Current Status of the SHINE Muon Source

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MIP2025 workshop | Hunan Univ.

17 May 2025

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

Current Muon Sources

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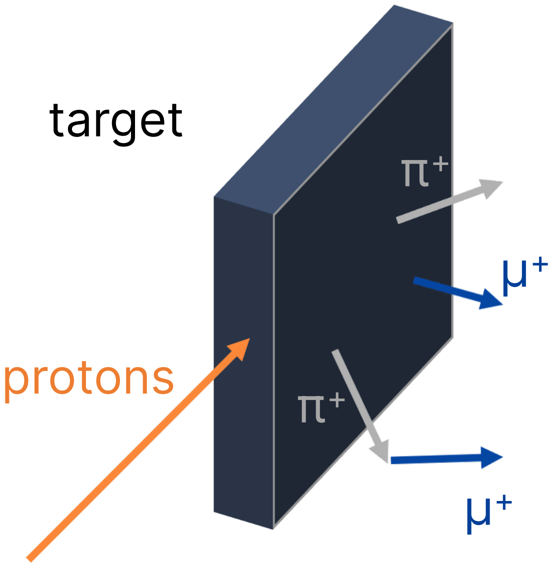
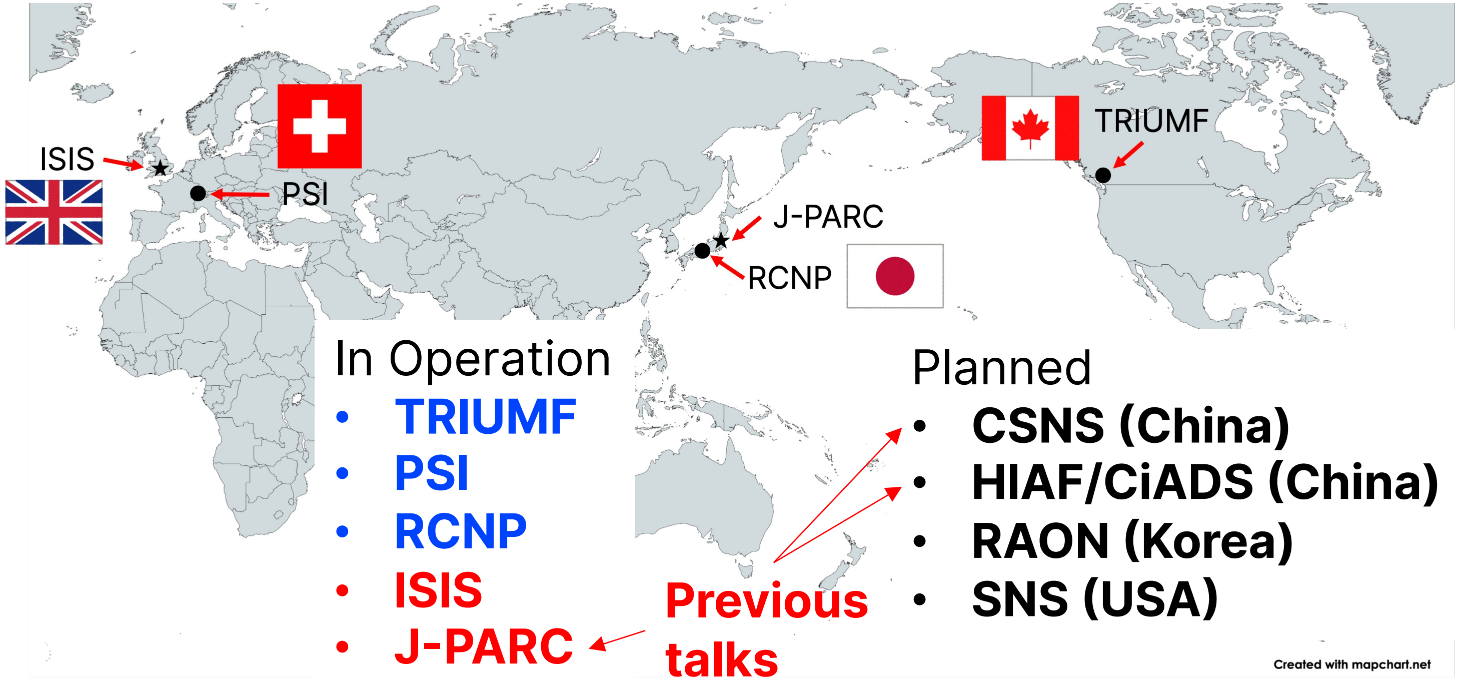
Proton-Driven Muon Source

pp collision

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





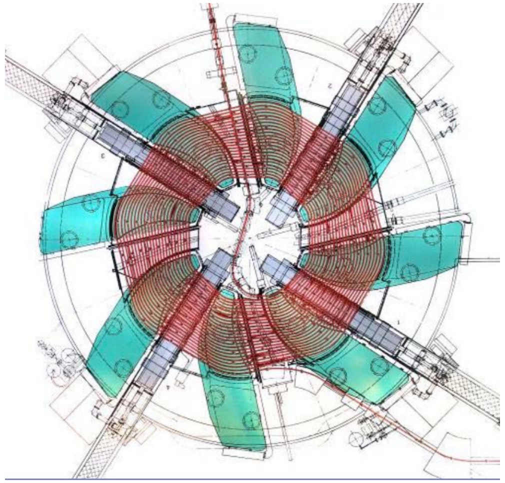
Requires a high-intensity proton accelerator
⇨ limited facilities available

Two types of muon sources depend on *p*-accelerator
- **Continuous (DC) muon sources**
- **Pulsed muon sources**

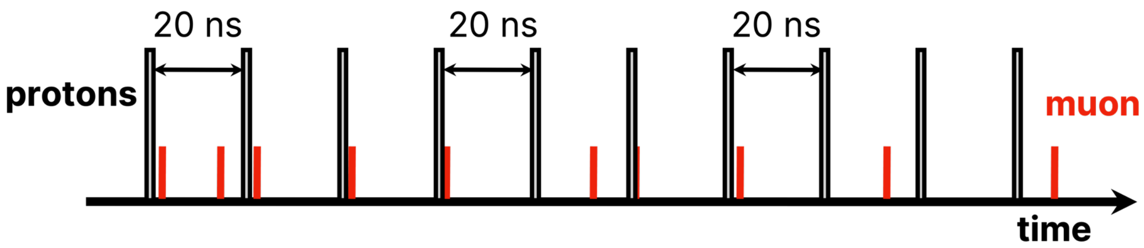
Two Types of Muon Sources

DC muon source

PSI



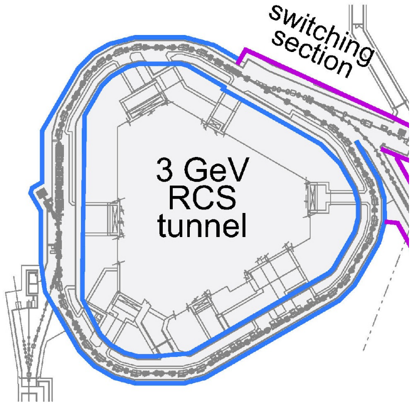
PSI Ring Cyclotron, 50 MHz continuous beam: muons arrive randomly (time structure smeared out by pion life time of 26 ns ~ order of rep-rate)



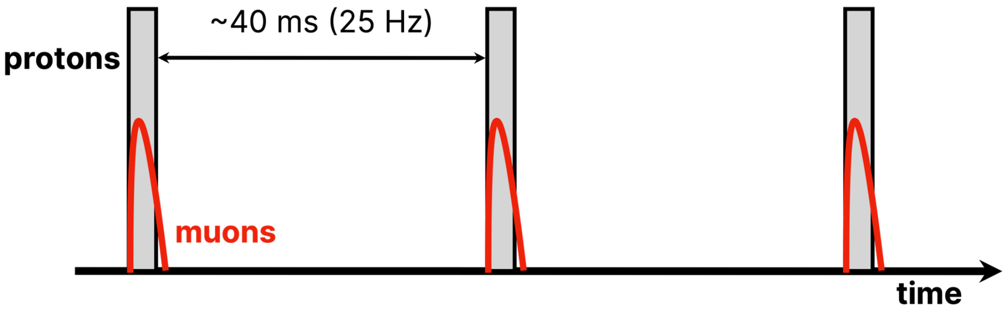
- Muon counter required to measure arrival time
- Muon event rate is limited to avoid pile-up
- Less muon (positron) at a once
  ⇨Only a few positron detector needed

Pulsed muon source

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



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



- Can be synchronized with accelerator
  ⇨ No muon counter required
- Long interval helps us to reduce background
- Large number of muons (positron) at a once
  ⇨ Large number of positron detector needed

A Muon Source with Ideal Time Structure?

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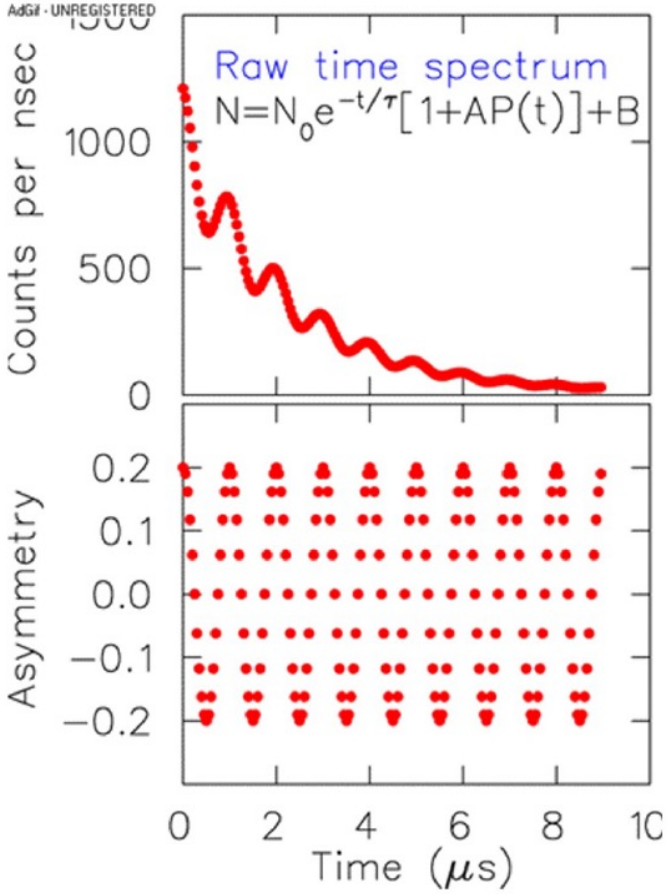
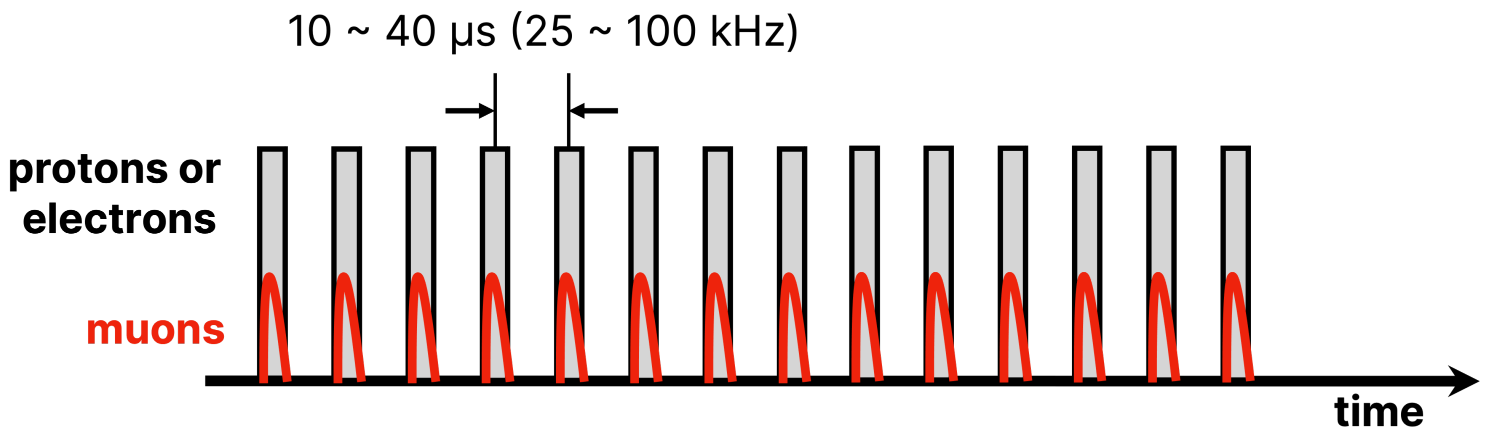
Certain type of experiment (e.g. μSR)



τ_μ ~ 2.2 μs → typical measurement duration :
10 μs ~ 20 μs (~ 5 to 10 muon lifetimes)

High-repetition-rate pulsed beam



- Higher duty cycle can compensate relatively low muon number in bunch
  ⇨Less muon per bunch, less pileup (~ 10^3 μ^+/bunch)
- Sufficiently long time interval to reduce background

Pulsed muon source with higher repetition rate is considered to be optimal

Calls for High-rep. Pulsed Beam

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

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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]

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μSR

SciPost

Mu-MuBar

SciPost Phys. Proc. 5, 009 (2021)

Muonium-antimuonium conversion

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PAUL SCHERRER INSTITUT PSI

Review of Particle Physics at PSI
doi:10.21468/SciPostPhysProc.5

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

Muon EDM

Compact storage ring to search for the muon electric dipole moment

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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

$\overline{\mathrm{M}}$ grows in time to a maximum at $2\tau_\mu$ (see Figure 9.5). Thus the ratio of M to $\overline{\mathrm{M}}$ decays grows with t^2. In case of a multiple coincidence, as in MACS, this implies that the potential $\overline{\mathrm{M}}$ 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 $\approx \mu s$ length would be ideal.
With a new experiment, from the viewpoint of signal to background ratio, an improved value for $G_{\mathrm{M\overline{M}}}$ 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].

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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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. Muon Source

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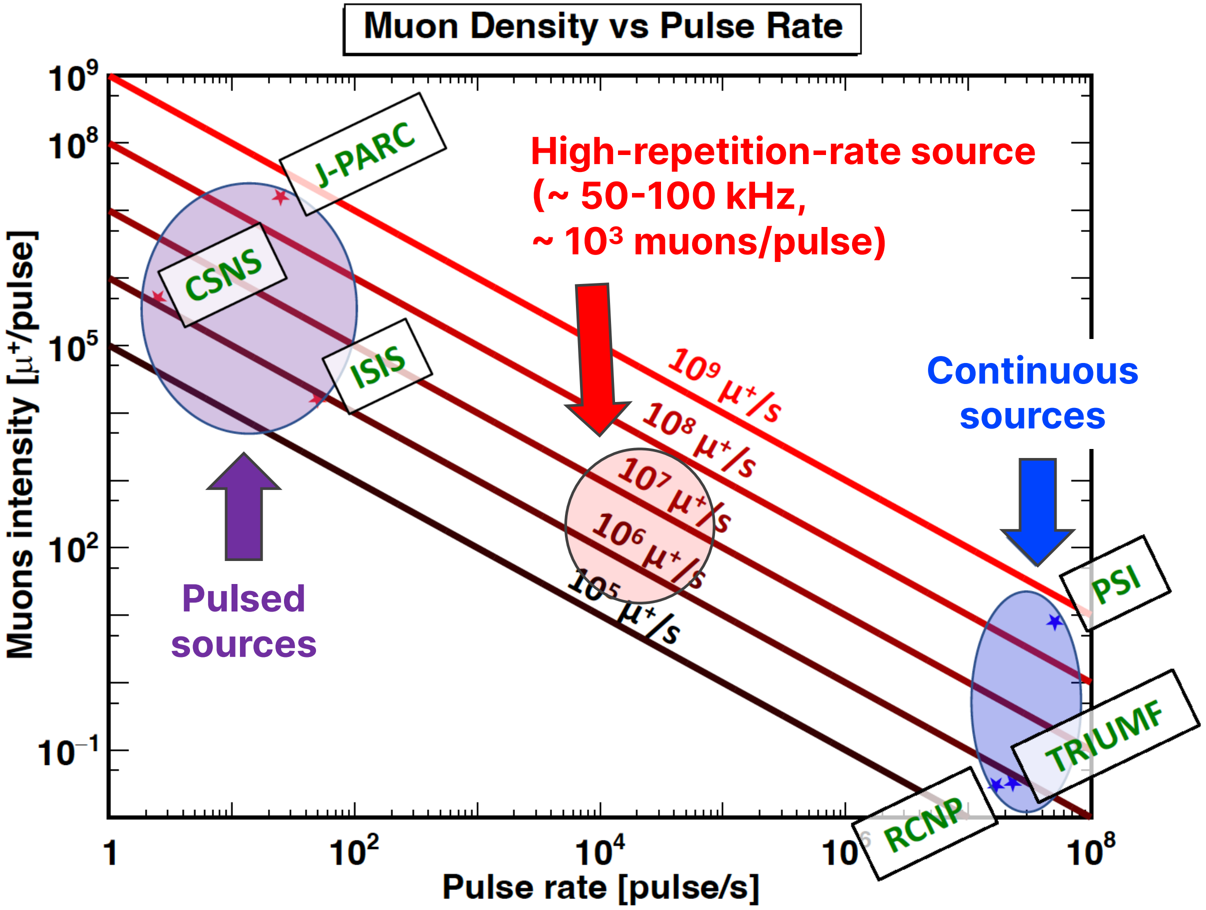
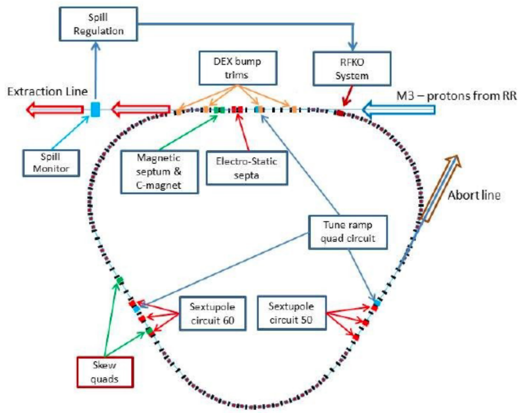


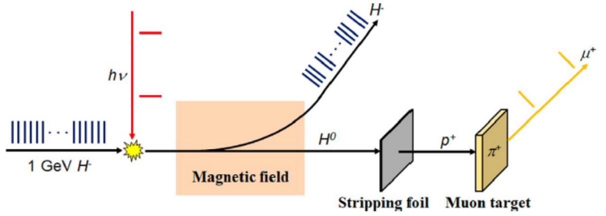
Some attempts with proton machines

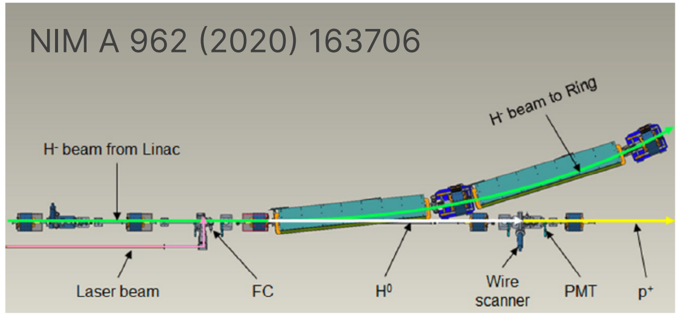
Resonant extraction Mu2e@FNAL



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

Laser neutralization @ ORNL



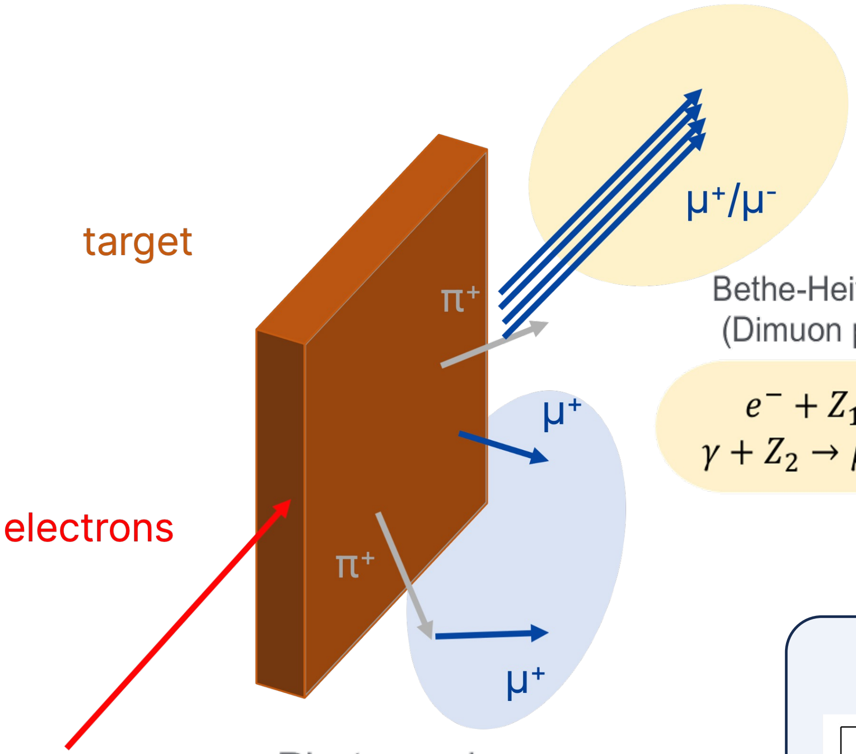


Successfully demonstrated
30 ns/50 KHz proton pulses

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

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

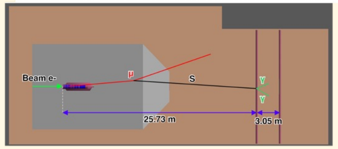
High energy CW e⁻ beam

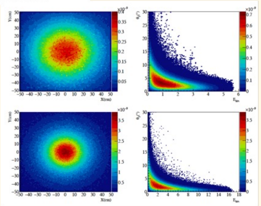
instruments

Article

Secondary Beams at High-Intensity Electron Accelerator Facilities

Marco Battaglieri[1], Andrea Bianconi[2,3], Mariangela Bondì[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]





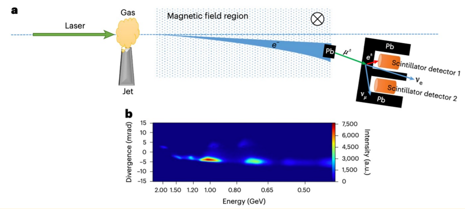
11 GeV, 50 μA CEBAF@JLAB
→ ~ 10^8 μ±/s

Based on LWFA

nature physics

Article

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

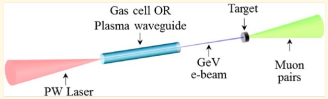


Based on LWFA

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]

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[4]University of Maryland, College Park, MD 20742, USA
(Dated: November 5, 2024)

More and more...

Relatively low energy CW e⁻ beam

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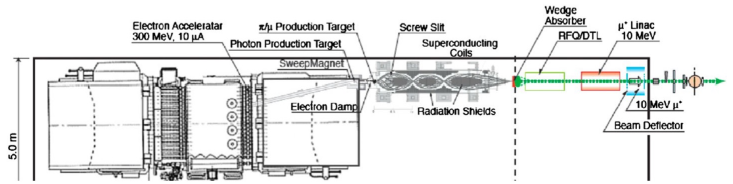
Compact muon source with electron accelerator for a mobile μSR facility

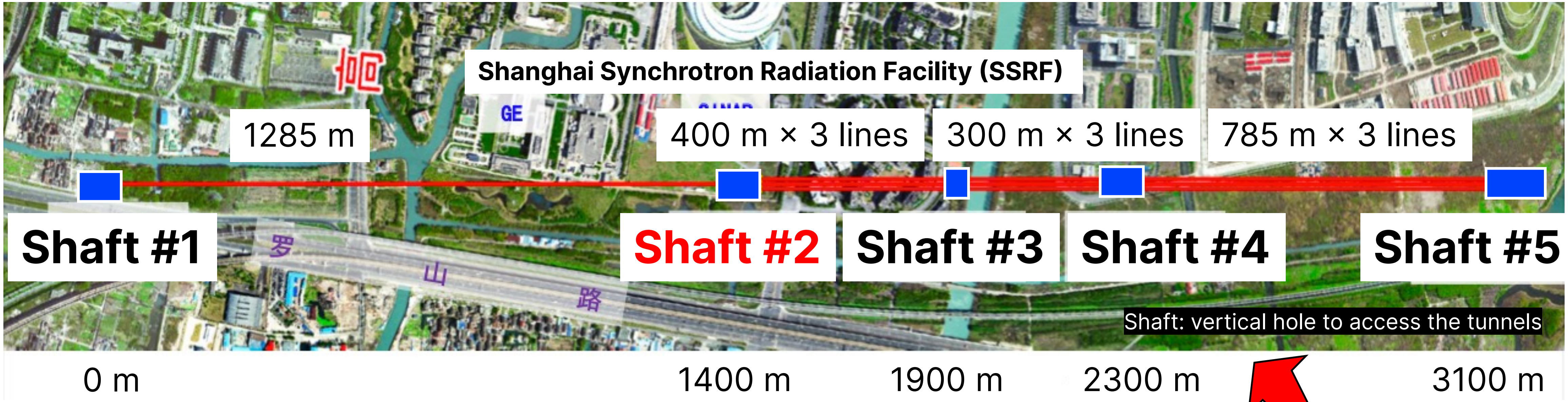
K. Nagamine[a,b,c,*], H. Miyadera[d], A. Jason[d], R. Seki[e]



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

Electron Beam at SHINE

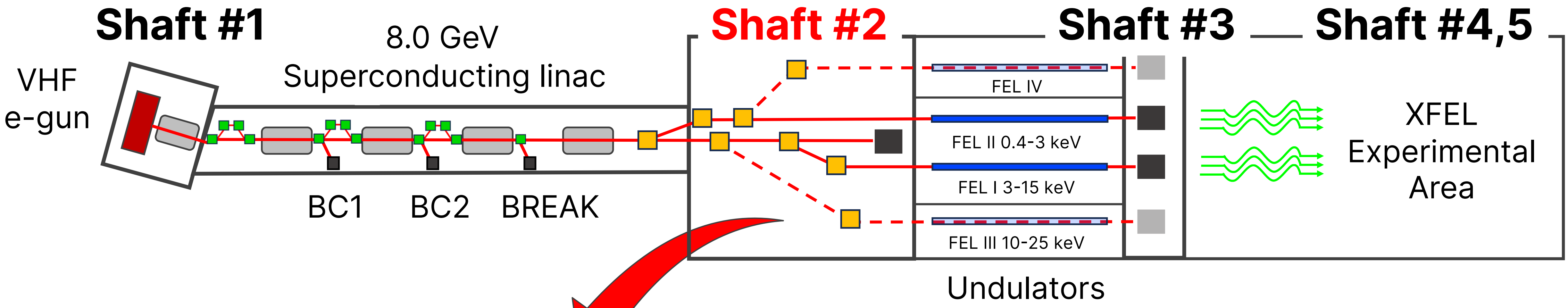
Tsung-Dao Lee Institute

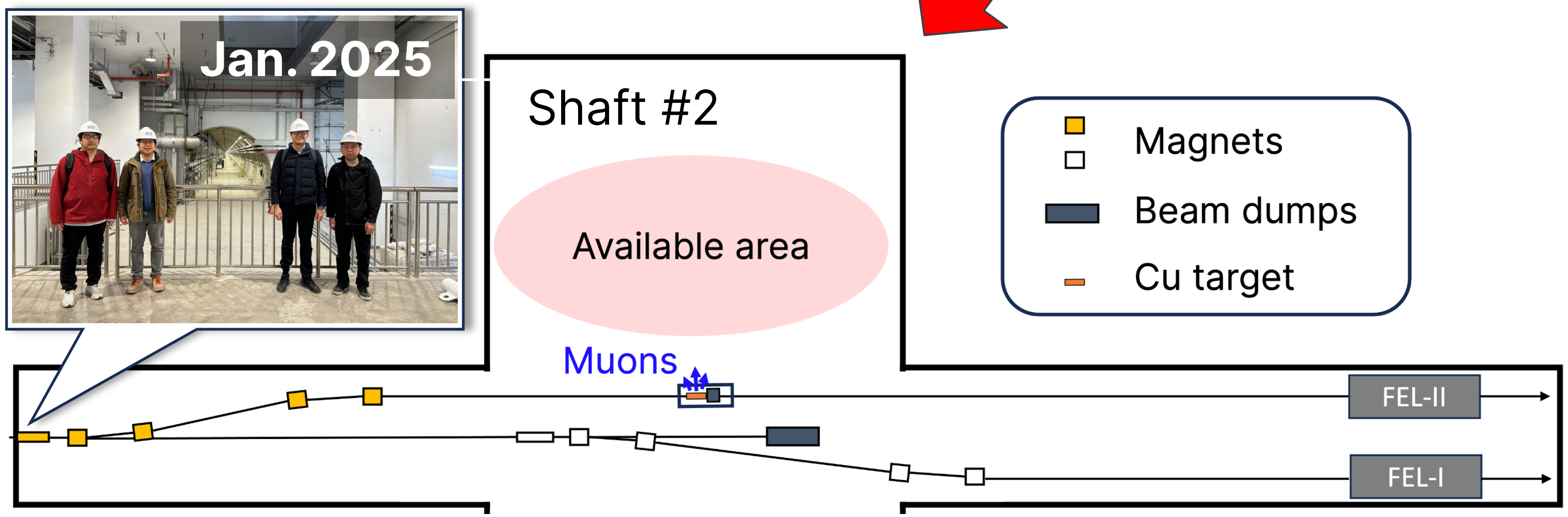


- Located in Zhangjiang, Shanghai
- To be commissioned in 2025
- Electron beam (design values):
  - 8 GeV energy
  - 1 MHz repetition rate
  - 100 pC charge (6.25×10^8 electrons) per bunch

Only 4 km from TDLI

Planned Locations





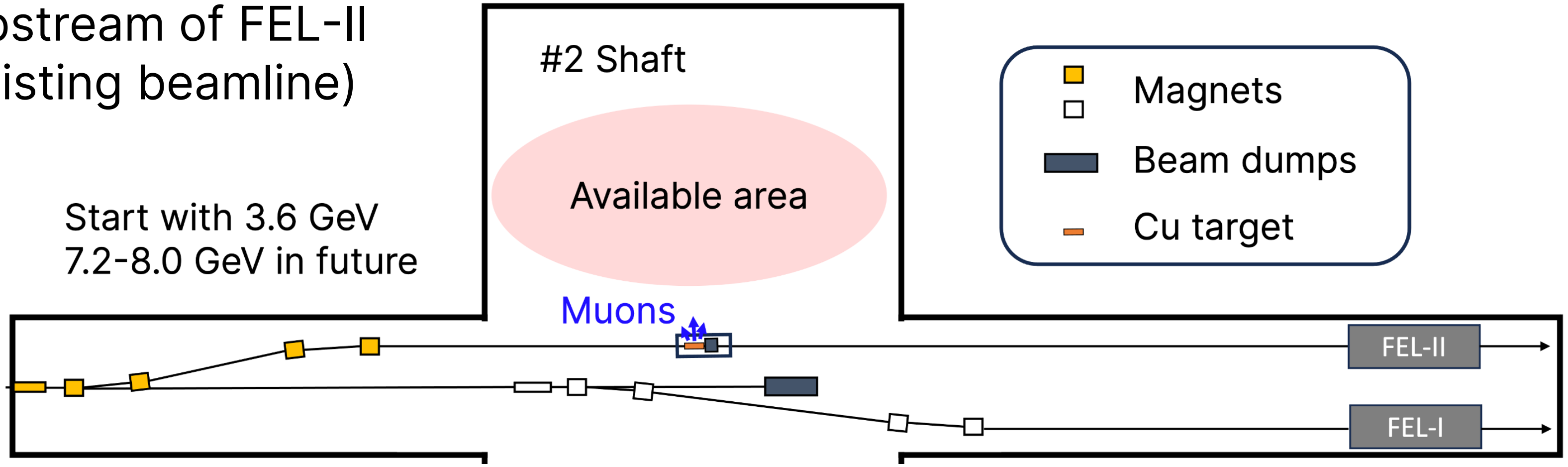
Shaft #2:

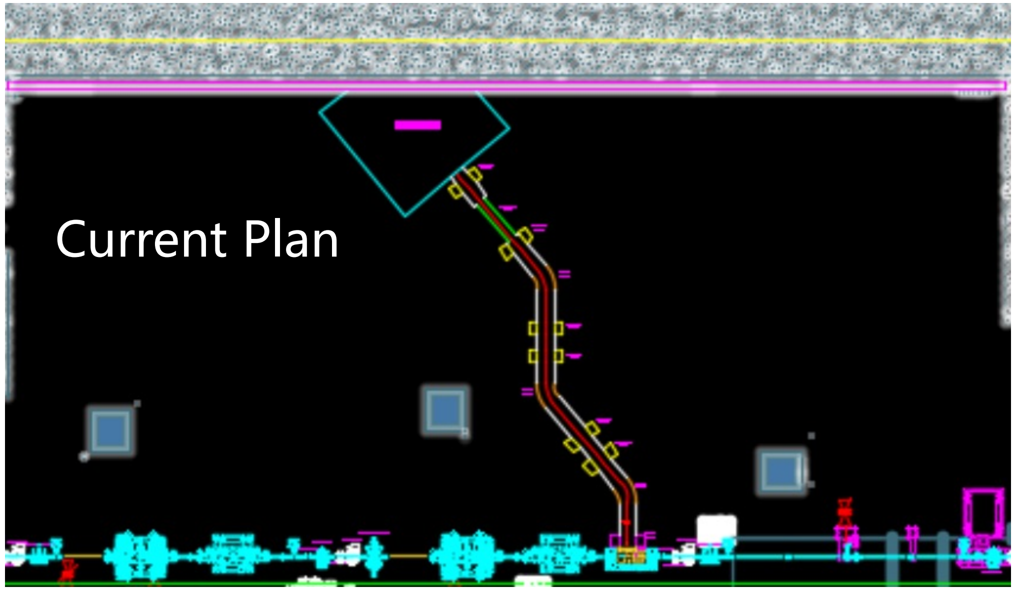
a good location for a muon source

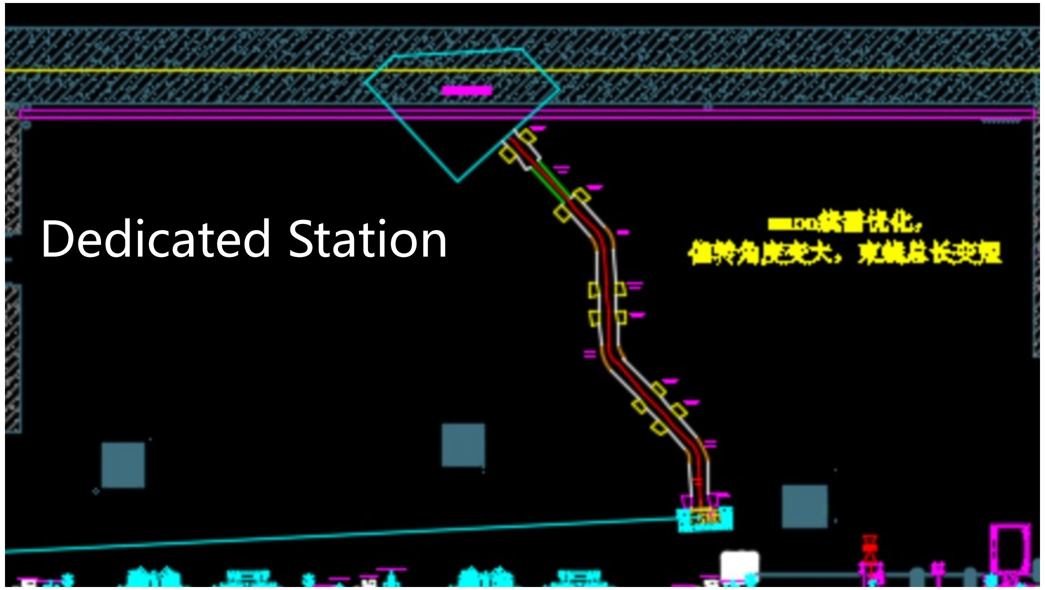
- Sufficient space
- Planned beamlines, cost efficient

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.







Target Design Concept

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Conventional Proton-Based Sources (e.g. PSI)

- Thin slab targets are standard
- Limited by downstream neutron source requirements
- Challenges:
  - Need for target tilting (~5°)
  - Complex heat management
  - Mechanical issues with rotating targets

Our Electron-Based Approach

- Direct beam dump allows thick target design
- Box-shaped target with improved cooling

Materials Evaluated

- Graphite (common for proton-drivers)
- Copper (Cu), Tungsten (W)

Evaluation Criteria (SHINE: 8 GeV, 100 μA)

- Shower maximum depth (X_{max})
- Heat load at maximum depth (dE/dz)
- 99% beam energy absorption depth (L_{99})

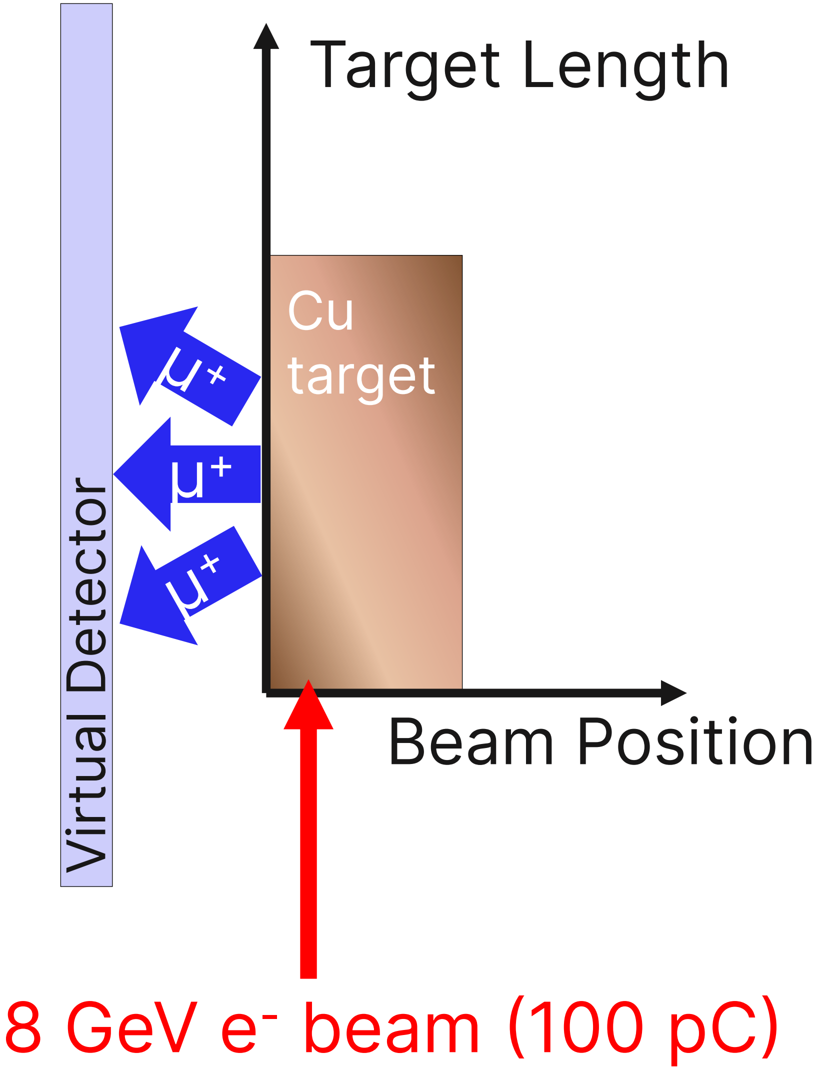
Current Design: Copper

- Moderate shower development length
- Lower heat load compared to W
- Superior thermal conductivity
- Established manufacturing processes
- Cost-effective solution

Materials	Graphite	Cu	W
Z	6	29	74
A	12	64	184
ρ [g/cm^3]	1.82	8.94	19.25
$X_{\max}$ [mm]	839	73.9	20.7
dE/dz [kW/cm]	0.24	3.26	13.2
L_{99} [mm]	3090	281	79.8

Target Optimization

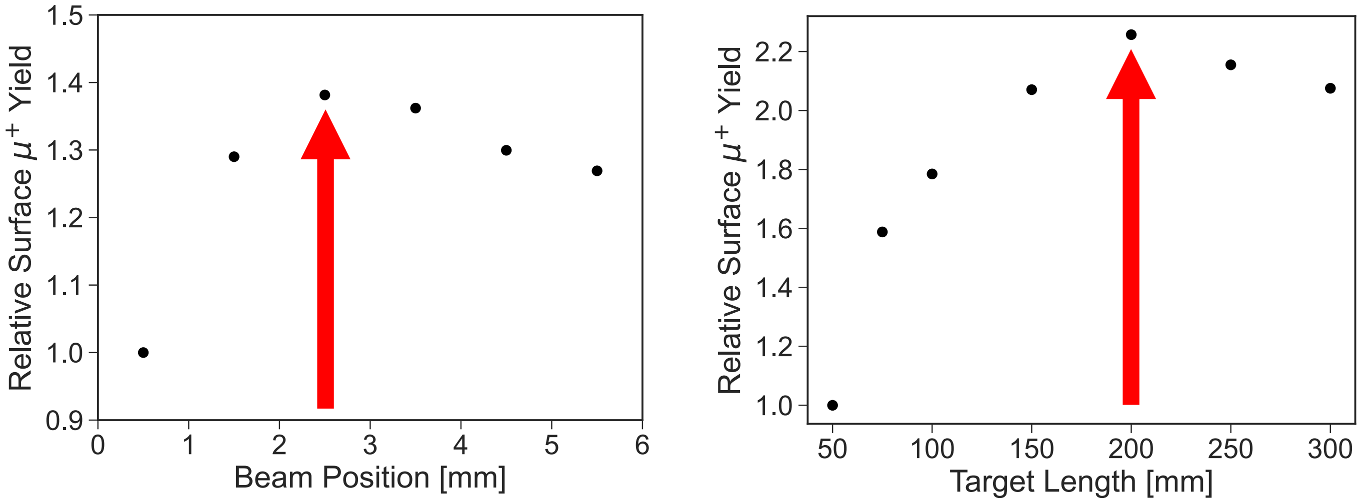
FLUKA simulation



Optimization Studies

- FLUKA code v4-4.0
- 8 GeV, 100 pC/bunch electron beam
- 2 mm RMS beam size
- Virtual detector: 100 cm × 100 cm at 35 mm

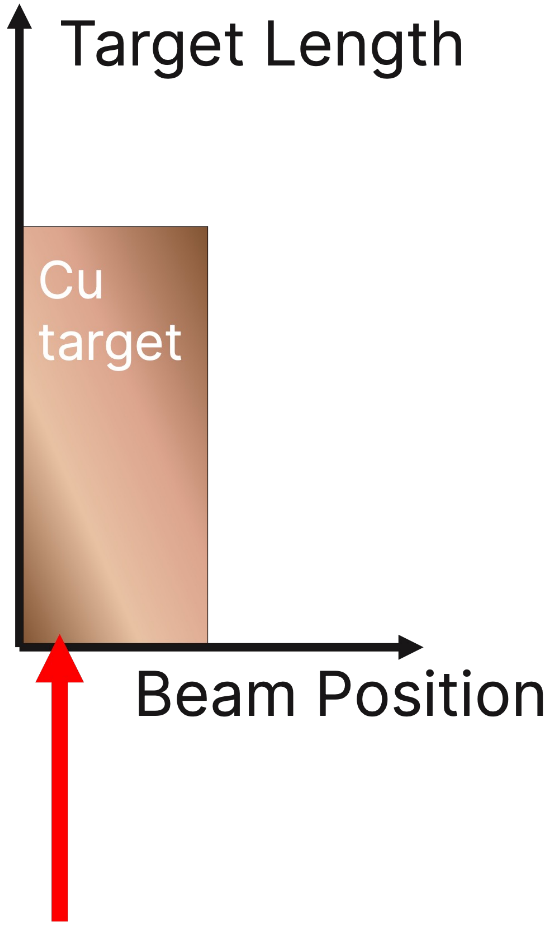
Scan with FLUKA for target dimension optimization



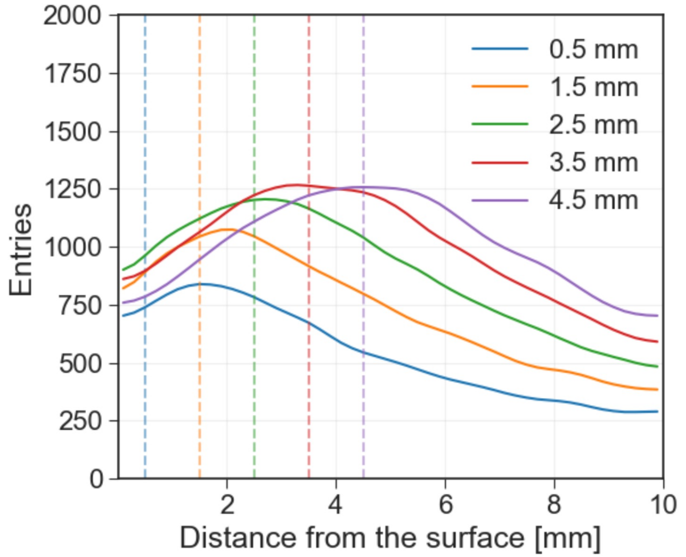
Results

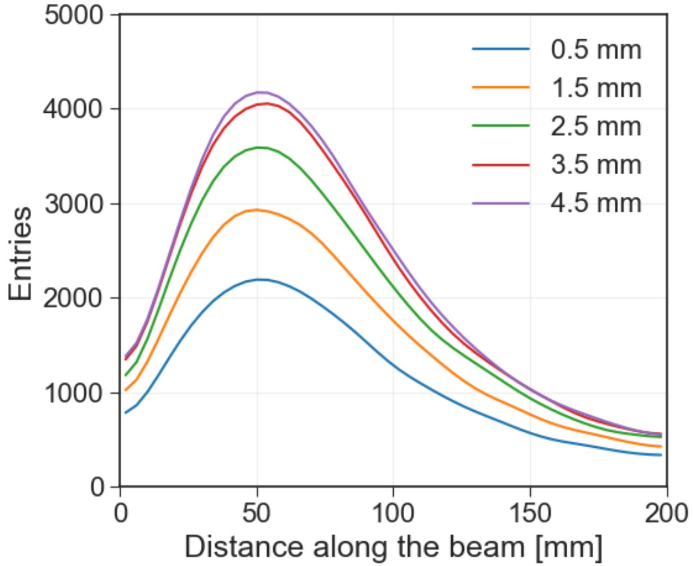
- Optimal beam position: 2.5 mm from target surface
- Optimal target length: 200 mm

Stopped Pion Density



8 GeV e^- beam (100 pC)





- < 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)

- Peak about 50 mm from the irradiated surface of the beam
  ⇒ Center the capture solenoid should be here
- No significant gain is expected in length over 200 mm.

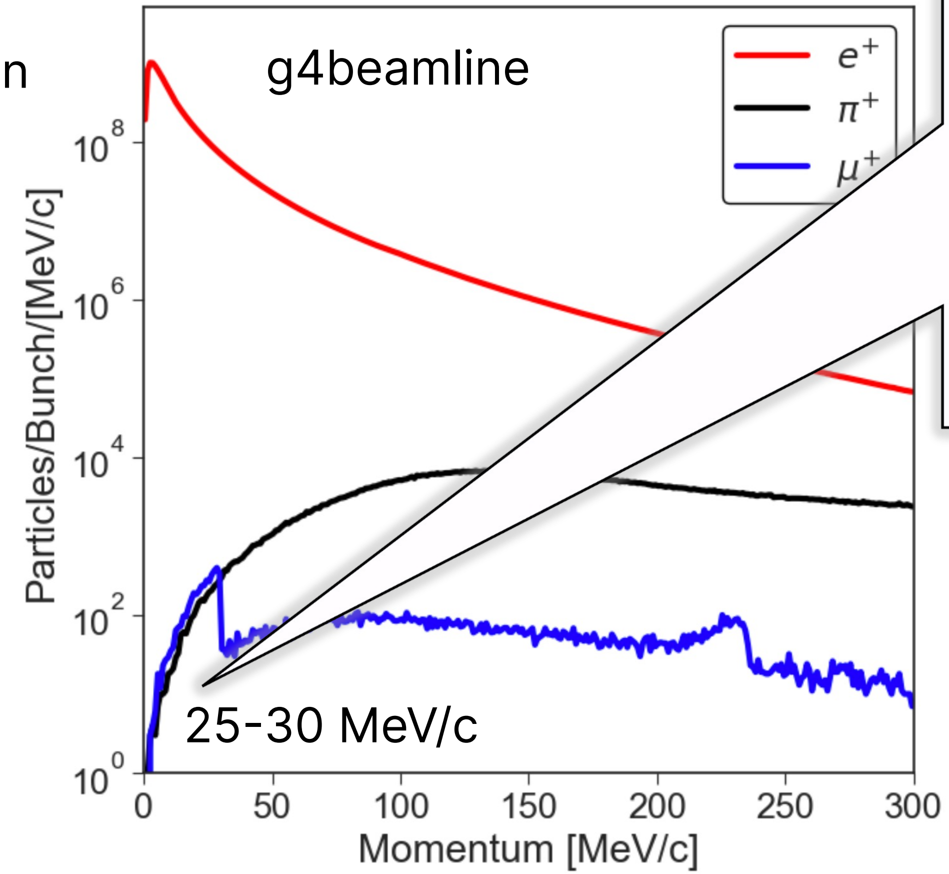
These studies will be also done on other materials

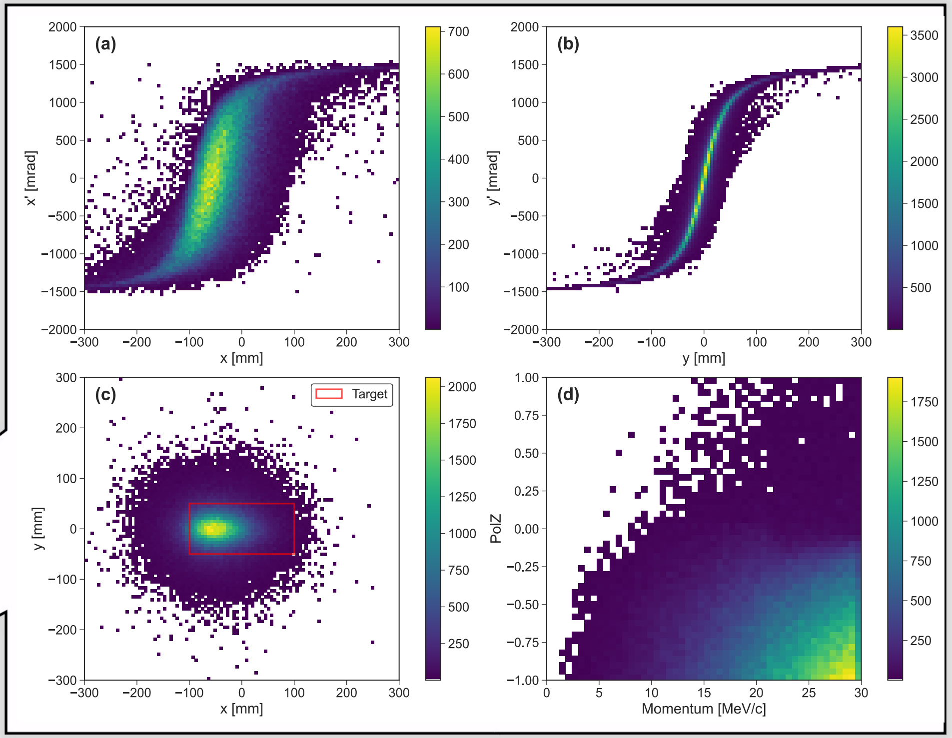
Particle Yields from Cu Target

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

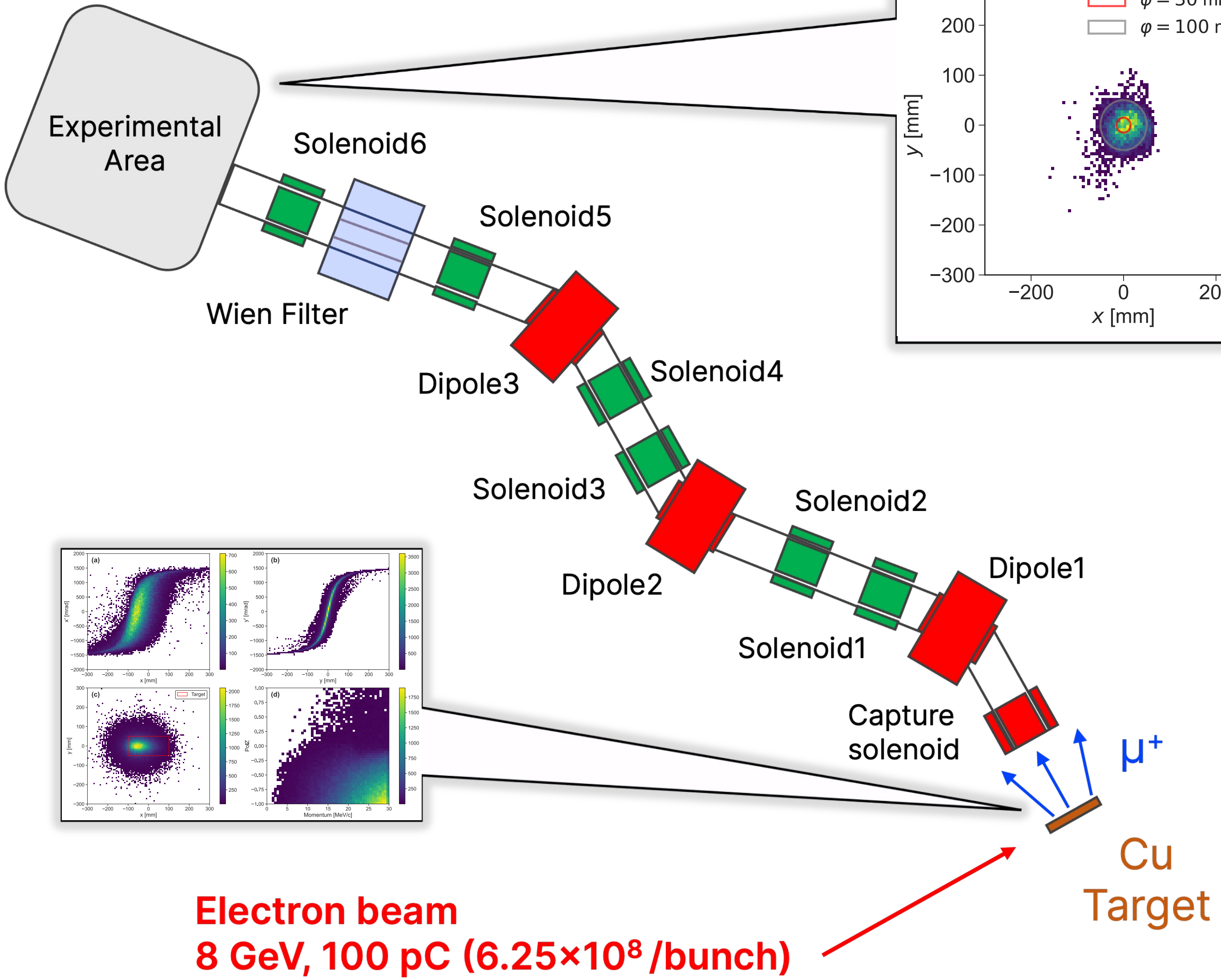


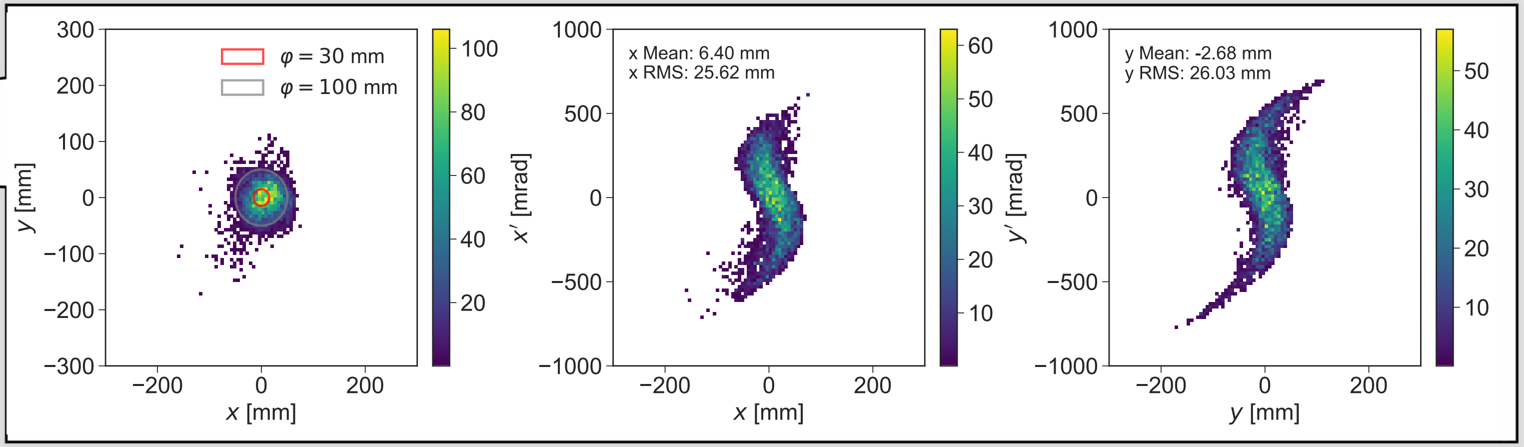


Parameters	Value
Mean Momentum P_0 / Momentum Spread σ_P	22.9 MeV/c / 5.5 MeV/c
Horizontal Position $< x >$/ Width σ_x	-45.2 mm / 73.7 mm
Horizontal Divergence $< x' >$/ Width $\sigma_{x'}$	-14.6 mrad / 696.7 mrad
Horizontal RMS Emittance	3814 π cm mrad
Vertical Position $< y >$/ Width σ_y	-0.1 mm /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





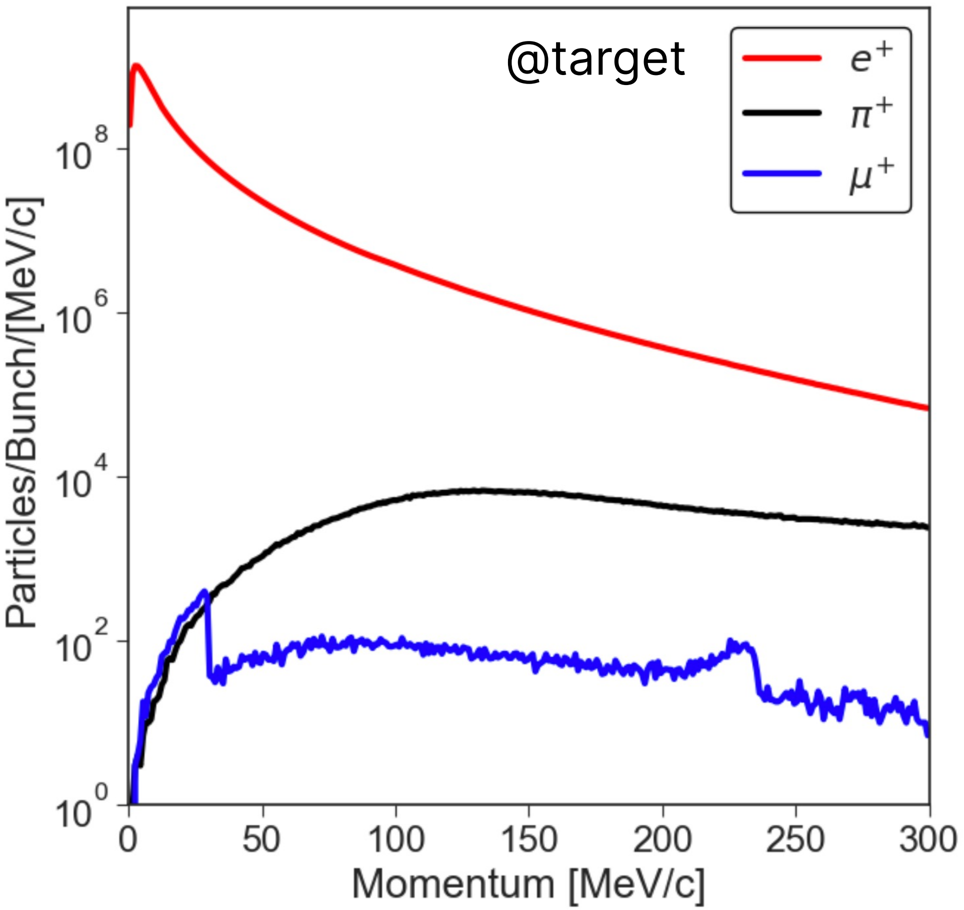
Parameters	Value
x/x' (RMS)	25.6 mm / 221 mrad
y/y' (RMS)	26.0 mm / 246 mrad
$\Delta p/p$	3.69%
Polarization	85%
μ^+ rate (All)	$3.1 \times 10^6\ \mu^+/s$
μ^+ rate (ϕ30 mm)	$4.7 \times 10^5\ \mu^+/s$

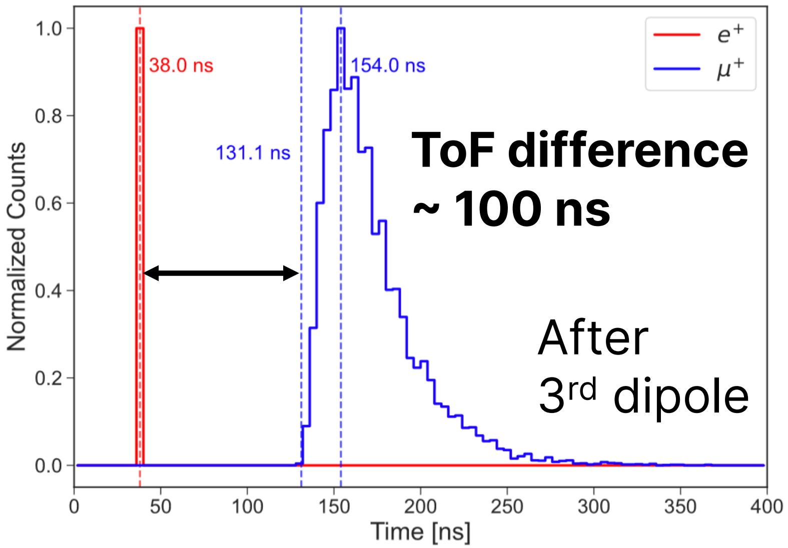
@50 kHz repetition rate
(1/20) of SHINE capability

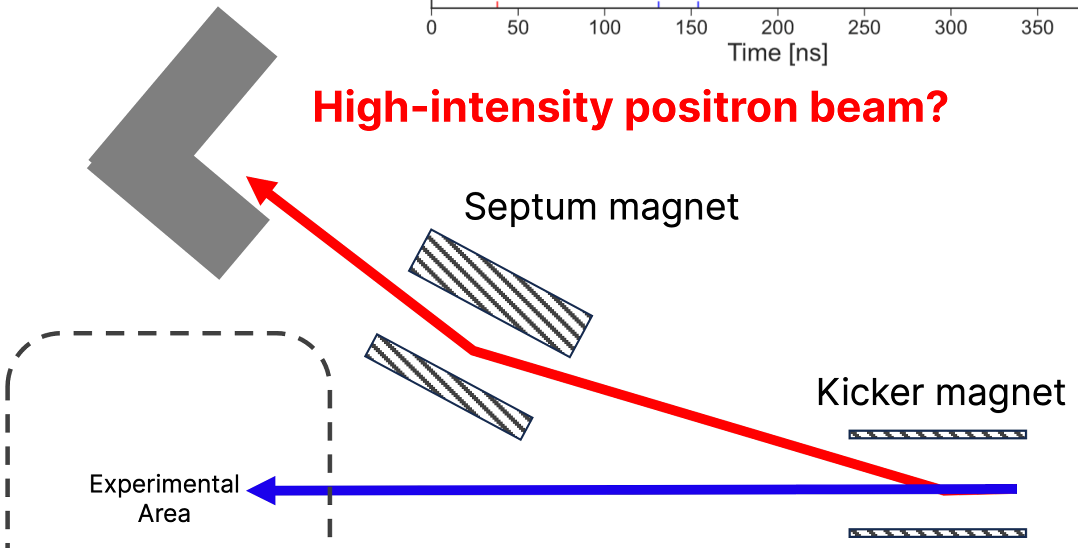
Positron Management

Lots of positrons!

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



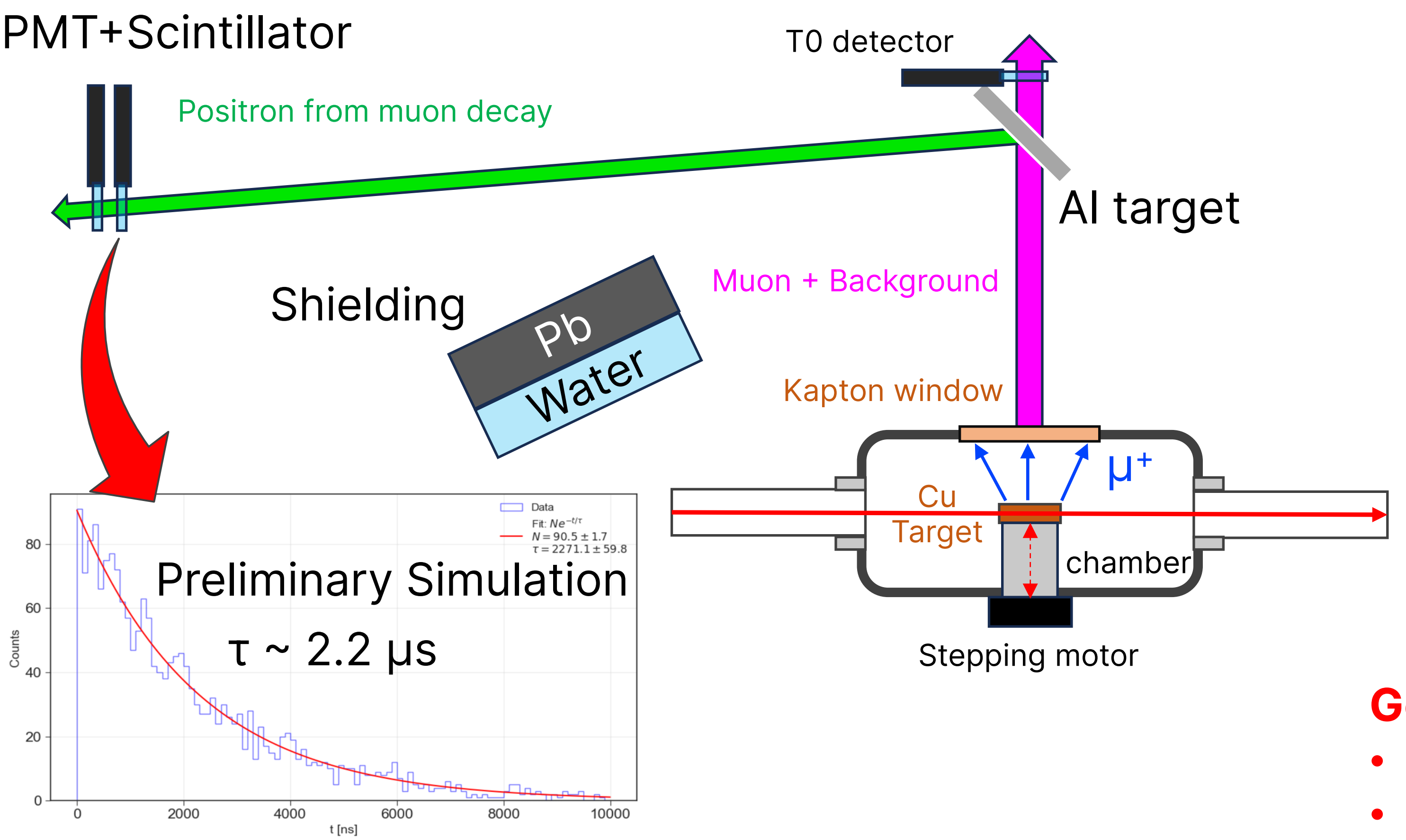




Dedicated fast kicker scheme could solve this (e.g. SHINE, Euro XFEL)

Test Beam at SHINE Shaft #2

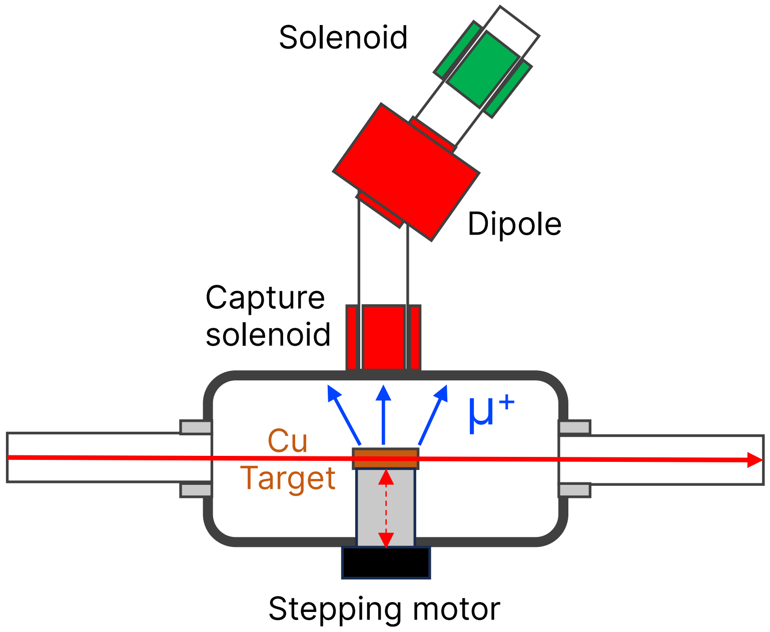
2025



Goals:

- **Examine muon generation and intensity**
- **Validate simulation framework**

2026



Goals:

- **Demonstration of the Extraction**
- **More detailed properties**
  - **μ^- yield from muonic X-ray**
  - **Momentum measurements**
  - **Profile measurements**

Collaboration and Acknowledgement

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SHINE Muon Source Collaboration

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Summary

- A muon source with high-repetition rate (~50 kHz) could provide an ideal time structure for various experiments.
- This study focused on surface muon production with a copper box-shaped target.
  - Important insights were obtained; this will be extended and further optimized in near future
- 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
  - Need to finalize detailed design including positron removal

Future plans

- In the next few years, beam tests at SHINE will establish the basis for our muon source, including evaluation of muon production, extraction, etc.
  - Completion of SHINE Shaft #2 beam tests (2025-2026)
  - Construction of full muon beamline at SHINE (~2030 target date)

- Initial science projects will be application-based: μSR, beam test
- Upgrades and further optimization needed for competitive fundamental physics
  - muon lifetime, muon EDM, MACE, etc
  - Your new ideas are highly welcome!

Backup

Components	Position (m)	Length (mm)	Aperture (mm)	Field (T)
Capture solenoid	0.47	373	500	0.432
Dipole1	1.93	640	400	-0.100
Solenoid1	3.17	373	500	0.241
Solenoid2	4.40	373	500	0.173
Dipole2	6.05	640	400	0.100
Solenoid3	7.17	373	500	0.136
Solenoid4	8.00	373	500	0.199
Dipole3	9.45	640	400	-0.104
Solenoid5	10.82	373	500	0.226
Wien Filter	11.75	1500	300	
Solenoid6	13.18	373	500	0.440
Exit	13.58			

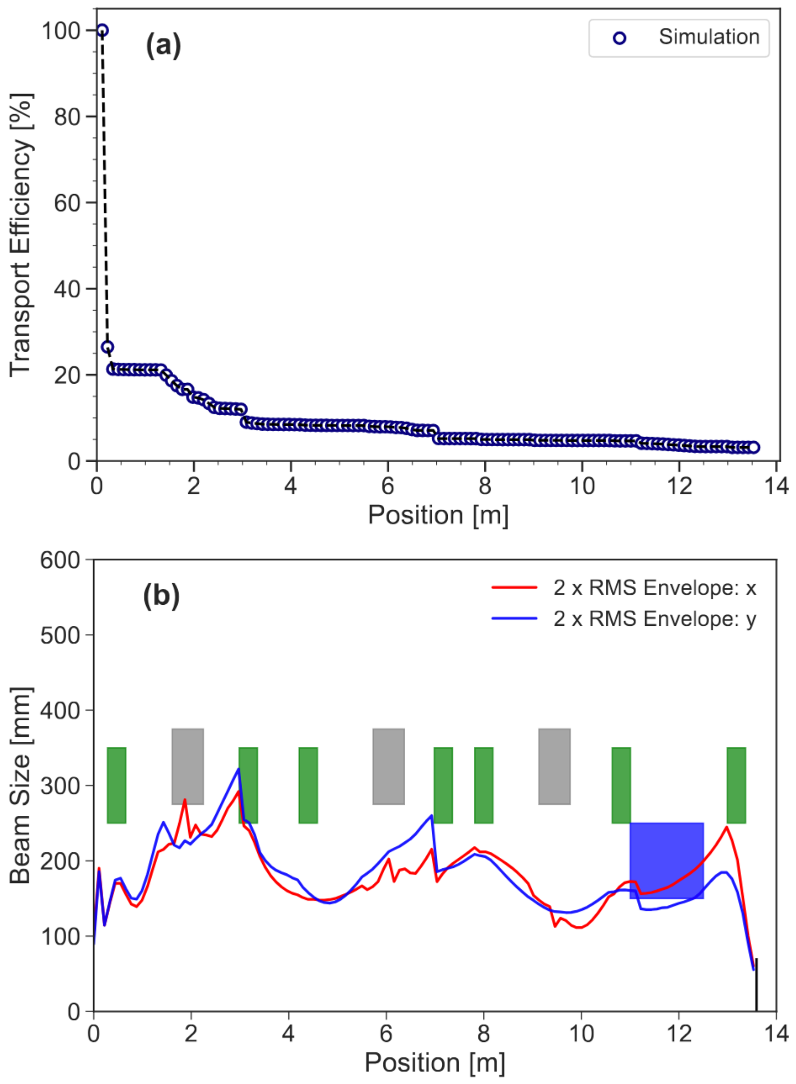
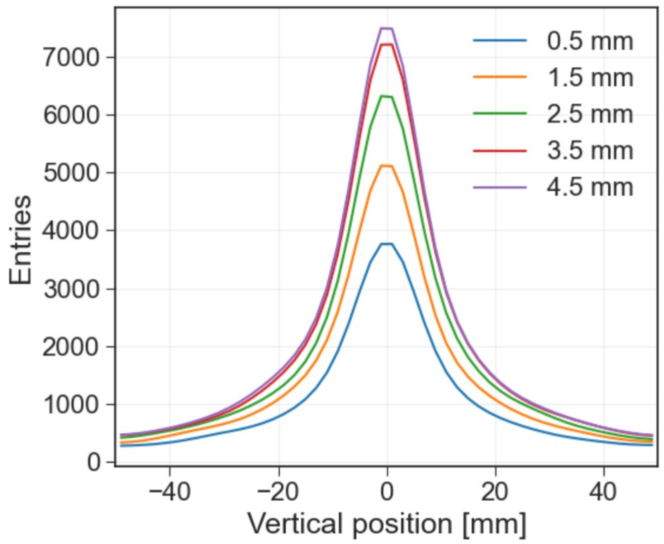


TABLE V. Main parameters of the Wien filter

Parameter	Value
Electric field (E_y)	-2.67 MV/m
Magnetic field (B_x)	0.0328 T
Length (L)	1500 mm
Plate Gap (g)	300 mm



0.5 mm
1.5 mm
2.5 mm
3.5 mm
4.5 mm
Entries
7000
6000
5000
4000
3000
2000
1000
0
−40
−20
0
20
40
Vertical position [mm]