Advances in the Laser Ion Source Development at BNL

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Laser ablation ion source?

This is **NOT** Laser plasma acceleration (Laser power density ~10^{20} W/cm^2)

Laser ion source for particle accelerators has long history since it was proposed by Peacock and Peace[1] and Byckovsky et al. [2] independently. in 1969

Laser ion source uses much lower laser power density

- 10^8 ~10^9 W/cm^2 for charge state 1+
- >10^{12} W/cm^2 for high charge state ions (Li^{3+}, C^{6+}, Al^{11+}, Fe^{20+})

Plasma electrons are heated by laser by inverse Bremsstrahlung process.
Source of pulsed very high current heavy ions

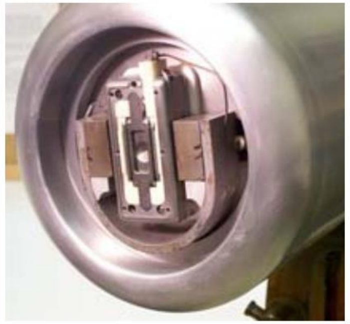
Once Laser ion source was investigated as heavy ion source for LHC but not successful.
Bottleneck was solved, and BNL group is leading Laser ion source development

[1] N. J. Peacock and R. S. Pease, "Sources of highly stripped ions," *Br. J. Appl. Phys. (J. Phys. D)*, vol. 2, p. 1705, 1969.
[2] Y. A. Byckovsky, V. F. Eliseev, Y. P. Kozyrev, and S. M. Silnov, "Laser generator of multi-charged ions for accelerators," Sov. Patent 324 938, Oct. 1969.

Beams at BNL Collider-Accelerator Department

120 mA H- beam

BNL magnetron source for BLIP



1 mA polarized H- beam

Optically Pumped Polarized Ion Source (OPPIS)

200 MeV LINAC

Few mA heavy ion beam

10 A Electron gun

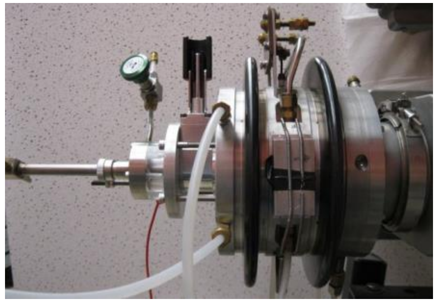
Electron Beam Ion Source (EBIS)

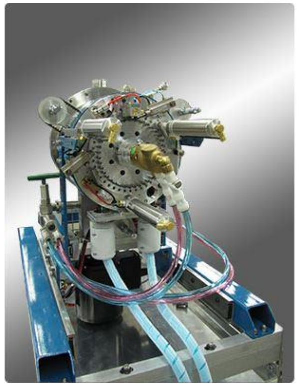
Developing few mA polarized ^{3}He beam from EBIS for EIC

2 MeV/u pre-injector (RFQ+IH linac)

100 uA heavy ion beam

Cesium sputter ion sources



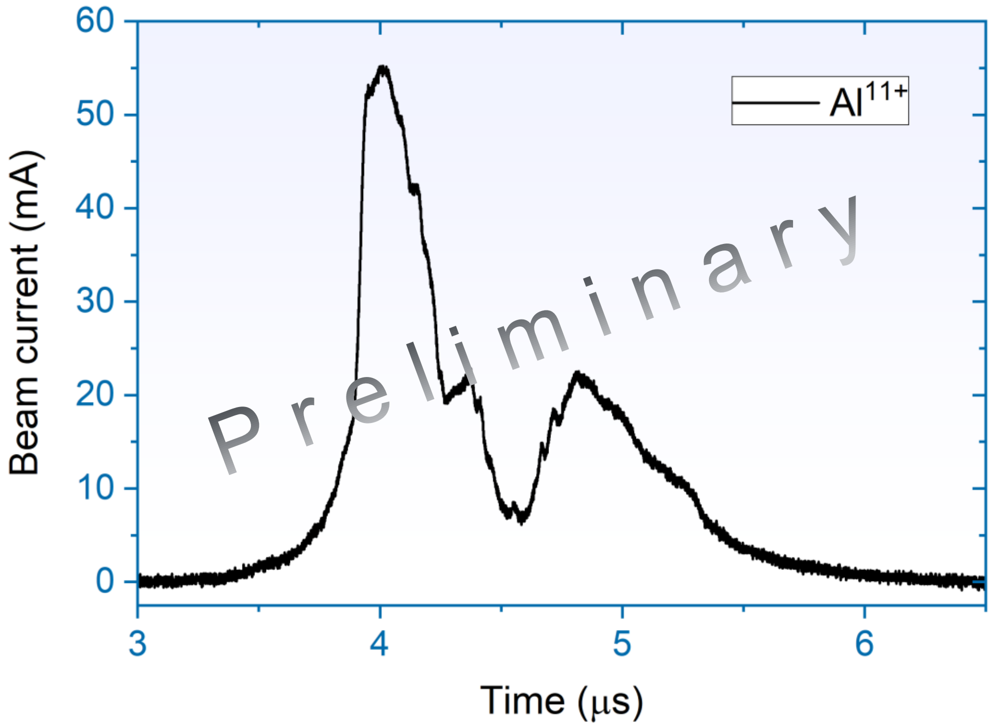


Tandem Van de Graaff

Heavy ion beam from Laser ion source can beat proton beam current

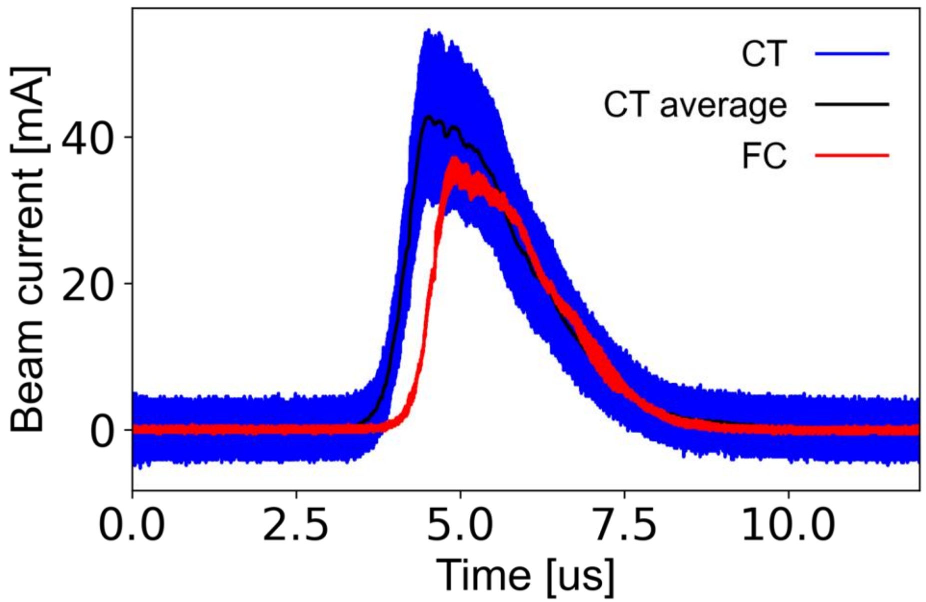
High current heavy ion beam acceleration

55 mA of Al^{11+} beam (204 keV/u) **after RFQ linac** has been just recently achieved



35 mA of Li^{3+} beam (204 keV/u)

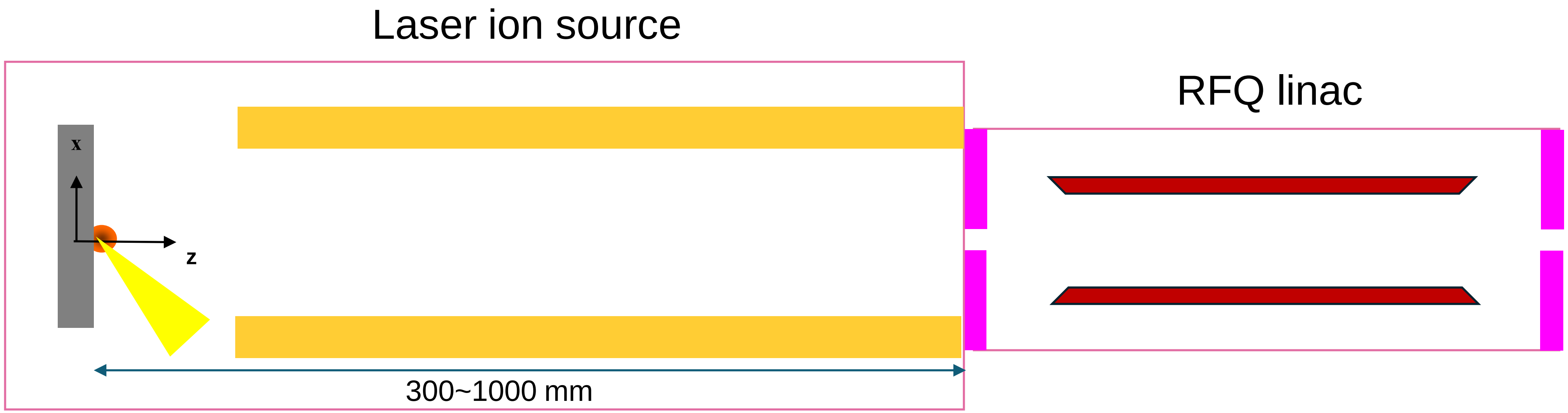
- Laser 800 mJ on target, 6 ns
- RF power 100 kW



New RFQ electrodes for >100 mA Li^{3+} will be delivered in a few month

High current heavy ion beam acceleration

How?

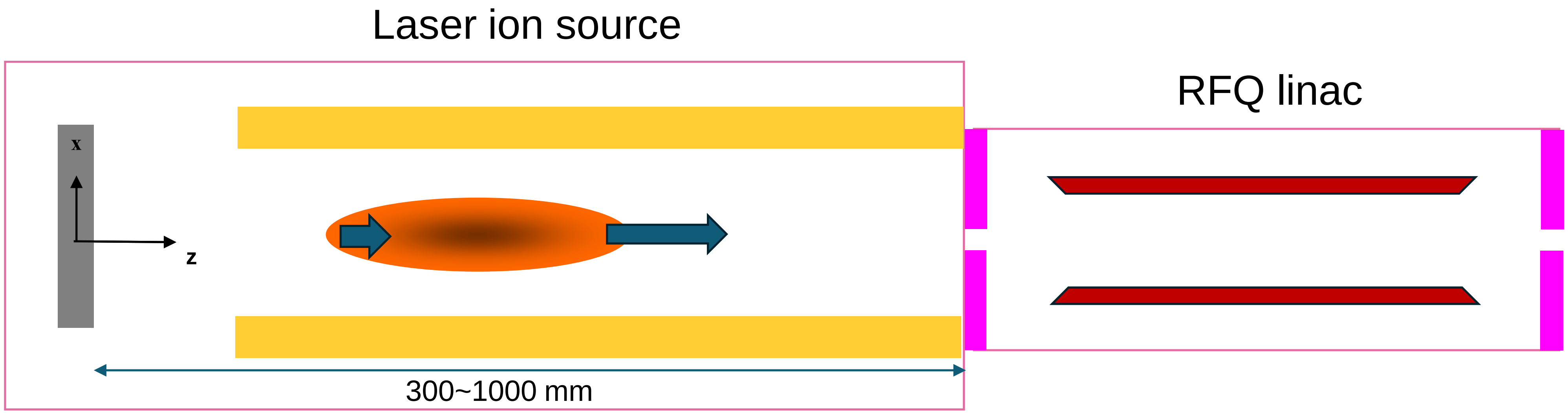


Ultra dense laser ablation plasma from solid target

Nd:YAG laser ~1 J on target / 6 ns, 1064 nm wave length

High current heavy ion beam acceleration

How?



Ultra dense laser ablation plasma from solid target

Expanding plasma + Transverse confinement by solenoid field (10~1000 G)

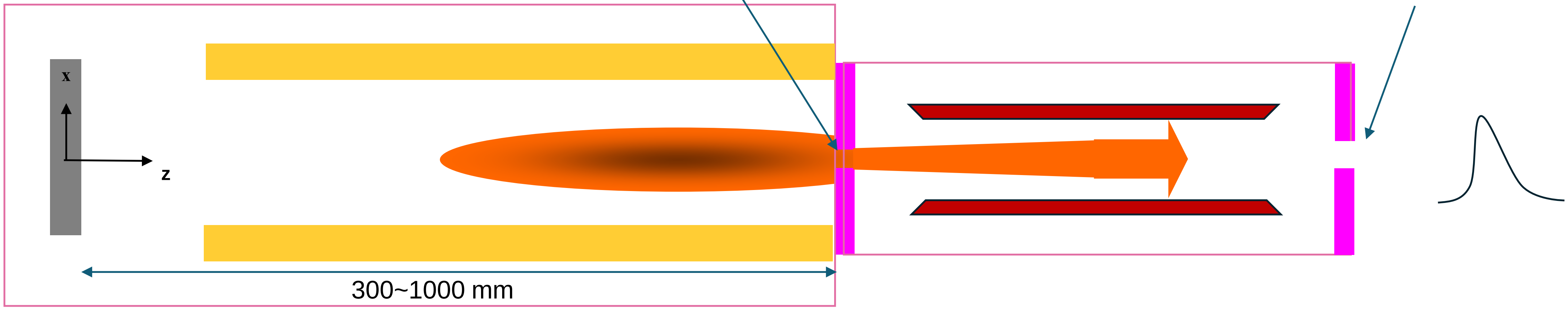
Nd:YAG laser ~1 J on target / 6 ns, 1064 nm wave length

High current heavy ion beam acceleration

How?

Hundreds mA of charge state of interest
(>1 A including other charge state)

>50 mA beam
accelerated by RFQ



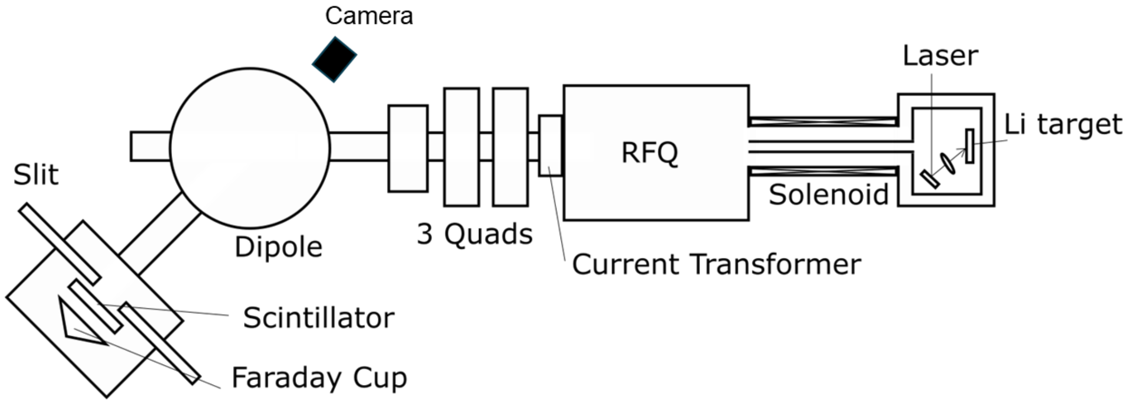
Ultra dense laser ablation plasma from solid target

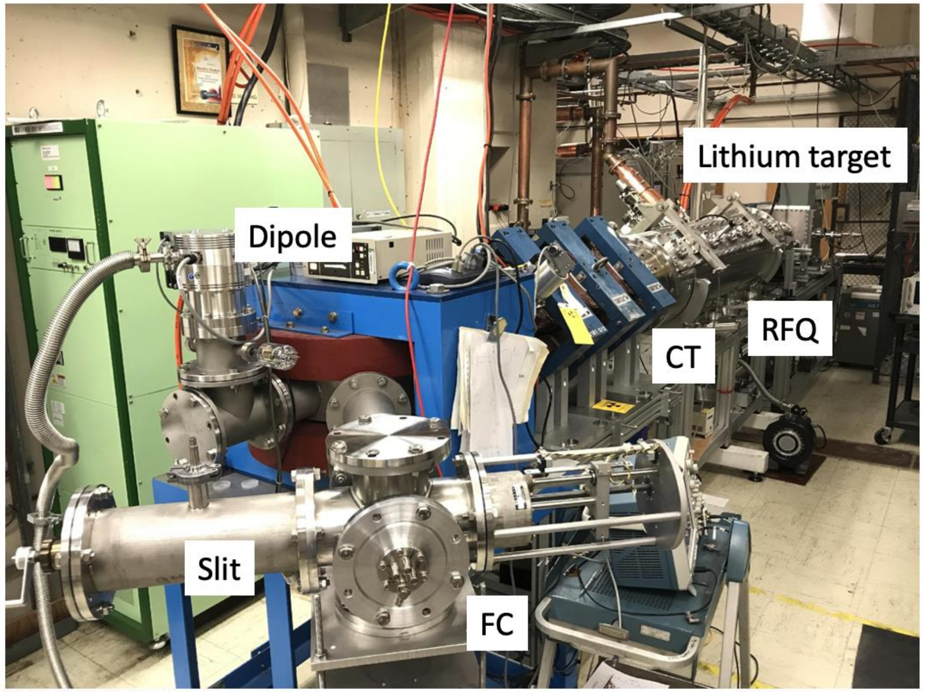
Expanding plasma + Transverse confinement by solenoid field (10~1000 G)

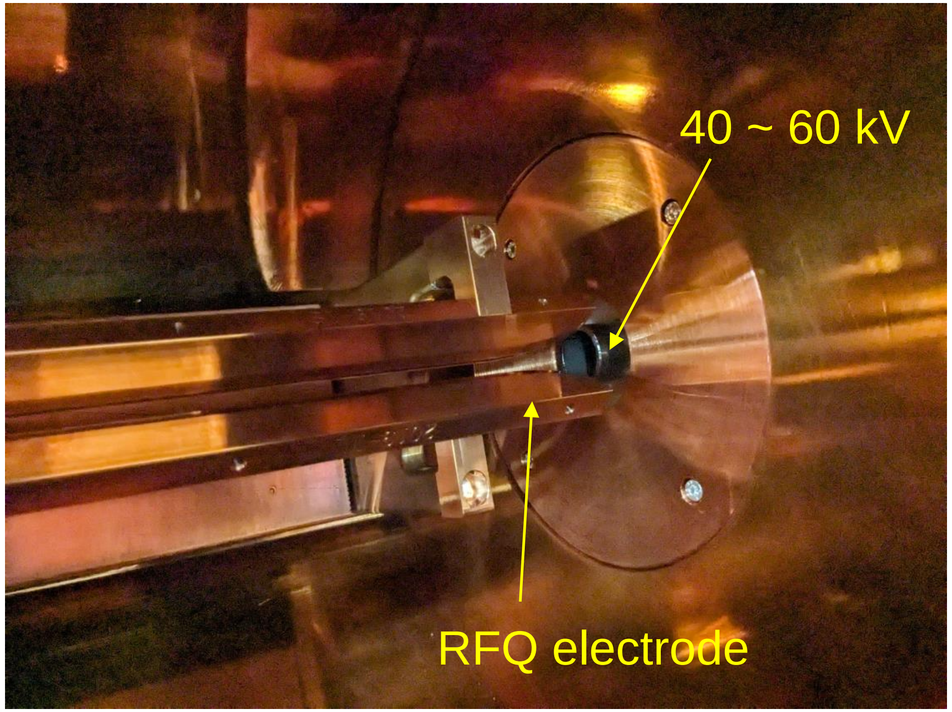
Immediate capture of extracted ion beam by RFQ field (10 mm)

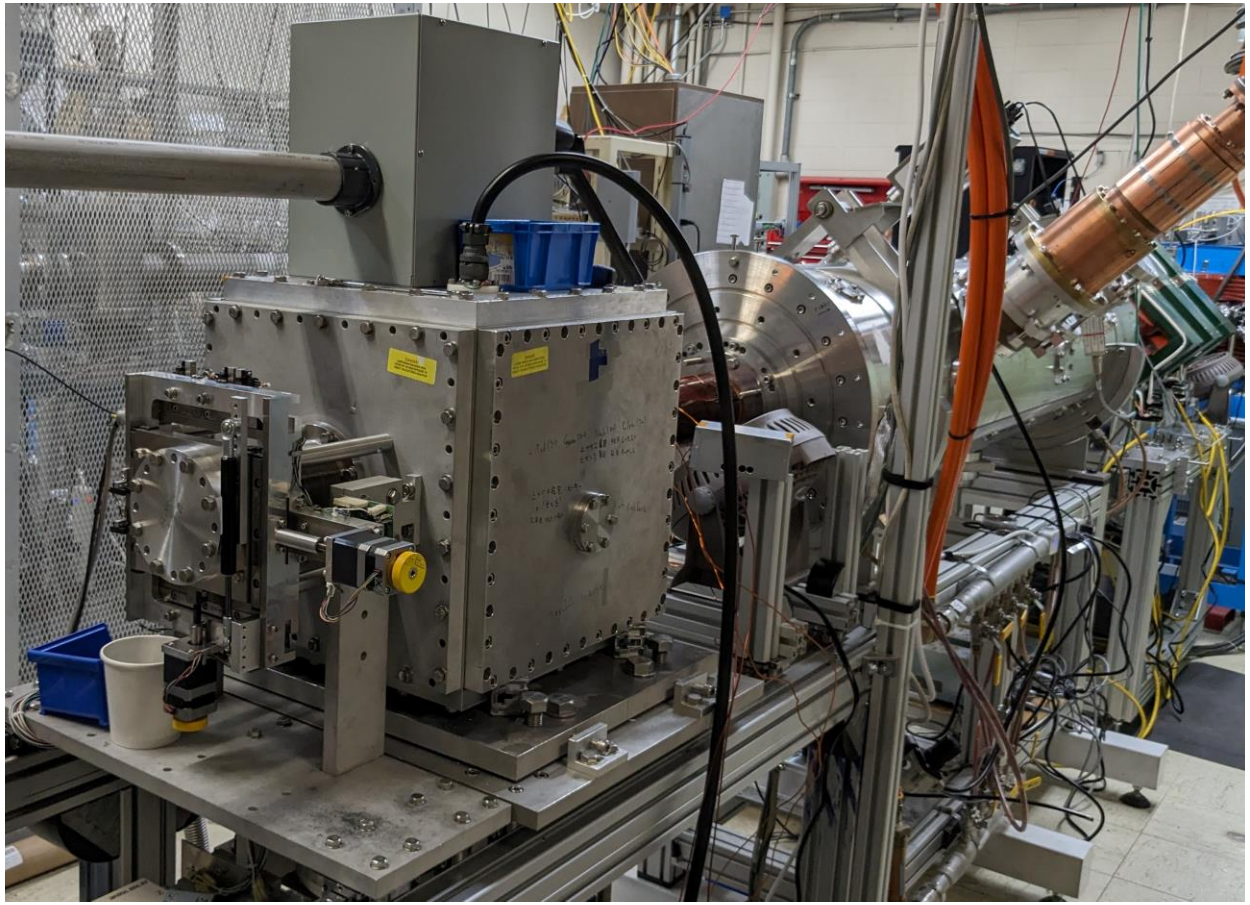
Minimum beam blow up caused by space charge

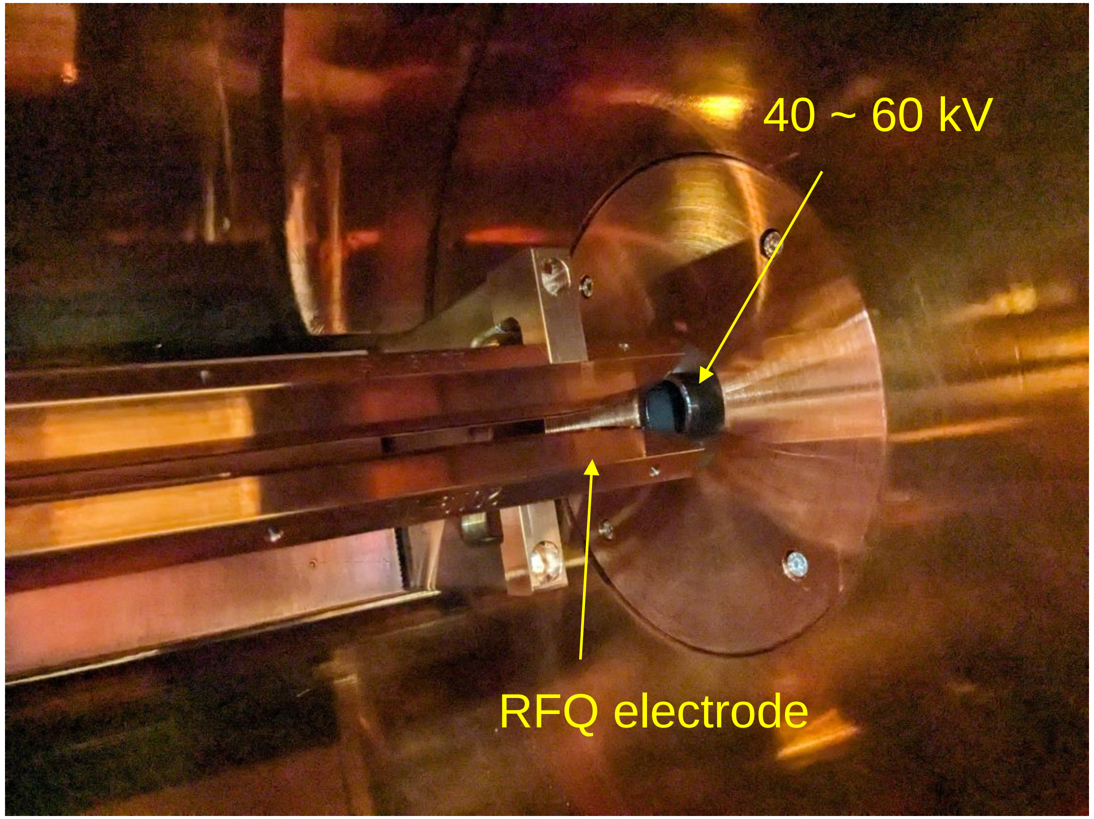
This was bottleneck


Camera
Laser
Li target
RFQ
Solenoid
Slit
Dipole
3 Quads
Current Transformer
Scintillator
Faraday Cup


Lithium target
Dipole
RFQ
CT
Slit
FC


40 ~ 60 kV
RFQ electrode




40 ~ 60 kV
RFQ electrode

Application?

Neutron production by inverse kinematics reaction

$$p\ (^7Li,n)\ ^7Be$$

Threshold energy 13.098 MeV
Primary 0 degree neutron energy 1.44 MeV

Forward directed neutrons are generated

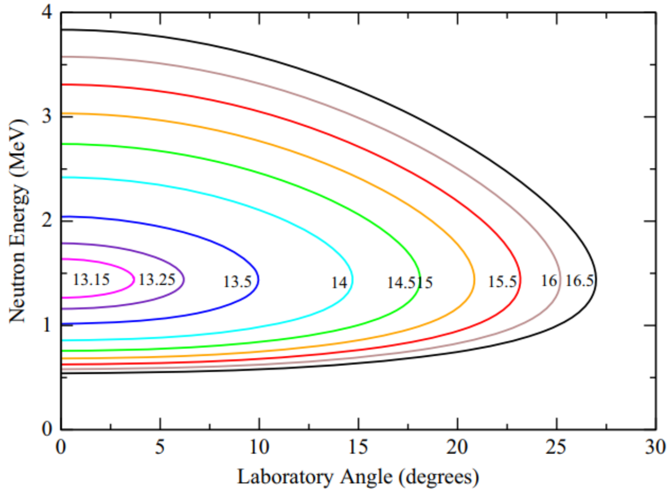


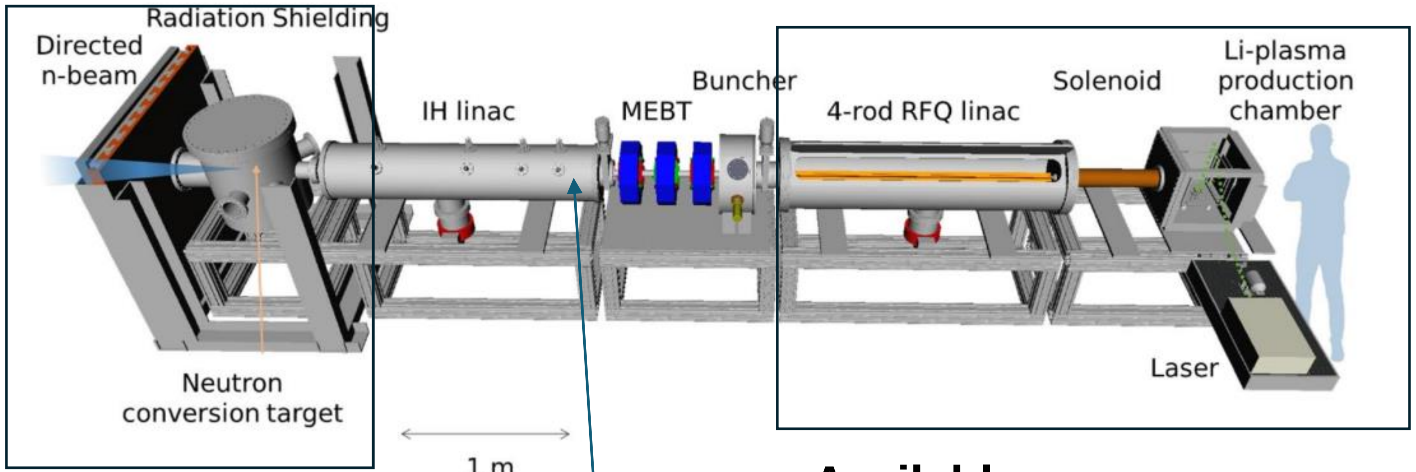
Fig. 1. Kinematic curves relating the angle of neutron emission to neutron energy in the laboratory frame for different ^7Li bombarding energies from 13.15 to 16.5 MeV, calculated using two-body relativistic kinematics.

M. Lebois et al. *Nuclear Instruments and Methods in Physics Research A* **735** (2014) 145-151

Lithium beam driven neutron generator is in operation at LICORNE at IJCLab in France using Tandem Van de Graaf (nA range)

Laser ion source based neutron source

Design study:



Missing

Available

Next: IH Linac

$1M material cost?

We are starting simulation study for neutron

Laser

>100 mJ / 6 ns, 400 Hz laser is available on market. Several units can be combined for higher rep. rate

Started liquid lithium target study

- This should be feasible
  - FRIB liquid lithium stripper
  - Liquid lithium neutron production target at SARAF

We are proposing from accelerator side

Now confident >100 mA is possible

Not much done yet on neutron side

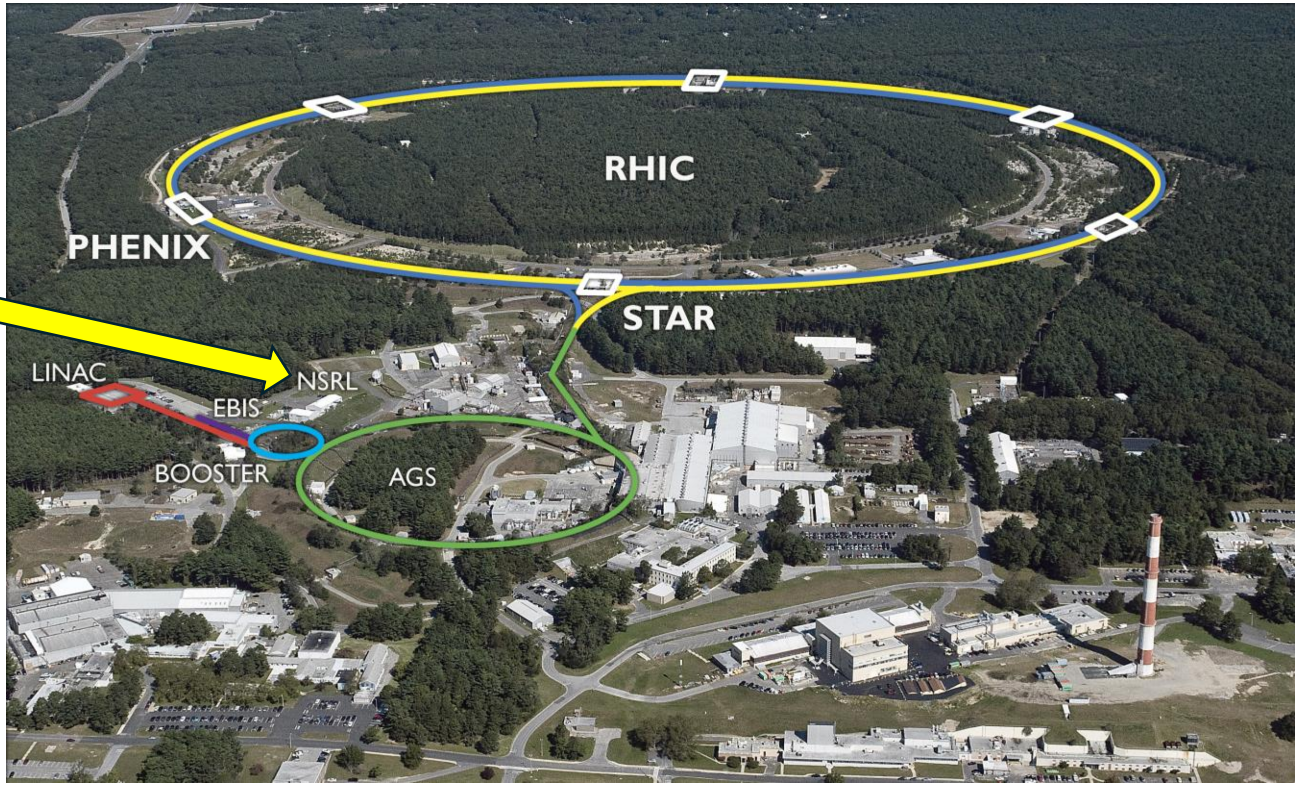
Okamura, M. *et al.* *Sci Rep* **12**, 14016 (2022).

Already operational application: Space radiation research

Laser ion source is producing initial heavy ions of all solid materials for both NSRL and RHIC

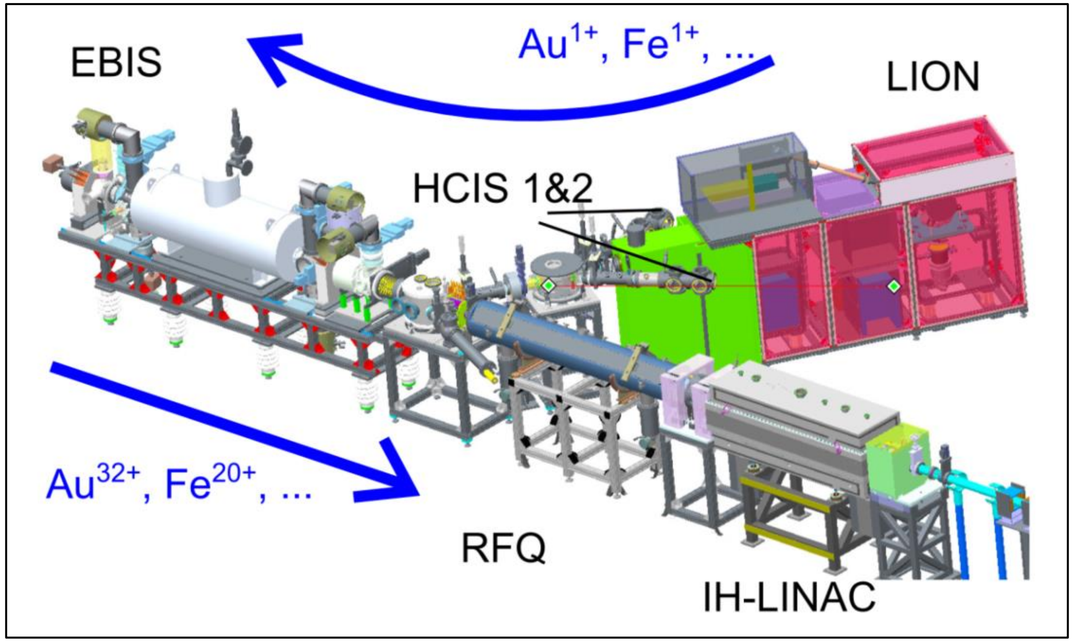
NASA Space Radiation Laboratory (NSRL)

- Ground based high energy particle source for space radiation research
- Up to 1.5 GeV/u heavy ions + 2.5 GeV roton
- Mixed radiation by sequences of exposures



LION for RHIC and NSRL (and for EIC)

EBIS increases charge state for further acceleration
(Need Q/M >1/6 for RFQ)



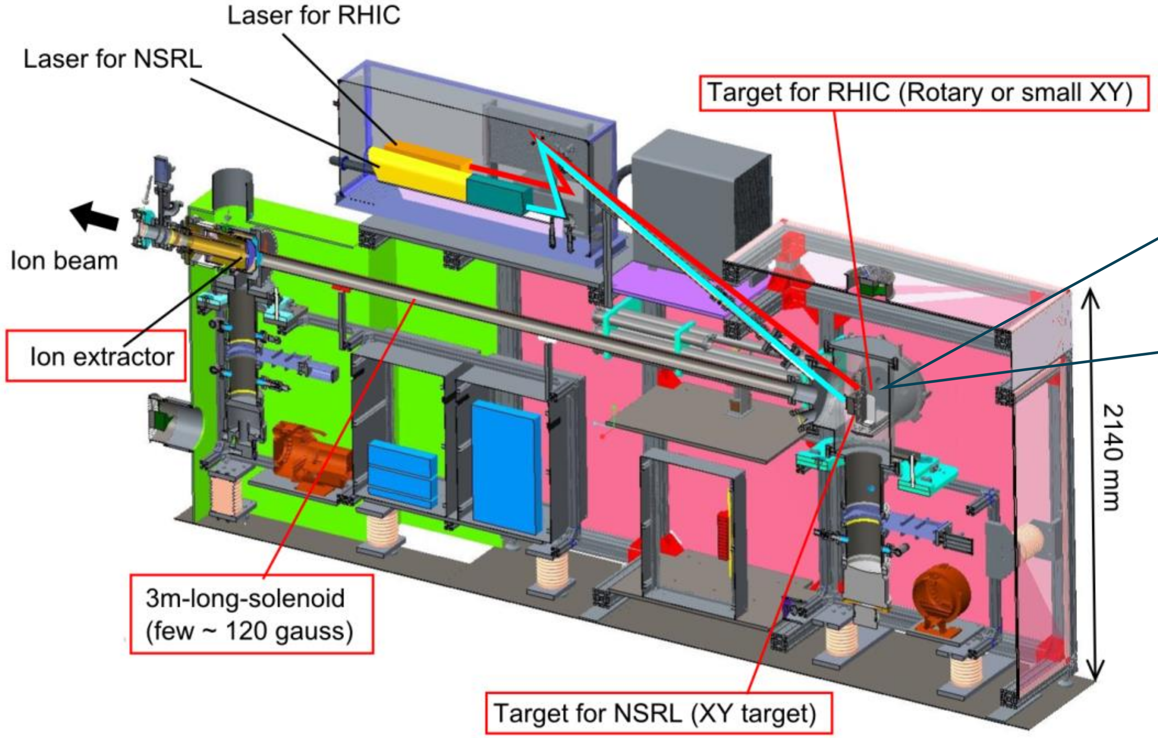
LION provideS charge state 1+ ions

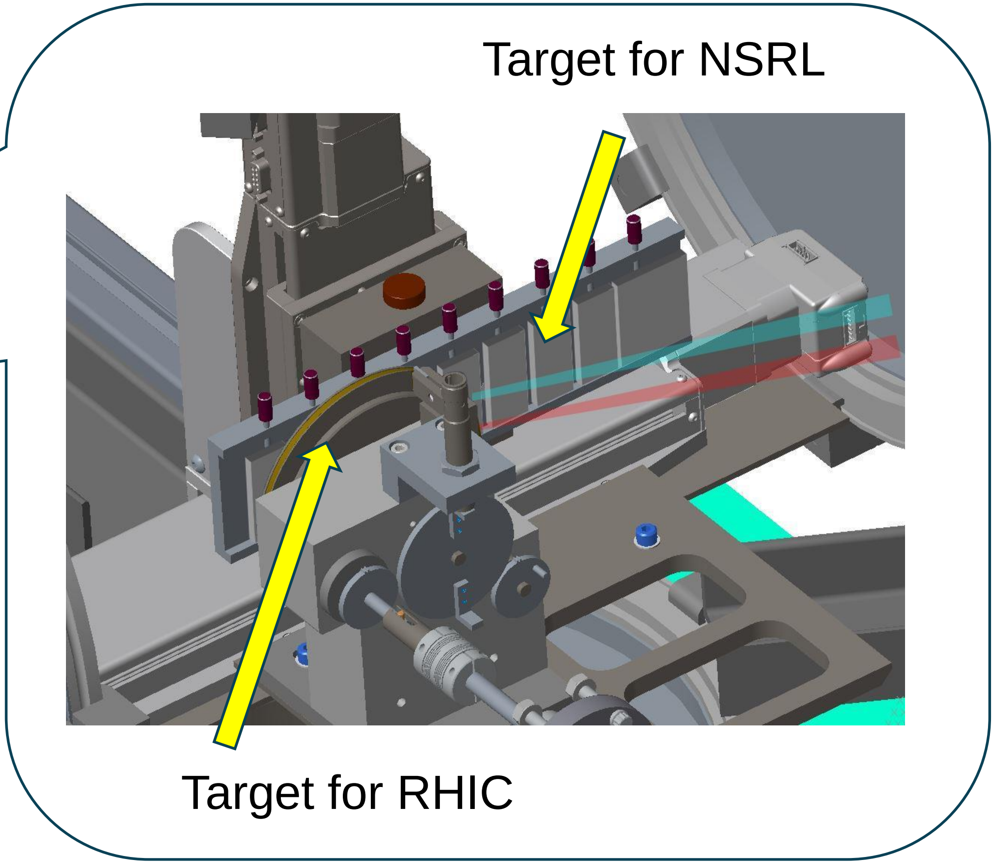
LION (laser ion source) has provided: **Li, B, C, O, Al, Si, Ca, Ti, Fe, Cu, Zr, Nb, Ag, Tb, Ta, W, Au, Bi, Th**

About 10 species are available in vacuum chamber at a time

* Gaseous target (He, Ne, Ar, Kr, Xe) are from Hollow Cathode Ion Source or direct gas injection into EBIS
* Proton comes from Tandem or 200 MeV LINAC

LION for RHIC and NSRL (and for EIC)



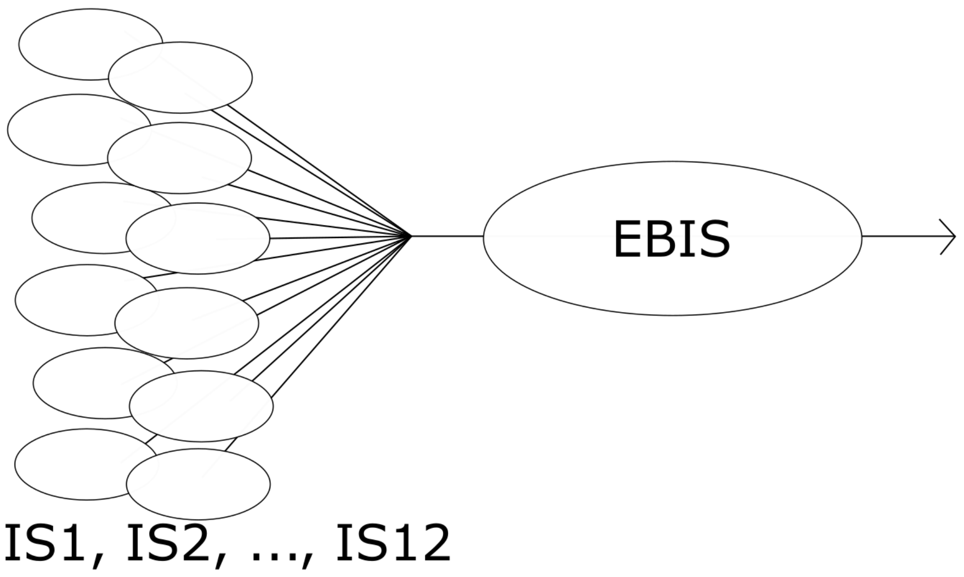


- Laser **ablation** ion source (pulsed ion source)
- Good vacuum (10^{-4} ~ 10^{-6} Pa)
- No memory effect from previous species
- **No warm-up needed**. Full performance from 1st pulse.
- For 1+, laser power density just above plasma generation (10^8~10^9 W/cm^2)
- Nd:YAG lasers (1064 nm, 200~500 mJ / 6ns)

LION for RHIC and NSRL (and for EIC)

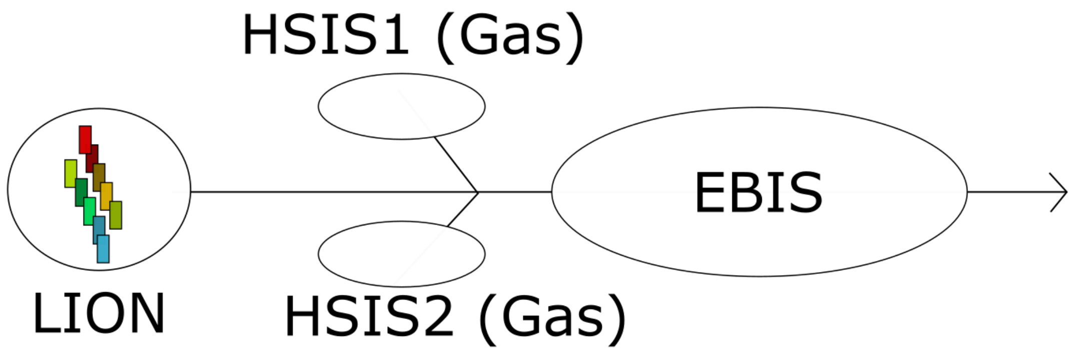
- Good vacuum (10^{-4} ~ 10^{-6} Pa)
- No memory effect from previous species
- **No warm-up needed**. Full performance from 1st pulse.

Without LION



Not feasible…

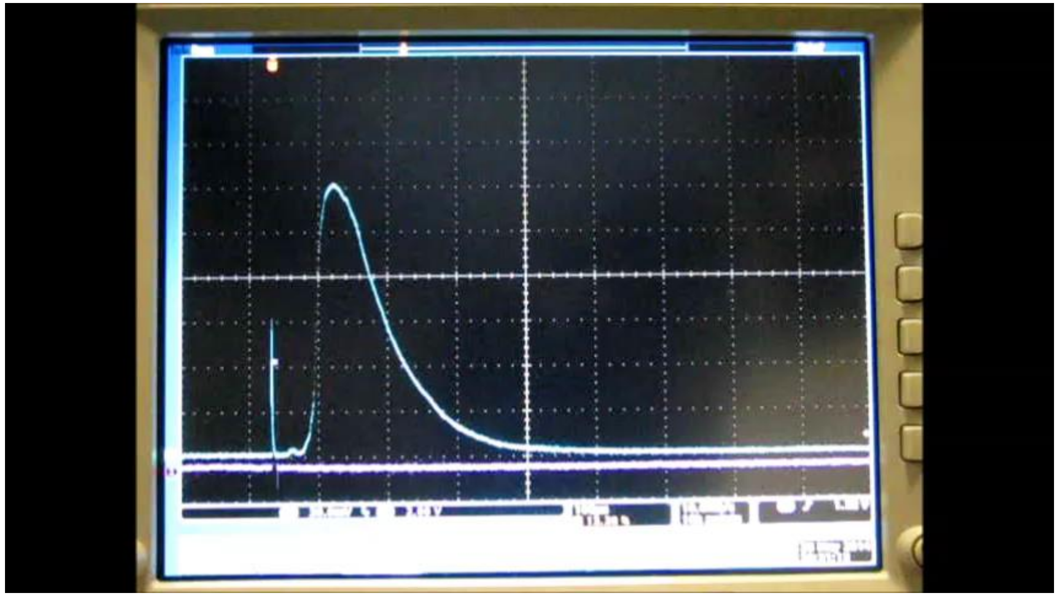
With LION

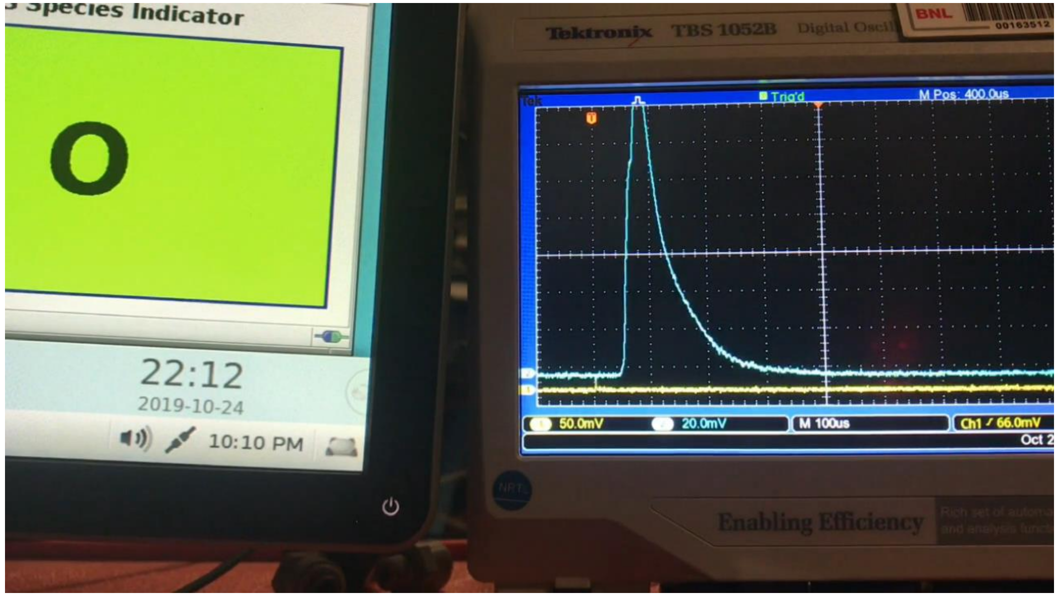


LION (and EBIS) is an essential device for GCR simulator

LION for RHIC and NSRL (and for EIC)

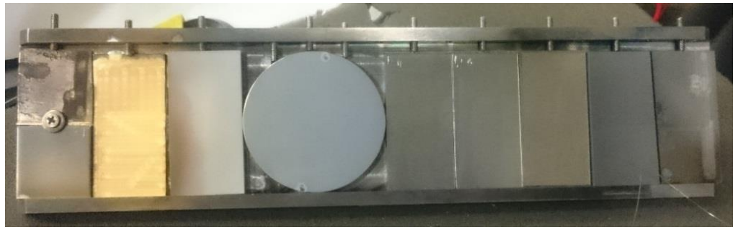
Rapid species change capability at LION (x1 Time)





Ti ↔ Au

O → Ti → Si → Ta → Fe

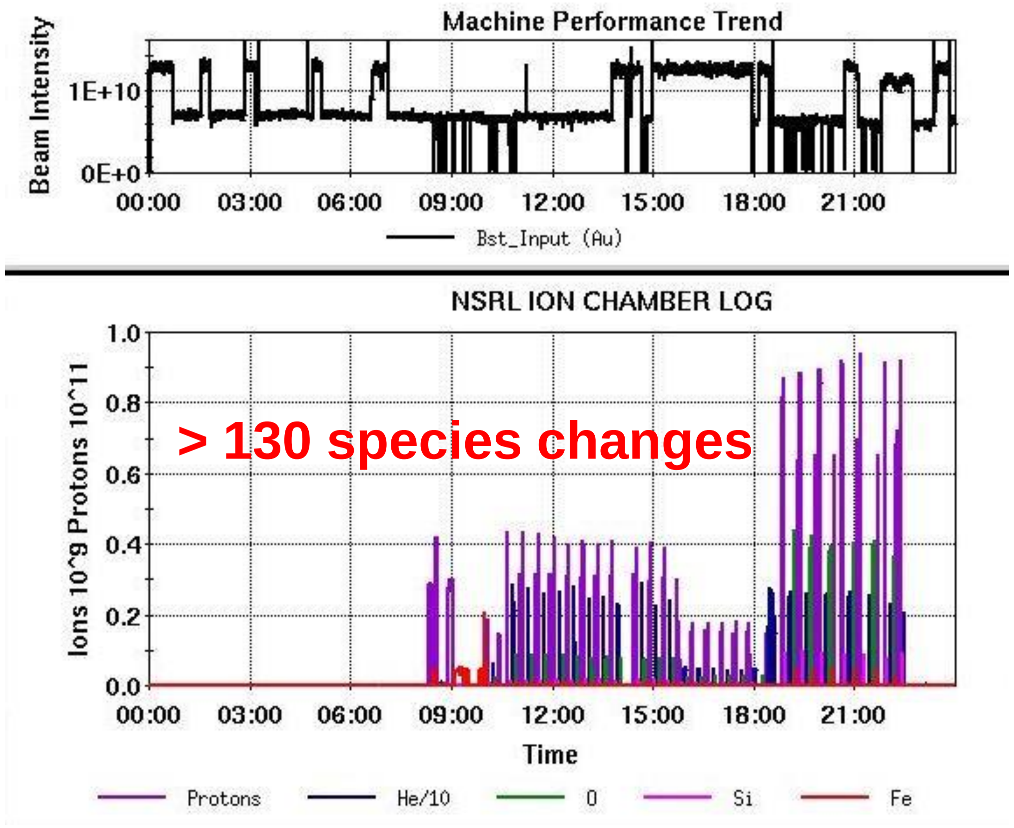


Movies are shown in this page

Quasi-simultaneous operation for NSRL and RHIC

Au for RHIC

Beam at NSRL

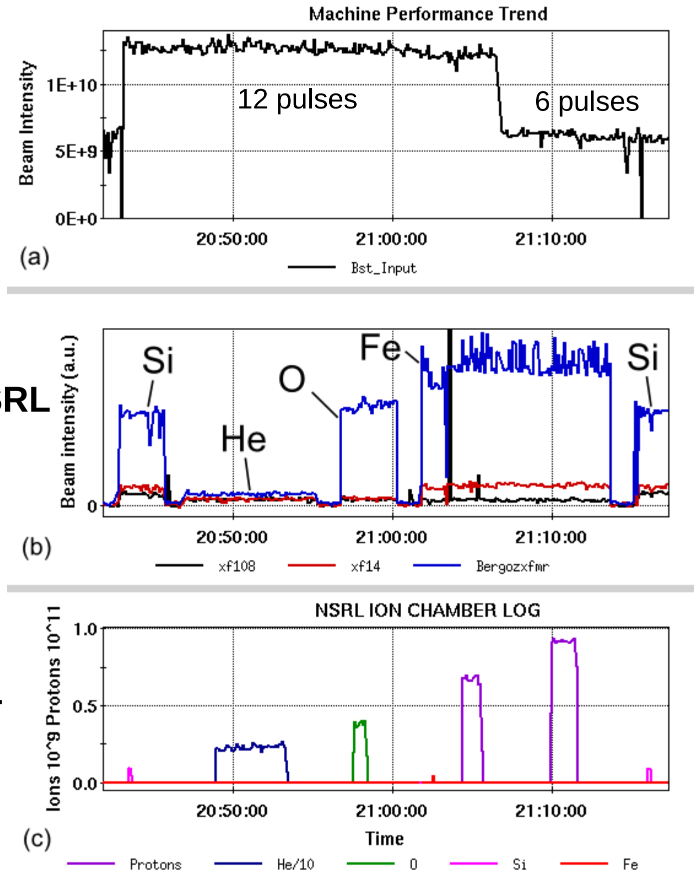


24 hours beam usage
with GCR simulator at NSRL

Au for RHIC

EBIS beam for NSRL

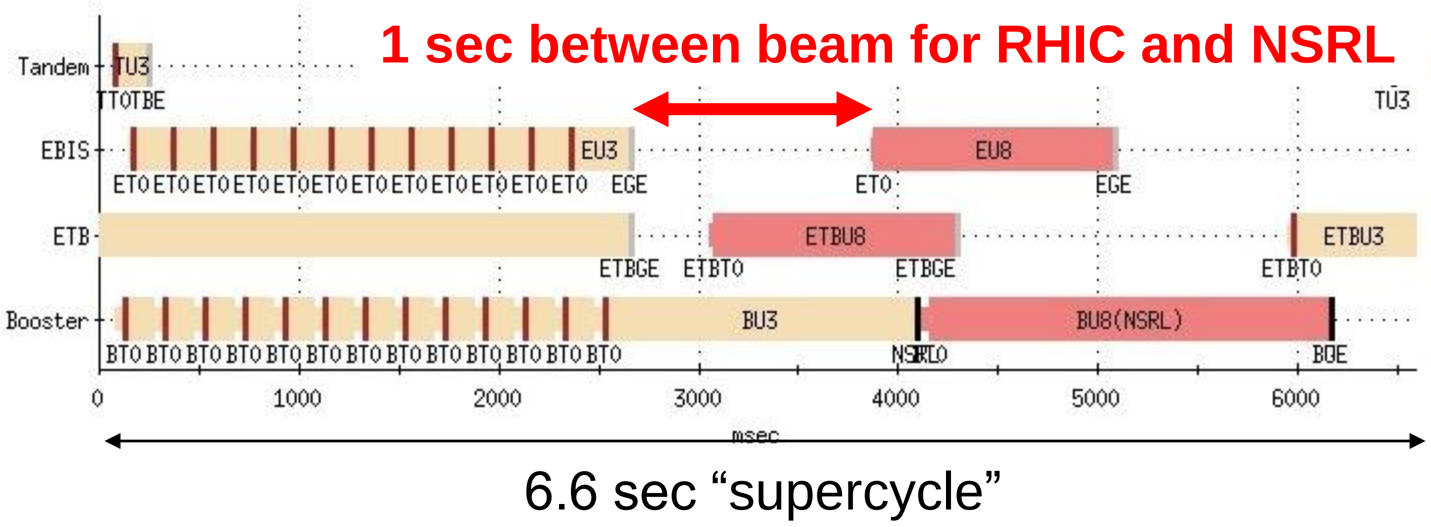
Beam at NSRL



30 min beam usage

No ion source operator is required for EBIS pre-injector operation

Quasi-simultaneous operation for NSRL and RHIC



- **This picture shows the highest load for RHIC EBIS**
  - 12 pulses for RHIC + 1 pulse for NSRL in supercycle (6.6 sec)
- **RHIC-EBIS always switch species between RHIC and NSRL within 1 second in a supercycle**
- **RHIC and NSRL uses independent external source**
- **Working well with large variation of duty and amplitude**

Brookhaven National Laboratory

Summary

- Laser ablation ion source is the only heavy ion source to enable >100 mA beam current
- One possible application is neutron source using inverse kinematics using lithium beam
- We are starting to study neutron generation related topics more
- LION source to produce charge state 1+ ions are in operation for NSRL and RHIC at BNL
  - EBIS increase charge state for further acceleration by RFQ and IH linac
- Li, B, C, O, Al, Si, Ca, Ti, Fe, Cu, Zr, Nb, Ag, Tb, Ta, W, Au, Bi, Th were geneated at LION
  - About 10 species is available at a time