The Nobel Prize in Physics 2018 and future applications for Laser-Driven Neutron Sources

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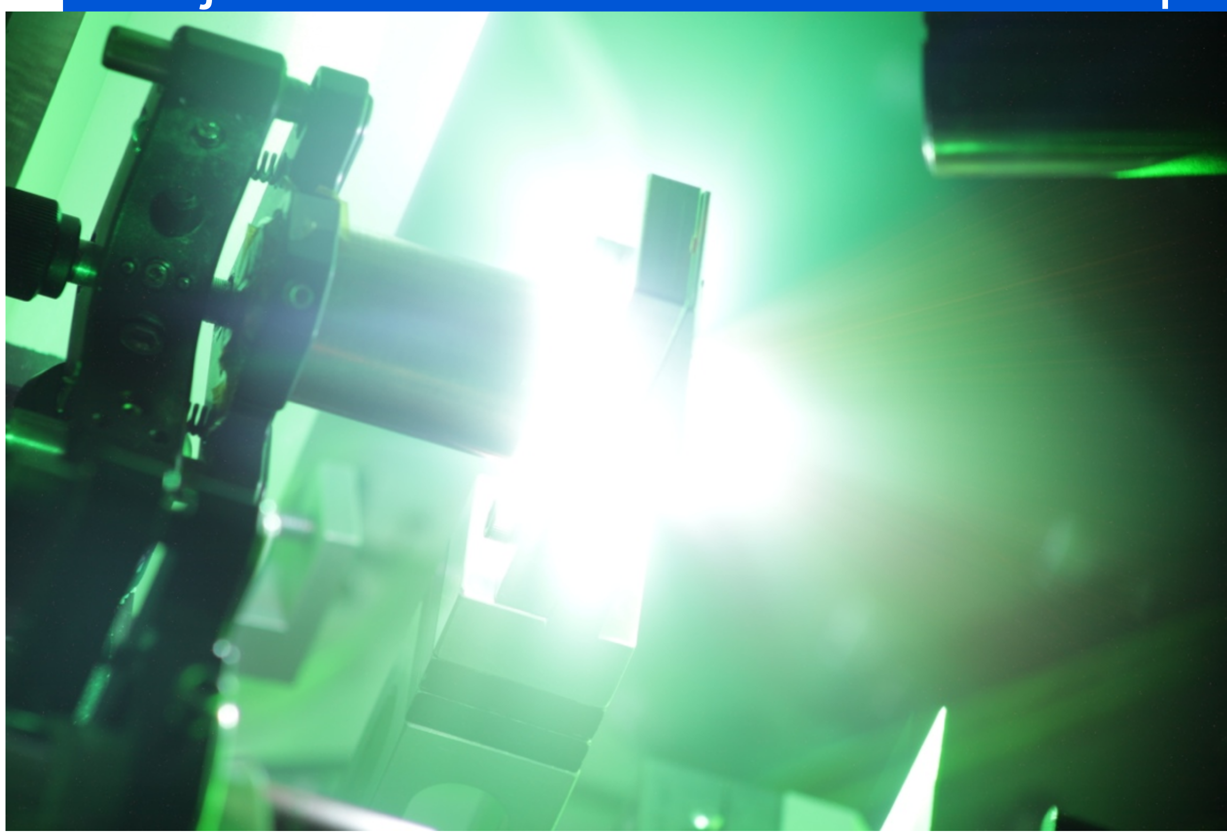
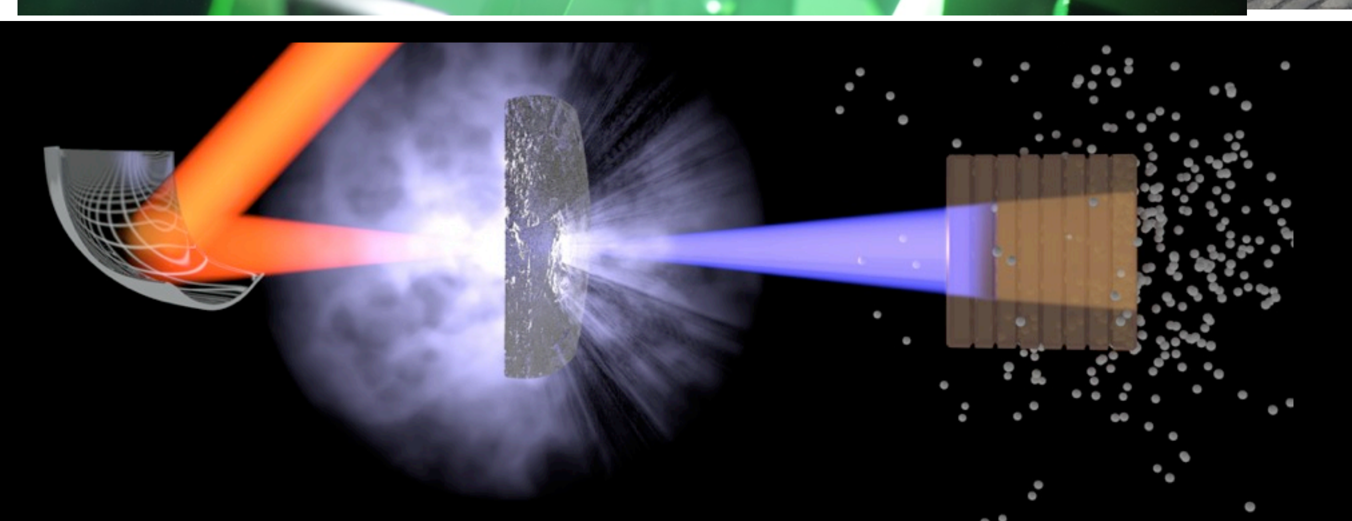
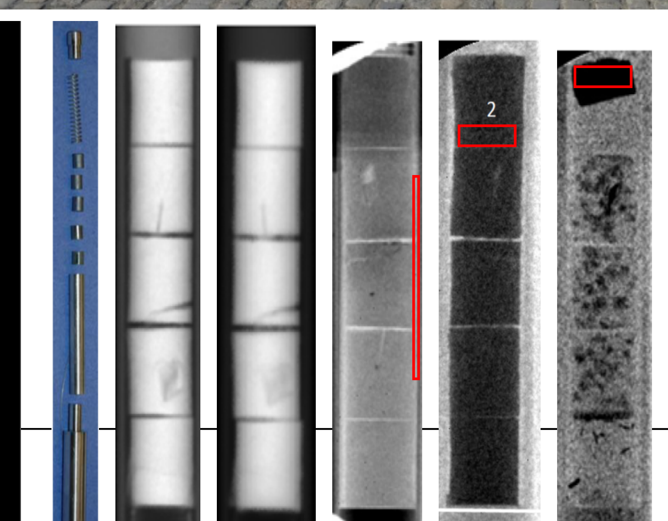
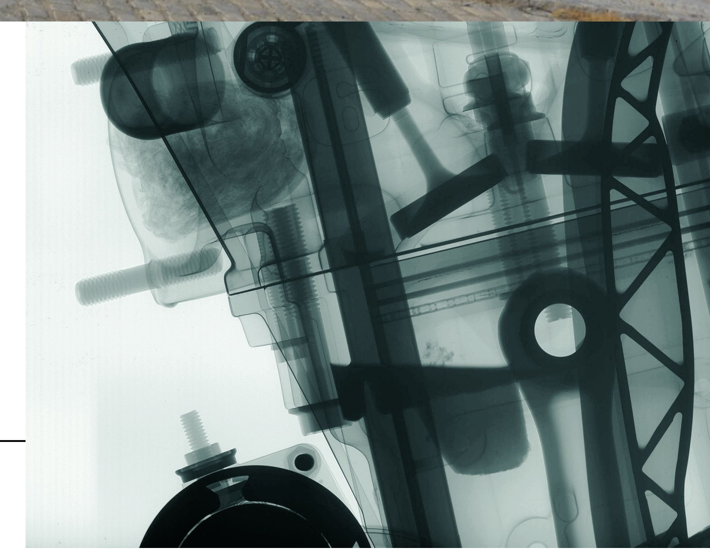
A joint effort from nuclear and laser-plasma scientists at TUD









Nuclear Photonics is becoming a new field of research

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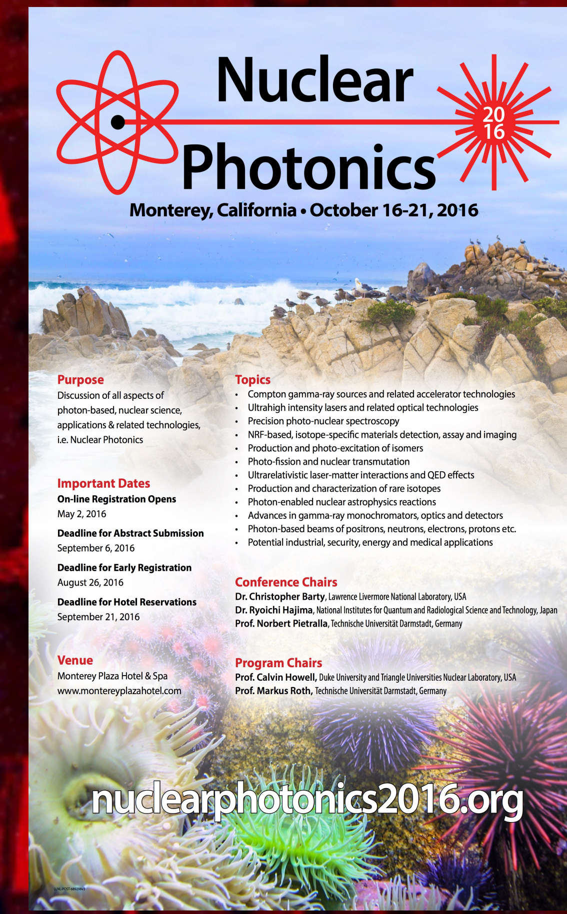
International center for Nuclear Photonics

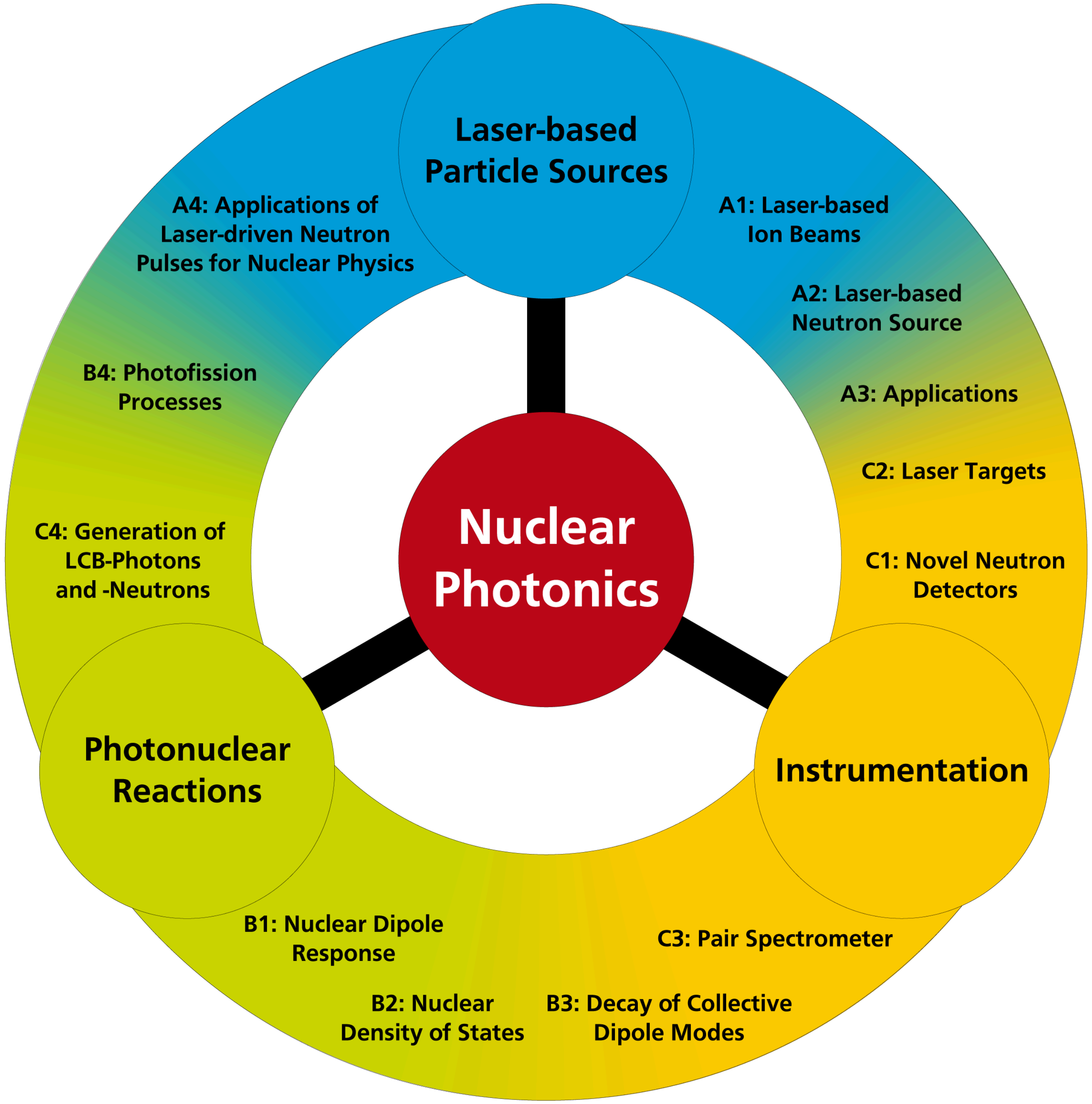


Michaela Arnold	Accel. Phys.
Thomas Aumann	Nuclear Phys.
Vincent Bagnoud	Laser Phys.
Oliver Boine-Frankenheim	Plasma Phys.
Joachim Enders	Nuclear Phys.
Thorsten Kröll	Nuclear Phys.
Norbert Pietralla	Nuclear Phys.
Markus Roth	Plasma Phys.

High-power laser-based radiation sources and nuclear methods for basic research and applications

LOEWE-Schwerpunkt at TU Darmstadt

Topics



Laser-based Particle Sources
A1: Laser-based Ion Beams
A2: Laser-based Neutron Source
A3: Applications
C2: Laser Targets
C1: Novel Neutron Detectors
Instrumentation
C3: Pair Spectrometer
B3: Decay of Collective Dipole Modes
B2: Nuclear Density of States
B1: Nuclear Dipole Response
Photonuclear Reactions
C4: Generation of LCB-Photons and -Neutrons
B4: Photofission Processes
A4: Applications of Laser-driven Neutron Pulses for Nuclear Physics
Nuclear Photonics

CPA (Chirped Pulse Amplification) can generate high energy pulses up to 10^{15} W

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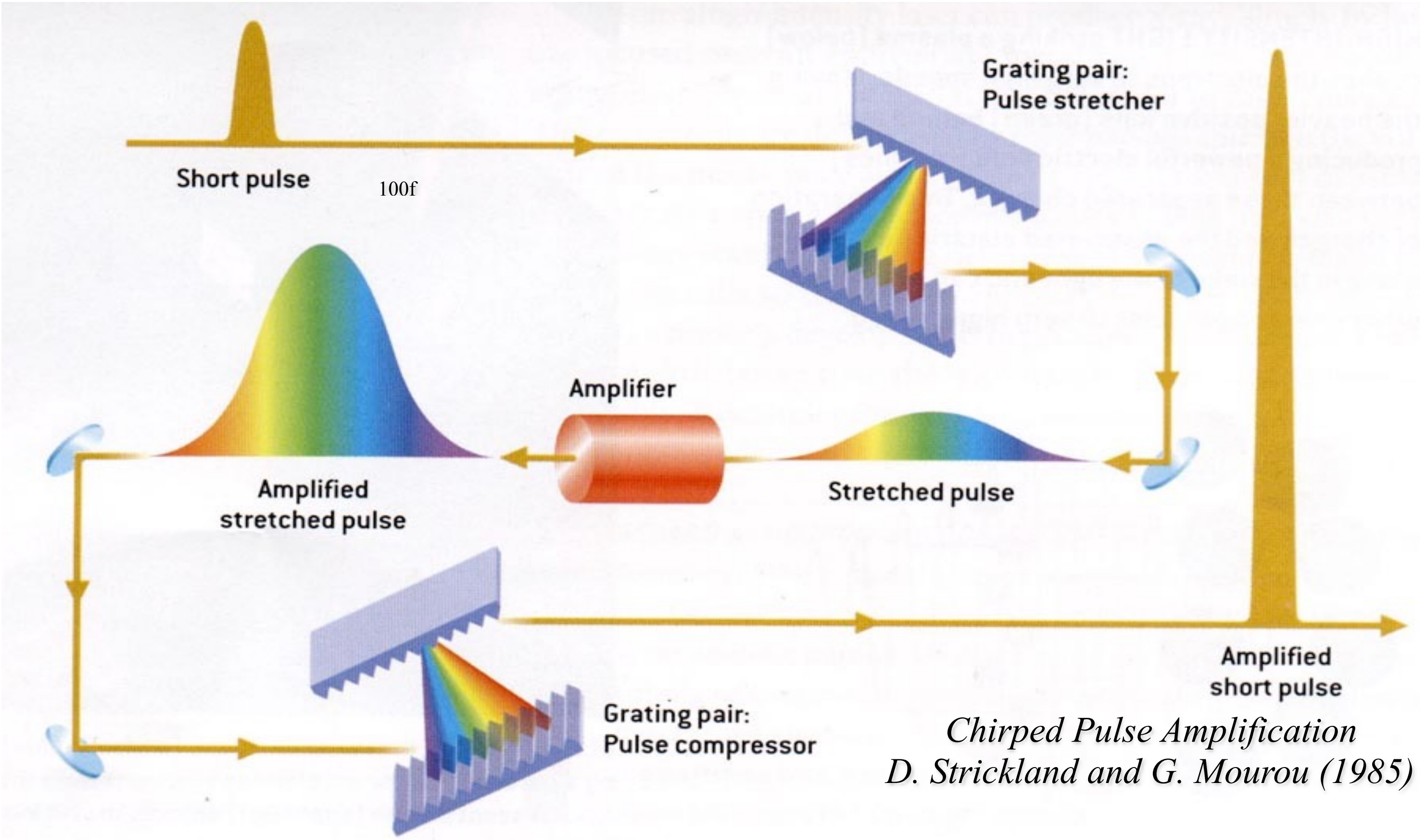
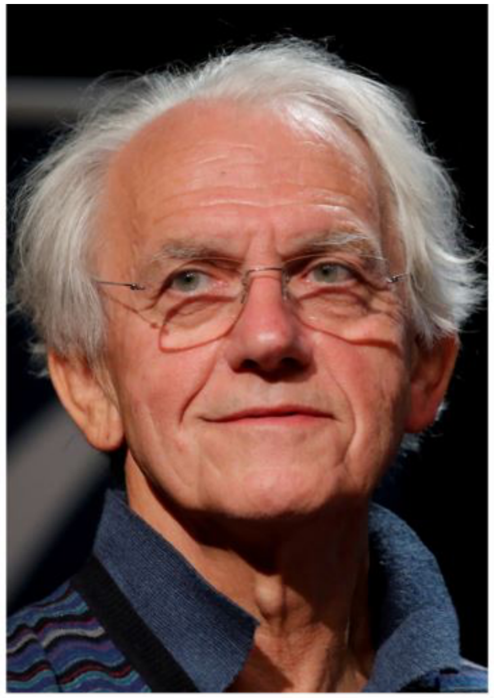
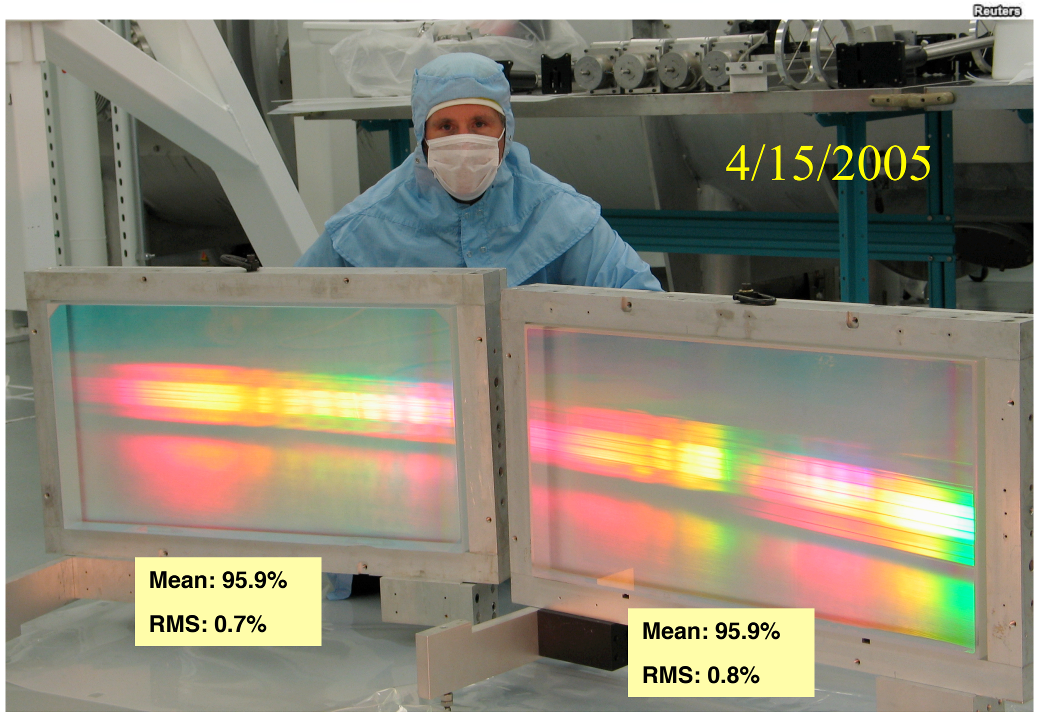


Chirped Pulse Amplification
D. Strickland and G. Mourou (1985)





Volume 55, number 6 OPTICS COMMUNICATIONS 15 October 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES

Donna STRICKLAND and Gerard MOUROU
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1].

We wish to report here a system which transposes the technique employed in radar to the optical regime, and that in principle should be capable of producing short ($\lesssim$1 ps) pulses with energies at the Joule level. A long pulse is deliberately produced by stretching a

sion system is shown in fig. 1. A CW mode-locked, Nd : YAG laser (Spectra-Physics Series 3000) is used to produce 150 ps pulses at an 82 MHz repetition rate. Five watts of average power are coupled into 1.4 km of single-mode non-polarization-preserving optical fiber. The fiber (Corning Experimental SMF/DS™) has a core diameter of 9 μm. The average power at the output of the fiber is 2.3 W. The pulses have a rectangular pulseshape with a pulse width of approximately 300 ps, as can be seen from the autocorrelation trace in fig. 2. The bandwidth of the pulses is 50 Å. The stretched pulses are injected into a pulsed, Nd : glass, regenerative amplifier, by reflection from an AR coated window. An AR coated window is used to protect the fiber end from being damaged by the

High Power laser development

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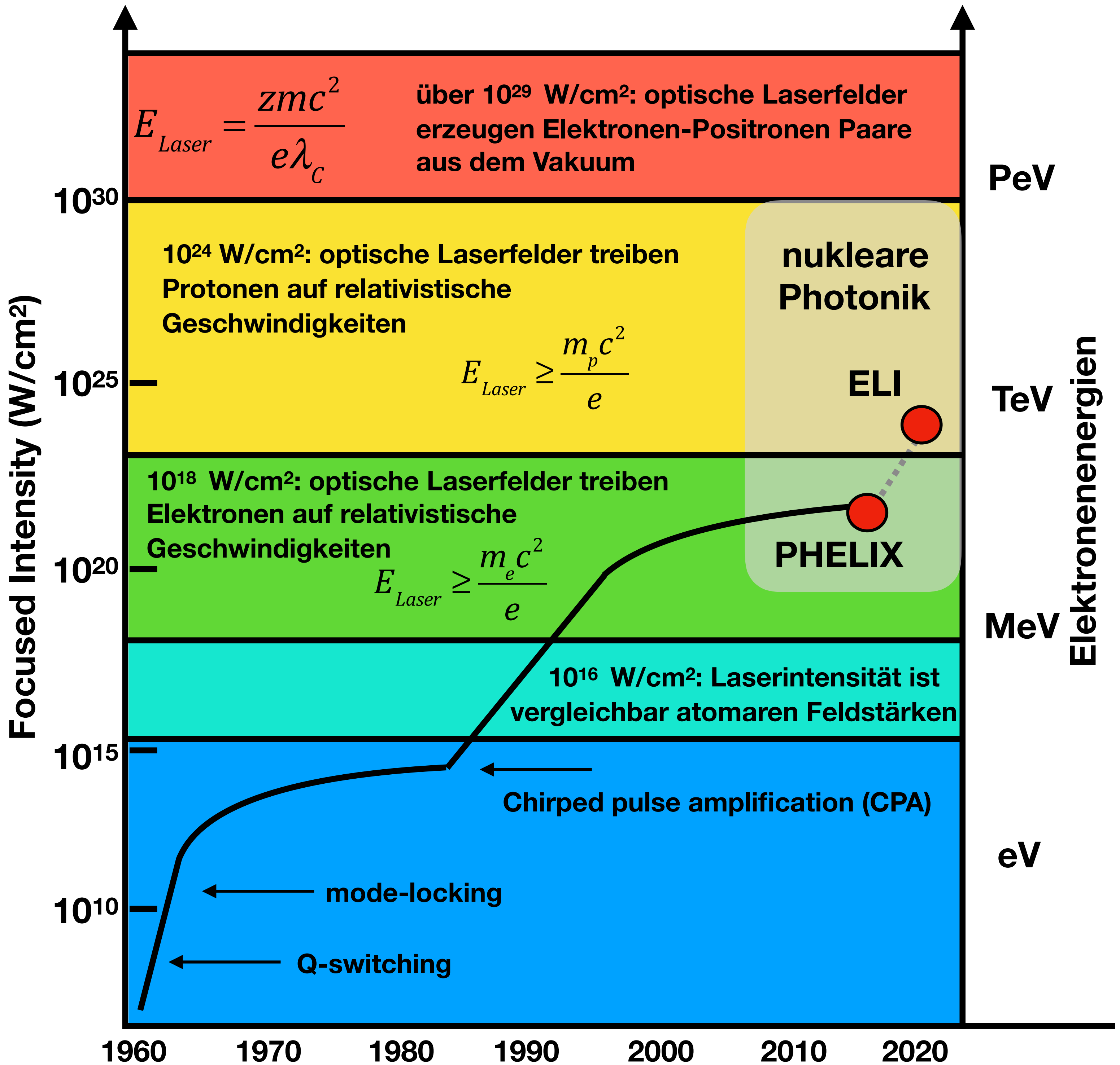
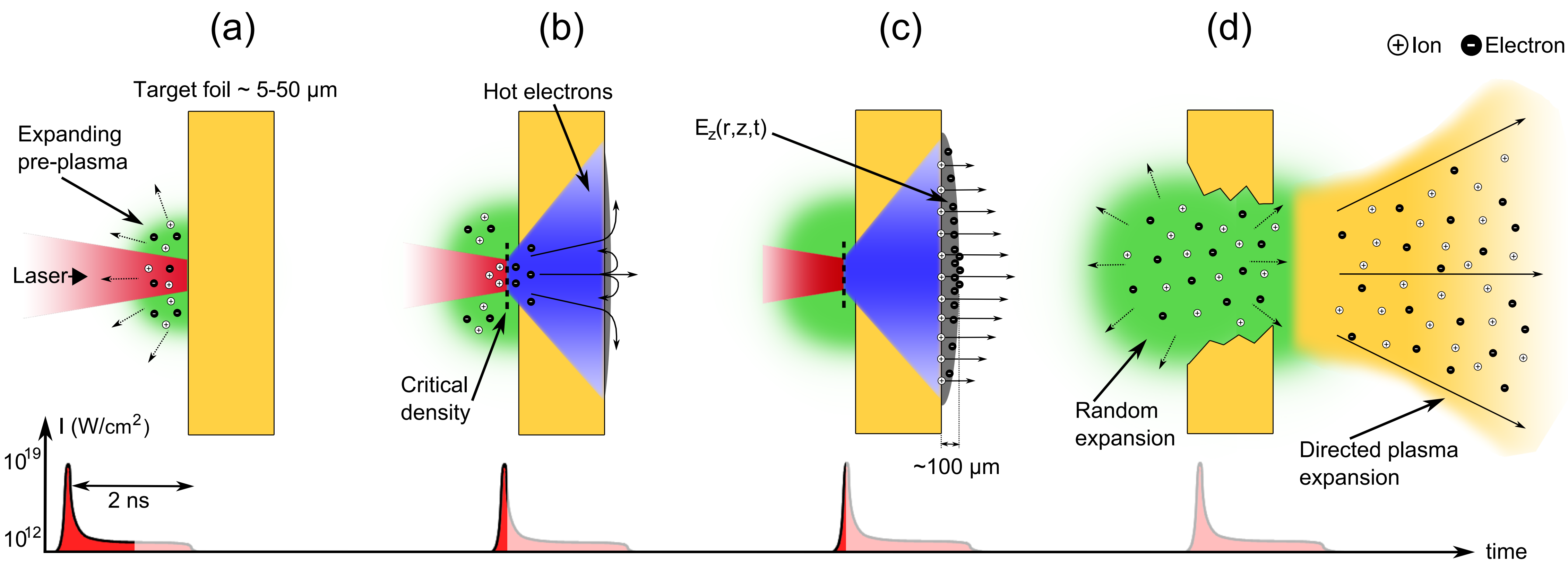


Proton acceleration with lasers : Static electric fields



Laser development and ion energies

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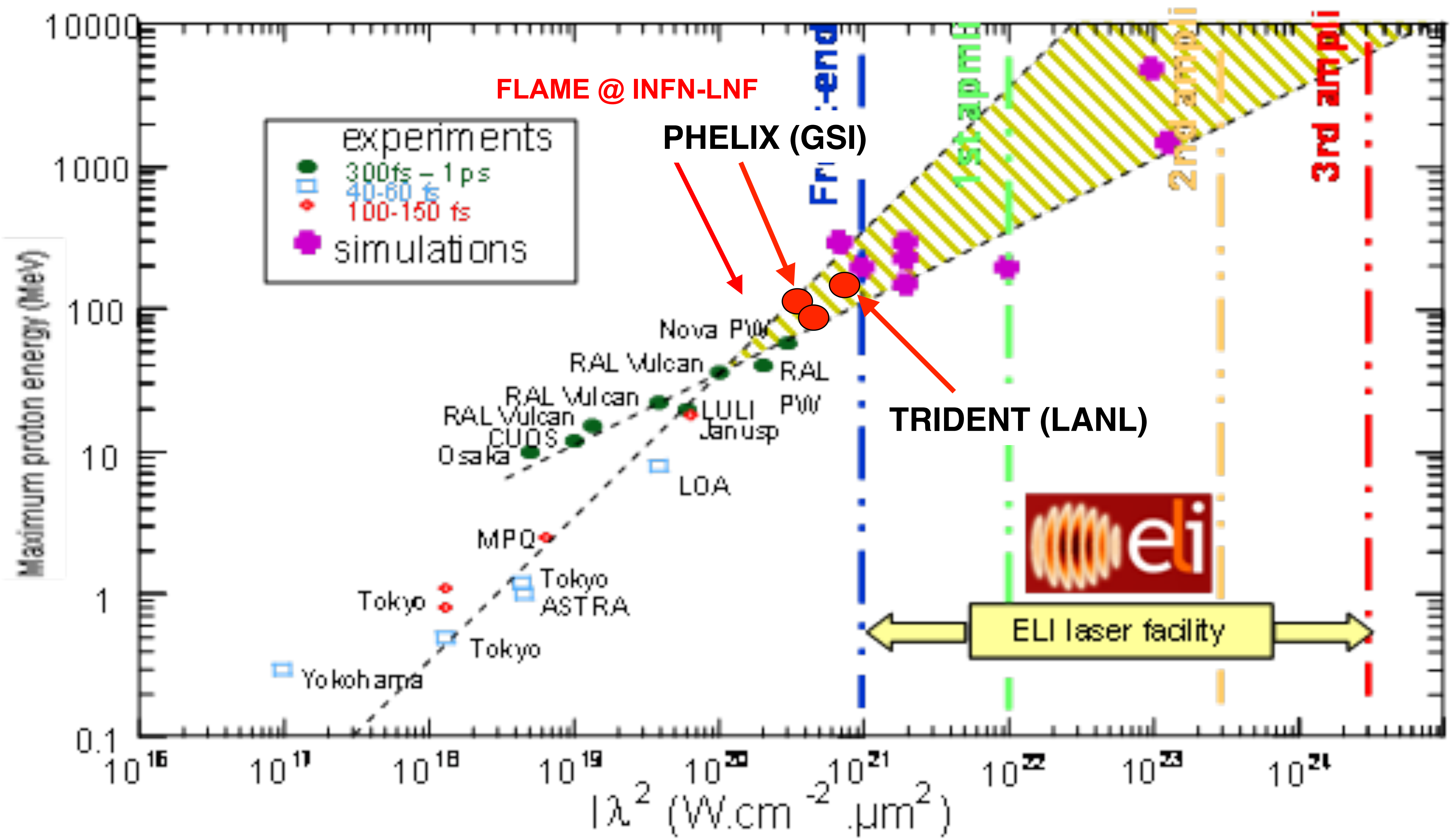

Why are we interested in Neutrons?

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Jülich Centre for Neutron Science

JÜLICH
FORSCHUNGSZENTRUM

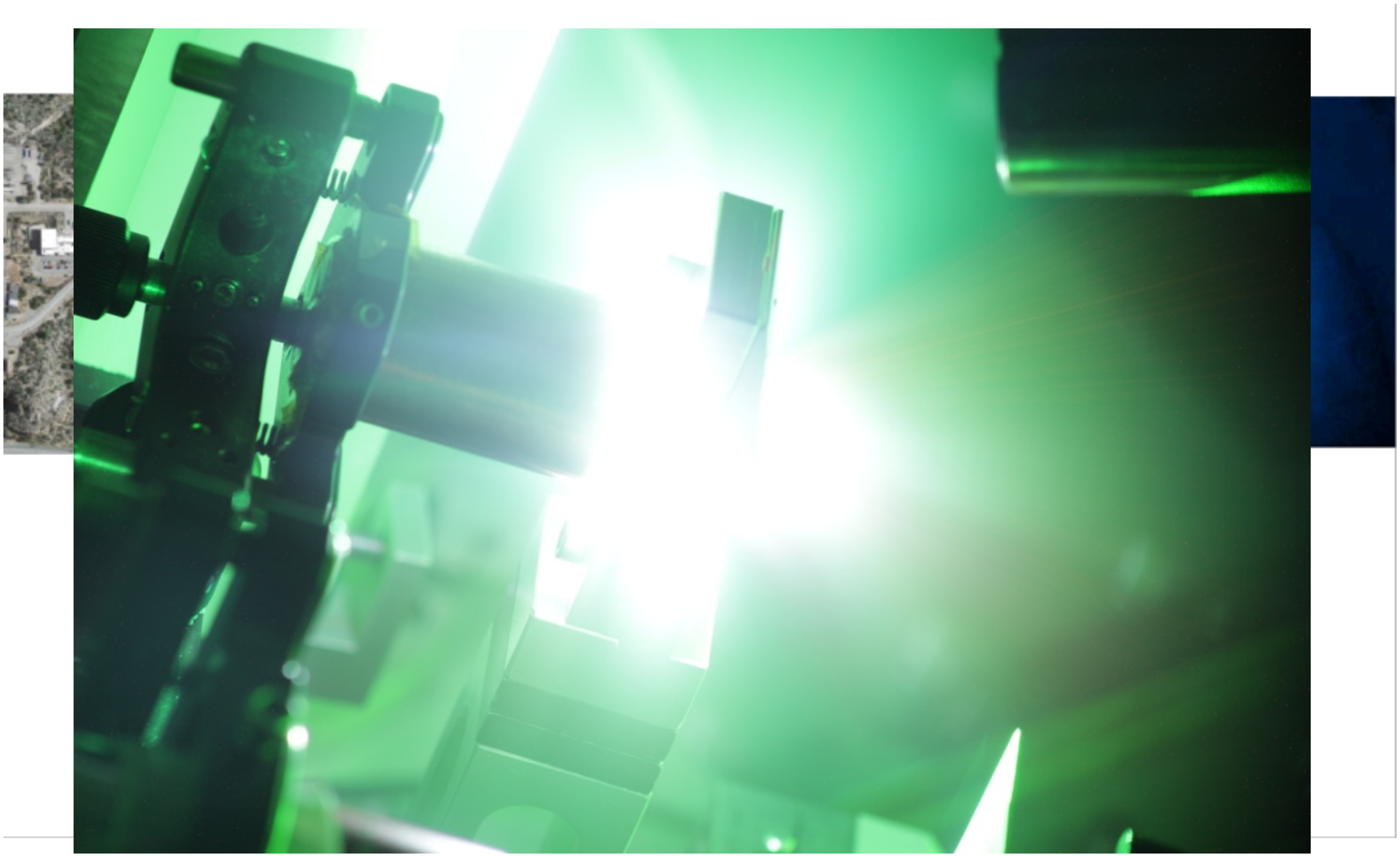
Neutrons:
A special gift for science

„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.

Neutron Sources



Compact neutron sources

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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 theses 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

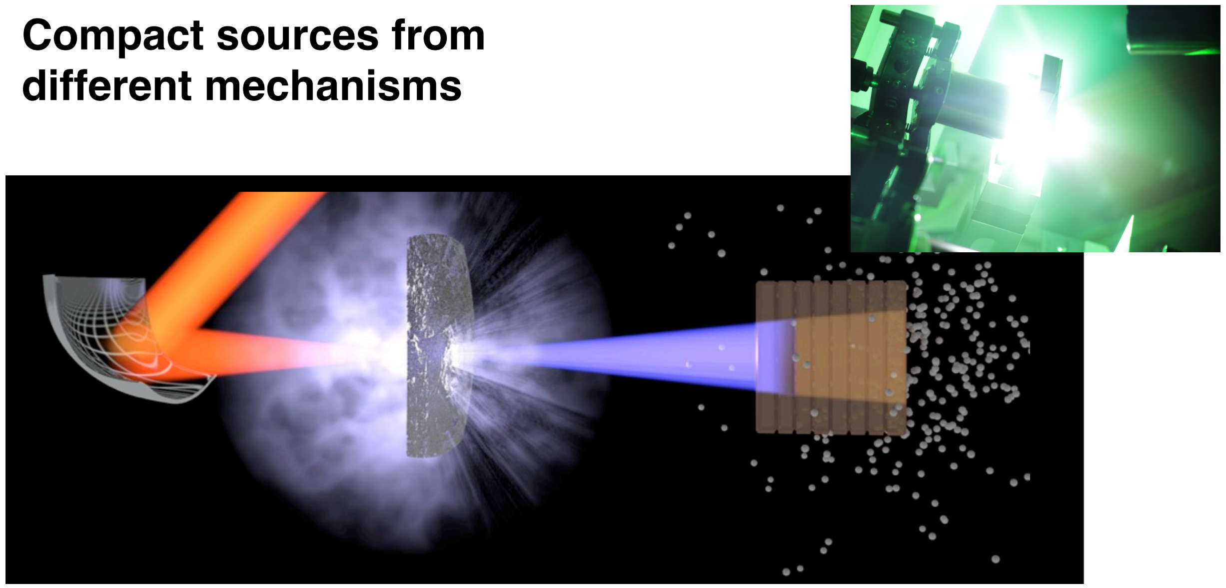
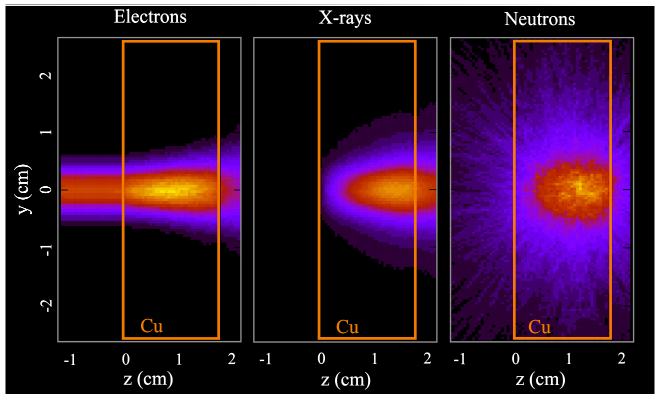
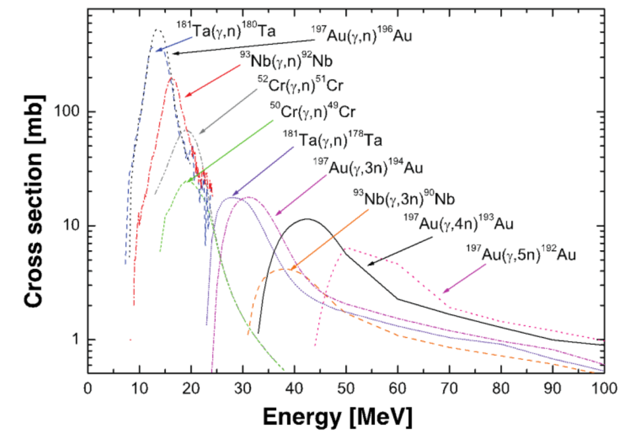


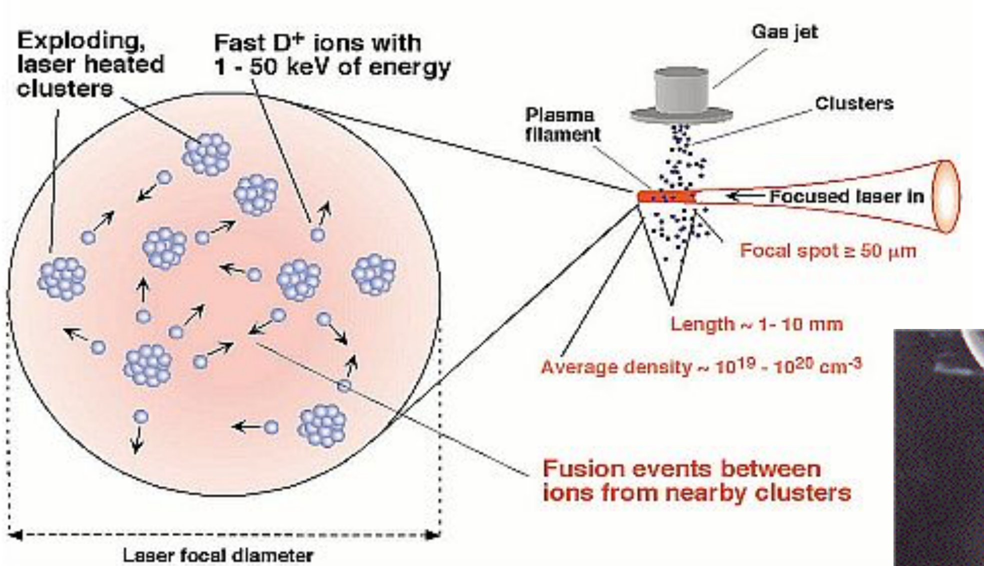
Photo-neutron production from electrons

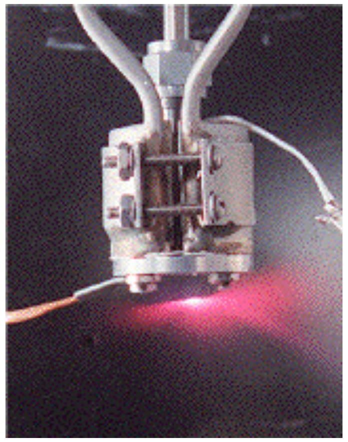


I. Pomerantz, UT



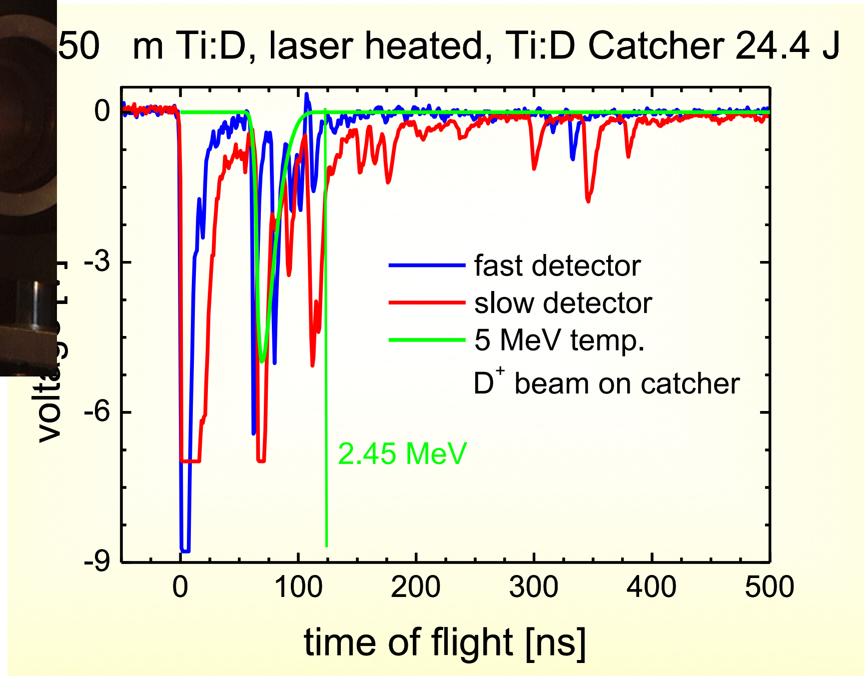
Neutrons from cluster fusion



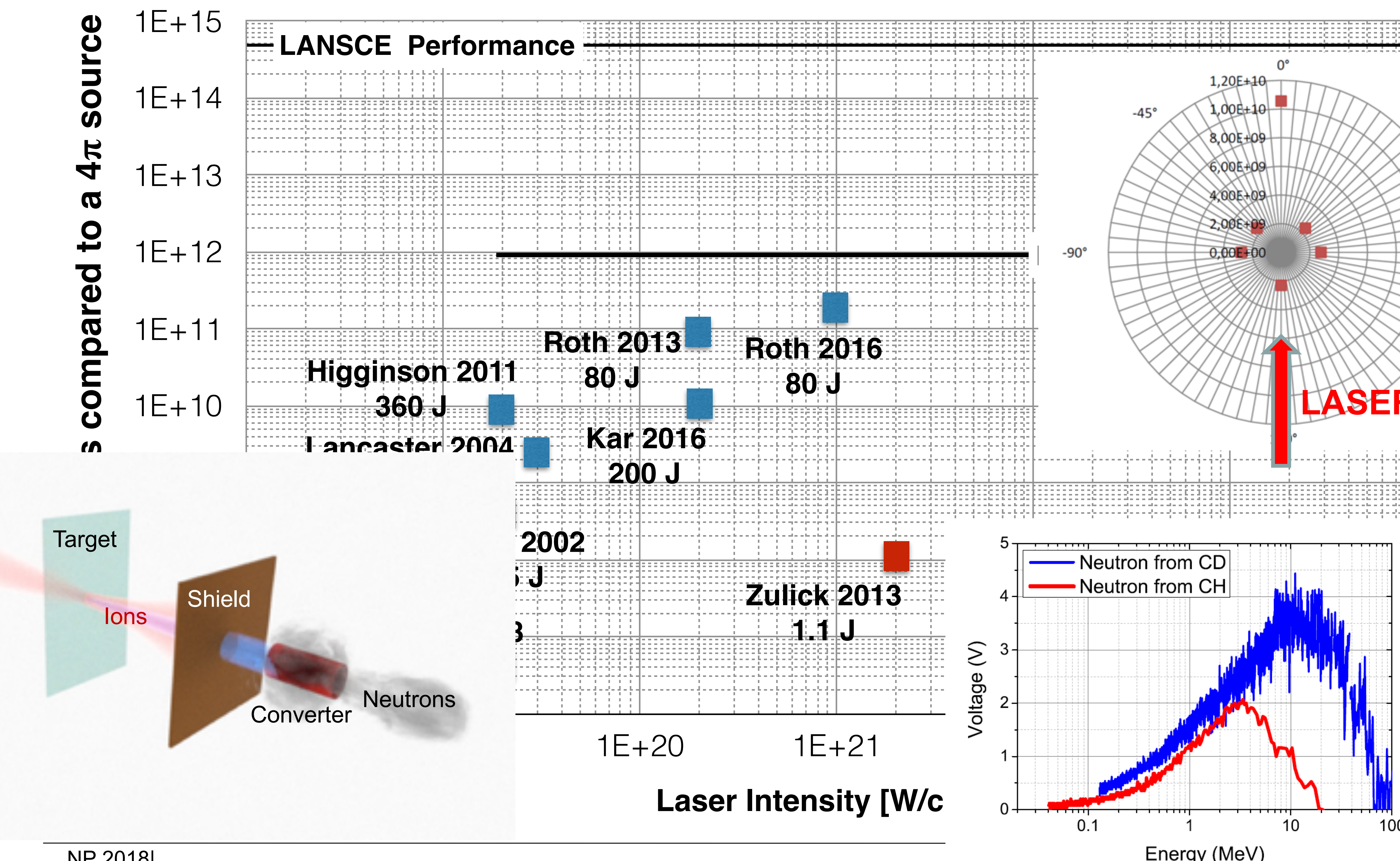


T. Dittmire, UT Austin

Neutrons from ion impact



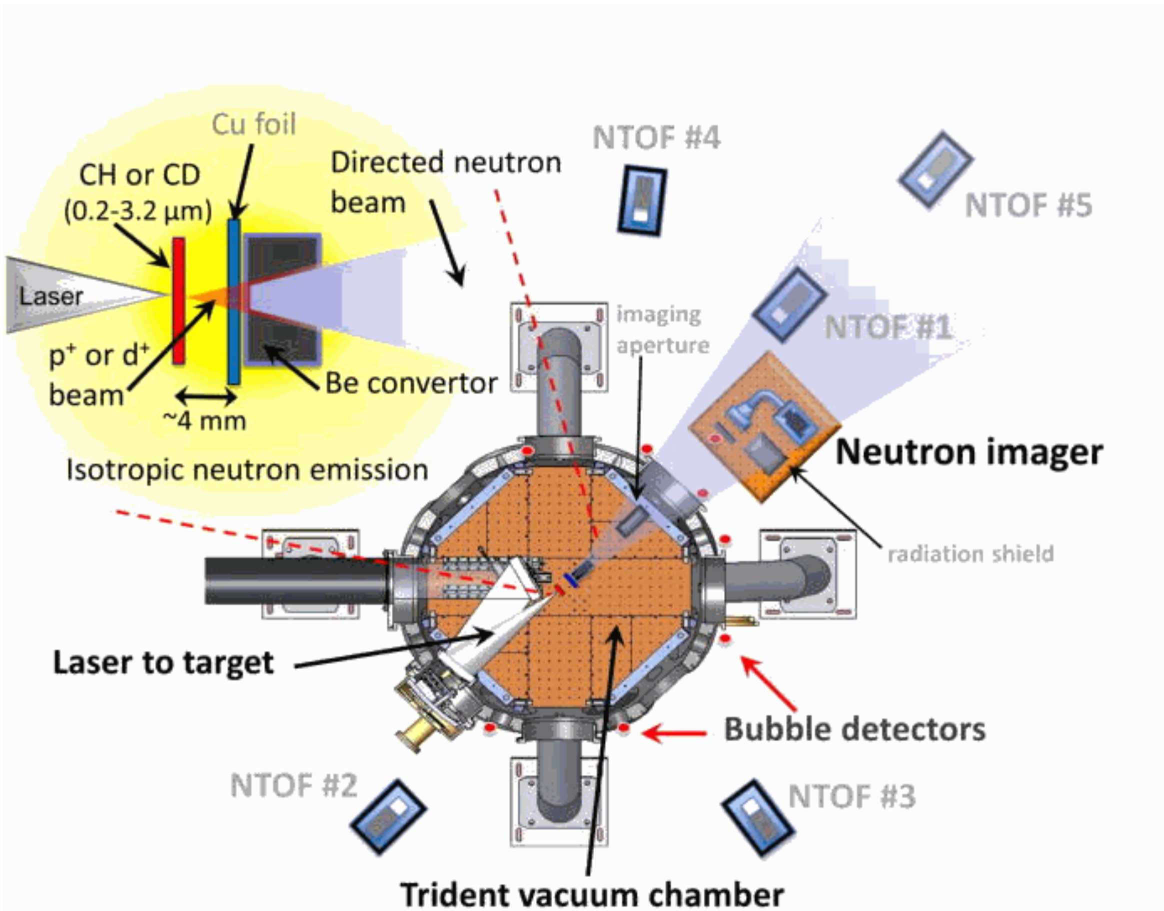
Highest yield directed neutron beam so far

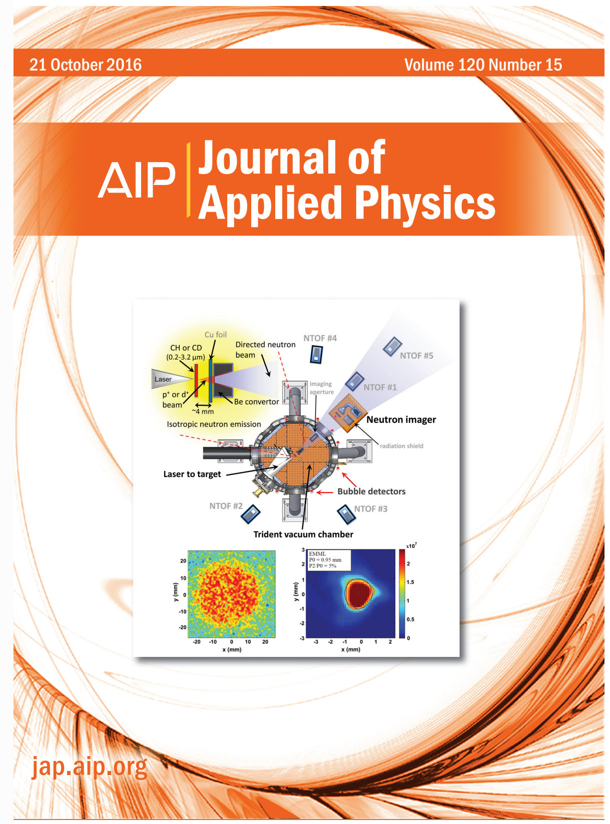


D. Jung et al., Phys. Plasmas **20**, 056706 (2013)

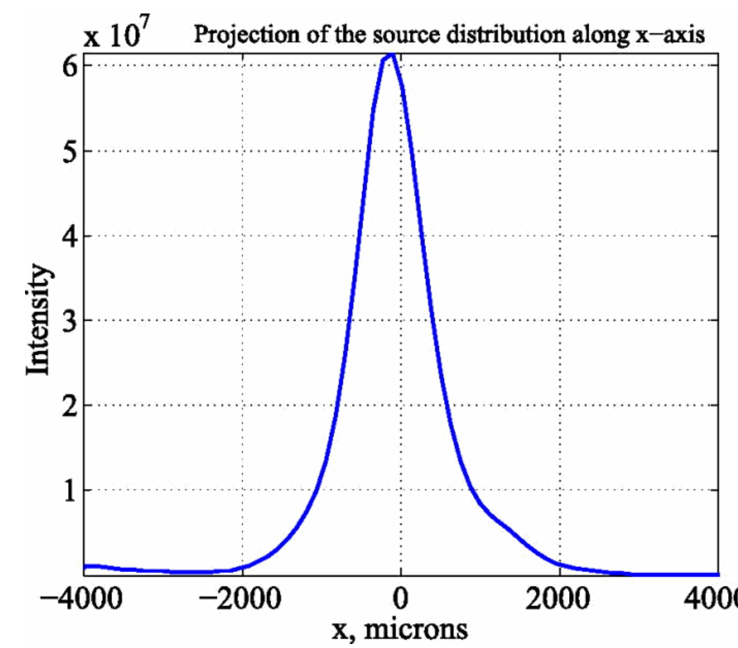
Fast neutron imaging

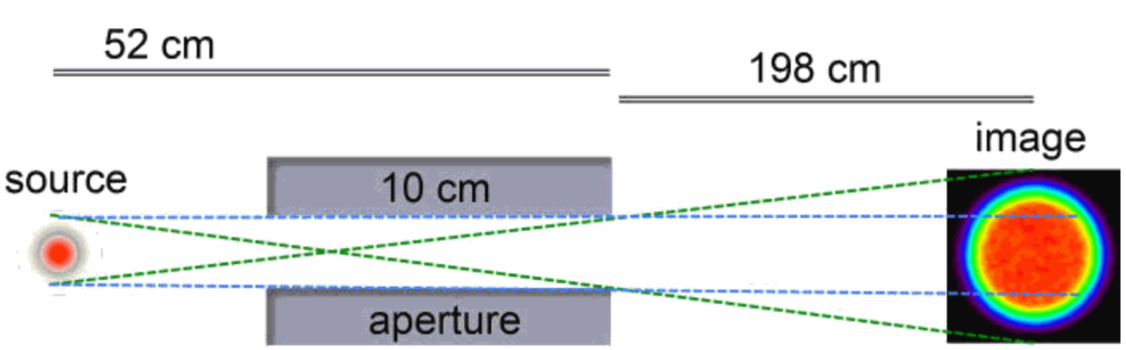
Single shot, ns exposure, compact laser

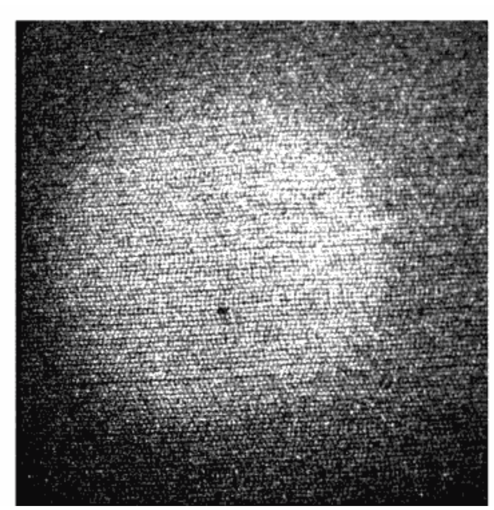




Journal of Applied Physics 10/17/2016







Source size 1.3 mm

Research to develop a compact, laser-driven, imaging neutron diagnostic to investigate nuclear material

NISRA
NEUTRON IMAGING SYSTEM FOR RADIOACTIVE-WASTE ANALYSIS

Radiographie mittels schneller Neutronen zur Charakterisierung radioaktiver Abfälle (Neutron Imaging)

Förderkennzeichen 02S9022A-C

gefördert mit Mitteln des Bundes

Editor: John Kettler[1] (Projektkoordinator)

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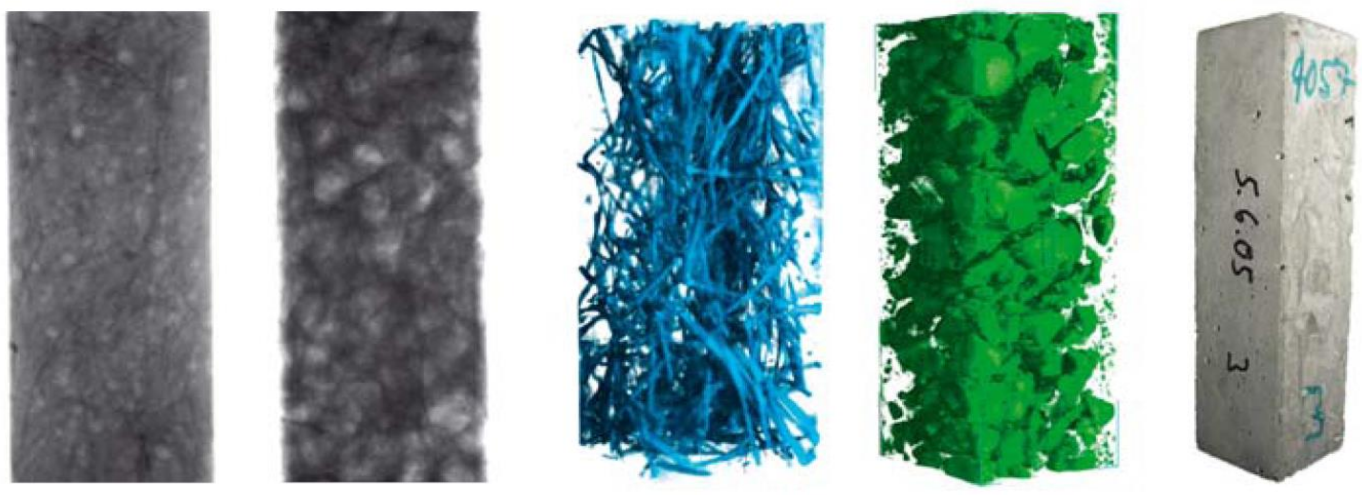
Zerstörungsfreie Analyseverfahren

radiologisch	stofflich	strukturell
Gamma-Scanning	Prompte Neutronenaktivierung	Gamma-Radiographie
Neutronen-Messung	Verzögerte Neutronenaktivierung	Neutronen-Radiographie

Ziel von F&E:
- Kopplung der Verfahren (Synergien)
- Zunahme der Leistungsfähigkeit/ Ergebnissicherheit

Röntgen Neutronen Röntgen Neutronen Fotografie



Possible Applications require a better compact neutron source

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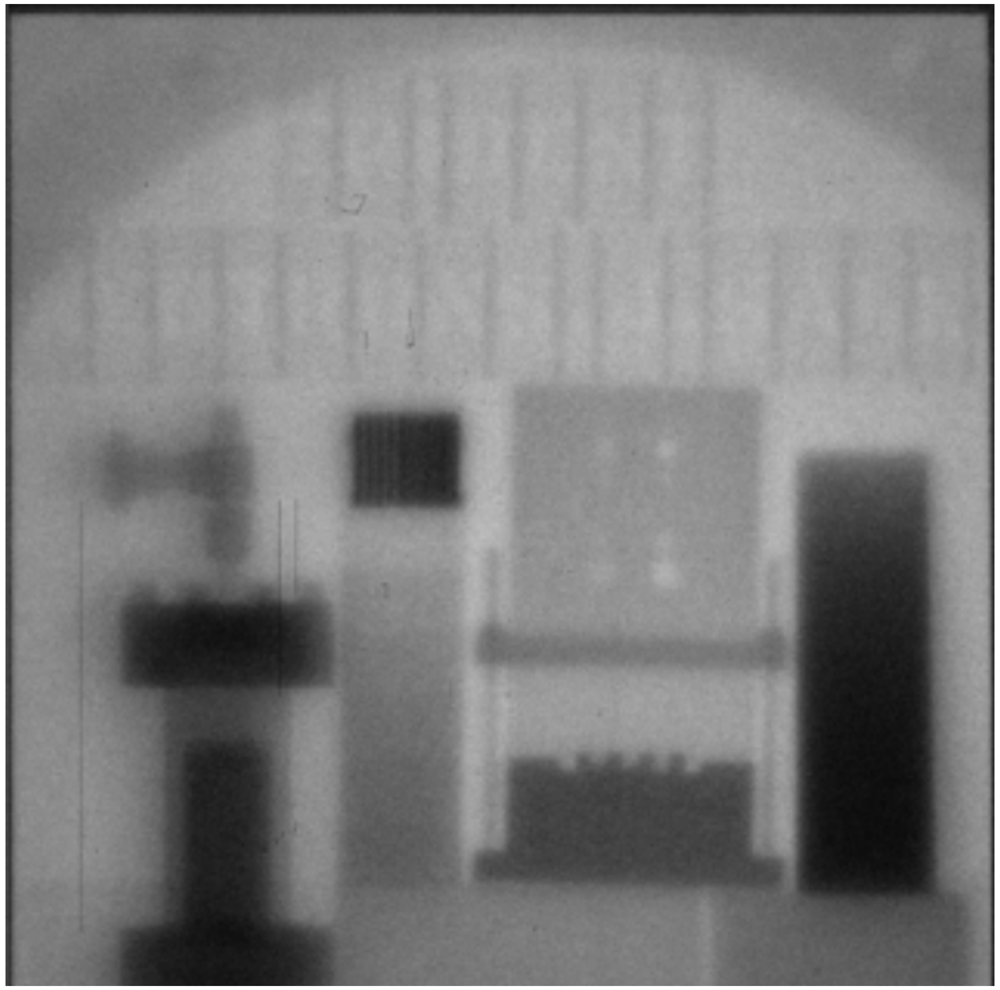
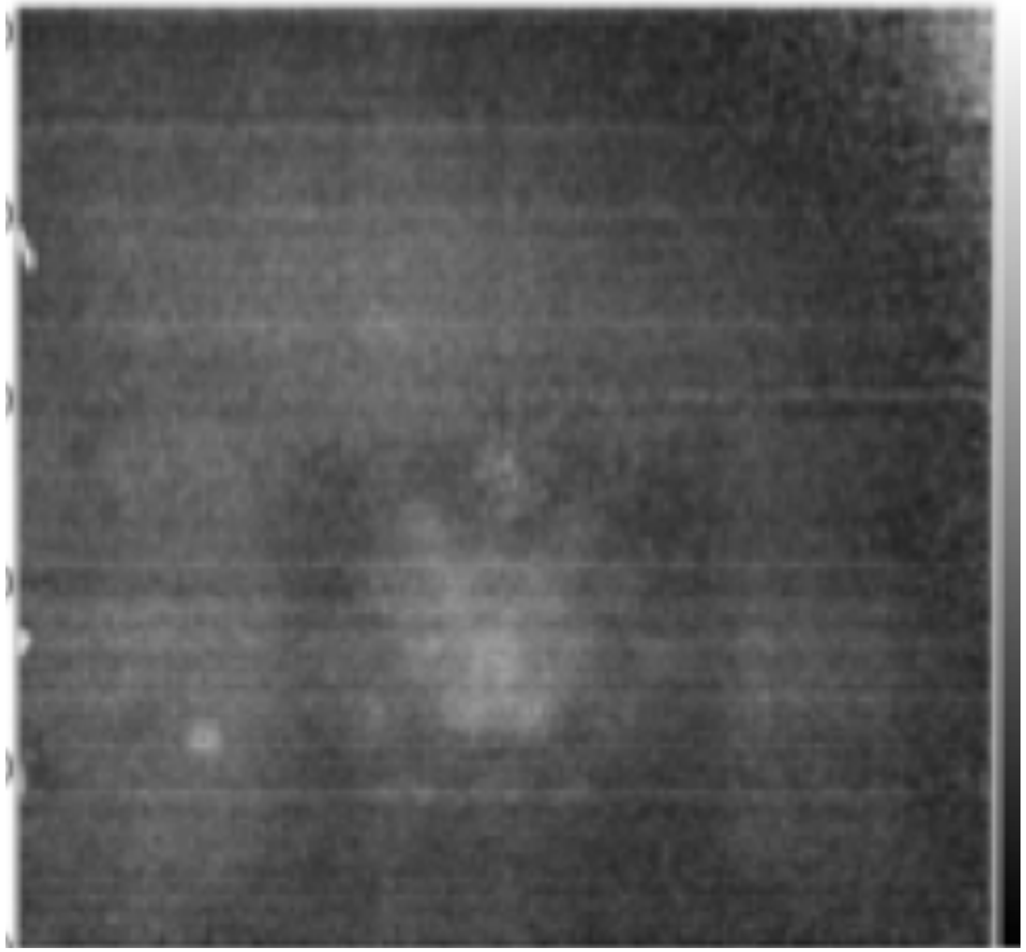
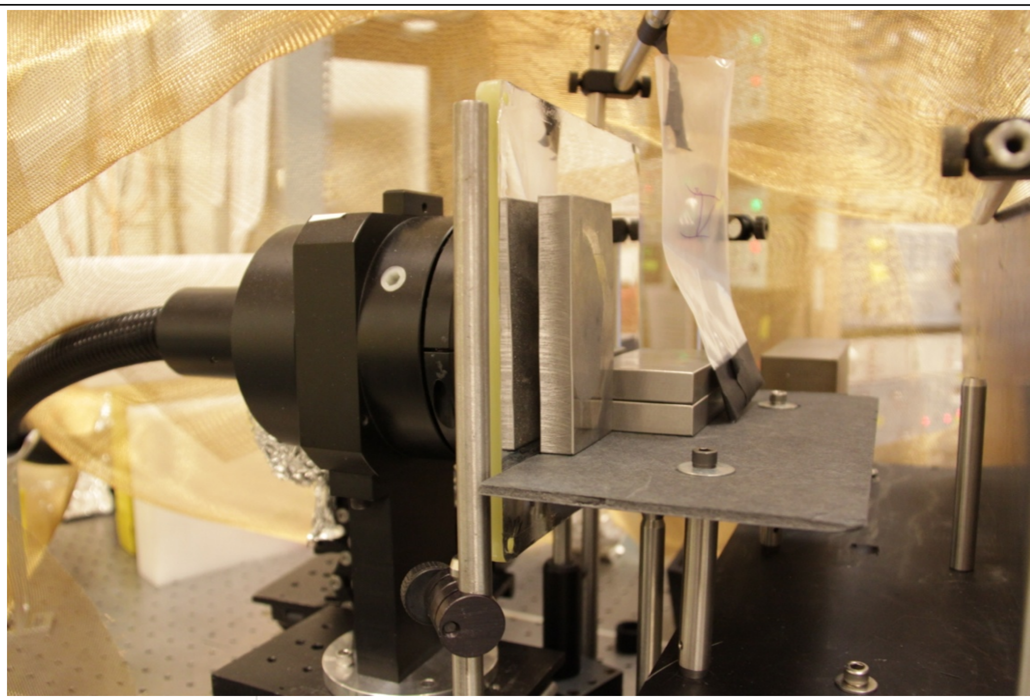


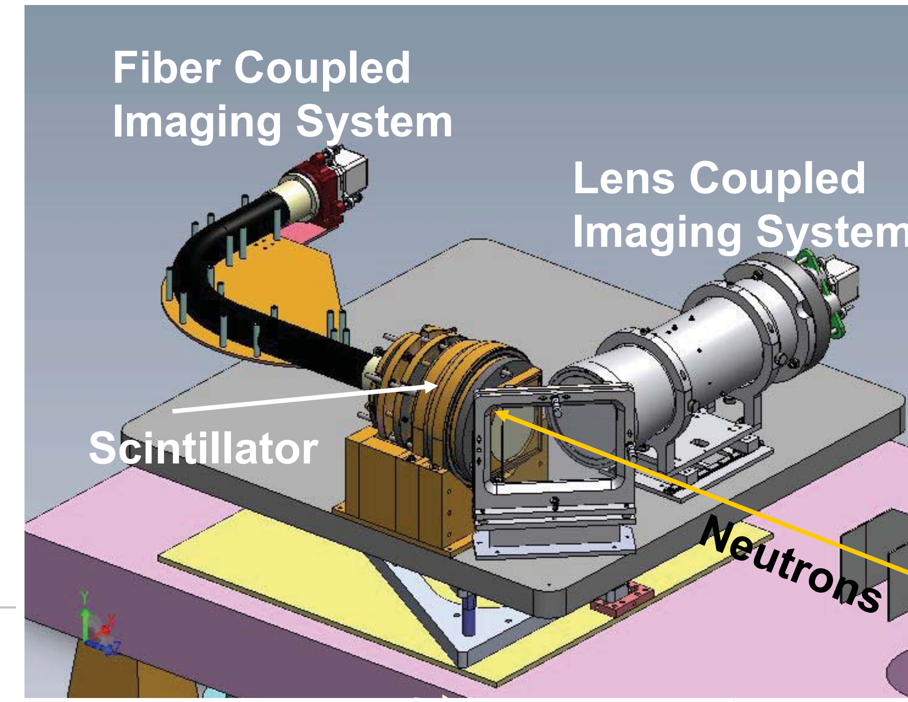
Laser-driven single-pulse neutron radiography (TRIDENT, LANL 2016)

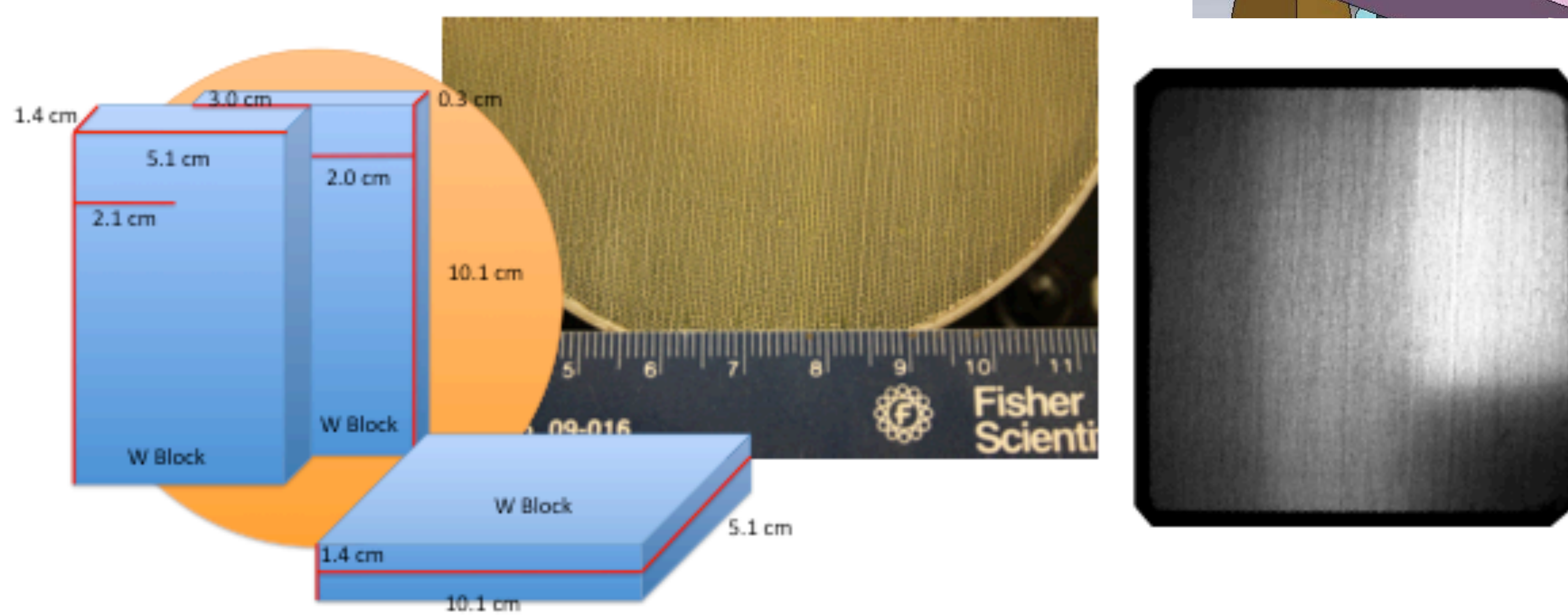


Neutron radiography using a DT-Plasma tube (15 min) (NISRA Report 2015)

Gated Neutron Imager







Prospects:
Fast Neutron Radiography

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

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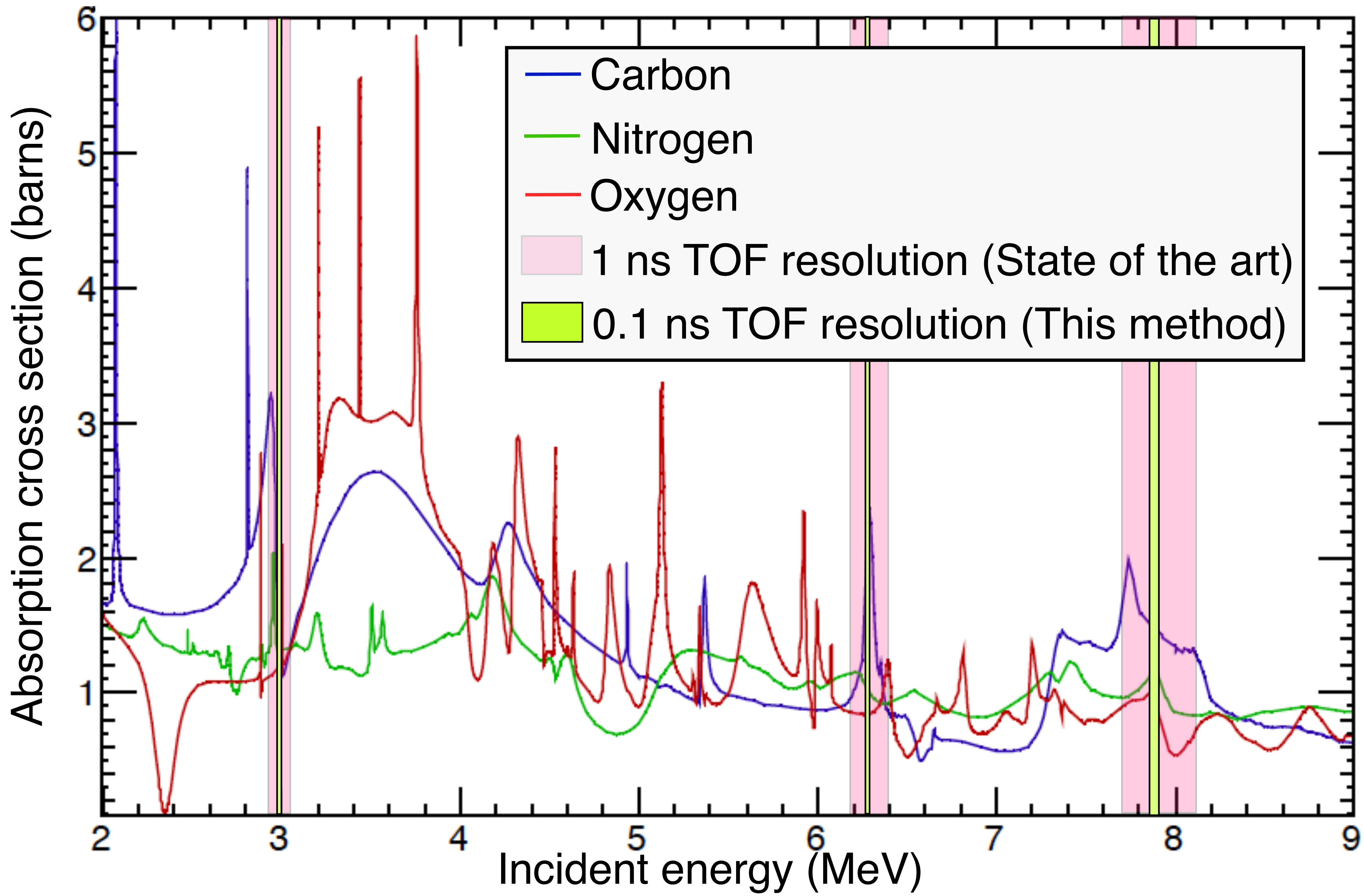

Complementary to p-rad or x-rays

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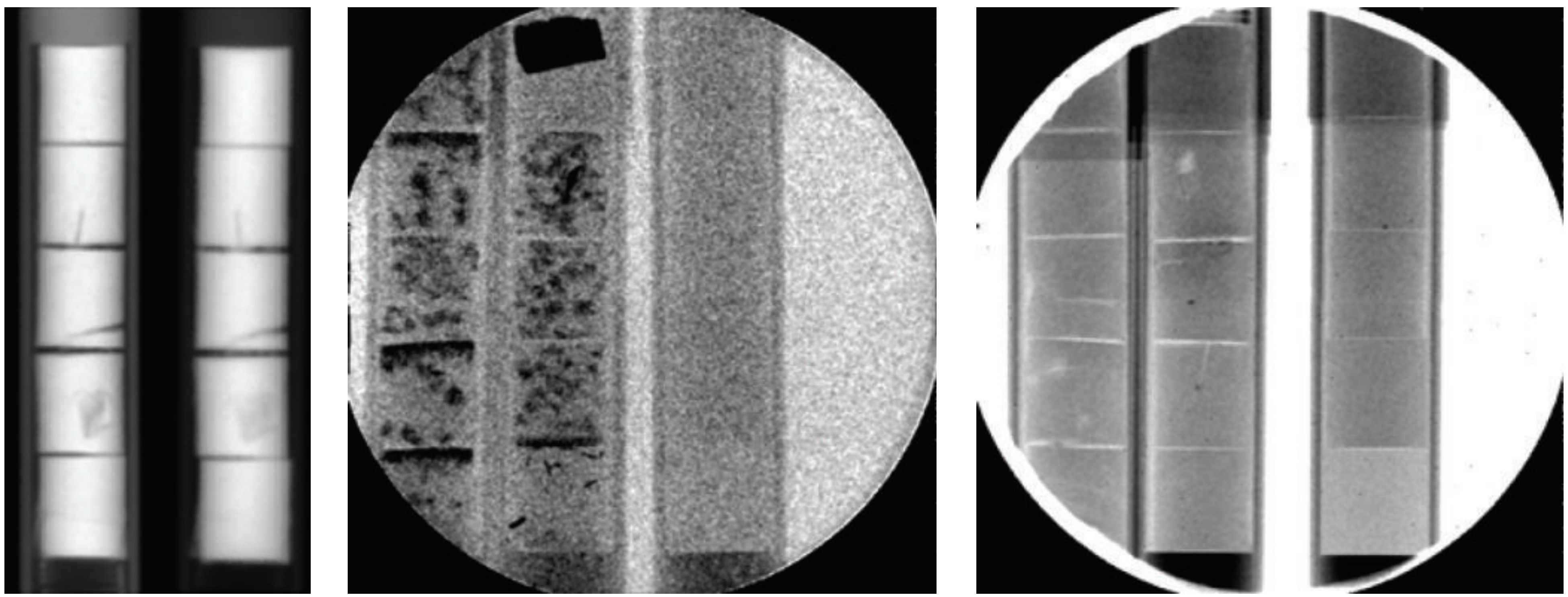
A Review of Neutron Scattering Applications to Nuclear Materials

Sven C. Vogel

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



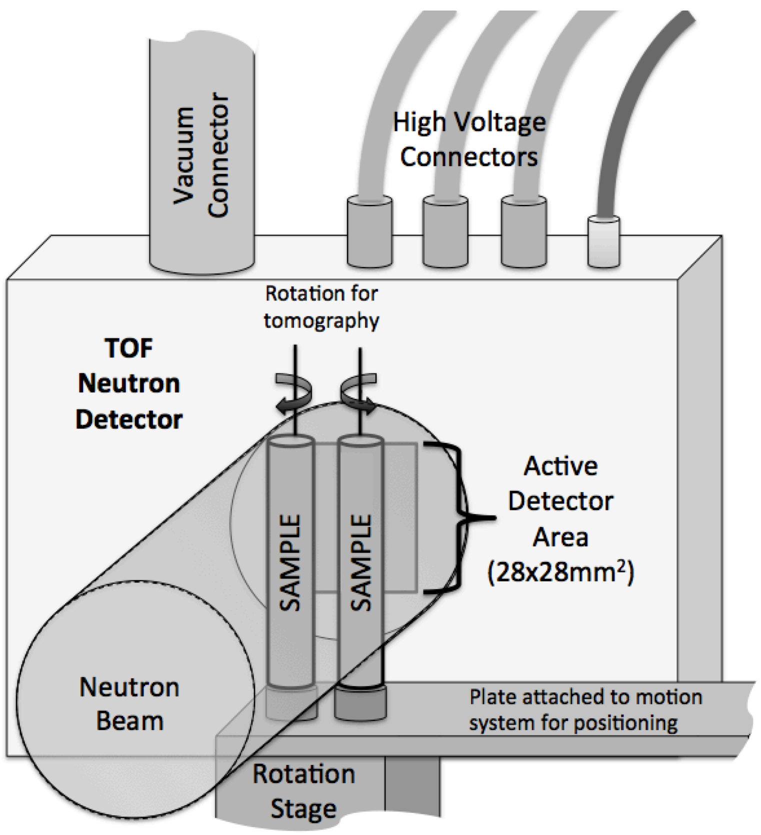
(a) (b) (c)

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 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).

Mobile source for fuel rod testing

Energy-Resolved Neutron Imaging for Interrogation of Nuclear Materials

A.S. Losko[1,2], S.C. Vogel[1], M.A.M. Bourke[1], A.S. Tremsin[2], A. Favalli[1], S.L. Voit[1], K.J. McClellan[1]



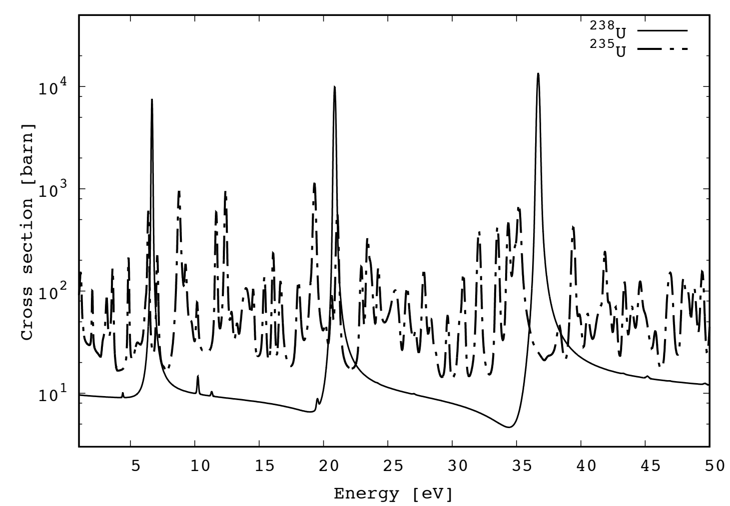


Fig. 2. ^{235}U and ^{238}U neutron cross sections, from ENDF\B-VII.1 database.

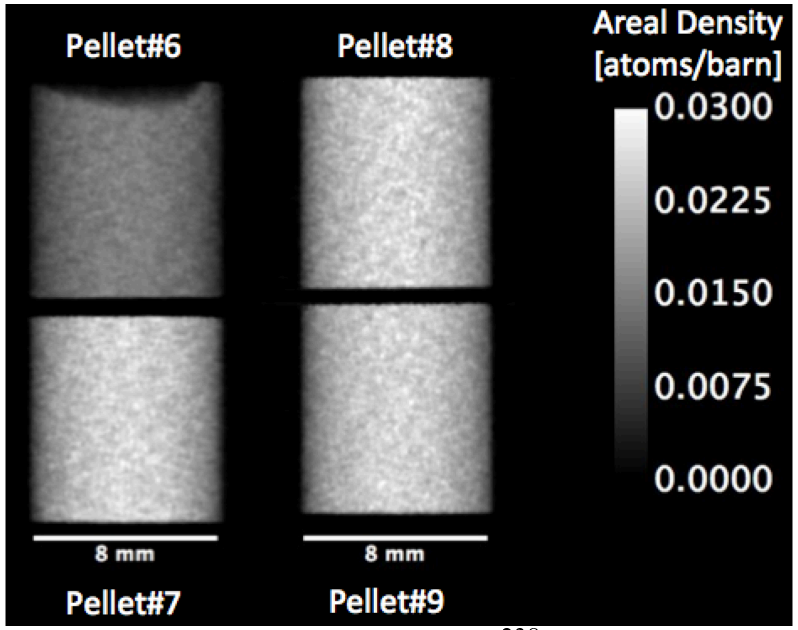


Fig. 5. Reconstructed projection for ^{238}U using the SAMMY code.

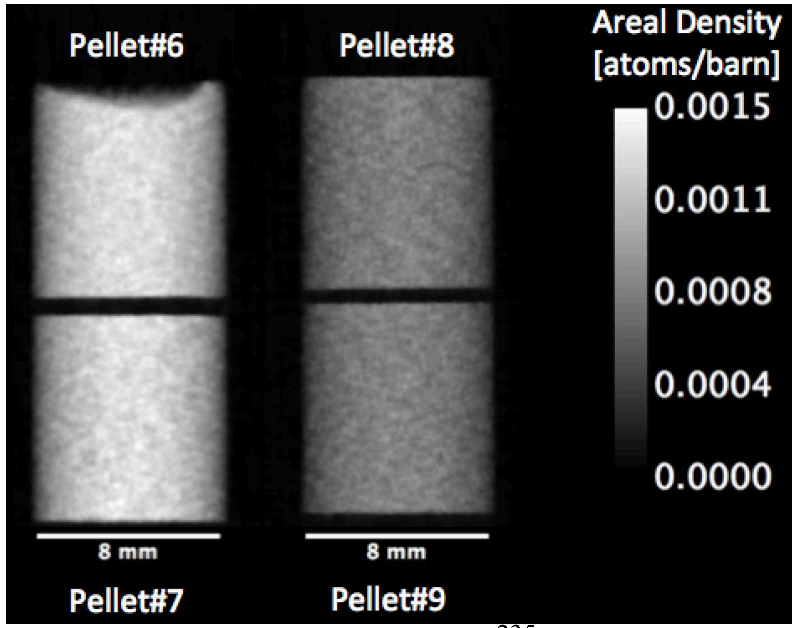


Fig. 6. Reconstructed projection for ^{235}U using the SAMMY code

Sample	^{235}U enrichment (Fabrication target)	^{235}U enrichment (SAMMY results)
PELLET#1	2.70%	2.27% (Cd)
PELLET#2	8.84%	6.97% (Cd)
PELLET#3	0.20%	0.14% (Cd)
PELLET#4	4.34%	3.72% (Cd)
PELLET#5	4.34%	3.79% (Cd)
PELLET#6	8.84%	8.68% (Ta)
PELLET#7	5.53%	5.58% (Ta)
PELLET#8	2.70%	2.65% (Ta)
PELLET#9	2.70%	2.65% (Ta)

Experiment at LANCSE FP5

How does a LDNS compares to LANSCE?

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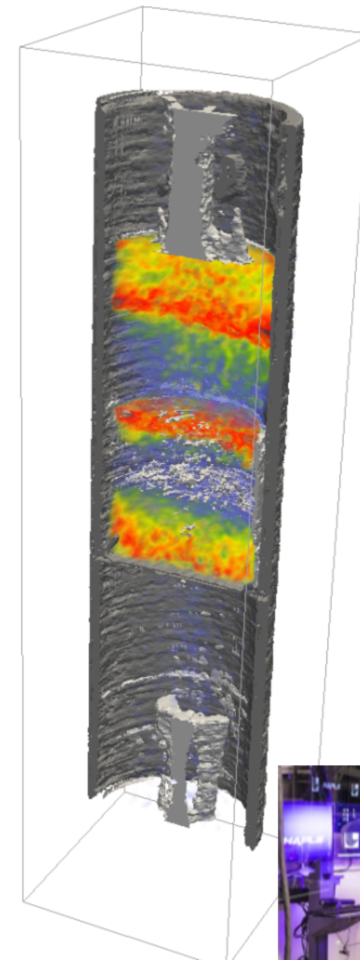
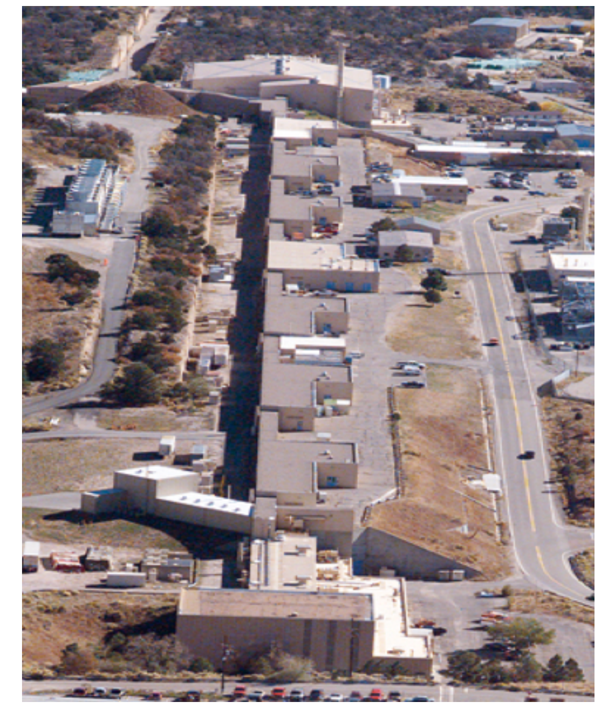
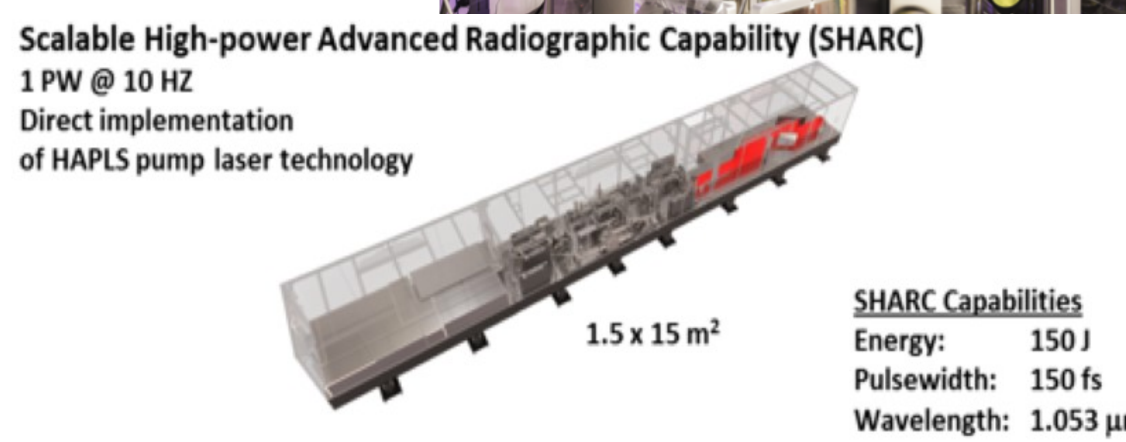
- time for an isotope selective image: 1 hour
- Neutrons / pulse (LANSCE): 10^{14}
- Repetition rate: 20 Hz
- Neutron required (produced): 7.2 x 10^{18}
- Closer due to less shielding and shorter pulse (1.2m vs 6.4 m): 2.5 x10^{17}
- Exp. verified difference in coupling efficiency (factor 10): 2.5 x 10^{16}





- Neutrons using a 100 J Laser: 5 x10^{11}
- At 10 Hz repetition rate: 5 x10^{12} /s
  Would require an exposure time of:
  5000 s (1 hour 23 min)
  with present technology…
- … and what about (BAT) 200 Hz? 4 minutes?



Active interrogation system to detect special nuclear material

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„Every morning you wake up there is new nuclear material to be safeguarded to make 18 nuclear warheads“

„Growing gap between responsibilities and capabilities“….

(Deputy director General and Head of department for Safeguard, IAEA…)

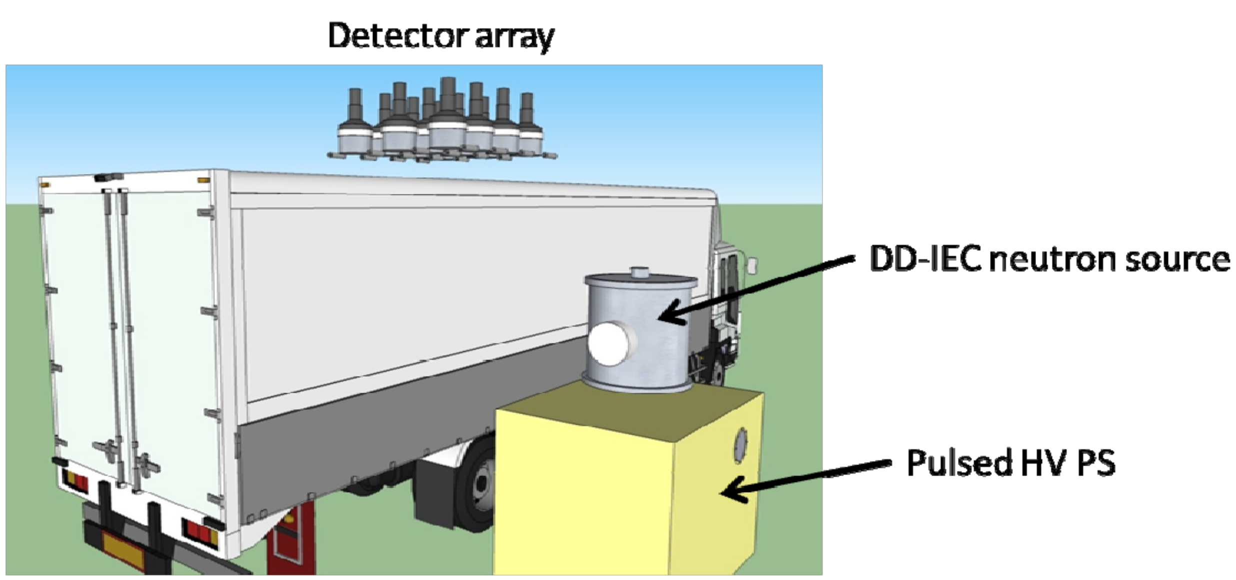
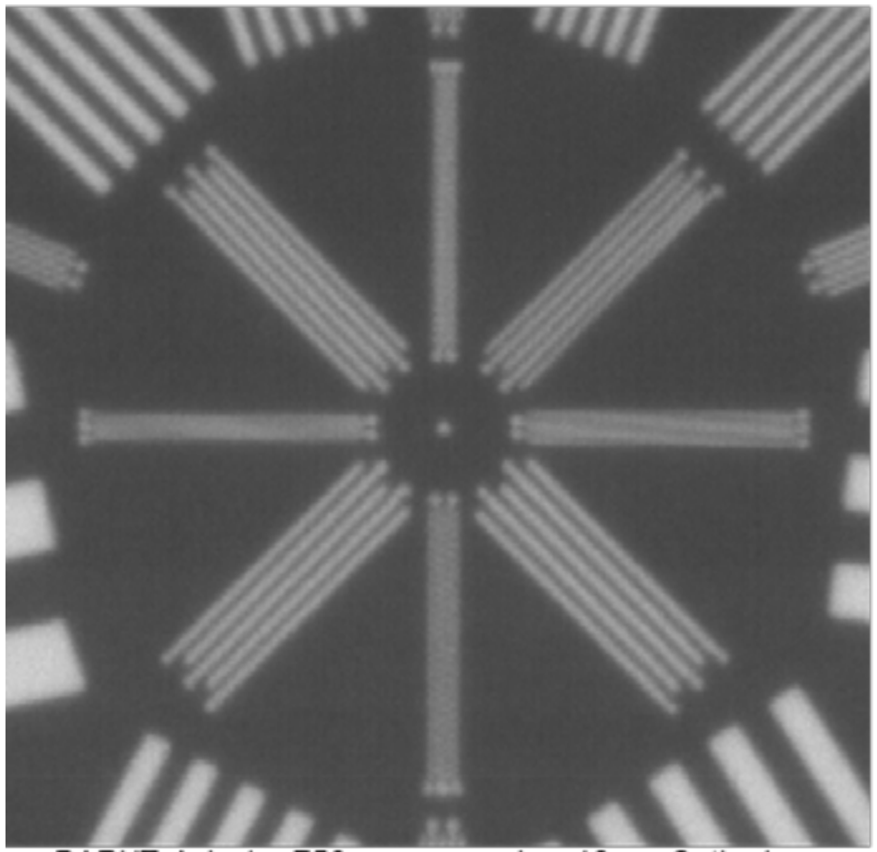


Figure from Masuda et al., IEA Kyoto

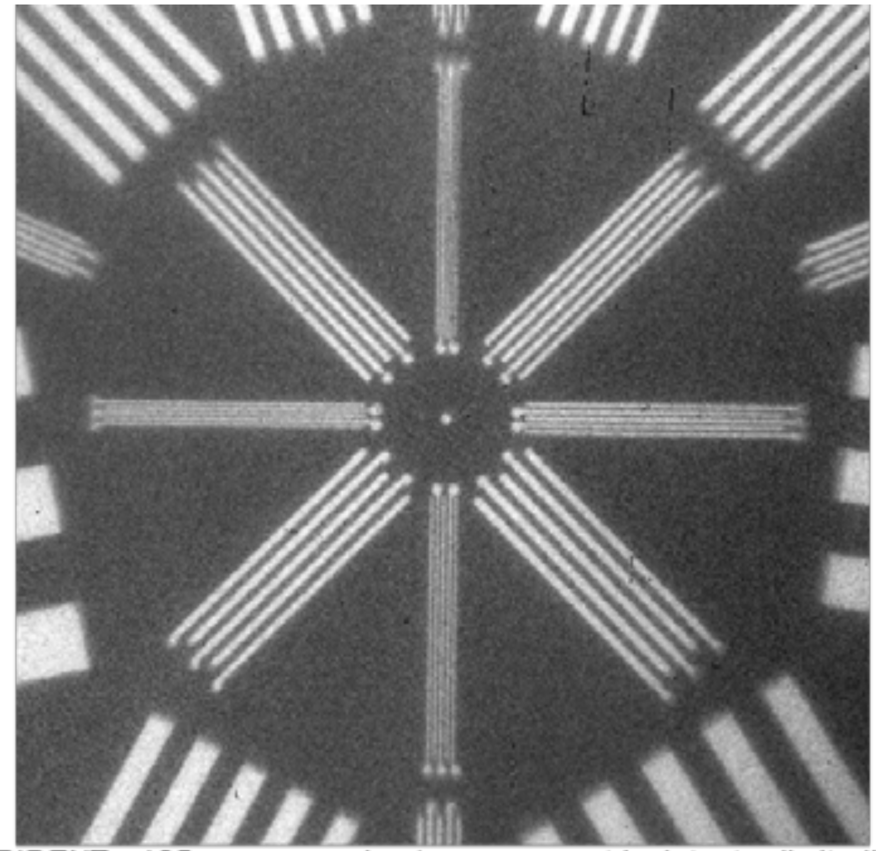
Need: Fast, movable, operationally safe neutron source featuring energy tunable, and high intensity directional neutron production

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

Hard X-ray production



DARHT Axis 1, ~750μm source size, 19mm Cathode



TRIDENT <125μm source size (measurement is detector-limited!!!)

- **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 μm (limited by detector at present)**

Experiments in 2014 @ LANL

PI: Andrea Favalli, LANL

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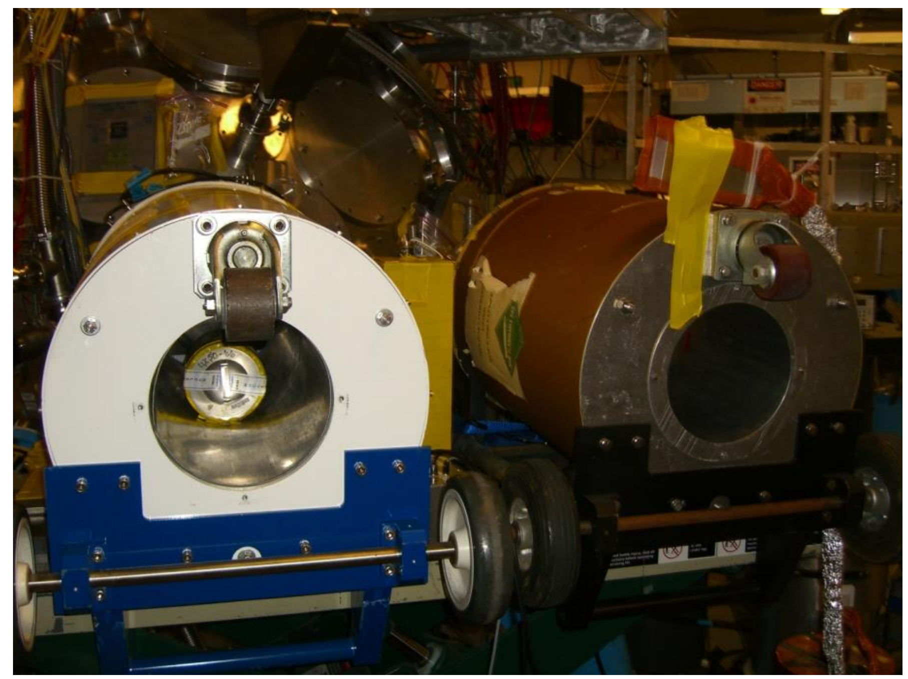
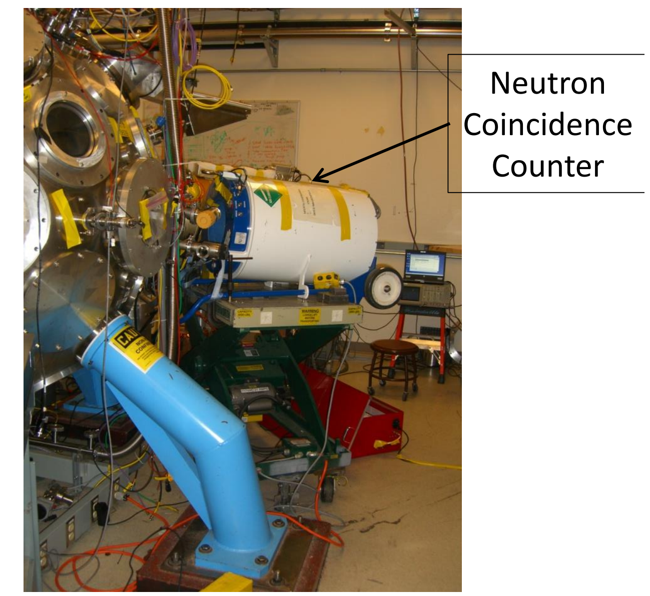
Uranium Samples

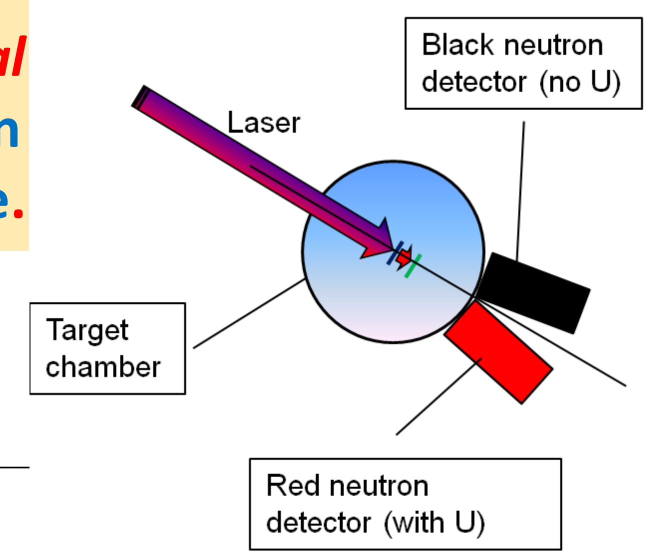




Uranium Samples tested:

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

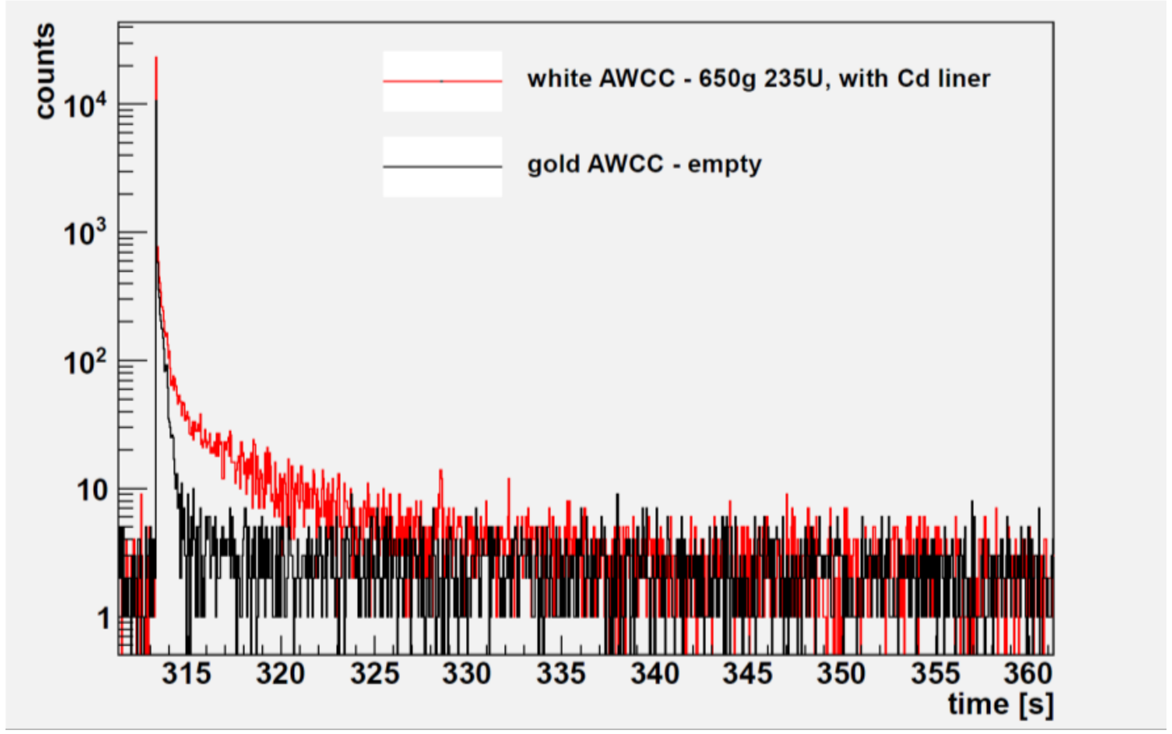
Neutron coincidence counter with single ring structure *of ^3He proportional detectors embedded in polyethylene*. In the *left* detector is visible the U sample.

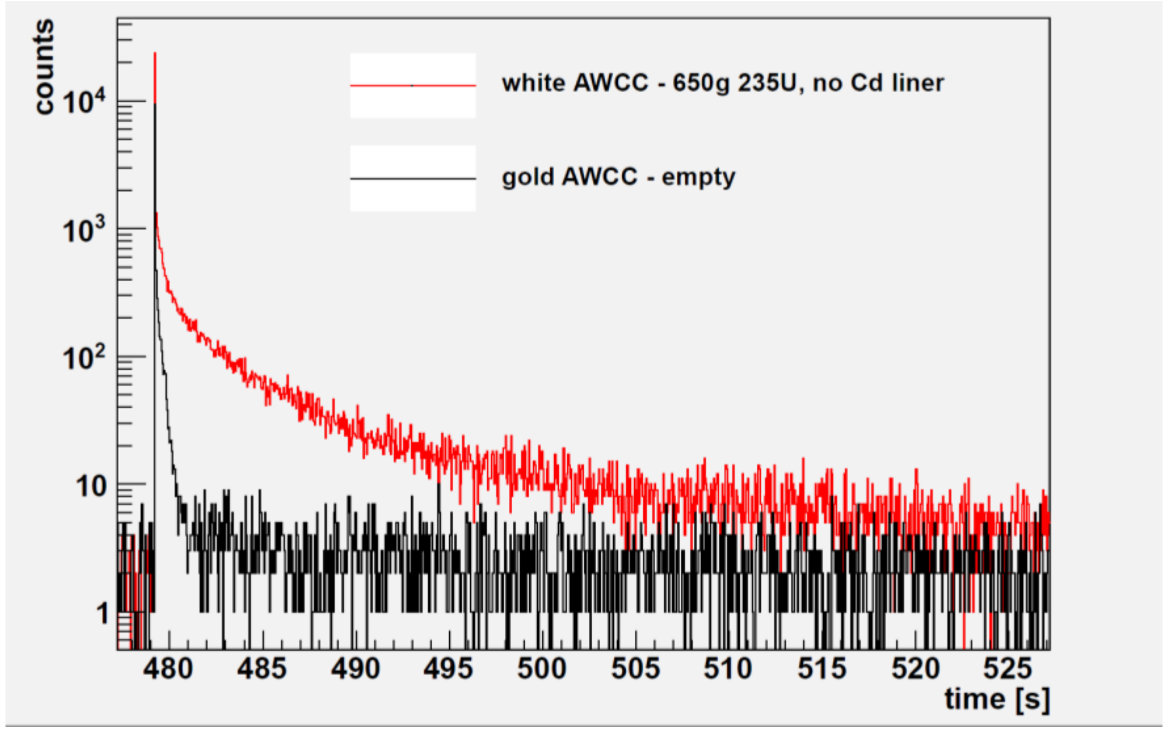


Interrogation of an enriched uranium sample

PI: Andrea Favalli, LANL

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

Numerous applications and contact to industry

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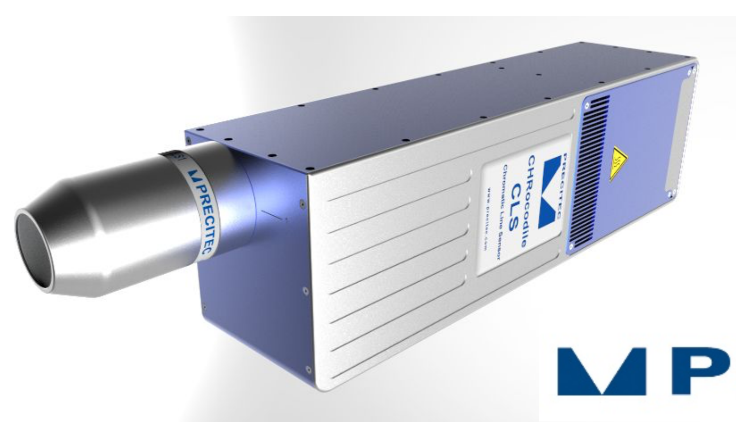
Aachen Institute for Nuclear Training

TRUMPF

smiths detection

Air Cargo Solutions

proxivision



PRECITEC

Performance versus accelerator driven systems

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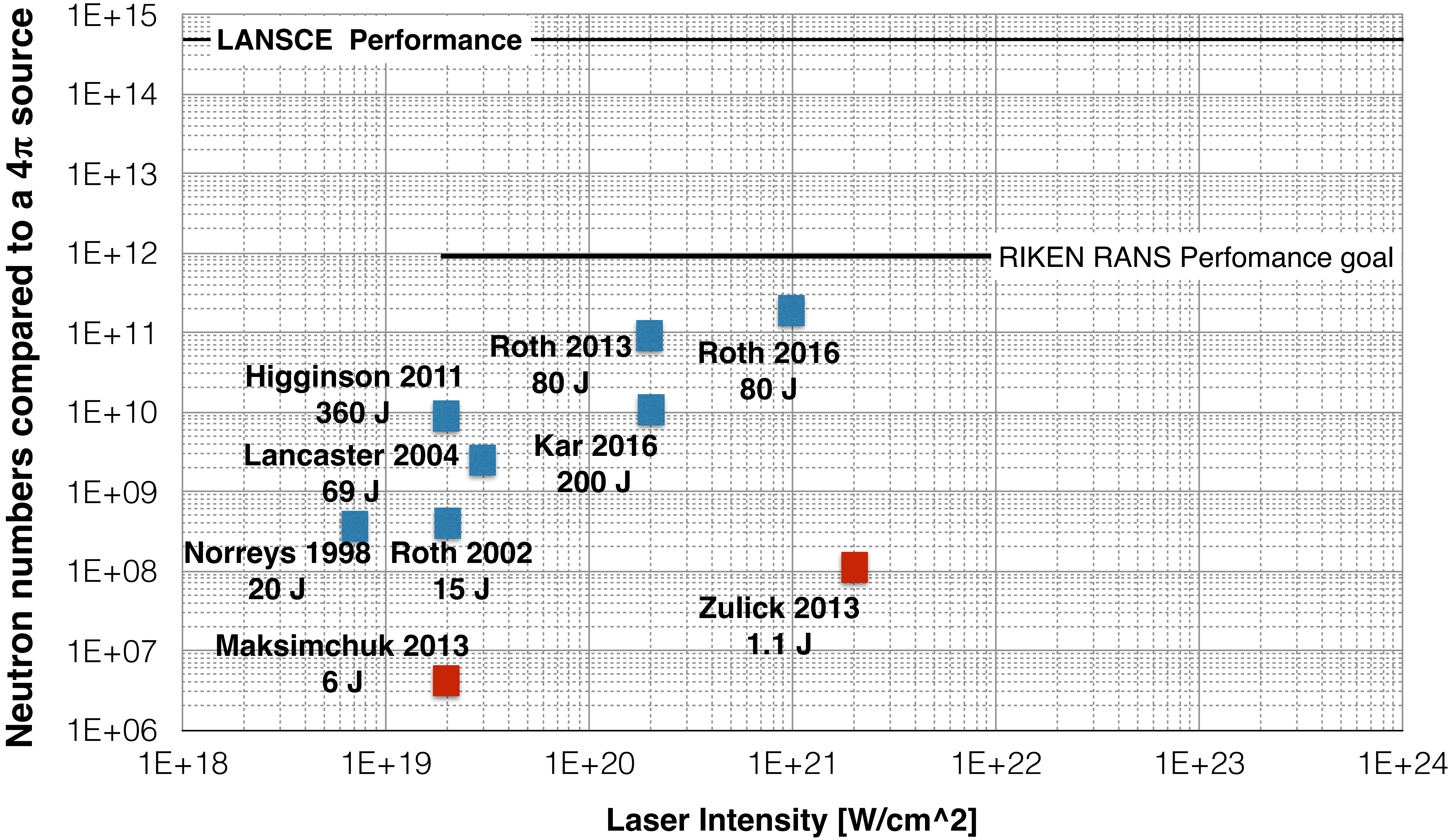
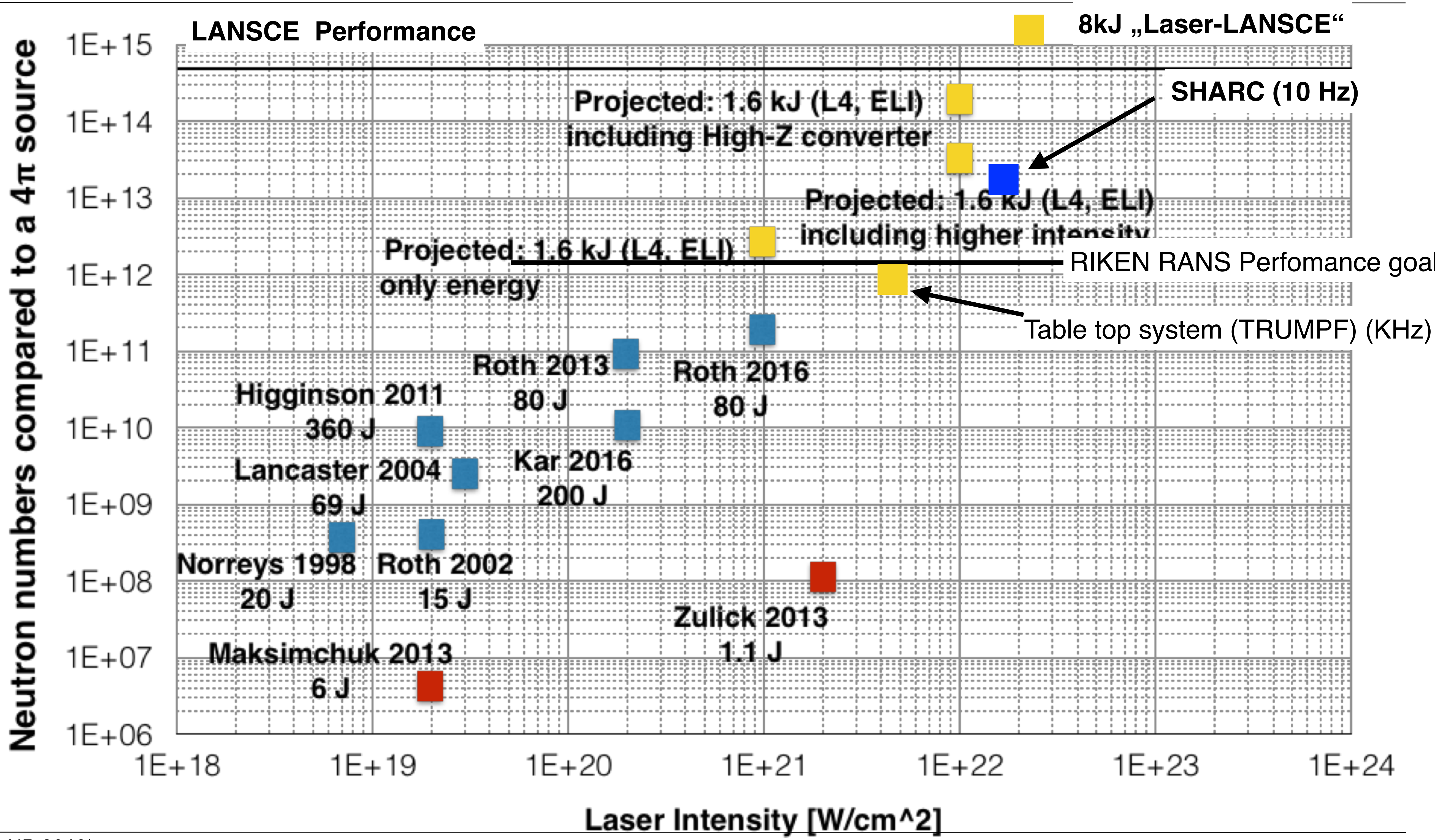


Prospects


LANSCE Performance
8kJ „Laser-LANSCE“
SHARC (10 Hz)
Projected: 1.6 kJ (L4, ELI)
including High-Z converter
Projected: 1.6 kJ (L4, ELI)
including higher intensity
Projected: 1.6 kJ (L4, ELI)
only energy
RIKEN RANS Perfomance goal
Table top system (TRUMPF) (KHz)
Roth 2013
80 J
Roth 2016
80 J
Higginson 2011
360 J
Kar 2016
200 J
Lancaster 2004
69 J
Norreys 1998
20 J
Roth 2002
15 J
Zulick 2013
1.1 J
Maksimchuk 2013
6 J
Neutron numbers compared to a 4π source
1E+15
1E+14
1E+13
1E+12
1E+11
1E+10
1E+09
1E+08
1E+07
1E+06
1E+18
1E+19
1E+20
1E+21
1E+22
1E+23
1E+24
Laser Intensity [W/cm^2]

White paper submitted to DOE NE

Assessment of Laser-Driven Pulsed Neutron Sources for Poolside Neutron-based Advanced NDE – A Pathway to LANSCE-like Characterization at INL

Nuclear Technology Research and Development

Prepared for U.S. Department of Energy Nuclear Technology Research and Development Program Advanced Fuels Campaign

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April 14, 2017

NTRD-FUEL-2017-000064

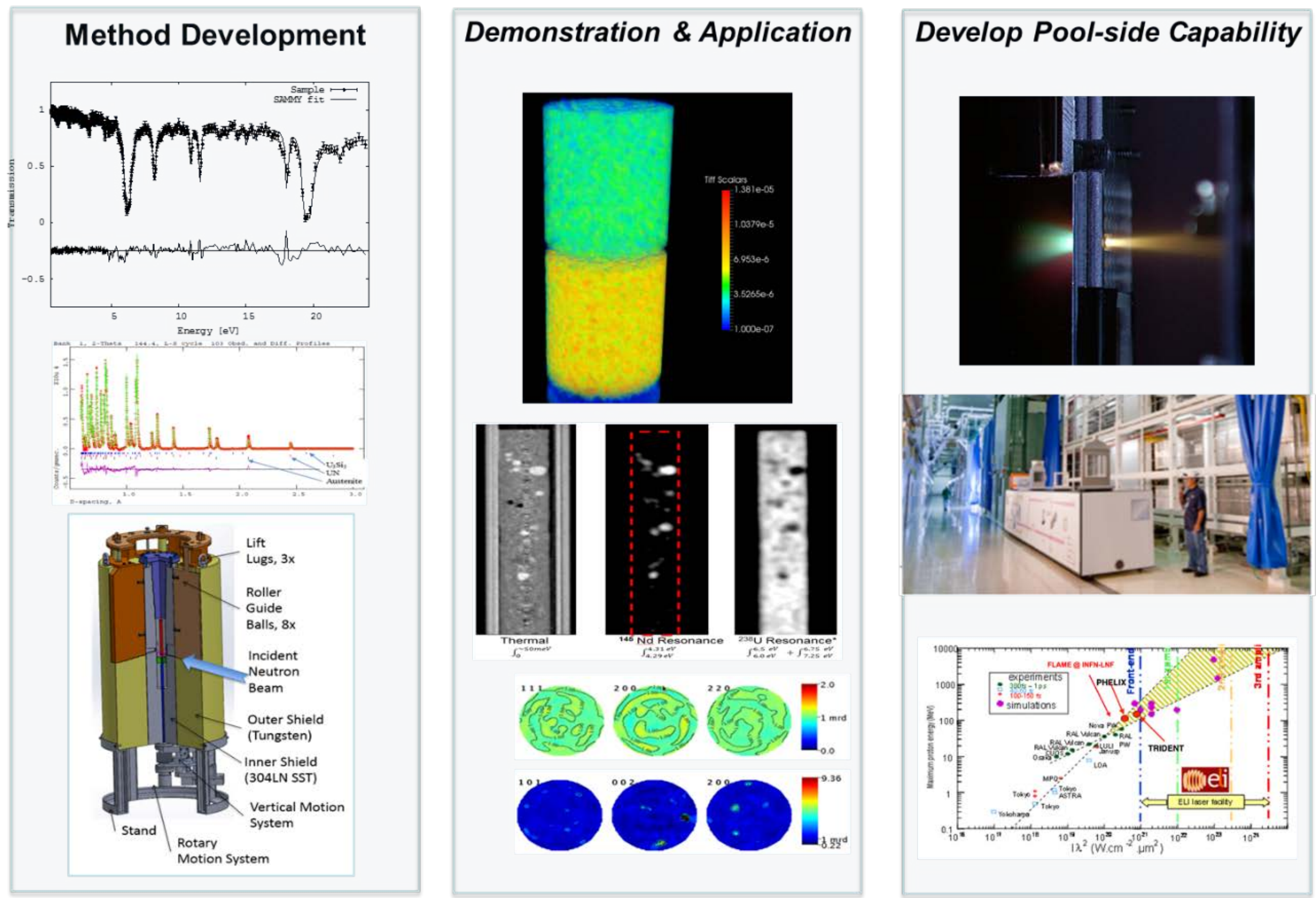

Figure 1: Three pillars of the LANL Advanced Non-destructive Evaluation and Advanced Post-irradiation Examination program.

Official IAEA TEC:DOC recommendation will come out in 2020

The future for nuclear photonics seems to look brighter every year…

Thank you!!