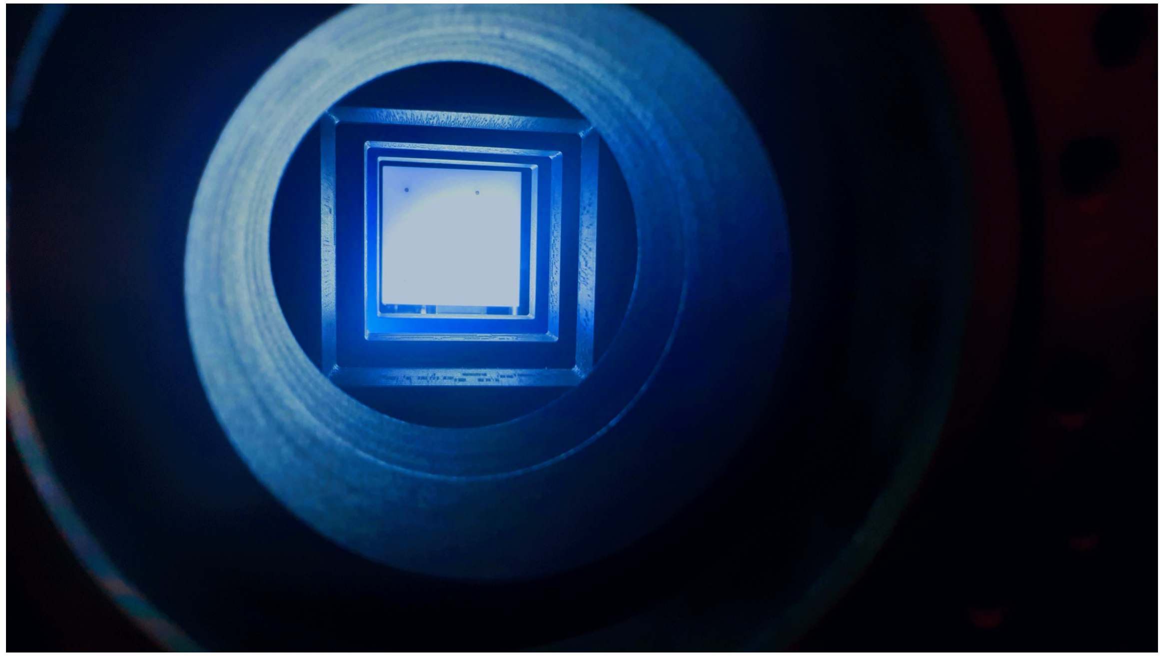
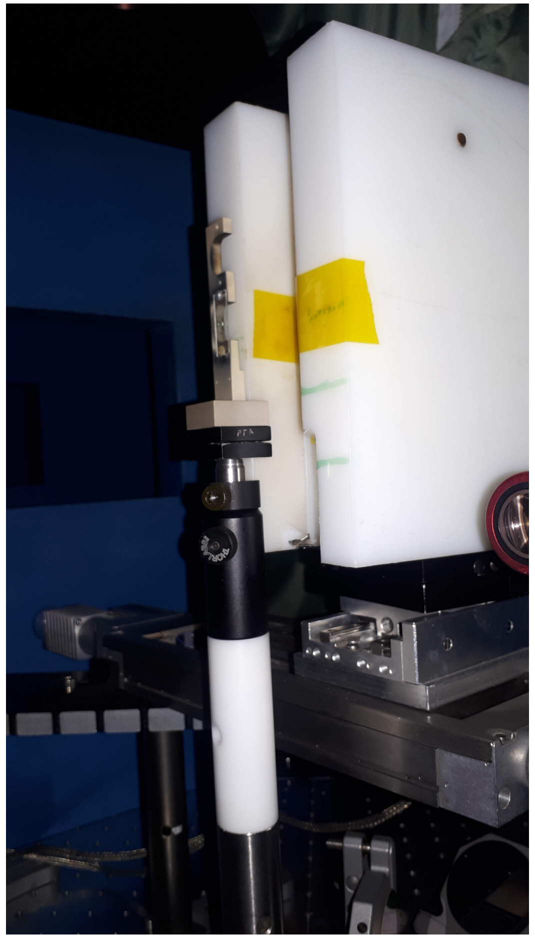
Laser-driven Ion Accelerators: Unique Beams and Compact Neutron Sources

M. Roth, M. Zimmer, S. Scheuren, A. Kleinschmidt, N. Mitura, A. Tebartz, G. Schaumann, T. Abel, T. Ebert, M. Hesse, S. Zähter, S. C. Vogel, O. Merle, R. Ahlers, S. Pinto, M. Peschke, T. Kröll, V. Bagnoud & C. Rödel





Lasers as ion accelerators

The requirements strongly depend on the application: a few examples

- Ion source as a new injector:
  - Rep rate matched to conventional accelerator structures (e.g. 50 Hz)
  - Ion energy a few tens of MeV
  - Radial beam shaping for divergence optimization
  - Ion species selectable
  - Energy matched to particle number acceptable to acc structure
- Medical Application:
  - Ion energy >250 MeV for protons and >400 MeV/u for e.g. Carbon
  - High contrast
  - Rep rate 10 to 30 Hz
  - Energy stability better 3%
  - Relatively low particle numbers required (10^{11} or 10^{9} per patient)
  - Uniform ion beam --> Laser beam shaping

Lasers as ion accelerators

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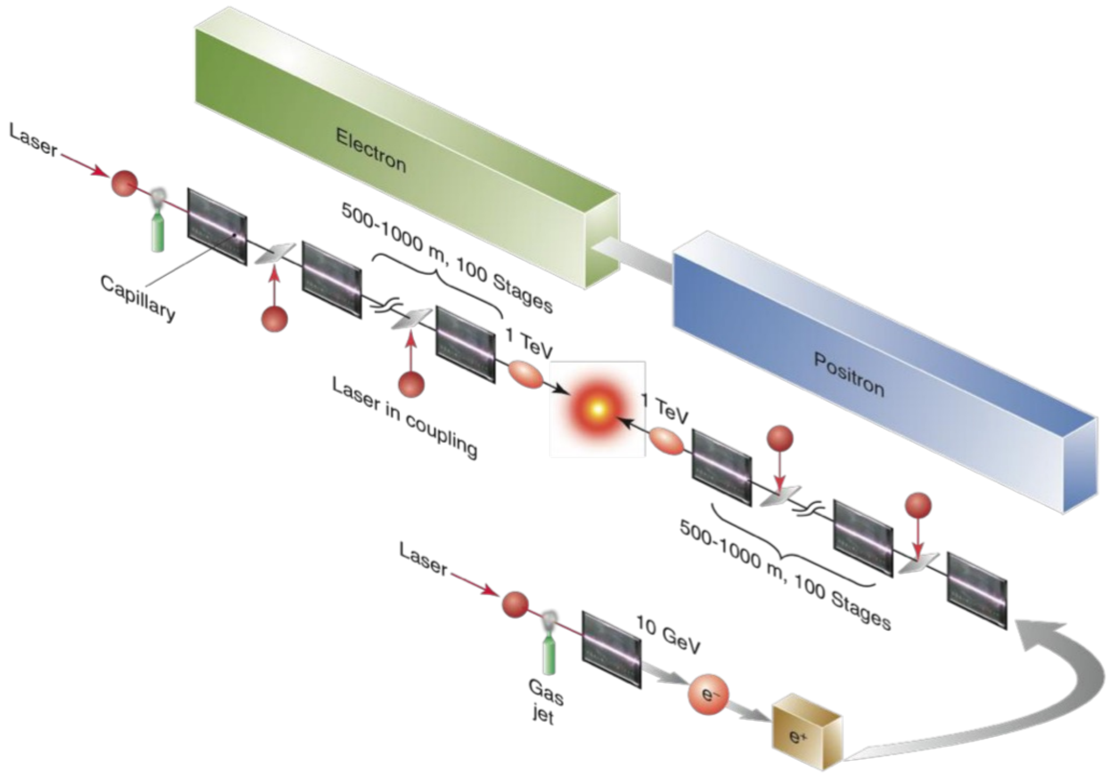
- Fusion (FI)
  - Tailored energy spectrum up to a few tens of MeV
  - High conversion efficiency
  - High particle numbers (high laser energy)
  - Pulse length can be up to ps
  - Beam overlay, beam synchronization
  - 10 Hz rep rate
- Security applications
  - relaxed rep rate
  - Ion energy up to GeV
  - High contrast
  - Mobile / compact

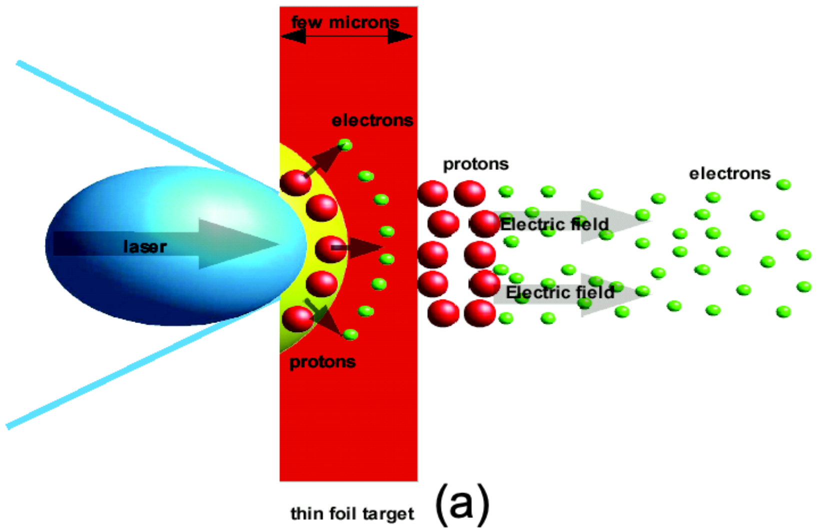
Nuclear Photonics

Lasers as ion accelerators

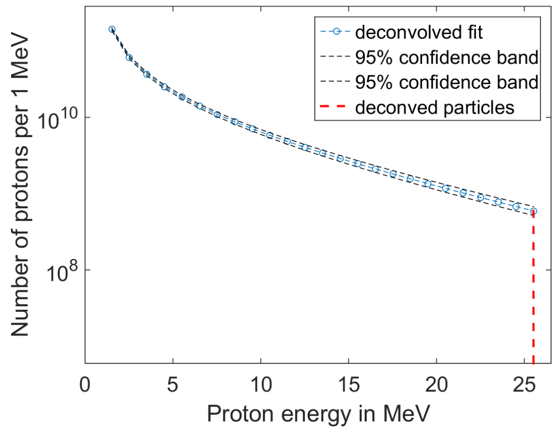
- Accelerators (all optical)
  - High gradients
  - High Particle numbers
  - High Rep Rate
  - Staging
  - High Average Power
  - Many Beamlines (...100)

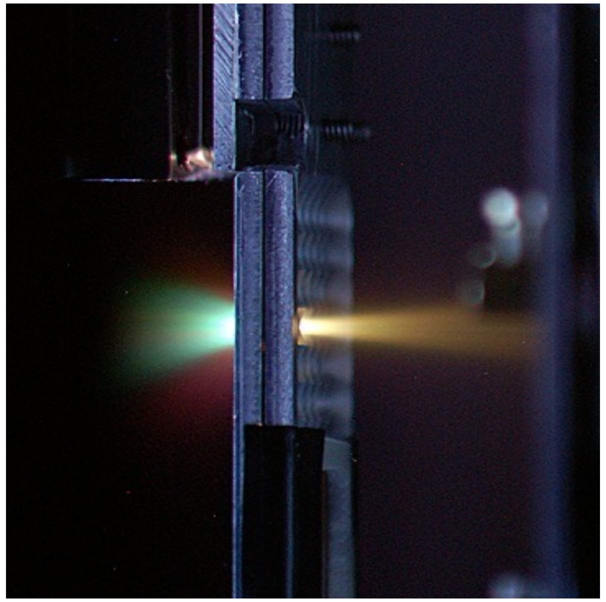


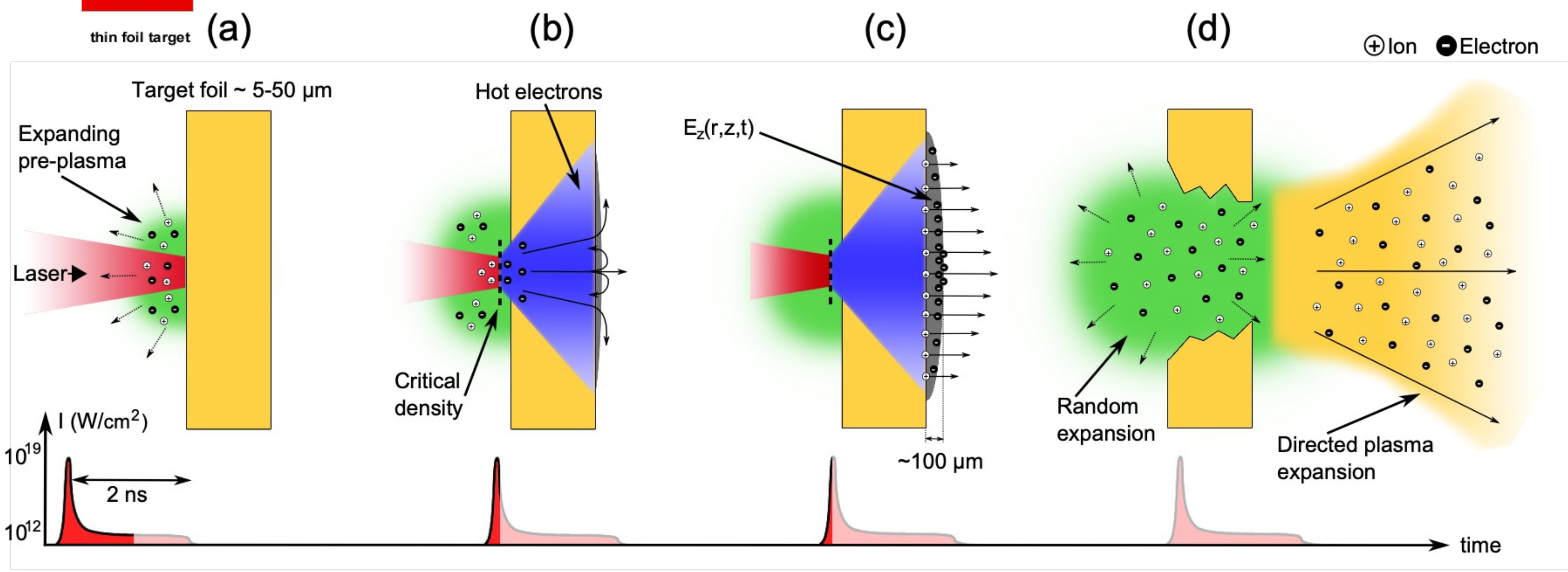
Proton acceleration with lasers :
Static electric fields



- **Accelerating fields: TV/m**
- **Ion energy: Up to 100 Mev**
- **Particle numbers: 10^{13} per bunch**





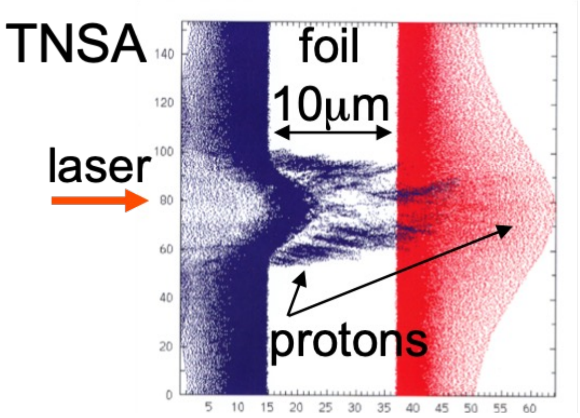


RMS emittance:
ε-norm ~ 0.06 π mm-mrad
Corresponds to a temperature of less than 40 eV !

The longitudinal emittance is also small
ΔEΔt ~ MeV-ps ~ keV-ns

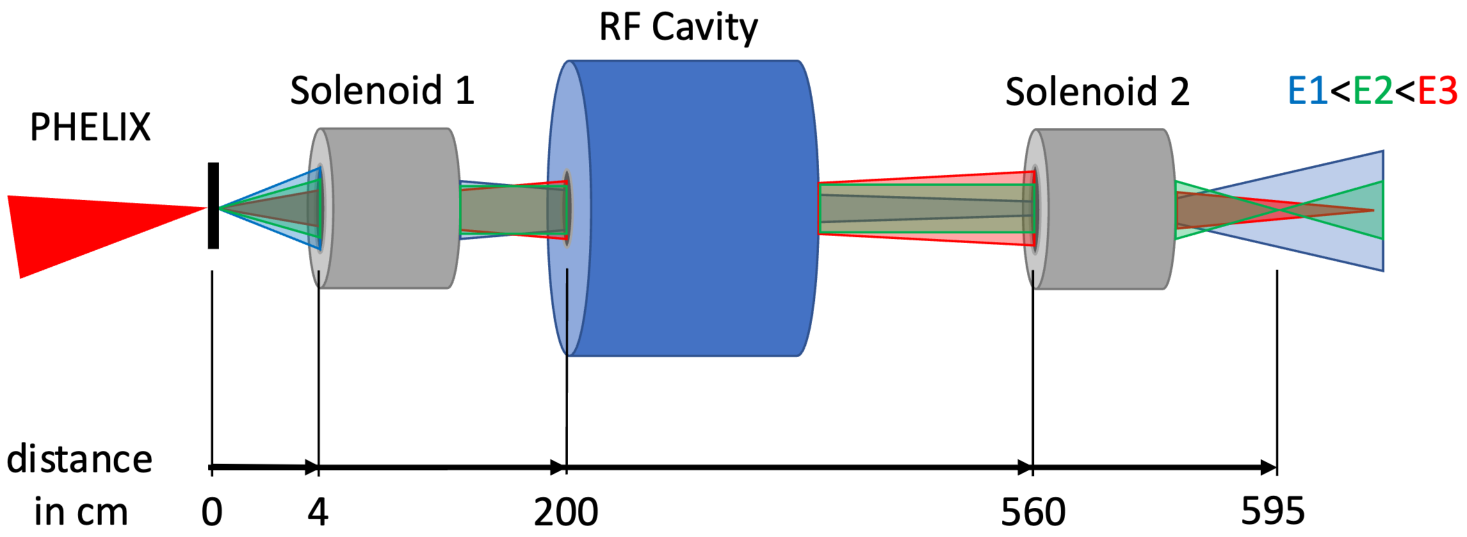
Ion Acceleration Mechanisms

Ion acceleration mechanism	Acronym	Ion Accel. process
Target-Normal Sheath Acceleration S. Hatchett *et al.*, Phys. Plas. **7**, 2076 (2000)	TNSA	Charge separation GeV protons? X



LIGHT Beamline Properties and Applications

work by Martin Metternich mmetternich@ikp.tu-darmstadt.de



Laser Ion Generation, Handling and Transport

Stopping power experiments

Ion source for conventional accelerators

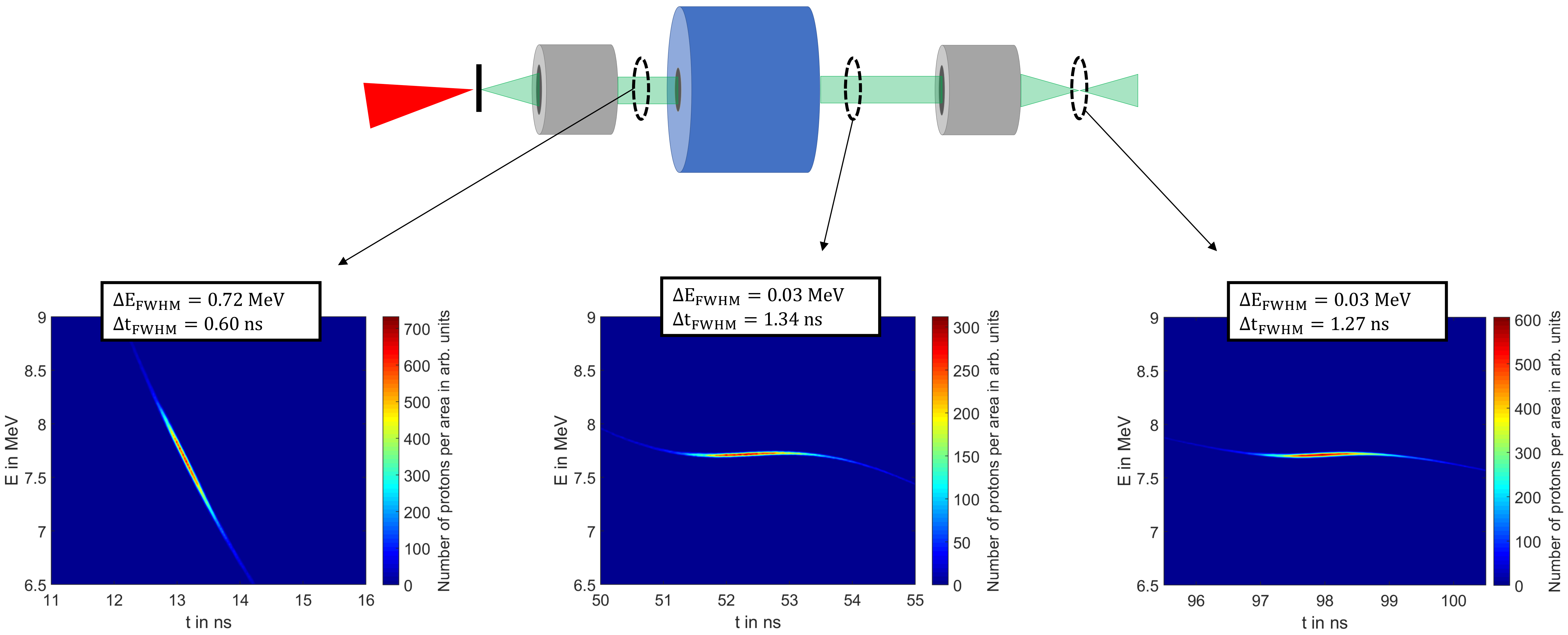
Investigations in the FLASH effect

Material science research

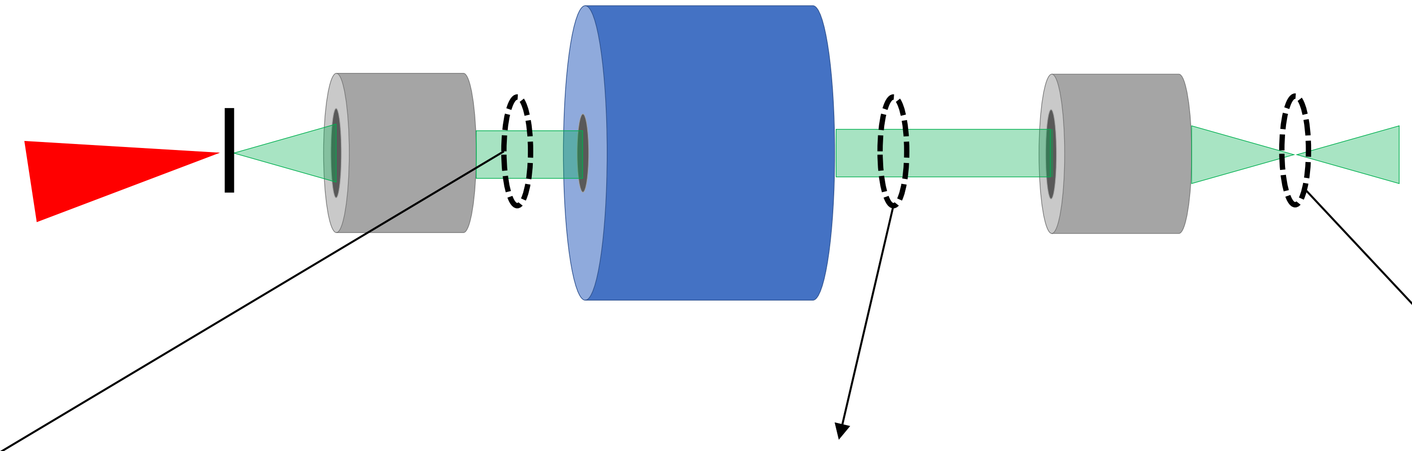
LIGHT beamline compared to conventional LINAC:

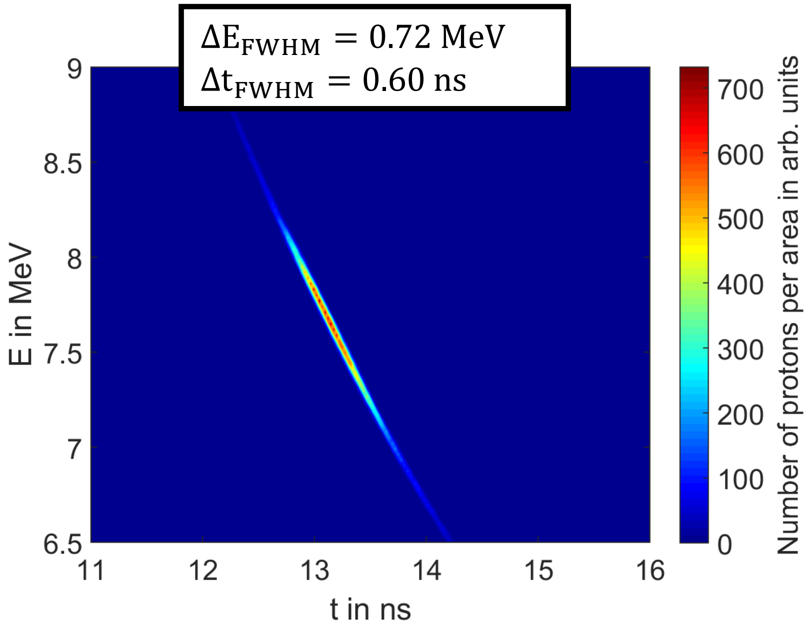
- Higher single bunch / peak intensities
- Lower temporal bunch length
- Lower mean intensity
- Lower repetition rate

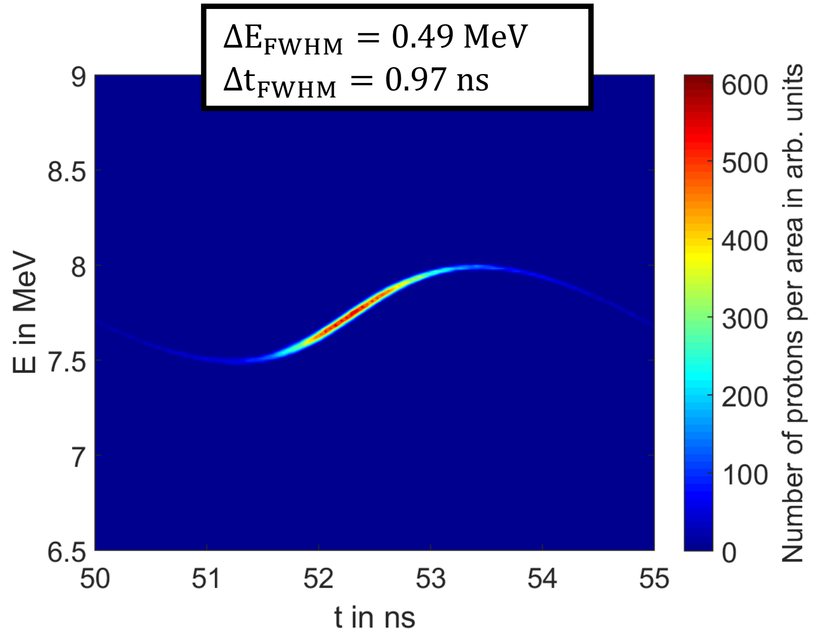
Energy compression

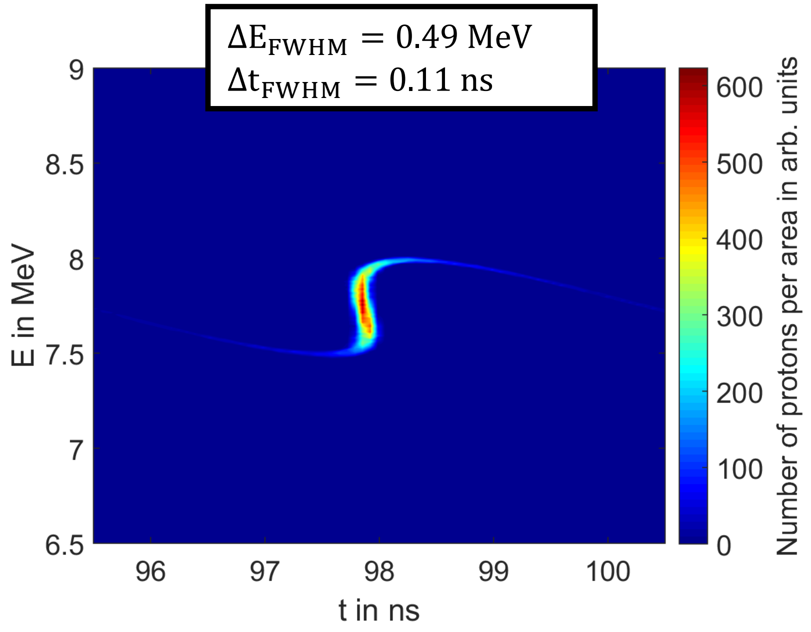


Longitudinal Focusing

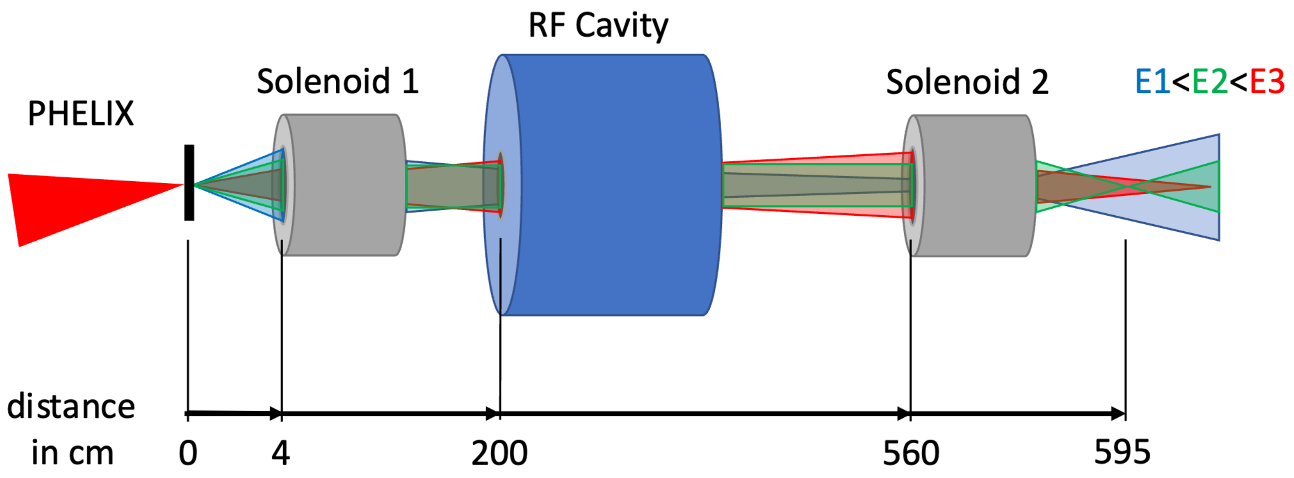




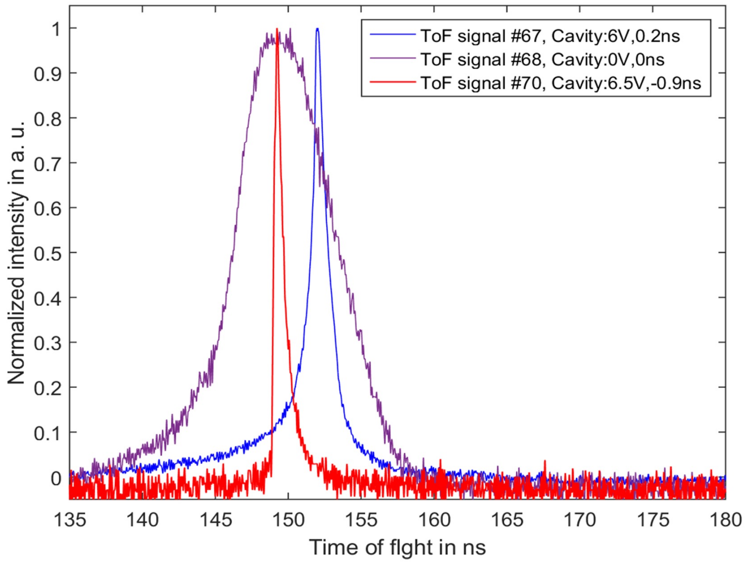


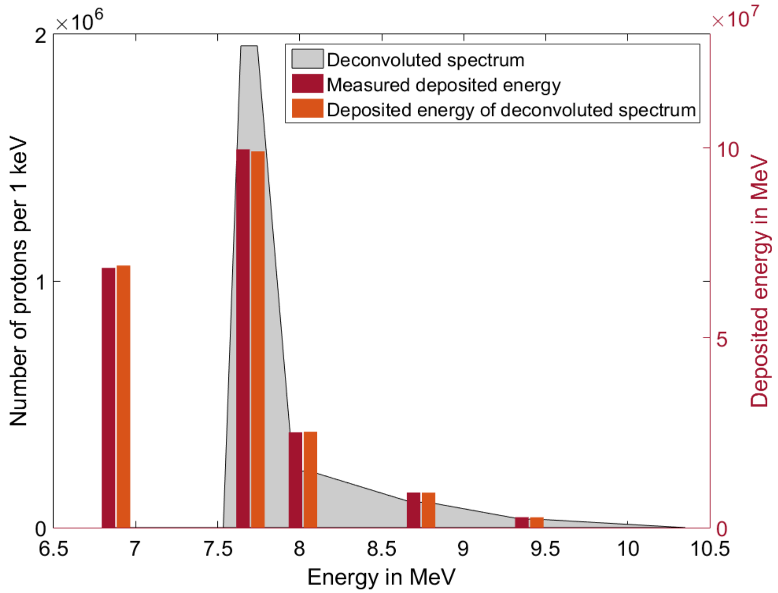


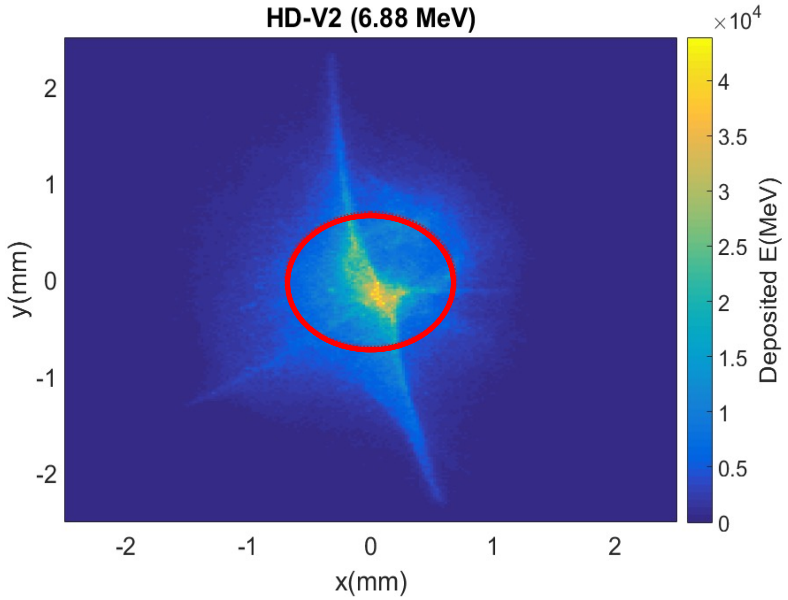
LIGHT Proton Beam Parameter



Parameter	Value
Peak energy	7.7 MeV
Number of particles (whole spectrum)	7.35×10^8
Focal spot size (50% of protons encircled)	1.38 mm
Temporal bunch width (FWHM)	742 ps







Several societal problems are waiting for a solution

Structural integrity of old bridges, smuggling of illicit materials, landmines and bombs of past wars, proliferation of nuclear materials, storage of nuclear waste

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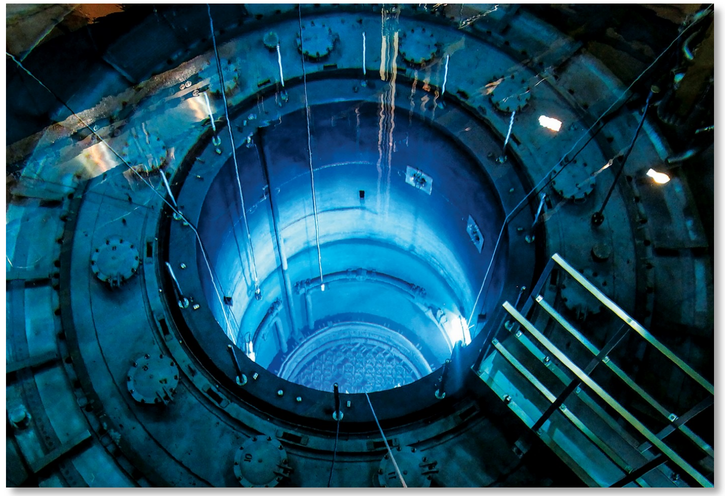
Lack of material detection capability limits several industries

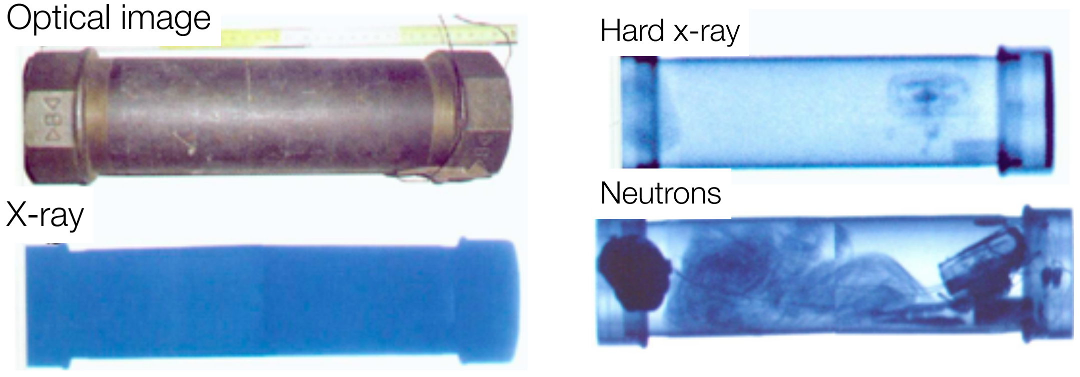
- Hidden bombs kill or maim people
- We can’t inspect our critical infrastructure like bridges and containers
- New reactors require continuous safety analysis
- Nuclear waste legacy



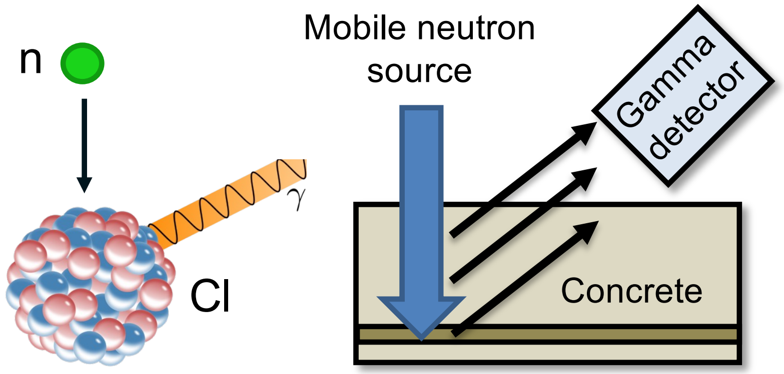
FOCUSED ENERGY

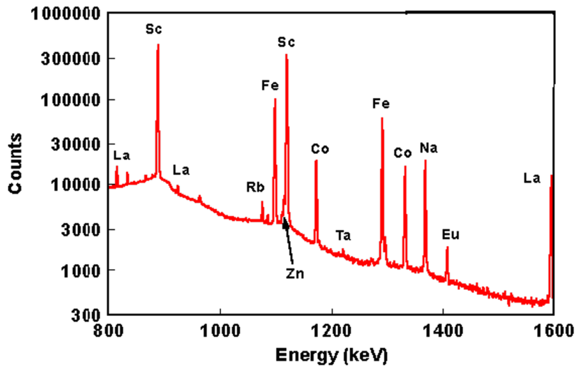
The solution: Non-destructive testing with hard X-rays and neutrons reveals what is otherwise invisible

Security

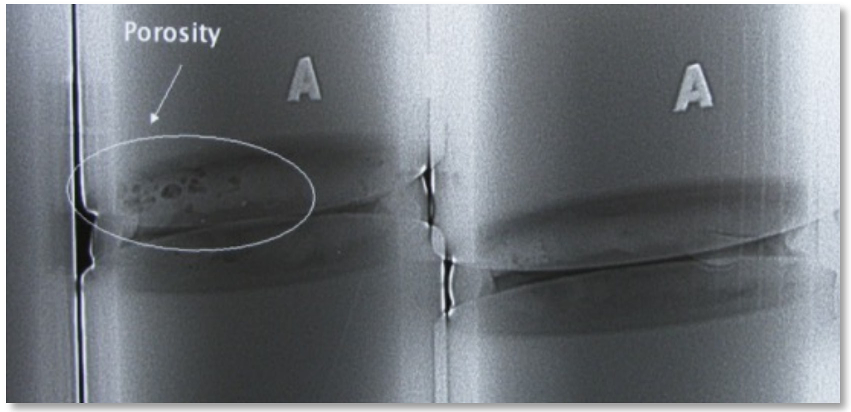


Construction inspection

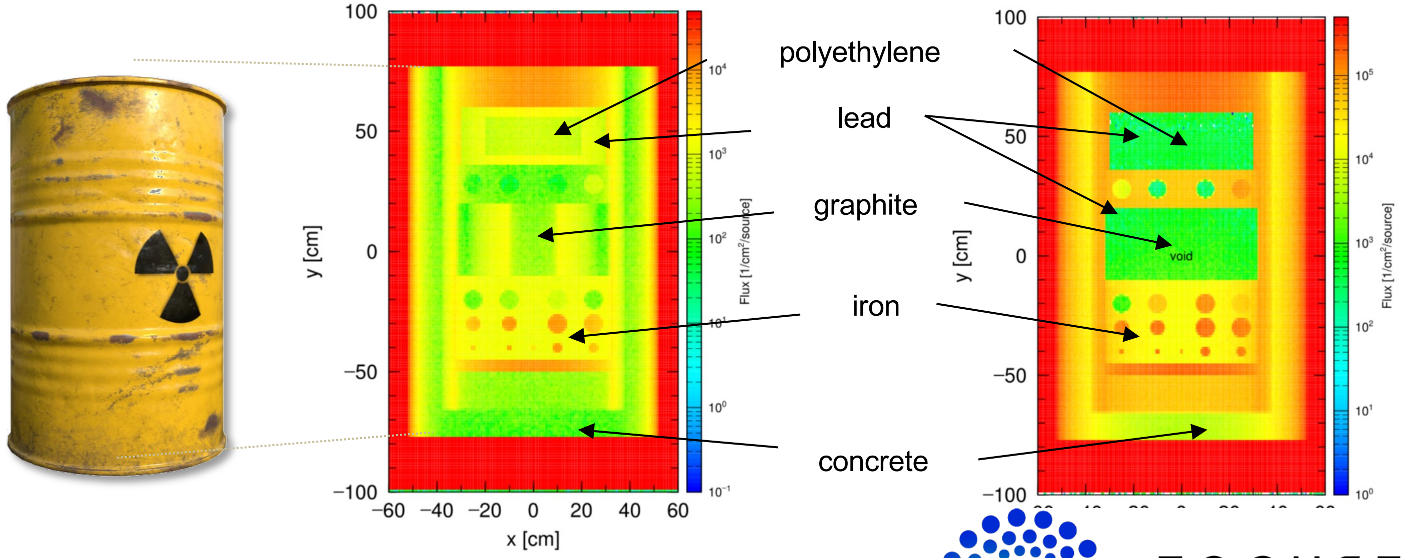




Weld inspection



Disposal of nuclear waste



Conventional radiation sources

So far, these radiation sources are either compact with low output and bad resolution or they are large, expensive and stationary

Portable neutron generators

Low flux
≈ 10^8 n/s

Portable X-ray generators

Low energy
< 300 keV

Immovable
expensive

Particle accelerator driven spallation neutron sources

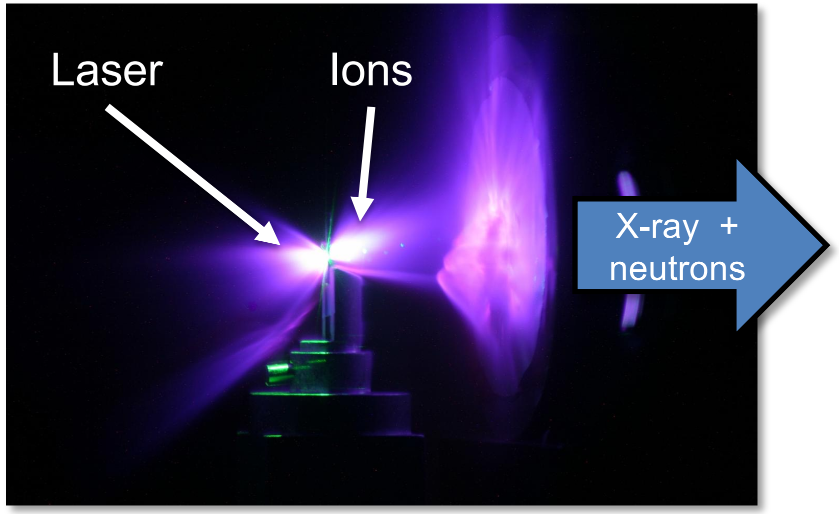
Immovable
expensive

Electron accelerators for high-energy X-rays

Laser-Driven Radiation Source

Compact, high yield, high energy and high resolution

Laser-driven radiation source



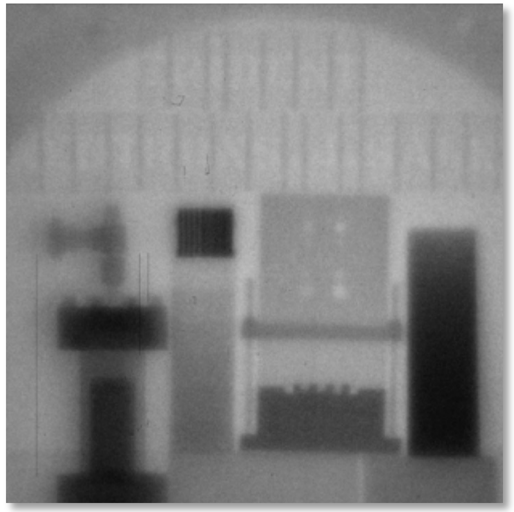
< 10 m

> 10^{11} neutrons / s

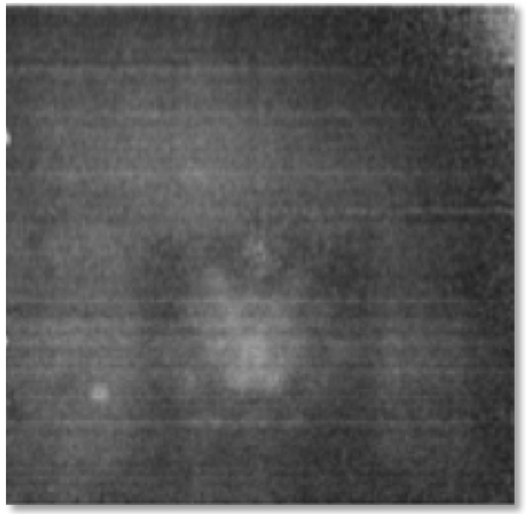
10 to 100‘s of MeV photons

≈ 4 -10 Million $ investment cost

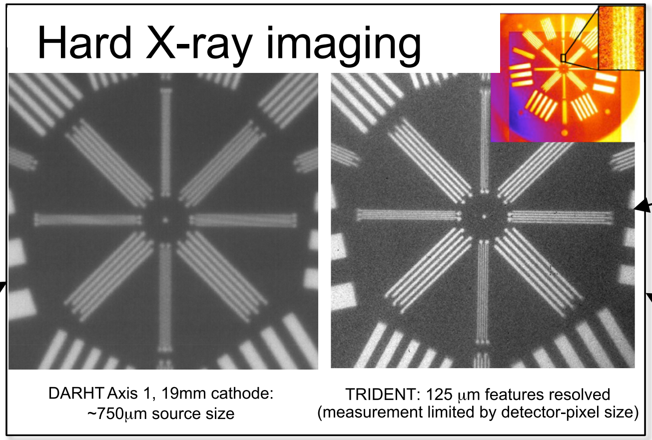
High resolution fast neutron imaging



Single shot laser-driven neutron radiography
(TRIDENT LANL 2016)



Neutron radiography using a **conventional** DT-neutron generator (**15 min**)
(NISRA-report 2015)



Conventional

Laser

sub-100 µm resolution
single shot (< 100 ps)

1 to 100‘s MeV X-rays
possible

Laser-Driven Neutron Sources

Under investigation since early 2010s: Higginson *et al.* 2010, Roth *et al.* 2013, and others

Maximum yield of ~5·10^{10} n/shot: Kleinschmidt *et al.* 2018

Proof-of-Principle of application was missing: Zimmer *et al.* 2022

nature COMMUNICATIONS

ARTICLE

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Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source

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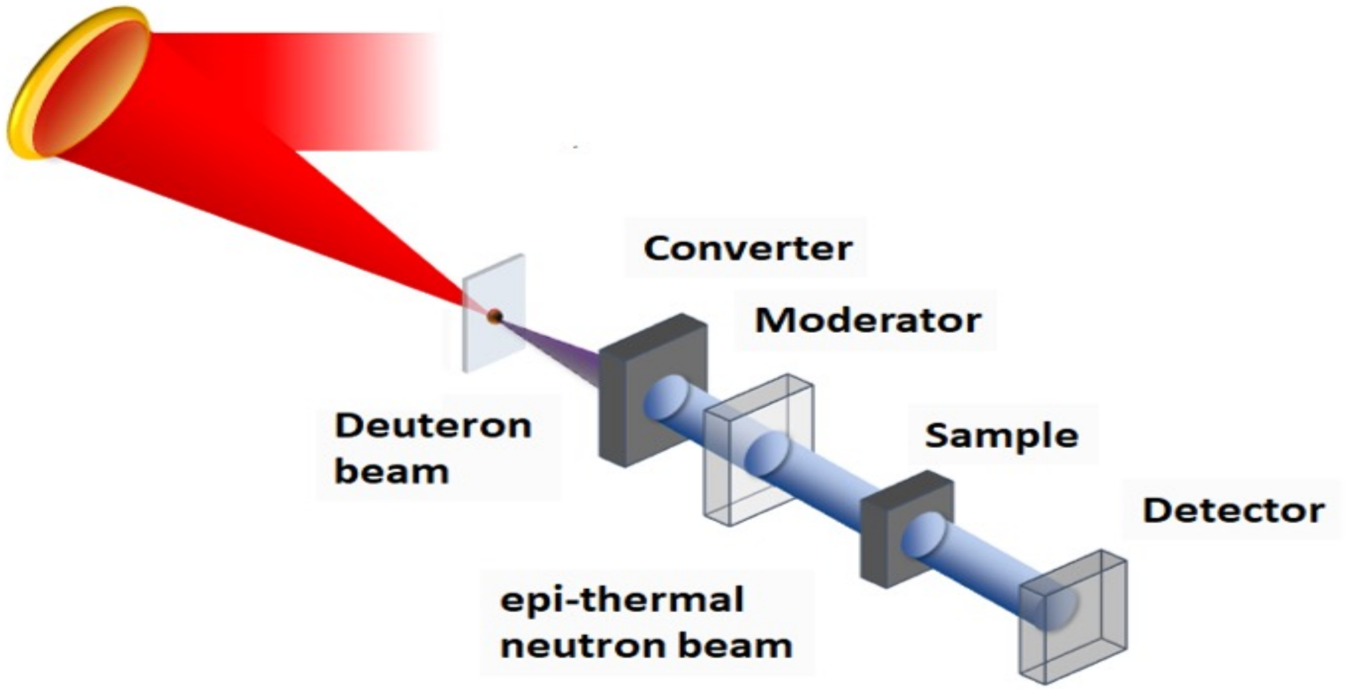
Neutrons are a valuable tool for non-destructive material investigation as their interaction cross sections with matter are isotope sensitive and can be used complementary to x-rays. So far, most neutron applications have been limited to large-scale facilities such as nuclear research reactors, spallation sources, and accelerator-driven neutron sources. Here we show the design and optimization of a laser-driven neutron source in the epi-thermal and thermal energy range, which is used for non-invasive material analysis. Neutron resonance spectroscopy, neutron radiography, and neutron resonance imaging with moderated neutrons are demonstrated for investigating samples in terms of isotope composition and thickness. The experimental results encourage applications in non-destructive and isotope-sensitive material analysis and pave the way for compact laser-driven neutron sources with high application potential.



Pitcher-Catcher scheme

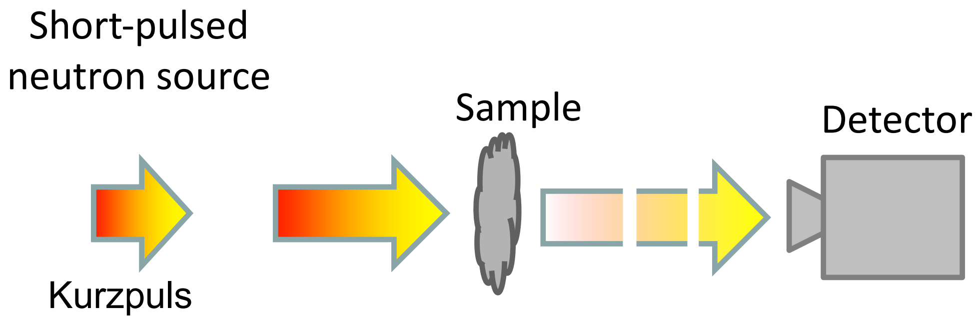
1) Ion generation

2) Ion conversion to neutrons

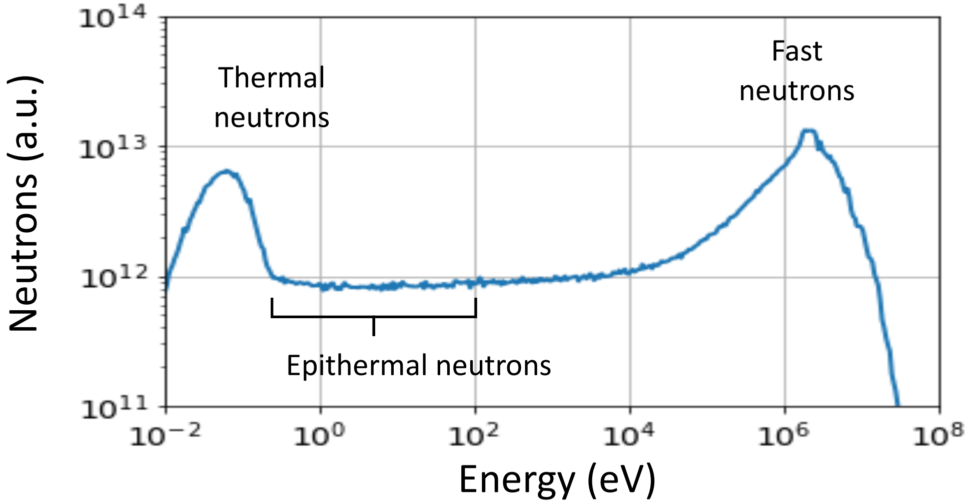
3) Neutron moderation

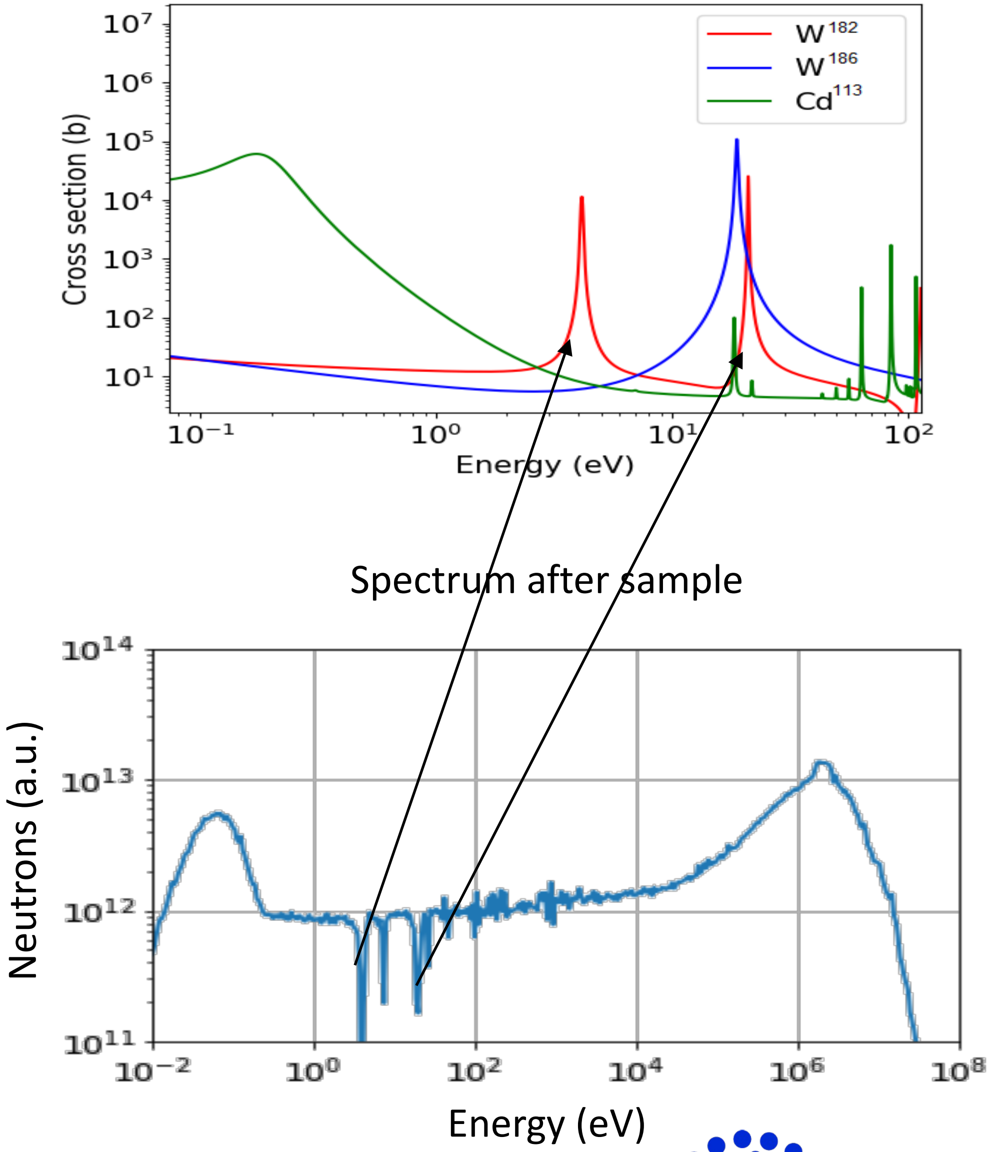
4) Neutron detection

How do neutrons help us?



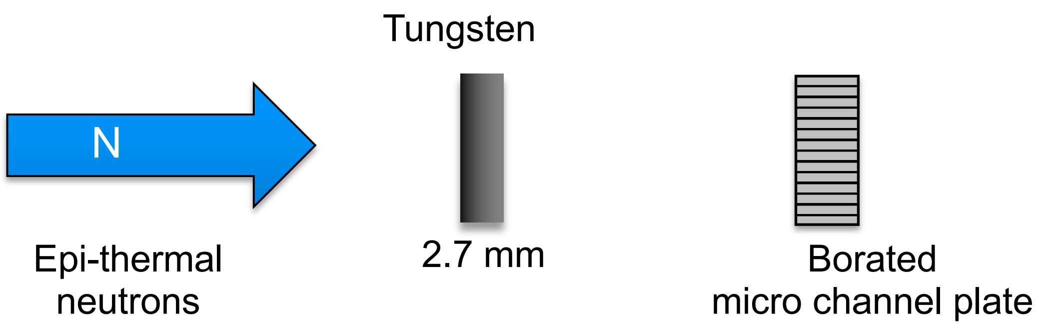
Spectrum before sample

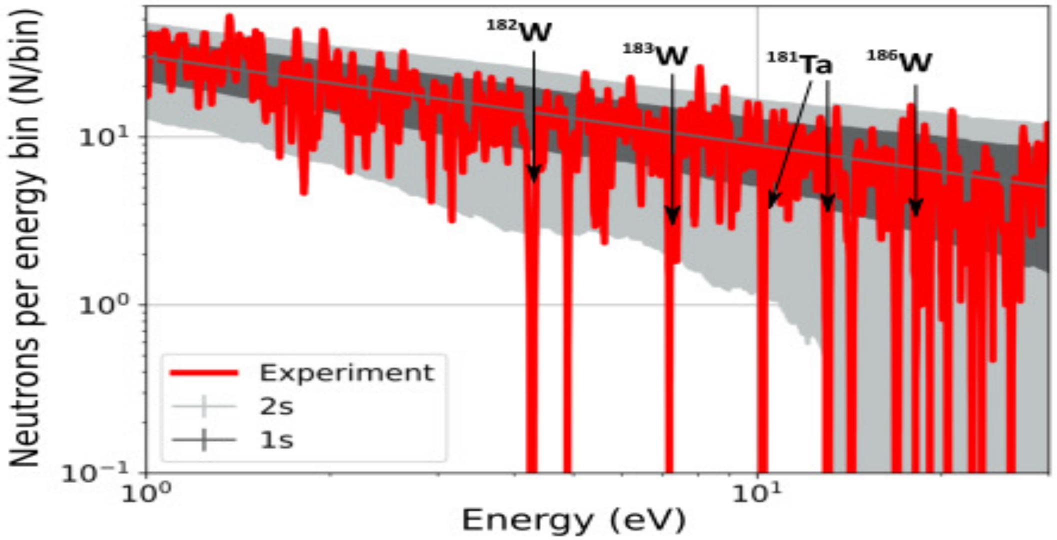


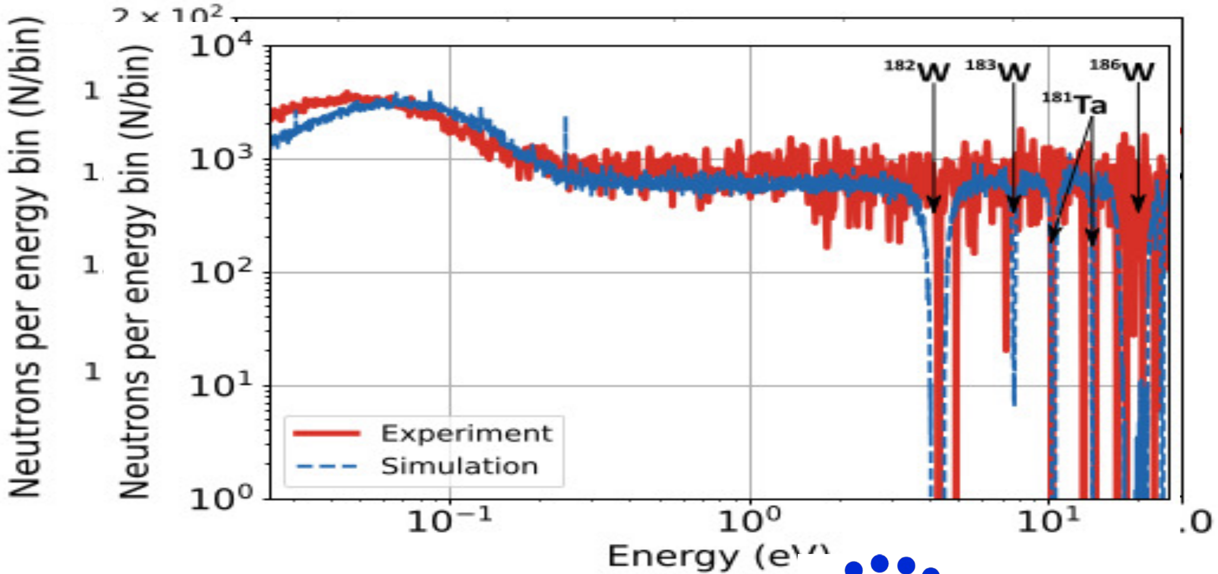


Neutron resonance transmission analysis

Neutron resonance spectroscopy setup







Three isotopes of tungsten

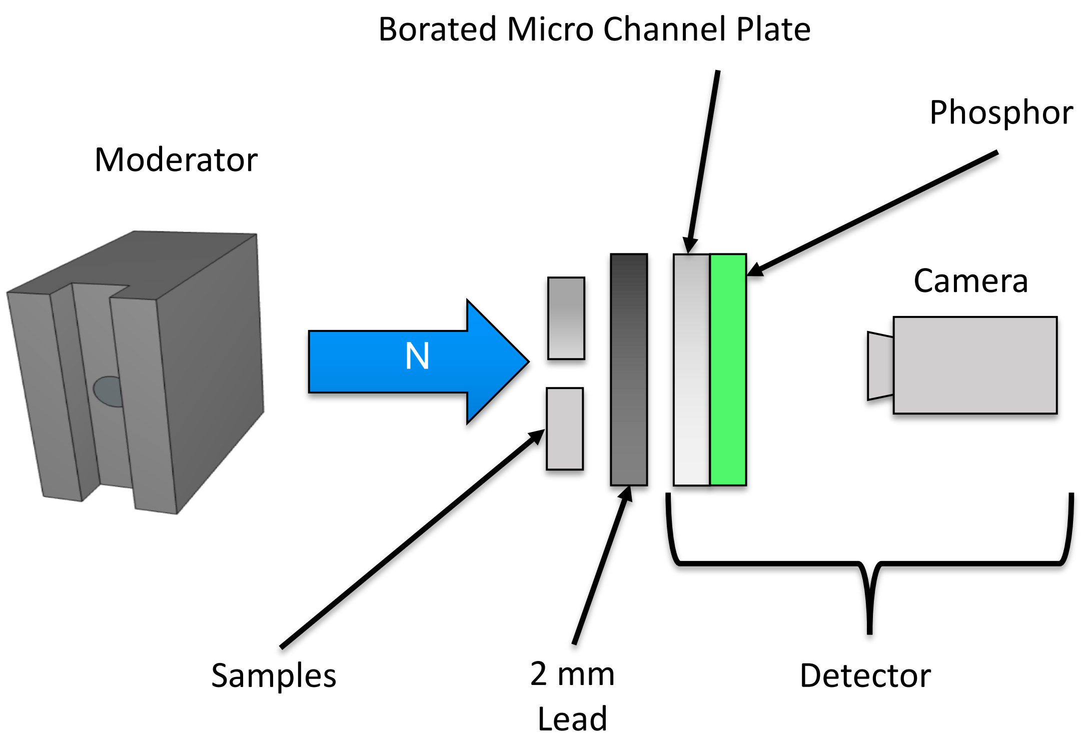
Detection of tantalum impurity

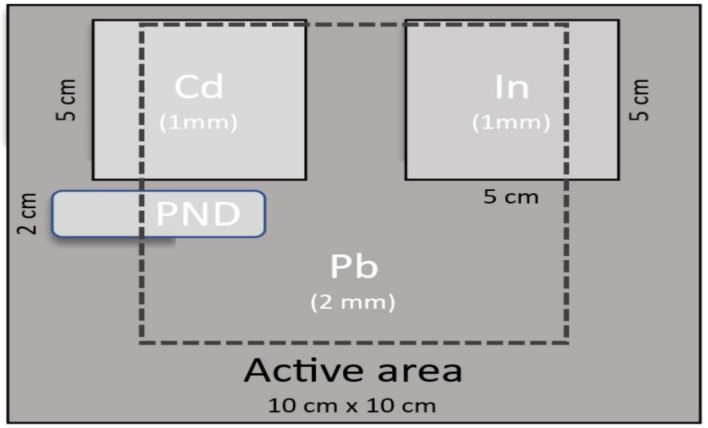
Verified with laser-driven neutron activation analysis as well as by X-ray diffraction to 1.23±0.07%

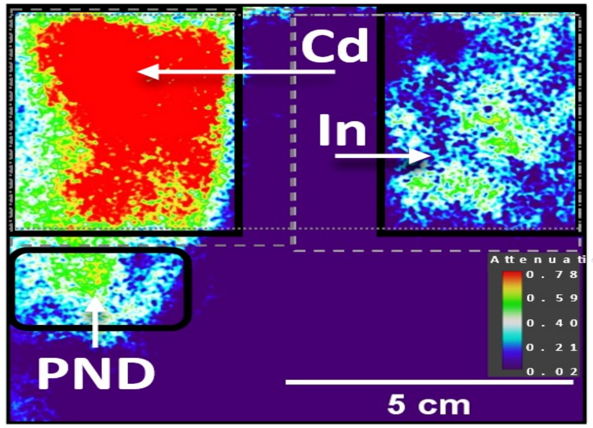
First Proof-of-Principle of NRS at a LDNS

Proof-of-Principle thermal neutron radiography

- Reconstructing material thickness from neutron attenuation

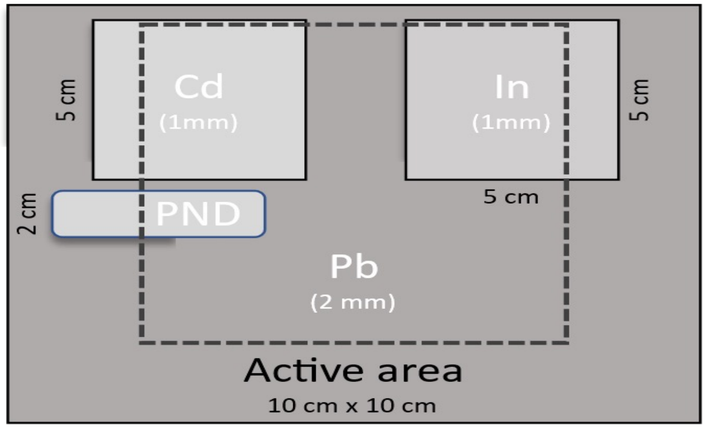


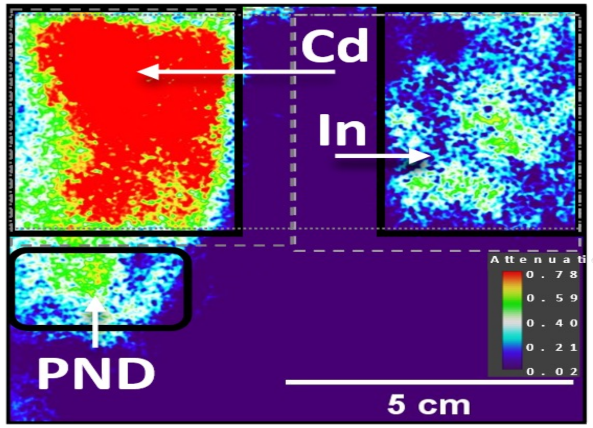




Proof-of-Principle thermal neutron radiography

- Reconstructing material thickness from neutron attenuation





Single shot
Neutron
radiography

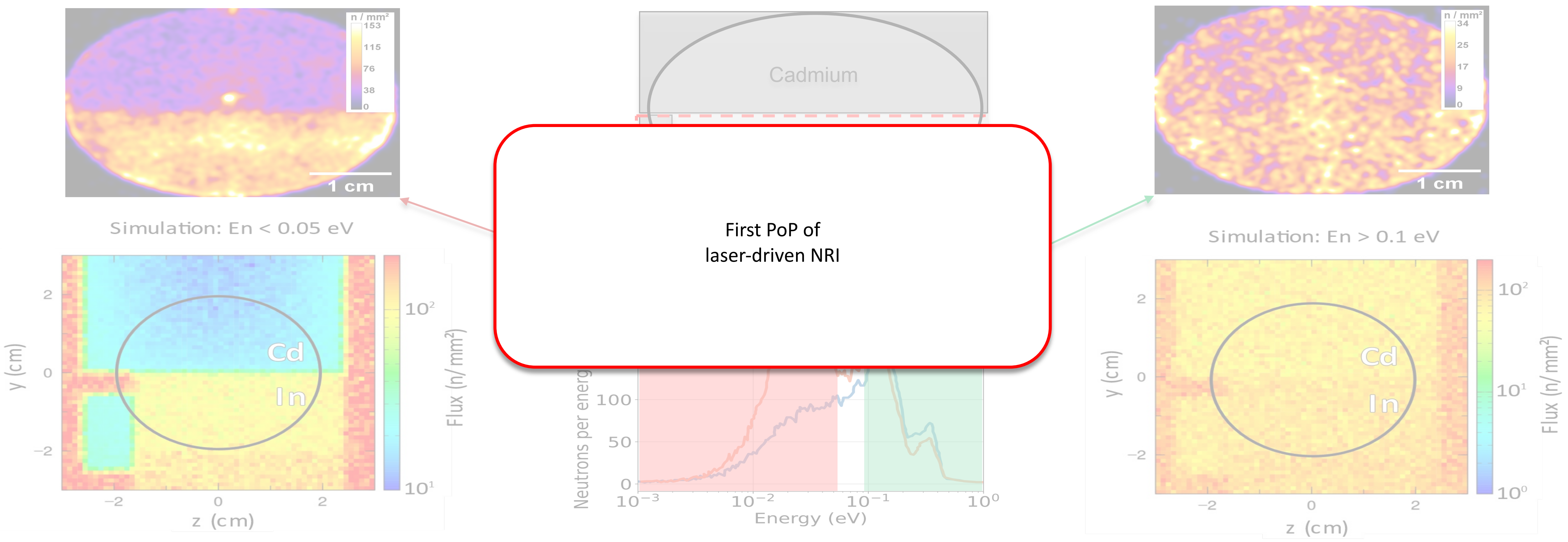
3 shots:
Determine
thickness
± 200 µm

Proof-of-Principle thermal neutron resonance imaging

- Spatially resolved isotope identification

Experiment < 0.05 eV

Experiment > 0.1 eV



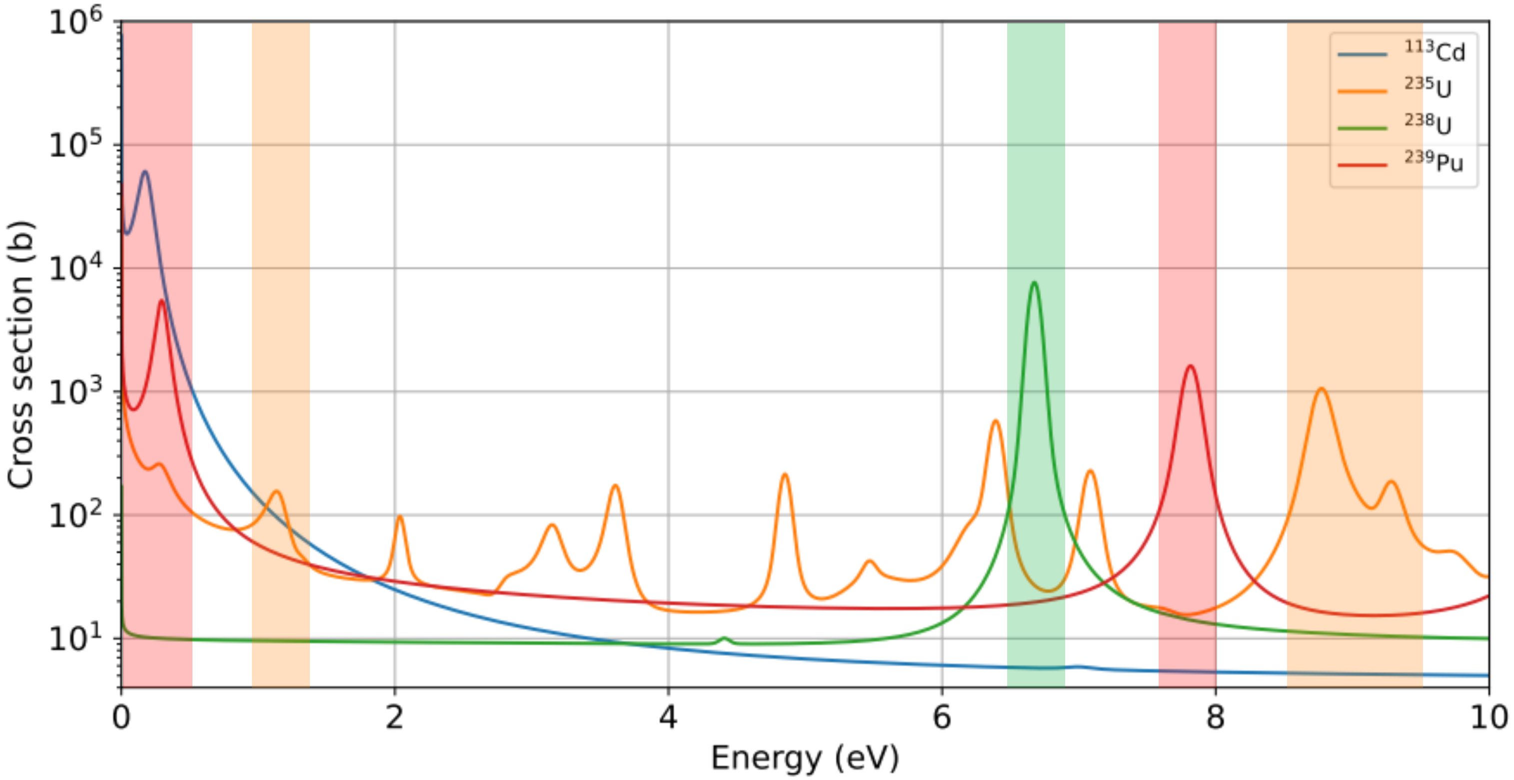
First PoP of
laser-driven NRI

Use cases of NRI

Detection and location of isotopes in a sample

^{235}U in natural uranium

Transuranics in waste

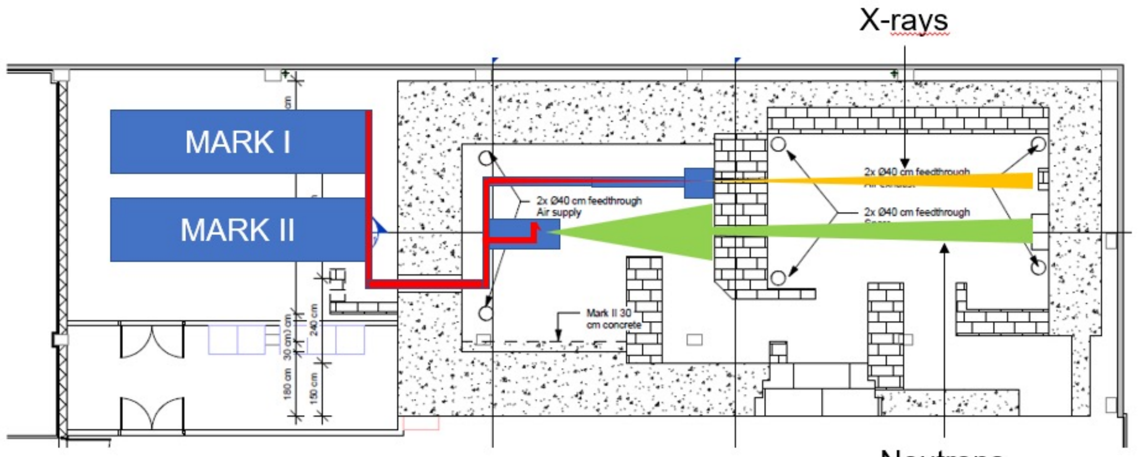


Isotope	Energy (eV)	# of shots	Time at 10 Hz
^{113}Cd	0.001-0.05	17	1.7 s
^{235}U	1.00-1.30 8.45-9.50	3.1E3 1.7E4	0.9 h 4.8 h
^{238}U	6.40-7.00	2.3E4	6.4 h
^{239}Pu	0.001-0.50 7.45-8.14	10 2.6E4	1 s 7.2 h

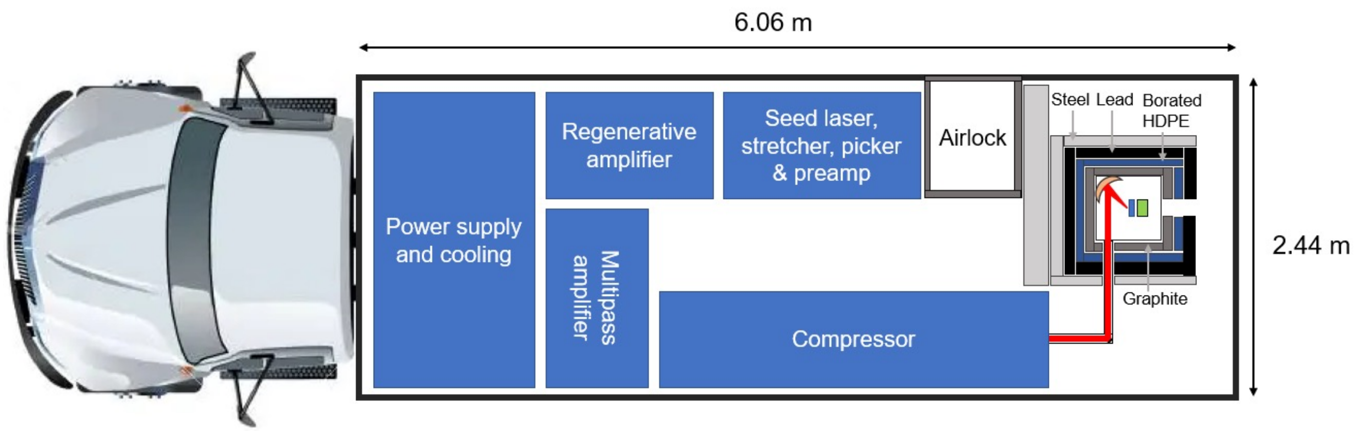
Compact non-destructive analysis systems

Designs for different applications based on the same source design

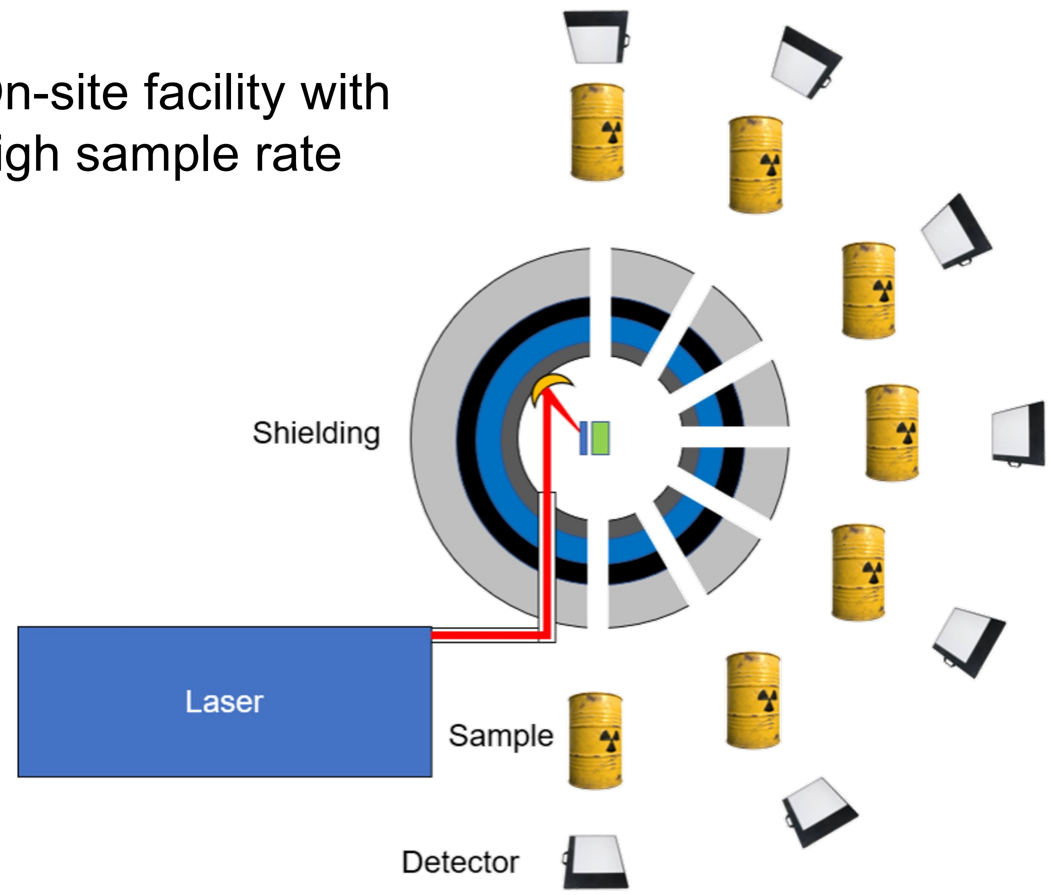
High-resolution testing lab



Mobile source



On-site facility with high sample rate



Example how lasers are becoming a powerful tool in technology

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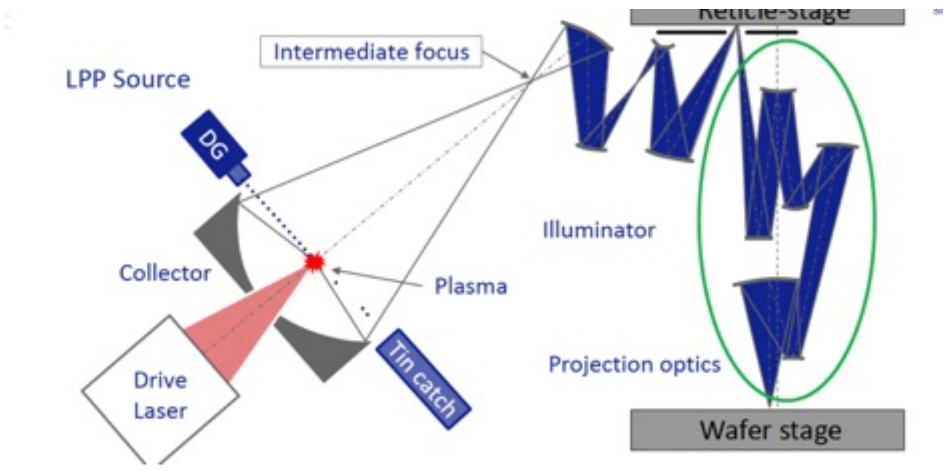


- **50 KW laser (CO_2)**
  - rep-rate: 50 kHz
- **~50 micron Sn micron target**
  - Injected & irradiated by laser @ ~10^{12} w/cm^2
  - Pulse shaping (~nsec duration)
- **"First wall protection"** (expensive EUV condensing optic and focusing lens)
- **>10^9 shots**
- **Capacity factor as high as ~90%**

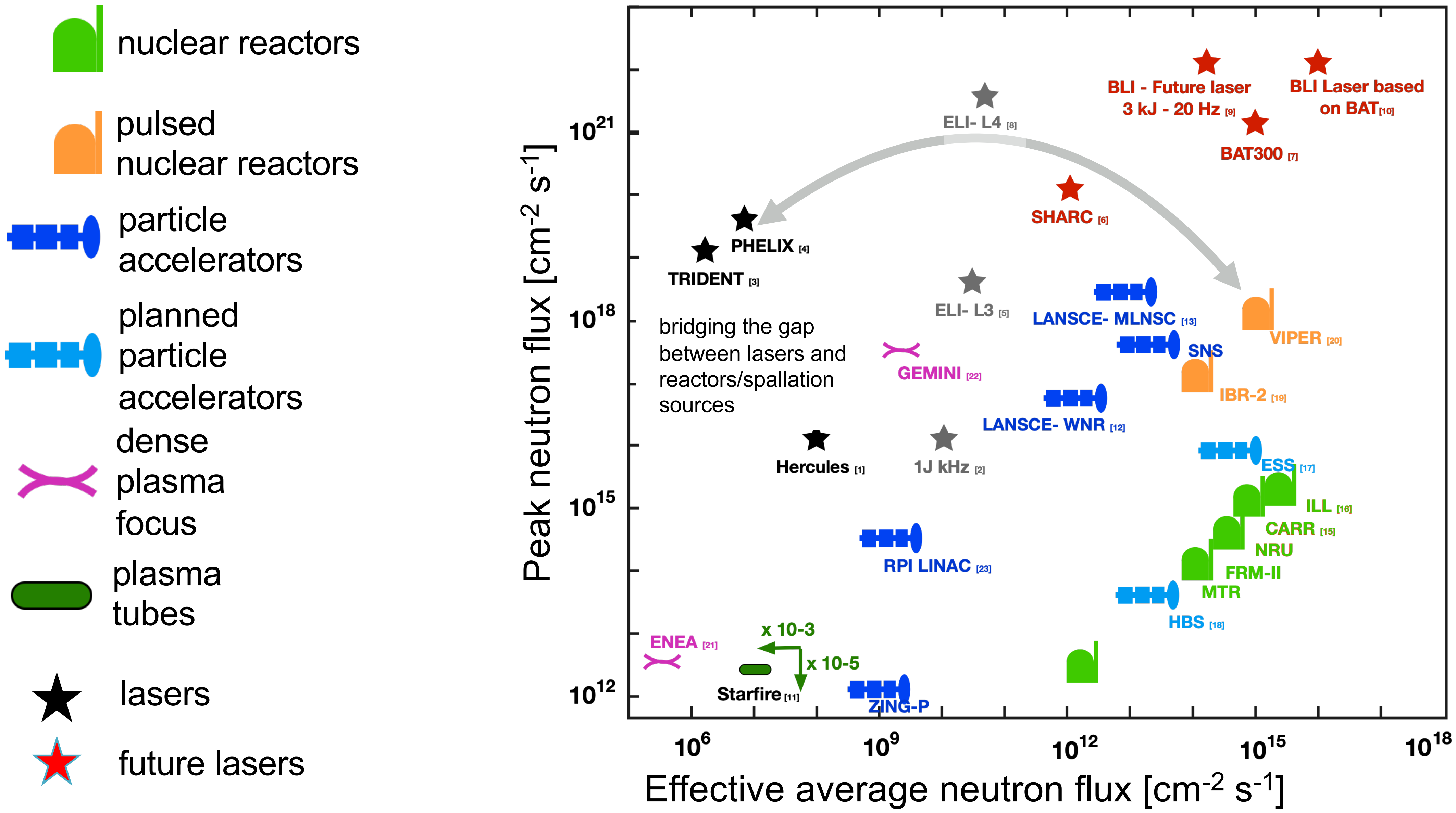
TWINSCAN NXE EUV lithography systems

- **7 nm node (Logic and DRAM markets)**
  - **Development underway for 5 nm and 3 nm node**
- **Shipments (units) 30 (2019) @ $120M/system**
  - **ASML has shipped 100 EUV steppers at end of CY2020**
- ***New Apple iPhone has 8 Billion transistors produced by EUV lithography!!****

Nuclear Photonics

Peak vs average neutron flux

(primary neutrons produced at closest accessible interaction point)



As laser sources become more powerful and their repetition rate approaches 100 Hz and beyond, their use as particle accelerators might be the next step in technology

Any Questions/Comments? Please ask.

Thank you for your attention!