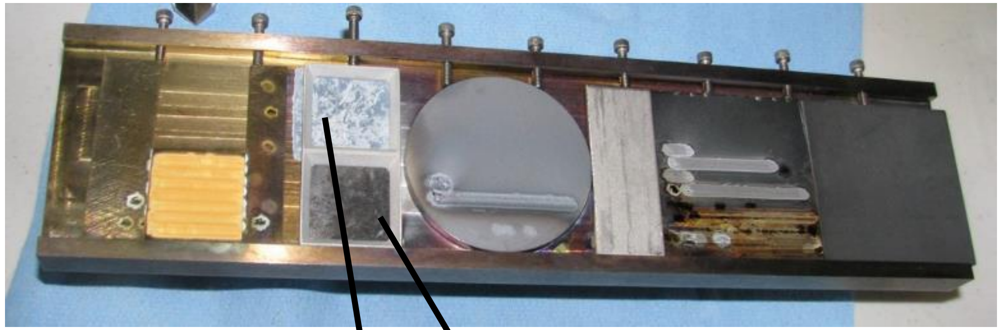
High Repetition Li Beam Driver with Li Target

Takeshi Kanesue, Shunsuke Ikeda, Masahiro Okamura

December 14, 2022

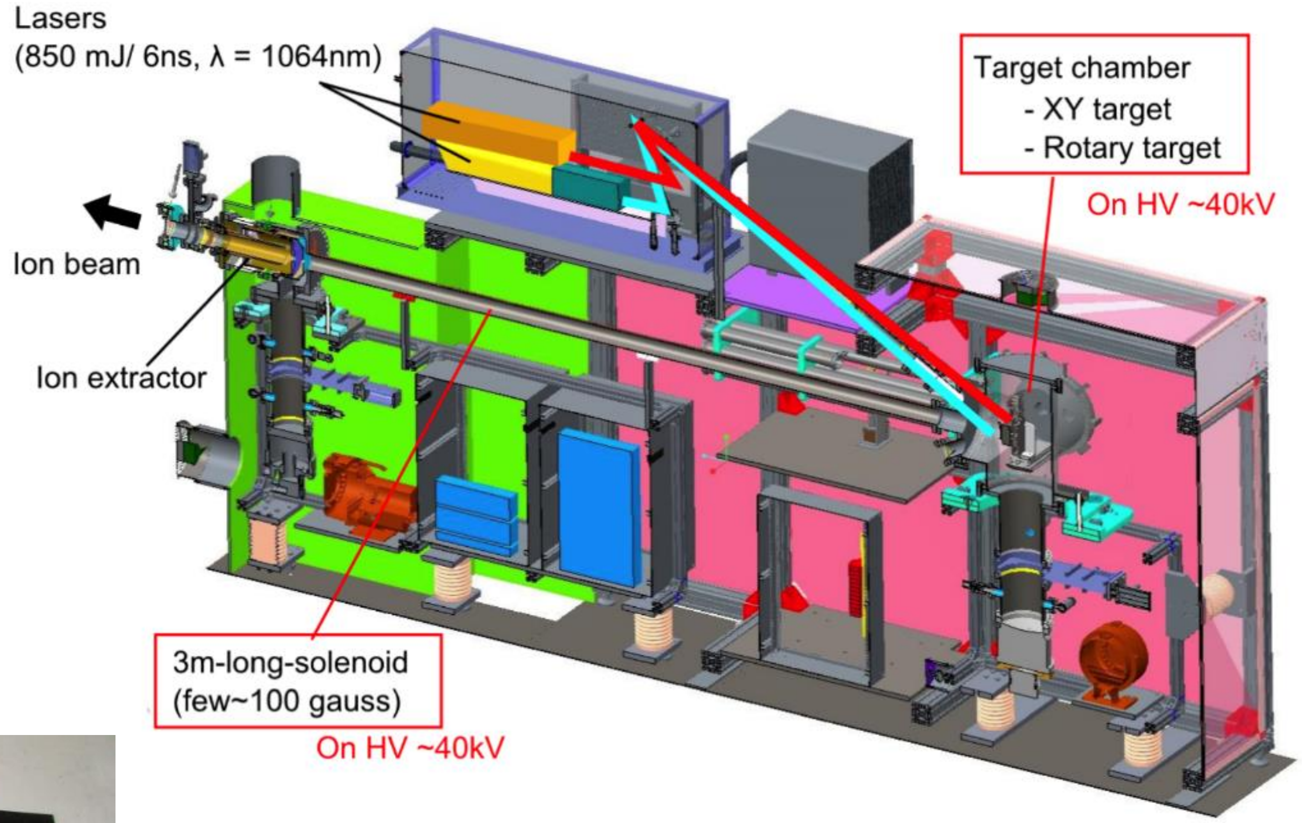
Laser ion source

Au for RHIC



Al Au Li Ca Si Ti Fe C

Targets for NSRL



- Any types of ions can be produced from solid material
- Pulsed source, no working gas. No “memory effect” of previous pulsed ion beam
- Fast species switch (within seconds, 130 switches/day)

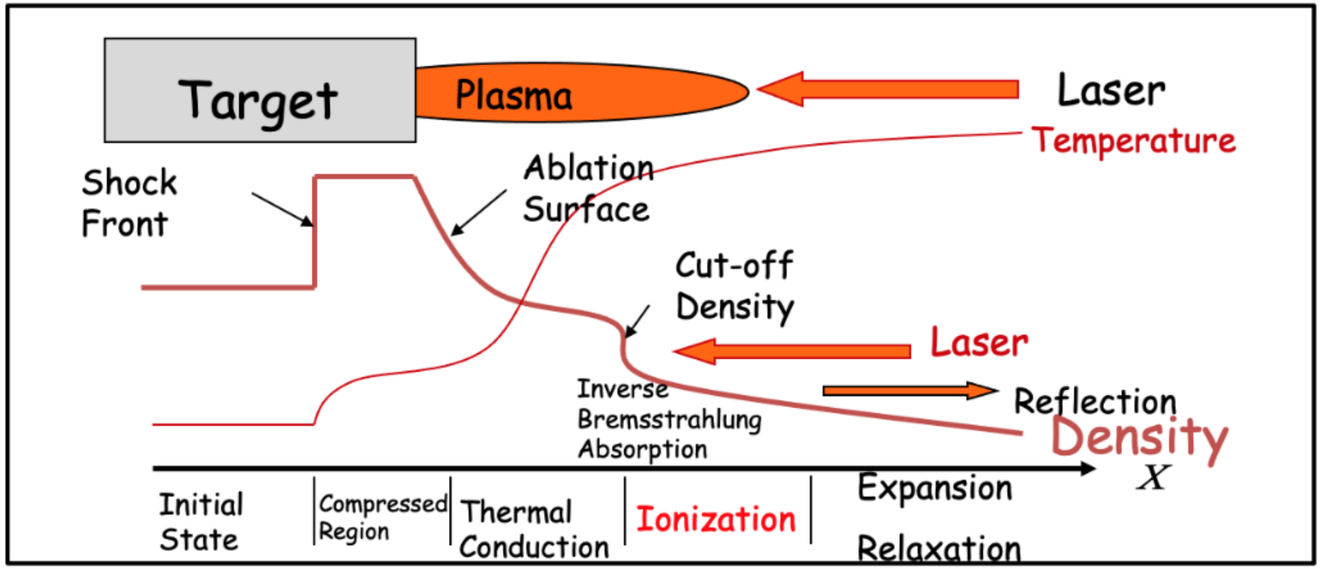
Plasma production by laser ablation process

Plasma generation

- Laser energy absorption and evaporation in a skin layer of a solid target
- Laser energy absorption by electrons in plasma by Inverse Bremsstrahlung absorption
- Ionization of atoms and ions in plasma by electron impact
- Recombination processes in plasma

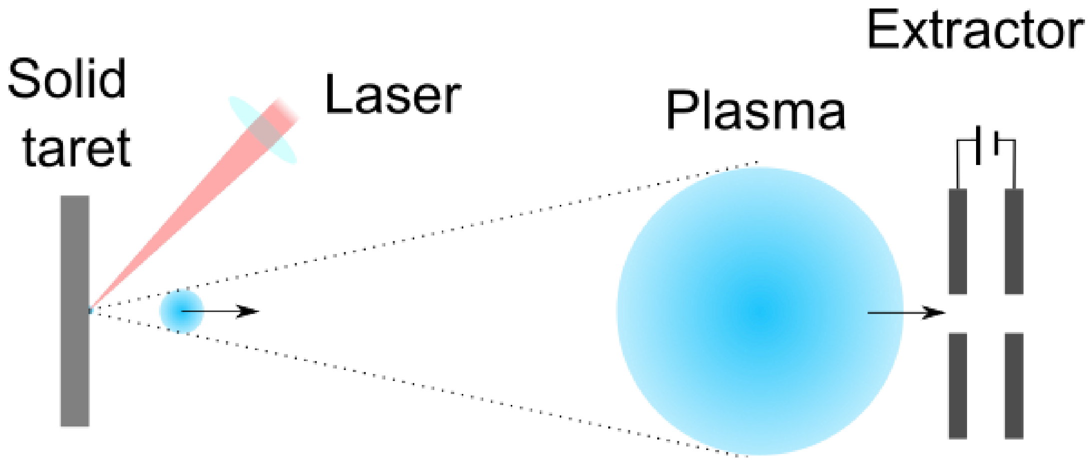
Plasma expansion into vacuum

- Hydrodynamic and coulomb acceleration



Brookhaven National Laboratory

Intense pulsed beam with focused laser pulse



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

- After hydrodynamic expansion, plasma becomes collisionless
- Charge state is “frozen” and plasma radius increases proportionally to time of flight
- Pulse duration and beam current depends on drifting distance
- Large number of ions (10^{14} – 10^{15}) are produced at target within laser pulse (<10 ns)
- Appropriate distance is selected for beam current and pulse width

Advantage for ion source

- 1A class ion beam can be produced
- pulse width can be very short < 1 μs
- Ions are emitted from point source -> low emittance

Application for compact neutron source is being studied.

Demand for compact accelerator driven neutron generator

Recently, as old reactors are being retired, compact accelerator driven neutron generators are getting more desired.

Not nuclear facility

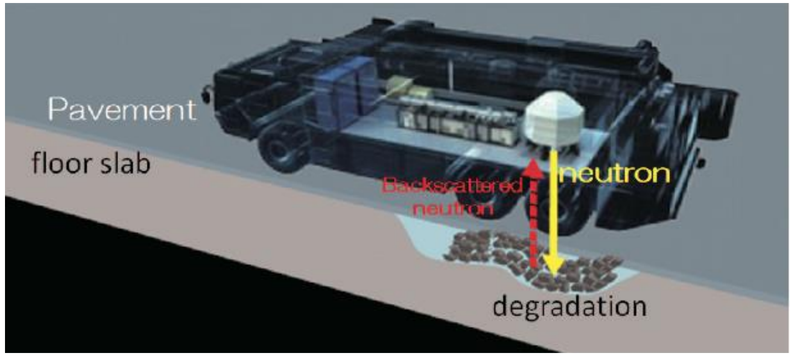
- Non-proliferation policies and difficulties of manufacturing fuel elements have prevented replacement of reactor

Low cost

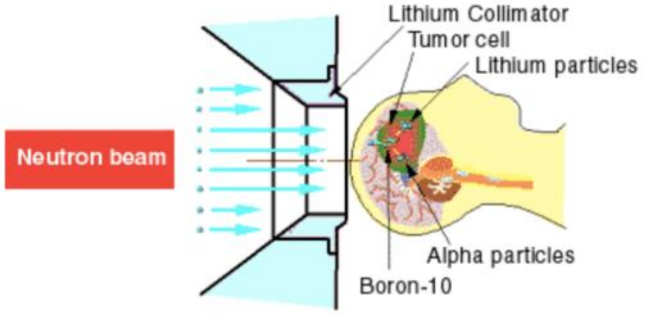
- Spallation source is expensive and machine time is limited

Wide range of applications

- Nondestructive inspection
  - residual stress in train rails and aircraft parts
  - hidden failures of buildings and bridges
  - cargo inspection
- Boron neutron capture therapy
- Detector development

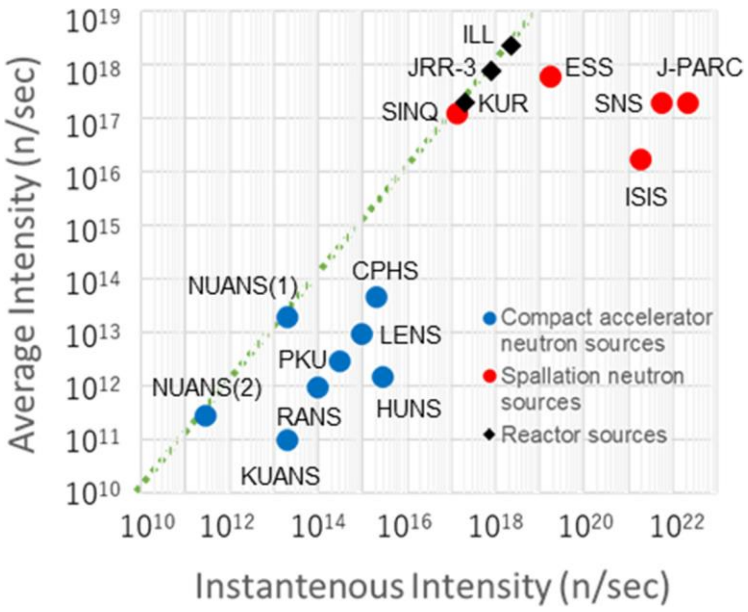


https://rap.riken.jp/en/labs/aptdg/nbtt/

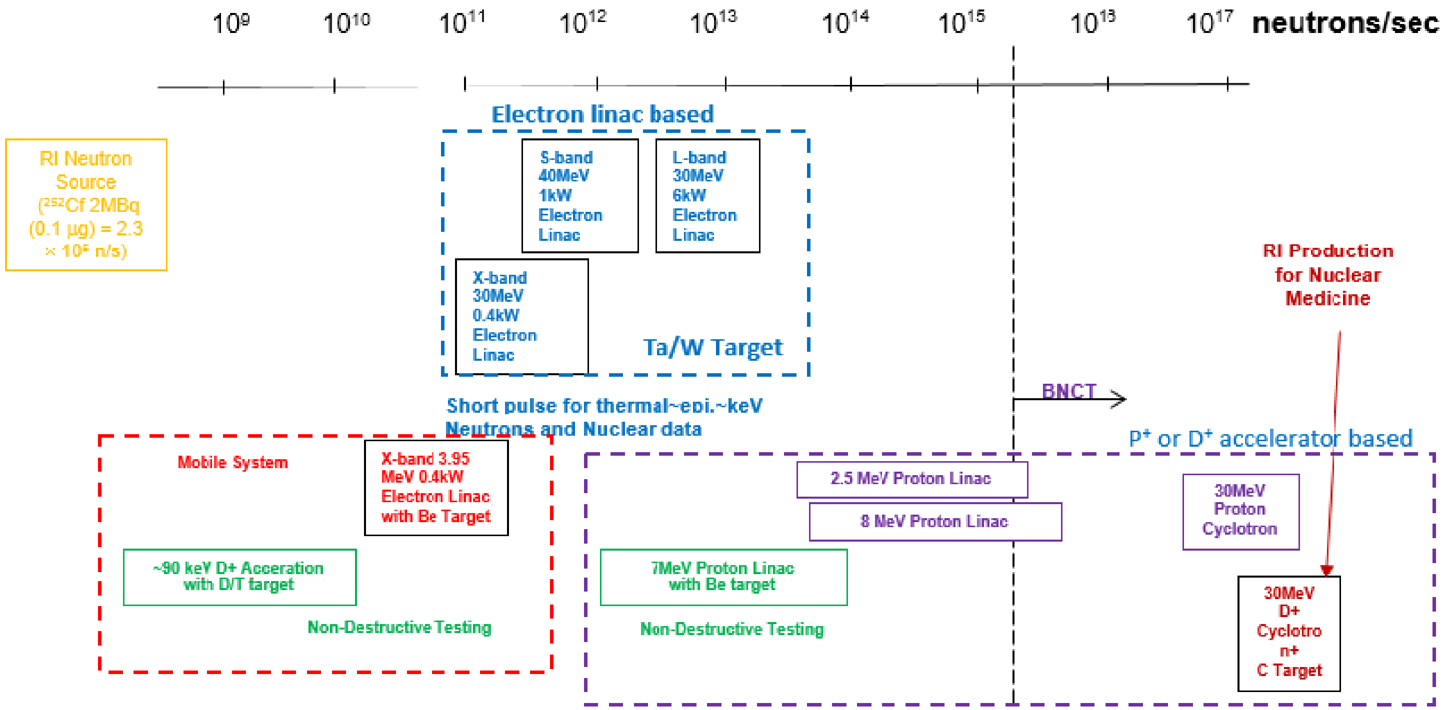


http://www.jaea.go.jp/jaeri/english/press/991025/fig03.htm

Compact neutron sources for different intensities and applications



Y. Kiyanagi "Neutron applications developing at compact accelerator-driven neutron sources" Kiyanagi AAPPS Bulletin (2021) 31:22

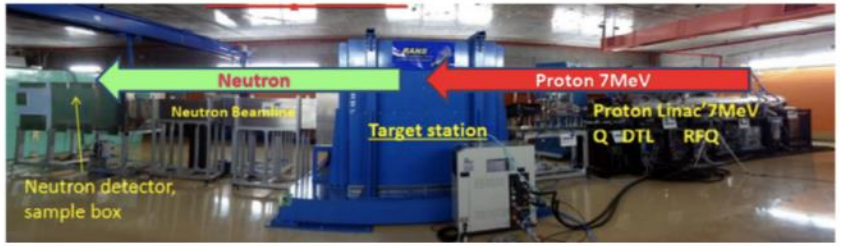


M. Uesaka and H. Kobayashi, "Compact Neutron Source for Energy and Security" Reviews of Accelerator Science and Technology Vol. 8 (2015) 181–207

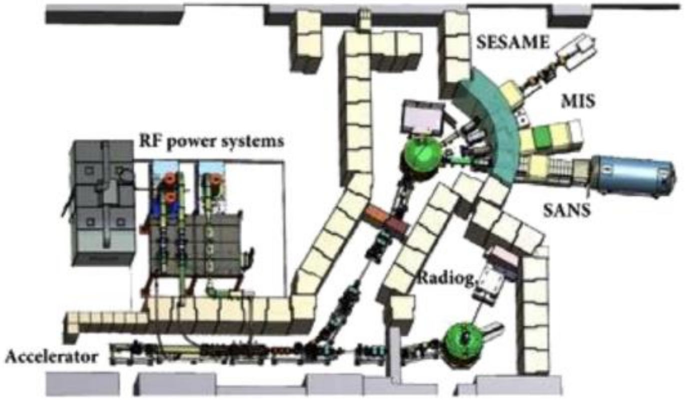
Brookhaven National Laboratory

Compact neutron generator with proton driver

- Neutron generation with $^{7}Li(p,n)^{7}Be$ or $^{9}Be(p,n)^{9}B$
- 2 ~ 30 MeV proton energy
- 10 ~ 30 m long
- Higher neutron flux compared with other types of compact sources

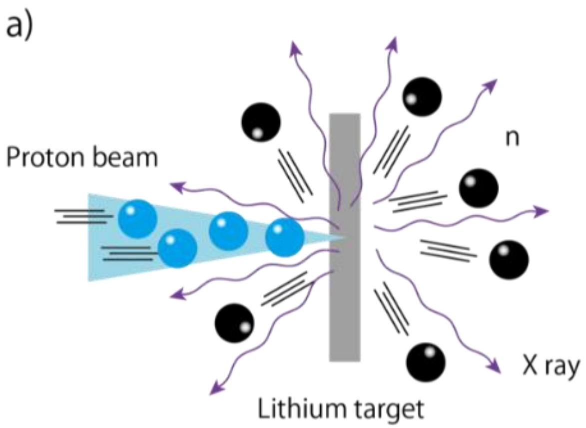


RANS (RIKEN, JAPAN)
Ep =7MeV;Iav =100μA



LENS (Indiana University, IN, US)
13MeV; 20mA; Iav = 0.24mA

Neutron production with proton beam



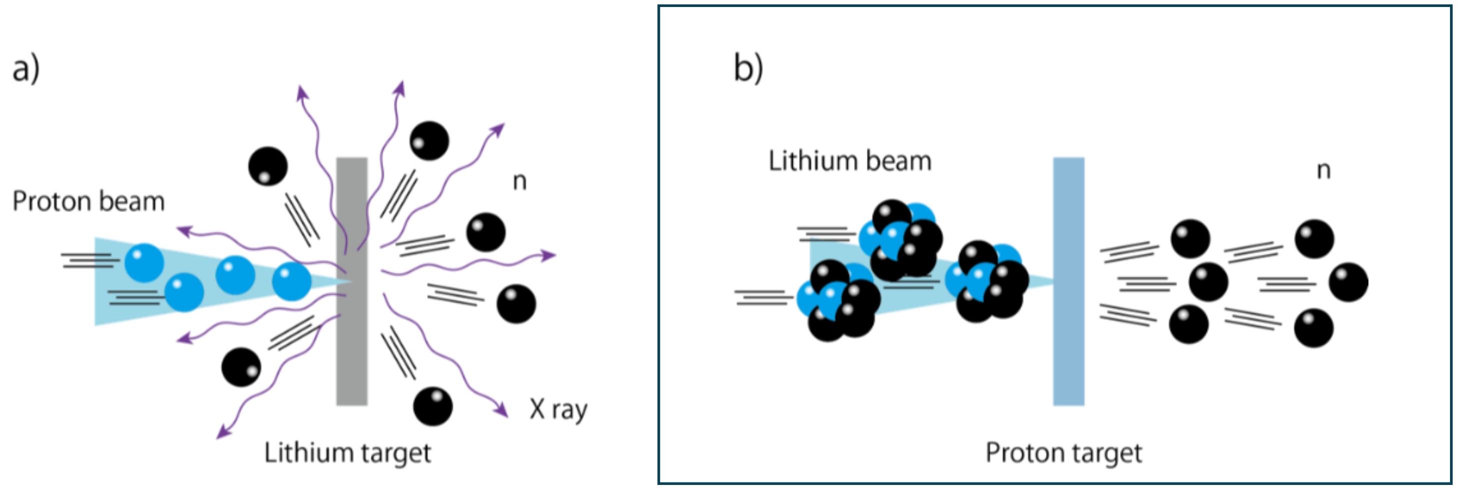
$$^{7}Li + p \rightarrow {}^{7}Be + n - 1.64\ MeV$$
$$^{9}Be + p \rightarrow {}^{9}B + n - 1.85\ MeV$$

Y. Zuo, et al, "Neutron yields of thick Be target bombarded with low energy deuterons"

- These reactions are endothermic and undesired radiations could be reduced if beam energy is near the thresholds.
- However, since the proton is lighter than target atoms, the neutrons are produced in all direction and only small fraction can be used.
- Therefore, higher beam energy is used to increase neutron flux.

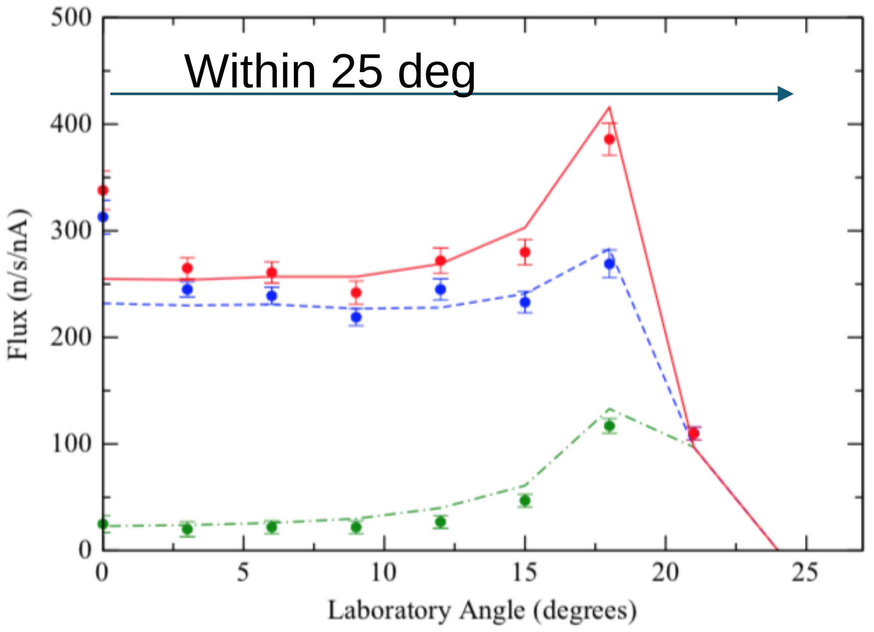
Brookhaven National Laboratory

Neutron source with Li ion driver



- If heavy ions are injected, neutrons are directed to forward direction because of the high center of mass velocity.
- Neutron flux can be increased while beam energy is kept near the threshold.

Neutron source with Li ion driver



Measured (symbols) and calculated (lines) angular distribution of neutron flux using beams from Tandem

Advantage

The kinematic focusing technique clearly offers some distinct advantages over standard isotropic quasi-monoenergetic sources:

1. The focusing enhances the available neutron flux by a factor of between 25 and 100.
2. The lack of neutron emission at most angles results in much lower fast and thermal scattered neutron backgrounds in the experimental hall.

Disadvantage **without** laser ion source

available beam current of ^{7}Li is much lower than that available for protons in the non-inverse reaction, because of the relative difficulty of extraction of ^{7}Li-ions from the ion source. Secondly,

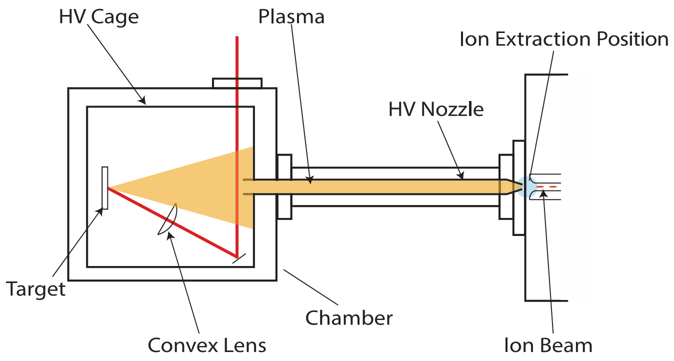
Tandem ~ μA, ECR ~ mA

Proton beam >10s mA

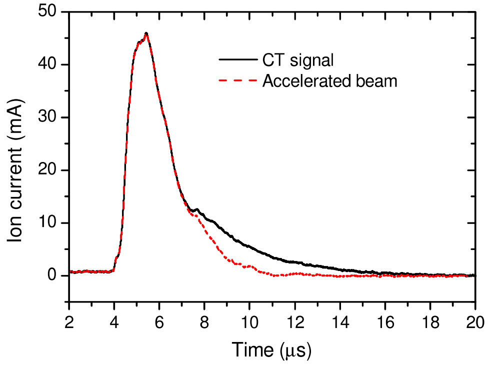
Brookhaven National Laboratory

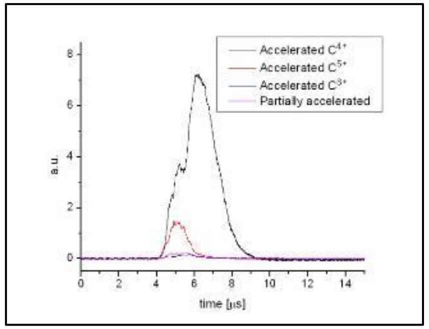
M. Lebois *et al.*, “Development of a kinematically focused neutron source with the p (7Li, n) 7Be inverse reaction,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 735, pp. 145–151, 2014.

Intense beam production using laser ion source and RFQ: Direct plasma injection scheme



35 mA C^{4+}

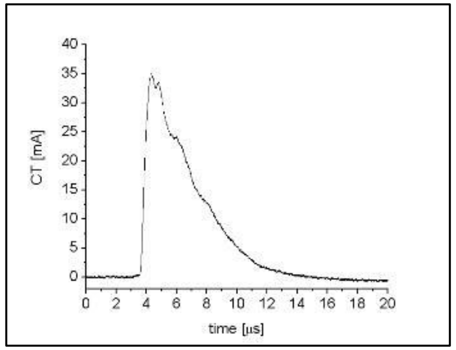


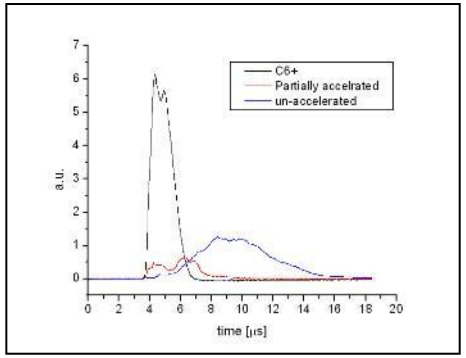


- Plasma is generated by laser ablation and injected into RFQ.
- Beam extraction is done in RFQ
- No need to build low energy beam transport (LEBT)

High density plasma directly converted to bunched beam.

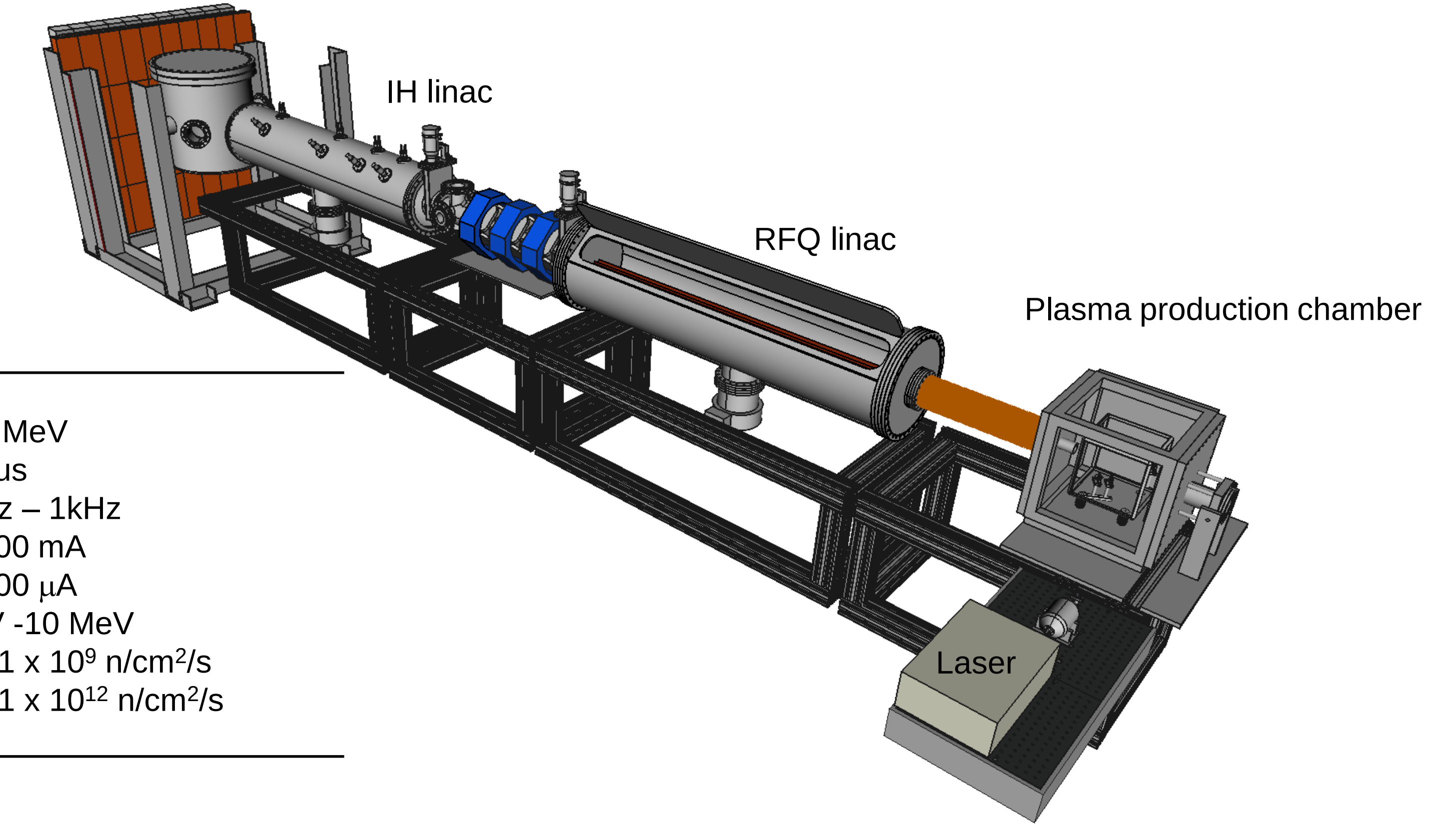
30 mA C^{6+}





"Laser ion source with solenoid field", APPLIED PHYSICS LETTERS 105, 193506 (2014)

Compact neutron source using intense Li ion beam driver based on laser ion source



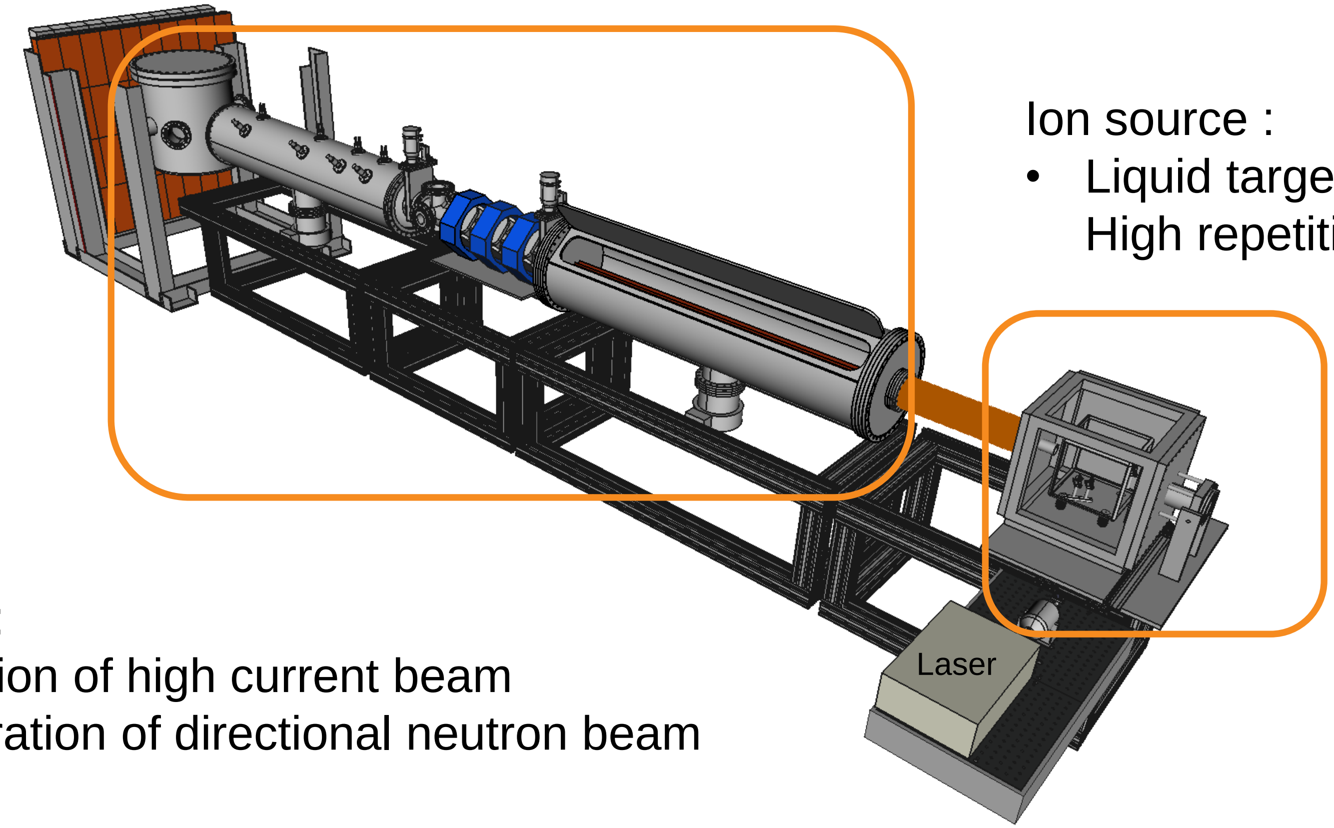
Ion	$^{7}Li^{3+}$
Ion beam energy	14-20 MeV
Beam pulse width	0.1-5 us
Repetition rate	100 Hz – 1kHz
Peak ion beam current	10 - 100 mA
Average ion beam current	10 - 100 μA
Neutron energy	1 MeV -10 MeV
Average neutron flux	Up to 1 x 10^{9} n/cm^{2}/s
Peak neutron flux	Up to 1 x 10^{12} n/cm^{2}/s
Length	< 8 m

Advantage1: Forward-directed neutrons = very small number of unwanted neutrons, small shielding

Advantage2: Short beam pulse = Background separation by TOF method

Brookhaven National Laboratory

Development topics to realize compact neutron source



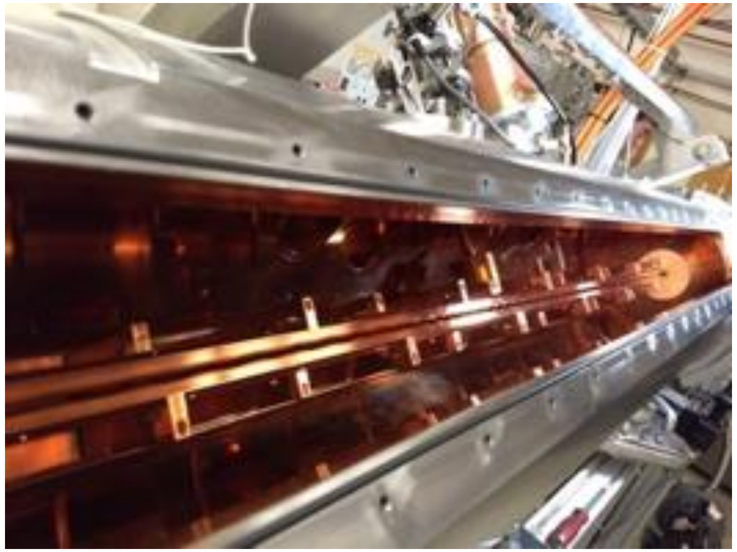
Ion source :

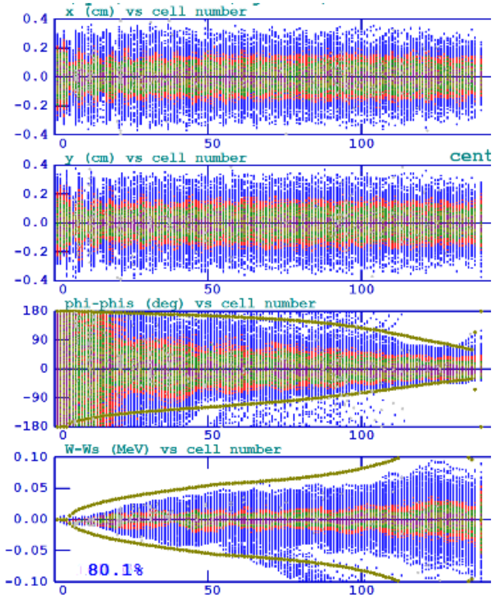
- Liquid target development for High repetition rate

Accelerator :

- Acceleration of high current beam
- Demonstration of directional neutron beam

Development of accelerators for high current beam



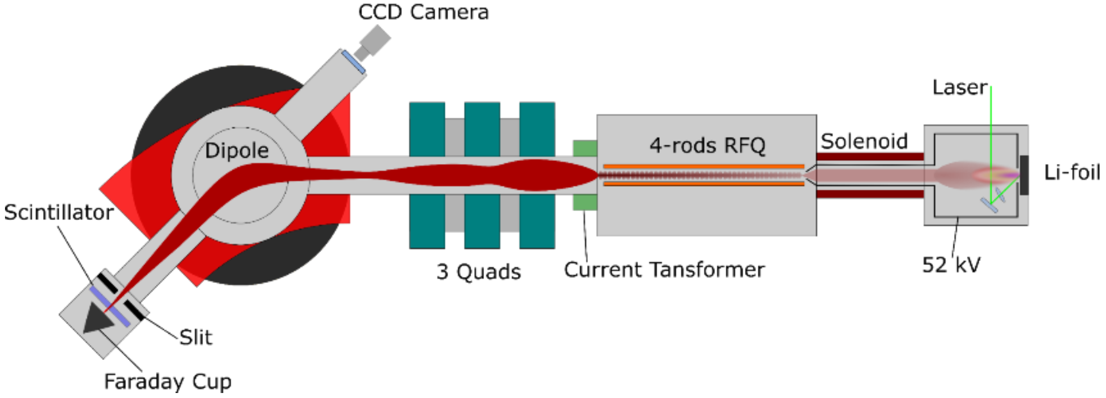


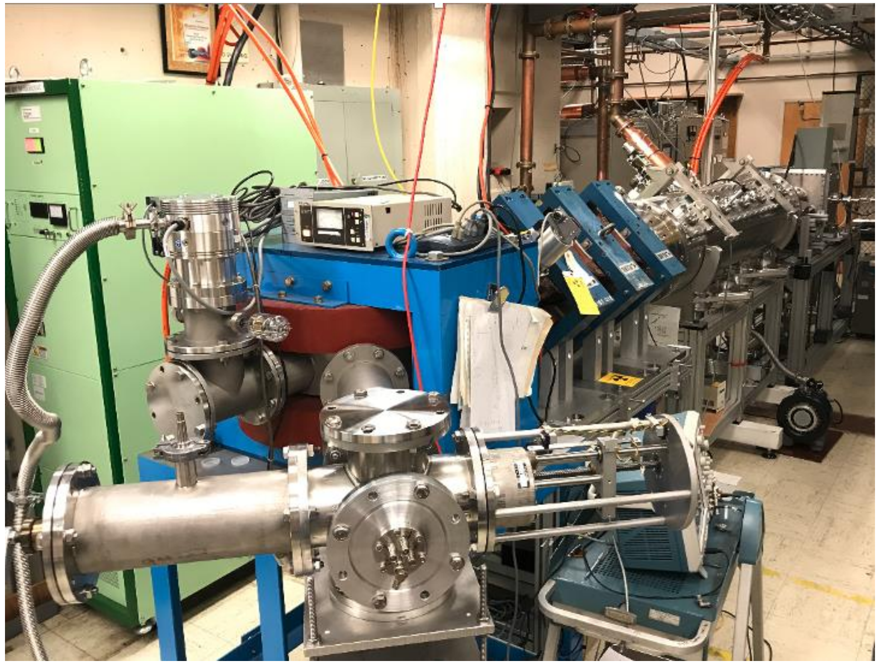
Parameter	Value
Structure	4 Rod
Frequency	100 MHz
Input energy	22 keV/n
Output energy	204 keV/n
Input beam current	50 mA
Transmission	80 %
RFQ length	1977 mm

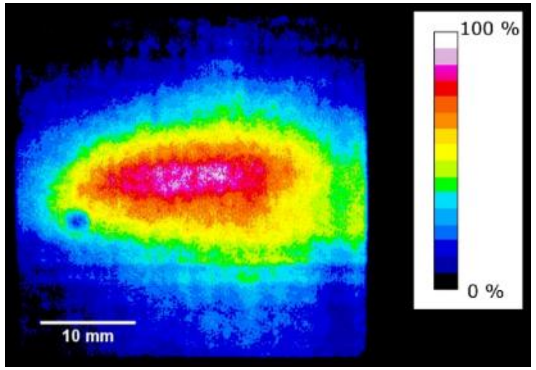
Design of RFQ linac with parmteq for 40 mA Li beam output

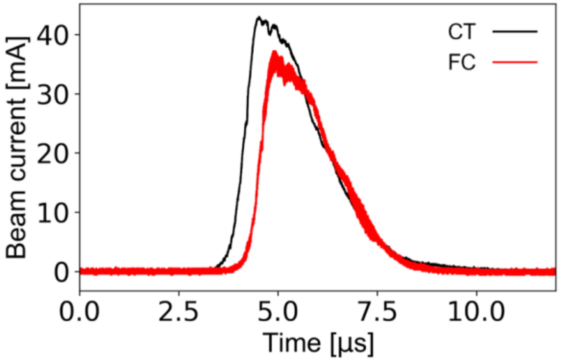
Brookhaven National Laboratory

Success of 35 mA $^{7}Li^{3+}$ beam acceleration by first stage accelerator (RFQ linac)







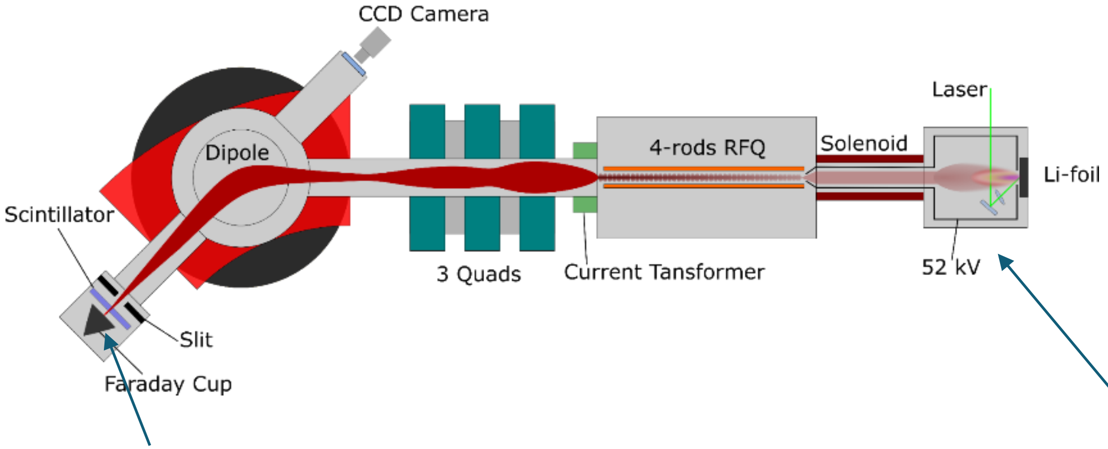


10-100 times higher than other machines

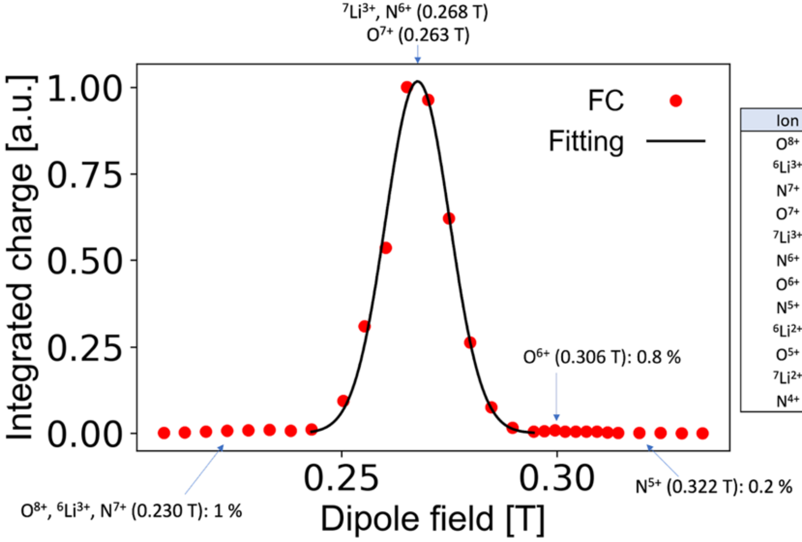
35 mA of $^{7}Li^{3+}$ was accelerated (world record)

Tandem ~ µA, ECR ~ mA

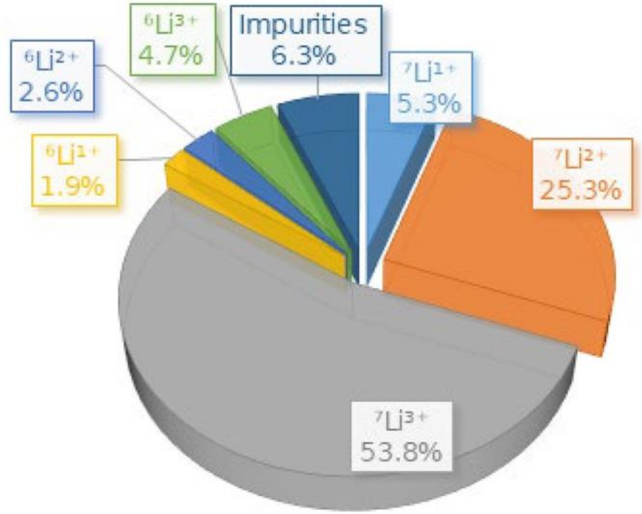
Low impurity in beam



No working gas is used in ion source



Ion	Q/A
O^{8+}	0.500
$^{6}Li^{3+}$	0.500
N^{7+}	0.500
O^{7+}	0.438
$^{7}Li^{3+}$	0.429
N^{6+}	0.429
O^{6+}	0.375
N^{5+}	0.357
$^{6}Li^{2+}$	0.333
O^{5+}	0.313
$^{7}Li^{2+}$	0.286
N^{4+}	0.286

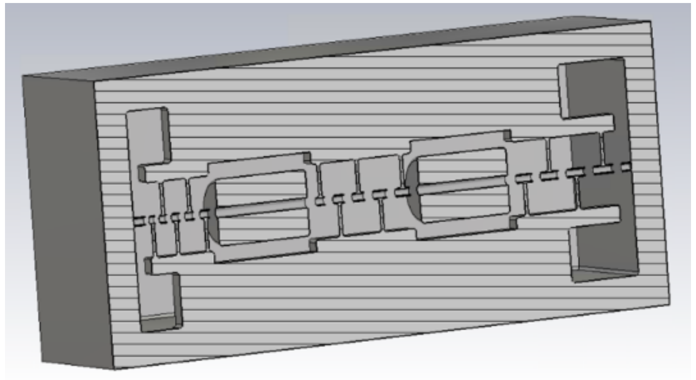


Ions in beam after RFQ linac analyzed by dipole magnet: Impurity < 2 %

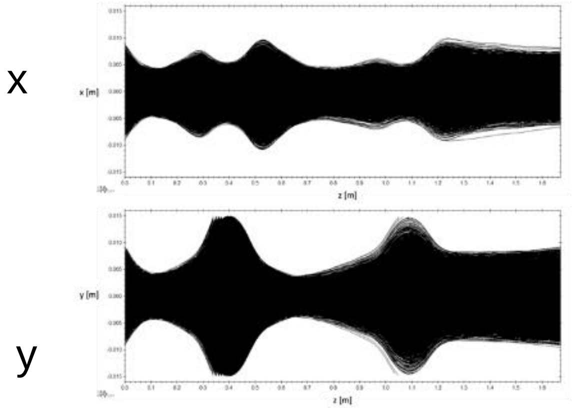
Ions in plasma analyzed by off-line electrostatic analyzer

Brookhaven National Laboratory

Next step 1: Demonstration of directional neutrons



IH linac (second stage accelerator)



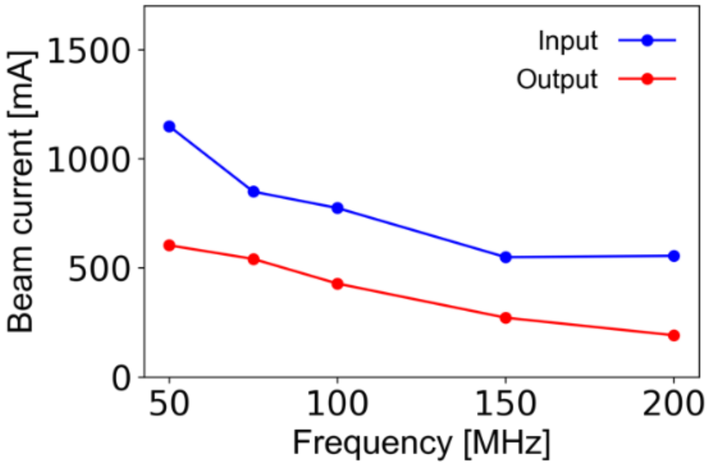
Z (Longitudinal position)

- Demonstration of directional neutron beam by increasing Li energy for nuclear reaction
- Interdigital H-type linac (IH linac) is being designed
- One example of accelerator design was completed
    - 204 keV/n, 40 mA beam bunch injection from existing RFQ
    - Conventional -30-degree fixed synchronous phase
    - Reasonable drift tube gap voltages (< 460 kV)
    - 1 strong focusing element before IH linac and 2 strong triplets in accelerator cavity
    - Design work is being continued
    - Higher input energy may be better

Next step 2: Design study for higher beam current

- In the previous research, beam current was limited by existing experimental devices
- Beam current limit was explored under relaxed (but realistic) restrictions below
  - 100 kV extraction
  - Any RF frequency
  - 2.3 Kilpatrick factor in RFQ linac
  - Up to 1 MW RF power
- Parmteq was used to design RFQ after radial matching section
- For each of 50, 75, 100, 150, and 200 MHz, the maximum output currents were searched by changing a_{GB} and ϕ_{GB}, and input current.
  - a_{GB}, ϕ_{GB} : minimum aperture and synchronous phase at gentle buncher end
  - In contrast to conventional accelerator, transmission does not need to be high because large input current can be provided by laser ion source

Next step 2: Design study for higher beam current



f [MHz]	r_0 [mm]	V_{RFQ} [kV]	L_{RFQ} [mm]	Q_0	P [MW]
200	3.2	85.3	2520	5534	0.402
150	4.6	108	2630	5930	0.436
100	7.8	155	2840	6971	0.581
75	12.6	219	3380	8962	0.857
50	22.3	328	3460	10343	1.06

- RF power was estimated by CST MWS
- 75 MHz was selected to have RF power < 1 MW

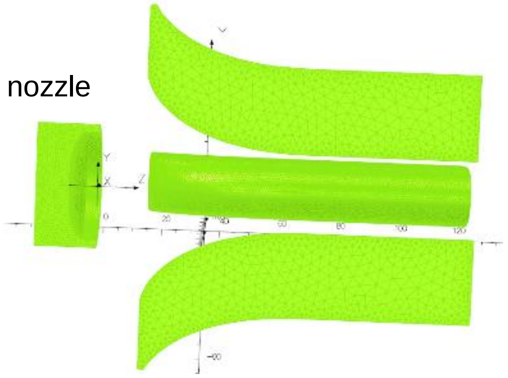
Resonant Frequency (f)	75 MHz
Minimum Aperture (a_{GB})	9.3 mm
Modulation (m_{GB})	1.56
Synchronous phase (f_{GB})	-50 deg
Input current	850 mA
Output current	520 mA
Emittance in x-x’	1.8 π mm mrad
Emittance in y-y’	1.4 π mm mrad
Emittance in df-dw	3.9 π deg-MeV

Brookhaven National Laboratory

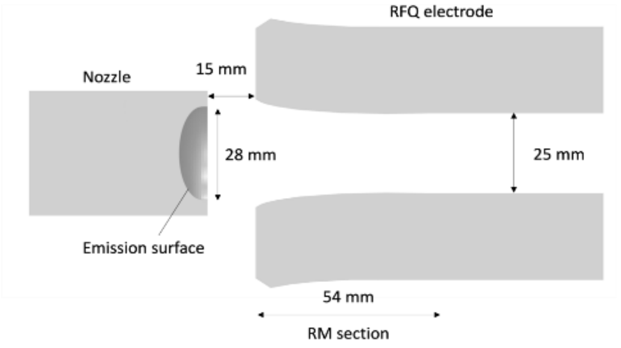
Next step 2: Design study for higher beam current

- In typical RFQ linac, ions are focused outside and not accelerated around RFQ entrance
- At RFQ entrance in DPIS scheme, ions are significantly accelerated
- In DPIS, converging angle depends on the shape of meniscus of plasma-ion boundary
- Geometries of anode and radial matching section were optimized for beam matching specialized for DPIS scheme
- Fractions of ions ($^{7}Li^{1+}$, $^{7}Li^{2+}$, $^{7}Li^{3+}$,,,) in injected beam was based on experimental result.

Anode nozzle



Parmteq design



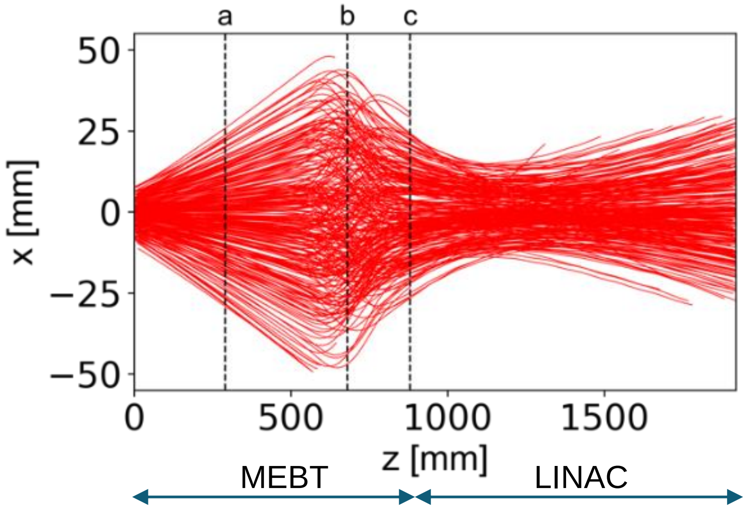
Optimized design

350 mA output current was suggested in optimized design

Brookhaven National Laboratory

Next step 2: Design study for higher beam current

- Based on simulation study, high current beam from RFQ linac can be transported to and accelerated by second stage accelerator (IH linac)



Z=0 : RFQ exit
(a) 300 kV buncher
(b) 2.5 T, 200 mm solenoid center
(c) IH linac entrance

Beam current	320 mA
Beam energy	14.3 MeV
Rms normalized emittance in x-x' plane	3.0 π mm mrad
Rms normalized emittance in y-y' plane	3.3 π mm mrad
Rms normalized emittance in f-w plane	2.3 π deg-MeV
Energy spread (98 % $^{7}Li^{3+}$)	±5%

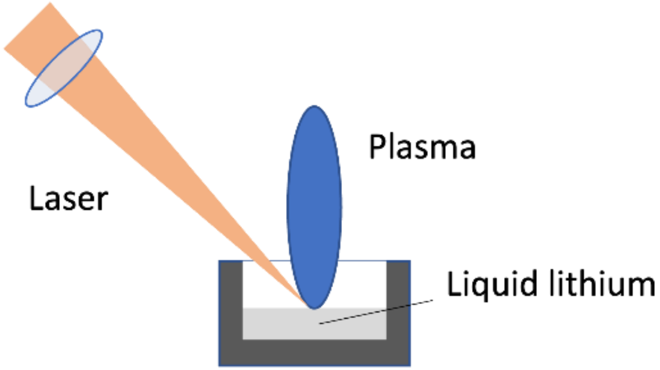
Laser target development for high repetition rate and long-time operation

Present technology

- Solid target should be moved every shot to provide a fresh surface ~ 1Hz
- Enormously large surface area is needed for long time operation
- This limits the total yield of lithium ions

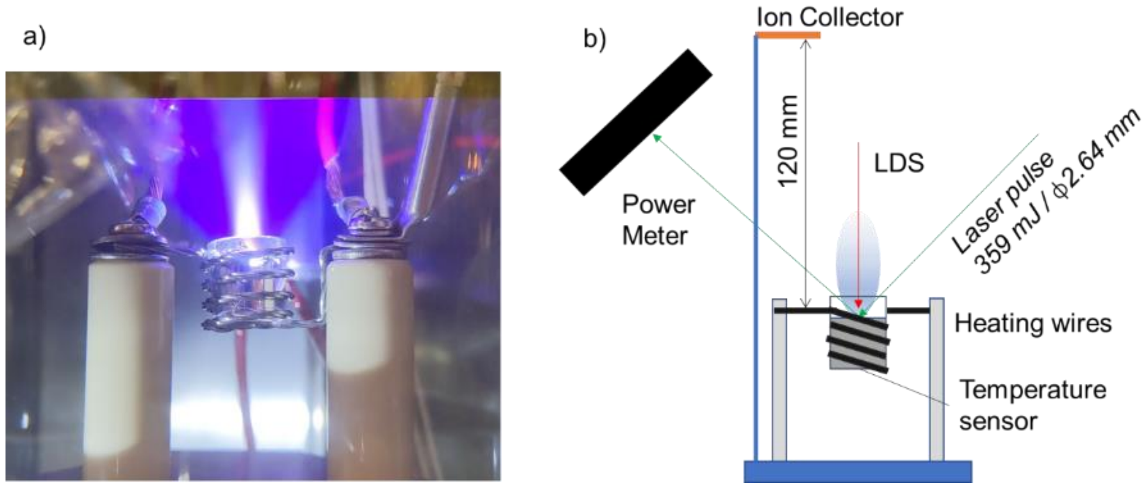
Liquid target to overcome limitation

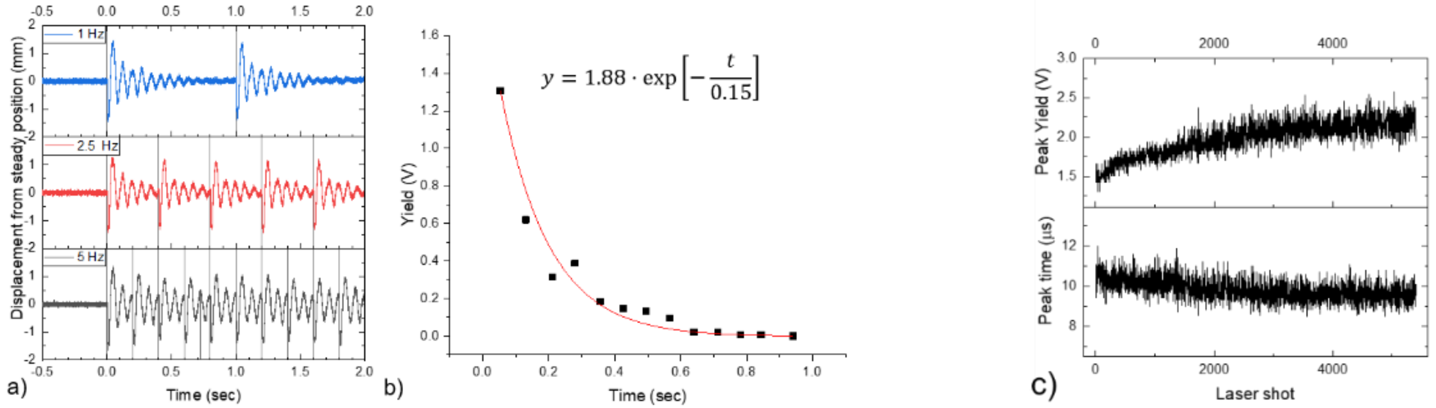
- a liquid target can fully recover surface flatness after any laser shot
- laser shots can be fired on the same spot
- e.g.) 100 mA peak, 1 μs pulse width,
  - 100 Hz = 10 μA average,
  - 1 kHz = 100 μA average
  - Enough for imaging
  - Possible to use it for isotope production



Brookhaven National Laboratory

Liquid target experiments using liquid Ga

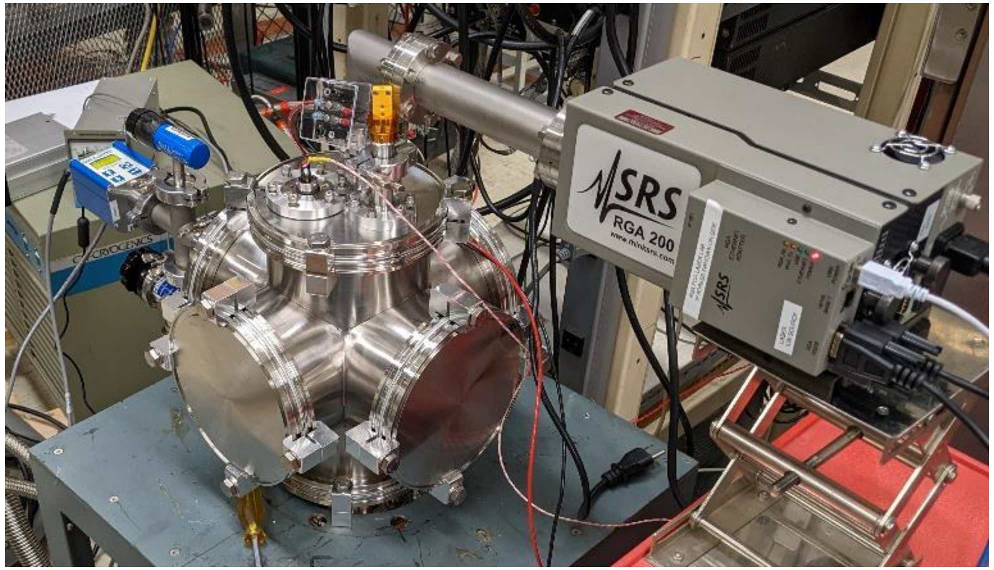




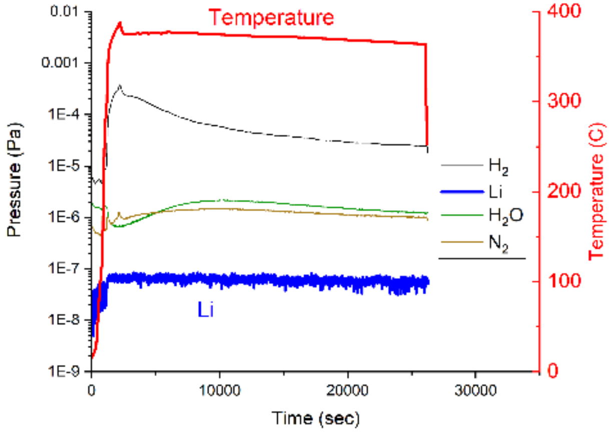
- Method to evaluate effect of liquid surface oscillation on plasma was established
- Stable plasma production was shown up to 5 Hz (device limit)

Brookhaven National Laboratory

Wall temperature and lithium accumulation



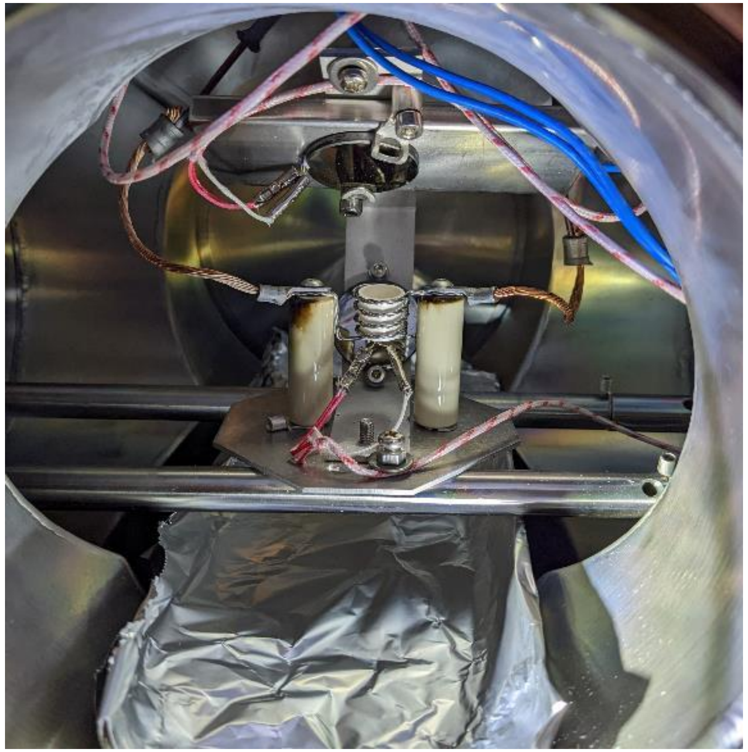
Vapor pressure of lithium
- 10^{-7} Pa at 200 C
- 10^{-4} Pa at 300 C
- 10^{-2} Pa at 400 C

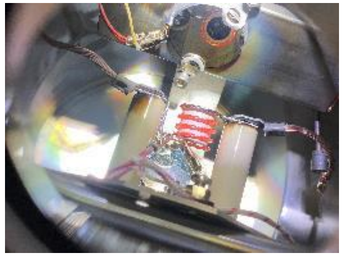


- We tried to measure the vapor pressure using a residual gas analyzer.
- A piece of solid lithium contained by a boron nitride crucible was heated by an electric heater.
- However, we could not see any lithium vapor.
- Lithium could not pass the elbow pipe

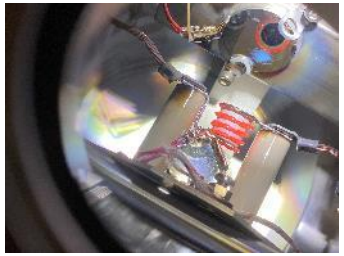
Brookhaven National Laboratory

Wall temperature and lithium accumulation

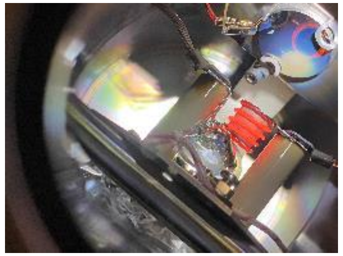




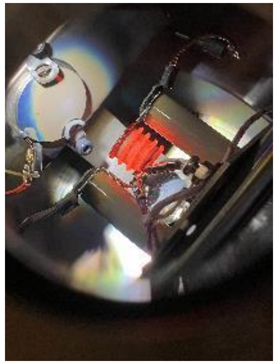
(a)
Crucible: 260 C
Mirror: 206 C



(b)
Crucible: 255 C
Mirror: 185 C



(c)
Crucible: 248 C
Mirror: 170 C



(d)
Crucible: 243 C
Mirror: 164 C

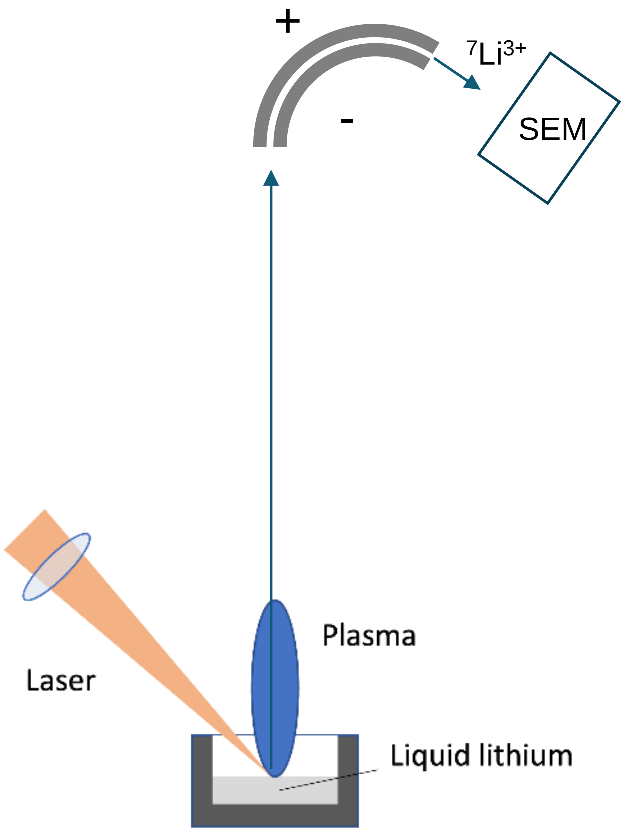
LDRD project : Stable plasma production with liquid Li target

•Shielding structure and temperature control

- Liquid lithium is highly reactive to most of materials
- Lithium plasma from laser ablation may break welding part of vacuum chamber or turbo fans
- Shielding is needed
- The structure should be designed to control expose to material
- Shielding temperature should be controlled to guide liquid vapor to a part prepared for accumulation

LDRD project : Stable plasma production with liquid Li target

- Laser condition optimization: focusing length and energy
  - Laser spot size on target should not be changed for stable production of plasma
  - Surface oscillation induced by laser may change distance between focusing lens and target, and then spot size
  - With long focusing lens, spot size is less dependent on distance
  - However, spot size becomes larger and larger energy is needed
  - Lower laser energy is preferable
  - Optimum condition should be searched for robust operation with sufficient $^{7}Li^{3+}$



LDRD project : stable plasma production with liquid Li target

- Crucible shape investigation
- Maximum damping
  - Surface oscillation should be small
  - Damping depends on geometry, viscosity, and surface tension
  - Damping can be maximized by using appropriate geometry or obstacles
- Splashing prevention
  - Instantaneous impulse by laser may cause splashing
  - This should be prevented to avoid

where h = dep

a = rad

w = cru

References: (35)

Cruciform baffles
horizontal component
les are also slightly
l fluid velocities ex
s the tank walls.

where ζ = amplitude of li

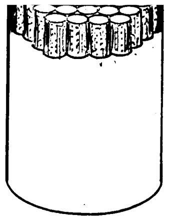
h = depth of liquid

d = depth of ring b

a = radius of right

w = ring width

eferences: (32, 35, and 41)



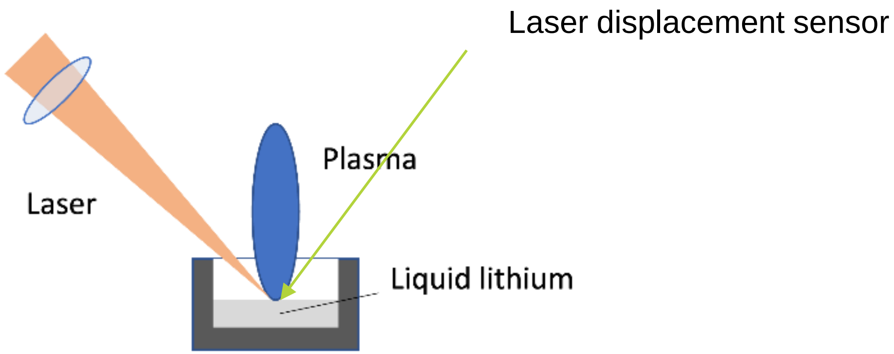
(40, 42, 43)

ons by Eulitz (40) have been made
l and enclosing a hollow air-tight
r, which provides the necessary bu
can necessary for adequate buoyanc
determined in the following manner
he enclosed ball λ is given by

J. R. Roberts et al. "Slosh design handbook", NASA CR-406

LDRD project : stable plasma production with liquid Li target

- Plasma production experiment with a repetition rate of existing laser
  - Check plasma stability and surface oscillation
- Double pulse laser experiment
  - Simulate high repetition rate operation
  - Evaluate feasibility of burst mode operation (e.g., 10 μs interval for 100 μs with 100 Hz repetition rate)



Brookhaven National Laboratory

Summary

- Compact neutron source using intense lithium beam driver is being developed
- Highly directional neutron beam can be generated
- The neutron source will be incomparably clean because of very low amount of unwanted neutron radiation at large angle
- Achieved:
  - RF acceleration of high current Li beam (35 mA, world record)
- Ongoing research
  - Demonstration of directional neuron beam by increasing Li energy
  - Pursuing higher current (Tandem ~μA, ECR ~mA, LIS (present) 35 mA, LIS (next) 150 mA)
  - Liquid target for high repetition rate operation