Mono-energetic photon sources

Photon source

Cameron G.R. Geddes,
cgrgeddes@lbl.gov

Hai-En Tsai, Sven Steinke, Jeroen van Tilborg,
Carlo Benedetti, Eric Esarey, Hann-Shin Mao,
Kei Nakamura, Tobias Ostermayr,
Carl B. Schroeder, Csaba Toth, Jean-Luc Vay,
Remi Lehe, Brian J. Quiter, Paul Barton,
Kai Vetter, Wim Leemans *
Lawrence Berkeley National Laboratory
^ BELLA Center director

David Grote, Alex Friedman
Lawrence Livermore National Laboratory

David Chichester
Idaho National Laboratory

Applications

Cameron G.R, Geddes,
Bernhard Ludewigt, John Valentine,
Brian J. Quiter,
Lawrence Berkeley National Laboratory

Marie-Anne Descalle
Lawrence Livermore National Laboratory

Glen Warren
Pacific Northwest National Laboratory

Mathew Kinlaw
Idaho National Laboratory

Cameron Miller
U. Michigan, Ann Arbor

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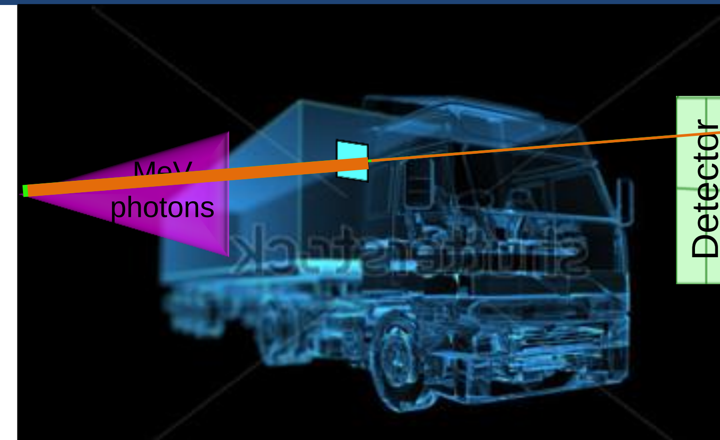
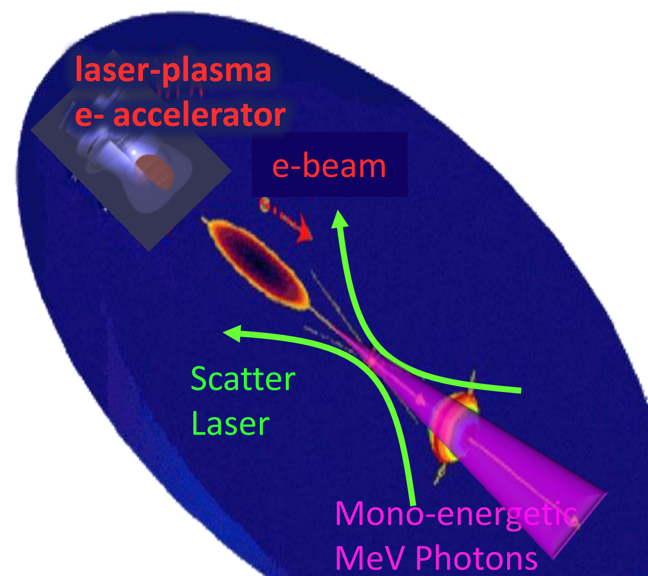
Improved container, rail, air cargo and vehicle scanning enabled by mono-energetic photon sources

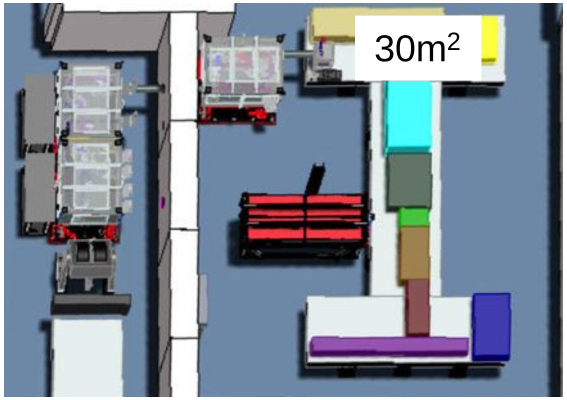
- Application space: Screening of container, rail, and air cargo as well as vehicles
- Problem: Xray and CT material identification, resolution, and penetration currently limited
  - bremsstrahlung dose, energy & angle spread
- Solution: Photon source producing mono-energetic, narrow angle, pulsed beam
- Results: Mono-energetic source reduces dose 10-100x, improves discrimination ~10x
  - Present project: demonstrate path to compact system using plasma based accelerators
  - Path to applications: development of robust, kHz laser drivers and systems
- TRL: 3
- Contact: cgrgeddes@lbl.gov, 510-495-2923





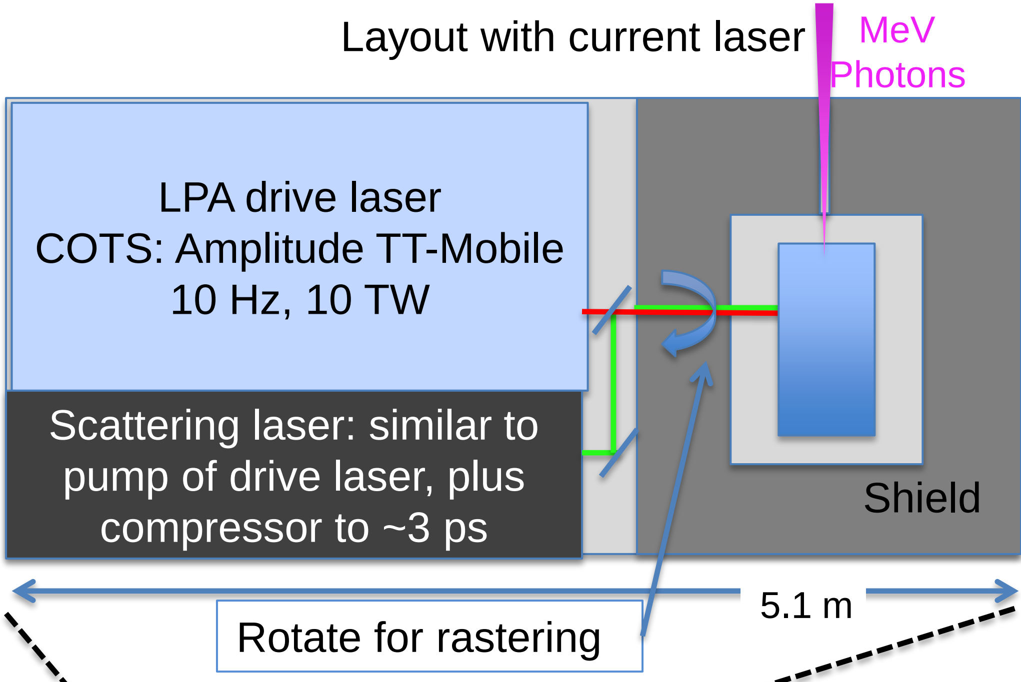
Laser-driven systems are shrinking rapidly
Already at trailer scale, smaller systems in development

- Lab experiments set needs:



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

- 2 MeV concept fits 20' van
  - Smaller systems anticipated
  - kHz laser needed for applications

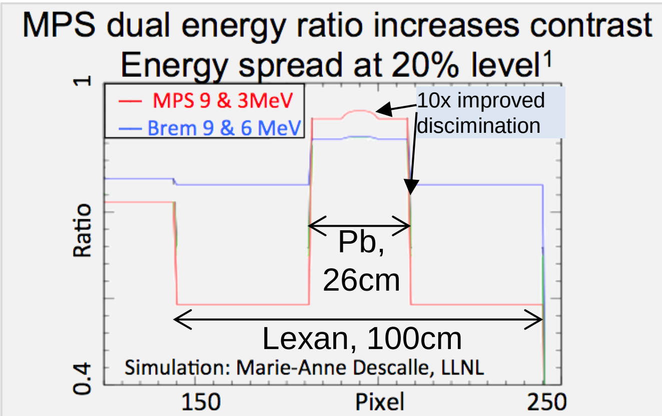


1: Amplitude Technologies

One to two orders of magnitude improved dose and signal accessible with mono-energetic photon sources

Energy selection: enhance signal

- **Radiography:** maximize transmission and material contrast, reduce dose
  - Removes beam hardening



1: 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)

Related:
S. Melton et al., 'Study of the Requirements for Monoenergetic Photon Sources,' DNDO report 2016.

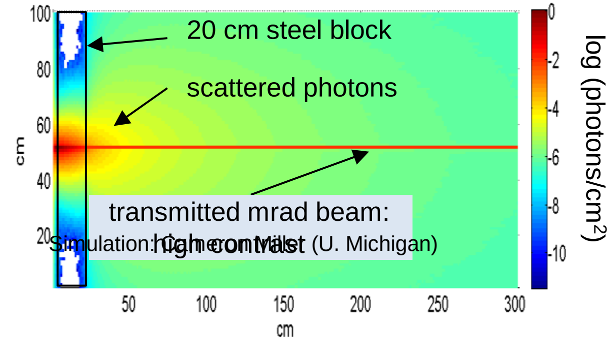
H. Martz et al., 'Poly- versus Mono-energetic Dual-spectrum Non-intrusive Inspection of Cargo Containers,' IEEE TNS 2017.

Joe Harms, PhD Dissertation Georgia Tech, 2018 (Erickson group).

- **NRF:** enable specific detection based on atomic ratios with greatly reduced dose

- **Photofission:** lower dose for Rad/Nuc

mrad divergence: mitigate scattter, target dose



also: EZ3D type methods

Pulsed beam: 3D

- Enable backscatter timing, 3D without tomography (INL)

micron emission spot:

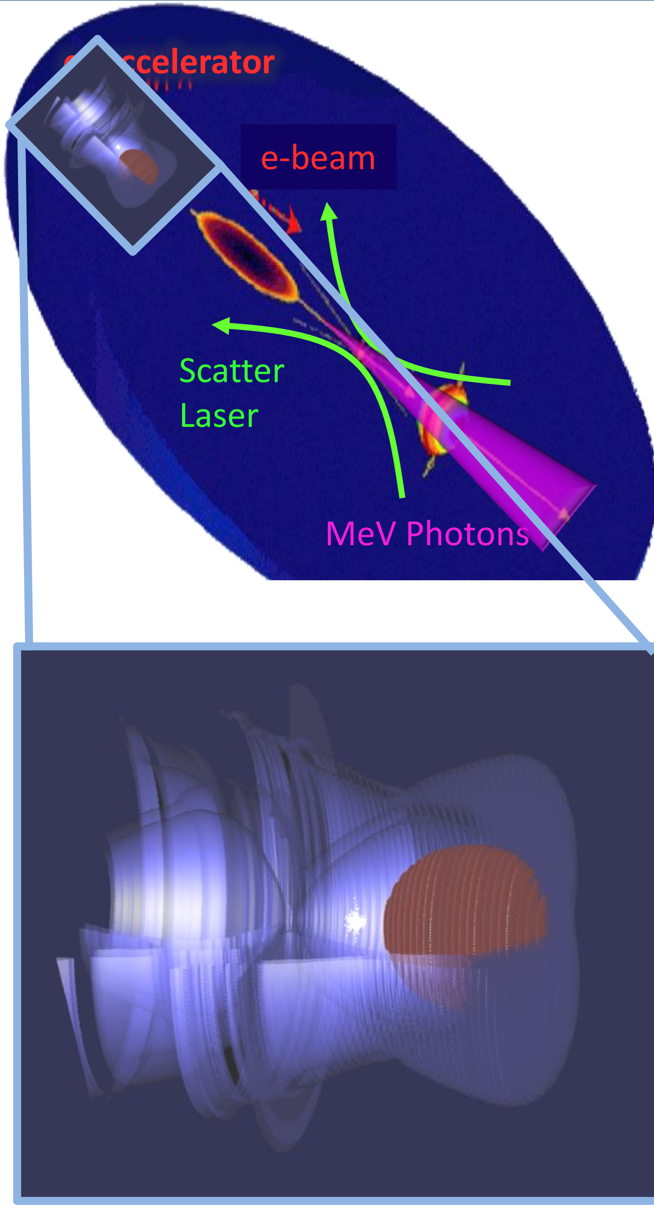
- Potential micron-scale resolution

Enables precision measurements: Cargo, single sided detection cases simulated[1]

Dose reduced 10x-100x with energy control + narrow divergence
Material discrimination improved 10x
Spatial resolution improved
NRF material identification and backscatter 3D enabled/improved

Monoenergetic, narrow-angle, pulsed & small spot size photon sources offer new capabilities if compact

- Applications use bremsstrahlung due to size
- Thomson scattering a laser from an e-beam produces high performance photon sources
  - Low energy spread: enhanced signal, low dose
  - Tunable energy: material discrimination
  - mrad divergence: high contrast, low dose
  - Small spot, short duration: resolution & 3D
  - Adjustable per-shot: flux, energy, polarization
- Proven on large fixed science facilities
  - Size limits deployment: 0.5 GeV class accel.
- Laser plasma acceleration (LPA): GeV in cm (vs 10's of m): path to a compact system[1]



1) W.P. Leemans and E.H. Esarey, "Laser-driven plasma-wave electron accelerators," Physics Today 62 (3), 44 (2009)

Demonstration addresses key enabling techniques for a compact MPS in integrated experiment

<u>Requirement & conventional limit</u>

- **High-energy, high quality e-beam at 0.2-0.6 GeV for MeV photons**
  - Conventionally, long accelerator
- **High flux photon production from low scattering cross-section**
  - Conventionally, requires very large accelerator current or laser
- **Shielding increases with energy and current, limits source size**
  - Conventionally, larger than accel.

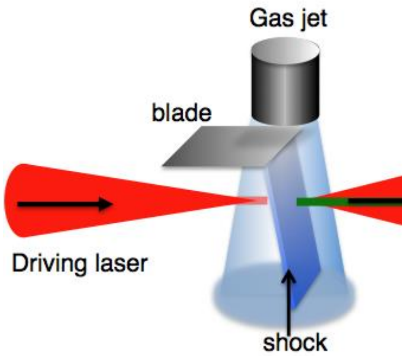
<u>Project: integrate solutions</u>

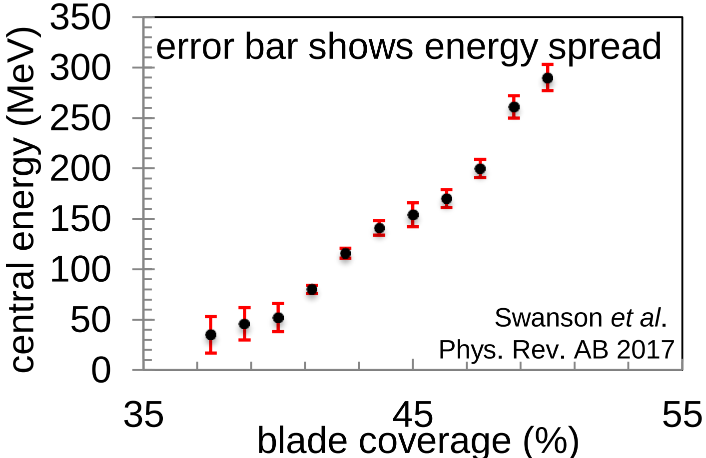
- **High quality cm-scale LPA**
  - Meets photon source need
- **Techniques to increase photon yield, reduce current/laser size**
  - Diffraction: Guide scatter laser
  - Nonlinearity: shaped pulse
- **Deceleration of electrons by LPA: reduce beam dump size**
  - Demonstrated in staged exp.

Current Project: Integrated prototype to demonstrate key per-shot elements
Newly constructed laboratory based 50 TW laser at 5Hz repetition rate
Provides test-bed for evaluations of application utility, signatures

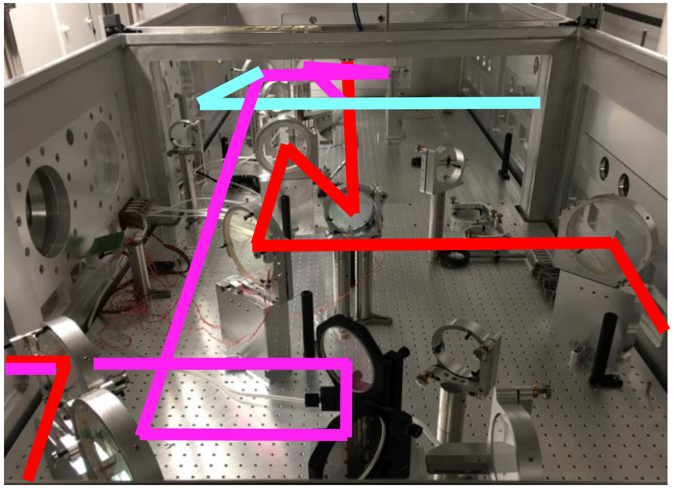
Photon source integrates past individual results
New facility enables combined test

Controllable LPA at Photon-Source Energies
Up to 1 GeV in few-cm plasmas (for 20 MeV photons)

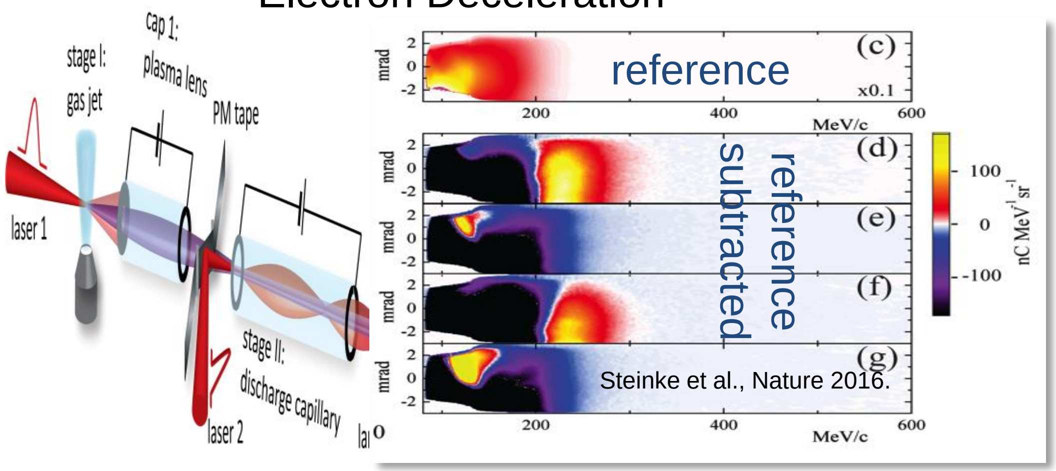




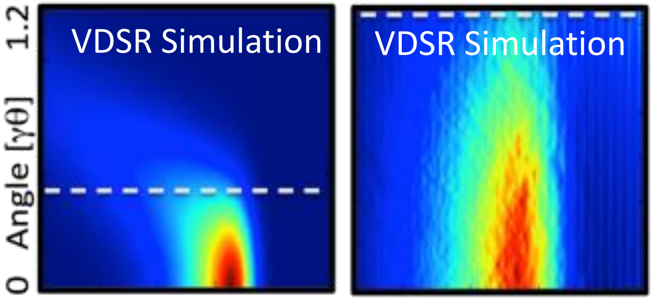
Photon source experiment running



Electron Deceleration



Controlled Thomson Scatter
Photon to produce 10% ΔE, mrad



0.5 $E_{photon,\,1\omega}$[MeV] 1 2.3 $E_{photon,\,1\omega}$[MeV] 6.5
1 $E_{photon,\,2\omega}$[MeV] 2 4.6 $E_{photon,\,2\omega}$[MeV] 13

0.1 μm photon emission spot size
fs-class short pulse

Plateau et al., PRL 2012.
van Tilborg et al., PRL 2006.

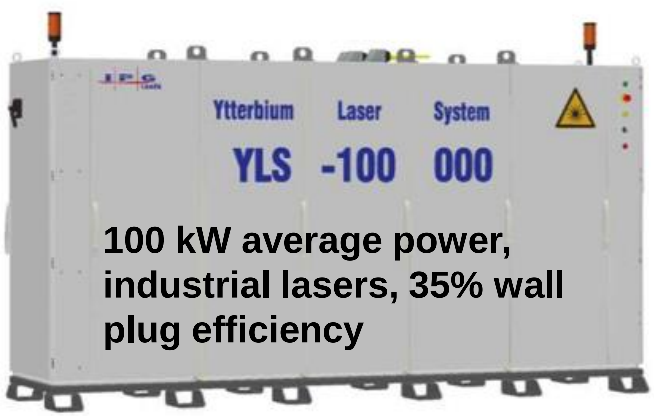
Capable of ≤ 1% ΔE for NRF
Geddes *et al*. NIM-B 2015

kHz laser drivers are being developed to enable application-motivated scan rates

High **peak** power,
low average power

1 Hz, PW BELLA laser

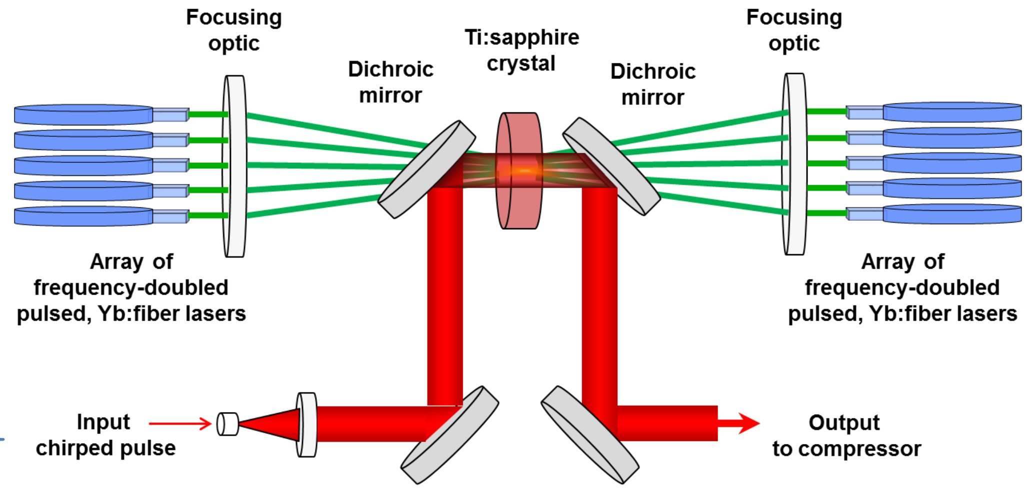
High **average** power,
low peak power



100 kW average power, industrial lasers, 35% wall plug efficiency

High average and peak power

Near term: kBELLA kHz, 3 Joule demonstrate photon source driver



Long term: Coherent combining of fiber lasers offers efficient path to 10's of kHz

Conclusion and future work

- Compact near-monoenergetic photon sources provide strong benefit
  - Moderate (10-30%) energy spread improves radiography and material discrimination, scalable to narrow (<1%) to enable/improve NRF
  - mrad angular spreads – mitigate scattering, improving contrast & dose
  - ≤μm emission spot – very high spatial resolution
  - fs-class short pulse – facilitates backscatter 3D methods
- Improved signal > 10x in many cases, with > 10x reduction in dose
  - Cargo, vehicle, pallet and other scanning and detection applications

- Compact source demonstration commissioned, in progress: control energy & energy spread , photon production, e- deceleration
  - Test applications/benefit: test cases & collaboration welcome

- Laser drivers are being developed to deliver ≥ kHz repetition rates motivated by applications

Backup material

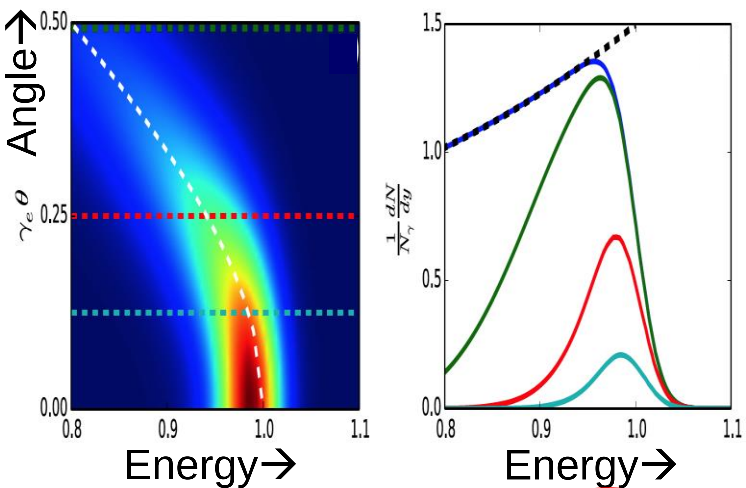
Primary references, available at http://geddes.lbl.gov

Survey of applications impact:
C.G.R. Geddes, B. Ludewigt, J. Valentine, B.J. Quiter, M.-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, S. Pozzi, "Impact of Monoenergetic Photon Sources on Nonproliferation Applications," [OSTI 1376659, INL/EXT--17-41137 (2017)]

Plans for development of the source:
C.G.R. Geddes, S. Rykovanov, N.H. Matlis, S. Steinke, J.-L. Vay, E. Esarey, B. Ludewigt, K. Nakamura, B.J. Quiter, C.B. Schroeder, C. Toth, W.P. Leemans, "Compact quasi-monoenergetic photon sources from laser-plasma accelerators for nuclear detection and characterization," [Nuclear Instruments and Methods in Physics Research B 350, 116 (2015).]

Backup slides – Photon Source

Thomson/Compton photon sources require precise control of accelerator electron beam and scattering laser



$$\omega \approx \frac{4\gamma_e^2}{1+\gamma_e^2\theta^2+a_0^2/2}\omega_L$$

$\gamma \sim 2E_e[\text{MeV}]$

→ 0.5 GeV e-

Narrow ΔE_γ requires high quality e-beam

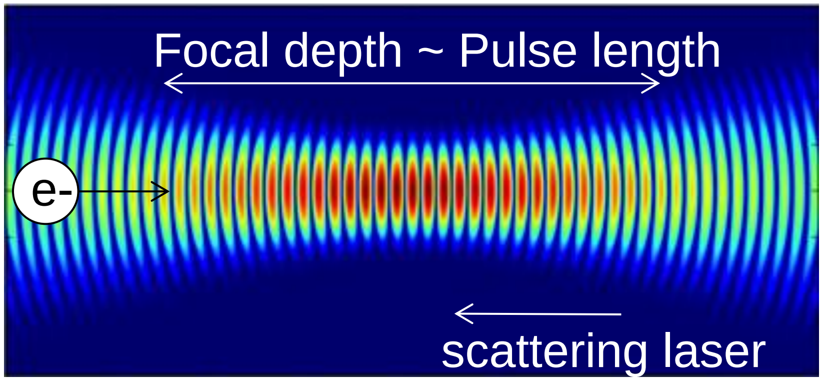
laser bandwidth usually negligible if ≥ ps

$$\sqrt{\frac{\gamma_e^4\sigma_{\theta,\mathrm{FWHM}}^4}{16}+\frac{4\sigma_{\gamma_e,\mathrm{FWHM}}^2}{\gamma_e^2}+\frac{a_0^4}{4}+\left[N_{sc}\cdot 2\gamma_e\frac{\hbar\omega_L}{m_ec^2}\right]^2} < \mathrm{BW}$$

- e- divergence
- e- energy spread
- laser amplitude
- multiple scatter

- ΔE_{ph} ~ 10 % → ΔE_e~ 5%, ≤ mrad
- ΔE_{ph} ~ 2% → ΔE_e~ 1%, ≤ 0.1 mrad

Low scattering cross section : quality & flux trade off



$$\frac{N_{\gamma ph}}{N_e} \approx 4.7\, a_{0,max}\cdot\sqrt{\frac{E_L}{\lambda_{L,\mu m}}}.$$

1 ph/e- in 10% ΔE_{ph}: 40J at a_0=0.3

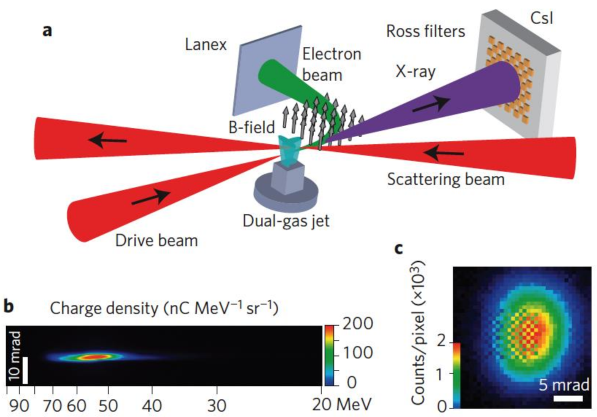
Rykovanov et al., AAC 2012 & in prep., Chen et al., PR ST-AB 2013, Leemans et al. PRL 1996.
Related include: Thomas et al PRST-AB 2010; Ghebregziabher PRSTAB 2013, P. Chen, et al., a, NIMA 355 (1995) 107. Hartemann PRE 54 (2956) 1996.

LPA based Thomson photon sources
Intensively developed worldwide

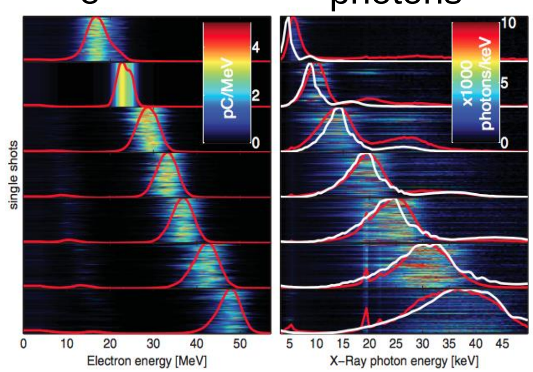
<u>Selected highlights</u>

- United States
  - U. Nebraska – multi-MeV energies, energy control
  - U.T. Austin – back reflection, 0.2 MeV
  - U. Michigan – high brightness nonlinear at MeV
  - LLNL – high energy density physics applications
  - LBNL – facility for MeV + guiding and deceleration
- Europe
  - Jena – LPA demonstration, theory
  - LMU and MPI Garching – keV energy spread control
  - Helmholtz-Zentrum Dresden - Rossendorf
  - LOA – foil back-reflection at 50 keV, control
  - ELI Beamlines – upcoming experiments
- Asia
  - SIOM-CAS – MeV energy spread measurement
  - KAERI, Korea – experiment in progress
  - AIST and U. Tokyo, Japan – source control

UNL: Powers et al. Nat Phys 2013

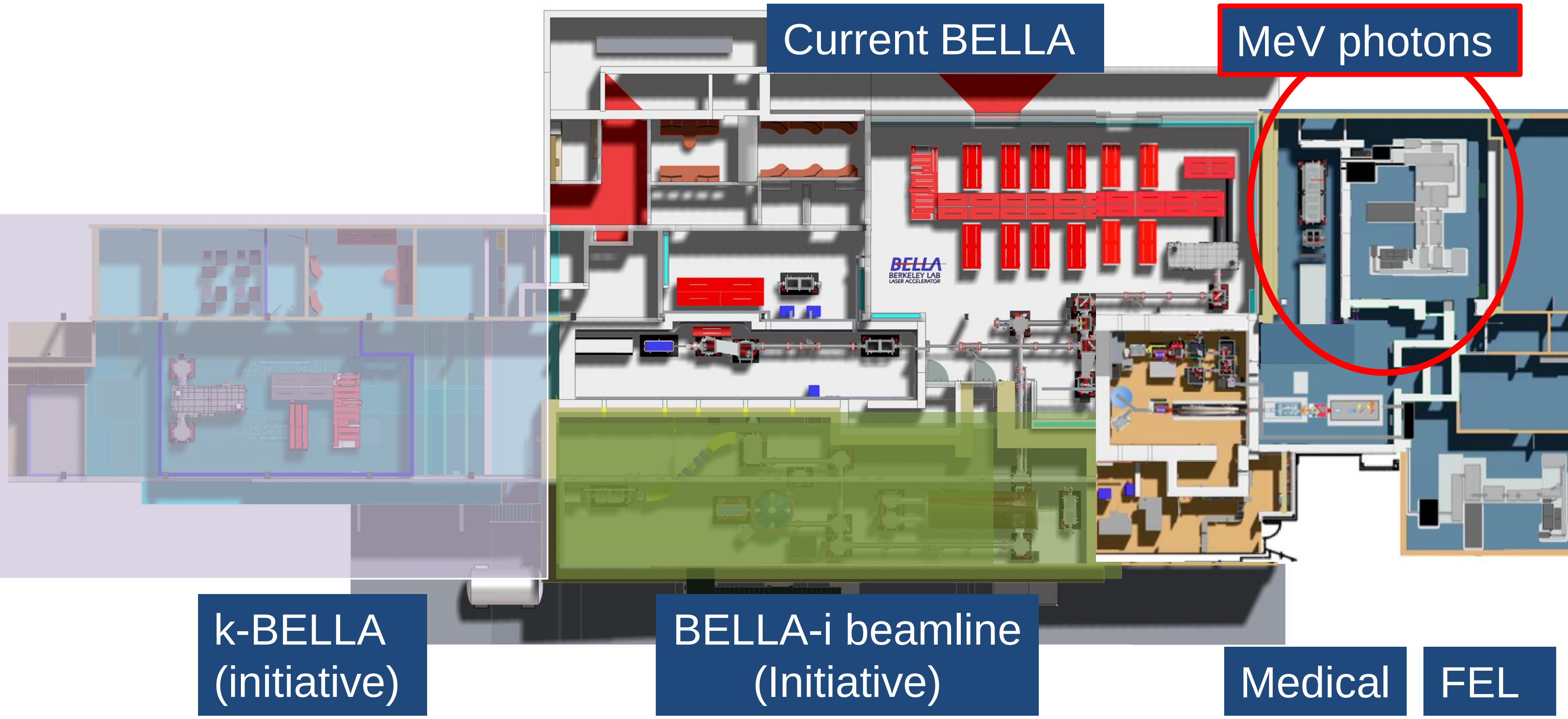


LMU: Khrennikov et al., PRL2015

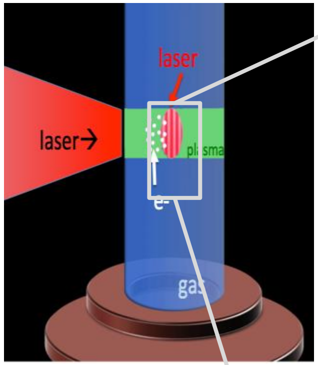


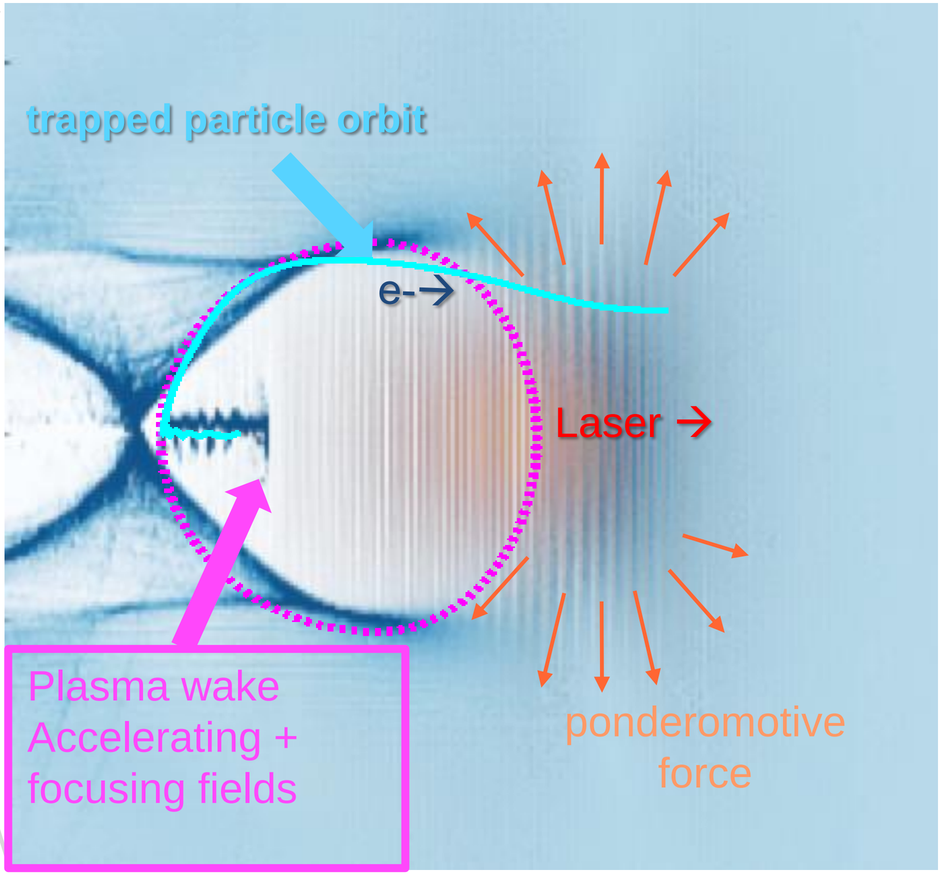
Photon source is part of BELLA Center, driving LPA technology for high energy physics and applications

Exisiting and planned laser facilities in Building 71 at LBNL



Plasma wave driven by radiation pressure of TW, fs laser GeV/cm gradients: compact accelerator for Thomson sources

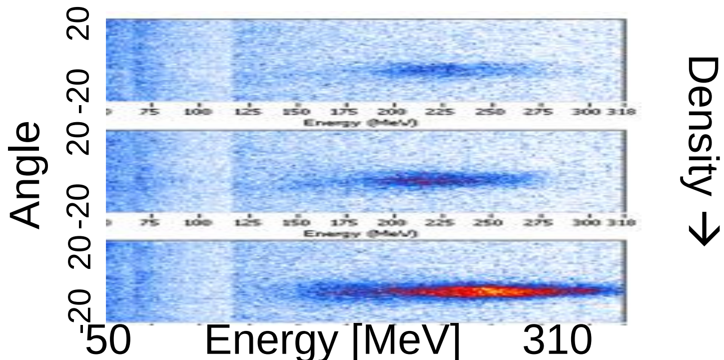




1: W.P. Leemans, Phys. Plasmas 1998, 2: C. Geddes et al., Nature 2004. 3: W.P. Leemans et al., PRL 2014, 4: S. Steinke et al., Nature 2016

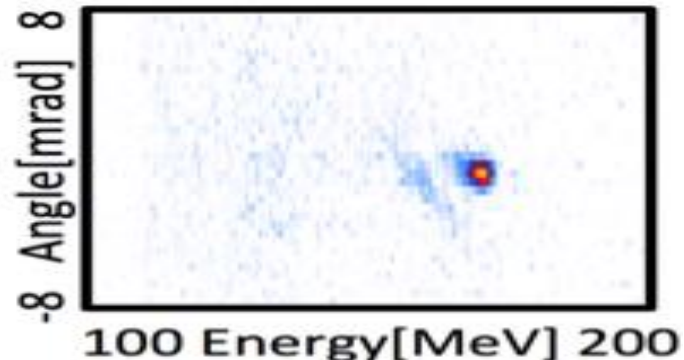
Recent GeV-class LPA development demonstrates high quality beams needed for 1-9 MeV photon sources

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



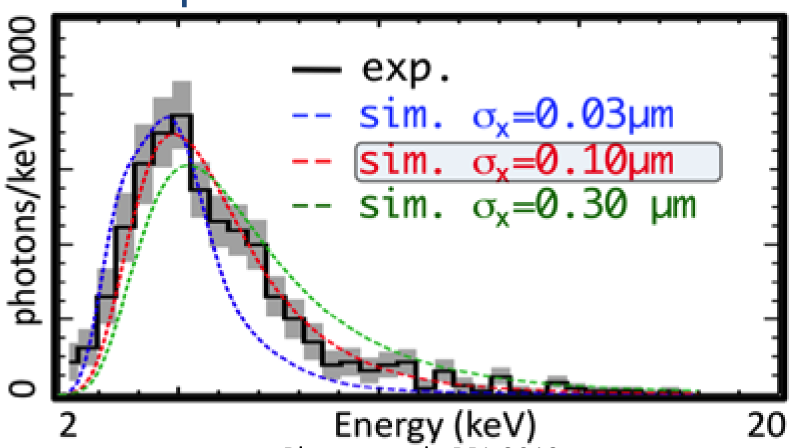
Matlis et al., Proc. AAC 2012

ΔE_e < 1.4 % FWHM from Colliding pulse injection control



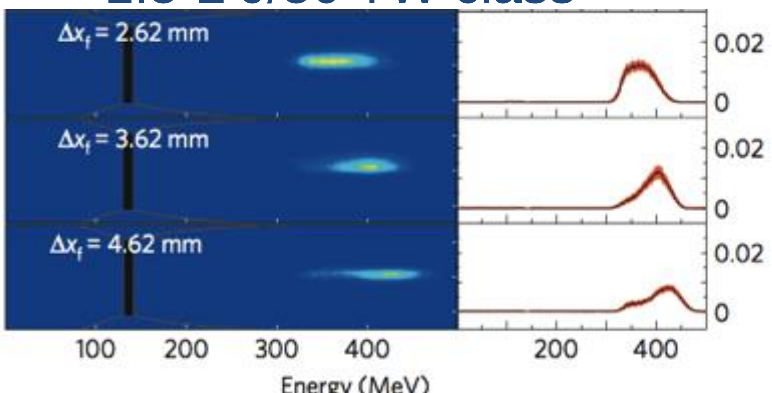
Geddes et al., Proc. AAC 2014; NIM-B 2015

ε~0.1µm via Betatron emission



Plateau et al., PRL 2012

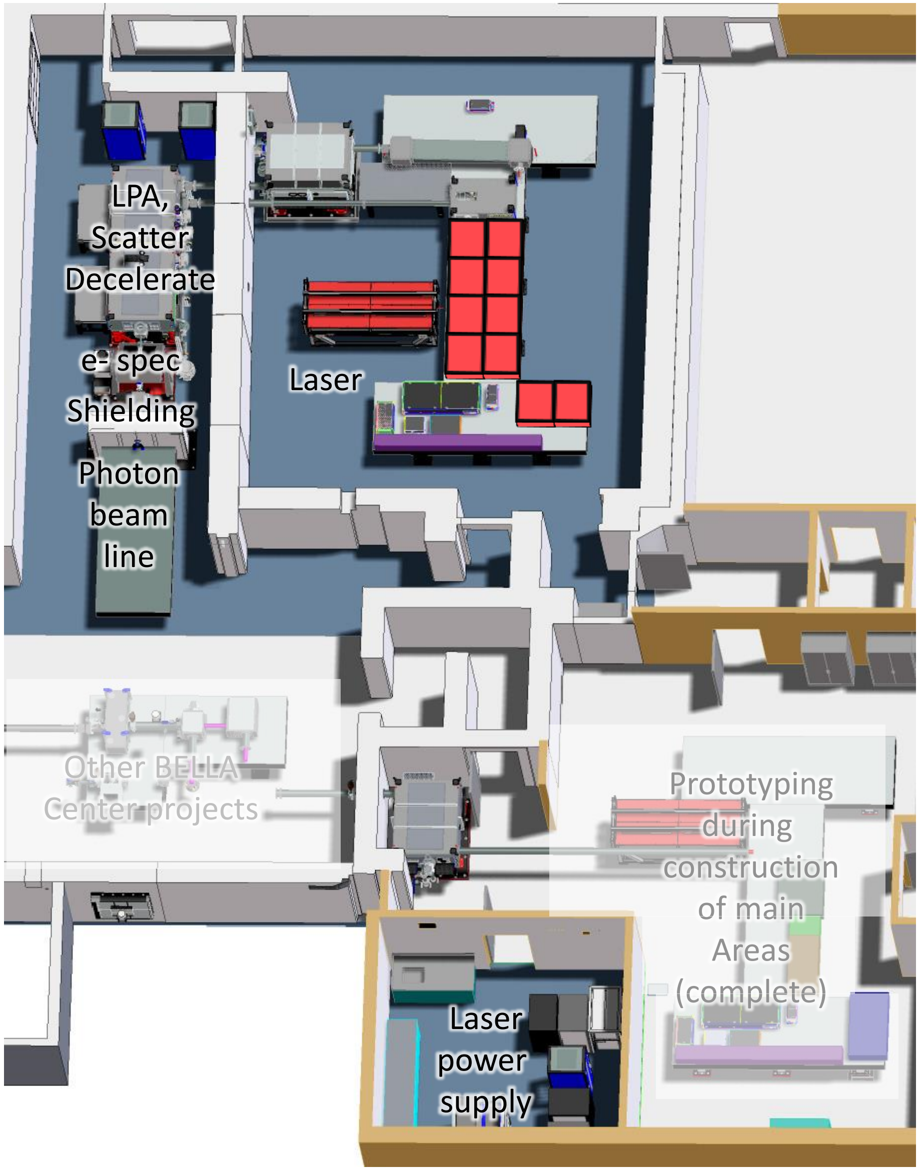
Tunable 0.5 GeV - modulated density 1.5-2 J/50 TW class



Gonsalves et al., Nat. Physics 2011

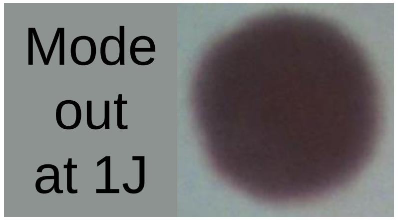
Integrated experiment to demonstrate, laser-plasma driven, compact photon system concept

- 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

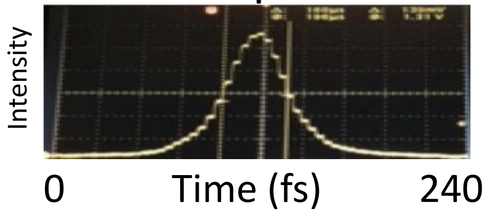


LPA experiment running to prepare for laser-plasma driven, compact photon source work

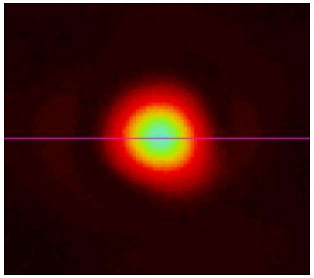
Laser operating at 0.6J/42fs; 3J amp ready



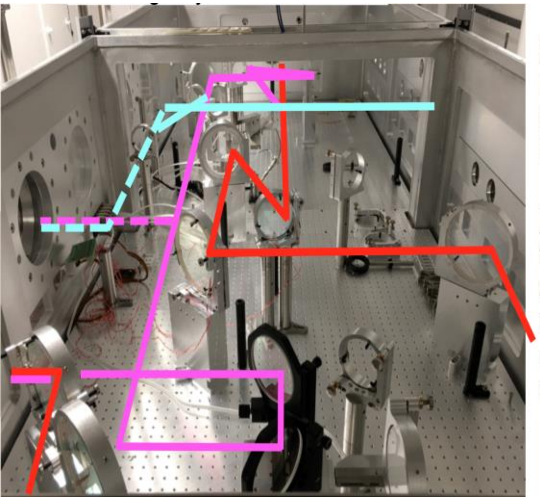
42 fs pulse



High quality focal mode



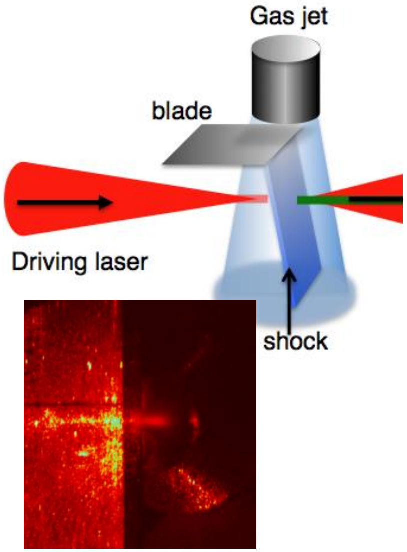
LPA running, photon experiment ready

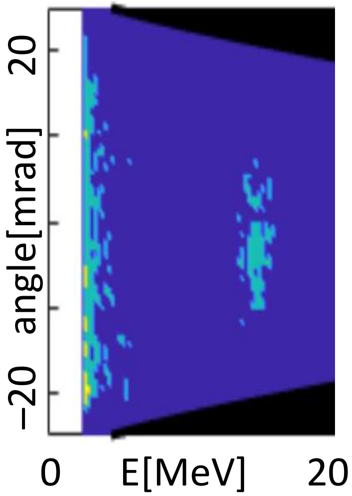


Solid current:
Drive
Scatter
Probe

Dashed:
future
second
amplifier
array for
scatter laser

First electron beams produced





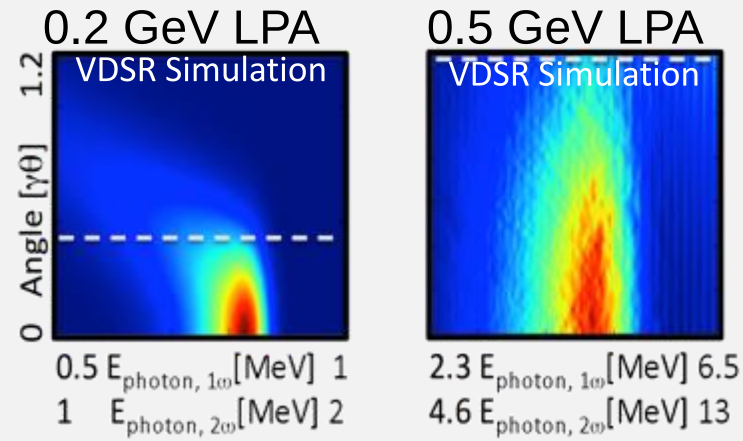
Simulations show that narrow energy spread photon sources are enabled by high performance LPAs

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

Demonstrated LPAs allow ΔE_{ph} ~ 10%

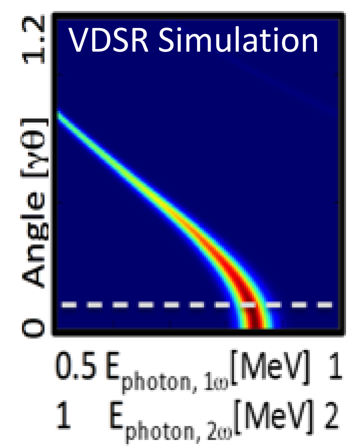
- E_{ph} of 1-10 MeV
- Electron emittance dominates ΔE_{ph}
- Divergence still dominant for scatter in plasma

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



- Scattering laser control separate from LPA laser required for high photon yield/low ΔE_{ph}
  - Low amplitude to avoid nonlinearity
  - ~1-10 ps >> LPA driver duration for~ 1 photon/e-

Percent-level ΔE_{ph} with divergence control



Demonstrated 1% ΔE_e allows ΔE_{ph} ~2 %

- Experiments indicate potential for <1%
- e-beam refocusing or emittance reduction required to reduce divergence

Rykovanov et al., J. Phys. B 2014, Chen et al., PR ST-AB 2013, 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

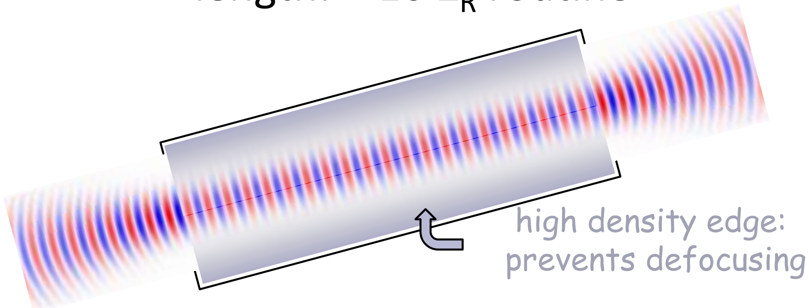
- 10^8 ph/shot possible w/ scatter energy ~LPA driver, in range of applications

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

Further improvement: Laser shaping[3]

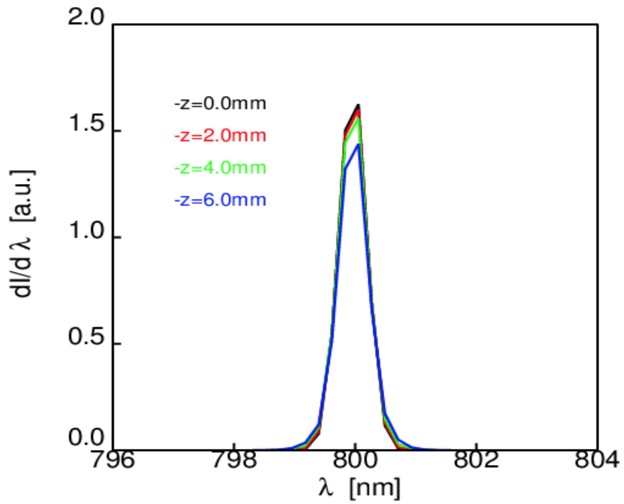
– Mitigates nonlinearity, intense scattering

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



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

Simulations indicate minimal broadening



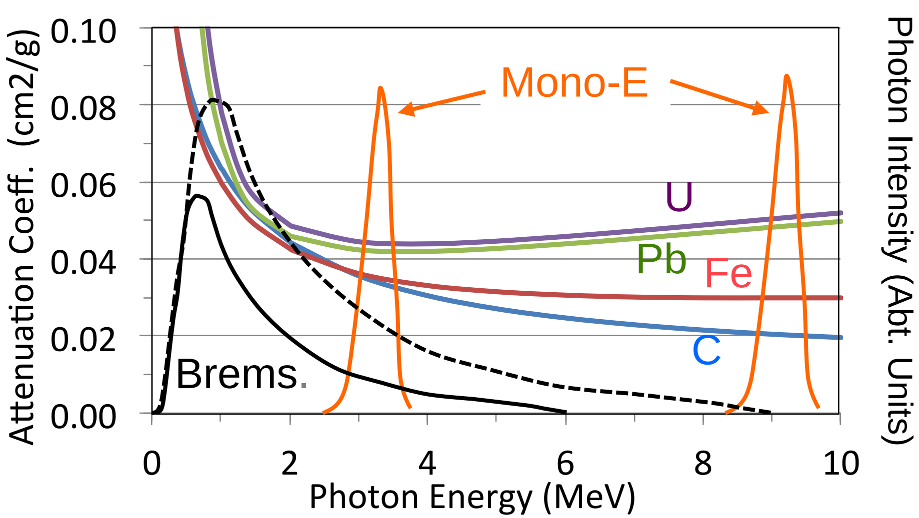
1: many experiments, including Durfee PRL 1993, Butler PRL 2002, Geddes PRL 2005, Leemans Nat. Phys 2006.
2 ;Rykovanov, J. Phys. B 2014
3: Harteman PRE1996, Ghebregziabher et al., Phys. Rev.ST-AB16, 2013 , Rykovanov et al., PRSTAB 2016

Backup slides – Mono-energetic photon applications

Monoenergetic photon sources could enhance radiography, fission signatures, NRF

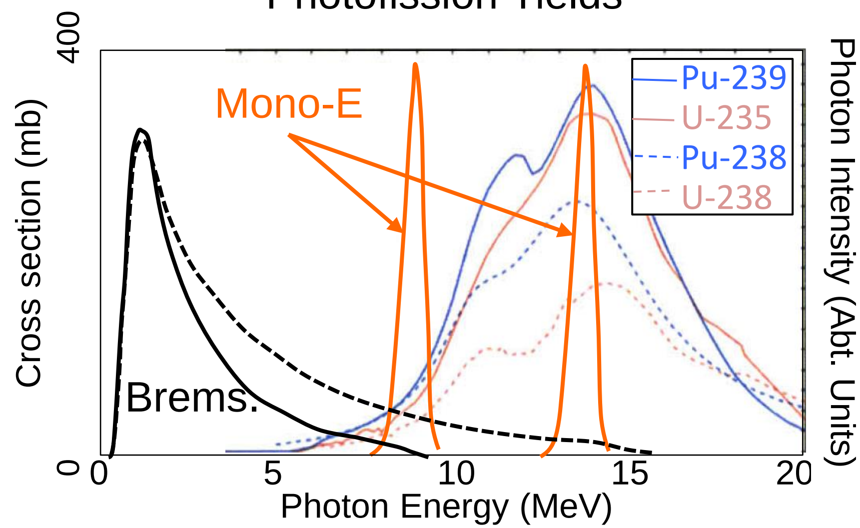
- **Radiography:**
  - Energy selection for maximizing transmission and Z-contrast, minimizing dose

Energy & Z Dependence of Mass Attenuation



- **Photofission:**
  - Energy selection to maximize fission signatures

Photofission Yields



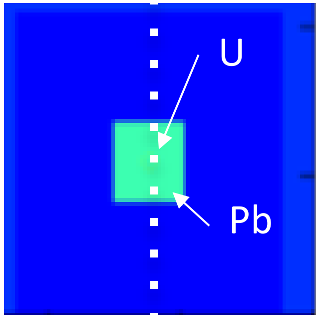
- **Nuclear Resonance Fluorescence:** narrow line → low energy spread / high spectral density greatly improve signal to noise

Quasi- monoenergetic photons at ~10% ΔE improve radiography and material discrimination

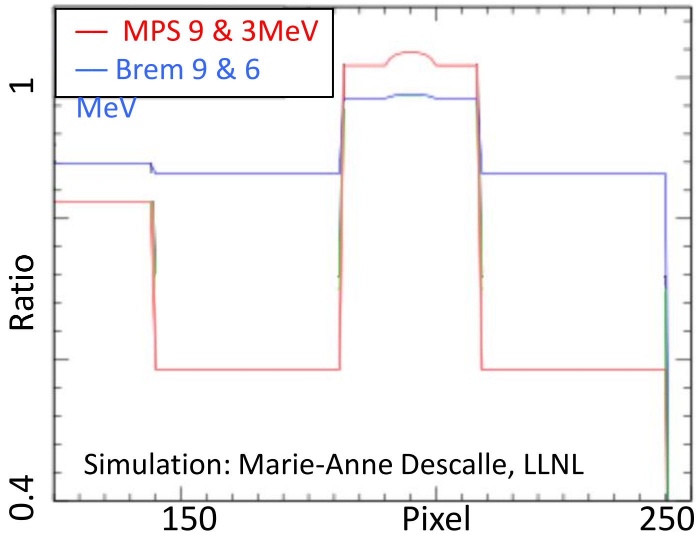
- Application survey[1] shows high potential impact, including:
  - Screening & Inspection (Cargo)
  - Resolution of different materials
  - Penetration of thick targets
  - High resolution radiography of fine features

- Controlling photon energy improves signal
  - Mitigate contrast degradation by scattering/hardening
  - Remove low energy photons: reduce dose 3x-4x
  - Multiple energies: improve material discrimination

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



MPS dual energy ratio increases contrast
Energy spread at 20% level[1]

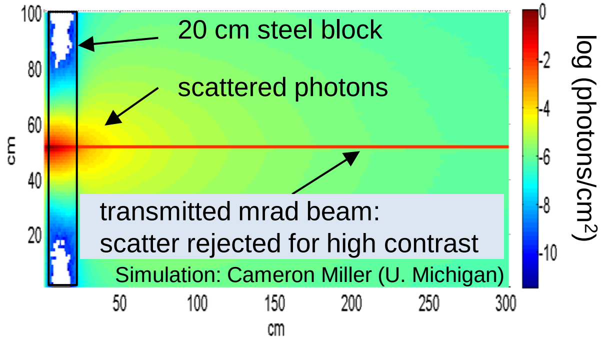


1: Final report of project "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," Cameron Geddes, Bernhard Ludewigt, John Valentine, Brian Quiter, Marie-Anne Descalle, Glen Warren, Matt Kinlaw, Scott Thompson, David Chichester, Cameron Miller, Sara Pozzi (2017)

Narrow-angle beams further improve mono-energetic photon applications

- milliradian (mrad) divergence 'pencil beam' isolates scattering-induced degradation
  - Improves contrast, resolution
  - Allows dose targeting
  - Dose reduced 1-2 orders
  - Clear signal through thick objects

mrad divergence: improved contrast & lower dose by mitigating scattter



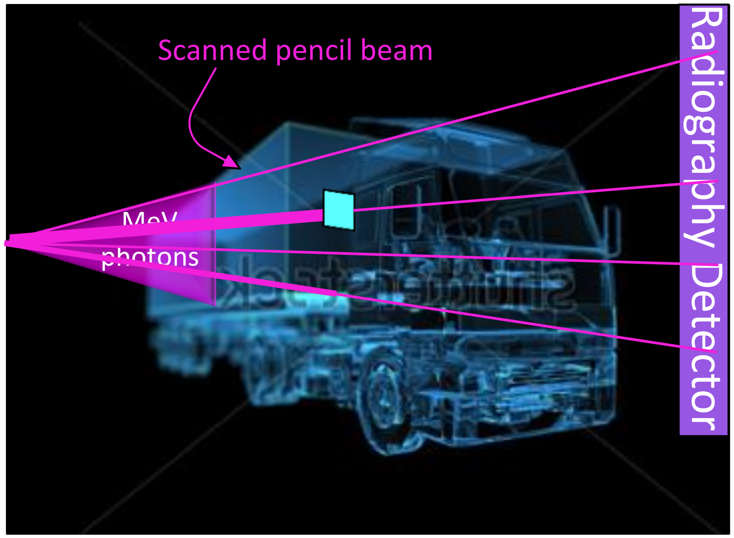
- dual-E ratio for distinguishing materials improved >10x
- Requires high pulse rate and scanning of beam
  - Example: container scan at 80cm/sec, 1cm res. =20kHz
  - 20-40cm steel: 10^6-10^8 ph/pulse in mrad cone

Improved Z

Type & Energies	Ratio
Brems: Fe 9MeV/6MeV	1.57
Brems: Fe+Pb 9MeV/6MeV	1.61
MPS: Fe 9MeV/3MeV	2.87
MPS: Fe+Pb 9MeV/3MeV	2.04

2% (Brems) ; 41% (MPS)

Scanned pencil beam concept

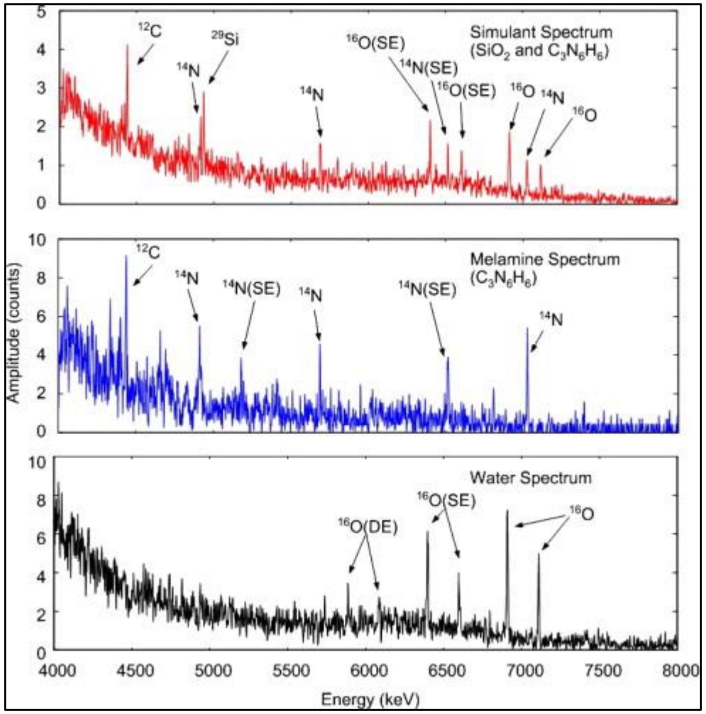


Screening and interdiction alarm resolution: Reduced photofission dose, NRF enabled

- Pencil beam of ≤3 mrad important to isolate dose to area of interest
- Photofission:
  - MPS dose per fission ~50x lower than bremsstrahlung dose near 10 MeV
  - Detection of 2 kg HEU shielded by 20-30 cm thick steel box in seconds
    - KHZ MPS of a few 10^{11}ph/second in few mrad divergence at ΔE_{ph} ~20%
- 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 filled container (0.6 g/cc)
    - ~2 kg HEU in Fe box with 10 cm thick walls
    - MPS: $3x10^7$ photons/pulse, 20 kHz or ~ $1.7x10^7$ph/eV/s at 1.733 MeV
- Improved signal vs. active and passive backgrounds

Low-Z material identification for cargo/IEDs

- Address a key CBP priority on contraband and explosives
- NRF: High explosive measurement via atomic ratios of C, O, N
  - MPS advantage increases at high energies (O: 7 MeV)
  - Presently simulating Treaty/Dismantlement only
  - Cargo scenarios require consideration of larger volumes and shielding thickness
- Photoneutron spectroscopy
  - Monoenergetic photons produce neutrons at isotope specific energies via (γ,n) reactions ($^{14}N(\gamma,n)^{13}N$)
  - Percent-level photon energy spread
  - High resolution, high rate detector required
- Use radiograph/Z_{eff} information to localize volume for interrogation



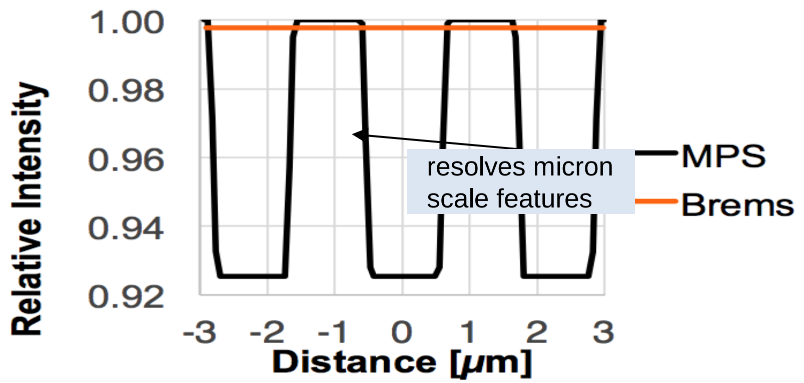
NRF spectra for a simulant explosive, melamine and water ; 8.3 MeV bremsstrahlung.
Reproduced from Bertozzi et al. 261: 1-2, 331-336 NIMB 2007

*J.E. McFee et al., Nuclear Instruments and Methods in Physics Research A704 (2013) 131–139.

Narrow energy spread, small emission spots, further extend capability

- Emission spot size drives spatial resolution improvement
- Nuclear Resonance Fluorescence[1]: enable high-specificity identification of explosives, contraband and other materials
  - Lines 2 -10 MeV
  - $\Delta E_{photon} \leq 2\%$ enables signal; strong benefit if lower
  - Dose reduced orders of magnitude
  - Very low ΔE_{photon} may enable isotopic/enrichment image

≤ micron emission spot: resolution



Simulation: Glen Warren (PNNL)

NRF: Reduce time to detect ~80x
Cargo relevant objects in minutes

IO	#5	#8	#10
Isotope	^{235}U	^{239}Pu	^{12}C
Time-to-Detection [min]			
MPS-scattering	8	13	1
MPS-transmission	3	160	2
Brems-scattering	640	940	3
Brems-transmission	690	530	2

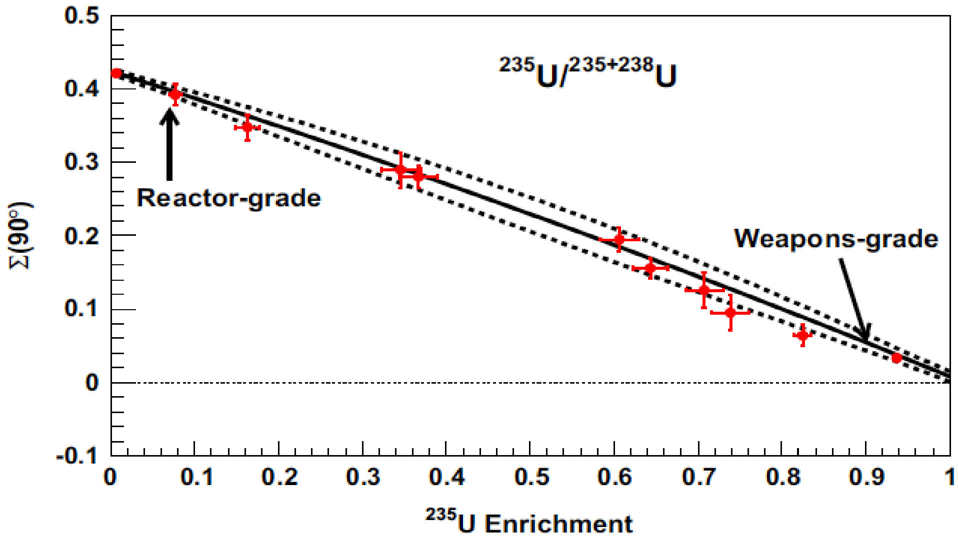
Simulation: Glen Warren, PNNL

Pulsed, polarized beams enable novel signatures
Access to 3D information, isotopics, and more

- Pulsed, narrow-angle 'pencil' beam enables 3D resolution
  - Backscatter to date limited by brems. pulse structure & broad energy spread
  - Thomson scattering: pulsed pencil beam would enable high resolution
    enhance other 3D methods such as EZ3D (Passport)

J. Callerame, AS&E, Advances in X-ray Analysis, Volume 49, 2006
M. Kinlaw et al, INL

- Polarized photon beam: photo-fission signal in and out of plane reveals isotope ratios



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