Laser-driven neutron sources and their applications

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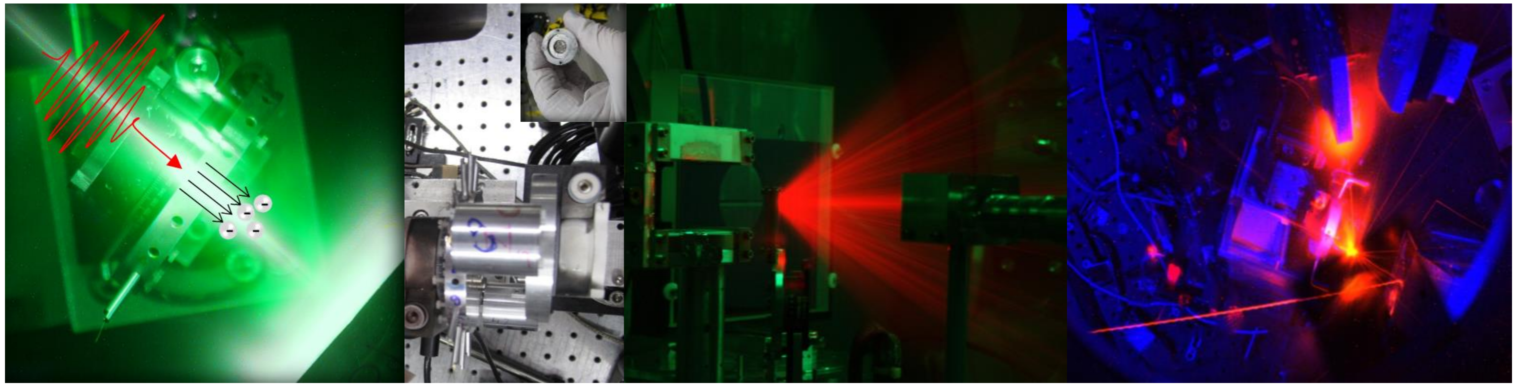


Agenda

- Introduction to neutron production
- Production of fast neutrons (>100 keV)
- Laser-driven low energy neutron source (<100 keV)
  - Epithermal beam
- Low energy neutrons applications
  - BNCT
  - Imaging
- Conclusion

Neutron Applications

Introduction

Neutrons are categorised based on their energy as fast (> 100 keV), useful for wide range of applications:

- Activation, i.e. U-238
- Imaging
- Material testing for fusion reactor vessels
- ….

However, the arena of neutron science and applications mainly requires slow neutrons!

Neutron Applications

Introduction

Neutrons are categorised as epithermal (0.5 eV> E_n >100 keV), useful for wide range of applications:

- ❑Deep Inelastic Neutron Scattering (DINS)
- ❑Non-invasive elemental and isotopic identification by Neutron Resonance Absorption (NRA)
- ❑Nuclear waste transmutation by neutron capture,
- ❑Medical radioisotope production
- ❑Boron Neutron Capture Therapy (BNCT)
- ❑….

Neutron Applications

Neutrons are categorised as thermal (0.001 eV < E_n <0.5 eV) , useful for wide range of applications:

- Material activation via Differential Die Away Analysis (DDAA)
- Atomic studies for their similar energy to energy of excitation in matter to probe material structures and give information about lattice vibrations
- ….

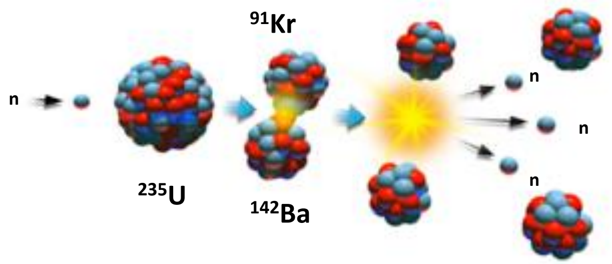
Introduction

Production of Neutrons

Introduction: Fission vs. Spallation

Fission

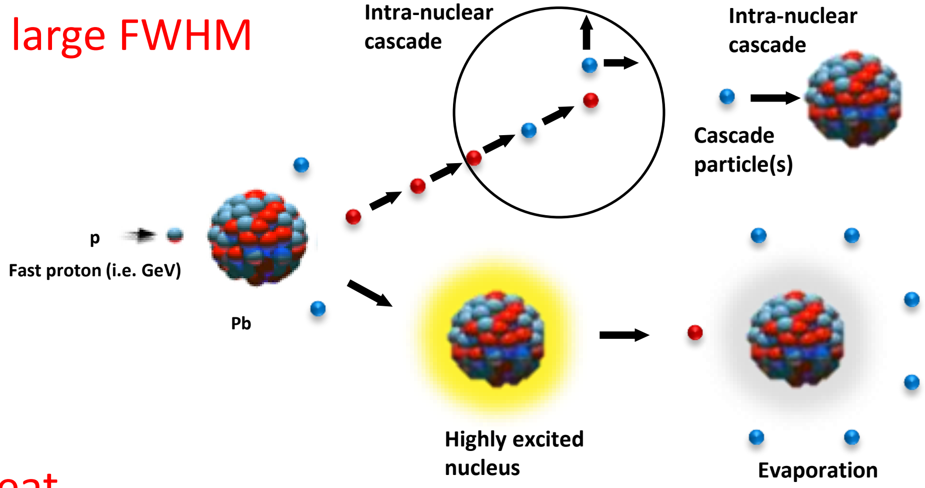
- Chain Reaction
- Continues Beam
- 3+1 neutron/fission



- Large facility
- Nuclear waste production
- Enrichment required
- Continues beam or large FWHM

Spallation

- No chain reaction
- Pulsed operation
- 30 neutron/proton



- Large facility
- Large amount of heat
- Large FWHM

WORLD AROUND RESEARCH REACTORS

- CRNL-Chalk River, Canada (135 MW),
- IAEA Beijing,China (125 MW),
- DRHUVA-Bombay, India (100 MW),
- ILL-Grenoble, France (57 MW),
- NLHEP-Tsukuba, Japan (50 MW),
- NERF-Petten, The Netherlands (45 MW),
- Bhabha ARCBombay,India (40 MW),
- IFF-Julich, Germany (23 MW),
- JRR3-Tokai Mura, Japan (20 MW),
- KFKI-Budapest, Hungary (15 MW),
- HWRR-Chengdu, China (15 MW),
- LLB-Saclay, France (14MW),
- HMI-Berlin, Germany (10 MW),
- Riso-Roskilde, Denmark (10 MW),
- VVR-M Leningrad, Russia (10 MW).

MAJOR SPALLATION SOURCES

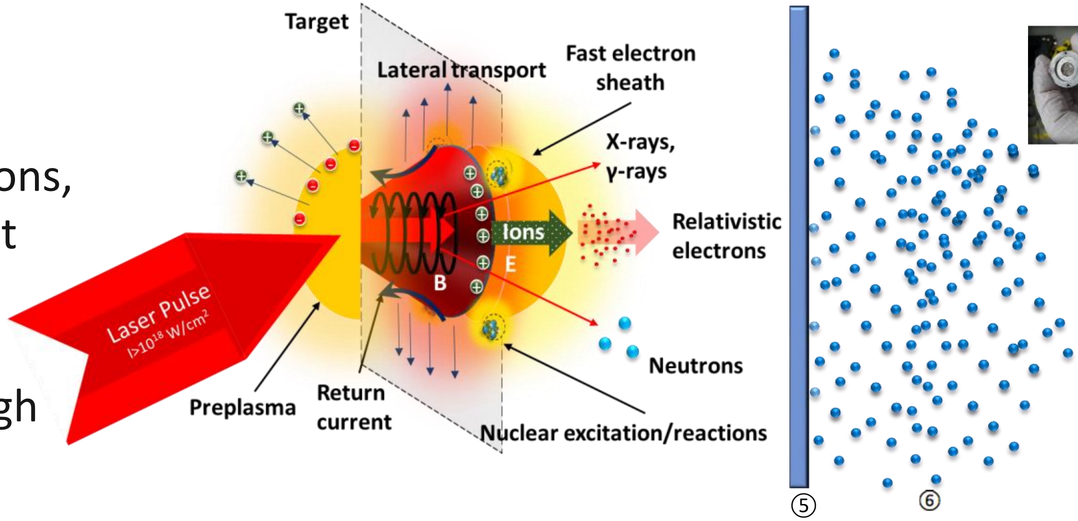
- IPNS (Argonne): 500MeV protons, U target, 12 μA (30 Hz), pulse width = 0.1μsec, flux = 1.5 x10^{15} n/sec, operating since **1981**.
- ISIS (Rutherford, UK): 800MeV protons, U target, 200 μA (50 Hz), pulse width = 0.27μsec, flux= 4 x 10^{16} n/sec, operating since **1984**.
- WNR/PSR LANSCE (Los Alamos): 800MeV protons, W target, 100 μA (12 Hz), pulse width =0.27μsec, flux = 1.5 x10^{16} n/sec, operating since **1986**.
- KENS (Tsukuba, Japan): 500MeV protons, U target,100 μA (12 Hz), pulse width = 0.07 μsec, flux = 3 x 10^{14} n/sec, operating since **1980**

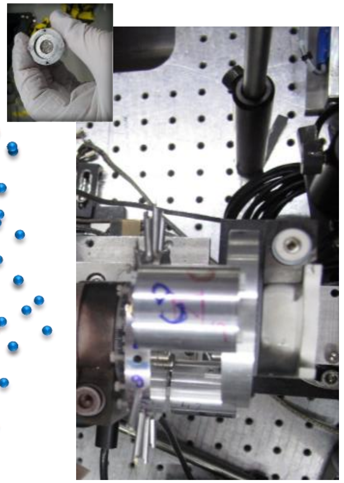
Production of Neutrons

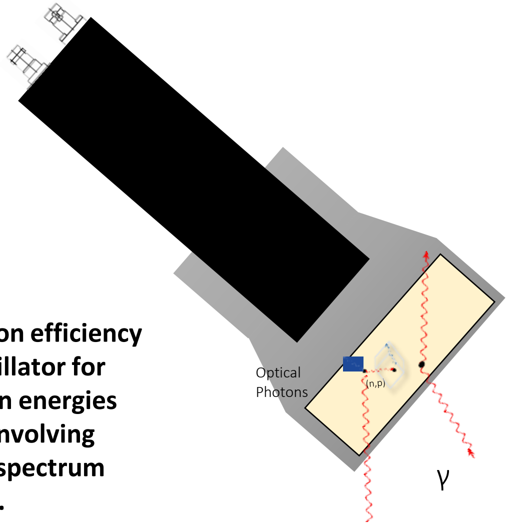
Introduction: Laser-driven Source

TNSA

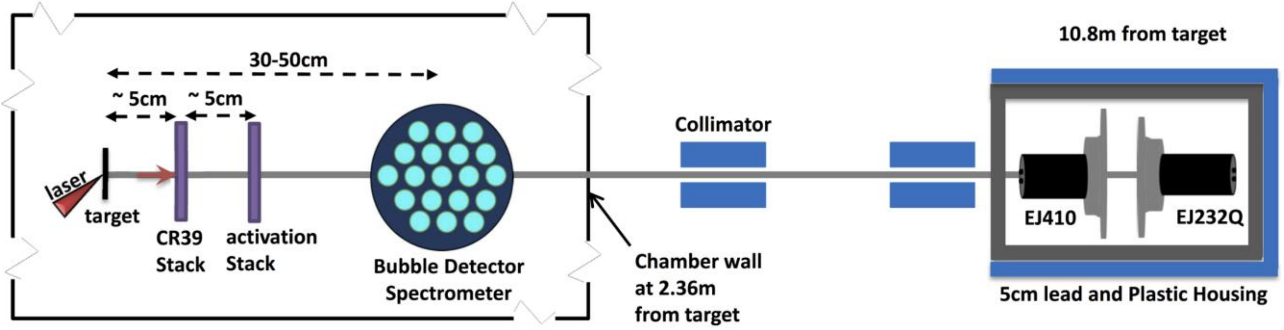
- Laser strikes a target (i.e. Au ~25µm),
- The laser pondermotive force pushes away the electrons,
- Conversion of laser radiation into kinetic energy of hot collisionless electrons,
- Giving rise to longitudinal electric field,
- Ions accelerated will be used to create neutron through nuclear fusion.







Neutron detection efficiency for EJ232Q scintillator for different neutron energies calculated by convolving recoiled proton spectrum and light output.



S. R. Mirfayzi, S.Kar, et al., Rev. of Sci. Inst. 86.7 (2015): 073308.

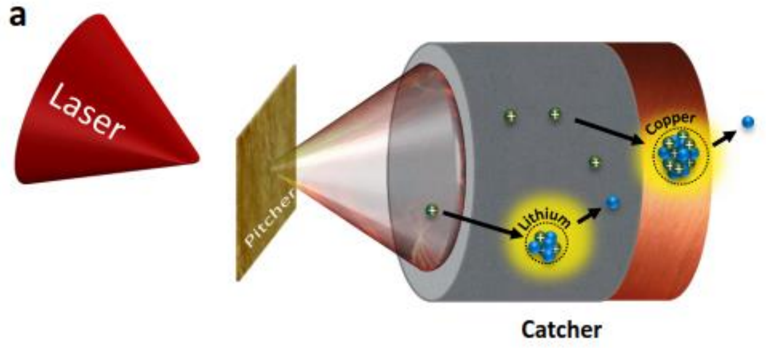
FAST NEUTRON

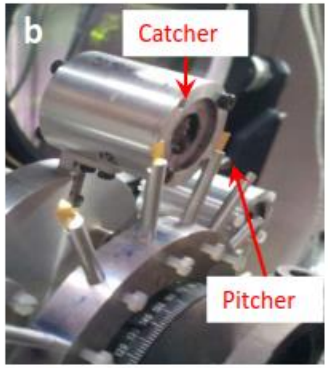
Production of Neutrons

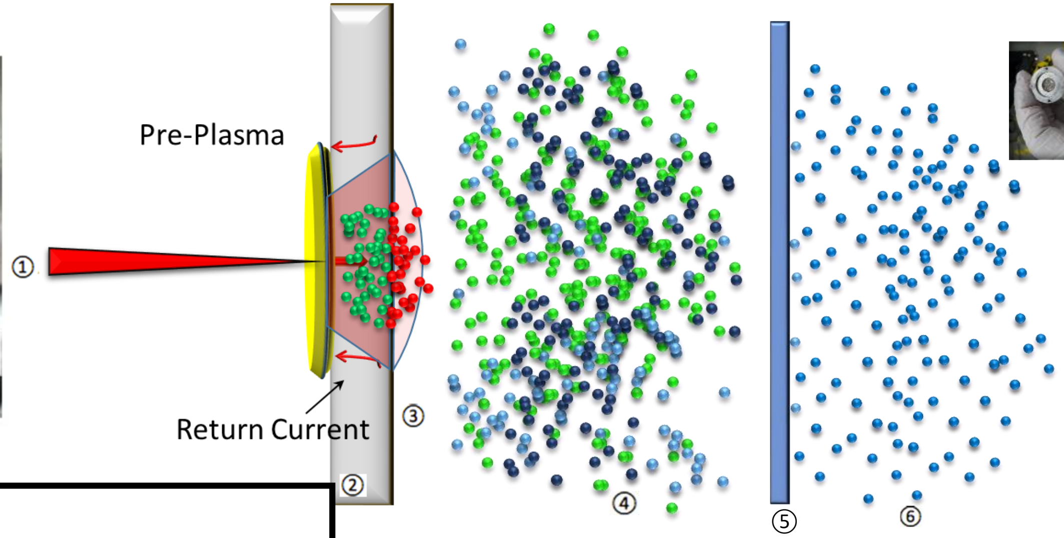
Laser-driven Source: Thick Targets

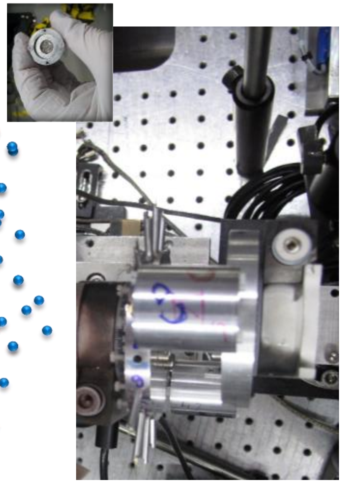
TNSA

C M Brenner, S R Mirfayzi, et. al. NPCF. 58.1 (2015): 014039.

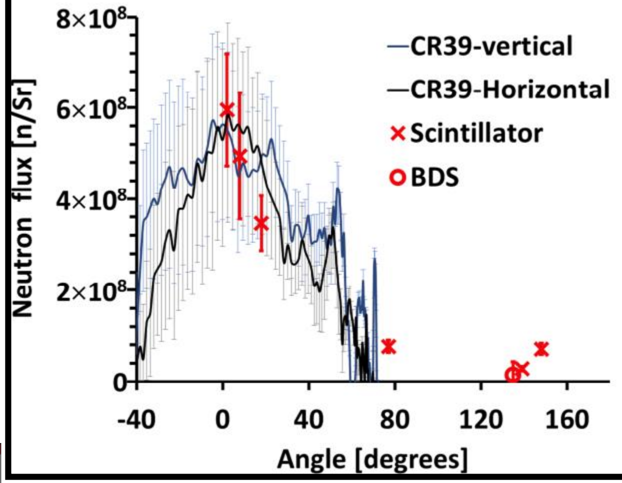


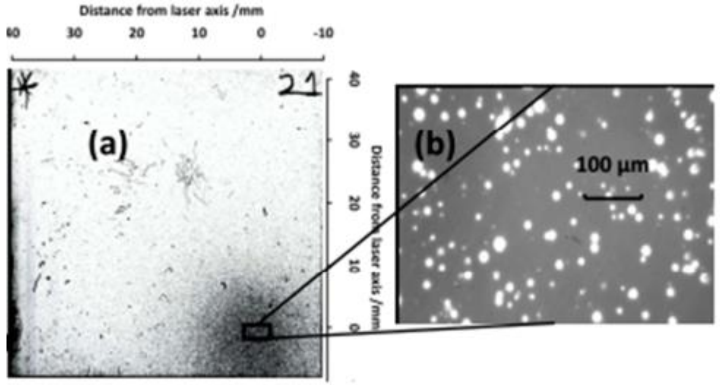




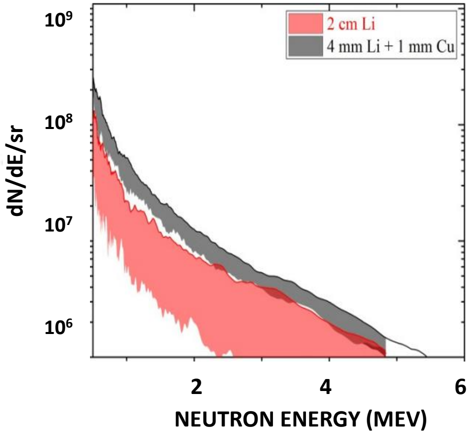


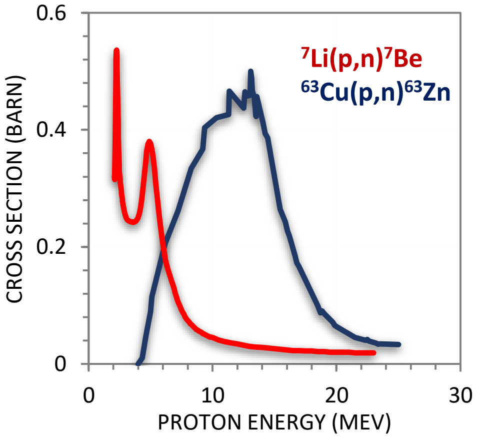
CD Target





S. Kar, et al. N.J.P. 18.5 (2016): 053002.

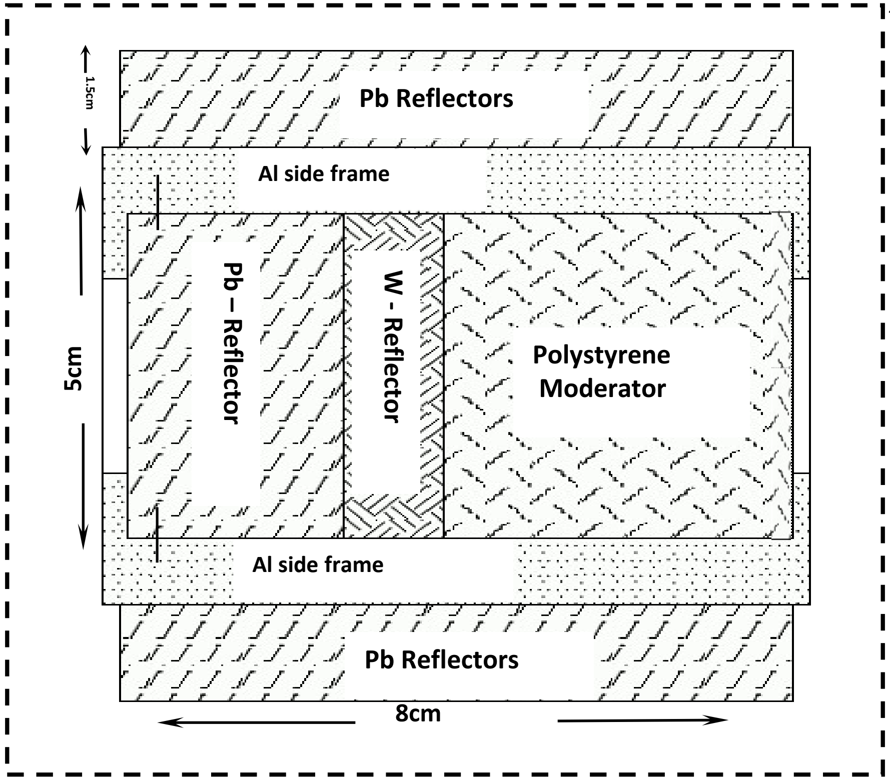




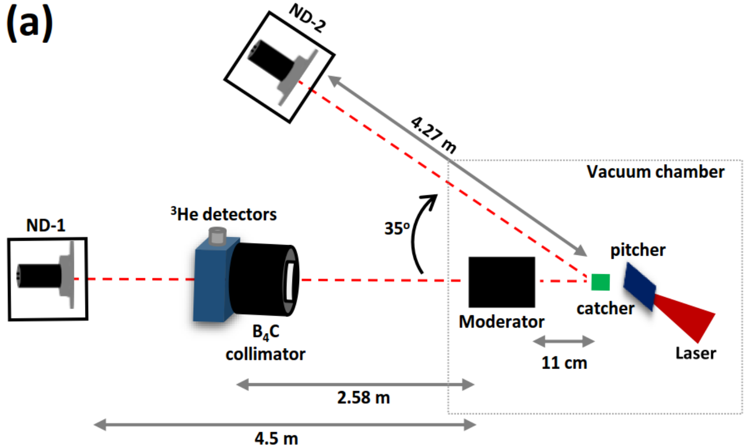
Epithermal Neutron Source

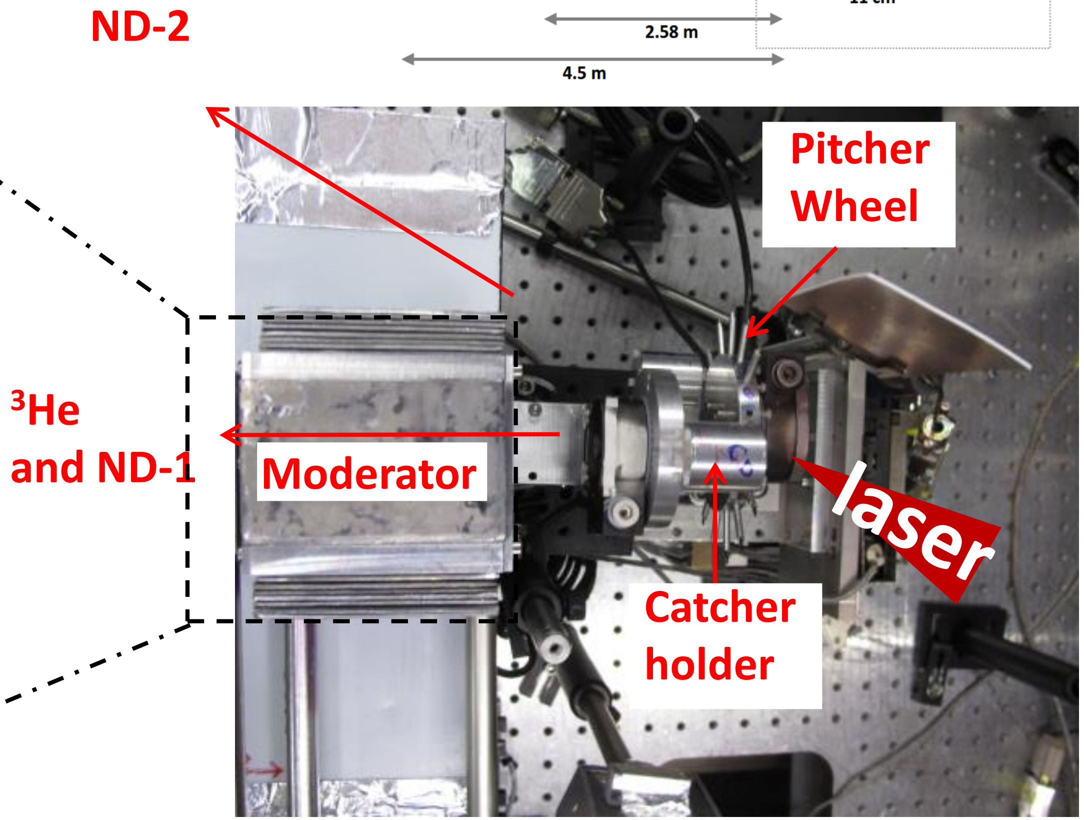
Low energy neutron source

- Neutron transport (Boltzmann equation) describes the change of neutron number density, flux density gradient, absorption in/out-scattering.



(a)

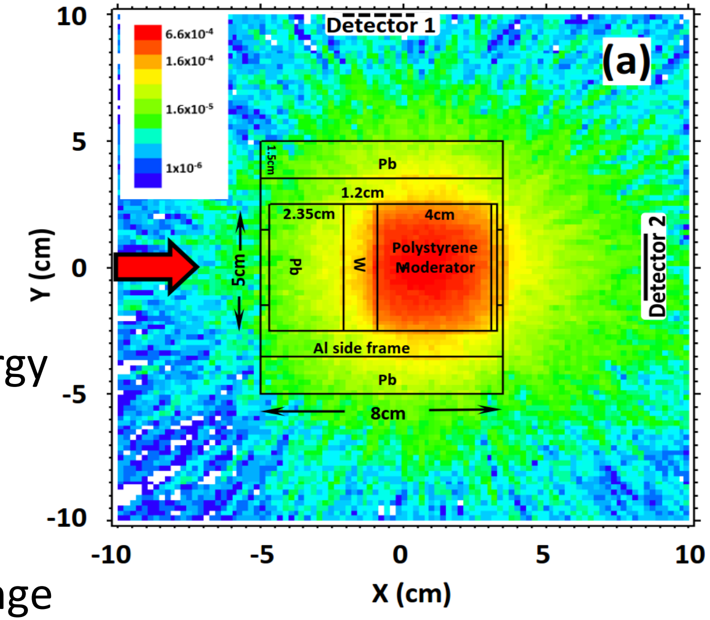




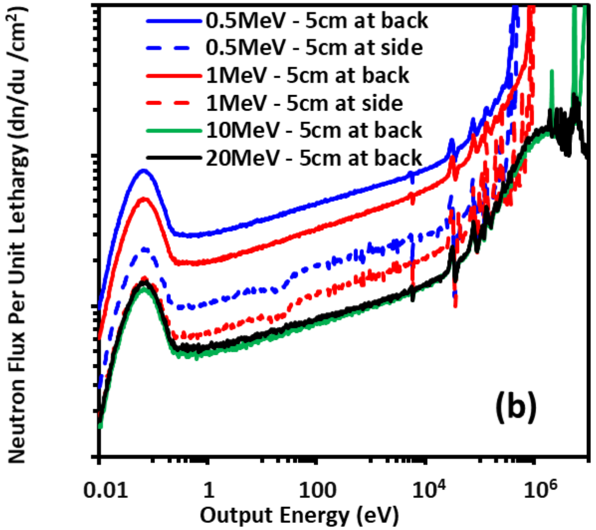
S. R. Mirfayzi, et al. "Experimental demonstration of a compact epithermal neutron source based on a high power laser." Applied Physics Letters 111.4 (2017): 044101.

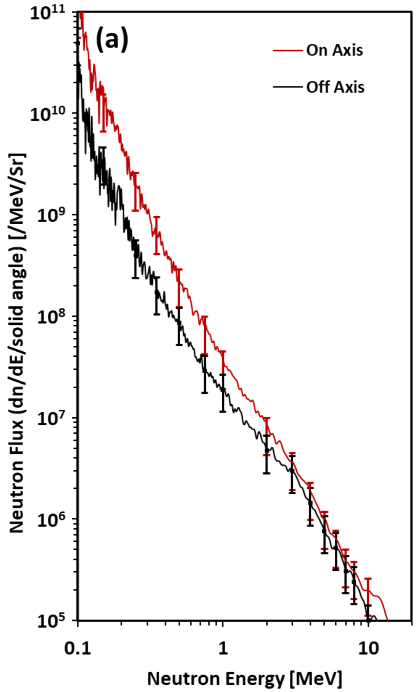
Epithermal Neutron Source

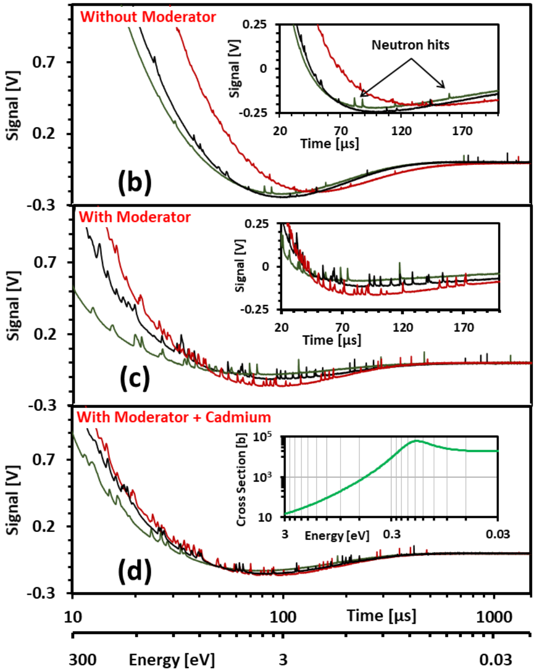
Low energy neutron source

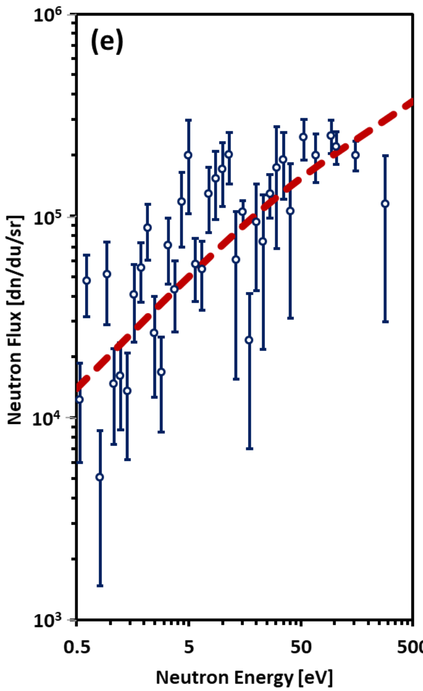


- Experiment performed with 750fs FWHM laser pulse of Vulcan petawatt with 50J energy delivered to the target.
- Moderated neutrons were detected using He-3 Proportional counters located at 2.8m away from the source.
- The background subtracted neutron flux produced by the moderator in the energy range of 0.5–300 eV was $(5.1 \pm 0.15)10^5$ n/sr/pulse.







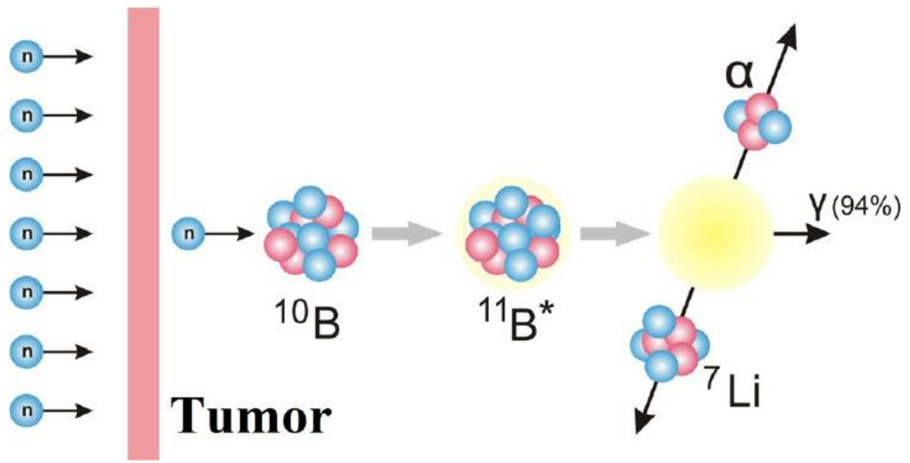


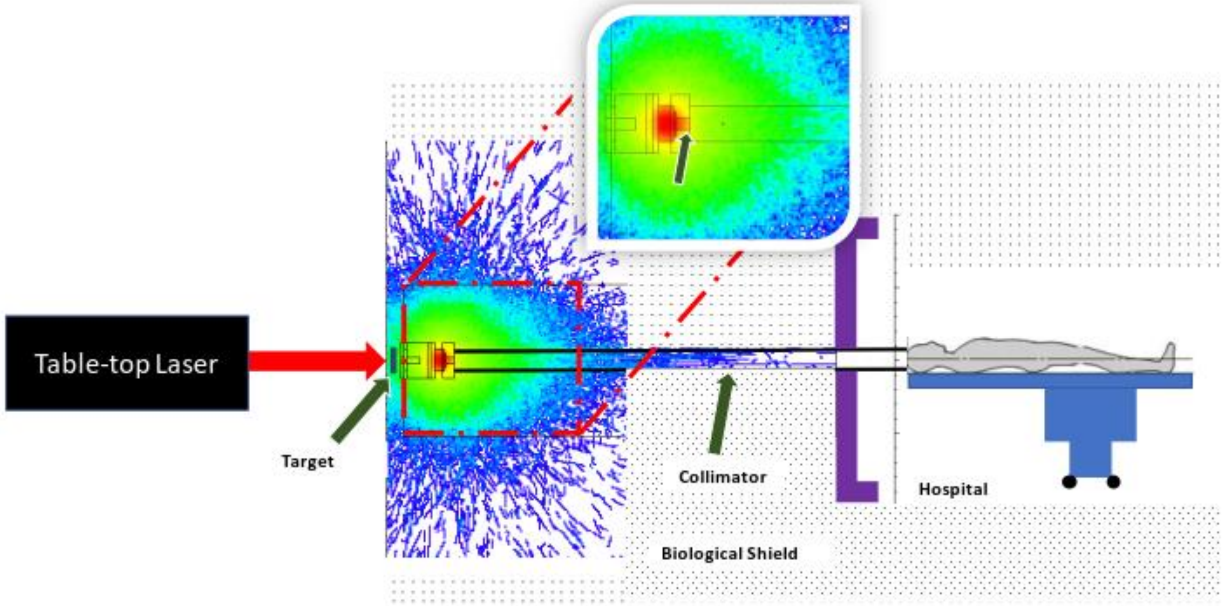
S. R. Mirfayzi, et al. "Experimental demonstration of a compact epithermal neutron source based on a high power laser." Applied Physics Letters 111.4 (2017): 044101.

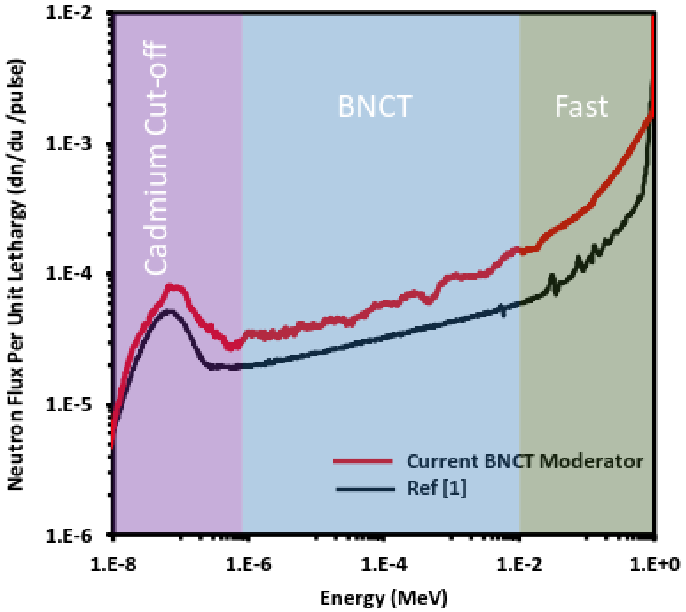
Epithermal Neutron Source

Application: BNCT

- Thermal Flux improved by nearly an order of magnitude, make it feasible for application studies such as:
    - ❑ Future BNCT, with unique beam shaping assembly (BSA)







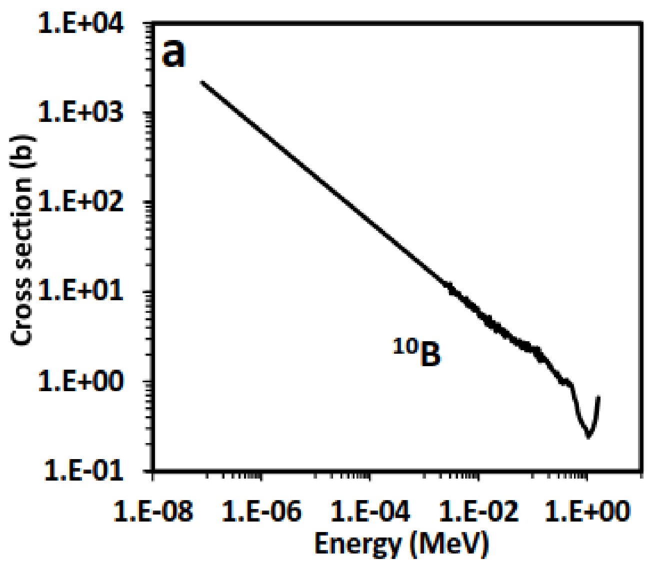
Epithermal Neutron Source

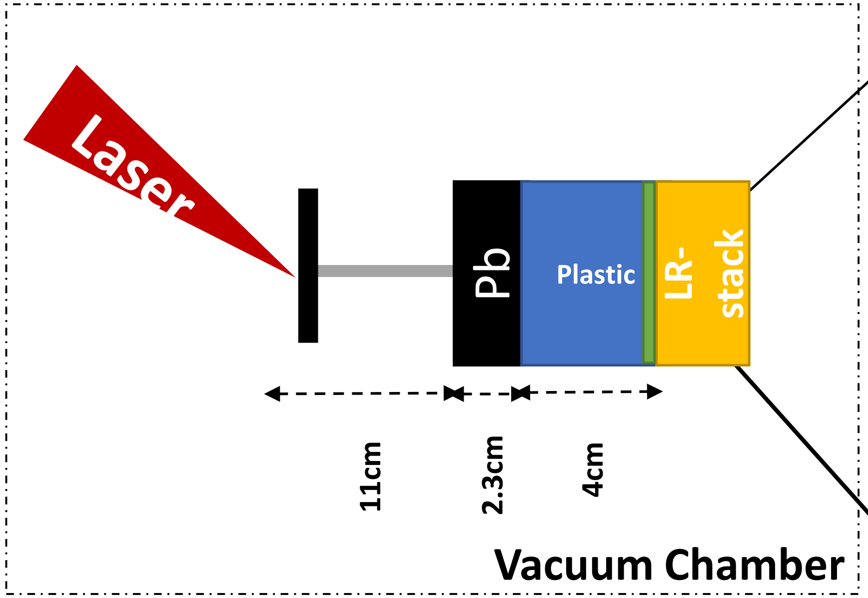
S. R. Mirfayzi, et al., JINST. 11.10 (2016): C10008.

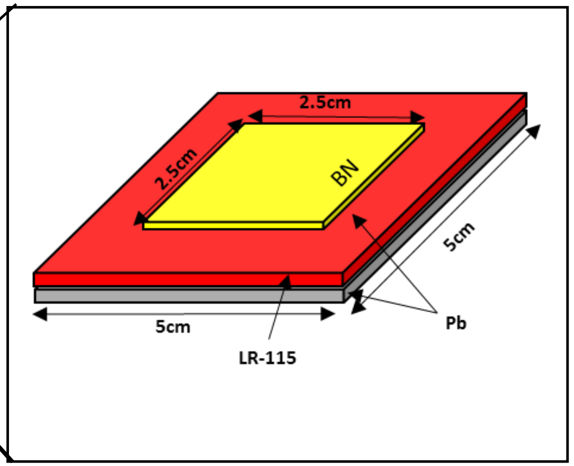
Application: Imaging

- The attached BN plate leads to generation of **alphas through (n,α) reaction** by the impinging epithermal neutrons,

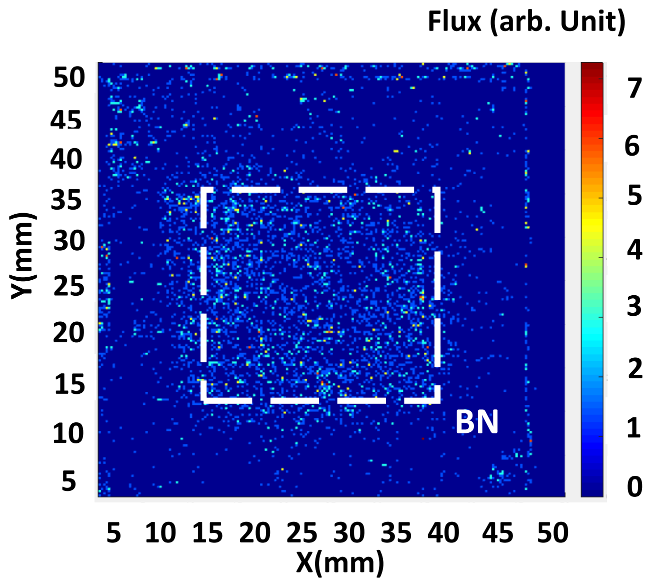
$$n + {}^{10}_{5}\mathrm{B} \rightarrow \begin{cases} {}^{7}_{3}\mathrm{Li}^{*}(0.83\ \mathrm{MeV}) + {}^{4}_{2}\mathrm{He}(1.47\ \mathrm{MeV})\ 93.7\% \\ {}^{7}_{3}\mathrm{Li}(0.01\ \mathrm{MeV}) + {}^{4}_{2}\mathrm{He}(1.77\ \mathrm{MeV})\ 6.3\% \end{cases}$$







Stack Configuration



Conclusion

- Laser-based sources are fast approaching a crucial stage in their development for neutron science and applications to complement large-scale facilities.
- The current flux is adequate for many applications such as eV neutron spectroscopy, activation, BNCT in a closely coupled beam line.
- Development in laser facilities around the glob such as ELI, can lead to higher neutron fluxes.
- The future of a laser-based approach would be reliant on the progress in diode-pumped technologies, such as the DiPOLE and HAPLS projects, aiming towards developing 10 Hz, Petawatt-class laser systems.

APPLIED PHYSICS LETTERS **111**, 044101 (2017)

Experimental demonstration of a compact epithermal neutron source based on a high power laser

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Epithermal neutrons from pulsed-spallation sources have revolutionised neutron science allowing scientists to acquire new insight into the structure and properties of matter. Here, we demonstrate that laser driven fast (~MeV) neutrons can be efficiently moderated to epithermal energies with intrinsically short burst durations. In a proof-of-principle experiment using a 100 TW laser, a significant epithermal neutron flux of the order of 10^5 n/sr/pulse in the energy range of 0.5–300 eV was measured, produced by a compact moderator deployed downstream of the laser-driven fast neutron source. The moderator used in the campaign was specifically designed, by the help of MCNPX simulations, for an efficient and directional moderation of the fast neutron spectrum produced by a laser driven source. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4994161]