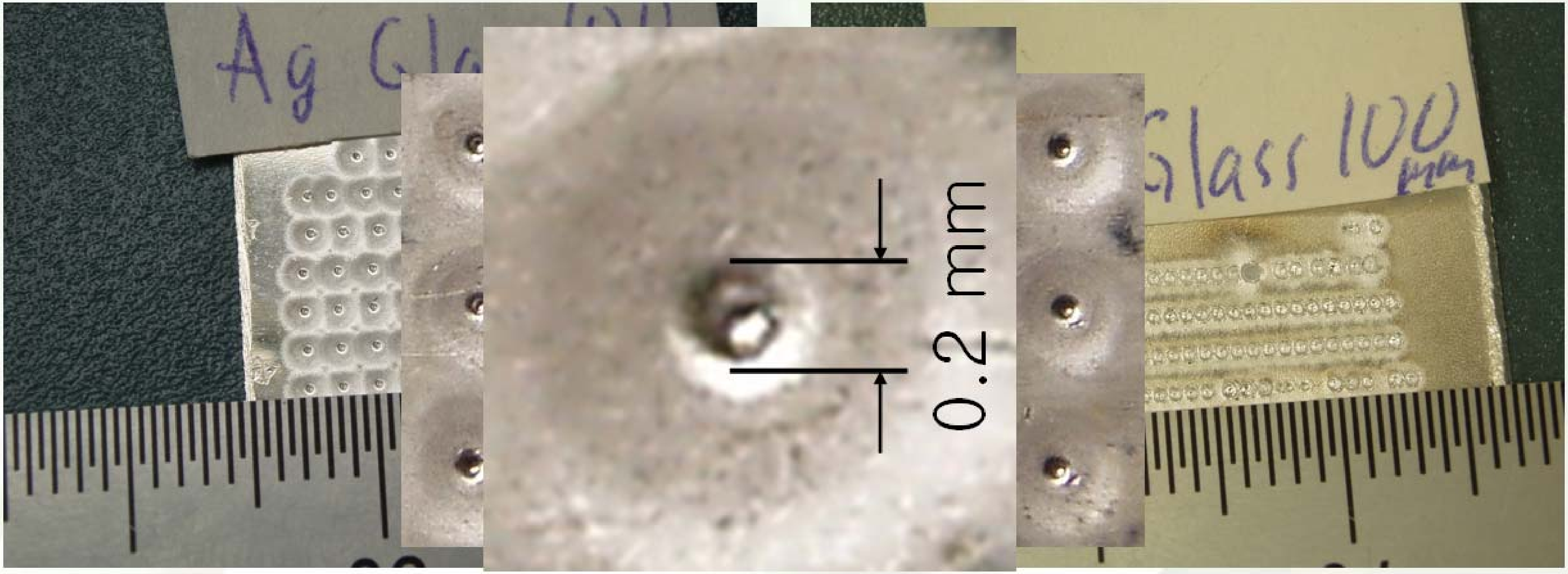

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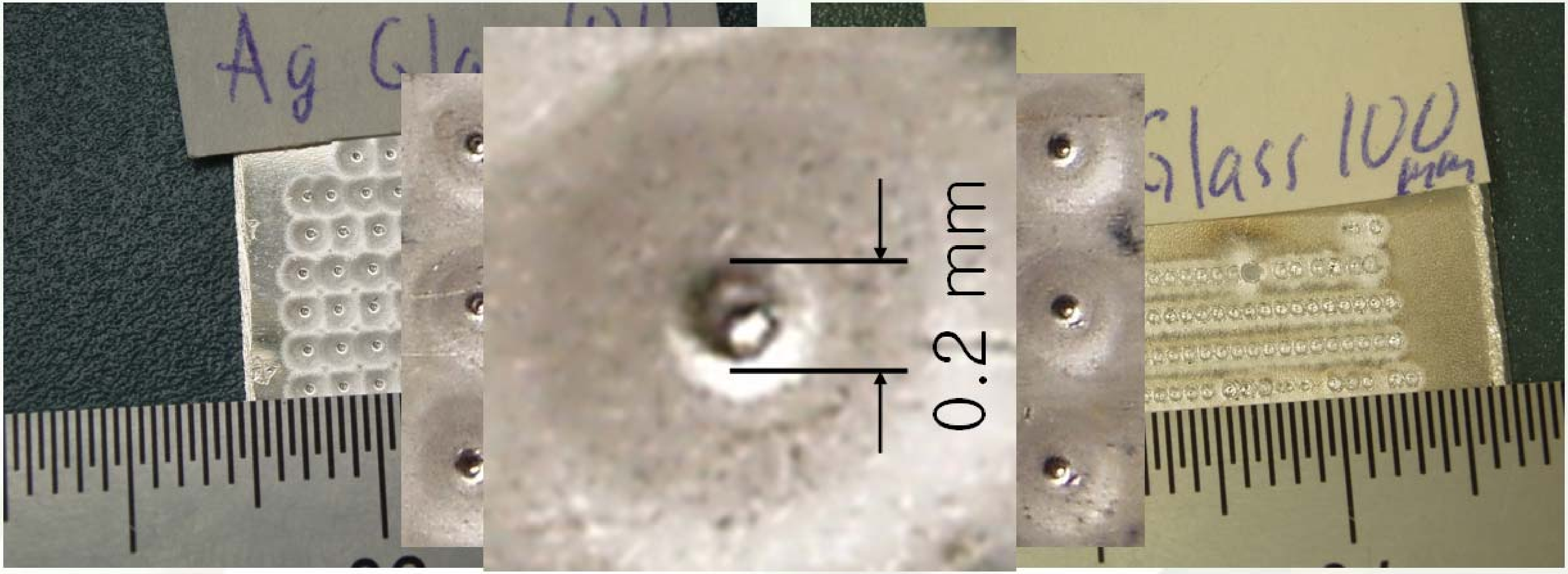

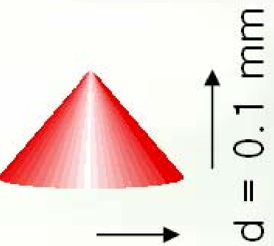

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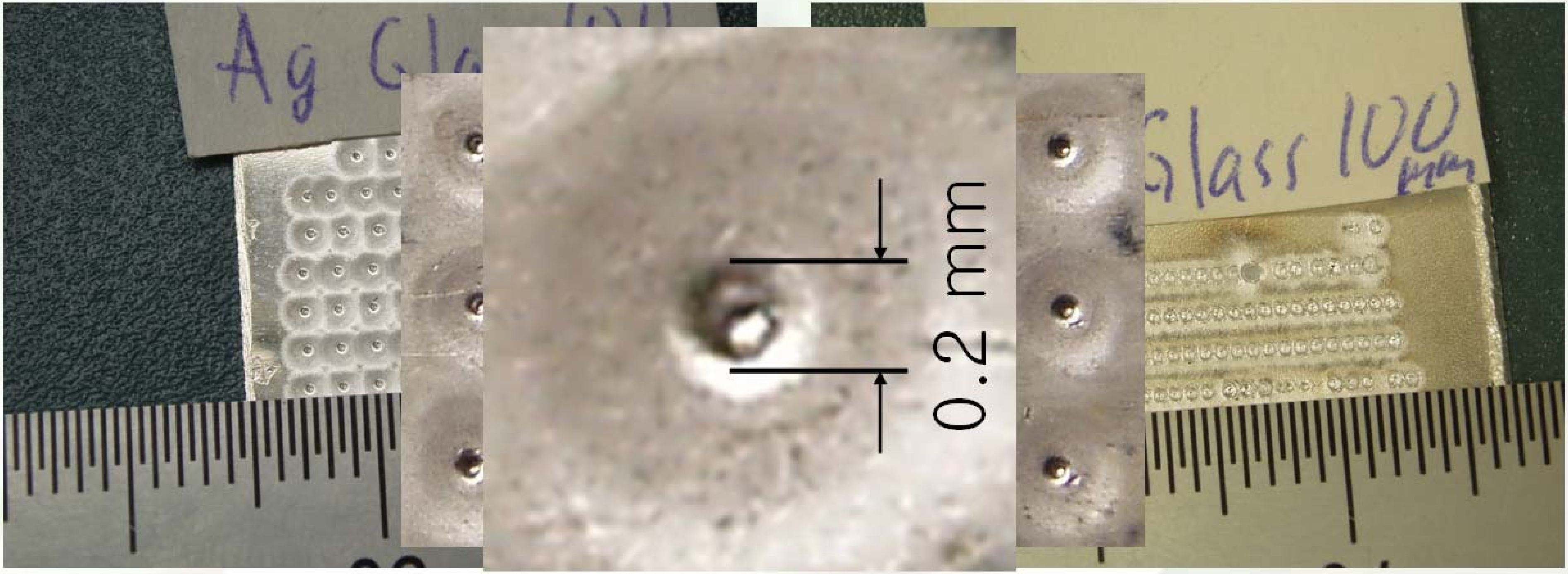
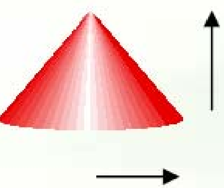


The volumeis :

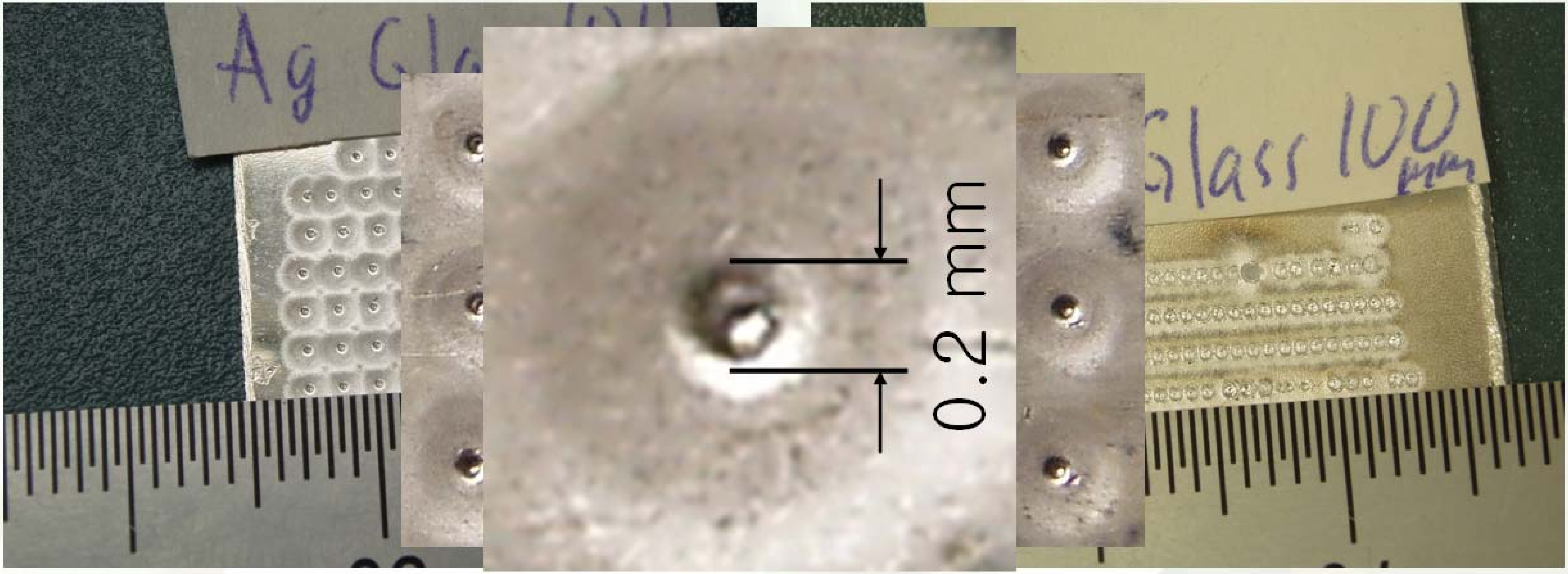
$$\frac{1}{3}r^2 d = 3.33\times10^{-13} \quad m^3$$

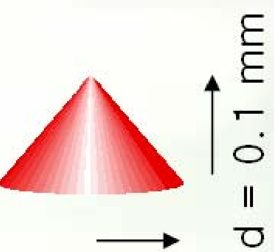


d = 0.1 mm

r = 0.1 mm

Solid targets





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Assuming an Alminum target,

the density is about 2.7g/cm^3,

and the volume contains;

2.0×10^{16} ions.

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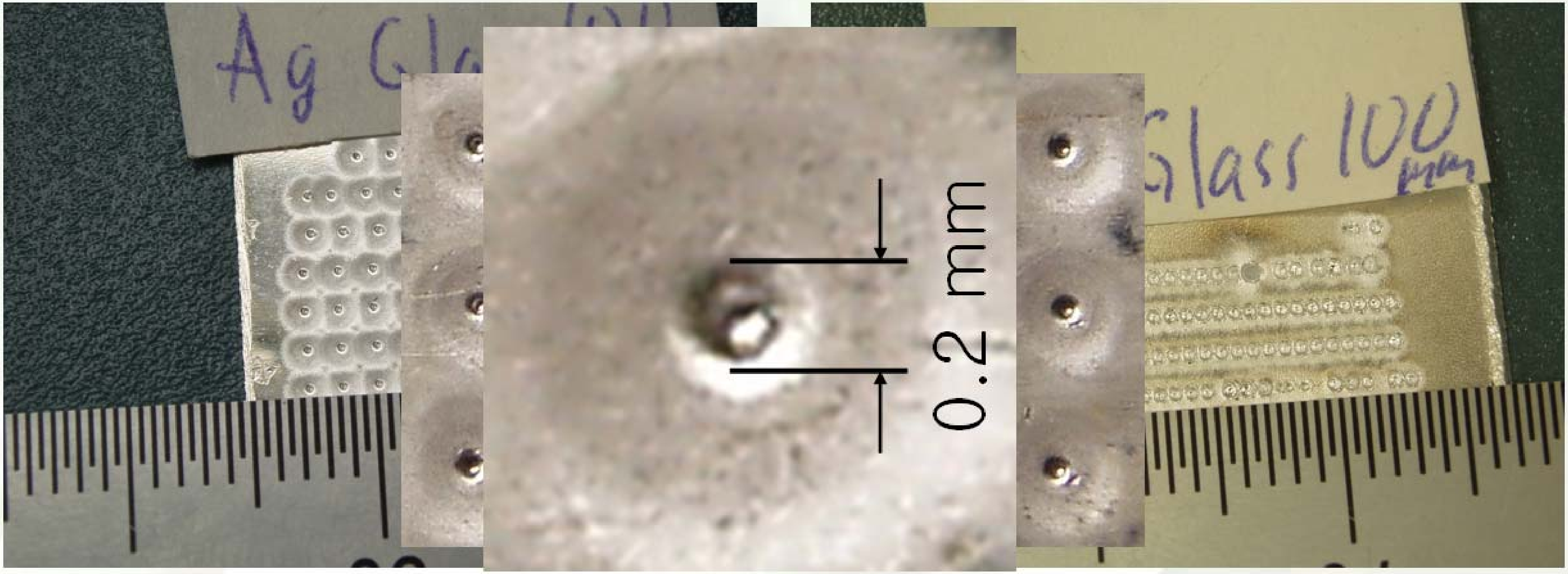

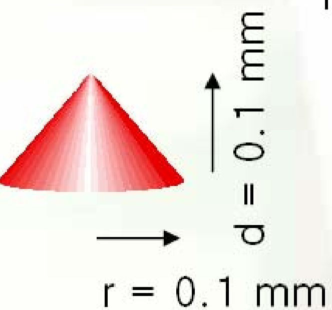

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If we get 1 μs pulse with charge state 10+ beam,

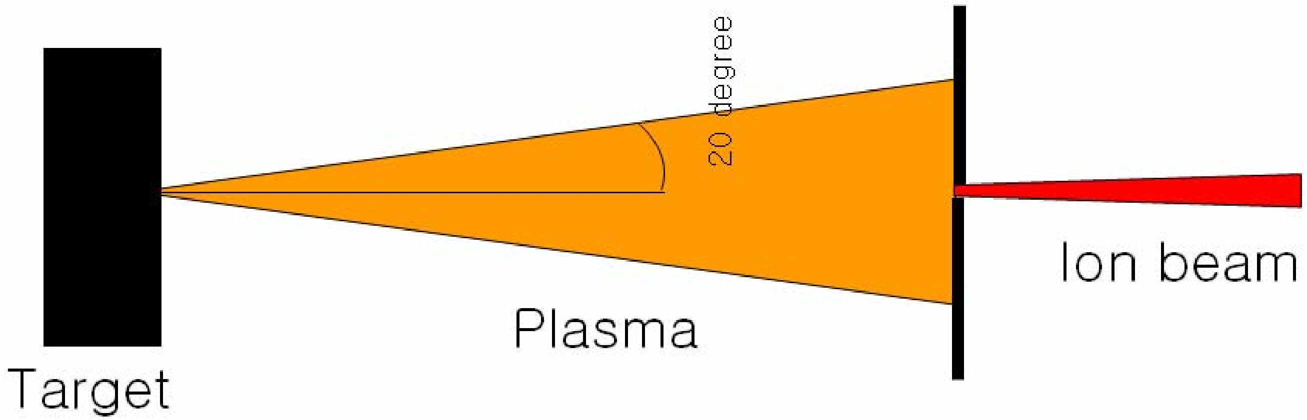
$$6.02\times10^{23} \times \frac{2700\times\frac{1}{3}r^2 d}{27/1000} \times \frac{10\times1.60\times10^{-19}}{10^{-6}}$$

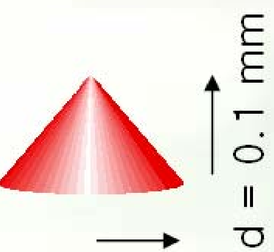
$$= 32200 \text{ A}$$

Probably only 1% are ionized.

Roughly 320 A beam is producted.

Solid targets





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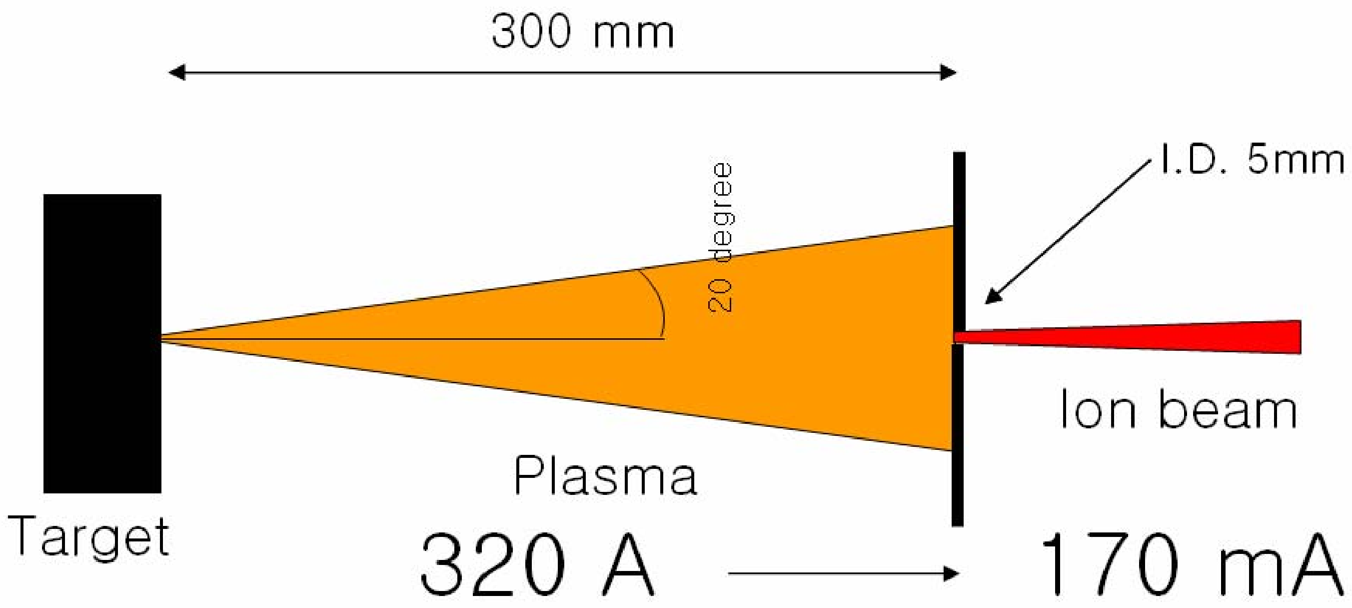

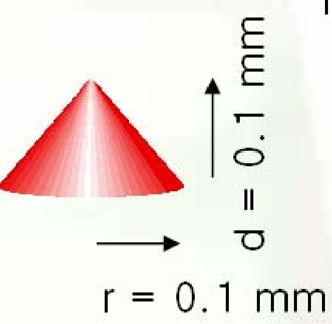

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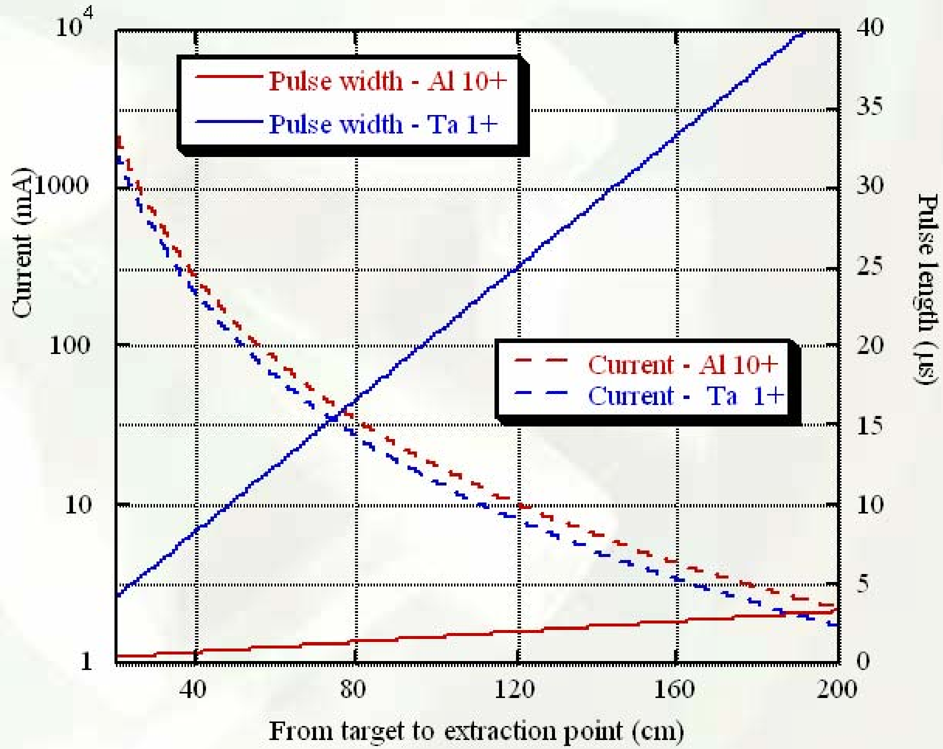
Beam current and Pulse length

$^{27}Al^{10+}$ and $^{181}Ta^{1+}$ 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

100 J/1 Hz MO-PA CO_2-laser system

Requirements

- Ion species – Pb^{25+}
- Current – 8 mA
- Pulse length – 5.5 μs
- Rep-rate – 1 Hz

High current

High charge states

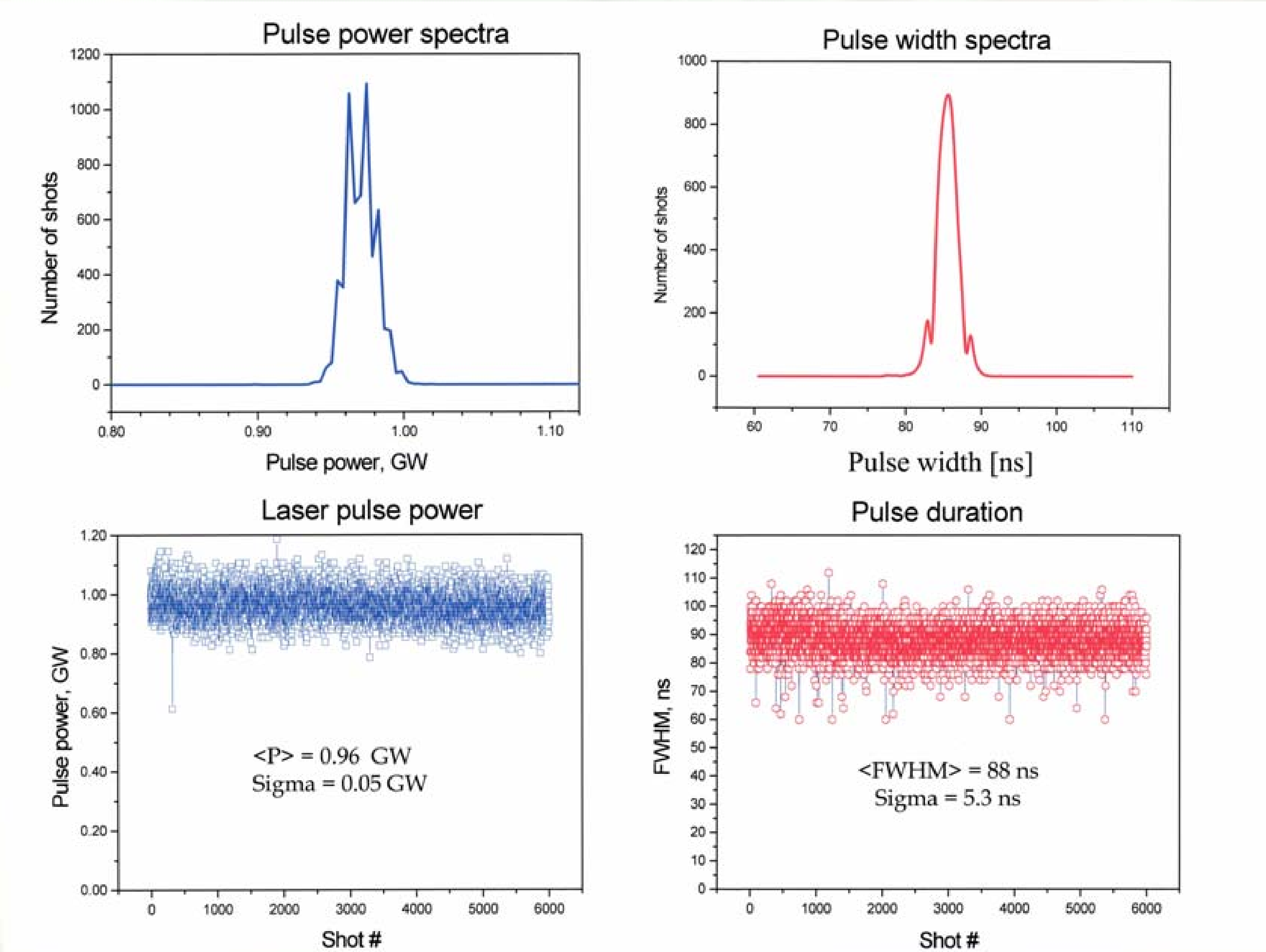
Long pulse

⇩

Powerful laser

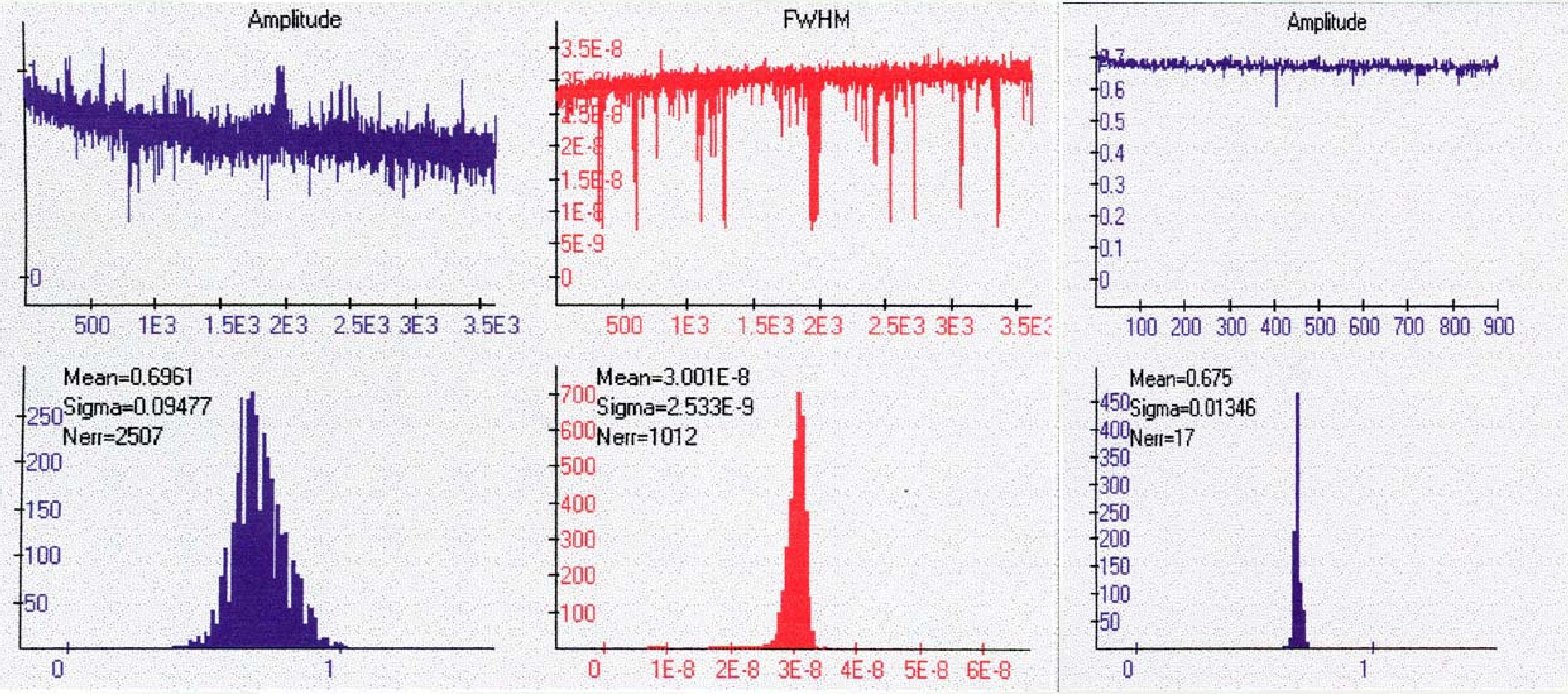
LIS development for LHC

Laser pulse statistics (generator mode)



LIS development for LHC

Laser pulse statistics (MO-PA mode)



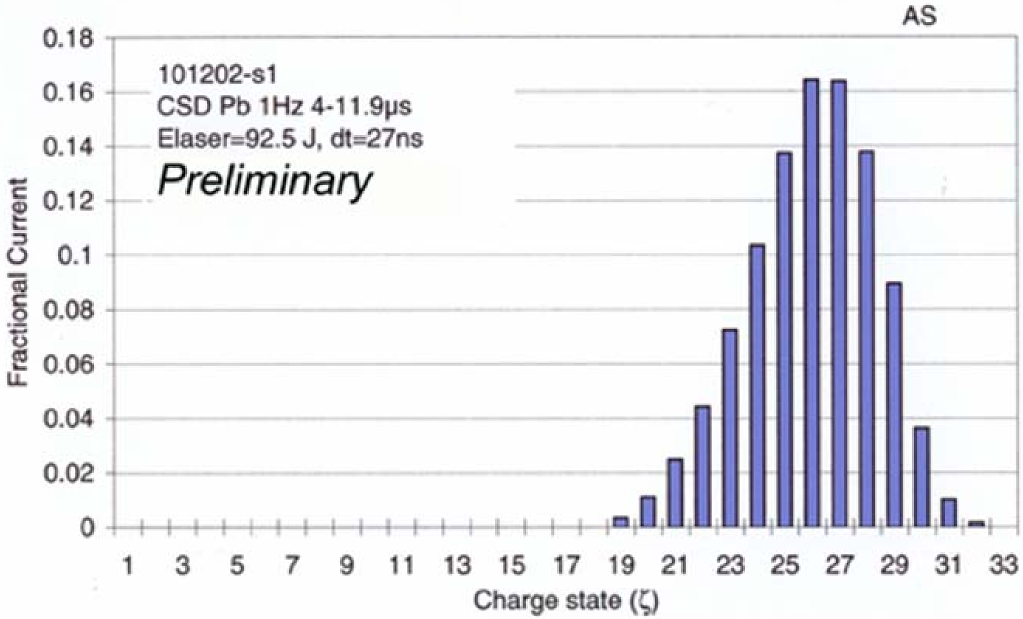
MO&PA 90 J operation of 1 hr 15 min at 1 Hz

1 hr 0.25 Hz

LIS development for LHC

Lead ion generation

First results from LIS - December 2002



This charge - state distribution, combined with an average current of 0.363 mA over 4 microseconds, 1750 mm from the target, leads to

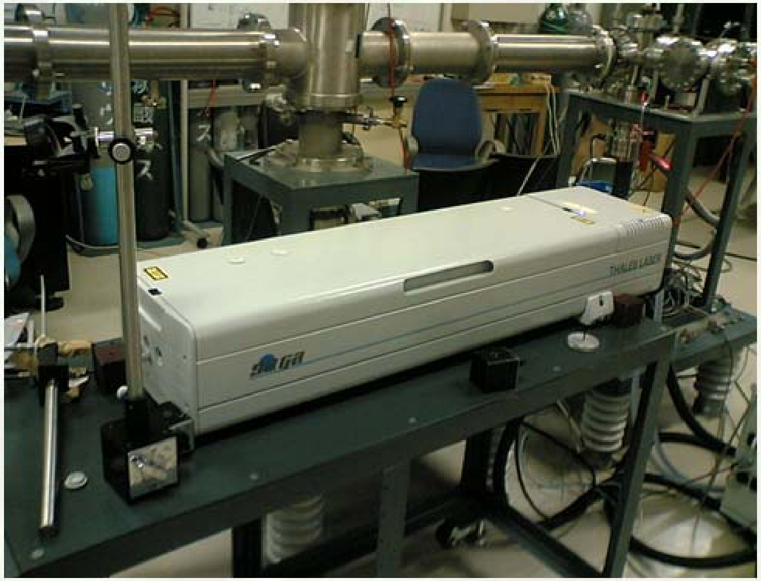
2.3 x 10^10 Pb27+ ions at a pulselength of 3.6 microseconds

for the standard extraction geometry (aperture 34 mm)

The project was unfortunately stopped in 2003.

Need a powerful laser ??

Glass-laser



YAG-laser

Nd-Glass-Laser	B.M.industries SERIE 5000
Maximum energy	3.45 J – 30 ns
Wave length	1062 nm
Spot size	10 mm
Divergence	0.8 mrad
Repetition rate	45 second cooling time needed per shot

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

Nd-YAG-Laser	Thales SAGA230
Maximum energy	2.36 J – 6 ns
Wave length	1064 nm
Spot size	17 mm
Divergence	0.5 mrad
Repetition rate	Maximum 10 Hz

$\sim 10^{12}$ W/cm^2

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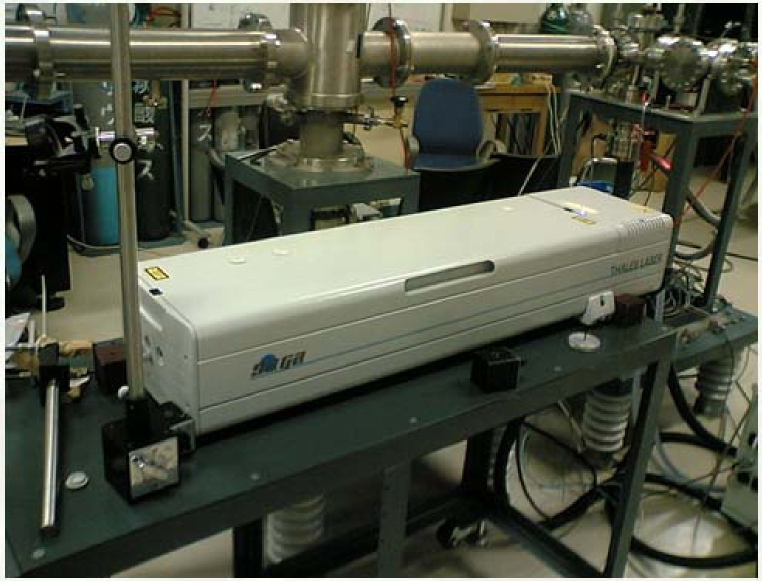

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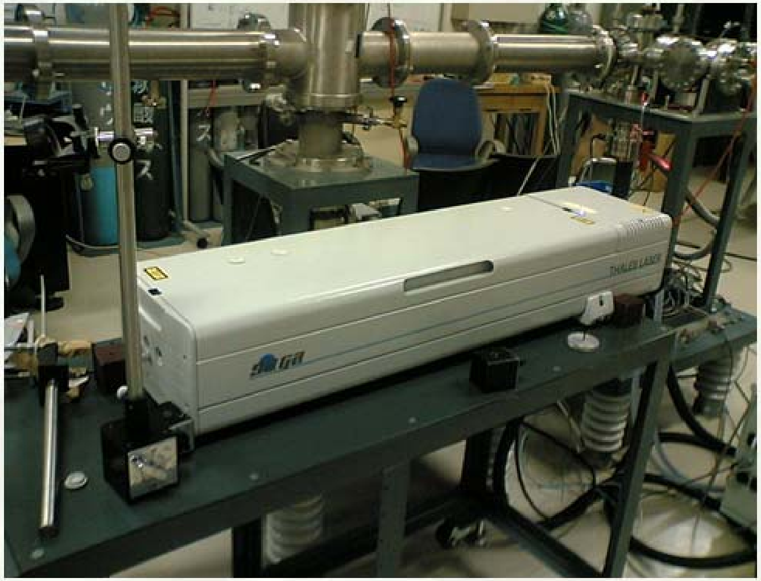
Plasmas using conventional lasers in RIKEN

Glass-laser



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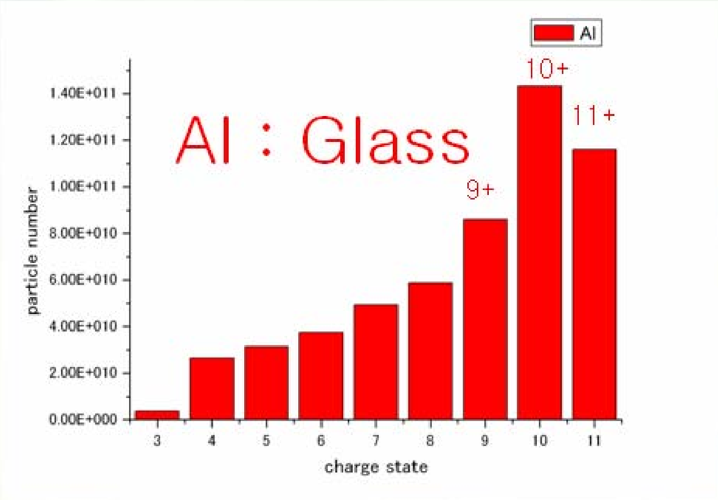
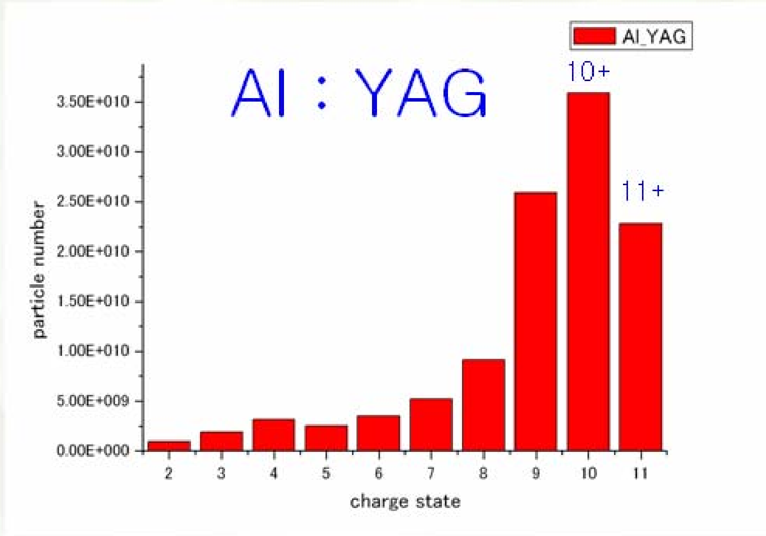
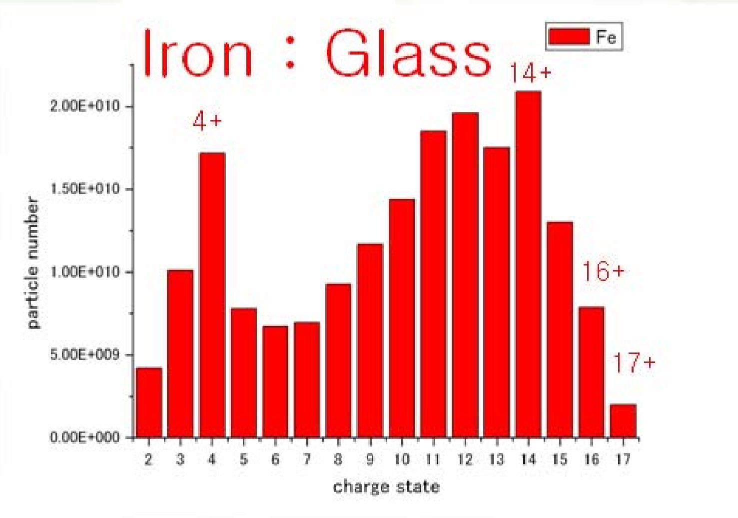
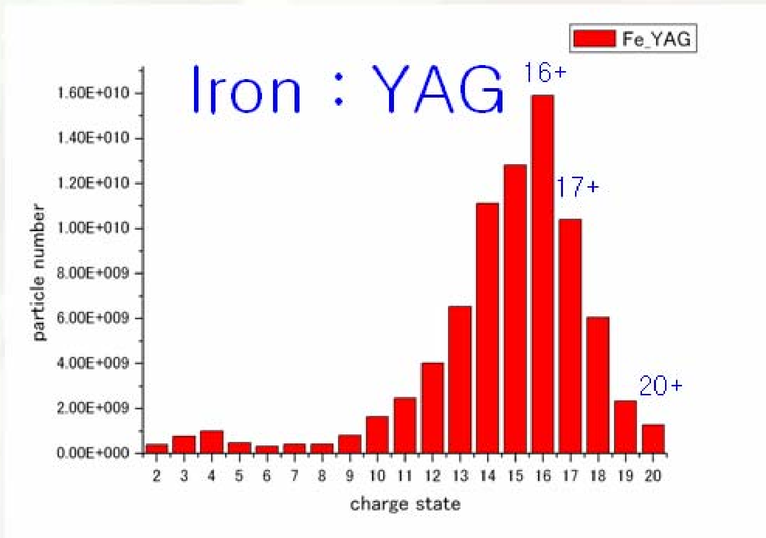
Charge states distribution using small lasers









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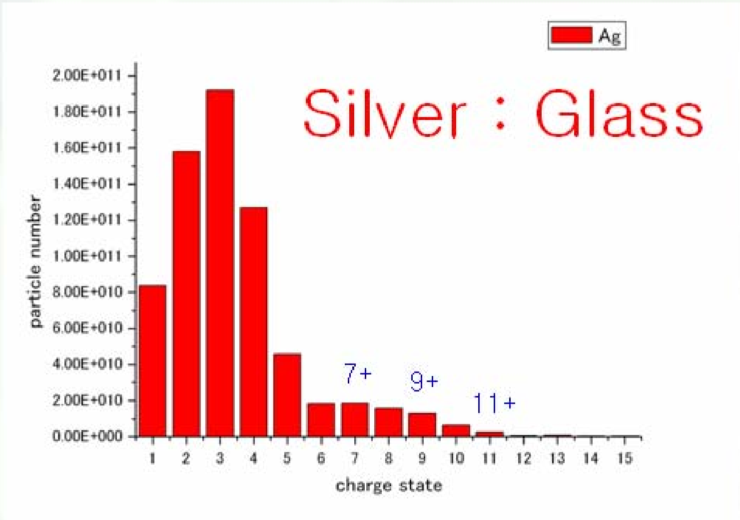

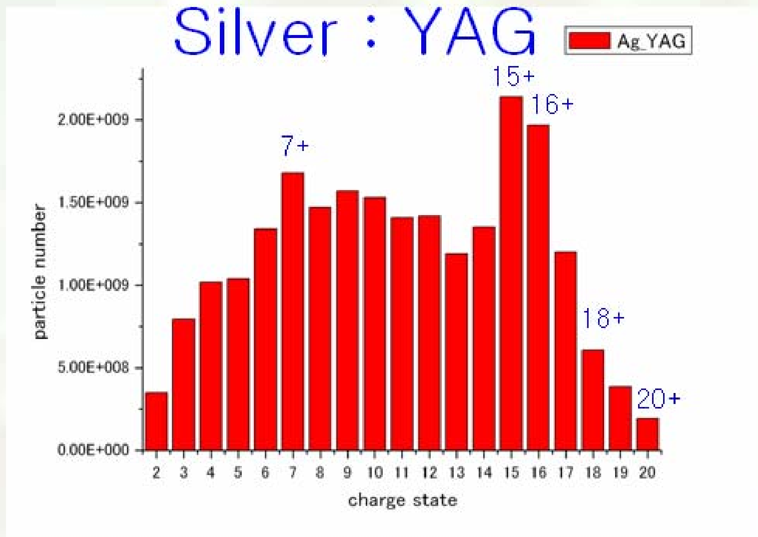

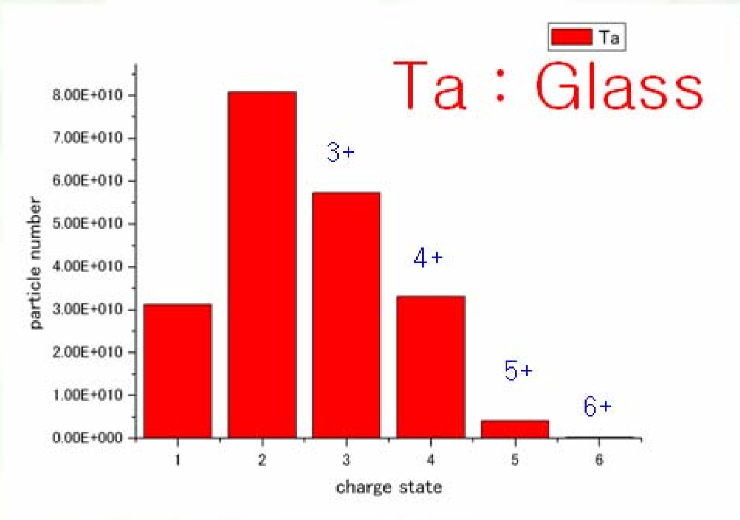

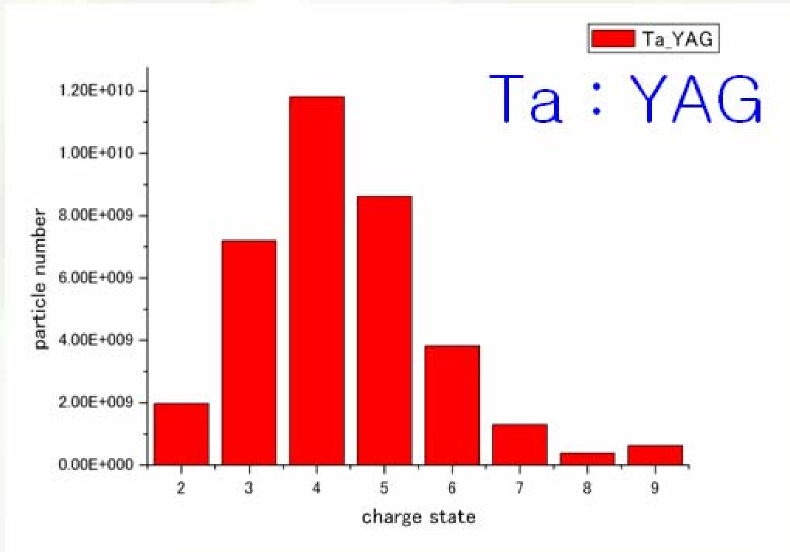

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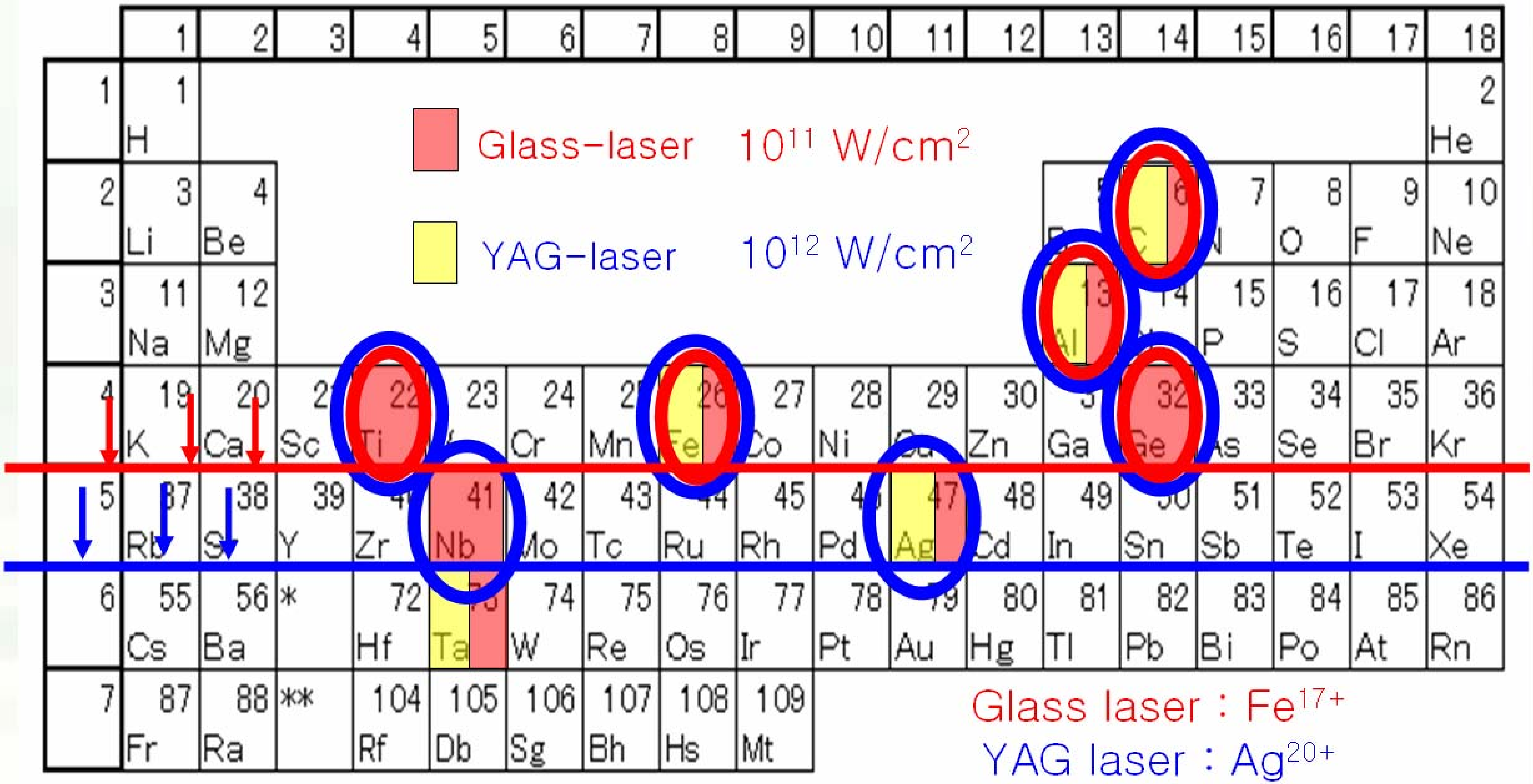


The heavier species need the higher laser power density.

→ High power laser

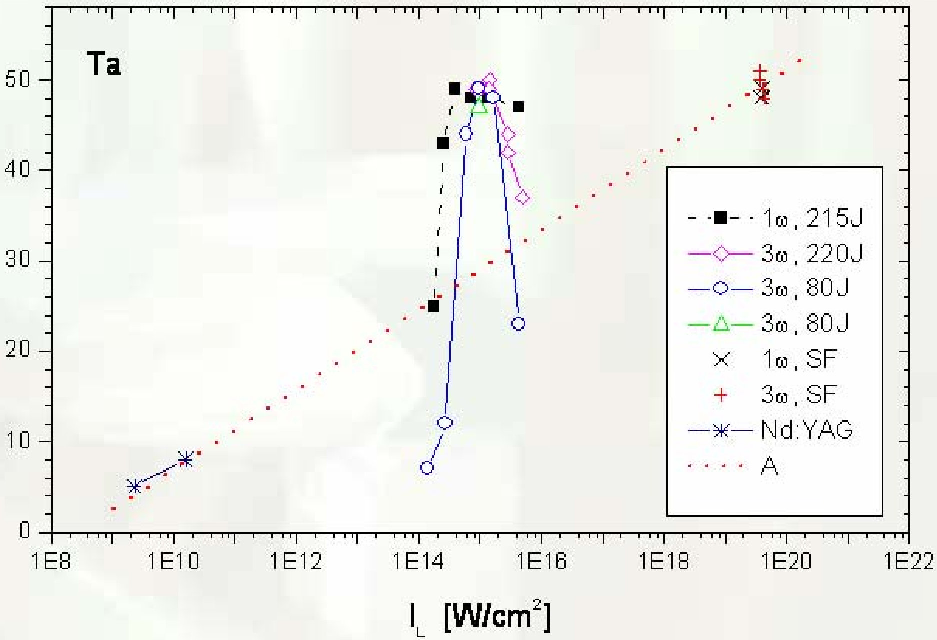
or

→ Short pulse laser

Need really high charge states ??

Iodine laser at the PALS Research Center in Prague

$\lambda = 1.315\ \mu m$, $E \leq 1$ KJ, 8×10^{16} W/cm^2



Obtained maximum charge states from Ta.

Element	$_{27}Co^{59}$	$_{28}Ni^{59}$	$_{47}Ag^{108}$	$_{50}Sn^{119}$	$_{73}Ta^{181}$	$_{74}W^{184}$	$_{78}Pt^{195}$	$_{79}Au^{197}$	$_{82}Pb^{207}$	$_{83}Bi^{209}$
z_{max}	25	26	38	38	55	49	50	51	51	51
$E_{i\,max}$ (MeV)	2.6	2.5	3.6	3.5	34	4.9	8.5	4.8	5.1	5.1
j^* (mA/cm^2)	32.4	24.2	27.5	22.3	49.0	24.2	19.2	21.9	19.8	13.0

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

Plasmas with a high power laser density

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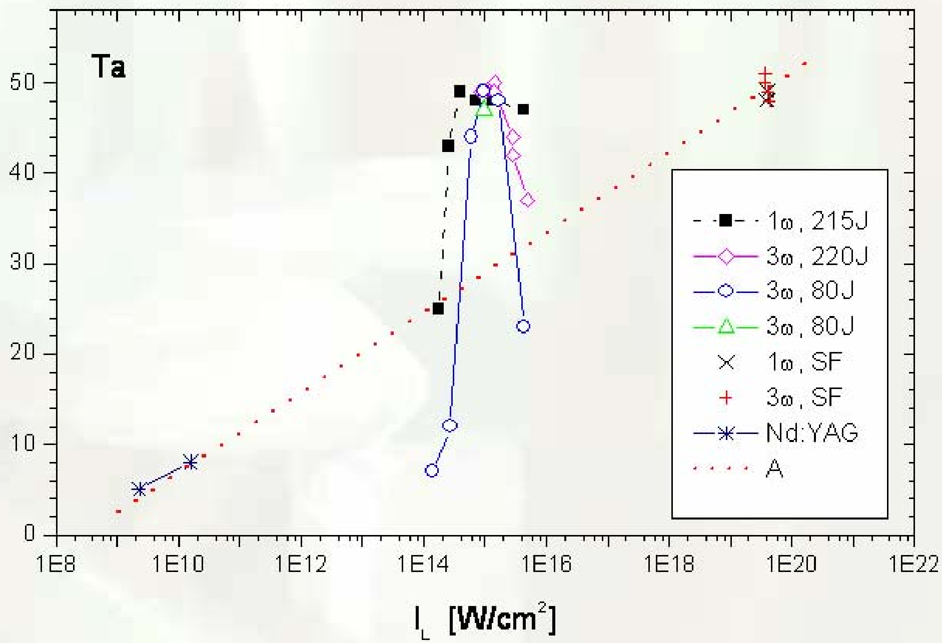

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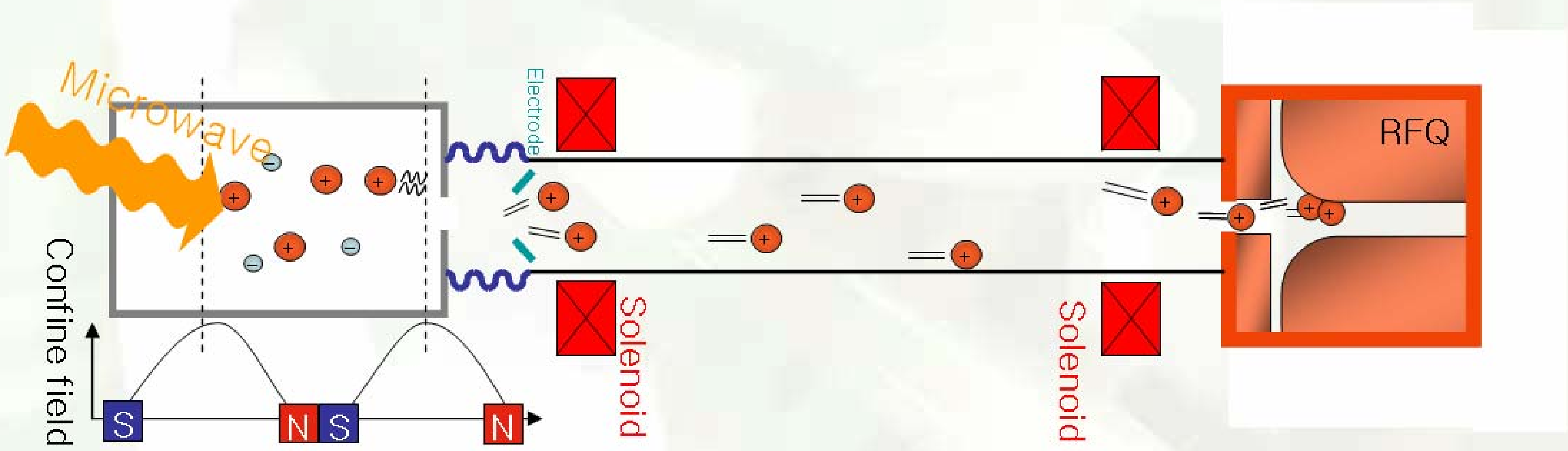
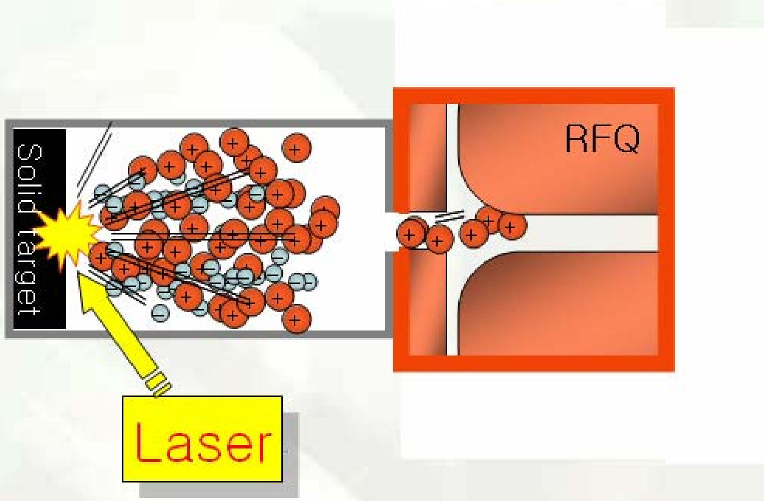
We can provide ultra high current, but,,

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



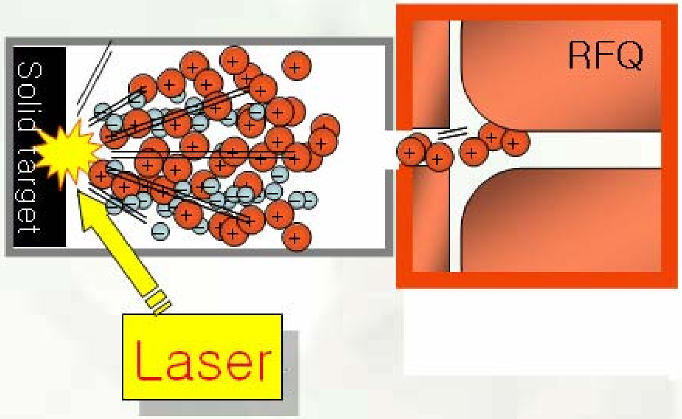
Traditional injection scheme

Direct Plasma Injection Scheme (DPIS)



DPIS source

Direct Plasma Injection Scheme (DPIS)



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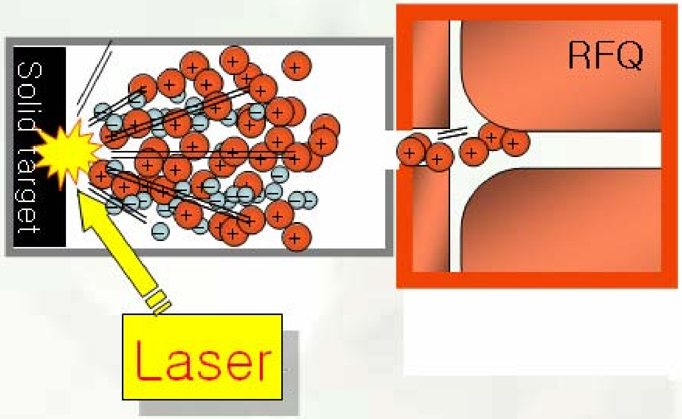
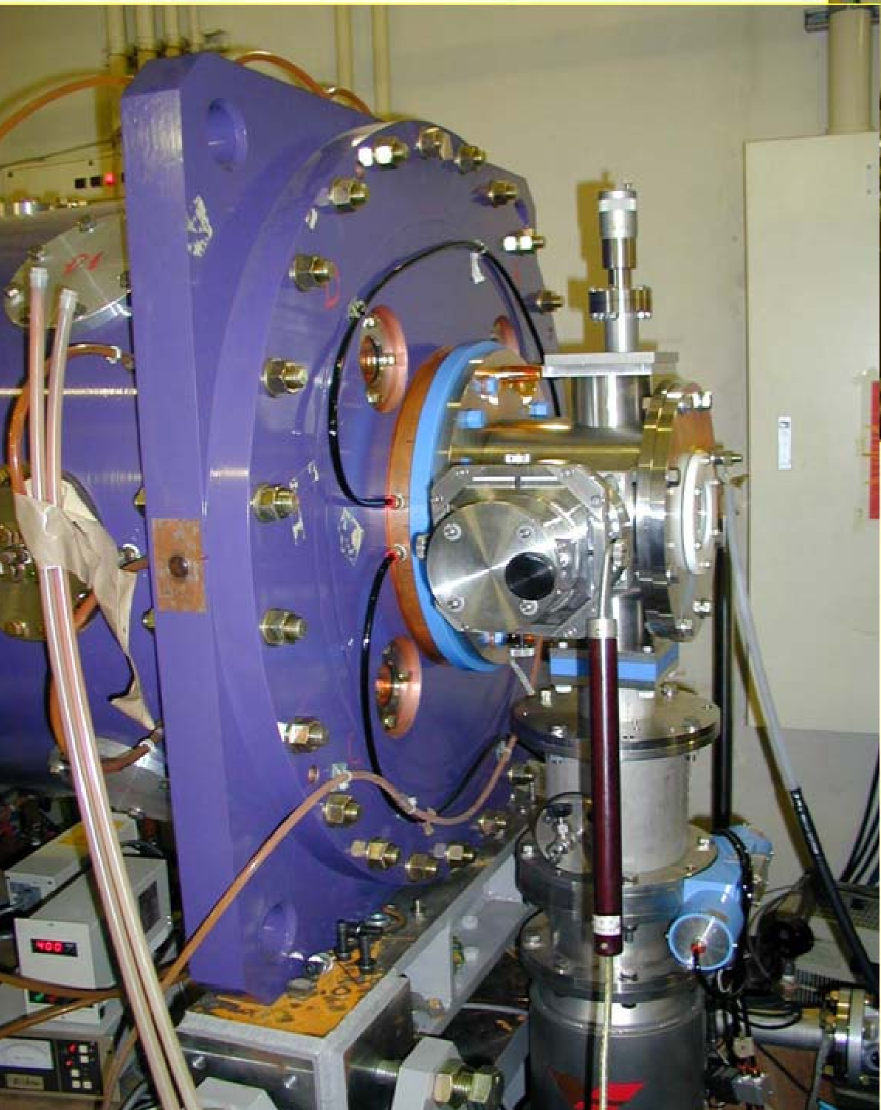


- Dense expanding plasma from solid targets.
- Retaining high brightness, heavy ions can be delivered to RFQ.
- Since ions in plasma, space charge effect can be neglected.
- No focusing lenses.
- No high voltage cage, no isolating transformer.
- Low construction cost.
- Low operation cost.

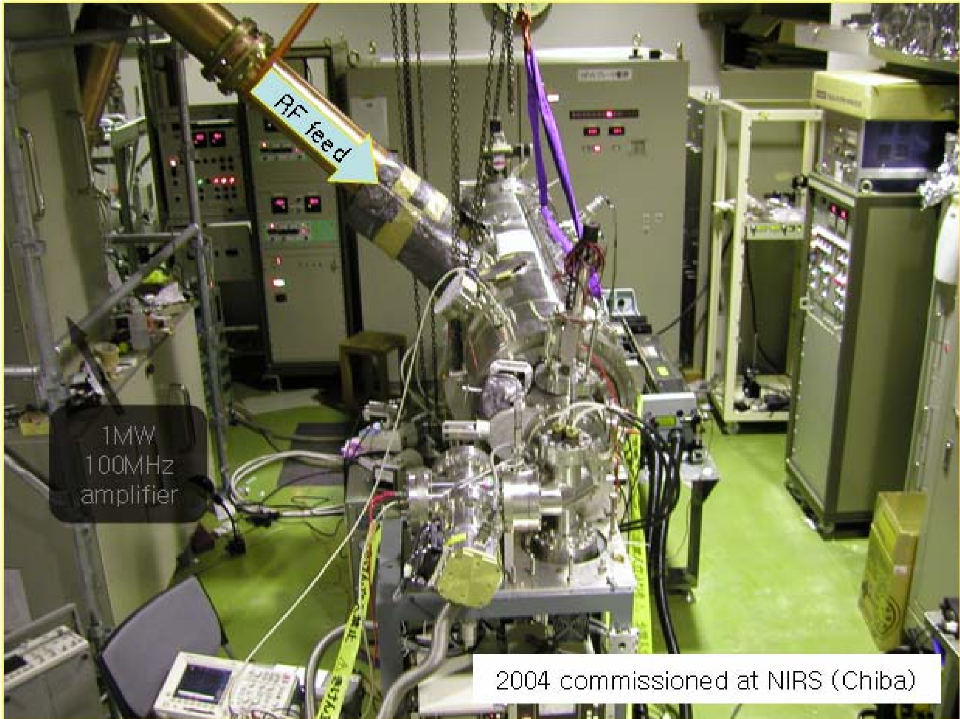
First DPIS (2001) at TITech (Tokyo)



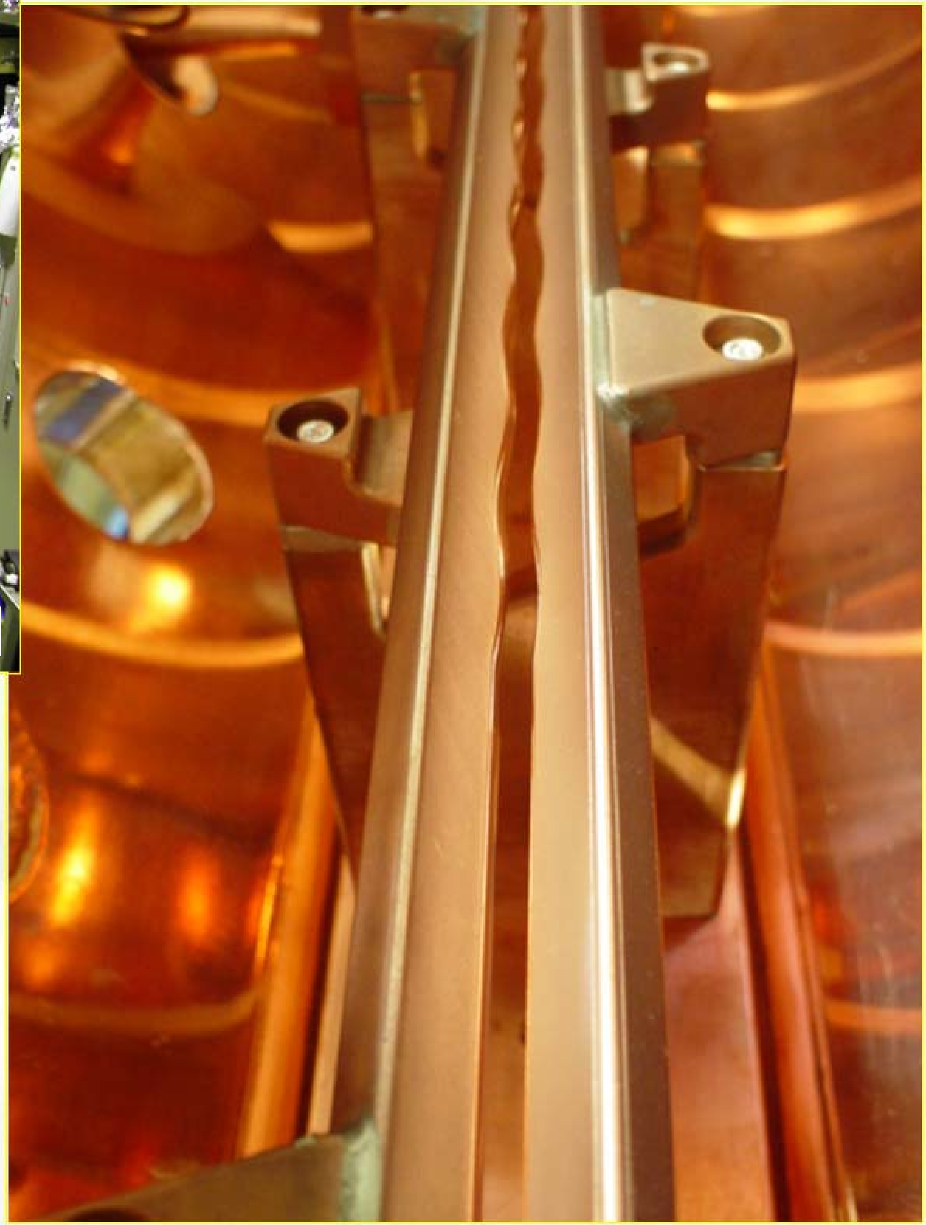
9 mA (peak total) Carbon was obtained.

Charge to mass ratio	≥1/16
Operating frequency (MHz)	80
Input energy (keV/amu)	5
Output energy (keV/amu)	214
Normalized emittance(100%) (cm·mrad)	0.05p
Vane length (cm)	422
Total number of cells	273
Characteristic bore radius, r_0 (cm)	0.466
Synchronous phase, ϕ_s	-90° to -20°
Transmission for q/A=1/16 beam 10 mA input	6.84 mA

Newly designed RFQ for DPIS



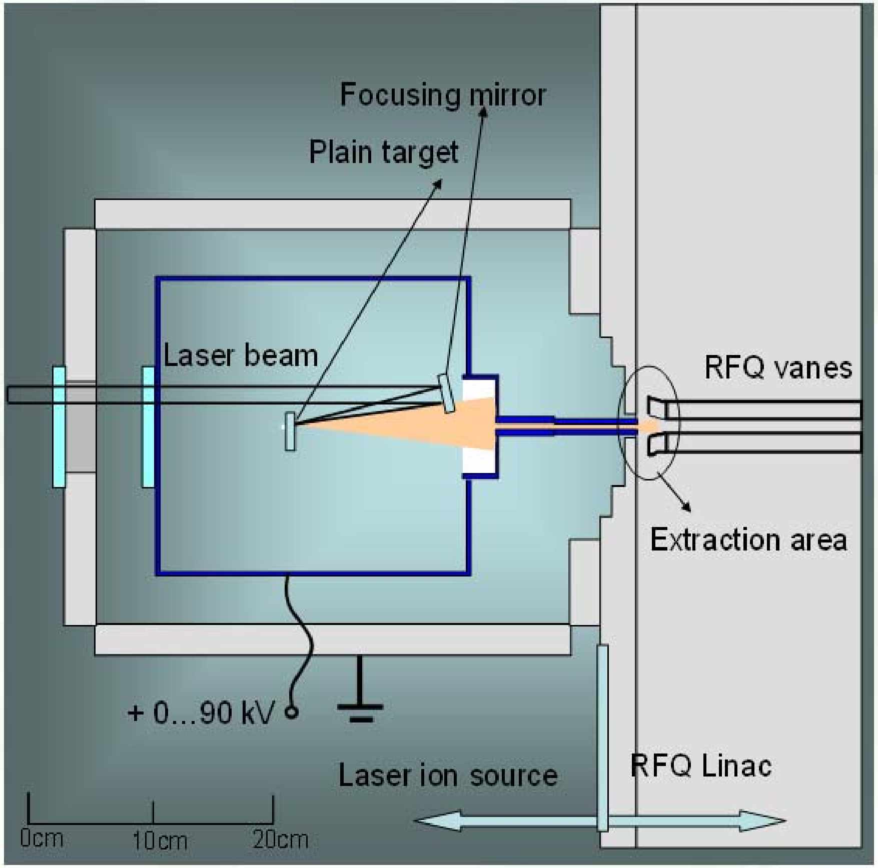
2004 commissioned at NIRS (Chiba)



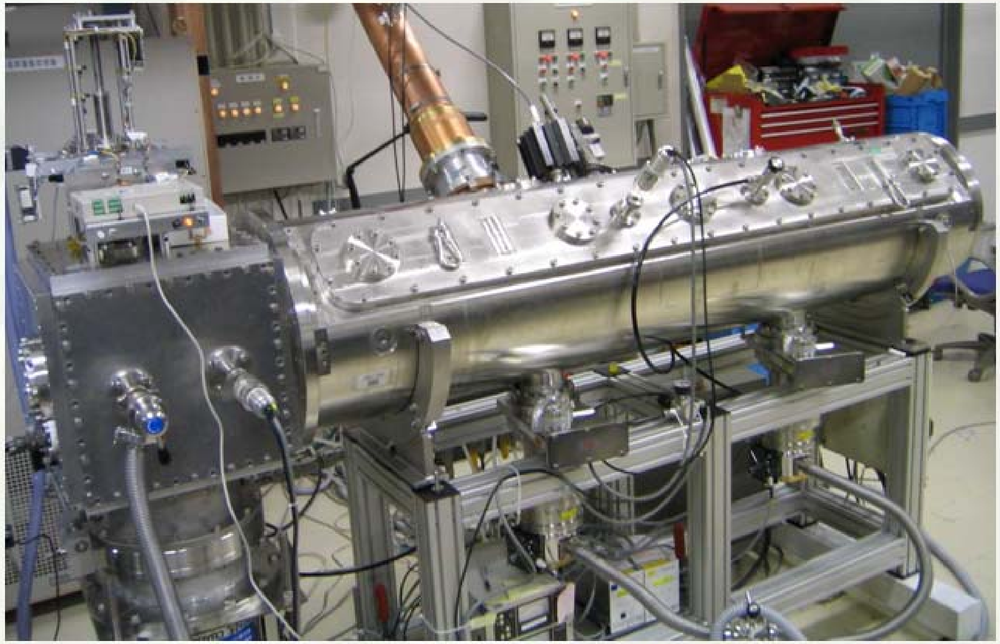
Length of Vane Modulated portion	1.42 m
Frequency	100 MHz
Radius of Aperture	6.55 mm
Nominal RF Voltage	120 kV
Nominal RF Power	200 kW
Ion Charge State-to-Mass Ratio (Z/A)	≥ 1/3
Input Energy	20 keV/u
Output Energy	100 keV/u
Output Current for 100 mA $^{12}C^{4+}$ Ion Injection (Result of Simulations)	76 mA

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

Ion source box



Source box

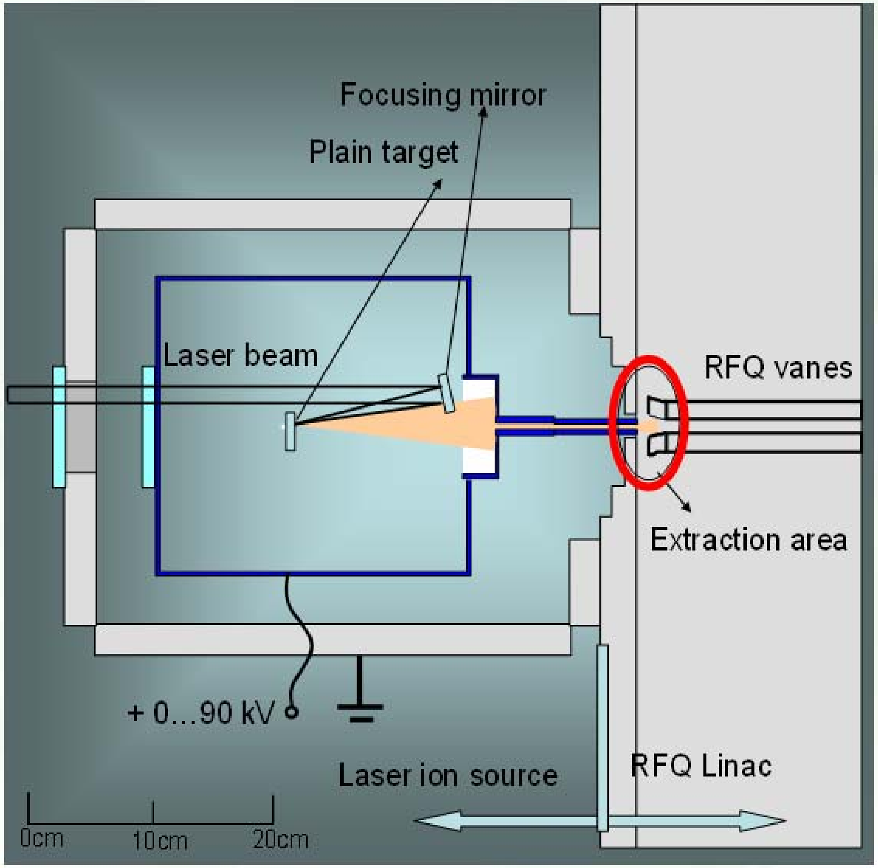


DPIS at RIKEN

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

2004 Carbon beam with 4 J CO_2 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



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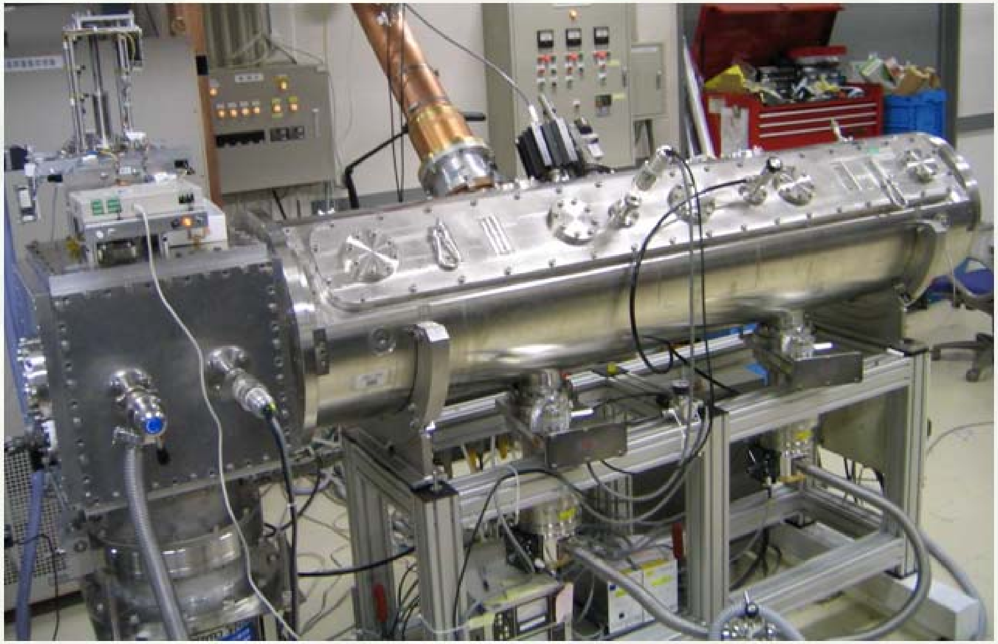

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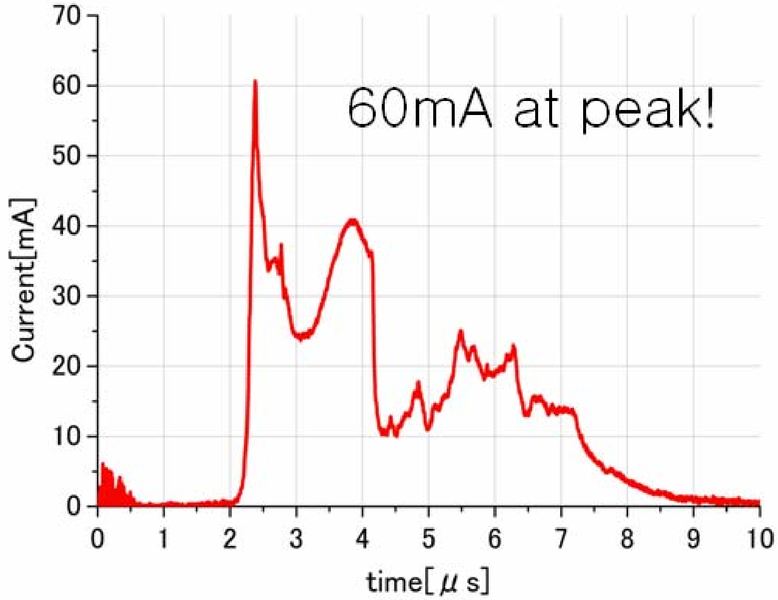
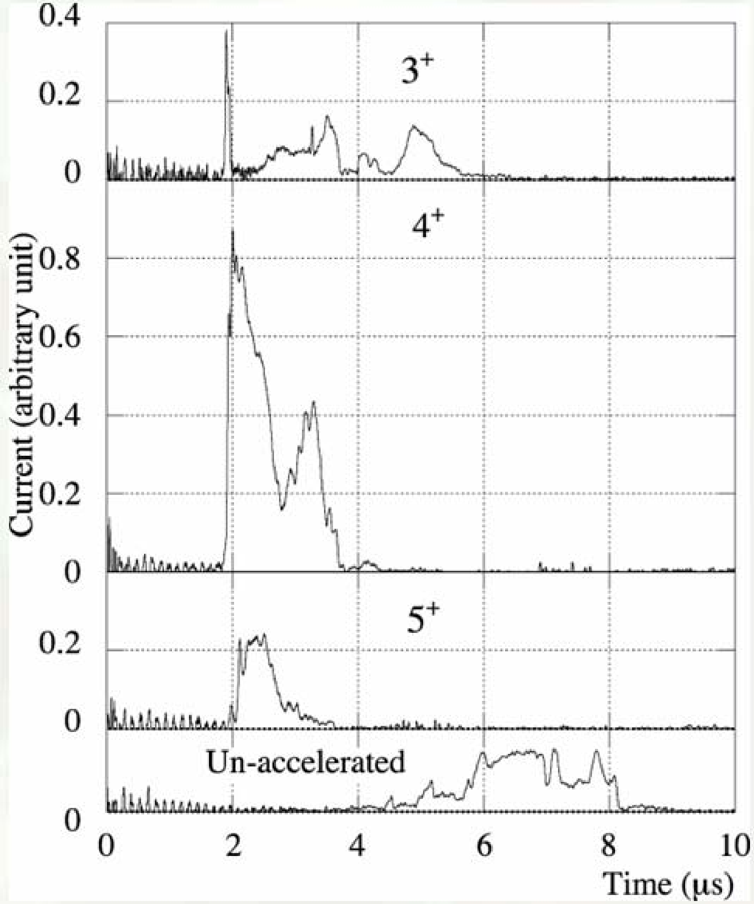
Carbon with 4 J CO_2 laser

Total current after RFQ



Analyzed signals

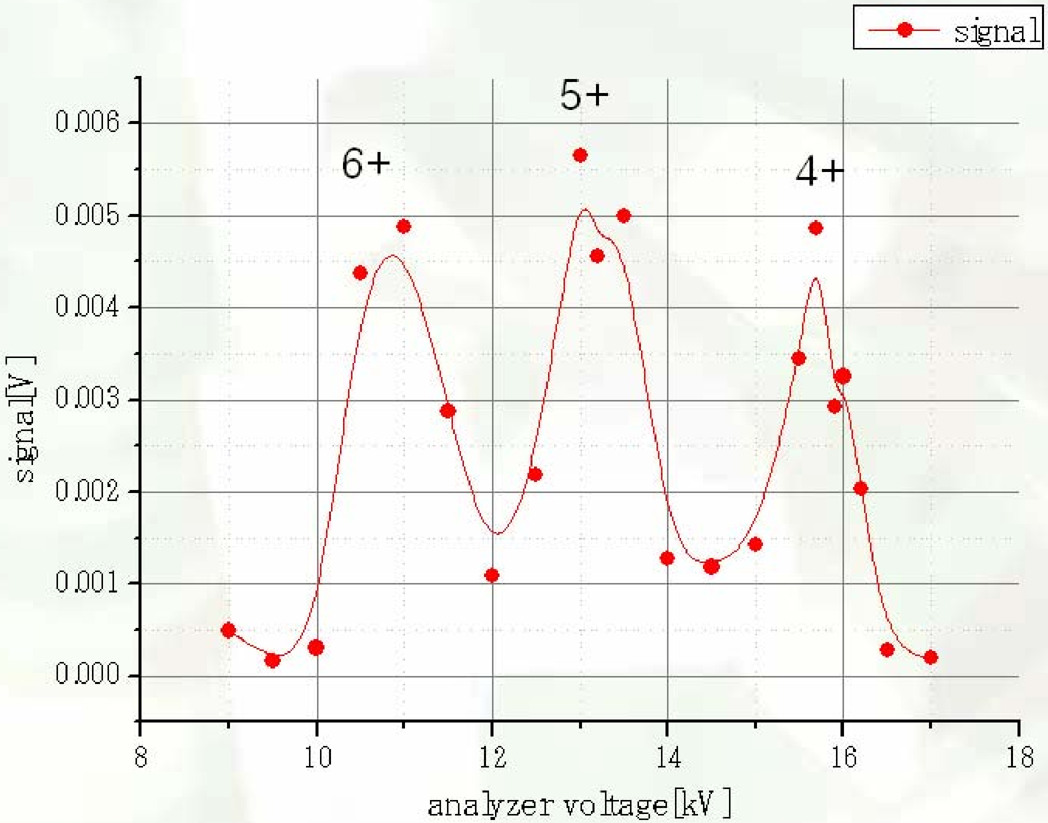


	Peak	Integral
C^{5+}	26%	24%
C^{4+}	64%	60%
C^{3+}	10%	16%

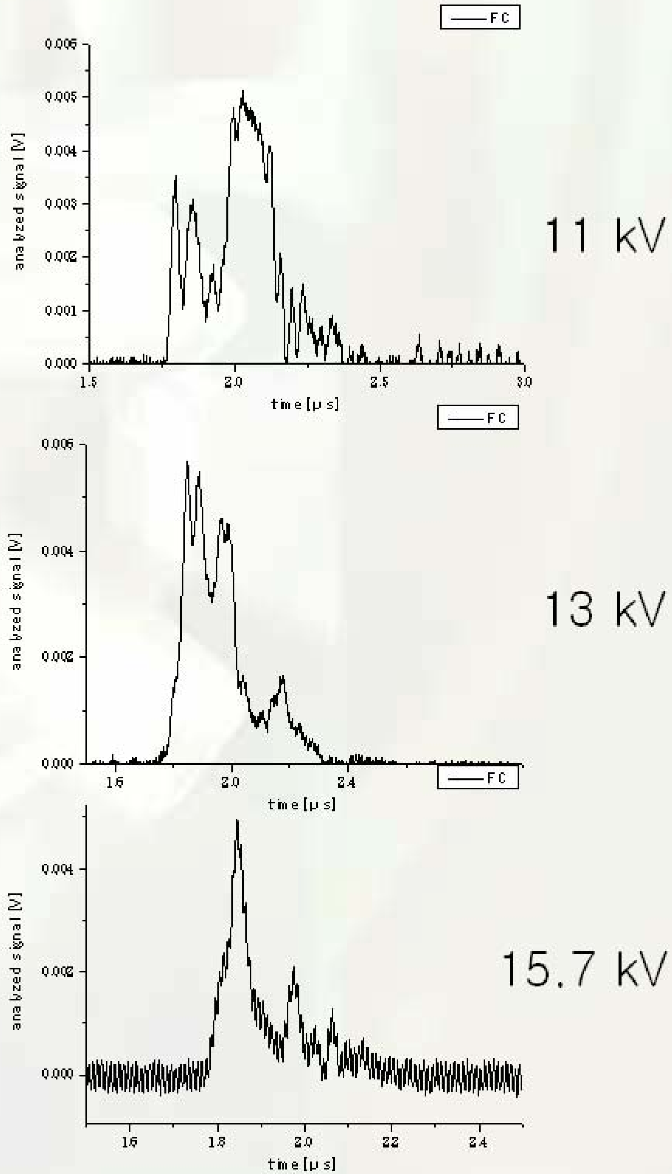
35mA at peak C^{4+}
6.3×10^{10} C^{4+} particles

Carbon with 300 mJ YAG laser

RFQ voltage : 100 %

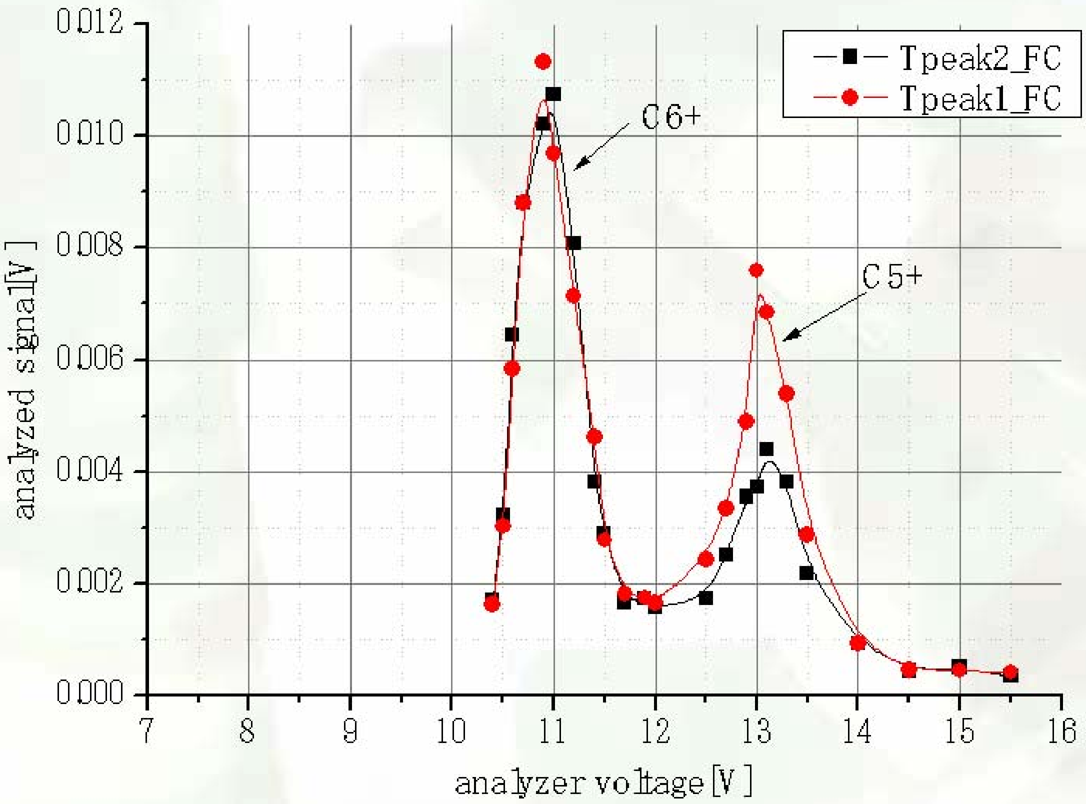


Extraction voltage 40 kV

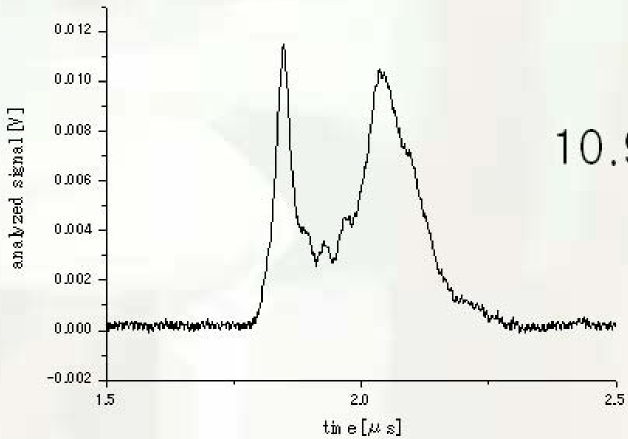


Carbon with 300 mJ YAG laser

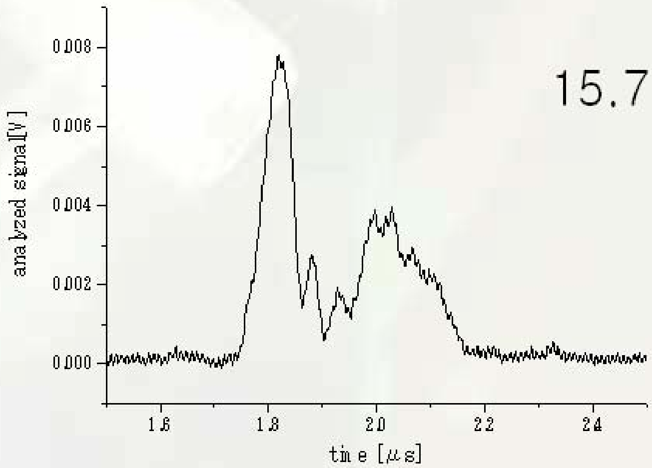
RFQ voltage : 75 %



Extraction voltage 40 kV



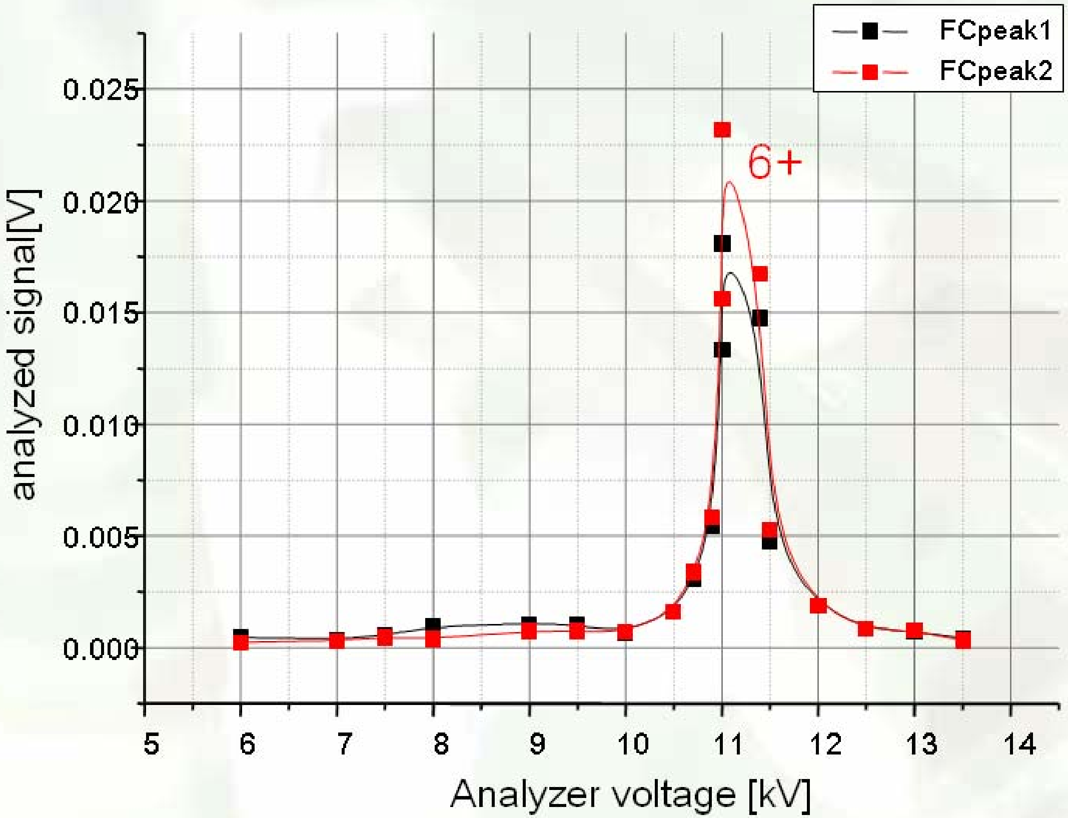
10.9 kV



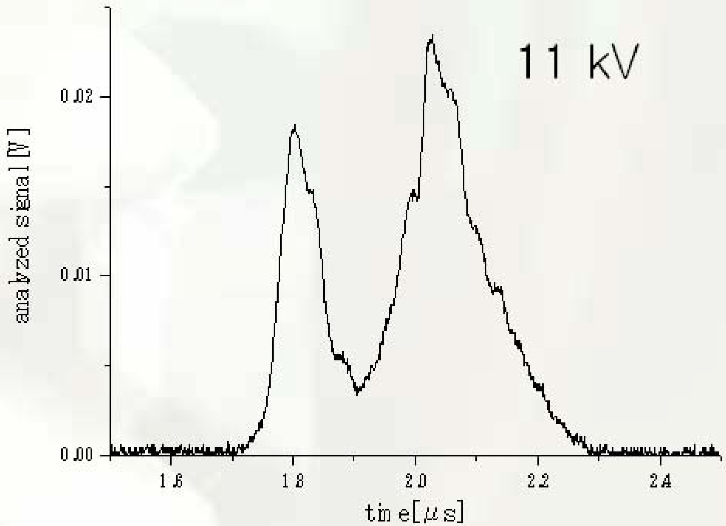
15.7 kV

Carbon with 300 mJ YAG laser

RFQ voltage : 61 %



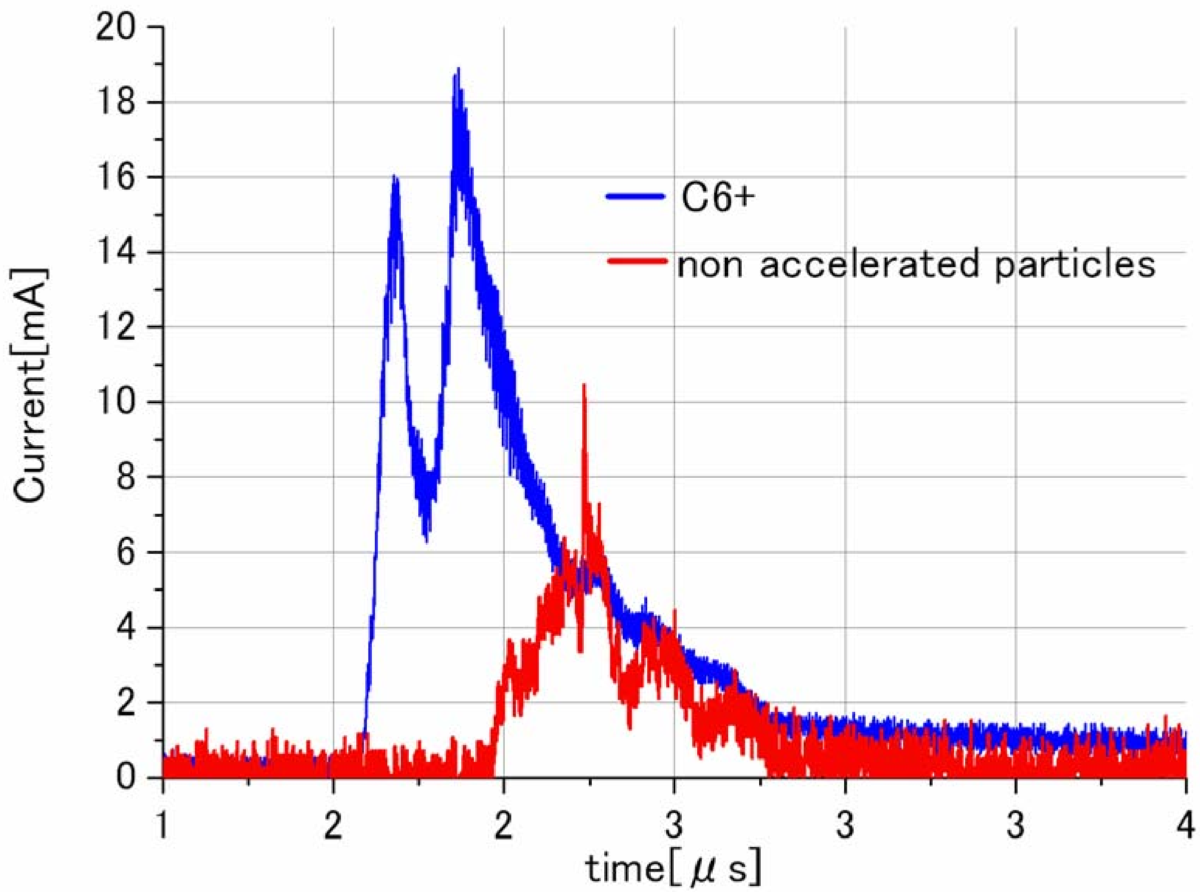
Extraction voltage 40 kV



Pure 6+ beam can be delivered by adjusting operating condition of the RFQ.

Carbon with 300 mJ YAG laser

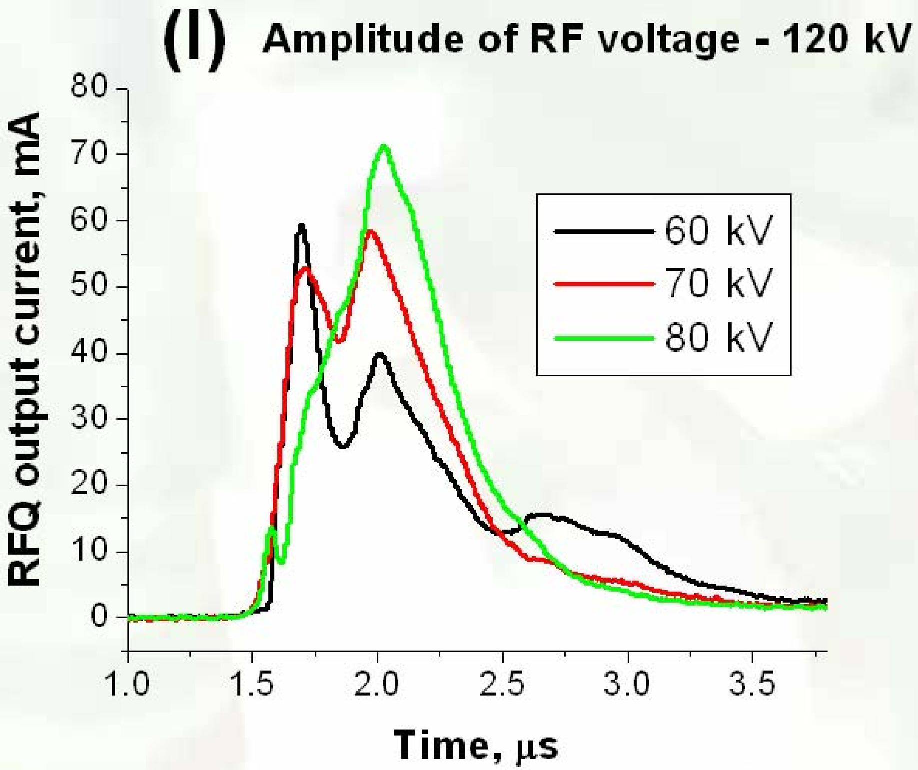
RFQ voltage : 61 %



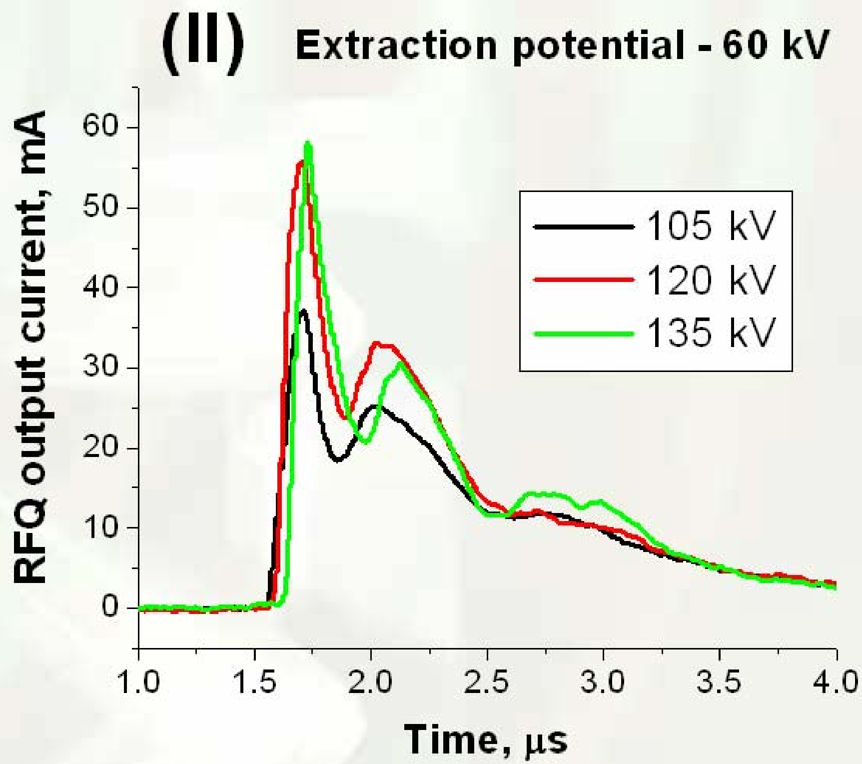
17mA C^{6+} peak current

Number of particles : 6.0×10^{9}

Aluminum with 2.3 J YAG laser



Extraction voltage scan



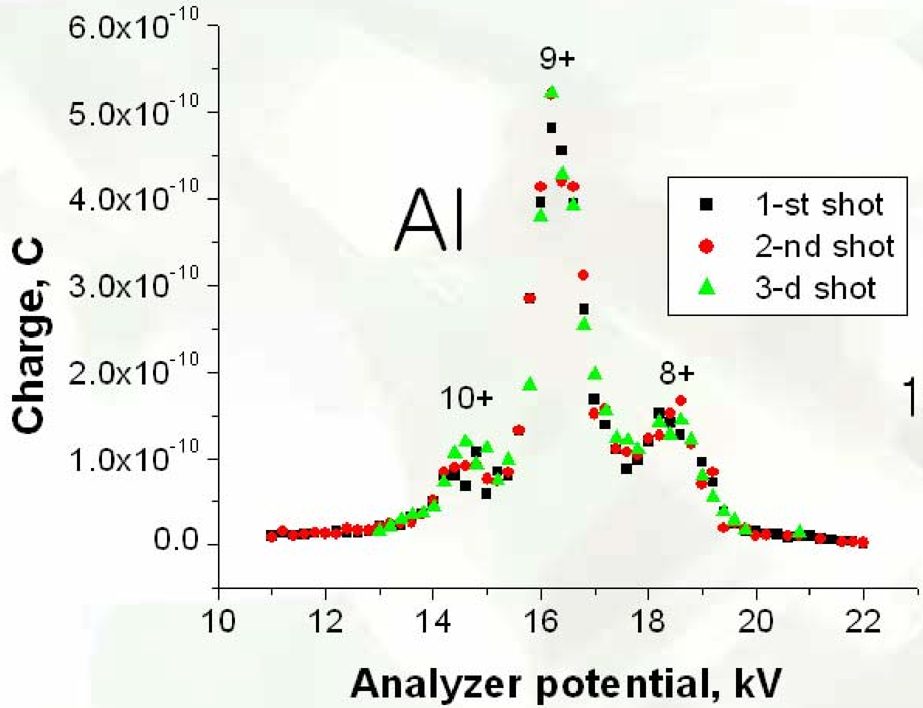
RFQ voltage scan

Laser spot size setting was optimized to get Al^{9+}.

Aluminum with 2.3 J YAG laser

Charge state distribution

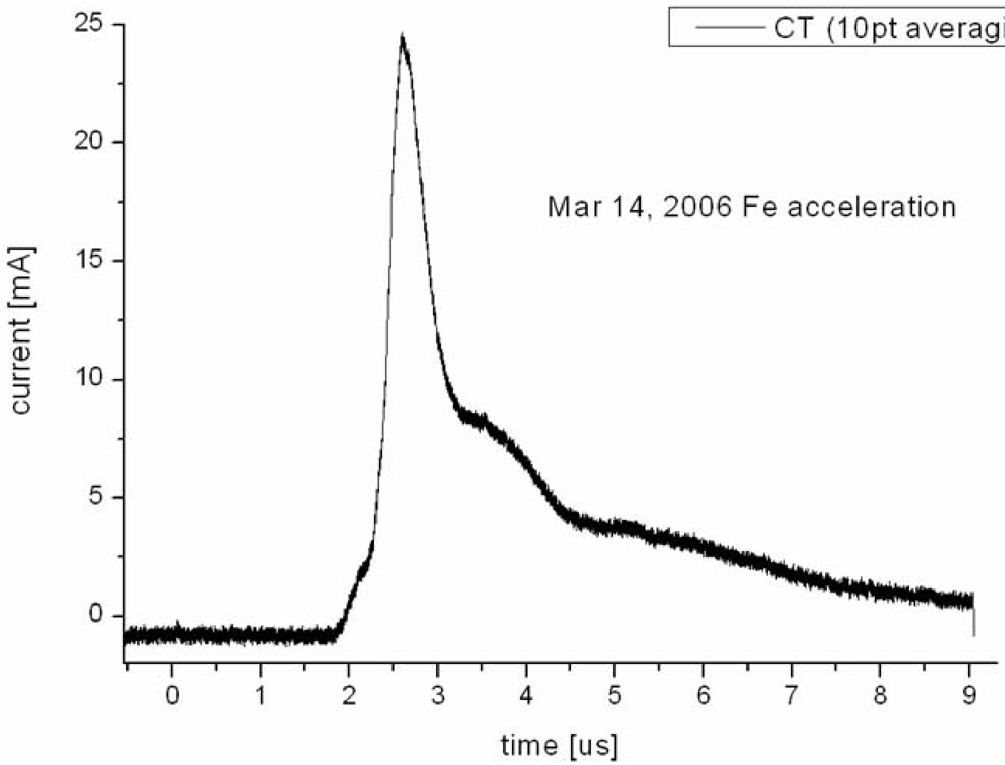
Extraction potential – 60 kV, Amplitude of RF voltage – 120 kV

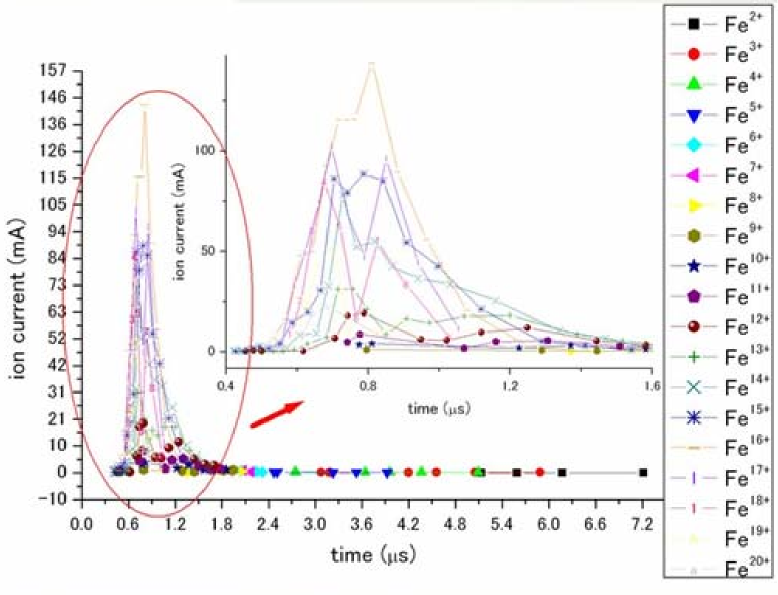


100 keV/u

- ^{27}Al ion beam with total current up to 70 mA, 0.65 μs
- $^{27}Al^{9+}$ ions occupy about 65%.

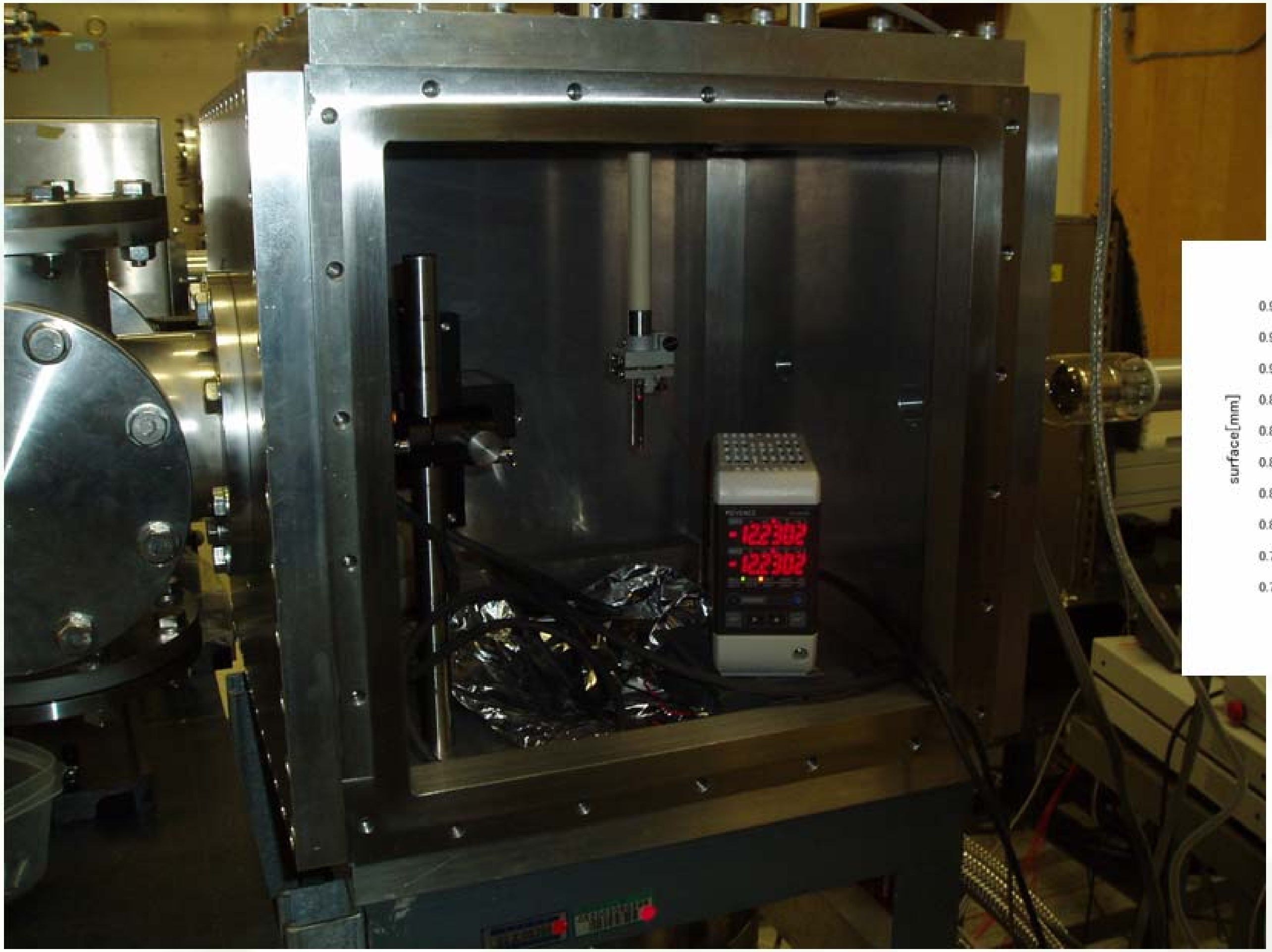
Iron with 2.3 J YAG laser

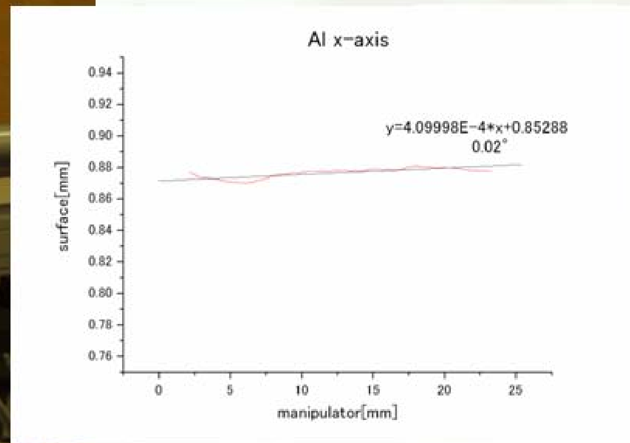




Mainly Fe^{16+} injected

Shot-to-shot stability

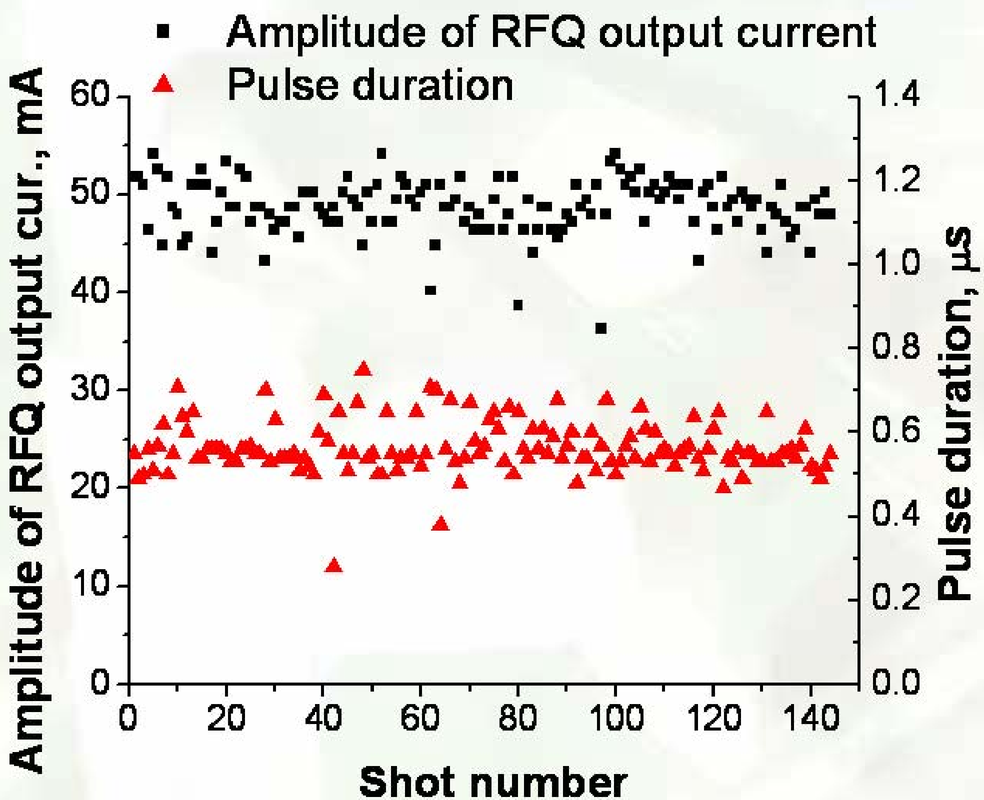




- A 3D manipulator provides every new surface.
- The target position controlled within 0.1 mm accuracy.

Shot-to-shot stability

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



$\langle I \rangle = 49$ mA $\pm$ 6%

$\langle \tau \rangle = 0.56$ μs $\pm$ 11%

Can be improved more.

Easy to get more stability on lower mass element like Carbon.

Hybrid (LIS for ECR)

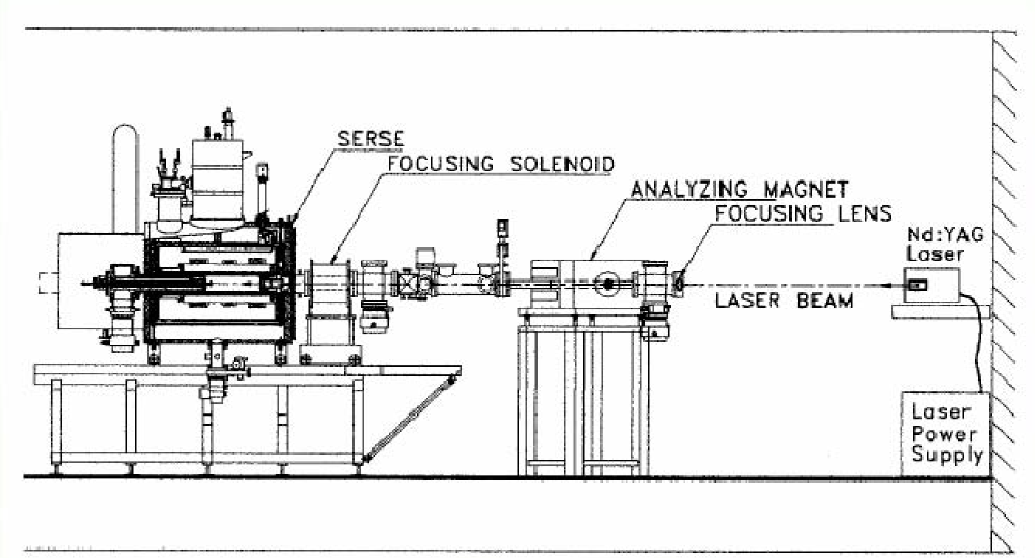
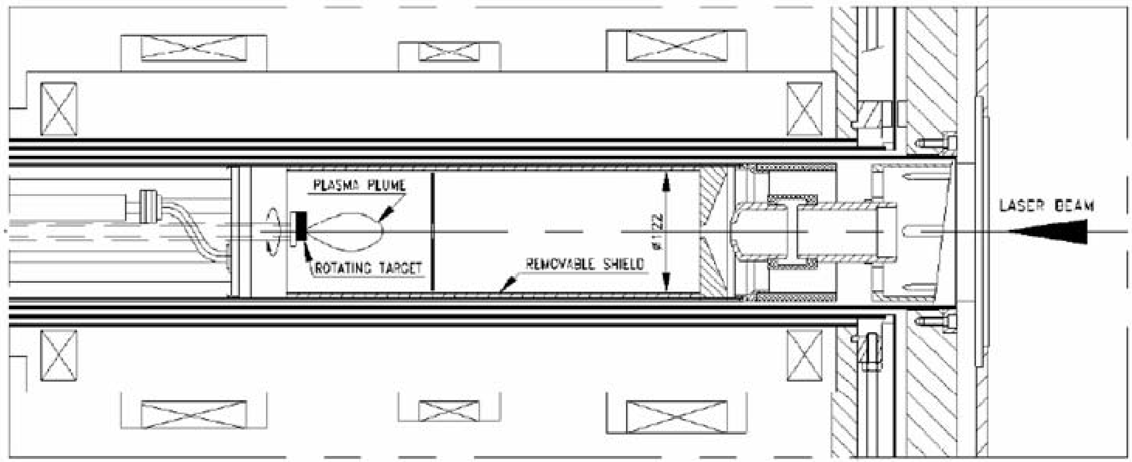


TABLE III. The best current for Ta and Au beams (** indicates the presence of the collimator above the extractor and a reduction of a factor 3 in current).

Charge state	Ta current (e μA)	Au current (e μA)
22	40	
23	40	
24	45	
25	50	
26	40	
27	32	
28	22	20**
29	12	17**
30	—	16**
31	8	14**
32	5	12**
33	2	—
34	0.6**	6**
35	0.3**	4.5**
36	—	3.5**
37	0.2**	—
38	0.15**	1**
40		0.4**
41		0.2**



YAG laser (0.9 J /9 ns,,5×10^{10} W/cm^2)
SERSE superconducting ECRIS (18 GHz)

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

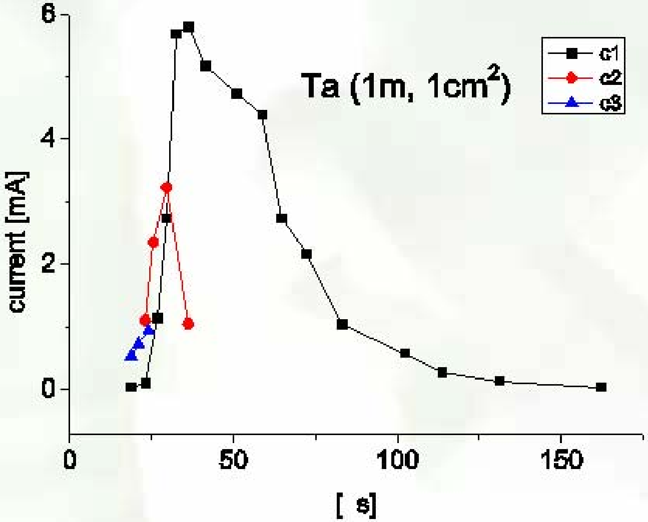
INFN–Laboratori Nazionali del Sud,

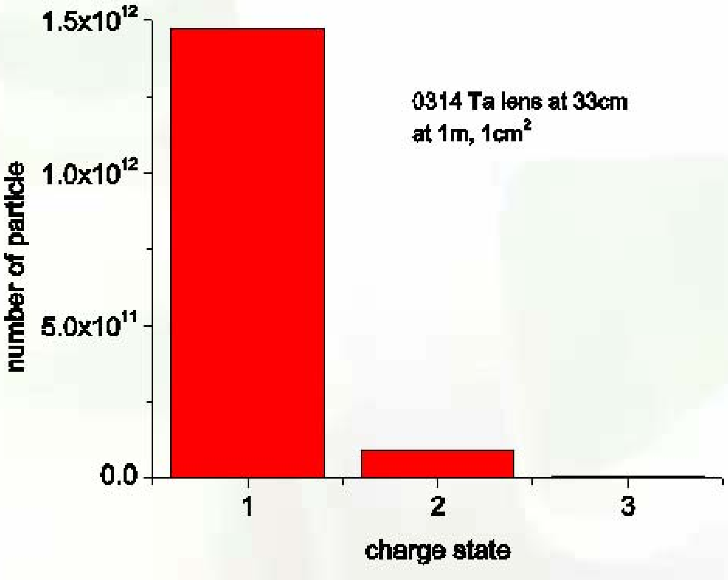
JOURNAL OF APPLIED PHYSICS VOLUME 96, NUMBER 5 1 SEPTEMBER 2004
Courtesy of Prof. Torrirsi

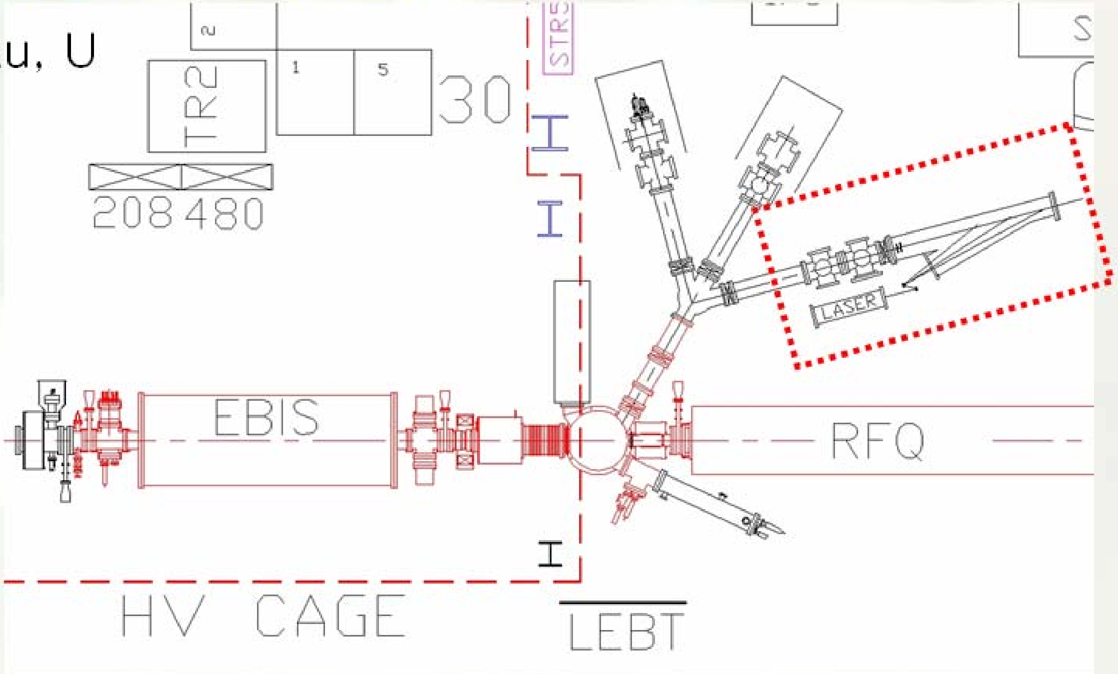
Hybrid (LIS for EBIS)

C, Mg, Si, S, Ca, Ti, Cr, Mn, Fe, Au, U

10^{10} particles





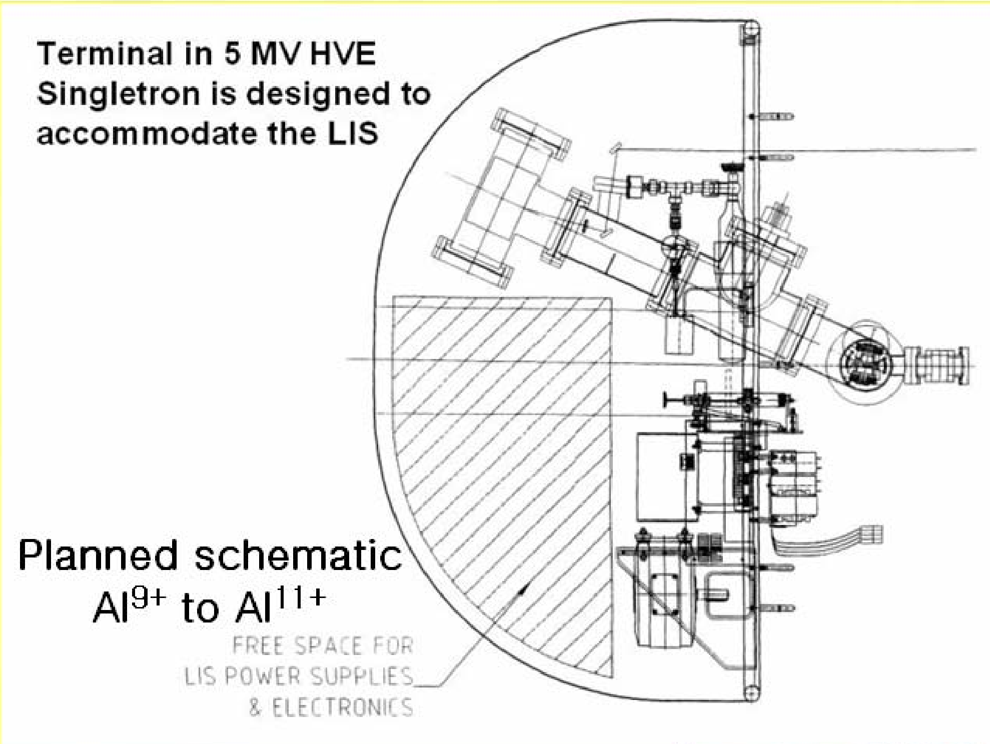


BNL EBIS project

LIS for 1+ ion injection to EBIS

- mA class low charge state ion.
- 30 to 50 μs
- Multiple targets (species switching pulse to pulse)
- Targets last very long time. (no crater)

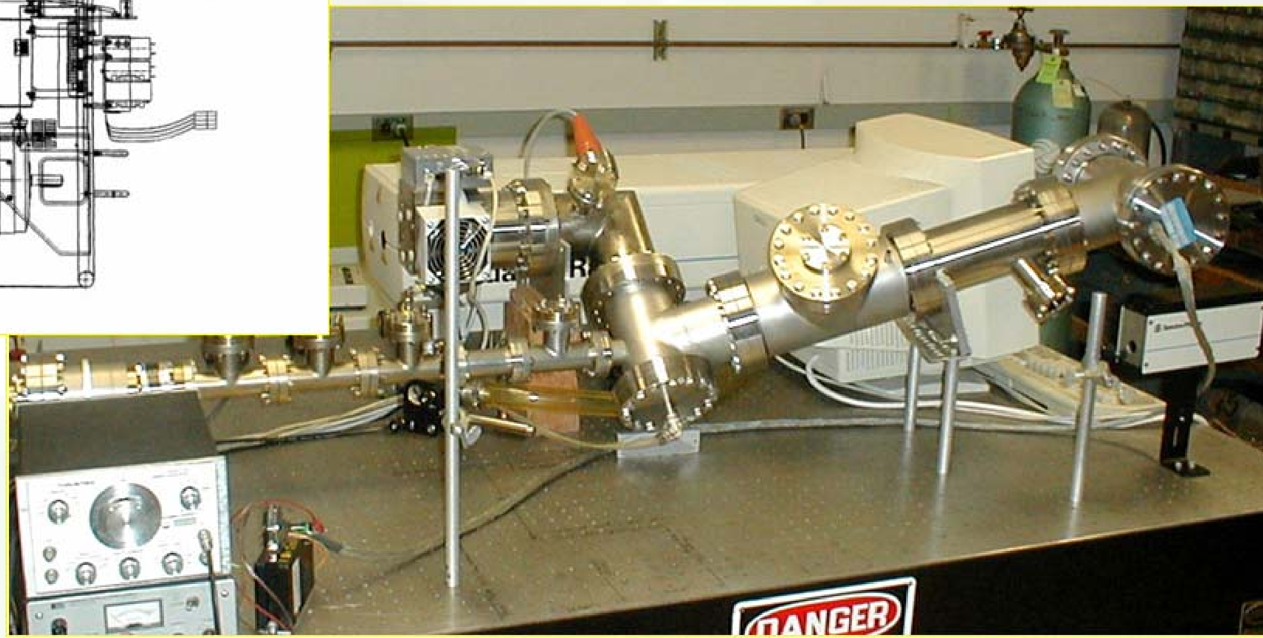
LIS for Electrostatic accelerator



RARAF, Columbia University

Micro-beam for the Biology

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

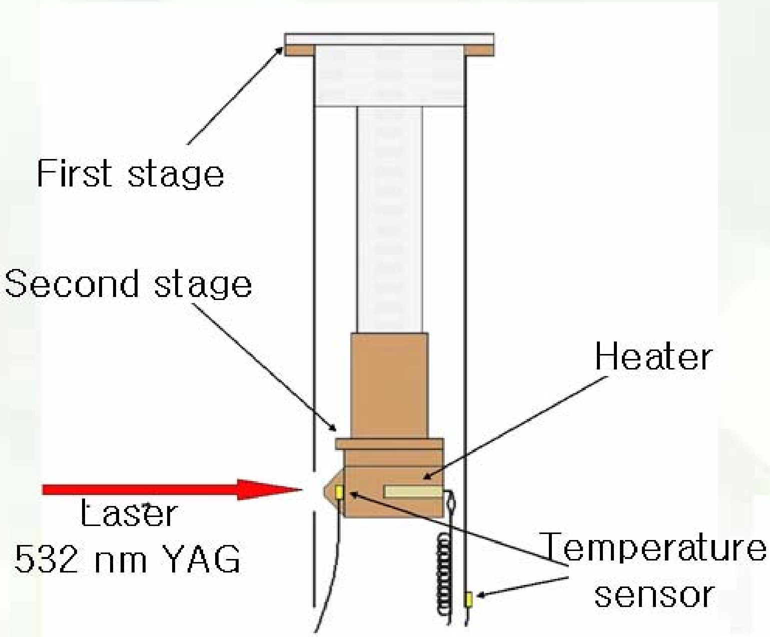


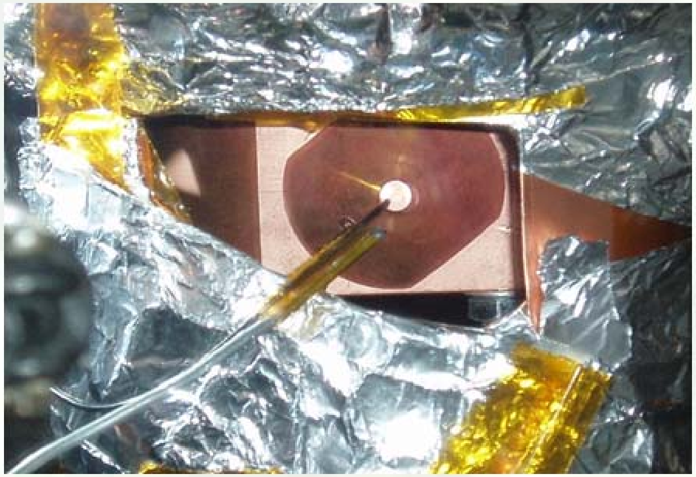
Quanta-Ray LAB-190-100
Nd:YAG
(100 Hz-325 mJ/pulse, 10 ns)

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

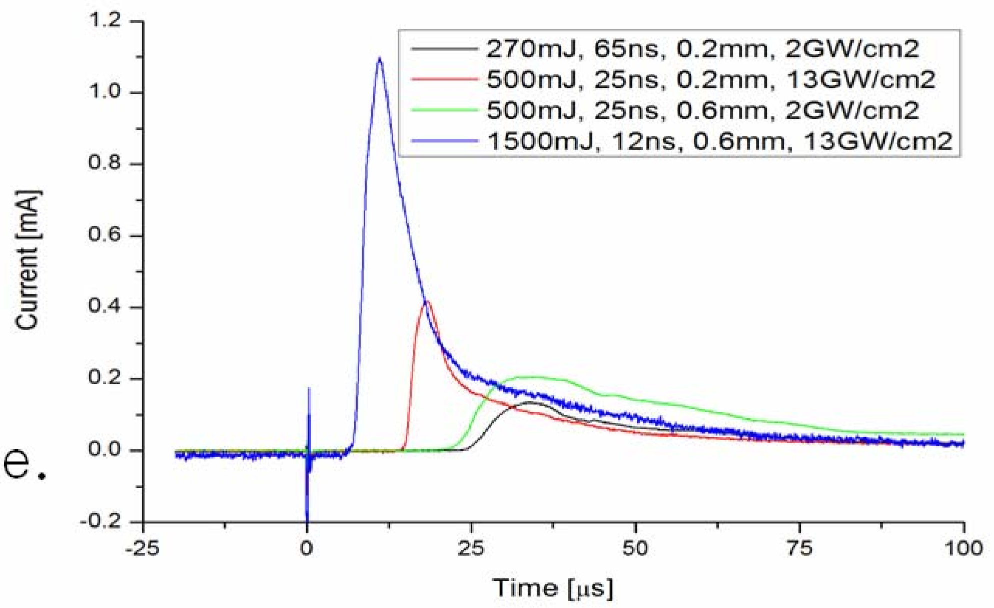
Cryo target for LIS





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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AEC
NIRS
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IMP
Frankfurt U.
CERN
PALS
INFN
BNL
Columbia U.
Thank you for your attention.