Near-monoenergetic Photon Sources for Nonproliferation Applications

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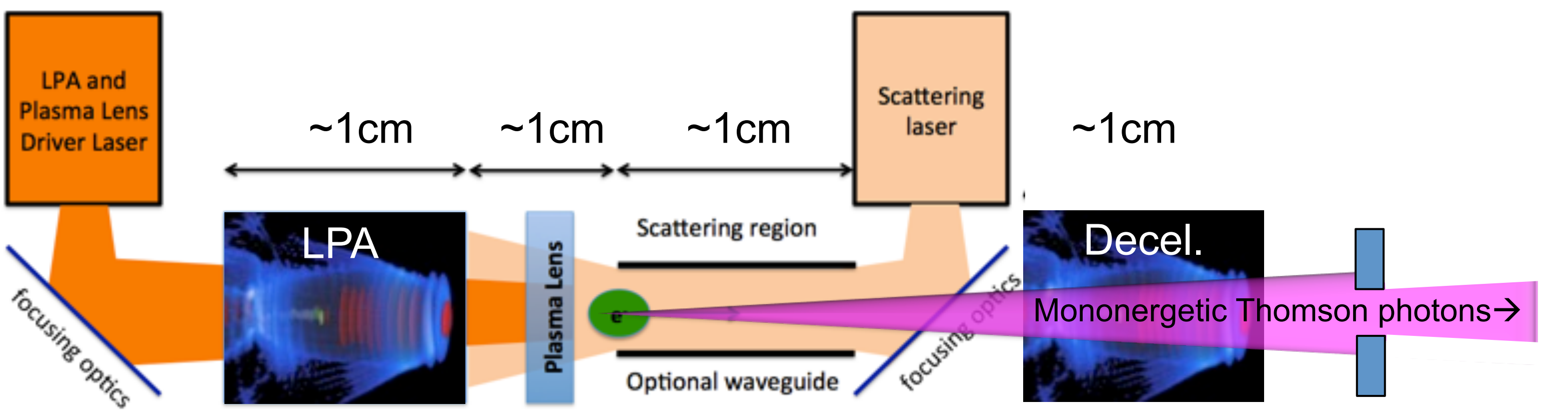
Crete, Greece

Outline

- Motivation for monoenergetic photon sources
- Nonproliferation application benefits and requirements
- Compact, near-monoenergetic photon source
- Path to address application requirements



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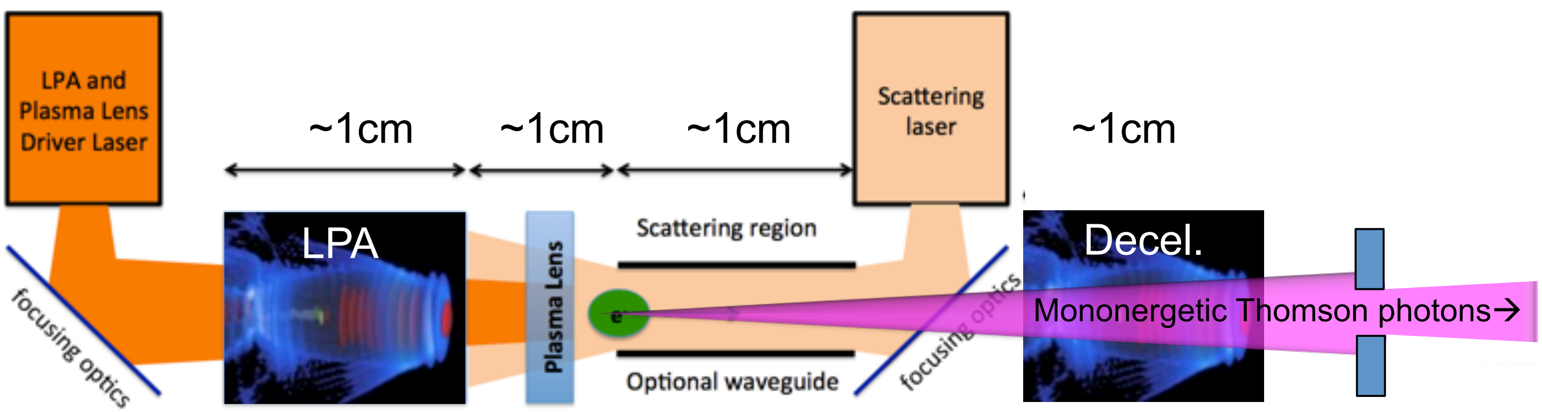
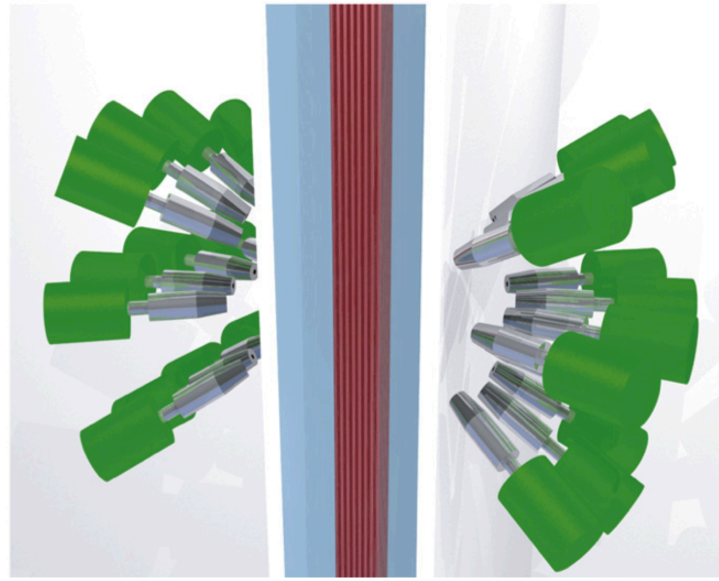
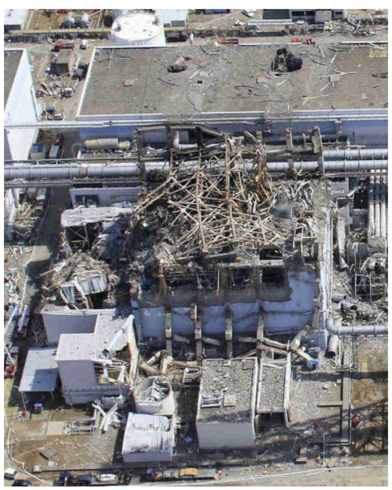
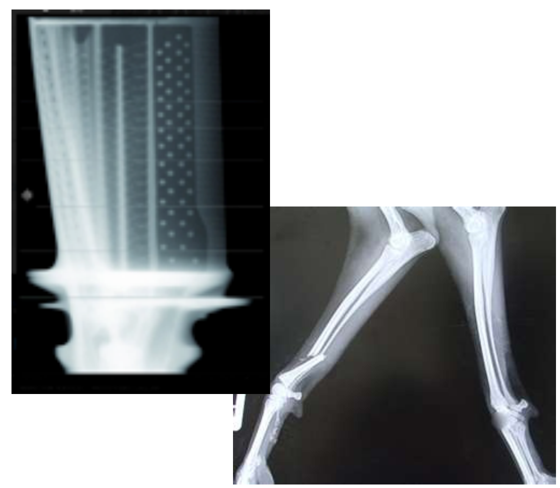


Photon sources detect & characterize in targets impenetrable to passive methods







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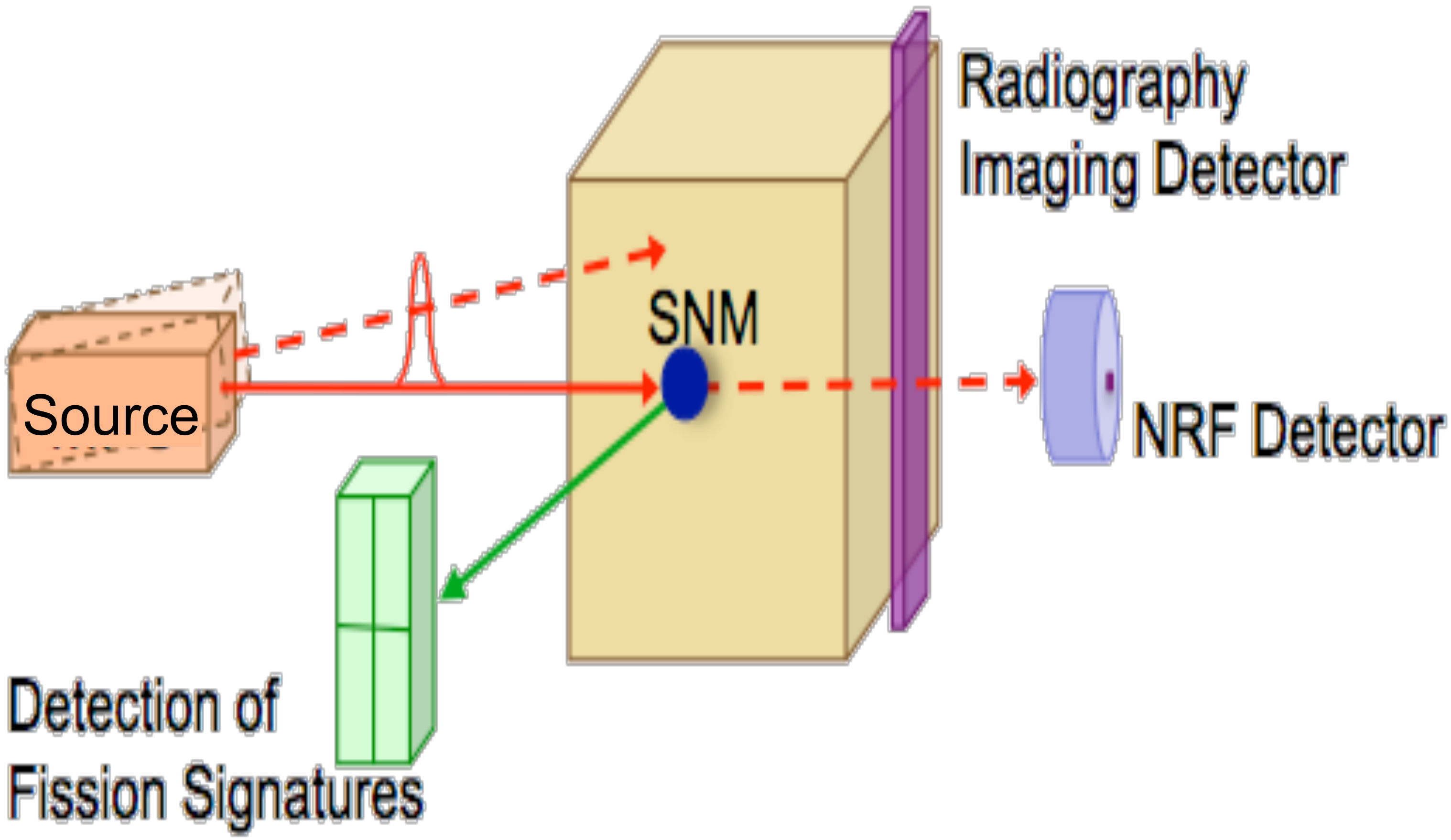
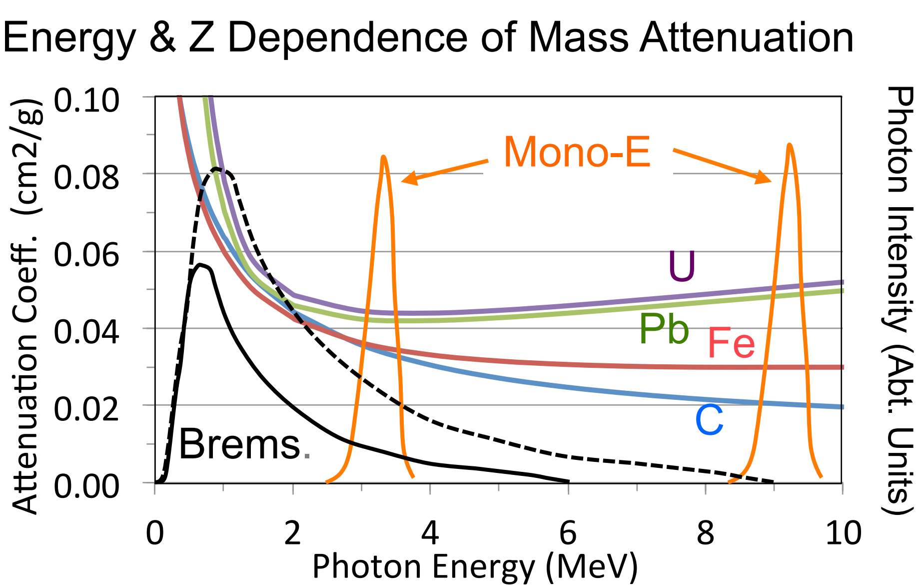
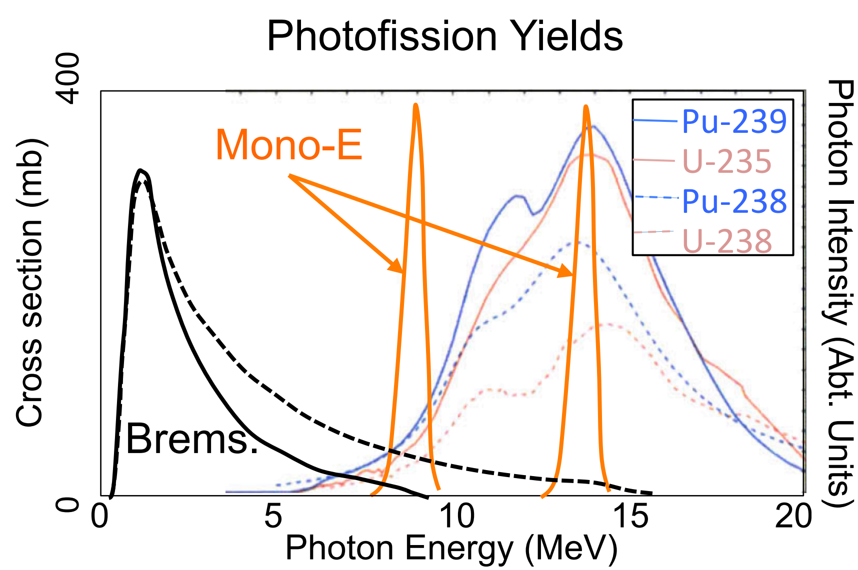


Requires MeV-class photons

Monoenergetic photon sources could enhance radiography, fission signatures, NRF

- **Radiography:**
  - Energy selection for maximizing transmission and Z-contrast, minimizing dose
- **Photofission:**
  - Energy selection to maximize fission signatures

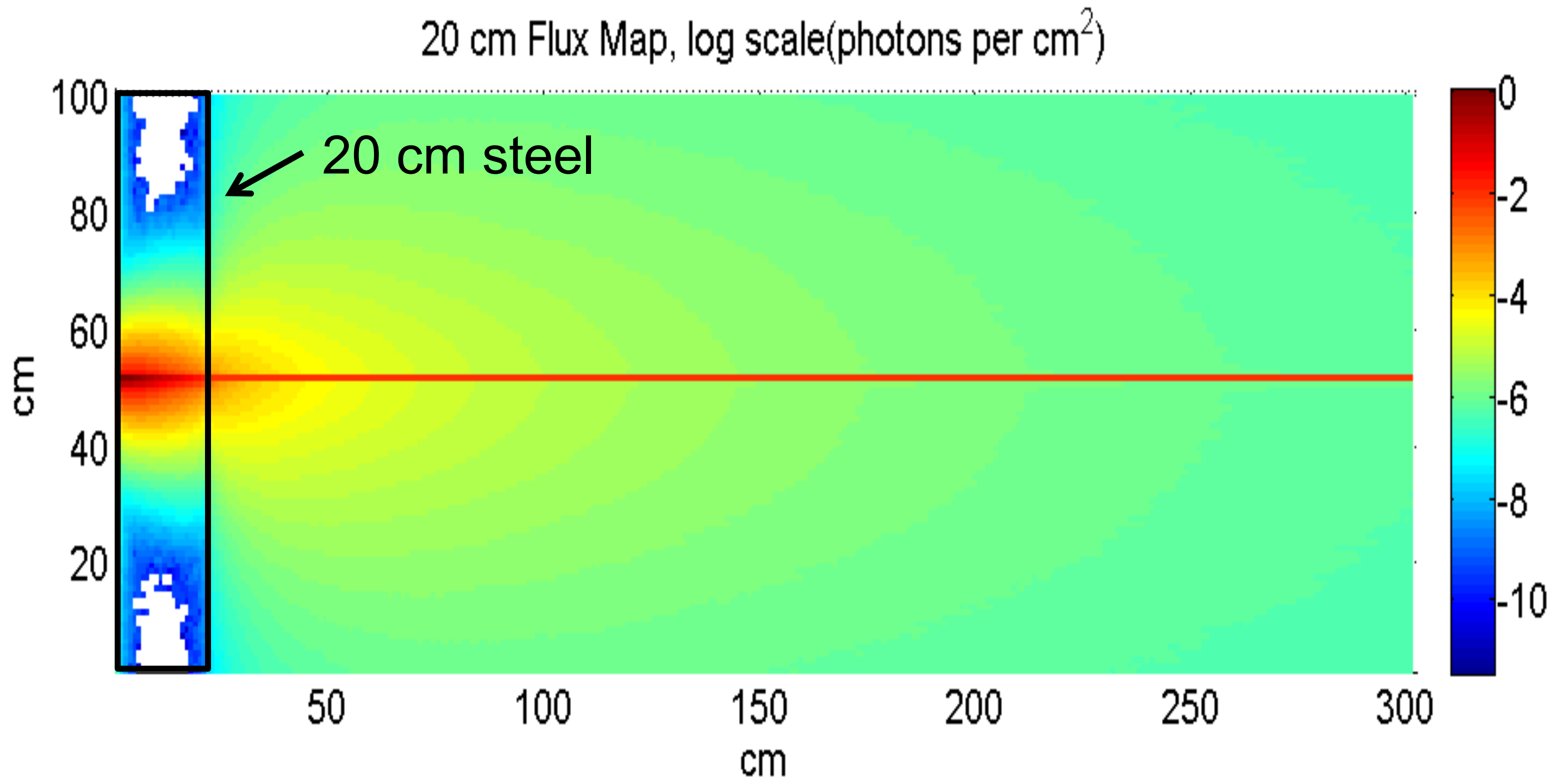




- **NRF:** low energy spread / high spectral density, greatly improved signal to noise

Narrow-angle emission mitigates scattering degradation of measurement

9 MeV monochromatic, 1cm beam propagating through steel



- Severe scattering – scattered flux diverges rapidly from collimated beam
  - for 1cm beam, high contrast at 1m distance ~ 2000:1
- Broad divergence input (i.e. fan or cone) degrades contrast
  - For Brems sources, tight collimation discards almost all available flux

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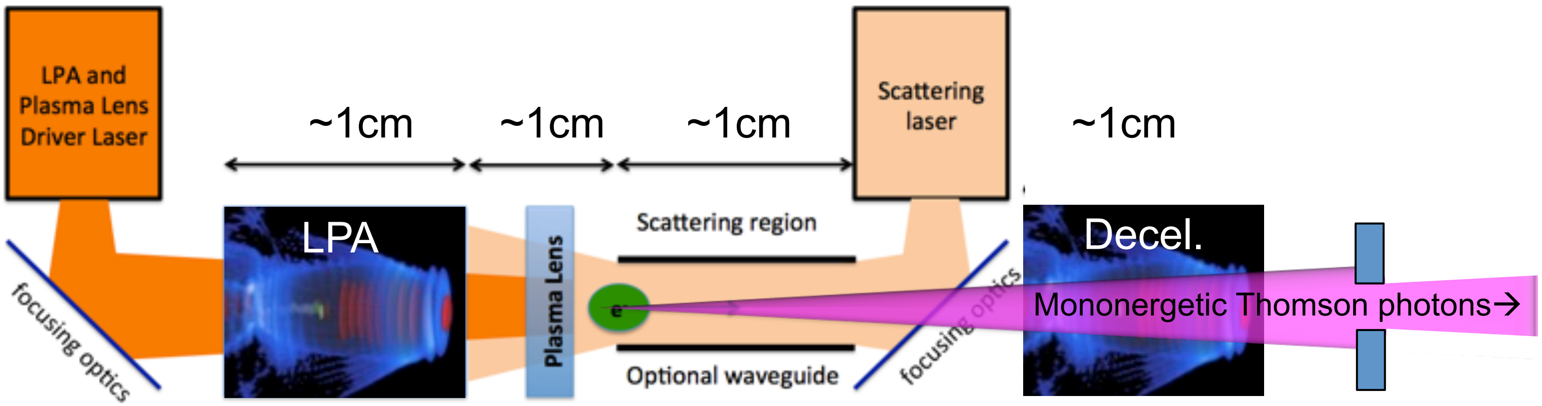

Broad survey of nonproliferation applications identified potential impact & priority

Application	Potential Impact	Stake-holder Priority *	Study Priority
Screening and interdiction - Cargo containers, trucks	SNM & contraband detection at lower dose, higher contrast, Z resolution.	High	High
Detection of hidden SNM - Single-sided inspection	SNM Detection at lower doses, larger distances, or behind thicker shielding	High	High
Treaty/Dismantlement Verification	Warhead/dismantlement confirmation, unique identifier of warhead & components	High	High
Safeguards - dry-storage cask verification	Determination of assembly basket occupancy	High	Medium
Emergency response	Similar to screening; <mm spatial resolution Requires highly portable source – longer term.	Medium - high	Medium
Photonuclear data	Measurements at nuclear laboratories	Medium	Medium
SNF and materials assay	Reestablish inventory after loss of CoK; measure Pu isotopic content	Low	Low
Pu accountancy & monitoring in pyroprocessing	Measure Pu in SNF before dissolution; monitor Pu in refiner vessel	Low	Low
Fresh fuel verification in transport containers	MPS-based system capable but simpler solutions likely becoming available	Medium	Low
UF_6 enrichment verification	No capability enhancement	High	None
Nuclear forensics	No capability improvement	Low	None

*Engaged user agencies (DNDO, DTRA, International Safeguards, Arms Control and Treaty Verification.

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- Simulations assess
  - Energy spread
  - Divergence, scattering
  - Penetration
  - Signatures and backgrounds
- Derive
  - Source performance need
  - Applications improved or enabled

Final report of project "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," C. Geddes, B. Ludewigt, J. Valentine, B. Quiter, M.-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, S. Pozzi (2017)

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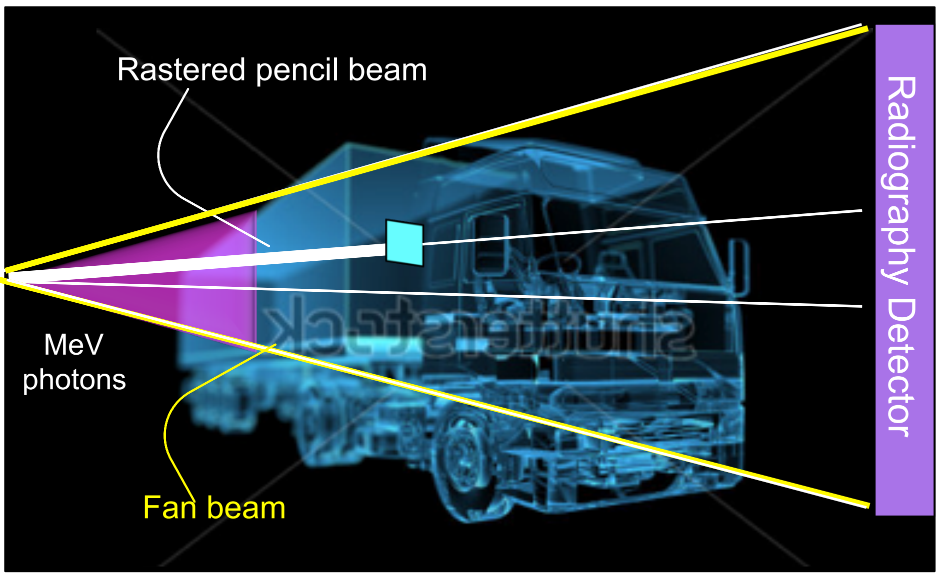
Screening and interdiction:
Radiography with MPS pencil beam

- Key radiography challenges:
  - Dose (on target - stowaways, bystander - exclusion zone)
  - Contrast (scattering)
  - Z-discrimination



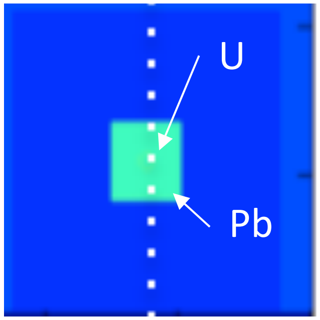
- Example: scan container at 80 cm/s with 1 cm resolution.
  - 1 cm pencil beam: 1-5 mrad div
  - 20 kHz pulse rate
  - 20-40 cm steel: 10^6-10^8 ph/pulse

- Adapt dose to attenuation (shot by shot variation)

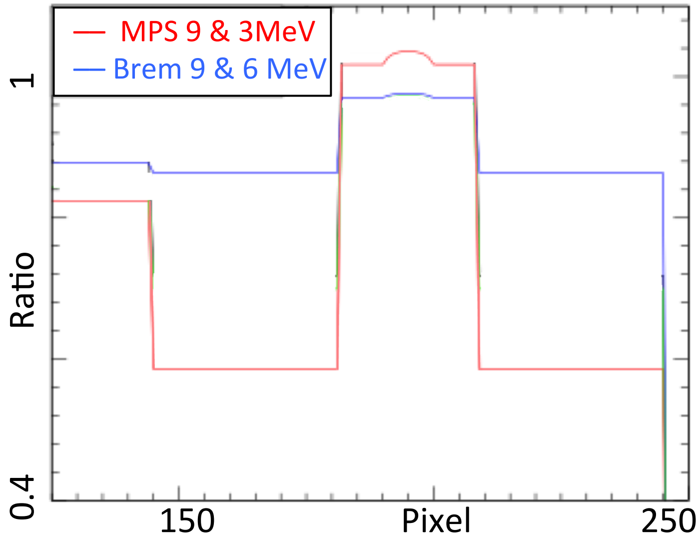
Cargo screening and Interdiction of shielded SNM: Monoenergetic photons improve radiography + Z

- 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
- Small emission spot: high spatial resolution (µm-scale)
- Related benefits:
  - Reduce beam hardening
  - Improve backscatter radiography

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



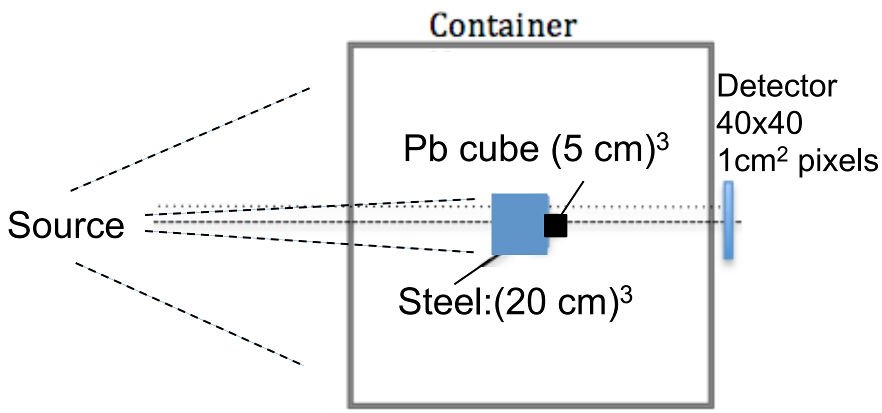
MPS dual energy ratio increases contrast



Marie-Anne Descalle, LLNL

Screening and interdiction: Beam divergence key to scatter & contrast

- MCNP simulations:



Collimation	Pencil Beam		Narrow Fan Beam	1.6 deg. Cone Beam*
Source	MPS	Brems.	Brems.	Brems.
Contrast	0.92	0.89	0.75	0.063

- For small scattering object (20 cm x 20 cm steel), pencil beam provides
  - Large increase in contrast vs wider cone/fan beam (1.6 degree ½ angle)
  - Modest increase in contrast vs narrow fan beam (0.2 degree ½ angle)

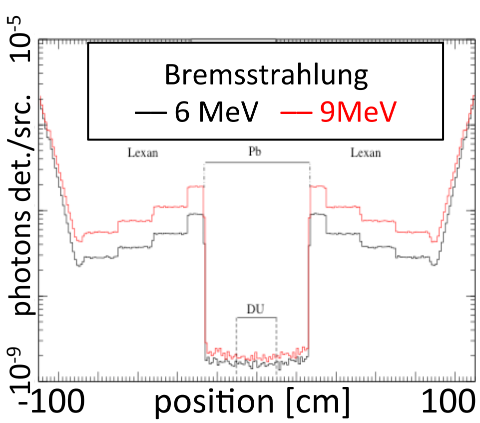
- Container filled with low-density material (realistic), with same object:
  - Narrow fan beam contrast degrades to 0.3
  - **Pencil beam contrast not significantly affected : strong benefit for mrad-divergence 'pencil' beam.**

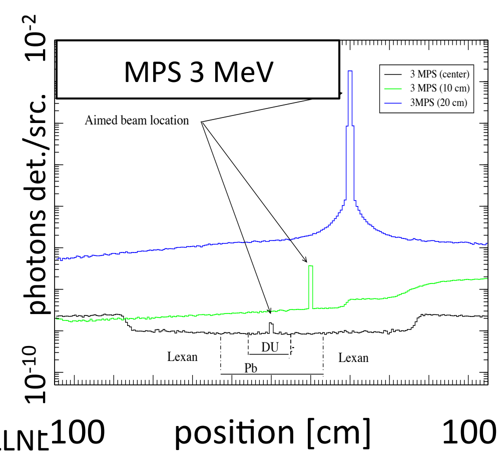
Mononergetic photon beams of narrow divergence angle enable high performance radiography + Z

- 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 5cm 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)

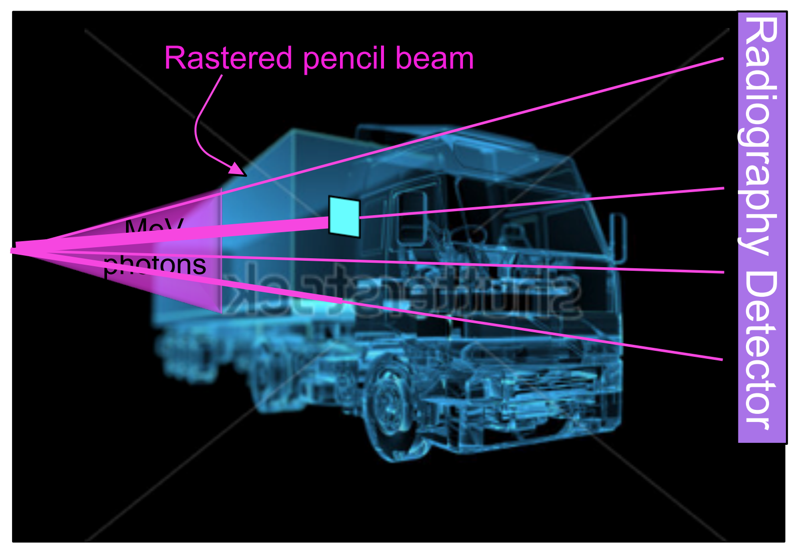




Simulation: Marie-Anne Descalle, LLNL

- **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

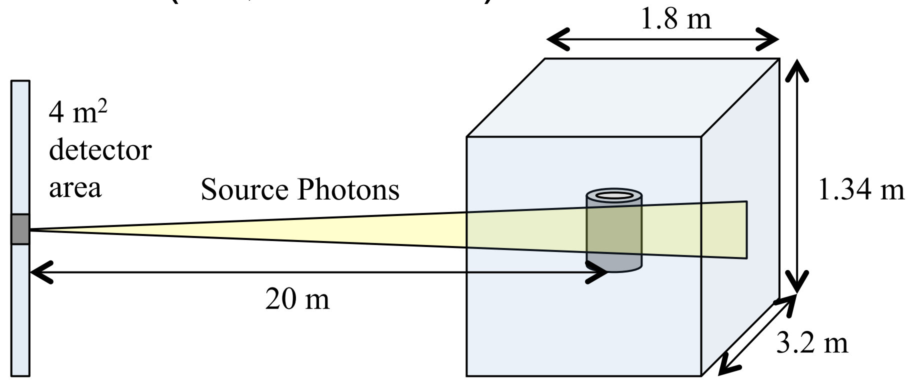


Screening and interdiction alarm resolution: Reduced photofission dose, NRF enabled

- Pencil beam of ≤3 mrad important to isolate dose to area of interest
- Photofission: ≤9MeV for cargo, prompt neutron signature strongest
  - MPS dose per fission ~50x lower than bremsstrahlung dose near 10 MeV
  - Detection of 2 kg HEU shielded by 20 cm thick steel box in seconds
    - MPS of a few 10^{11}ph/second in few mrad divergence at ΔE_{ph} ~20%
    - MPS puts all photons at effective energy, facilitates prompt n signature
- NRF: isotope specific, SNM and non-SNM
  - Enabled at ΔE_{ph} at or below 2% range
  - Examples for HEU detection (6-σ) with backscatter in <100 seconds:
    - 0.65 kg HEU sphere centered in container with attenuation equiv. to 12 cm Fe
    - 100 cm cube (~2 kg) HEU in Fe box with 10 cm thick walls
    - MPS: 3×10^{7} photons/pulse, 20 kHz or ~ 1.7×10^{7}ph/eV/s at 1.733 MeV
- Improved signal vs. active and passive backgrounds

Single-sided inspection: Detect SNM via MPS-induced fission signatures

- General search for hidden SNM, with conditions:
  - Pre-determined search location: NOT a wide-area, random search
- Physical access limited (i.e., one-sided): no transmission measurements

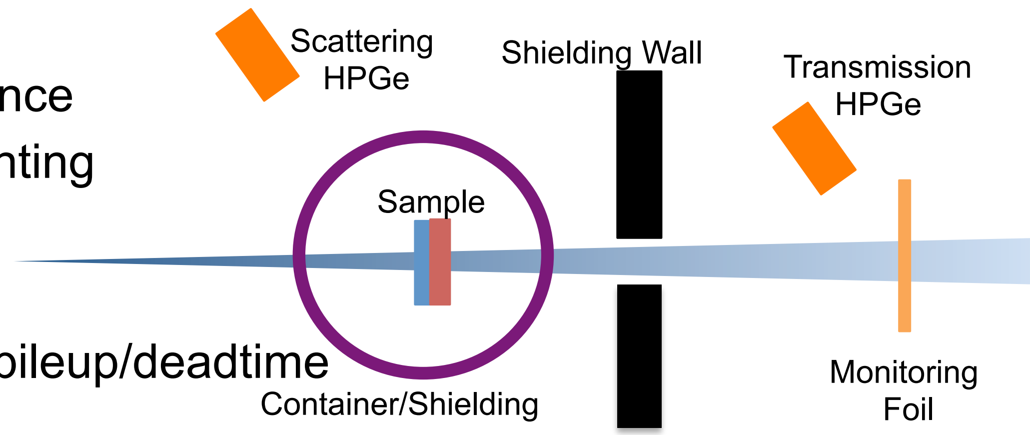


- Photofission is principal signature: narrow divergence beam key to target object
  - Delayed gamma-rays (count between macro pulses, cut prompt region, $E_\gamma \geq 3$ MeV)
  - Delayed neutrons (count between macro pulses, cut prompt region, all energies)
  - Prompt neutrons (count between micro pulses, $E_n \geq 3.5$ MeV) – strongest signature

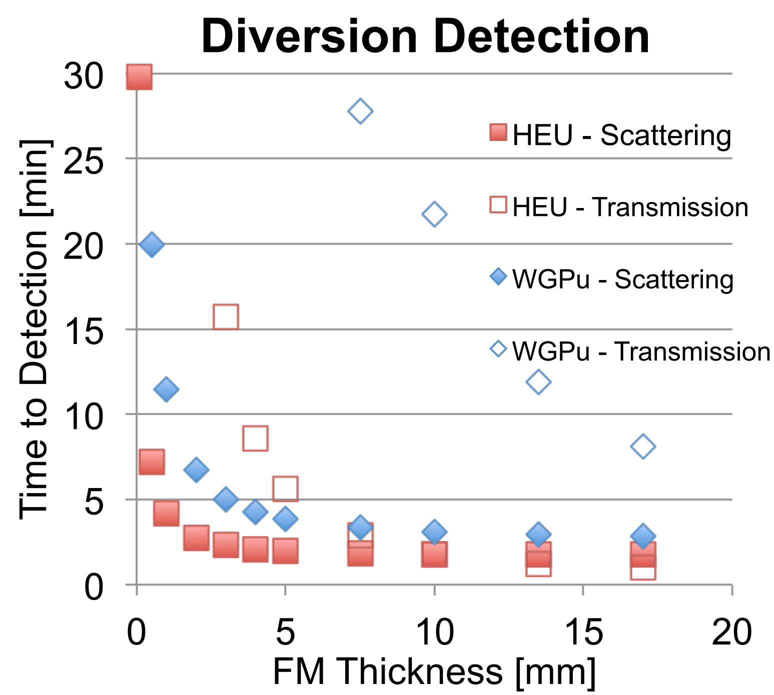
- Object detected up to 30cm of SSTL or composite Pb/BPE in 300sec at 1kHz
- Localizing interrogation volume/determining shielding volume key for verification of absence of SNM – e.g. backscatter imaging

Treaty/Dismantlement verification: MPS–based NRF for material verification feasible

- **Possible approaches:**
  - Nuclear Resonance Fluorescence
  - Imaging: Potential for fingerprinting
- **Assumptions:**
  - Use of single 80% HPGe
  - Limit on MPS intensity to limit pileup/deadtime



- **Source Requirements:**
  - Rep Rate: 10 kHz, Intensity: 10^5-10^7 ph/shot, Energy spread: 2% FWHM
- **Warhead Confirmation:**
  - MPS: detect HEU, WGPu and "HE" in INL IO in < 3 minutes
  - Brems: requires a few hours
- **Dismantlement Confirmation:**
  - Confirm HE, FM<0.5mm: 20 min
  - Confirm FM, HE<1 cm: 65 min
- **Diversion Detection:**
  - Detect ½ mm FM: 20 minutes
  - Detect 1 cm HE: 1 hour



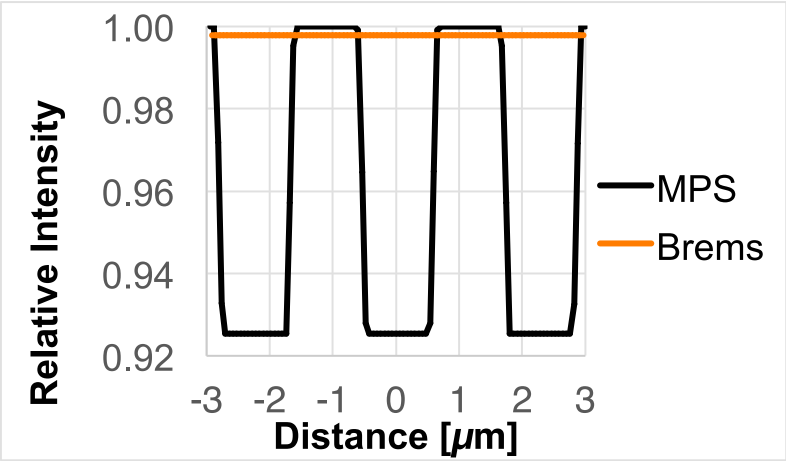
Glen Warren, PNNL

Tomography for Stockpile Stewardship: Potential for micron-scale resolution

- **Setup:**
  - Same geometry for MPS, Brems
  - Able to raster

- **Potential benefits of MPS:**
  - Reduced scatter
  - Reduced beam-hardening
  - Smaller emission spot size

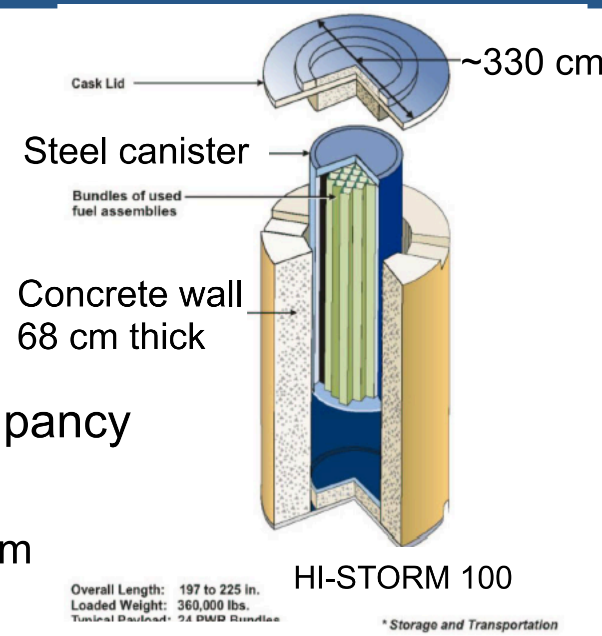
MPS with 1 μm emission spot resolves 1 μm features. Brems. can not.



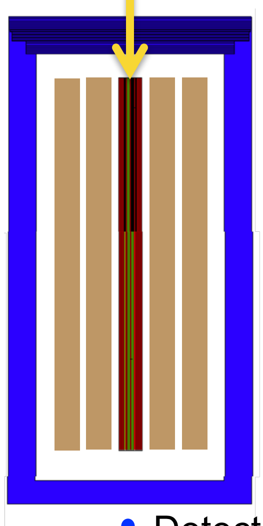
MPS with small emission spot may provide micron-scale resolution for stockpile stewardship or warhead fingerprinting.

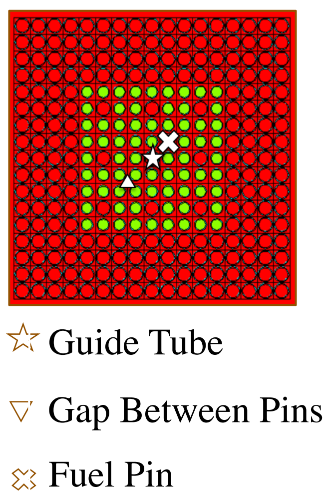
Dry-storage cask verification (safeguards) via transmission measurement with narrow MPS beam

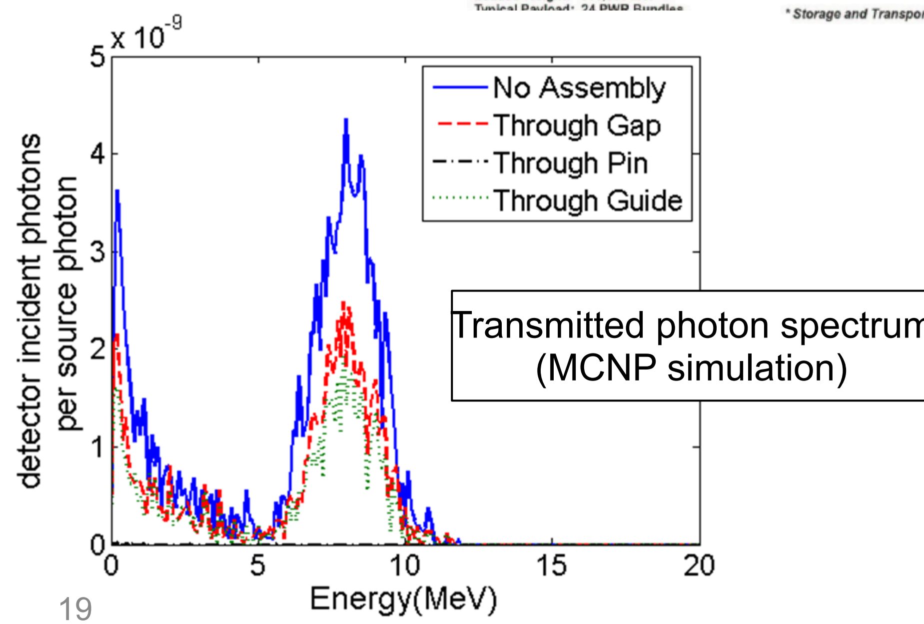
- Re-verification of cask content (missing fuel bundles)
  - Scattering and attenuation severe
  - Narrow divergence ‘pencil’ beam reduces scatter
  - Fuel background mitigation by gating detector



- Longitudinal 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



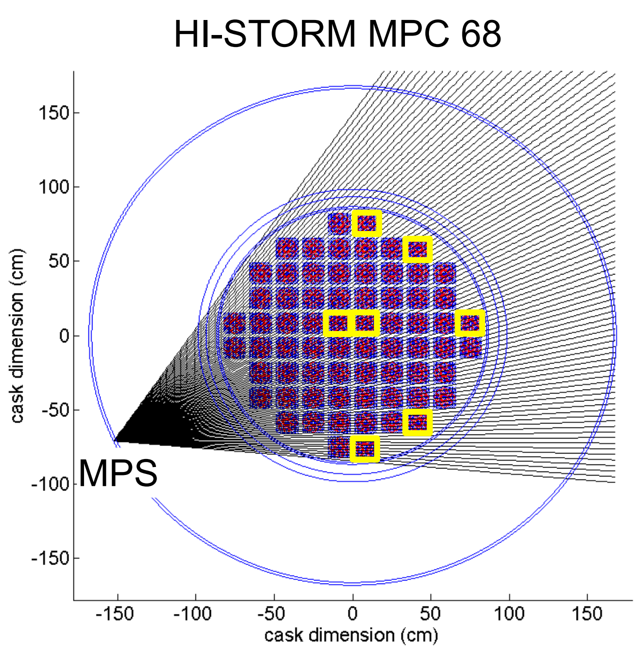


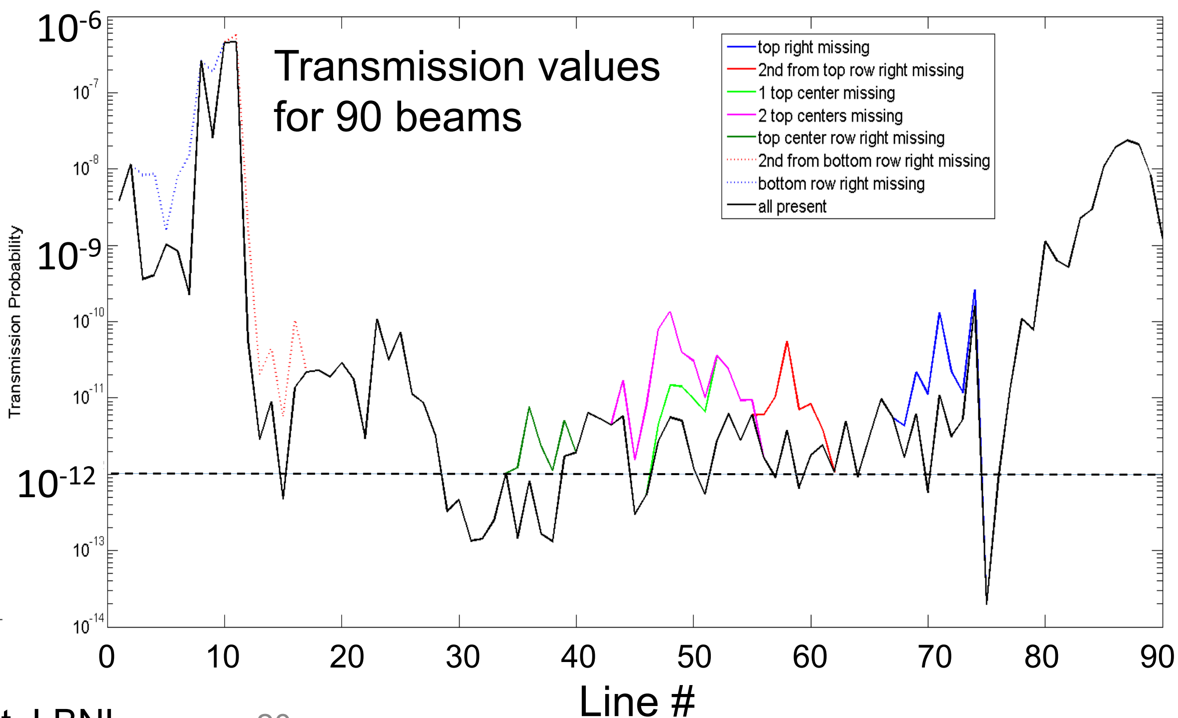


Cameron Miller, UM & Bernhard Ludewigt, LBNL

Safeguards dry cask verification: MPS enables transverse transmission scan

- **Transmission calculated analytically**
  - Check against MCNP simulations shows good agreement
  - Several scan angles and cask types evaluated
- **Missing assemblies can be detected:**
  - ~10x higher transmission
  - Transmission > 10^{-12} if one assembly missing
  - At 10^{-12} transmission, 3×10^{8} ph/pulse, 10 kHz → 3 ph/s, acceptable measurement times.





Cameron Miller, UM & Bernhard Ludewigt, LBNL

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
- Additional signatures (e.g. backscatter) could increase impact.
- Brief assessment of other applications: related benefit to emergency response (size constrained), and other safeguards and nuclear data applications.

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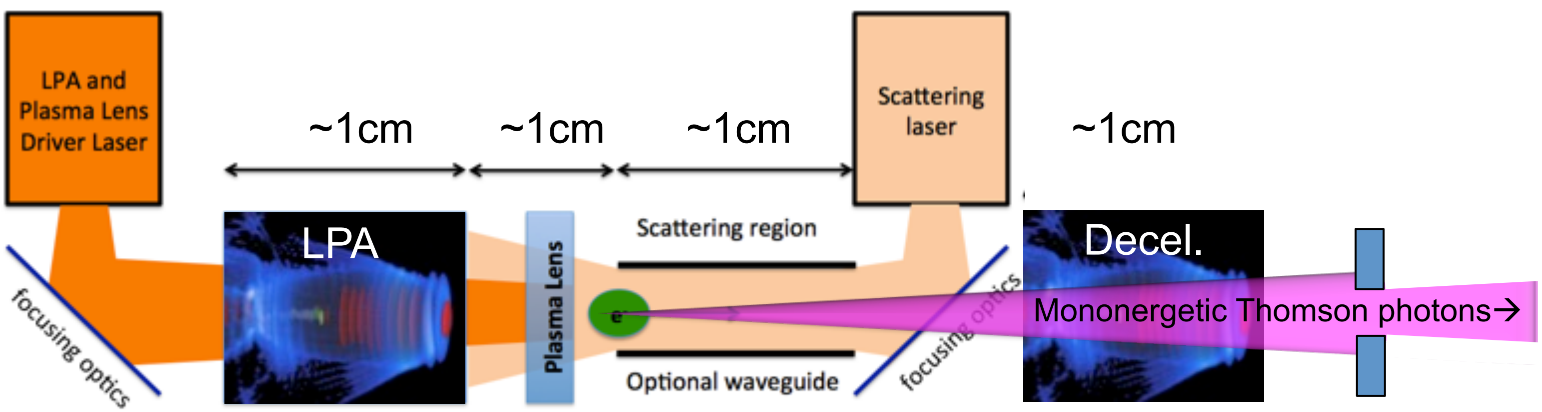
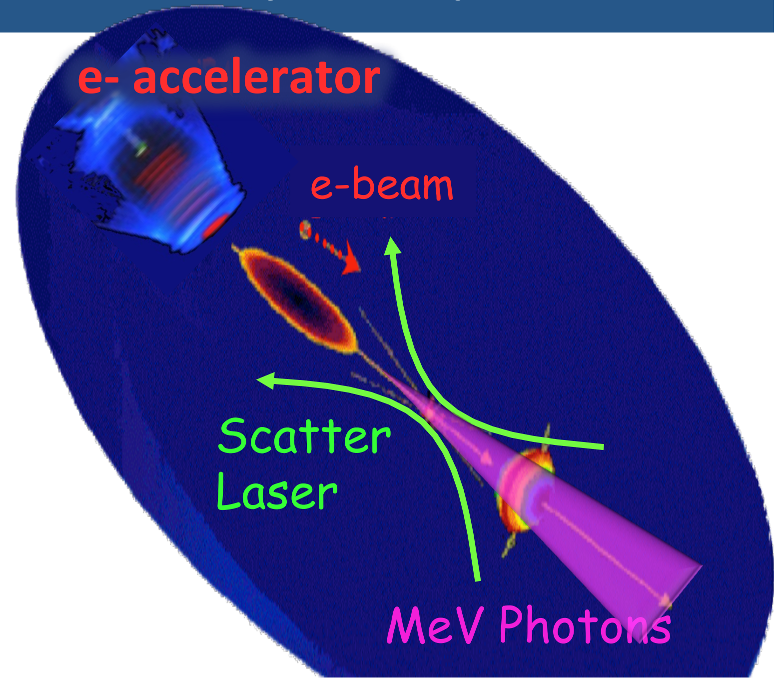


Thomson/Compton scattering source: Desirable photon properties, not conventionally transportable

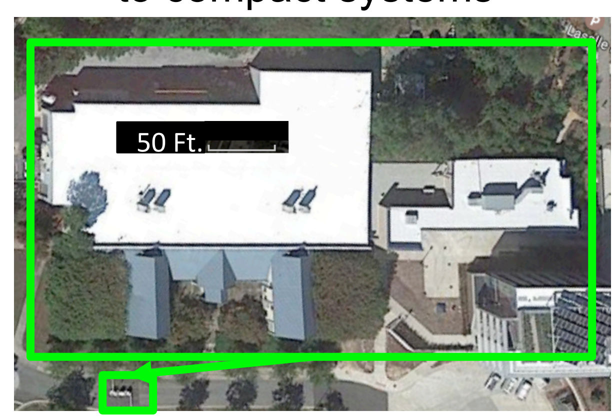
- MeV photons produced by scattering a laser from a relativistic electron beam[1]

- Desirable source properties:
  - Low energy spread: enhanced signal, low dose
  - Tunable energy: Z, Photofission, and NRF
  - mrad divergence: mitigate scattering, adapt dose
  - Adjustable per-shot: flux, energy, <u>polarization</u>
  - Short-duration pulses: study of fast processes

- Proven on fixed facilities, used for nuclear signature development



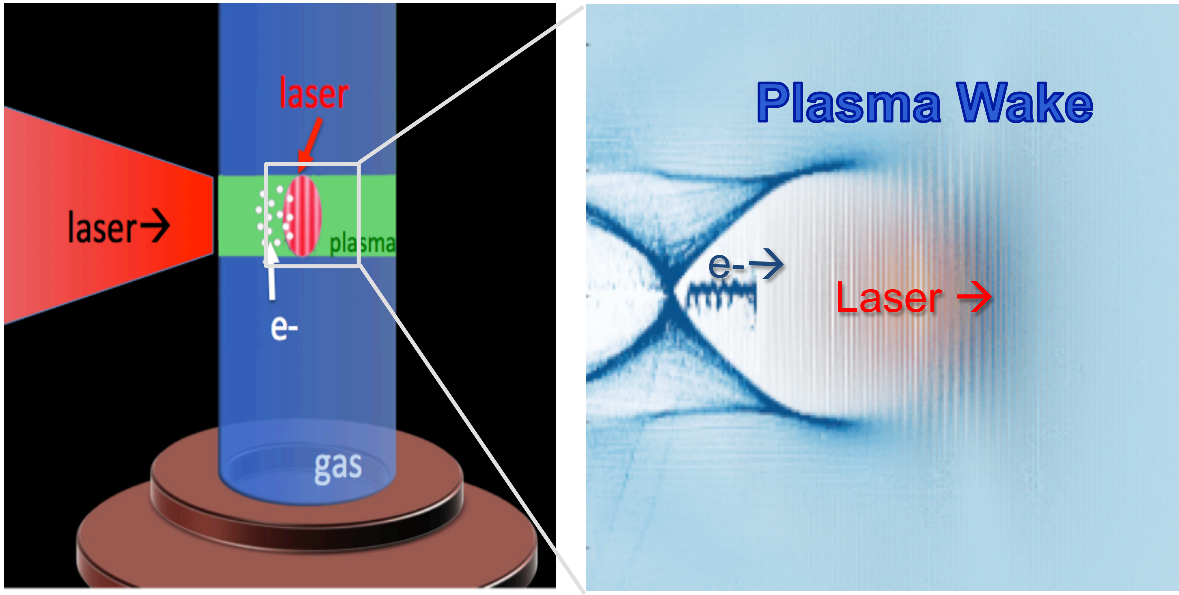
Move from large facilities
to compact systems



Key problem for applications use is electron accelerator requirement: ~0.5 GeV + high current + shielding

1: P. Sprangle et al, J.Appl. Phys 1992, W.P. Leemans et al., PRL 1996
Albert et al PoP2012, Kawase et al, NIMA 2011, W.P. Leemans TPS 2005;

Laser-plasma acceleration (LPA): GeV electrons at cm-scale + laser guiding



- Plasma wave driven by radiation pressure of TW, fs laser: GeV/cm
  - Laser guided through plasma over cm by shaped plasma density profile ('channel')

- LBNL developments[1] include laser guiding/monoenergetic beams in 2004[2] through recent record 4.2 GeV[3] and combination of stages[4]
- Apply to photon source acceleration and systems
  - Joule-class laser for 0.5 GeV electrons, 9 MeV Photons
  - Single bunch: no recirculation of scattering laser

1: W.P. Leemans, Phys. Plasmas 1998, 2: C. Geddes et al., Nature 2004. 3: W.P. Leemans et al., PRL 2014, 4: S. Steinke et al., Nature 2016

Compact source must address e-beam acceleration, scattering and disposal

<u>Requirement & conventional issue</u>

High-energy, high quality e-beam at 0.2-0.6 GeV required

- Conventionally, long accelerator

High flux photon production limited by scattering laser diffraction and nonlinearity

- Conventionally, requires large laser spot and low intensity
- High current or large scattering laser required – large facility

Shielding requirement increases with energy and current

- Conventionally, many tons

<u>Past focus: individual techniques</u>

High quality cm-scale LPA demonstrated in experiments

- Meets photon source requirements: energy, energy spread, divergence

Techniques to increase photon yield simulated: reduce current and scattering laser requirements

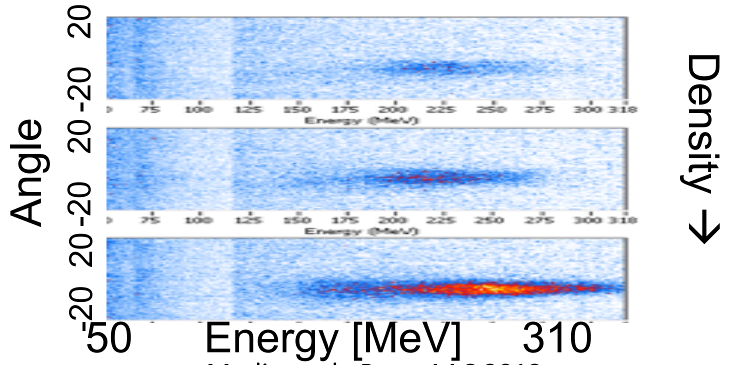
- Diffraction: Scatter laser guided in plasma channel (like LPA)
- Nonlinearity: shaped pulse allows higher intensity

Deceleration of electrons by LPA: proof-of-concept experiment

- Reduce shielding by reducing e- energy

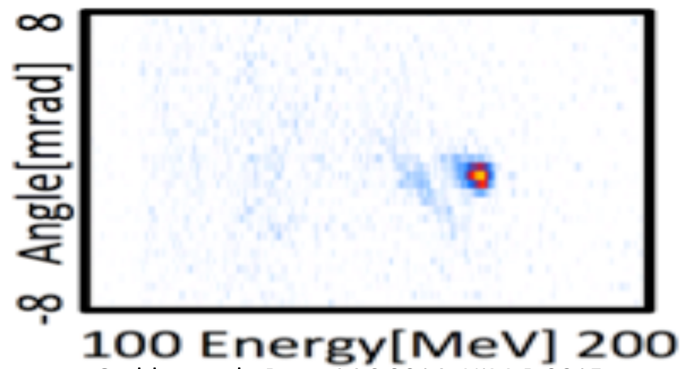
Recent GeV-class LPA development, leveraging our HEP program, demonstrates high quality beams needed for photon sources

Electrons to 250 MeV using 0.5J/10TW + laser phase front control



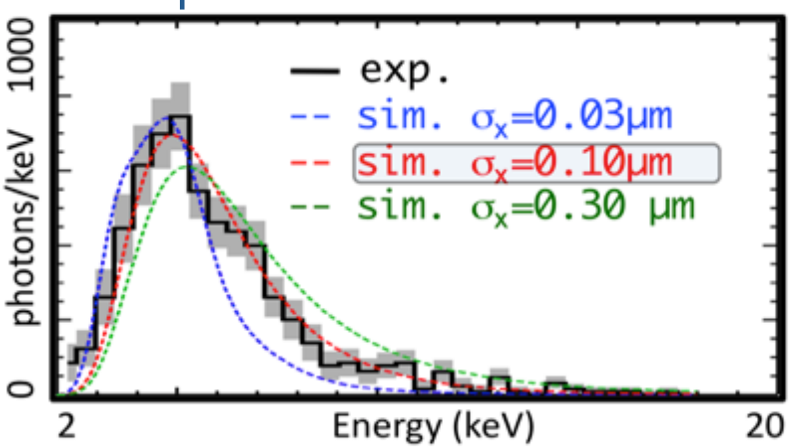
Matlis et al., Proc. AAC 2012

ΔE_e < 1.4 % FWHM from Colliding pulse injection control



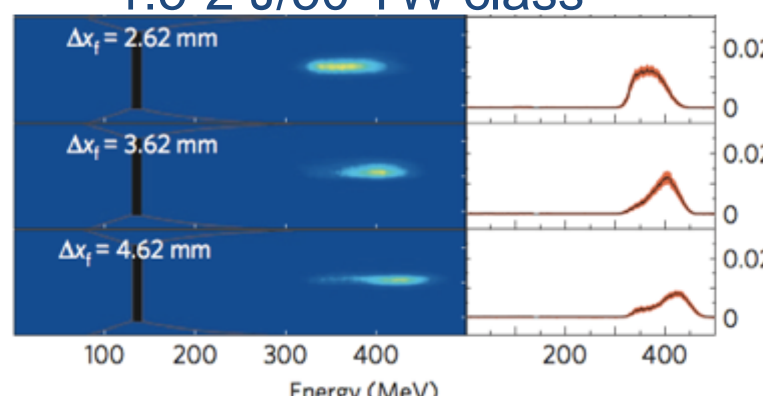
Geddes et al., Proc. AAC 2014; NIM-B 2015

ε~0.1μm via Betatron emission



Plateau et al., PRL 2012

Tunable 0.5 GeV - modulated density 1.5-2 J/50 TW class



Gonsalves et al., Nat. Physics 2011

Key: separate control of laser propagation & electron injection

Simulations show narrow energy spread photon sources are enabled by high performance LPAs

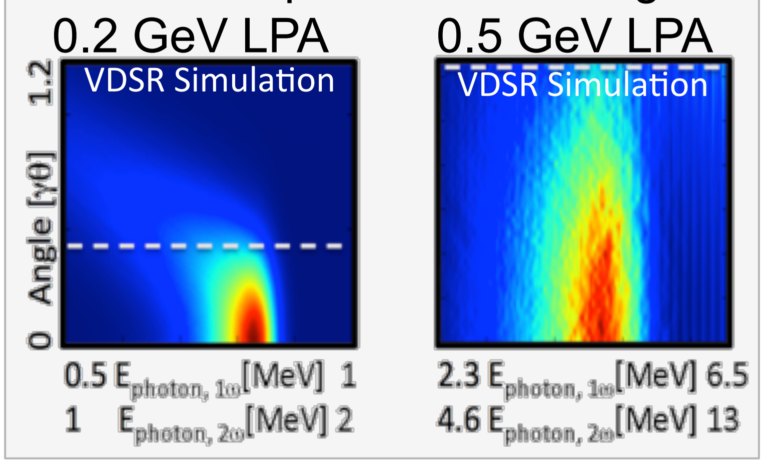
- ΔE_{ph} limited by electron quality: div_e, ΔE_e

- Demonstrated LPAs allow ΔE_{ph} ~ 10%
  - E_{ph} of 1-10 MeV
  - Electron emittance dominates ΔE_{ph}

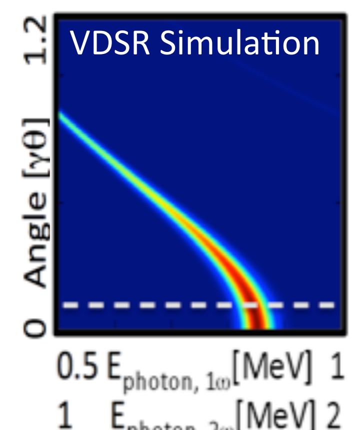
- Demonstrated 1% ΔE_e allows ΔE_{ph} ~2 %
  - Experiments indicate potential for < 1%
  - e-beam refocusing or emittance reduction required to reduce divergence

Other LPA-Thomson source experiments also in progress: Chen et al., PR ST-AB 2013 UNL), Phuoc Nat. Phot. 2012 (LOA) Khrennikov, PRL2015 (LMU), others

10-20% ΔE_{ph} simulated from direct in-plasma scattering



Percent-level ΔE_{ph} with divergence control



Rykovanov et al., J. Phys. B 2014, Leemans et al. PRL 1996.
Related A.G.R. Thomas et al PRST-AB 2010 (U. Michigan); Ghebregziabher PRSTAB 2013 (UNL)
P. Chen, et al., a, NIMA 355 (1995) 107. (CAIN code)

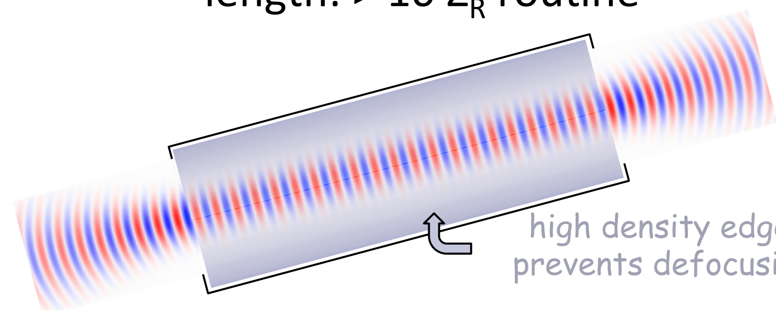
Simulations show high photon yield with realistic scattering laser & e- current by controlling scattering laser

- Issue: large laser spot, high energy typically required for ps scatter laser
  - Wastes energy, requires larger laser
- Reduce scatter laser energy: guiding[1,2]
  - Mitigates diffraction, lengthens scattering
- 10^8 ph/shot possible w/ scatter energy ~LPA driver, in range for applications

Requirement: separately controlled scattering laser pulse, $E_{scatter}$~Joule

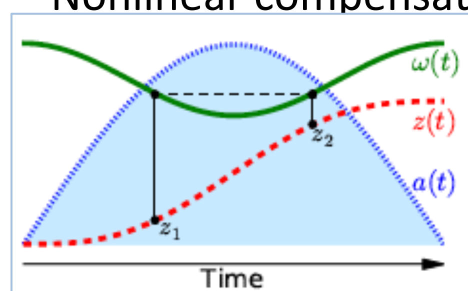
- Further improvement: Laser shaping3
  - Mitigates nonlinearity, allows higher intensity/more efficient scattering

Guiding increases focused propagation length: > 10 Z_R routine[2]

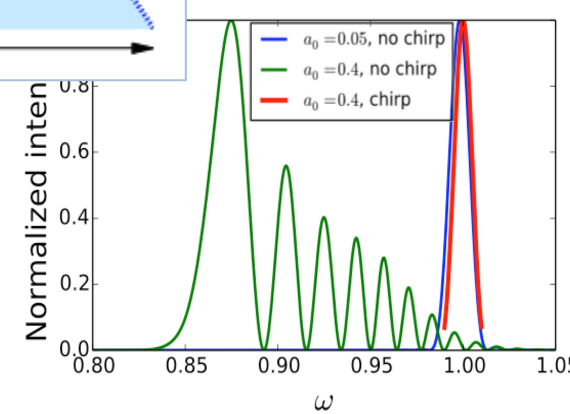


40J Unguided
1J Guided w=6um } 5ph/e- at a_0=0.15

Nonlinear compensation allows higher a_0



Flat top or chirped pulse

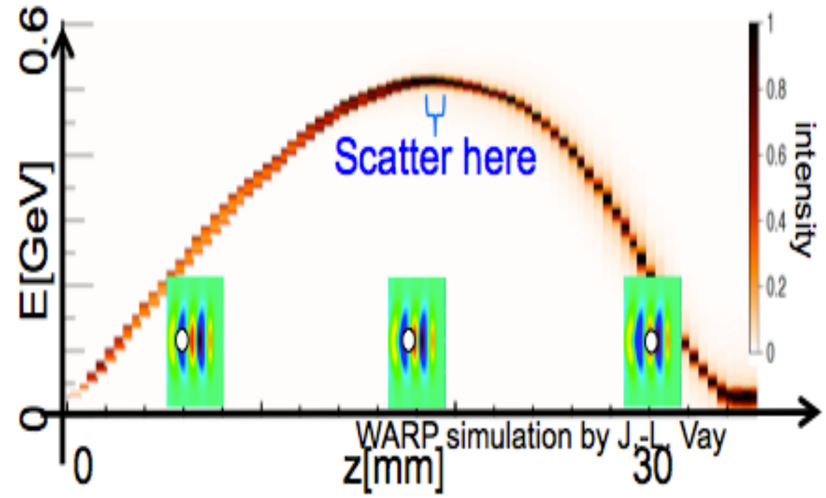


1: Many experiments, including Durfee PRL 1993, Butler PRL 2002, Geddes PRL 2005, Leemans Nat. Phys 2006.
2 ;Rykovanov, J. Phys. B 2014
3: Harteman PRE1996, Ghebregziabher et al., Phys. Rev.ST-AB16, 2013 , Rykovanov et al., PRSTAB 2016

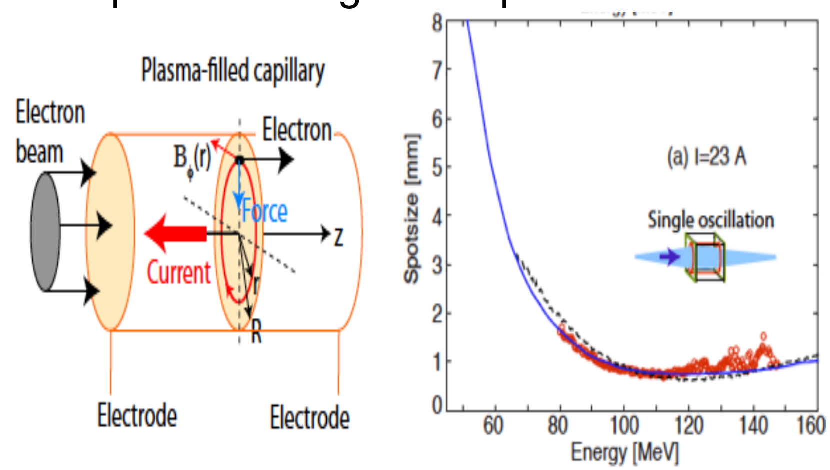
Deceleration of electrons after photon production can reduce undesired bremsstrahlung & beam dump shielding

- Key to practical Thomson photon source
  - 0.3 -0.6 GeV electron beam required
  - Decelerate to reduce undesired bremsstrahlung from beam stop[1]
- Experiment[2] to prove of concept: independent plasma stages for control
  - Uses stable LPA developed
- Plasma electron focusing lens[3] – increases coupling efficiency
  - Also: e-beam divergence control for photon source energy spread

Concept: > 90% deceleration possible[1]

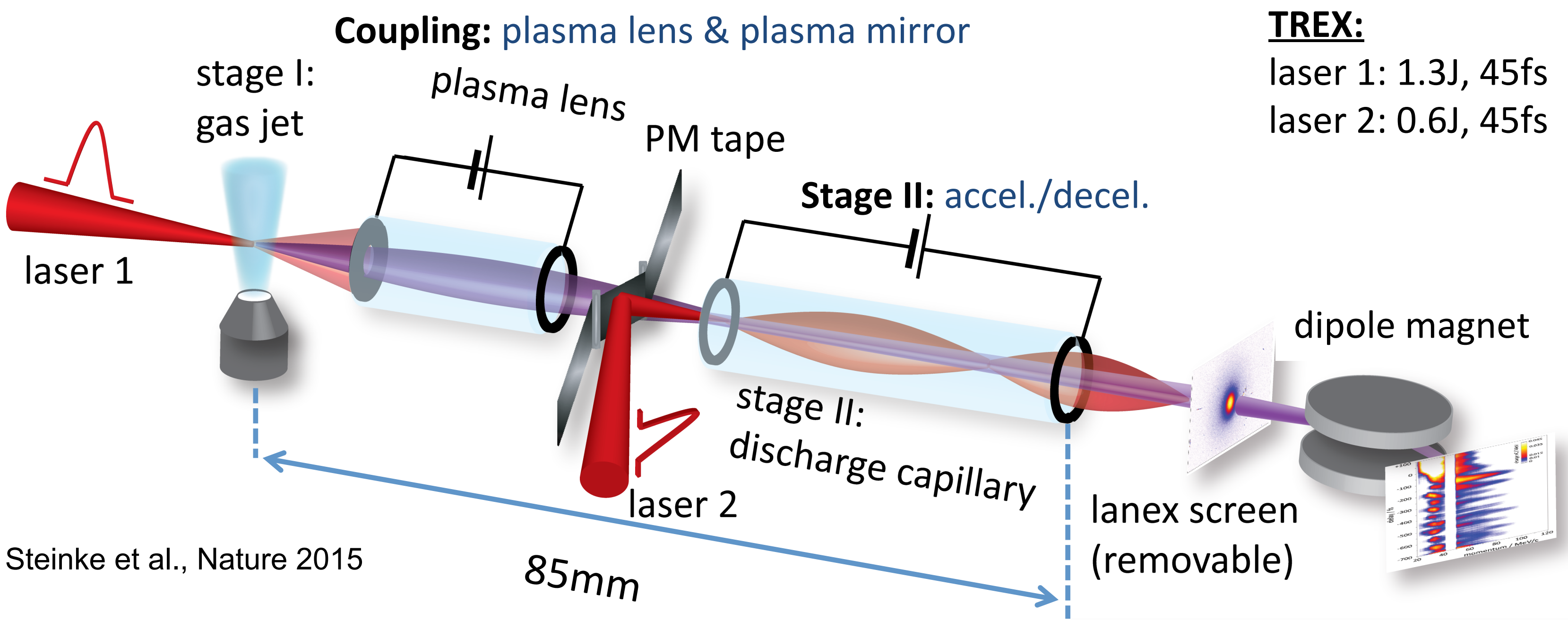


Compact focusing developed[3]



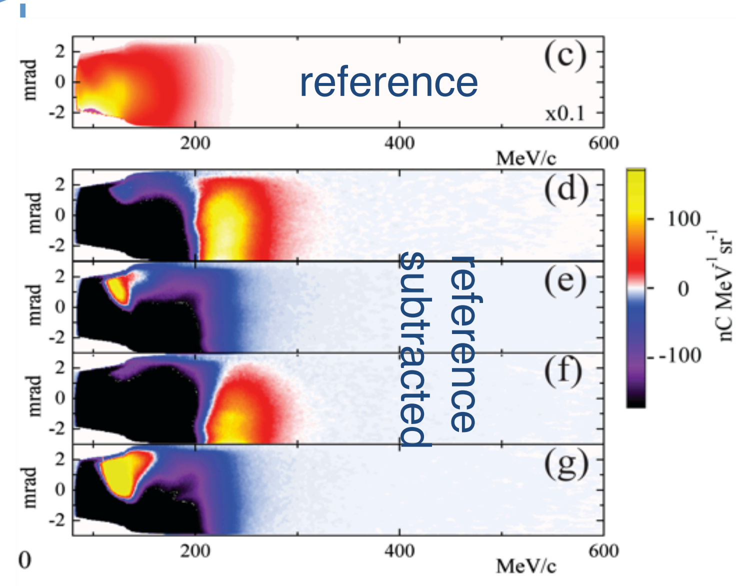
1; Rykovanov J. Phys. B 2014. 2: Steinke et al., Nature 2015. 3: van Tilborg *et al*. PRL 2015

All plasma-based staging of laser plasma accelerators used to evaluate deceleration



Steinke et al., Nature 2015

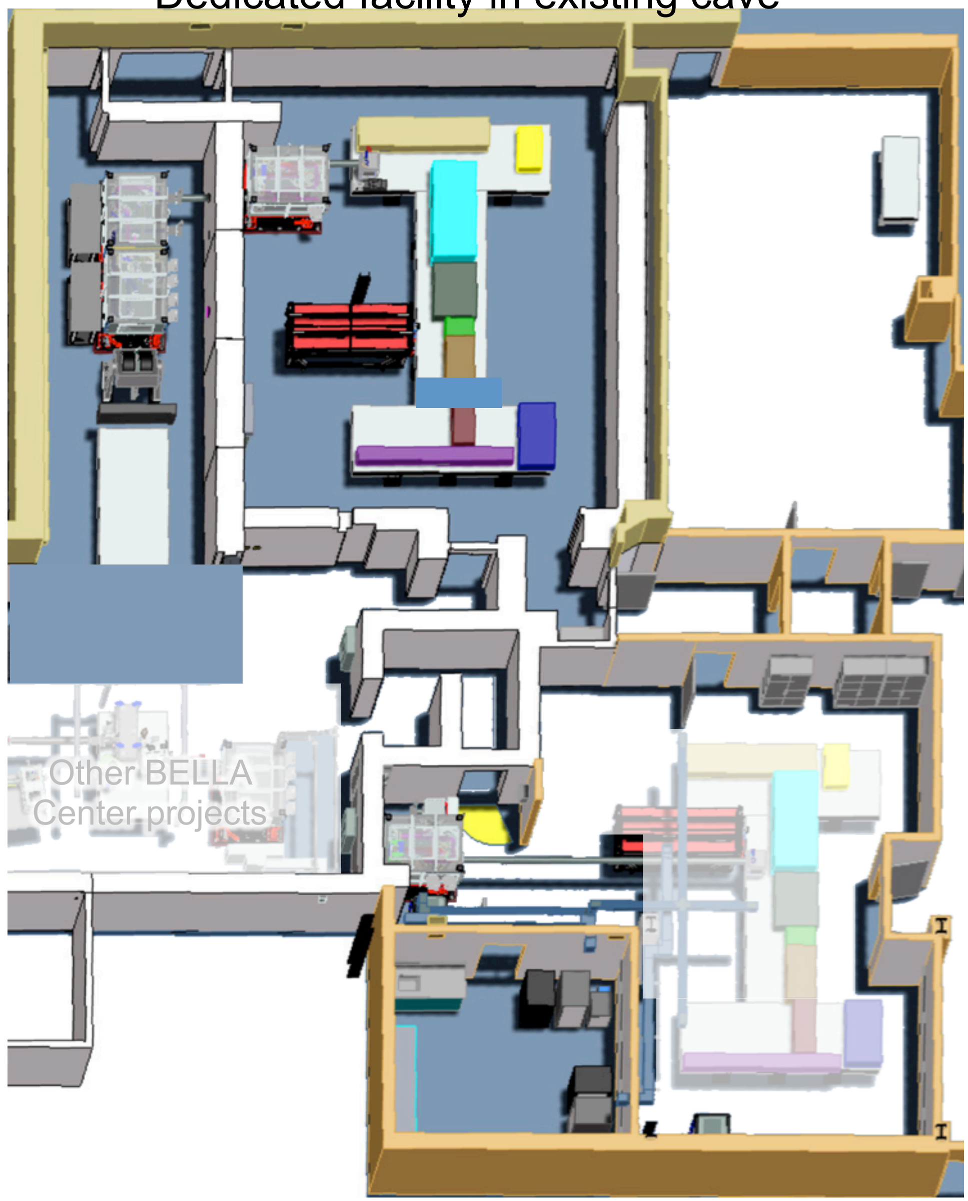
- Proof-of –principle demonstration of acceleration/ deceleration successful
  - Use of two separate plasmas allowed control of phase for precise measurement
- Simulations provide interpretation of experiment and extrapolation
  - Limited by coupling & energy spread
  - Source can use single plasma- eliminate coupling



Integrated experiment to demonstrate, laser-plasma driven, compact photon system concept

- Build and test concept for a compact source & system
  - Electron beam produced by compact cm-scale laser plasma accelerator (LPA)
  - Produce 1-9 MeV photons
  - Increase photon production: control scattering laser length & focusing
  - Reduce shielding: decelerate electrons after scattering

Dedicated facility in existing cave



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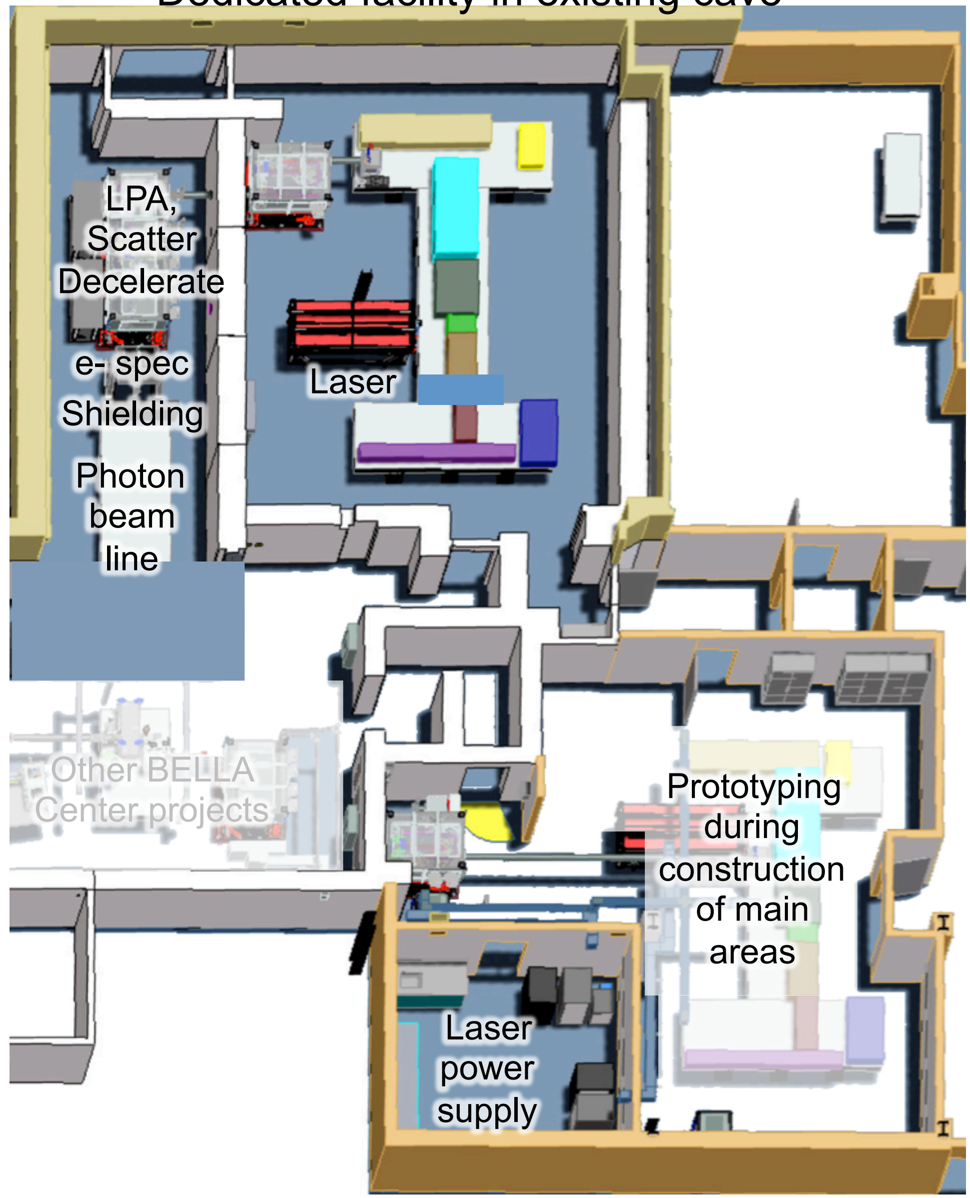
- Facility constructed

- Laser prototyped, installation started: dual-arm 3J/100TW class
  - Independent shaping for LPA. Scatter

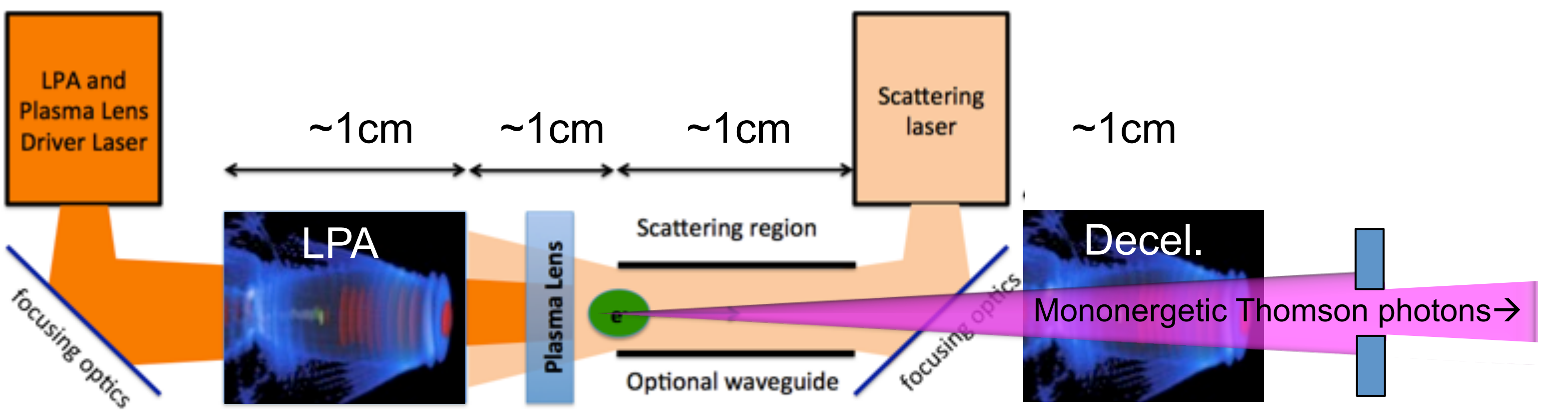
- Operation to start in 2017

Dedicated facility in existing cave



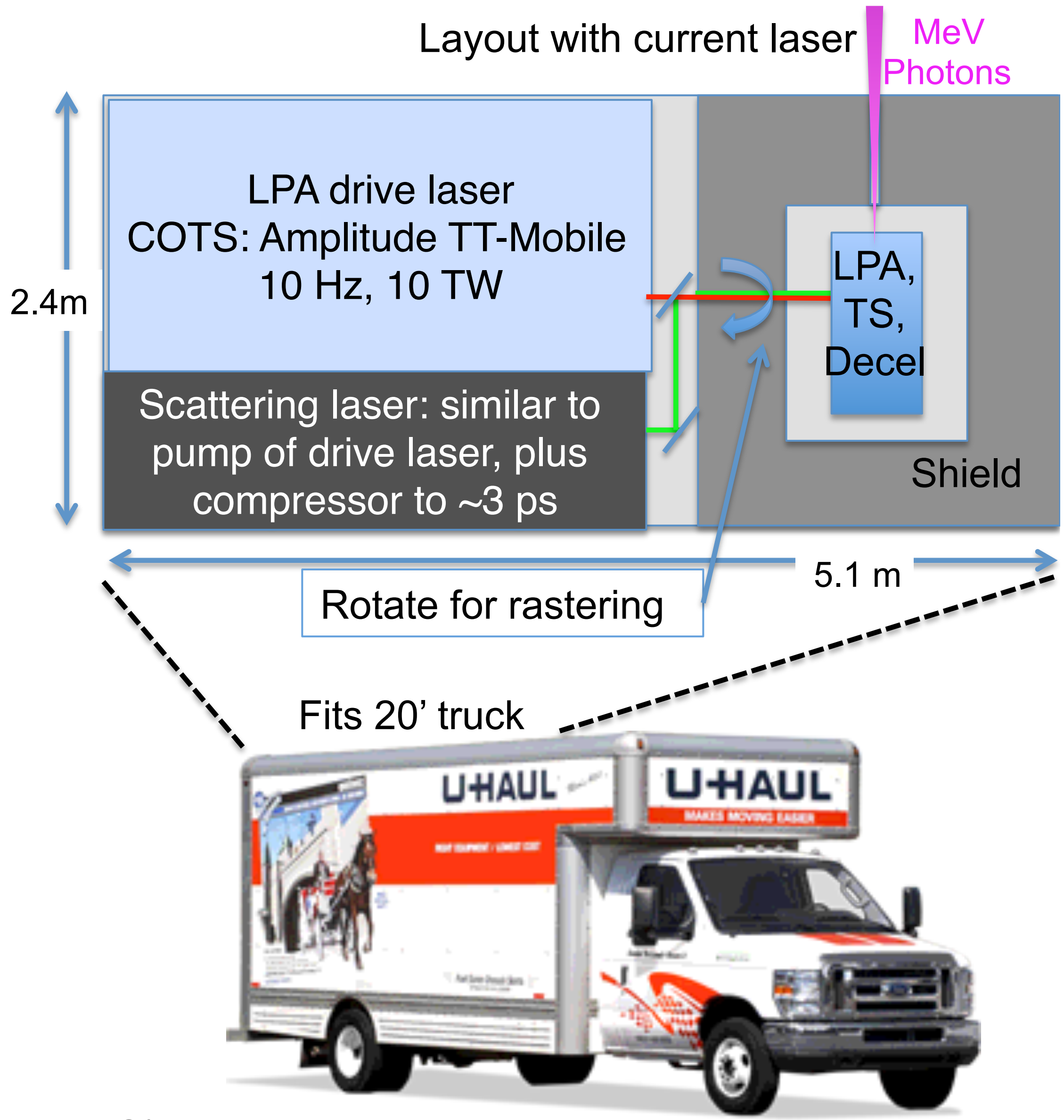
Outline

- Motivation for monoenergetic photon sources
- Nonproliferation application benefits and requirements
- Compact, near-monoenergetic photon source
- Path to address application requirements



Laser-plasma (LPA) MeV photon source system concept: Lasers trailerable now and reducing in size rapidly

- COTS 10 TW, 10 Hz, trailer[1']

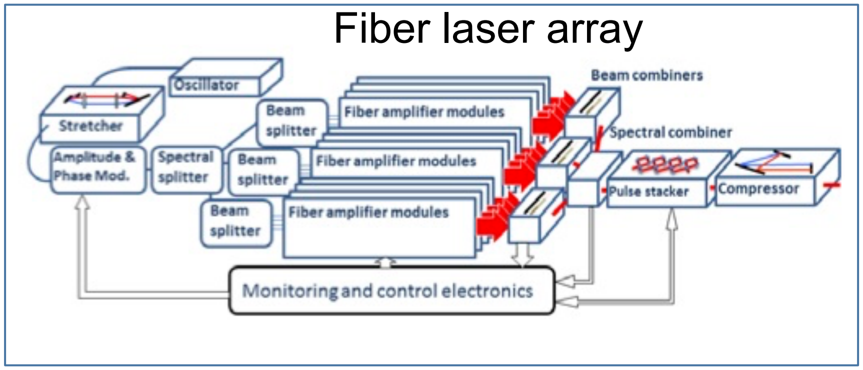


- 2 MeV concept fits 20' van
- Rep rate too low for applications:
  - requires laser development

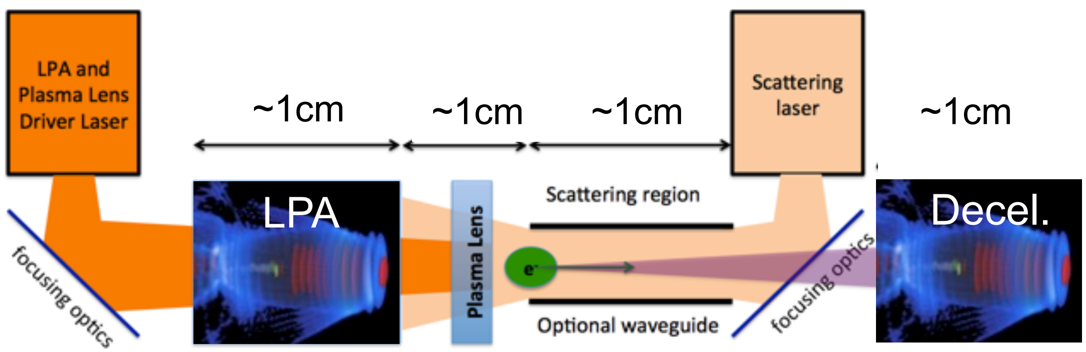
1: Amplitude Technologies

Path to applications, beyond the current project: High average flux, rastering, advanced control, integration

- Rep rate: ≥kHz laser drivers
  - DOE Sc. program
  - Project work for scatter laser
  - Future k-BELLA test bed at LBNL[1]



- Reduce system size: advanced plasma control of accelerator, scattering, deceleration



- Reduce ΔE_{ph} to ≤ 1%: e-beam focusing + hollow plasma channel guiding[2]

- Raster scanning: per shot dose/energy control

1; http://science.energy.gov/hep/research/accelerator-rd-stewardship/workshop-reports/
http://newscenter.lbl.gov/2015/02/12/grants-give-particle-accelerator-technologies-boost/

2; Rykovanov et al. J. Phys. B 2014.

Summary

- Nonproliferation application motivate a monoenergetic source with:
  - Moderate (10-30%) to narrow (≤ 2%) energy spread
  - mrad angular spreads,
  - Rep rate range from kHz to 10s of kHz, flux range of 10^9-10^{12} photons/sec

- LPA-based Thomson scattering source in development to address need
  - Deceleration proof of principle successful - path for realistic shielding
  - Facility established and laser installation in progress

- Photon source experiment starting in 2017: integrate energy/energy spread control, photon production efficiency, e^- deceleration at 5Hz repetition rate
  - Demonstrate key physics elements of transportable system
  - Collaboration opportunities across the experiment: photon source, applications modeling, detector development, photon beam measurement

- Path to application relevant flux & system via kHz, compact lasers