INL/CON-21-62780-Revision-0

Applications of laser-driven monoenergetic MeV photon-sources and source development at BELLA Center

May 2021

Changing the World's Energy Future

Tobias Ostemayr, David L Chichester, Scott J Thompson

Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Tobias Ostermayr, BELLA Center

SORMA, May 2021

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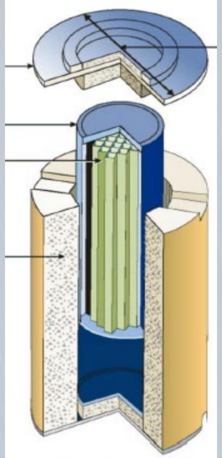
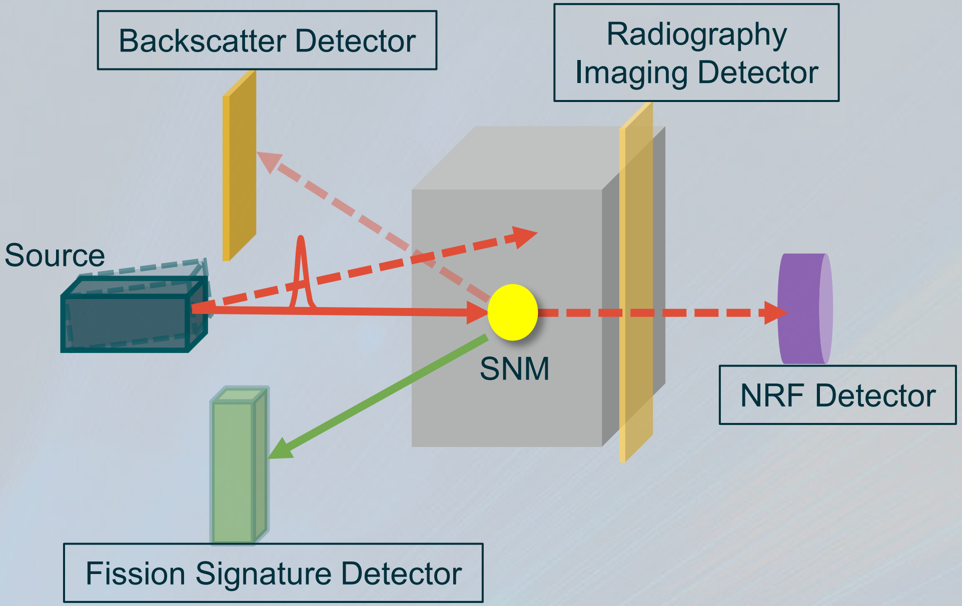
Outline

- Monoenergetic photon sources – Thomson/Compton scattering
- Nuclear nonproliferation and related applications
  - Radiography, Photofission, Nuclear Resonance Fluorescence

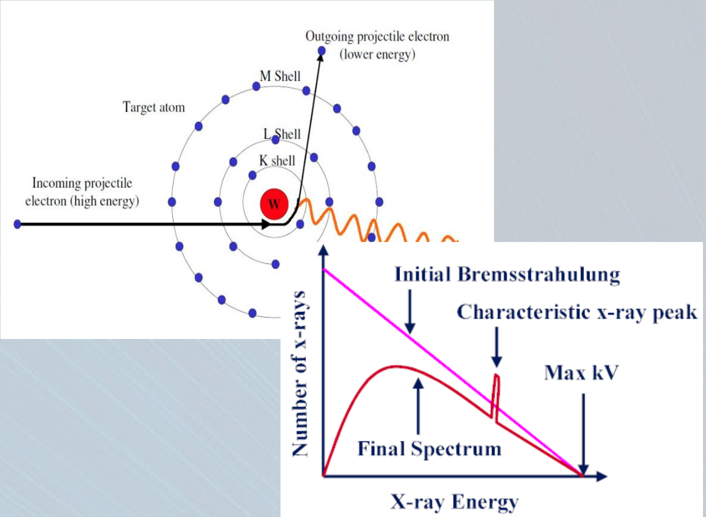
Photon sources detect & characterize in targets impenetrable to passive methods



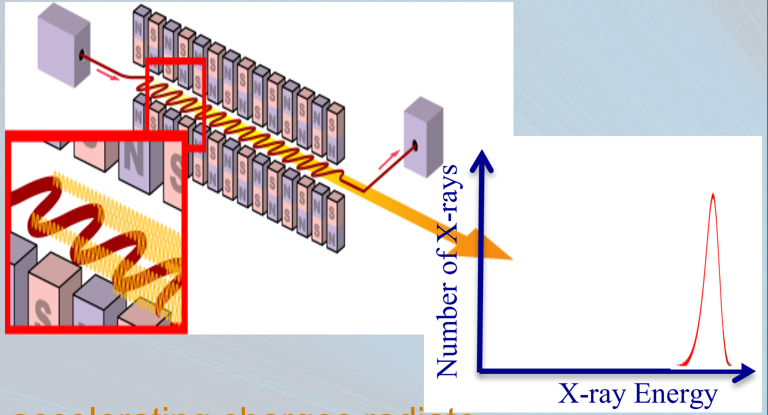


Thomson scattering as a MeV photon source prospect

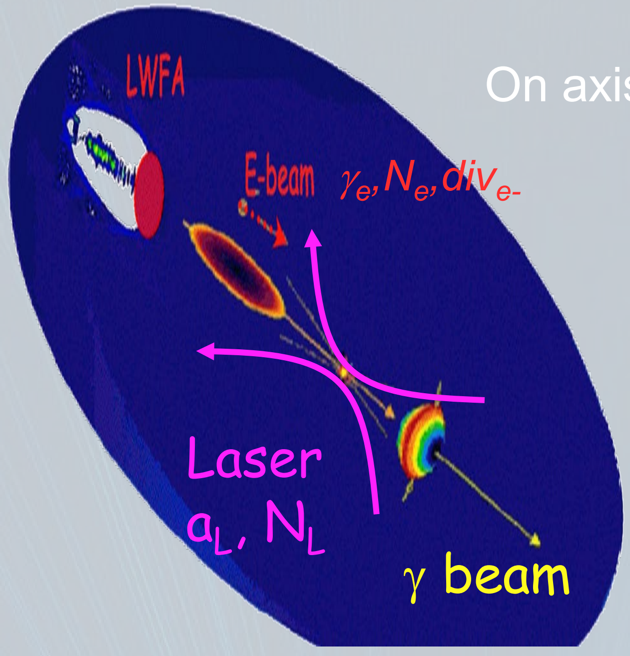
Bremsstrahlung: E_{photon} ~ $E_{electron}$, broad

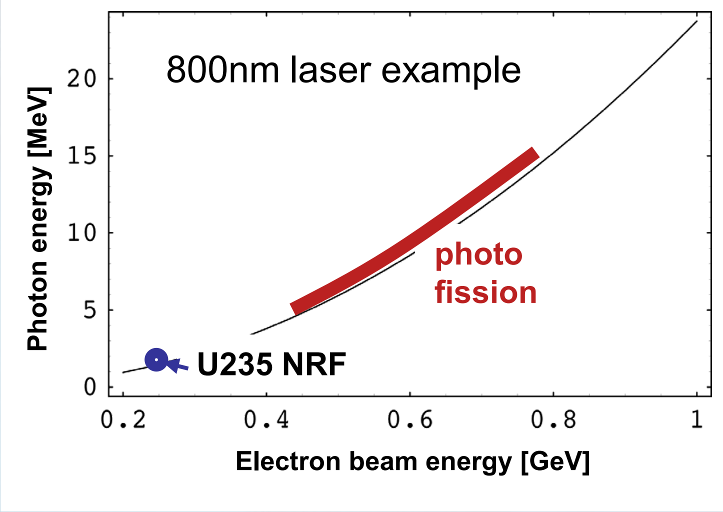


Undulators, Thomson (laser) scattering
E_{photon} << $E_{electron}$ but narrow

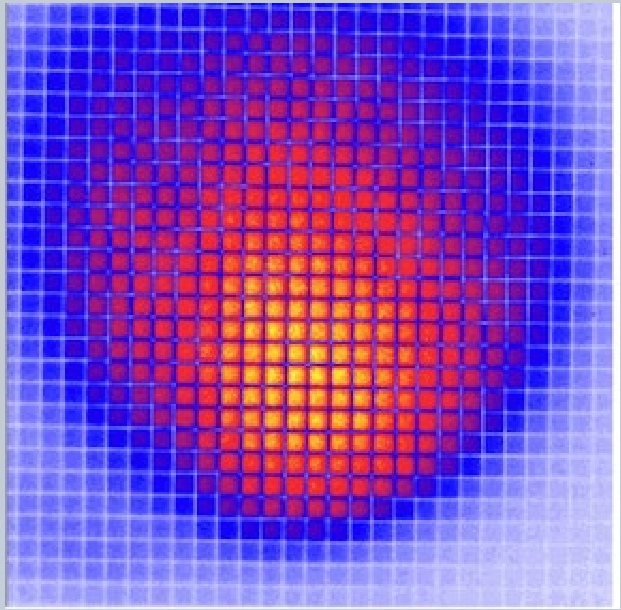


accelerating charges radiate
…control particle beam & accelerating force





Dedicated test facility at BELLA Center, LBNL

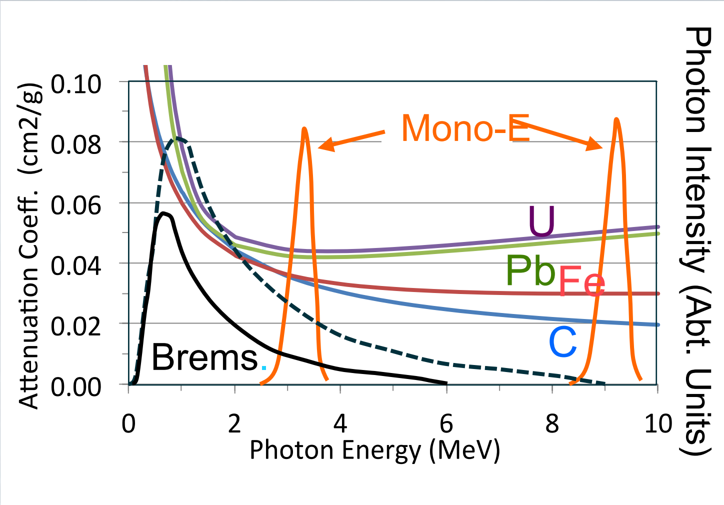


Presentation by Hai-En Tsai

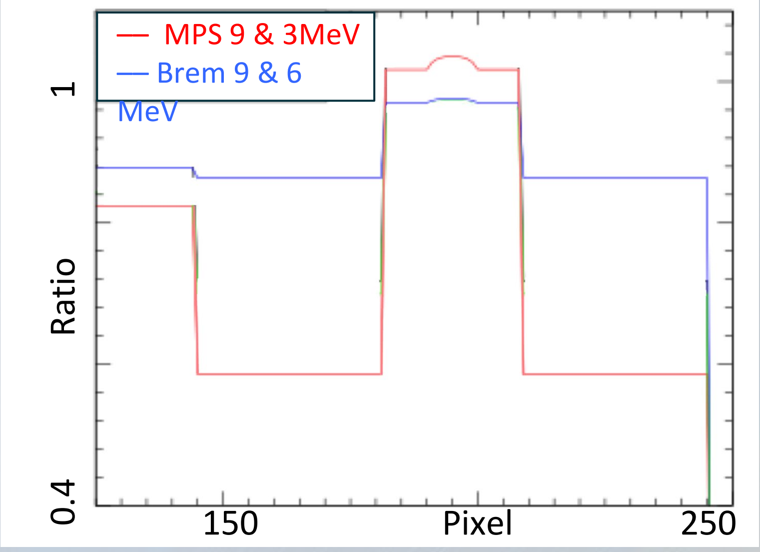
Cargo screening and Interdiction of shielded SNM: Monoenergetic photons improve radiography + Z

- Select energy to reduce dose/increase contrast, 1-9 MeV
  - Energy spread at 20% level resolves variation
  - Minimal gain at narrower spread
  - Reduces dose 2x-4x
- Multiple energies enhance Z contrast: tunable source required
- Attenuation sets photons per resolution element:
  - 40 cm steel ~ 10^{-5} attenuation -> order 10^{8} photons
- Small emission spot: high spatial resolution (µm-scale)
- Related benefits:
  - Reduce beam hardening
  - Improve backscatter radiography

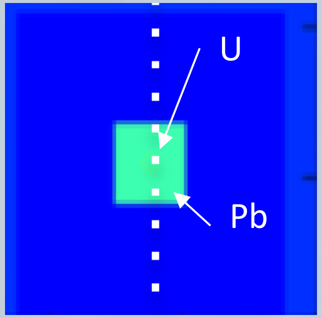
Energy & Z Dependence of Mass Attenuation



MPS dual energy ratio increases contrast



Bremsstrahlung sources- limited resolution
CAARS radiography/Z: U sphere in Pb box



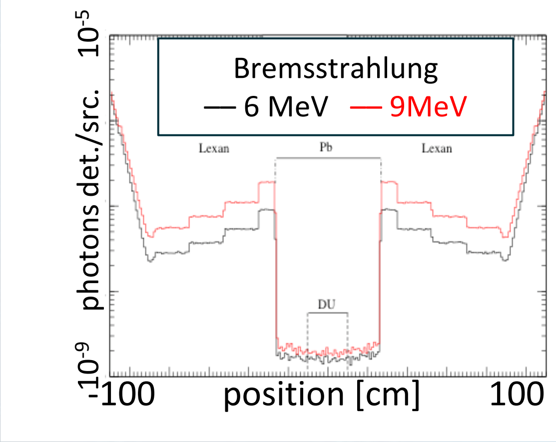
Marie-Anne Descalle, LLNL

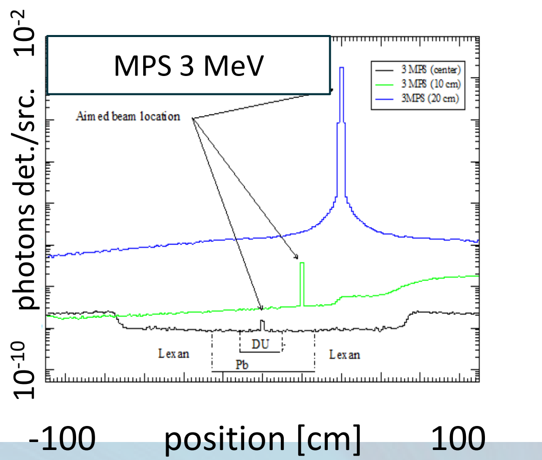
Mononergetic photon beams of narrow divergence angle enable high performance radiography + Z

- milliradian (mrad) divergence 'pencil beam' – cm size at target
  - Mitigate scattering contribution to image contrast degradation
  - Adapt dose to attenuation
- Tenfold improvement in dual-E ratio for 5 cm Pb behind 20cm steel

Beam & Energy ratio	Steel	Steel+Pb
Brems 9 MeV/6 MeV	1.57	1.61
MPS 9 MeV/3 MeV	2.87	2.04

Penetrate thick objects (e.g., CAARS obj. 4)

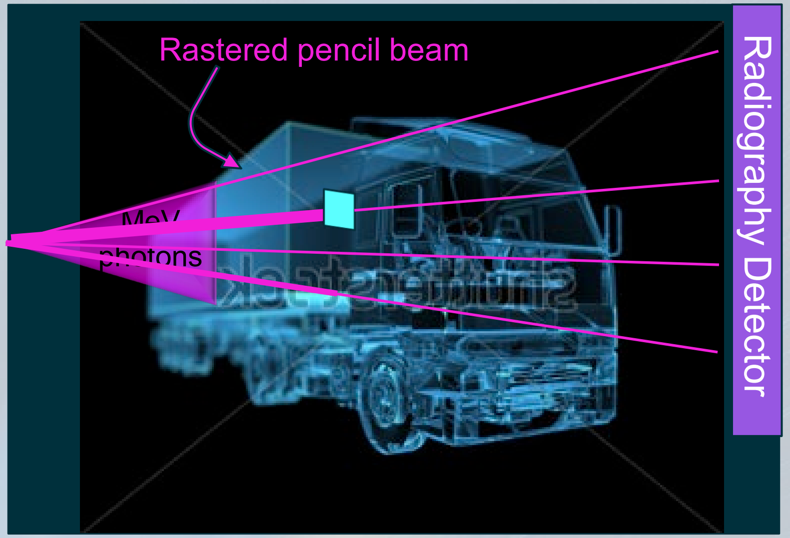




Simulation: Marie-Anne Descalle, LLNL

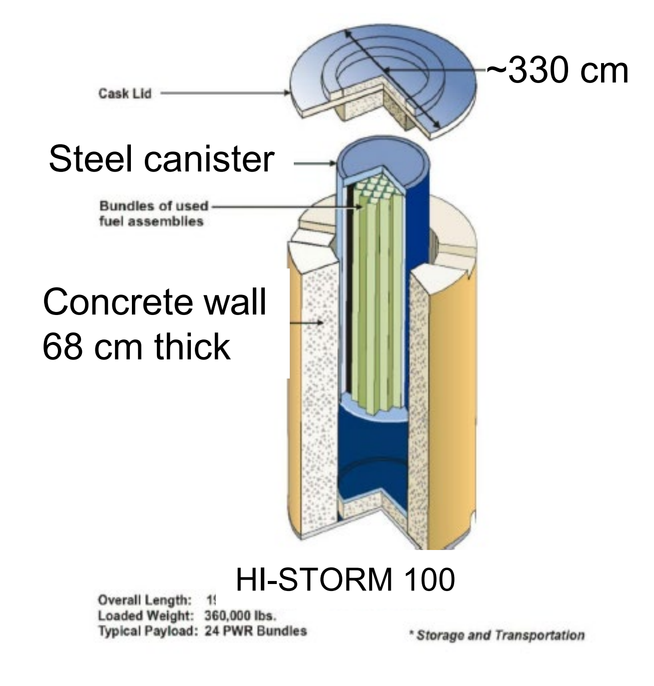
- Requires rastering of beam
- Example: Scan container at 80cm/s and 1cm resolution
  - mrad divergence ~ cm spot
  - 20kHz pulse rate
  - 20-40cm steel:10^6-10^8ph/pulse
- Dose reduced 1-2 orders of magnitude for assessed objects

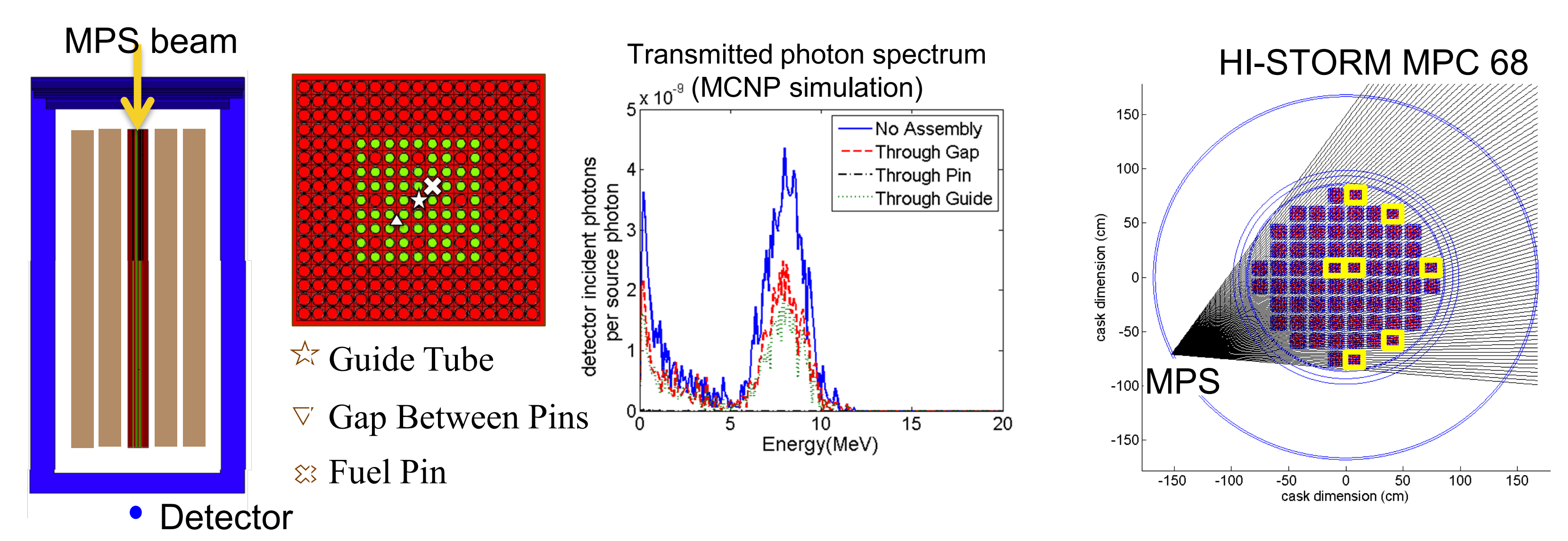
Rastered pencil beam concept



Dry-storage cask verification (safeguards) via transmission measurement with narrow MPS beam

- Re-verification of cask content (missing fuel bundles)
  - Scattering and attenuation severe
  - Narrow divergence 'pencil' beam reduces scatter
  - Fuel background mitigation by gating detector
- Transmission scan can verify assembly occupancy
  - At 3×10^8 ph/pulse, 1 kHz, 10^{-8} transmission → 3000 ph/s
  - Missing single pin detectable with narrow divergence beam



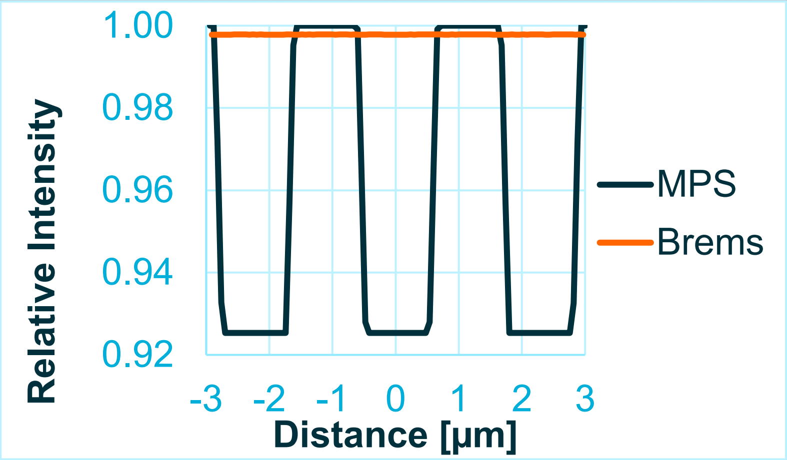


Cameron Miller, UM & Bernhard Ludewigt, LBNL

Tomography for Stockpile Stewardship: Potential for micron-scale resolution

- Setup:
  - Same geometry for MPS, Bremsstrahlung
  - Able to raster
- Potential benefits of MPS:
  - Reduced scatter
  - Reduced beam-hardening
  - Smaller emission spot size

MPS with 1 μm emission spot resolves 1 μm features. Brems. can not.



Glen Warren, PNNL

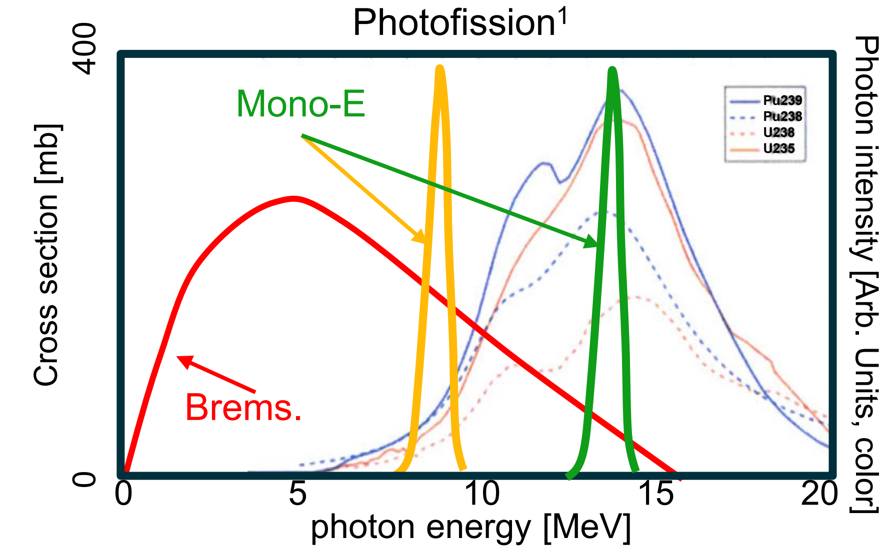
MPS with small emission spot may provide micron-scale resolution for stockpile stewardship or warhead fingerprinting.

Note: Beyond security applications, industrial and medical radiography/CT can benefit from 0.1μm emission spot & narrow divergence

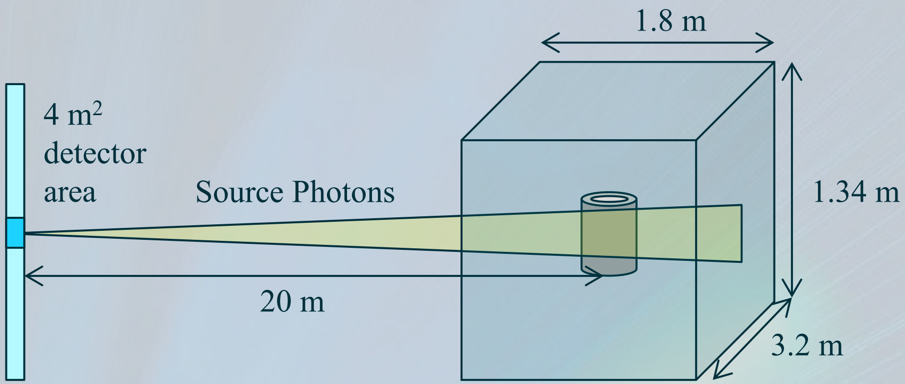
Excite photofission with reduced dose via controlled monoenergetic photons

Identify or exclude presence of quantities of interest in m-scale objects

- Broad resonance E_g~7-20 MeV
  - Bremsstrahlung – fractional overlap
- Object detected up to 30cm of SSTL or composite Pb/BPE in 300sec at 1kHz
- MPS could increase fissions/dose
  - E_g ~ 14 MeV maximizes signal
  - E_g < 10 MeV reduces photoneutrons
  - moderate energy spread ~ DE_g ~10%-20%
- Photoneutron signals for non-SNM[2]
- Pencil beam (low divergence):
  - Isolate dose to object of interest
  - Increase signal to background ratio



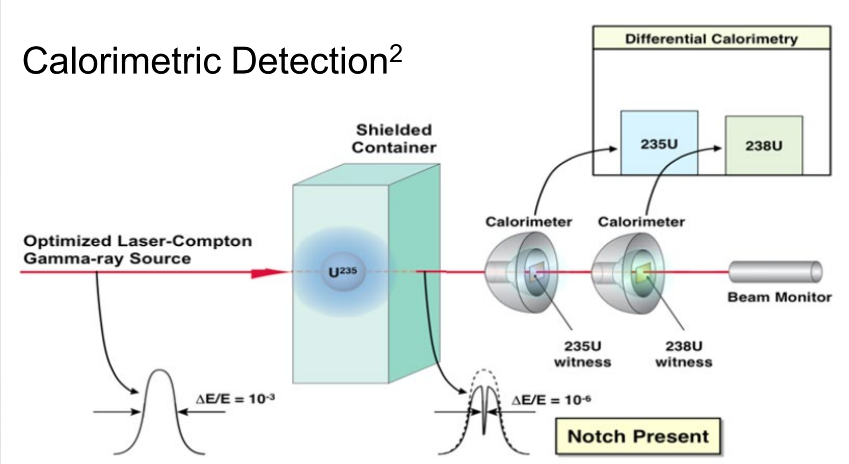
Glen Warren, PNNL

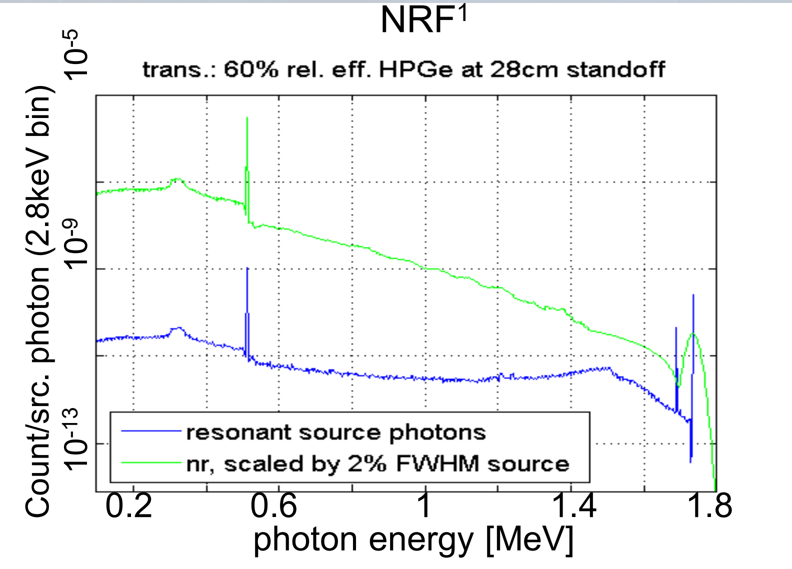


1: US20020169351 A1
simulations: M.T. Kinlaw (INL), T.P. Lou (LBNL). Related: Campbell (PNNL), M. Johnson et al., AIP Proc. 1336 no 1 (2011)
2: J. Clayton, Varian. Related: B.J. Quiter et al, J. Appl. Phys. **103**, 064910 (2008) ; R. B. Firestone,et al, Table of Isotopes Wiley, New York, 1996

Narrow energy spreads important to highly-specific Nuclear Resonance Fluorescence

- Isotope specific line energy
  - E_g ~ 2 MeV – isotope specific SNM identification and enrichment
  - E_g to 7 MeV – high specificity non-SNM
    (e.g., explosives, contraband…)
- $\Delta E_{NRF\text{-}line} \sim 10^{-6}$ << MPS candidates
- $\Delta E_\gamma \leq$ few %: isolate NRF line using energy resolved detector.
  - $\Delta E_\gamma \leq 1$ %: calorimetric detection
  - Dose ~ ΔE_γ
- Pencil beam (low divergence):
  - Isolate dose to object of interest if known
  - Increase signal to background ratio
  - Isotopic concentration image (high flux)
- Low-Z identification for cargo





Glen Warren, PNNL
Brian Quiter, LBNL

1: B. Quiter, LBNL. Related: Hayakawa et al. NIM A 621 (2010);Hajima et al. NIMA (2009) Pruet, et al. J. Appl. Phys. 99 (2006).
2: C.P.J. Barty et al, LLNL.; US8369480 B2; also proc. NPNSNP 2014

Thomson MPS properties enable new signatures that could improve detection

Polarized photofission and scattering enhance material discrimination

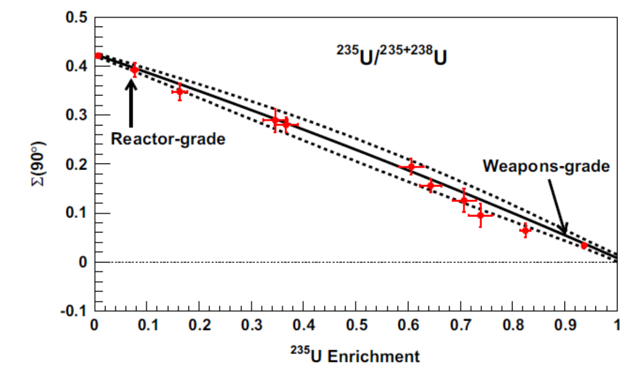


Fig. 2. The polarization asymmetry at a scattering angle of 90° is shown as a function of the enrichment of a sample composed entirely of ^{235,238}U. The red points indicate experimental measurements. The error bars on the points are statistical and systematic combined. The solid black line is an interpolation between the two data points with smallest and largest enrichments. The dashed black lines indicate the combined statistical and systematic uncertainties on the interpolation. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

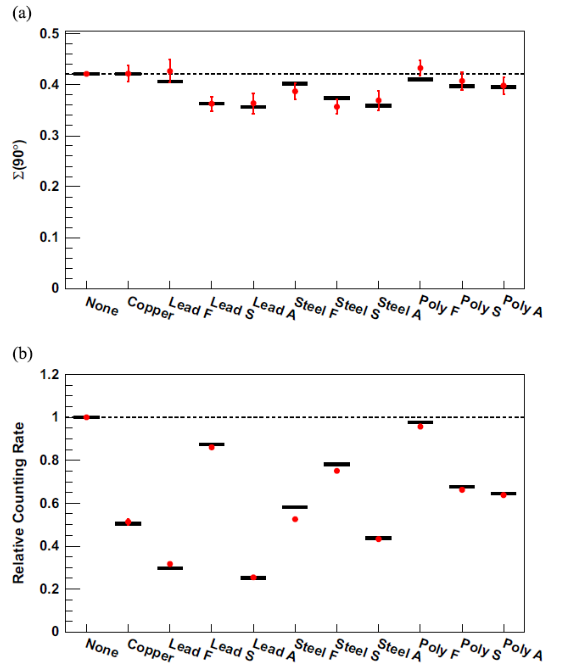
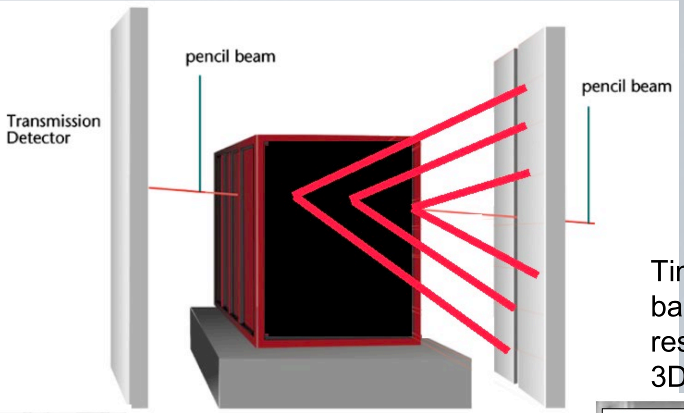


Fig. 4. The polarization asymmetry at a scattering angle of 90° (a) and the counting rate relative to the unshielded counting rate (b) are shown as a function of the location of copper, lead, steel, or polyethylene shielding. "F" indicates shielding between the target and the beam, "S" indicates shielding between the target and the detectors, and "A" indicates "F" and "S" shielding combined. All shielding materials were 2.54 cm thick, except for copper which was 2.45 cm thick and only placed in the front of the target. The red points are the experimental measurements, while the black lines are the simulated results. The error bars are statistical and systematic uncertainties combined. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

J. M. Mueller et al., Nuclear Instruments and Methods in Physics Research A 776 (2015)107–113

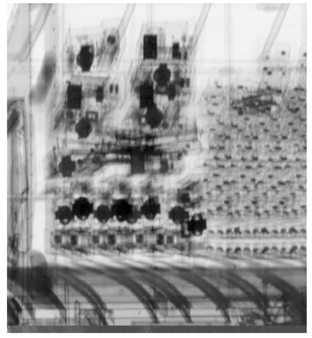
Backscatter resolution of 3D structure enabled by short pulse duration

Depth resolution requires pulsed, pencil beam
Past measurements limited by linac pulse structure & broad brems. fan
Thomson scattering: pulsed pencil beam would enable high resolution

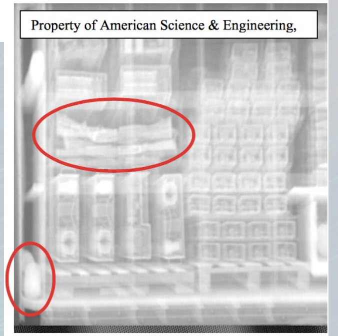


Transmission integrates over depth

Time-resolved backscatter signal resolves depth:
3D without tomography



Transmission



Backscatter

1:CW non-depth resolved: J. Callerame, AS&E, Advances in X-ray Analysis, Volume 49, 2006
Also M. Kinlaw et al, INL

Conclusions

- MPS with narrow energy and angular spreads, and high rep rate will provide strong benefits for assessed applications.
- Selectable energy (1–15 MeV) at moderate 10-50% energy spread
  - Lower radiography dose, higher materials contrast
  - High photofission yield without interfering activation
- Narrow energy spread ≤ 2% enables NRF in treaty verification, cargo inspection
  - ΔE_{ph}<0.1% would enable nuclear materials assay
- Narrow 'pencil' beam (~mrad divergence) a strong benefit:
  - Scatter rejection in radiography, higher contrast & lower doses
  - Transmission measurements on massive objects, e.g., dry-storage casks
  - Adapt dose for radiography
  - Target flux for strong photofission signature
- Flux range 10^9-10^{12} photons/sec, rep rate range from kHz to 10s of kHz
- Small emission spot, fs pulses and polarization enable new signatures (e.g., backscatter) with strong impact

- Talk by Hai-En Tsai: LWFA driven MPS at BELLA Center (LBNL)

Thank You!