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Laser Ion Source for Highly Charged Ions

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Content

- Features and brief history of laser ion source (LIS)
- LIS structure
- Main physical and technical aspects
- Source development for CERN LHC
- Some recent results on ion generation
- Direct plasma injection scheme (DPIS)
- Present status of LIS development
- Summary

Different types of ion sources called "LIS"

- Ion source for selective ionization of isotopes
- Multi-photon ionization of atoms

- Ion source using extremely high power density (> 10^{18} W/cm^2) of fs-lasers
- Irradiation of thin foil
- Ionization by extremely strong electric field caused by separation of hot electrons and cold ions in space

- **Ion source using moderate laser power densities (< 10^{15} W/cm^2)**
- **Irradiation of thick target**
- **Ionization by electron impact into laser produced plasma**

Milestones of LIS development

- 1969 – LIS was proposed simultaneously and independently by Bykovskii et al. and by Peacock and Pease
- 1977 – Injection of ions from LIS to synchrotron in JINR, Dubna, Russia
- 1988 – LIS has been employed for Van-de-Graaf accelerator in TU, Munich, Germany and in ITEP, Moscow, Russia
- 1994 – LIS has been employed for RFQ at GSI (in collaboration with ITEP-Moscow)
- 1993-2003 – LIS development for CERN LHC (ITEP-CERN-TRINITI collaboration)
- Since 2000 – LIS is in routine operation for ITEP-TWAC accelerator facility
- 2000-2006 – Direct Plasma Injection Scheme (DPIS) has been proposed and tested in RIKEN (Japan)

Ion sources for highly charged ions

- Electron cyclotron resonance ion source (ECR)

- Both CW and pulsed operation

- Electron beam ion source (EBIS)

- Pulsed operation

- Laser ion source (LIS)

- Pulsed operation

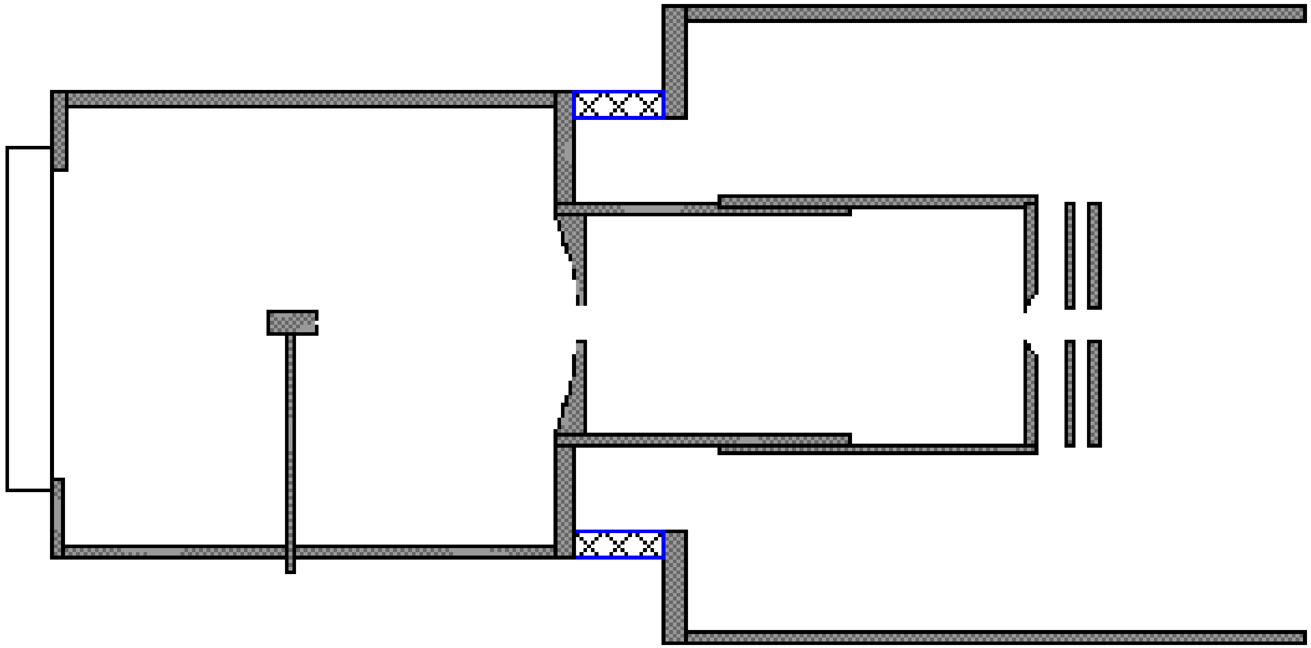
CW accelerators (cyclotrons, linacs) --> ECR; EBIS and LIS – low duty factor

Pulsed accelerators (synchrotrons, FFAGs) --> ECR, EBIS and LIS

LIS in comparison with ECR: comparable charge states, higher current, shorter pulse duration

LIS in comparison with EBIS: slightly lower charge states, higher current, comparable pulse duration (for high current EBIS operation)

How LIS works



Laser beam

Expanding plasma

Ion beam

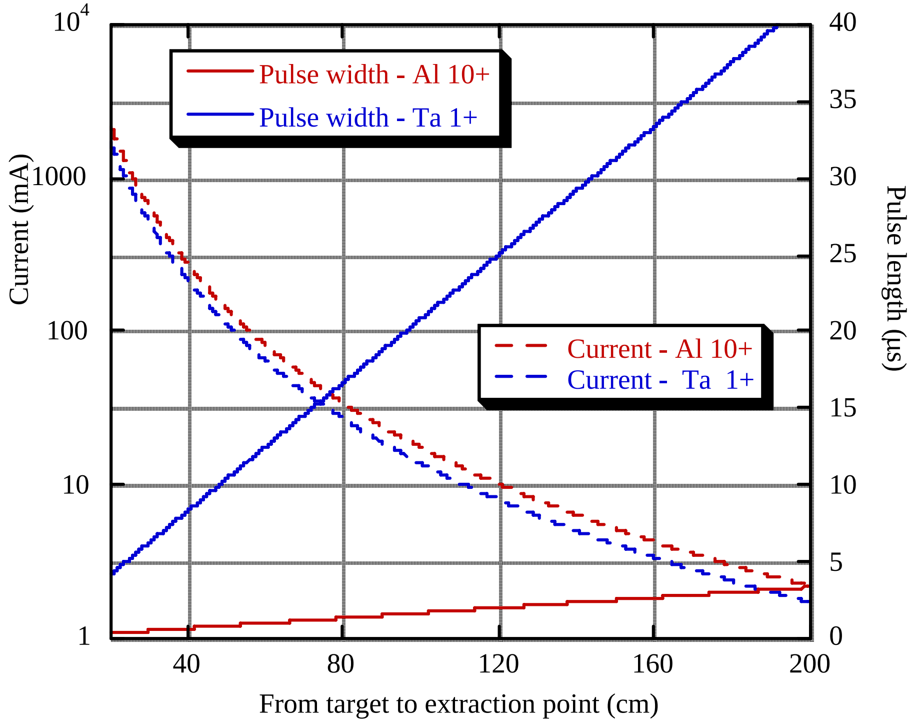
Beam current and Pulse length

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

$$\tau \propto L$$

$$I \propto L^{-3}$$

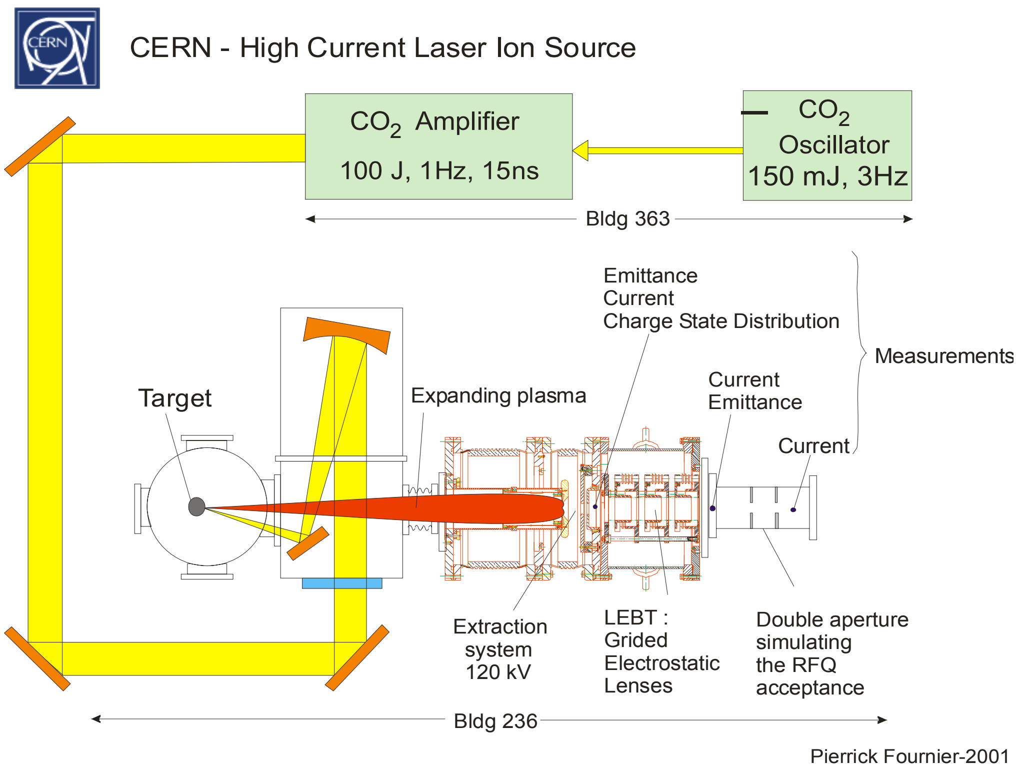
L - Distance from target to extraction point



Pulse length - 3÷30 μs, current – 10÷100 mA ---> well matched to fill synchrotron or FFAG rings up to space charge limit in a single turn

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 lay-out and subsystems



- Laser
- Target illumination unit
- Plasma expansion region
- Extraction system
- LEBT

Main physical processes in laser-produced plasma

I) Plasma heating stage

- Laser energy absorption and evaporation in a skin layer of a solid target
- Laser energy absorption by electrons in plasma by the classical Bremsstrahlung absorption (absorption in electron ion collisions) in the region of plasma with critical density n_{cr}: $n_{cr} = 10^{19}$ cm^{-3} for $\lambda = 10.6$ μm and $n_{cr} = 10^{21}$ cm^{-3} for $\lambda = 1.06$ μm
- Energy transfer from absorption area by electron heat conductivity
- Ionization of atoms and ions in plasma by electron impact
- Recombination processes in plasma:

- radiative recombination
- dielectronic recombination
- three-body recombination (TBR) through high exited levels

II) Plasma expansion stage

- Transfer of plasma energy into ion kinetic energy during hydrodynamic acceleration
- Recombination losses of highly-charged ions mainly due to TBR as $R_{TBR} \sim T_e^{-9/2}$

Estimation of plasma parameters

- Electron temperature (T_e in eV) and average ion charge state (Z) at a heating stage:

1) λ = 1.06 μm – coronal equilibrium

$$T_e \approx 100 \bullet (ZP/d)^{2/7}$$
$$e^{I_Z/T_e} \approx 10^7 T_e m / (I_Z Z)^2$$

2) λ = 10.6 μm – equilibrium between impact ionization and dielectronic recombination

$$T_e \approx 100 \bullet (ZP/d)^{1/3}$$
$$I_Z / T_e \approx 56 / \left(I_Z^{1/4} Z^{3/4}\right)$$

P and d are the laser power in GW and the focal spot diameter in mm

I_Z is the ionization potential in eV

m is the number of equivalent electrons of (Z-1)-stripped ions

- Ion charge states significantly drop at expansion stage because of TBR (in some cases recombination has influence up to about 1 m distance from the target)
- Being accelerated hydrodynamically, ions acquire kinetic energy that is much greater than the plasma temperature on a heating stage:

$$E_{kin}^{max}[eV] \approx 15/2(Z+1)T_e[eV]$$ in adiabatic case

Specification of LIS parameters

Accelerator requirements to the source

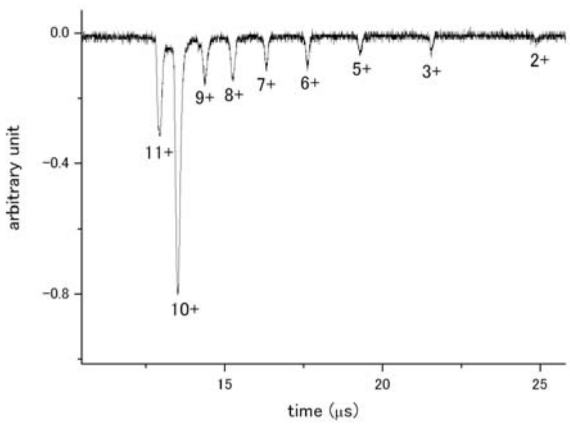
- Ratio of ion charge state to ion mass **Z/A**
- Ion pulse length $\boldsymbol{\tau_z}$ (for charge state Z)
- Ion current $\mathbf{I_z}$ (for charge state Z)
- Emittance $\boldsymbol{\varepsilon}$
- Injection energy $\mathbf{E_{inj}}$
- Energy spread $\Delta\mathbf{E/E_{inj}}$
- Rep-rate
- Number of operation cycles between interventions
- Pulse-to-pulse fluctuations

What should be measured?

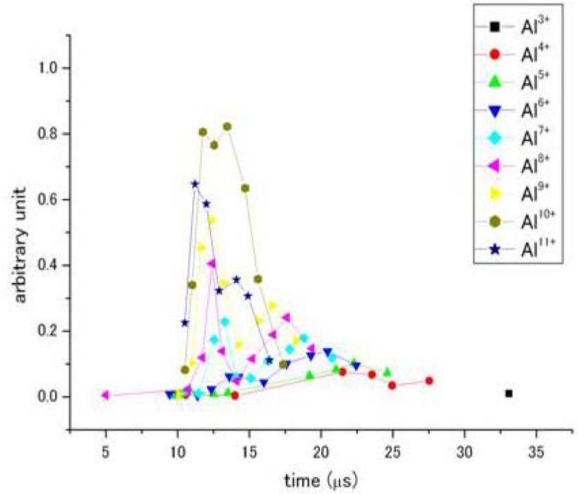
•Laser power density which provide required charge state as the most abundant in the distribution
•Current of ions for charge state Z
•Energy distribution of ions with charge state Z
•Beam emittance

Tools for ion parameter measurements

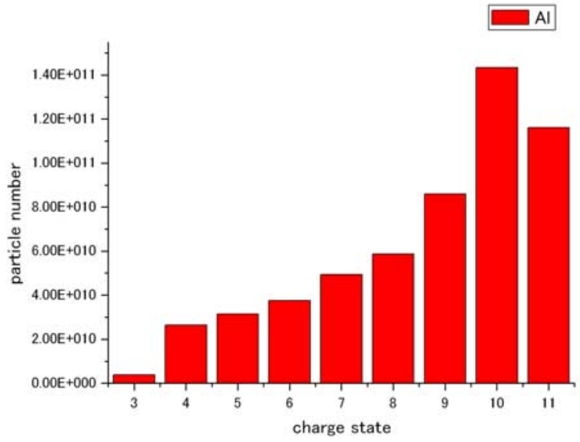
- Ion current in plasma – meshed Faraday cup (FC)
- Current of extracted ion beam – FC with suppression ring
- Charge states and energy distributions – electrostatic ion analyzer (EIA)
- Emittance – pepper-pot – scintillator – CCD camera system



EIA signal for Al ions



Time dependences of ion currents for different charge states



Absolute numbers of ions for different charge states

Beam extraction and matching to accelerator

- Three electrodes exel-decel extraction system is used
- Plasma boundary is defined by Child-Langmuir law

$$J = \frac{4}{9}\varepsilon_0 \sqrt{\frac{2q}{M}} \frac{U^{3/2}}{d^2} \alpha(r)\beta(V_{pl})$$

J is extracted ion current density
U is the voltage across extraction gap
q and *M* are the ion charge and mass respectively
ε_0 is vacuum permittivity
$\alpha(d, r)$ and $\beta(V_{pl})$ are coefficients to take into account restricted extraction aperture and initial velocity ions in plasma
r is radius of extraction aperture
V_{pl} is ino velocity inside plasma

- Temporal fluctuations of ion current in plasma cause spatial fluctuations of plasma boundary (can be stabilized by placing of fine mesh at extraction electrode)

- LEBT: total ion current about 100 mA ---> strong space charge + significant temporal ion current fluctuations
  The best results were obtained using solenoid and gridded electrostatic lens (GEL): 50% transmission of extracted ion beam (about 100 mA) into RFQ acceptance

Technical aspects

- Life-time of different subsystems

  - laser

  - optical elements (damage by laser beam and surface covering by plasma atoms and ions), special attention to protection of focusing mirror or lens is required

- De-coupling of laser from photons reflected by target and plasma

  - avoid target irradiation by normal incident angle

  - optical delay between laser and plasma

- Keep required vacuum for rep-rate operation

Parameters of CERN LIS for LHC

TABLE I. Specification parameters of the laser ion source (laser system scheme: master–oscillator/power amplifier).

Parameter	Value
Total laser energy	$\geqslant$100 J
useful laser energy	$\geqslant$80 J
Laser pulse duration	30–50 ns
Diameter of the focal spot	170–250 μm
Laser power density	(0.8–1.2) 10^{13} W/cm^2
Laser beam diameter	160 mm
Focal length of the focusing mirror	200–300 cm
Incident angle at the target	$<5°$
Plasma expansion length	200–260 cm
Total extraction current density	8.8 mA/cm^2
Diameter of the extraction hole	34 mm
Number of Pb^{208} particles with $Z=25+$	1.4×10^{10}
Ion pulse length	1.5; 3; 6 μs
Emittance of extracted Pb^{208} ion beam ϵ (4 rms at 9.6 keV/u)	44 mm mrad
Extraction potential	80 kV
Source repetition rate	1 Hz
Energy spread dE/E	$<\pm2.5\%$
Number of LIS operation cycles between interventions	2×10^6

LIS development for LHC

ITEP (Moscow, Russia)-CERN-TRINITI (Troitsk, Russia) collaboration

Requirements

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

High current

High charge states

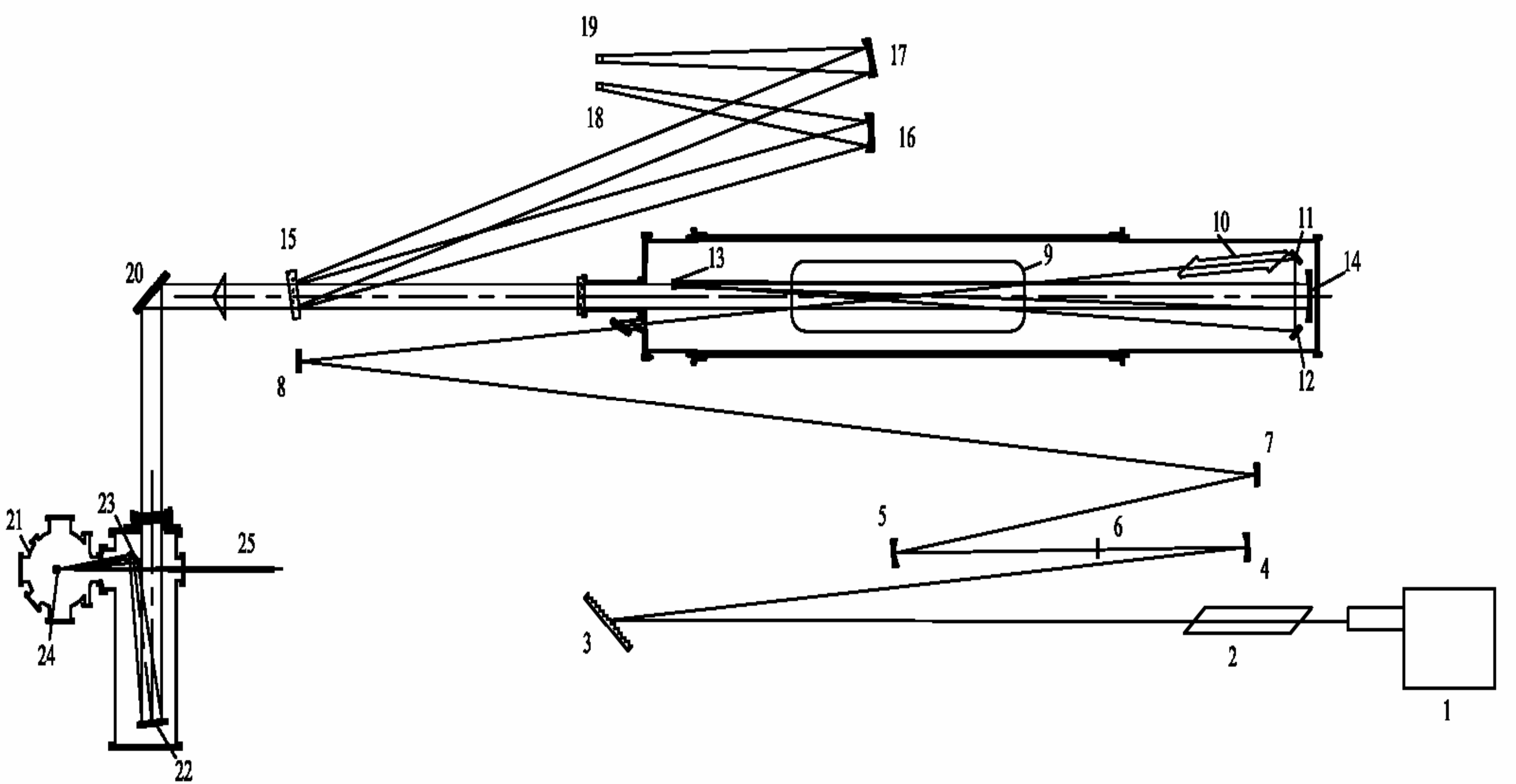
Long pulse

⇩

Powerful laser

100 J/1 Hz MO-PA CO_2-laser system has been developed and build

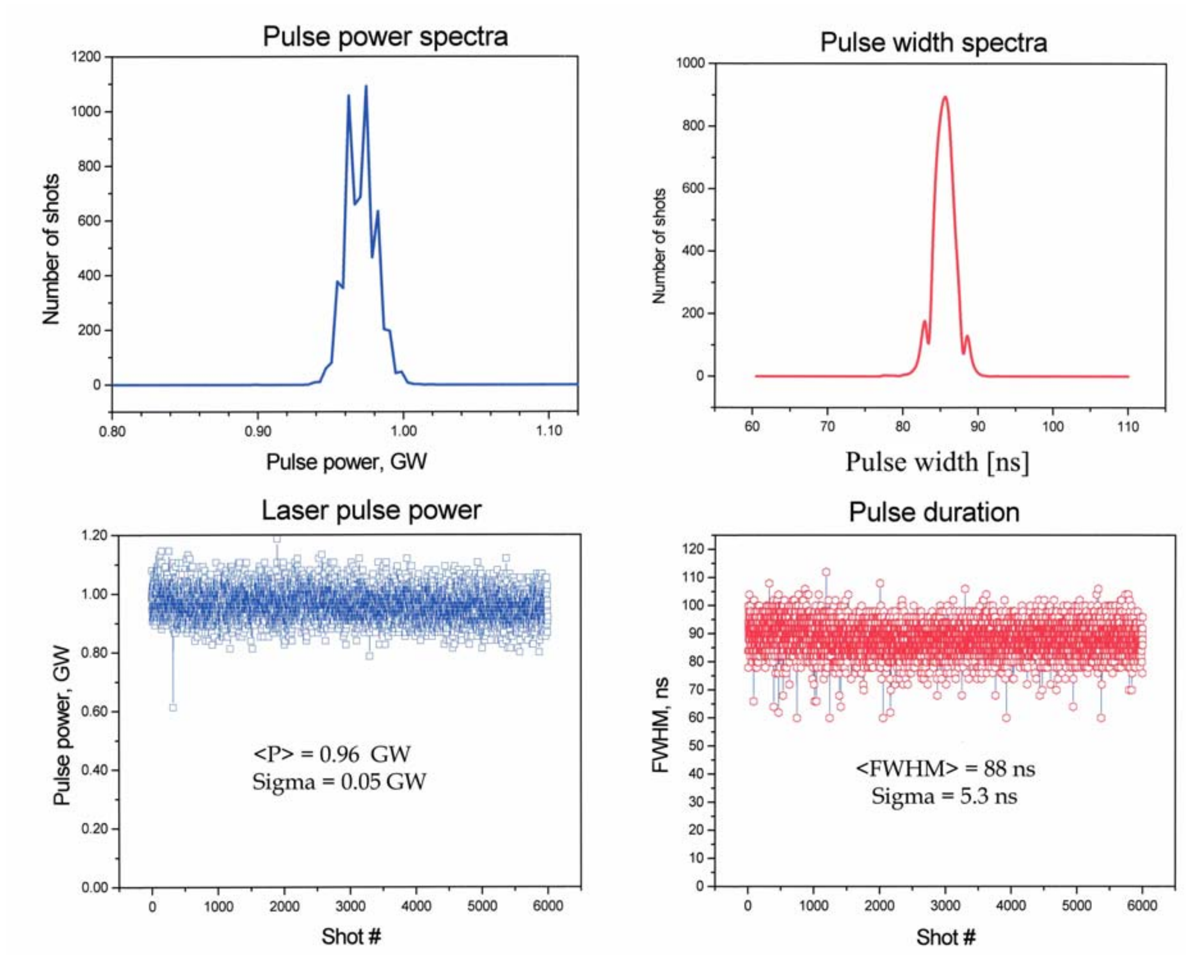
Optical scheme of MO-PA 100 J/1 Hz CO_2-laser



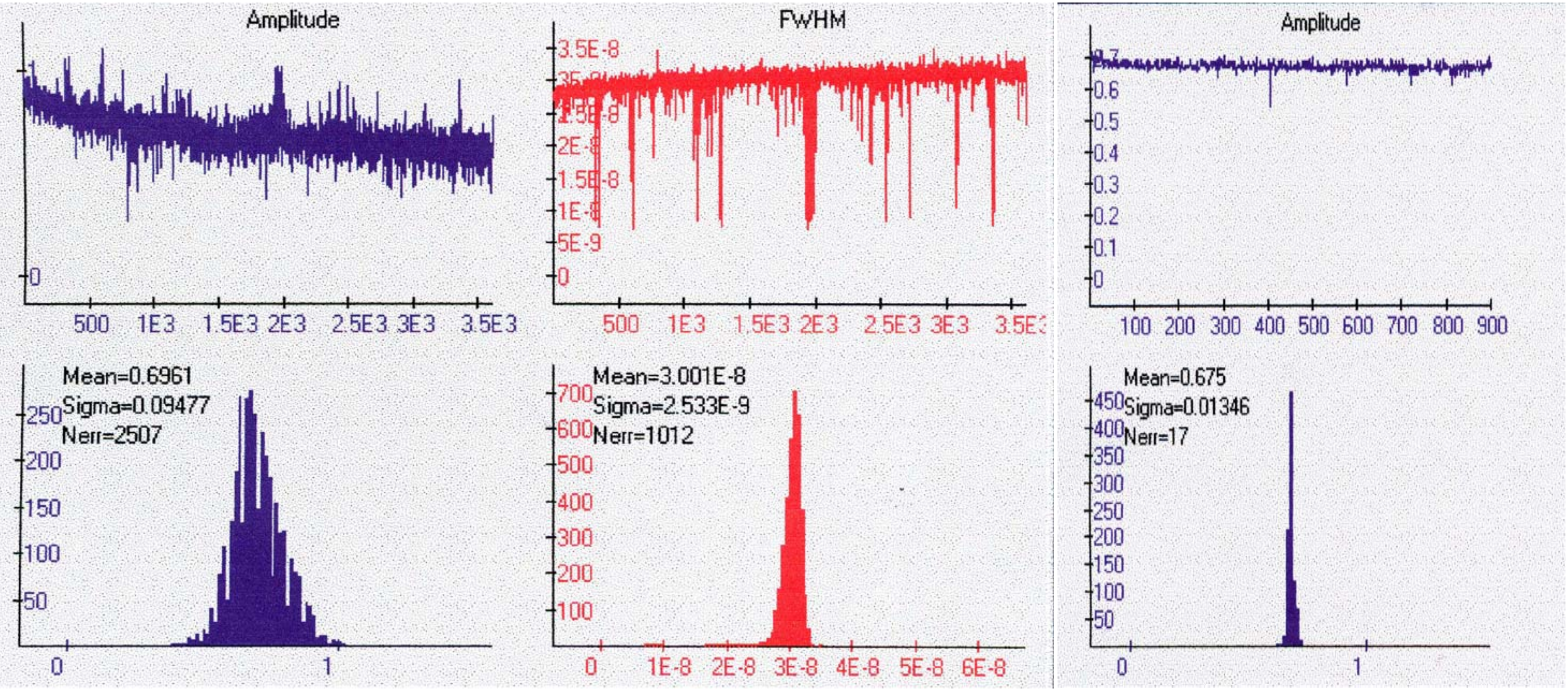
1 - Master Oscillator (MO), 2,10 - absorber cells, 3 - grating , 4,5 – spatial filter, 6 - diaphragm of spatial filter, 7, 8, 11, 12, 20, 23 – flat mirrors, 9 - active volume of Power Amplifier (PA), 13 – convex mirror of telescope, 14 – concave focusing mirror of telescope, 15 - salt wedge laser beam splitter, 16, 17 – focusing mirrors, 18 - energy meter, 19 - laser pulse shape detector, 21 – source vacuum chamber, 22 - focusing objective spherical mirror, 24 - target, 25 - expanding plasma.

LIS development for LHC
Laser pulse statistics (generator mode)

The most difficult task was to achieve required stability and life-time



LIS development for LHC
Laser pulse statistics (MO-PA mode)

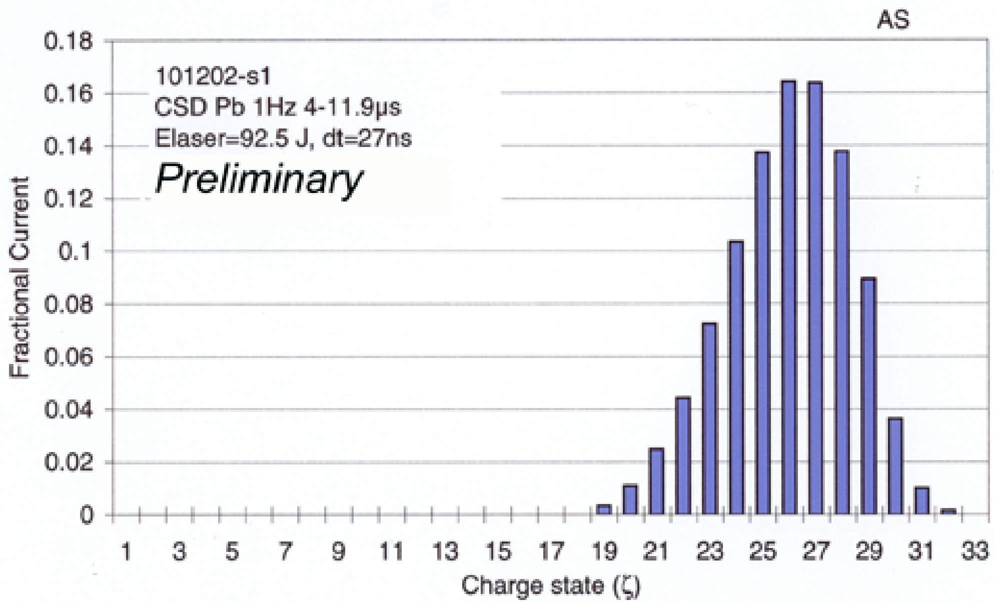


MO&PA 90 J operation of 1 hr 15 min at 1 Hz

1 hr 0.25 Hz

LIS development for LHC
Lead ion generation

First results from LIS - December 2002

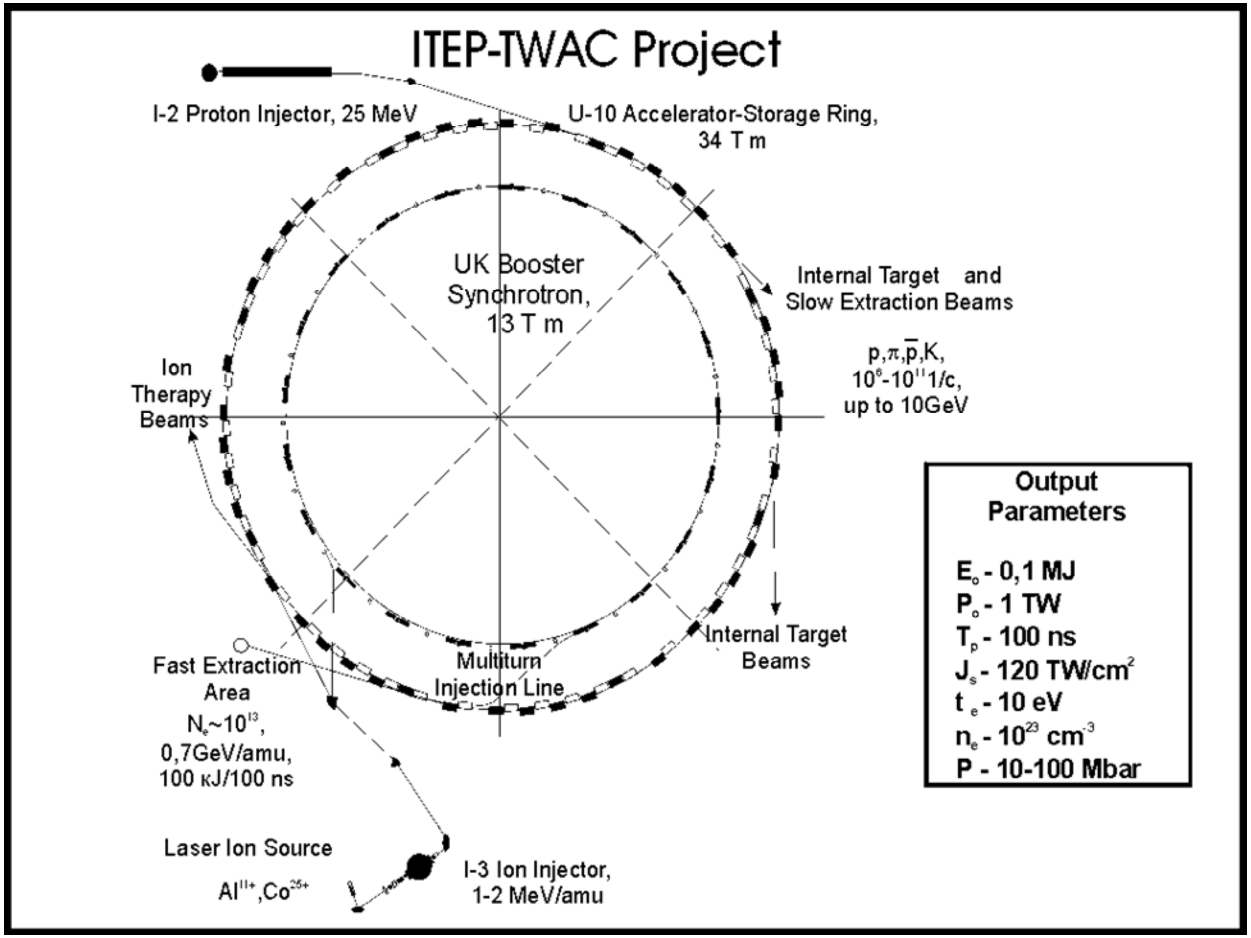


This charge - state distribution, combined with an average current of 0.363 mA over 4 microseconds, 1750 mm from the target, leads to

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

for the standard extraction geometry (aperture 34 mm)

LIS for ITEP (Moscow)-TWAC project



Requirements to the source

- Element - as heavy as possible
- Ion charge state - in the range C-like – He-like ions
- Ion pulse length (for 95% of ions with desirable charge state) – 10 ÷ 15 μs
- The number of ions with desirable charge state - about $5 \cdot 10^{10}$ ions/pulse,
- The emittance of extracted beam – below 500 π mm·mrad
- Repetition rate – 1 Hz
- The number of source operation cycles between interventions – more than 10^4

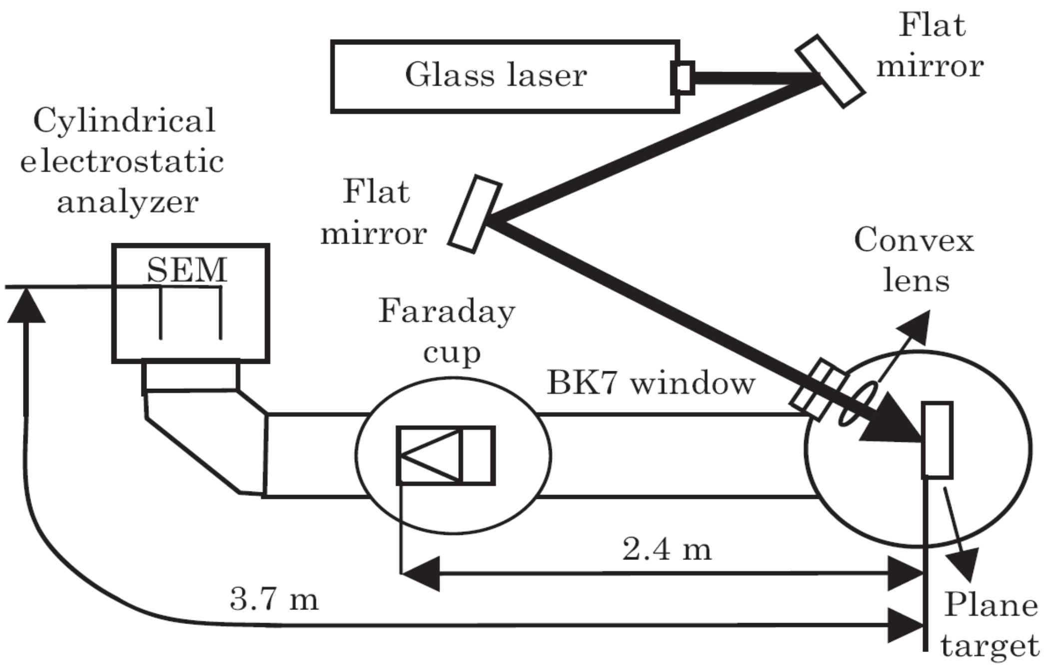
- LIS for $^{12}C^{4+}$ (5 J/0.25 Hz CO_2-laser) ions is in routine operation since 2000
- LIS for $^{27}Al^{11+}$ ions (20 J/1 Hz CO_2-laser) will be used in the end of 2007 + new injector I-4
- LIS for $^{48}Ti^{18+}$ ions (100 J/1 Hz CO_2-laser) planned to be used in 2008-2009 +new injector I-4

Ion generation by 75 J/16 ns CO_2-laser

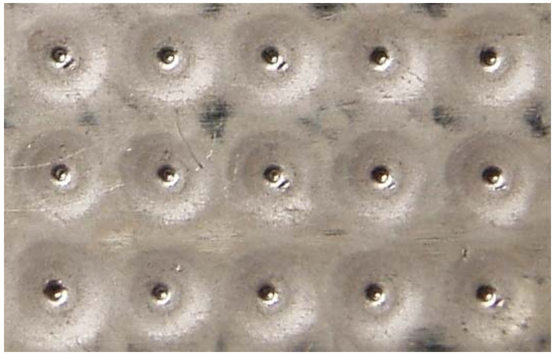
Numbers and pulse durations for ions with different charge states (focal spot diameter – 65 μs, laser power density – up to 10^{14} W/cm^2, distance from the target 308 cm, aperture – 3,4 cm)

Z	^{10}F (CaF_2-targ.)		^{24}Mg		^{27}Al		^{40}Ca (CaF_2-tar.)		^{48}Ti	
	N, 10^{10}	Δt,μs	N, 10^{10}	Δt,μs	N, 10^{10}	μs	N, 10^{10}	Δt, μs	N, 10^{10}	Δt, μs
4	0.1	5	0.2	3.6	-	-	-	-	-	-
5	0.3	5	0.4	4	-	-	-	-	0.15	23
6	1.1	4.5	1.4	4.8	-	-	-	-	0.25	12
7	3.7	4	3.5	6.7	0.15	6.5	-	-	0.3	19
8	-	-	7.0	6.6	0.8	8.5	0.05	4	0.75	16
9	-	-	14.	6.2	2.6	8	0.15	6	0.6	18
10	-	-	18	5.7	6.3	7.5	0.6	5.5	1.0	17
11	-	-	0.6	4.5	12	7	1.0	5	1.8	16
12	-	-	-	-	0.1	5	2.0	4.5	3.8	15
13	-	-	-	-	-	-	3.4	4	4.7	12
14	-	-	-	-	-	-	3.0	4	5.5	7.5
15	-	-	-	-	-	-	1.4	3.5	4.0	5.5
16	-	-	-	-	-	-	0.3	3	1.3	5
17	-	-	-	-	-	-	0.2	3	0.2	5.5

Features of ion generation using Nd-glass laser



- Fresh target surface for each shot
- Target position control within 100 µm accuracy



<u>Craters for Ag (silver) target:</u>

distance between craters - 1 mm

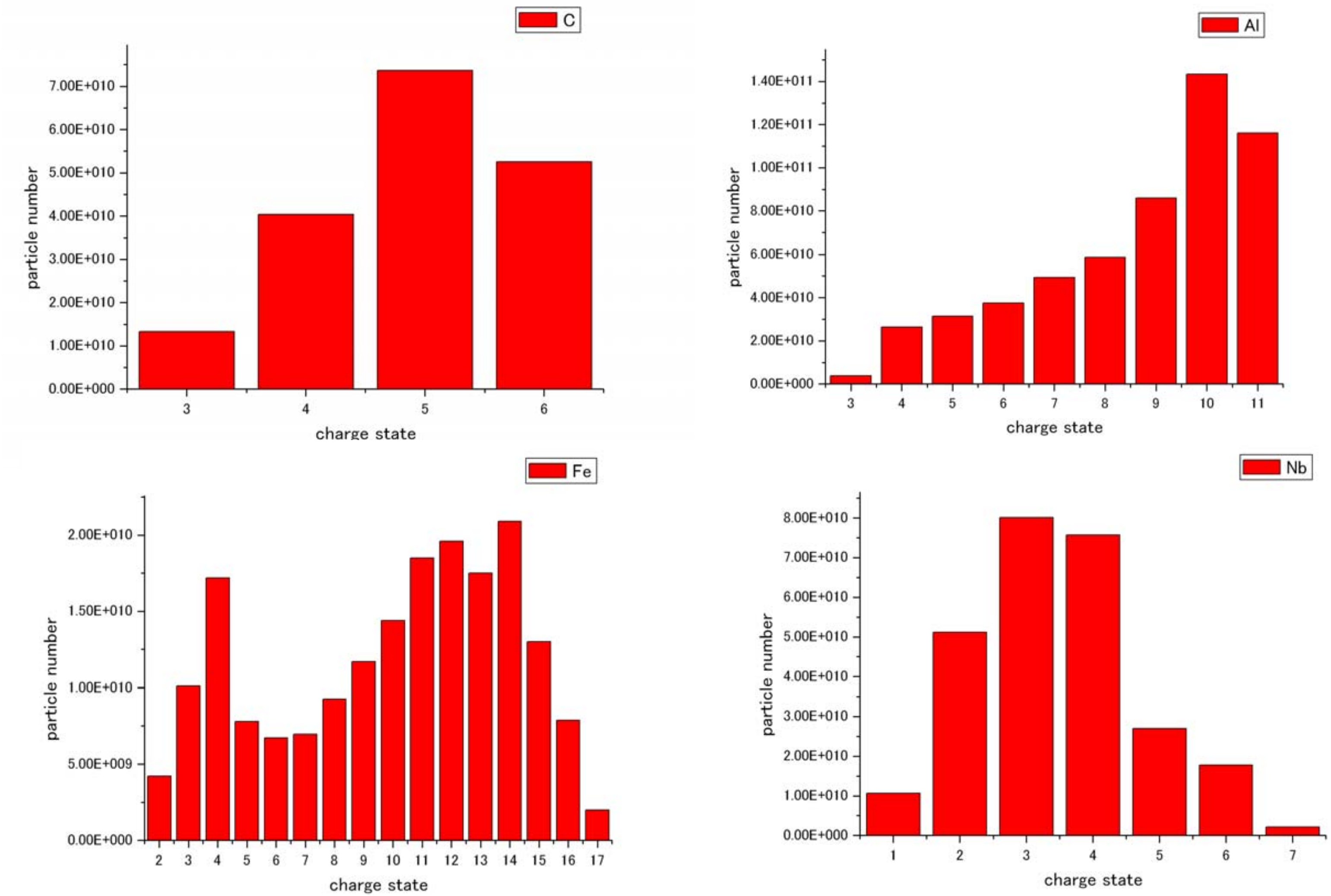
Crater radius ~ 100 µm

Crater depth ~ 100 µm

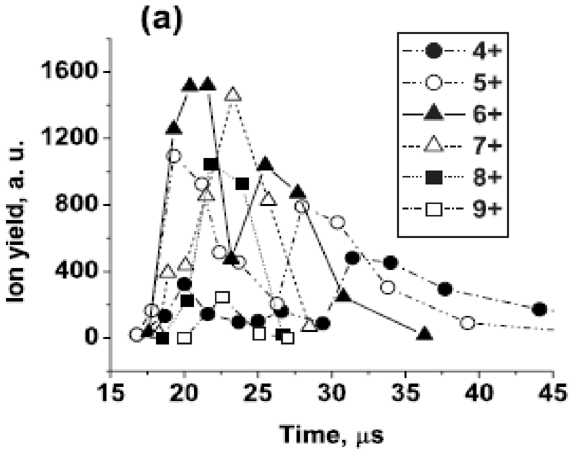
Energy/pulse width	3.45 J/ 30 ns
Wave length	1.06 µm
Laser beam diameter	10 mm
Divergence	0.5 mrad
Power density	10^{11} W/cm^2 (F = 300 mm), 10^{12} W/cm^2 (F = 100 mm)

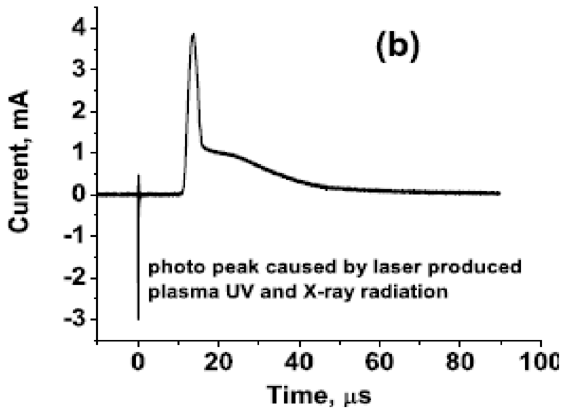
Features of ion generation using Nd-glass laser

Charge state distributions for different elements



Features of ion generation using Nd-glass laser
Influence of recombination





Time dependences of ion yield for different charge states (a) and the total ion current (b) measured for ^{27}Al target and laser power density of 10^{11} W/cm^2

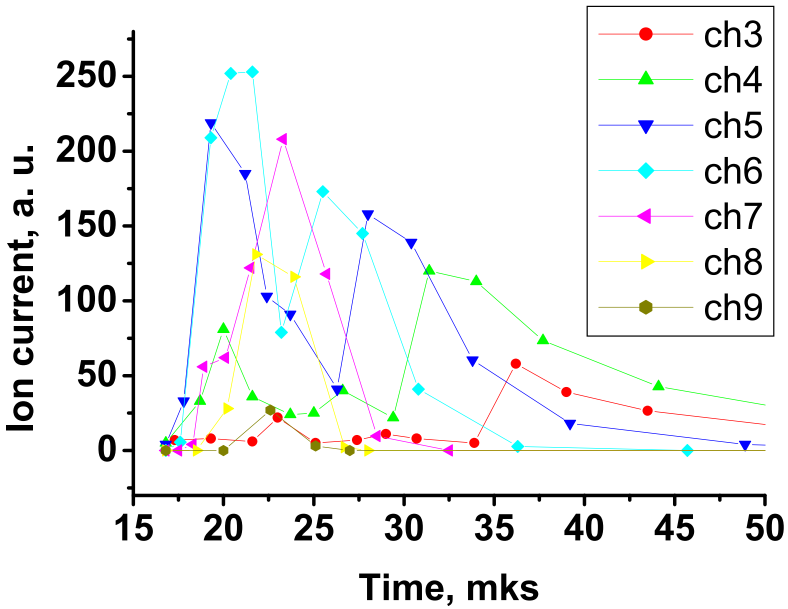
	Laser Power Density 10^{12} W/cm^2		Laser Power Density 10^{11} W/cm^2	
Element	Highest Yield Charge State	Highest Charge State Measured	Highest Yield Charge State	Highest Charge State Measured
^{12}C	6+ (476 eV)	6+ (476 eV)	4+ (67.6 eV)	6+ (476 eV)
^{27}Al	10+ (427 eV)	11+ (471 eV)	6+ (207 eV)	9+ (207 eV)
^{48}Ti	10+ (227 eV)	13+ (738 eV)		
^{56}Fe	14+ (404 eV)	17+ (1168 eV)		
^{74}Ge	5+ (87 eV)	8+ (200 eV)		
^{93}Nb	4+ (39.6 eV)	7+ (120 eV)	4+ (39.6 eV)	7+ (120 eV)
^{181}Ta	4+ (36.3 eV)	6+ (92.7 eV)	2+ (14.5 eV)	6+ (92.7 eV)

Reason for almost order of magnitude ionization potential drop between ^{56}Fe and ^{74}Ge is recombination losses

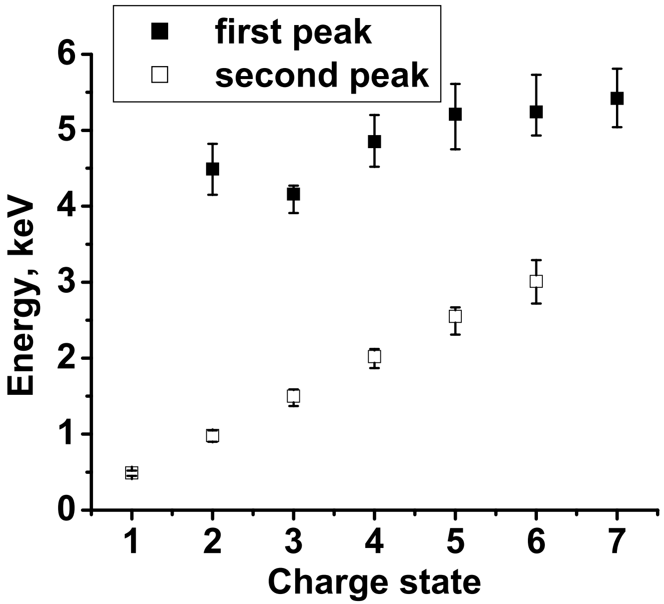
Special measurements have shown that recombination processes Should take place at distances shorter than 30 cm from the target

Features of ion generation using Nd-glass laser

Linear dependence of energy on charge states



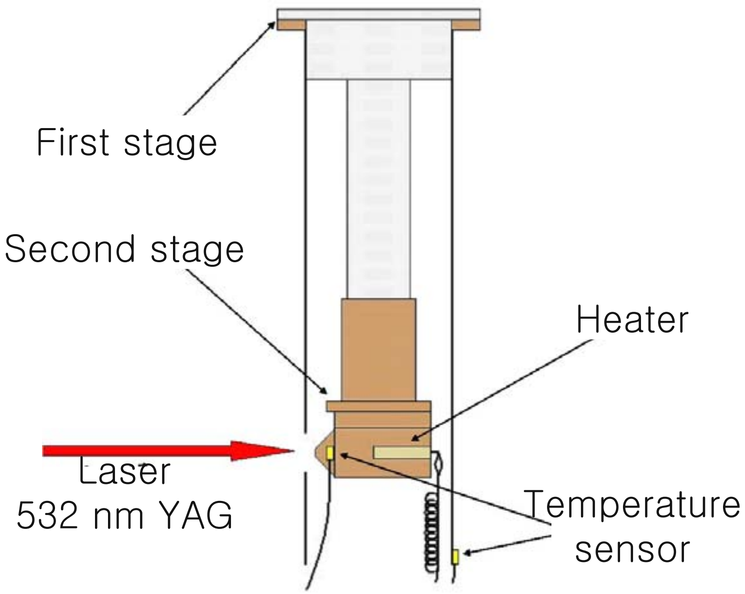
Time dependences of ion yield for different charge states measured for ^{27}Al target and Laser power density of 10^{11} W/cm^2

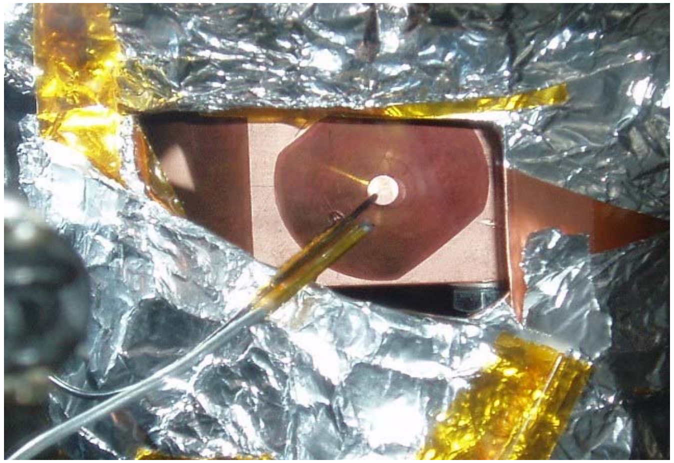


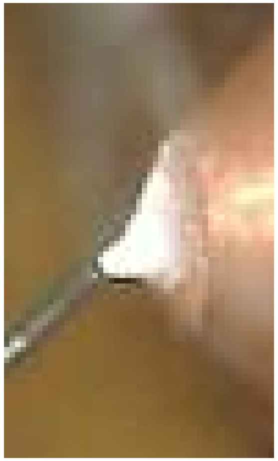
First and second peak ion energies of different charge states for ^{93}Nb target and laser power density of 10^{11} W/cm^2

The energy of slower ion group follows precisely the simple relation E_z(keV) = (0.5 keV)·z independently on element and laser power density !!! How to explain???

Generation of gas ions – Cryogenic target



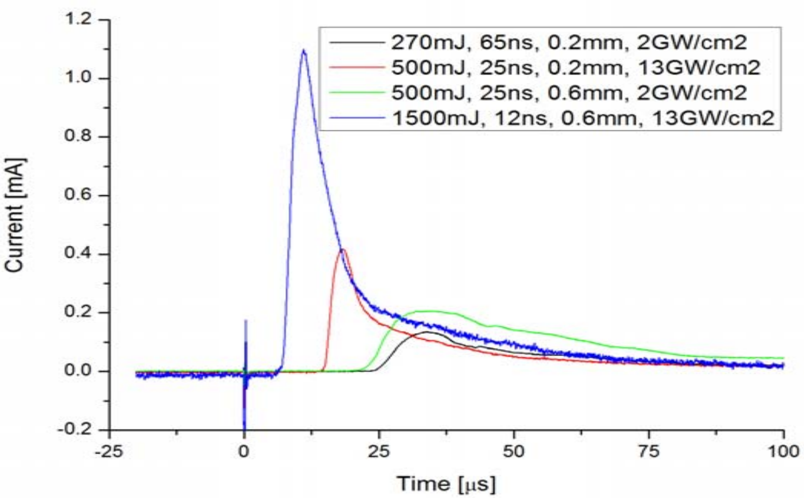




Frozen Ne (3-d lowest freezing point – 10 K) used a target

All gases, except He, can be used in this way

Target movement between shorts is not required



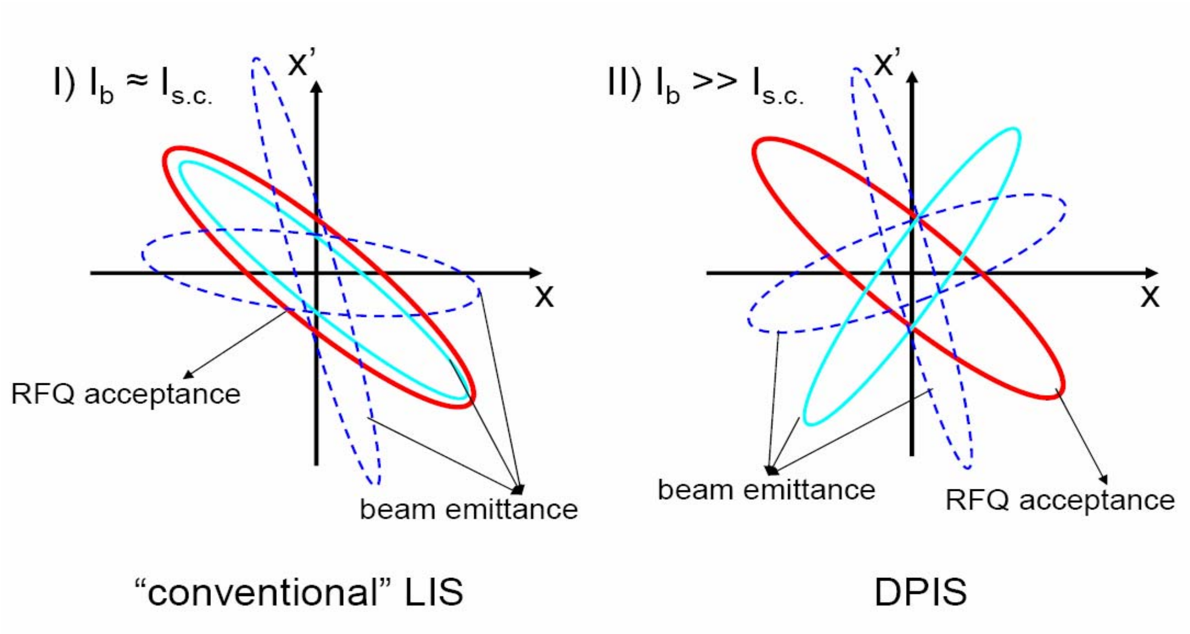
Ne ions with charge state up to 6+ and current density up to 15 mA/cm^2 (at 1 m from the target) have been generated at 1 Hz rep-rate

Direct plasma injection scheme (DPIS)

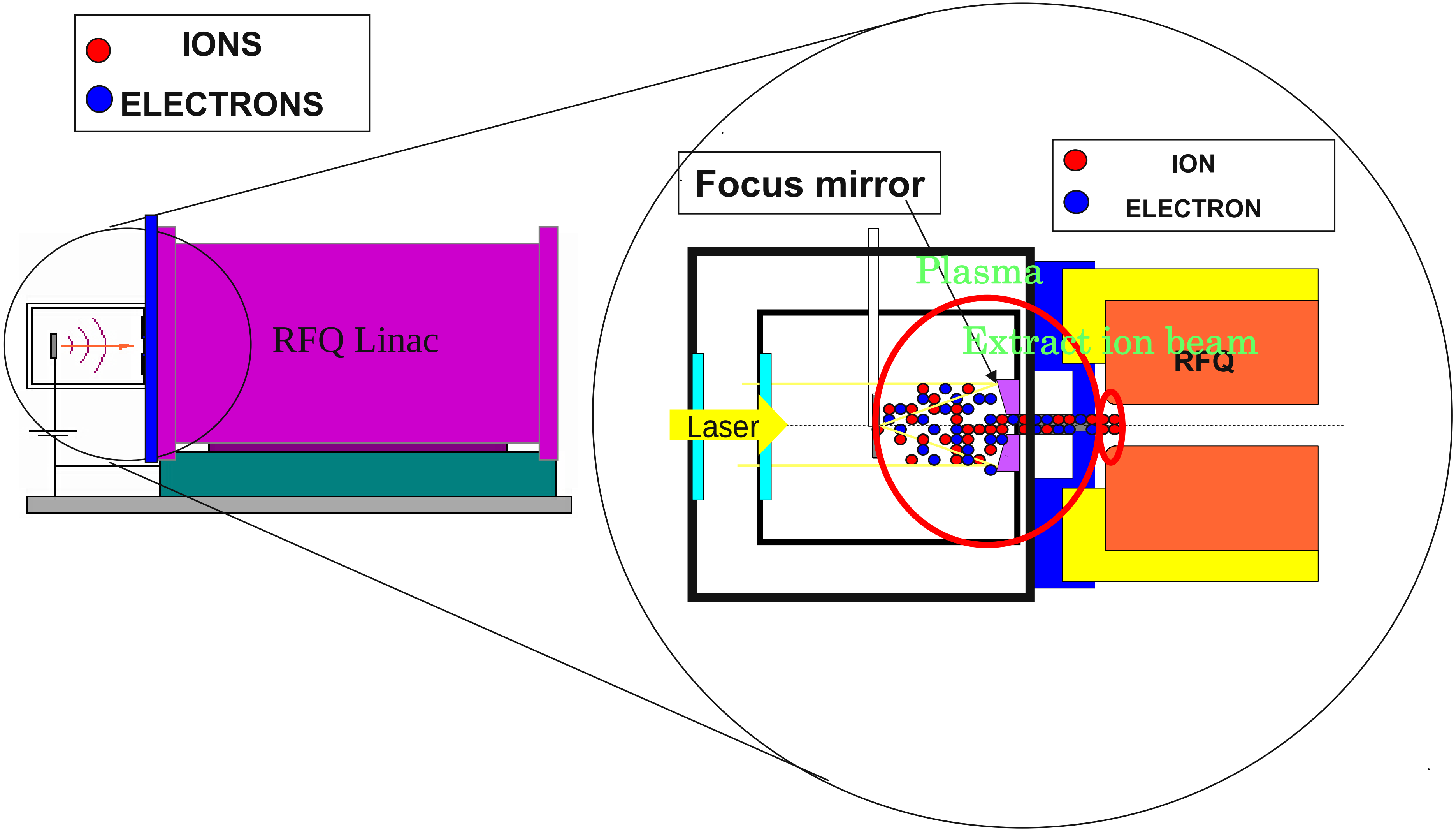
DPIS was proposed by Masahiro Okamura (RIKEN) in 2000

Main idea: take advantage of very high LIS current, merge source extraction and RFQ injection areas in space, avoid LEBT and related space charge problems

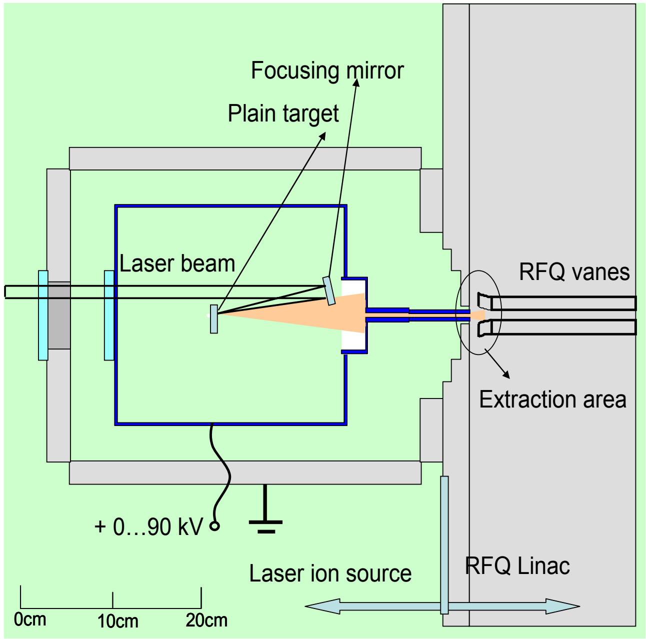
RFQ injection placed at the distance about 30 cm from the target: will laser-produced plasma causes RF breakdowns or not?



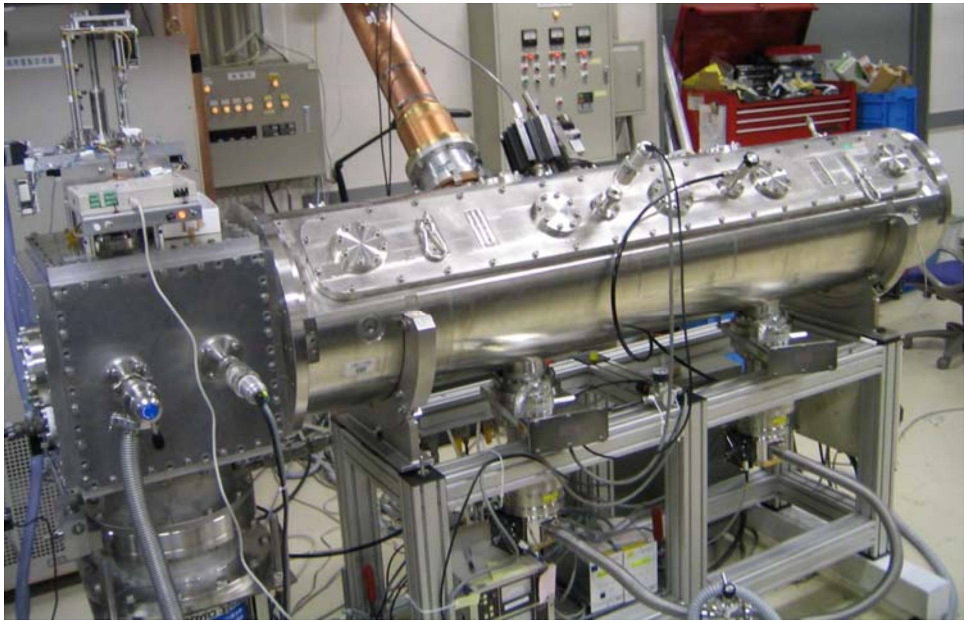
Direct plasma injection scheme lay-out



DPIS Geometry



Source geometry



DPIS in RIKEN

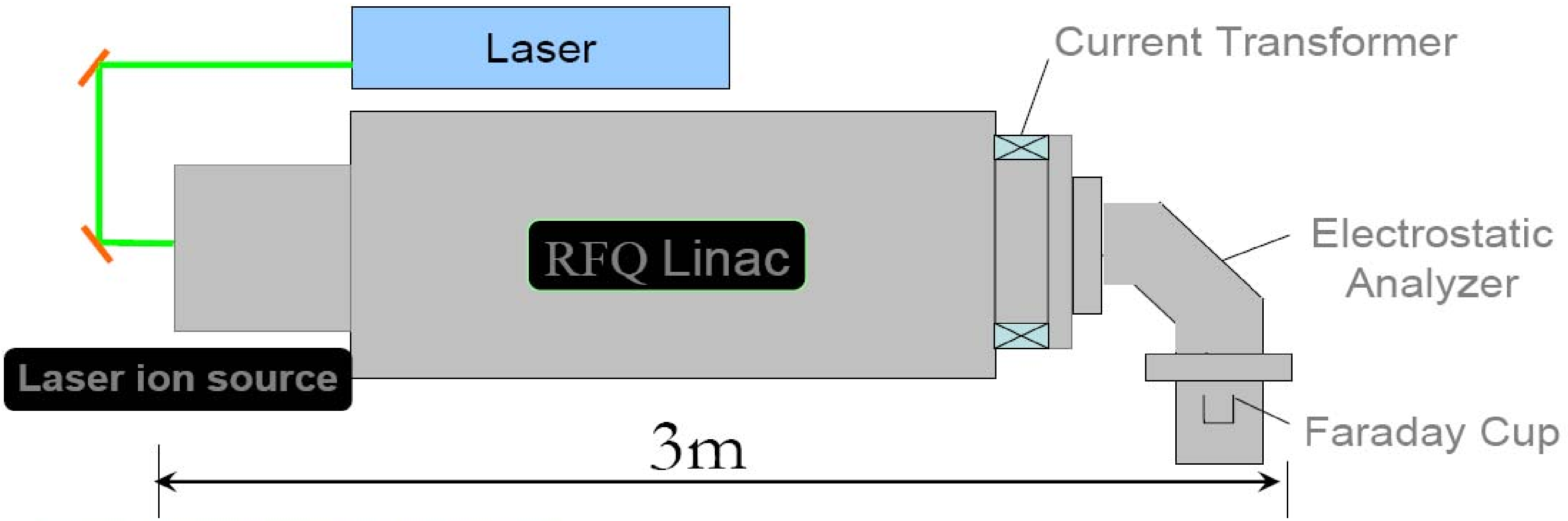
Achieved total peak current at RFQ output:

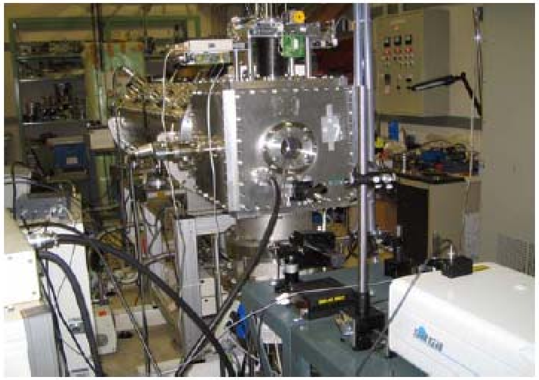
2004 C^{4+} (60%) beam with 4 J CO_2 laser - 60 mA

2005 C^{6+} beam with 300 mJ YAG laser - 17 mA

2006 Al^{9+} (65%) beam with 2.3 J YAG laser - 70 mA

Lay-out of DPIS acceleration experiment



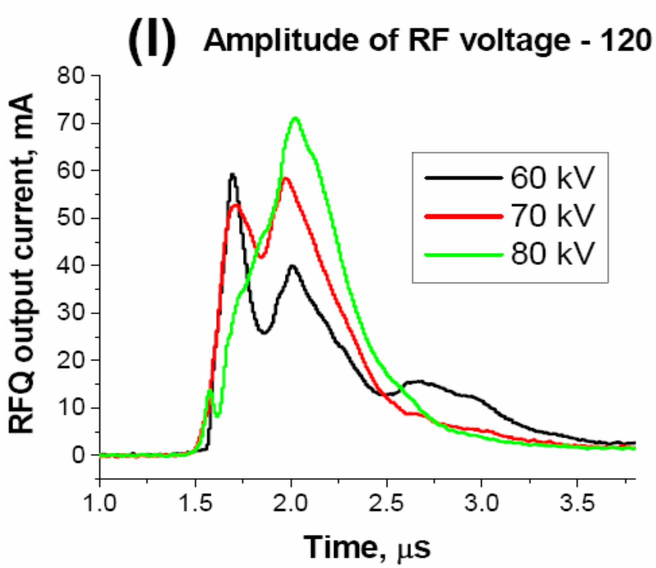


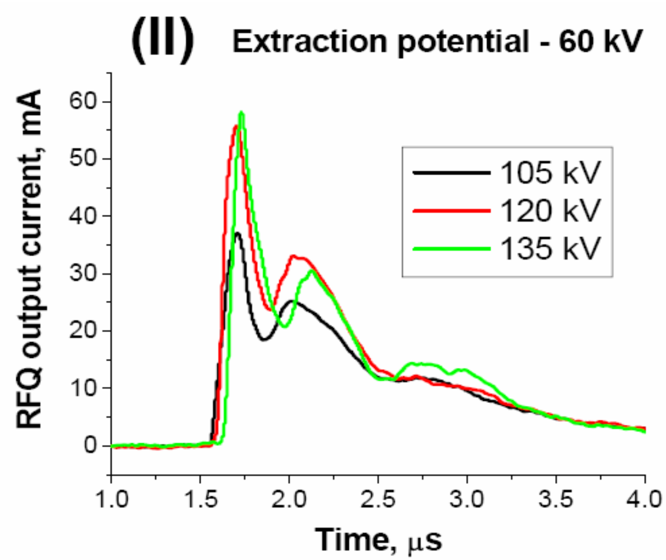
RFQ linac + laser ion source

Electrostatic analyzer

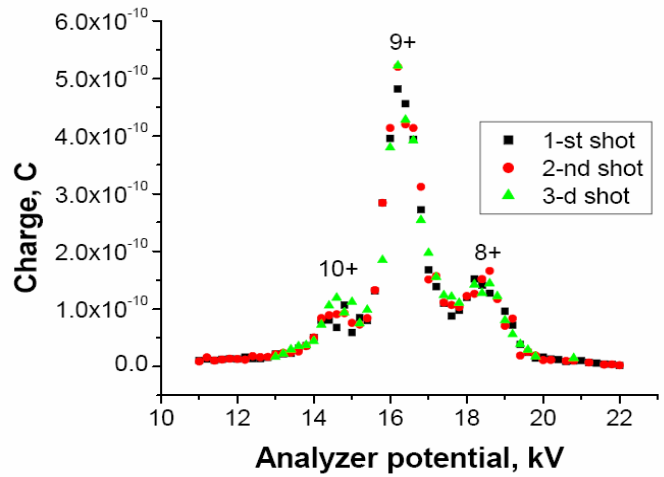
S. Kondrashev, HB2006

Al^{9+} ion acceleration results





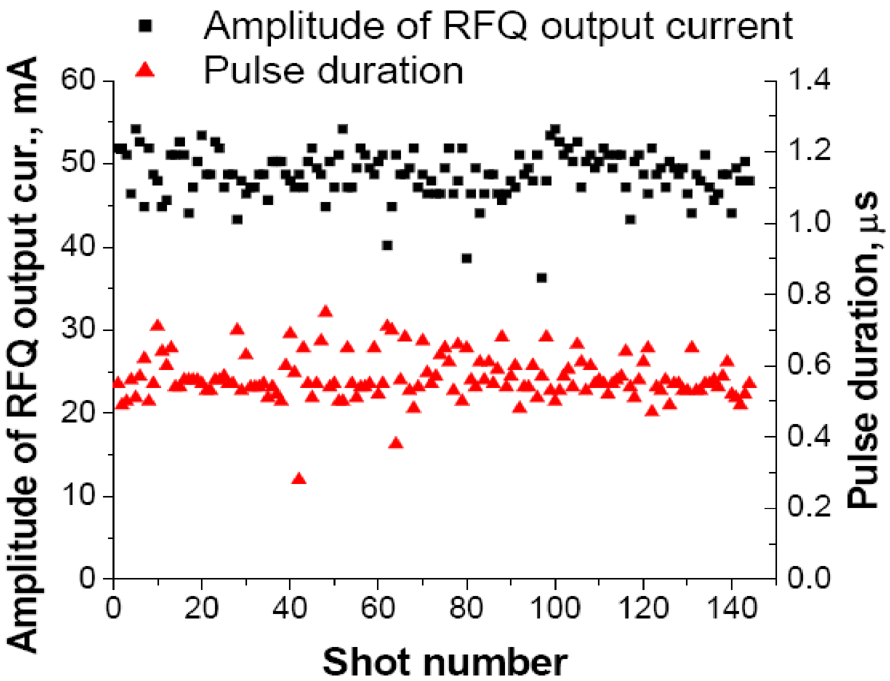
Extraction potential – 60 kV, Amplitude of RF voltage – 120 kV



RFQ output shot-to-shot stability

Al ion beam

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



<I> = 49 mA ± 6%

<τ> = 0.56 µs ± 11%

Present status of LIS development

LIS as injector to accelerators:

- LIS is in routine operation for ITEP (Moscow, Russia) TWAC project
- LIS is in routine operation for synchrotron in JINR (Dubna, Russia)
- DPIS study by group of M. Okamura (now in BNL)

  - accelerate heavy ions by RFQ
- 100 Hz LIS is in operation for 5 MV electrostatic accelerator at Columbia University's Radiological Research Accelerator Facility (RARAF)
- LIS for implantation in INFN (Catania, Italy) (under development)
- Carbon ions for synchrotron based radiotherapy facility which is under construction in IMP (Lanjoy, China)
- LIS for FFAG in Kyushu University (Fukuoka, Japan)

Injection of ions (or atoms) into another type of source:

- Into ECR - INFN (Catania) and others
- Into EBIS - BNL

Summary

- At present, LIS is the most intense pulsed source of highly-charged ions of all elements of periodic table
- Temporal structure of LIS ion pulses well meet the requirements of single turn injection into synchrotron and FFAG rings
- After more than 30 years R&D LIS physical and technical aspects are relatively well understood and LIS was successfully implemented at few accelerator facilities for routine operation
- Recently developed DPIS is very effective to provide intense beams with short pulse length
- Current development of FFAG accelerators should enhance interest to LIS in the nearest future because LIS is almost ideally matched to FFAG requirements