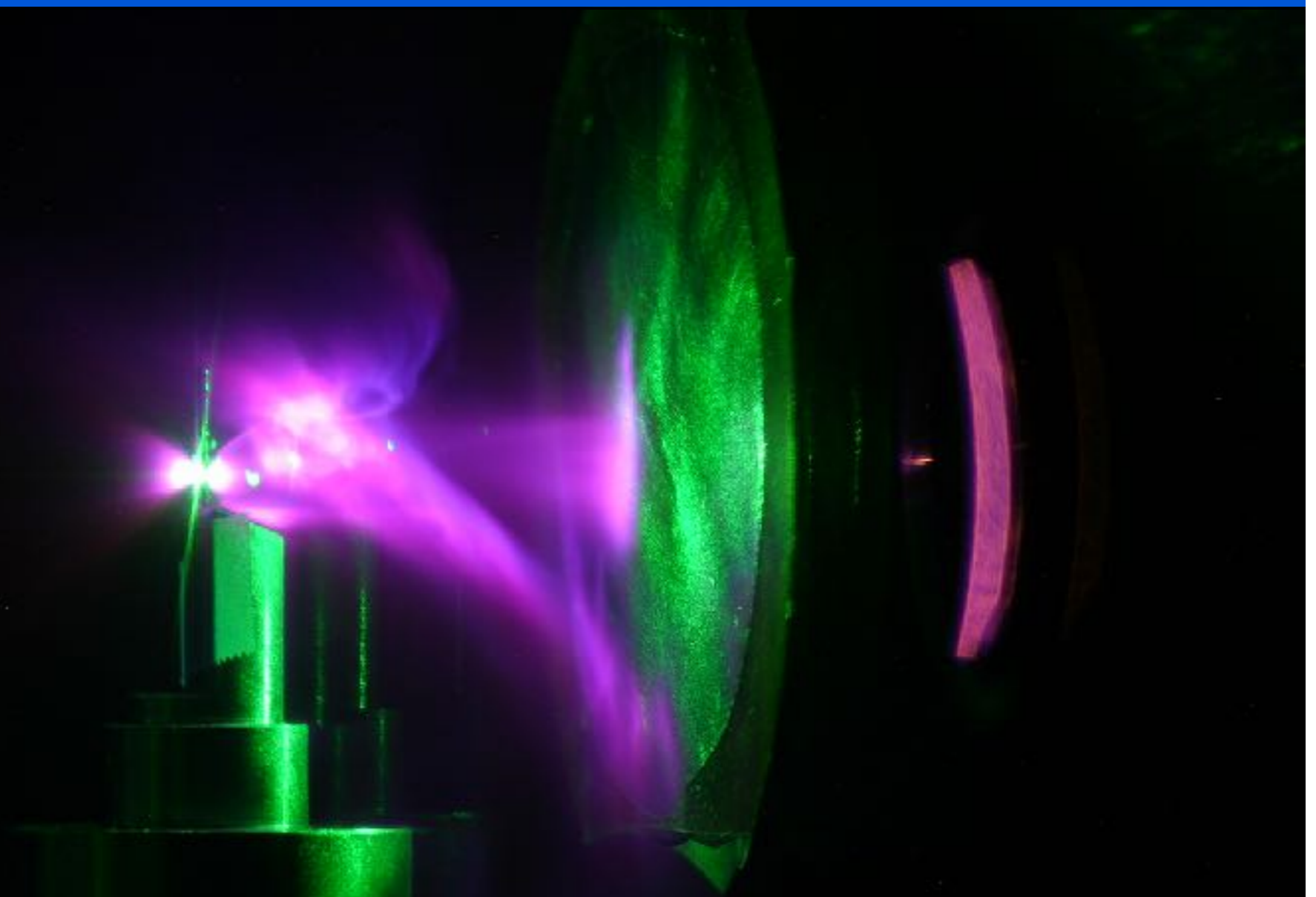


# RECENT ADVANCES IN LASER-BASED NEUTRON SOURCES



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DARMSTADT

Can lasers complement or even replace particle accelerators for radiation facilities?



**Markus Roth**  
**Technische Universität Darmstadt**

# Outline



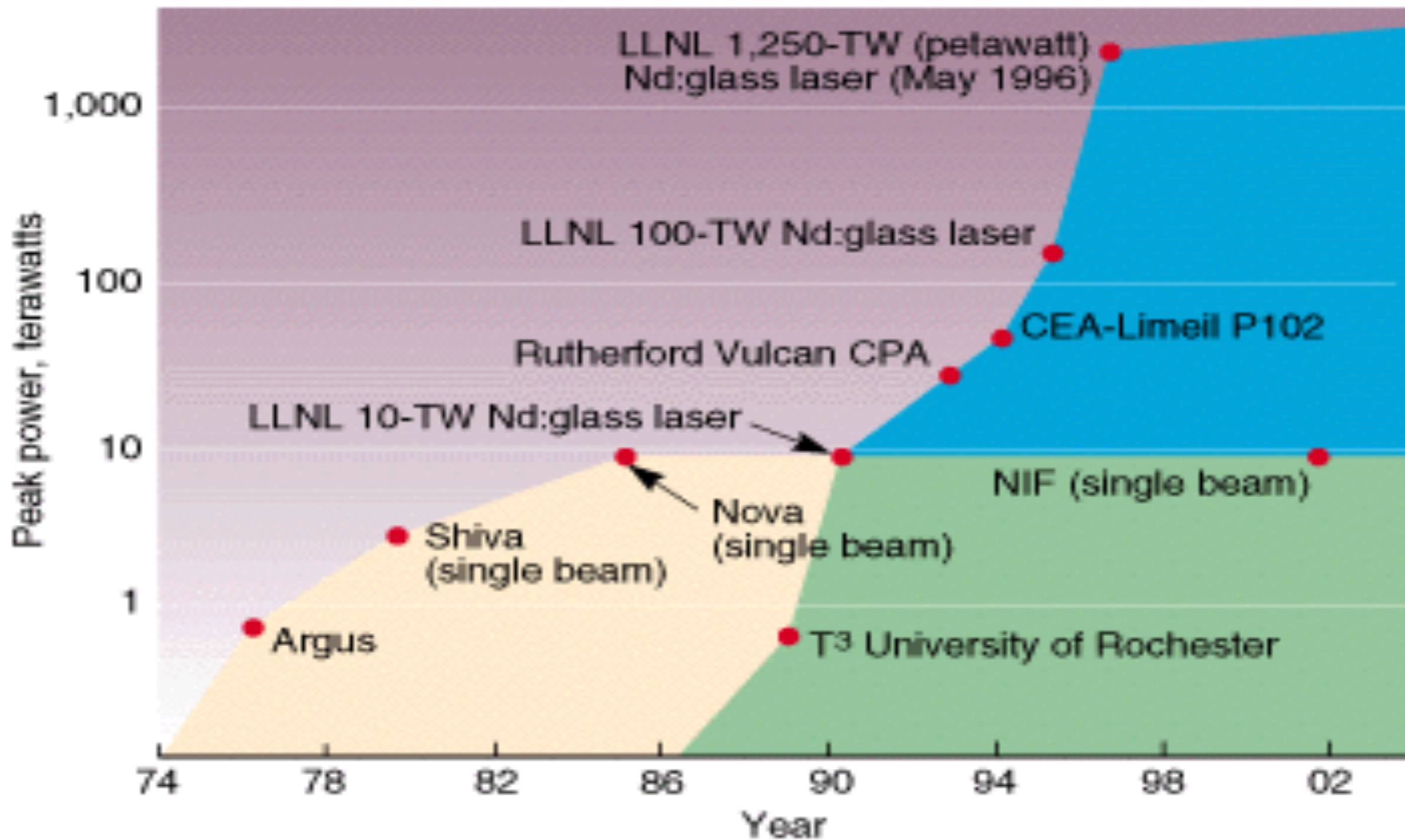
- Modern Laser Development
- Laser driven ion beams
- Neutrons
- Applications
- NRS
- Prospects



**Vincent Bagnoud, Abel Blazevic, Oliver Deppert, Matthew Devlin, Katerina Falk, Andrea Favalli, Juan Fernandez, Simon Frydrych, Cort Gautier, Matthias Geissel, Dirk Gericke, Nevzat Guler, Robert Haight, Chris Hamilton, Manuel Hegelich, Jan Helfrich, Randall P Johnson, Daniel Jung, I. Kishon, Annika Kleinschmidt, Dominik Kraus, Adrian Losko, Oliver Merle, Frank Merrill, Michael Mocko, Bernhard Müller, Sasi Palaniyappan, Ishay Pomerantz, Philip Poth, Victor Schanz, Gabriel Schaumann, Kurt Schoenberg, Marius Schollmeier, Tsutomu Shimada, Alexandra Tebartz, Joshua L. Tybo, Sven Vogel,**



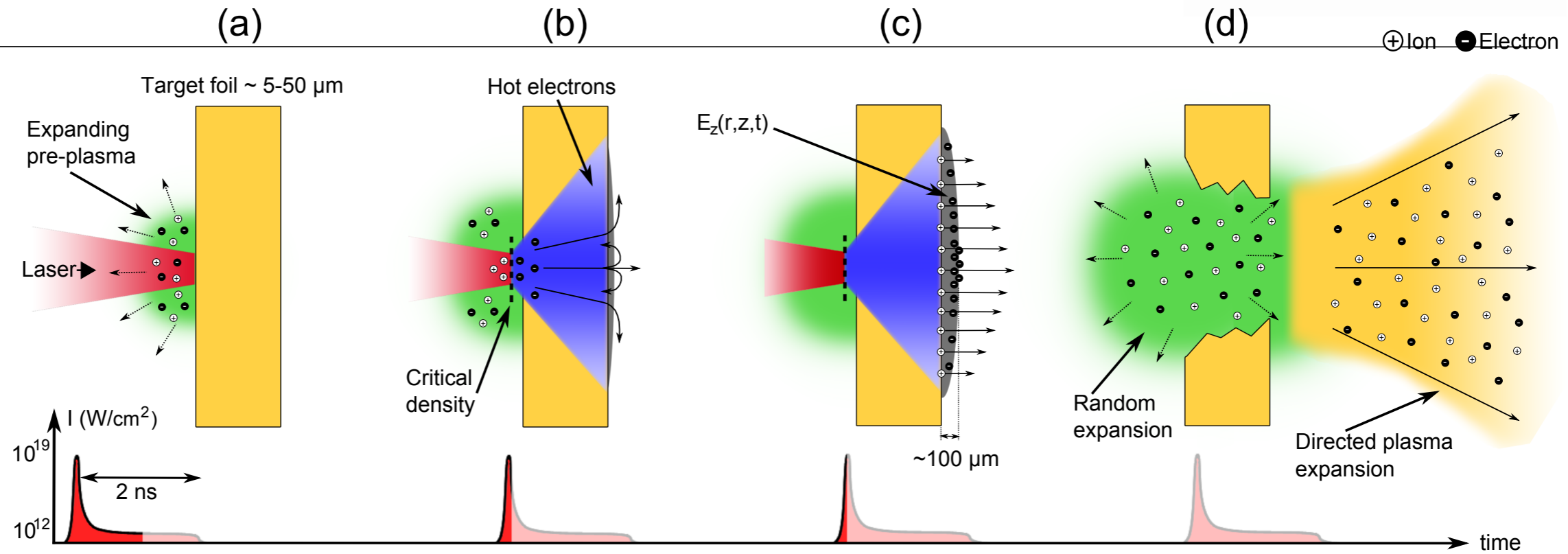
# Ultra-intense Lasers



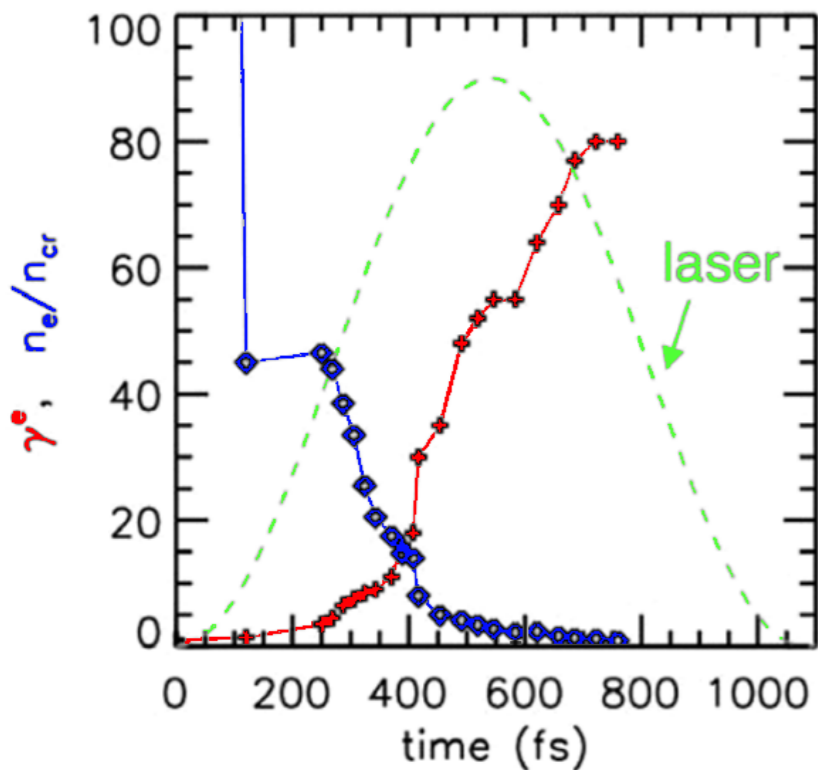
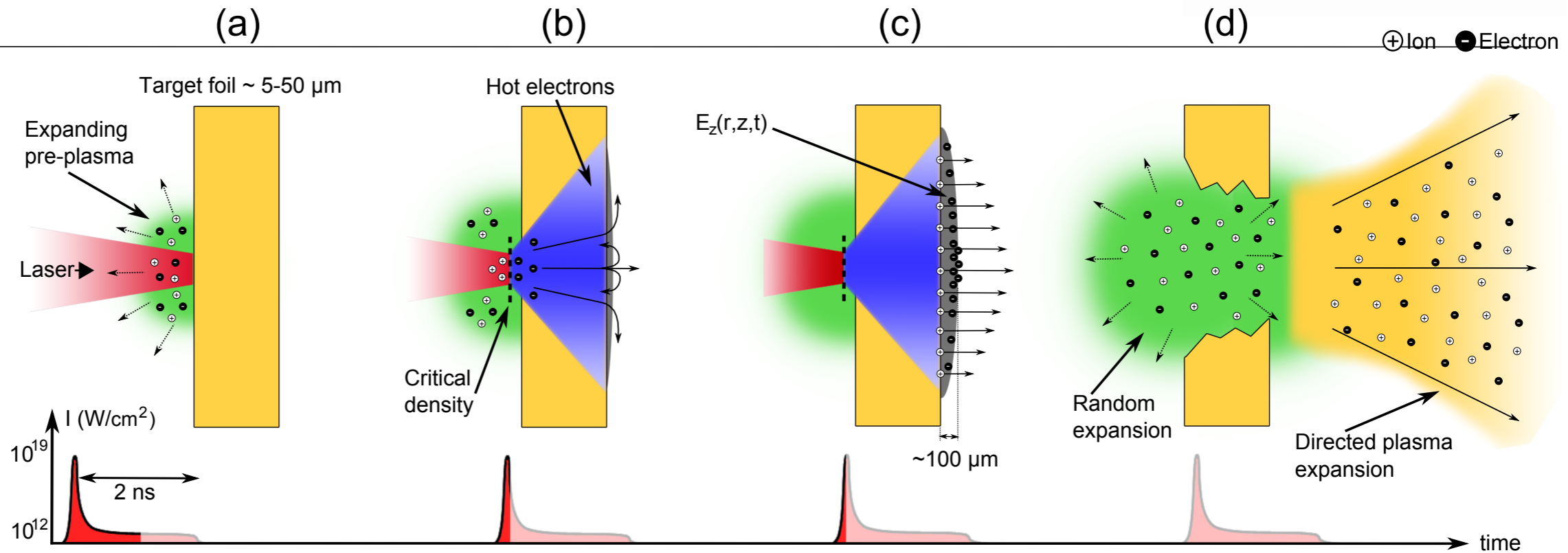
# Proton acceleration with lasers : Static electric fields



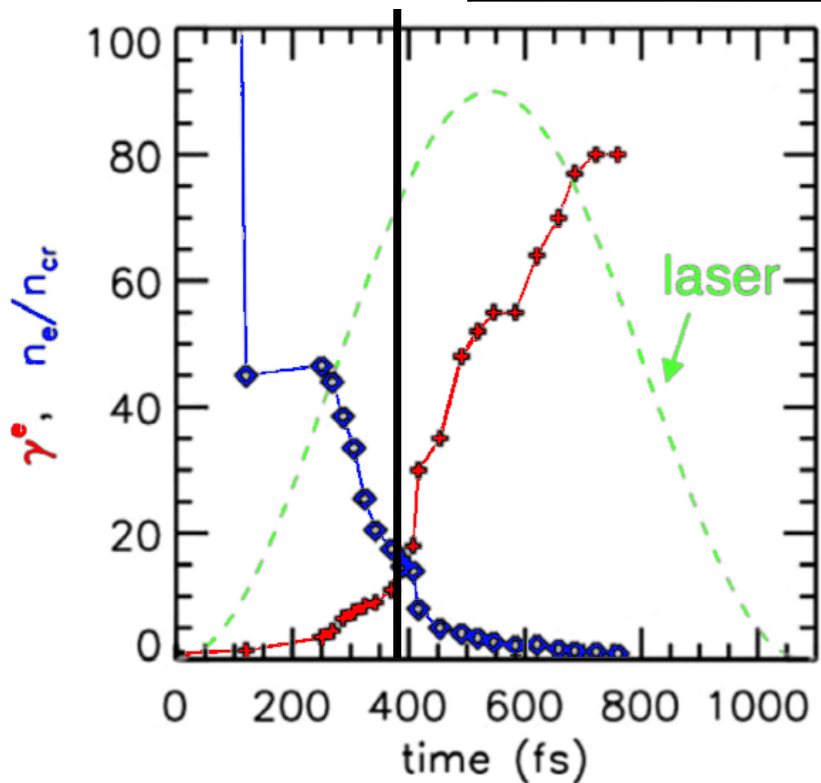
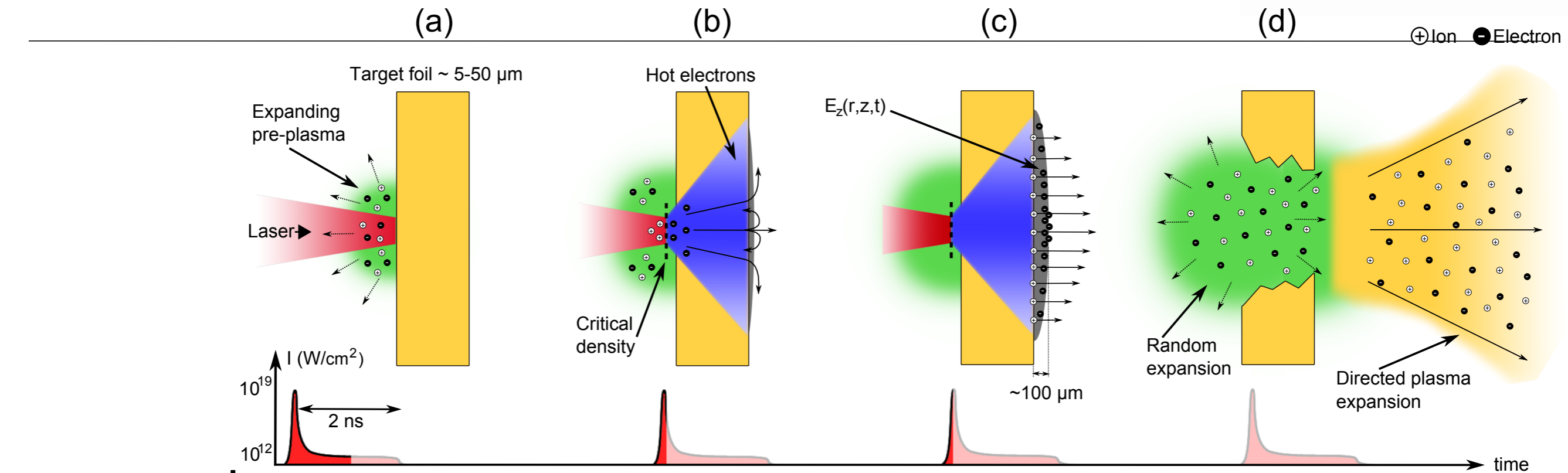
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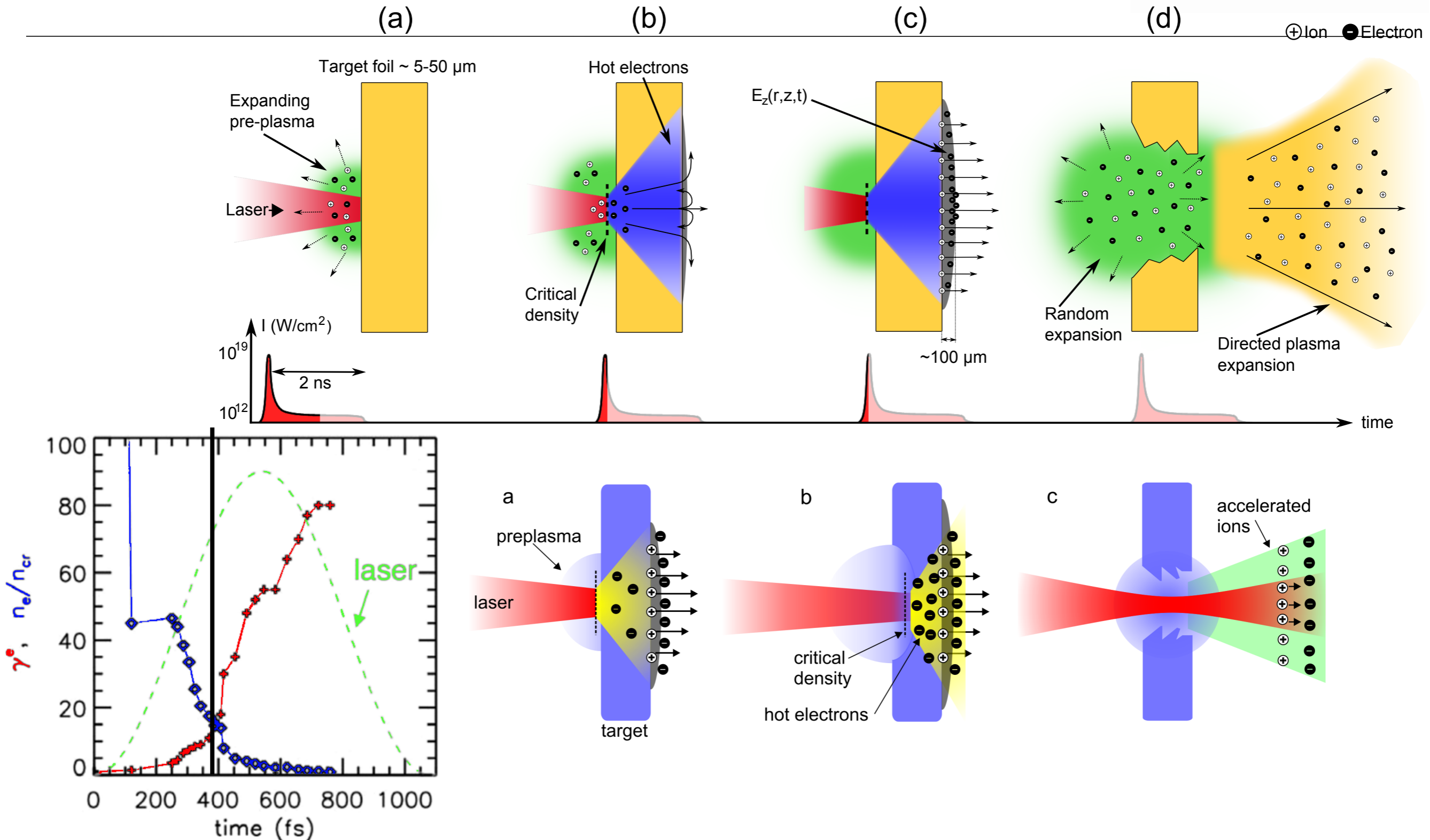
# Proton acceleration with lasers : Static electric fields



# Proton acceleration with lasers : Static electric fields



# Proton acceleration with lasers : Static electric fields



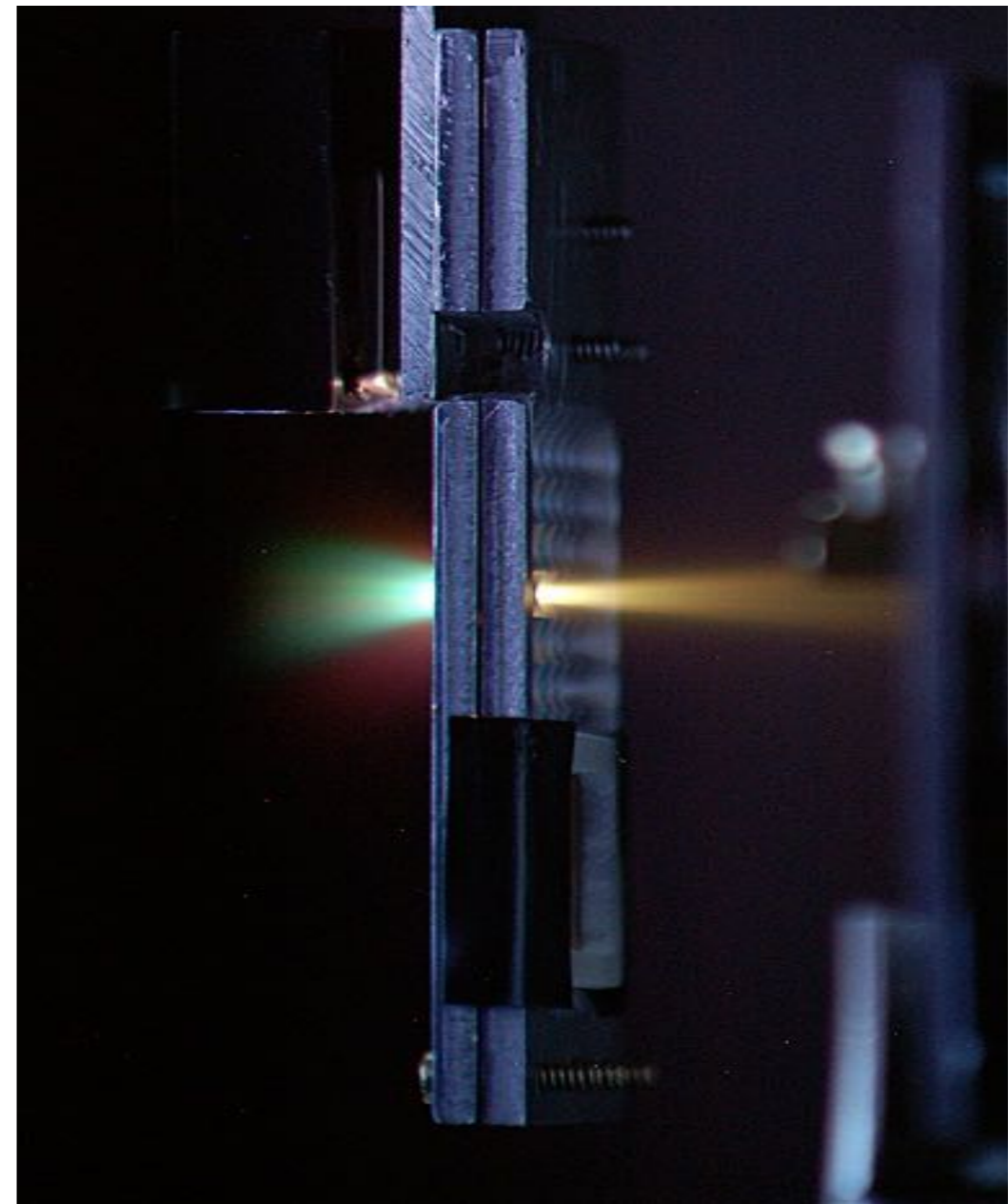
# What to do with LIA?



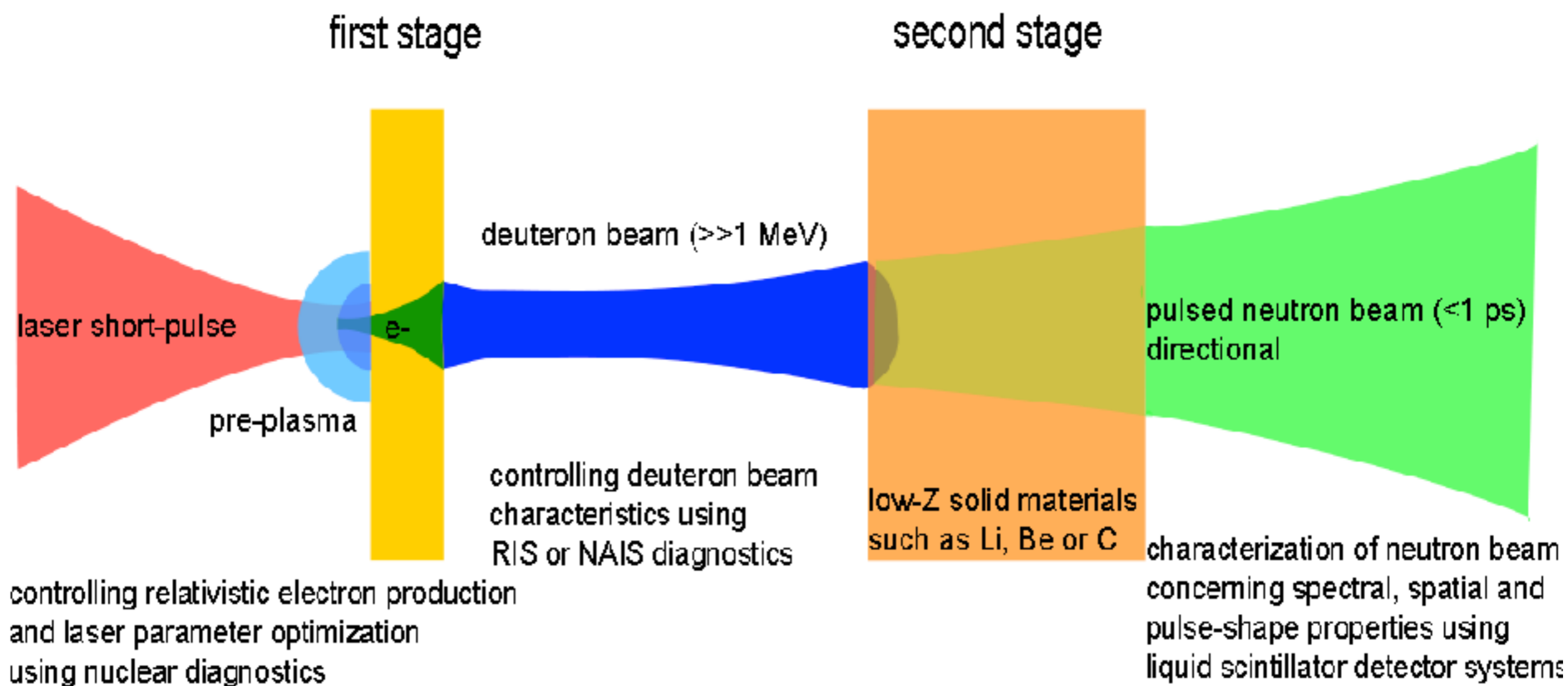
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# What to do with LIA?



# What to do with LIA?



# Why are we interested in Neutrons?



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## Neutrons:

## A special gift for science



„Neutrons tell us  
where the atoms are  
and how they move.“

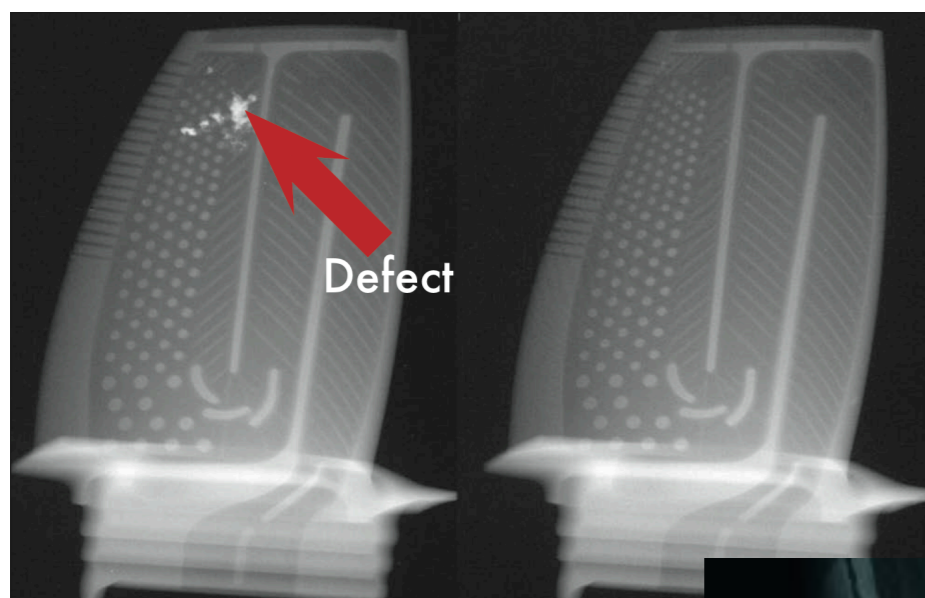
→ macroscopic functionalities of materials



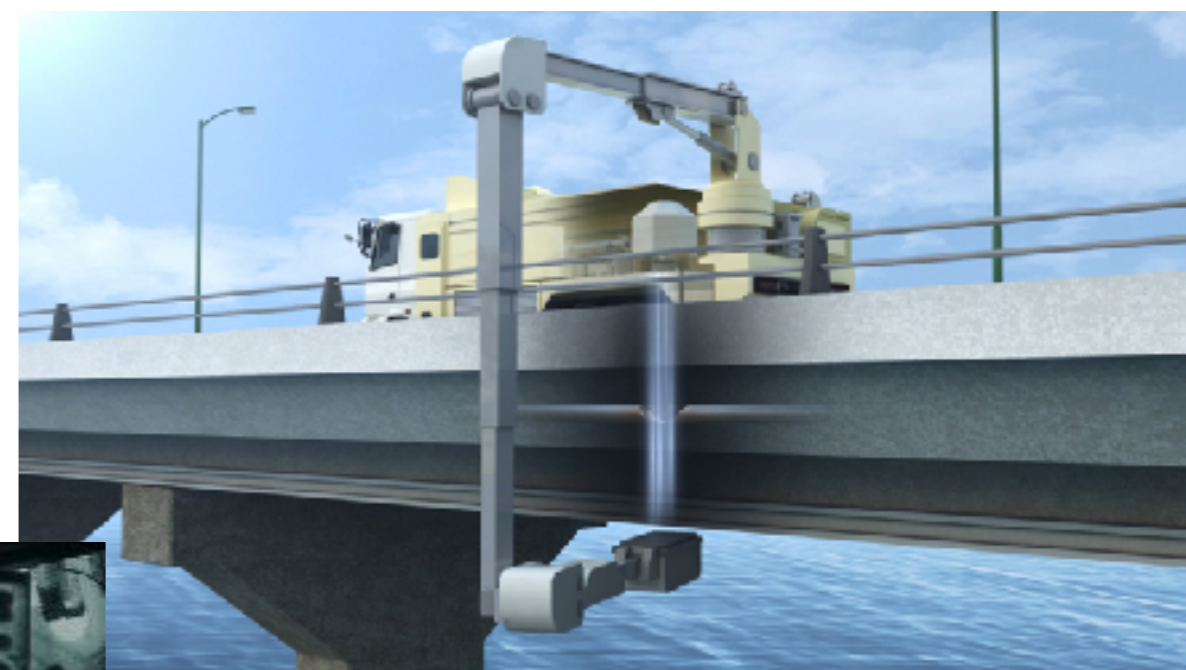
Clifford Shull  
Nobel Prize Physics

Neutrons are rarely the first,  
but often the last probe  
for new materials or new phenomena.

# Applications for neutrons



*Thermal neutron radiograph of two jet engine turbine blades*



The rendering image of non-destructive inspection of bridges with compact neutron source and data analysis system (RIKEN)

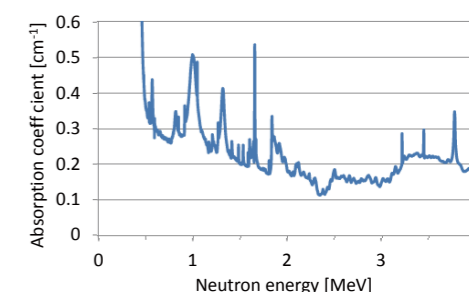


Fig. 2. Effective absorption coefficient of OC.

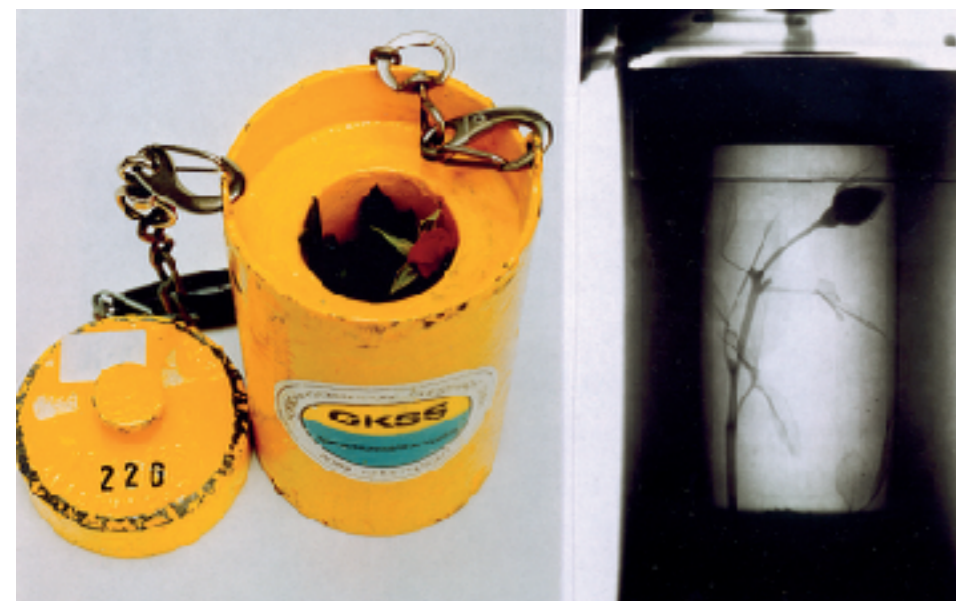
Neutron radiography of a motorcycle engine. FRM II/ANTARES

# Compact neutron sources



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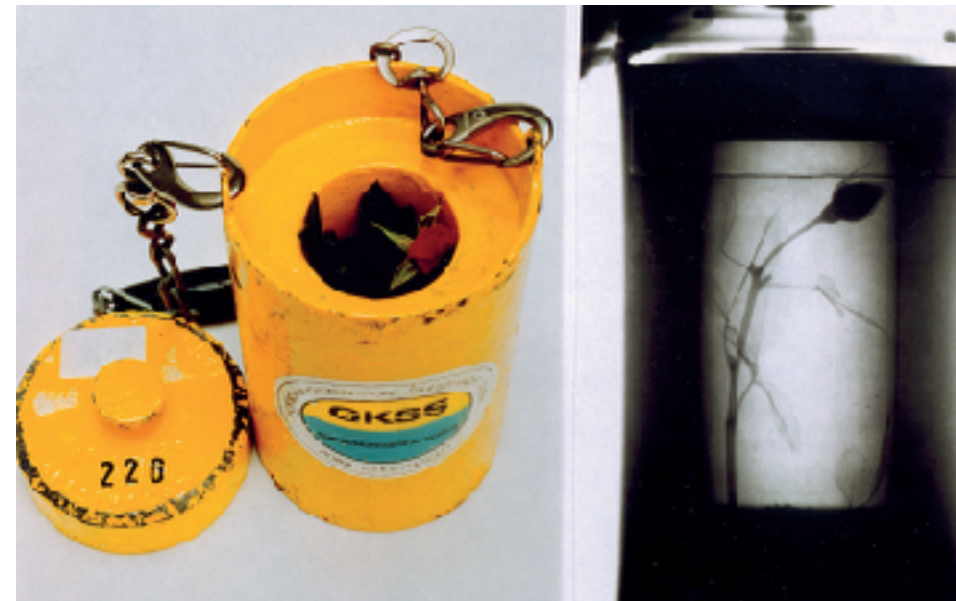
Highly penetrating



GKSS, Geesthacht

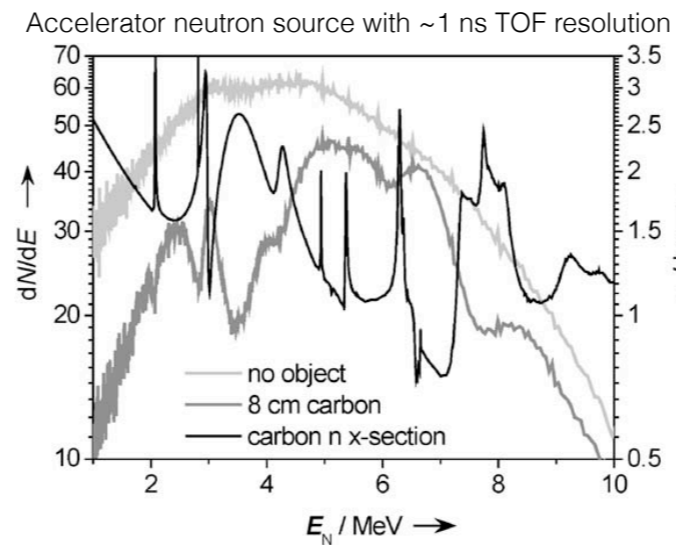
# Compact neutron sources

## Highly penetrating

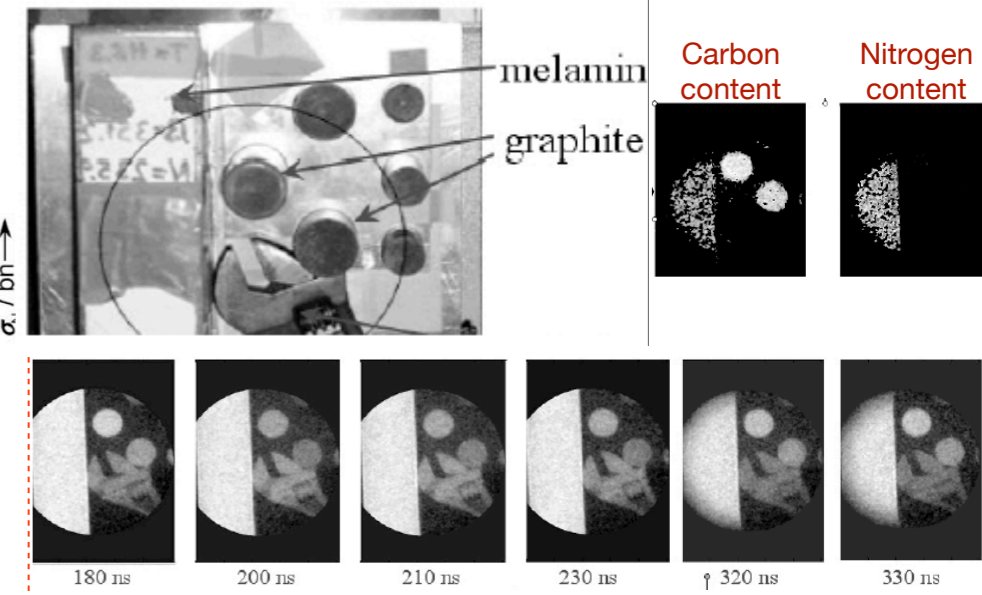


GKSS, Geesthacht

## Material selective (fast neutron radiography)



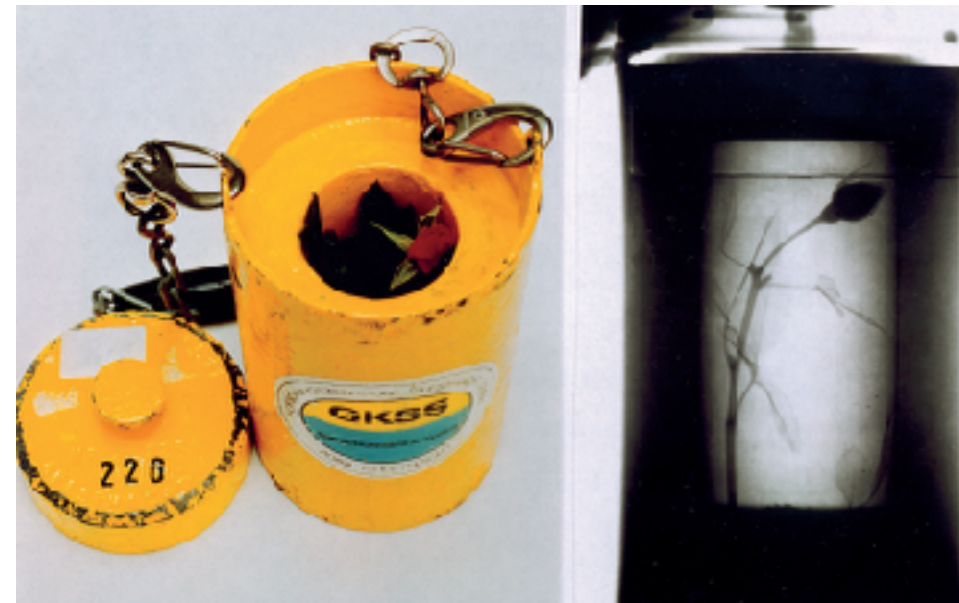
Ishay Pomerantz / U. Texas



Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

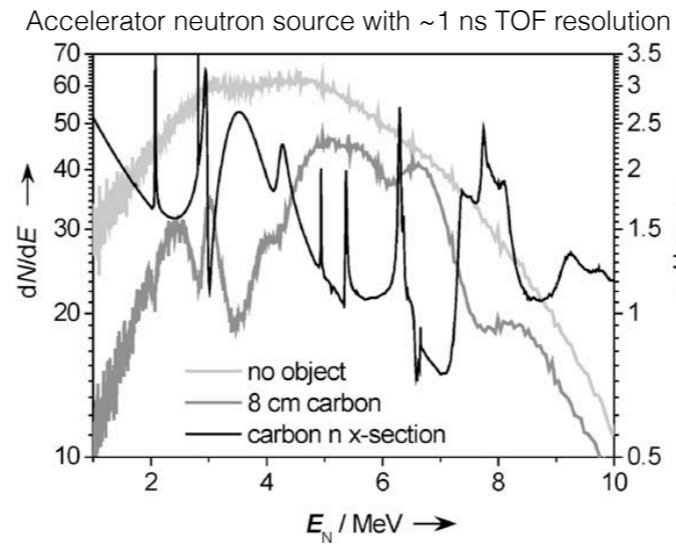
# Compact neutron sources

## Highly penetrating

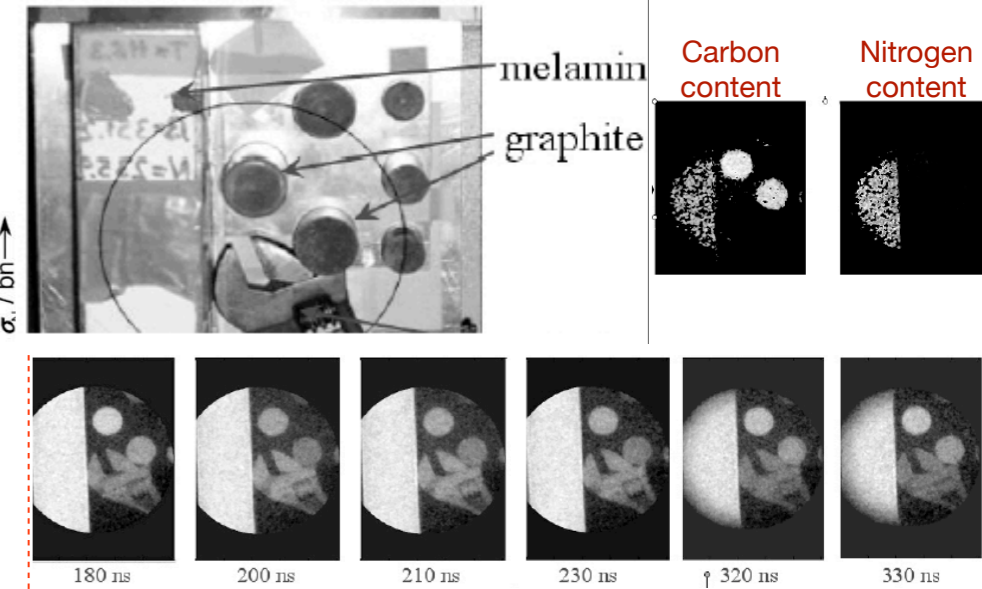


GKSS, Geesthacht

## Material selective (fast neutron radiography)

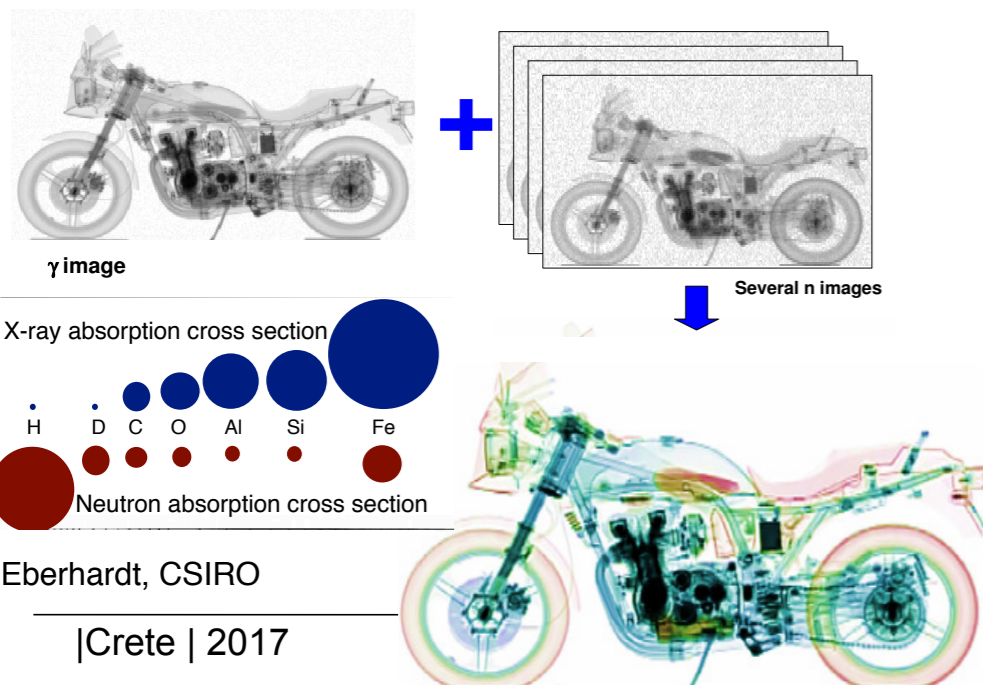


Ishay Pomerantz / U. Texas



Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

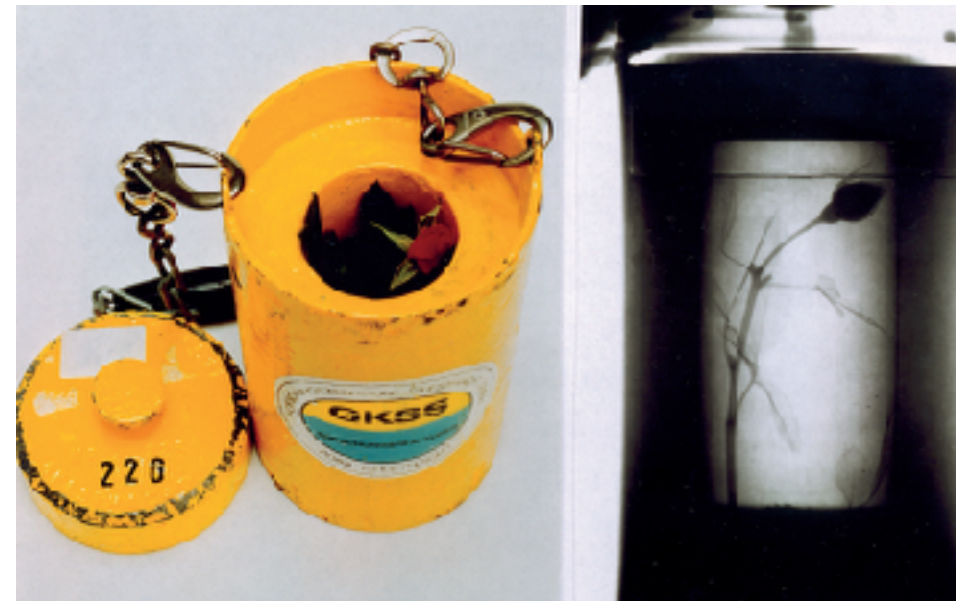
## Complementary to X-rays



Eberhardt, CSIRO

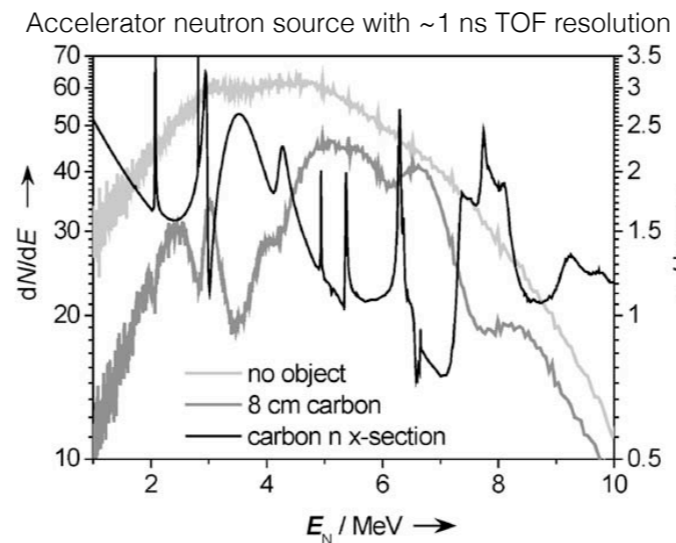
# Compact neutron sources

## Highly penetrating

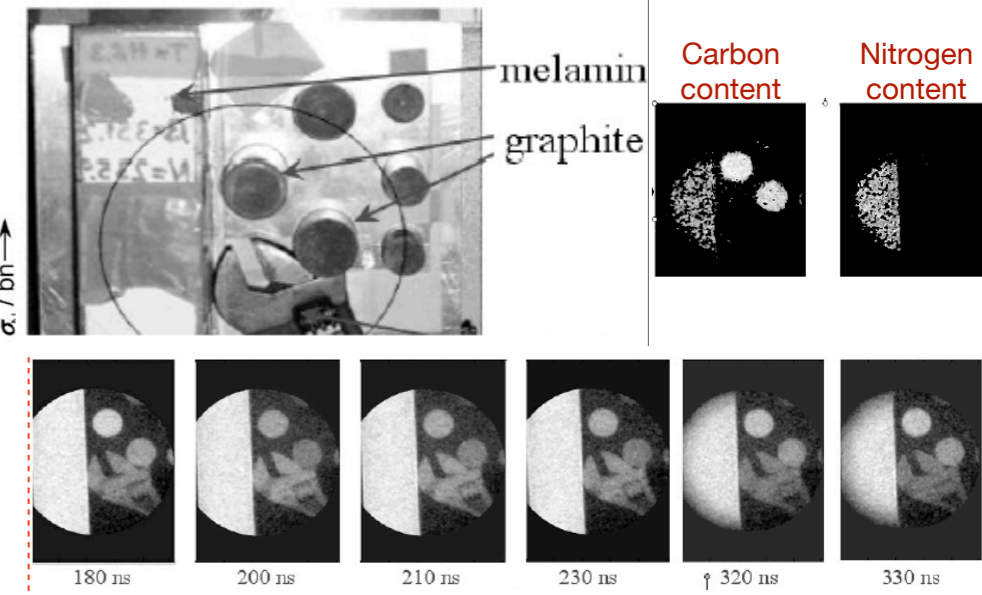


GKSS, Geesthacht

## Material selective (fast neutron radiography)

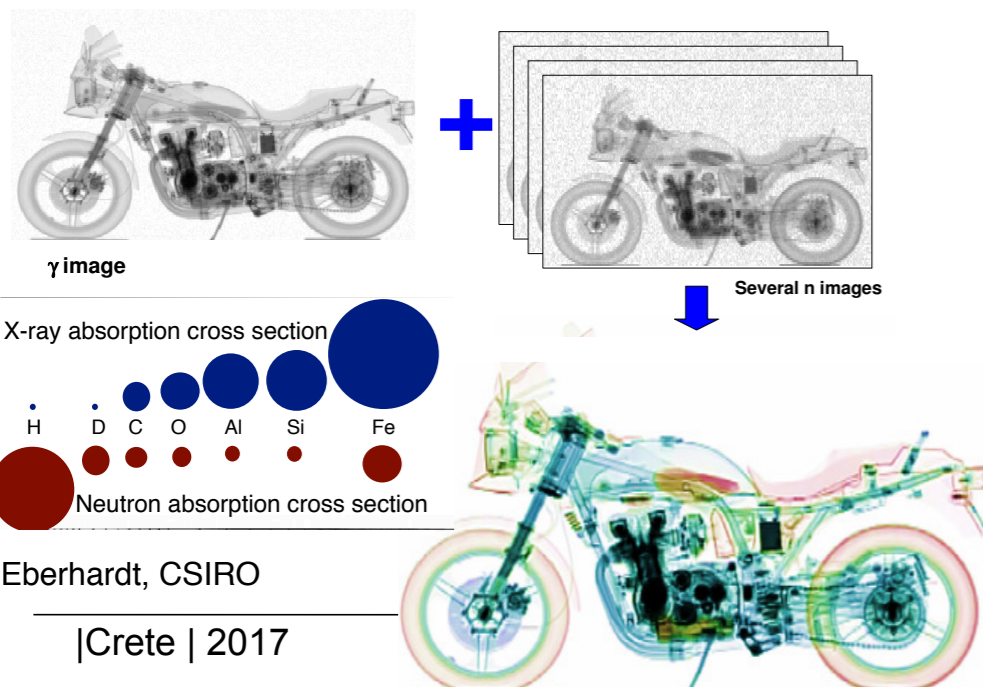


Ishay Pomerantz / U. Texas

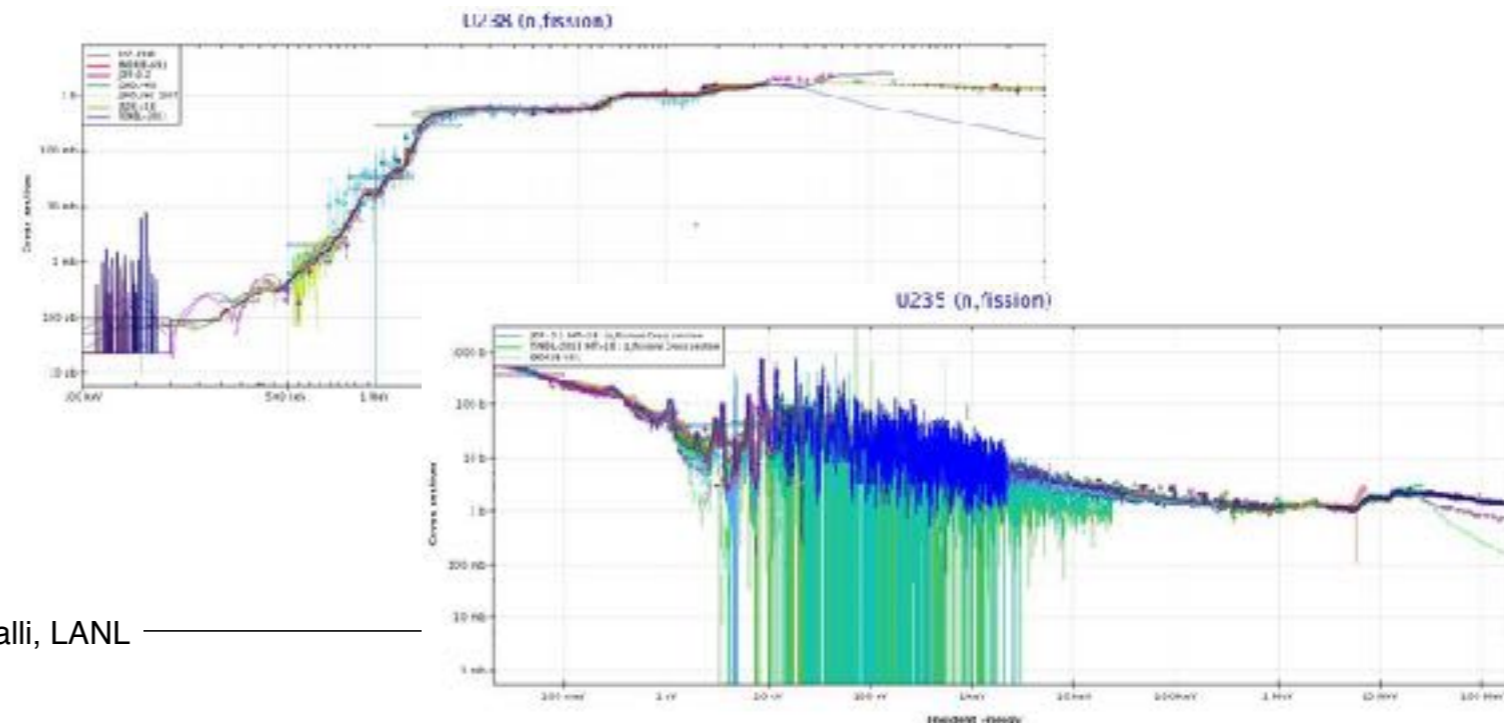


Vartsky, D. et al. Nuclear Instruments and Methods A623, 603–605 (2010)

## Complementary to X-rays



## Activating fissible material



A. Favalli, LANL

# Compact neutron sources

IAEA-TECDOC-1439

## ***Development opportunities for small and medium scale accelerator driven neutron sources***

*Report of a technical meeting  
held in Vienna, 18–21 May 2004*



**IAEA**  
International Atomic Energy Agency

February 2005

*Development opportunities for small scale and medium scale accelerator driven neutron sources [IAE04]:*

*Foreword: „[...] Small and medium power spallation sources will become more important as many small neutron producing research reactors are being phased out. [...] In addition to basic research these alternate neutron sources will be important for educational and training purposes. [...] Neutron applications in life sciences will be a rapidly growing research area in the near future. Neutrons can provide unique information on the reaction dynamics of complex biomolecular systems, complementing other analytical techniques such as microscopy, X rays and NMR. 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.“*

# Laser neutron sources

Compact sources from  
different mechanisms

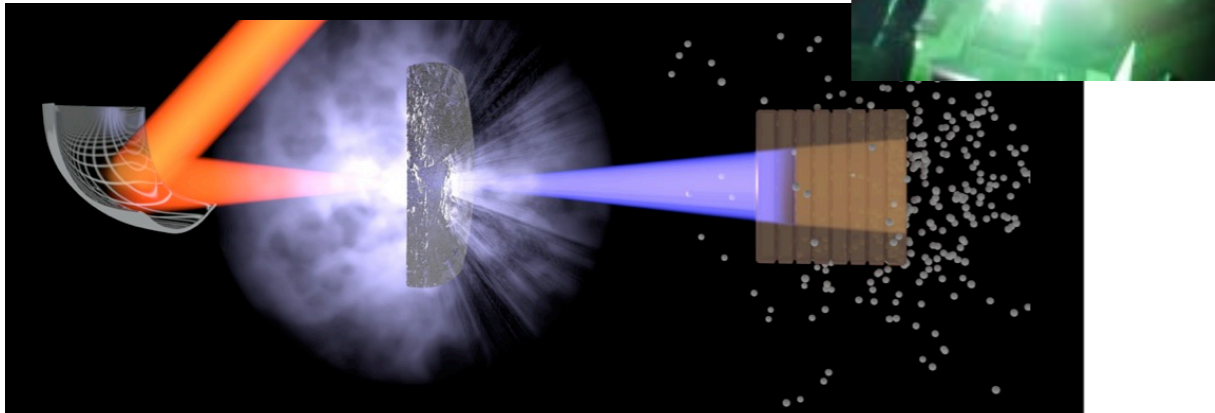
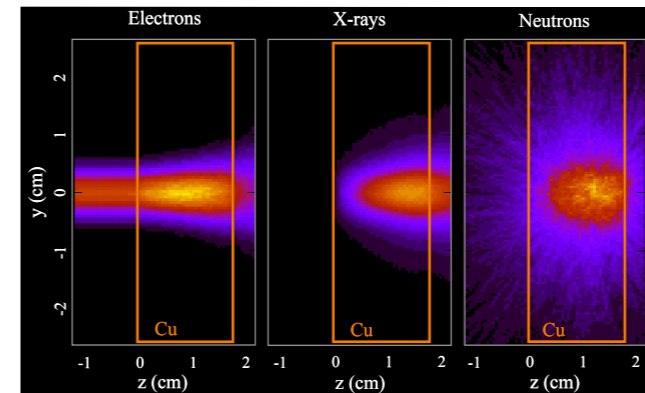
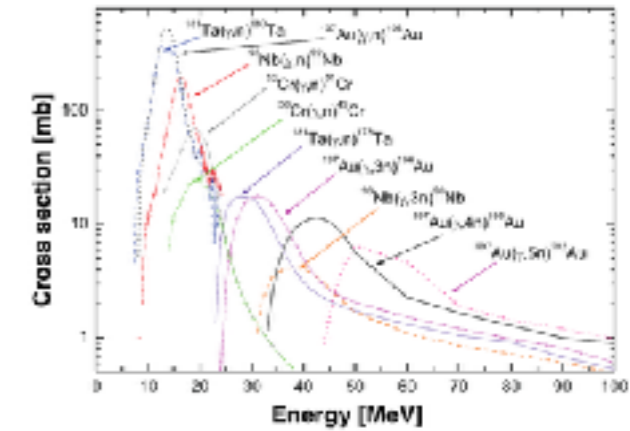


Photo-neutron production from electrons

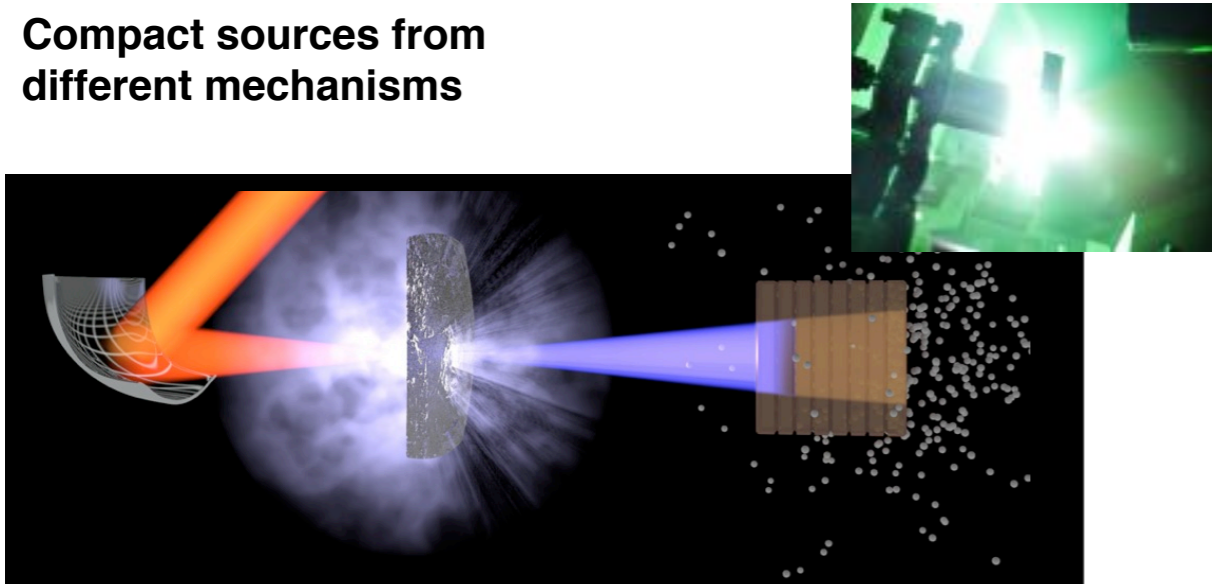


I. Pomerantz, UT

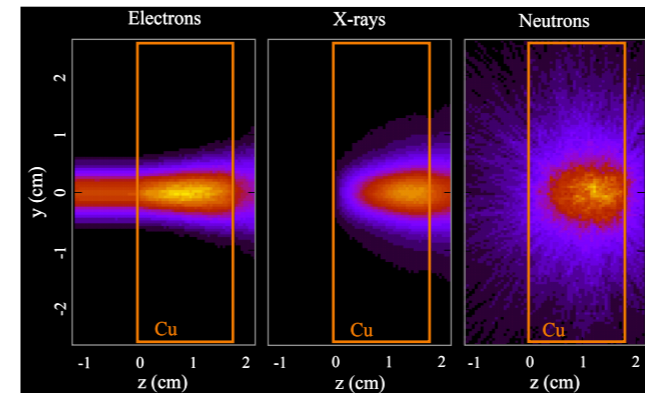


# Laser neutron sources

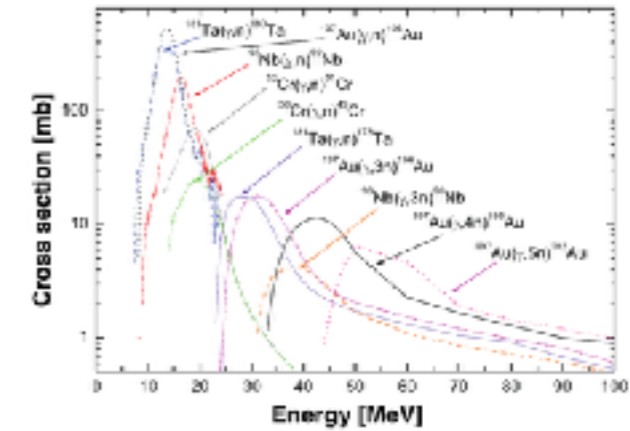
## Compact sources from different mechanisms



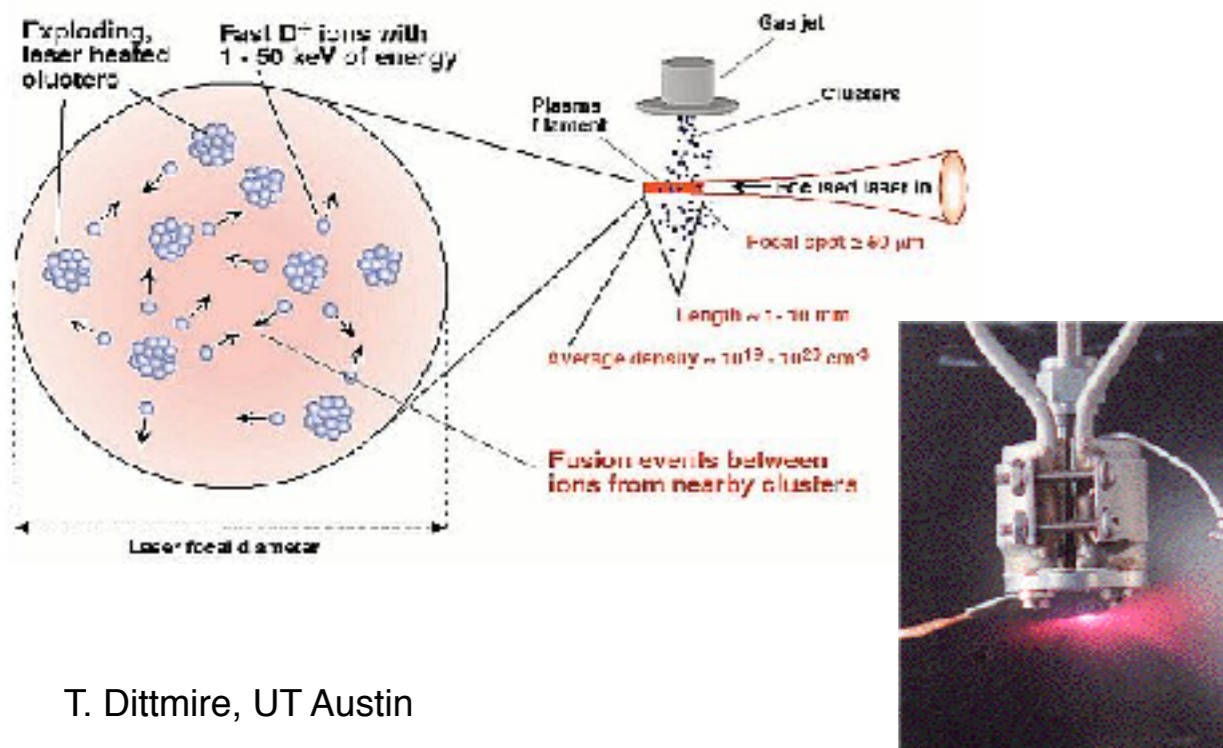
## Photo-neutron production from electrons



I. Pomerantz, UT



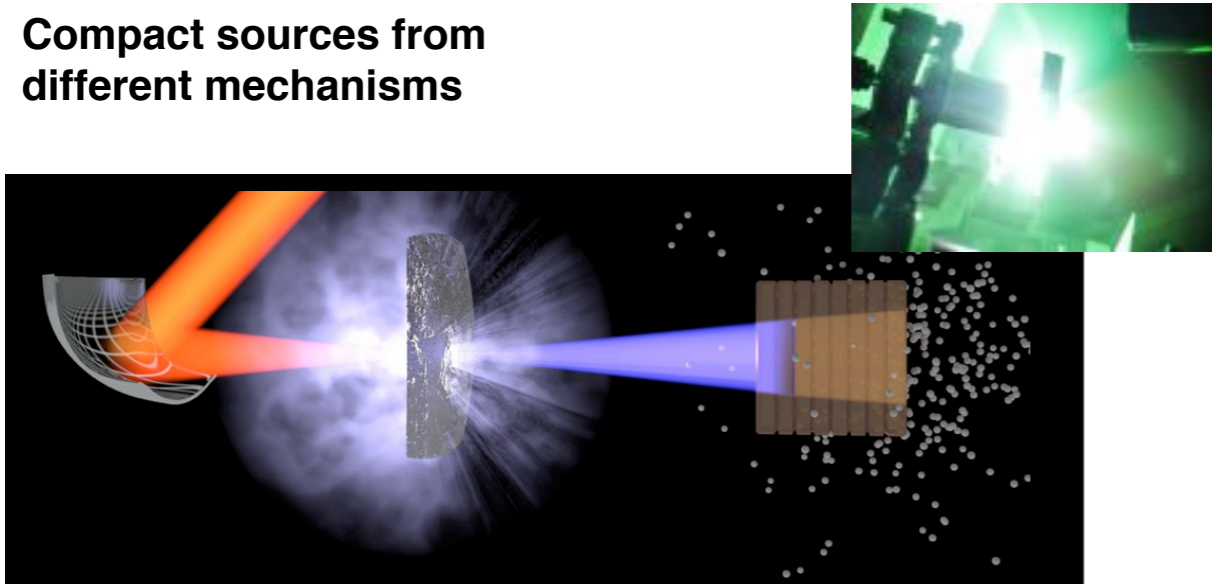
## Neutrons from cluster fusion



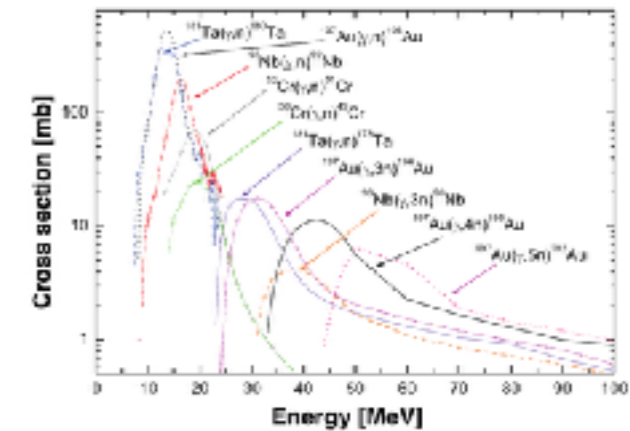
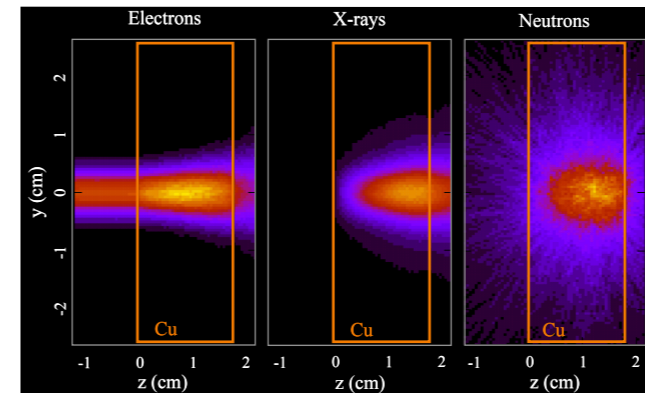
T. Ditmire, UT Austin

# Laser neutron sources

## Compact sources from different mechanisms

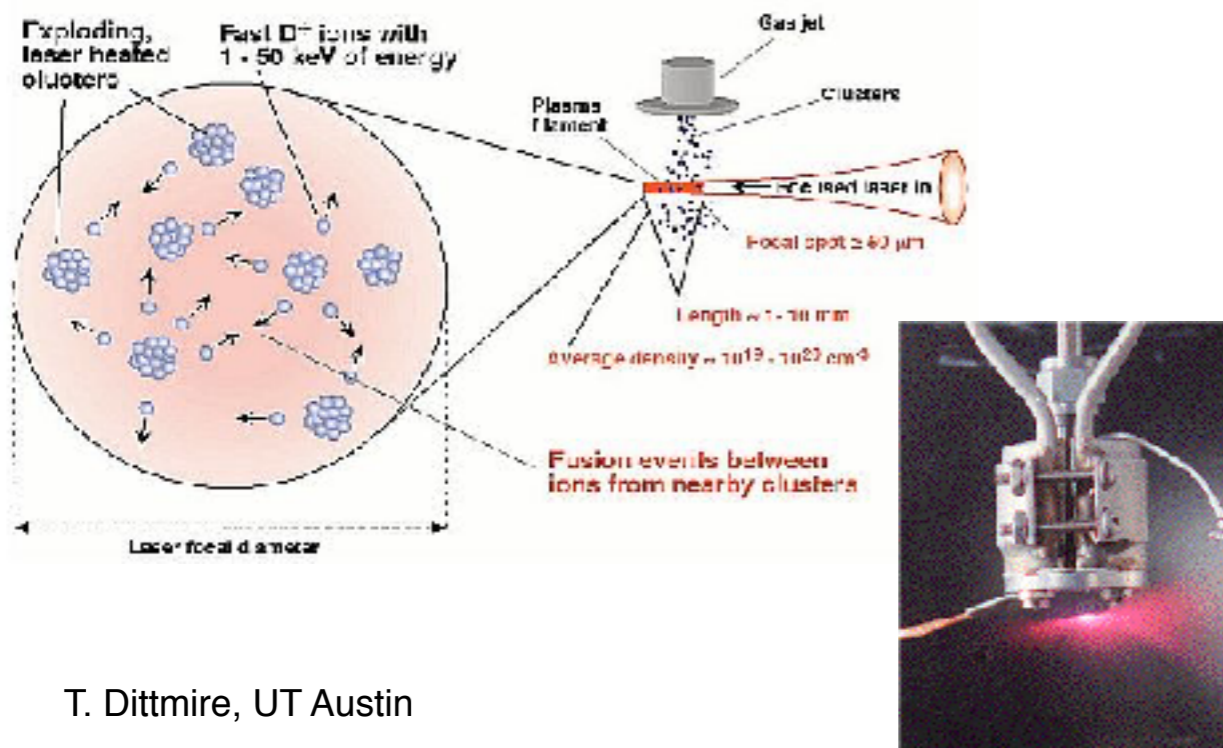


## Photo-neutron production from electrons

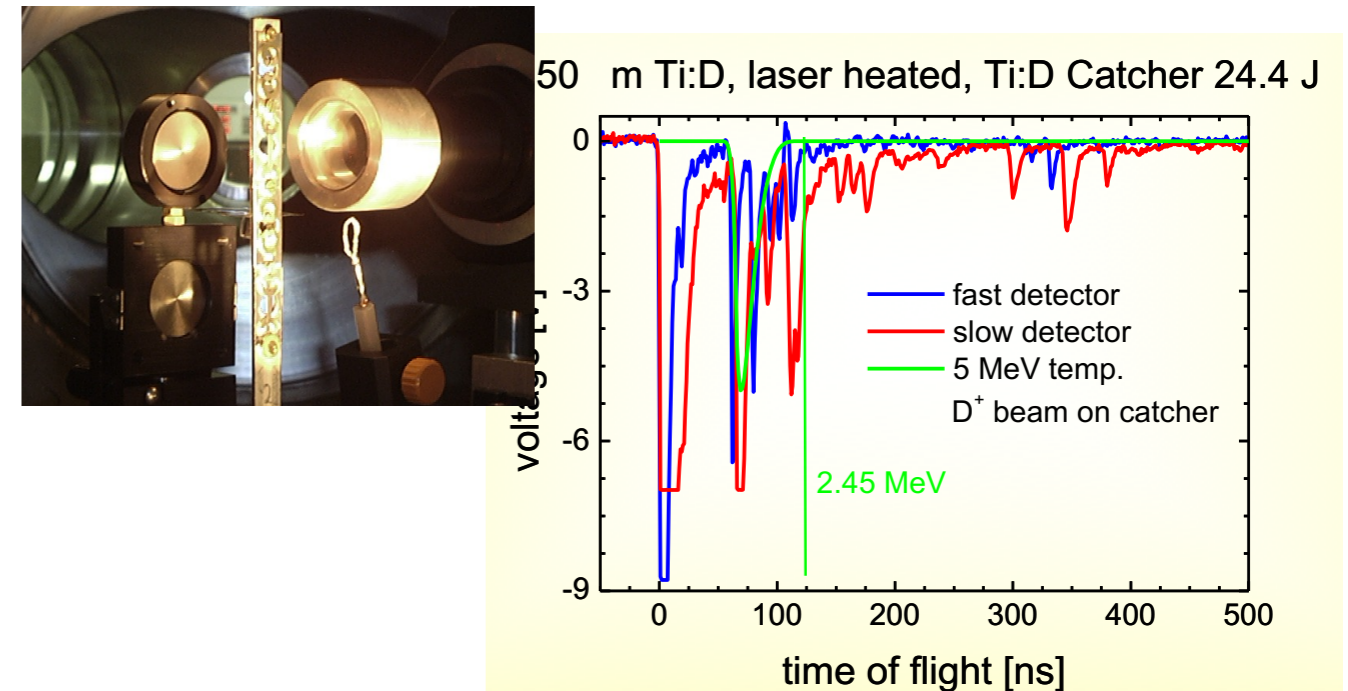


I. Pomerantz, UT

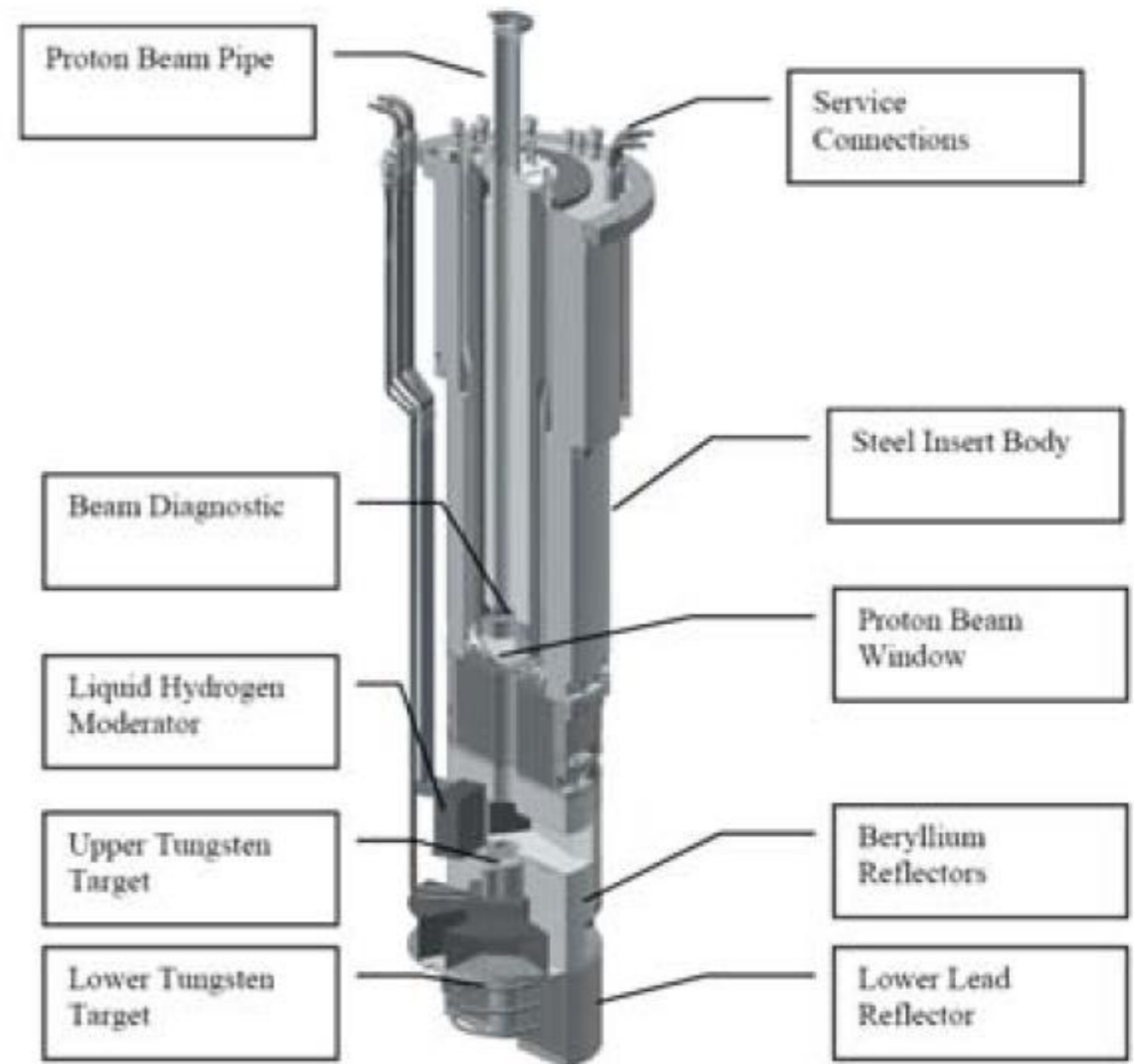
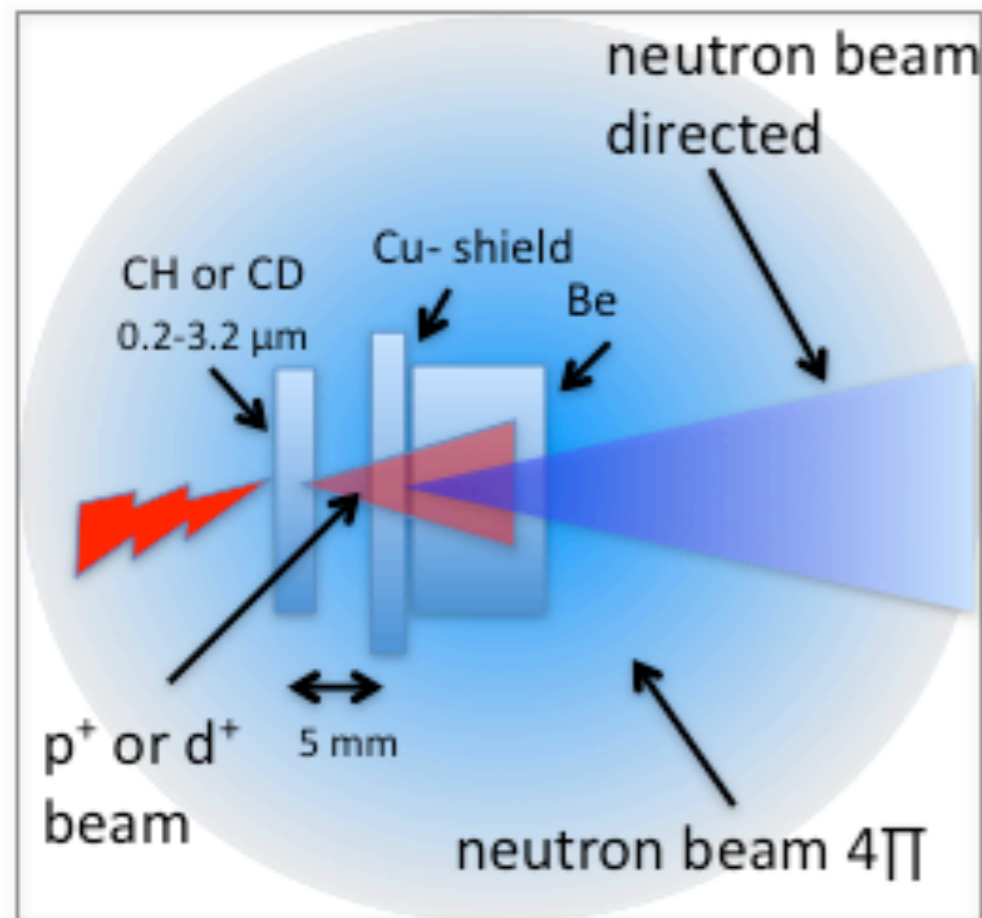
## Neutrons from cluster fusion



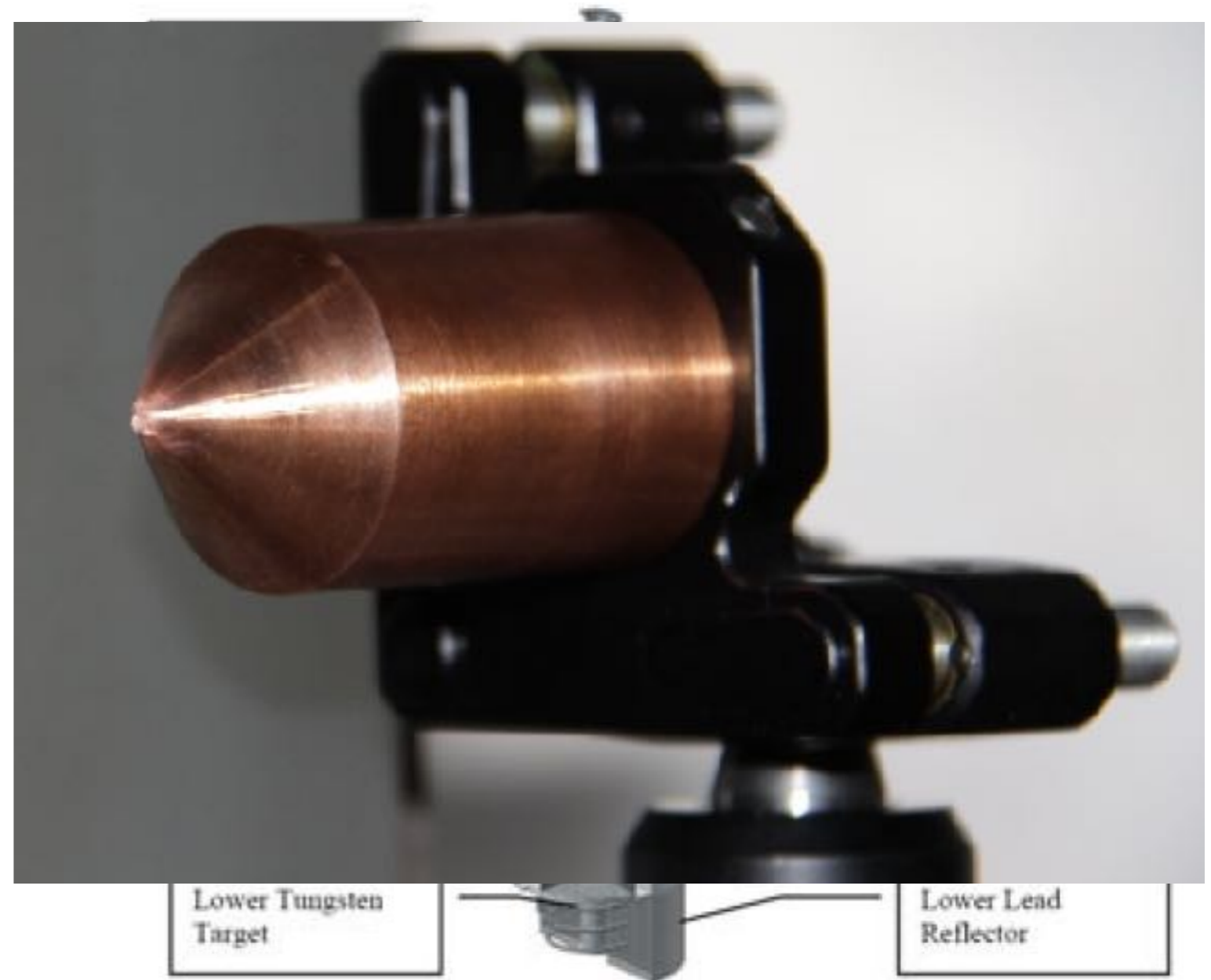
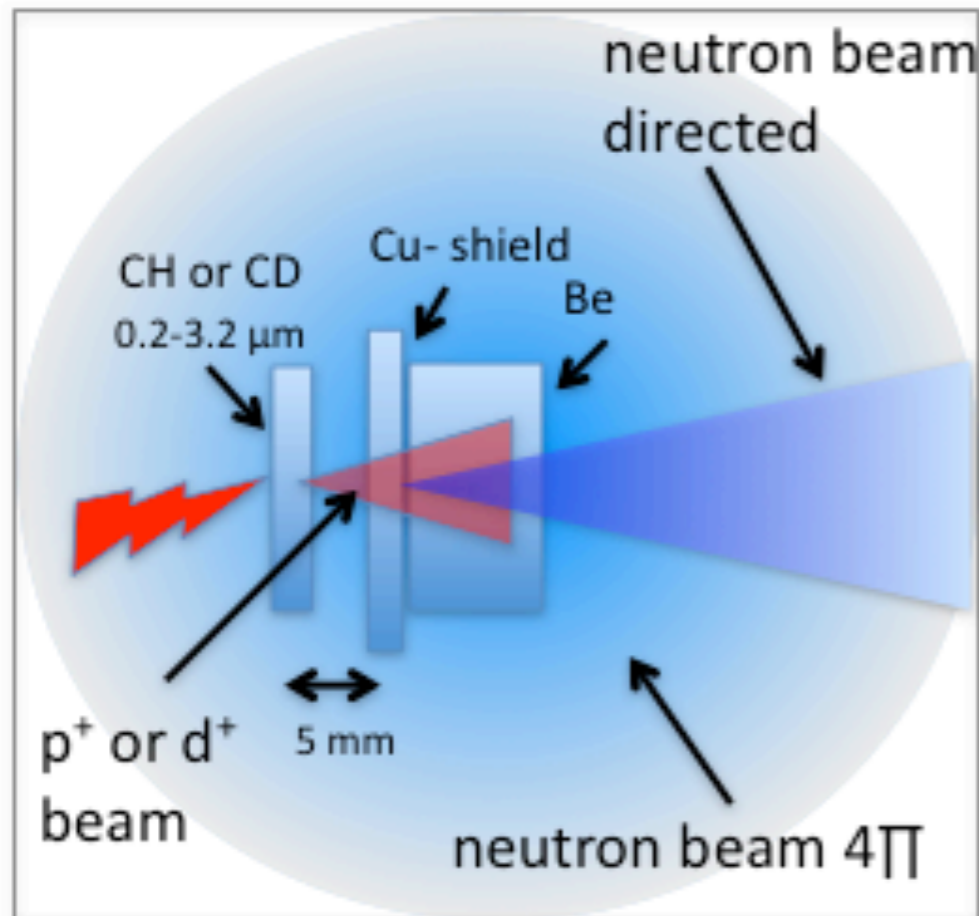
## Neutrons from ion impact



# Laser-driven neutron sources can be very compact



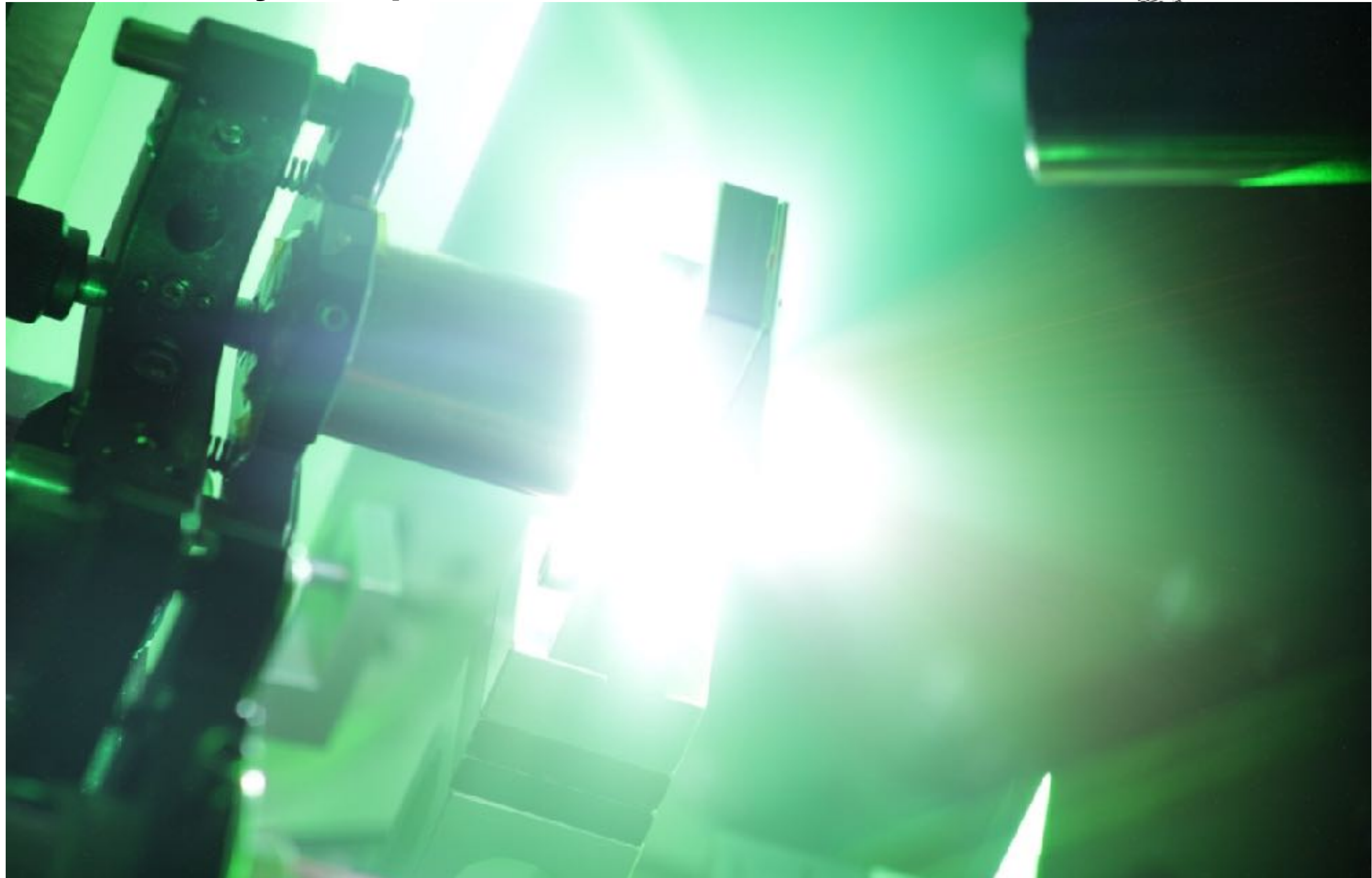
# Laser-driven neutron sources can be very compact



# Laser-driven neutron sources can be very compact



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# Neutron Economy at SNS

- 1.4 MW SNS produces:  $2 \times 10^{17}$  n/s
- Thermal neutrons at beamline start:  $2 \times 10^{12}$  n/s
- Neutrons at sample position (white):  $2 \times 10^{11}$  n/s
- Neutrons at sample (chopped):  $2 \times 10^{10}$  n/s
- Neutrons scattered:  $2 \times 10^8$  n/s
- Neutrons counted:  $5 \times 10^7$  n/s

Neutron counted/Neutrons produced:  $3 \times 10^{-10}$

# Previous attempts on laser driven neutron production (not including fusion)



PHYSICS OF PLASMAS 17, 100701 (2010)

## Laser generated neutron source for neutron resonance spectroscopy

D. P. Higginson,<sup>1,2</sup> J. M. McNaney,<sup>2</sup> D. C. Swift,<sup>2</sup> T. Bartal,<sup>1,2</sup> D. S. Hey,<sup>2</sup> R. Kodama,<sup>3,4</sup> S. Le Pape,<sup>2</sup> A. Mackinnon,<sup>2</sup> D. Mariscal,<sup>1</sup> H. Nakamura,<sup>3</sup> N. Nakanii,<sup>1,3,4</sup> K. A. Tanaka,<sup>3,4</sup> and F. N. Beg<sup>1</sup>

<sup>1</sup>Department of Mechanical and Aerospace Engineering, University of California-San Diego, La Jolla, California 92093, USA

<sup>2</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA

<sup>3</sup>Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>4</sup>Graduate School of Engineering, Osaka University, 2-1, Yamada-oka, Suita, Osaka 565-0871, Japan

(Received 6 May 2010; accepted 9 August 2010; published online 14 October 2010)

PHYSICS OF PLASMAS 18, 100703 (2011)

## Production of neutrons up to 18 MeV in high-intensity, short-pulse laser matter interactions

D. P. Higginson,<sup>1,2</sup> J. M. McNaney,<sup>2</sup> D. C. Swift,<sup>2</sup> G. M. Petrov,<sup>3</sup> J. Davis,<sup>3</sup> J. A. Frenje,<sup>4</sup> L. C. Jarrott,<sup>1</sup> R. Kodama,<sup>5</sup> K. L. Lancaster,<sup>6</sup> A. J. Mackinnon,<sup>2</sup> H. Nakamura,<sup>5</sup> P. K. Patel,<sup>2</sup> G. Tynan,<sup>1</sup> and F. N. Beg<sup>1</sup>

<sup>1</sup>Mechanical and Aerospace Engineering, University of California-San Diego, La Jolla, California 92093, USA

<sup>2</sup>Lawrence Livermore National Laboratory, Livermore, California 94440, USA

<sup>3</sup>Naval Research Laboratory, Plasma Physics Division, Washington, DC 20375, USA

<sup>4</sup>Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

<sup>5</sup>Institute of Laser Engineering, Osaka University, 2-5 Yamada-oka, Suita, Osaka 454-0871, Japan

<sup>6</sup>STFC Rutherford Appleton Laboratory, Chilton, Oxon OX110QX, United Kingdom

(Received 29 June 2011; accepted 29 September 2011; published online 24 October 2011)

PHYSICS OF PLASMAS

VOLUME 11, NUMBER 7

JULY 2004

## Characterization of ${}^7\text{Li}(p,n){}^7\text{Be}$ neutron yields from laser produced ion beams for fast neutron radiography

K. L. Lancaster,<sup>1,2</sup> S. Karsch,<sup>1</sup> H. Habara,<sup>1</sup> F. N. Beg,<sup>2</sup> E. L. Clark,<sup>2</sup> R. Freeman,<sup>3</sup> M. H. Key,<sup>4</sup> J. A. King,<sup>3,4</sup> R. Kodama,<sup>5</sup> K. Krushelnick,<sup>2</sup> K. W. D. Ledingham,<sup>6</sup> P. McKenna,<sup>6</sup> C. D. Murphy,<sup>1,2</sup> P. A. Norreys,<sup>1</sup> R. Stephens,<sup>7</sup> C. Stöeckl,<sup>8</sup> Y. Toyama,<sup>5</sup> M. S. Wei,<sup>2</sup> and M. Zepf<sup>9</sup>

<sup>1</sup>CCLRC Rutherford Appleton Laboratory, Chilton, Oxon OX11 0QX, United Kingdom

<sup>2</sup>The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

<sup>3</sup>Department of Applied Science, University of California, Davis, 1 Shields Ave., Davis, California

<sup>4</sup>Lawrence Livermore National Laboratory, Livermore, California 94550

<sup>5</sup>Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565, Japan

<sup>6</sup>Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom

<sup>7</sup>General Atomics, P.O. Box 85608, San Diego, California 92186-5608

<sup>8</sup>Laboratory of Laser Energetics, University of Rochester, Rochester, 250 E. River Road, New York 14623-1299

<sup>9</sup>Queens university of Belfast, Belfast BT7 1NN, United Kingdom

(Received 7 November 2003; accepted 7 April 2004; published online 27 May 2004)

IOP PUBLISHING

PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion 52 (2010) 045015 (15pp)

doi:10.1088/0741-3335/52/4/045015

## Neutron production from ${}^7\text{Li}(d,xn)$ nuclear fusion reactions driven by high-intensity laser-target interactions

J Davis<sup>1</sup>, G M Petrov<sup>1</sup>, Tz Petrova<sup>1</sup>, L Willingale<sup>2</sup>, A Maksimchuk<sup>2</sup> and K Krushelnick<sup>2</sup>

<sup>1</sup> Naval Research Laboratory, Plasma Physics Division, 4555 Overlook Ave SW, Washington, DC 20375, USA

<sup>2</sup> Center for Ultrafast Optical Science, University of Michigan, 2200 Bonisteel Blvd, Ann Arbor, MI 48109, USA

E-mail: jack.davis@nrl.navy.mil

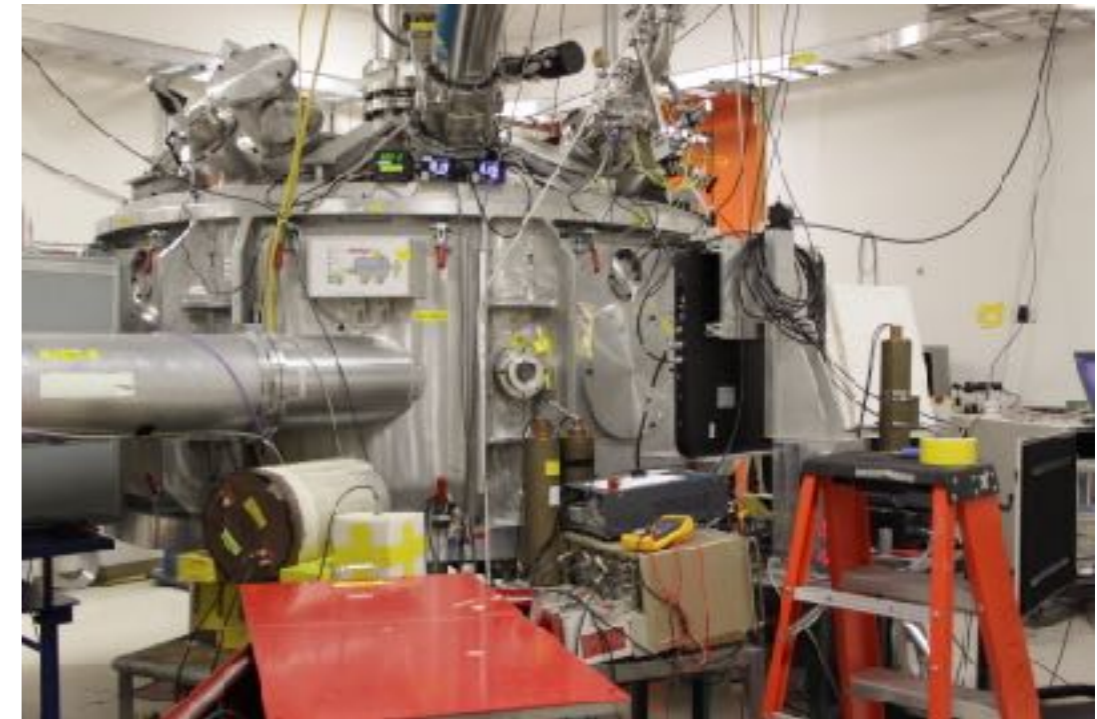
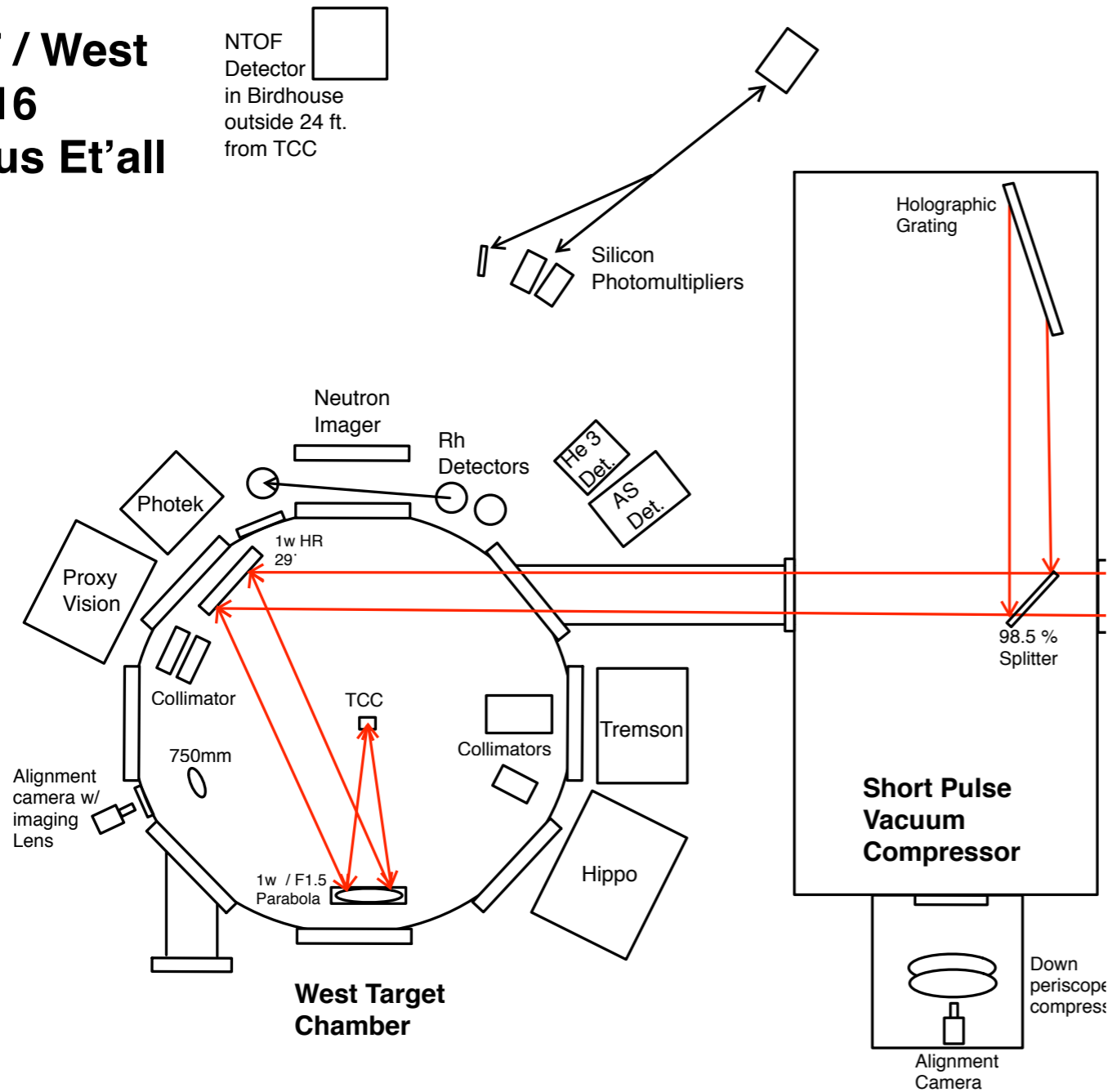
Received 22 December 2009, in final form 24 February 2010

Published 19 March 2010

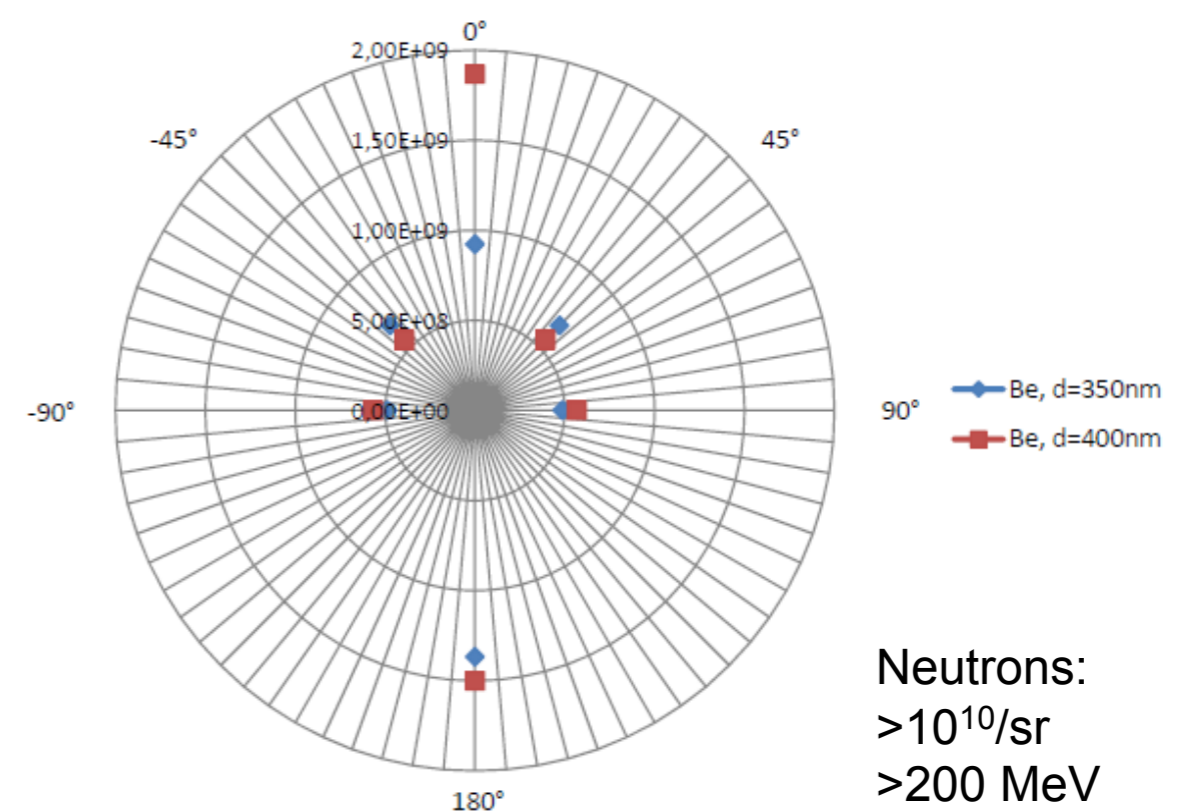
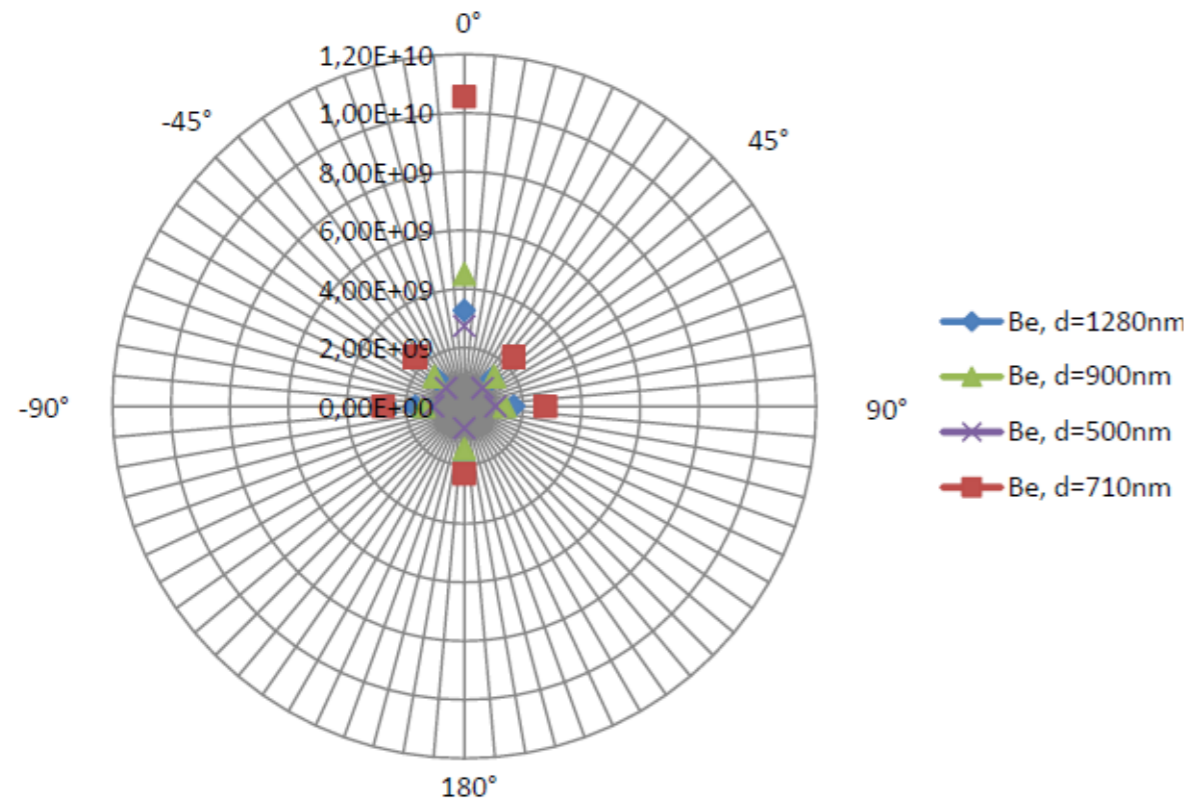
Online at [stacks.iop.org/PFCF/52/045015](http://stacks.iop.org/PFCF/52/045015)

# So what is the experimental status?

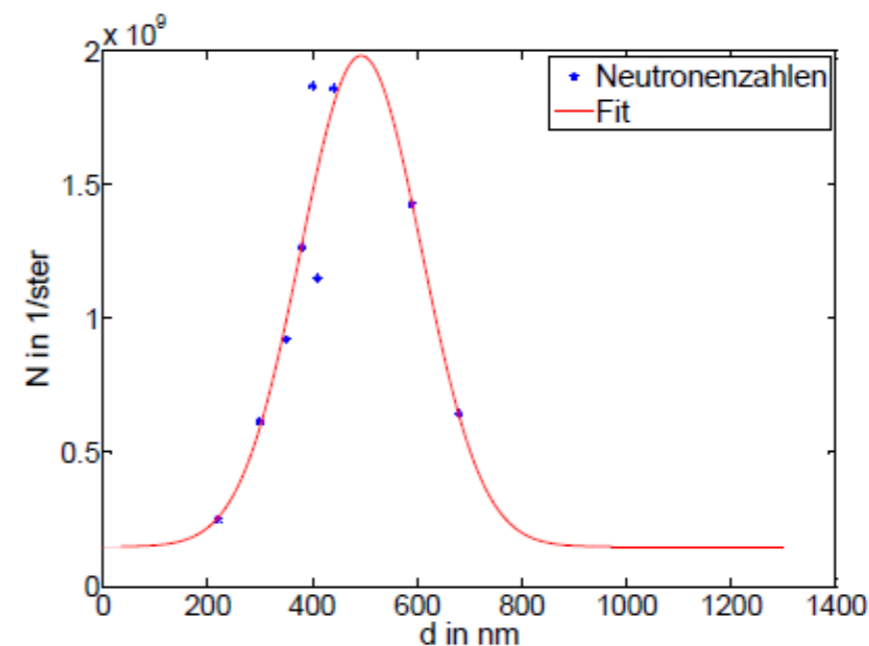
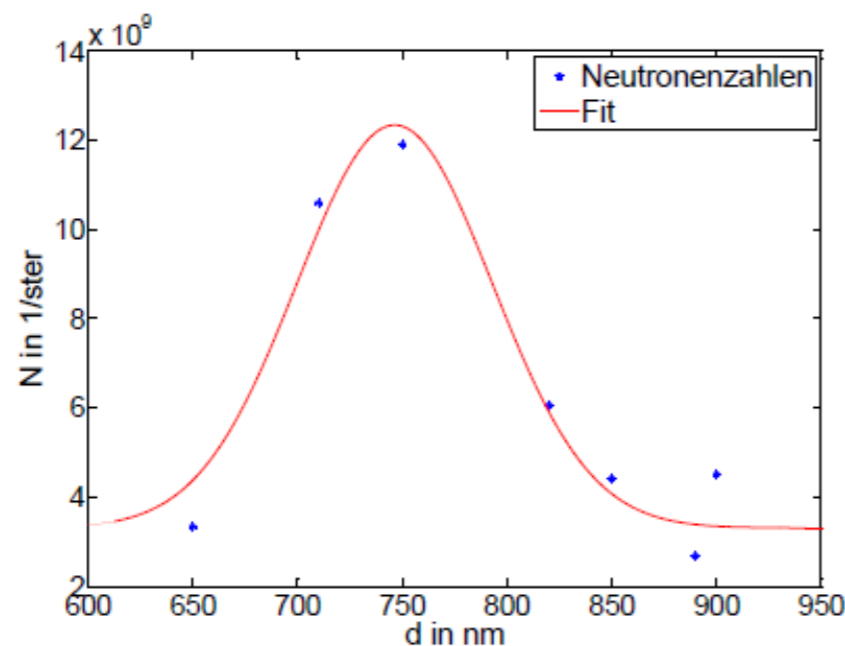
**NTTF / West**  
**6/27/16**  
**Marcus Et'all**



# For different laser intensities there is a strong optimum in target thickness, expected for BOA



Neutrons:  
>10<sup>10</sup>/sr  
>200 MeV  
Peak @ 70 MeV



60 J of Laser energy  
1x10<sup>21</sup> W/cm<sup>2</sup>

# For different laser intensities there is a strong optimum in target thickness, expected for BOA



## Neutron-beam performance @ Trident & PHELIX lasers greatly exceeds that of work elsewhere.

neutrons

Table 1 from review by A. Alejo, *et al.*, II  
Nuovo Cimento **38 C** (2015) 188

Ref.	Laser E (J)	L. Inten. (W/cm <sup>2</sup> )	On axis n-flux (n/sr)	Flux/E laser (n/sr/J)
1	1	2.0×10 <sup>21</sup>	3.0×10 <sup>6</sup>	2.7×10 <sup>6</sup>
2	6	2.0×10 <sup>19</sup>	1.2×10 <sup>4</sup>	2.0×10 <sup>3</sup>
3	6	2.0×10 <sup>19</sup>	4.0×10 <sup>5</sup>	6.7×10 <sup>4</sup>
4	69	2.0×10 <sup>19</sup>	2.0×10 <sup>8</sup>	2.9×10 <sup>6</sup>
<b>5</b>	<b>80</b>	<b>8.0×10<sup>20</sup></b>	<b>1.0×10<sup>10</sup></b>	<b>1.3×10<sup>8</sup></b>
6	127	7.0×10 <sup>20</sup>	3.5×10 <sup>8</sup>	2.8×10 <sup>6</sup>
7	150	2.0×10 <sup>20</sup>	1.0×10 <sup>9</sup>	6.7×10 <sup>6</sup>
8	360	2.0×10 <sup>19</sup>	7.5×10 <sup>8</sup>	2.1×10 <sup>6</sup>

1. C. Zulick, *et al.*, Appl. Phys. Lett. **102**, 124101 (2013)
2. L. Willingale, *et al.*, Phys. Plasmas **18**, 083106 (2011)
3. A. Maksimchuk, *et al.*, Appl. Phys. Lett. **102**, 191117 (2013)
4. K. Lancaster, *et al.*, Phys. Plasmas **11**, 3404 (2004)
5. **M. Roth, *et al.* PRL **110**, 044802 (2013) – early work @ Trident**
6. D. P. Higginson, *et al.*, Phys. Plasmas **18**, 100703 (2011)
7. S. Kar, *et al.*, New J. Phys. **18**, 053002 (2016)
8. G. Petrov, *et al.*, Phys. Plasmas **19**, 093106 (2012)

- Performance @ LANL Trident laser: > 10<sup>10</sup> n/steradian in ~ 1 steradian, 10-100 x better than any comparable or larger shot-pulse laser
- Reason: a better D-beam generated with the Breakout Afterburner (BOA) mechanism pioneered at LANL (and good TNSA beams too!)

# Echo of the publication...

## Bright Laser-Driven Neutron Source Based on the Relativistic Transparency of Solids

M. Roth,<sup>1,2</sup> D. Jung,<sup>2</sup> K. Falk,<sup>2</sup> N. Guler,<sup>2</sup> O. Deppert,<sup>1</sup> M. Devlin,<sup>2</sup> A. Favalli,<sup>2</sup> J. Fernandez,<sup>2</sup> D. Gautier,<sup>2</sup> M. Geissel,<sup>3</sup> R. Haight,<sup>2</sup> C. E. Hamilton,<sup>2</sup> B. M. Hegelich,<sup>2</sup> R. P. Johnson,<sup>2</sup> F. Merrill,<sup>2</sup> G. Schaumann,<sup>1</sup> K. Schoenberg,<sup>2</sup> M. Schollmeier,<sup>3</sup> T. Shimada,<sup>2</sup> T. Taddeucci,<sup>2</sup> J. L. Tybo,<sup>2</sup> F. Wagner,<sup>1</sup> S. A. Wender,<sup>2</sup> C. H. Wilde,<sup>2</sup> and G. A. Wurden<sup>2</sup>  
<sup>1</sup>Institut für Kernphysik, Technische Universität Darmstadt, Schloßgartenstrasse 9, D-64289 Darmstadt, Germany  
<sup>2</sup>Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA  
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 (Received 6 November 2012; published 24 January 2013)

Neutrons are unique particles to probe samples in many fields of research ranging from biology to material sciences to engineering and security applications. Access to bright, pulsed sources is currently limited to large accelerator facilities and there has been a growing need for compact sources over the recent years. Short pulse laser driven neutron sources could be a compact and relatively cheap way to produce neutrons with energies in excess of 10 MeV. For more than a decade experiments have tried to obtain neutron numbers sufficient for applications. Our recent experiments demonstrated an ion acceleration mechanism based on the concept of relativistic transparency. Using this new mechanism, we produced an intense beam of high energy (up to 170 MeV) deuterons directed into a Be converter to produce a forward peaked neutron flux with a record yield, on the order of  $10^{10}$  n/sr. We present results comparing the two acceleration mechanisms and the first short pulse laser generated neutron radiograph.

DOI: 10.1103/PhysRevLett.110.044802 PACS numbers: 29.25.Dz, 52.38.Kd, 52.50.Jm, 52.59.-f

## Science Highlights (04-03-13)

The Joint DoD/DOE Munitions Program (Thomas Mason, LANL Joint Munitions Program Manager) funded the work, which supports the Lab's Global Security and Nuclear Deterrence mission areas and the Materials for the Future Science Pillar. Technical contact: *J. Pablo Escobedo*

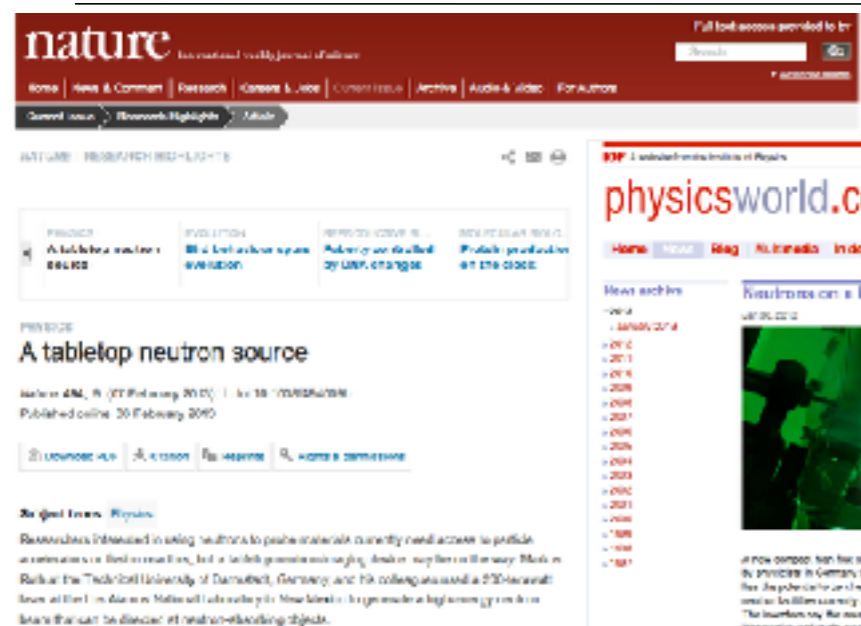
### LEAR ENGINEERING AND NONPROLIFERATION

**nuclear material detection by one short-pulse laser-driven neutron source**  
 et of experimental campaigns in 2012, scientists working at the Lab's Trident laser system created a world's record for short-pulse laser-generated neutron flux. The team produced the beam by sending pulses into a deuterium-rich plastic target, knocking deuterons (consisting of a proton and a neutron) into a beryllium rod that then shot neutrons forward. The technique used less than one-quarter laser energy and generated an order of magnitude more neutrons in a forward directed beam than previous methods. One of the main motivations to develop a bright pulsed neutron source is for the assay of nuclear materials for accountability, safeguards, and security. An intense neutron burst offers potential for a high signal-to-noise ratio in difficult to measure cases (for example, the high passive ion rate of spent fuel) and the important prospect of a short assay time for high item throughput. Building on this success in generating a neutron flux at the Trident laser, A. Favalli and M. Swinhoe Guards Science and Technology, NEN-1) led a team that has made the first experimental demonstration of active interrogation of nuclear material by a short-pulse laser-driven neutron source.

Researchers conducted an experimental campaign at the Lab's Trident Facility to explore: 1) the ability of active interrogation of nuclear material by a laser-driven neutron source, and 2) the ongoing problem of active interrogation of nuclear material by a single pulse. The scientists chose delayed neutrons as the signature for nuclear material because these neutrons are characteristic signatures for nuclear fissions (very few other processes yield delayed neutrons). The detection system consisted of two identical neutron detector well counters. One detector contained a 2 kg sample of depleted uranium, and the other one was empty for background comparison. The team used the neutrons generated from the laser pulse to induce fission in uranium and detect the resultant delayed neutrons. A single shot interrogation of the depleted uranium sample revealed a clear signal from the delayed neutrons in the detector with uranium, compared with the background, and with the typical time behavior of delayed neutrons.

Trident laser shot.

The team includes M. Roth (Technical University of Darmstadt and Experimental Physical Sciences, P-5), J. S. Bridgewater, A. Favalli, D. Henzlova, K. Ianakiev, M. Iliev, and M. Swinhoe (Safeguards and Technology, NEN-1); K. Falk, J. Fernandez, D. Gautier, R. P. Johnson, D. Jung, and T. Shimada (Plasma Physics, P-24); N. Guler (Neutron Science and Technology, P-23); C. E. Hamilton (Materials and Coatings, MST-7), and S. Croft (Oak Ridge National Laboratory).



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**A tabletop neutron source**  
 Nature 494, 9 (27 February 2013) | doi:10.1038/nature12100  
 Published online: 30 February 2013

**Physics**  
 A tabletop neutron source

**Research Highlights**  
 Evolution of the electron spin Hall effect  
 Polymerization of a protein  
 Protein production at the atomic level

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 Neutrons on a lab bench

**Neutrons on a lab bench**  
 A new compact, high flux source of energetic neutrons has been built by physicists in Germany and the US. The new tabletop device has the potential to be used in a wide range of applications, from materials science to nuclear physics. It will also be used to study the structure of materials.

**Frontiers**  
 In brief  
 Emitting indistinguishable electrons

**TRIDENT**



**Forbes**  
 New Posts Most Popular Lists  
 William Pentland, Contributor  
 I write about energy and environmental issues.  
 Follow (242)

**Small, Laser-Beam Box Detects Clandestine Nuclear Materials**  
 Comment Now Follow Comments  
 More bad news today for bad guys. The scientific brain trust at the Los Alamos National Laboratory in New Mexico has discovered a powerful new method for detecting clandestine nuclear materials.

**In February, an international team of researchers used laser-driven neutrons to confirm the presence and quantity of nuclear material inside of a closed container. The experiment is likely to lead to the development of nuclear material detection systems that could be used to catch nuclear smugglers.**

**So what is a laser-driven neutron pulse?**  
 It is a neutron beam generated by shooting a short-pulse laser at an ultra-thin plastic foil. The pulse contains about 10 times more energy than the entire production of worldwide electrical power. The pulse lasts for...

**BRENNPUNKT**  
 ■ Mit Terawatt zu Teilchenstrahlen

Hochleistungslaser versprechen kompakte und günstige Teilchenbeschleuniger für verschiedene Anwendungen.

Während der letzten Jahre haben sich Hochleistungslaser rasant entwickelt. Solche Lasersysteme erzeugen Pulse, die – je nach verwendetem aktivem Lasermedium – zwischen 25 und etwa 1000 Femtosekunden dauern. Innerhalb dieser kurzen Zeit transportieren sie Energien von einigen bis hin zu mehreren 100 Joule, sodass Spitzenleistungen von einigen 10 Terawatt bis hin zu 1 Petawatt möglich sind. Fokussiert auf wenige  $\mu\text{m}^2$ , entstehen so Spitzenintensitäten von  $10^{21}$  W/cm<sup>2</sup> und mehr. Die damit verbundenen elektrischen Felder reichen aus, um Materie im Fokus des Lasers zu ionisieren und die dabei frei werdenden Elektronen innerhalb des Bruchteils einer Schwingungsperiode des Lichts nahezu auf Lichtgeschwindigkeit zu beschleunigen. Die naheliegende Idee, diese immensen Felder zur Beschleunigung geladener Teilchen zu verwenden und damit deutlich kompaktere Beschleuniger als die konventionellen zu bauen, ist ein Motor für die weltweite Forschung mit diesen Lasern. Kürzlich ist es einem internationalen Forscherteam in einem zweistufigen Prozess gelungen, erstmals brillante Neutronenstrahlen mit kinetischen Energien von bis zu 150 MeV und einem maximalen Neutronenfluss von bis zu  $10^{10}$  n/sr pro Puls zu erzeugen und damit Materialien zu untersuchen [1]. Bereits zuvor hatte ein Münchner Team gezeigt, dass sich mit laserbeschleunigten Protonen von einigen MeV grundsätzlich Tumorzellen bestrahlen lassen [2]. Die Felder der Laser sind zwar um mehrere Größenordnungen höher als diejenigen in konventionellen Beschleunigern, da sie aber mit der Frequenz des Lichts oszillieren, ändert sich auch die Beschleunigungsrichtung der geladenen Teilchen periodisch, sodass sich mit den Feldern nicht direkt gerichtete und kollimierte Teilchenstrahlen erzeugen lassen. Anders ist die Situation, wenn ein Laserpuls auf eine dünne Folie fällt und dabei das Material ionisiert. Die Elektronen des entstehenden Plasmas ist so hoch, dass das Licht nicht mehr in die Folie eindringen kann, sondern auf der Vorderseite bei Erreichen einer kritischen Dichte  $n_c$  zum Teil absorbiert oder reflektiert wird. Anschaulich kann hierbei der Lichtdruck (präziser: die ponderomotive Kraft des Laserpulses) die Elektronen in die ionisierte Targetfolie hineindrücken. Die mit der Ladungstrennung verbundenen elektrischen Felder beschleunigen dann auch die positiven Ionen. Spezielle Folien, die nur wenige Nanometer dick sind, z. B. Diamant-ähnliche Kohlenstoff-folien (DLC-Folien), haben es in der jüngsten Vergangenheit erlaubt, mit Hochleistungslasern sehr effizient Ionenstrahlen mit kinetischen Energien von 10 bis über 100 MeV zu erzeugen [3–4]. Bei so dünnen Folien ist entscheidend, dass der Kontrast des Laserpulses möglichst hoch ist, d. h. die Intensität bis zu wenigen Pikosekunden vor dem Hauptpuls möglichst niedrig bleibt. Ansonsten stören solche Vorpulse den Beschleunigungsvorgang [5].

Auf diese Weise erzeugte Ionenstrahlen wurden jetzt erfolgreich für erste Anwendungen verwendet. Zur Erzeugung eines intensiven Neutronenstrahls hat ein internationales Team aus Forschern der TU Darmstadt sowie der Natis Laboratories von Los Alamos Sandia in den USA das Laser-TRIDENT in Los Alamos verwendet, um zunächst Deuteronen beschleunigen, die aus einem Rytillium-Konverter die gewünschten Neutronen heraus schlagen [1], der 200-TW-Laserpuls auf eine dünne Folie aus drittem Plastik (CDs), so beschriftet er die Elektronen über die Querschnittsfläche des Laserpuls auf hochrelativistische Energie. Die relativistische Massezunahme der Elektronen und die damit verbundene Erhöhung der kritischen Dichte  $n_c$  machen die Folie bei im Verlauf des Laserpulses für Laserlicht transparent, sodass der Puls über die restliche Dauer seiner Energie nicht nur auf der Folie vordringt, sondern auch im Inneren der beschleunigten Elektronen erzeugen elektrische Felder, die wiederum die zugehörigen positiven Ionen auf Energien von mehr als 100 MeV beschleunigen. Auf diese Weise entstand ein Deuteronenstrahl, der auf ein Beryllium-Konverter gelenkt wurde. Niedrige Deuteronenergie führen über <sup>9</sup>Be(d,n)-Reaktion zu einem Neutronenpuls mit isotroper Richtungsverteilung, während bei Energien über 150 MeV durch „break-up Reaktionen“ Deuteronen der Neutronenstrahl vorwärts gerichtet ist (Abb. 1). Ionenenergiequelle hat – aufgrund der Divergenz des Deuteronenstrahls und des Abstands zwischen Laserpuls und Konverter – einen Durchmesser von ca. 3 mm, die erzeugte Neutronenpulse auf Flugzeitdifferenzen einer Dauer etwa 250 ps. Erste Radiographien Aufnahmen unterschiedlicher Materialien mit diesem Neutronenstrahl.

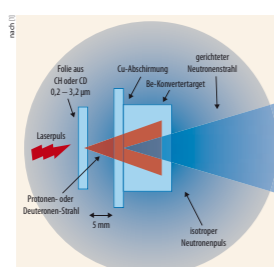
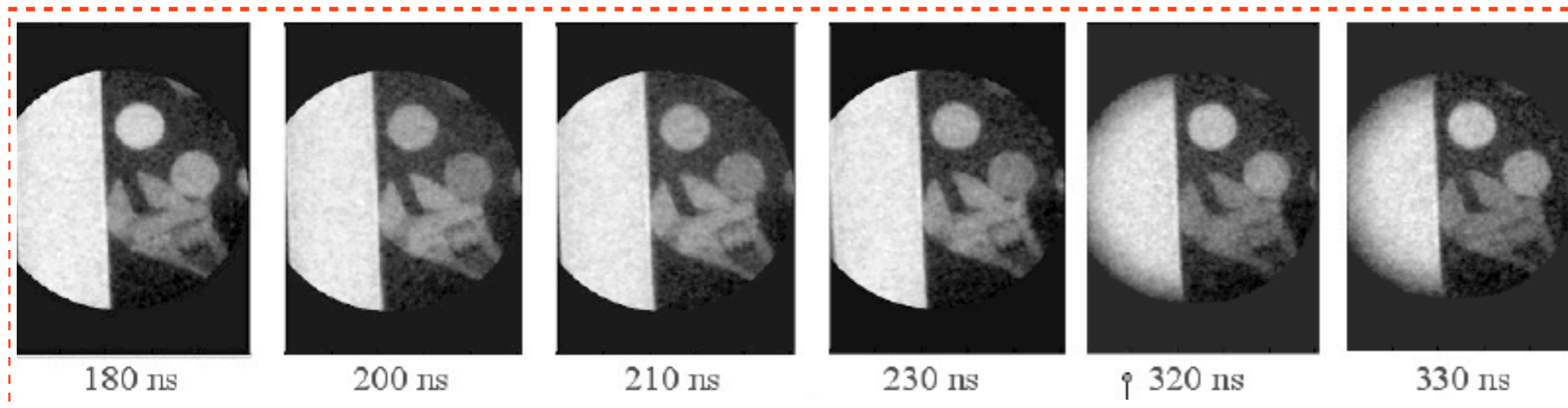
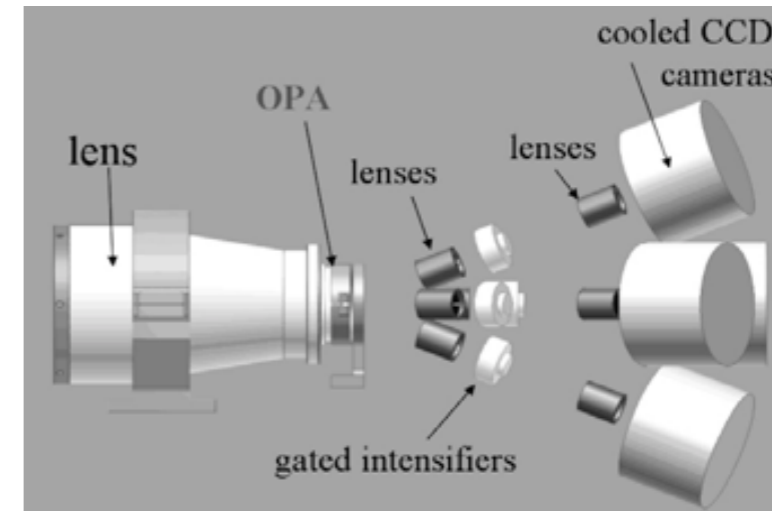
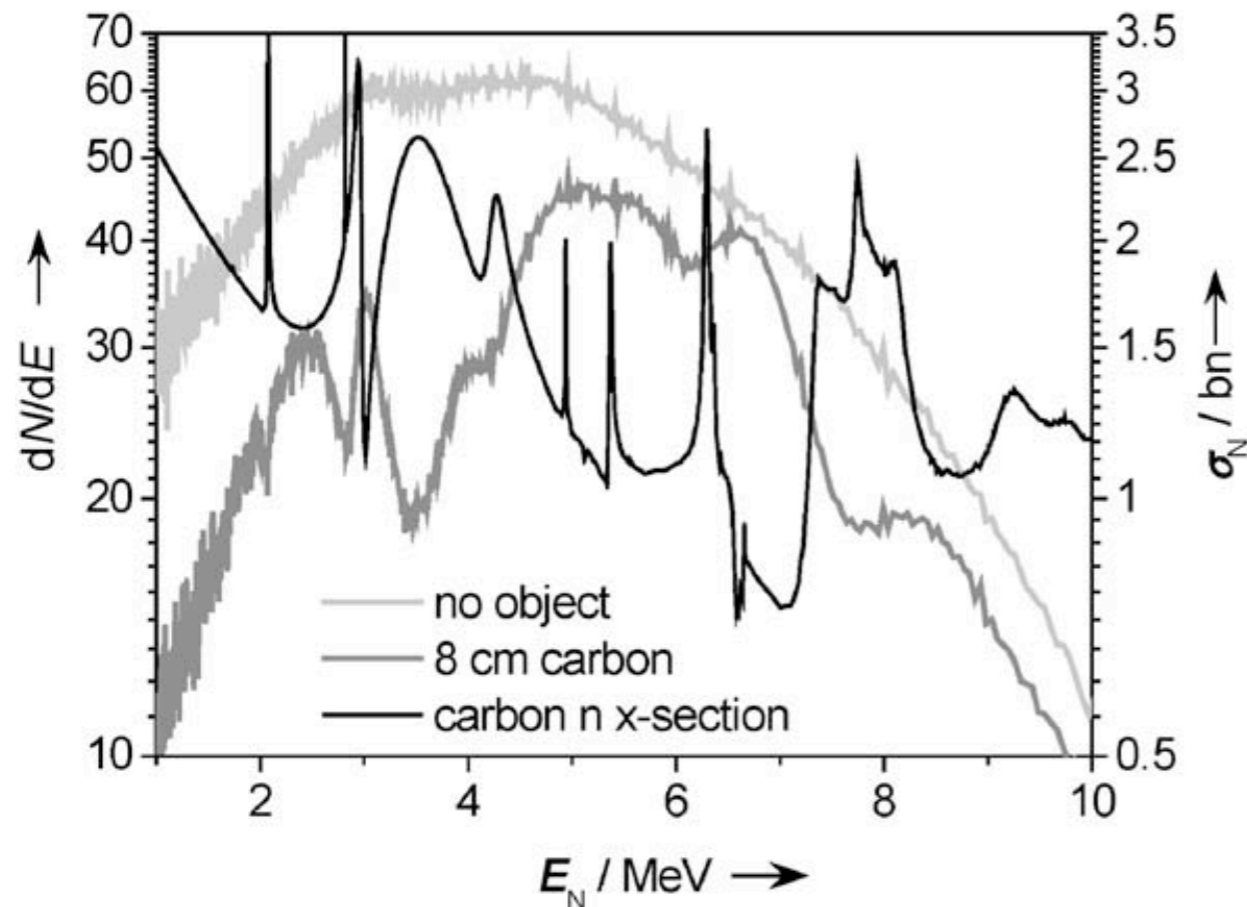


Abb. 1 Ein hochintensiver Laserpuls wird auf eine dünne Plastikfolie fokussiert und beschleunigt dort – abhängig von der Folienstärke – Protonen oder Deuteronen auf unterschiedliche kinetische Energien. In einem zweiten Be-Konverter-Target entstehen durch verschiedene Kernreaktionen Neutronen, die je nach der Energie der Ionen unterschiedliche Richtungsverteilungen aufweisen.

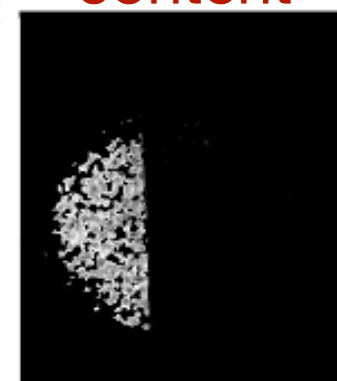
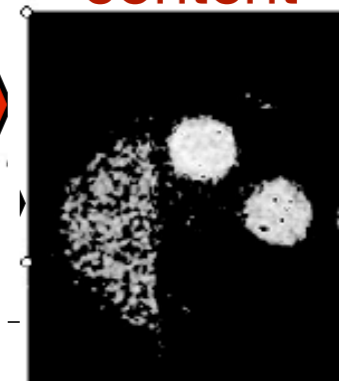
# Fast neutron radiography

Accelerator neutron source with ~1 ns TOF resolution



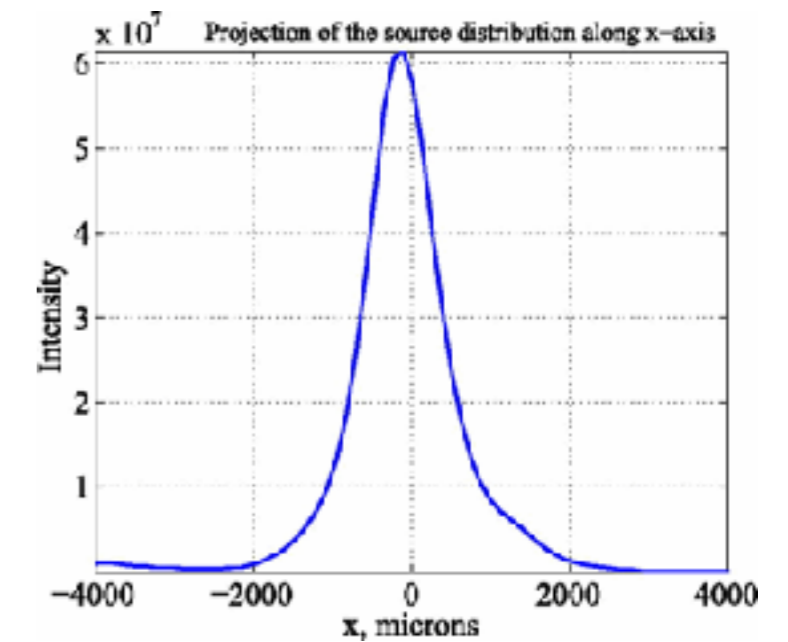
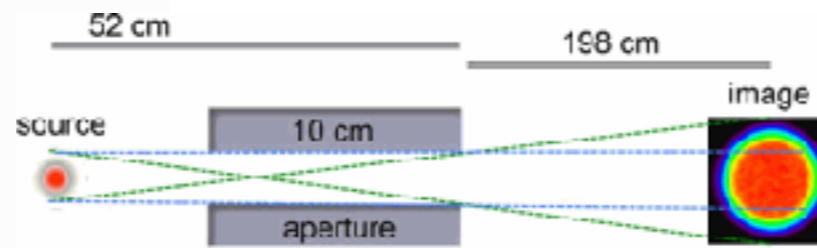
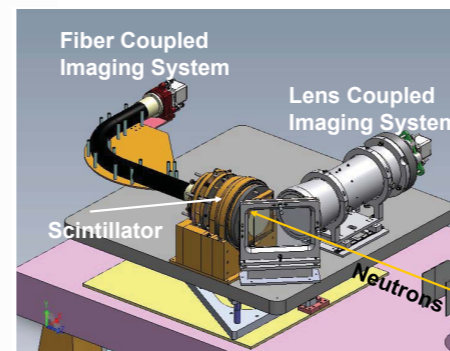
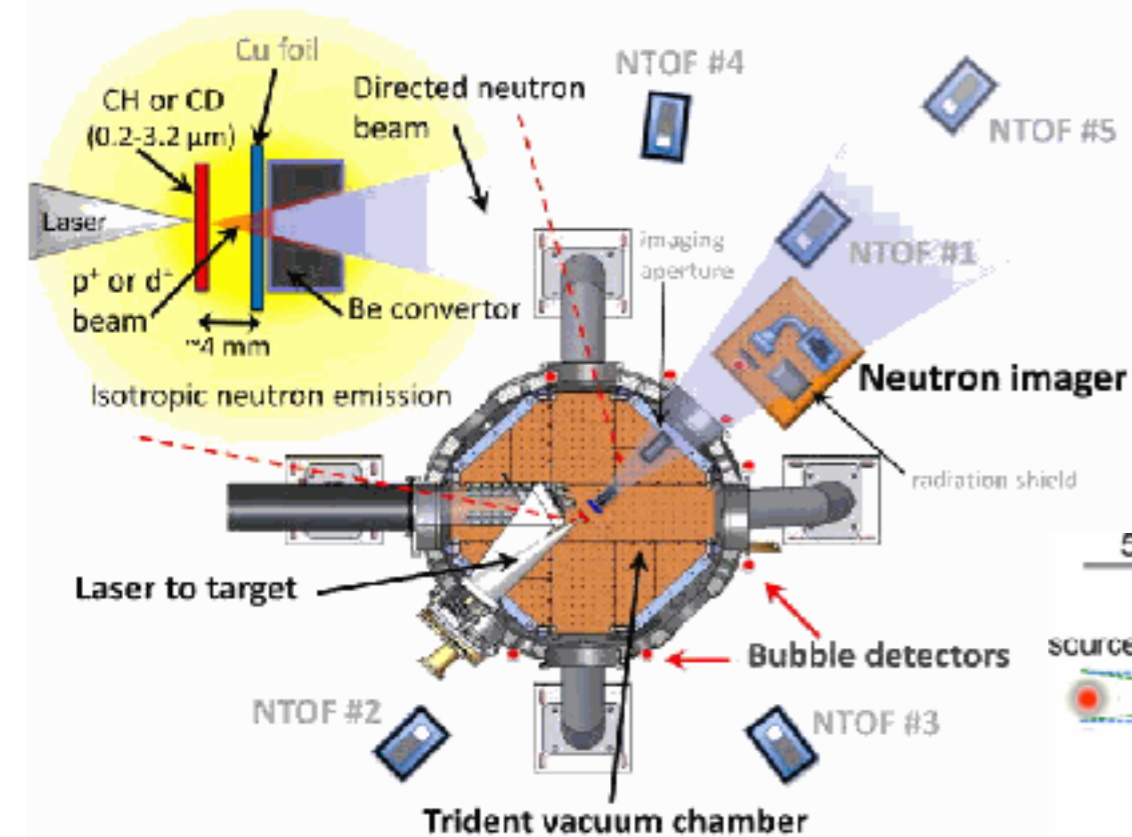
Carbon  
content

Nitrogen  
content

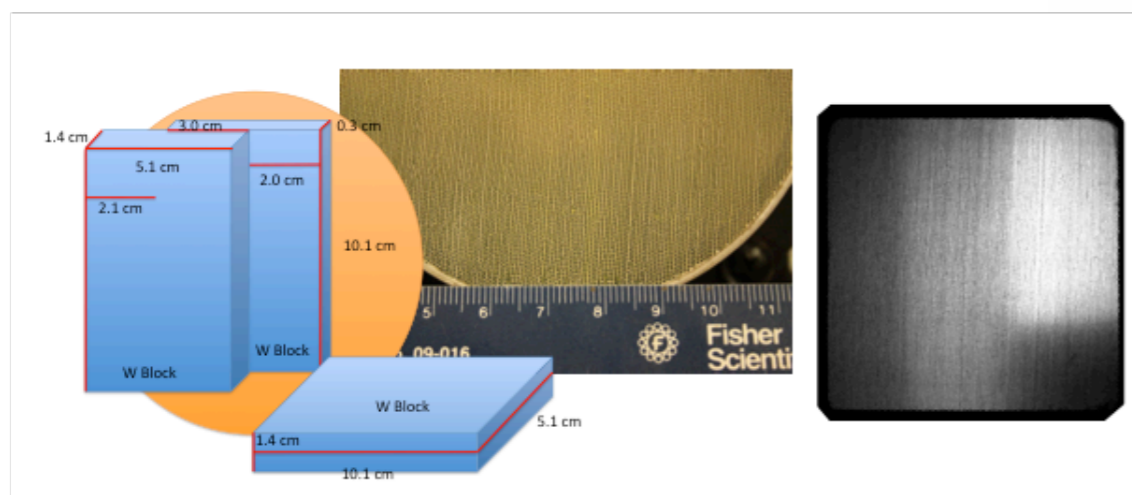


# Fast neutron imaging

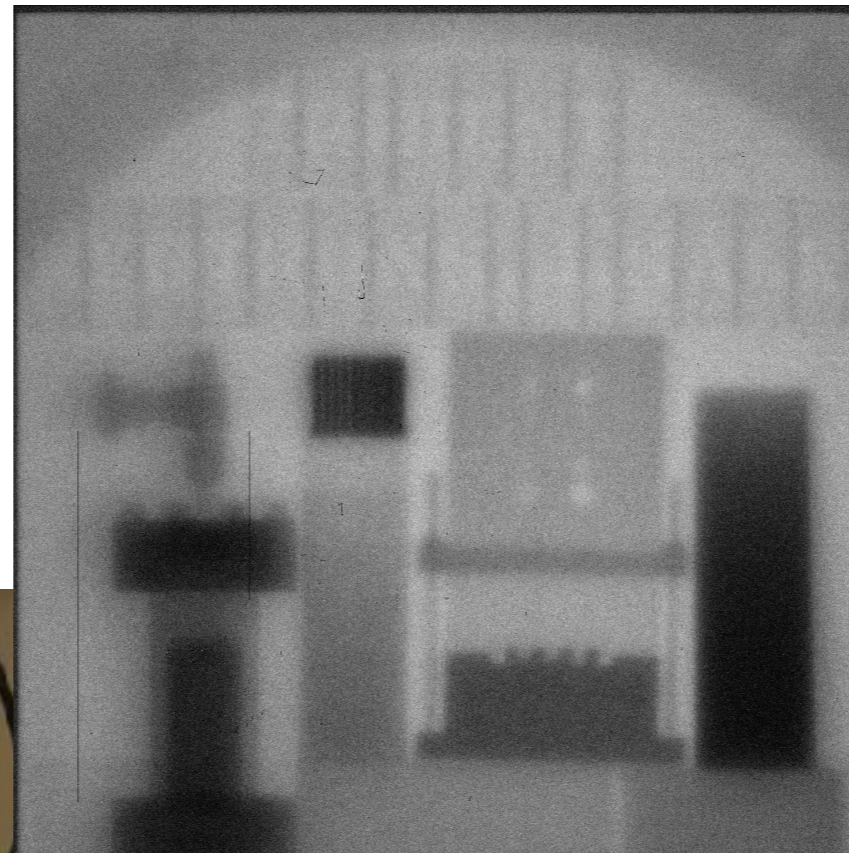
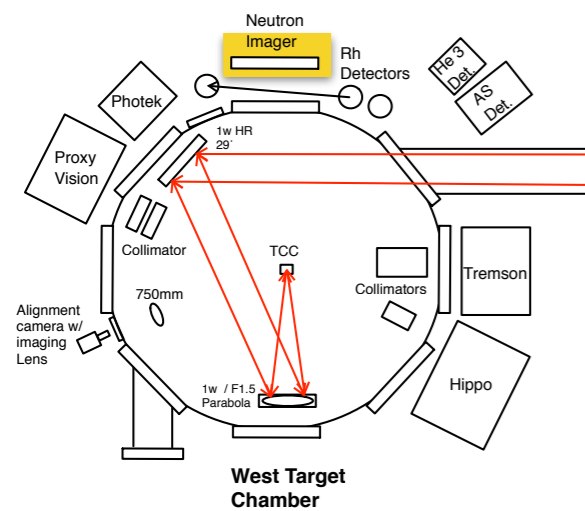
Journal of Applied Physics  
10/17/2016



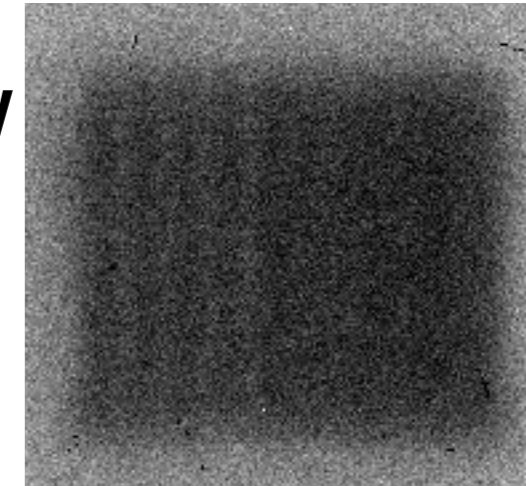
Source size



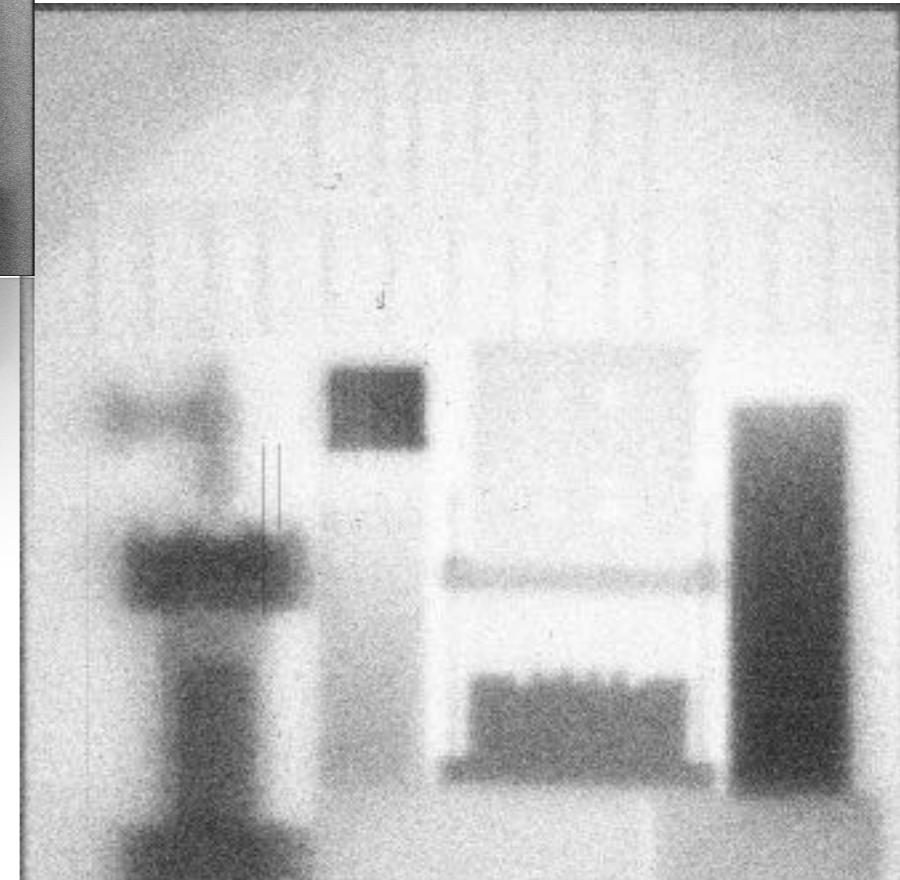
# Fast neutron imaging



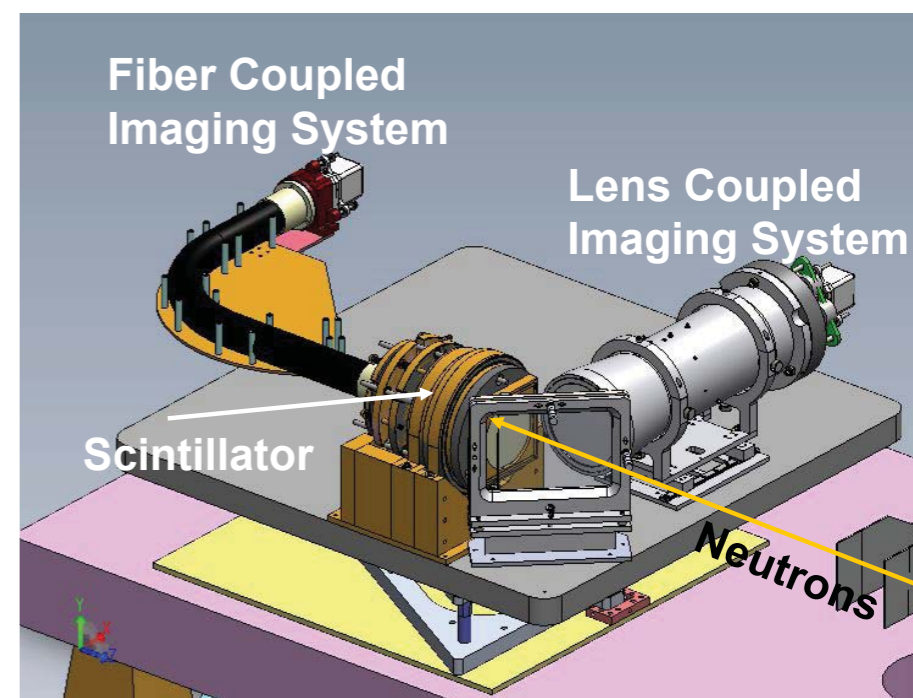
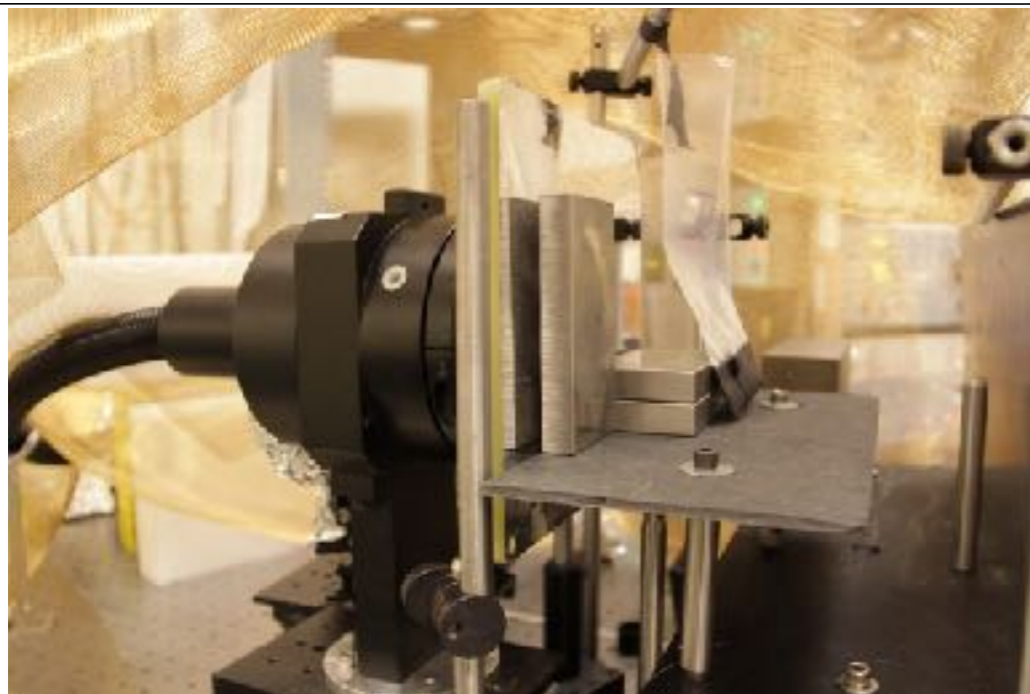
**0.25cm W  
and Poly  
also  
1mm  
visible**



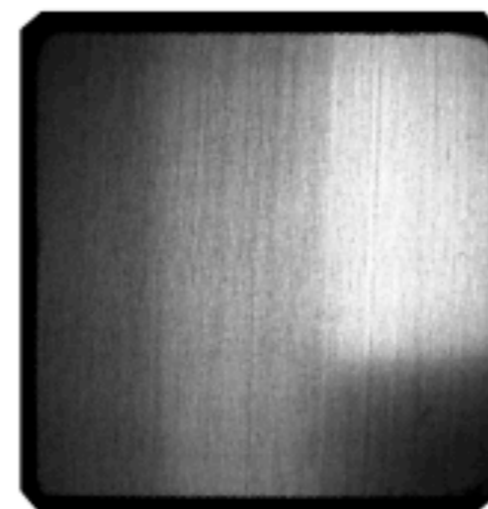
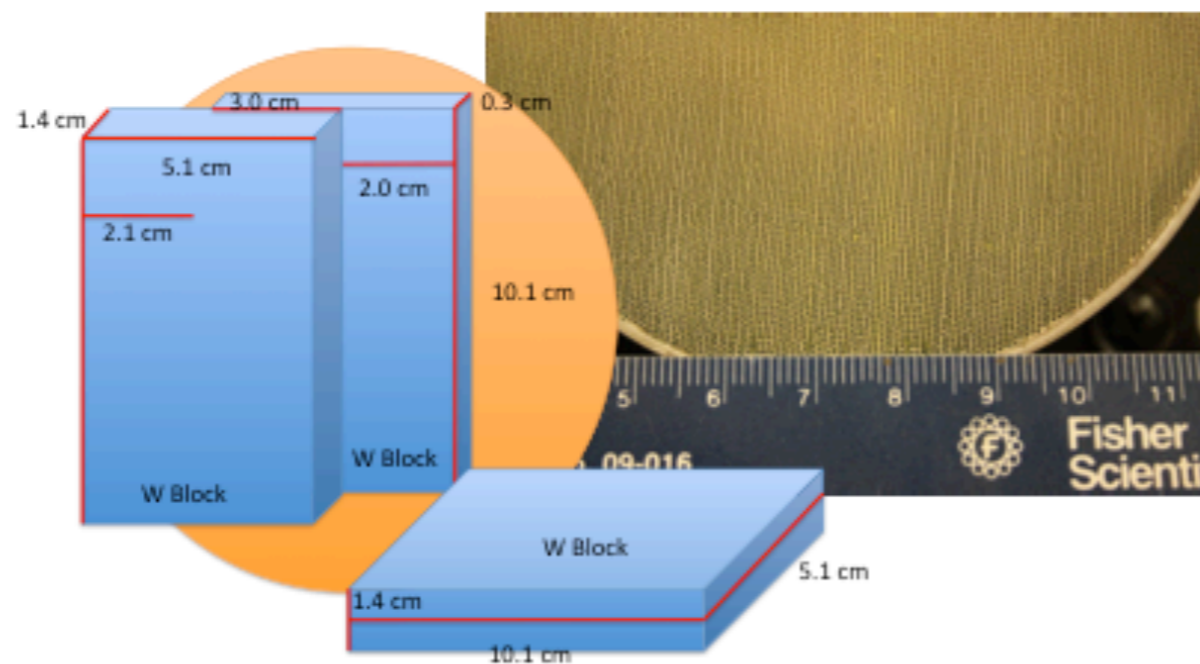
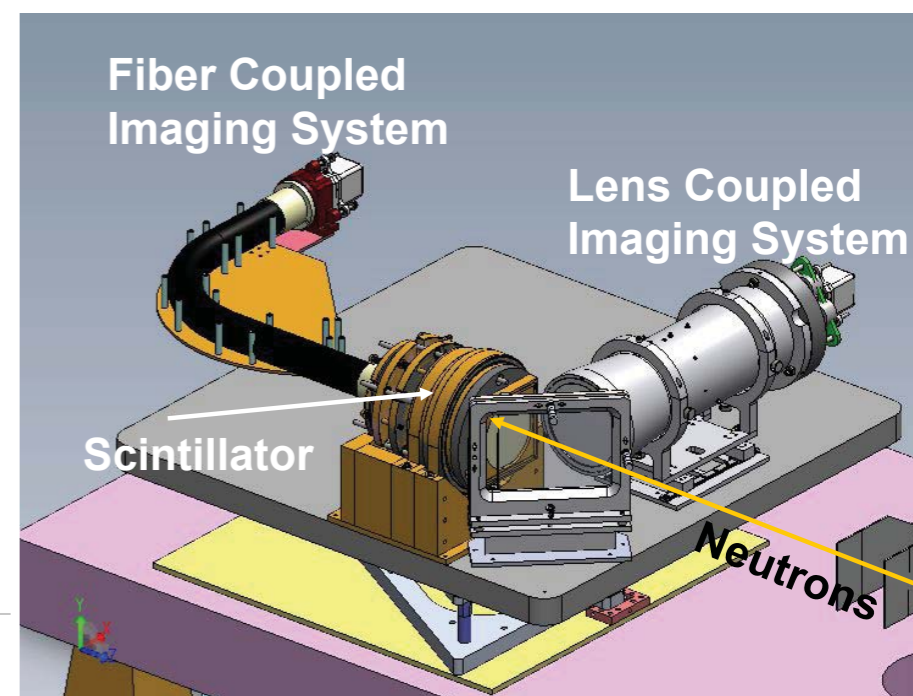
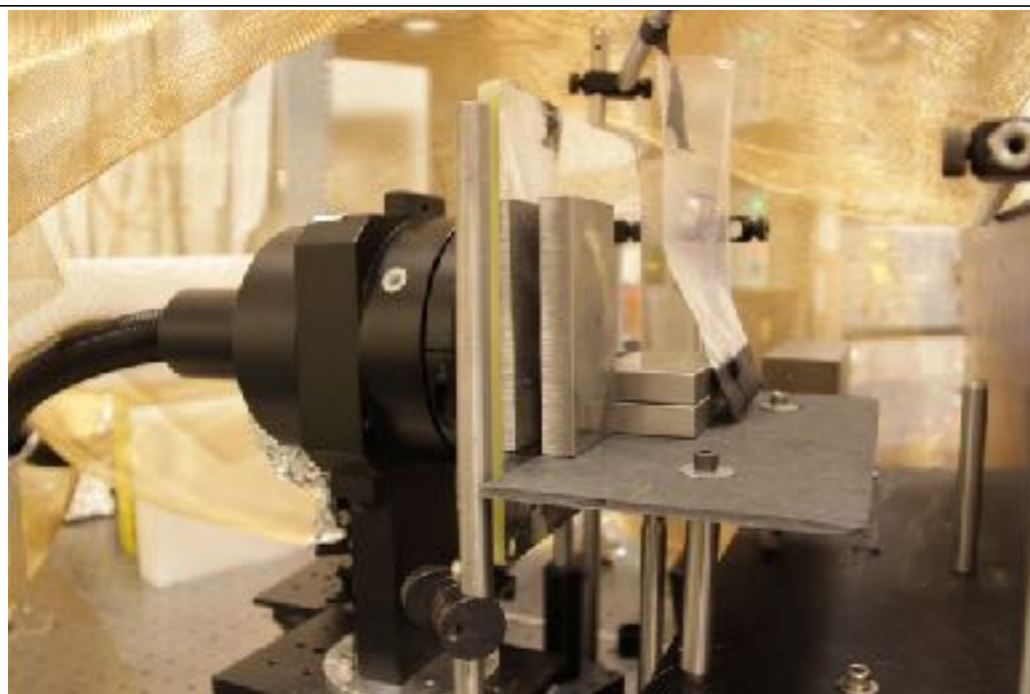
**1 cm Poly  
Cu doped Zn Selenide  
30x30 cm @ 1.5 m from  
converter**



# Gated Neutron Imager



# Gated Neutron Imager

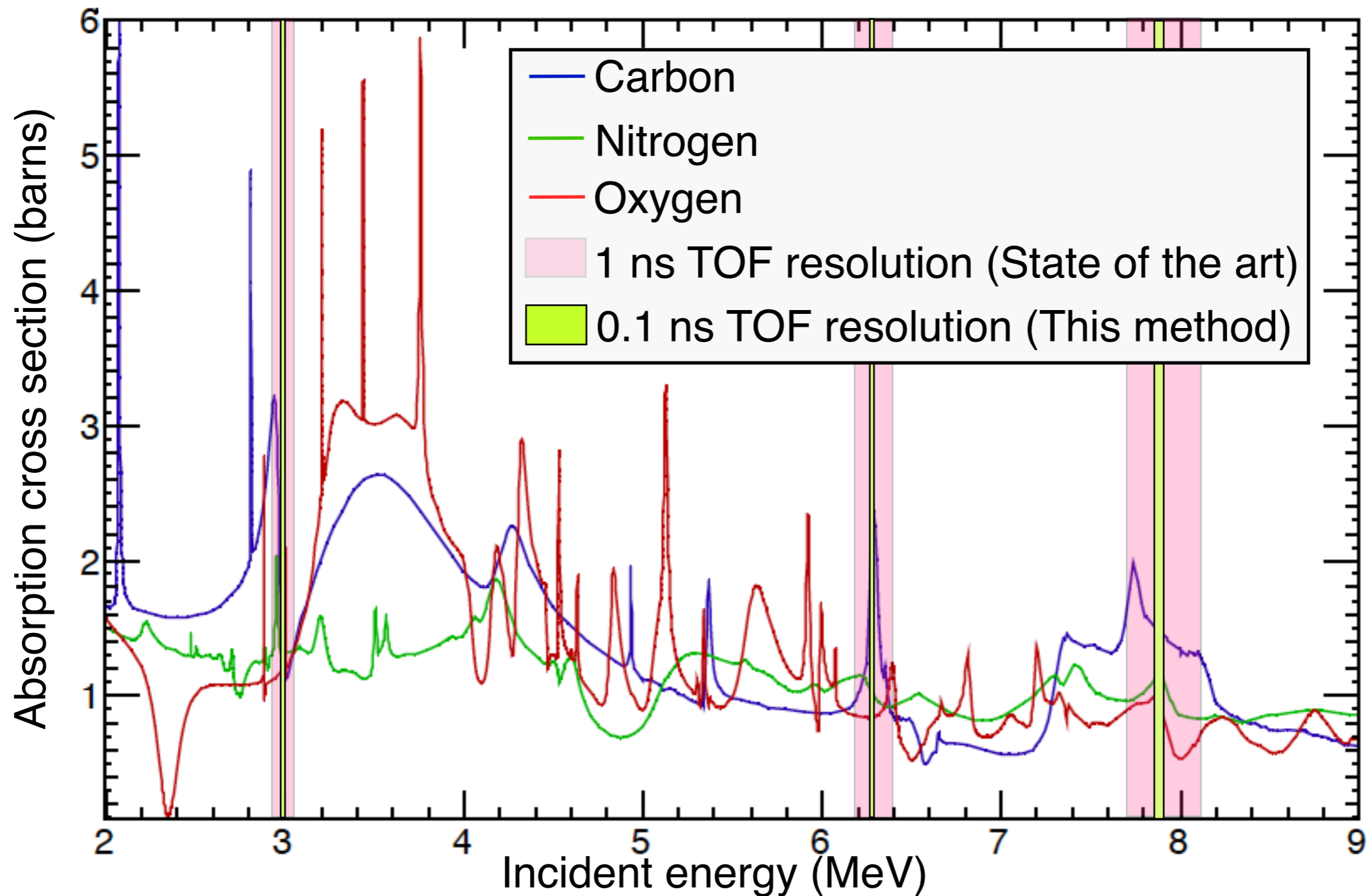


# Prospects: Fast Neutron Radiography

(from I. Pomerantz, PRL 113, 184801 (2014) )



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DARMSTADT



# Complementary to p-rad or x-rays

## A Review of Neutron Scattering Applications to Nuclear Materials

**Sven C. Vogel**

*Los Alamos Neutron Science Center, MS H805, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

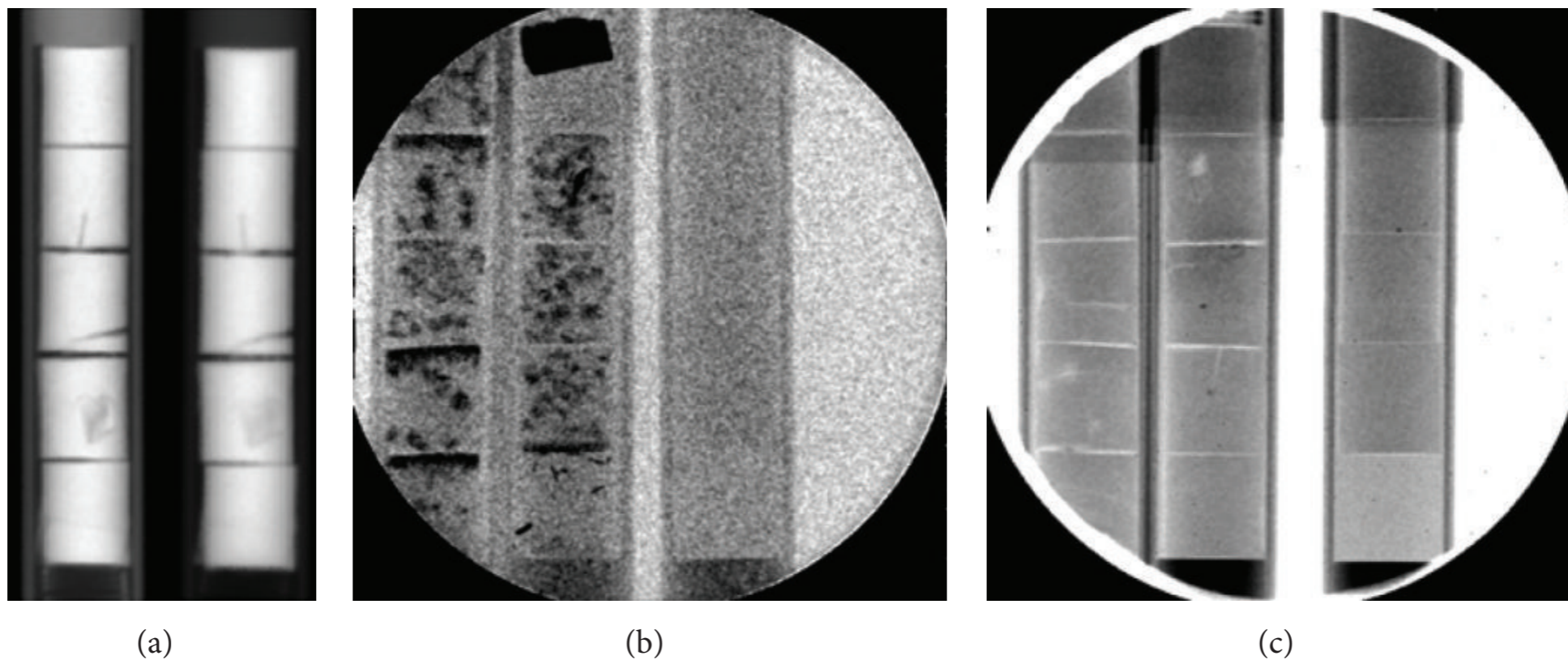


FIGURE 8: (a)–(c) Comparison of high-energy proton radiography, X-ray radiography (a) [116], energy-dispersive neutron radiography (b), and thermal neutron radiography (c) [117] of mock-up  $\text{UO}_2$  fuel pins in stainless steel cladding with artificially introduced cracks or tungsten inclusions (visible as black areas in (b) by energy-dispersive neutron radiography).

# Neutron resonance spectroscopy



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

PHYSICS OF PLASMAS 17, 100701 (2010)

## Laser generated neutron source for neutron resonance spectroscopy

D. P. Higginson,<sup>1,2</sup> J. M. McNaney,<sup>2</sup> D. C. Swift,<sup>2</sup> T. Bartal,<sup>1,2</sup> D. S. Hey,<sup>2</sup> R. Kodama,<sup>3,4</sup>  
S. Le Pape,<sup>2</sup> A. Mackinnon,<sup>2</sup> D. Mariscal,<sup>1</sup> H. Nakamura,<sup>3</sup> N. Nakanii,<sup>1,3,4</sup>  
K. A. Tanaka,<sup>3,4</sup> and F. N. Beg<sup>1</sup>

<sup>1</sup>*Department of Mechanical and Aerospace Engineering, University of California-San Diego, La Jolla, California 92093, USA*

<sup>2</sup>*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

<sup>3</sup>*Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka 565-0871, Japan*

<sup>4</sup>*Graduate School of Engineering, Osaka University, 2-1, Yamada-oka, Suita, Osaka 565-0871, Japan*

# Neutron resonance spectroscopy

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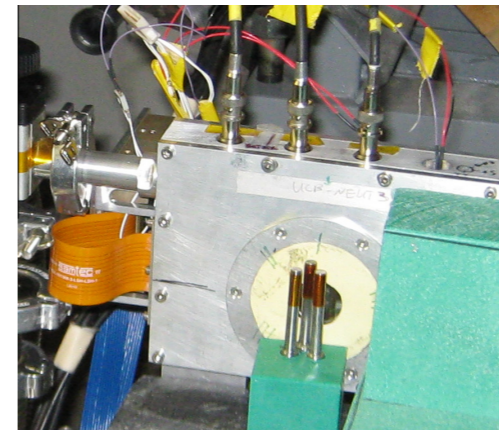
<sup>2</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA

<sup>3</sup>Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>4</sup>Graduate School of Engineering, Osaka University, 2-1, Yamada-oka, Suita, Osaka 565-0871, Japan

## Non-destructive studies of fuel pellets by neutron resonance absorption radiography and thermal neutron radiography

A.S. Tremsin<sup>a,\*</sup>, S.C. Vogel<sup>b</sup>, M. Mocko<sup>b</sup>, M.A.M. Bourke<sup>b</sup>, V. Yuan<sup>b</sup>, R.O. Nelson<sup>b</sup>, D.W. Brown<sup>b</sup>,  
W.B. Feller<sup>c</sup>



# Neutron resonance spectroscopy

PHYSICS OF PLASMAS 17, 100701 (2010)

## Laser generated neutron source for neutron resonance spectroscopy

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<sup>3</sup>Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>4</sup>Graduate School of Engineering, Osaka University, 2-1, Yamada-oka, Suita, Osaka 565-0871, Japan

## Remote determination of sample temperature by neutron resonance spectroscopy

H.J. Stone<sup>a</sup>, M.G. Tucker<sup>a,c</sup>, Y. Le Godec<sup>b</sup>, F.M. Méducin<sup>a,1</sup>, E.R. Cope<sup>a</sup>,  
S.A. Hayward<sup>a</sup>, G.P.J. Ferlat<sup>a,2</sup>, W.G. Marshall<sup>c</sup>, S. Manolopoulos<sup>c</sup>,  
S.A.T. Redfern<sup>a</sup>, M.T. Dove<sup>a,\*</sup>

Nuclear Instruments and Methods in Physics Research A 547 (2005) 601–615

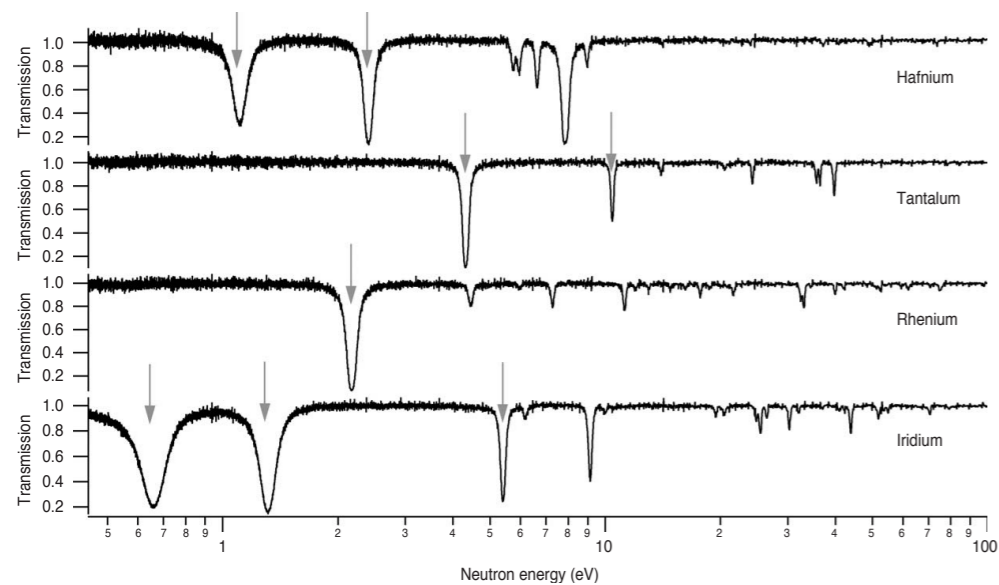


Fig. 2. Normalised transmission spectra obtained from 50  $\mu\text{m}$  thick foils of natural tantalum, hafnium, iridium and rhenium at room temperature with the ISIS data acquisition electronics in 250 ns time bins. Arrows indicate the eight resonance peaks used to extract sample temperatures.

## Non-destructive studies of fuel pellets by neutron resonance absorption radiography and thermal neutron radiography

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W.B. Feller<sup>c</sup>

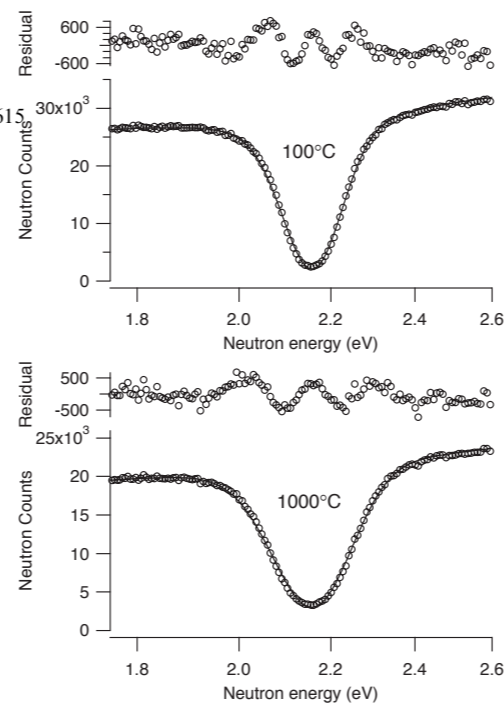
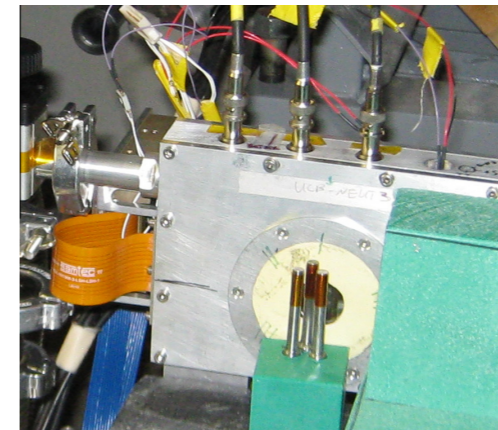


Fig. 7. Examples of the fits obtained with a pseudo-Voigt function to the data gathered with the FAST ComTec P7886 multiscaler PCI data acquisition card for the  $^{185}\text{Re}$  2.156 eV resonance at 100 and 1000  $^{\circ}\text{C}$ .

# Neutron resonance spectroscopy

PHYSICS OF PLASMAS 17, 100701 (2010)

## Laser generated neutron source for neutron resonance spectroscopy

D. P. Higginson,<sup>1,2</sup> J. M. McNaney,<sup>2</sup> D. C. Swift,<sup>2</sup> T. Bartal,<sup>1,2</sup> D. S. Hey,<sup>2</sup> R. Kodama,<sup>3,4</sup>  
S. Le Pape,<sup>2</sup> A. Mackinnon,<sup>2</sup> D. Mariscal,<sup>1</sup> H. Nakamura,<sup>3</sup> N. Nakanii,<sup>1,3,4</sup>  
K. A. Tanaka,<sup>3,4</sup> and F. N. Beg<sup>1</sup>

<sup>1</sup>Department of Mechanical and Aerospace Engineering, University of California-San Diego, La Jolla, California 92093, USA

<sup>2</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA

<sup>3</sup>Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>4</sup>Graduate School of Engineering, Osaka University, 2-1, Yamada-oka, Suita, Osaka 565-0871, Japan

## Remote determination of sample temperature by neutron resonance spectroscopy

H.J. Stone<sup>a</sup>, M.G. Tucker<sup>a,c</sup>, Y. Le Godec<sup>b</sup>, F.M. Méducin<sup>a,1</sup>, E.R. Cope<sup>a</sup>,  
S.A. Hayward<sup>a</sup>, G.P.J. Ferlat<sup>a,2</sup>, W.G. Marshall<sup>c</sup>, S. Manolopoulos<sup>c</sup>,  
S.A.T. Redfern<sup>a</sup>, M.T. Dove<sup>a,\*</sup>

Nuclear Instruments and Methods in Physics Research A 547 (2005) 601–615

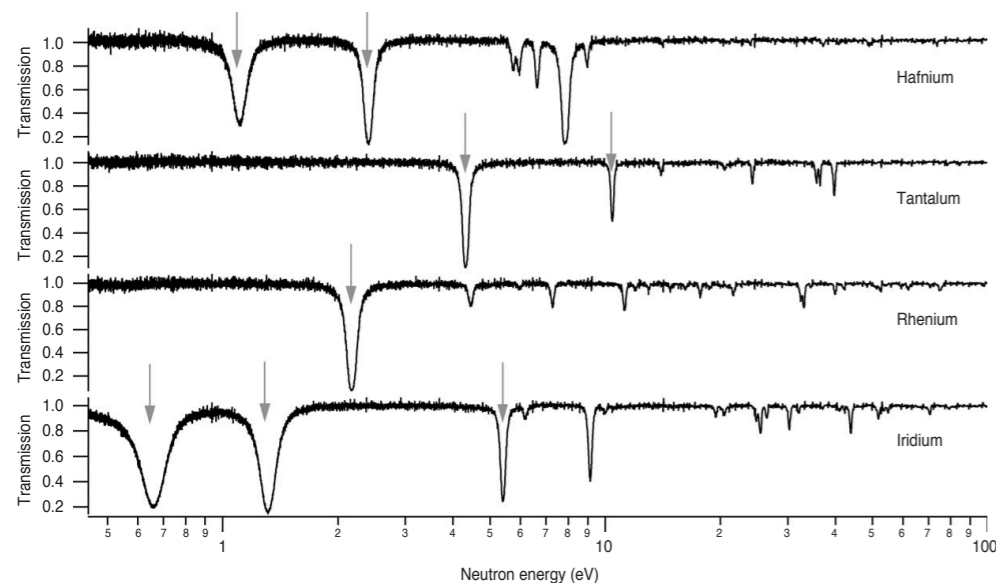
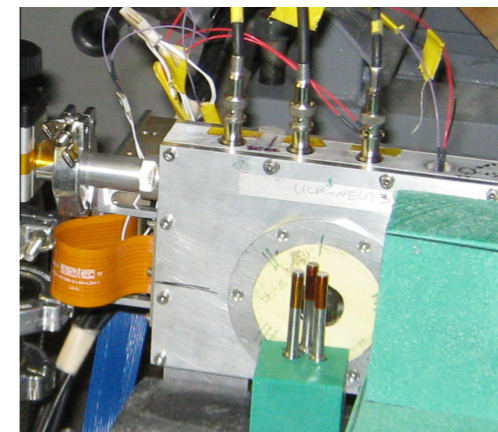


Fig. 2. Normalised transmission spectra obtained from 50  $\mu\text{m}$  thick foils of natural tantalum, hafnium, iridium and rhenium at room temperature with the ISIS data acquisition electronics in 250 ns time bins. Arrows indicate the eight resonance peaks used to extract sample temperatures.

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W.B. Feller<sup>c</sup>



## Shock Temperature Measurement Using Neutron Resonance Spectroscopy

V. W. Yuan, J. David Bowman, D. J. Funk, G. L. Morgan, R. L. Rabie, C. E. Ragan, J. P. Quintana, and H. L. Stacy

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

(Received 3 September 2004; published 30 March 2005)

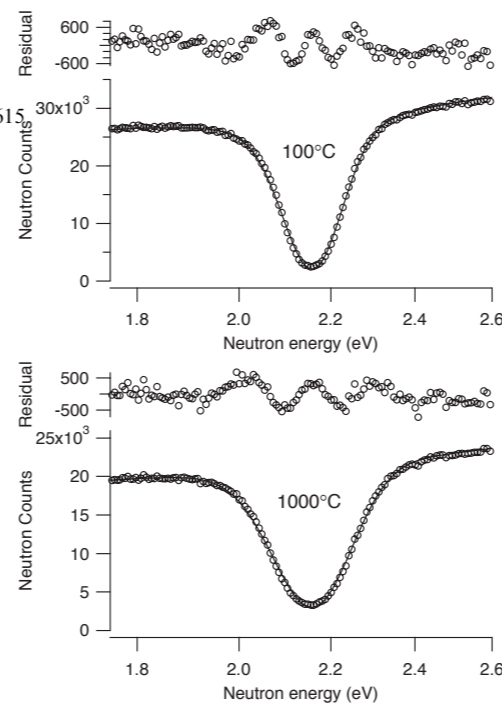


Fig. 7. Examples of the fits obtained with a pseudo-Voigt function to the data gathered with the FAST ComTec P7886 multiscaler PCI data acquisition card for the  $^{185}\text{Re}$  2.156 eV resonance at 100 and 1000  $^{\circ}\text{C}$ .

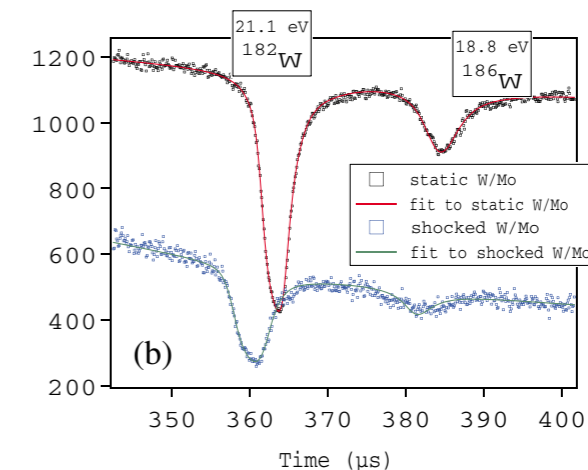
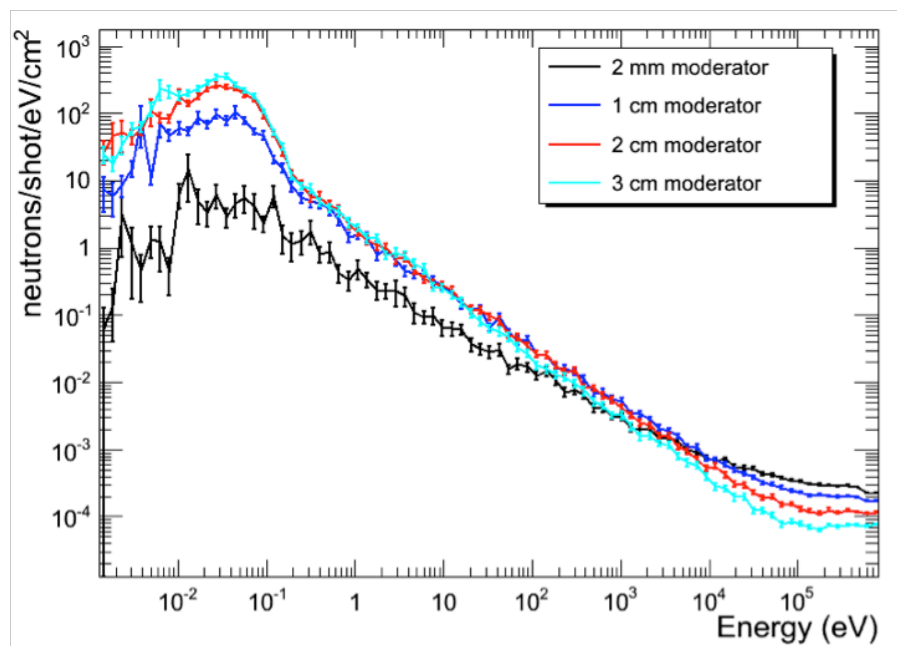
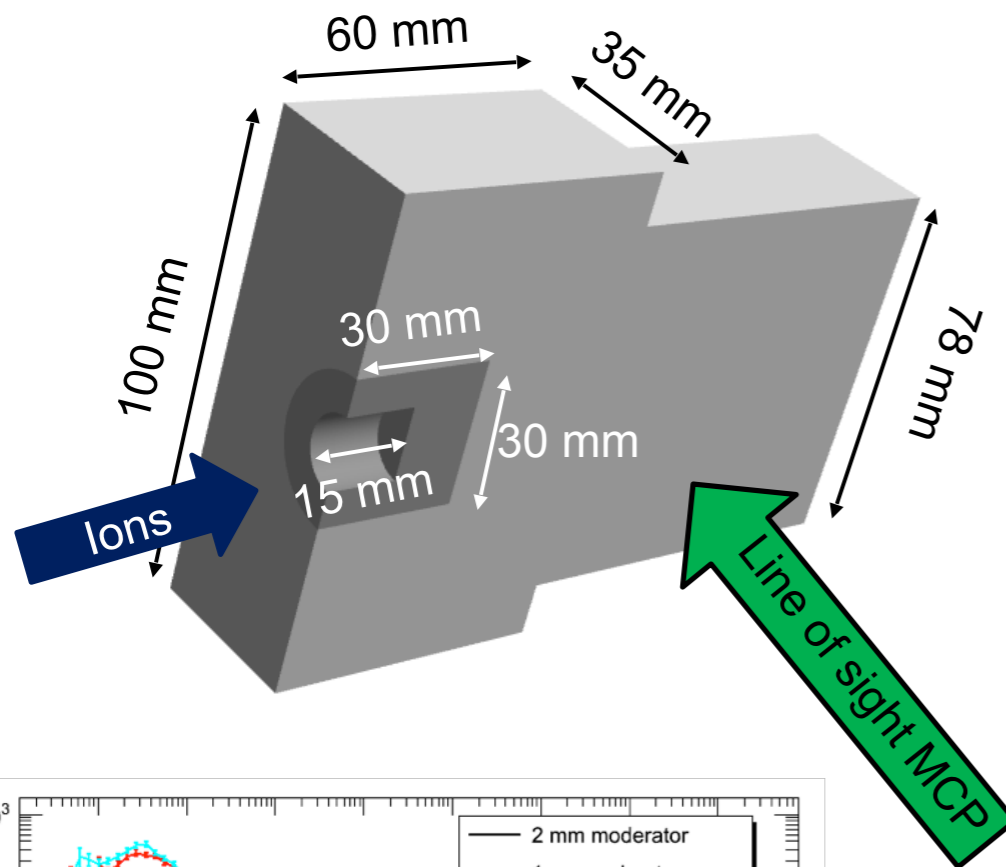
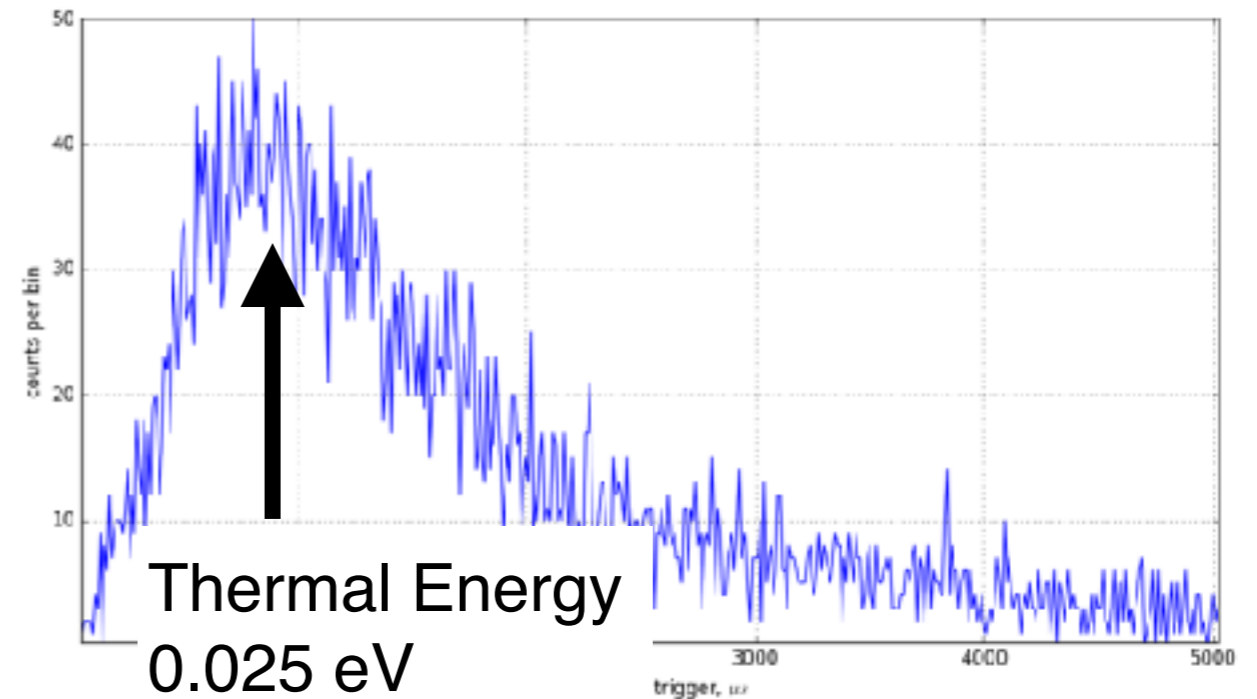
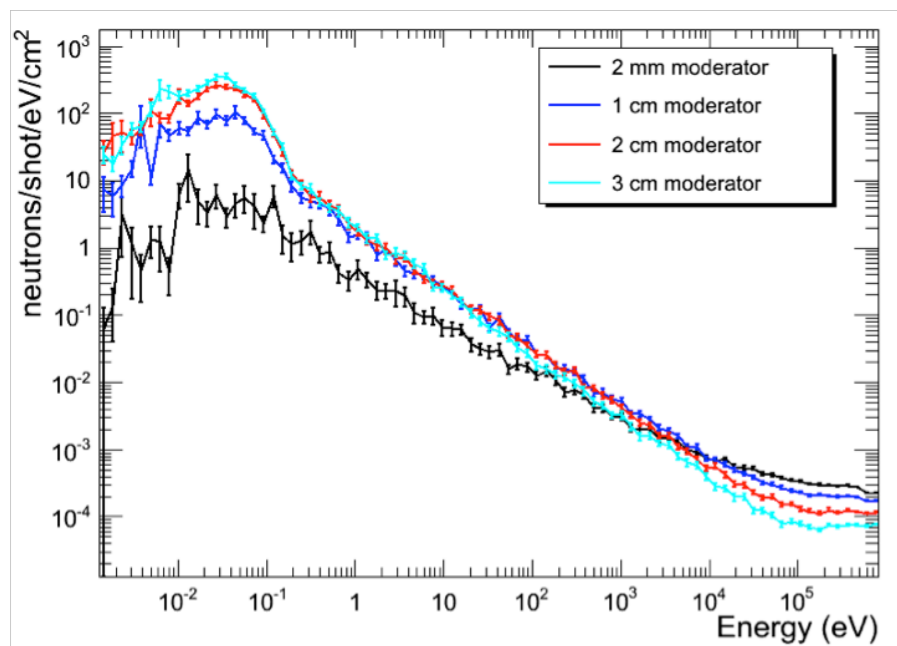
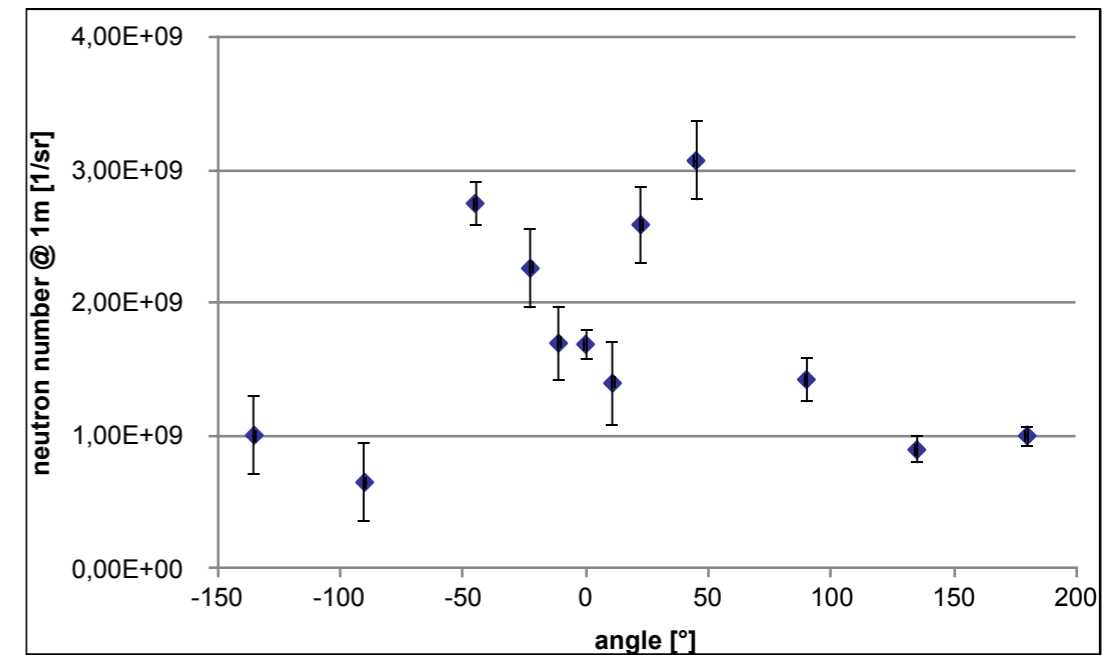
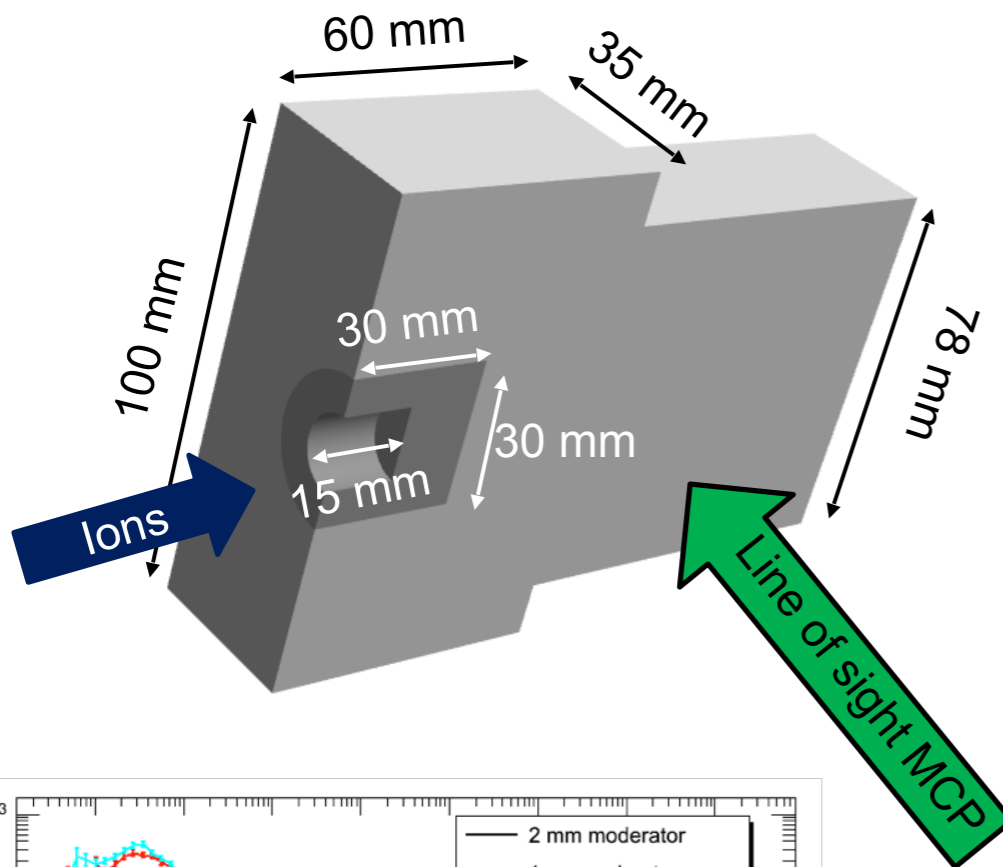


FIG. 2 (color). (a) Static (upper) and dynamic (lower) TOF spectra for shocked molybdenum. (b) Expanded view of data with fits (red and green curves) to the data. The horizontal scale for both (a) and (b) is time in microseconds.

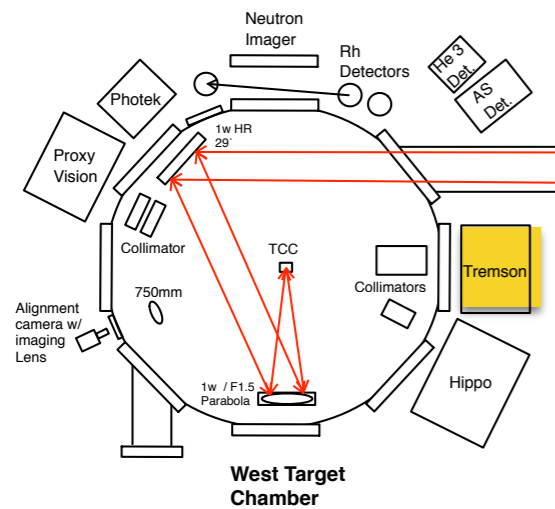
# First results on neutron moderation



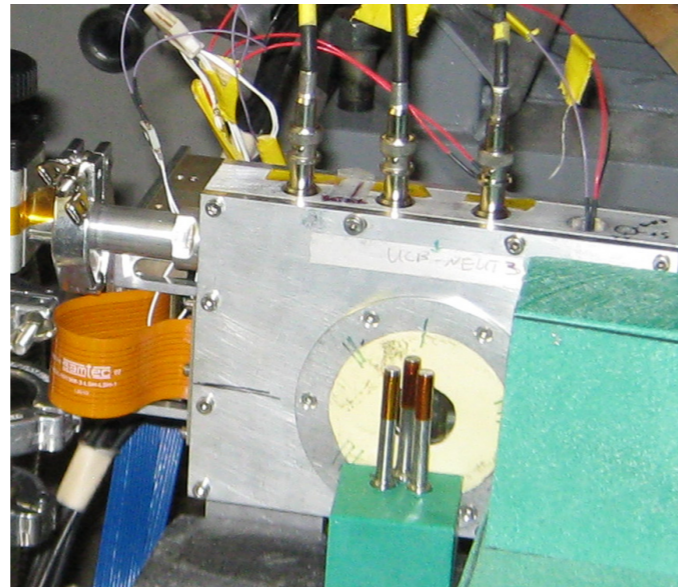
# First results on neutron moderation



# Novel thermal neutron detectors (basically an imaging n-ToF detector)



- Boron doped MCP and Timepix readout



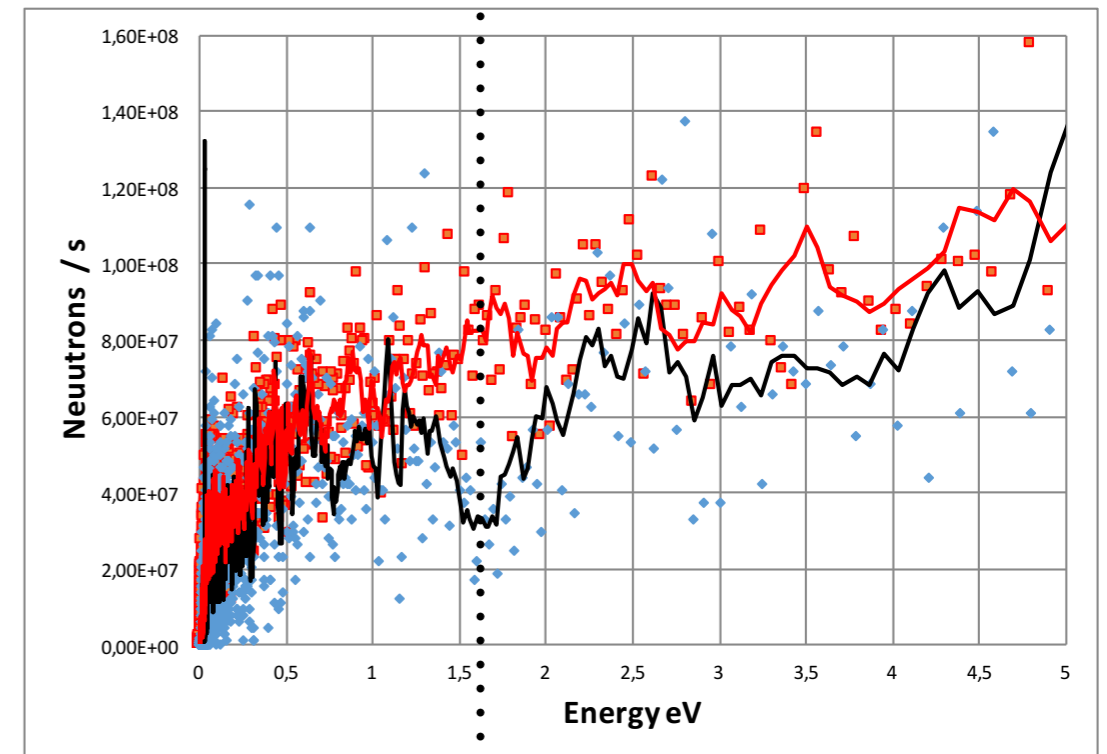
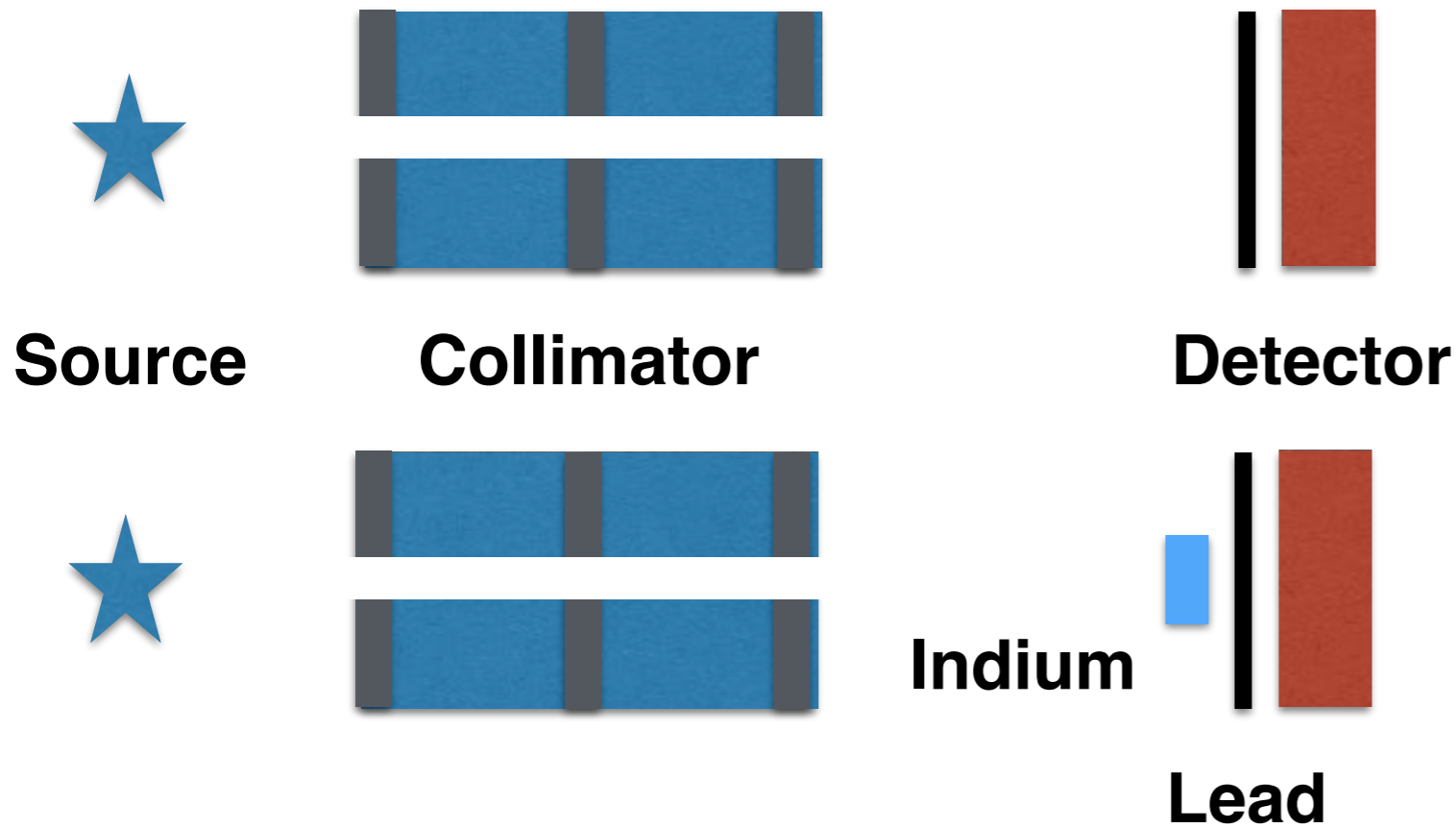
- Shielding for EMP

- Neutron collimator of Boron doped plastic and steel

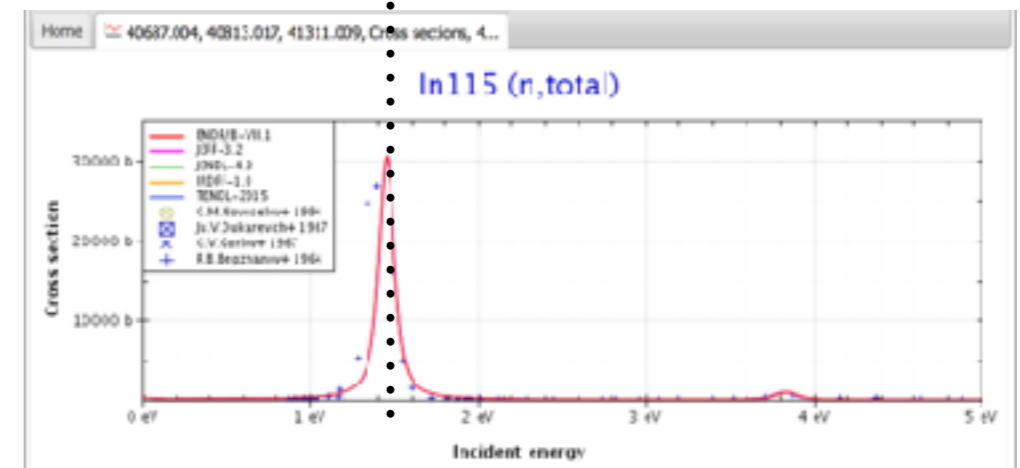
- Lead and B-doped HDPE



# Laser-driven neutron resonance spectroscopy



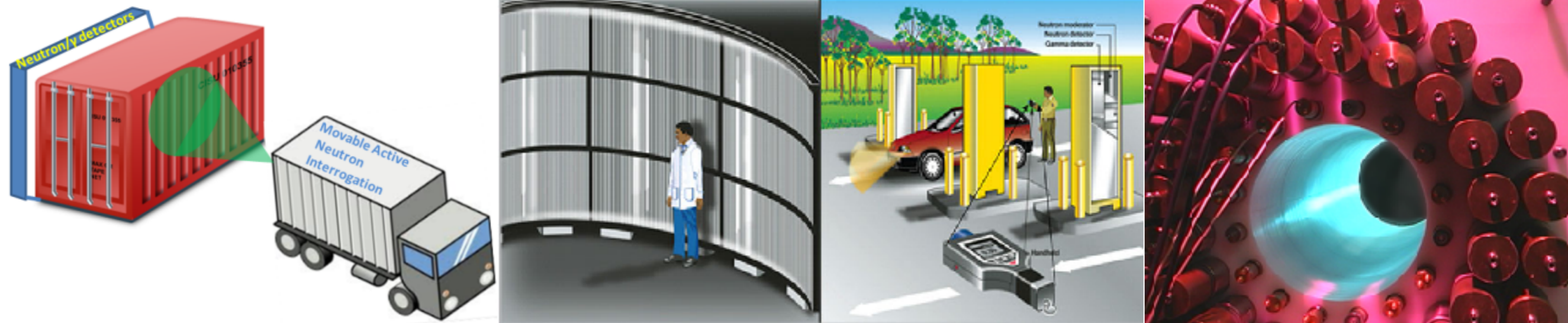
Low energy neutron resonances at 1.5 eV  
averaged two shot at TRIDENT using  
only 160 J of laser energy total



# New detectors for applications avoiding $^3\text{He}$



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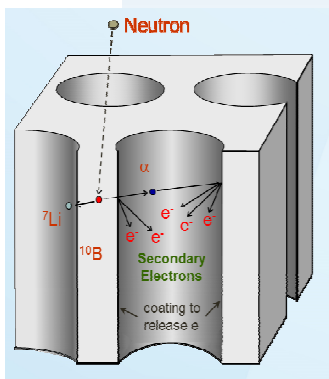
Large area detectors are needed for cargo inspection



New detectors are currently tested  
those are also dedicated for FAIR



The price for He3 tubes has skyrocketed



# Active interrogation system to detect special nuclear material

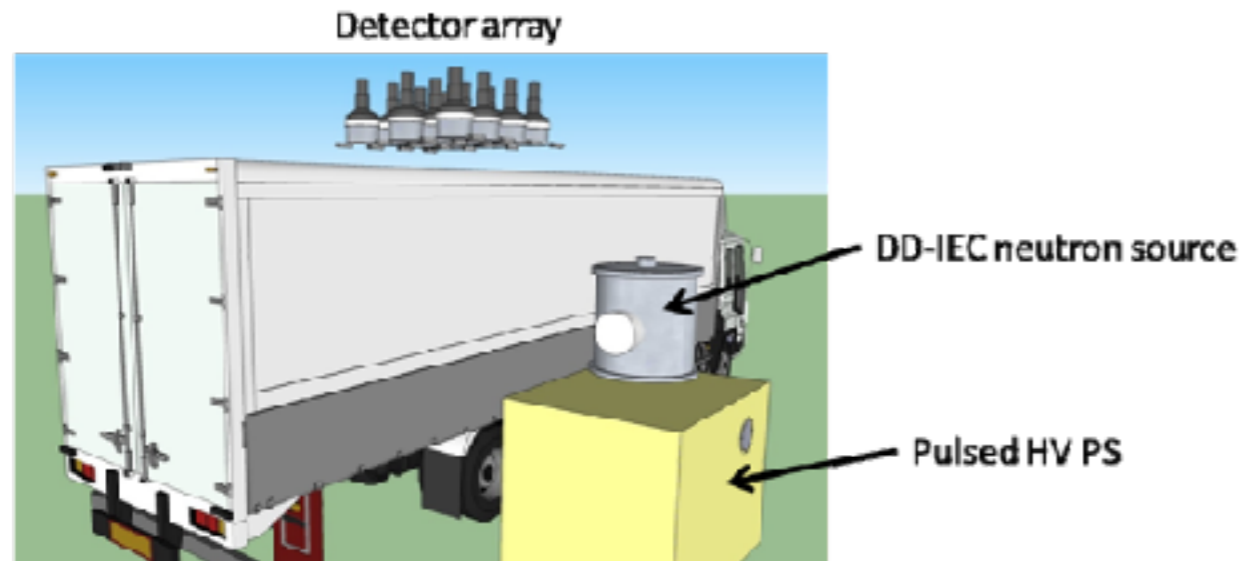


Figure from Masuda et al., IEA Kyoto

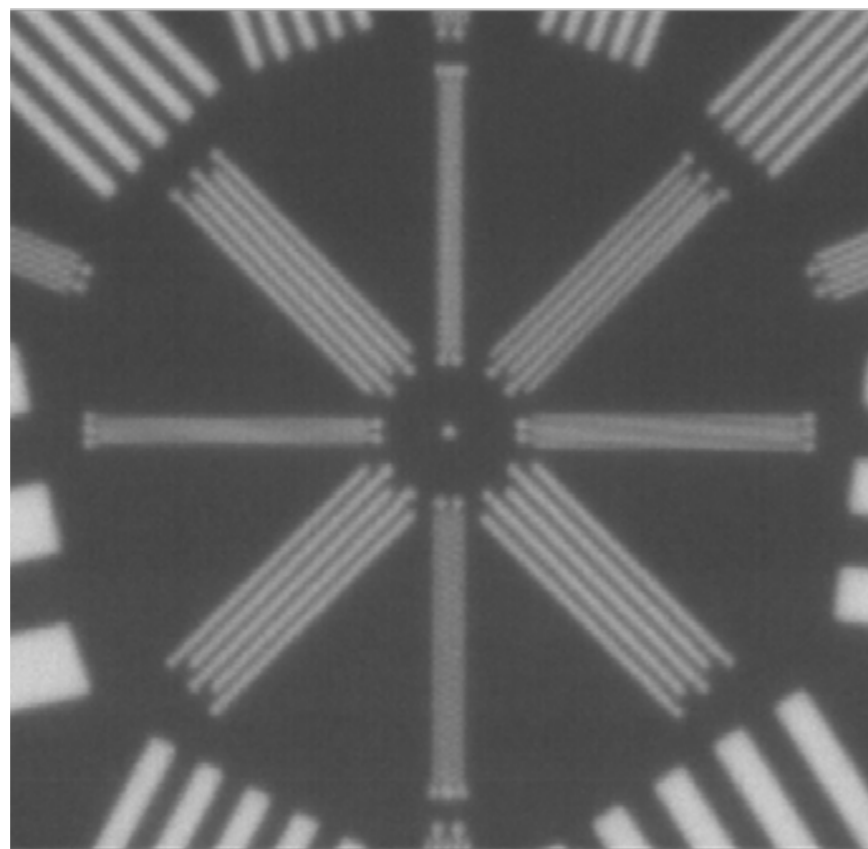
**Need:** Fast, movable, operationally safe neutron source featuring energy tunable, and high intensity directional neutron production

Investigation of the viability of a laser-driven neutron source for active interrogation

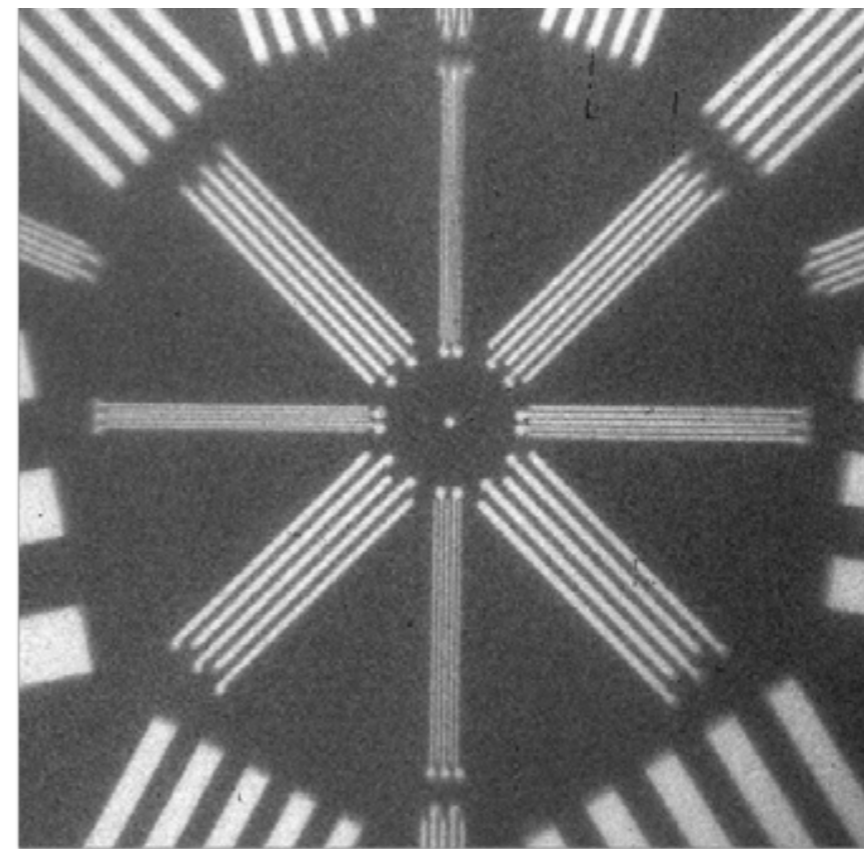
# Hard X-ray production



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DARHT Axis 1, ~750 $\mu$ m source size, 19mm Cathode



TRIDENT <125 $\mu$ m source size (measurement is detector-limited!!!)

Figure 22: Comparison of an AWE tungsten kaleidoscope used to determine resolution in radiography experiments. On the left, a radiograph from the Dual Axis Radiographic Hydrodynamic (DARHT) facility is shown. On the right, the same target is shown with a radiograph measured at Trident (Radiographs courtesy of R. Nelson & J. Hunter/LANL).

- **Single shot x-ray imaging of a 1 cm tungsten plate**
- **500 keV to 1 MeV Photons**
- **exposure time about 1 ps**
- **spatial resolution better 100  $\mu$ m (limited by detector at present)**

# Experiments in 2014 @ LANL

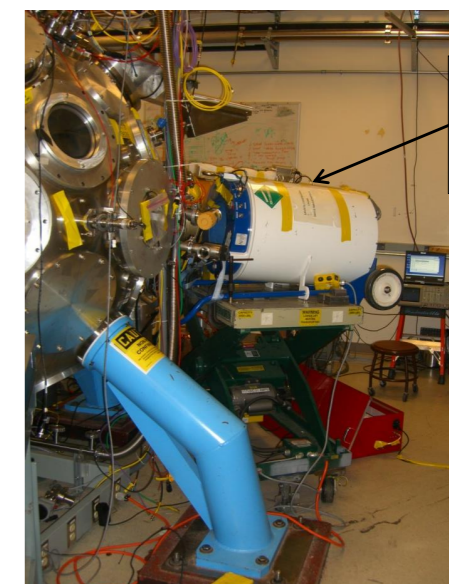
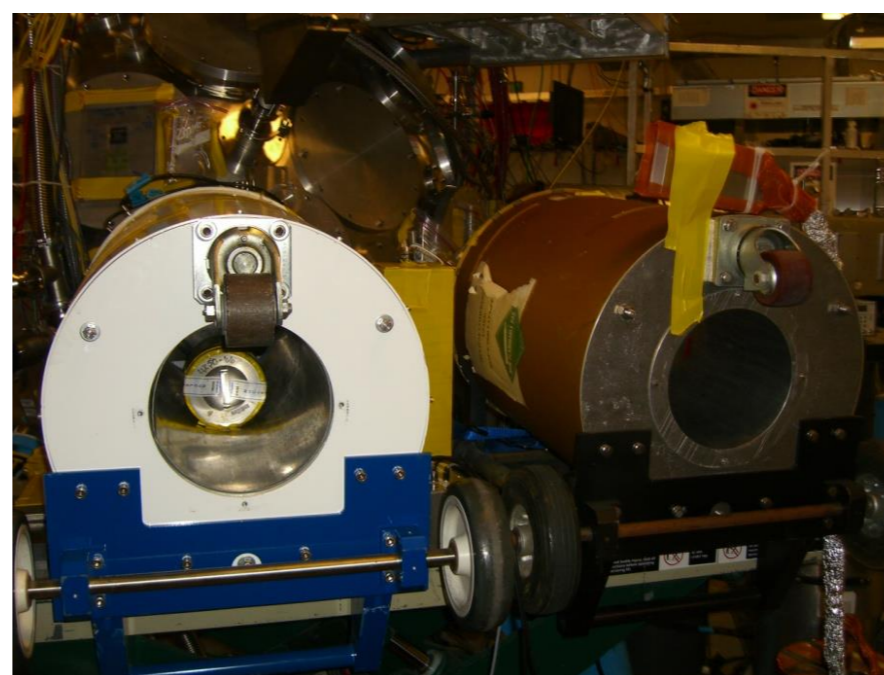
PI: Andrea Favalli, LANL



## Uranium Samples

### Uranium Samples tested:

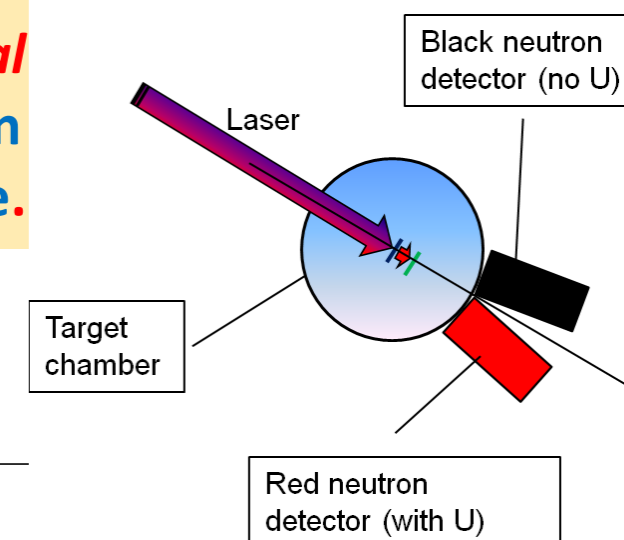
- Depleted Uranium with mass up to 4.5kg
- Sample of enriched uranium up to 65%(w.t.) enrichment in  $^{235}\text{U}$



Neutron Coincidence Counter

Neutron coincidence counter with single ring structure of  $^3\text{He}$  proportional detectors embedded in polyethylene. In the left detector is visible the U sample.

Slide 11



# Experiments in 2014 @ LANL

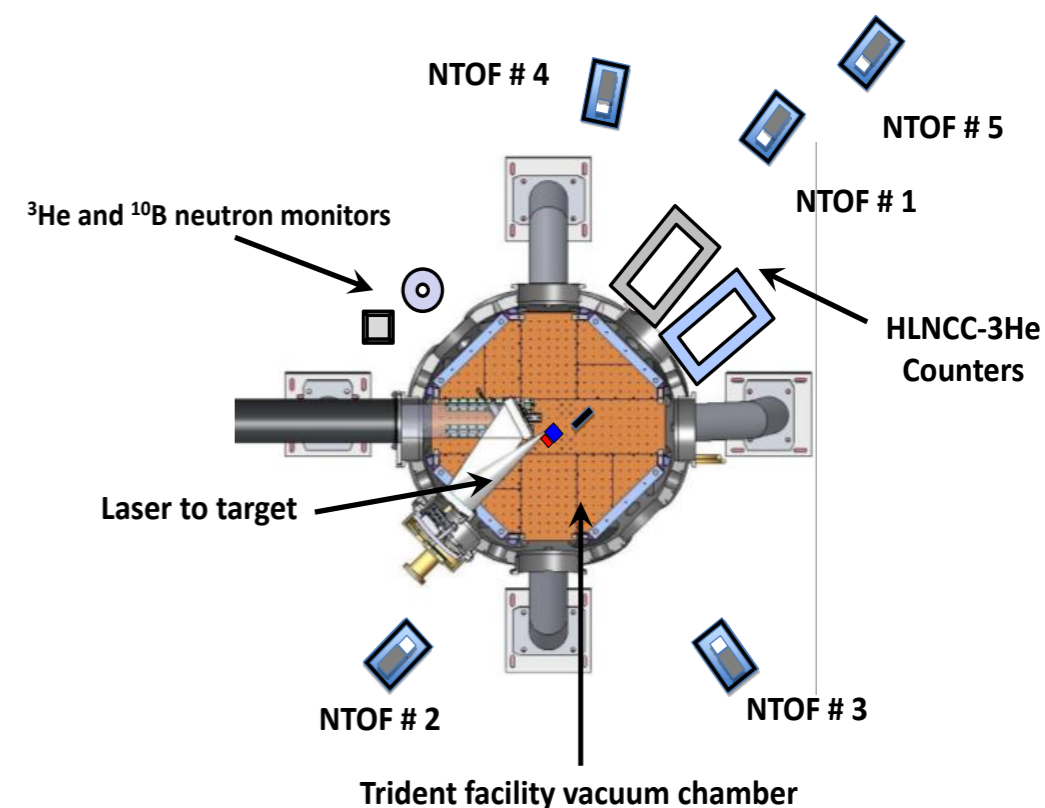
PI: Andrea Favalli, LANL



Active interrogation: identify nuclear material with a single pulse

## Diagnostic for the neutron production:

- **Bubble detectors** (insensitive to  $\gamma$ 's)
- **nTOF: with plastic scintillator + PMT**  $\rightarrow$  neutron energy spectrum
- **Neutron yield detectors based on  $^3\text{He}$  + polyethylene** (have been developed in the project specifically for the one shot measurement)

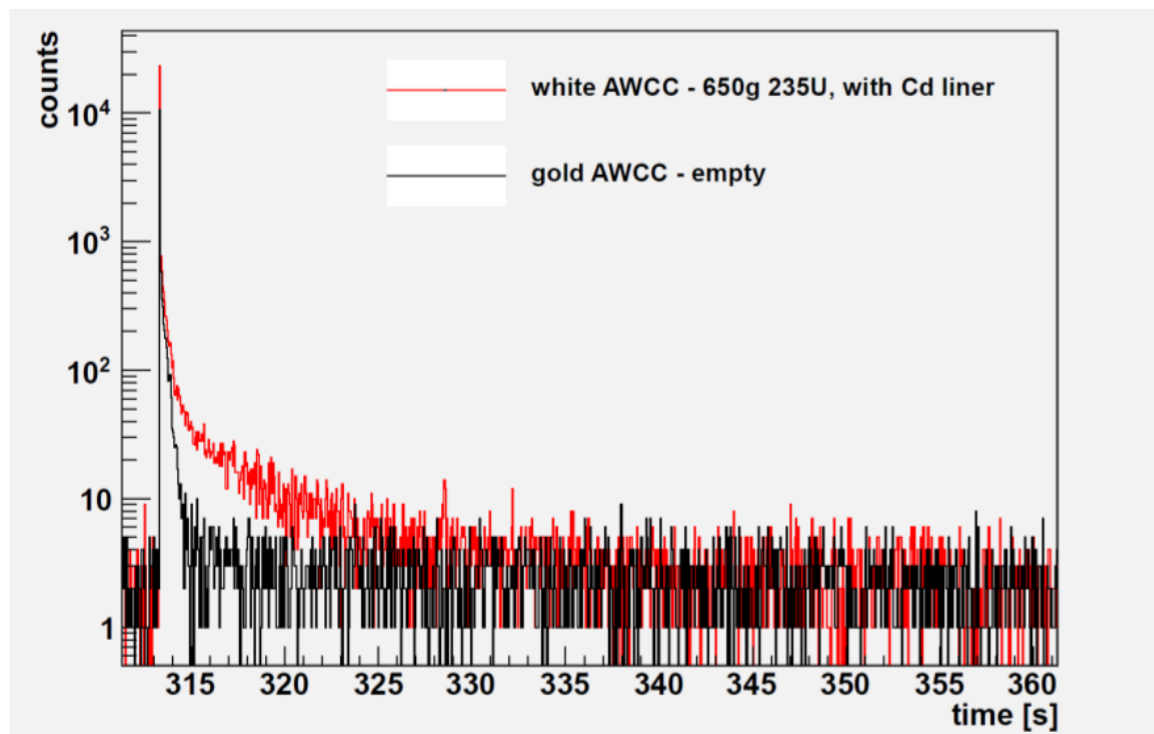


# Interrogation of an enriched uranium sample

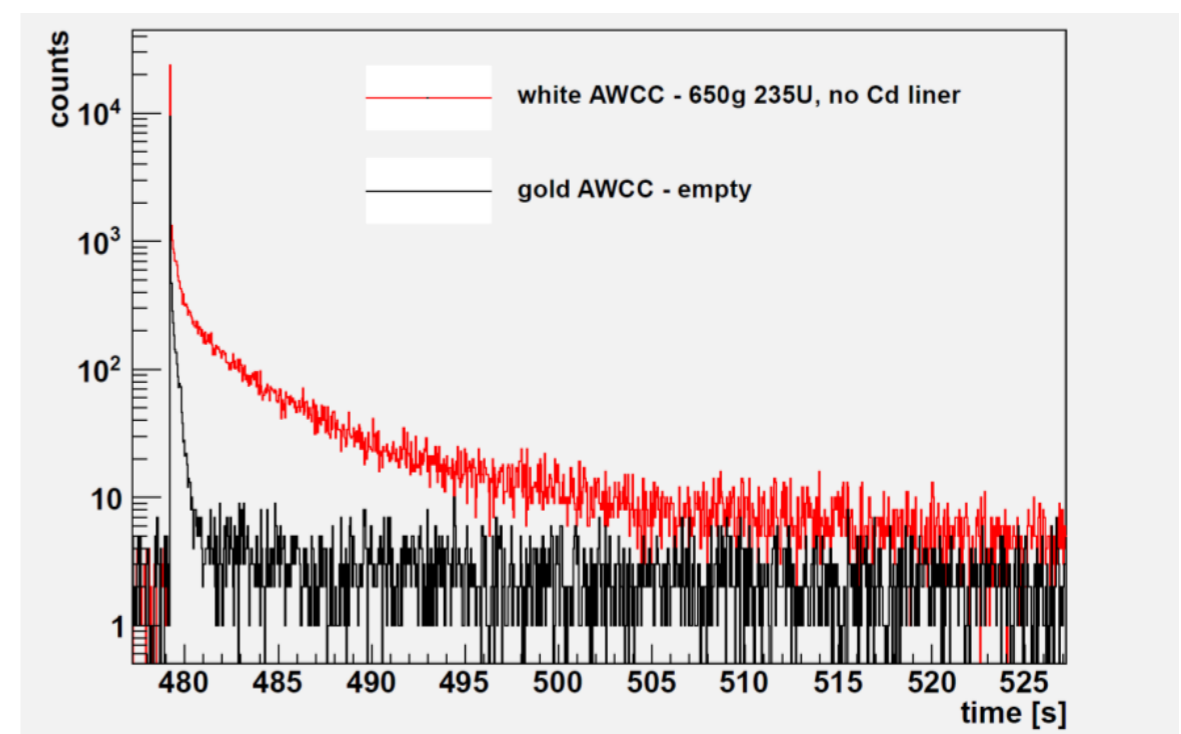
PI: Andrea Favalli, LANL



Sample: High Enriched Uranium (990 g U, of which 650g  $^{235}\text{U}$ )



Fast Mode (*with Cd sleeve*)



Thermal Mode (*without Cd sleeve*)

Delayed Neutrons chosen as signature, these neutrons are characteristic signatures for nuclear fission ( few other process yield delayed neutrons)



- Where do we go from here?

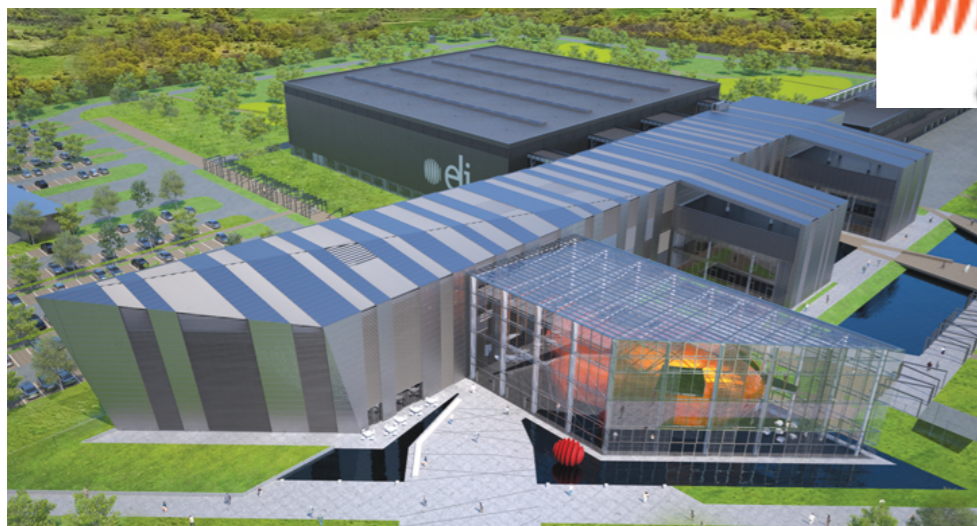


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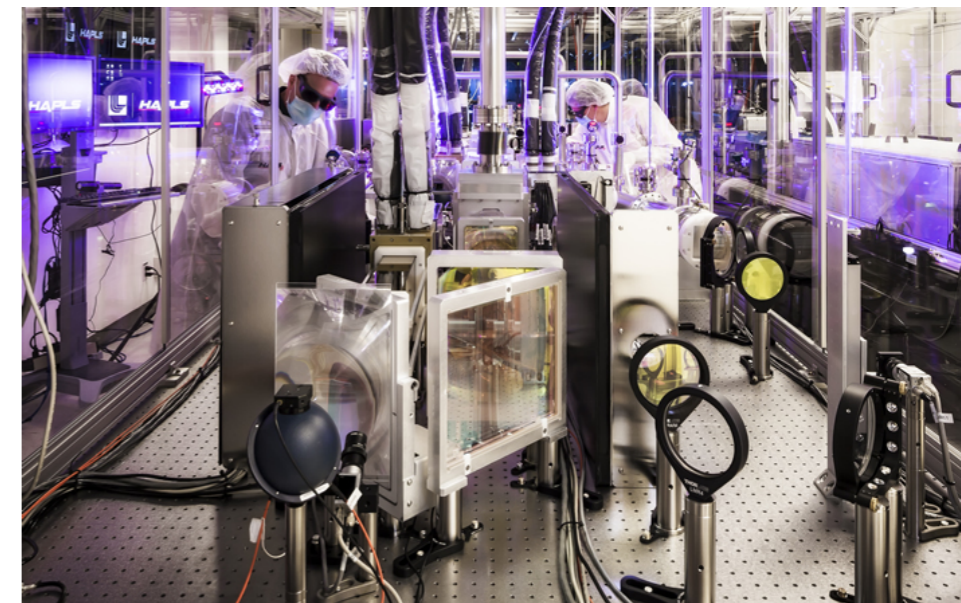


ELI-NP in Măgurele, RO [[www.eli-np.ro](http://www.eli-np.ro)]

ELI-BL in Dolní Břežany, CZ [[www.eli-beams.eu](http://www.eli-beams.eu)]



ELI-ALPS in Szeged, HU [[www.eli-hu.hu](http://www.eli-hu.hu)]



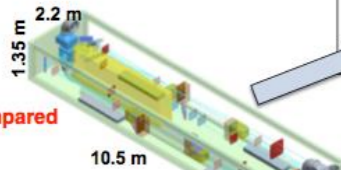
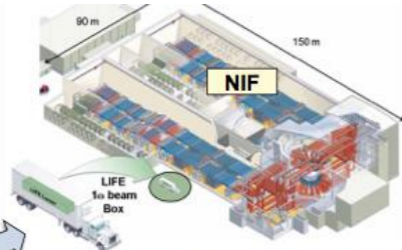
# Next generation laser systems



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## Beam in the Box 8.1 kJ @ 20 ns @ 16/ Hz

Beam in a Box  
Laser



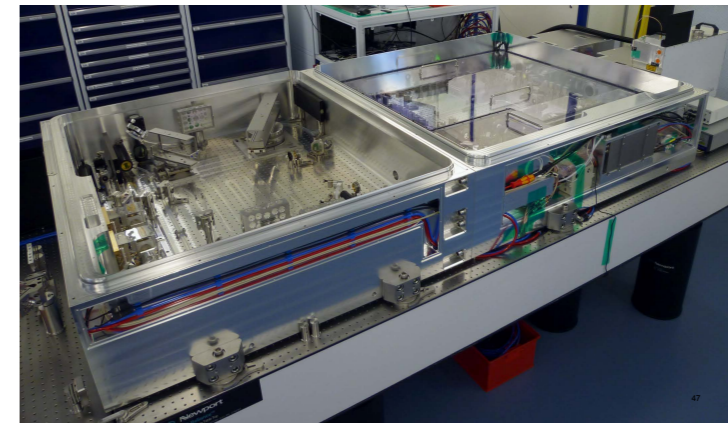
Imagine:

$10^{14}$  to  $10^{15}$  n/shot  
at 16 Hz

a big laser, but small compared  
to Lancse.

... and for a lot less \$\$\$

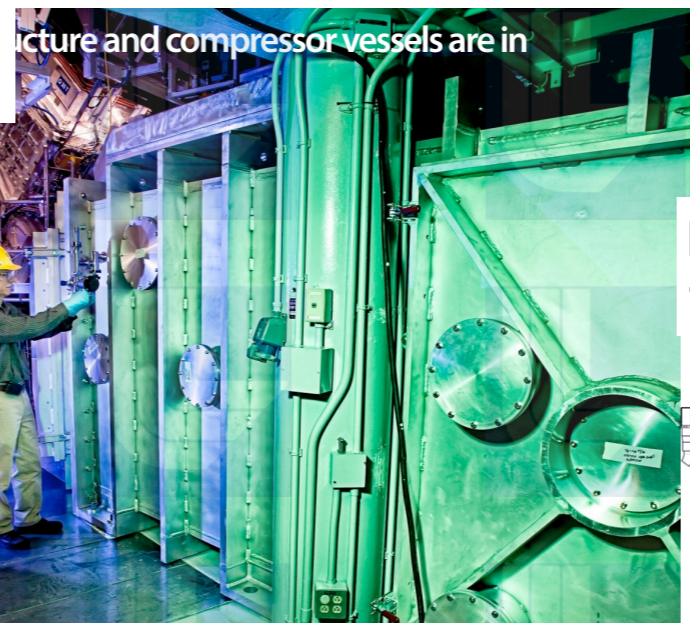
Details of the proposed solid-state IFE driver:  
based on neodymium-doped APG  
A single module would operate at  
130 kW (IR)/91 kW (UV) average power  
8.1 kJ (IR)/5.7 kJ (UV) output pulse energy  
at 16 Hz repetition rate.  
aperture size is 25 x 25 cm



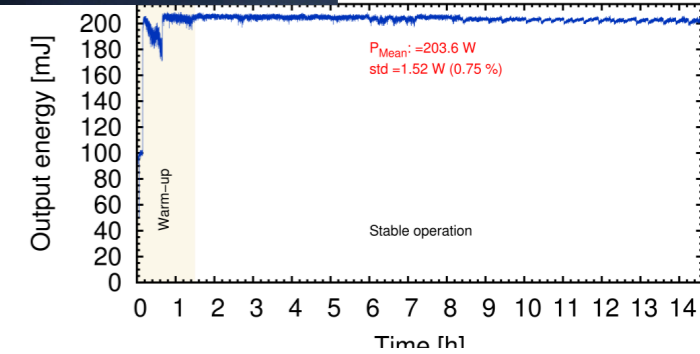
: Longterm Measurement

## ARC @ NIF

8.5 kJ @ 1.5 ps @ 1/ 90 min

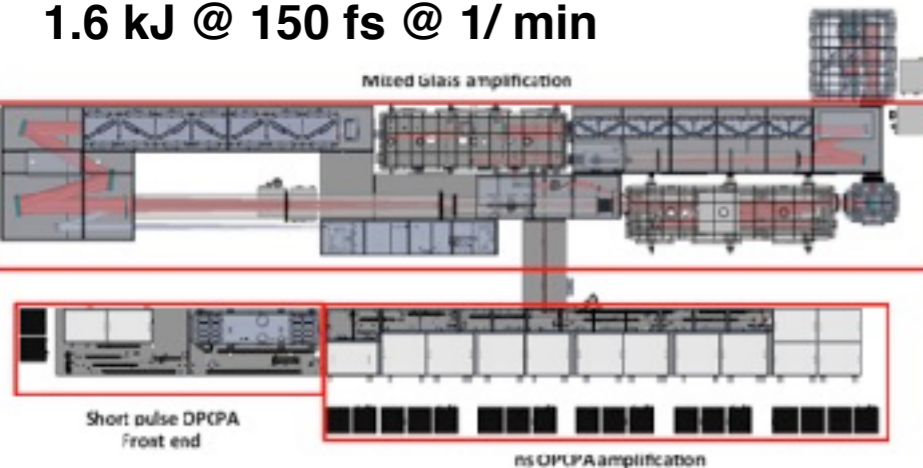


picture and compressor vessels are in



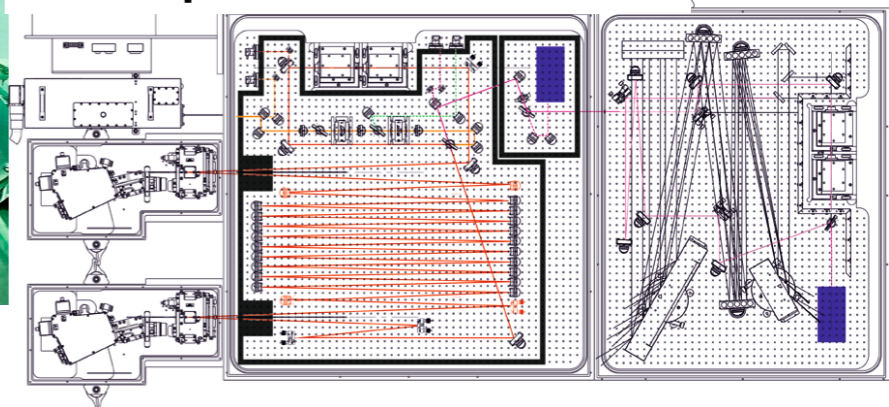
## L4 @ ELI

1.6 kJ @ 150 fs @ 1/ min

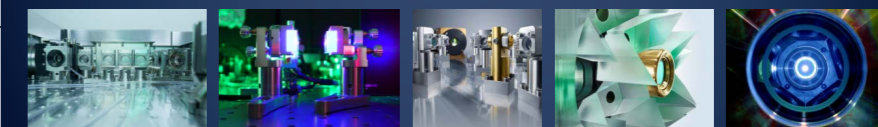


## FET Project @ TRUMPF

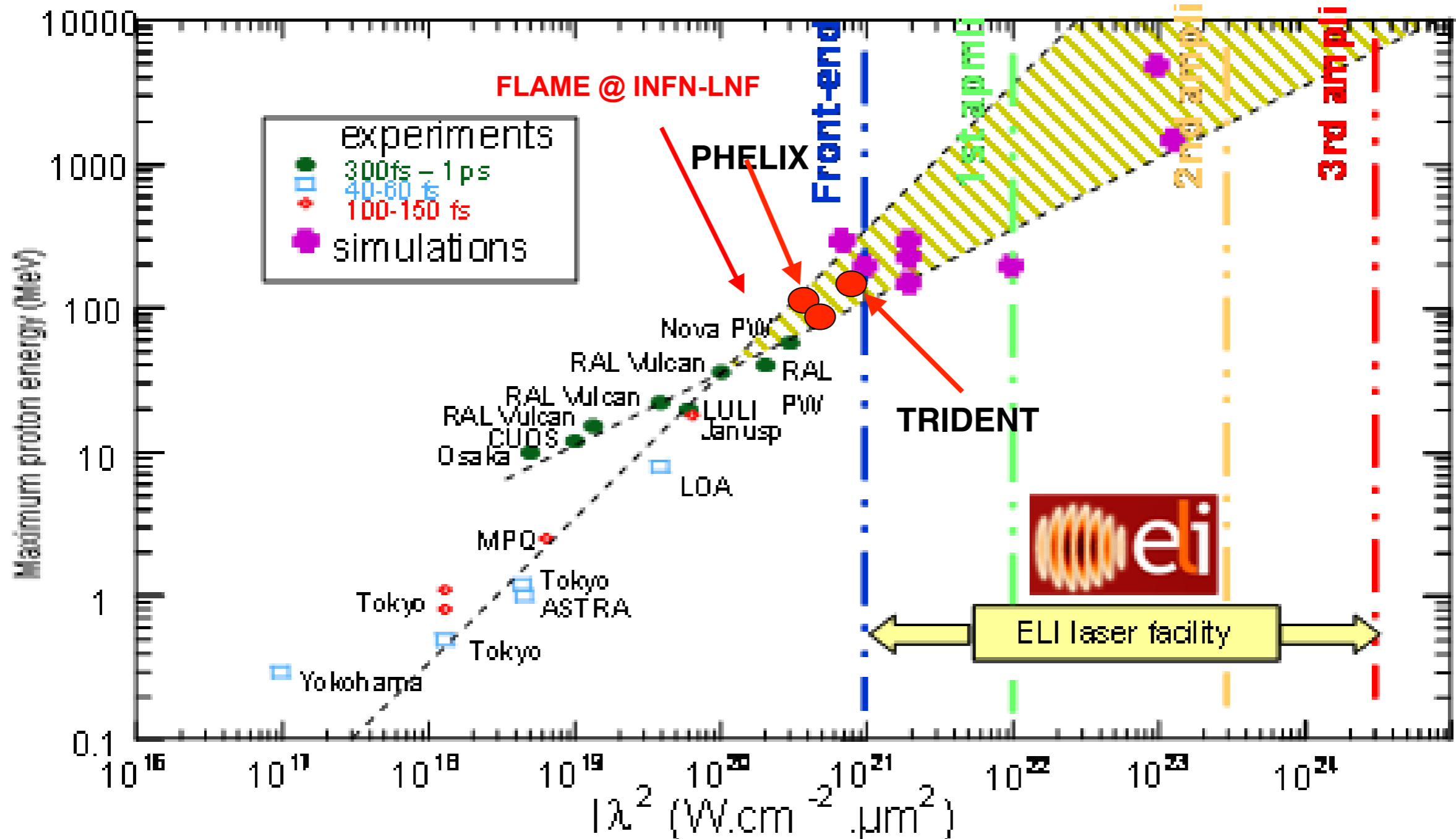
1J @ 1 ps @ 1kHz



## TRUMPF SCIENTIFIC LASERS

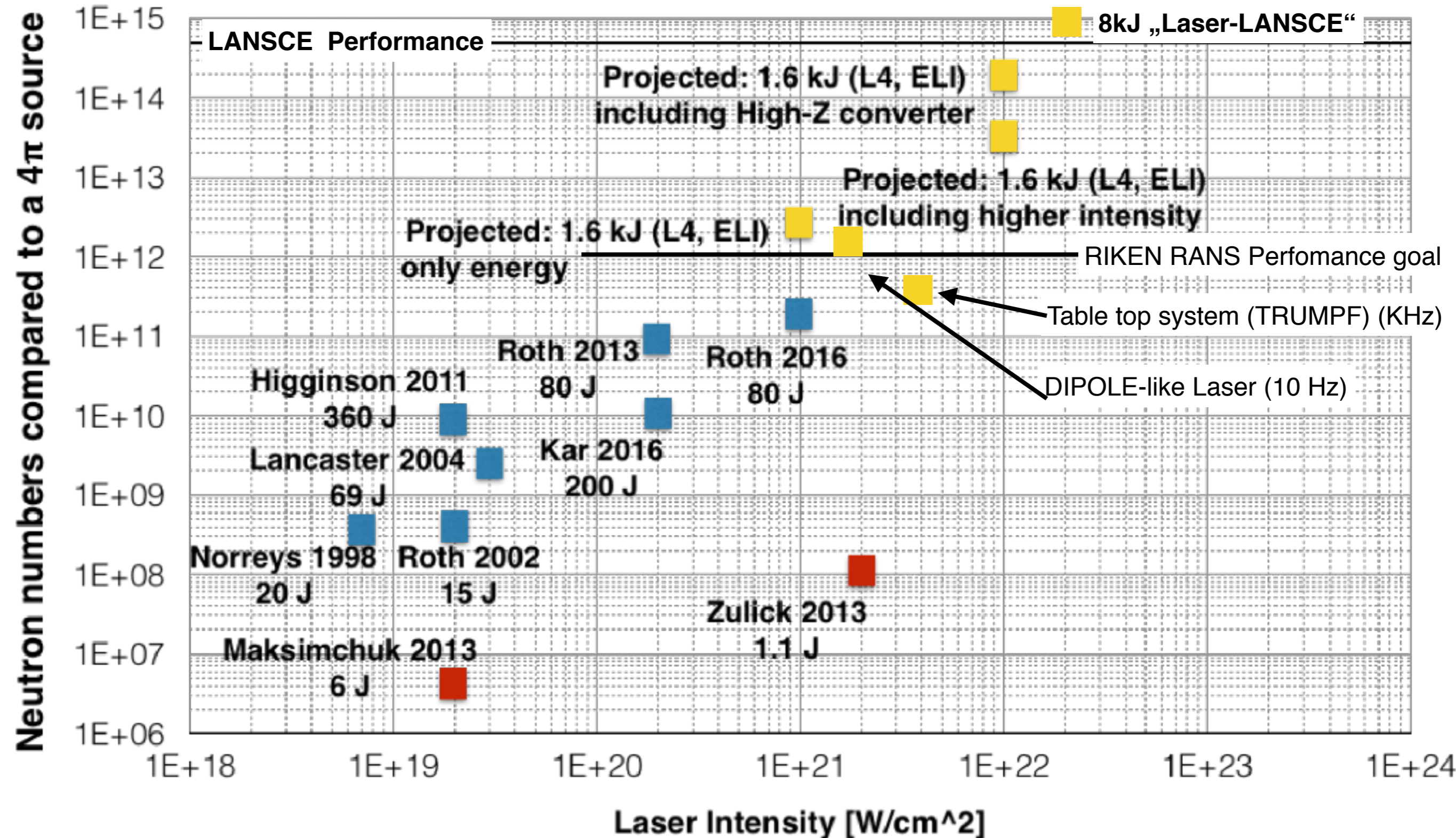


# Laser development and ion energies





# Prospects



The future for laser-driven neutron sources seems to look brighter every year...

**Thank you!!**

