李政道研究所
TSUNG-DAO LEE INSTITUTE

SHINE
SHANGHAI HIGH REPETITION RATE XFEL
AND EXTREME LIGHT FACILITY
硬X射线自由电子激光装置

SHINE Muon Source

Yusuke Takeuchi（TDLI/SJTU)

首届SHINE缪子源及其应用研讨会 | TDLI

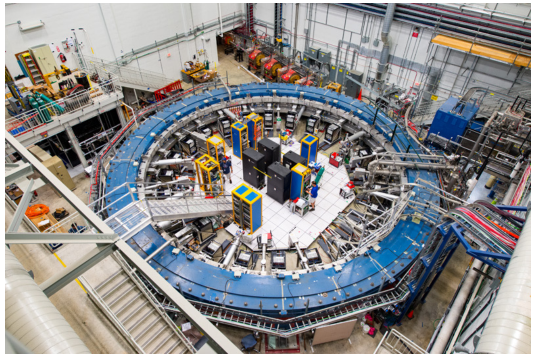
28 Nov 2025

Muon and its applications

Tsung-Dao Lee Institute

Particle & Nuclear Physics

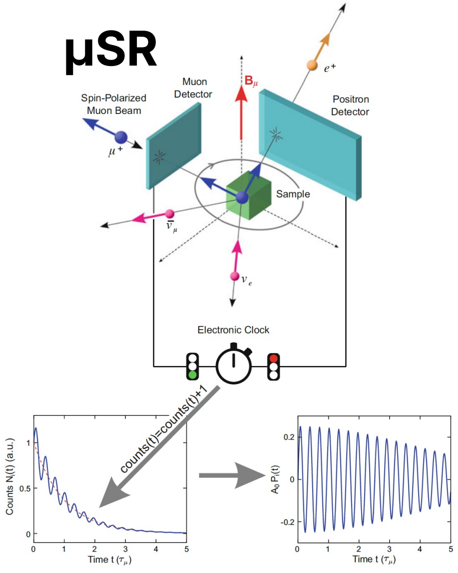
FNAL $g-2$ etc.



Afternoon sessions

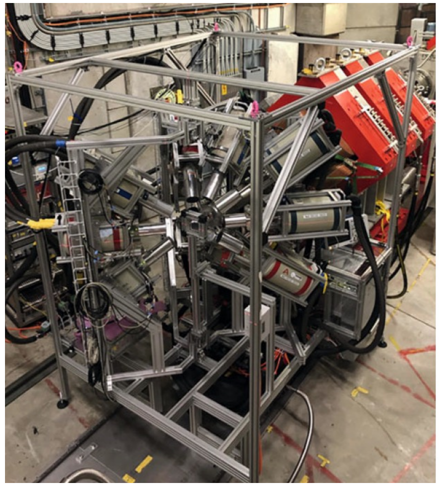
Material science

μSR

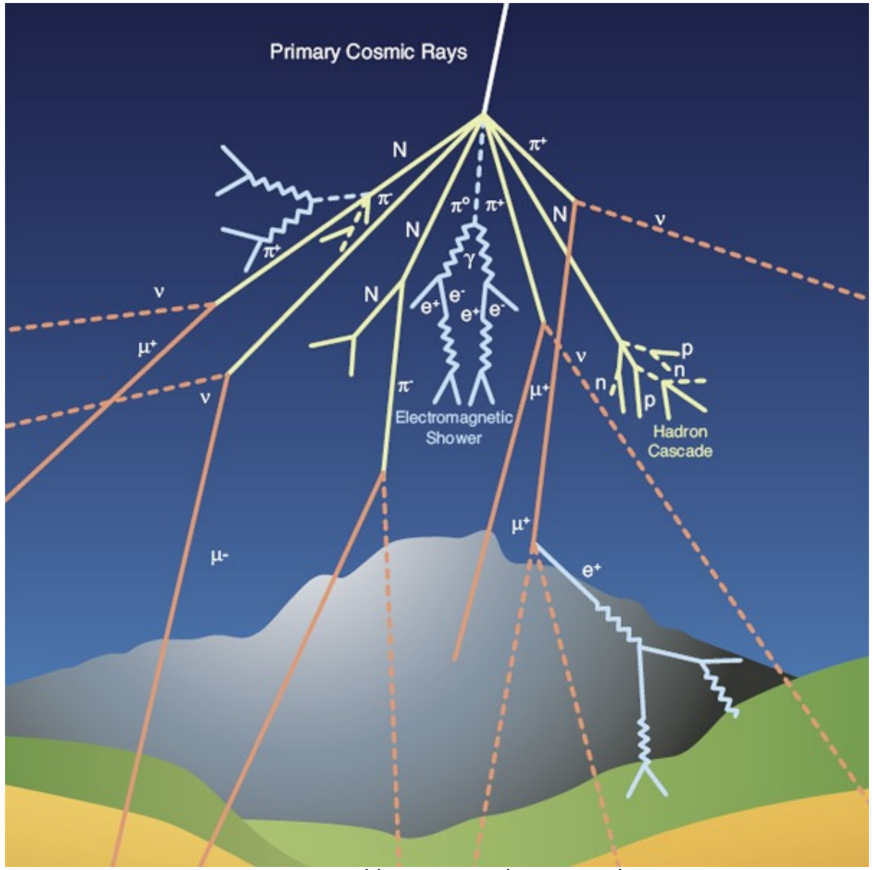


taken from "Introduction to Muon Spin Spectroscopy"

MIXE



Muon intensity in nature is limited



https://cms.cern/content/muon-tomography

Cosmic-ray muon at sea level:
1 muon per square centimeter per minute

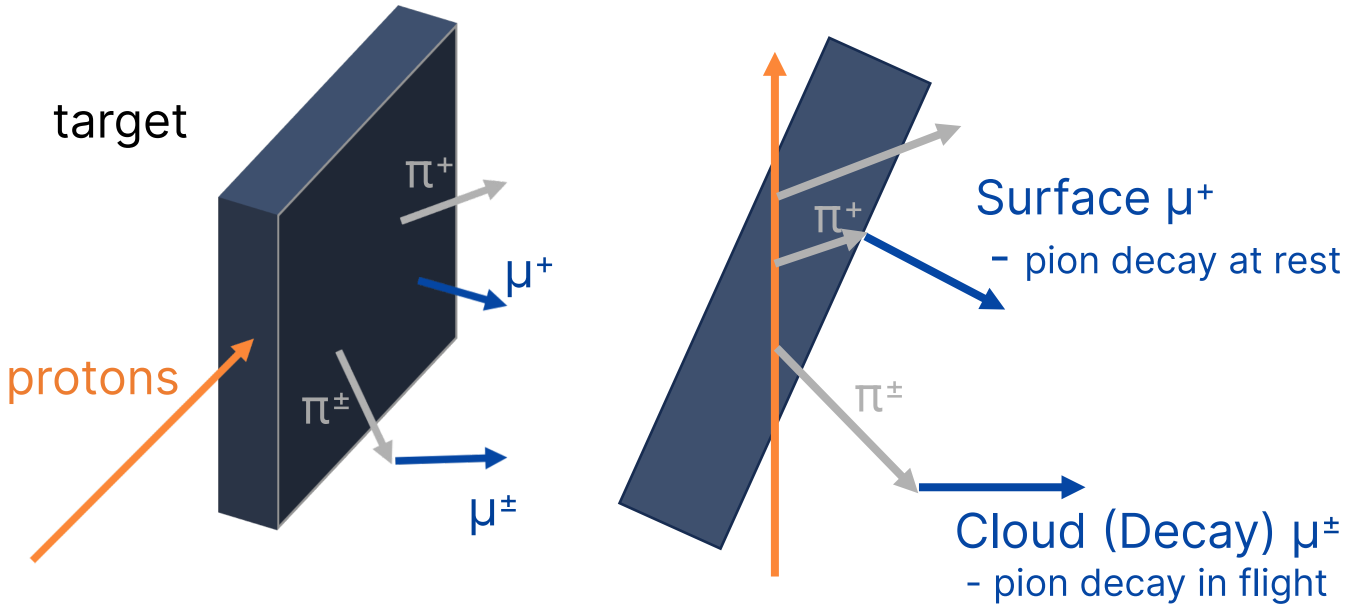
Muon production

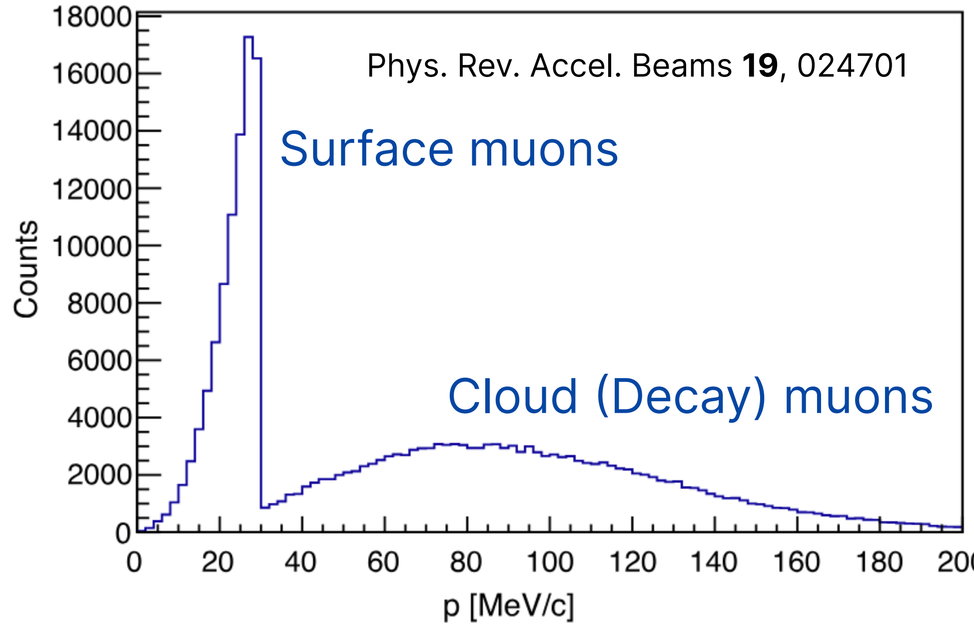
Proton-Driven Muon Source

pp collision

$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^+ + \pi^-$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Single pion production > 280 MeV, Multiple pion production > 600 MeV





Momentum:

Surface muons ⇨ monoenergetic (~29.8 MeV/c)
Cloud muons ⇨ broad spectrum

Polarization (spin):

Surface muons ⇨ highly polarized
Cloud muons ⇨ low/random polarization

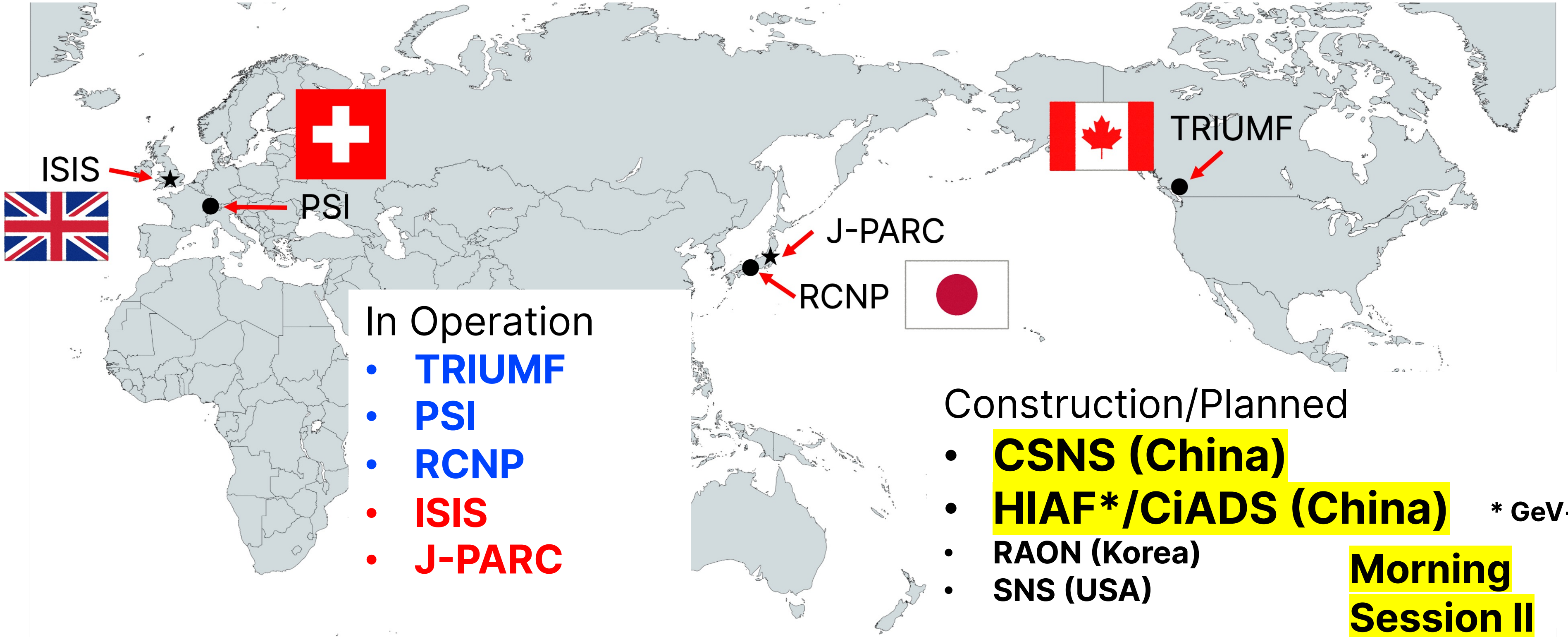
Charge (+/-):

Surface muons ⇨ primarily μ^+
Cloud muons ⇨ both charges

Surface muons have preferred features for μSR, etc.

Low-energy muon facilities

Requires a high-intensity proton accelerator
⇨ limited facilities available



In Operation
- **TRIUMF**
- **PSI**
- **RCNP**
- **ISIS**
- **J-PARC**

Construction/Planned
- **CSNS (China)**
- **HIAF*/CiADS (China)**
- **RAON (Korea)**
- **SNS (USA)**

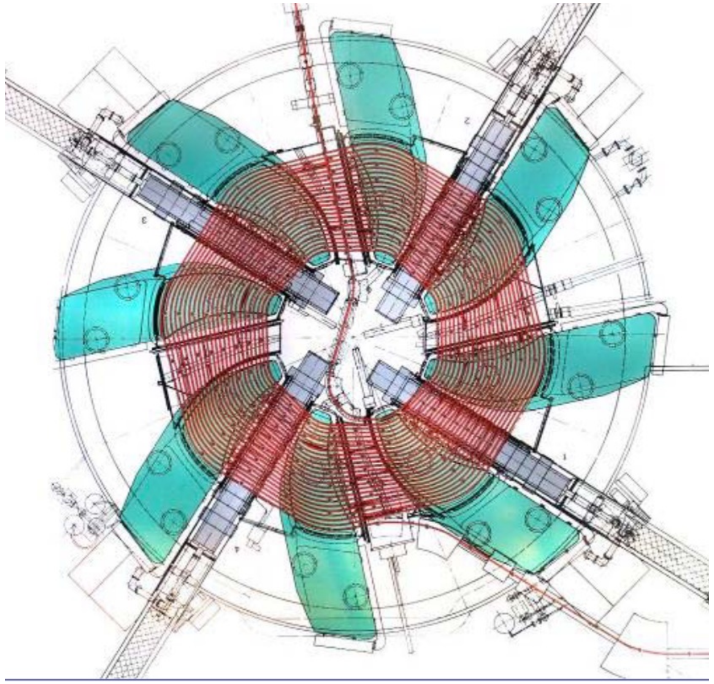
*** GeV-energy**

Morning Session II

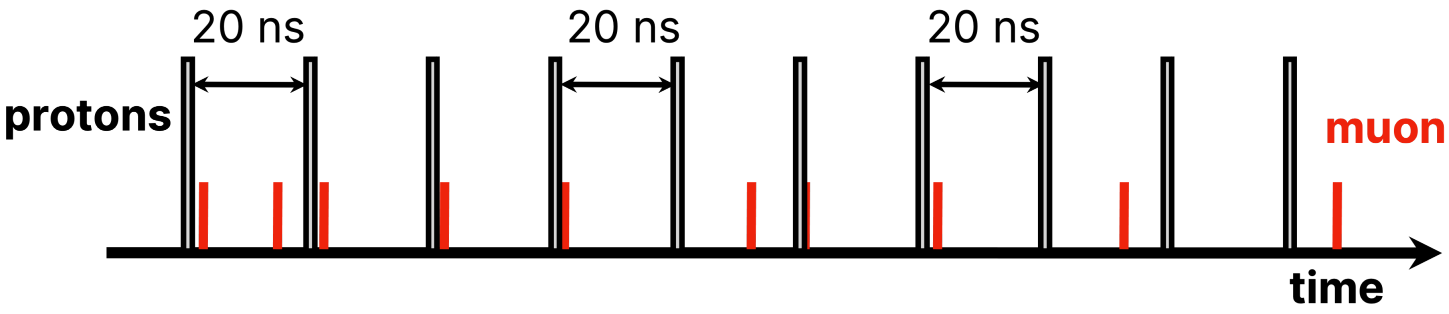
Two types of muon sources depending on the proton accelerator
- **Continuous (DC) muon sources**
- **Pulsed muon sources**

Continuous (DC) muon sources

PSI Ring Cyclotron (Proton)



PSI Ring Cyclotron, 50 MHz continuous beam: muons arrive randomly (time structure smeared out by pion life time of 26 ns ~ order of rep-rate)



- Arrival timings are random
  - ⇨ Muon counter is required to tag each event
  - ⇨ Muon event rate is limited to avoid pile-up
- Few muons (decay positrons) arrive at a time
  - ⇨ Only a few positron detectors are needed

https://doi.org/10.1016/j.nima.2016.05.026

Pulsed muon sources

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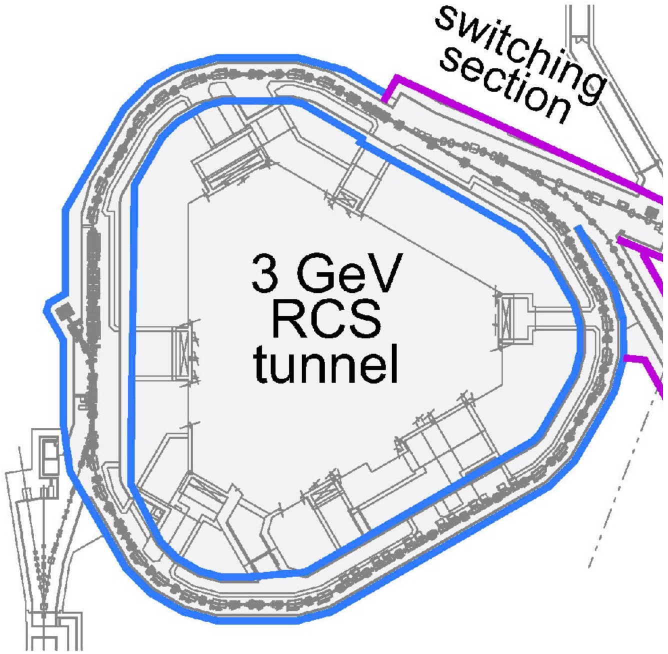
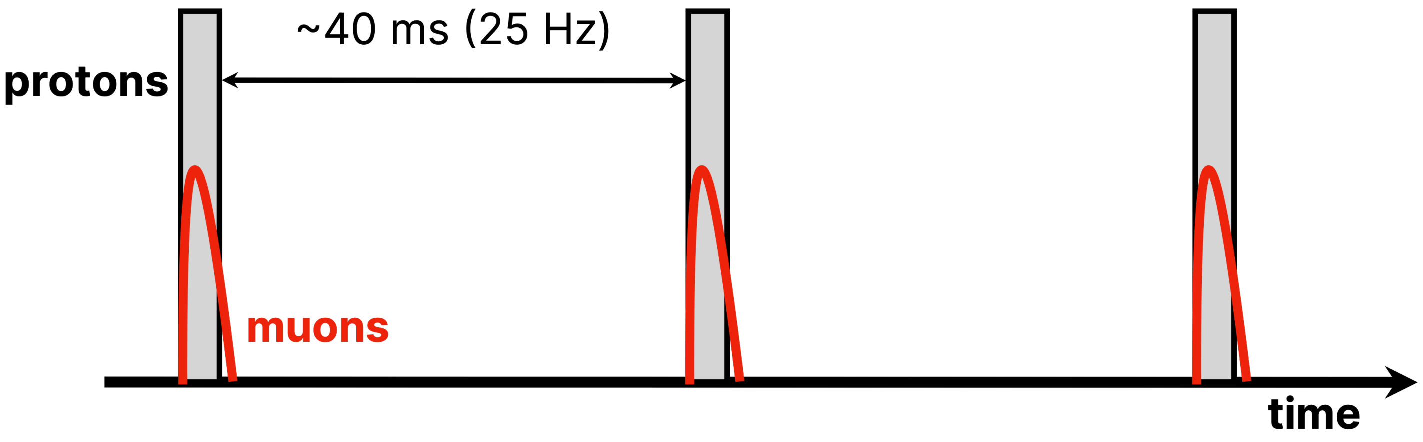
J-PARC RCS (Proton)

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex



Quantum Beam Sci. **2017**, *1*(1), 11

J-PARC RCS, 25 Hz pulsed beam: all protons/muons in one bunch



- Arrival timings are synchronized with the accelerator
  - ⇨ No muon counter required to tag events
- Long intervals between pulses help reduce background
- Many muons (decay positrons) arrive at a time
  - ⇨ A large number of positron detectors are needed

High-repetition pulsed beam

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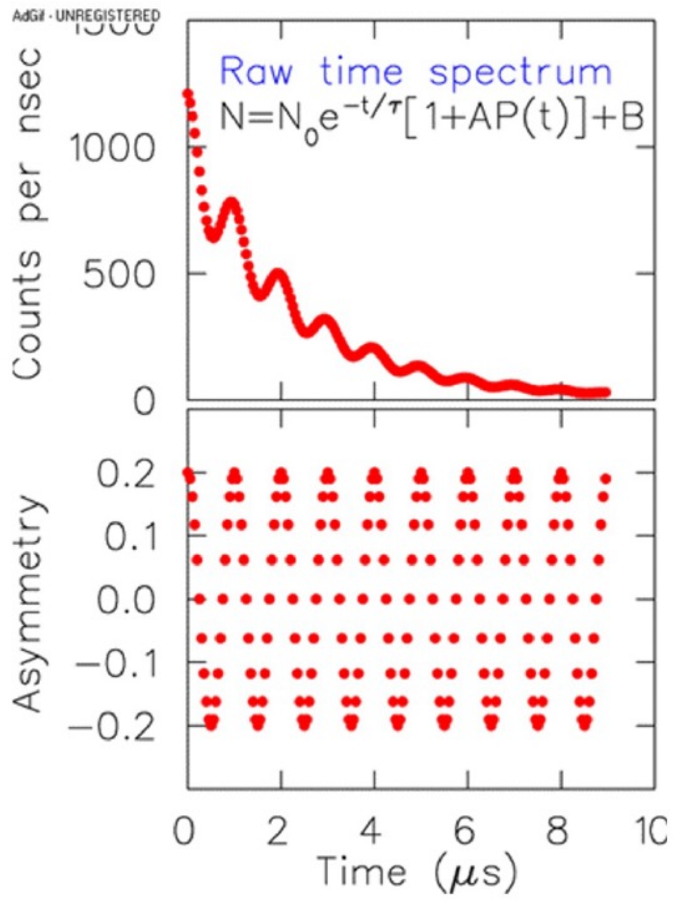
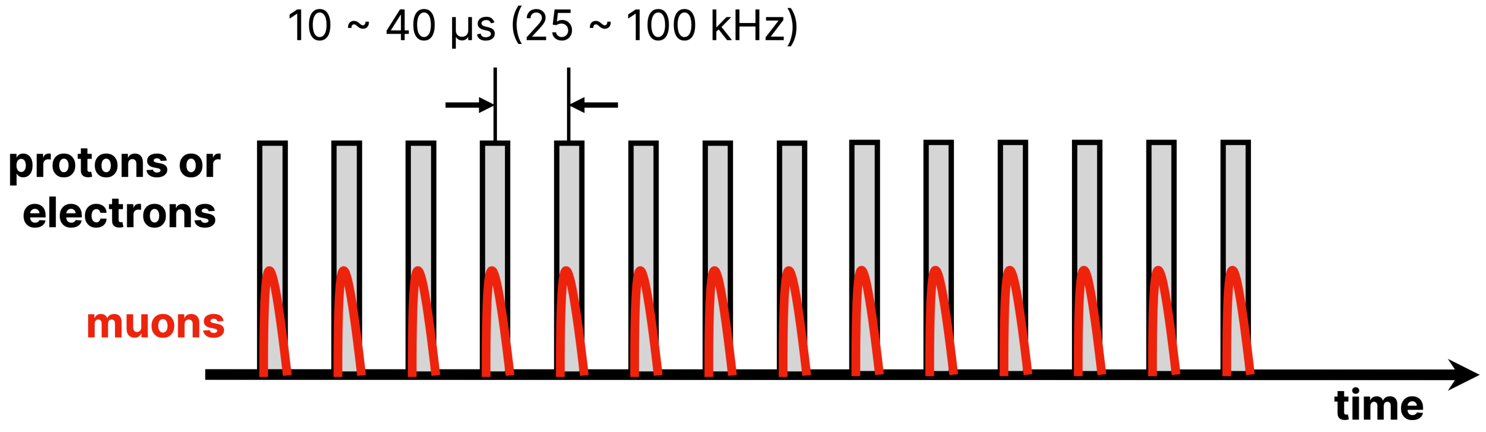
Certain type of experiment (e.g. μSR)



Typical measurement duration : 10 μs ~ 20 μs
(~ 5 to 10 muon lifetimes, τ_μ ~ 2.2 μs)

High-repetition-rate pulsed beam



- Higher duty cycle with relatively low muon count per bunch
  - ⇨ Fewer muons per bunch (~10^3 μ^+/bunch) reduces pile-up
  - ⇨ Higher average rate is maintained by more frequent bunches
- Sufficient interval between bunches
  - ⇨ Background can decay between pulses.

Pulsed muon source with higher repetition rate is perfect match to muon lifetime
⇨ ideal for μSR-type experiments

Calls for high-rep. pulsed beams

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An O(10-100) kHz pulsed muon beam is highly desired!

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Physica B
journal homepage: www.elsevier.com/locate/physb

Towards a dedicated high-intensity muon facility

R. Cywinski [a,*], A.E. Bungau [a], M.W. Poole [b], S. Smith [b], P. Dalmas de Reotier [c], R. Barlow [d], R. Edgecock [e], P.J.C. King [e], J.S. Lord [e], F.L. Pratt [e], K.N. Clausen [f], T. Shiroka [f]
[a] School of Applied Sciences, University of Huddersfield, Huddersfield HD1 3DH, UK
[b] ASTeC, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK
[c] CEA/INAC, 17, rue des Martyrs, 38054 Grenoble cedex 9, France
[d] School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[e] ISIS Facility, STFC Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK
[f] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

μSR

that the threshold for double pion production is ∼600 MeV, the second alternative affords higher muon production rates and, therefore, represents the preferred choice.

Proton driver frequency: The 50 Hz pulsed operation of ISIS is sub-optimal for μSR studies. Typically, time resolved spectra are collected over no more than 32 μs (i.e. ∼15 muon lifetimes), giving an effective duty cycle of only 0.16%. While advantageous for some types of experiments (e.g. those involving pulsed sample environments), the 50 Hz operation is generally inefficient: ideally a muon-source proton driver should operate at ∼25 kHz.

It is important to note that operation at this frequency, with an associated gain in intensity of 100 over ISIS (see above), would actually alleviate detector dead time problems by a factor of 5 with respect to those presently encountered at ISIS. This is illustrated in Fig. 1, where it can be seen that the available muons will be distributed over 500 (i.e. 25 kHz/50 Hz) as many

Mu-MuBar

SciPost SciPost Phys. Proc. 5, 009 (2021)

Muonium-antimuonium conversion

Lorenz Willmann* and Klaus Jungmann
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PAUL SCHERRER INSTITUT PSI
Review of Particle Physics at PSI
doi:10.21468/SciPostPhysProc.5

$\overline{M}$ grows in time to a maximum at $2\tau_\mu$ (see Figure 9.5). Thus the ratio of M to $\overline{M}$ decays grows with t^2. In case of a multiple coincidence, as in MACS, this implies that the potential $\overline{M}$ signal/background increased. Therefore a new experiment should be considered, e.g., in connection with the muon source of a muon collider, provided high muon beam quality, i.e. a narrow μ^+ momentum band at subsurface μ^+ momentum. We note that for such an improved experiment beam repetition rates of up to several 10 kHz with μ^+ bunches of up to ≈ μs length would be ideal.
With a new experiment, from the viewpoint of signal to background ratio, an improved value for $G_{M\overline{M}}$ by at least 2 orders of magnitude should be possible, i.e., 4 orders of magnitude in the conversion probability. At such sensitivity there would be strong constraints for the development of models beyond standard theory [5–8].

Muon EDM

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 37 (2010) 085001 (7pp) doi:10.1088/0954-3899/37/8/085001

Compact storage ring to search for the muon electric dipole moment

A Adelmann[1], K Kirch[1,2], C J G Onderwater[3] and T Schietinger[1]
[1] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[2] Eidgenössische Technische Hochschule Zürich, CH-8093 Zürich, Switzerland
[3] Kernfysisch Versneller Instituut and University of Groningen, NL-9747AA Groningen, The Netherlands

J. Phys. G: Nucl. Part. Phys. 37 (2010) 085001 A Adelmann *et al*

of the difference between the measured anomalous magnetic moment and its SM prediction. It would furthermore test various SM extensions, in particular those that do not respect lepton universality.

In view of the possible advent of new, more powerful pulsed muon sources, the same experimental scheme can be realized but with considerably more muons per bunch being injected into the ring. It appears realistic to expect accelerators with on the order of 100 kHz repetition rates and more than 10^4 muons stored per bunch. The statistical sensitivity of the described approach would then reach down to a few times 10^{-25} *e* cm. Although systematic issues at this level of precision have been discussed in some detail in [19], more detailed studies would be needed.

Toward a high-precision measurement of the muon lifetime with an intense pulsed muon beam at J-PARC

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E-mail: kanda@post.kek.jp

Muon Lifetime

In the MuLan experiment, a continuous muon beam was pulsed with an electrostatic kicker to achieve high statistical precision. In general, an experiment using a pulsed beam is statistically efficient because no trigger pileup occurs. On the other hand, the higher the beam intensity, the higher the requirement on the high-rate tolerance of the detector. The MuLan's positron detector covered 70% of 4π steradians with 170 segments. The contribution of the statistical uncertainty to the precision of 1.0 ppm was 0.95 ppm, and the main systematics was 0.2 ppm each for muon spin rotation (μSR) and detector's gain variations.

Towards a high-rep. pulsed source

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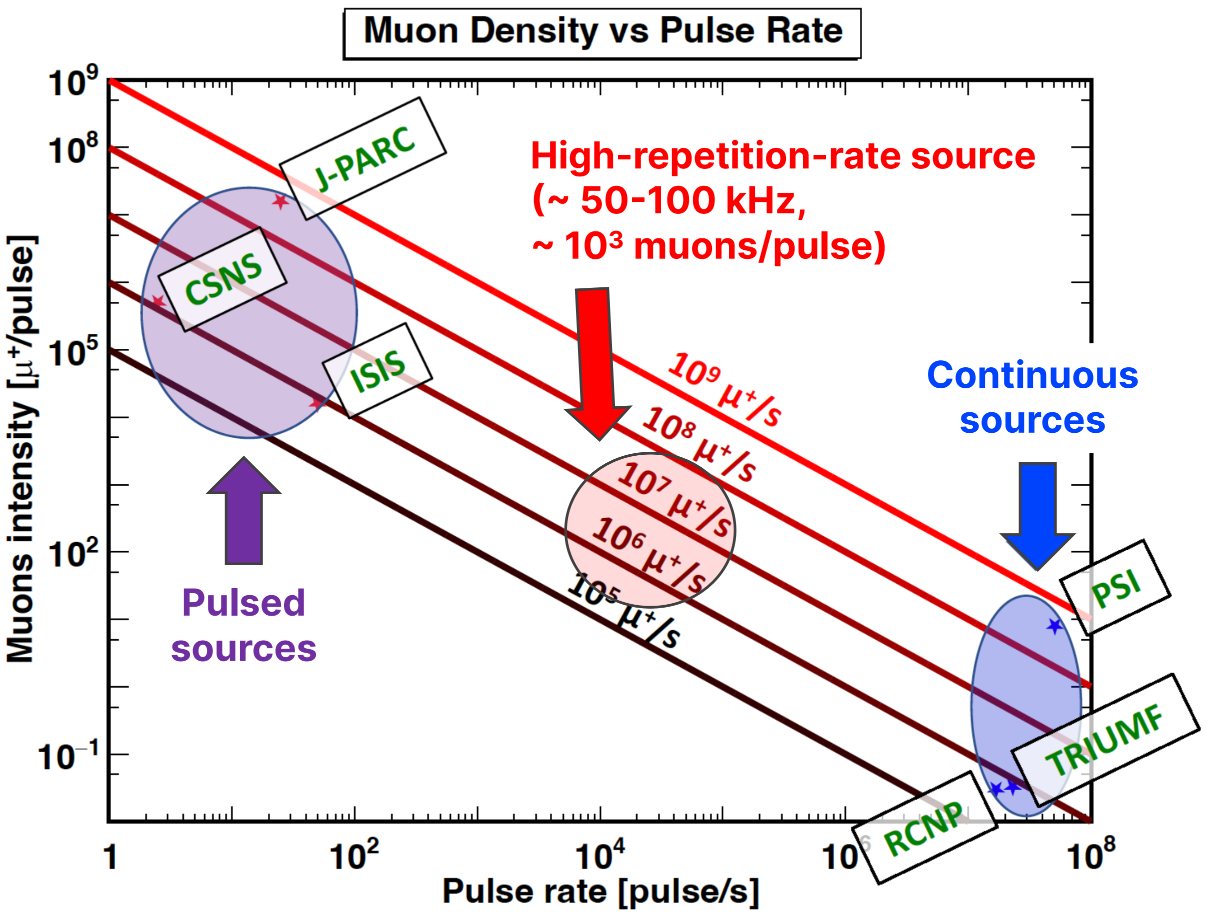
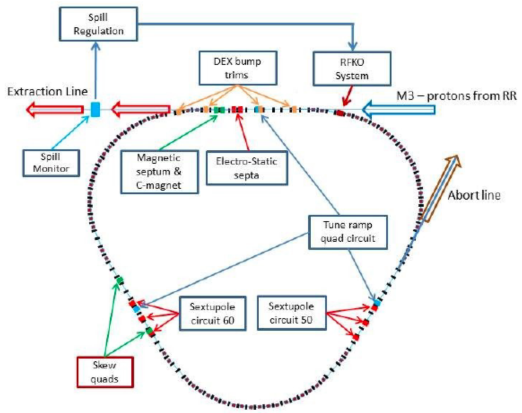


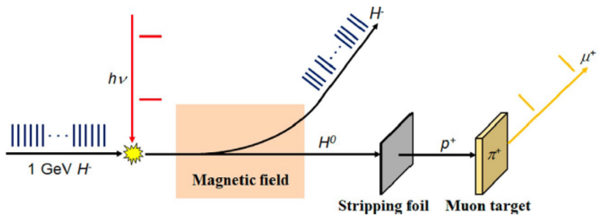
Some attempts with proton machines

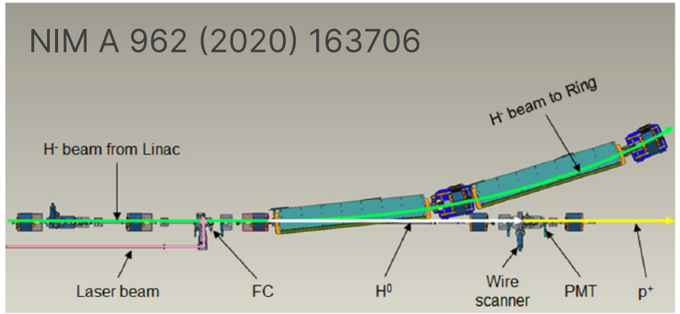
Resonant extraction Mu2e@FNAL



Effectively achieve 0.59 MHz
Same idea for COMET @J-PARC

Laser neutralization @ ORNL



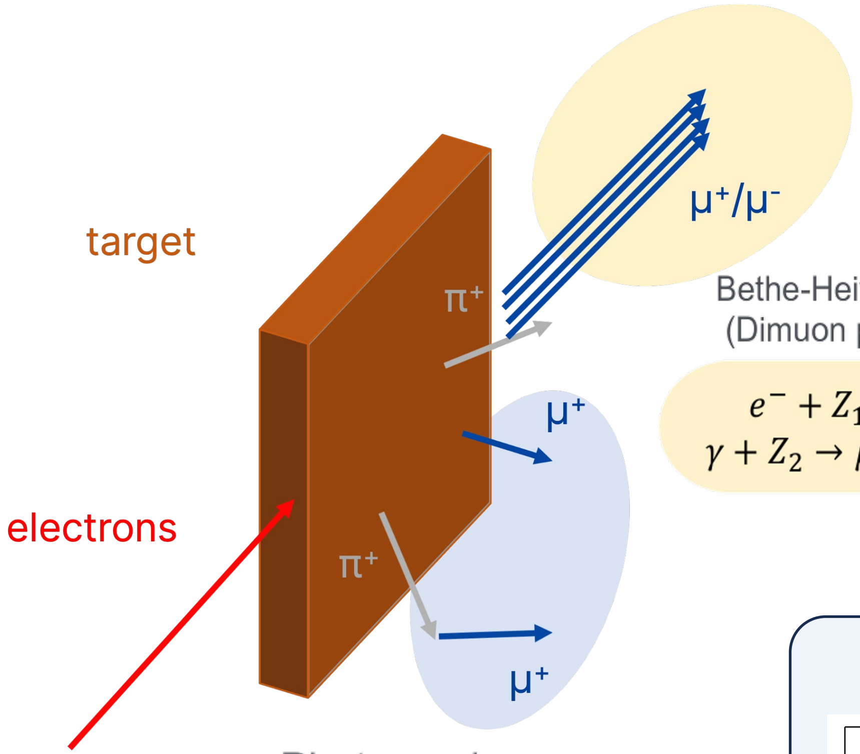


Successfully demonstrated
30 ns/50 KHz proton pulses

Need some dedicated techniques

Alternative drivers: electron

Potential driver for muon sources?



Bethe-Heitler process (Dimuon production)

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \mu^+ + \mu^- + Z_2$$

Photo-nuclear process

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \pi^\pm + Z_3$$

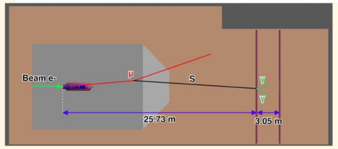
High energy CW e^- beam

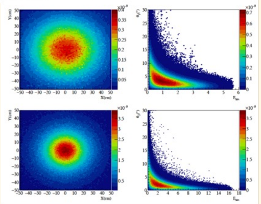
instruments

Article

Secondary Beams at High-Intensity Electron Accelerator Facilities

Marco Battaglieri [1], Andrea Bianconi [2,3], Mariangela Bondí [4], Raffaella De Vita [1], Antonino Fulci [4,5,*], Giulia Gosta [2], Stefano Grazzi [1,5], Hyon-Suk Jo [6], Changhui Lee [6], Giuseppe Mandaglio [4,5], Valerio Mascagna [2,3], Tetiana Nagorna [1], Alessandro Pilloni [4,5], Marco Spreafico [1,7], Luca J. Tagliapietra [8], Luca Venturelli [2,3] and Tommaso Vittorini [1,7]





11 GeV, 50 μA CEBAF@JLAB → ~ 10^8 μ±/s

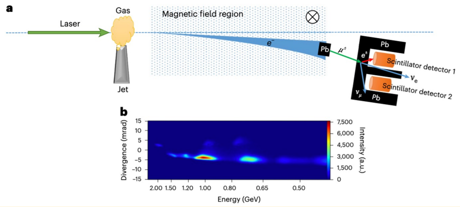
Based on LWFA

nature physics

Article

https://doi.org/10.1038/s41567-025-02872-2

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

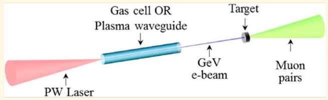


Based on LWFA

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]



100 pC 10 GeV electron → 8 x 10^3 μ±/s

Based on LWFA

Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator

Davide Terzani,[1] Stanimir Kisyov,[1] Stephen Greenberg,[1,2] Luc Le Pottier,[1,2] Maria Mironova,[1] Alex Picksley,[1] Joshua Stackhouse,[1,3] Hai-En Tsai,[1] Raymond Li,[1,3] Ela Rockafellow,[4] Timon Heim,[1] Maurice Garcia-Sciveres,[1] Carlo Benedetti,[1] John Valentine,[1] Howard Milchberg,[4] Kei Nakamura,[1] Anthony J. Gonsalves,[1] Jeroen van Tilborg,[1] Carl B. Schroeder,[1,3] Eric Esarey,[1] and Cameron G. R. Geddes[1]

[1]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[2]Department of Physics, University of California, Berkeley, CA 94720, USA
[3]Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
[4]University of Maryland, College Park, MD 20742, USA

(Dated: November 5, 2024)

More and more...

Relatively low energy CW e^- beam

Physica B 404 (2009) 1020–1023

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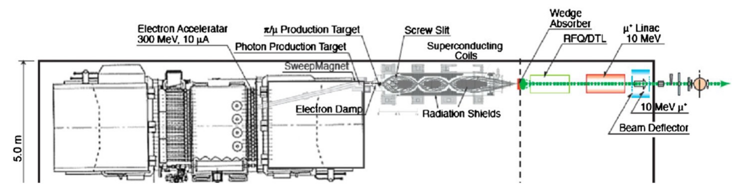
journal homepage: www.elsevier.com/locate/physb

ELSEVIER

Compact muon source with electron accelerator for a mobile μSR facility

K. Nagamine [a,b,c,*], H. Miyadera [d], A. Jason [d], R. Seki [e]



300 MeV, 10 μA electron microtron → 8 × 10^3 μ⁺/s

Electron beam at SHINE

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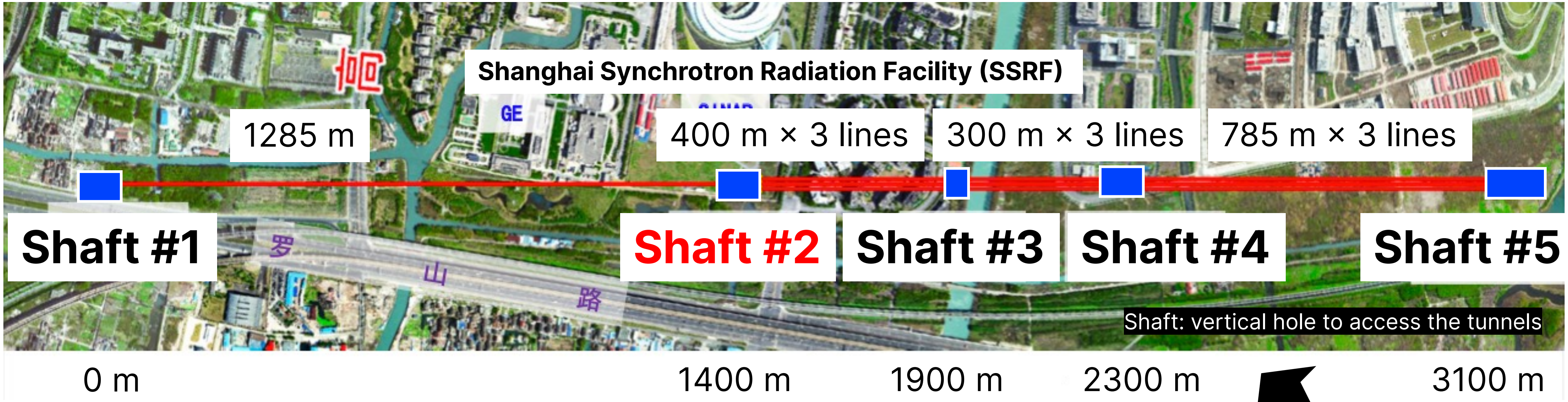
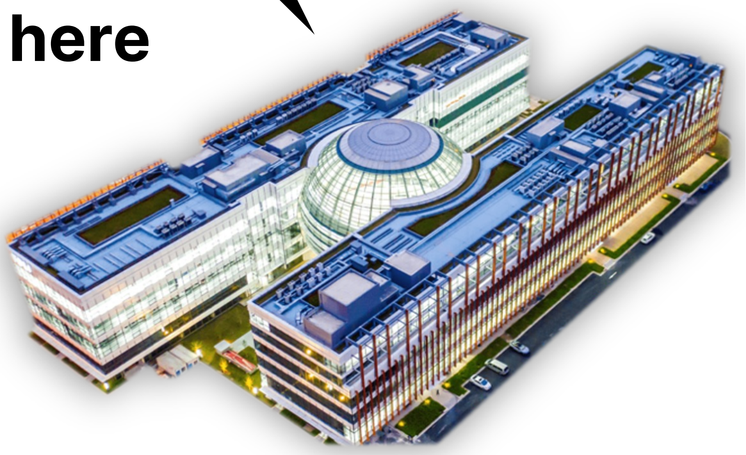
Tsung-Dao Lee Institute



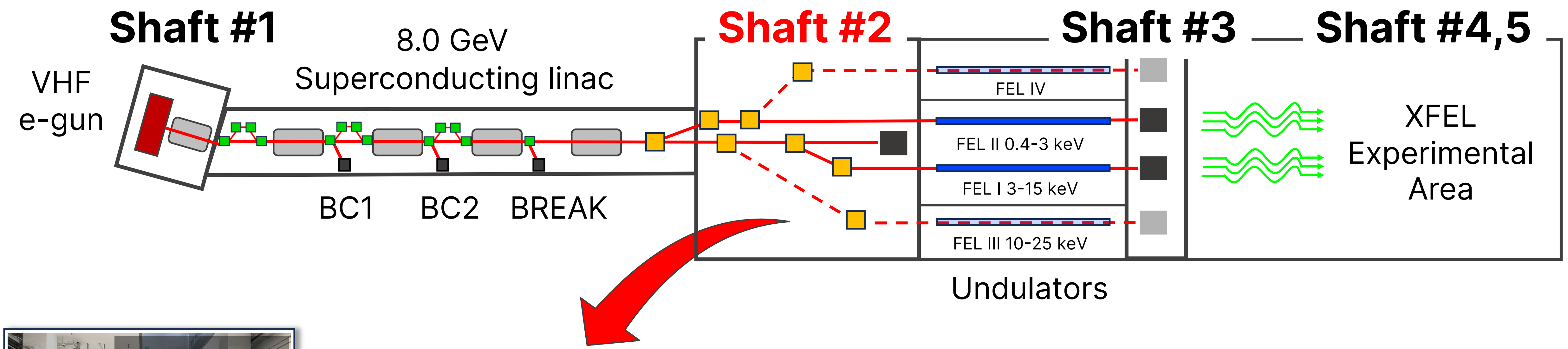
- Located in Zhangjiang, Shanghai
- Commissioning is ongoing
- Electron beam (design values):
  - 8 GeV energy
  - 1 MHz repetition rate
  - 100 pC charge (6.25×10^8 electrons) per bunch

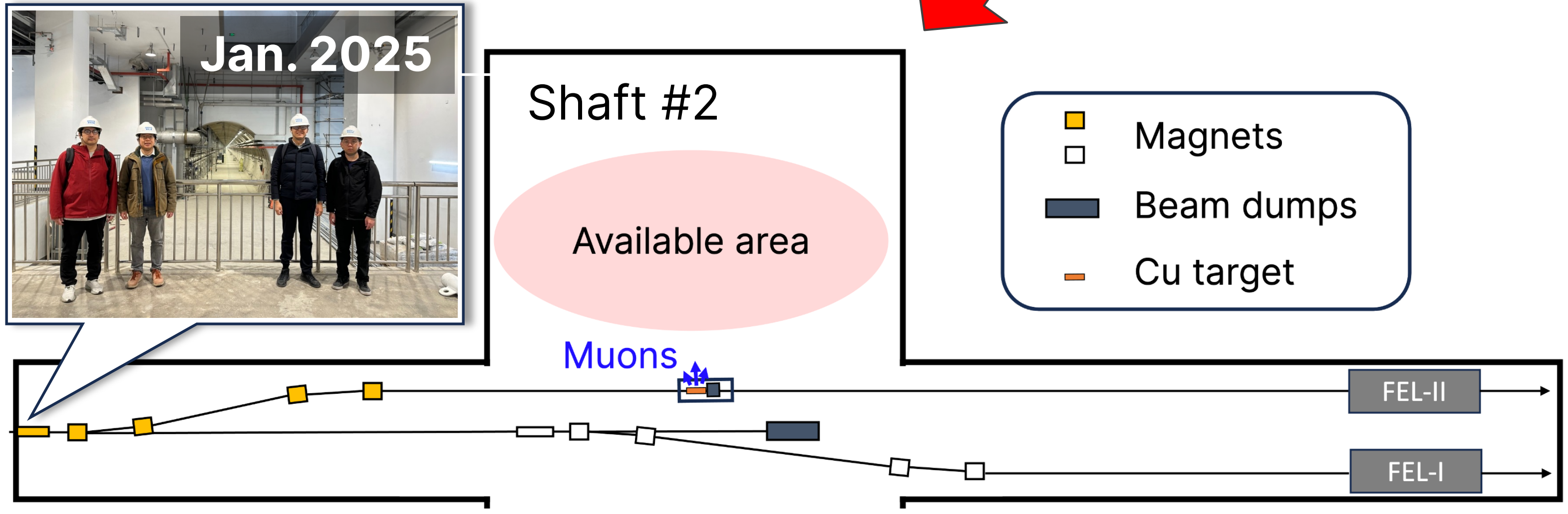
⇦ **Some are dumped**

Only 4 km from here



Planned location





Shaft #2:

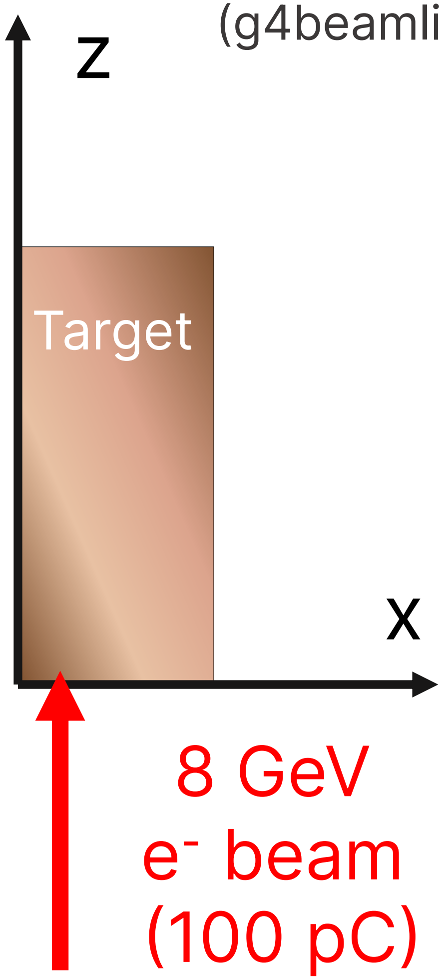
a good location for a muon source

- Sufficient space
- Planned beamlines, cost effective

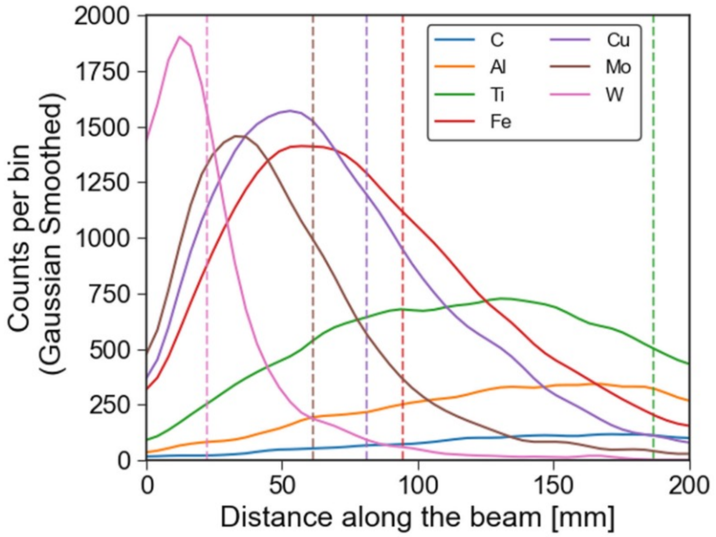
Material selection

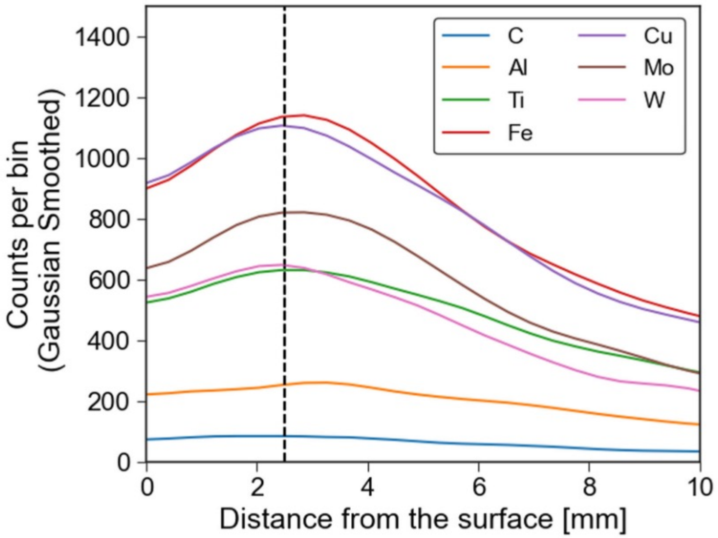
Tsung-Dao Lee Institute

Simulation Setup
(g4beamline)



Pion distributions





Along the beam (Z):

- Peak ⇨ slightly below z_{max}
- Depth of EM shower maximum

$$z_{max} \approx X_0 \left[\ln(E_0/E_c) - 0.5 \right]$$

E_0: incident beam energy
E_c: critical energy
X_0: radiation length

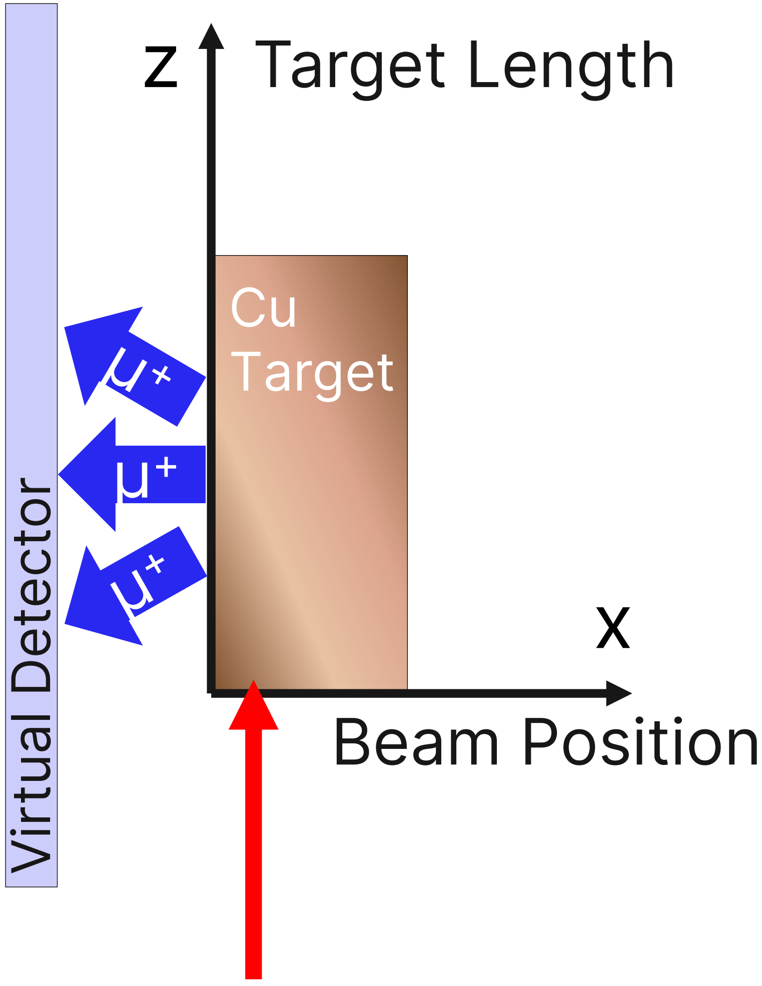
From the surface (X):

- The number of pions near surface contributing to surface muon is important
- Medium-Z materials (e.g., Fe, Cu) show highest number
- Copper is considered to be the optimal choice
  ⇨ good thermal conductivity (~400 W/mK)

Cu target optimization

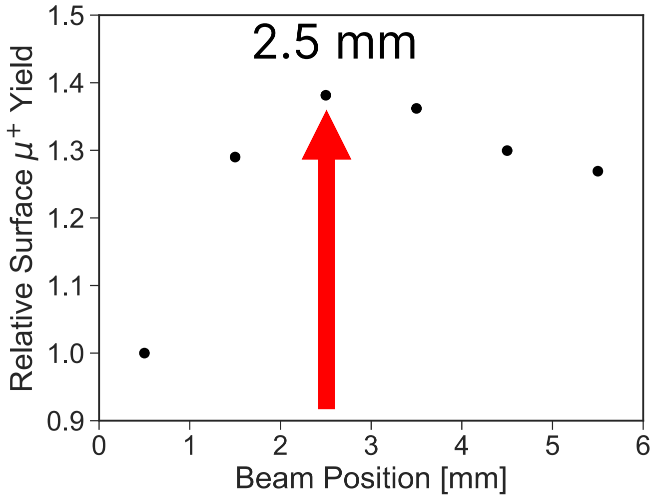
Tsung-Dao Lee Institute

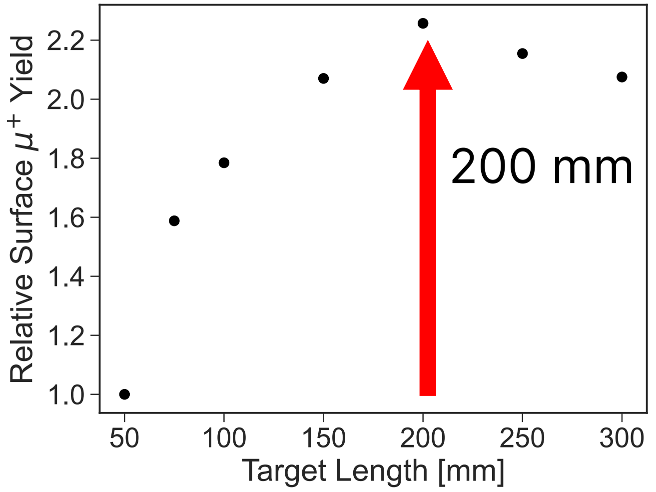
Simulation Setup



8 GeV e⁻ beam (100 pC)

Scan beam position and target length





- < 2.5 mm:
  Insufficient development of electron shower (too close to target surface)
- > 2.5 mm:
  The number of pions resulting in surface muons is reduced (too far from target surface)

- No significant gain is expected in length over 200 mm.
- Consistent with the pion distribution

Results

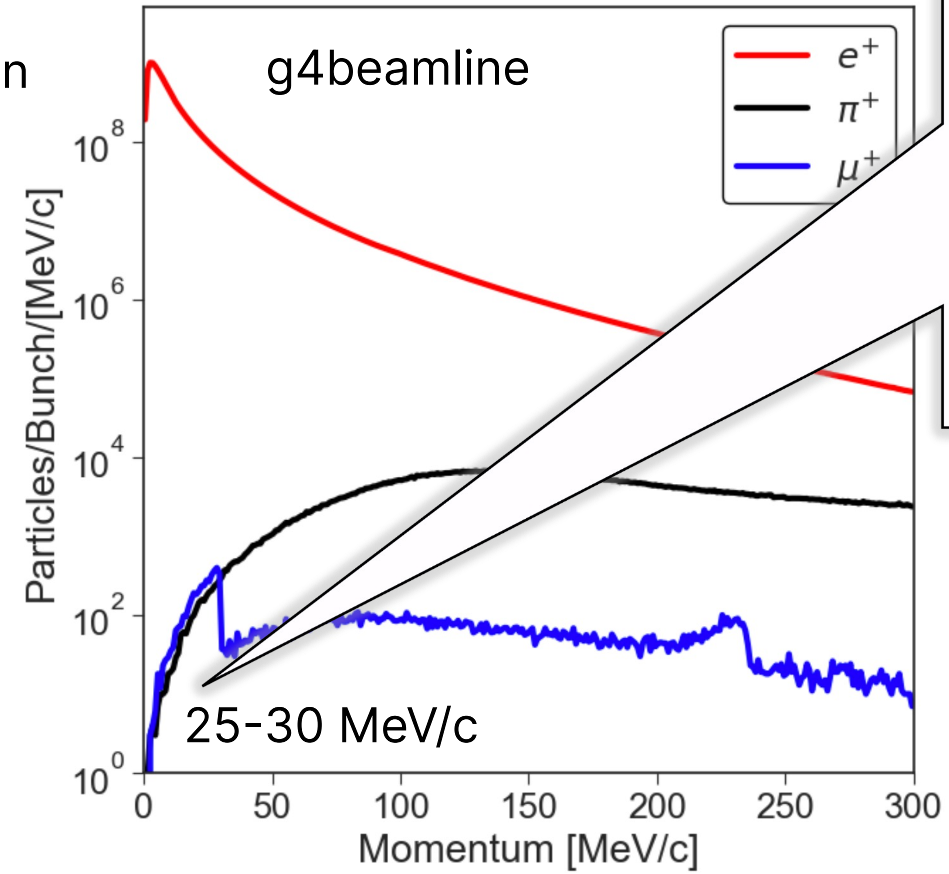
- Optimal beam position: **2.5 mm** from target surface
- Optimal target length: **200 mm**

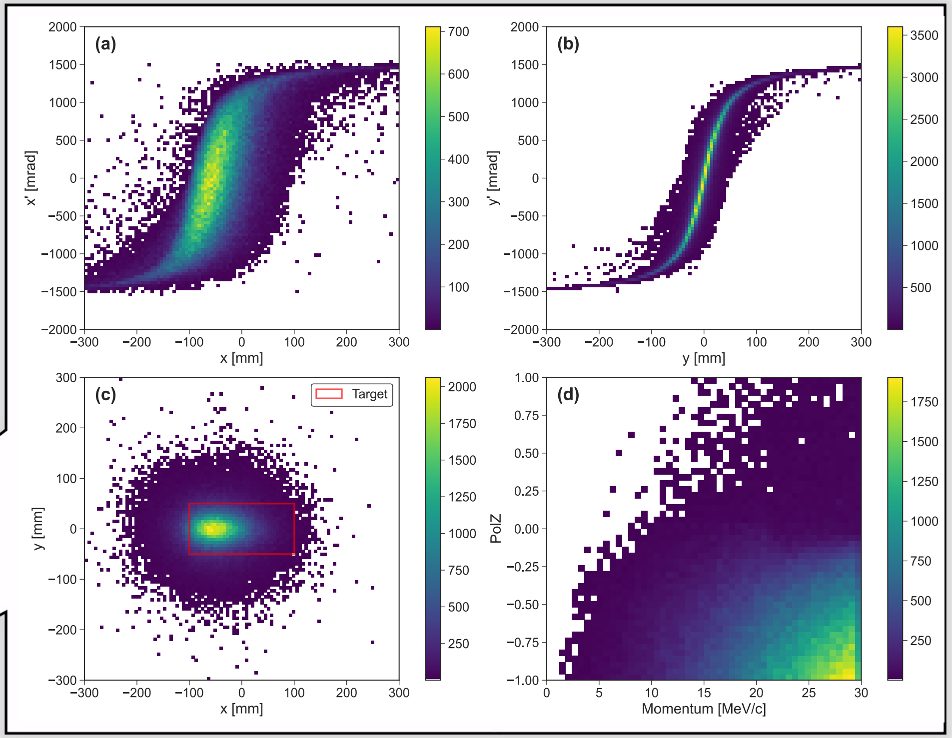
Particle yields from Cu target

Full simulation with g4beamline for beamline design

- Total muon yield: ~10^4 per bunch (below 300 MeV/c)
- Surface muon yield: 2×10^3 per bunch (25-30 MeV/c range)
- Expected intensity: 1×10^8 μ^+/s at 50 kHz operation

• Momentum distribution characteristics:
  - Two distinct peaks were observed:
    - Pion decay: ~30 MeV/c
    - Kaon decay: ~230 MeV/c
  - Broad energy distribution, decreasing at higher energies

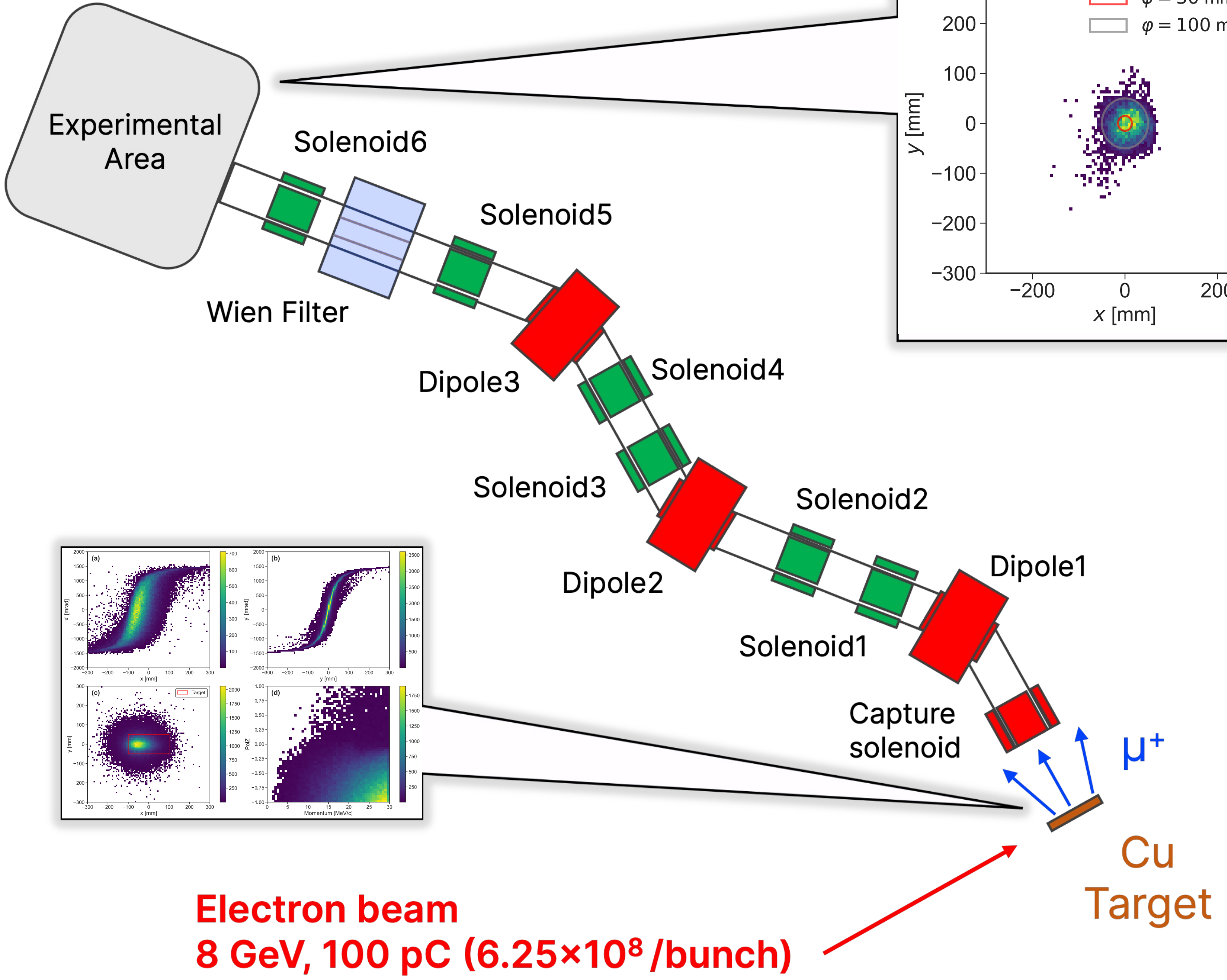


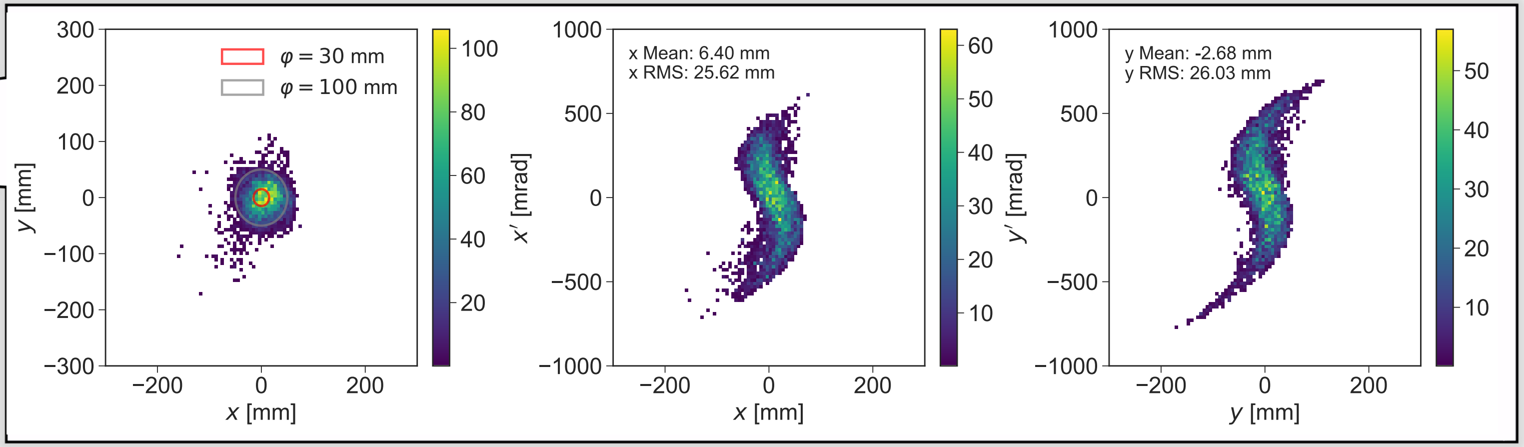


Parameters	Value
Mean Momentum P_0 / Momentum Spread σ_P	22.9 MeV/c / 5.5 MeV/c
Horizontal Position $< x >$/ Width σ_x	-45.2 mm / 73.7 mm
Horizontal Divergence $< x' >$/ Width $\sigma_{x'}$	-14.6 mrad / 696.7 mrad
Horizontal RMS Emittance	3814 π cm mrad
Vertical Position $< y >$/ Width σ_y	-0.1 mm / 67.5 mm
Vertical Divergence $< y' >$/ Width $\sigma_{y'}$	-1.2 mm / 696.9 mrad
Vertical RMS Emittance	3180 π cm mrad
Mean Polarization	-0.63

Similar to those of existing facilities.

Surface muon beamline design





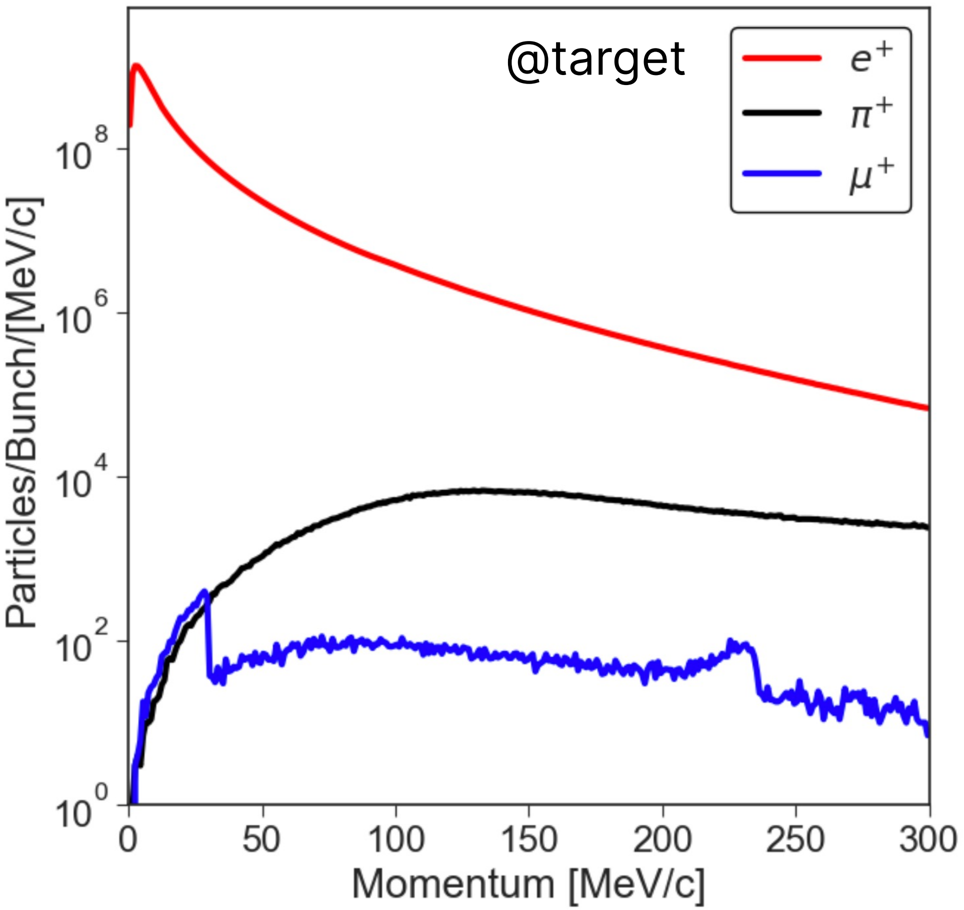
Parameters	Value
x/x' (rms)	25.6 mm/221 mrad
y/y' (rms)	26.0 mm/246 mrad
Mean momentum	27.6 MeV/c
$\Delta p/p$	3.69%
Polarization (before Wien filter)	97%
Polarization (after Wien filter)	88%
μ^+ rate (all)	$3.1 \times 10^6\ \mu^+/s$
μ^+ rate (ϕ30 mm)	$4.7 \times 10^5\ \mu^+/s$

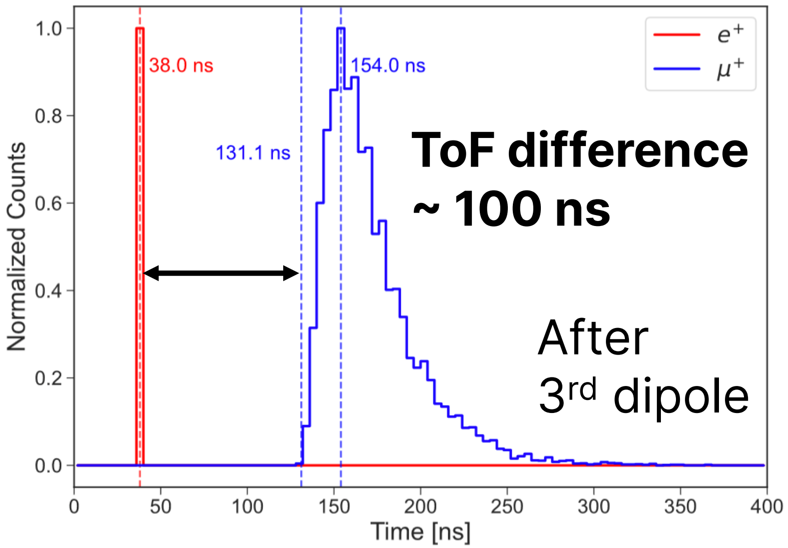
@50 kHz repetition rate
(1/20) of SHINE capability

Positron background

Many positrons!

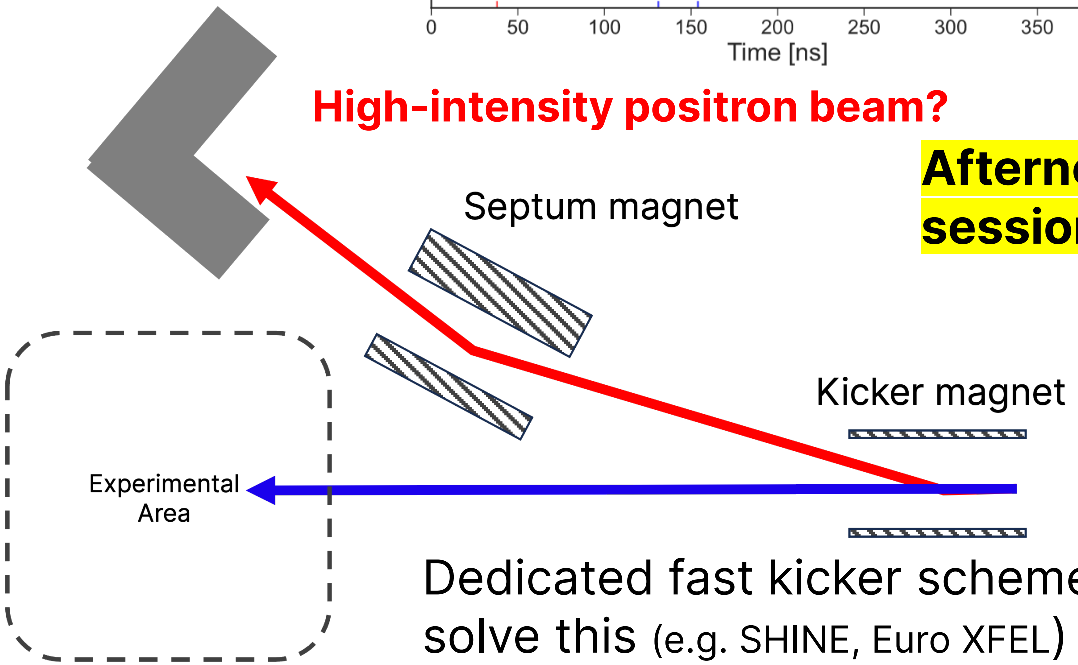
⇨ Conventional way (Wien filter) may not be sufficient.





High-intensity positron beam?

Afternoon session



Dedicated fast kicker scheme could solve this (e.g. SHINE, Euro XFEL)

Milestones and plans

TSUNG-DAO LEE INSTITUTE

2023

Target simulations

Poster @ IPAC23

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPA087

A PULSED MUON SOURCE BASED ON A HIGH-REPETITION-RATE ELECTRON ACCELERATOR

2025

This talk

End-to-end simulation studies

Poster @ IPAC25
PRAB paper

PHYSICAL REVIEW ACCELERATORS AND BEAMS **28,** 083401 (2025)

Simulation studies of a high-repetition-rate electron-driven surface muon beamline at SHINE

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2026

Test beam at SHINE shaft #2

May- 2026

- 2 GeV, 50 pC electron beam (10 Hz)
- Currently under preparation ⇨ **see next talk by Dr. Si Chen and Jun Kai**)

Nov 2026

- Based on the results from beam test, to demonstrate feasibility of electron-based **surface muon** source (**10^4 muons/s equivalent**)

2030s

Project approval, funding, construction...

Summary

- A muon source with high-repetition rate (~50 kHz) could provide an ideal time structure for various experiments
- We have completed the baseline design studies:
  - 3×10^6 (all muons) [surface μ /s]
  - 5×10^5 (within φ30mm) [surface μ /s] are expected
- Initial science cases will be application-based: μSR, beam test
- Upgrades and further optimization needed for competitive fundamental physics
- The test beam at SHINE shaft #2 is under preparation

Let's discuss potential applications and opportunities for collaboration!

Backup

Installation Plan

- Current Plan: to insert the target upstream of FEL-II (Priority on early realization with existing beamline)
- There is also the idea of a dedicated line with a kicker
- Flexible planning based on development and budget conditions.