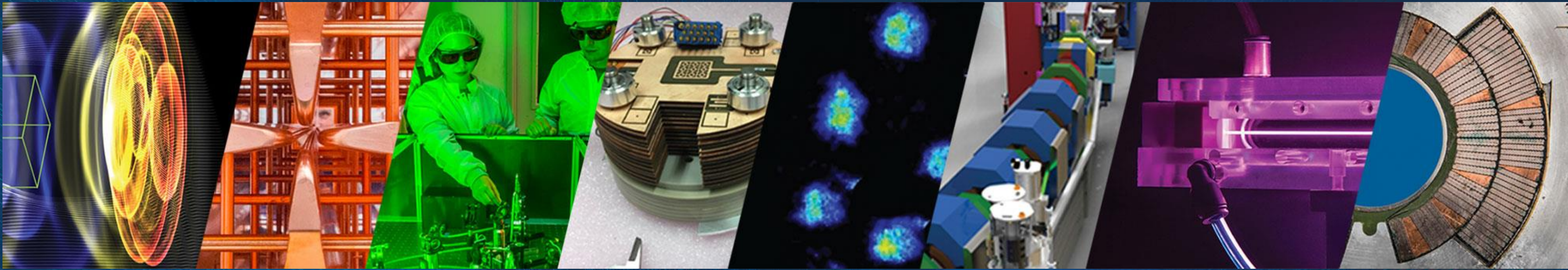
Laser-plasma accelerator (LPA) driven radiation generation and applications

Jeroen van Tilborg, BELLA Center – LBNL
+ large team of contributors at LBNL and partner institutions



LINAC-2026

Daejeon, South Korea, August 19th 2026

This work was supported by the Office of Science of High Energy Physics (HEP) and Basic Energy Sciences (BES) under Contract No. DE-AC02-05CH11231, by the Defense Advanced Research Projects Agency (DARPA), by the U.S. DOE National Nuclear Security Administration Defense Nuclear Nonproliferation R&D (NA-22), and through a collaborative grant from TAU Systems Inc.

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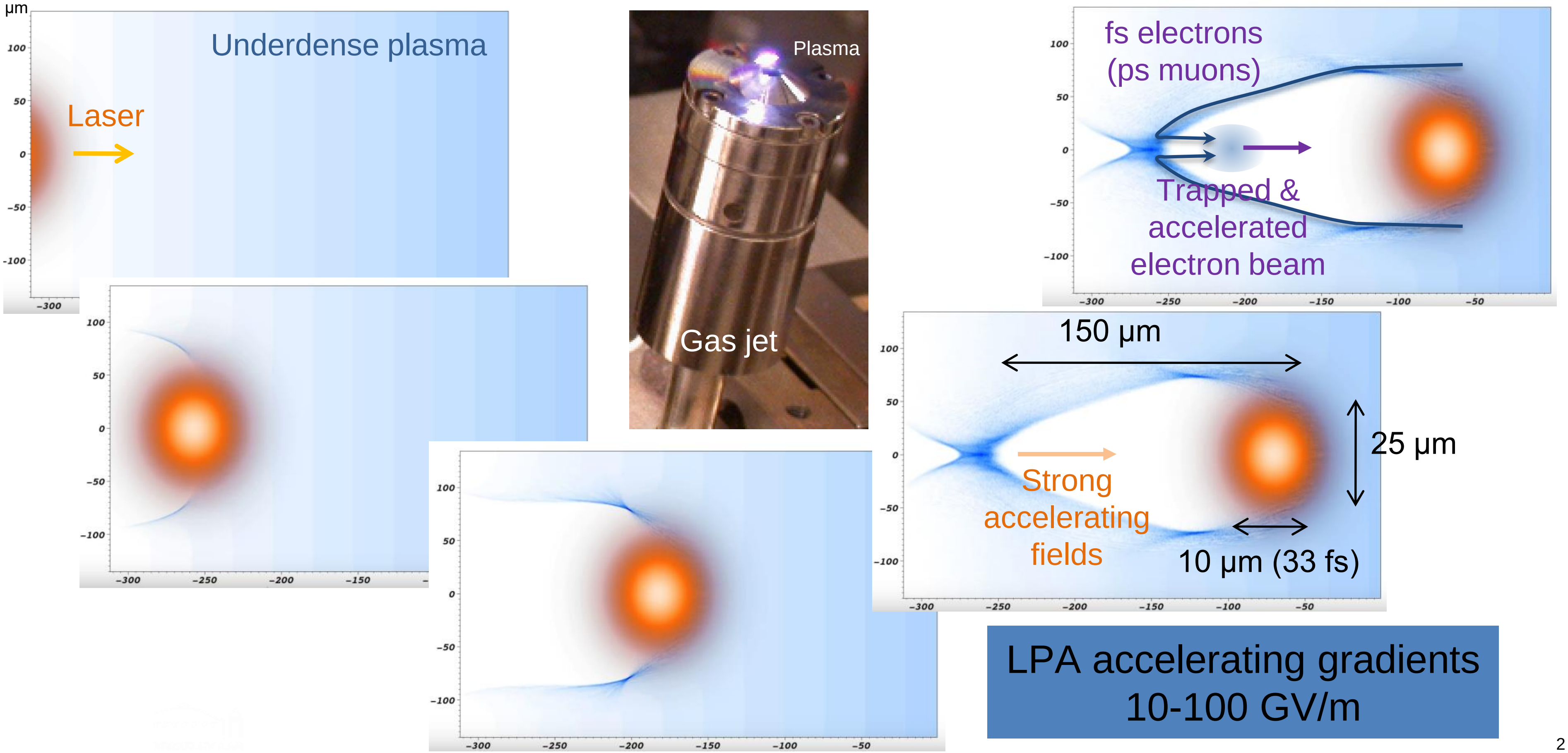
Compact, high-gradient (10-100 GV/m), Laser Plasma Acceleration from mm-cm plasma structures

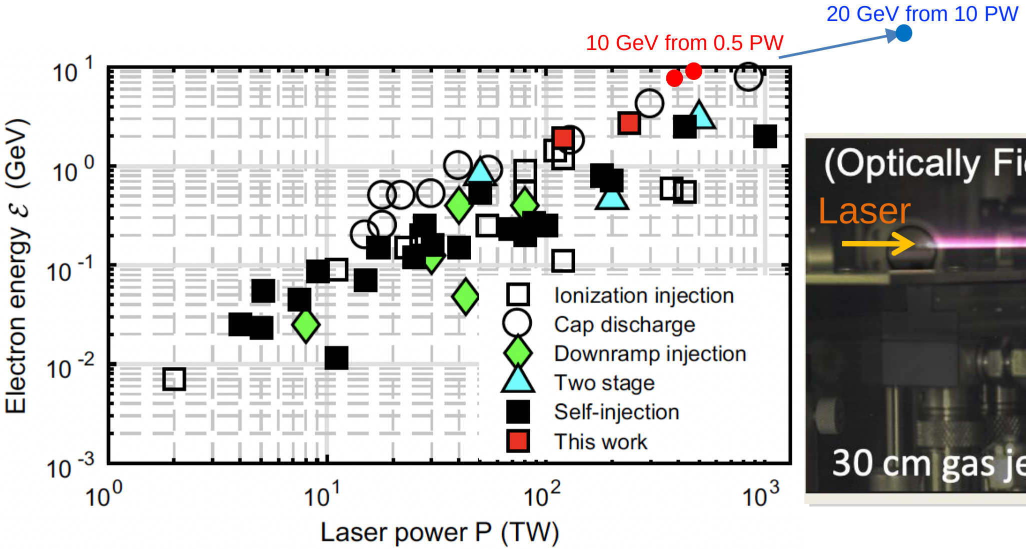


LPA accelerating gradients 10-100 GV/m

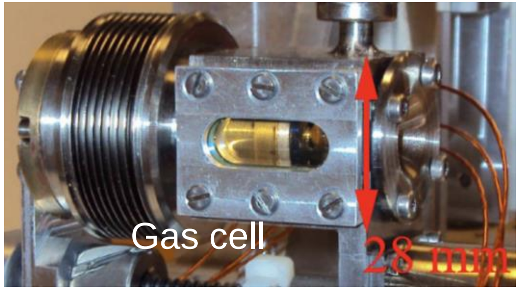
100s MeV with (sub)100 TW systems and >5 GeV with PW-class systems are maturing fast & plentiful → global pursuit of repetition rate increases & applications

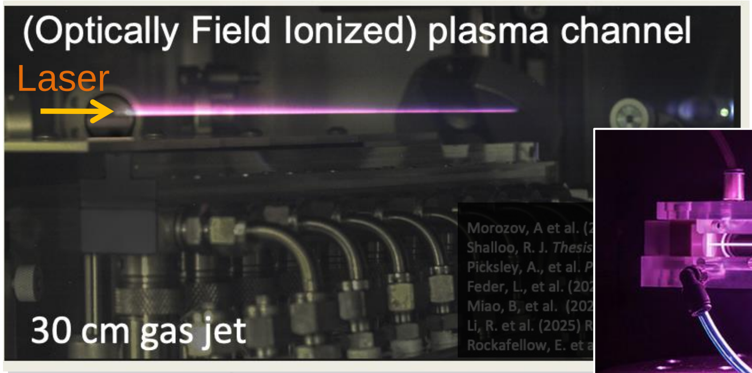
LPA unique as core accelerator technology

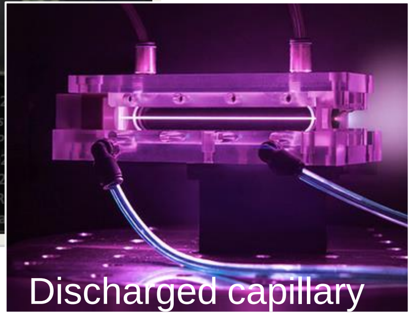
- High-gradient → compact "deployable" systems
- High-energy → deep penetration
- Point-source & low divergence → excellent resolution
- Strong peak current → high peak flux
- Control knobs → AI/ML optimization, active stabilization



S. Mangles "*An Overview of Recent Progress in Laser Wakefield Accel. Experiments*", Proc. CAS-CERN Accel. School (2014);
K. Poder Phys. Rev. Lett. 132, 195001 (2024)



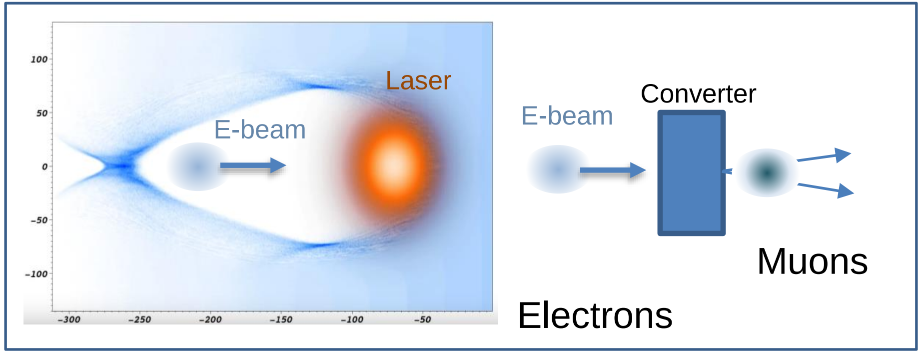


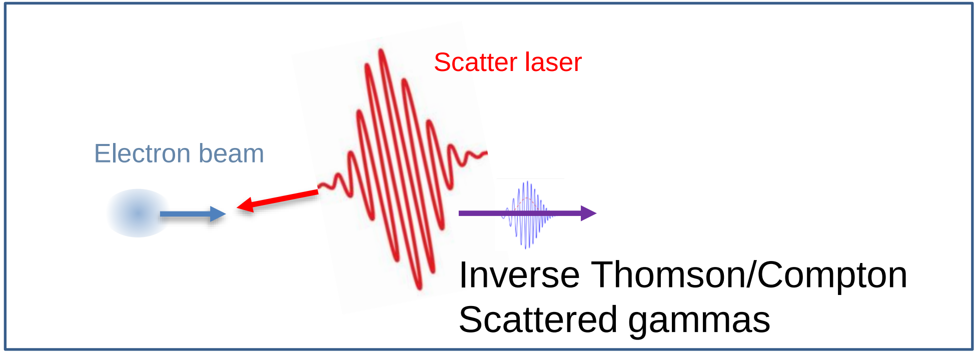


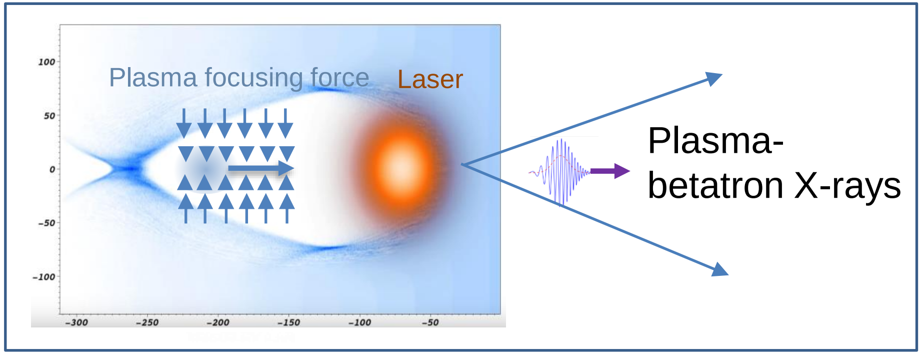
Max electron energy = Accelerating gradient x Length of accelerator

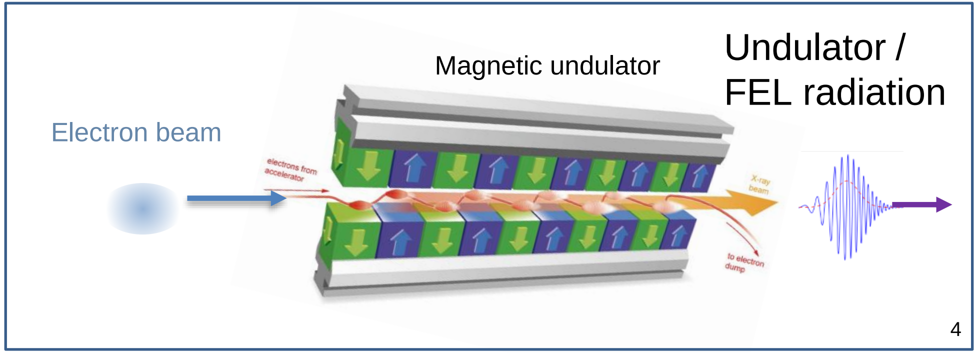
Outline

- Single-stage e-beams at 10 GeV & directional muons
- Plasma-betatron X-rays
- Inverse-Compton-Scattered /Thomson-scattered gamma rays
- LPA-driven free-electron lasers

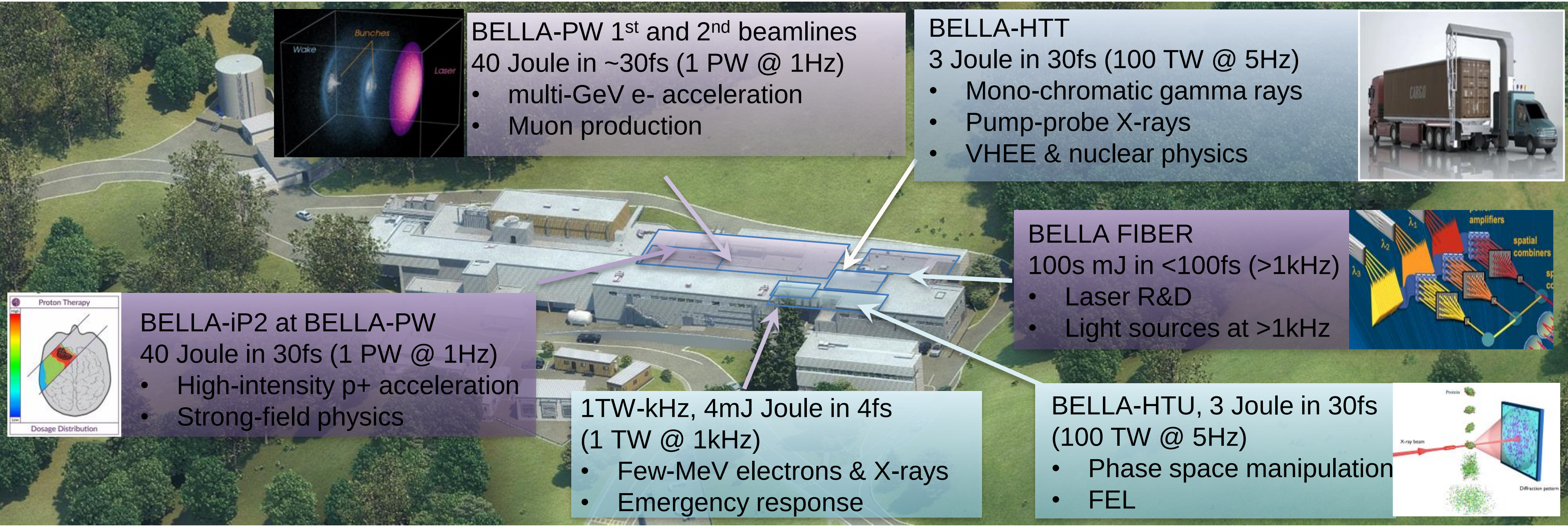






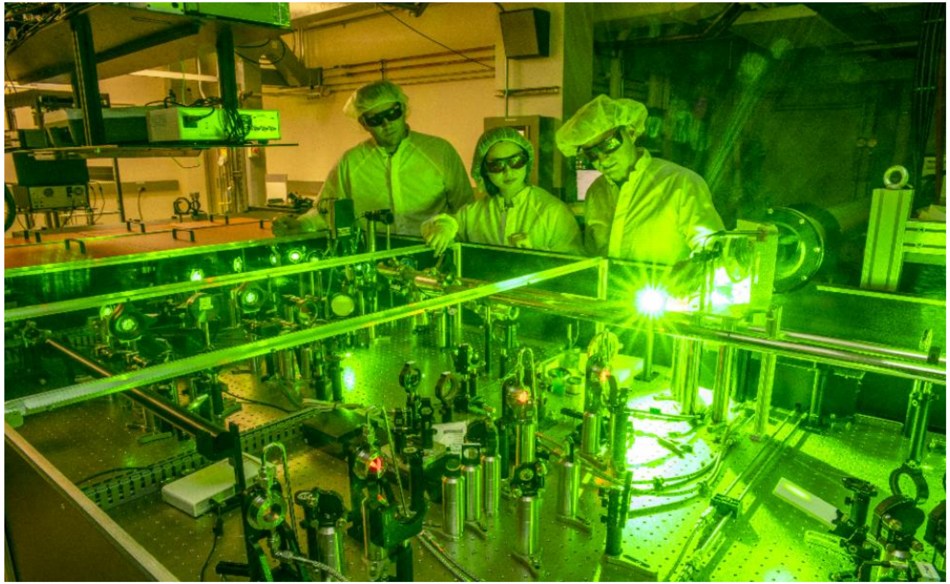


BELLA Center houses multiple laser facilities addressing laser, accelerator, and light source R&D and applications



Pictures of the HTU/HTT and PW laser systems at BELLA Center

BELLA “HTU / HTT” 100TW (2-3 Joule in 35 fs)

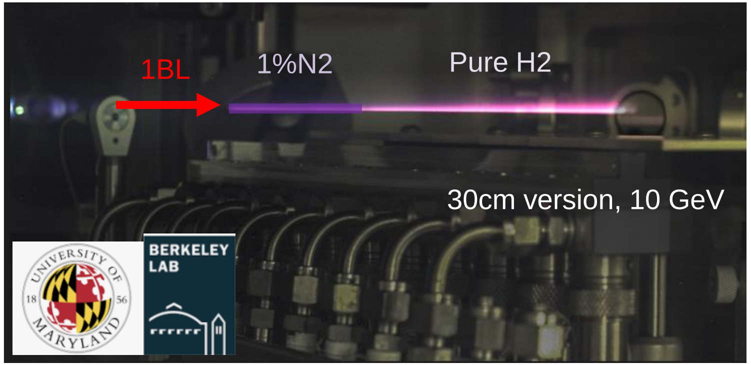


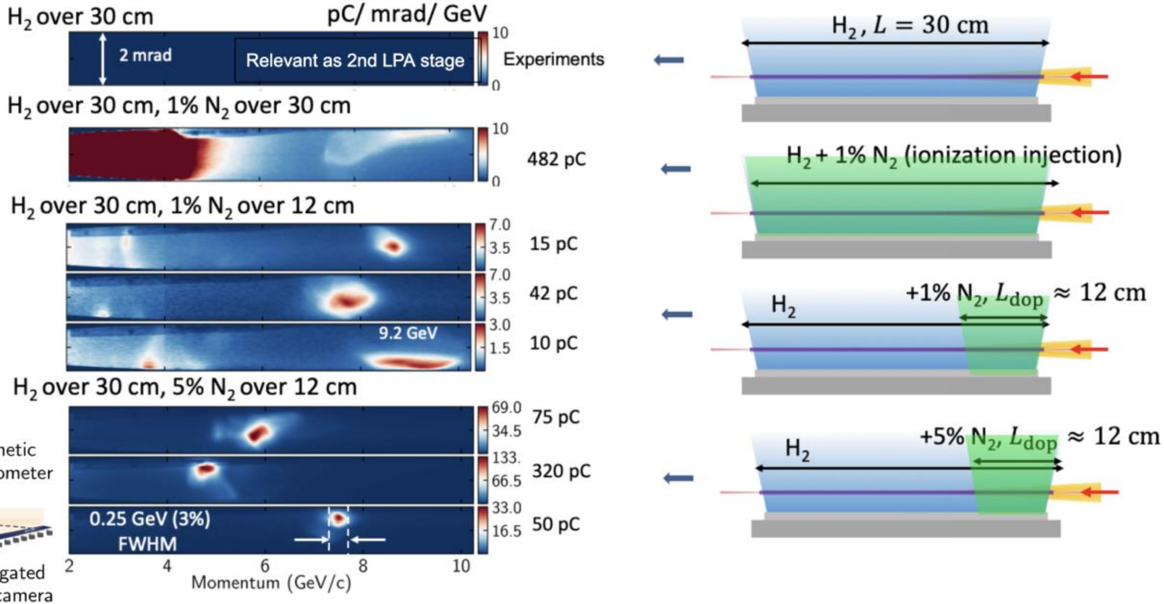
BELLA PW (40 Joule in 40 fs)

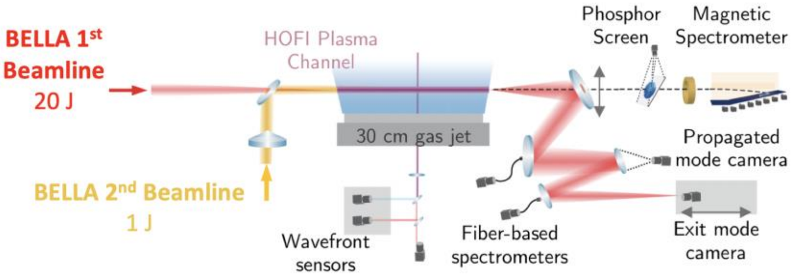
BELLA HTT, HTU & PW systems currently operate at 1 Hz

Controlling electron trapping using a nitrogen dopant demonstrated high-quality beams at the 5-10 GeV level (using 20 Joule laser driver)

BELLA Center: Picksley et al. Phys. Rev. Lett. 133, 255001 (2024)



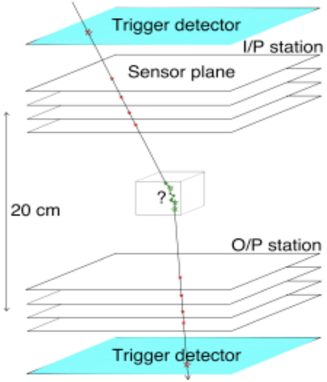


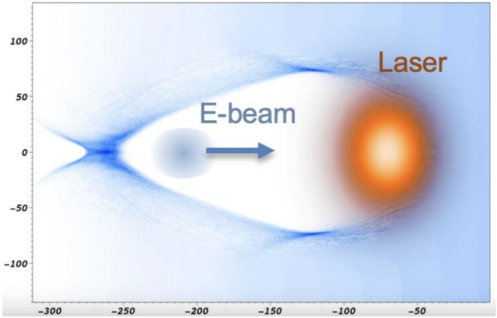


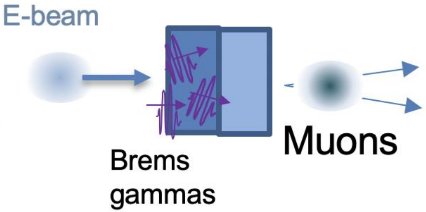
Picksley, A., et al. *Physical Review Letters* 133, 25 (2024)
OFI **Mode Leakage:** Clark, T. R., et al. *PRE* 61, 2 (2000).

Overcome OFI leakage by ionizing neutrals: Morozov, A et al. (2018). *PoP*, *25*(5), Shalloo, R. J. *Thesis 2018,* Picksley, A., et al. (2020). *PRE*, *102*(5), Feder, L., et al. (2020). *PRR*, *2*(4), Miao, B, et al. (2020) *PRL* 125.7, Rockafellow, E, et al. (2025) PoP

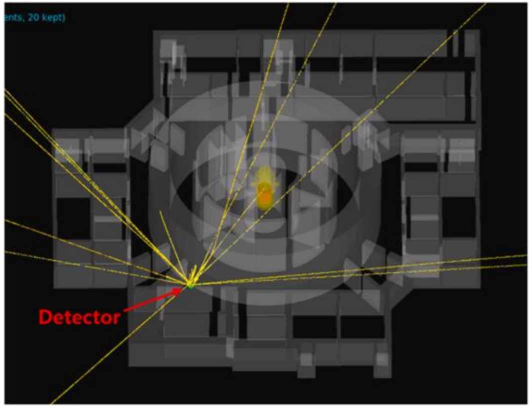
Muons penetrate deep (1.1 GeV/m in steel, 0.2 GeV/m water, 0.45 GeV/m rock), enabling radiography & scattering tomography



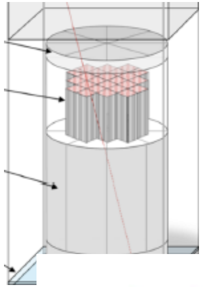


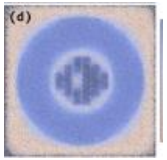


Pressurized water reactor
Y. Li et al. Nucl. Eng. Tech 58 (2026)

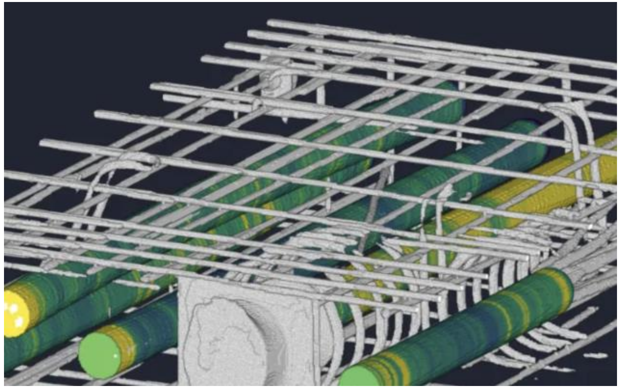


Bae et al. Sci Rep. 14 (2024)
Fuel rods in storage cask



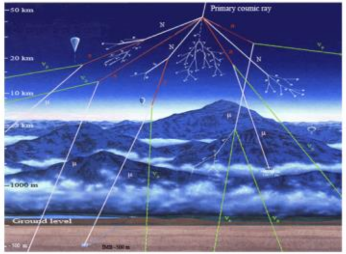


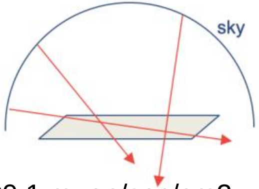
Bridge/infrastructure inspection



https://www.newcivilengineer.com/in-depth/national-highways-drives-forward-muon-scanning-for-bridge-inspections-30-04-2025/e/infrastructure inspection

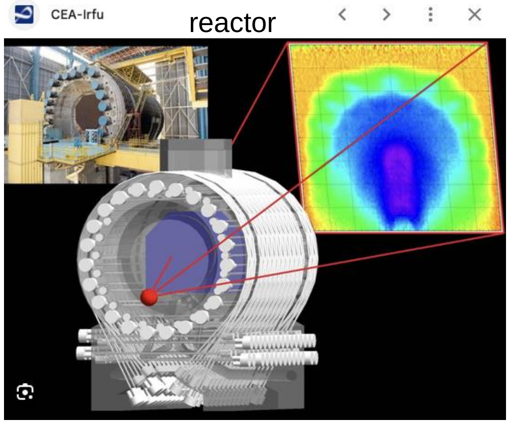
Source: cosmics





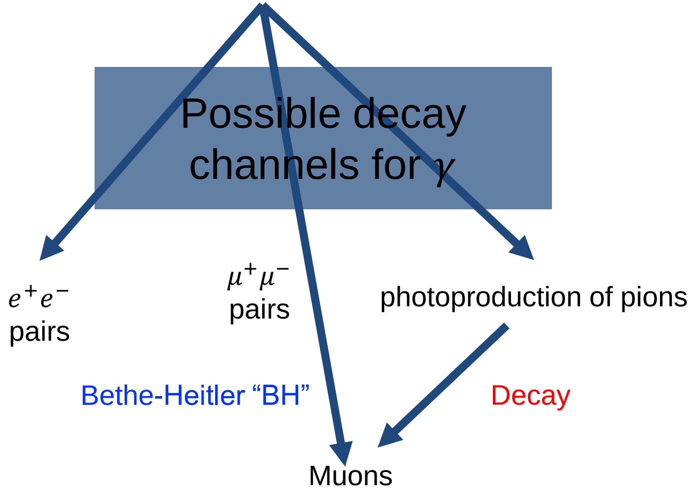
<0.1 muon/sec/cm2

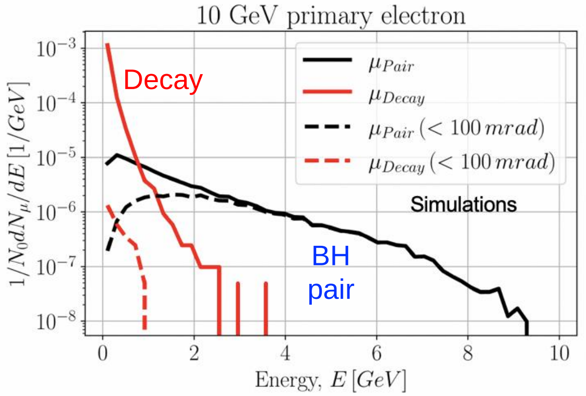
reactor

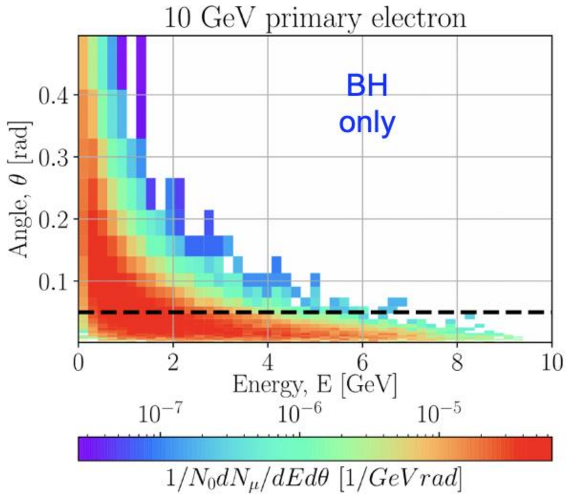


Bethe-Heitler process produces directional muons along LPA axis, at energies up to the electron beam energy

The dominating process is the production of gammas via Bremsstrahlung

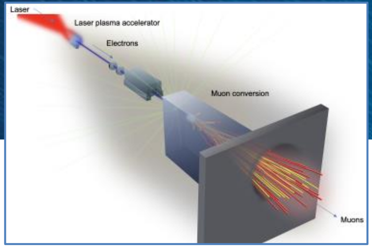




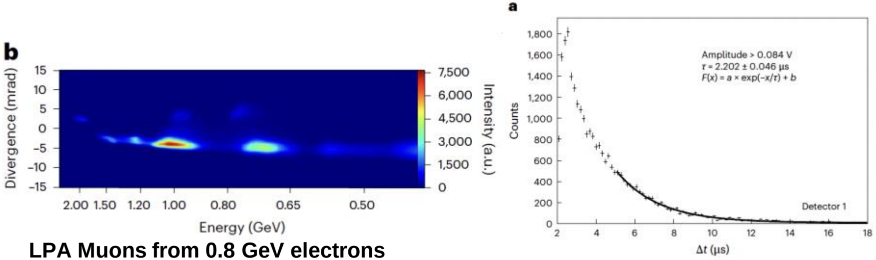


- Max muon energy up to max electron energy
- High-flux pion decay, isotropic
- BH at higher energies, 1/gamma low-divergence
- Transition point decay muons to BH muons is around 1 GeV

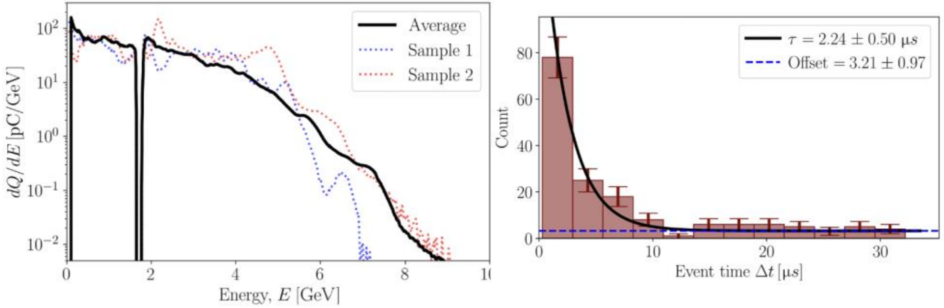
D. Terzani et al. Phys. Rev. AB 28, 103401 (2025)



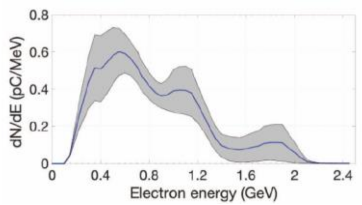
Recent years have seen surge in experimental demonstrations of a compact (LPA-based) active muon source

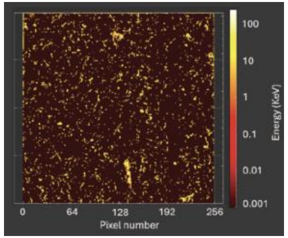


LPA Muons from 0.8 GeV electrons
Shanghai Superintense Ultrafast Laser Facility (SULF) – 1 PW laser
F. Zhang et al. "Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser" Nature Physics 21, 1050 (2025)

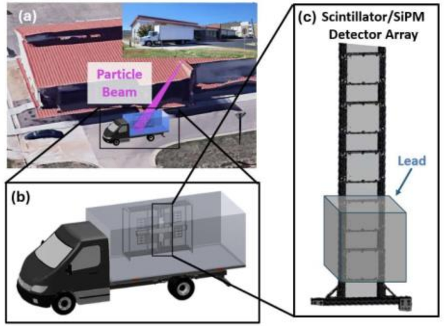


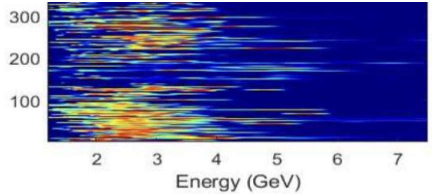
LPA Muons from 5+ GeV electrons
BELLA Center, LBNL – 1 PW laser
D. Terzani et al. " Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator" Phys. Rev. AB 28, 103401 (2025)





LPA Muons from 2 GeV electrons
ELI NP - 1 PW laser
I. Calvin et al. "Experimental evidence of production of directional muons from a laser-wakefield accelerator" Plasma Phys. Contr. Fusion 68, 035015 (2026)





LPA Muons from 5+ GeV electrons
ALEPH Colorado State - 1 PW laser
K. Zhu et al. "Single-Shot High-Energy Muon and Particle Radiography with a Multi-GeV LWFA-Driven Source" ArXiv *https://arxiv.org/pdf/2607.12984*

Simulations: Titov et al. PR-STAB (2009); Rao et al. Plasma Phys. Control Fusion 60 (2018); Calvin et al. Advances Laser-Driven Nucl. Phys (2023); Geng et al. Phys. of Plasmas (2024)

At BELLA PW, we use the front section of 10-feet beam dump as muon converter source & detector shielding: muons lose 3-4 GeV before exiting

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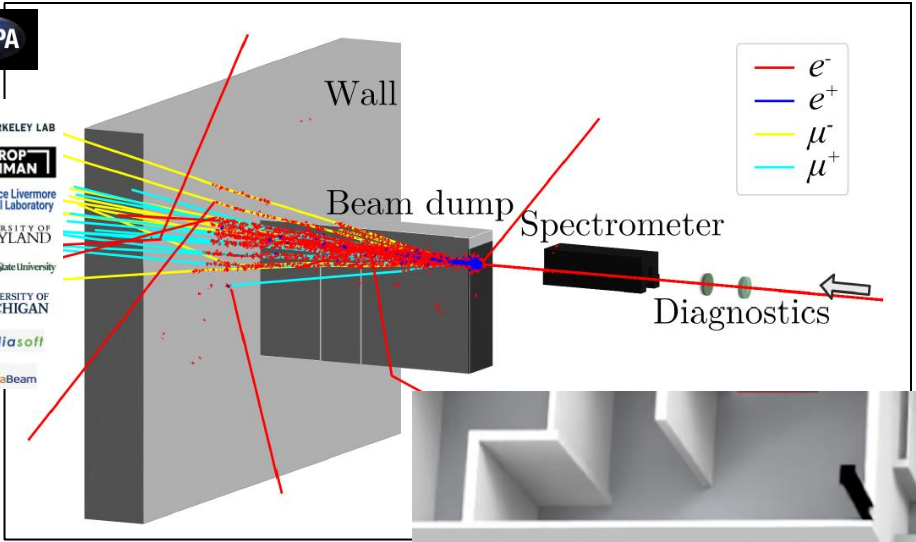
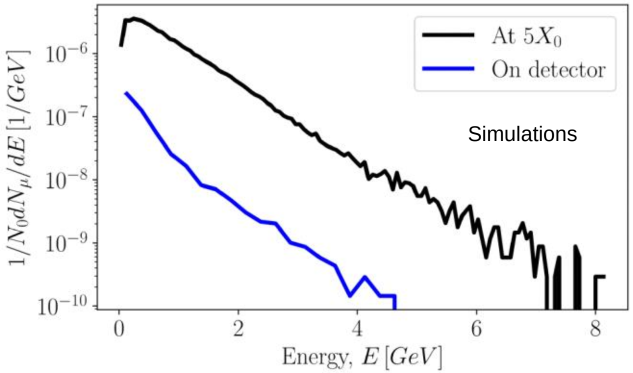
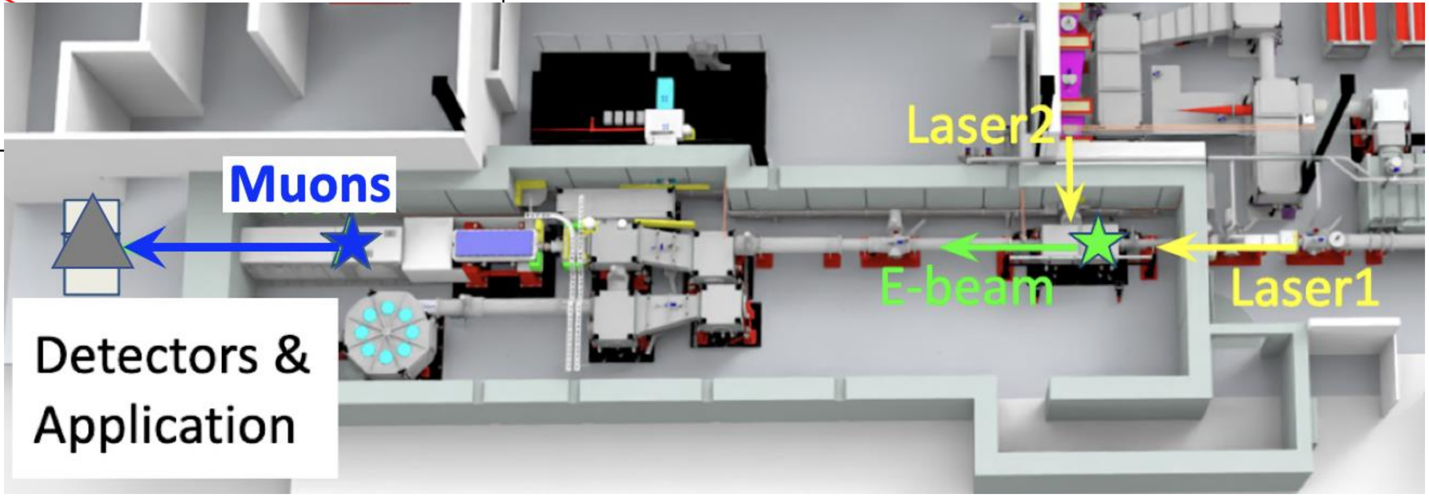
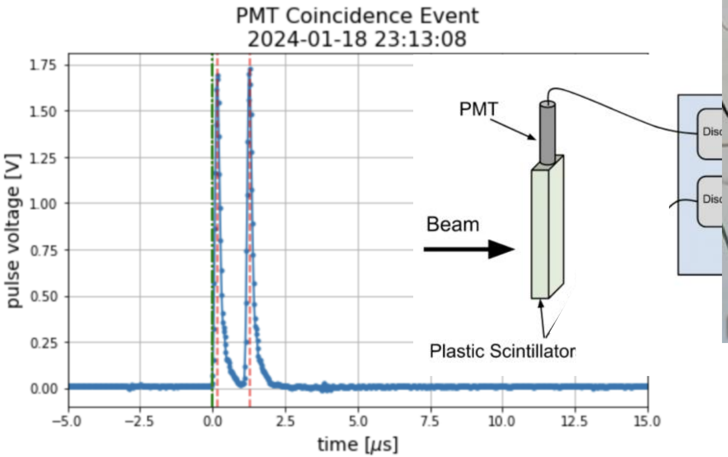




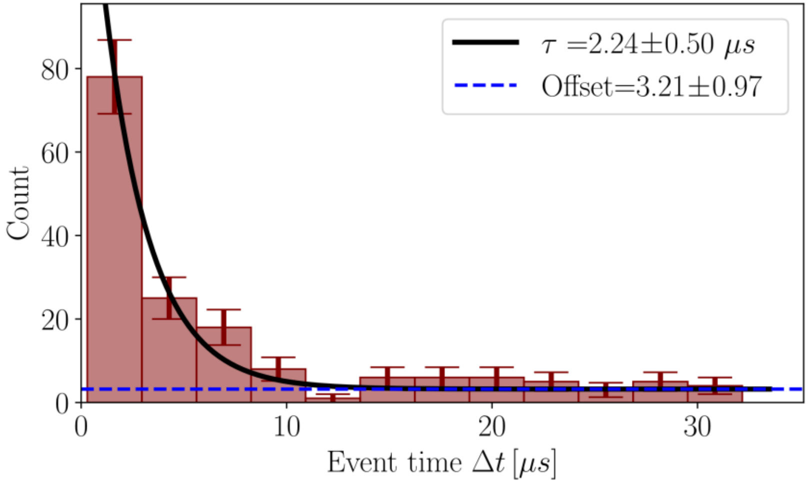


D. Terzani et al. " Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator" Phys. Rev. AB 28, 103401 (2025)

First verification of LPA muons involved measuring the life time of the particles when stopped inside the scintillator detector



Fitting all the data collected by the scintillators with an exponential distribution + a constant background



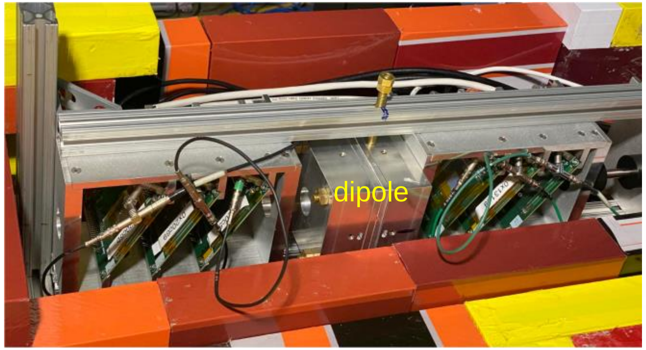
Data show muon decay ($\tau \simeq 2.2\ \mu s$)

Agrees with muon life time

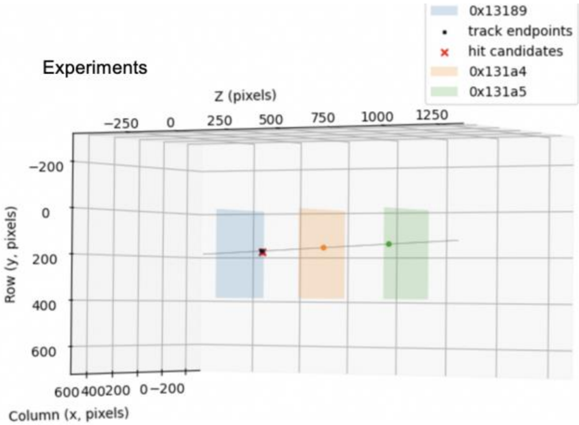
D. Terzani et al. Phys. Rev. AB 28, 103401 (2025)

Stacked 2D detectors to take advantage of active source directionality: roughly same counts in 15 minutes of intermittent LPA as 10 days of cosmics

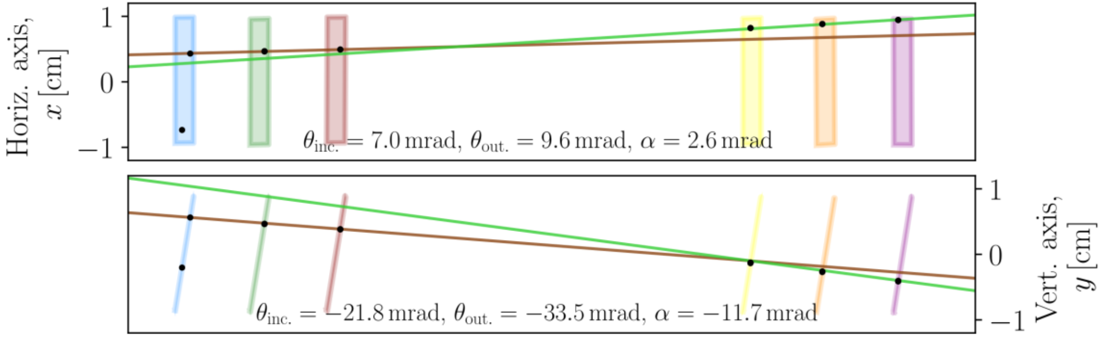
2x2cm Si track detector (3-stack)



BELLA beam telescope with 6 ITkPixV2 Single Chip Cards



Experiments



Tracking muon vectors

- From LBNL Physics group
- Allows discrimination against background
- Two stacks: scattering angle, e-beam energy
- Minimal cosmics due to small acceptable angle
- Next steps: bigger detectors (>2x2cm) to increase count rate → muography & spectrum
- Mote, and higher-energy BH muons from single-stage/staging LPA (>>10 GeV)

D. Terzani et al. submitted, ArXiv at *https://arxiv.org/abs/2607.21830*

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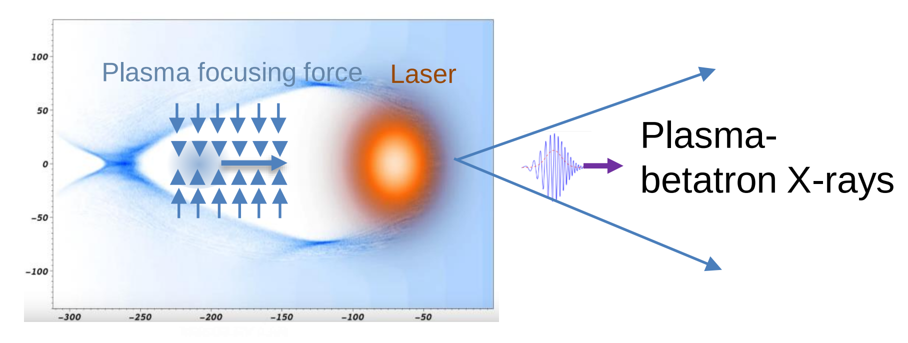
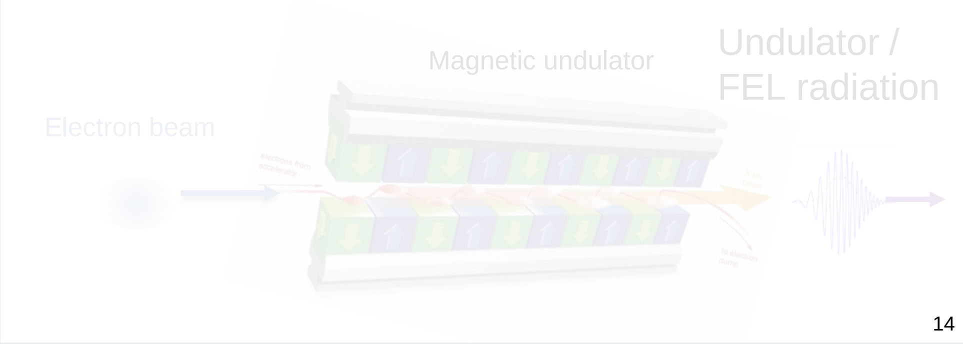




LPA betatron: 2025 Nature Comm; Phase-Contrast imaging in 30 micron “laser-shocked” water jet at BELLA HTT; e-beam deflectometry as ”2nd messenger”

nature communications

Article

https://doi.org/10.1038/s41467-025-67224-3

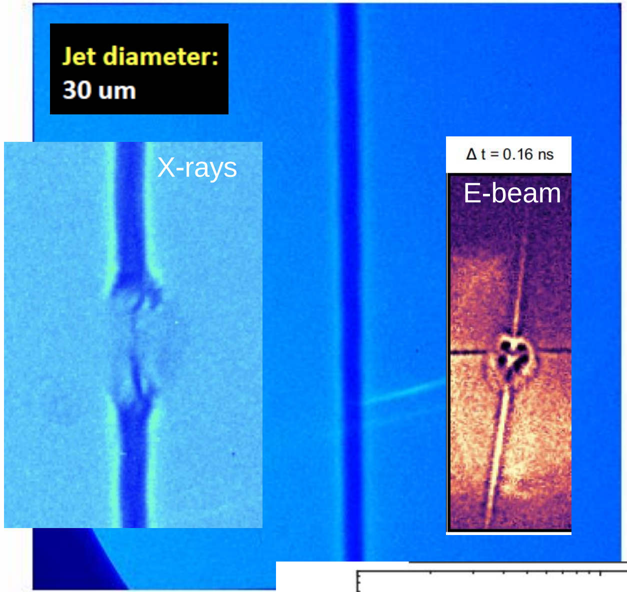
Multi-messenger dynamic imaging of laser-driven shocks in water using a plasma wakefield accelerator

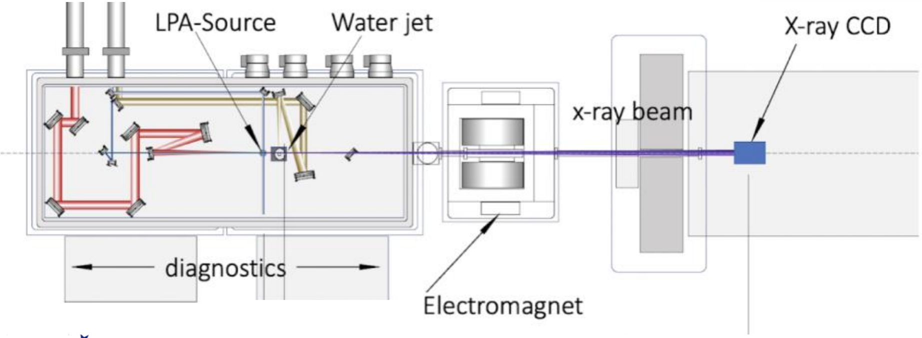
Published online: 16 December 2025

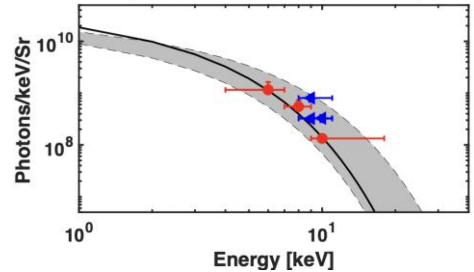
Mario D. Balcazar[1,2], Hai-En Tsai[3], Tobias M. Ostermayr[3],

LaserNetUS Experiment at BELLA;

M. Balcazar, C. Kuranz, *et al.* (**U Mich**), Nat. Comm. 17, 529 (2026)







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Outline

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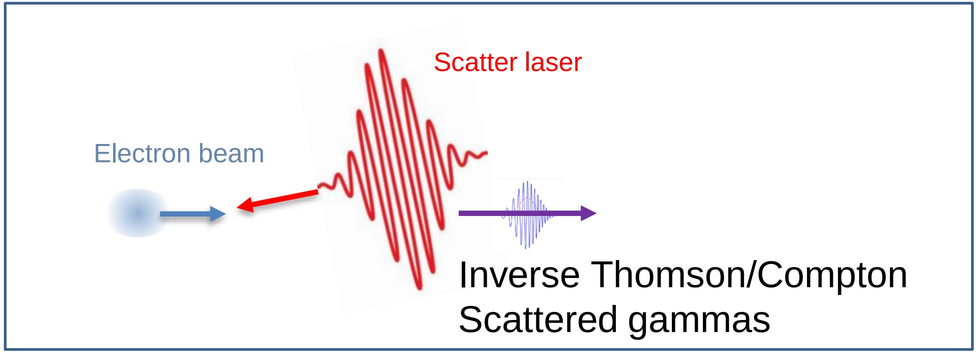
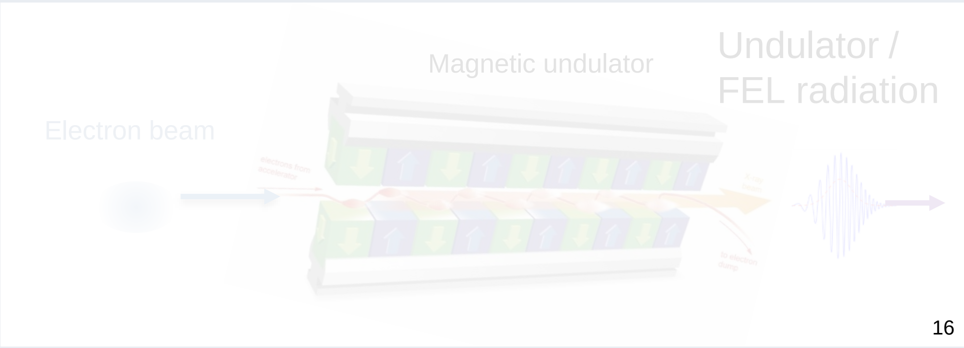
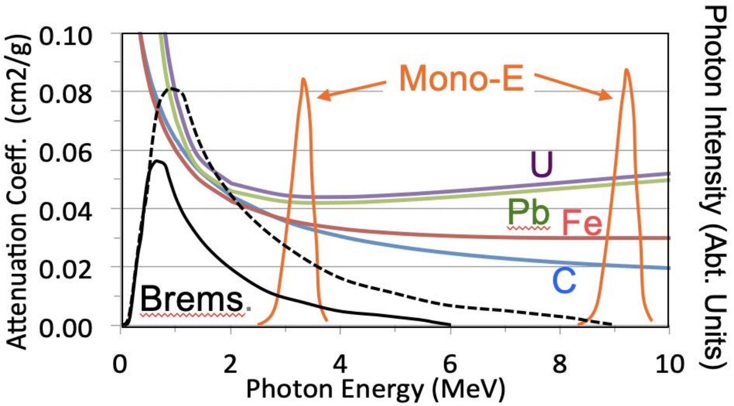




Tunable, mono-energetic hard X-rays & gammas accessible through LPA Thomson scattering

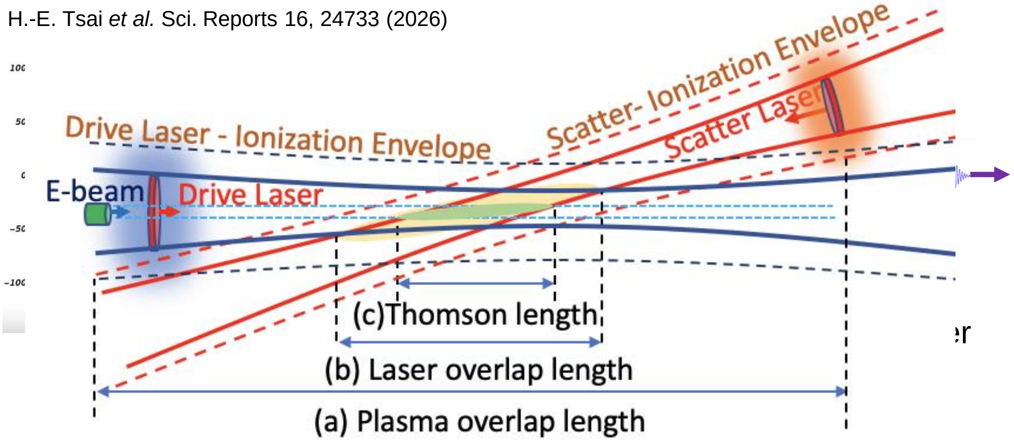


ICS (Thomson scattering)

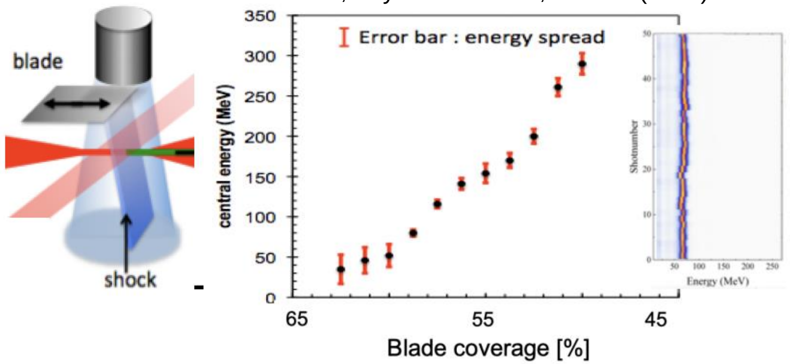
- Multi-MeV photons from 100s MeV electrons: deep-penetrating (~10cm)
- Small bandwidth (few%-10%) possible
- Tunable central photon energy
- Radiography, Nuclear Resonance Fluorescence, Photo-fission signatures with precision excitation (strongly reducing dose needed), with material specificity
- Femtosecond & micron source size
- "Pencil beam", low divergence
- Focused beams at <180º → geometric overlap

$$\omega_x \underset{\theta_L=\pi}{\simeq} \omega_L \frac{4\gamma^2}{1+\gamma^2\theta_x^2},$$

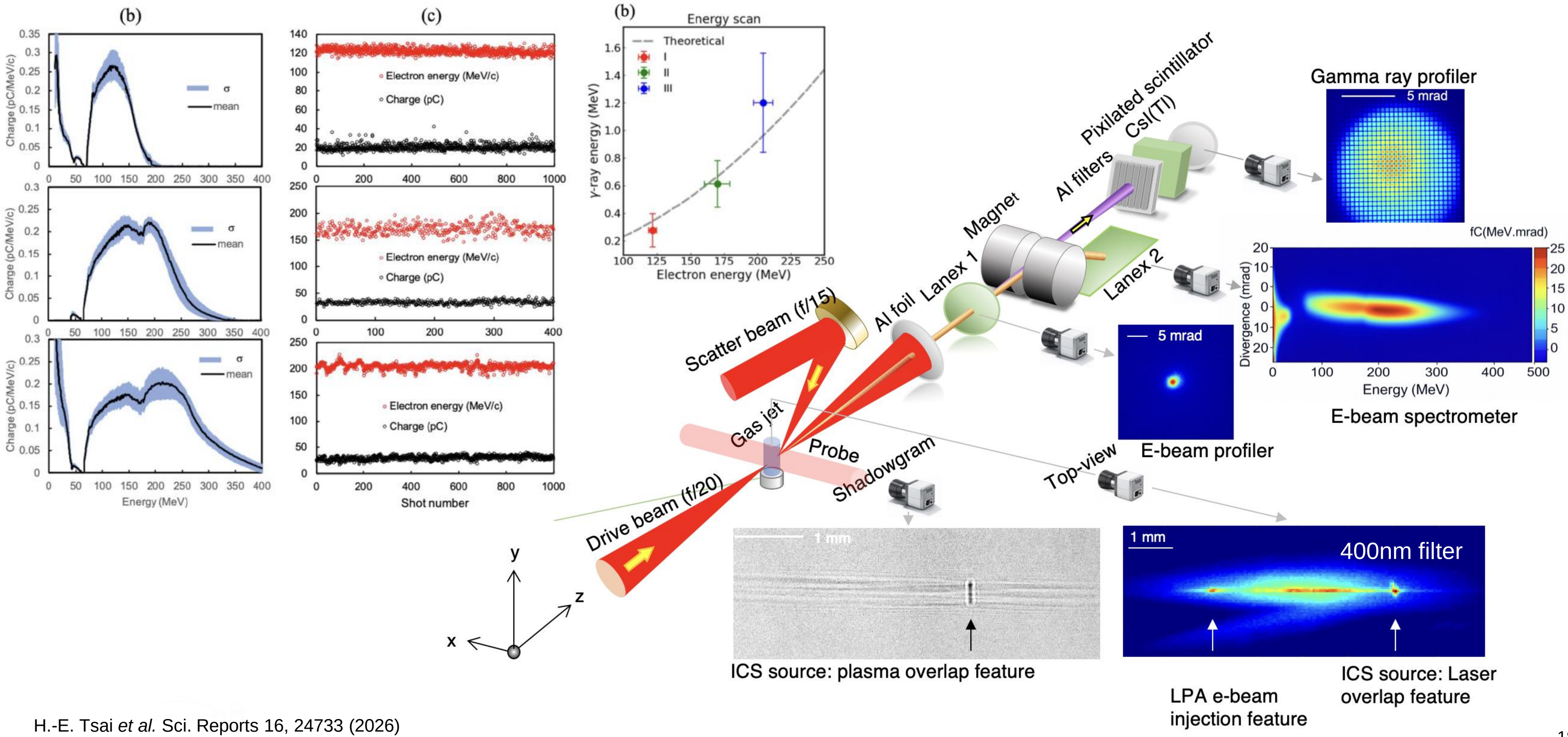
H.-E. Tsai *et al.* Sci. Reports 16, 24733 (2026)



H.-E. Tsai, Phys Plasmas 25, 043107 (2018)

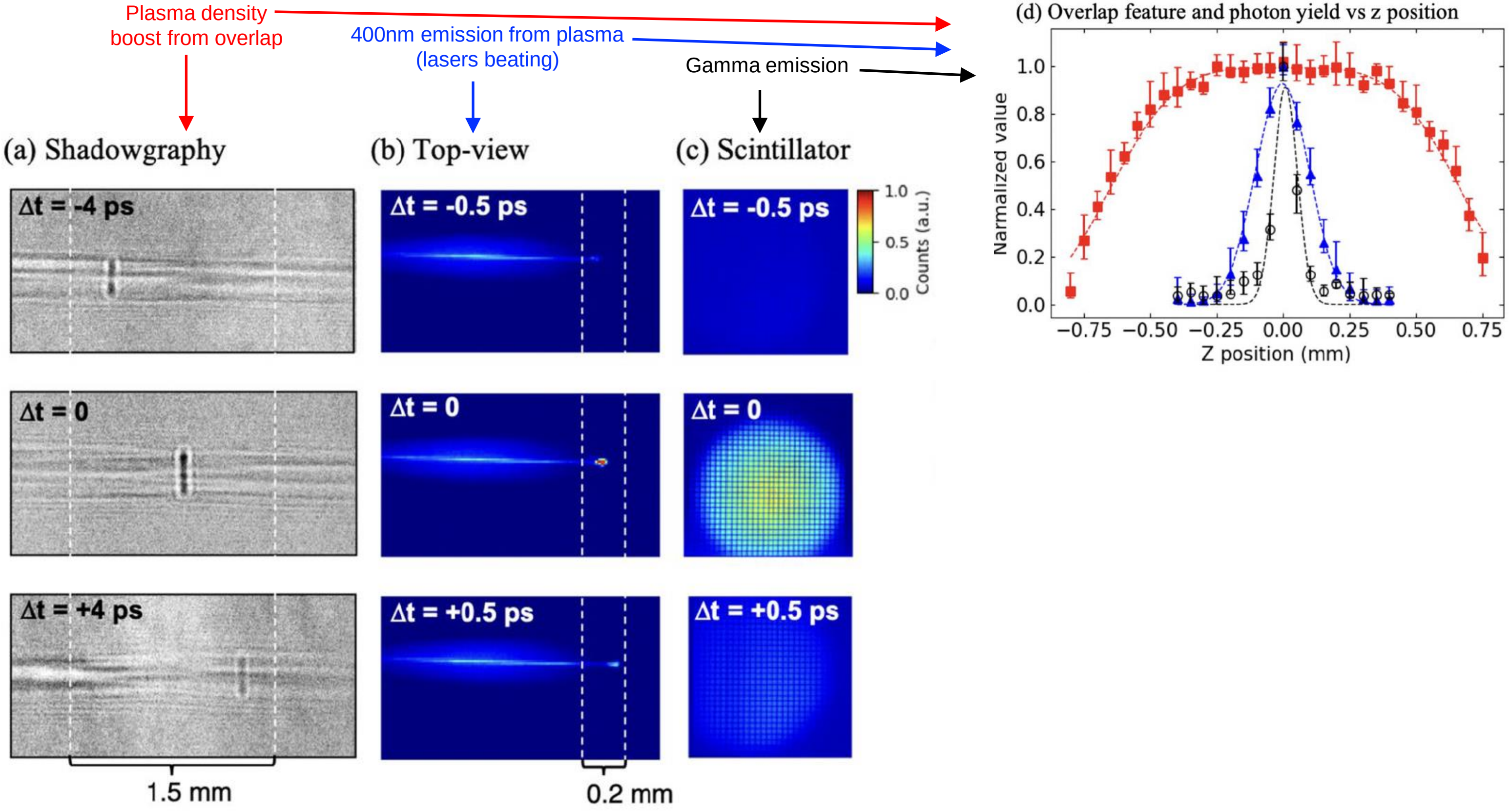


Experiments on BELLA HTT conducted over a series of campaigns, with emphasis on diagnostics for Thomson source optimization



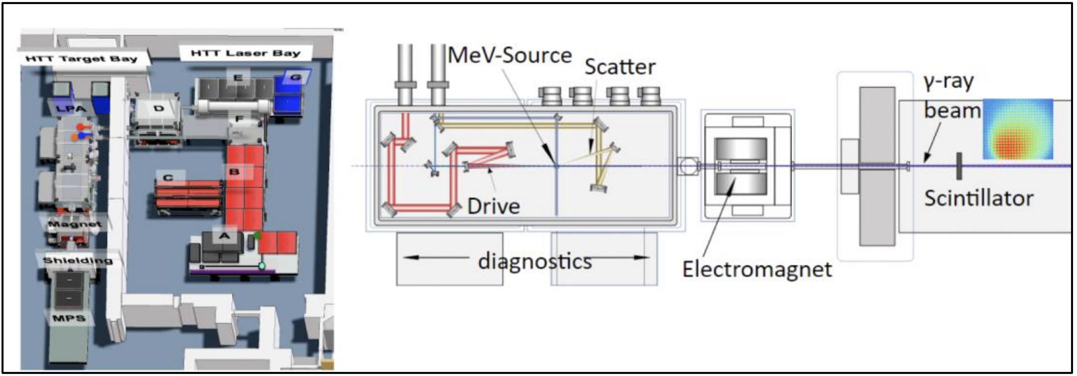
H.-E. Tsai *et al.* Sci. Reports 16, 24733 (2026)

Plasma, optical, and gamma diagnostics assist in source optimization (temporal overlap & flux increase) → foundation for applications in next slide

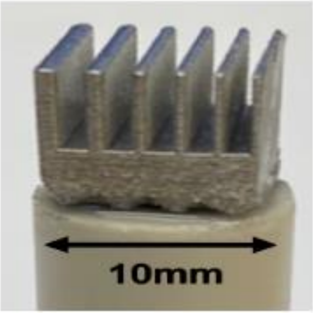


H.-E. Tsai *et al.* Sci. Reports 16, 24733 (2026)

Several key applications demonstrated: high-resolution lens-less imaging (radiography), multi-shot 3D tomography, and LIDAR time-of-flight characterization



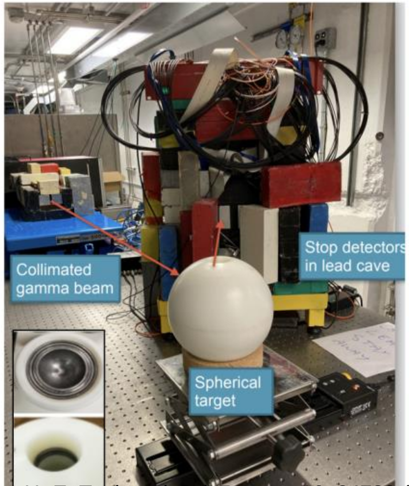
Test object (Inconel alloy)



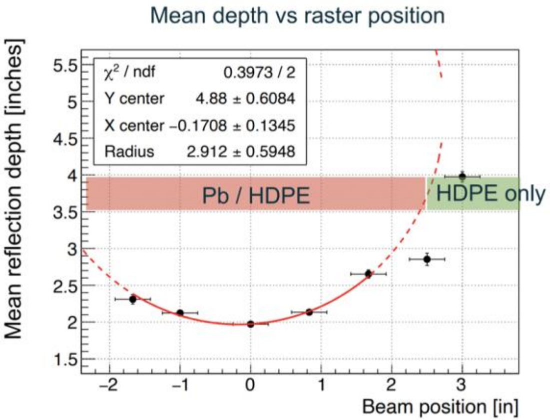
Measured with BELLA HTT gamma ray source

C. Thornton et al.,
arxiv.org/html/2404.09270v1

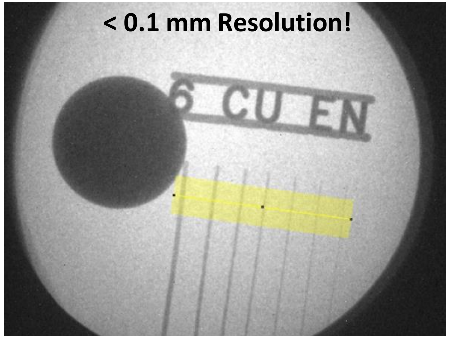
Multi-shot, multi-angle tomographic imaging
(takes advantage of shot-to-shot source stability)



H.-E. Tsai *et al.* Sci. Reports 16, 24733 (2026)



Heller R, Cates JW, Chen Q et al. First experimental demonstration of Gamma-ray LiDAR with a quasi-monoenergetic photon beam [version 1; not peer reviewed]. Nucl Sci Technol Open Res 2024, 2:53 (https://doi.org/10.21955/nuclscitechnolopenres.1115144.1)



H.-E. Tsai *et al.*
Sci. Reports 16, 24733 (2026)

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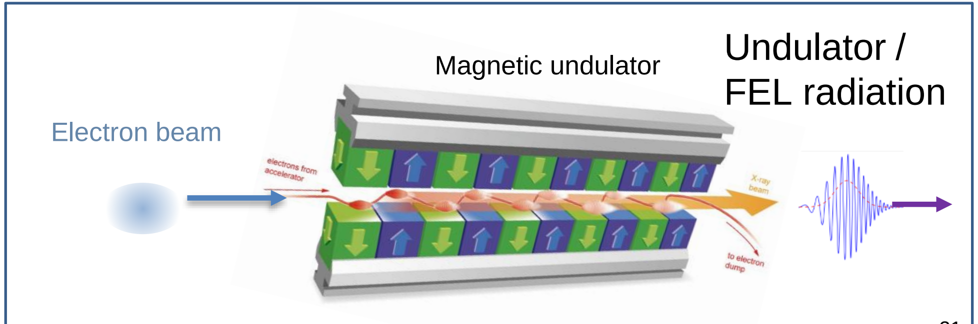
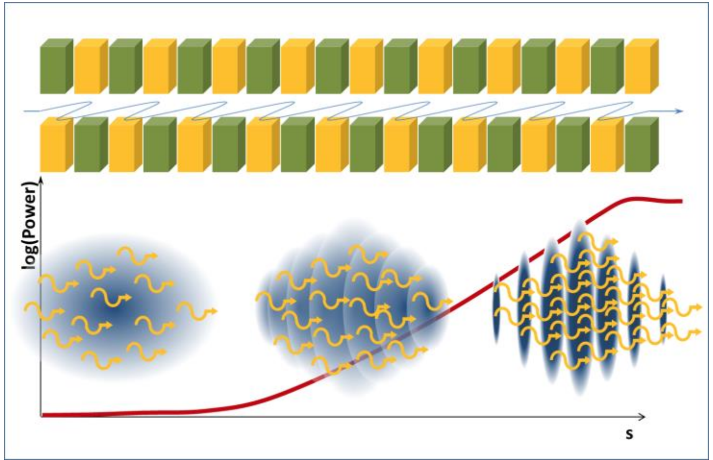
Outline

- Single-stage e-beams at 10 GeV & directional muons
- Plasma-betatron X-rays
- Inverse-Compton-Scattered /Thomson-scattered gamma rays
- LPA-driven free-electron lasers

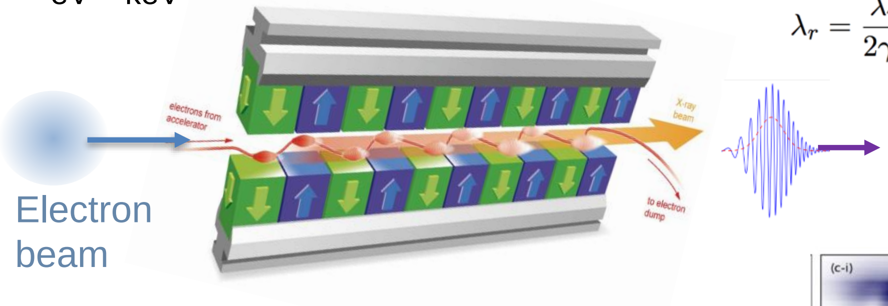


FELs driven by LPAs represent a great validation of electron beam brightness (beam quality) and stability… strong international & industrial interest

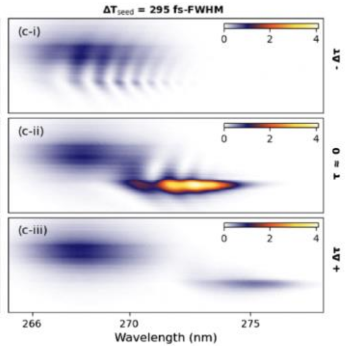


Electrons oscillate in periodic B-field
- Incoherent & coherent (FEL) undulator radiation is emitted
- eV – keV

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$



Labat *et al* Nat. Phot 2022;
PRL 136, 245001 (2026)



PHYSICAL REVIEW LETTERS 136, 245001 (2026)

Laser-Plasma Based Seeded Free Electron Laser in the High-Gain Regime

Marie Labat,[1,*] Susanne Schöbel,[2,3] Amin Ghaith,[2] Franziska Marie Herrmann,[2,3] Maxwell LaBerge,[2] Eléonore Roussel,[4] Ulrich Schramm,[2,3] Patrick Ufer,[2,3] Marie-Emmanuelle Couprie,[1] and Arie Irman[2]
[1]Synchrotron SOLEIL, L'Orme des Merisiers, Départementale 128, 91190 Saint-Aubin, France
[2]Helmholtz-Zentrum Dresden - Rossendorf, Bautzner Landstrasse 400, 01328 Dresden, Germany
[3]Technische Universität Dresden, 01062 Dresden, Germany
[4]Université de Lille, CNRS, UMR 8523–PhLAM–Physique des Lasers Atomes et Molécules, F-59000 Lille, France

Wang *et al* Nature 2021

Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

https://doi.org/10.1038/s41586-021-03678-x
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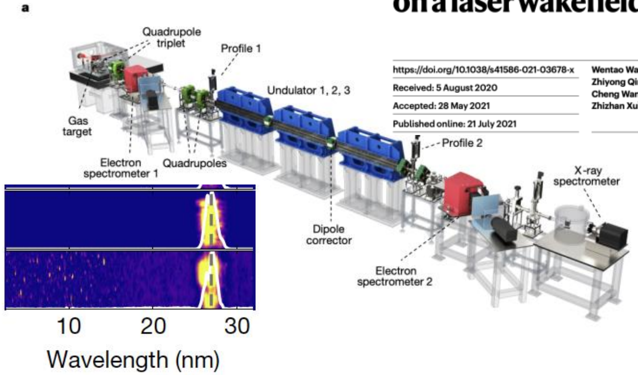
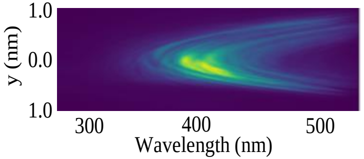
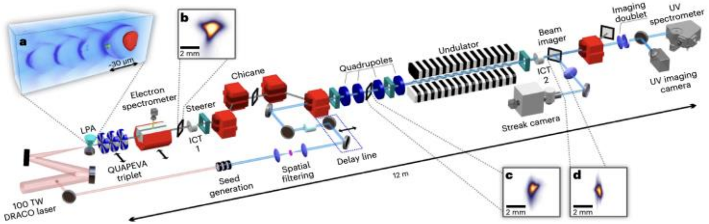
Wentao Wang[1,4], Ke Feng[1,4], Lintong Ke[1,2], Changhai Yu[1], Yi Xu[1], Rong Qi[1], Yu Chen[1], Zhiyong Qin[1], Zhijun Zhang[1], Ming Fang[1], Jiaqi Liu[1], Kangnan Jiang[1,3], Hao Wang[1], Cheng Wang[1], Xiaojun Yang[1], Fenxiang Wu[1], Yuxin Leng[1], Jiansheng Liu[1], Ruxin Li[1,3] & Zhizhan Xu[1]

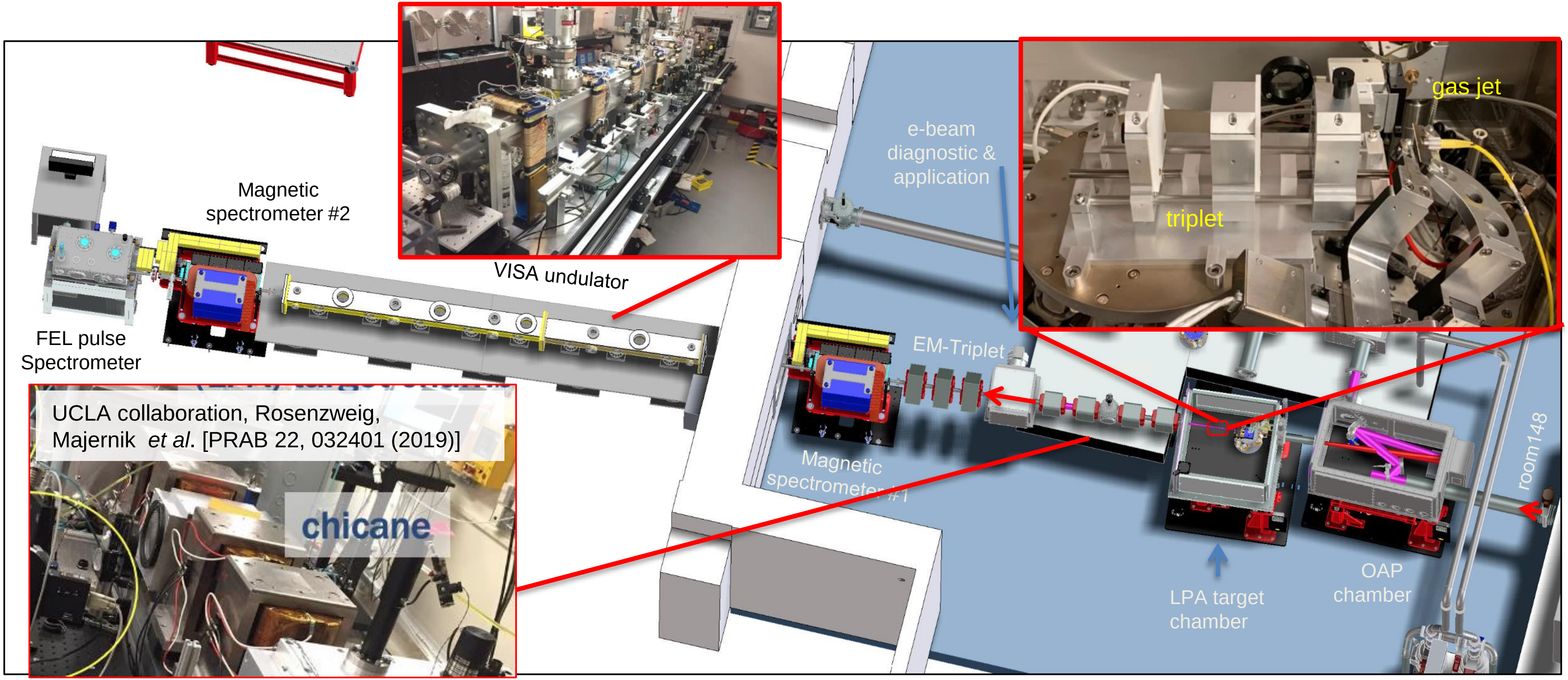


S. Barber (BELLA) Phys. Rev. Lett. 135, 055001 (2025)



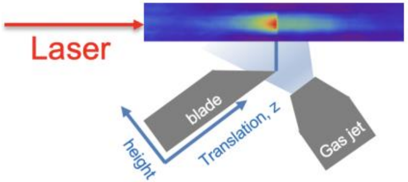


100 TW "HTU – undulator" system is developed for precision delivery of high-quality electron beams to (FEL) undulator



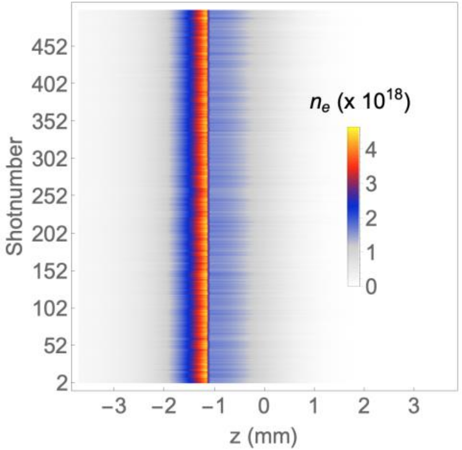
Accurate non-perturbative high-power laser focus monitoring system developed: key to active stabilization of laser on target & e-beam production

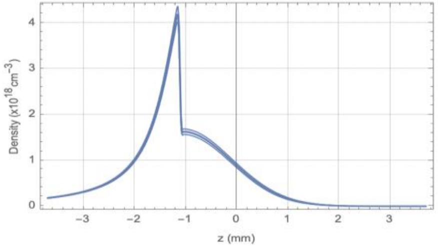
Robustness gas jet + shock plasma profile: S. Barber, unpublished



Density down-ramp

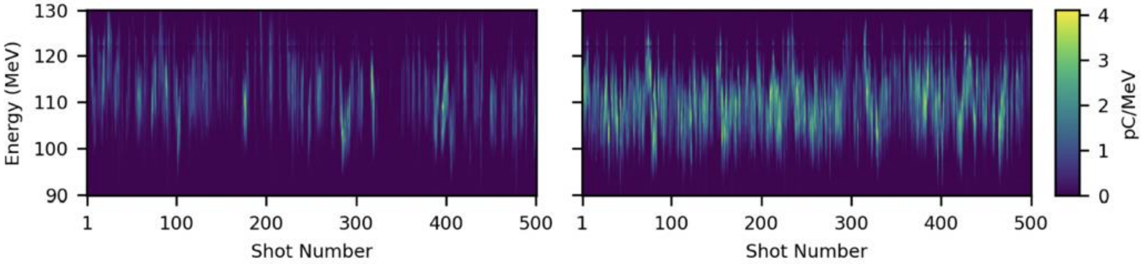
H. Suk et al., Phys. Rev. Lett. 86, 1011 (2001).
G. Fubiani, et al. Phys. Rev. E 73, 026402 (2006).
K. Schmid, et al. Phys. Rev. ST Accel. Beams 13, 091301 (2010).
J. Faure, et al.Phys. Plasmas 17, 083107 (2010).
Buck, et al.Phys. Rev. Lett. 110, 185006 (2013).
M. Hansson, et al. Phys. Rev. ST Accel. Beams 18, 071303 (2015).
S. K. Barber, et al. Phys. Rev. Lett. 119, 104801 (2017).



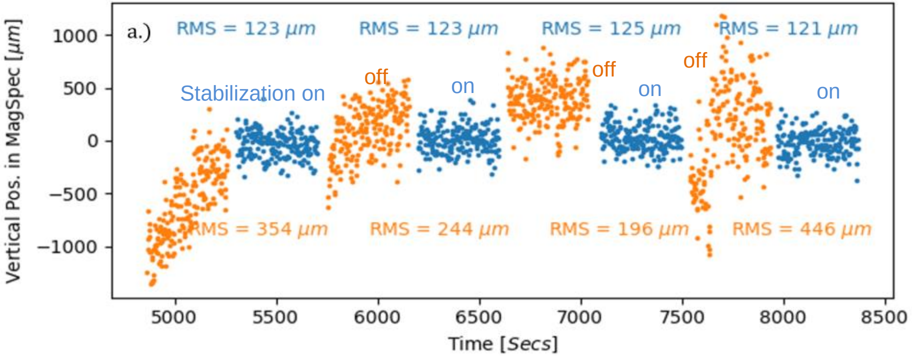


Active stabilization longitudinal laser focus position

--> e-beam stabilization: K. Jensen et al. PRAB 28, 092802 (2025)



Laser "witness" stabilization → stabilizes electron beam centroid

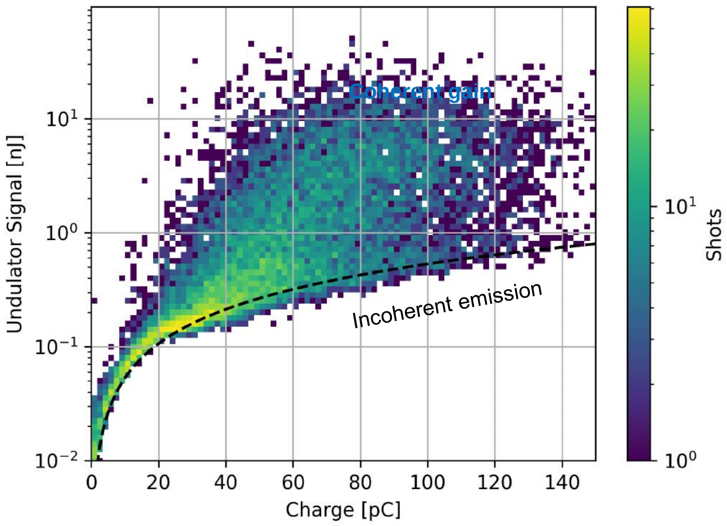


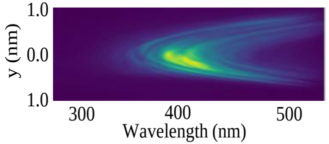
Active stabilization transverse laser pointing

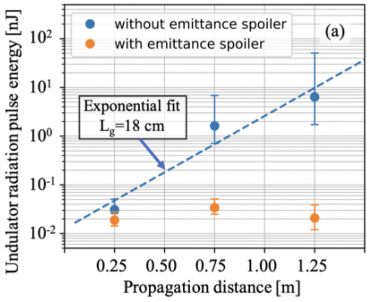
Non-perturbative high-power laser diagnostic: F. Isono et al. HPLSE 8, e25 (2021)
Active stabilization: C. Berger et al, NIM-A 1078, 170561 (2025); A. Amadio et al, HPLSE. 13, e35 (2025)
--> e-beam stabilization: C. Berger et al, PRAB 26, 032801 (2023)

E-beam matching into strong-focusing undulator results in observation of FEL gain

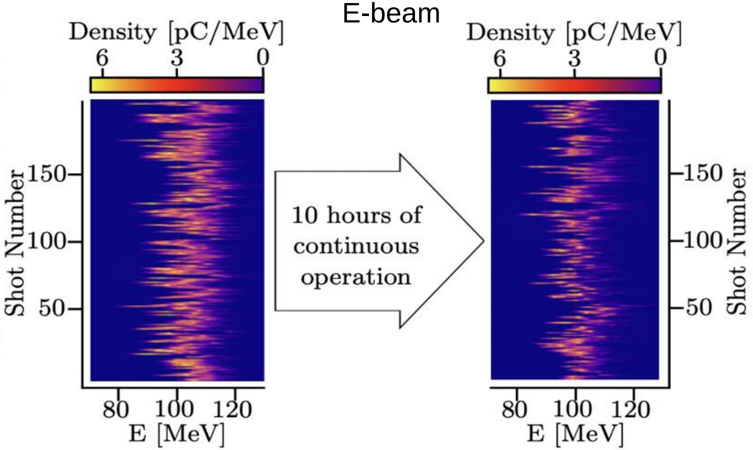
Excellent LPA and e-beam stability enables demonstration of >100x gain



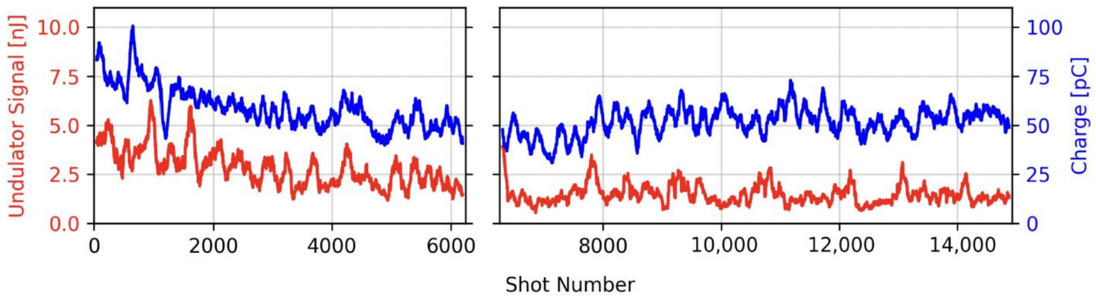




E-beam



FEL gain over 8+ hours



S. Barber et al. Phys. Rev. Lett. 135, 055001 (2025);
F. Kohrell et al. Phys. Rev. AB 29, 041301 (2026)

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Summary

- Laser Plasma Accelerators are compact drivers of high-energy electron beams & secondary radiation
- From particles (electrons, protons, muons) to incoherent photons (gammas, betatron X-rays) & coherent radiation (FEL lasing)
- Unique parameters (point source → lens-less imaging, high-energy → deep penetration, very directional → stand-off interrogation, femtosecond duration → blur-free dynamics studies)
- Higher repetition rates (average power) & active stabilization → a bright future of applications awaits