2.6.2026

Overview of Laser-Driven Multi-GeV Muon Sources and the ELI Beamlines plan

A. Cimmino, T. Ditmire, G. Grittani, R. Versaci

EXTREME LIGHT INFRASTRUCTURE

A EUROPEAN RESEARCH INFRASTRUCTURE CONSORTIUM

A STORY IN FOUR CHAPTERS

I. Laser Acceleration
II. The laser community and the muons
III. Muon production experiments with lasers
IV. ELI ERIC, ELI Beamlines, and the muons

CHAPTER ONE

Laser Acceleration

A bit of history

LASER: **Light Amplification by Stimulated Emission of Radiation**


©AP

- 1960: first laser by Theodore Maiman at Hughes Research Laboratory

  Maiman, T., "Stimulated Optical Radiation in Ruby" *Nature* **187**, 493–494 (1960)

- 1979: first idea of laser driven acceleration

  Tajima, T., Dawson, J. M., (1979), "Laser electron accelerator", PRL 43, 267


©TAE

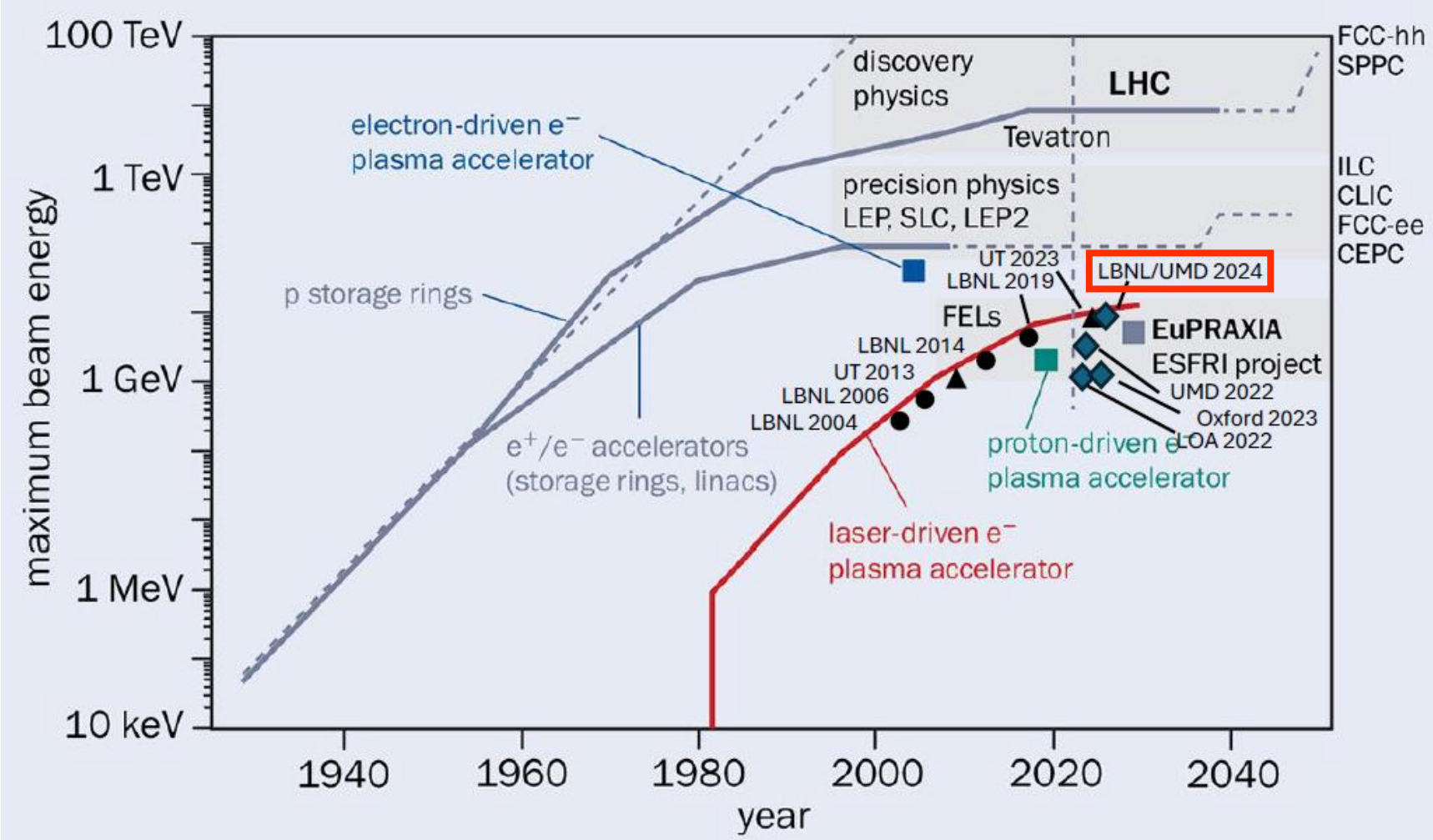
- 1985: Development of Chirped Pulse Amplification

  Strickland, D., Mourou, G., "Compression of amplified chirped optical pulses", Optics Communications, 56, 3 (1985)



©Wikipedia

Laser Acceleration



© B. Miao @ LAMU workshop (2025), after M. Ferrario & R. Assmann @ CAS arXiv:2103:10843 (2021)

Laser Acceleration of Protons

- Proton acceleration world record @ HZDR

  Ziegler, T., *et al.* "Laser-driven high-energy proton beams from cascaded acceleration regimes" *Nat. Phys.* **20**, 1211–1216 (2024)

- "Here we generate proton beams with a spectrally separated high-energy component of up to 150 MeV…"

Article | Open access | Published: 13 May 2024

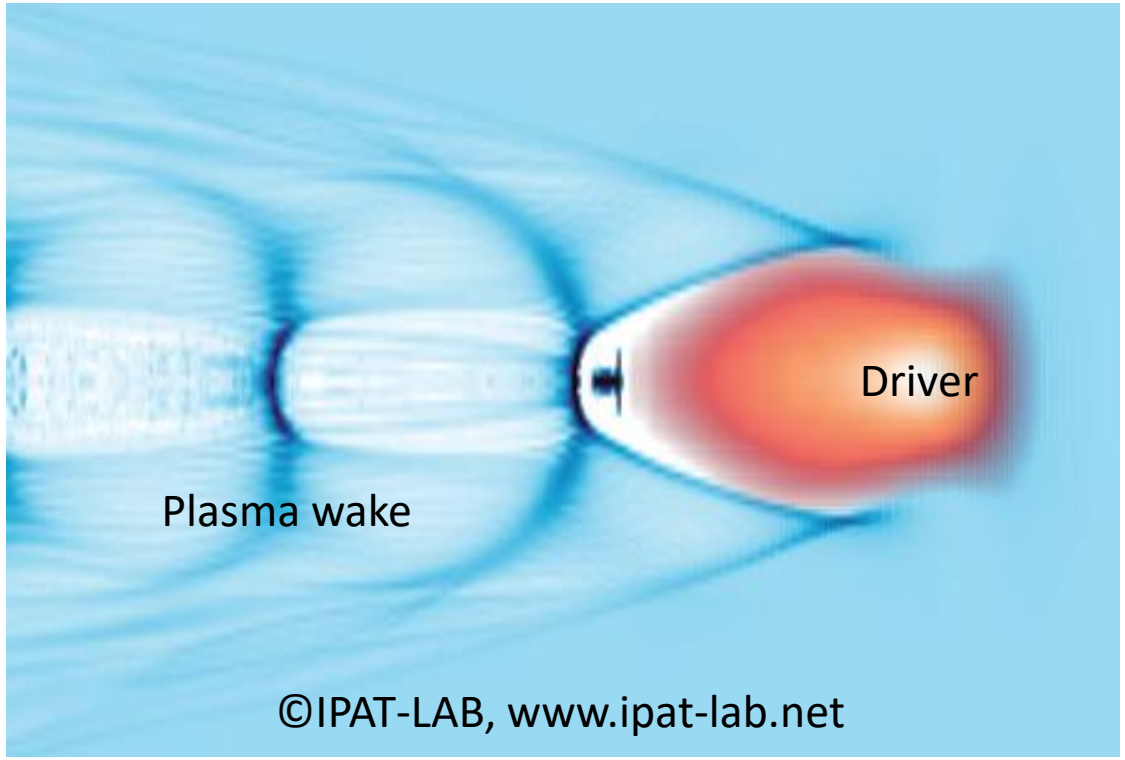
Laser-driven high-energy proton beams from cascaded acceleration regimes

Tim Ziegler ✉, Ilja Göthel, Stefan Assenbaum, Constantin Bernert, Florian-Emanuel Brack, Thomas E. Cowan, Nicholas P. Dover, Lennart Gaus, Thomas Kluge, Stephan Kraft, Florian Kroll, Josefine Metzkes-Ng, Mamiko Nishiuchi, Irene Prencipe, Thomas Püschel, Martin Rehwald, Marvin Reimold, Hans-Peter Schlenvoigt, Marvin E. P. Umlandt, Milenko Vescovi, Ulrich Schramm & Karl Zeil

Nature Physics **20**, 1211–1216 (2024) | Cite this article

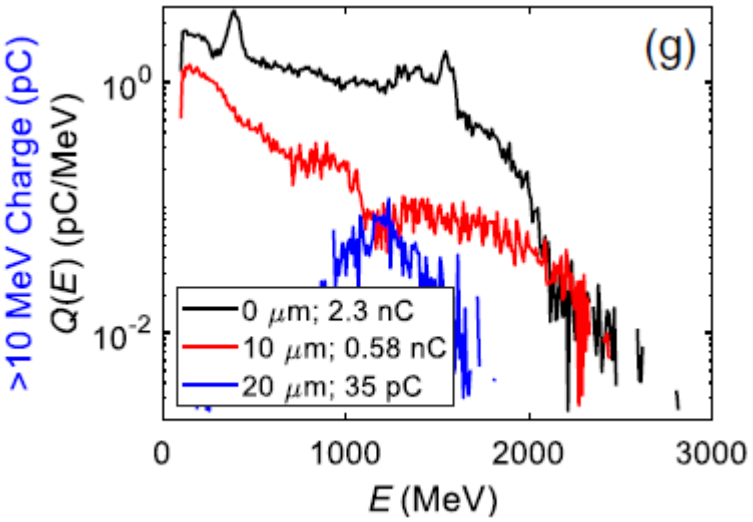
Laser Wakefield Acceleration

- Electron acceleration
- Based on two steps:
  1. Use a driver to generate a plasma
  2. Use a laser to accelerate the electrons in the plasma
- Several techniques with different injection mechanisms
- Electron spectrum can “look strange”

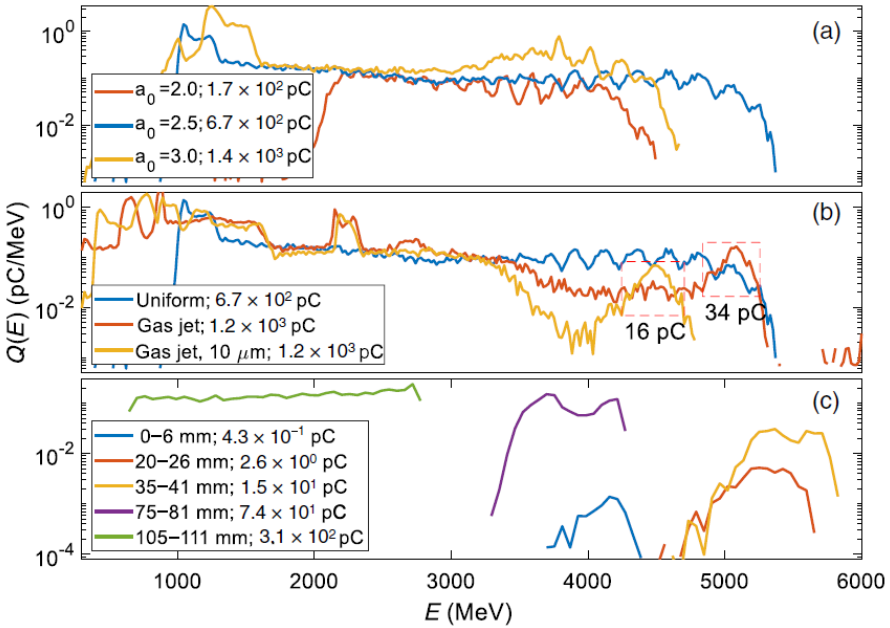


Laser Wakefield Acceleration

- Electron spectrum can “look strange”



Miao B., *et al*. “Multi-GeV Electron Bunches from an All-Optical Laser Wakefield Accelerator”, Phys. Rev. X **12**, 031038



PIC (WarpX) simulations

- Spoiler alert: Given several GeV electron beam, muons are bound to be:
  - $\mu^+ \mu^-$ pair production
  - Decay of photo-produced pions

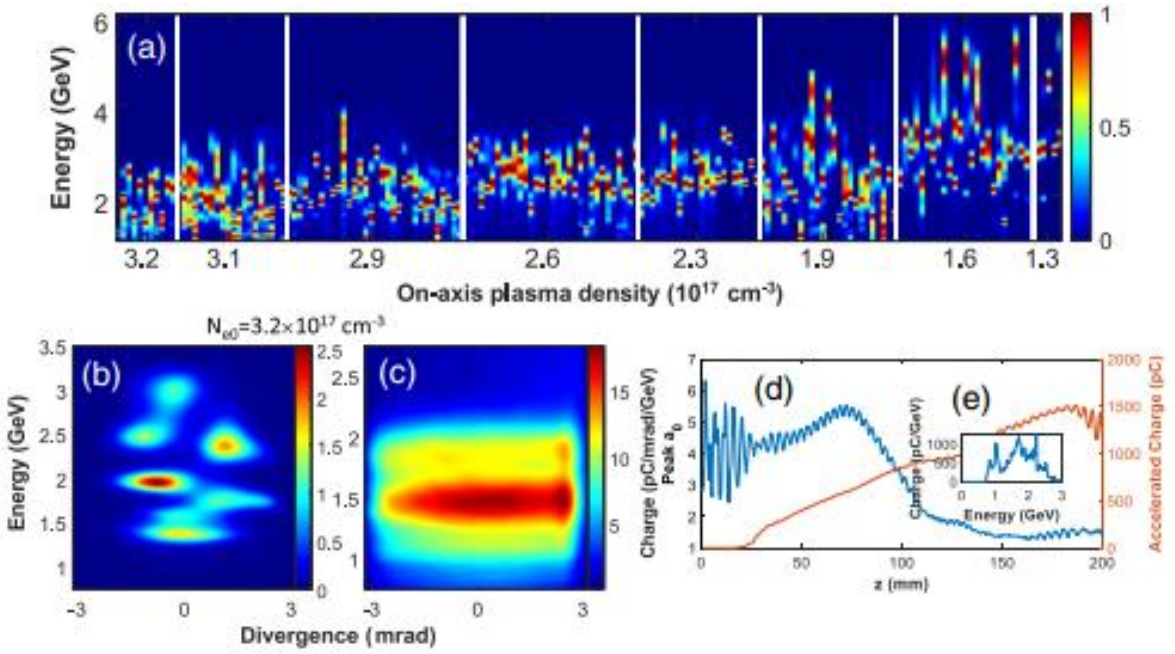
Laser Wakefield Acceleration

- Coming of age: increased repeatability, more “stable” beams
- Repeated shots with GeV electrons produced

PHYSICAL REVIEW LETTERS **133,** 045002 (2024)

Guided Mode Evolution and Ionization Injection in Meter-Scale Multi-GeV Laser Wakefield Accelerators

J. E. Shrock,[1] E. Rockafellow,[1] B. Miao,[1] M. Le,[1] R. C. Hollinger,[2] S. Wang,[2] A. J. Gonsalves,[3] A. Picksley,[3] J. J. Rocca,[2,4] and H. M. Milchberg[1,5]



UMD, CSU, LBNL @ ALEPH laser system @ CSU 300 TW laser

“Guided Mode Evolution and Ionization Injection in Meter-Scale Multi-GeV Laser Wakefield Accelerators”, PRL **113**, 045002 (2024)

CHAPTER TWO

The laser community and the muons

LWFA as potential muon source

- 10-15 yrs ago laser scientists “discover” the muon

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 111301 (2009)

Dimuon production by laser-wakefield accelerated electrons

A. I. Titov,[1,2,3] B. Kämpfer,[1,4] and H. Takabe[3]
[1]*Forschungzentrum Dresden-Rossendorf, 01314 Dresden, Germany*
[2]*Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna 141980, Russia*
[3]*Institute of Laser Engineering, Yamada-oka, Suita, Osaka 565-0871, Japan*
[4]*Institut für Theoretische Physik, TU Dresden, 01062 Dresden, Germany*
(Received 17 July 2009; published 11 November 2009)

We analyze $\mu^+\mu^-$ pair production generated by high-energy electrons emerging from a laser-wakefield accelerator. The $\mu^+\mu^-$ pairs are crea
accelerating plasma region. Numerical estimates
expected to be reliable in the nearest future. Rea
dominate the dimuon production. According to
1 (10) GeV may create about 100 (5000) muon
aspects of muon-related physics in tabletop inst
towards the investigation of more complicated e

DOI: 10.1103/PhysRevSTAB.12.111301

“Dimuon production by laser-wakefield accelerated electrons”

Phys. Rev. ST Accel. Beams **12**, 111301 (2009)

Detection of Petawatt Laser-Induced Muon Source for Rapid High-Z Material Detection

Wendi Dreesen, *Member IEEE*, J. Andrew Green, Mark Browder, James Wood, David Schwellenbach, *Member IEEE*, Todd Ditmire, Ganesh Tiwari, and Craig Wagner

2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)

Laser Wakefield Acceleration

- Increased interest in particle physics

Making pions with laser light

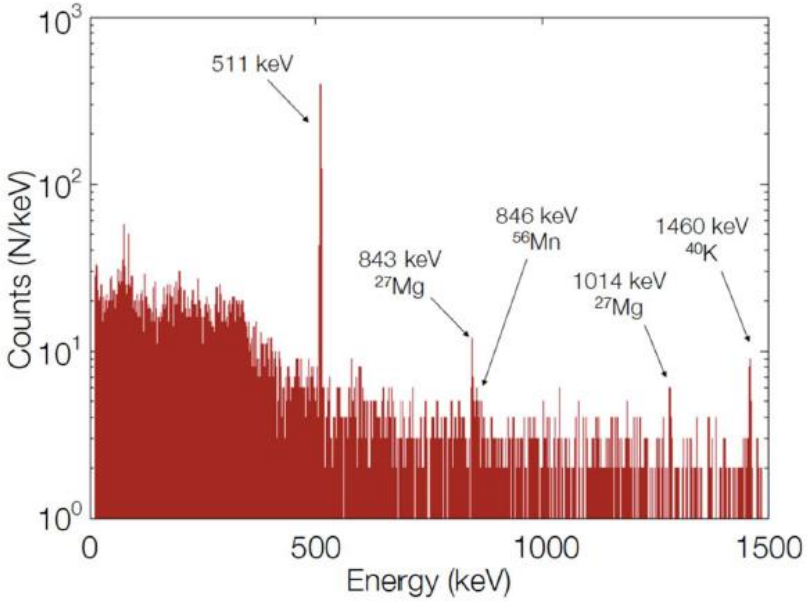
W Schumaker, T Liang, R Clarke, J M Cole, G Grittani, S Kuschel, S P D Mangles, Z Najmudin, K Poder, G Sarri, D Symes, A G R Thomas, M Vargas, M Zepf and K Krushelnick ▲ Hide full author list

Published 4 July 2018 • © 2018 The Author(s). Published by IOP Publishing Ltd on behalf of Deutsche Physikalische Gesellschaft

New Journal of Physics, Volume 20, July 2018

Citation W Schumaker *et al* 2018 *New J. Phys.* **20** 073008

DOI 10.1088/1367-2630/aace0c



$^{27}Al(\gamma,\pi^{+})^{27}Mg$

Large group lead by U. Mich.
@ Astra-Gemini 300 TW
@ RAL
New J. Phys. **20** 073008 (2018)

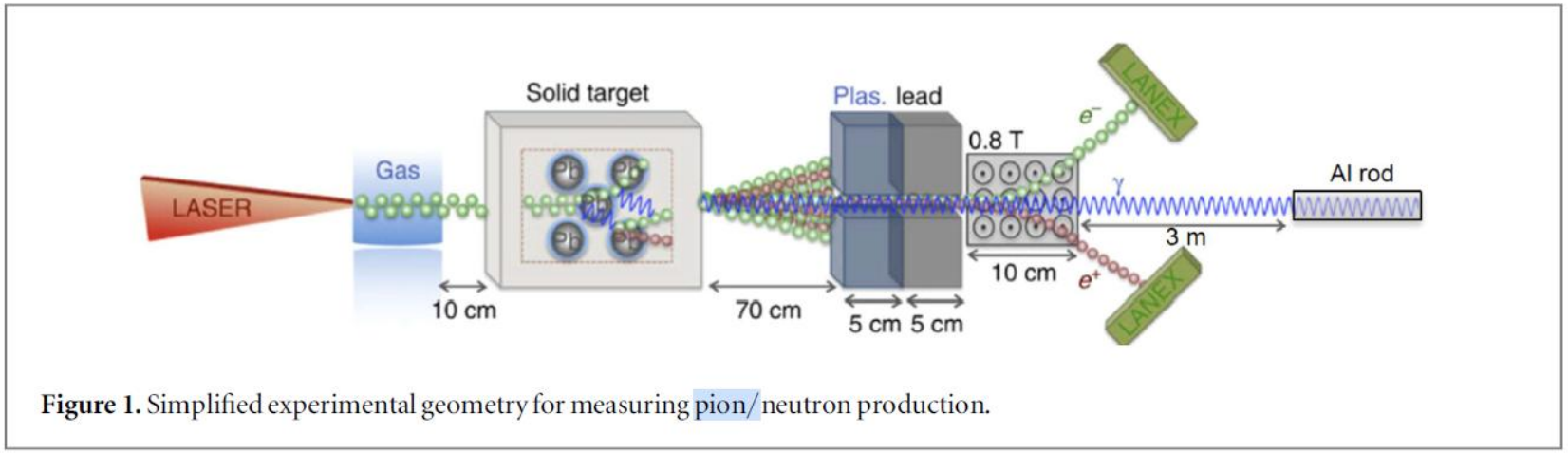
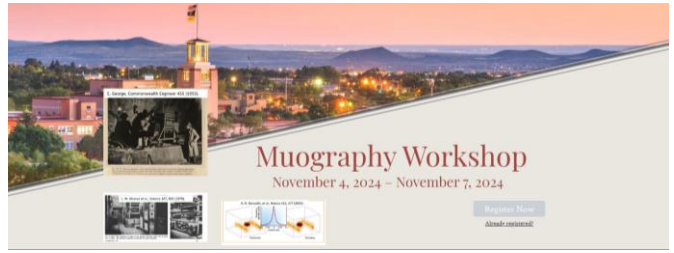
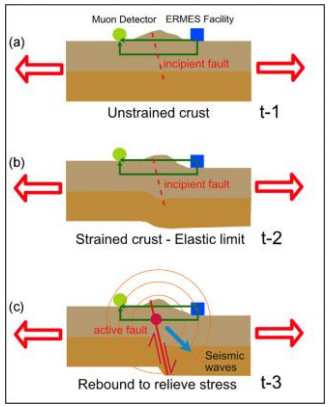


Figure 1. Simplified experimental geometry for measuring pion/neutron production.

Why so much interest in laser muons?

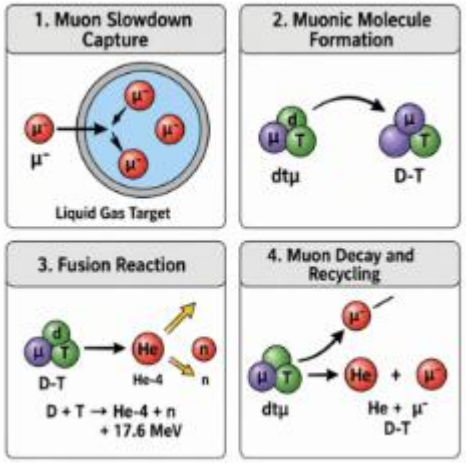
- Muons are fashionable
- Possibility of performing muography without cosmic rays constraints, namely directionality and rate
- Possibility of a limited dimension and movable muon source





L. Serafini *et al.*, **Remote-sensing of tectonic-induced stress across faults using high energy muon beams**, Phys. Rev. Research **7**, 043336

International MUON Collider Collaboration



X. Yin *et al.*, **Muon-Catalyzed Nuclear Fusion: Physical Mechanism, Bottleneck Breakthroughs, and an Engineering Pathway**, arXiv:2605.26432v1

Muography potential

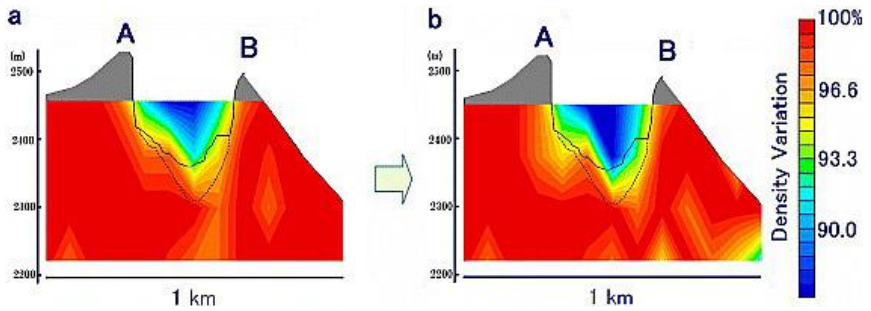
- 1970: L. Alvarez first to look inside pyramids

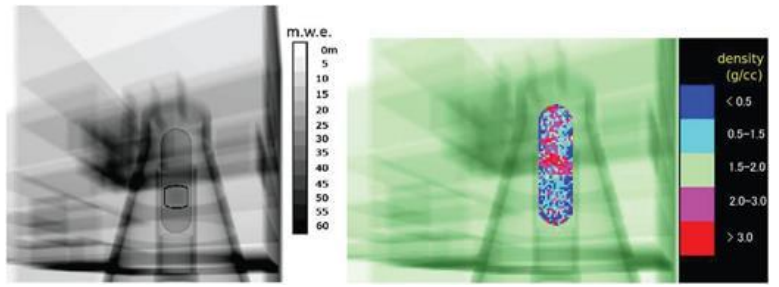
  Science, New Series, Vol. 167, No. 3919. (Feb. 6, 1970), pp. 832-839
- 2009: First volcano muography

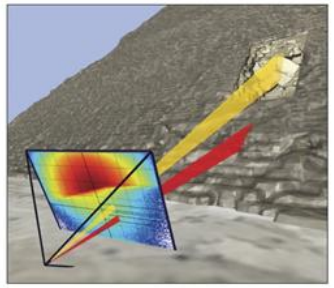
  Tanaka, H. K. M., *et al.* (2009), "Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan", *Geophys. Res. Lett.*, 36, L17302
- 2013: Muography of the Fukushima reactor

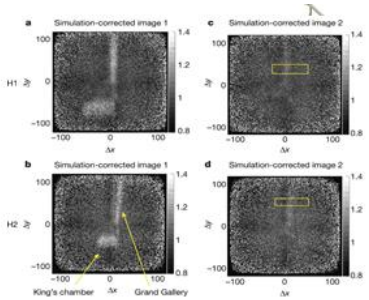
  H. Fujii, et al., "Performance of a remotely located muon radiography system to identify the inner structure of a nuclear plant", *Progr. of Theor. and Exp. Physics*, Volume 2013, Issue 7, July 2013, 073C01
- 2017: Discovery of a secret chamber in Khufu's Pyramid

  Morishima, *et al.* "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons". *Nature* **552**, 386–390 (2017)



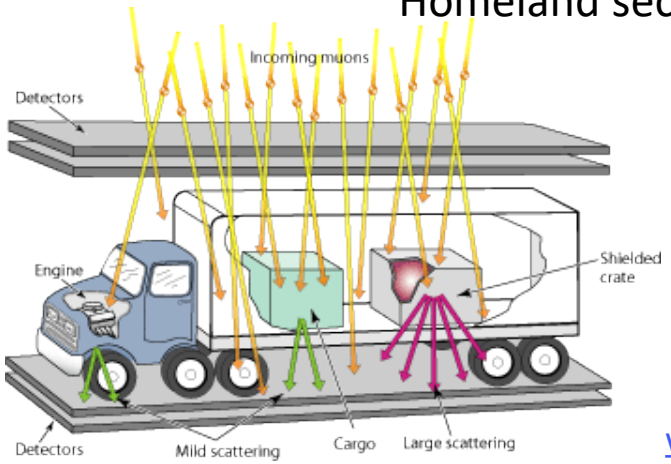






Muography potential

Homeland security



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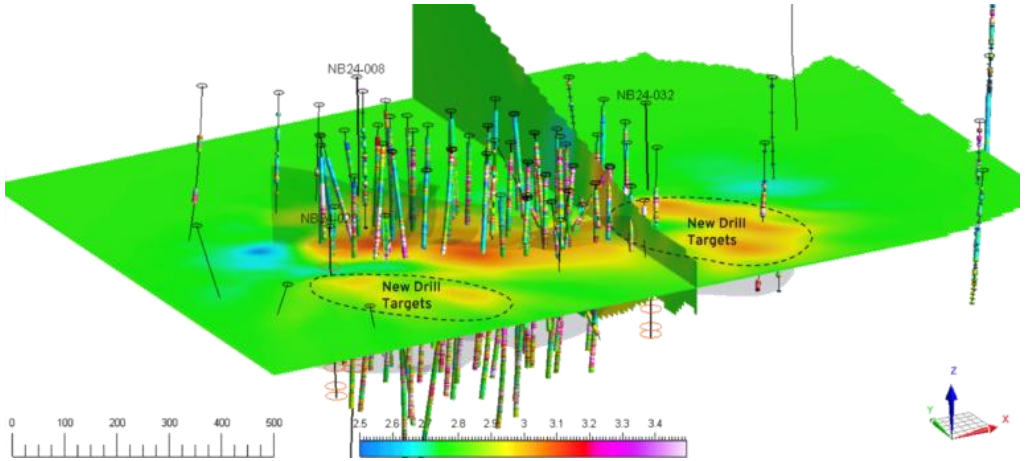
https://science.osti.gov/np/Benefits-of-NP/Applications-of-Nuclear-Science/Archives/Muon-Radiography-at-LANL

www.bbc.com/news/articles/c98y4n853vmo (2025)

Mining opportunities



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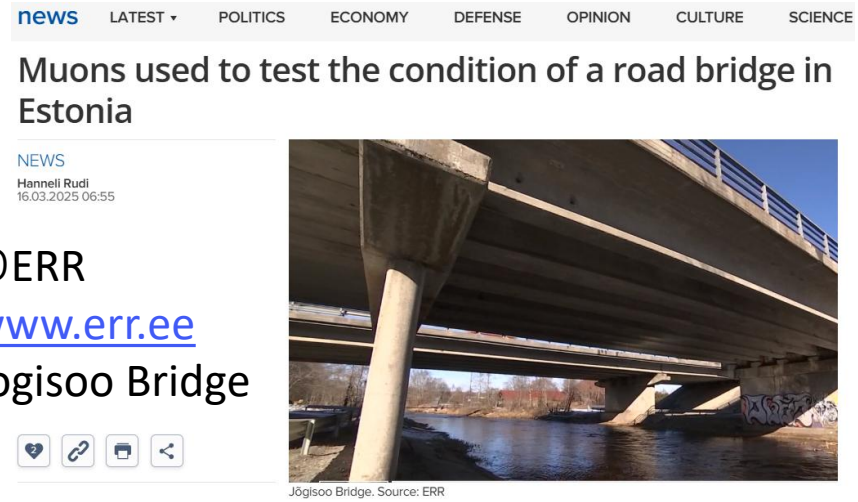
Civil engineering



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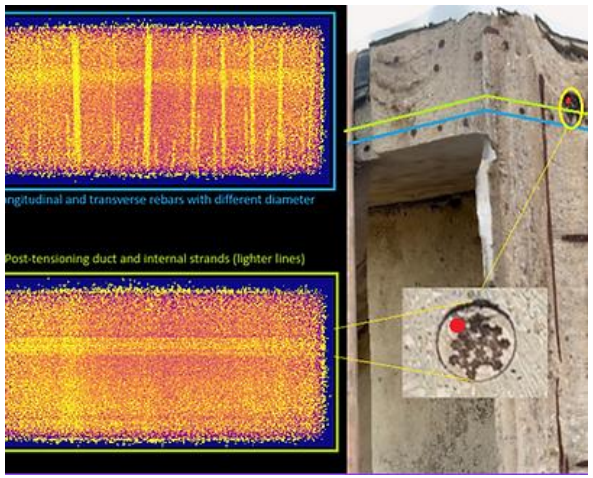
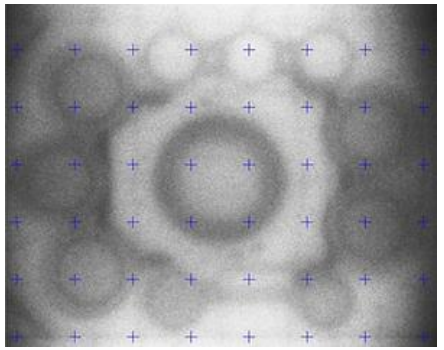
Jogisoo Bridge



Sunk nuclear submarine



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MuS2 DARPA project

- DARPA: Defense Advanced Research Projects Agency
- MuS2: Muons for Science and Security Program launched in 2023

- **Develop of a directional and portable muon source**
- 2 projects funded, each 2x 24-month phases
- One project led by Berkeley
- One project led by LLNL

- Both produced very good results (see next slides), but neither made it to phase 2!

CHAPTER THREE

Muon production experiments with lasers

A bit of competition

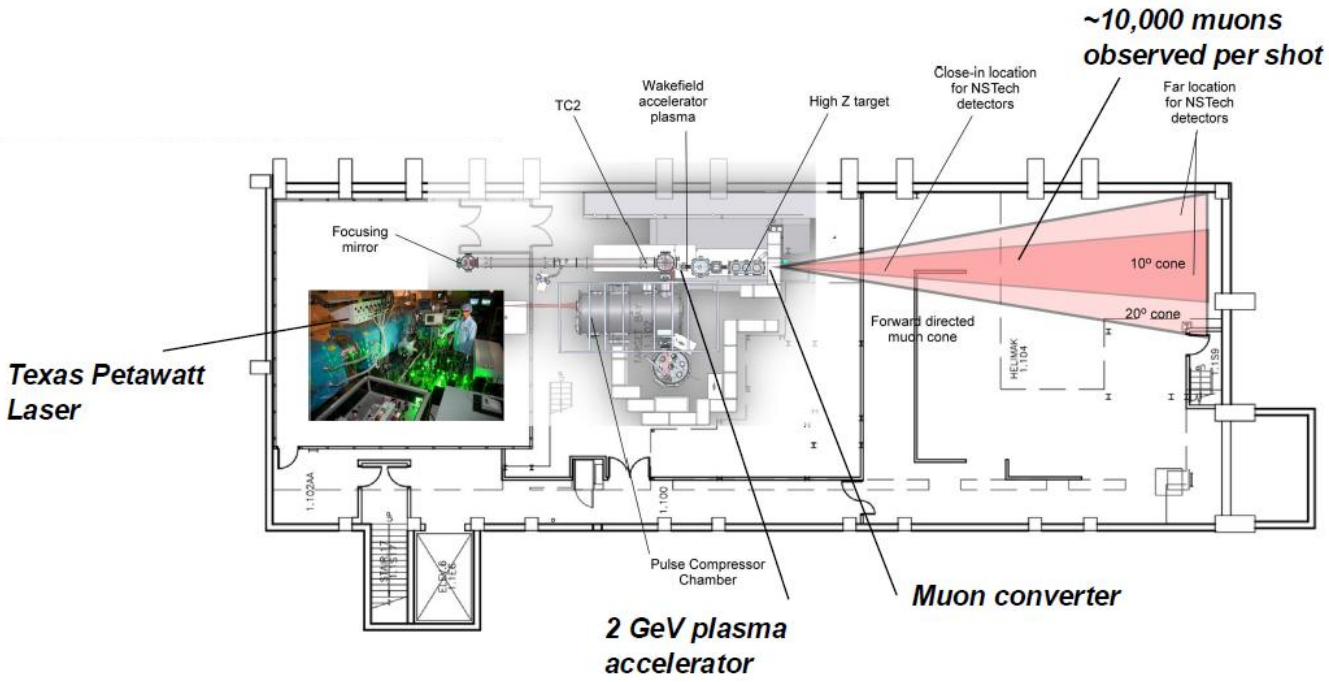
- Several laser groups attempted to produce and detect muons

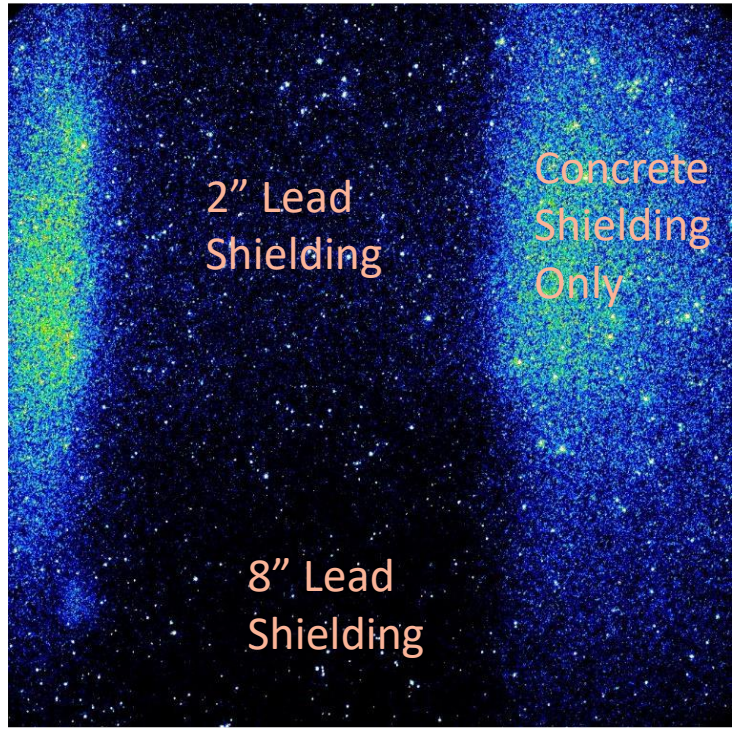
- National Security Technology @ Texas PetaWatt
- Laser Fusion Research Center @ China Academy of Engineering Physics
- Berkeley Lab @ BELLA @ Lawrence Berkeley National Laboratory
- Queen's University Belfast @ ELI-NP
- Lawrence Livermore National Laboratory @ Colorado State University

NB: each experiment was a collaborative effort, only the leading group is indicated

National Security Technology

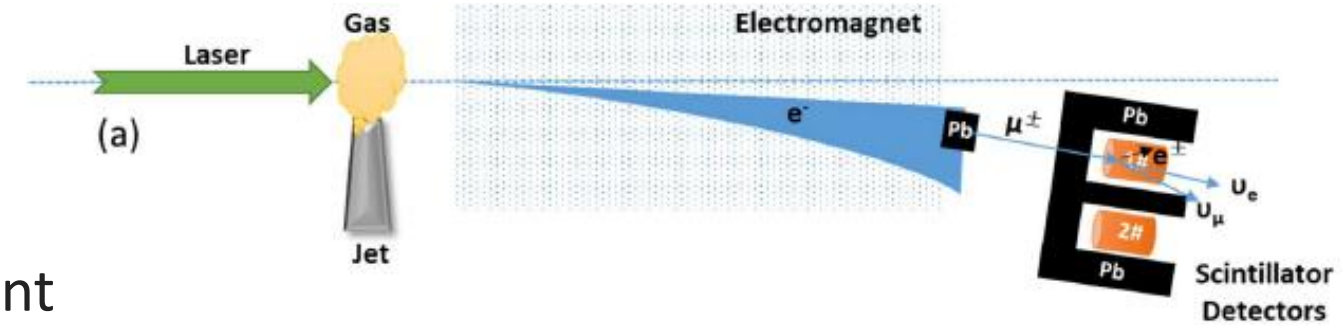
- At IEEE Nuclear Science Symposium & Medical Imaging Conference (2014)
- Dressen, W., *et al*. "*Detection of Petawatt Laser-Induced Muon Source for Rapid High-Z Material Detection*", Oct 2014.
- 1PW laser at TexasPetaWatt
- Drift tubes and scintillators

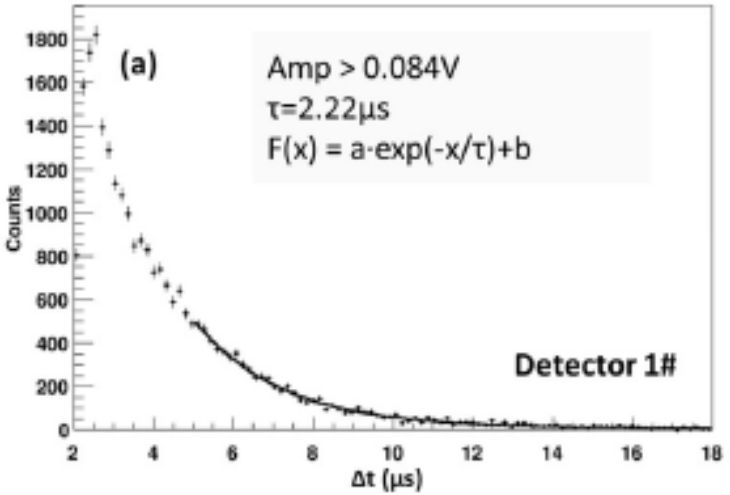


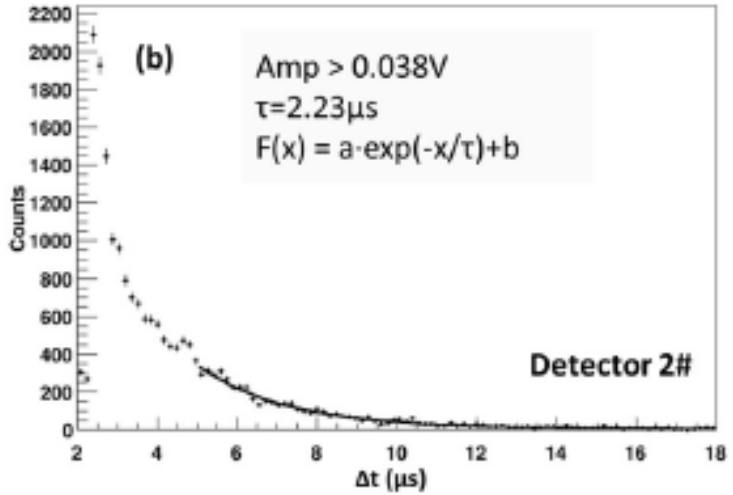


Laser Fusion Research Center

- Zhang, F. *et al.* "Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser" *Nat. Phys.* (2025)
- 1PW laser @ SULF (Shanghai)
- 178 shots @ 0.1Hz
- Electrons up to 1.5 GeV, ~200 pC/shot
- Liquid scintillator with MCP
- Laser as trigger for a time measurement







Article | Published: 06 May 2025

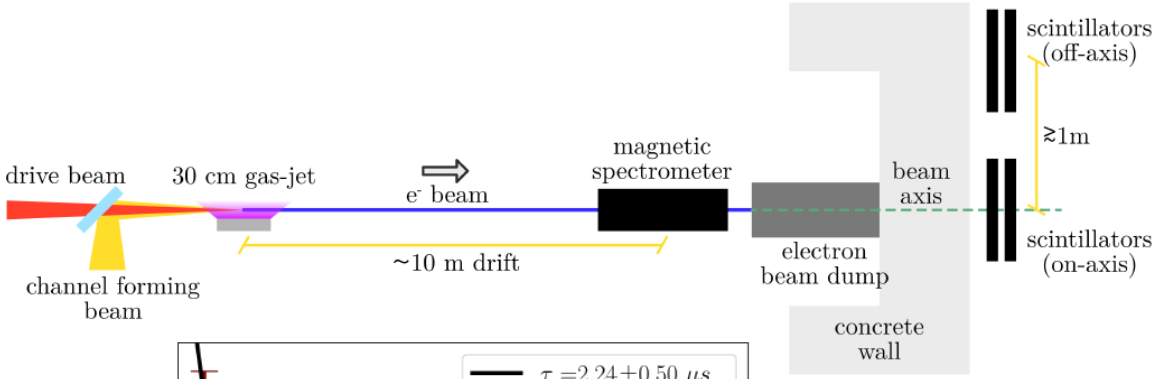
Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser

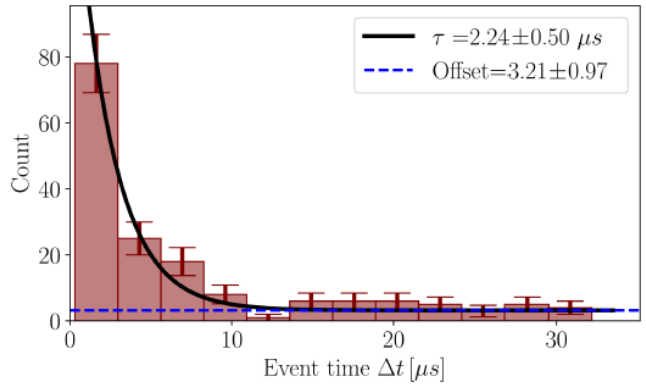
Feng Zhang, Li Deng, Yanjie Ge, Jiaxing Wen, Bo Cui, Ke Feng, Hao Wang, Chen Wu, Ziwen Pan, Hongjie Liu, Zhigang Deng, Zongxin Zhang, Liangwen Chen ✉, Duo Yan, Lianqiang Shan, Zongqiang Yuan, Chao Tian, Jiayi Qian, Jiacheng Zhu, Yi Xu, Yuhong Yu, Xueheng Zhang, Lei Yang, Weimin Zhou ✉, ... Ruxin Li + Show authors

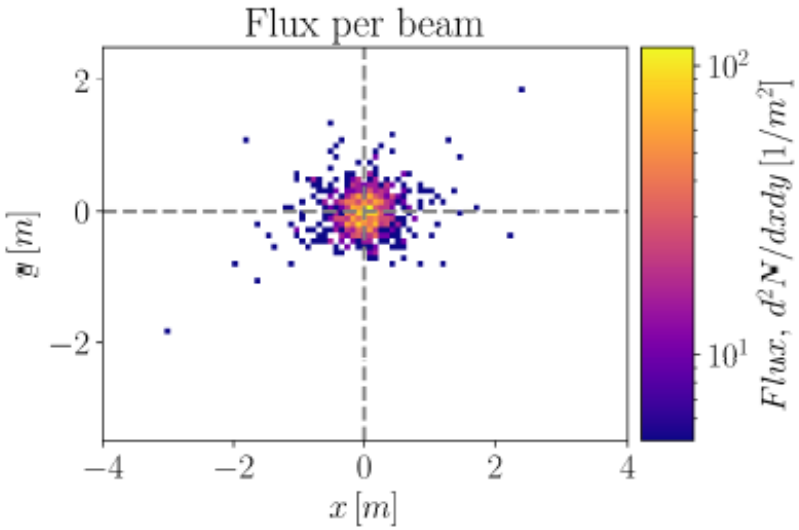
Nature Physics (2025) | Cite this article

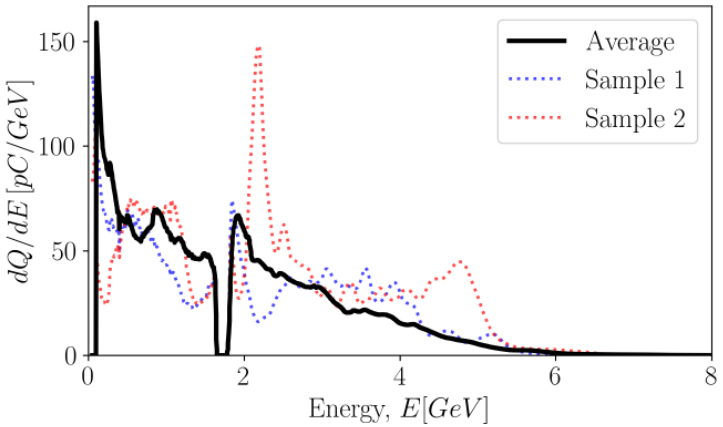
Berkeley Lab

- Terzani, D. *et al.* "Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator", *Phys. Rev. Accel. Beams 28, 103401* (2025)
- 1PW laser at BELLA
- Electrons up to 8 GeV, ~50-250 pC/shot 0.1 Hz
- Plastic scintillator with PMT
- Laser as trigger for a time measurement



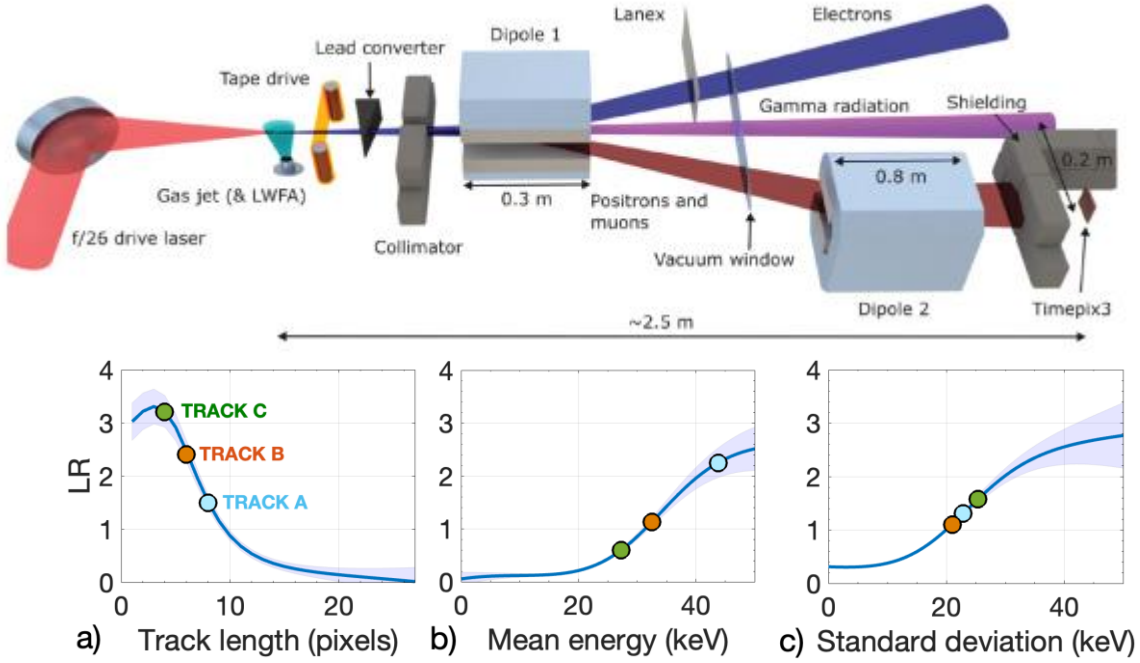


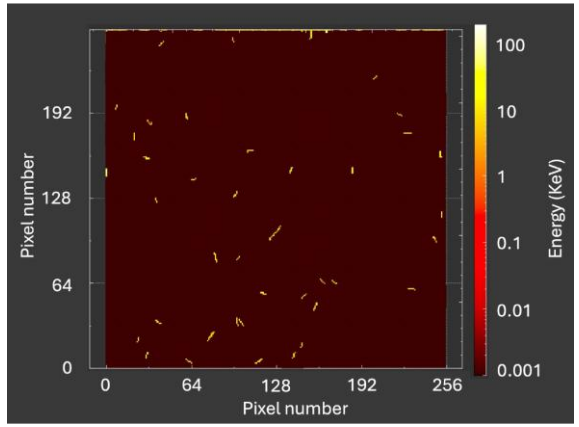


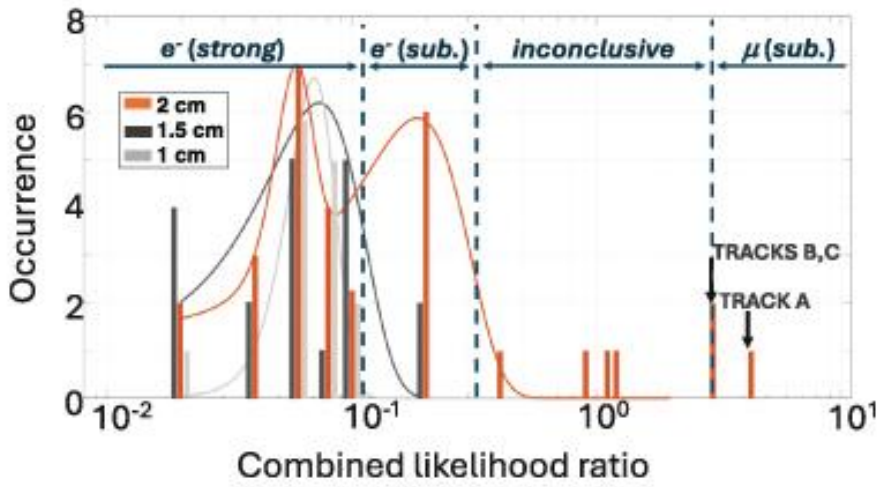


QUB @ ELI-NP

- Calvin, L. *et al.* "Experimental evidence of production of directional muons from a laser-wakefield accelerator", *Plasma Phys. Control. Fusion* **68** 035015, (2026)
- 1PW laser at ELI-NP
- Electrons up to 1 GeV, ~560 pC/shot
- Timepix3
- Likelihood test based on MC study

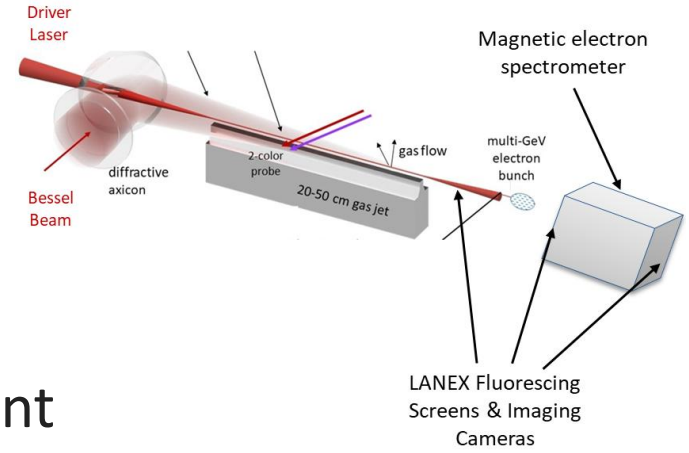


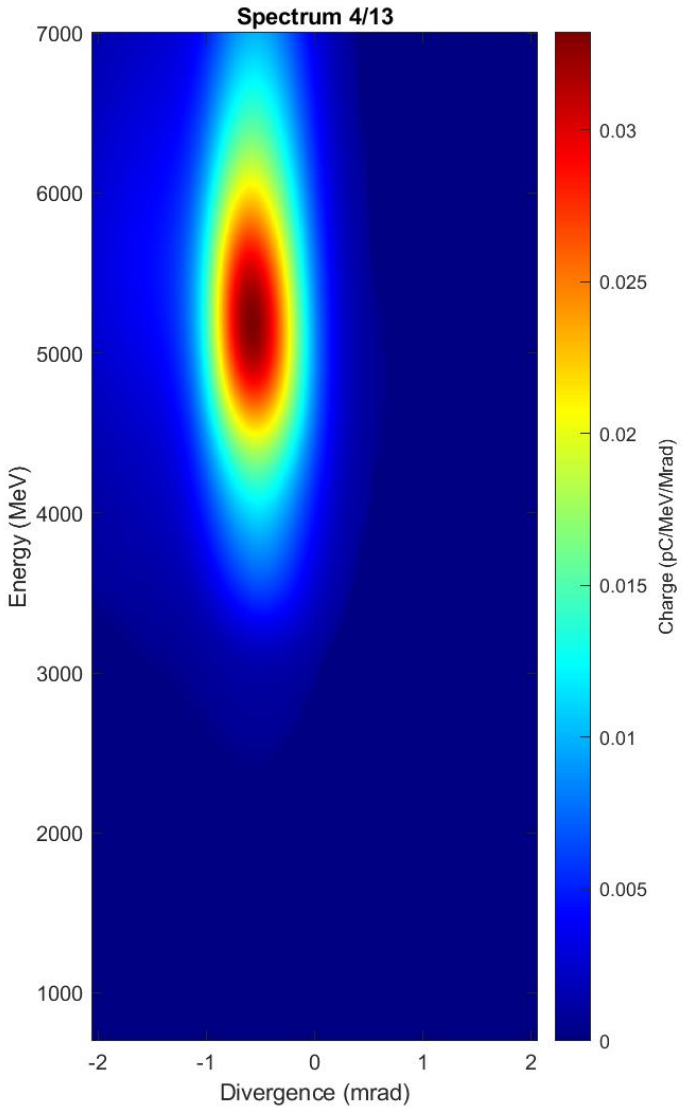


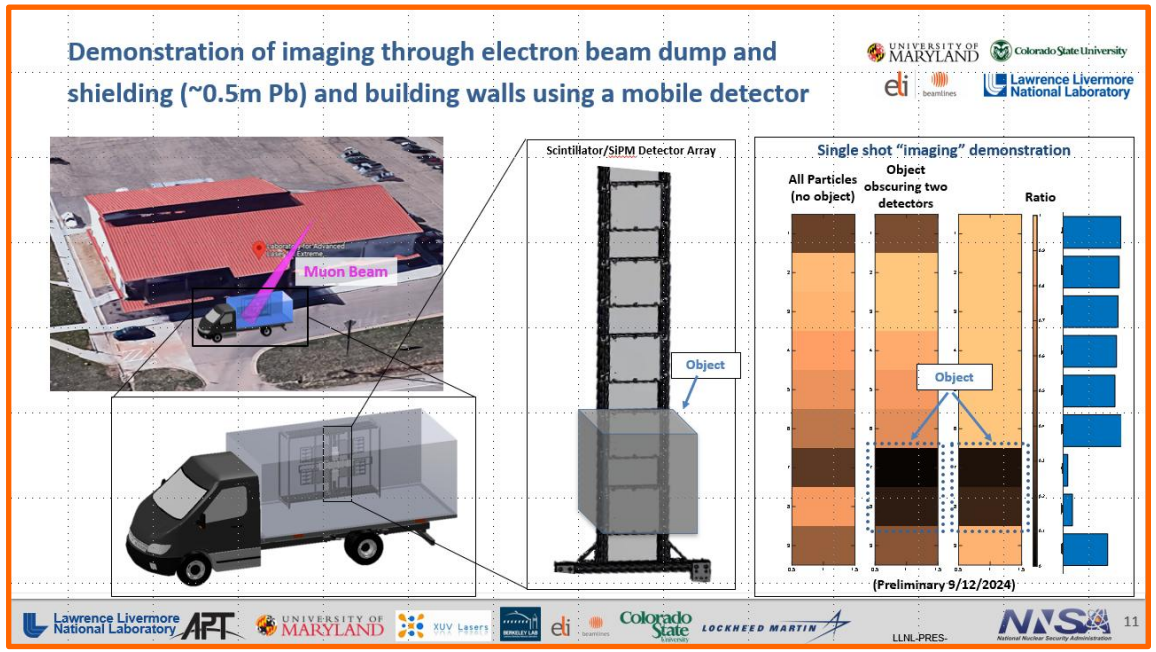


LLNL @ CSU

- Paper in preparation
- 0.85PW laser at CSU
- Electrons in 6-10 GeV, >1 nC/shot
- Plastic scintillator
- Laser as trigger for a time measurement
- First imaging application from LPA beam







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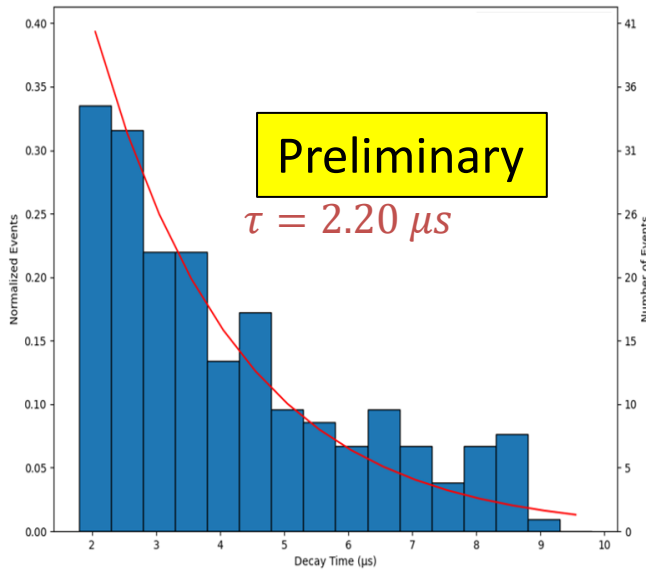
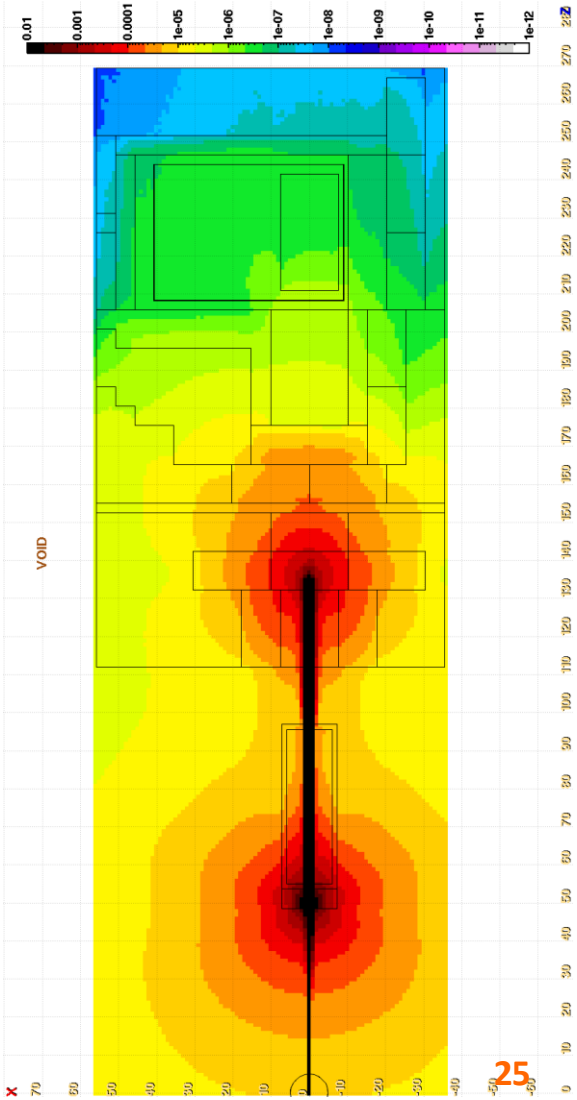


An LPA muon beam is not a beam

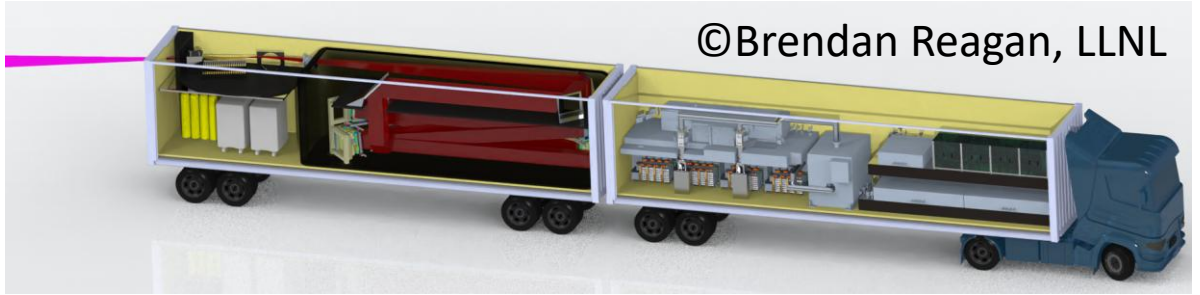
An LPA muon beam is not a beam

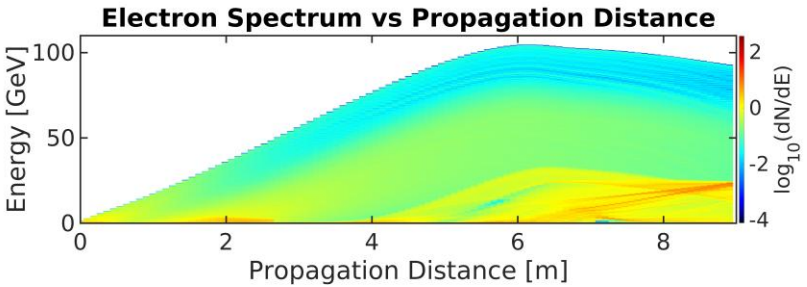
- An LPA electron beam has larger divergence than conventional beam
- Laser scientists focus on the most accelerated electrons
- Electrons shower in the converter (or in any object they hit)
- Converters are at least a few cm thick
- Electrons do not convert all in the same point
- **Muons are more in a cloud than a beam**
- All sort of secondaries are generated
- Dedicated set up design needed to select a single particle type
- Radiation protection is a big challenge

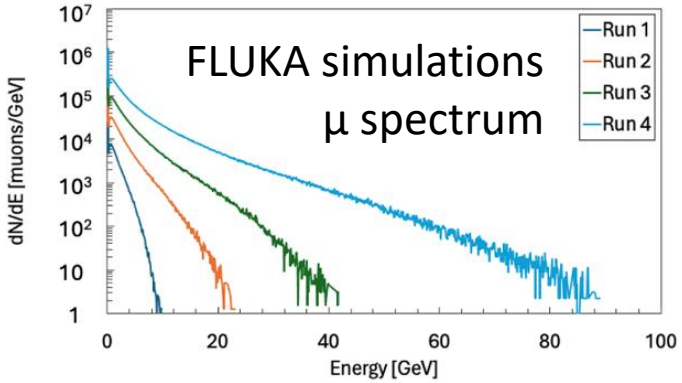


What's next in the laser world?

- There is still widespread interest in the laser community to:
  - Build a portable source
  - Achieve higher energy
    - Modular gas jet target
    - PIC simulations up to 100 GeV



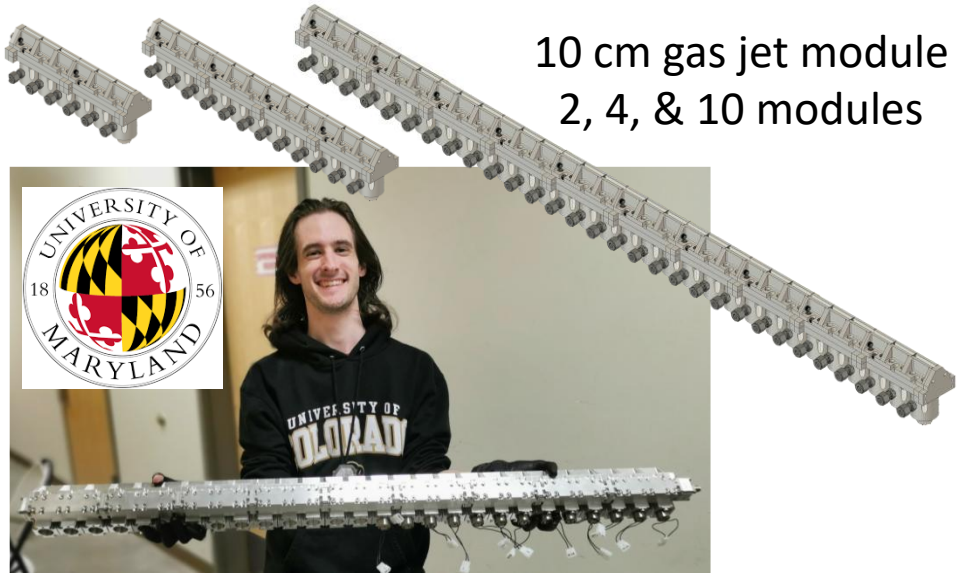




Sci Rep **15**, 25902 (2025)

Laser-Based 100 GeV Electron Acceleration Scheme for Muon Production

J. D. Ludwig,[1] S. C. Wilks,[1] A. J. Kemp,[1] G. J. Williams,[1] N. Lemos,[1] E. Rockafellow,[2] B. Miao,[2] J. E. Shrock,[2] H. M. Milchberg,[2] J.-L. Vay,[3] A. Huebl,[3] R, Lehe,[3] A. Cimmino,[4] R. Versaci,[4] V. Tang,[1] and B. A. Reagan[1]



- **Enters ELI Beamlines**

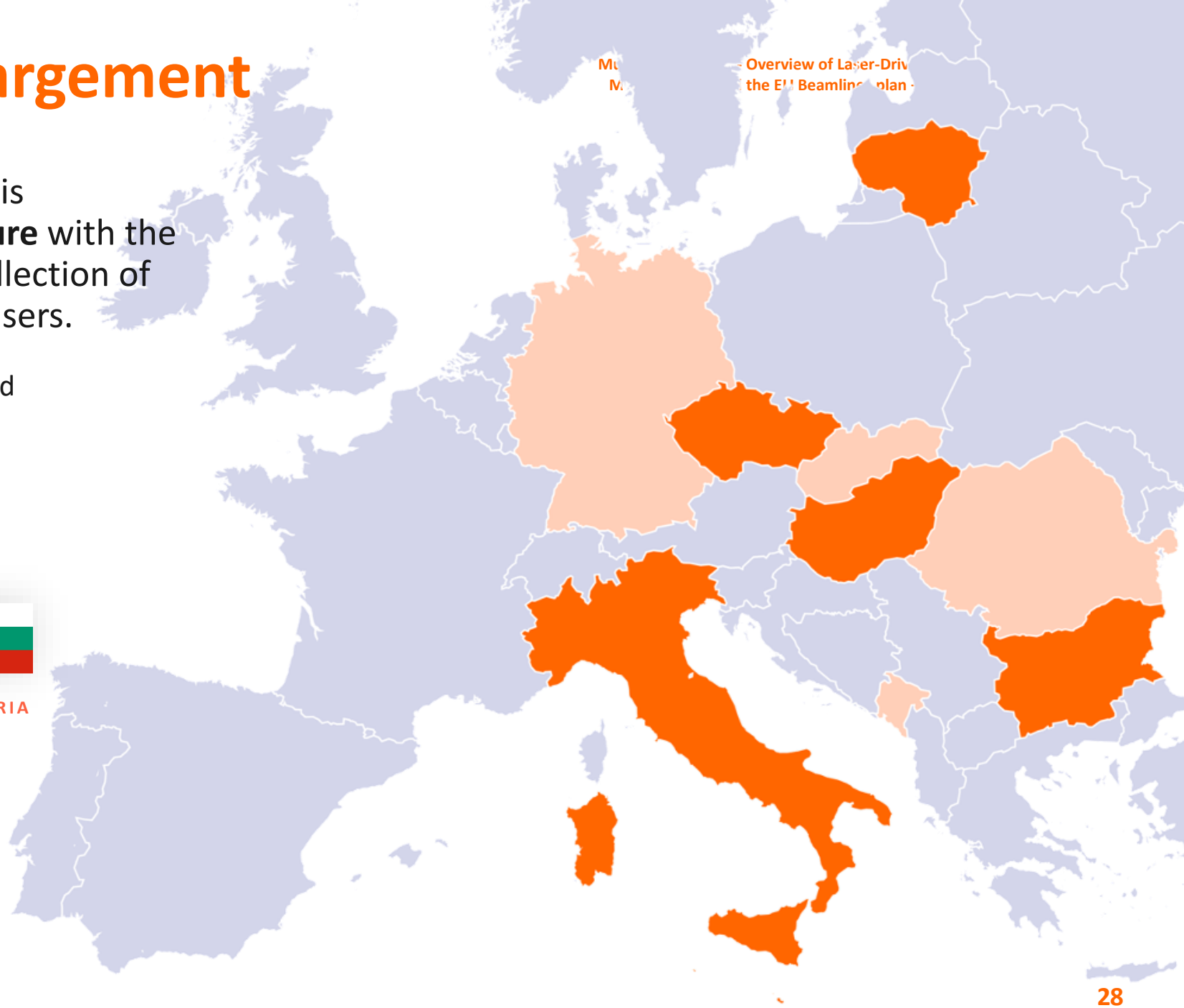
CHAPTER FOUR

ELI ERIC, ELI Beamlines, and the muons

ELI Membership Enlargement

The Extreme Light Infrastructure (ELI) is an **international research infrastructure** with the world's largest and most advanced collection of high-power and high-repetition-ratelasers.

ELI is dedicated to **multi-disciplinary science** and research applications of ultra-intense and ultra-short laser pulses and offers unprecedented capabilities in intense light-matter interactions.



MEMBERS


CZECH REPUBLIC*


HUNGARY*


ITALY


LITHUANIA


BULGARIA

OBSERVERS


ROMANIA*


GERMANY


SLOVAKIA


MONTENEGRO

* Host Countries

Integration of the 3 ELI Facilities in ELI ERIC

1 consortium, 3 facilities, 2 user calls per year www.eli-laser.eu up.eli-laser.eu

ELI Beamlines Facility

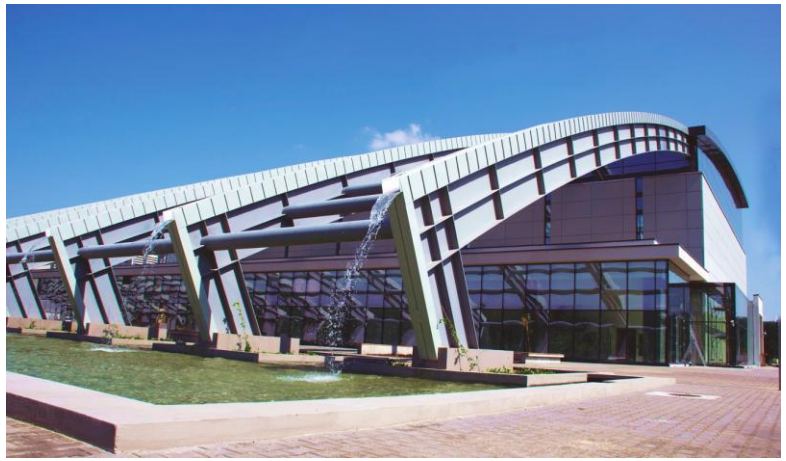
High-Energy Beam facility, develops and applies ultra-short pulses of ultra-intense radiation to explore extreme conditions or produce high-energy particles and radiation.

DOLNÍ BŘEŽANY, CZECH REPUBLIC
SINCE 1 JANUARY 2023

ELI Attosecond Light Pulse Source Facility

Attosecond Light Pulse Source, offers unique time-resolved investigation possibilities for both nonrelativistic and relativistic interaction of light with all the four states of matter.

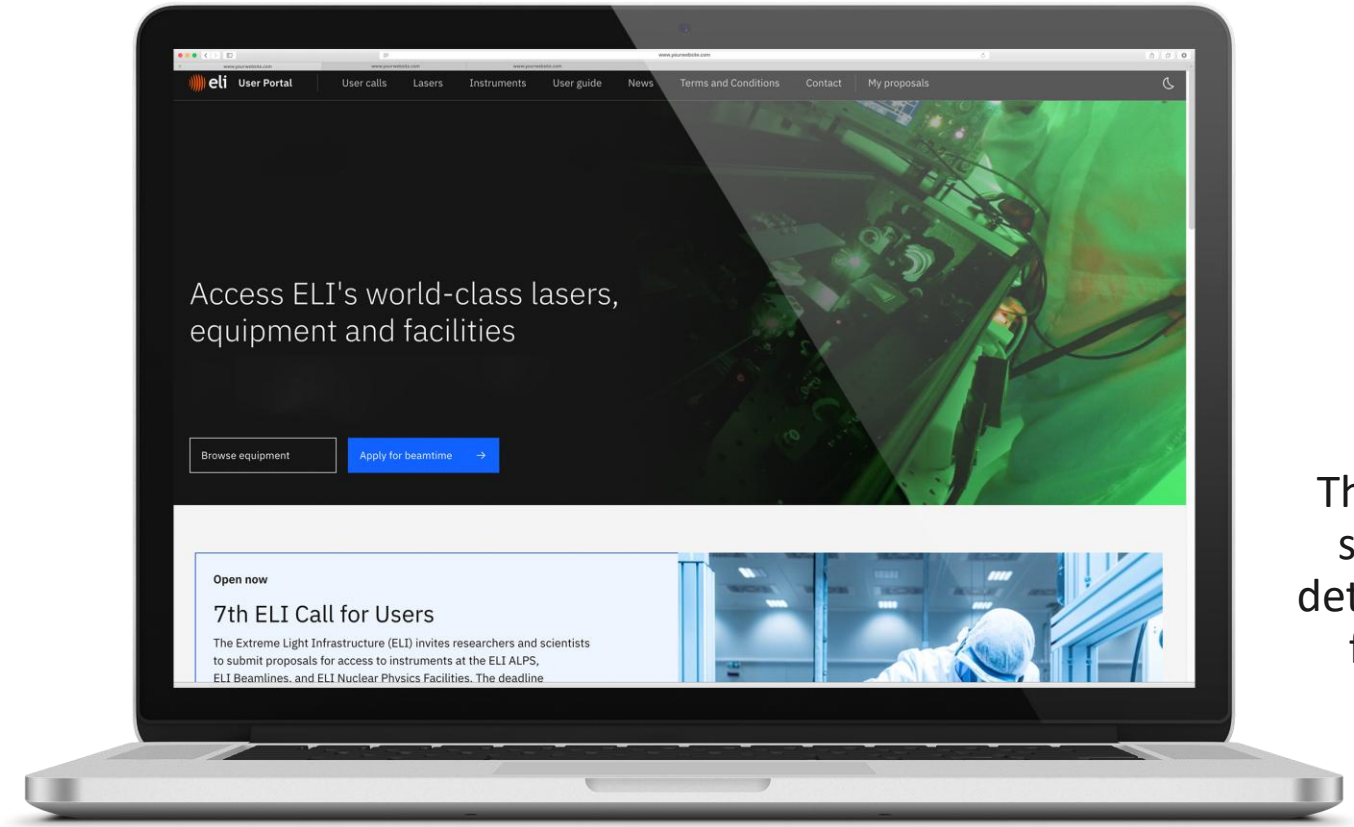
SZEGED, HUNGARY
SINCE 1 JANUARY 2024



ELI Nuclear Physics Facility

Nuclear Physics facility with ultra-intense lasers and brilliant gamma beams (up to 19 MeV) to produce and explore new nuclear states or generate neutron beams.

MĂGURELE, ROMANIA
NOT YET IN ELI ERIC



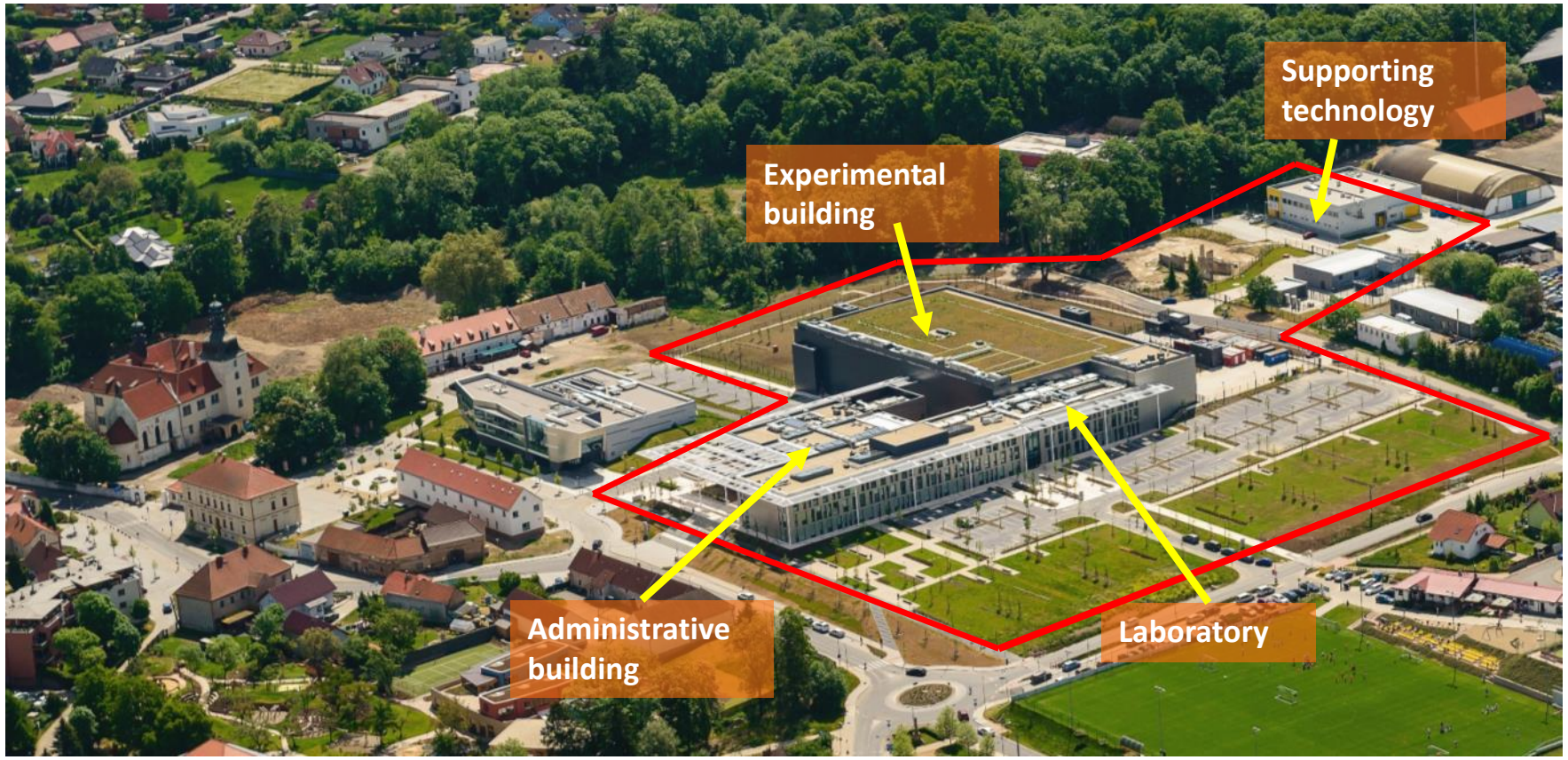
The ELI User Portal

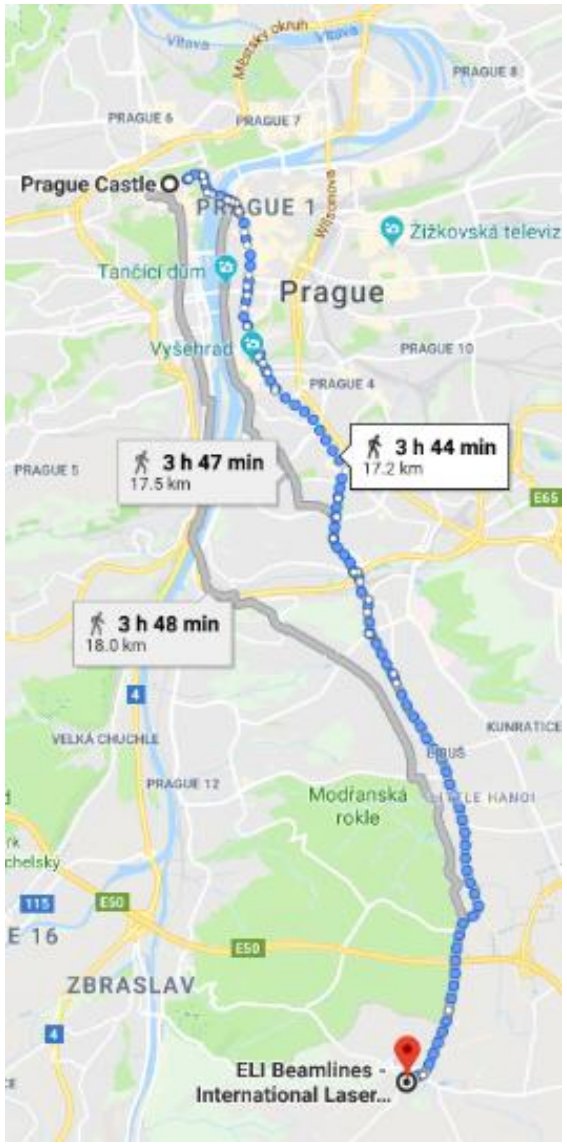
The ELI User Portal is a portal for researchers and scientists to explore and access comprehensive details on ELI's cutting-edge lasers, equipment, and facilities available for groundbreaking science.

up.eli-laser.eu

ELI Beamlines

- www.eli-beams.eu
- Integrated in ELI ERIC since 1.1.2023
- Located on the outskirts of Prague





ELI Beamlines

- www.eli-beams.eu
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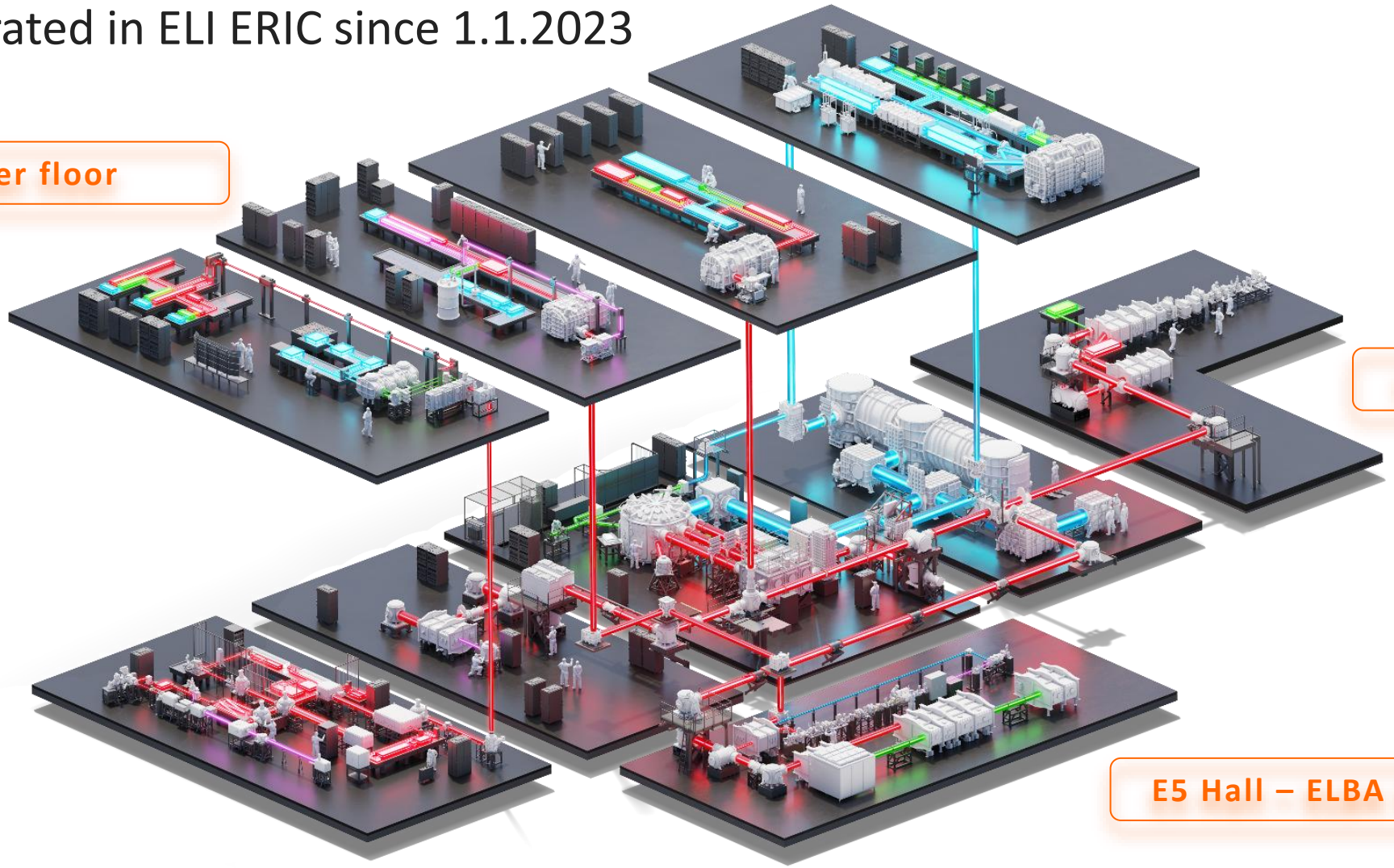
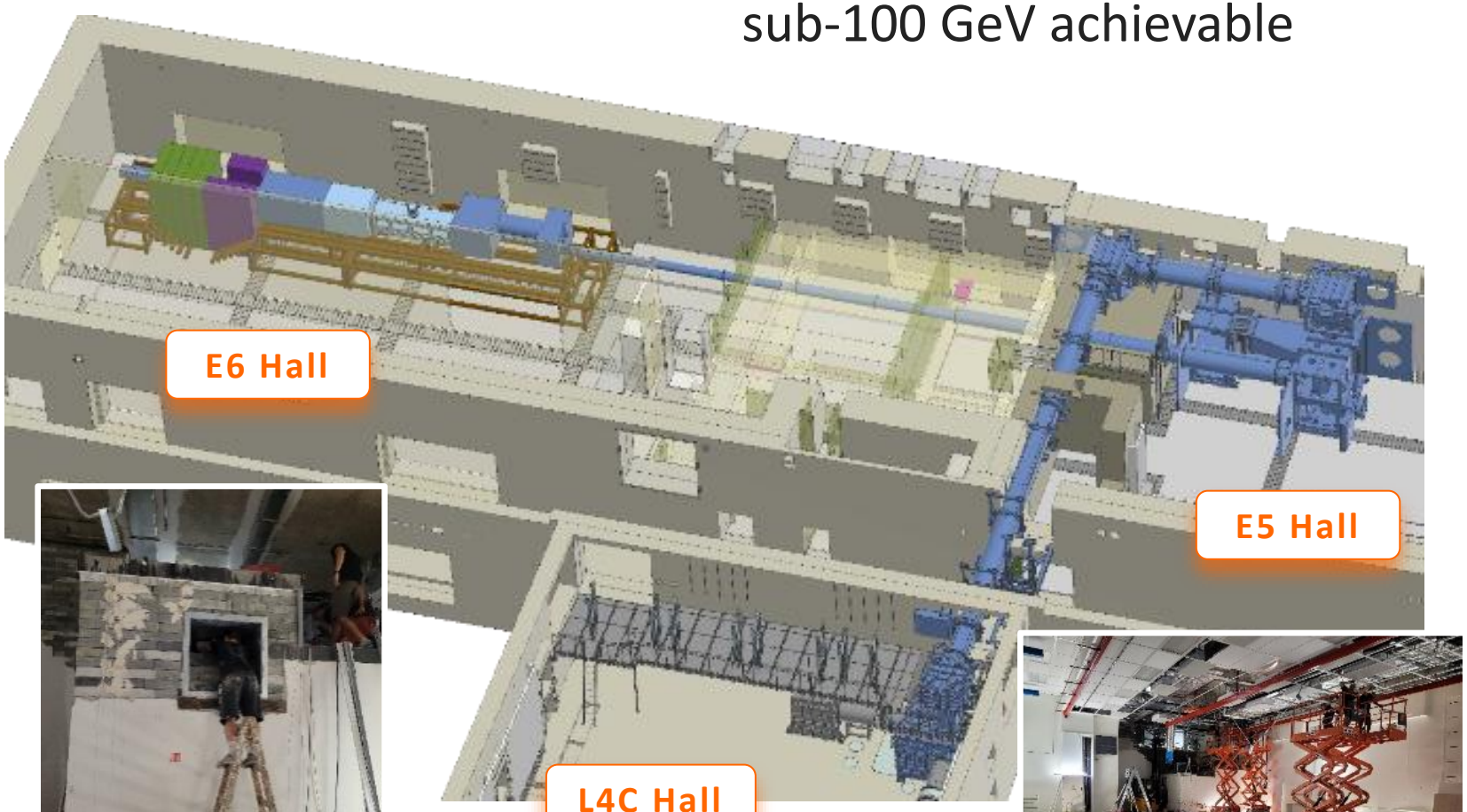


ELBA User Station

- Equipped with L3-HAPLS laser, 1 PW
  - Ti:Sa, 30 J, 20 fs, 10 Hz
  - Sub-10 GeV muons achievable
- First parasitic muon experiment
  - MuLASER, Spring-Summer 2025
  - CERN-INFN-UCLouvain-VUB collaboration
  - See Sumaira Ikram's talk later
- First main user muon experiment
  - MuLASER2, scheduled for September 2026
  - CERN-INFN-UCLouvain-VUB collaboration
- More muon user experiments
  already submitted in Spring 2026`

L4-ATON 10 PW beamline

- Plan to deliver to ELBA L4-ATON laser, 10PW, Nd:Glass, 1.5 kJ, 150 fs, 0.01 Hz
  sub-100 GeV achievable

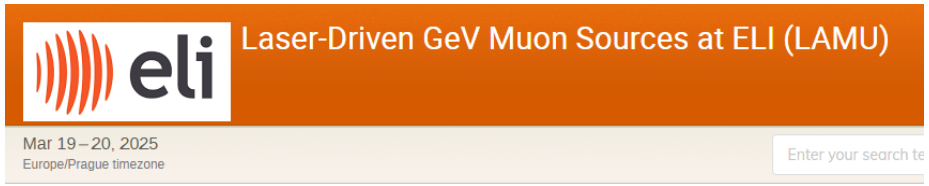


- L4C compressor:
  ready
- Beam transport to E5:
  designed
- E5 vacuum chamber:
  preliminary design
- Transport civil engineering:
  completed

- Collaborations with
  UMD & UT

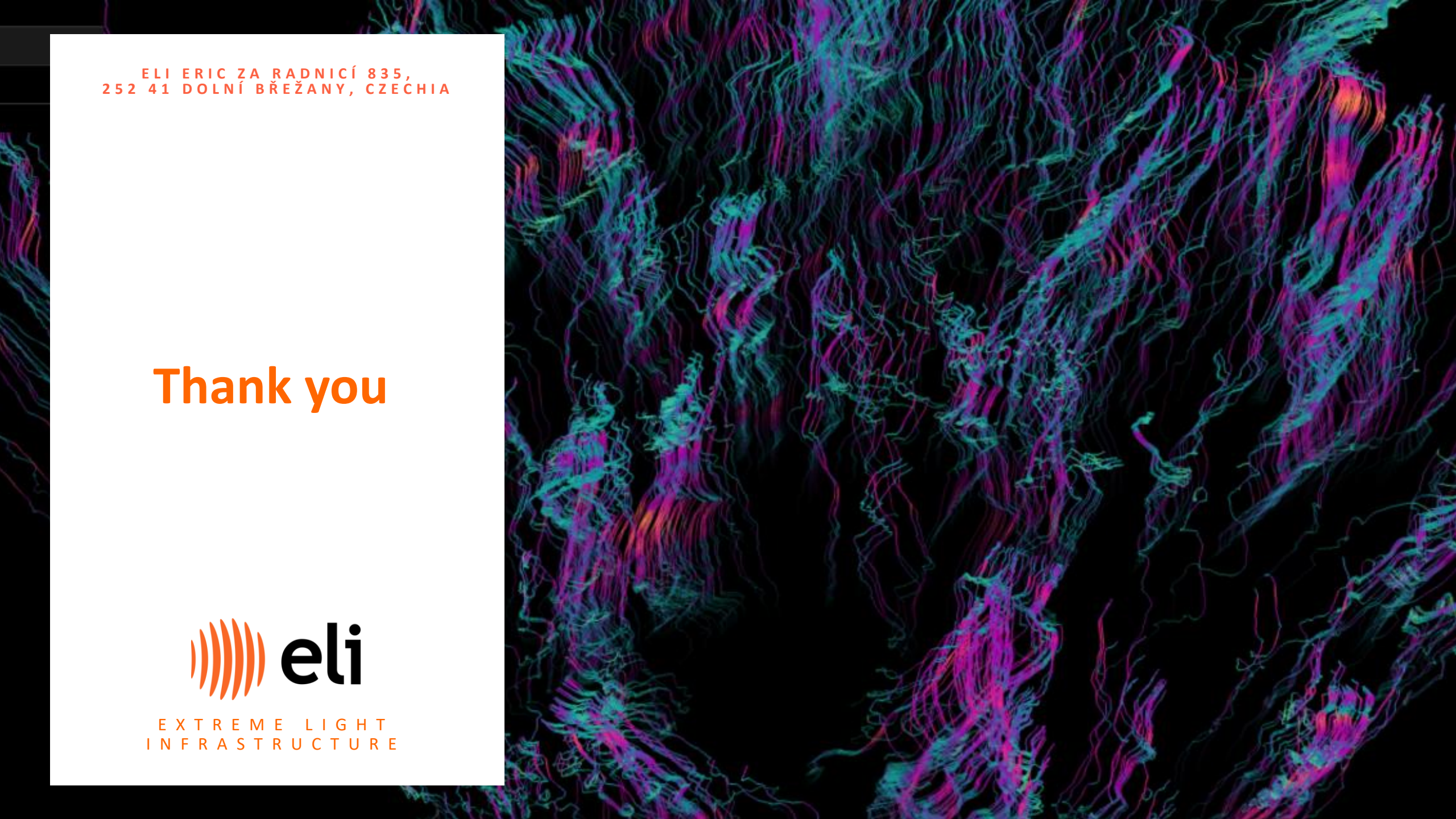
Future of muons @ ELI Beamlines

- Increased engagement with muon community
  - LAMU workshop in March 2025
    - Review paper submitted to High Power Laser Science and Engineering
- Expected increase in muon-based user proposals
- **Improvement of the 1 PW "muon offer"**
- Participation in AMBIT - Advancing Muon Beam facilities with Innovative Technologies
  - INFN-led proposal for HORIZON-INFRA-2026-TECH-01-01 call
  - Development of European muons facilities: ELI Beamlines, ISIS, PSI
- Search for funds for the development of the 10 PW muon beamline
  - Aiming at 2027 EU calls
- **Input from muon community and potential users is pivotal**
  - Improvement of E5 experimental area
  - E6 experimental area to be designed



ELI ERIC ZA RADNICÍ 835,
252 41 DOLNÍ BŘEŽANY, CZECHIA

Thank you



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