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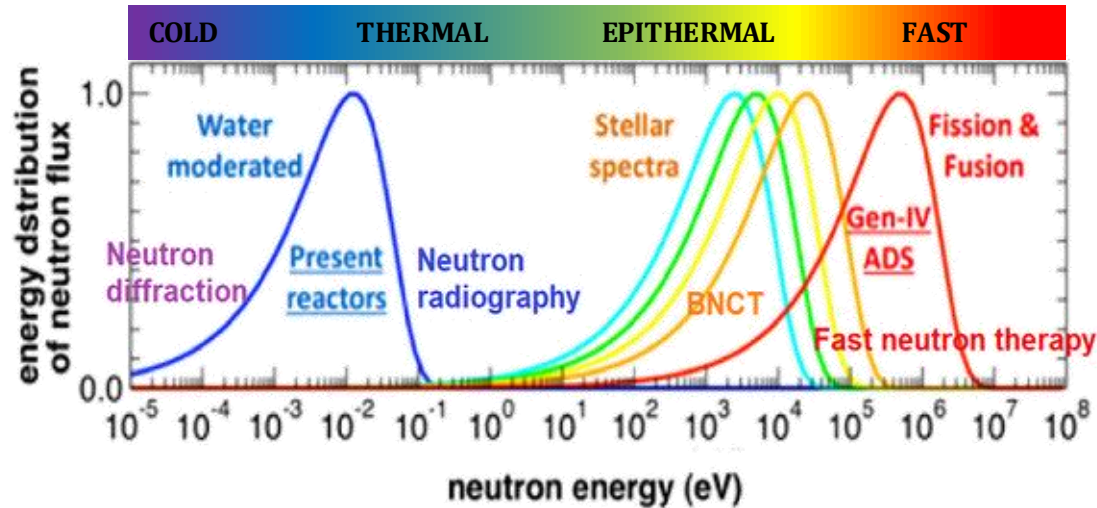
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25 → 1999
2024

Laser-Plasma Applications II: Experiments on neutron generation

Aarón Alejo

Why neutrons?



“ There is a general belief in the life sciences community that neutron methods are an emerging technique and not exploited to their full capacity. This is partly due to the fact that useful neutron beams can only be generated at advanced research reactors and/or high energy neutron spallation sources. ”

- IAEA-TECDOC-1439, Development opportunities for small scale accelerator driven neutron sources, Report of a technical meeting, Vienna, 18-21 May 2004

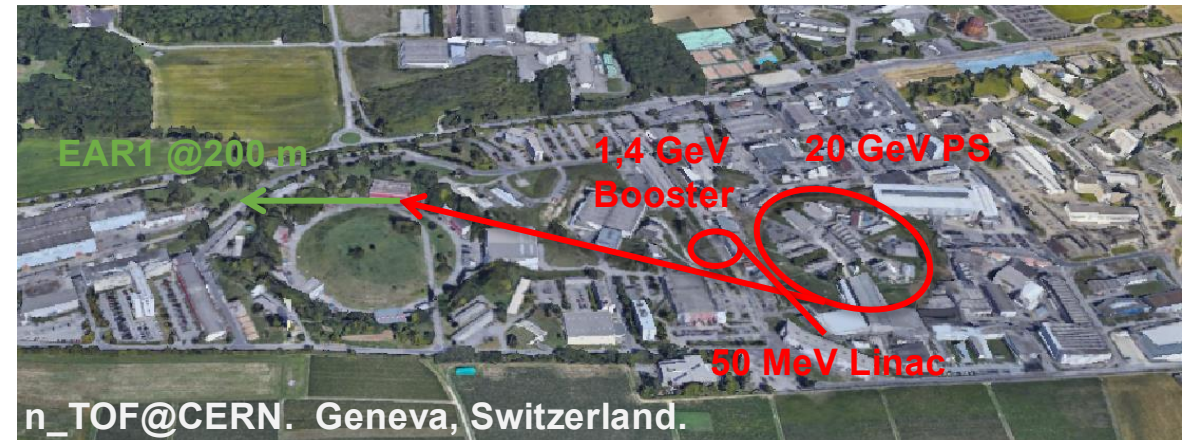
Huge size and complexity of high intensity neutron sources (spallation).

Progressive shut down of research reactors.



Restricted transfer of knowledge outside a research center.

Not exploited to their full capacity.



Applications of neutrons



Materials Science & NDT

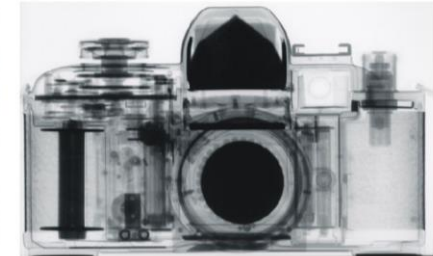
Deep penetration in dense metals with high spatial resolution.

- Stress/strain mapping in engineering alloys.
- Non-destructive testing of critical components.

Neutron radiography

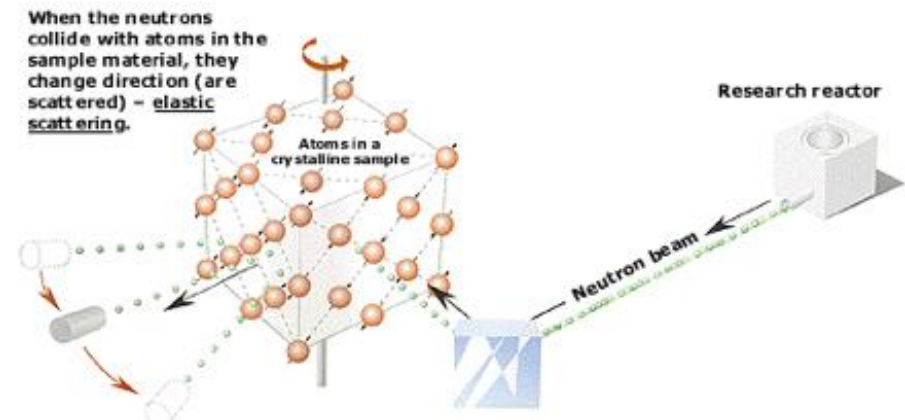


X-ray



Neutrons

Neutron diffraction



Applications of neutrons



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Materials Science & NDT

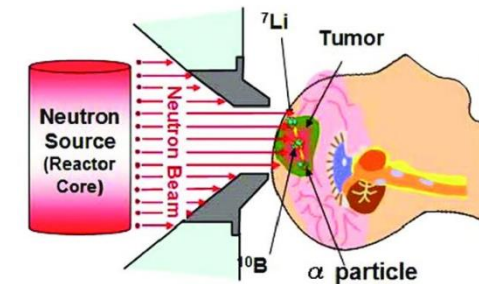
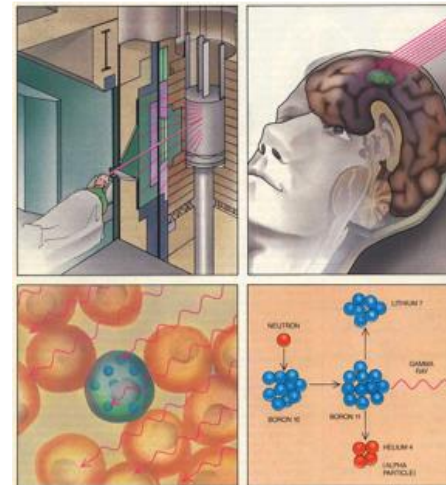
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Nuclear Medicine (BNCT)

Boron Neutron Capture Therapy ($^{10}\text{B}(n,\alpha)^7\text{Li}$).

- High-LET localized cancer therapy.
- Requires epithermal neutron flux (1 eV - 10 keV).



Applications of neutrons



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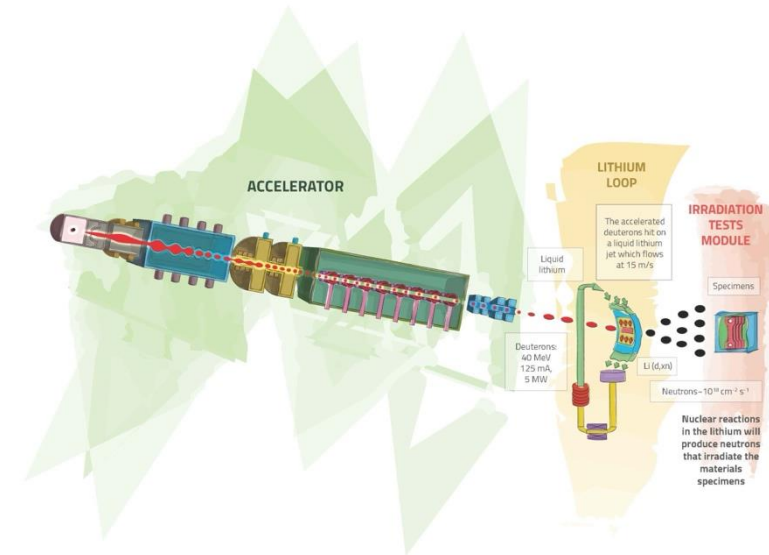
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Energy & Fusion Research

Diagnosing High Energy Density (HED) plasmas.

- First-wall material radiation damage testing.
- Time-resolved neutron time-of-flight (nToF).



Applications of neutrons



Materials Science & NDT

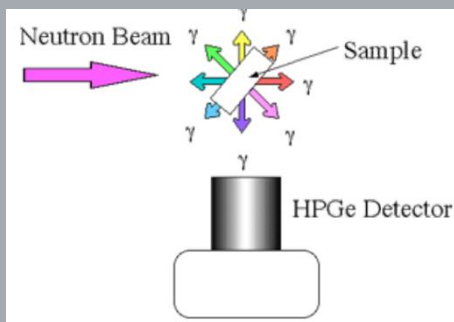
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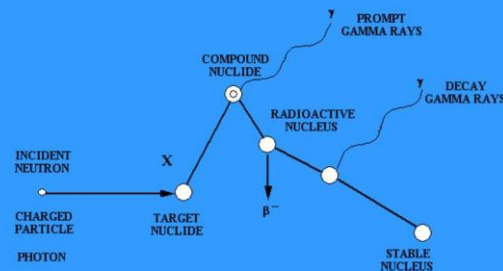
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Principle of activation analysis



Elemental – multi-elemental – trace elemental analysis

Security & Archeometry

Isotopic identification & element-specific imaging.

- High-contrast hydrogen detection in dense cargo.
- Non-invasive analysis of cultural heritage objects.

Applications of neutrons



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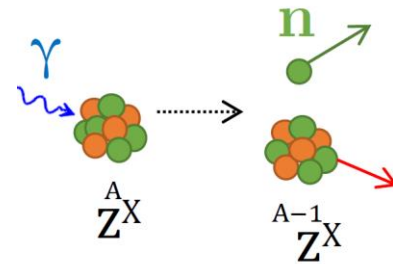
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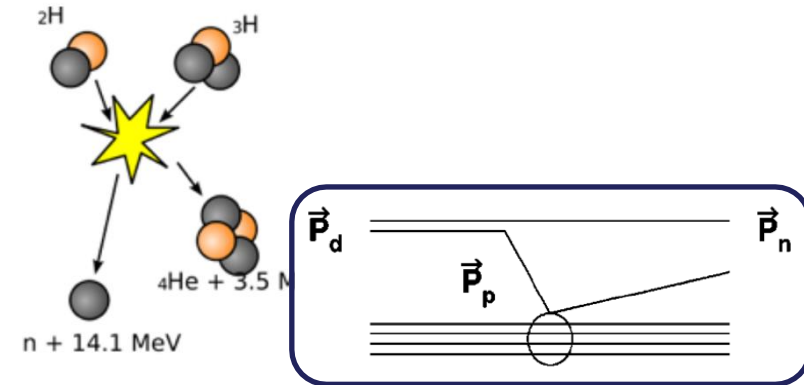
Neutron generation



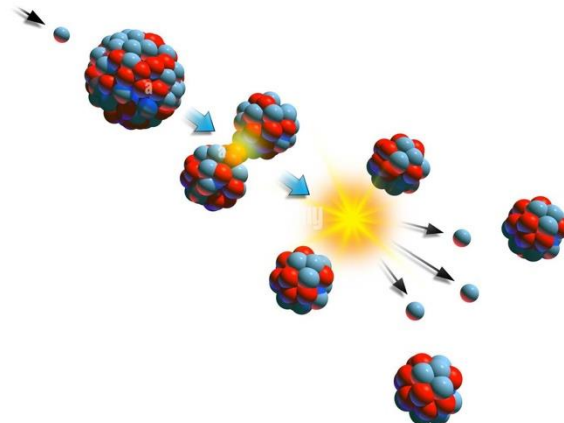
Photoneutrons



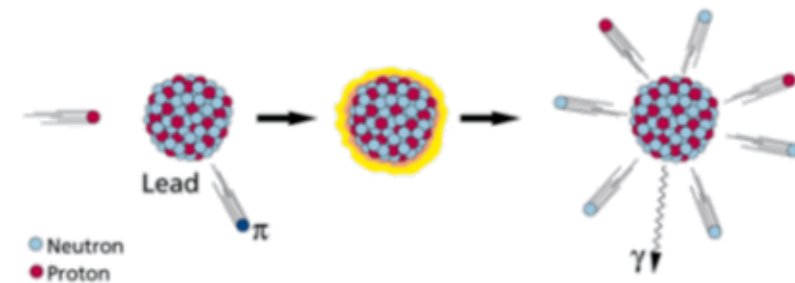
Fusion



Fission



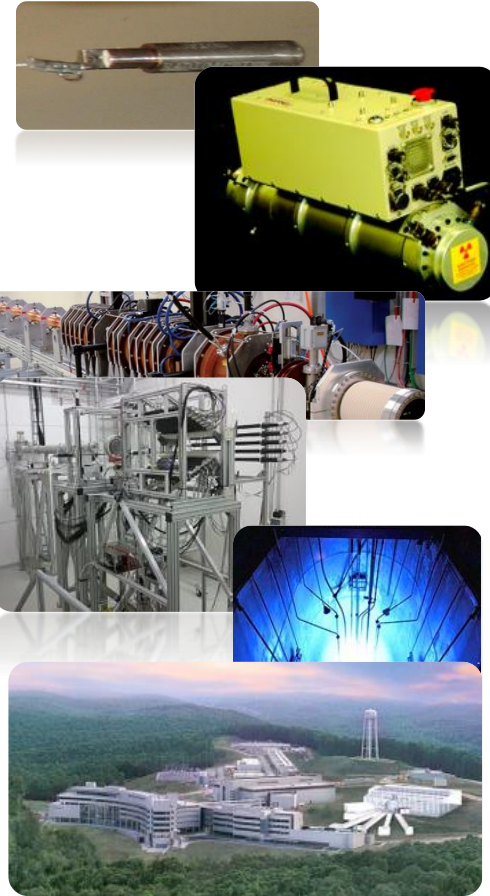
Spallation



Conventional neutron sources



Neutron Source Type	Mechanism	Temporal Structure	Peak Brightness ($n/(s \cdot cm^2 \cdot sr)$ or flux)	Footprint	Cost
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Conventional neutron sources

Neutron Source Type	Mechanism	Temporal Structure	Peak Brightness (n/(s·cm ² ·sr) or flux)	Footprint	Cost
Spontaneous Fission Isotopes (e.g., ²⁵² Cf)	Radioisotope decay / spontaneous fission	Continuous (CW)	Low (~ 10 ⁵ – 10 ⁷)	Handheld / Portable (< 1 m ²)	Very Low (< \$100k)
Sealed Fusion Neutron Sources (DT / DD Generators)	Electrostatic / RF ion beam colliding with target ($D + D$ or $D + T$)	Continuous (CW) or Pulsed (μs – ms)	Low to Moderate (~ 10 ⁶ – 10 ⁹)	Benchtop / Portable (1 – 5 m ²)	Low (\$50k – \$500k)
Light Ion Accelerators (Cyclotrons / Electrostatic)	Low-energy p^+ or d^+ on low- Z targets ($p - ^7\text{Li}$, $d - ^9\text{Be}$)	Continuous (CW) or High Rep-Rate Pulsed	Moderate (~ 10 ¹⁰ – 10 ¹³)	Room-scale (20 – 100 m ²)	Moderate (\$5M – \$15M)
LINAC-based Photofission	High-energy electron LINAC → Bremsstrahlung γ-rays → (γ, n) or (γ, f)	Pulsed (μs – ns)	Moderate to High (~ 10 ¹² – 10 ¹⁵)	Facility-scale / Building (100 – 500 m ²)	Moderate to High (\$10M – \$40M)
Fission Reactors (Research Reactors)	Sustained nuclear fission chain reaction (²³⁵ U)	Continuous (CW)	High (~ 10 ¹⁴ – 10 ¹⁵)	Large Facility (> 1,000 m ²)	High to Very High (\$100M – \$500M +)
Spallation Sources (High- Energy Heavy Accelerator)	GeV-scale p^+ beam on heavy metallic target (Ta, W, Hg)	Pulsed (μs – ms)	Very High (~ 10 ¹⁵ – 10 ¹⁷)	Large-Scale National Lab (> 10,000 m ²)	Extremely High (> \$1B)

Laser-driven neutron sources do not aim to replace steady-state high-average-flux reactors, but to offer a compact alternative with extreme peak brightness, sub-nanosecond resolution at a reduced cost





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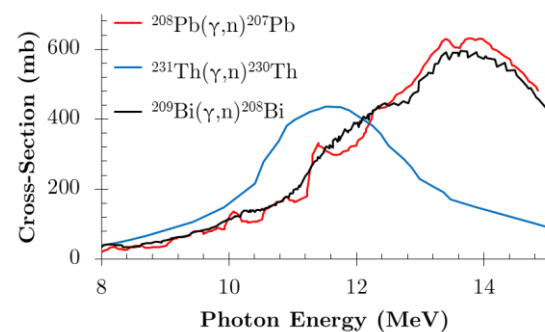
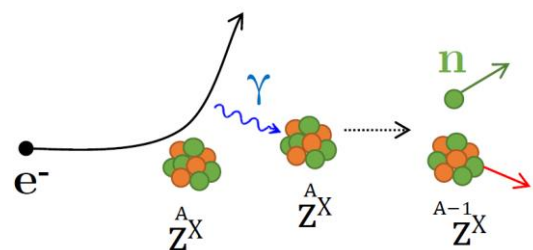
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Laser-driven neutron sources

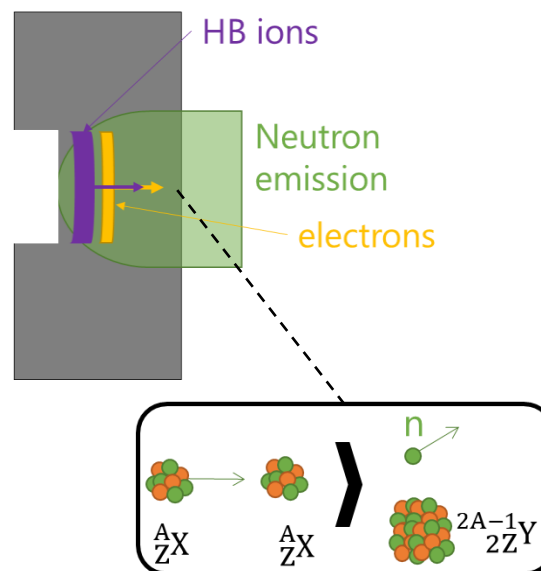
Routes to neutron sources

Indirect photoneutron generation



→ I. Pomerantz *et al.*, Phys. Rev. Lett., 113 (2014)

In-target

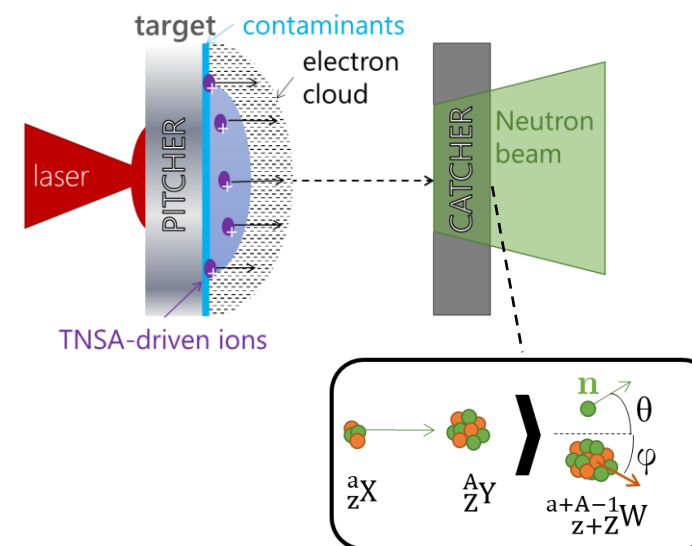


→ P. Norreys *et al.*, P.P.C.F. 40, 175 (1998)

→ S. Kar *et al.*, New J. Phys., 18 (2016)

→ A. Alejo *et al.*, Phys. Rev. Lett., 129(11) (2022)

Pitcher-catcher



→ M. Roth *et al.*, Phys. Rev. Lett, 110 (2013)

→ S. Kar *et al.*, New J. Phys., 18 (2016)

→ A. Alejo *et al.*, PPCF 59 (2017)

→ M.M. Millán *et al.*, Nat. Comms., 17 (2026)

LD-neutron sources



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Photo-neutrons

In-target

Pitcher-Catcher

LD-neutron sources



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Photo-neutrons

In-target

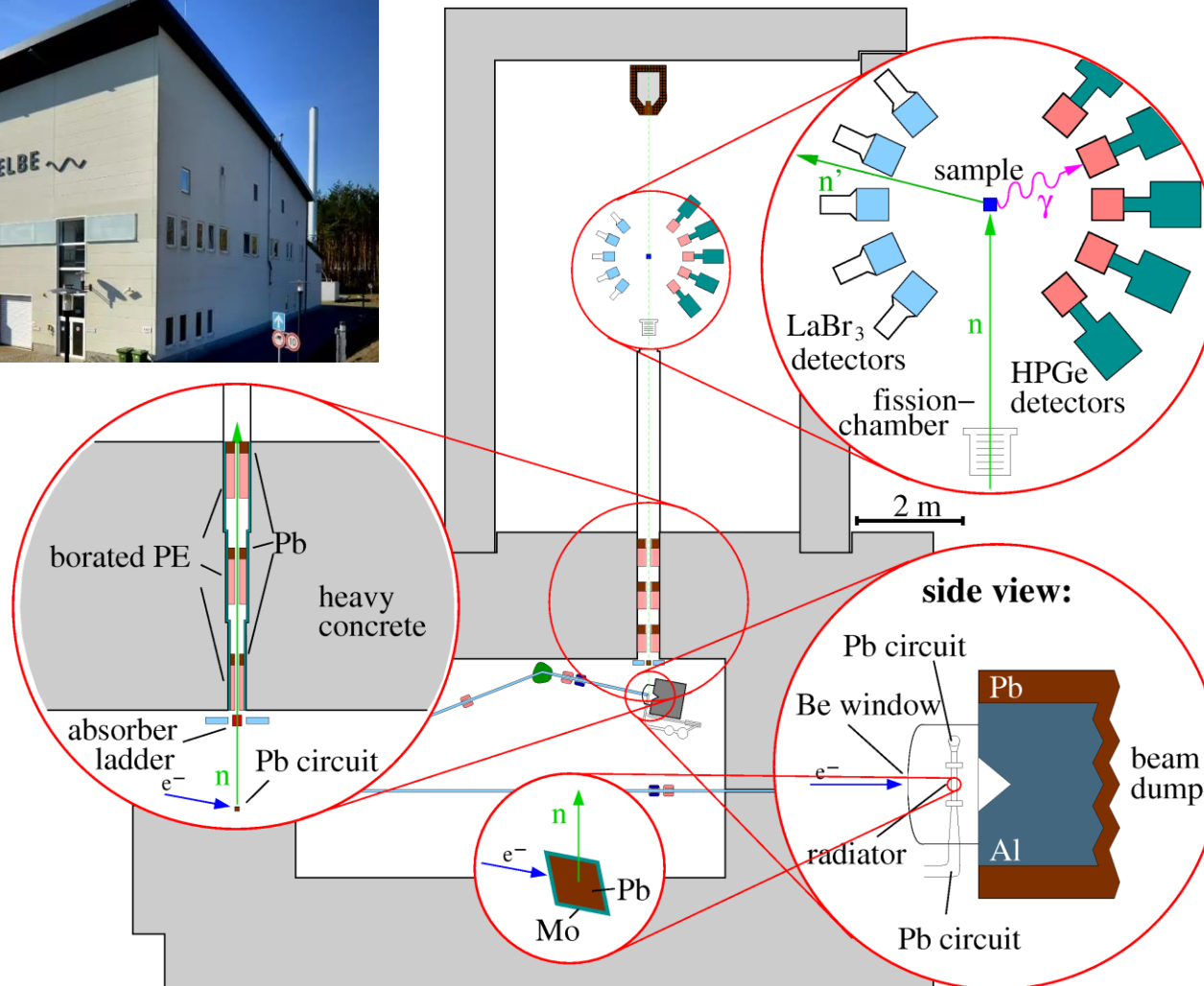
Pitcher-Catcher

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Photo-neutrons

In-target

Pitcher-Catcher



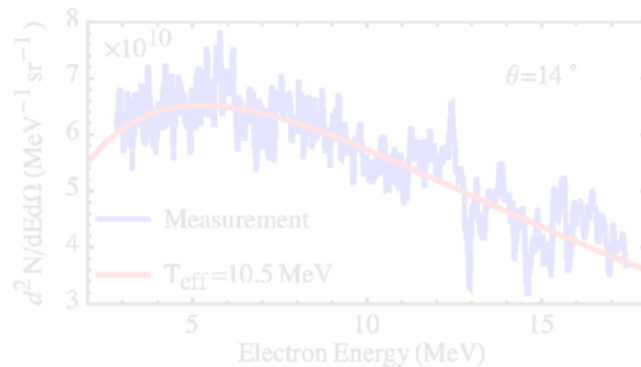
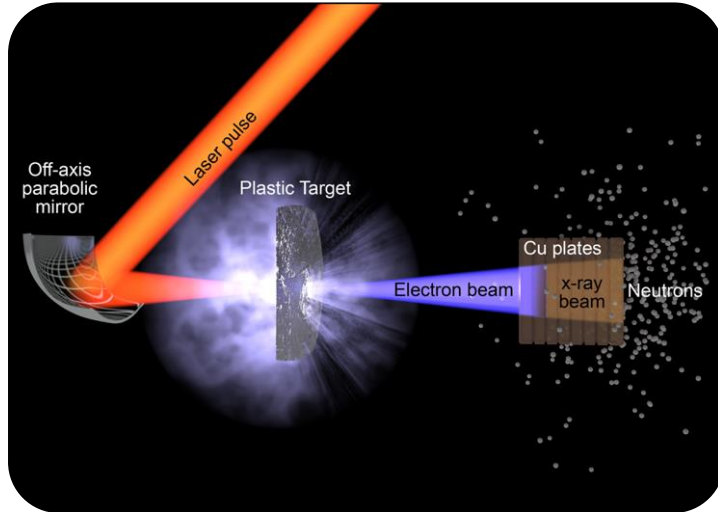
nELBE

HZDR

HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

LD-neutron sources

Photo-neutrons



In-target

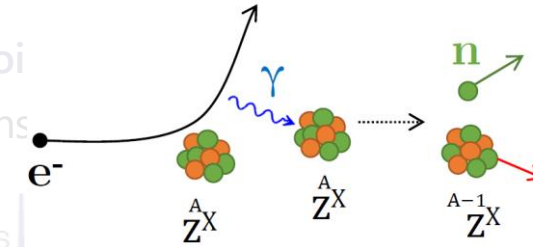
Electron acceleration from exploding foil

→ A low energy pre-pulse arrives ~100ns

□ Turns the ta

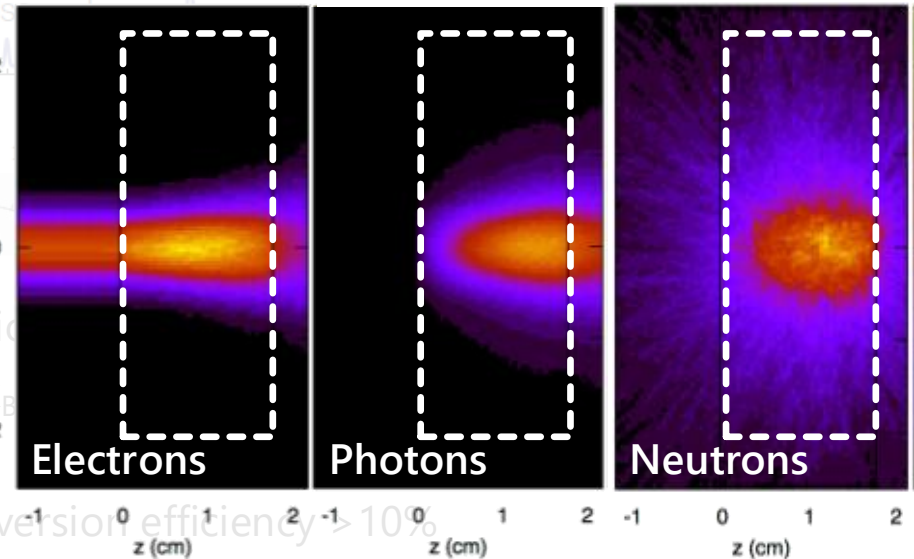
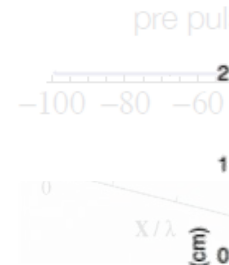
□ The main p
a jet of relat

main pulse
~100 J / 100 fs



MonteCarlo Simulations (FLUKA)

Laser pulse



→ Maxwellian energy distribution

→ Electron temperature $k_B T_{eff}$

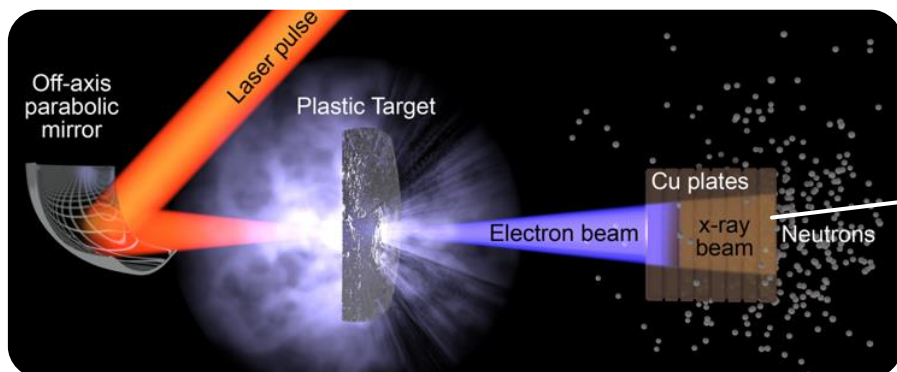
→ Large electron flux

→ Laser-to-electrons conversion efficiency > 10%

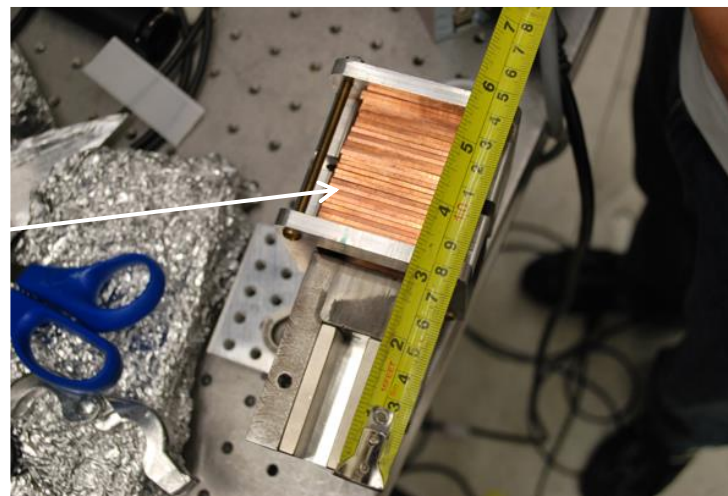
LD-neutron sources



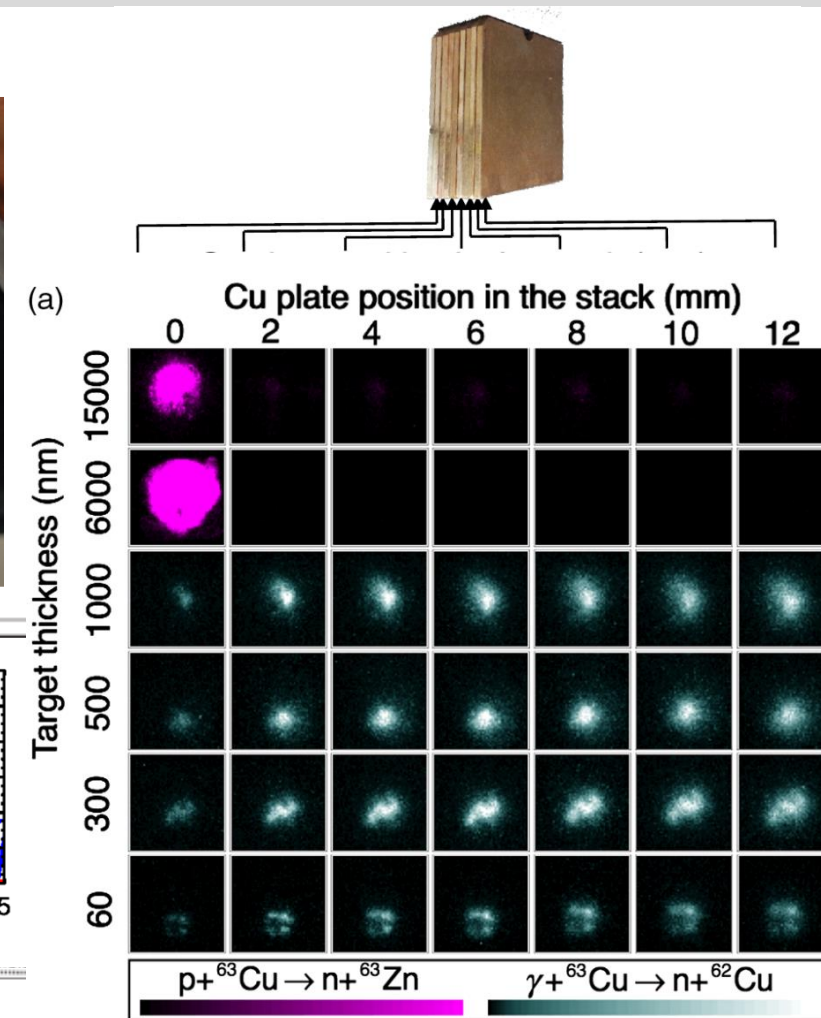
Photo-neutrons



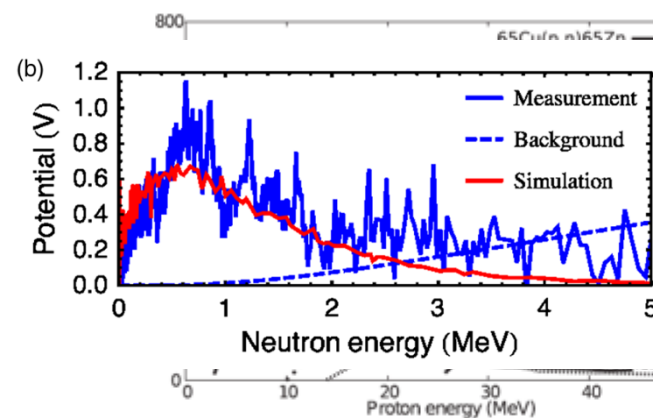
In-target



Pitcher-Catcher



- Copper plates used as converter
 - 2mm thickness
 - Natural Cu: ${}^{63}\text{Cu}$ (31%), ${}^{65}\text{Cu}$ (69%)
- Activation signal can be due to different sources (X-ray, proton, neutron)
 - Sources can be distinguished depending on the decay rates



LD-neutron sources



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Photo-neutrons

In-target

Pitcher-Catcher

LD-neutron sources



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Photo-neutrons

In-target

Pitcher-Catcher

LD-neutron sources



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Photo-neutrons

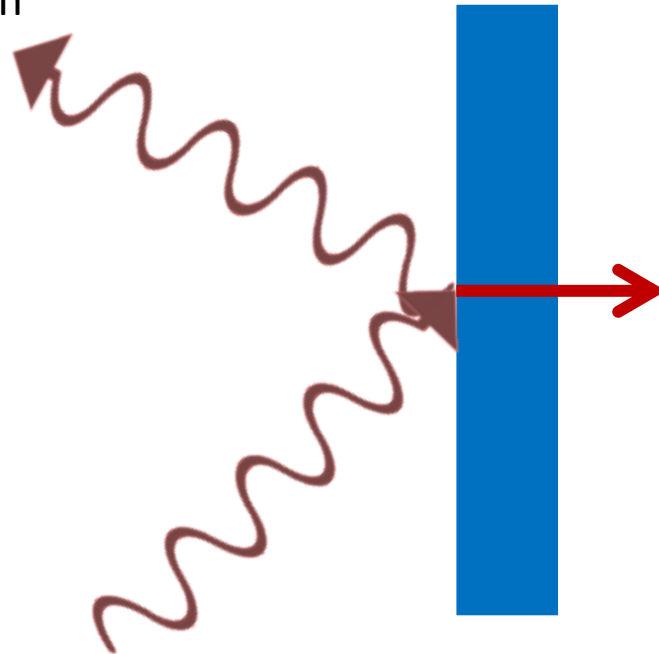
In-target

Pitcher-Catcher

Hole-boring RPA

Reflected photon

Incident photon



$$\text{Pressure} = dF/dS \sim (\Delta p/\Delta t)/A$$

$$P \sim (2R + A) I/c$$

LD-neutron sources



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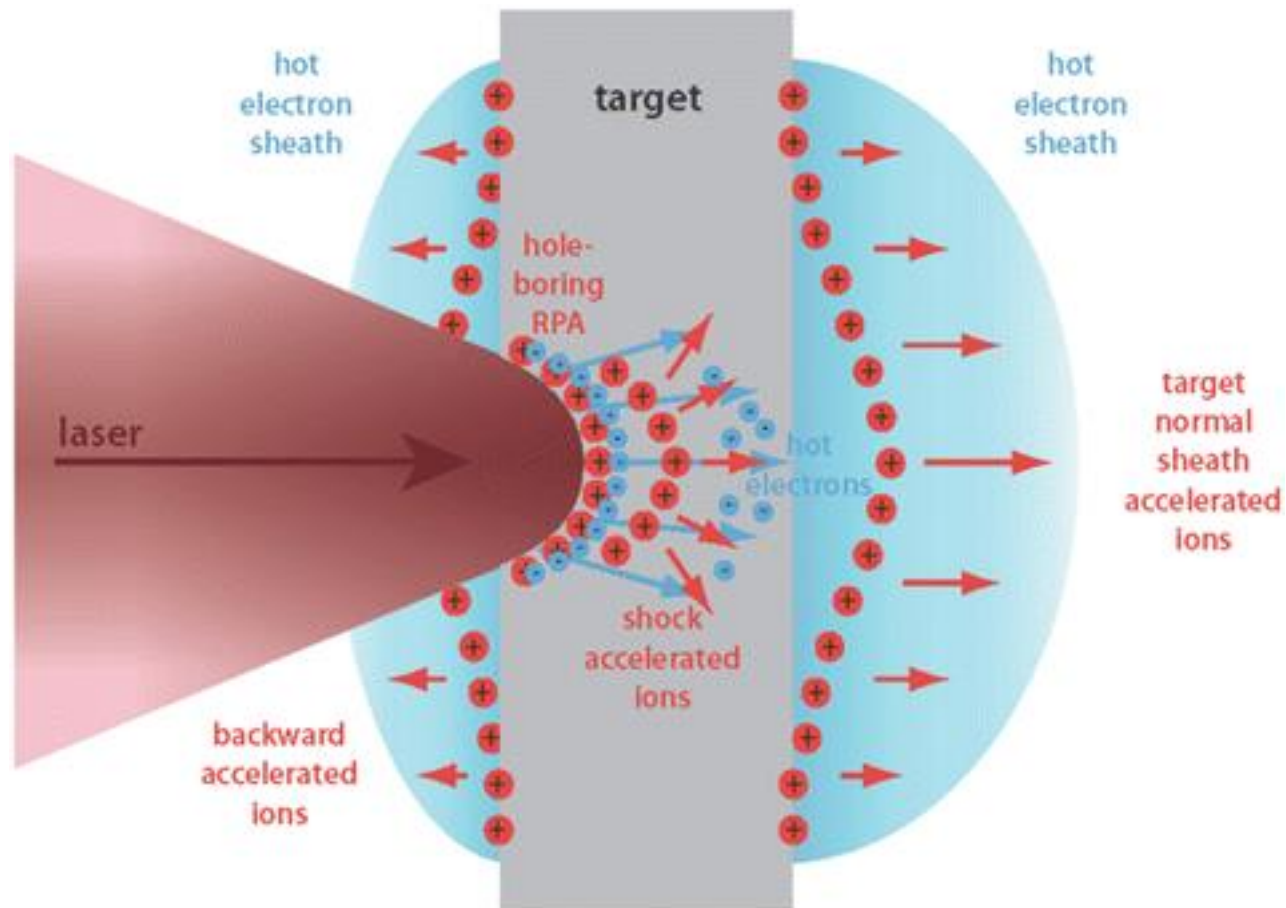
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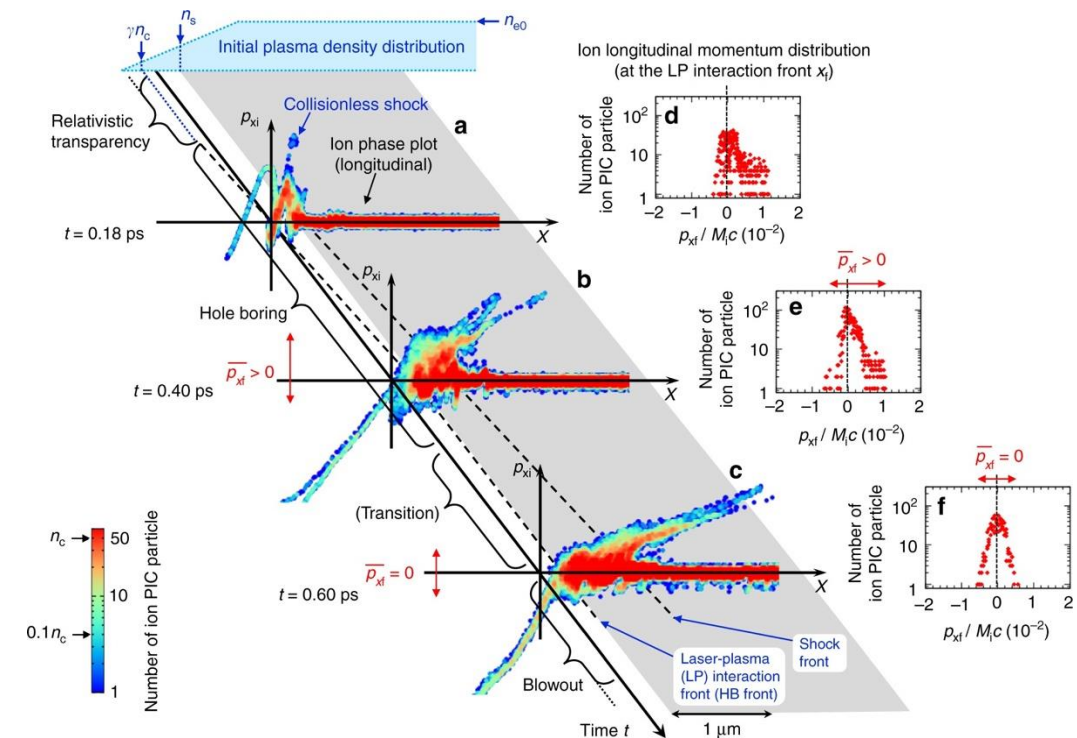
Photo-neutrons

In-target

Pitcher-Catcher



Hole-boring RPA



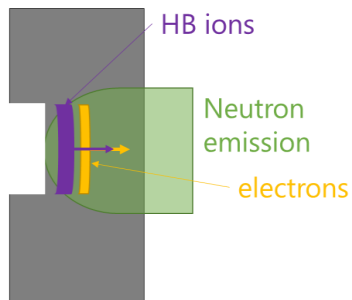
LD-neutron sources



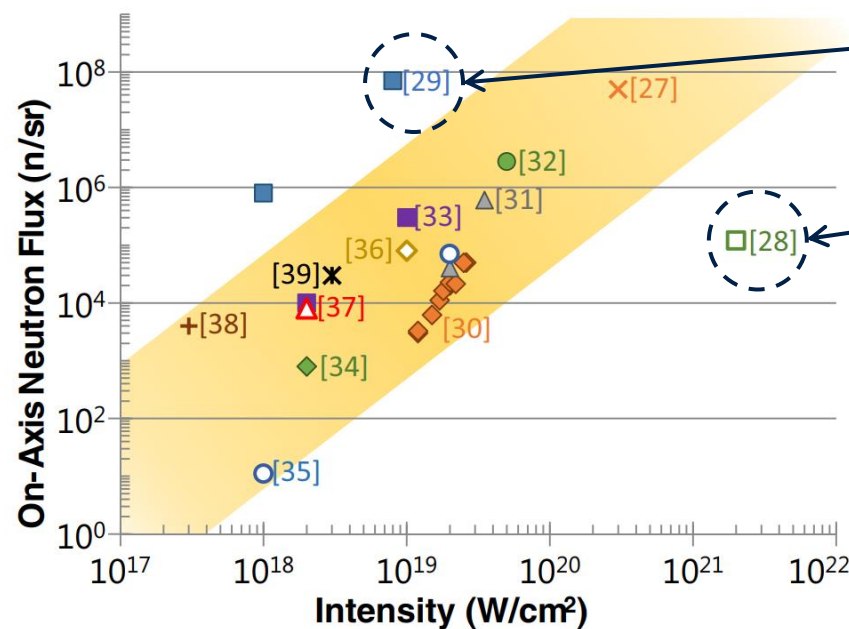
Photo-neutrons

In-target

Pitcher-Catcher



- The nuclear reactions are restricted by the target material
 - Most commonly, $d(d,n)He$ reaction using deuterated targets
 - Due to the reaction kinematics, emission is very divergent



Higher target density

(also first-ever neutron experiment!
Norreys et al., 1998)

Shorter laser pulse

Fairly promising scaling (rather slow)
Compared to other schemes, 2 orders of
magnitude lower flux

LD-neutron sources



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Photo-neutrons

In-target

Pitcher-Catcher

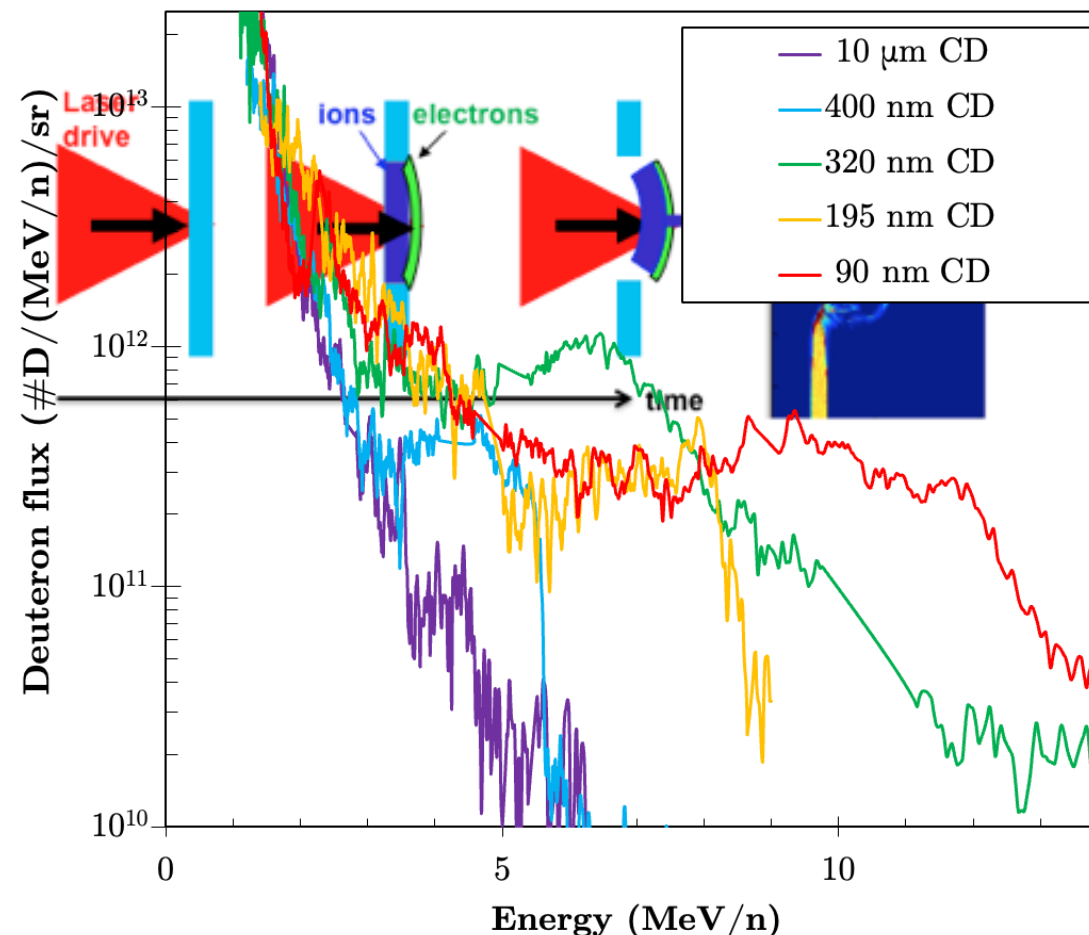
Light Sail

Acceleration mechanism based on the Radiation Pressure exerted by the laser reflected off an overdense plasma

- Quasi-monoenergetic spectrum
- Faster scaling with laser intensity
- Acceleration of bulk-target ions
- Can we generate neutrons if target contains D?

The energy and shape of the spectral peaks, under same laser conditions, varies depending on the thickness.

- Microns.** Exponential shape, typical of TNSA mechanism
- >300nm.** Spectral features appear at high energies, with central energy increasing as thickness decreases.
- <300nm.** Although peak energy continues to grow, the bunch shape turns into a *plateau* (→ Indicates transparency)



[Alejo *et al.*, Phys Rev Lett 129(11), 114801 (2022)]

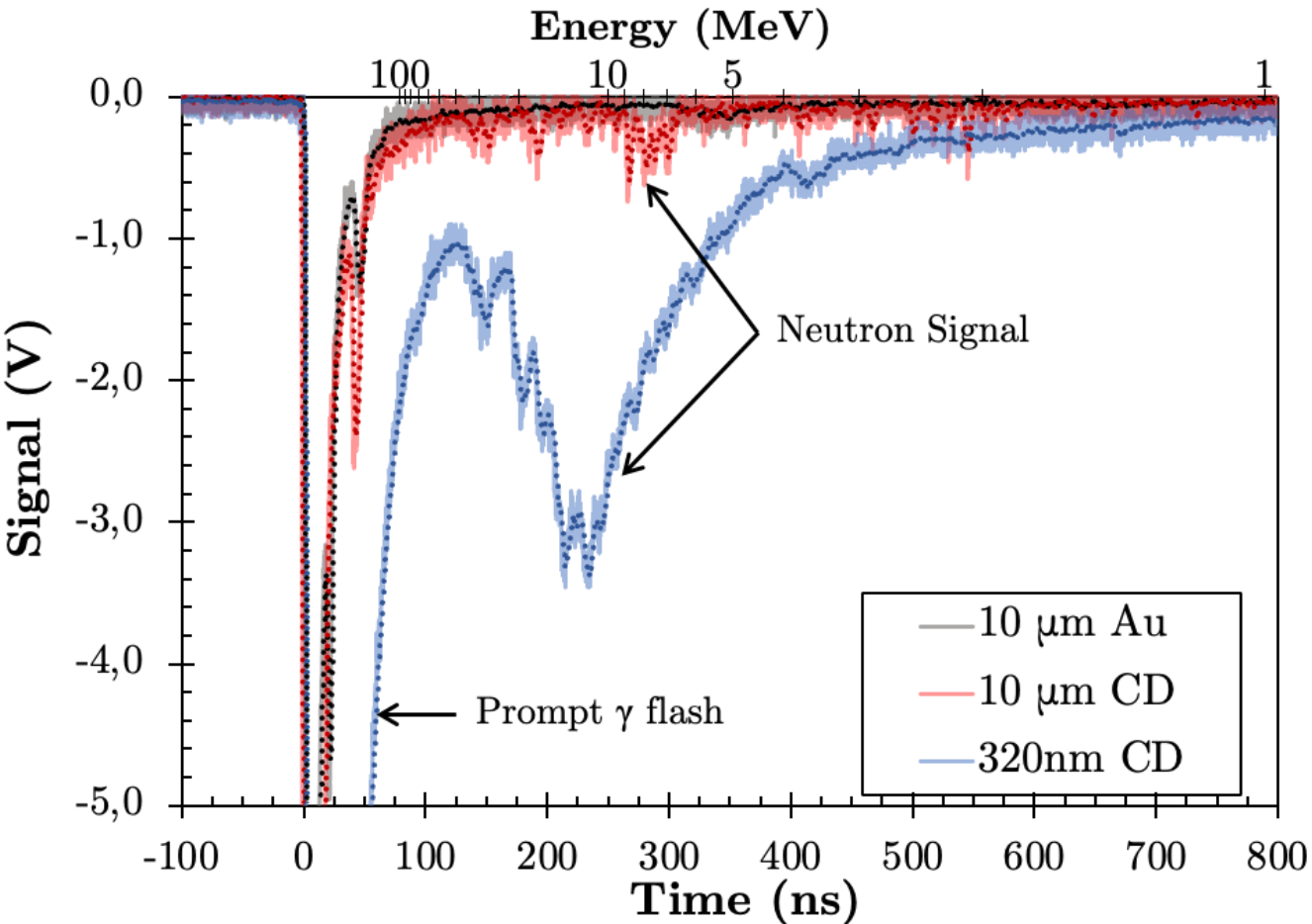
LD-neutron sources



Photo-neutrons

In-target

Pitcher-Catcher



$$Y_n \simeq \frac{\tau_{burn}}{2} \int n_d^2 \langle \sigma v \rangle dV,$$

~ (fusion burn time) × (deuteron density)² × (fusion reactivity) × (volume)

TNSA

- Low density of co-moving ions (exponential acceleration)
- Neutrons rather generated either due to HB or plasma expansion

LS

- Cohesively acceleration of ions co-moving in the form of a highly-dense bunch (ion spectra) ⇒ ↑ n_d
- Densities maintained for prolonged periods, of the order of the pulse duration ⇒ ↑ τ_{burn}

Transparency

- Sudden drop of density part way through the interaction, resulting in ↓ τ_{burn} and ↓ n_d

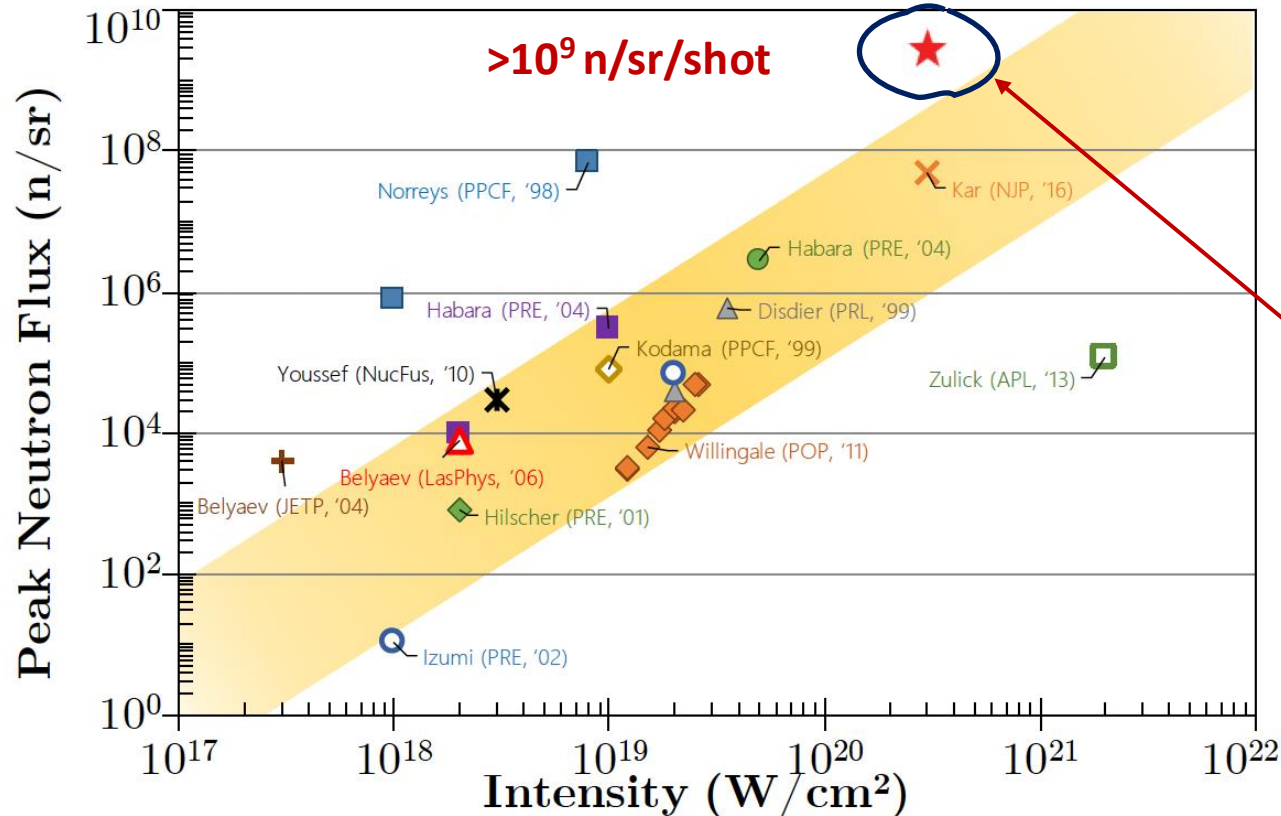
LD-neutron sources

Photo-neutrons

In-target

Pitcher-Catcher

Neutrons from pitcher-only experiments



$$Y_n \simeq \frac{\tau_{\text{burn}}}{2} \int n_d^2 \langle \sigma v \rangle dV,$$

 $\sim (\text{fusion burn time}) \times (\text{deuteron density})^2 \times (\text{fusion reactivity}) \times (\text{volume})$

TNSA

- Low density of co-moving ions (exponential acceleration)
- Neutrons rather generated either due to HB or plasma expansion

LS

- Cohesively acceleration of ions co-moving in the form of a highly-dense bunch (ion spectra) $\Rightarrow \uparrow n_d$
- Densities maintained for prolonged periods, of the order of the pulse duration $\Rightarrow \uparrow \tau_{\text{burn}}$

Transparency

- Sudden drop of density part way through the interaction, resulting in $\downarrow \tau_{\text{burn}}$ and $\downarrow n_d$

LD-neutron sources



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Photo-neutrons

In-target

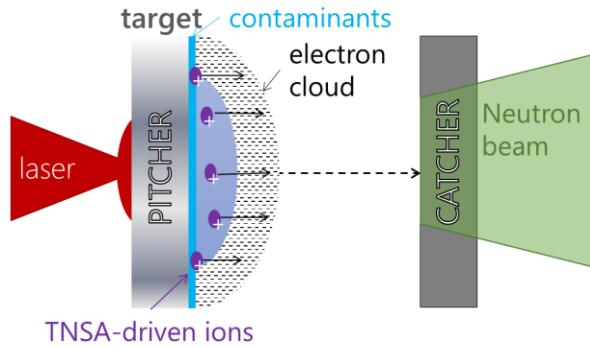
Pitcher-Catcher

LD-neutron sources

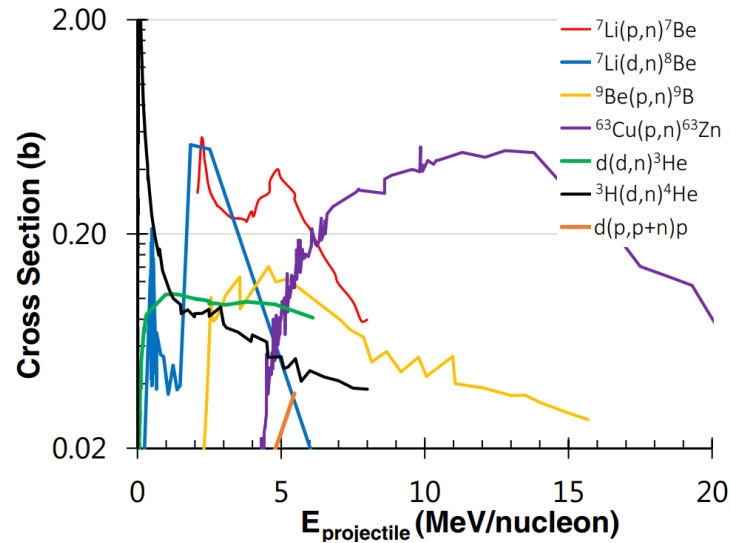
Photo-neutrons

In-target

Pitcher-Catcher



- Broad range of possible nuclear reactions
 - Most commonly, using p^+ or d^+ as projectile
 - Typical catchers include D, Li, Be
- Needed? High energy, low-Z projectile
 - Deeper penetration in catcher $\Rightarrow$ Higher yield
 - Higher on-axis cross section $\Rightarrow$ Beam-like emission



E_{laser} (J)	I_0 (W cm ⁻²)	Nuclear Reaction	Neutron Flux (n/sr)	Neutron energy [E_n] range (MeV)	Flux/ E_{Laser} (n sr ⁻¹ /J)
6.0	2.0×10^{19}	$d(d,n)^3\text{He}$	1.2×10^4	$1 < E_n < 5$	2.0×10^3
6.0	2.0×10^{19}	$d(d,n)^3\text{He}$	4.0×10^5	N.S. (BD)	6.7×10^4
1.1	2.0×10^{21}	$^7\text{Li}(d,n)^8\text{Be}$	3.0×10^6	$0.5 < E_n < 20$	2.7×10^6
69.0	2.5×10^{19}	$^7\text{Li}(p,n)^7\text{Be}$	2.0×10^8	N.S. (CR39)	2.9×10^6
127.0	7.0×10^{20}	$^7\text{Li}(d,n)^8\text{Be}$	3.5×10^8	N.S. (CR39)	2.8×10^6
360.0	2.0×10^{19}	$^7\text{Li}(d,n)^8\text{Be}$	7.5×10^8	N.S. (CR39)	2.1×10^6
150.0	2.0×10^{20}	$d(p,p+n)p$	1.0×10^9	$2.5 < E_n < 20$	6.7×10^6
200.0	2.0×10^{20}	$d(d,n)^3\text{He}$	2.5×10^9	$E_n > 2.5$	1.3×10^7
80.0	2.0×10^{20}	d breakup	1.0×10^{10}	N.S. (BD)	1.3×10^8

Beam emission

Pitcher species

Catcher species

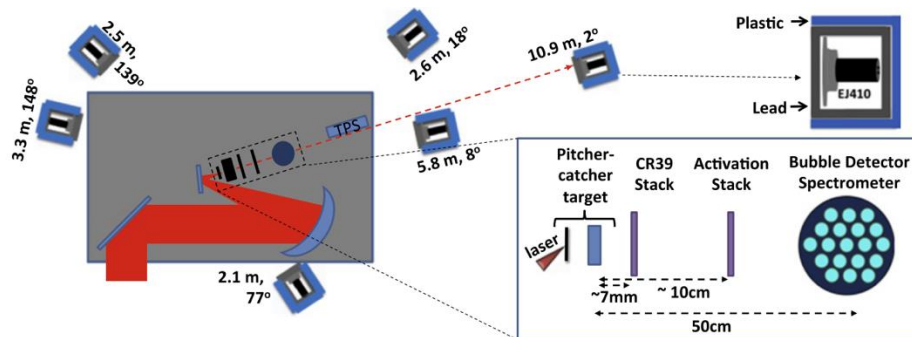
LD-neutron sources

Photo-neutrons

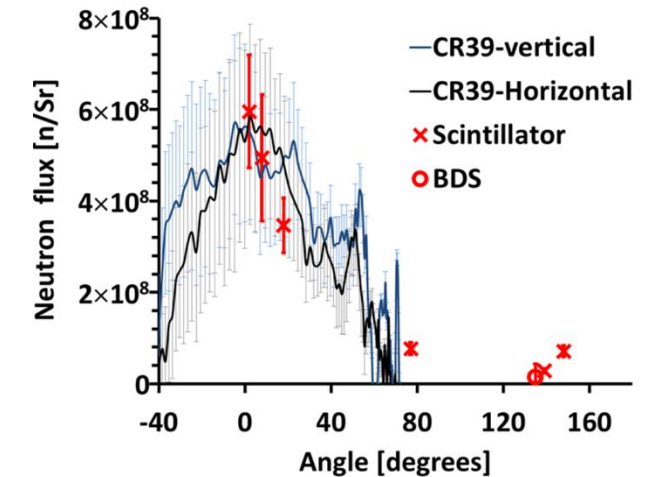
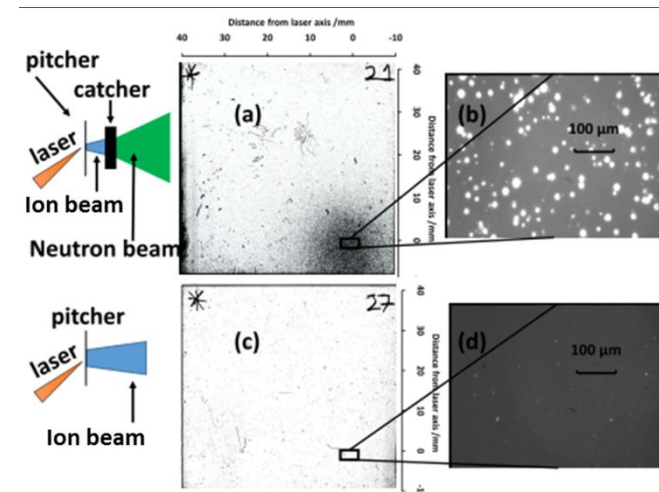
In-target

Pitcher-Catcher

Beam-like emission: Direct observation from DD reaction



- Using deuterated catcher pitcher and catcher to produce neutrons via (d,d) reaction
- High deuterium energy to improve directionality



- Using deuterated catcher pitcher and catcher to produce neutrons via (d,d) reaction
- High deuterium energy to improve directionality

LD-neutron sources



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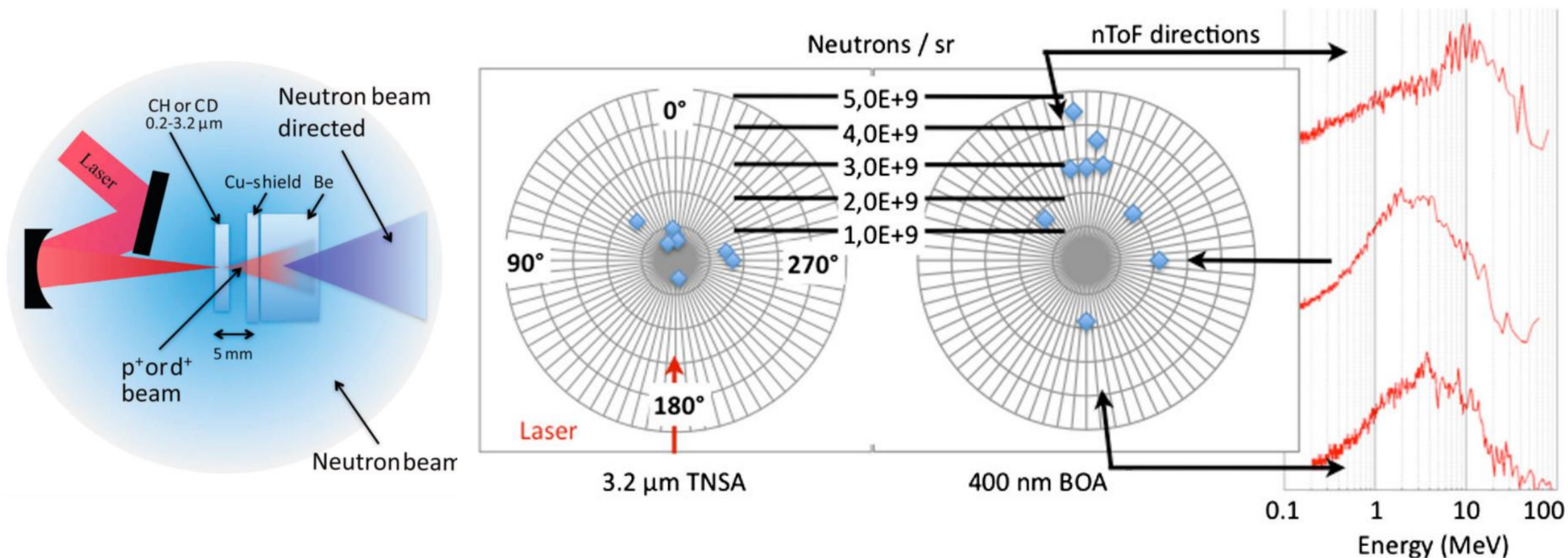
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Pitcher-Catcher

High flux optimising catcher



LD-neutron sources



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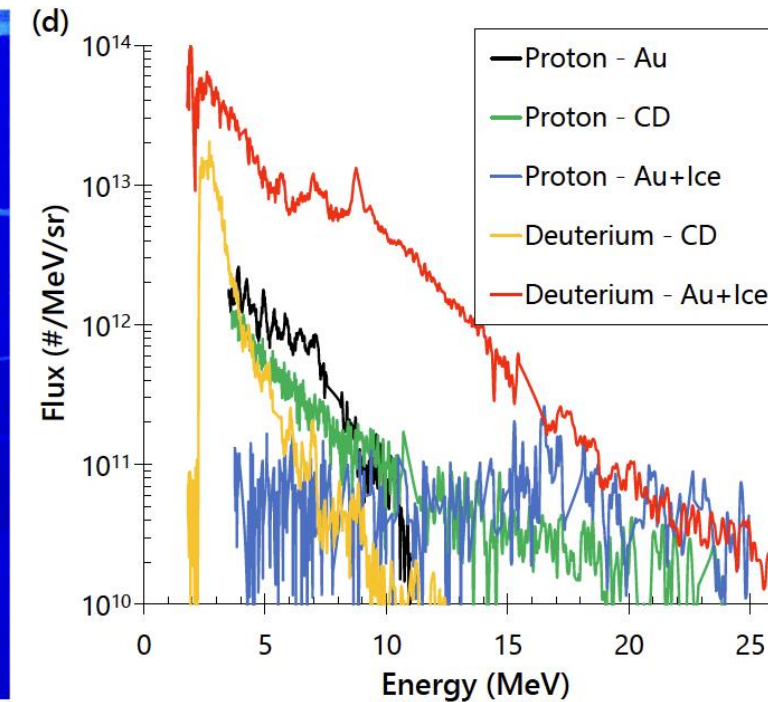
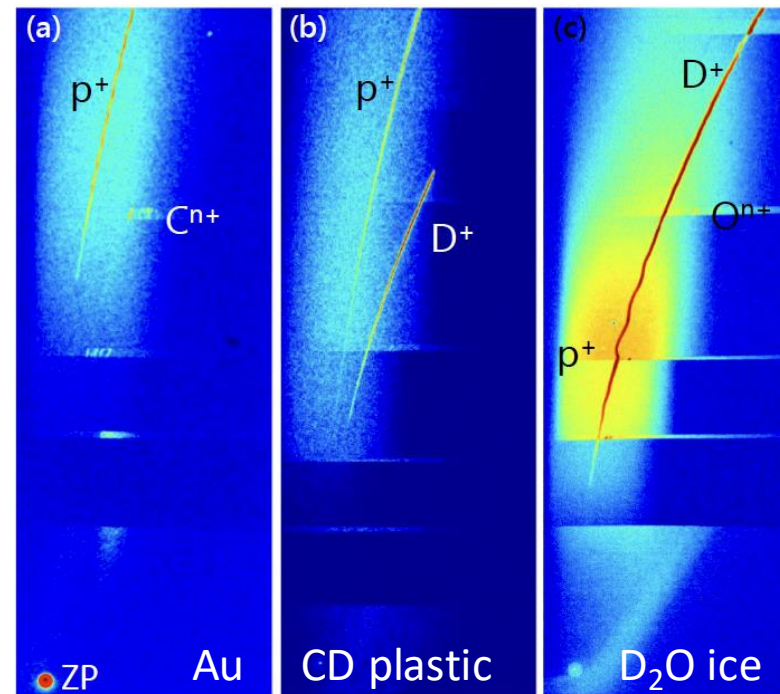
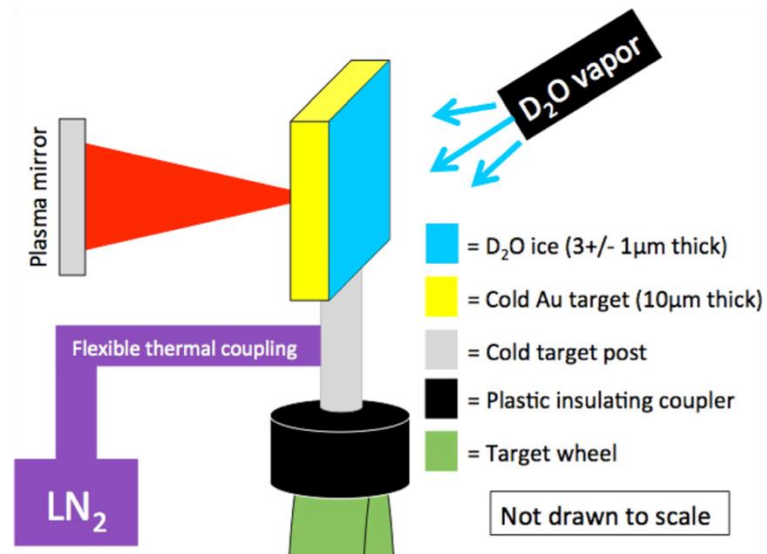
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Photo-neutrons

In-target

Pitcher-Catcher

High flux optimising pitcher



LD-neutron sources

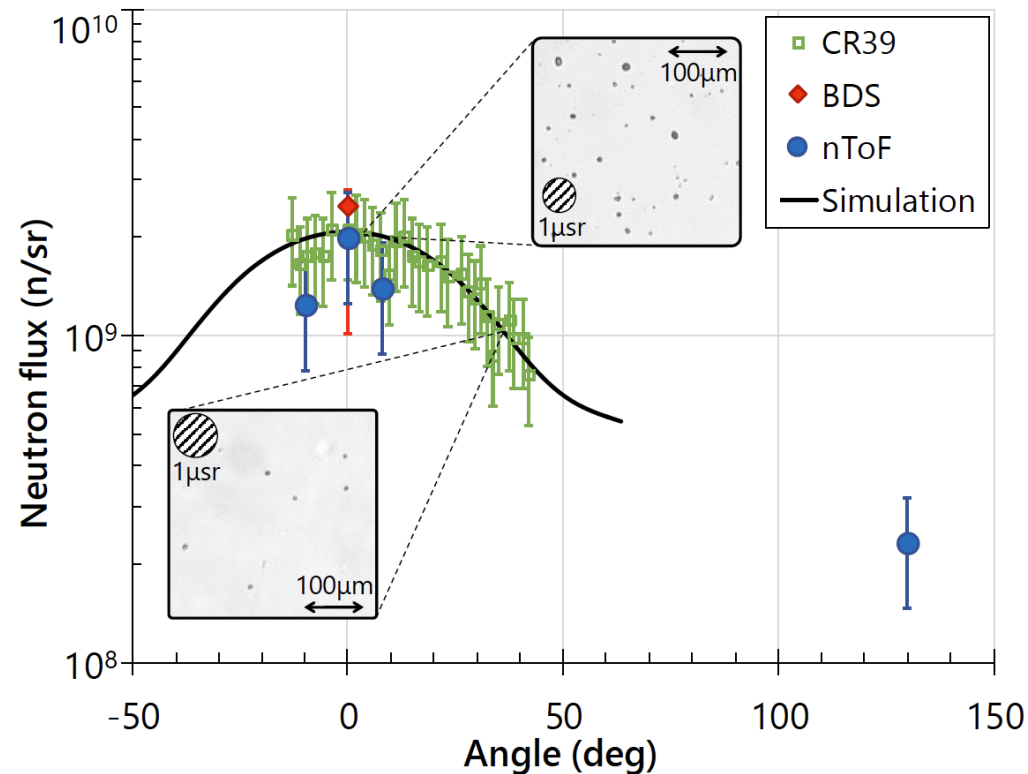
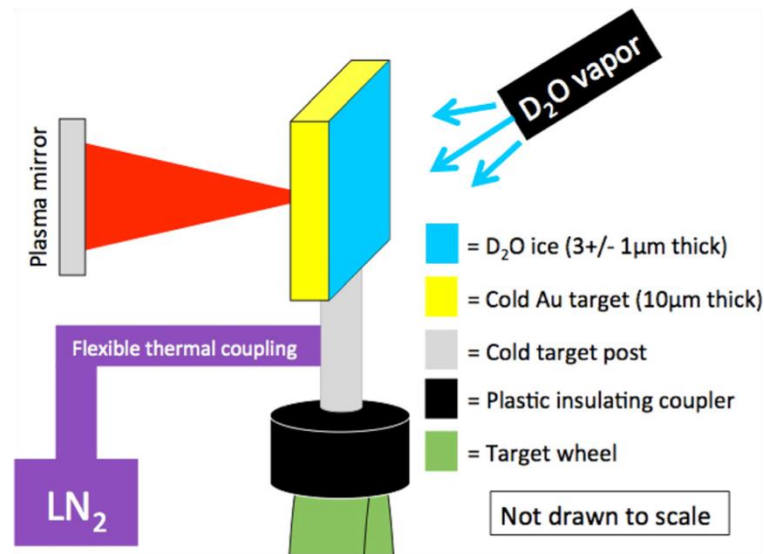


Photo-neutrons

In-target

Pitcher-Catcher

High flux optimising pitcher





LD-neutron sources

Photo-neutrons

In-target

Pitcher-Catcher

E_{laser}	I_0	Nuclear	Neutron Flux	Neutron energy	Flux/ E_{Laser}
(J)	(W cm ⁻²)	Reaction	(n/sr)	[E_n] range (MeV)	(n sr ⁻¹ /J)
6.0	2.0×10^{19}	d(d,n) ³ He	1.2×10^4	$1 < E_n < 5$	2.0×10^3
6.0	2.0×10^{19}	d(d,n) ³ He	4.0×10^5	N.S. (BD)	6.7×10^4
1.1	2.0×10^{21}	⁷ Li(d,n) ⁸ Be	3.0×10^6	$0.5 < E_n < 20$	2.7×10^6
69.0	2.5×10^{19}	⁷ Li(p,n) ⁷ Be	2.0×10^8	N.S. (CR39)	2.9×10^6
127.0	7.0×10^{20}	⁷ Li(d,n) ⁸ Be	3.5×10^8	N.S. (CR39)	2.8×10^6
360.0	2.0×10^{19}	⁷ Li(d,n) ⁸ Be	7.5×10^8	N.S. (CR39)	2.1×10^6
150.0	2.0×10^{20}	d(p,p+n)p	1.0×10^9	$2.5 < E_n < 20$	6.7×10^6
200.0	2.0×10^{20}	d(d,n) ³ He	2.5×10^9	$E_n > 2.5$	1.3×10^7
80.0	2.0×10^{20}	d breakup	1.0×10^{10}	N.S. (BD)	1.3×10^8

LD-neutron sources



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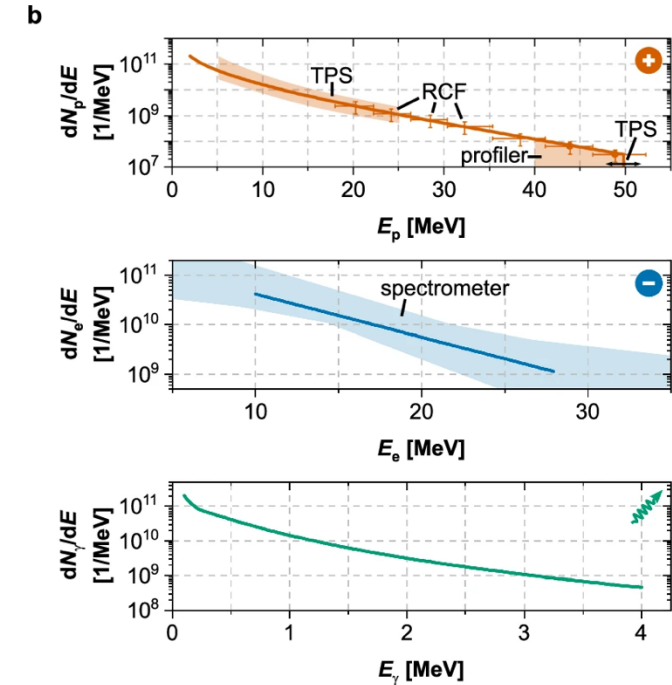
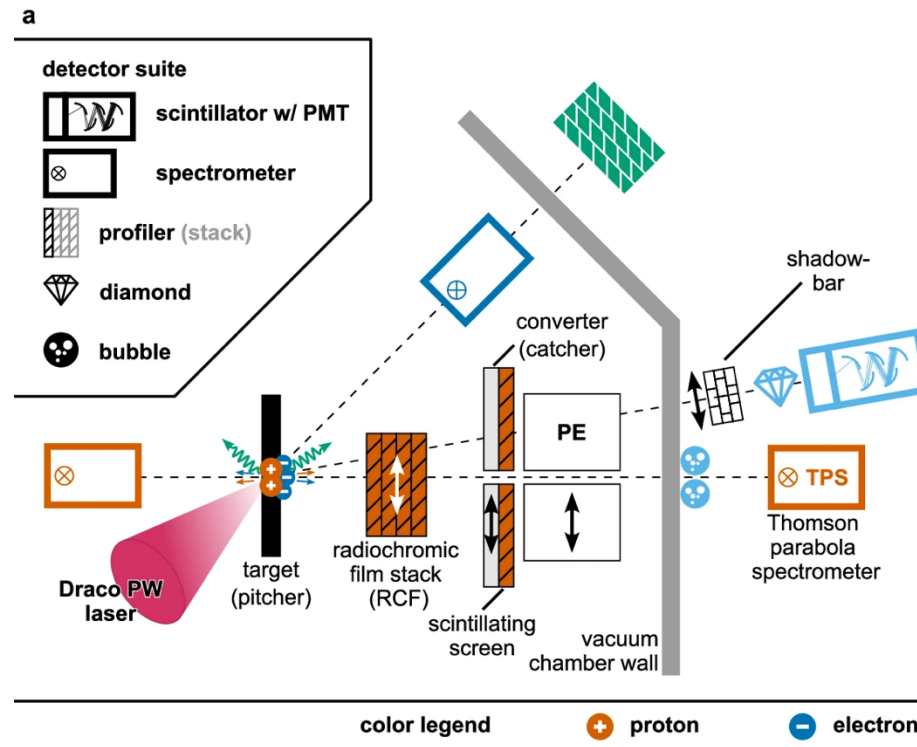
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Photo-neutrons

In-target

Pitcher-Catcher

Towards HRR neutron sources



[M.A. Millán-Callado, Nat. Comm. 17 (2026)]

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LD-neutron sources



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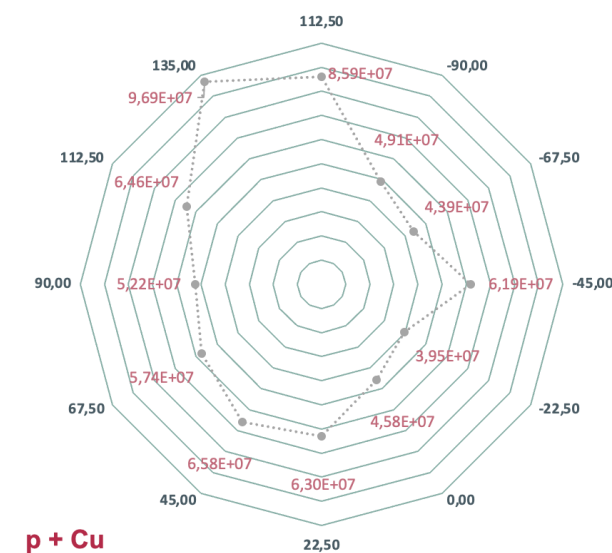
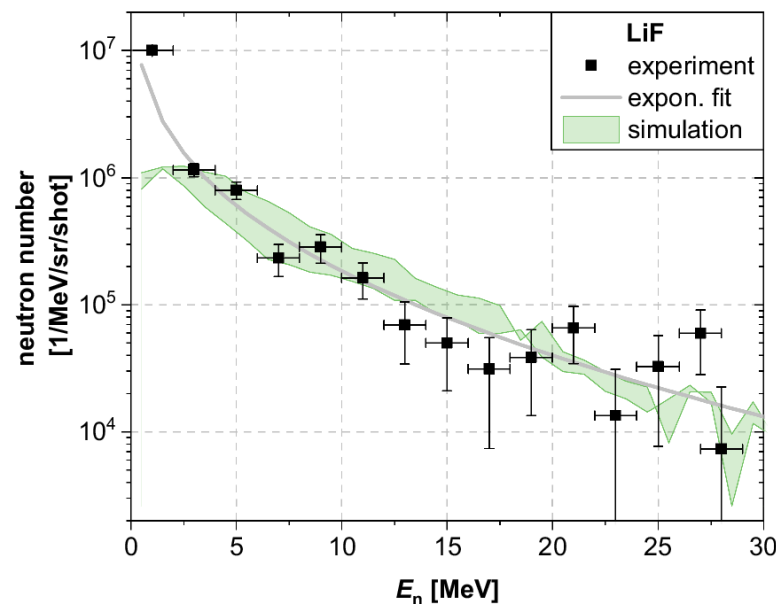
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Photo-neutrons

In-target

Pitcher-Catcher

Towards HRR neutron sources



10^8 n/shot

Average neutron flux of
Ti-Sa 10^8 n/s vs Nd:Glass $<10^7$ n/s

[M.A. Millán-Callado, Nat. Comm. 17 (2026)]

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Neutron moderation

Neutron moderation

Neutron moderation

Refers to the slowing down of neutrons following their interaction with a target material

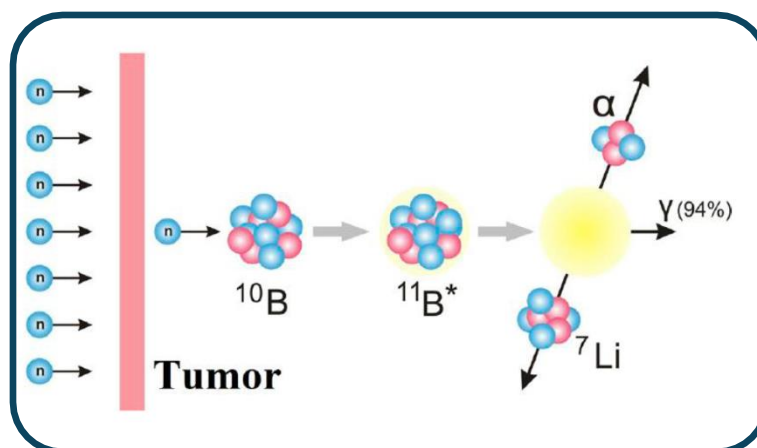
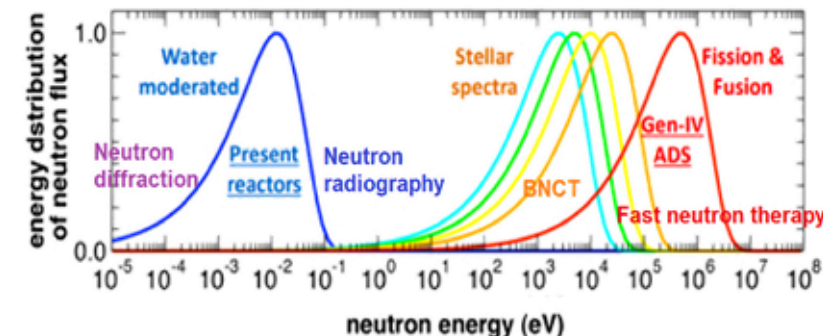
→ Neutrons are classified depending on their energy

→ Thermal and epithermal neutrons → Ultracold neutrons. $E_K < 2 \times 10^{-7}$ eV

- Boron Neutron Capture → *Very cold* neutrons. 2×10^{-7} eV $< E_K < 2 \times 10^{-5}$ eV

- Resonant spectroscopy → Cold neutrons. 5×10^{-5} eV $< E_K < 0.025$ eV

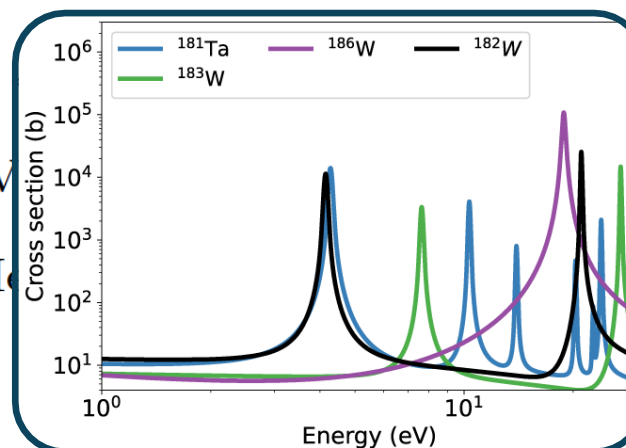
→ **Thermal neutrons.** $E_K \simeq 0.025$ eV



ons. 1 eV

ons. 1 keV

$E_K > 0.1$ MeV

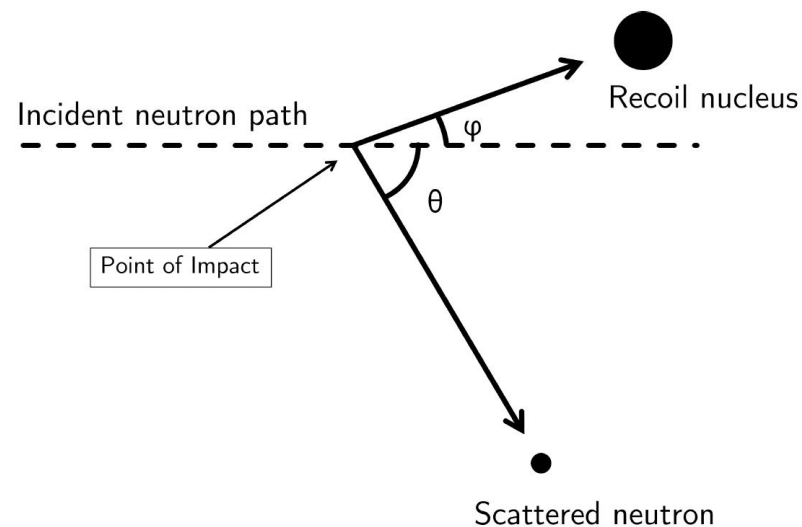


Neutron moderation

Neutron moderation

Refers to the slowing down of neutrons following their interaction with a target material

- Neutrons are classified depending on their energy
- Thermal and epithermal neutrons are useful for applications
- The thermalization is caused by repeated scattering of neutrons within a moderating material

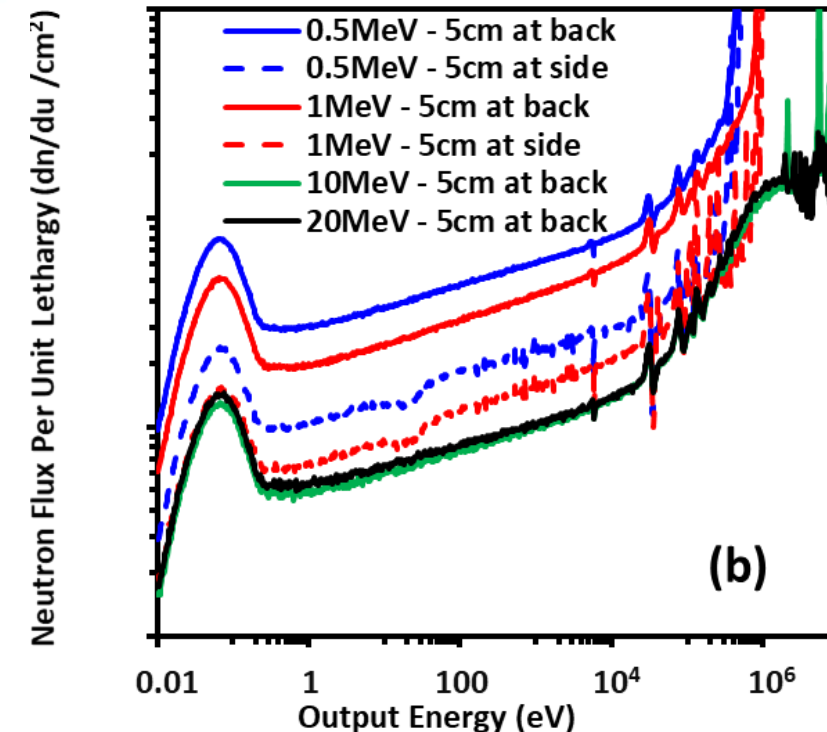
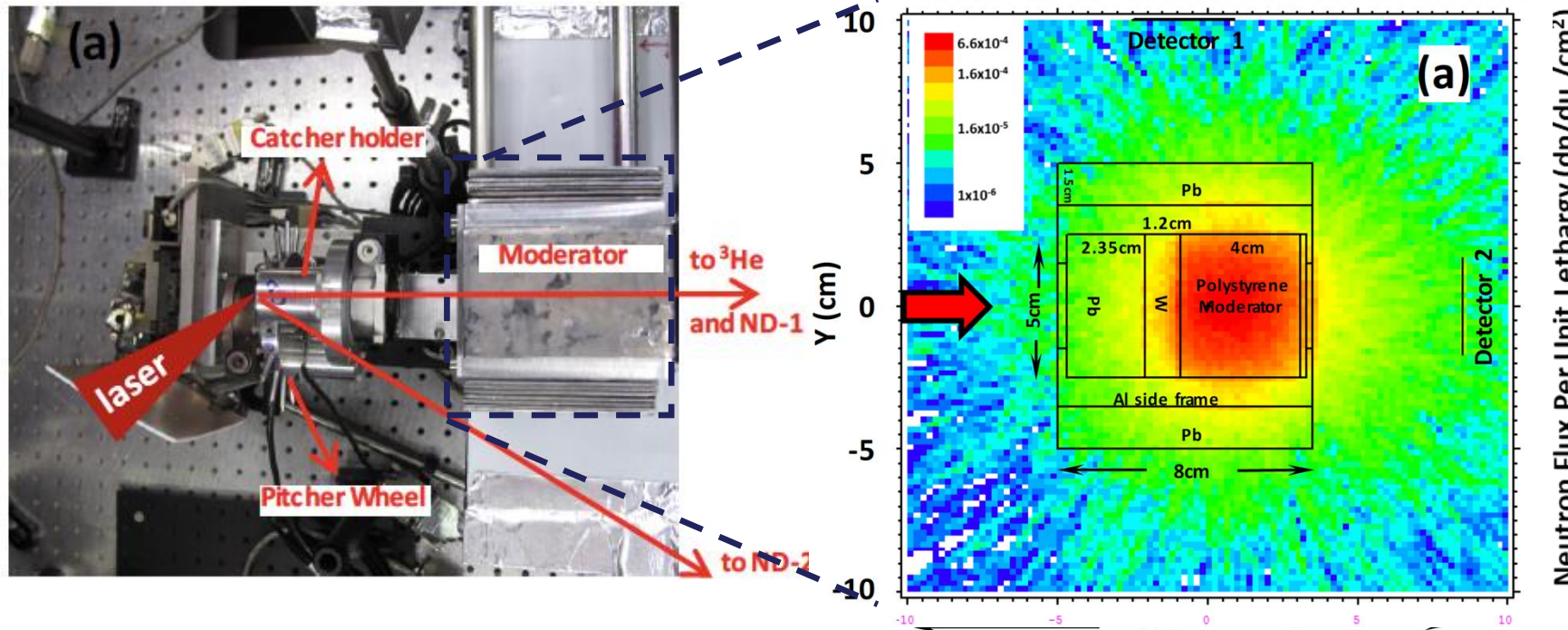


$$Q_{max} = E_K^R \Big|_{max} = \Delta E_K^n = (E_K)_i \frac{4m_n M}{(M + m_n)^2} = E_n \frac{4A}{(A + 1)^2}$$

Nucleus	$A = M/m_n$	Q_{max}/E_n
^1_1H	1	1.000
^2_1H	2	0.889
^4_2He	4	0.640
^9_4Be	9	0.360
$^{12}_6\text{C}$	12	0.284
$^{16}_8\text{O}$	16	0.221
$^{56}_{26}\text{Fe}$	56	0.069
$^{118}_{50}\text{Sn}$	118	0.033
$^{238}_{92}\text{U}$	238	0.017

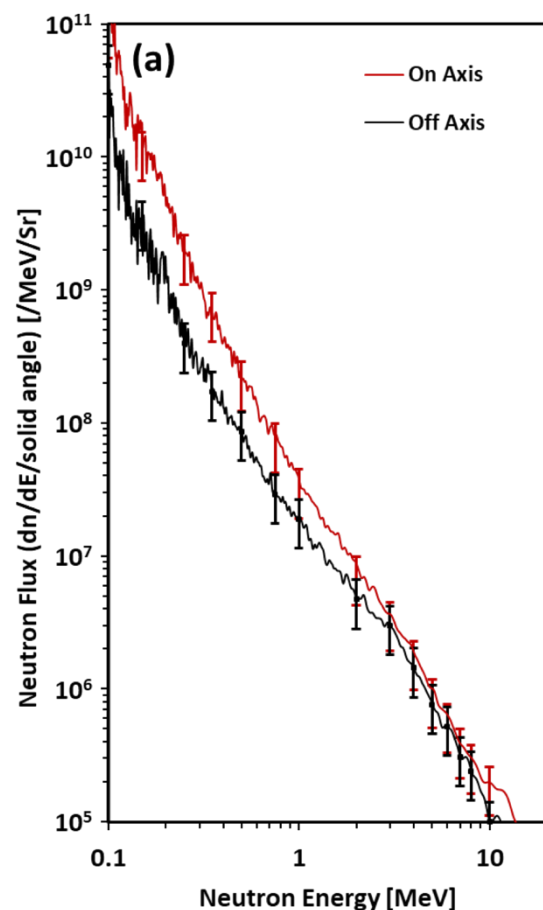
Proof-of-principle experiment

- Experiment carried out at the Vulcan laser facility (750fs pulses, 50J energy)
- Fast neutrons were generated using the pitcher-catcher configuration
- Moderator placed at the back of the catcher to maximise flux
- The moderated neutrons were detected using He-3 proportional counter

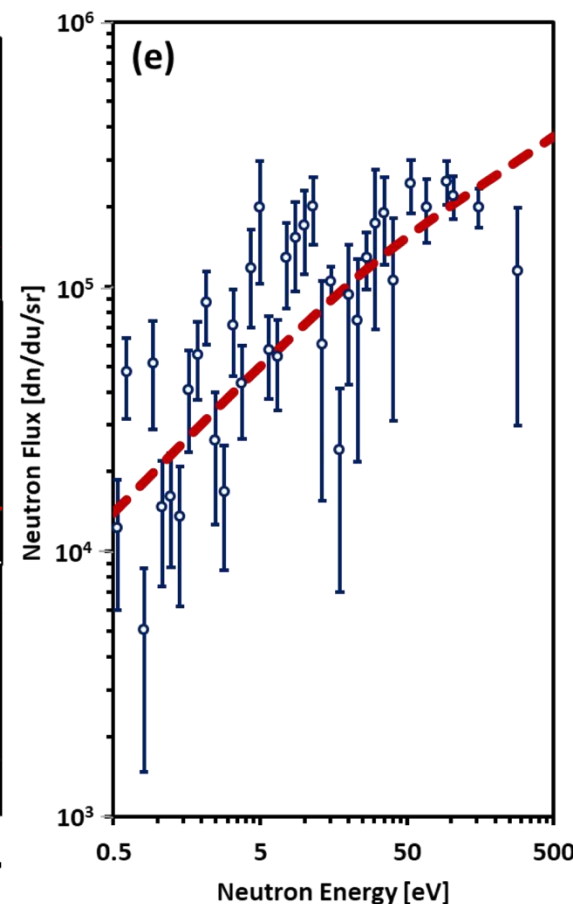
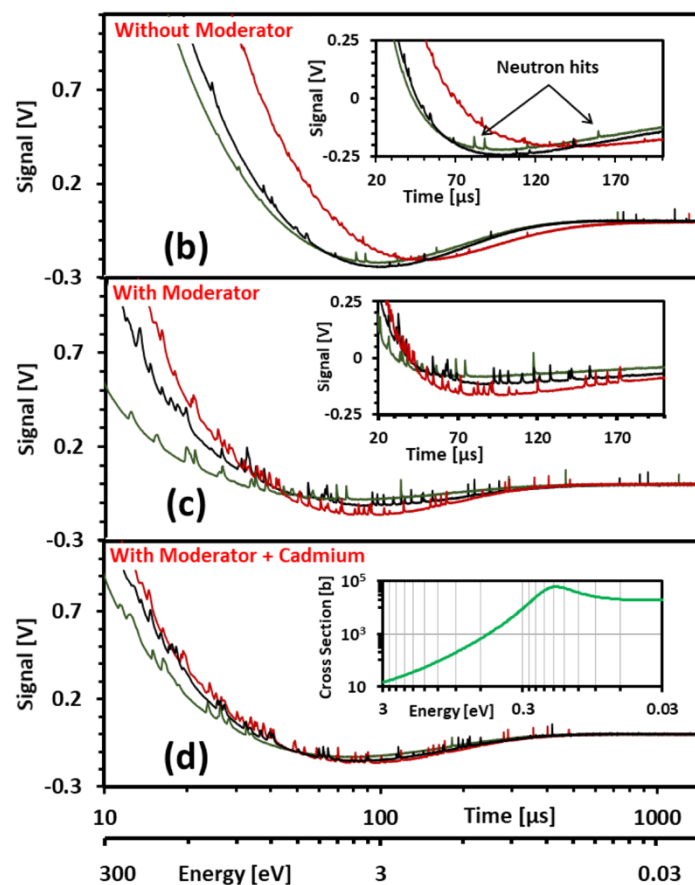


Proof-of-principle experiment

Fast neutrons
(no moderator)



Epithermal neutrons



- Measured 10^5 n/sr @ 0.5-300 eV
- Comparison with spallation source2 0.4eV – 100keV
 - Laser: $3 \cdot 10^4$ n/cm²
 - ISIS: $1 \cdot 10^5$ n/cm²



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Applications

Towards real applications

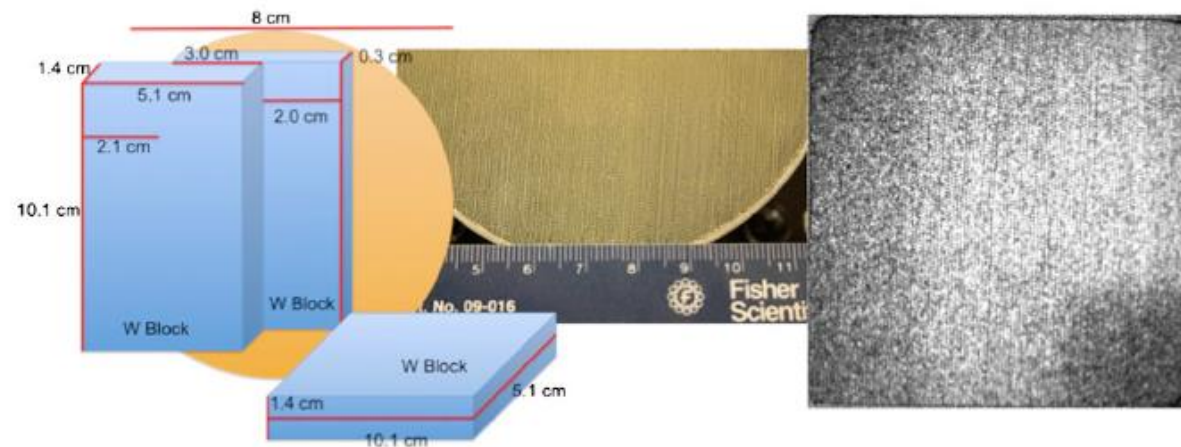
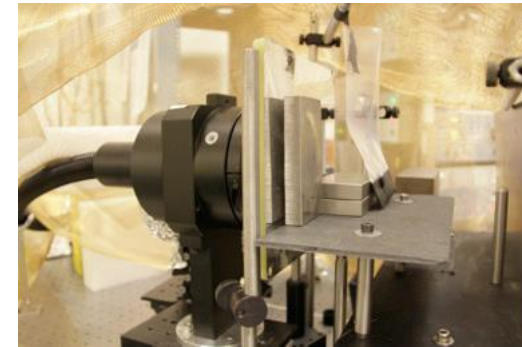
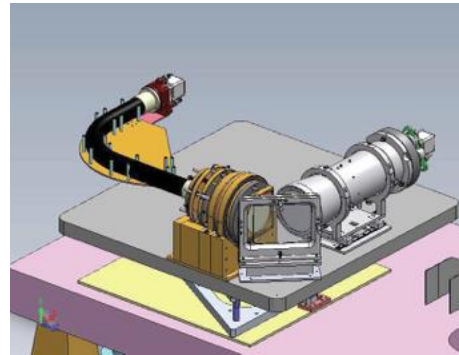


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Neutron radiography using fast neutrons



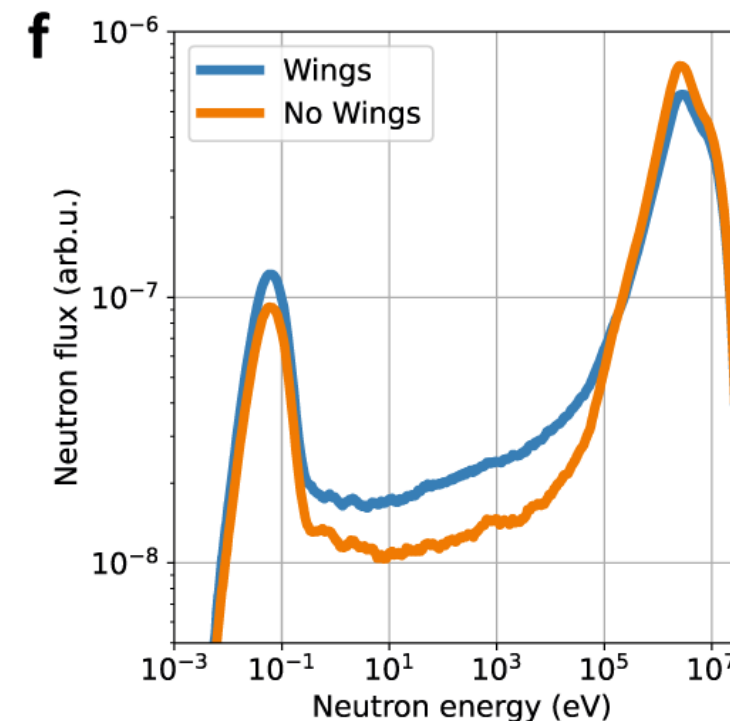
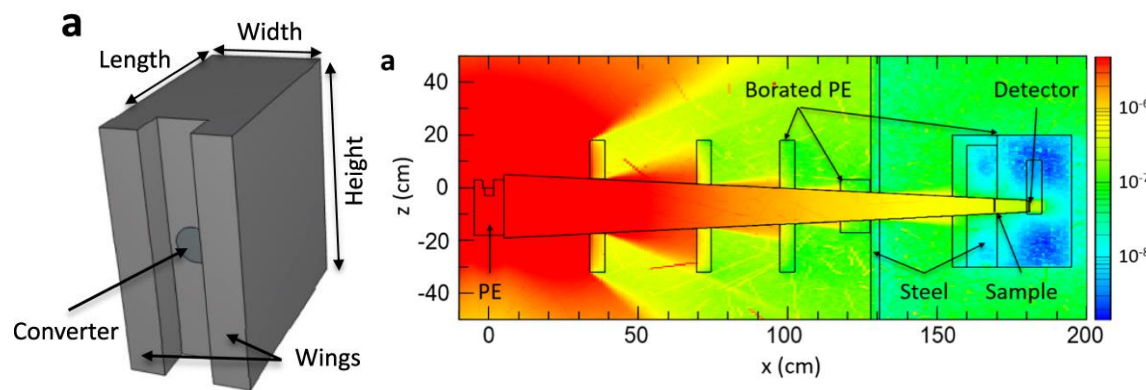
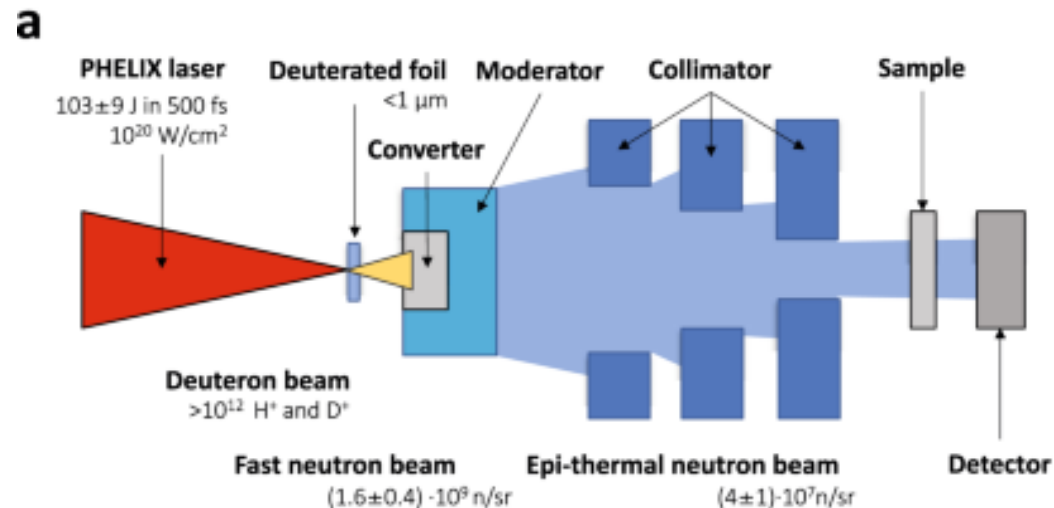
[M. Roth et al., Phys. Rev. Lett. 110 (2013)]

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Real applications: Moderated

ToF Energy resolution

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

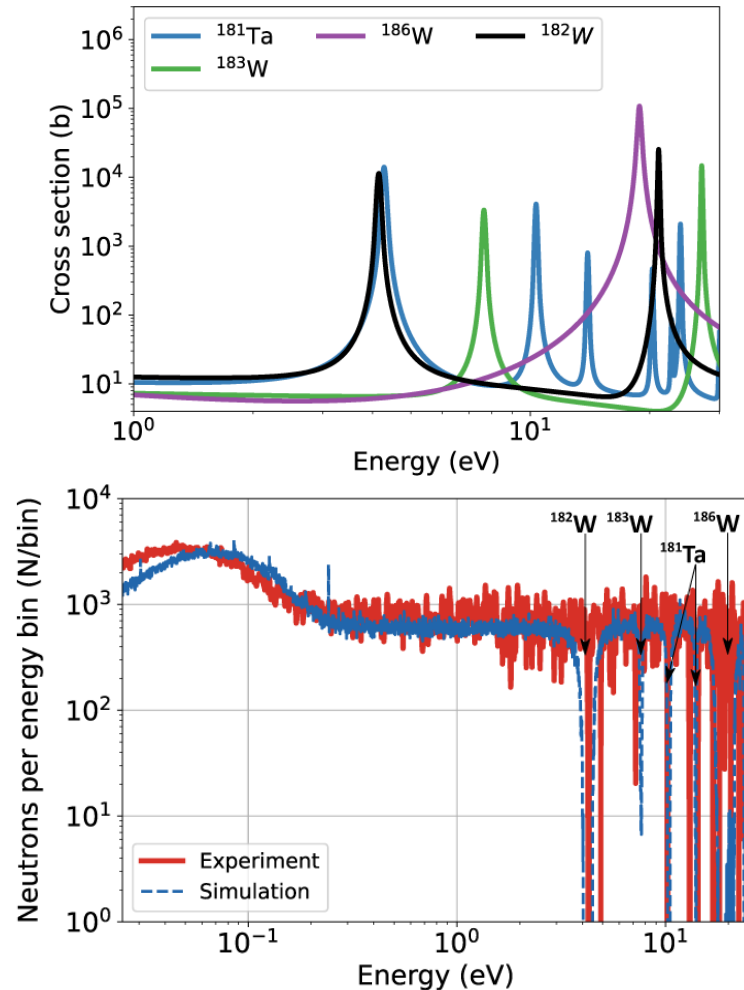


[M. Zimmer et al., Nat Commun 13, 1173 (2022)]

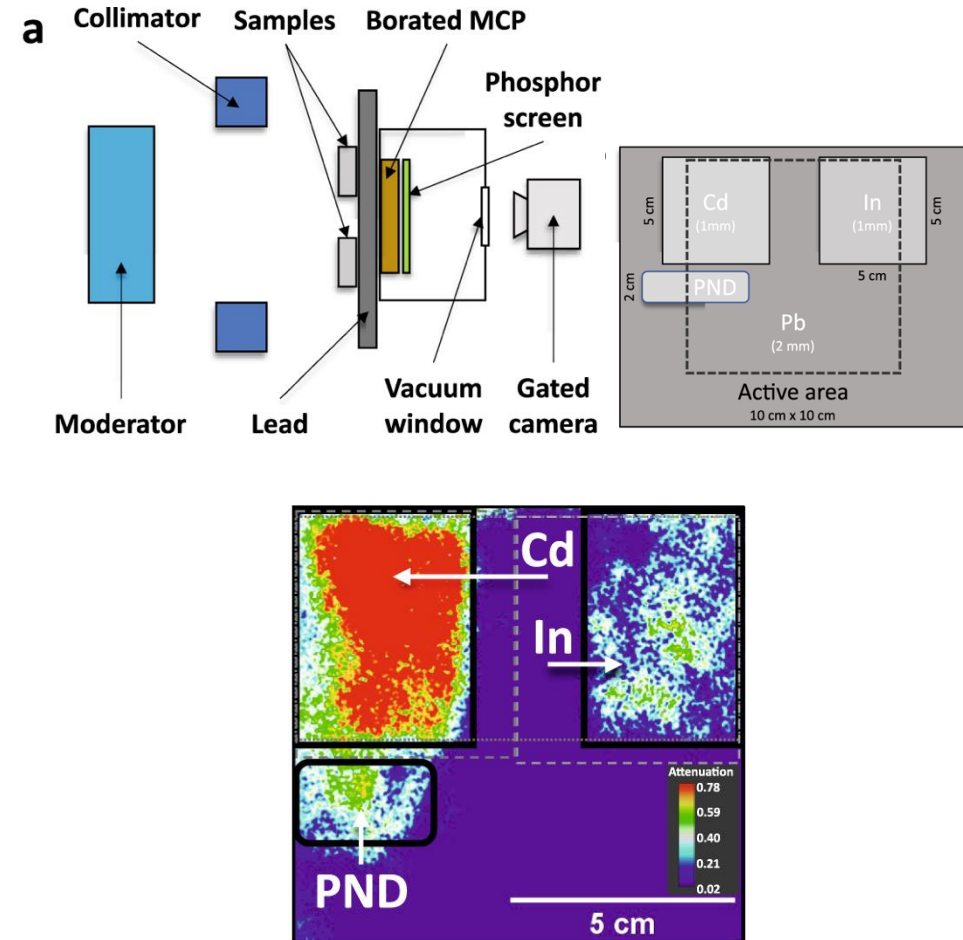
Towards real applications



Neutron resonant spectroscopy



Thermal neutron radiography



[M. Zimmer et al., Nat Commun 13, 1173 (2022)]



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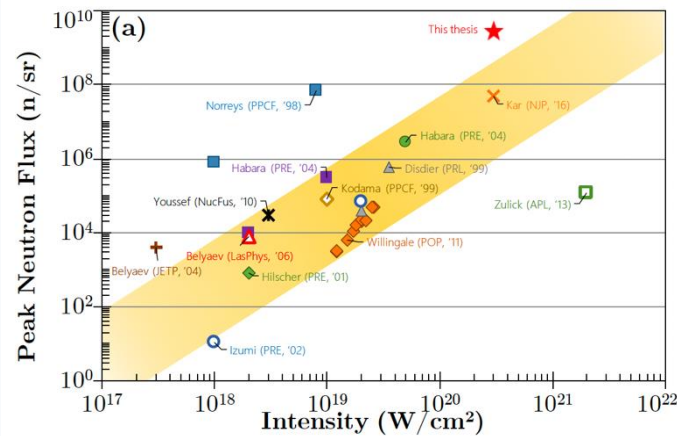
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Summary

Sources

Significant effort to **efficiently** produce laser-driven neutron beams, through different **mechanisms and nuclear reactions**.



HRR

Technology is reaching a point of maturity to work on **continuous neutron production** and studies using fast neutrons.



Moderation

Most applications require slower neutrons, **novel designs** for moderators are needed to maintain compactness and temporal duration.

