Muon production at laser facilities and ELI Beamlines Future plans

R. Versaci

Muon4Future, 26-30 May 2025, Venezia

Outline

- A bit of history
- Laser acceleration
- Why is there interest for muons from laser?
- Muon experiments in the laser community
- Laser community future plans
- ELI-ERIC and ELI-Beamlines
- ELI-Beamlines future plans

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


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- 1985: Development of Chirped Pulse Amplification

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



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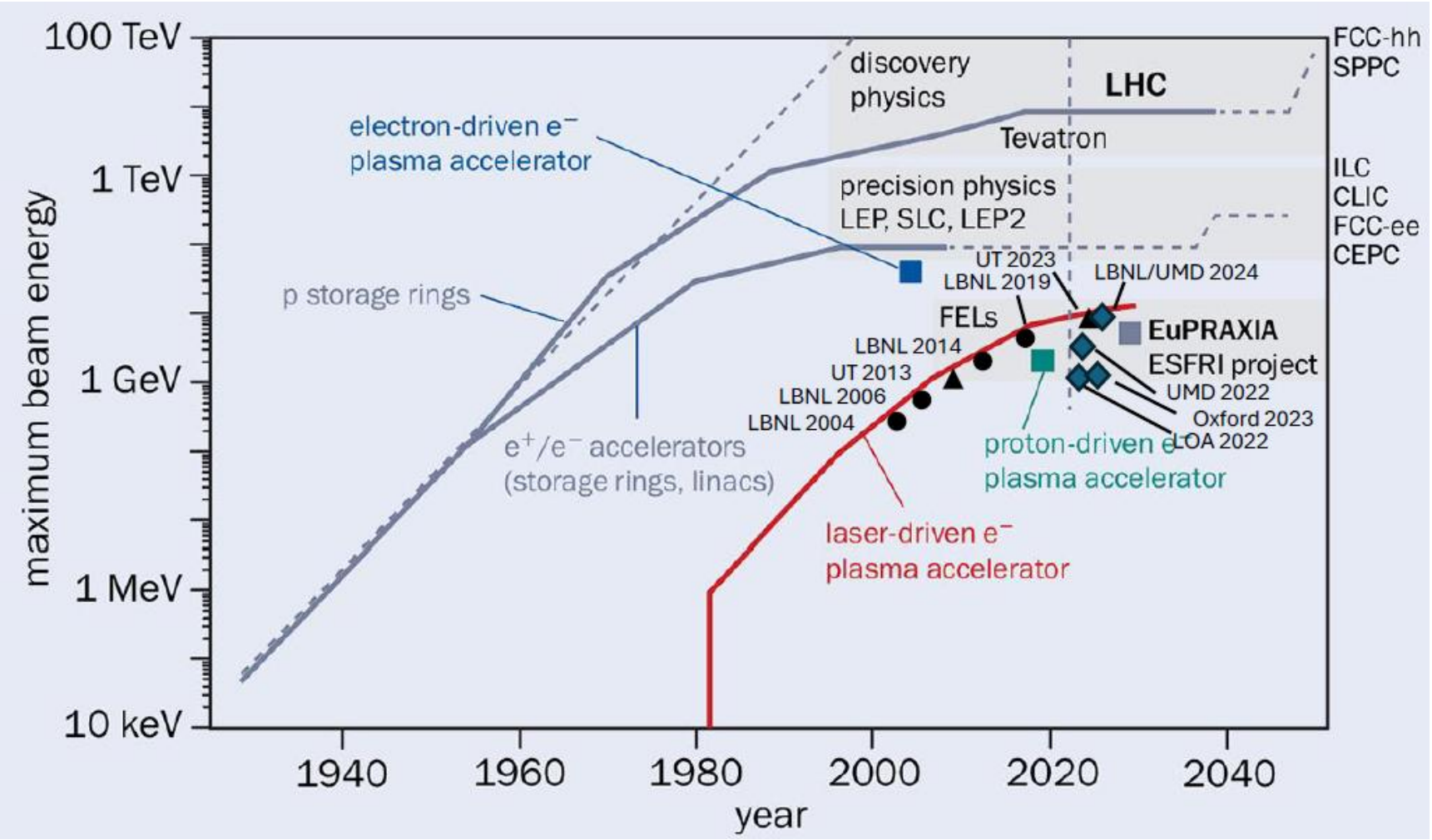
Laser Acceleration



© 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

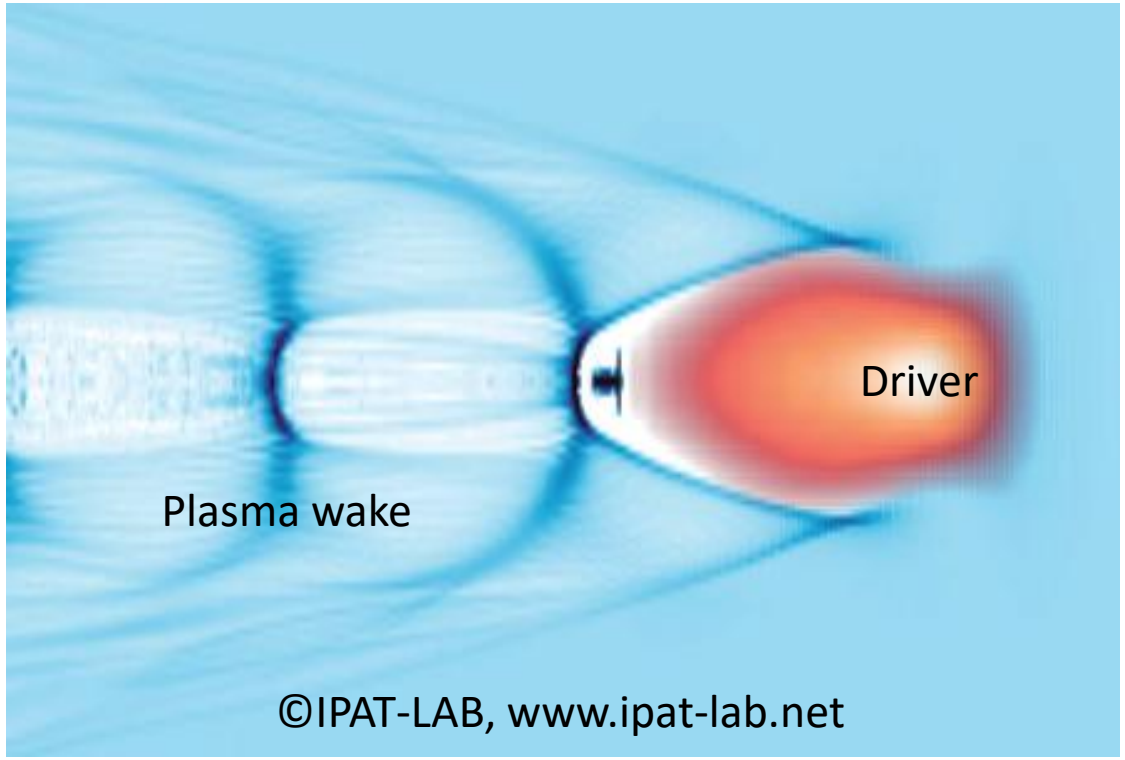
Laser-driven high-energy proton beams from cascaded acceleration regimes

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

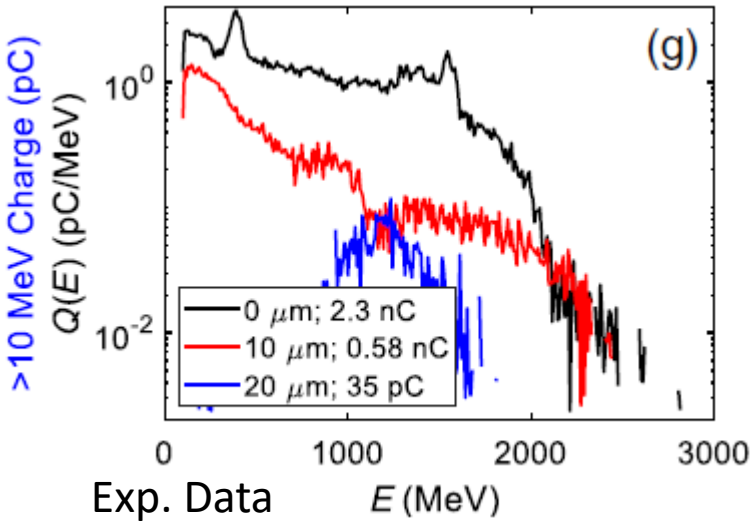
Laser Wakefield Acceleration

- 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”



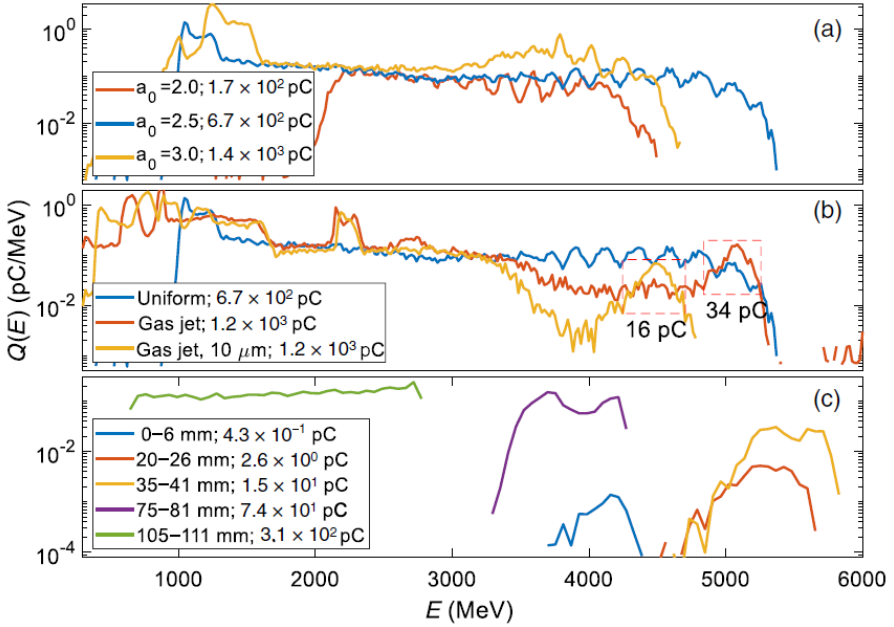
Laser Wakefield Acceleration

- Electron spectrum can “look strange”



Exp. Data

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

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 ge
wakefield accelerator. The $\mu^+\mu^-$ pairs are
accelerating plasma region. Numerical estim
expected to be reliable in the nearest future.
dominate the dimuon production. Accordin
1 (10) GeV may create about 100 (5000) mu
aspects of muon-related physics in tabletop
towards the investigation of more complicat

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)

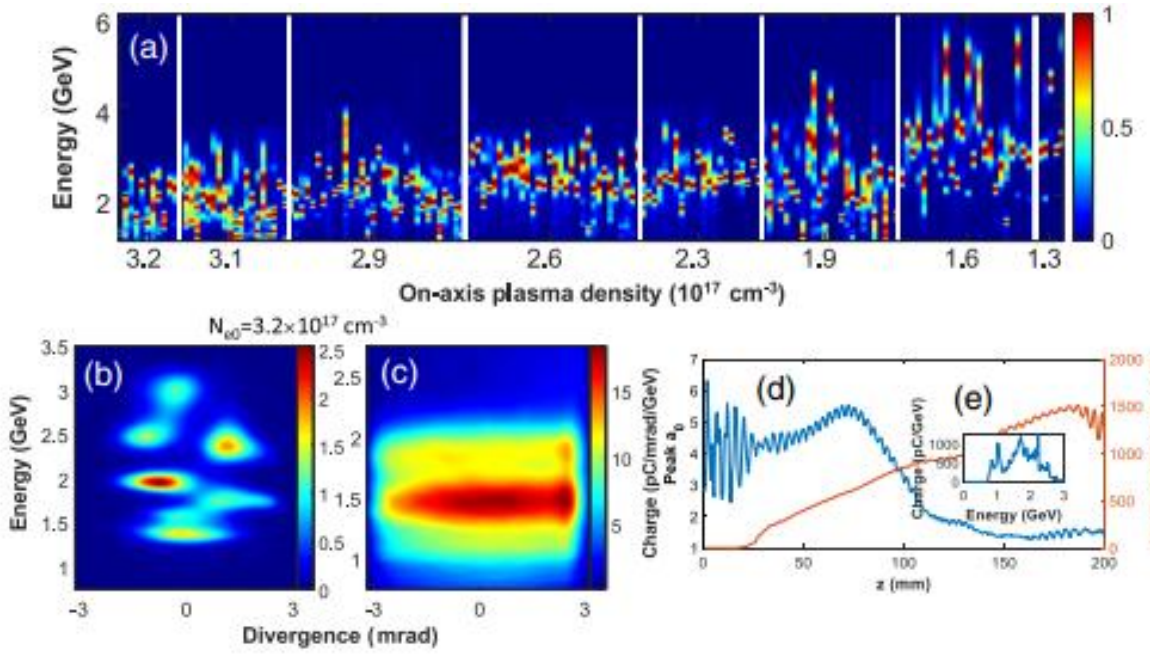
Laser Acceleration of Electrons

- 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)

Laser Acceleration of Electrons

- Increased interest in particle physics

Making pions with laser light

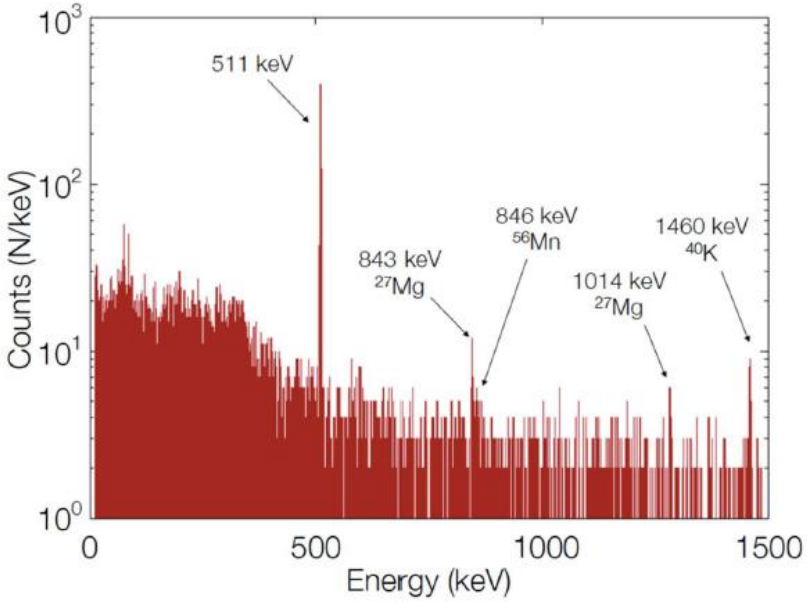
W Schumaker, T Liang, R Clarke, J M Cole, G Grittani, S Kuschel, S P D Mangles, Z Najmudin, K Poder, G Sarri, D Symes, A G R Thomas, M Vargas, M Zepf and K Krushelnick ▲ Hide full author list

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)

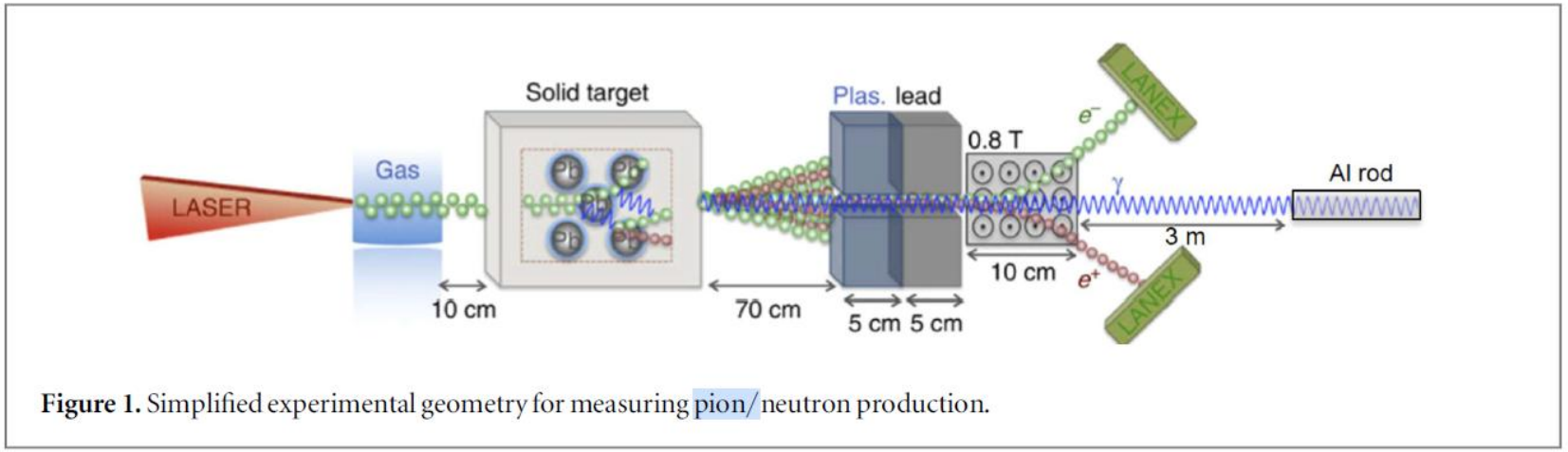
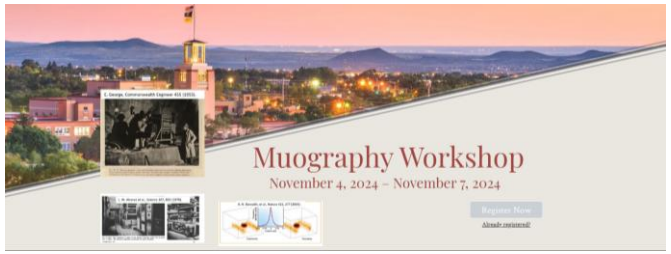


Figure 1. Simplified experimental geometry for measuring pion/neutron production.

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

International MUON Collider Collaboration



Muography of large objects

- 1970: L. Alvarez first to look inside pyramids

  Science, New Series, Vol. 167, No. 3919. (Feb. 6, 1970), pp. 832-839

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

- 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)

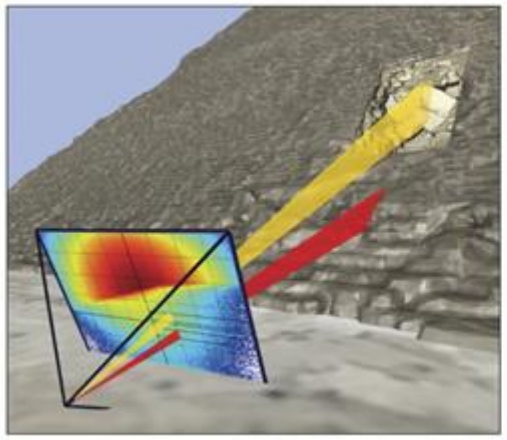
Letter | Published: 02 November 2017

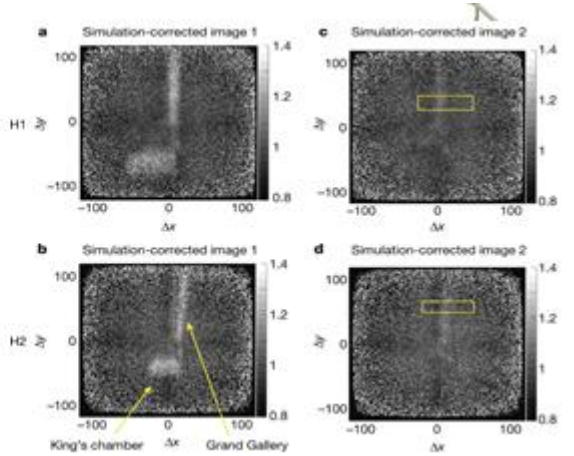
Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima, Mitsuaki Kuno, Akira Nishio, Nobuko Kitagawa, Yuta Manabe, Masaki Moto, Fumihiko Takasaki, Hirofumi Fujii, Kotaro Satoh, Hideyo Kodama, Kohei Hayashi, Shigeru Odaka, Sébastien Procureur, David Attié, Simon Bouteille, Denis Calvet, Christopher Filosa, Patrick Magnier, Irakli Mandjavidze, Marc Riallot, Benoit Marini, Pierre Gable, Yoshikatsu Date, Makiko Sugiura, ... Mehdi Tayoubi

+ Show authors

Nature **552**, 386–390 (2017) | Cite this article





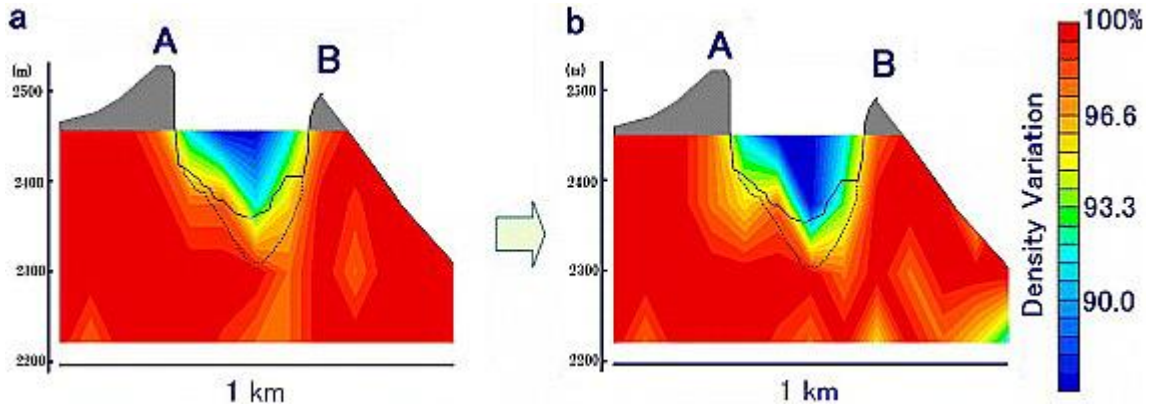
Muography of large objects

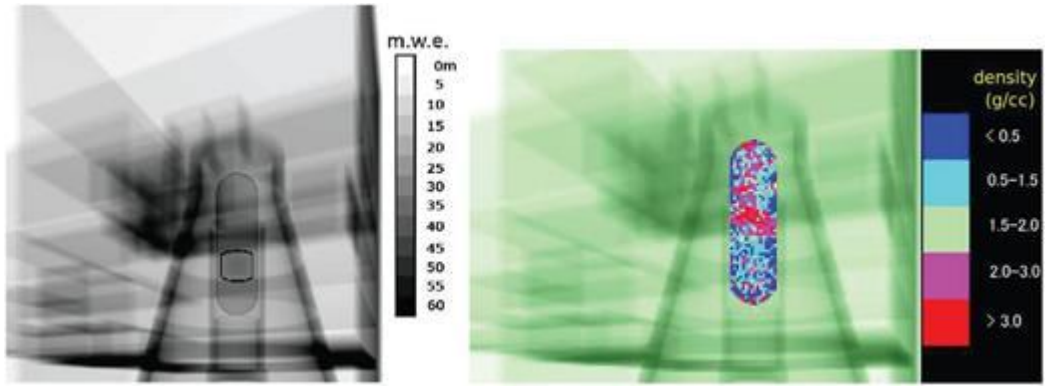
- 2009: First volcano muography

  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

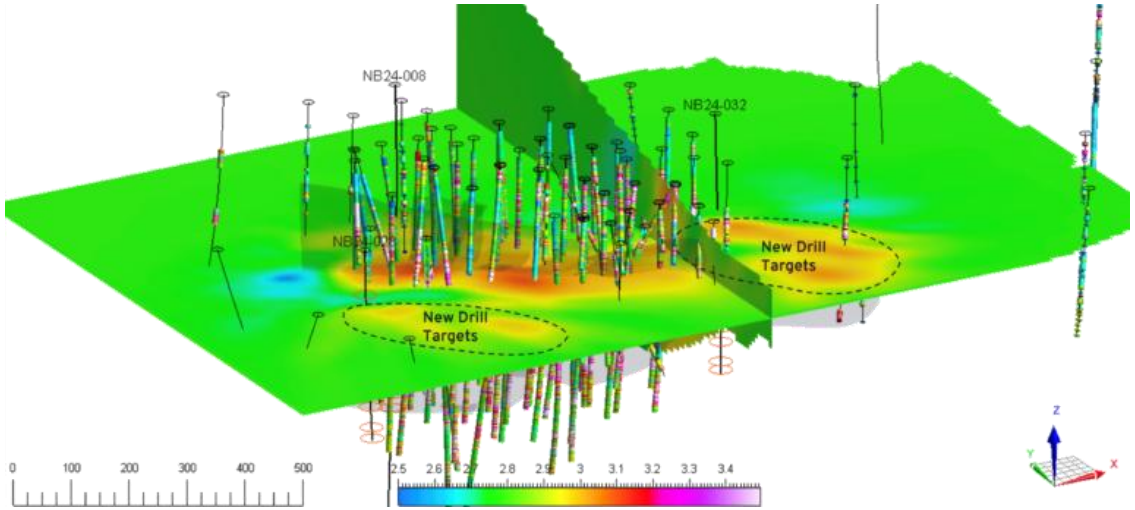
  H. Fujii, et al., “Performance of a remotely located muon radiography system to identify the inner structure of a nuclear plant”, *Progr. of Theor. and Exp. Physics*, Volume 2013, Issue 7, July 2013, 073C01





Commercial Muography

- Use of cosmic muons and AI to investigate:
  - Mining opportunities
  - Big engineering structures
  - Sunk Soviet nuclear submarines



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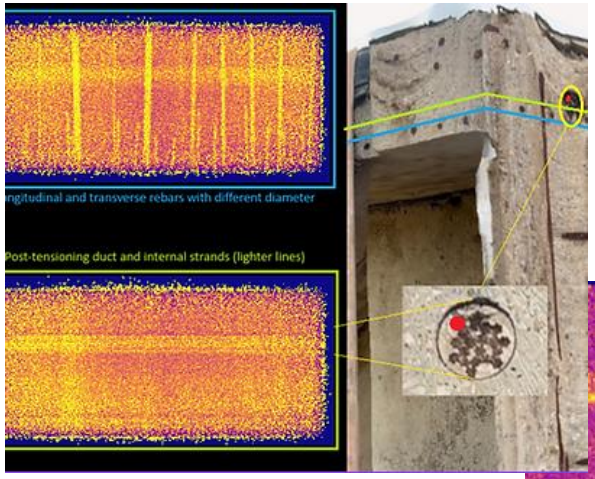

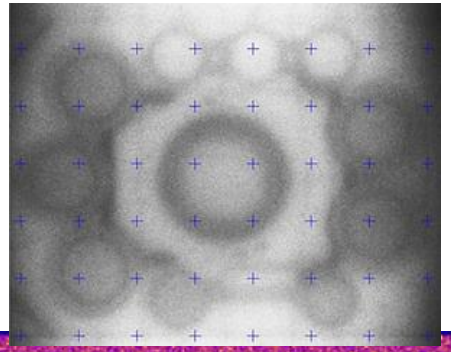

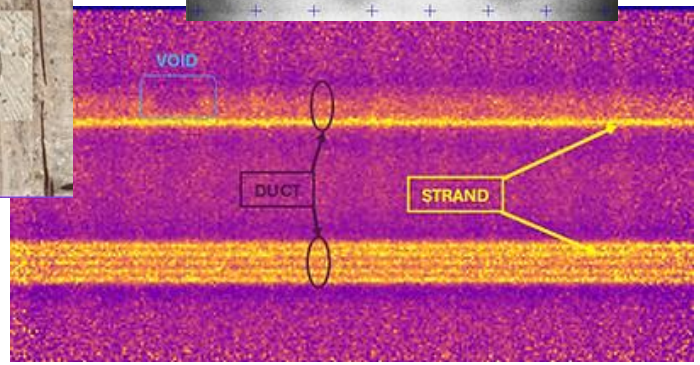

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Muons used to test the condition of a road bridge in Estonia

NEWS
Hanneli Rudi
16.03.2025 06:55

Jõgisoo Bridge. Source: ERR

©ERR
www.err.ee
Jogisoo Bridge

Muography for homeland security

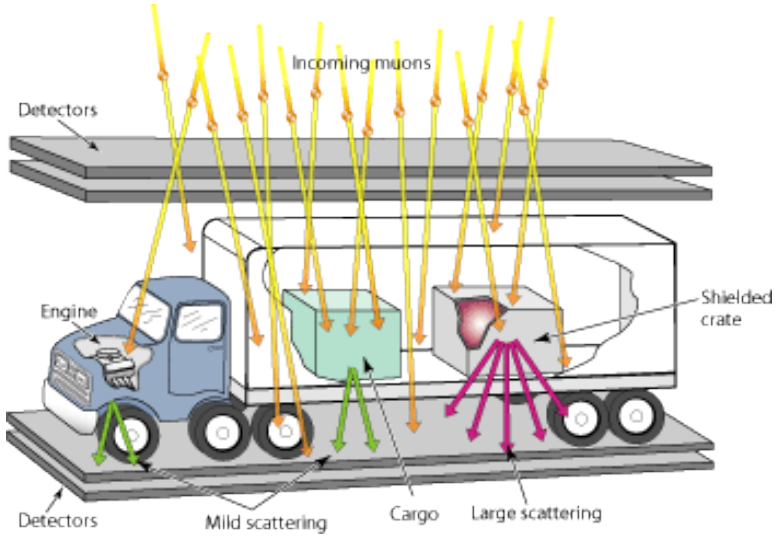
- Particularly hot topic in the USA after 9/11

  TSA requires 100% of cargo transported on passenger aircraft to be screened at a level of security commensurate with the level of security for the screening of passenger checked baggage ("Implementing Recommendations of the 9/11 Commission Act of 2007").
  Several documents available with TSA and CBP plans and milestones.

- Only a fraction of cargo are inspected with non-invasive methods
- Looking for new technologies: in 2002 LANL proposed to use cosmic muons

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

  unfortunately, not time efficient



Muography for homeland security

- Tunnels are also a hot topic
- From warfare…

  https://www.npr.org/sections/parallels/2014/07/26/335332220/the-long-history-of-the-gaza-tunnels (2014)

- …to smuggling

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

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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

A bit of competition

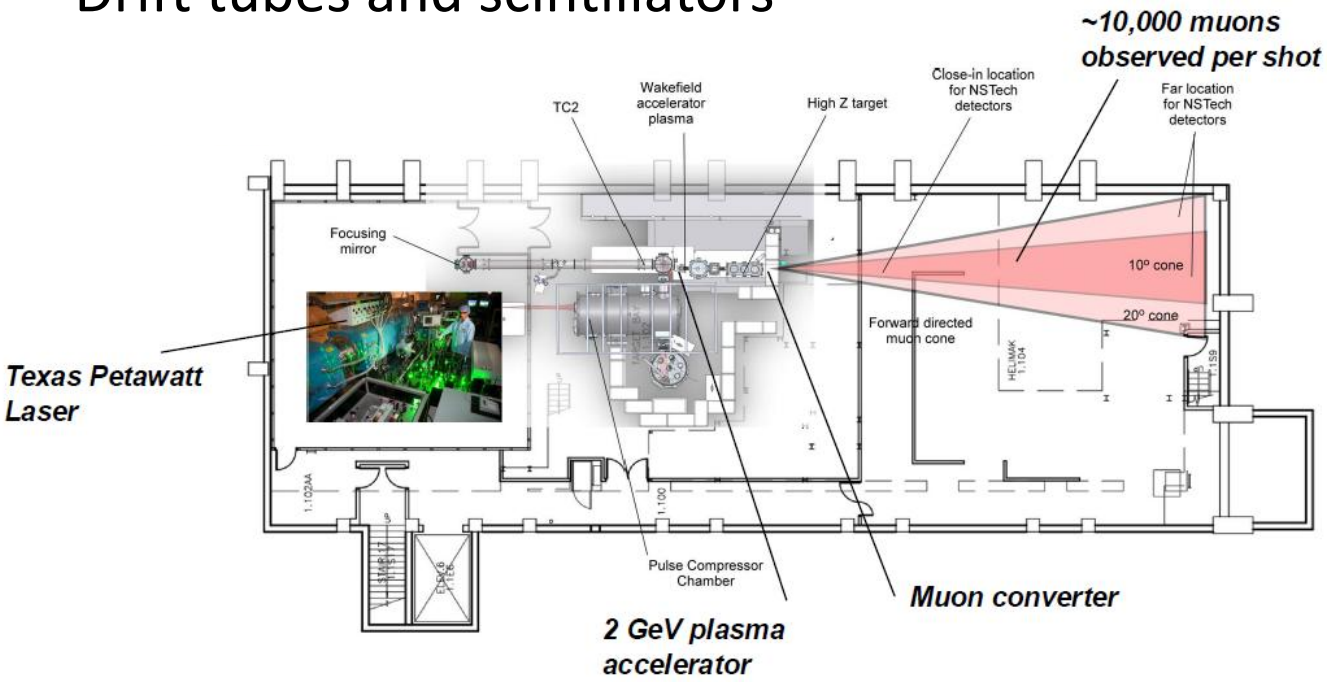
- Several laser groups attempted to produce and detect muons

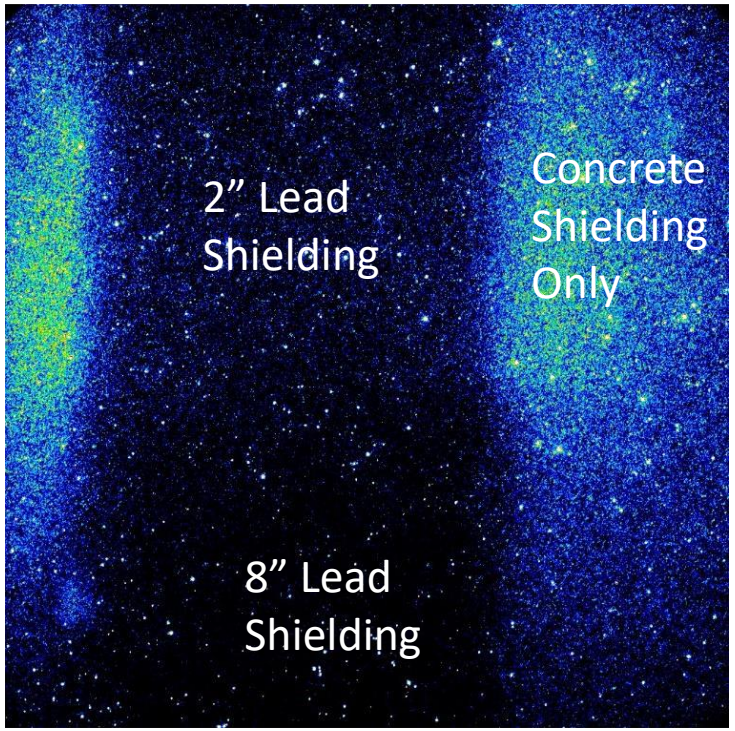
- National Security Technology @ Texas PetaWatt
- Laser Fusion Research Center @ China Academy of Engineering Physics
- Berkeley Lab @ BELLA
- QUB @ ELI-NP
- LLNL @ CSU

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

National Security Technology

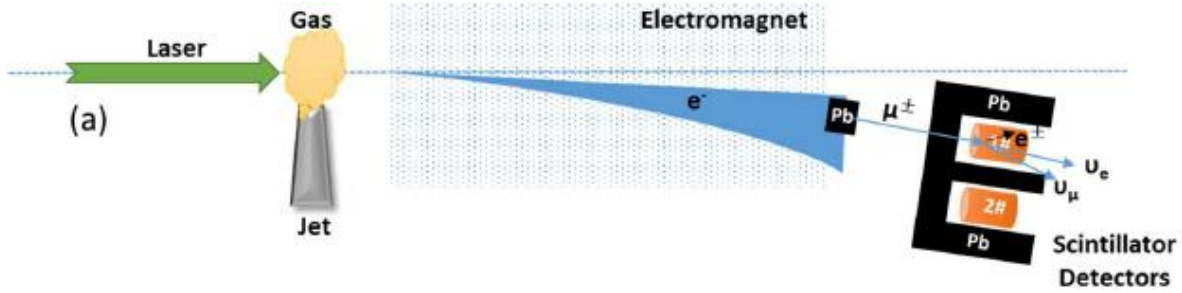
- At IEEE Nuclear Science Symposium & Medical Imaging Conference (2014)
- Dressen, W., *et al*. "*Detection of Petawatt Laser-Induced Muon Source for Rapid High-Z Material Detection*", Oct 2014.
- 1PW at TPW
- Drift tubes and scintillators

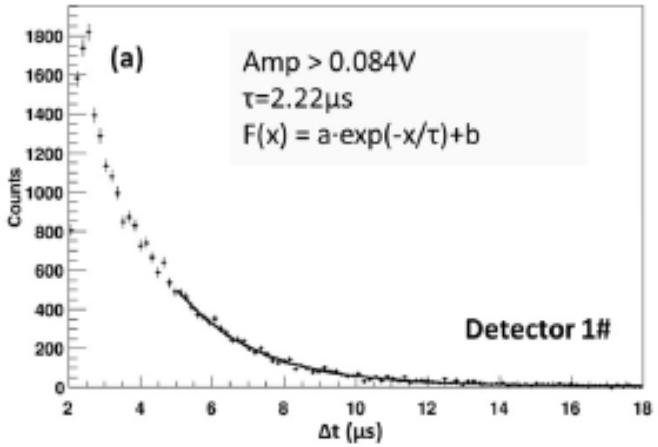


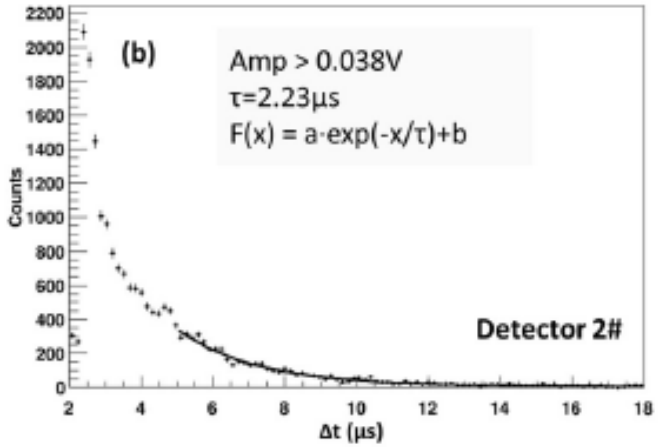


Laser Fusion Research Center

- Zhang, F. *et al.* "Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser" *Nat. Phys.* (2025)
- 1PW laser at SULF
- 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

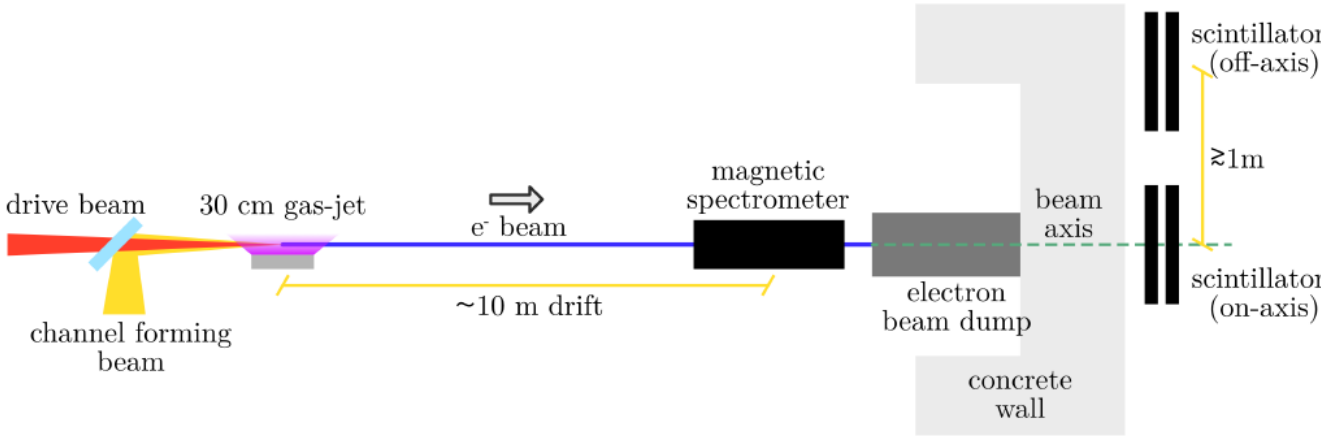
Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser

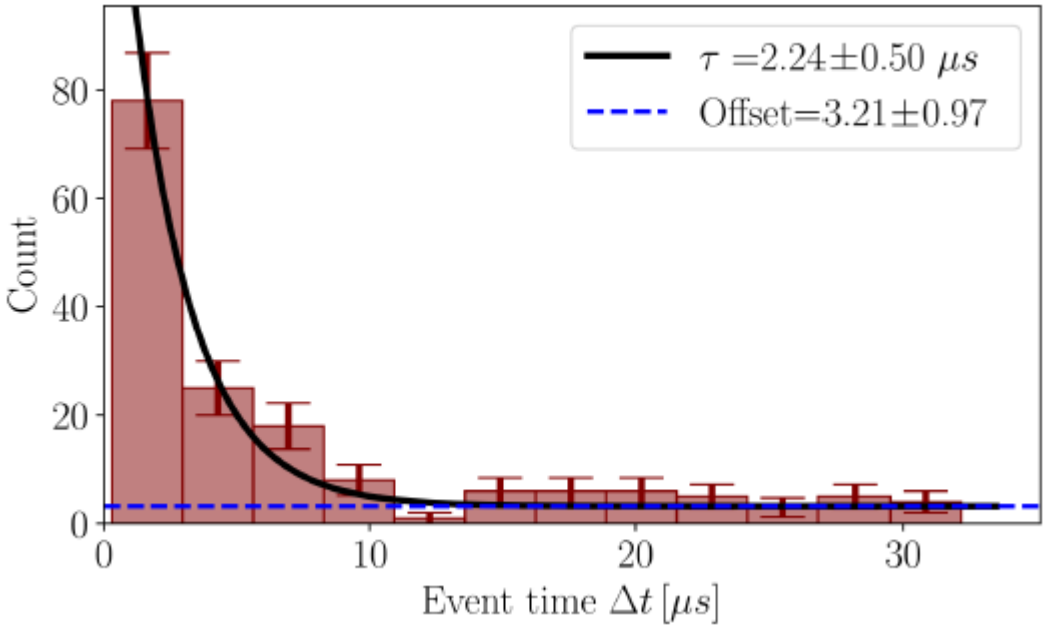
Feng Zhang, Li Deng, Yanjie Ge, Jiaxing Wen, Bo Cui, Ke Feng, Hao Wang, Chen Wu, Ziwen Pan, Hongjie Liu, Zhigang Deng, Zongxin Zhang, Liangwen Chen, Duo Yan, Lianqiang Shan, Zongqiang Yuan, Chao Tian, Jiayi Qian, Jiacheng Zhu, Yi Xu, Yuhong Yu, Xueheng Zhang, Lei Yang, Weimin Zhou, ... Ruxin Li + Show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

Nature Physics (2025) | Cite this article

Berkeley Lab

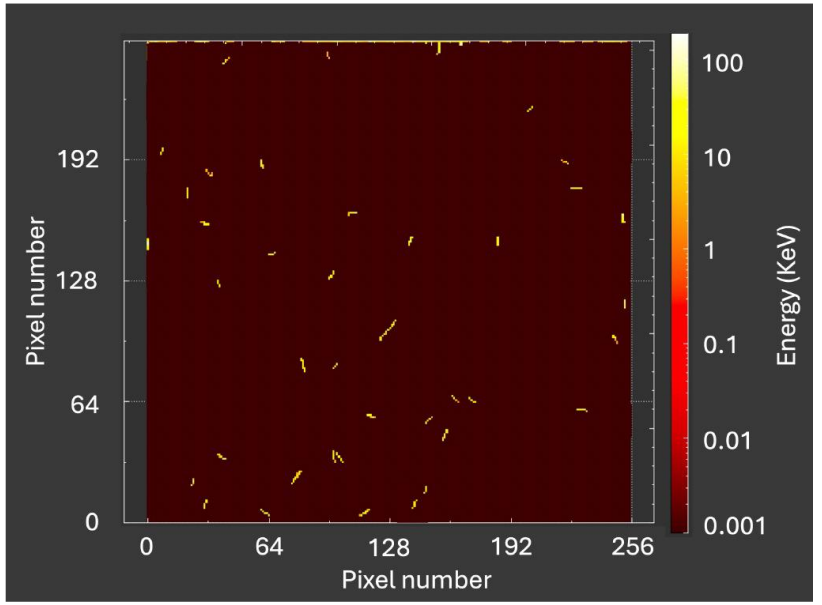
- Submitted to journal, *Terzani et al.*, arXiv:2411.02321v1
- 1PW laser at BELLA
- Electrons up to 8 GeV, ~50-250 pC/shot 0.1 Hz
- Plastic scintillator with PMT
- Laser as trigger for a time measurement

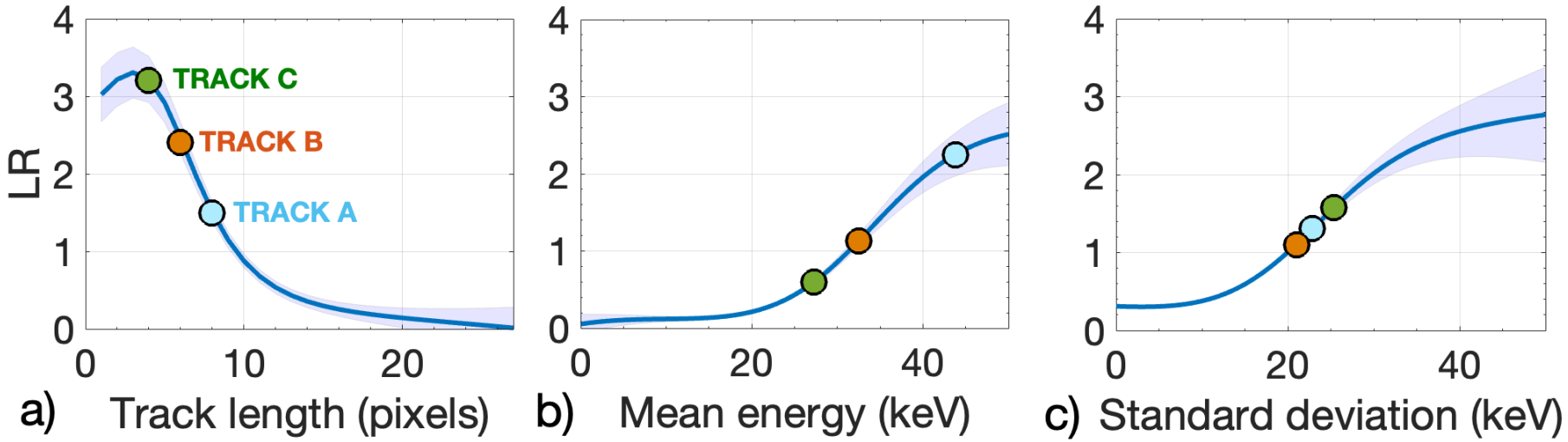




QUB @ ELI-NP

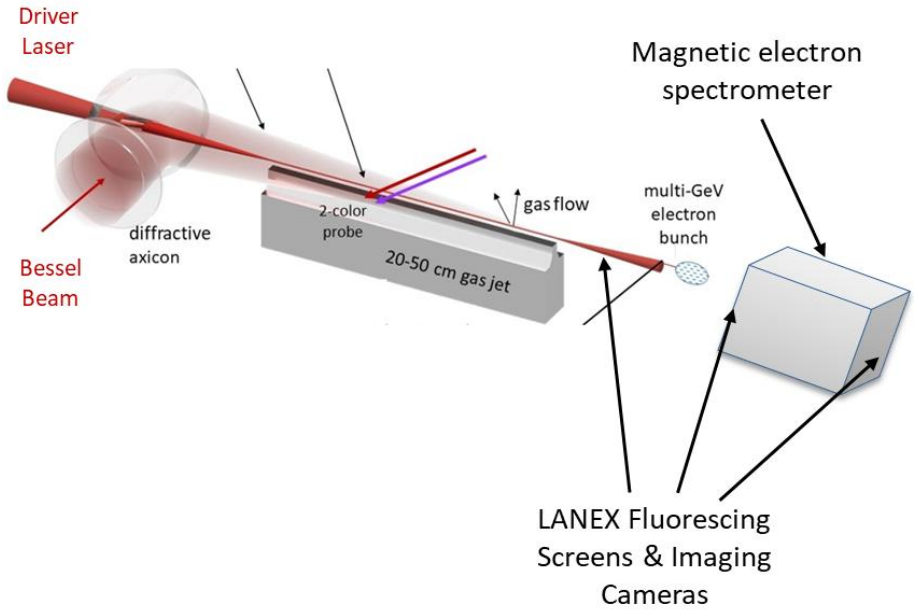
- Submitted to journal, *Calvin et al.,* arXiv:2503.20904
- 1PW laser at ELI-NP
- Electrons up to 1 GeV, ~560 pC/shot
- Timepix3
- Likelihood test based on MC study

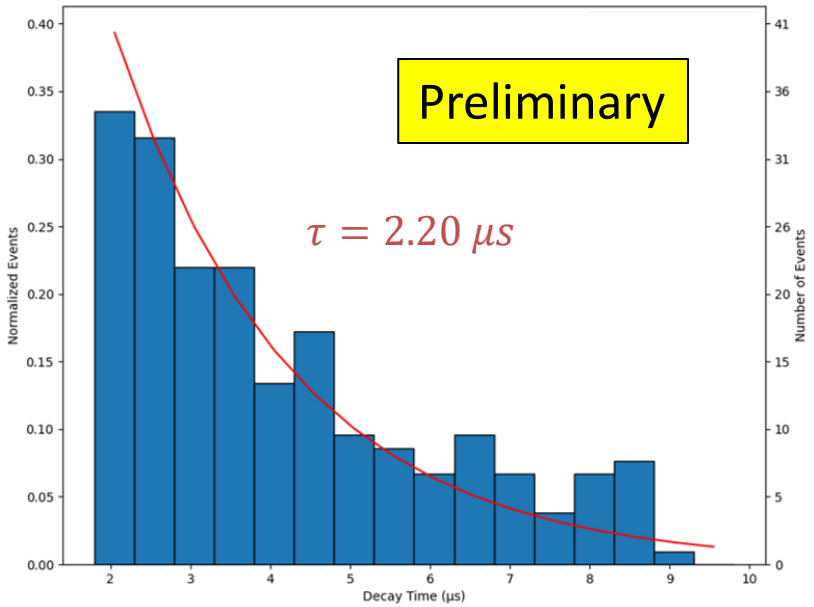


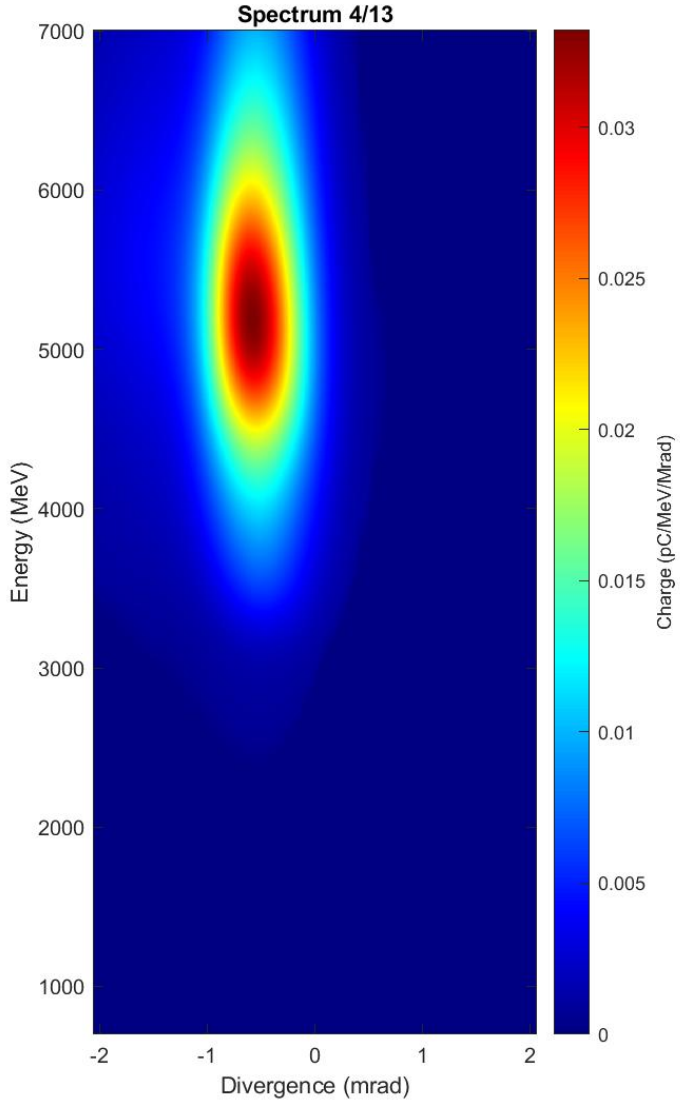


LLNL

- 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

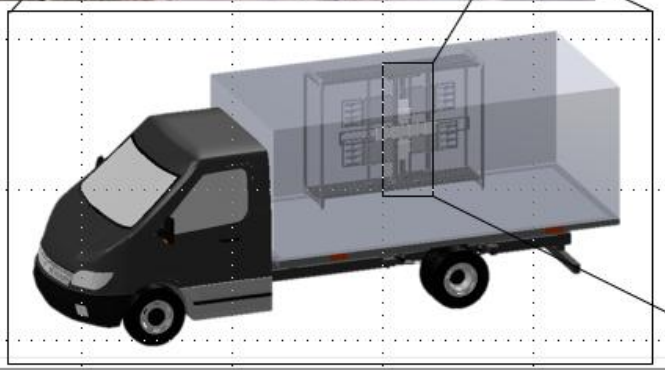


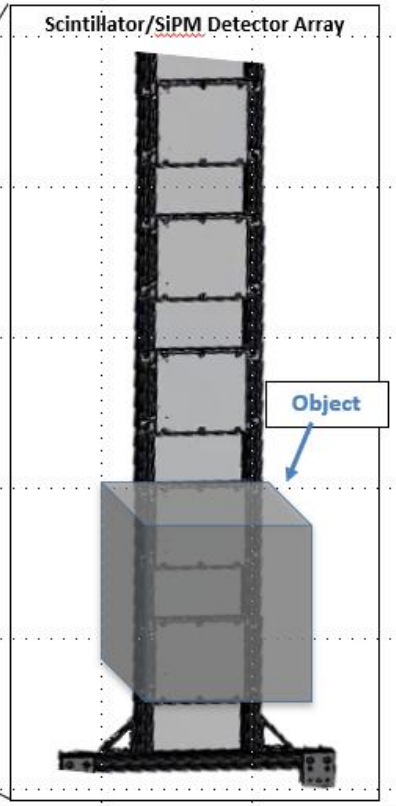


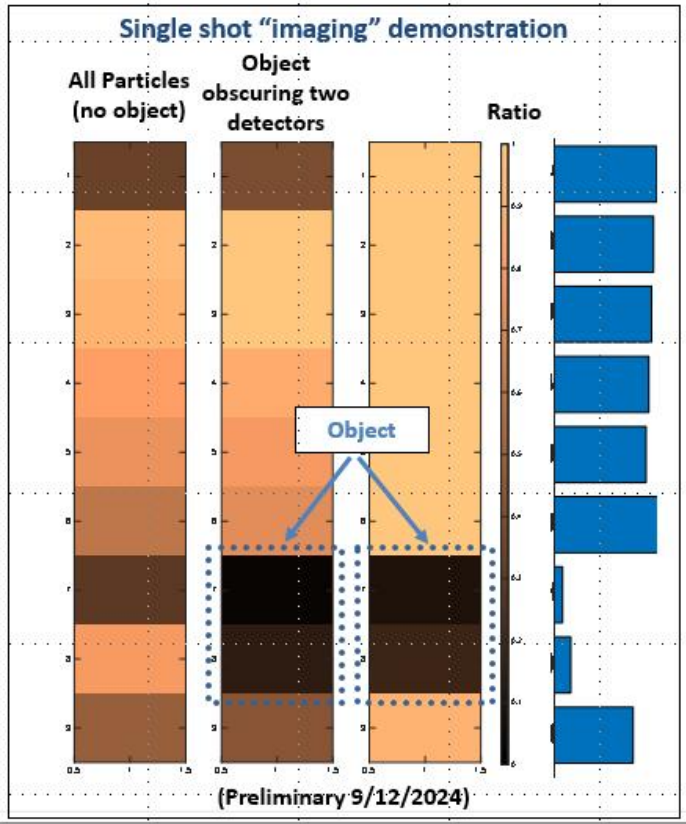


LLNL

Demonstration of imaging through electron beam dump and shielding (~0.5m Pb) and building walls using a mobile detector







LLNL-PRES-

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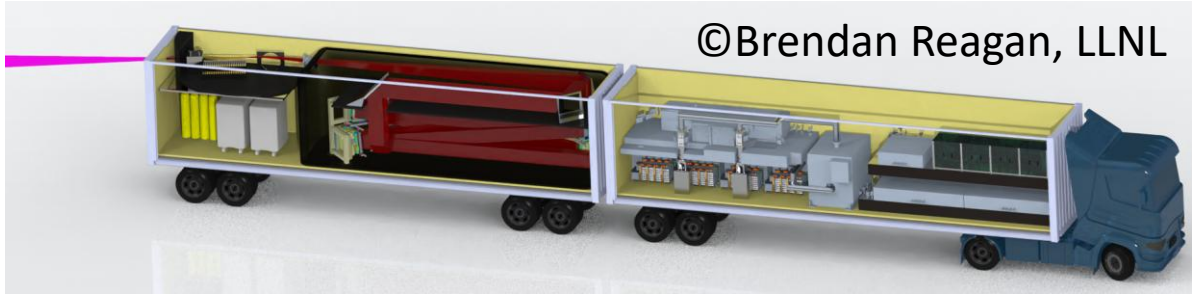
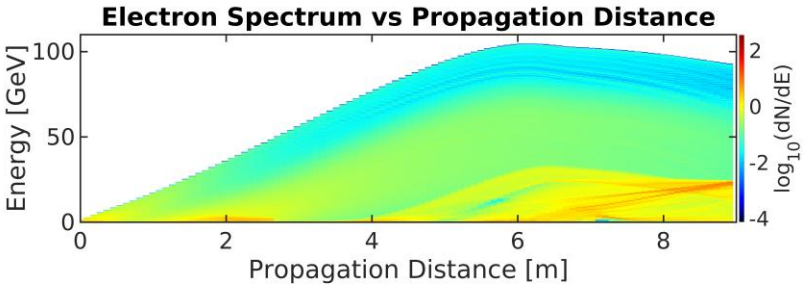
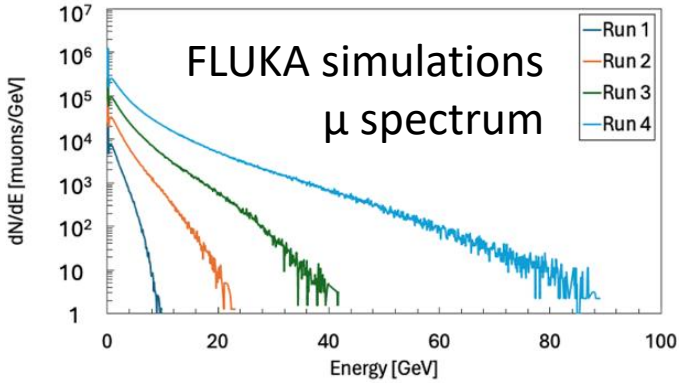
What's next?

- 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



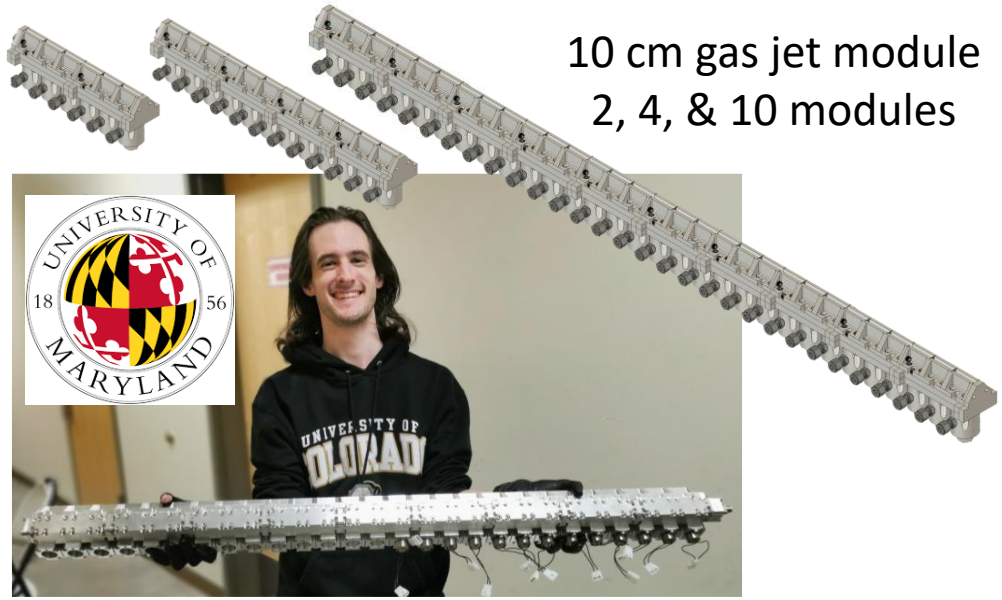


Accepted on Scientific Reports



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**

ELI ERIC

The **Extreme Light Infrastructure (ELI)**

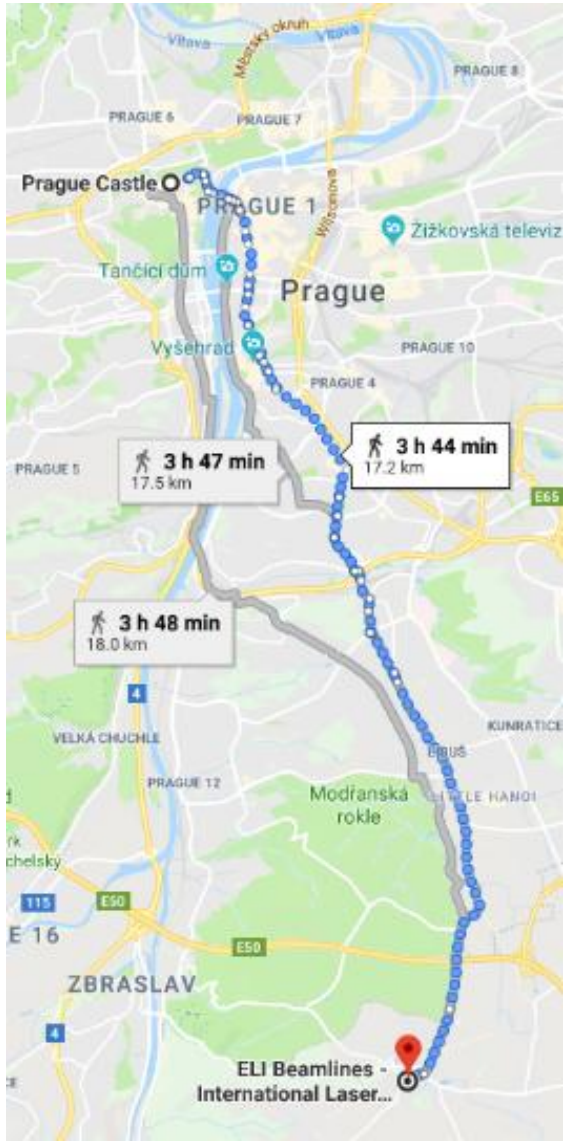
- Research Infrastructure, part of the European ESFRI Roadmap
- **User facility: 2 User Calls per year**

- 1.1.2011 start of parallel implementation of 3 sites
- 30.4.2021 ELI ERIC founded
- Founding members: CZ, HU, IT, LT
- Founding observers: DE, BG, RO

- Interested in joining: CH, ES, PL, PT

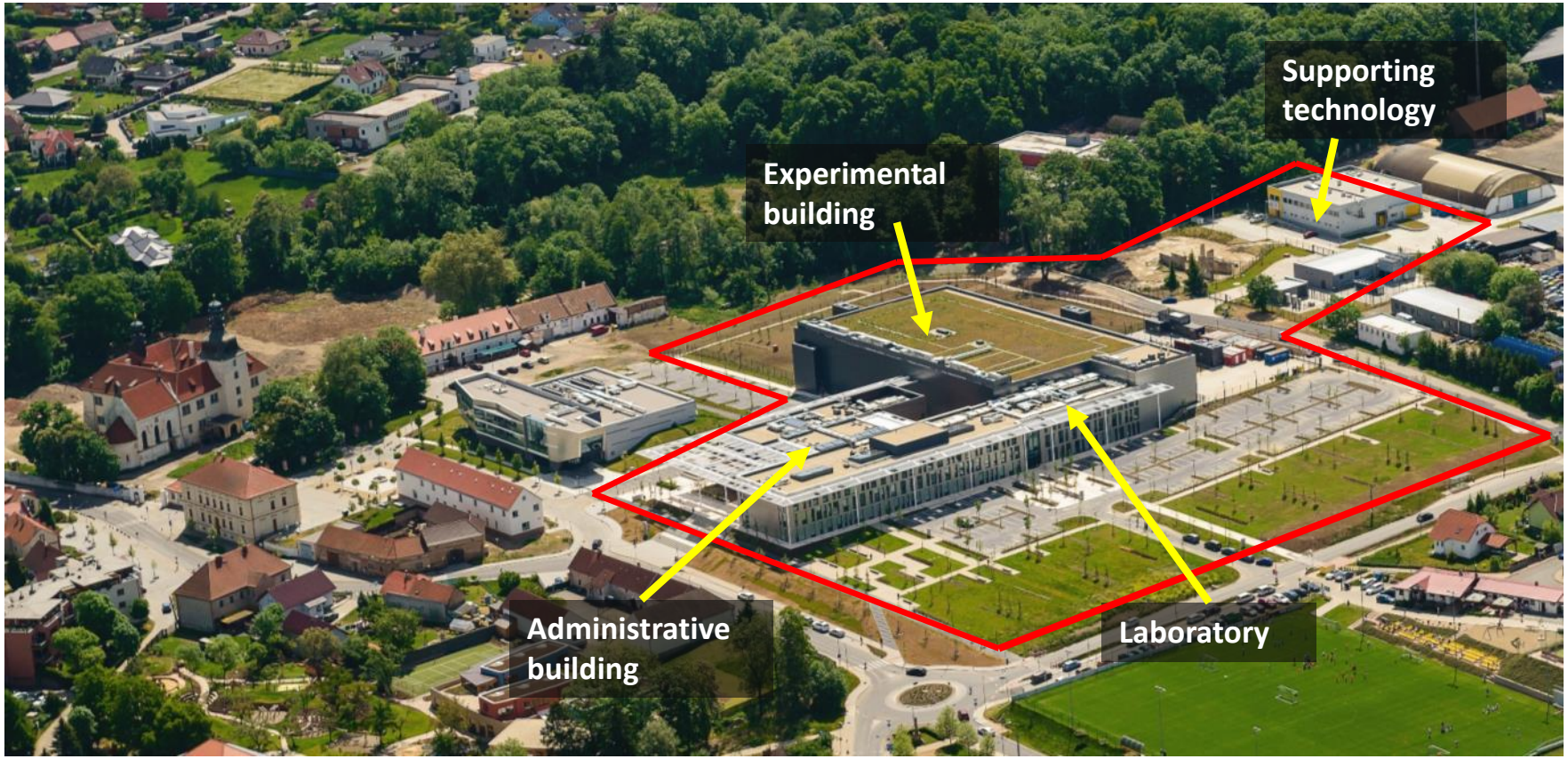
ELI Beamlines

www.eli-beams.eu



Integrated in the ERIC from 1.1.2023

Located on the outskirts of Prague



ELI Beamlines

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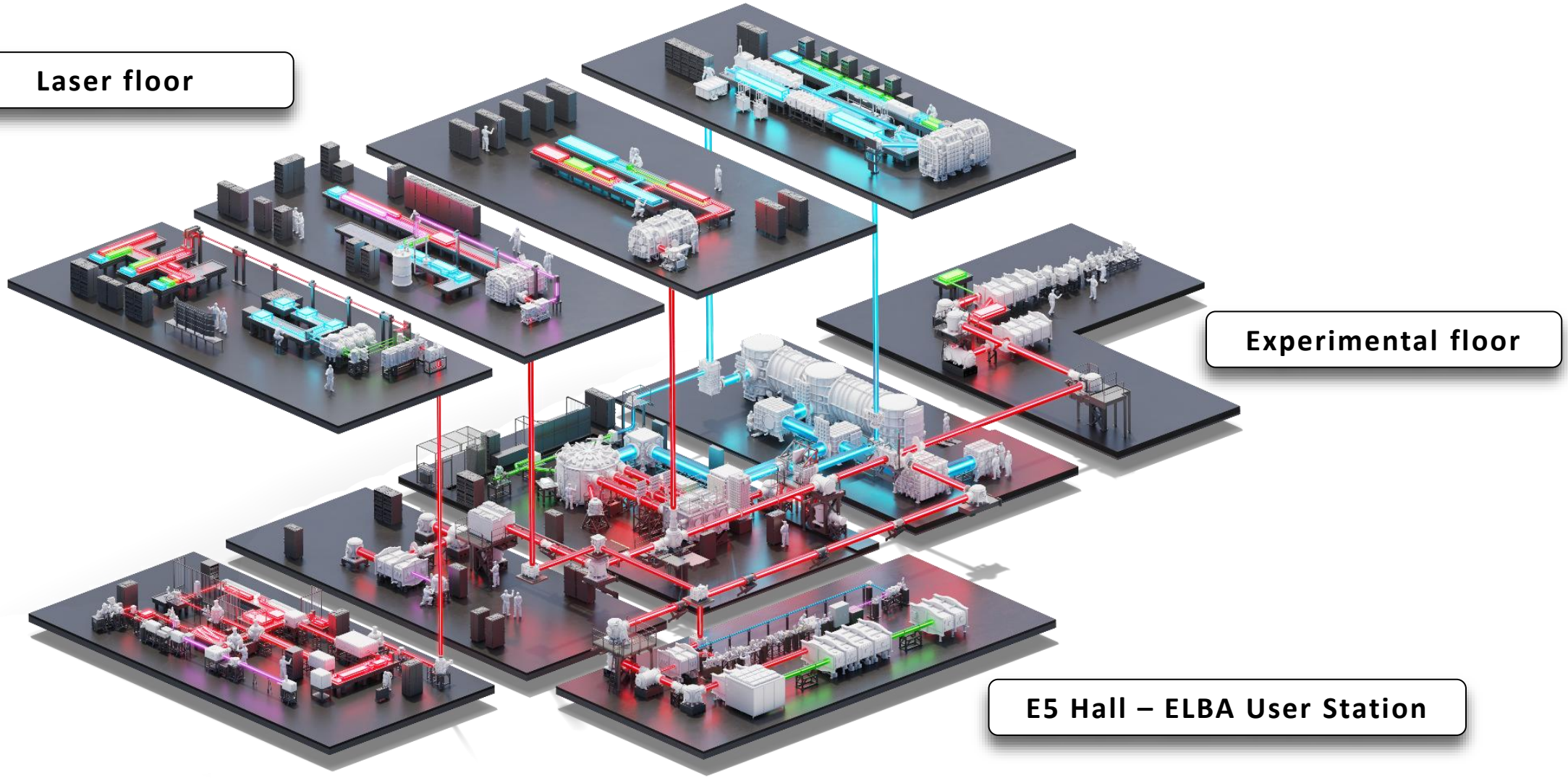


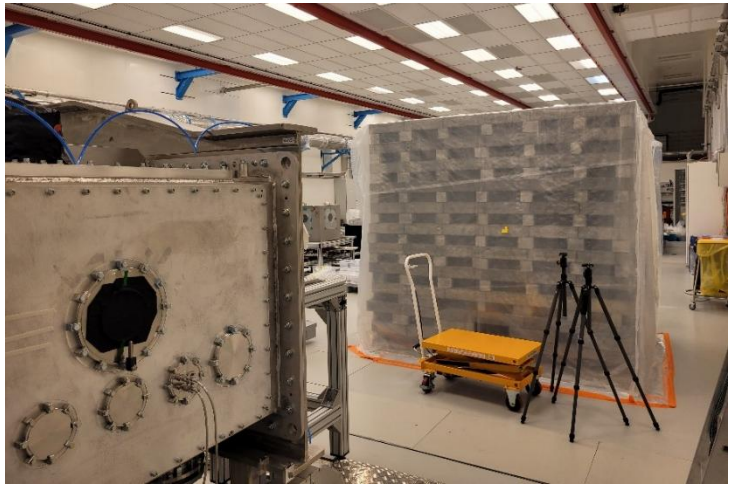
ELBA User Station

- Equipped with L3-HAPLS laser, 1PW
  - Ti:Sa, 30 J, 30 fs, 10 Hz
  - sub-10 GeV muons achievable

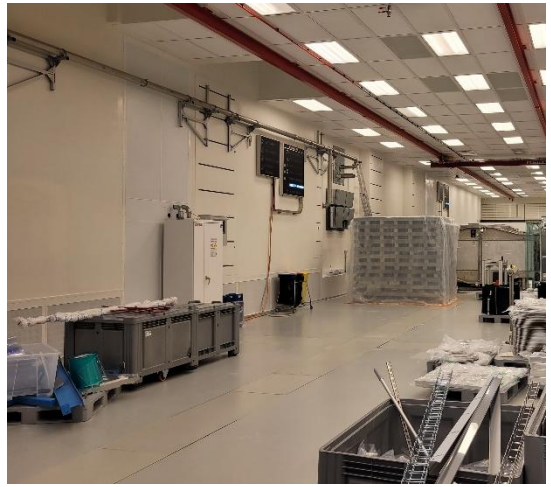
Already 2 user experiments relevant for muons:

- UMDLWFA, May 2025
  - from UMD
  - aim: record electron acceleration

- ELBA_MuLASER, August 2025
  - from CERN-INFN
  - aim: detect muons



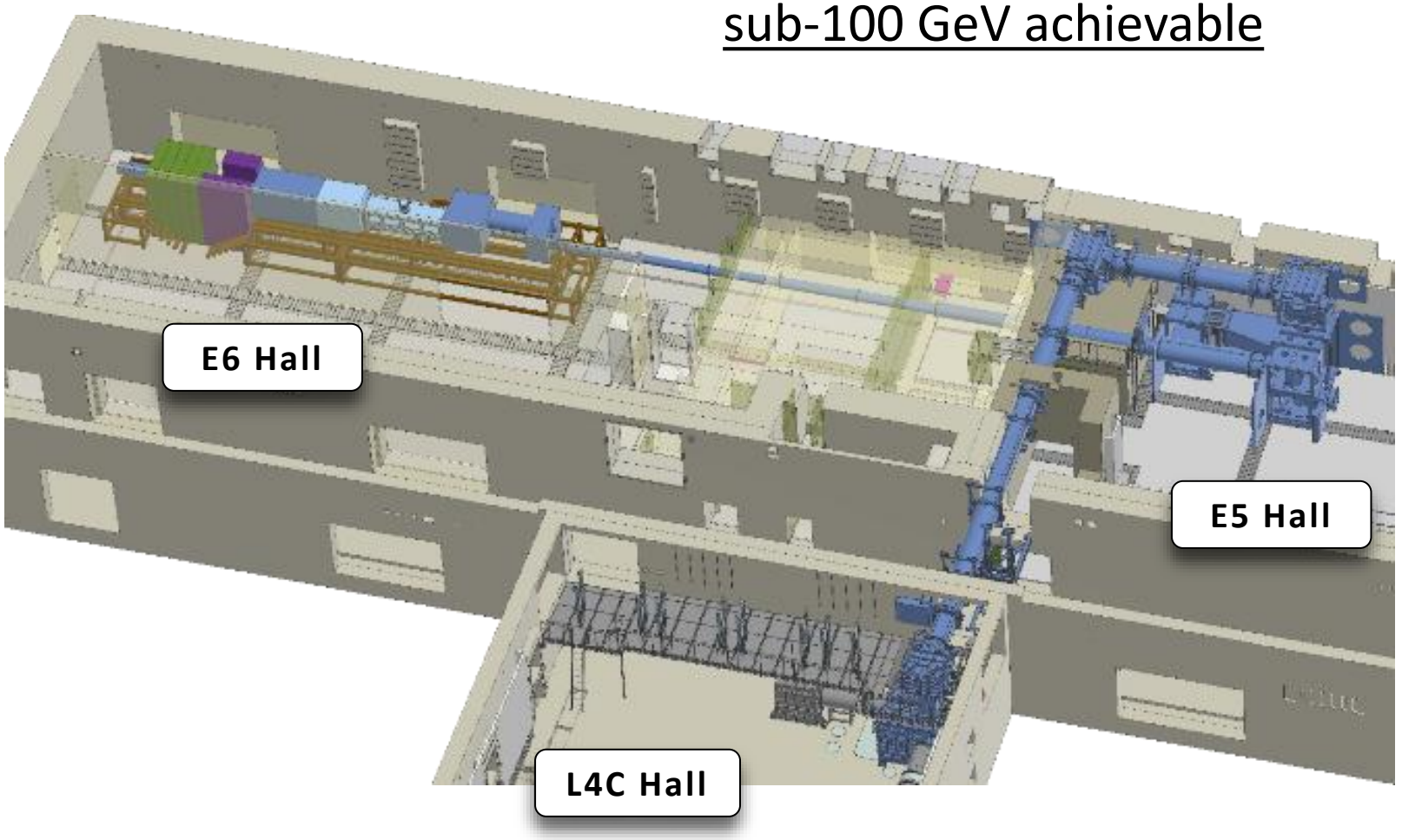
Beam dump



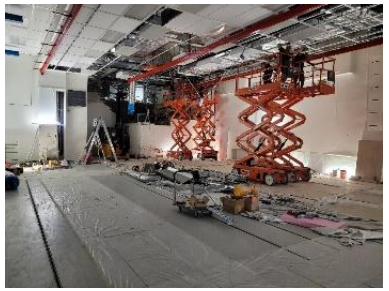
Muon experiments area

Future 10PW beamline

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

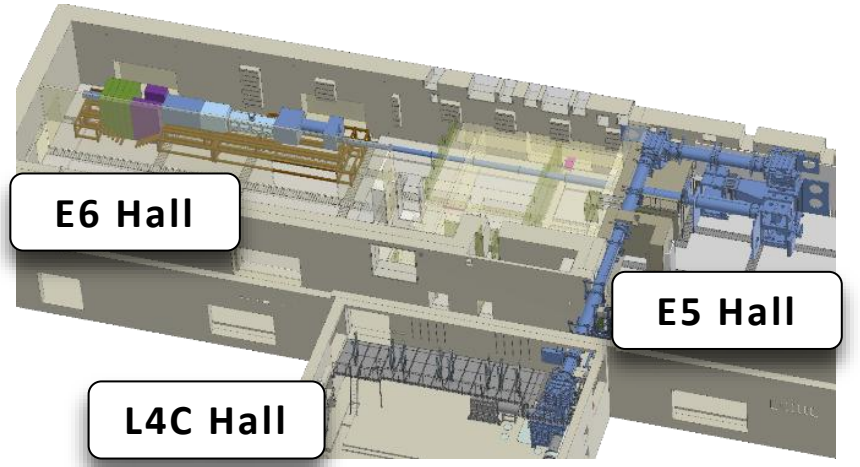


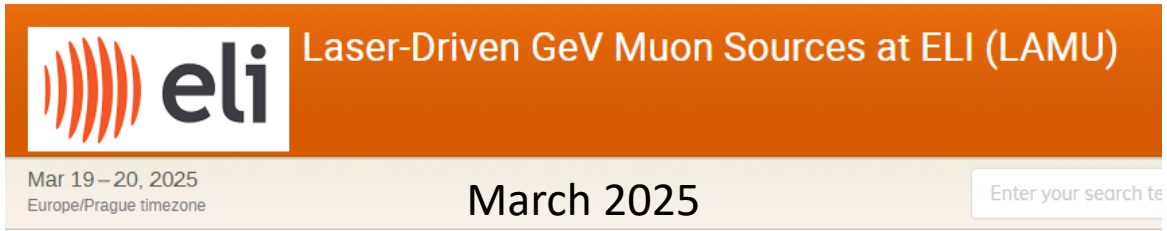
- L4C compressor ready
- Beam transport to E5 procurement
- E5 vacuum chamber design
- Transport civil engineering completed

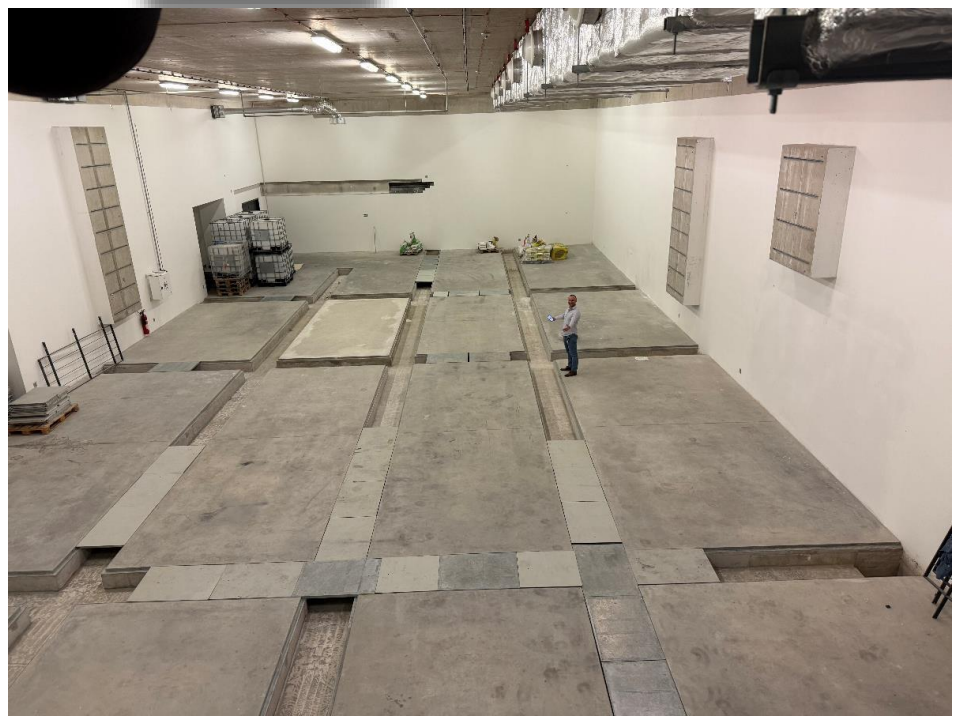


Future 10PW beamline

- Experimental area to be designed
- **Input from muon community and potential users is pivotal**
- ELI organized a workshop with this purpose







- Contacts with a few groups
- Contacted by potential new users (archeology)
- Target goal: first experiment in 2027

Acknowledgments

- Muon4Future organizers
- All speakers at LAMU workshop at ELI-BL
  https://indico.eli-laser.eu/event/200/
- Brendan Reagan at CSU (formerly LLNL)
- Anna Cimmino and Gabriele Grittani at ELI Beamlines