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Laser-Driven Pulsed Neutron/X-ray Sources for Nuclear Material Security and Scientific Applications

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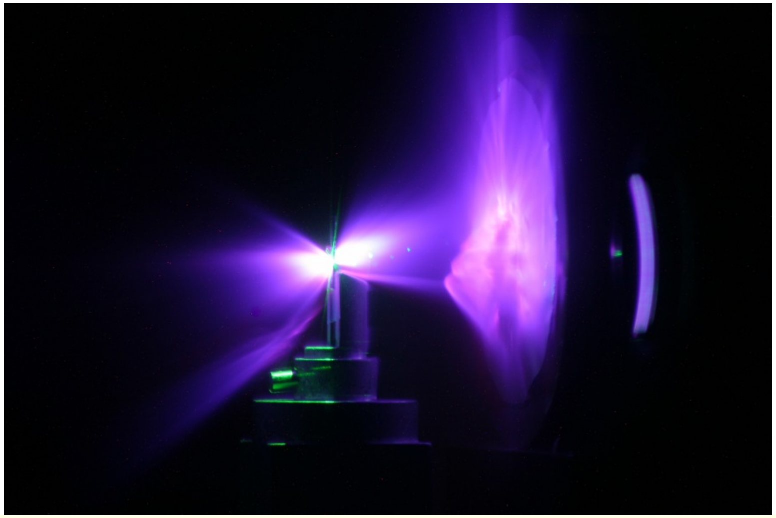
Laser-Driven Neutron and MeV X-ray Sources for Research and Global Security



- At Los Alamos's Trident facility, scientists used an **ultra-high intensity laser beam** to produce **high intensity short duration neutron and x-ray bursts**.
- Applications of this novel neutron source include improving upon current technologies for the detection of clandestine nuclear materials and treaty verification, as well as enabling a new generation of nuclear physics experiments and neutron therapy.

August 16, 2015. Picture of the week LANL,
http://www.lanl.gov/newsroom/picture-of-the-week/pic-week-22.php

List of collaborators

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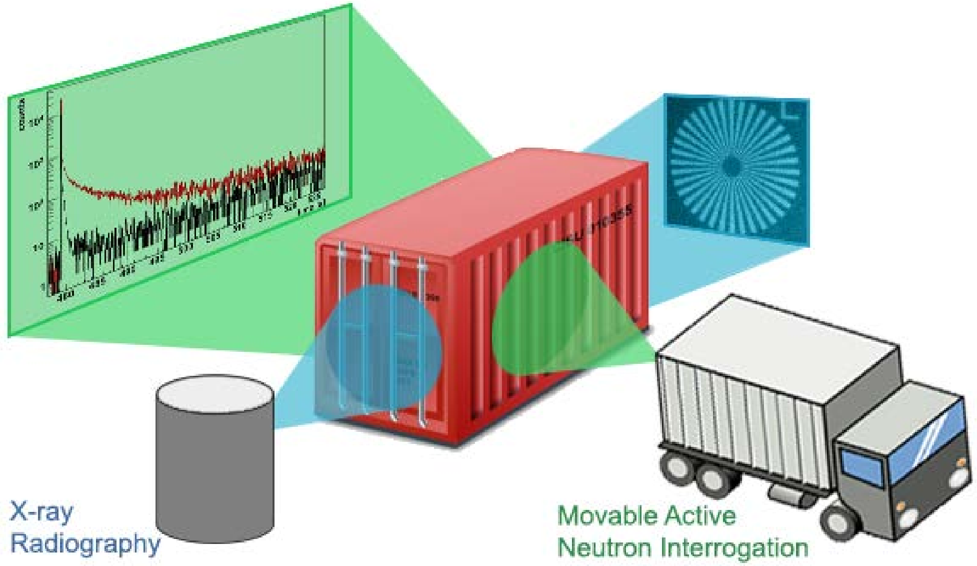
Laboratory Directed Research and Development (LDRD)

GOAL: Investigation of the feasibility of active interrogation using multiple laser-driven probing species

Active Interrogation systems to detect special nuclear material (SNM), including shielded materials:

- Passive signals are weak, especially for HEU
- Use external neutrons to induce fission
- Use external X-rays to image contents



Neutron Source: Requires a fast, transportable, operationally safe neutron source featuring tunable energy, and high intensity, directional neutron production

X-ray Radiography. Requires a high intense, MeV energy, collimated source, with small source size for high spatial resolution

Laser-neutron source

Laser-driven ion acceleration is the technological key to production of intense neutron bursts for interrogation.

Laser couples to target electrons → **Relativistic e⁻ population out of equilibrium** → **Relativistic e⁻ population couples to ions** → **Directed ion beam**

Laser couples to target electrons

- Ponderomotive force $-\nabla E^2$
- Electrons move mostly forward Result: heating, pressure, current

Relativistic e^- population out of equilibrium

- $I\lambda^2 > 1.33 \times 10^{18}$ $\mathrm{Wcm^{-2}\ \mu m^2}$,
- *Kinetic energy of e^- exceeds rest mass of e^-*
- Directed e^- motion, e.g., current
- Relativistic transparency with nano-foil targets (efficient volumetric interaction, ~ 80%)

Relativistic e^- population couples to ions

- Charge separation,
- Breakout afterburner mechanism(BOA)*
- Instability that creates an electrostatic wave accelerating ions

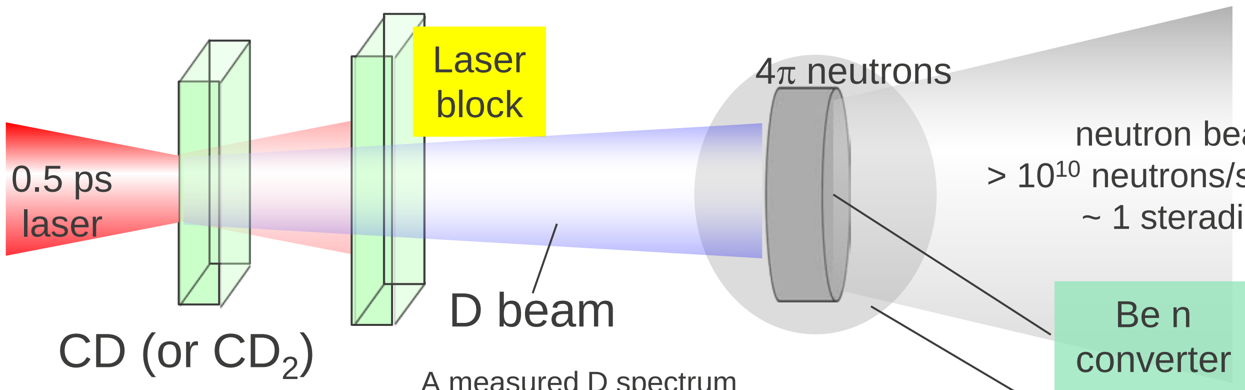
Directed ion beam

- MeV–GeV ions, up to ~100 MeV protons
- Efficient laser to ion energy transfer. (~ 10%)
- Broad or narrow energy spread
- Born in ~ ps

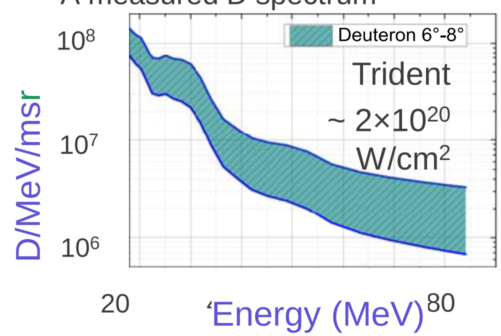
E:electric field, I:laser intensity, λ laser wave length

**L.Yin et al., PRL 107 (2011), L.Yin et al, PoP 18 (2011); B.J.Albright et al., PoP (2007), L.Yin et al., PoP (2007) , B.J.Albright , L.Yin, & A.Favalli, Laser and Particle Beam (2018)*

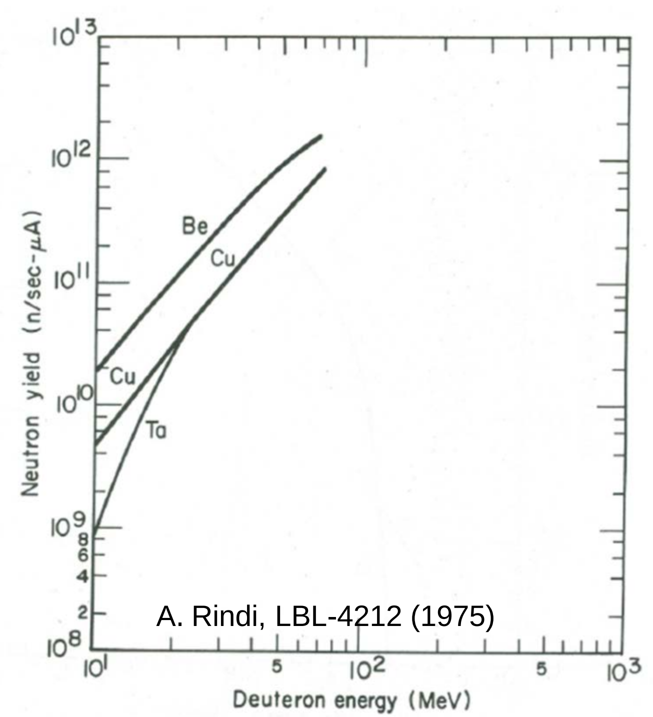
A laser-driven deuterium (ion) beam hitting a beryllium converter produces an intense neutron beam.



A measured D spectrum

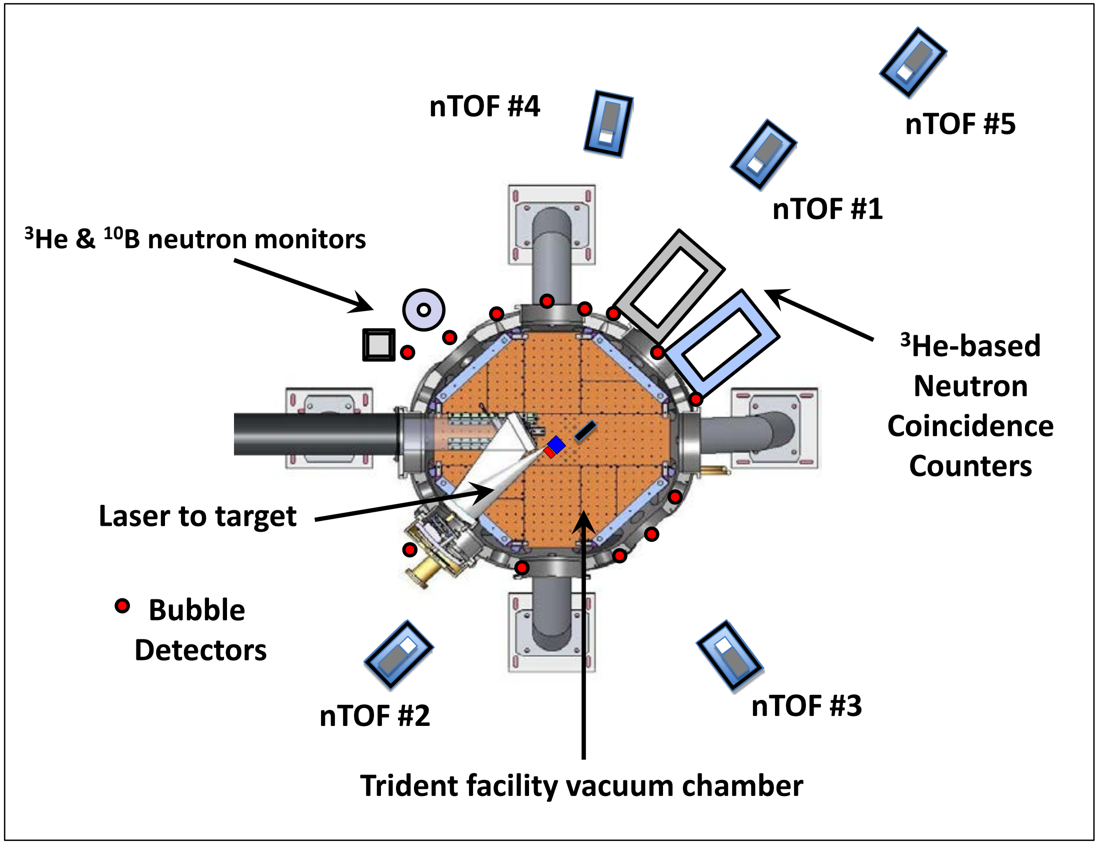


Neutron production by D-breakup



- D-Be interaction
  - D break-up (Binding energy deuteron 2.2 MeV) produces forward peaked neutrons (in addition to neutrons into 4π)
- Neutron-beam production
  - Inherently single pulse
  - ~ 10^{10} neutrons/sr in 1 sr forward cone
  - Yield depends strongly on D energy
  - Spectrum can be tailored via converter geometry

Experiments in Trident evaluate neutron production from laser driven ion beams.



Neutron Diagnostics:

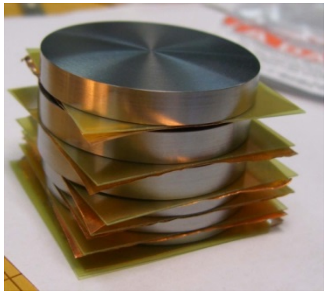
- Bubble detectors (insensitive to γ-rays) → low precision/large angular coverage neutron yield
- Neutron time of flight (NTOF) (nTOF) - plastic scintillator + Photomultiplier tube → energy spectrum
- ^{3}He+polyethylene detectors → fission signatures & single angle /high precision neutron yield

nTOF and prompt neutron monitors have been developed to handle the huge dynamic neutron flux in one Trident shot.

A Favalli et al., *Scientific Reports, 2019*

Innovative neutron (Be) converter design optimizes the conversion of laser-produced ion beams to neutron bursts.

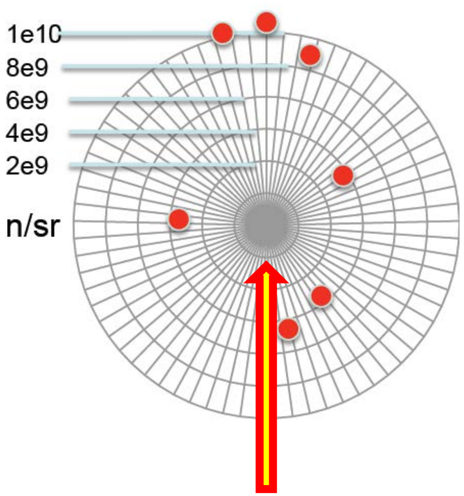
- Converter used in the first campaign: cylinder of 2 cm diameter, 4 cm deep (Be)
- Redesigned to be a flexible, modular Be converter composed of disks (*3 disks each 3 mm thick, 2 disks each 6 mm thick, 1 disk 12 mm thick, all disks 5 cm diameter*) based on MCNPX simulations*.
- Tungsten ring around Be as reflector & radiator (n,2n),(n,3n)…*
- Radio Chromic Films (RCF) used as ion diagnostic along the length of the converter, between disks, for validation of MCNPX simulations

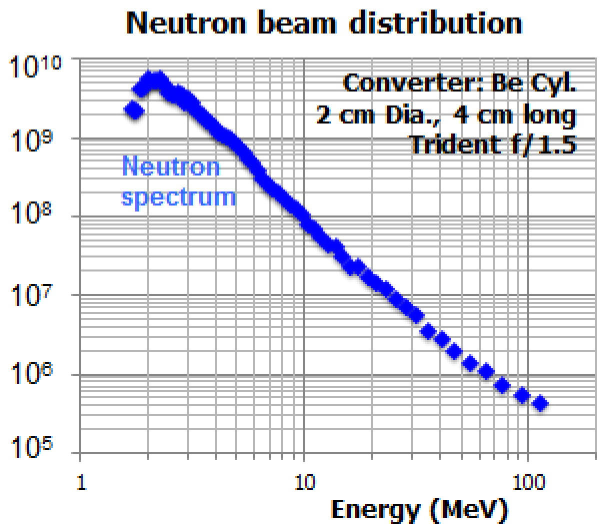


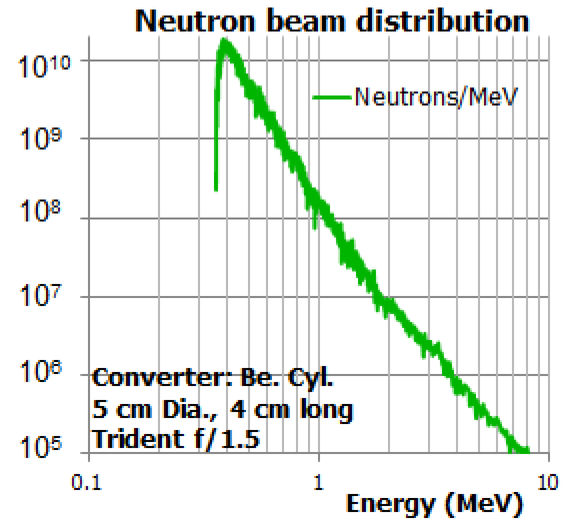
**A.Favalli et al., LAUR-14-25881; LAUR-14-25768; A.Favalli et al., IEEE Nuclear Science Symposium, 2014 Seattle*

Characterizing Neutron Production, Energy Spectrum & Angular Distribution

NEUTRON PRODUCTION IN TRIDENT $>10^{10}$ n/sr, per shot







Energy and Angular distributions can be **tuned** by combination of (1) optics+target-material, and (2) Be converter shape

Applying a laser-driven neutron source for Active Interrogation

Active Interrogation: “Let’s poke it and see what happens”

Principle: Neutron Induced fission in nuclear material (e.g. ^{235}U or ^{239}Pu).

Main neutron fission signatures of interest are :

- **Prompt –fission neutrons**
- **Delayed-fission neutrons**

Prompt: signature produced during the interrogation of the nuclear materials, neutrons emitted during the fission process

Delayed: delayed neutrons are produced from the decay of fission products (and their daughters) up to seconds/minutes after the fissions-> good separation from interrogation neutrons

Prompt neutron signature:

Pros: substantial production ~2-3 average neutron per fission;

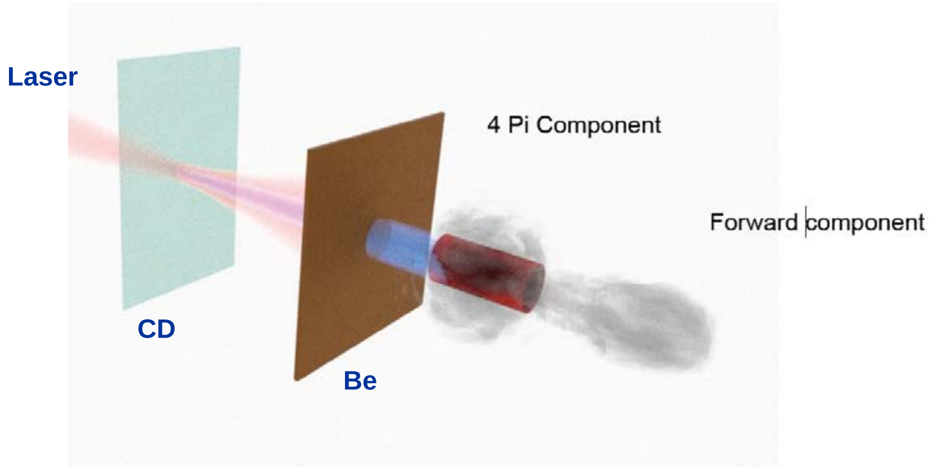
Cons: difficult to measure and distinguish from interrogation neutrons

Delayed neutron signature (DN):

Pros: easier to measure compared to prompt fission neutrons.

Cons: very low neutron yield per fission: e.g. 0.017 for ^{235}U and 0.0065 for ^{239}Pu.

Laser-driven neutron sources are especially well suited to active interrogation.



A short pulse-laser-driven neutron source features:

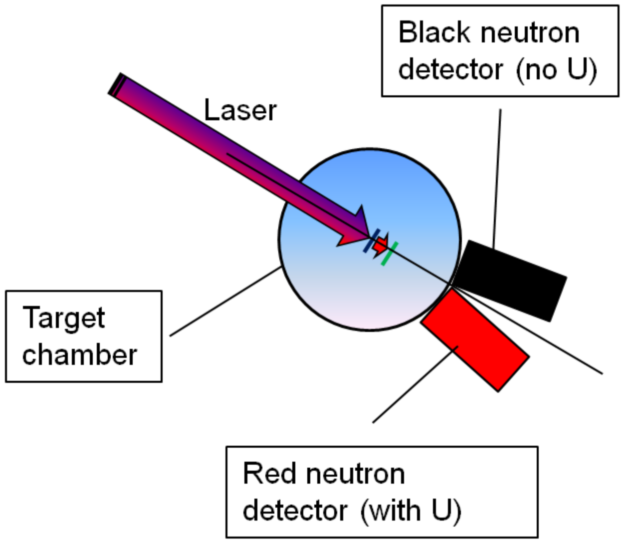
- *Short but high intensity pulsed neutron production, results in high throughput and high signal-to-noise*
- *Directionality; increases signal for the interrogation while helping the safety of the operators*
- *Energy tunability, gives an advantage for interrogation of variable types and thickness of shielding*
- *Can be made in a size suitable for a movable/ transportable source*

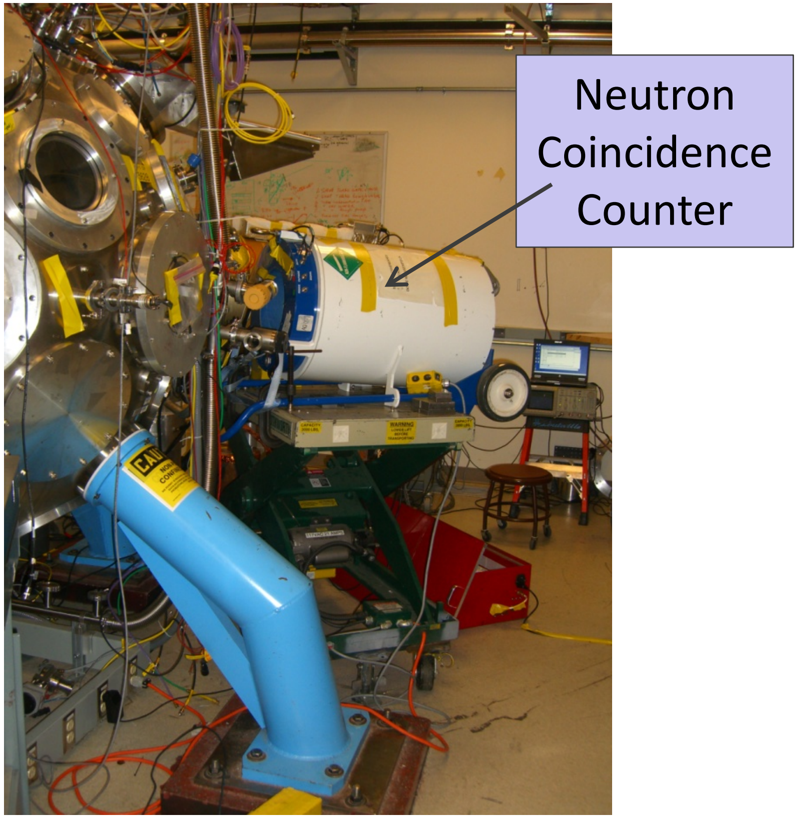
Active-Interrogation

Demonstration of Active Interrogation using a laser-driven neutron source and delayed neutron detection

Neutron Coincidence Counters

- **HLNCC-II**: composed of a single ring of 18 ^{3}He detectors embedded in polyethylene, Cd lined (efficiency=17.5%, die-away 43 µs)
- **AWCC** : double ring of 42 ^{3}He detectors embedded in polyethylene, Cd lined (efficiency=32.8%, die-away 50 µs)

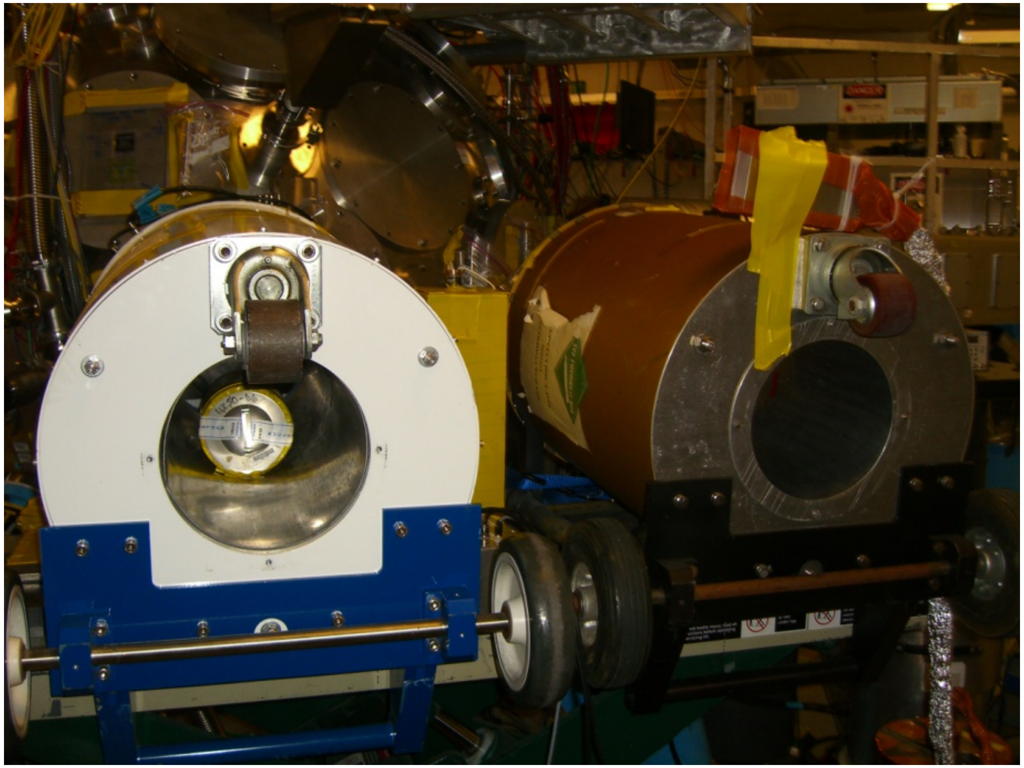




A Favalli et al., *LA-UR-13* (2013). LANL news release (2013). A.Favalli et al.,LA-UR-14-21661 (2014)

Uranium Samples tested

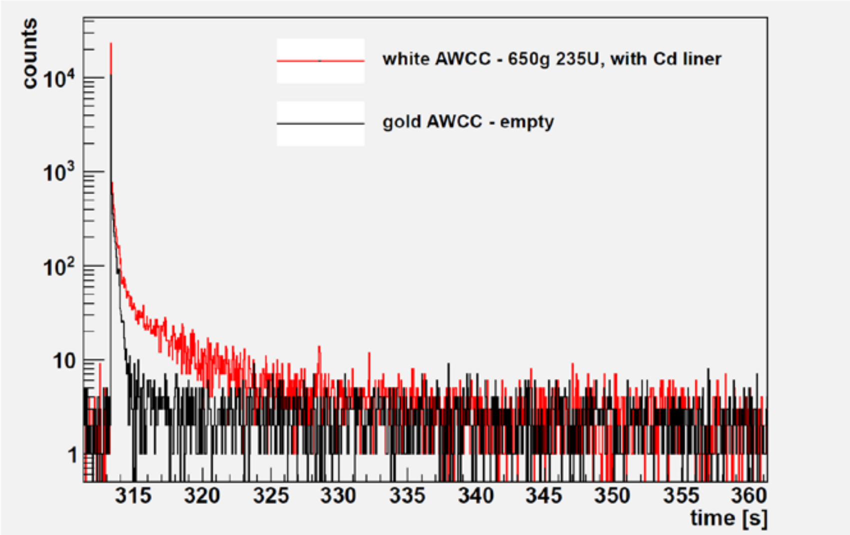
- Depleted Uranium with mass up to 4.5kg
- Samples of enriched uranium up to 65%(w.t.) enrichment in ^{235}U



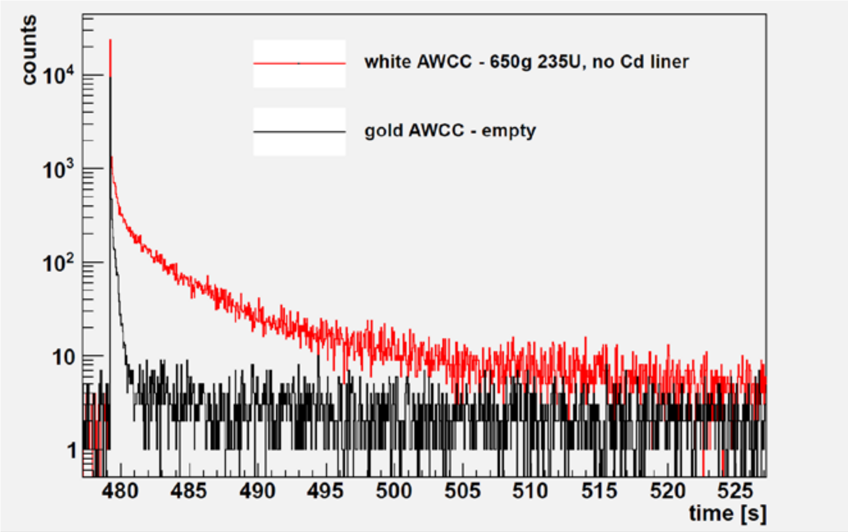
- Two neutron coincidence counters each using a ring *of ^{3}He proportional detectors embedded in polyethylene*.

- In the *left* detector the U sample is visible.
- The r*ight* detector is a baseline

Interrogation of an highly enriched uranium sample (990 g U, **65%** (w.t.)^{235}U)



Fast Mode (*with* internal Cd sleeve)

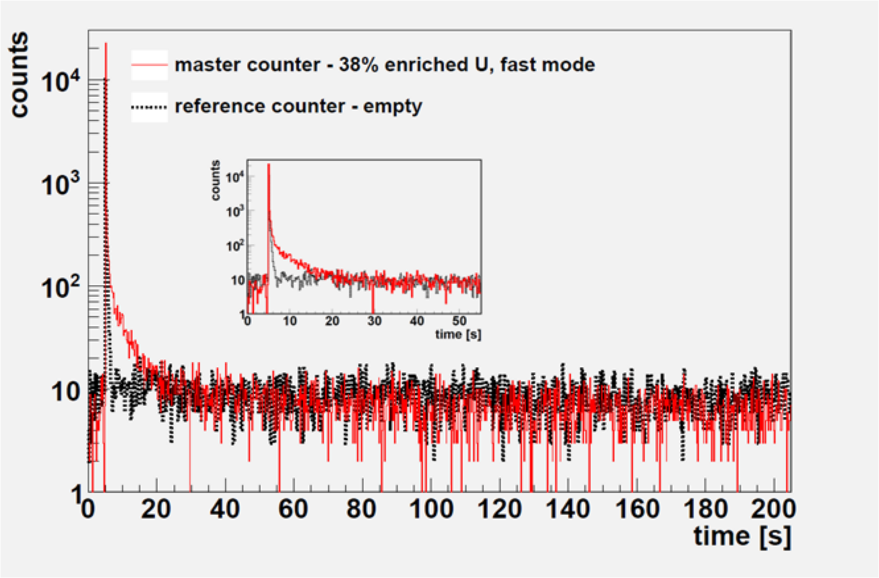


Thermal Mode (*without* Cd sleeve)

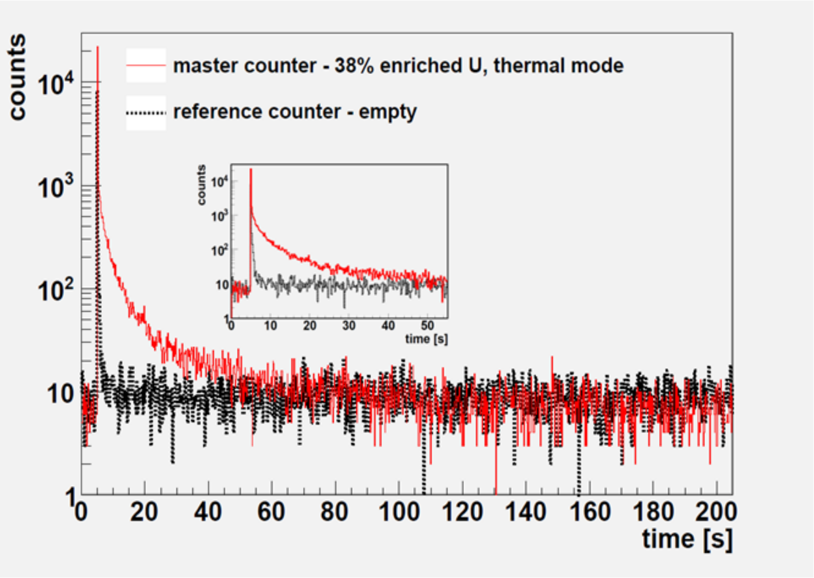
Delayed Neutrons chosen as signature, these neutrons are characteristic signatures for nuclear fission (few other process yield delayed neutrons)

Active-Interrogation

Interrogation of an lower enrichment uranium sample (990 g U, **38%** (w.t.)^{235}U)



Fast Mode (*with* internal Cd sleeve)



Thermal Mode (*without* Cd sleeve)

Enriched Uranium Samples: 12-65% (w.t.)

Toward a single-shot, neutron induced, prompt-fission based interrogation technique.

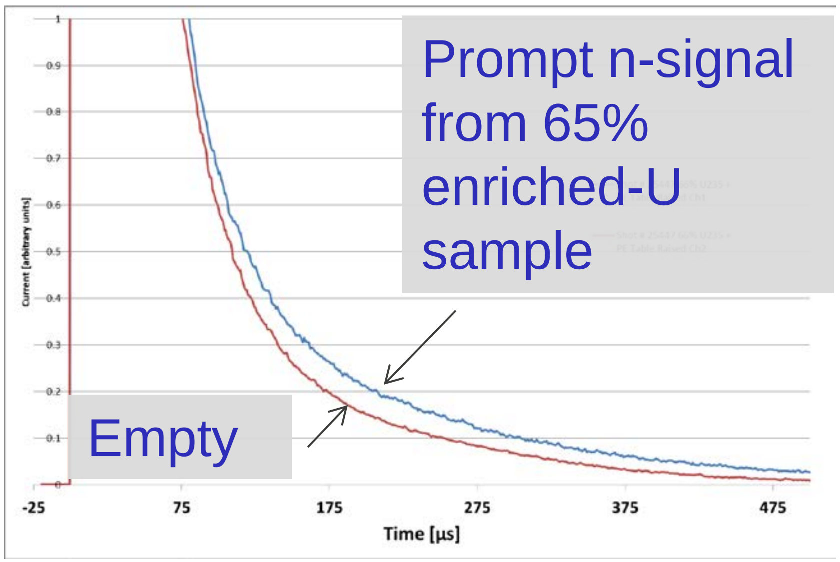
Advantages:

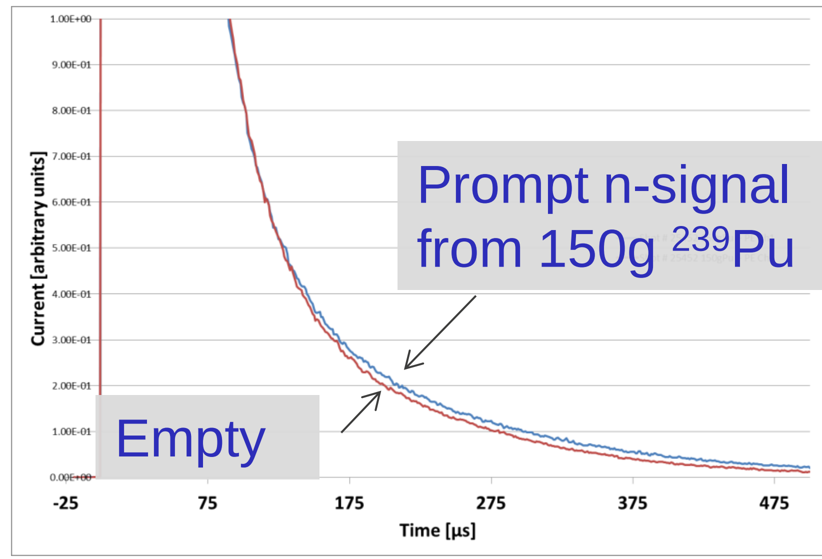
- Increased **sensitivity** of the detection of nuclear material because the prompt-fission neutron emission is in the order up to ~ 100 larger than the delayed neutron one,
- Significantly **increase the signal-to-noise ratio** in difficult to measure environments such as conditions with high background neutron emission rates, as is the situation for active interrogation of plutonium.

Active-Interrogation

Toward a single-shot, neutron induced, prompt-fission based interrogation technique.

In the **July-August 2015** experimental campaign: Prompt Fission Neutron? (we obtained permission to use a 170 g sample of Pu, of which ~150 g is ^{239}Pu)





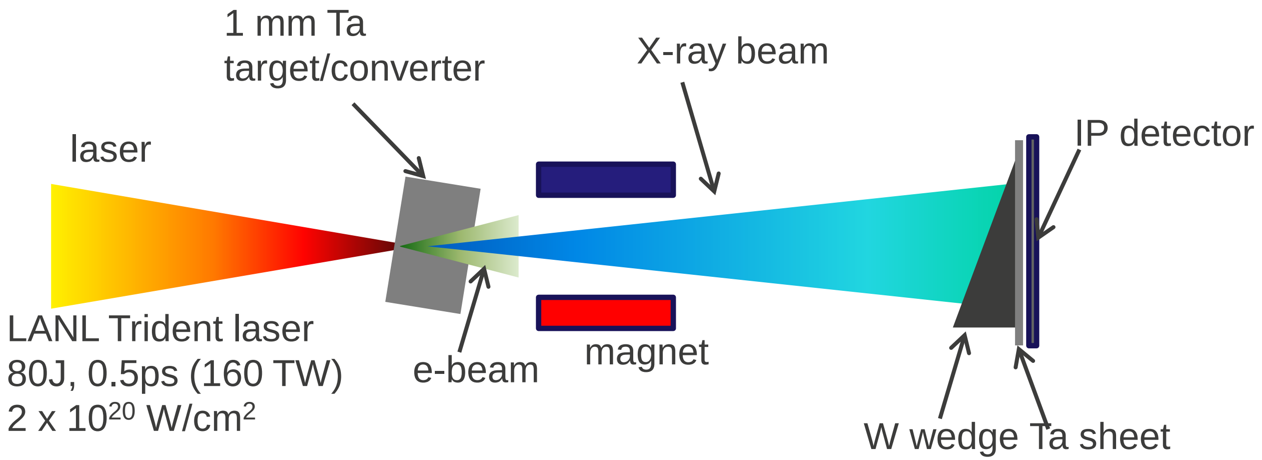
For the first time: we have **detected prompt-fission neutrons** from ^{235}**U** samples and from a ^{239}**Pu (*)** sample (final data are being analyzed, Provisional Plots)

*Pu signal from delayed neutron detected too

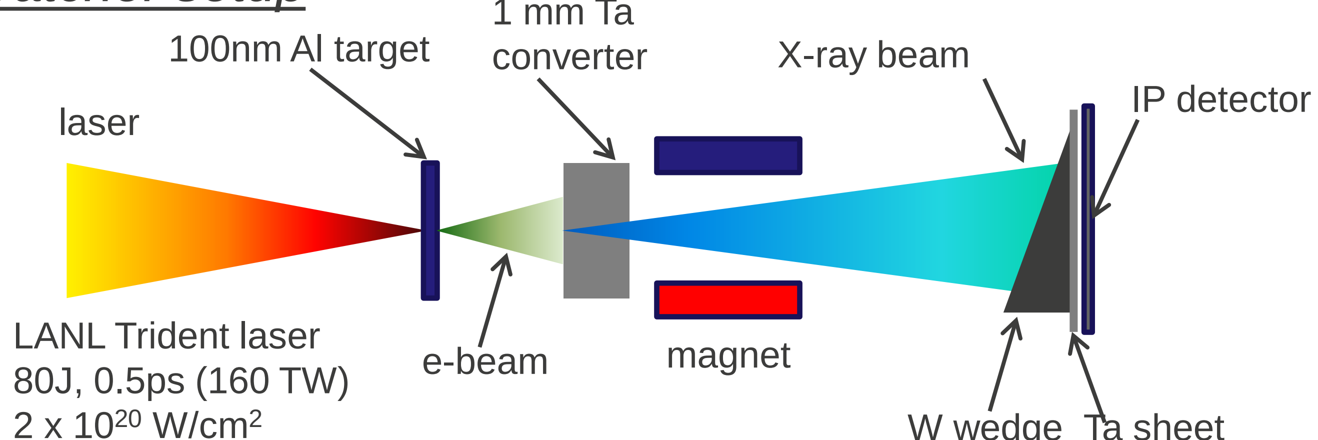
Developing a laser-driven x-ray source for radiographic imaging in Active Interrogation

We studied two different schemes for MeV X-ray generation at Trident

Scheme 1: Compound (integral target/converer) setup

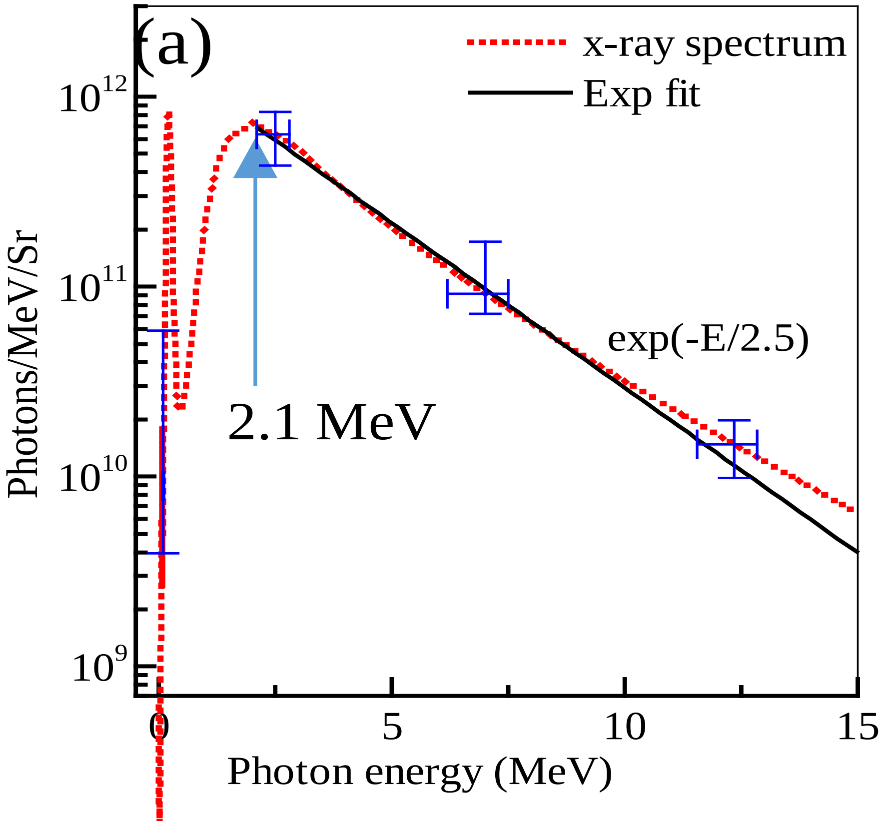


Scheme 2: Pitcher-Catcher setup



S. Palaniyappan et al, (2019) *Laser and Particle Beams*

Compound target produces efficient MeV X-rays



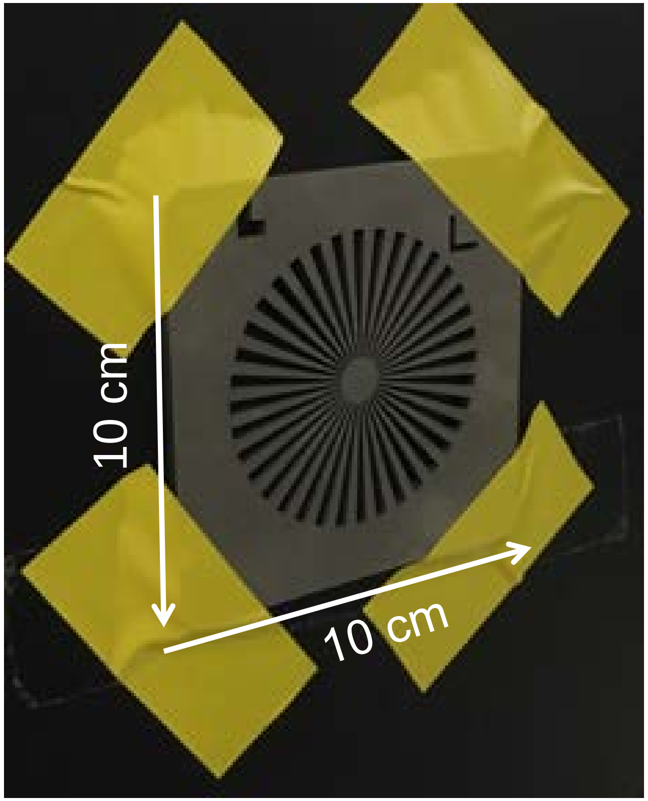
- Compound (1mm Ta) target/converter performs much better than pitcher-catcher target
- Much simpler setup
- Highly reproducible
- Does not require ***high laser contrast***

3 x10^{12} photons per shot
1J of MeV x-rays out of 80J incident laser (efficiency ~1%)

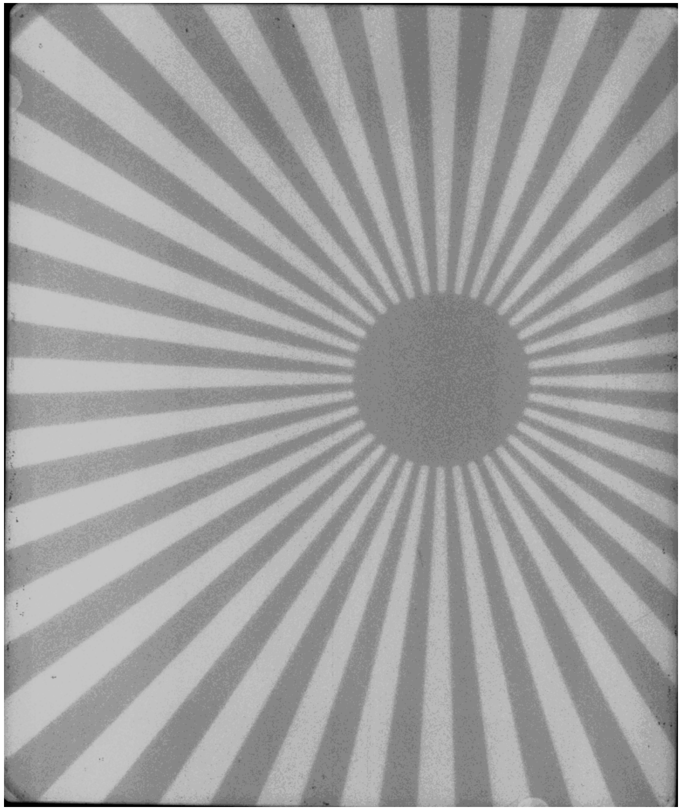
Laser MeV X-ray Source

80 μm x-ray source size inferred from radiographing a high-contrast resolution target (6 mm thick tungsten)

R2DTO object



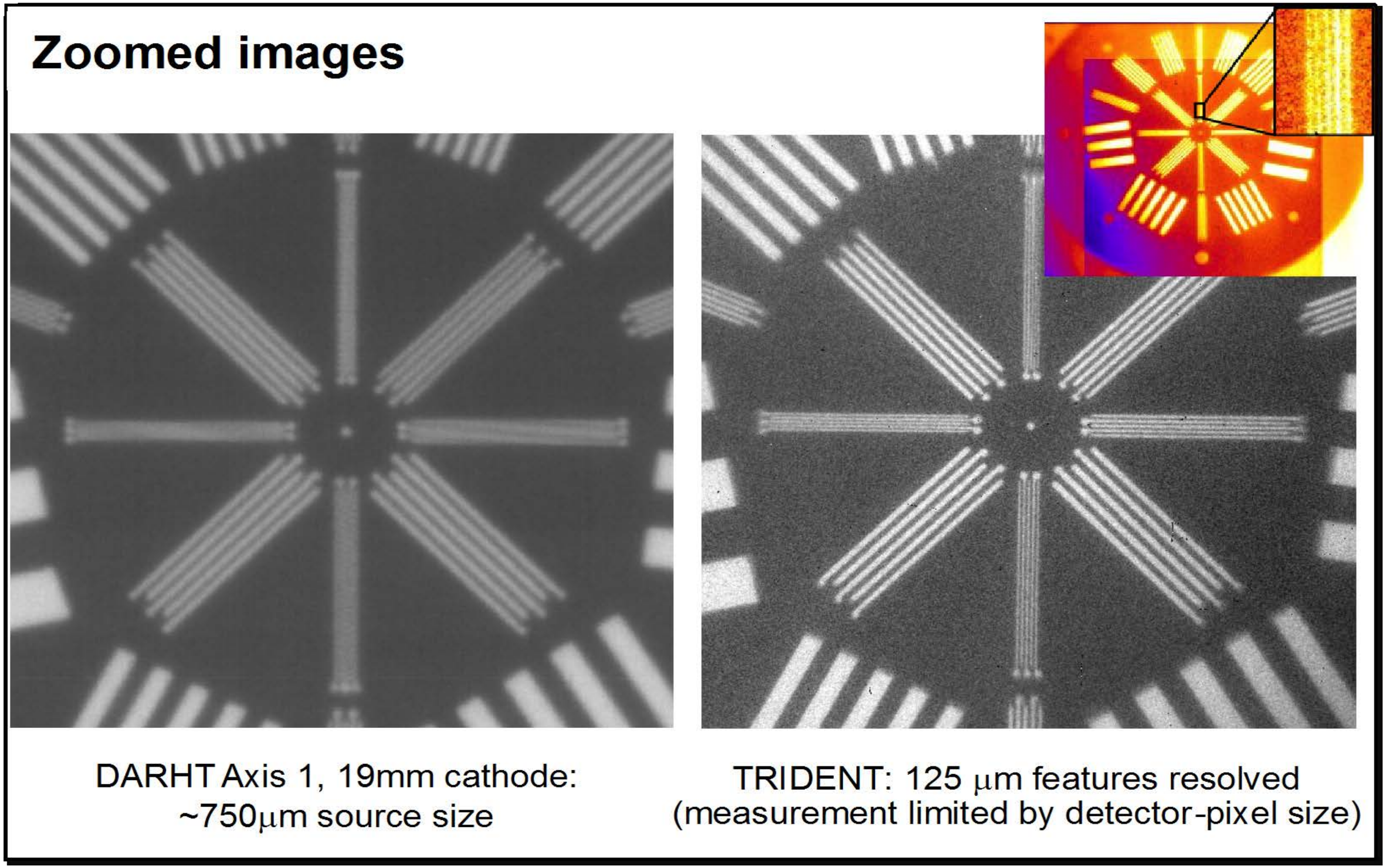
5.8 X magnified



Bayesian Inference Engine (BIE) analysis implies
80 um FWHM x-ray source size

Laser MeV X-ray Source

MeV x-ray point-projection radiography of the AWE Kaleidoscope object, taken at DARHT (left) and at Trident (right) demonstrates excellent resolution



Conclusions: Short-Pulse-Laser-Driven neutron source

- Demonstrated High Yield Neutron source at the TRIDENT Laser facility.

Active Interrogation using Laser-driven neutrons:

- First time experimental demonstration of active interrogation of nuclear material using short-laser-driven neutron source .
- Measurement of enriched Uranium samples from about 12% to 65%, with extraction of a calibration curve of ^{235}U mass versus counts *(Delayed neutron signature)*
- First time detection of *prompt-fission neutron si*gnature from nuclear material in a single interrogation shot from a laser.
- First time detection of a small Plutonium (150g) in a single shot laser-driven neutron source based on delayed neutrons.

Conclusions: Short-Pulse-Laser-Driven MeV X-ray source

- Demonstrated reproducible High Yield MeV X-ray sources at the TRIDENT Laser facility. →~10^{13} photons/s. Beam divergence 0.1 sr.
- High efficiency ~1% (1-J of MeV x-rays out of 80-J laser)
- Demonstrated radiography of resolution targets showing excellent resolution -- resolution adequate for Active Interrogation

Putting the method to work:

Potential Applications we are investigating*:

- Neutron interrogation of cargo (SNM, explosive, drug detection)
- Standoff detection
- Treaty verification (warhead & nuclear material signatures) and stockpile stewardship and certification
- Spent fuel assay (at storage facility, in cask, for nuclear debris from reactor accidents, such as Fukushima)
- Neutron therapy
- Nuclear physics experiments (e.g. neutron resonance spectroscopy, cross section measurements)
- Others (see references for details)

*From: A Favalli et al., *LA-UR-13* (2013). A.Favalli et al.,LA-UR-14-21661 (2014)

The Laboratory Directed Research and Development (LDRD) program funded the research at Los Alamos National Laboratory (LANL).