Muon source project at SHINE

MIP2024 workshop@Peking University

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20 April 2024

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

This project is supported by the Shanghai
Pilot Program for Basic Research (基础研究特区计划)

Muon as a powerful probe

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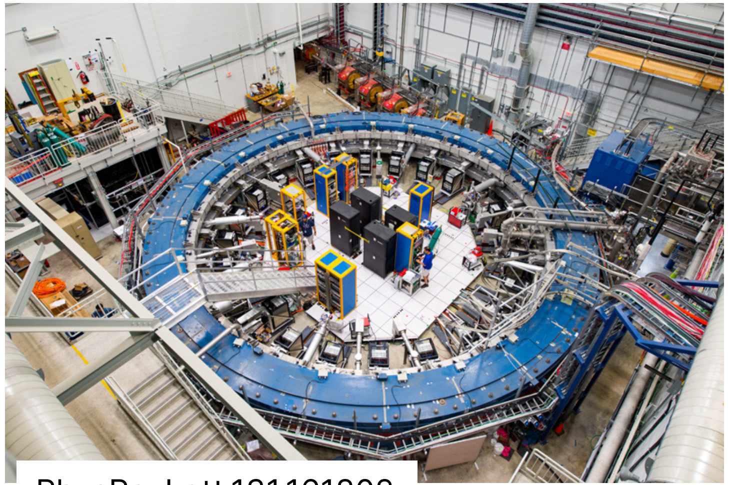
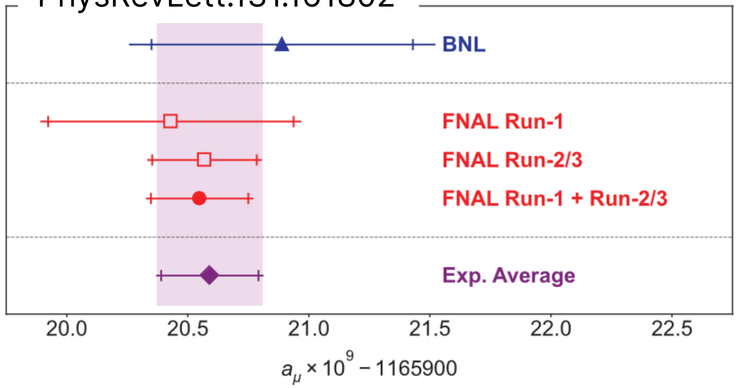
Particle & Nuclear Physics

FNAL $g-2$

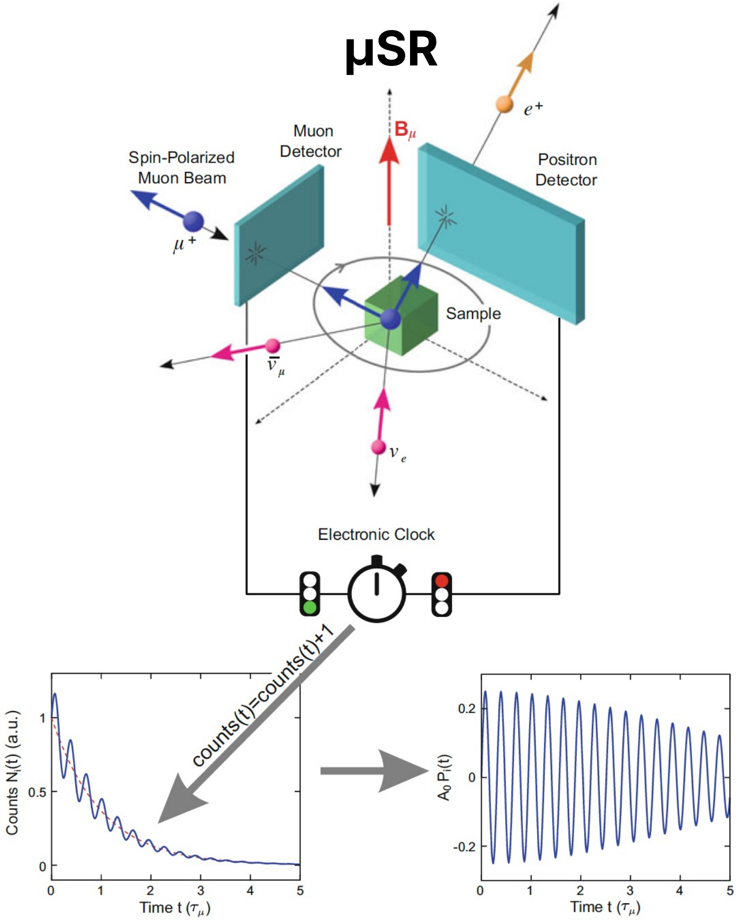


PhysRevLett.131.161802



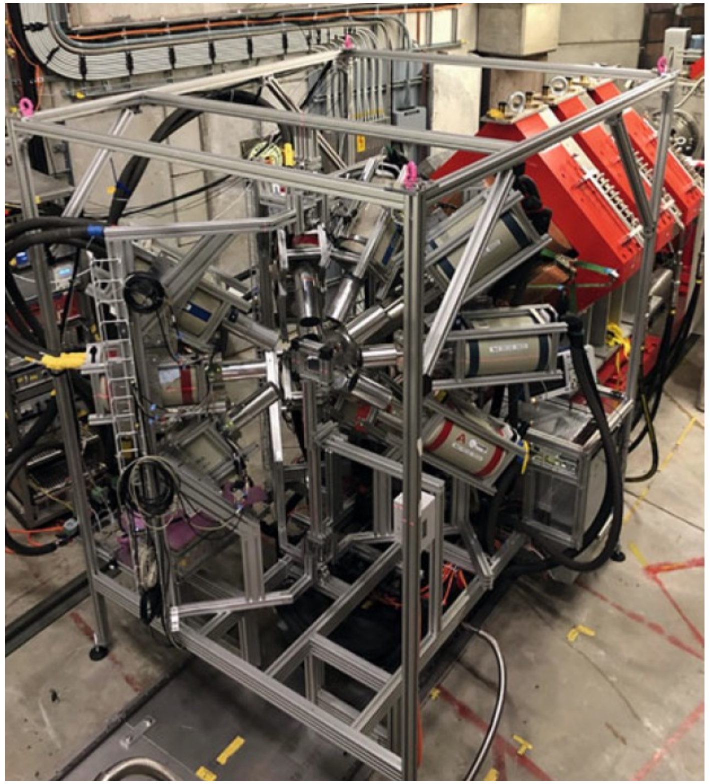
Condensed matter physics

μSR



taken from "Introduction to Muon Spin Spectroscopy"

MIXE



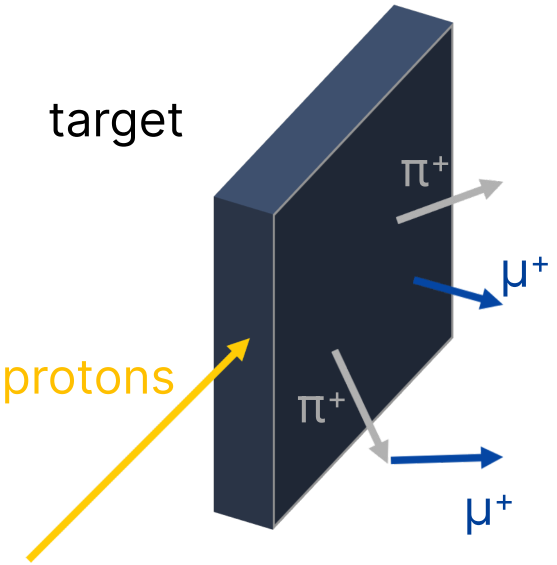
More and more applications

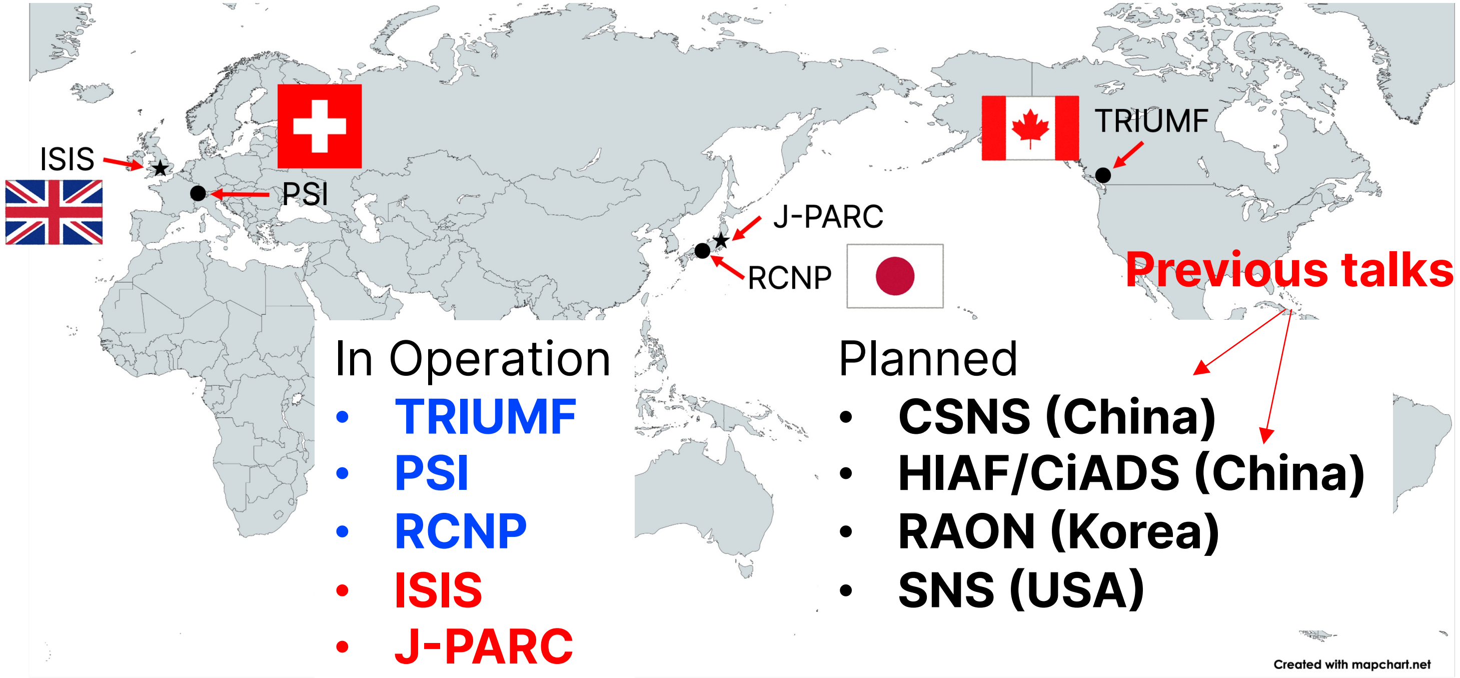
Conventional muon production

Proton-Driven Muon Source

pp collision

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





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

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

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**

Continuous (DC) muon source

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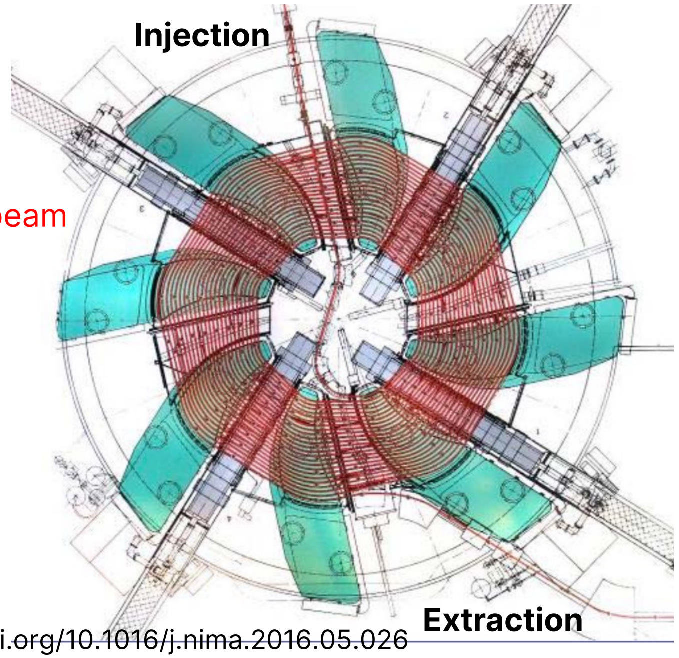
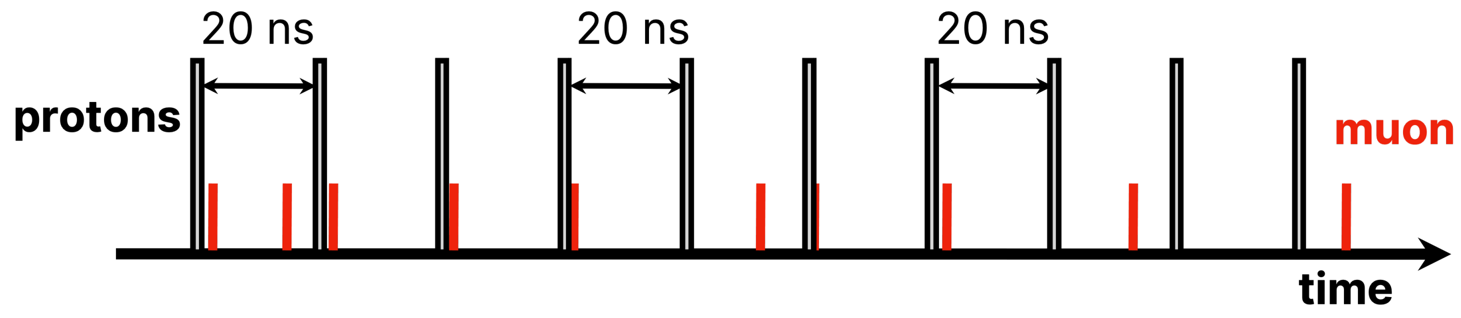
590 MeV Ring Cyclotron @ PSI



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

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
- Less muon (positron) at a once
  ⇨Only a few positron detector needed

A large number of bunches can be accelerated simultaneously (continuous beam)

Typical characteristics taken from “Introduction to Muon Spin Spectroscopy”

- Muon event rate: To avoid pile-up events, limited ~ 20 M events/h with 10 μs time window
- Time resolution: Limited only by detector and electronics ~ 60 ps
- Beam size: Can be reduced to a few mm^2

Pulsed muon sources

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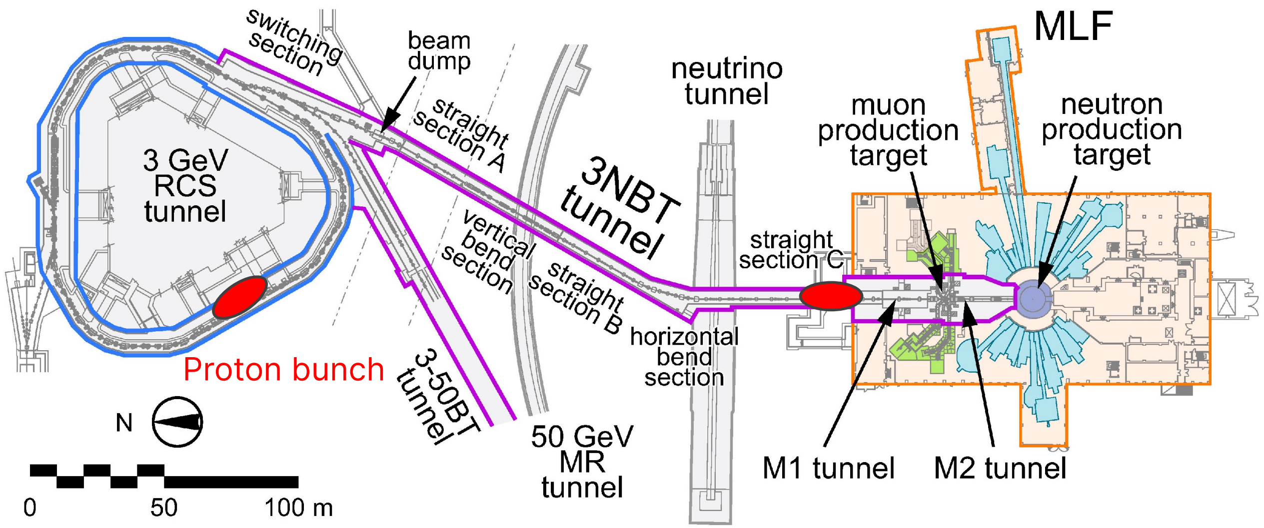
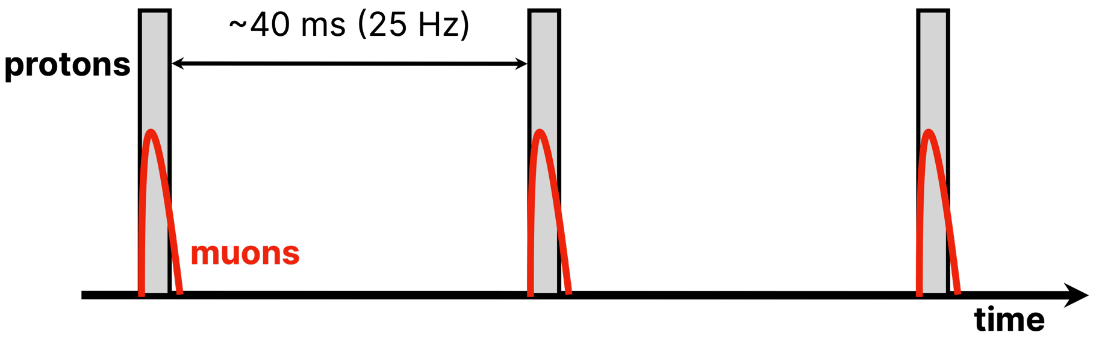
3 GeV Rapid-cycling Synchrotron @ J-PARC



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

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

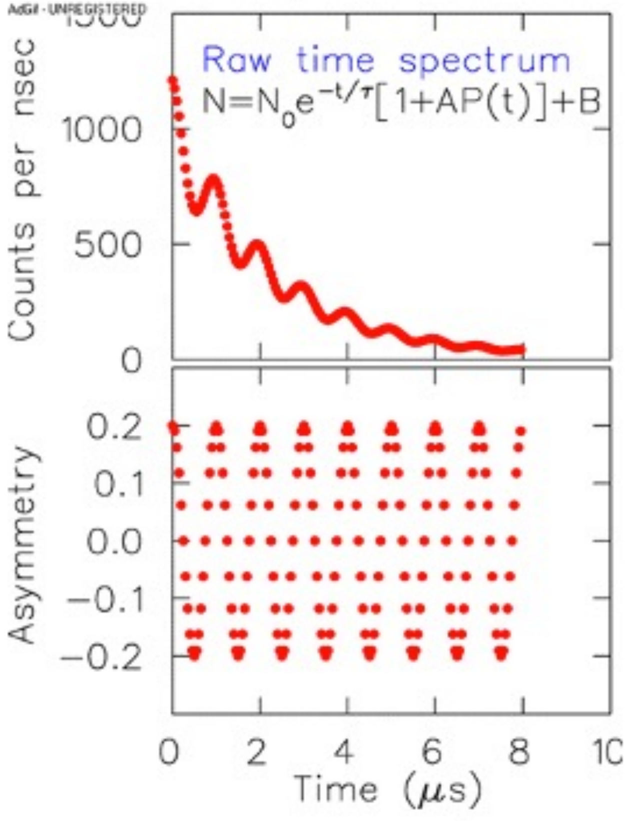
Only one (two) bunches can be accelerated at the same time (pulsed beam)

Typical characteristics taken from “Introduction to Muon Spin Spectroscopy”

- Muon event rate: Limited by detector granularity ~ 150 M events/h
- Time resolution: Limited only by muon pulse width ~ 40 ns
- Beam size: Basically a few cm^2

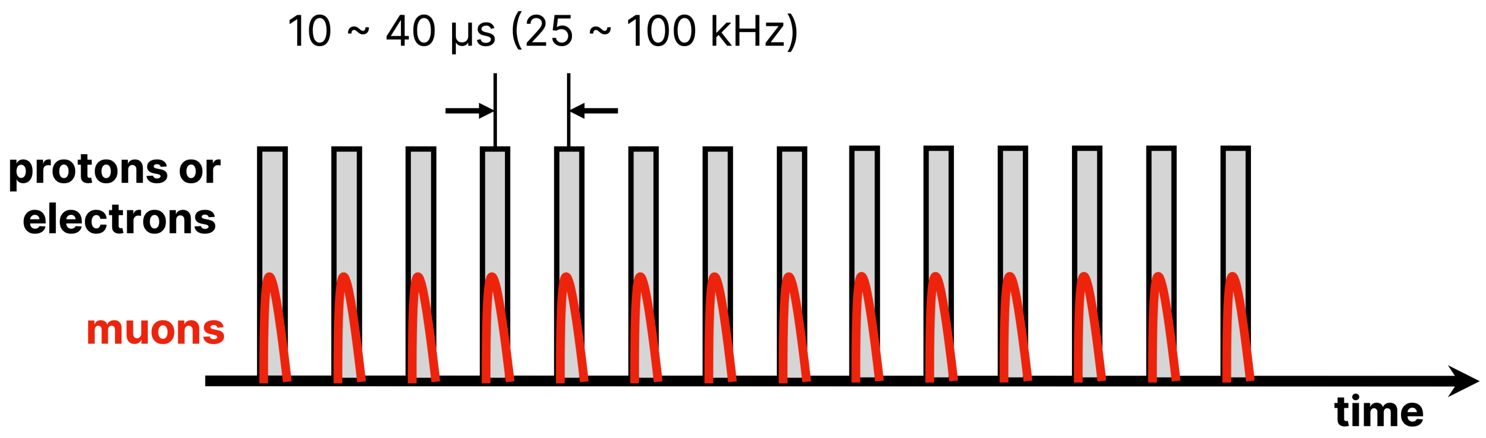
An ideal muon source?

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

Towards an ideal muon source

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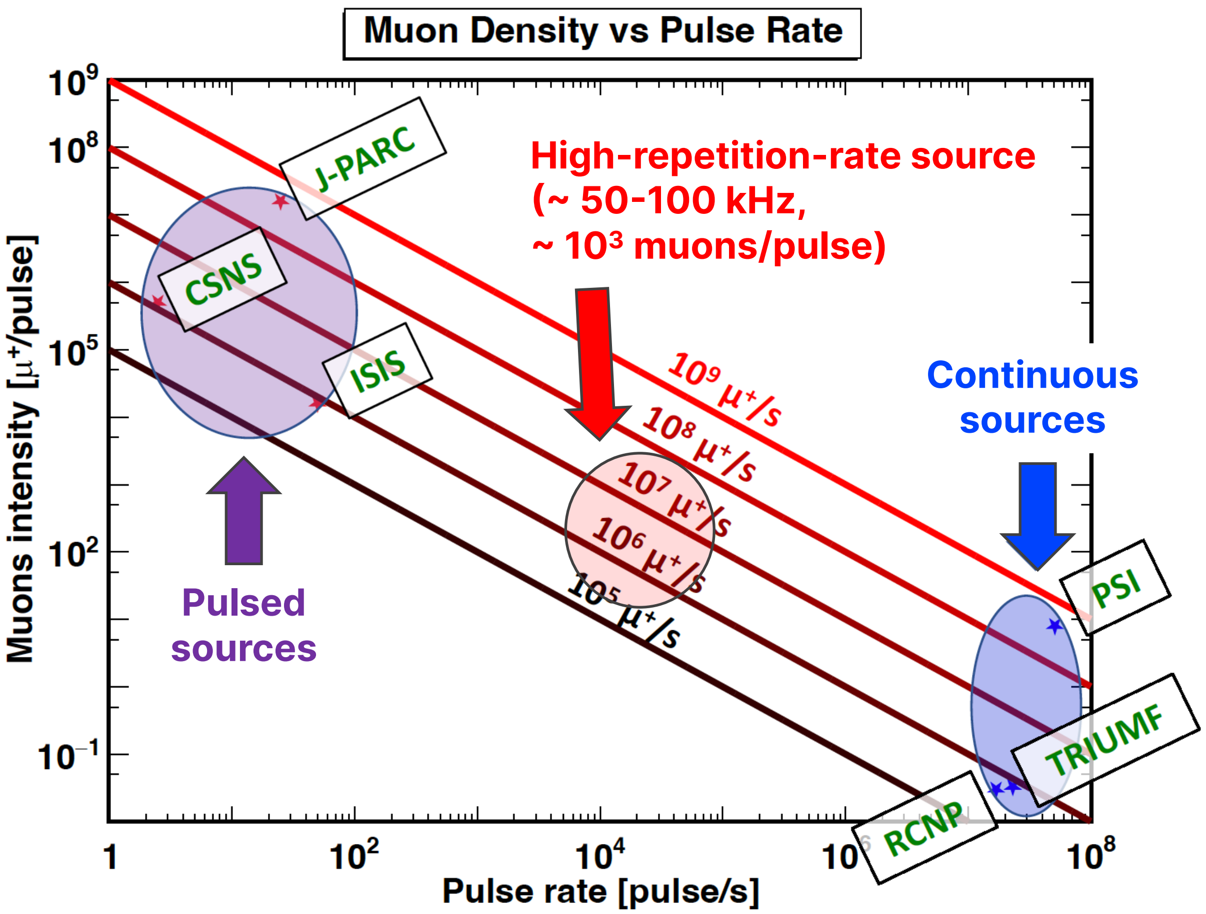
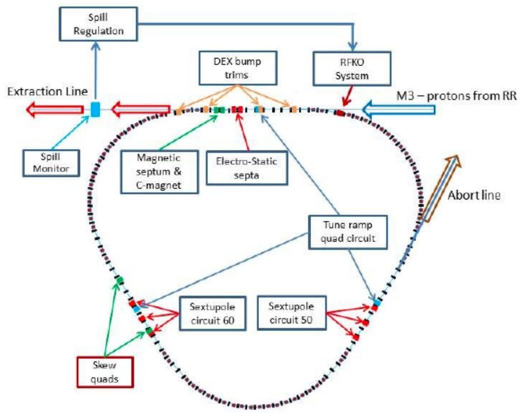


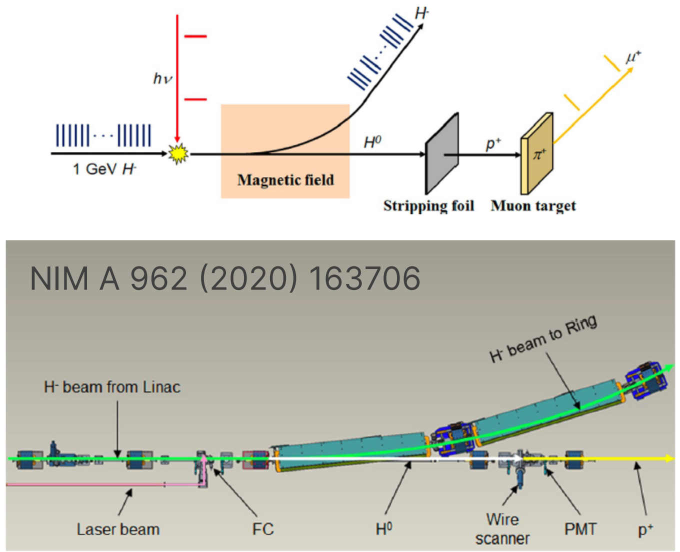
Some attempts with proton machines

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

Not versatile enough

Alternative drivers: Electron

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Photo-nuclear process

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

Bethe-Heitler process
(Dimuon production)

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

Relatively low energy CW e⁻ beam

Contents lists available at ScienceDirect

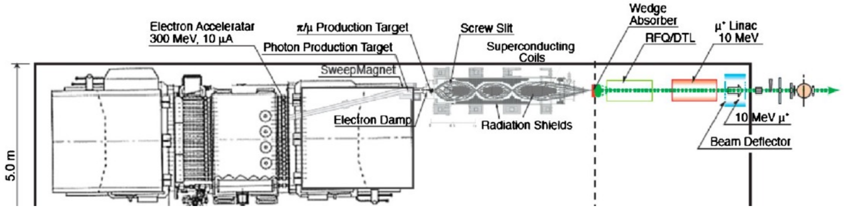
Physica B

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 × 10³ μ⁺/s

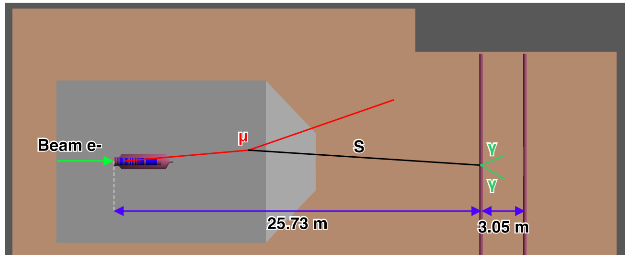
instruments MDPI

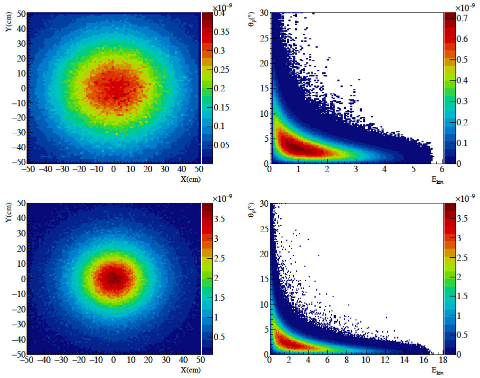
Article

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]

High energy CW e⁻ beam





11 GeV, 50 μA CEBAF@JLAB
→ ~ 10⁸ μ⁺/s

Potential driver for ideal muon sources?

Electron beam at SHINE

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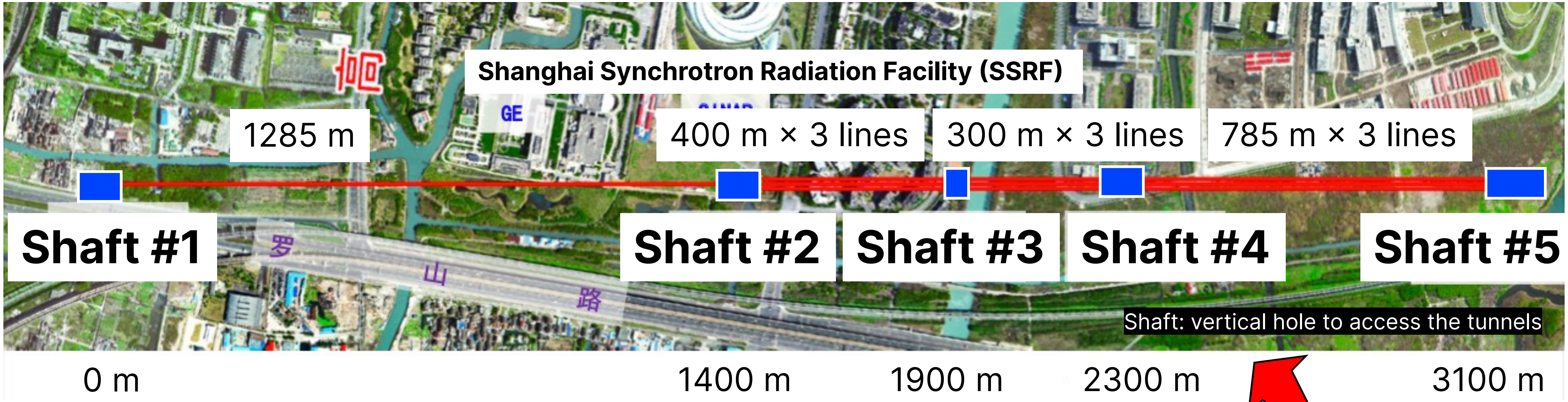
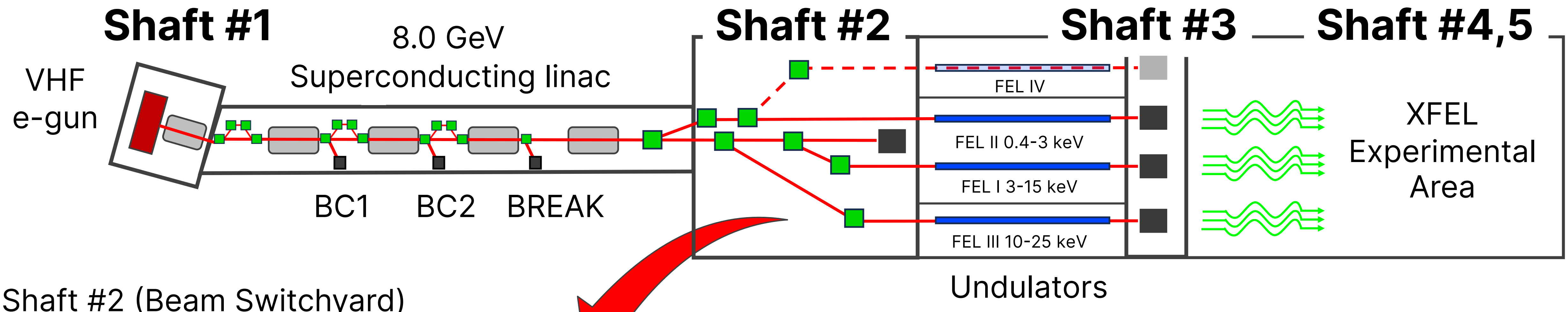


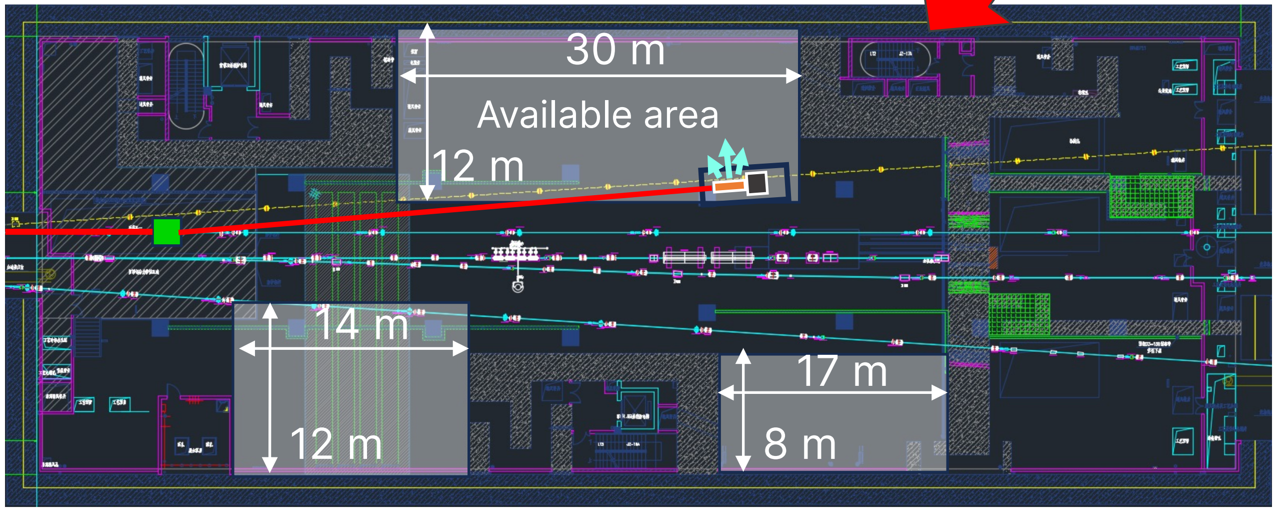
- Located in Zhangjiang, Shanghai
- To be commissioned in 2025
- Electron beam (design values):
  - 8 GeV energy
  - 1 MHz repetition rate
  - 100 pC charge (6.25 × 10^8 electrons) per bunch

Only 4 km from TDLI

Potential locations



Shaft #2 (Beam Switchyard)



The largest place in Shaft #2 is the best candidate

Shaft #2 is a good location for a muon beamline

- Sufficient space
- Existing beamlines, cost savings possible

Shaft #3 is also available

- There is no undulator line at the moment
- Not in the plan, will take 5-10 years

Simulation Tools

Design studies are conducted using multiple simulation packages to verify results against each other

Target study

musrSim (Geant4-based): Used for pion/muon yield estimation

Cross-check ↑

Geant4 results sometimes have large discrepancies compared to the experiment (from a PSI paper)

FLUKA: Used for pion/muon yield estimation (cross-check)

Transport beamline design

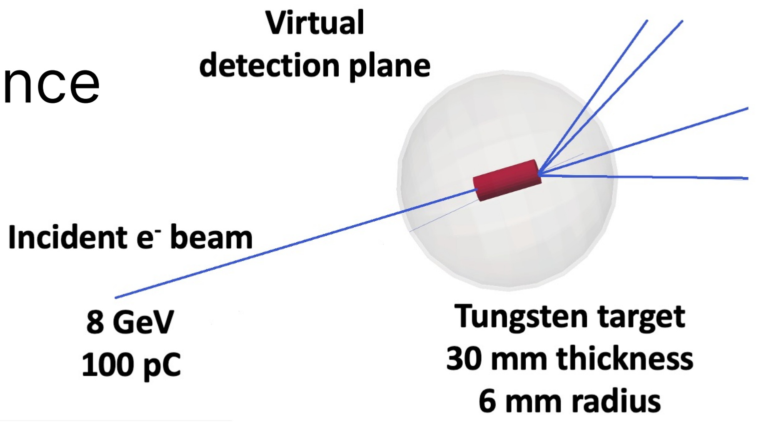
↓ Cross-check

g4beamline (Geant4-based): particle distribution and transport calculation

Target studies so far

- Simulation setup: 8 GeV, 100 pC, tungsten (W) target
- Photo-nuclear process: Low energy, high yield, large emittance
- $\gamma \rightarrow \mu^+\mu^-$ process: High energy, lower yield, low emittance
- Presented at IPAC'23 "A Pulsed Muon Source Based on A High-Repetition-Rate Electron Accelerator"

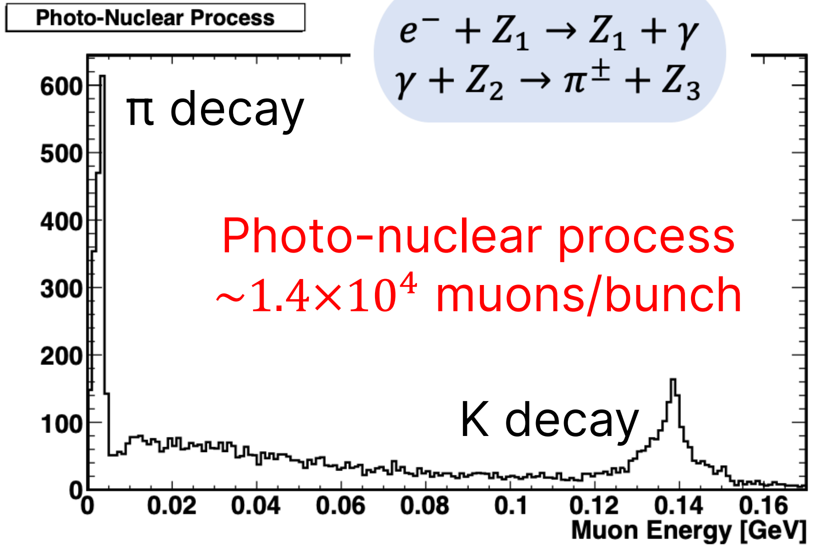
Target shape similar to beam dump



Using musrSim based on Geant4

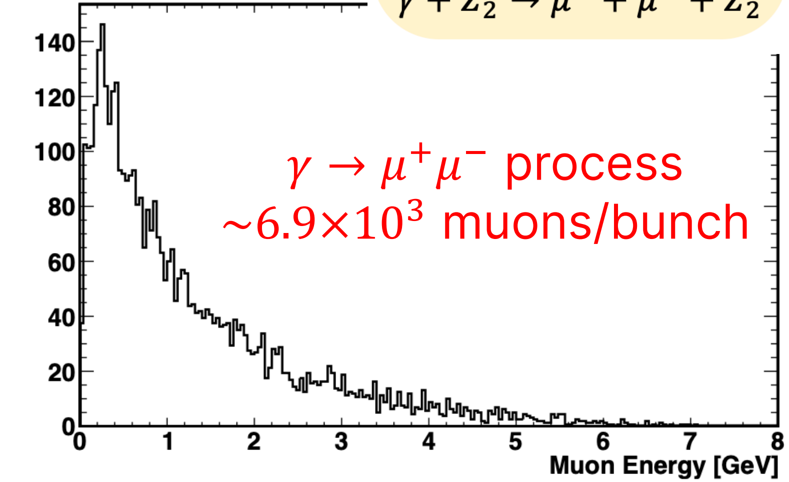
Photo-nuclear process

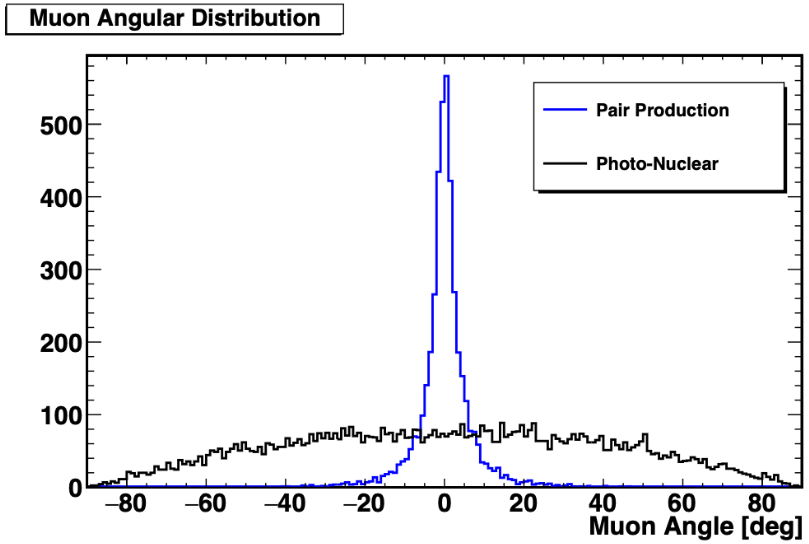
$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \pi^\pm + Z_3$$



Bethe-Heitler process

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





Recent updates for target studies

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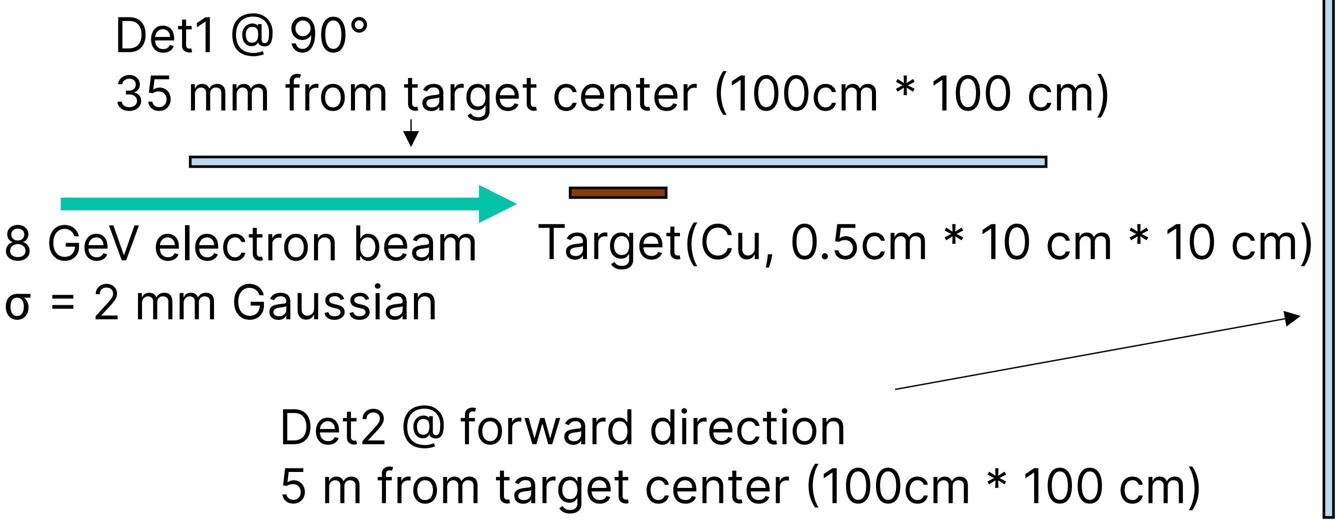
Detailed studies using FLUKA simulation

Simulation setup

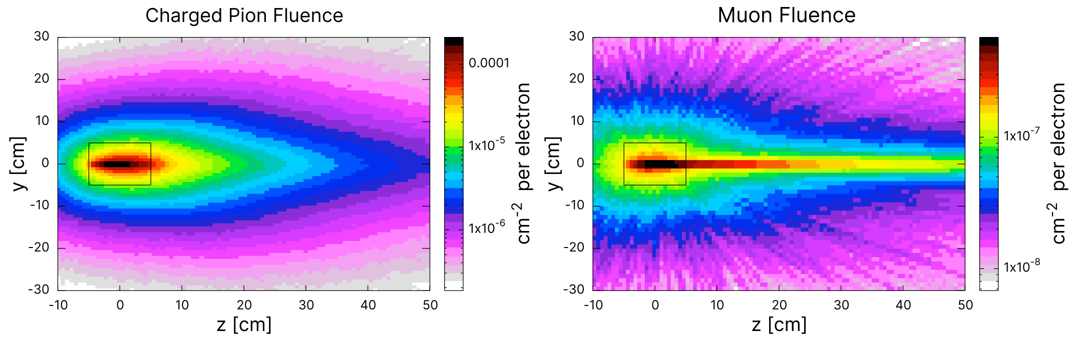
Not to scale



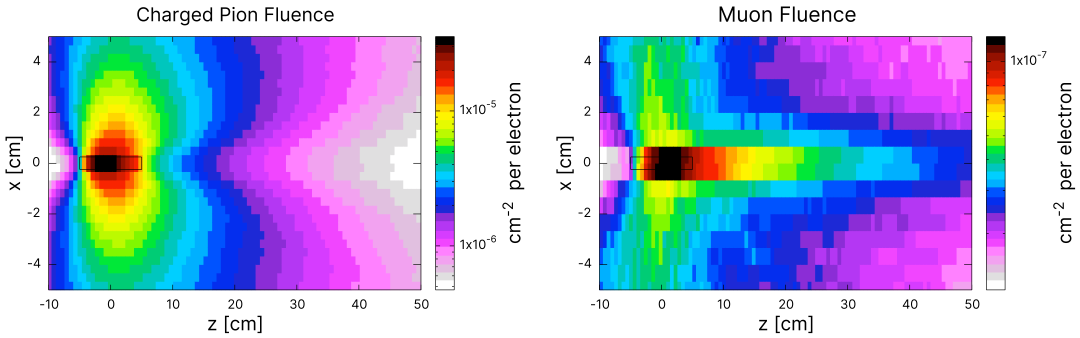
- Electron positron shower is maximized at ~7 cm
- Many pions and muons due to photo-nuclear process are observed in this region
- Muon production without pions is concentrated in the forward direction

Charged pion and muon fluence

Side view



Top view



Black line: target region

Particle yields from thin Cu target

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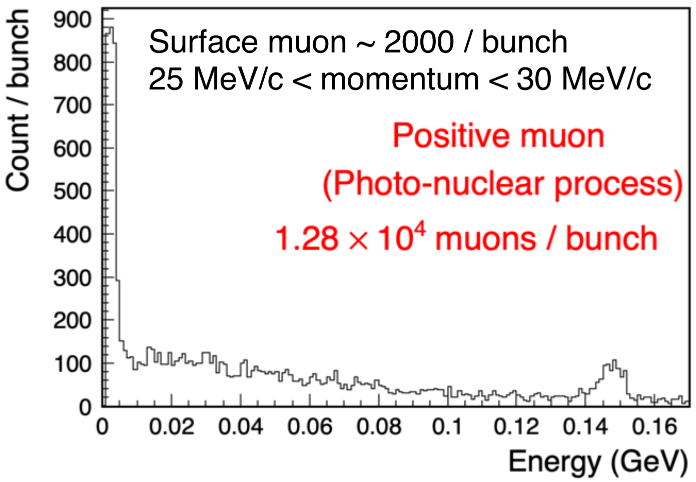
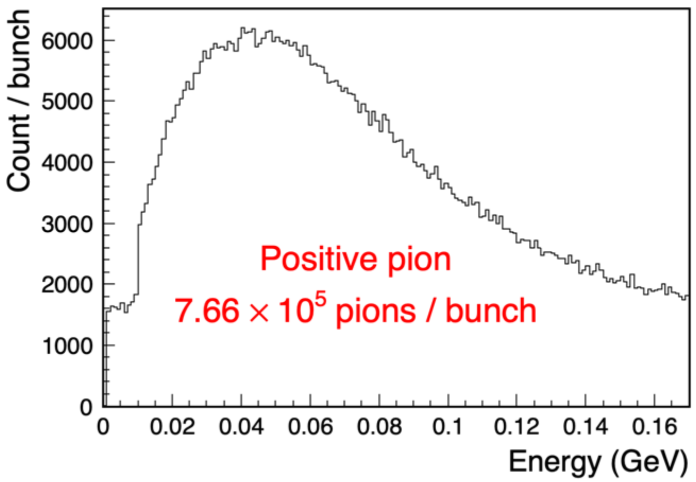
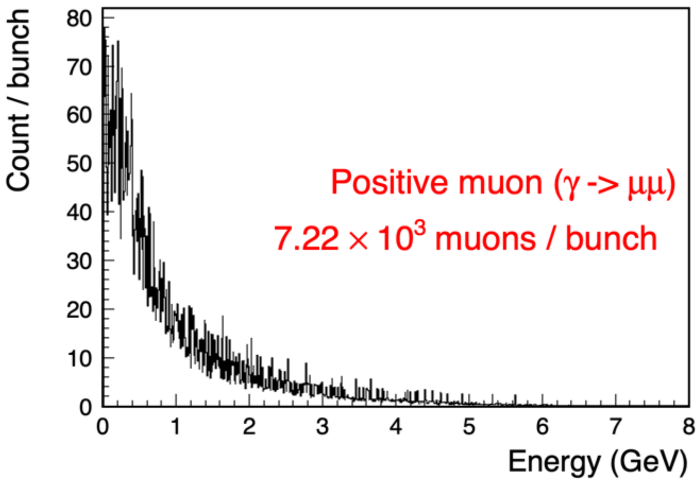
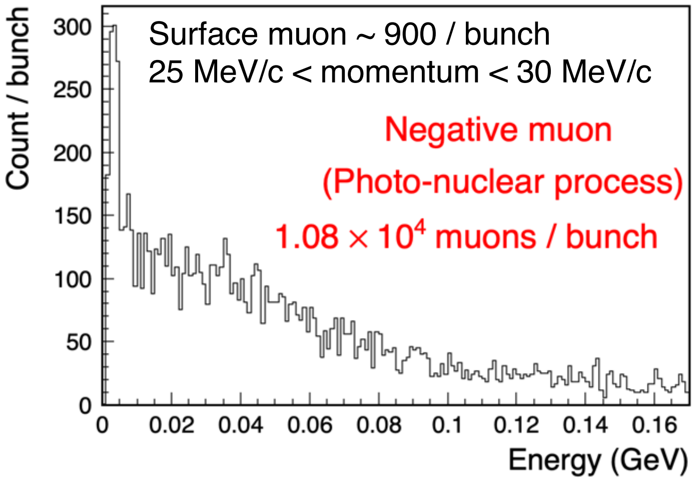
35 mm from target center @ 90° (Det1)

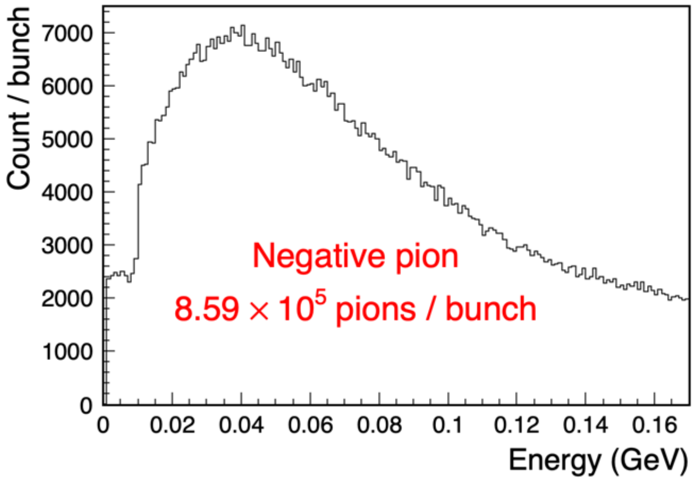
5 m forward from target (Det2)

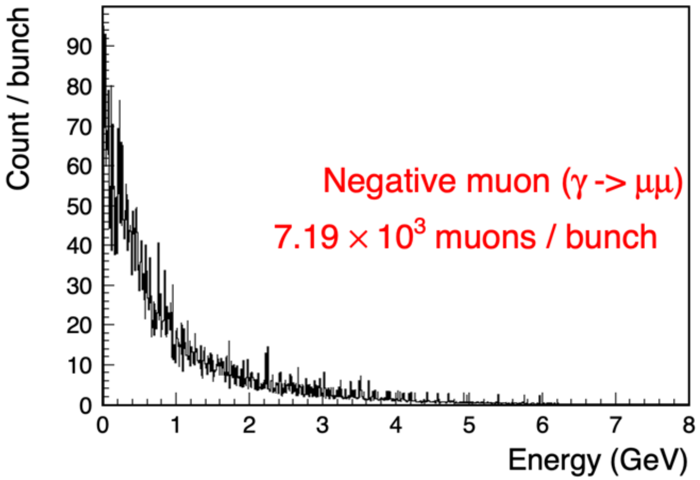








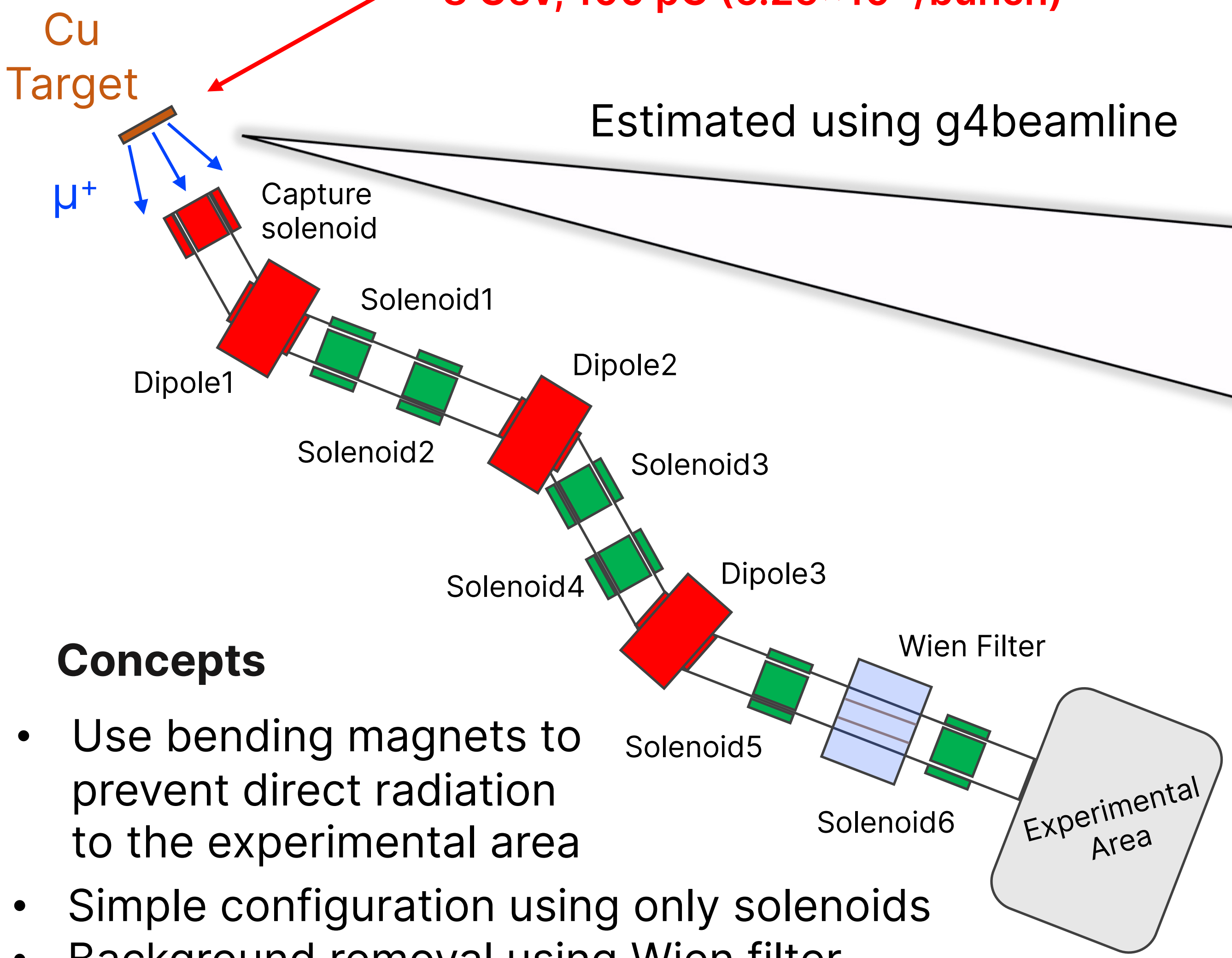




Sufficient yield is expected

Surface μ beamline design

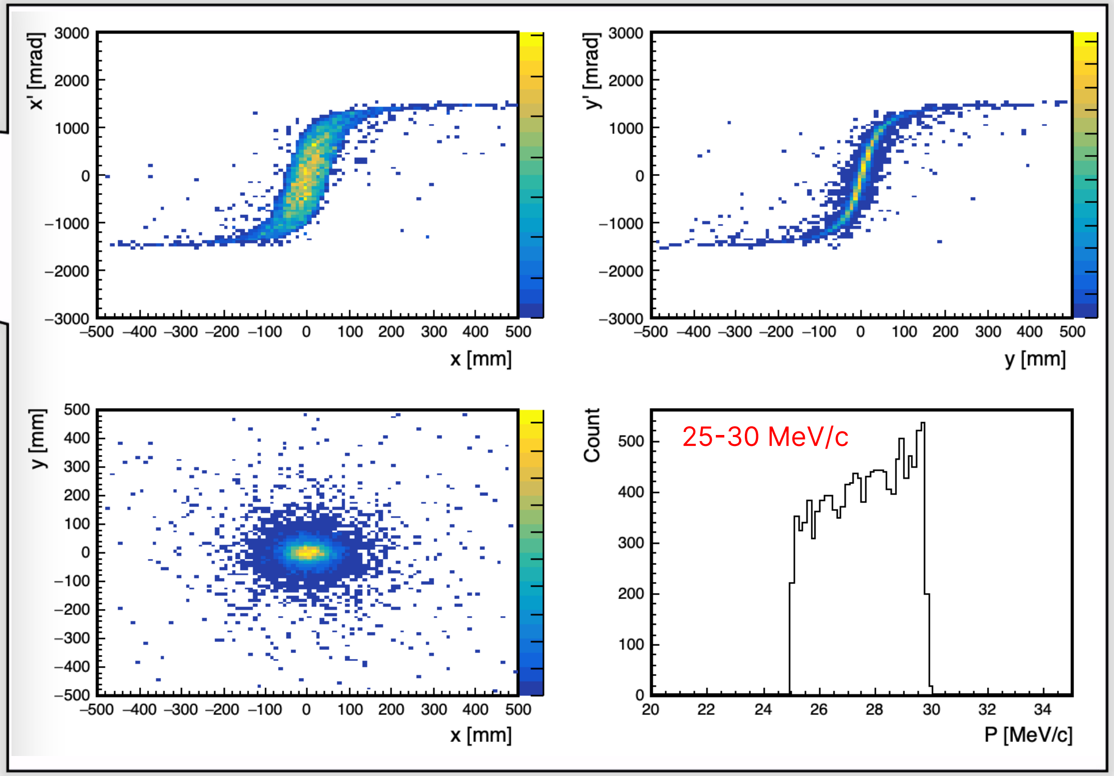
Electron beam
8 GeV, 100 pC (6.25×10^8 /bunch)



Estimated using g4beamline

Surface muon 35 mm from target @ 90 degrees

1650 surface μ^+/bunch



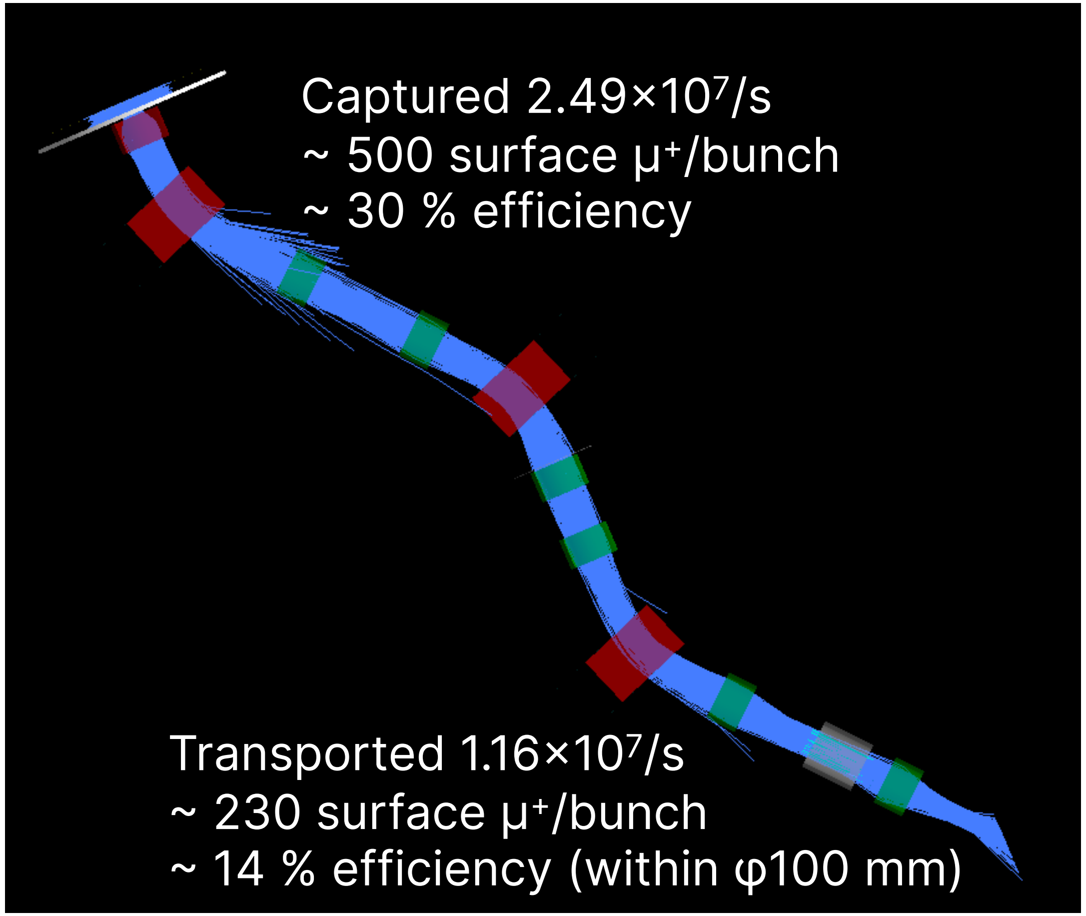
Concepts

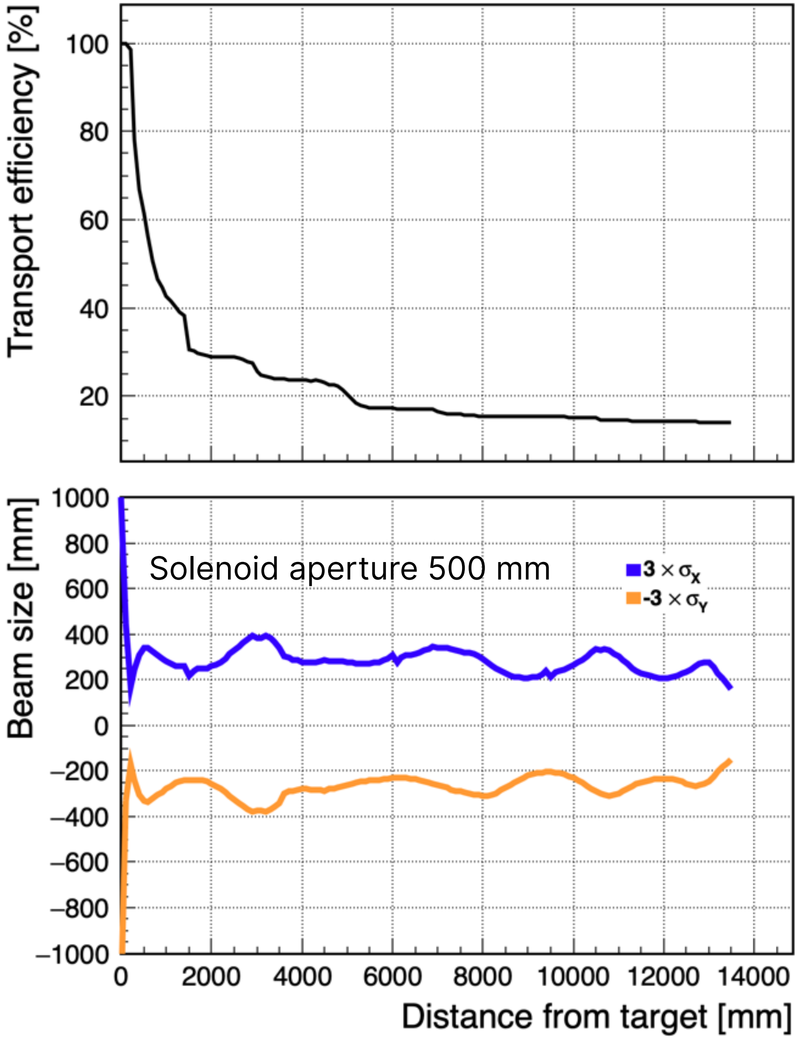
- Use bending magnets to prevent direct radiation to the experimental area
- Simple configuration using only solenoids
- Background removal using Wien filter

FLUKA simulation
~ 2000 surface μ^+/bunch
Need to validate the simulation

Surface μ beamline design

Source 8.24×10^7/s (assuming 8 GeV, 100 pC, 50 kHz)
~ 1650 surface μ^+/bunch





Poster presentation by F. Liu
"Research on Optimization Simulation of High Rep-Rate Pulsed Electron-Driven Muon Beamline"

Future plans

- Target study
  - Try another geometry; slanted target, thick block shape
  - Try different beam energy
  - Thermo-mechanical calculation
- Beamline design
  - More realistic simulation; magnet design, collimator, etc.
  - Study background elimination using Wien filter
  - Optics for transporting other particle (π, surface μ from K)
- Beam test
  - Will enable us to estimate accurate muon production rate
  - Shown in next few slides

Test beam at Shanghai soft XFEL

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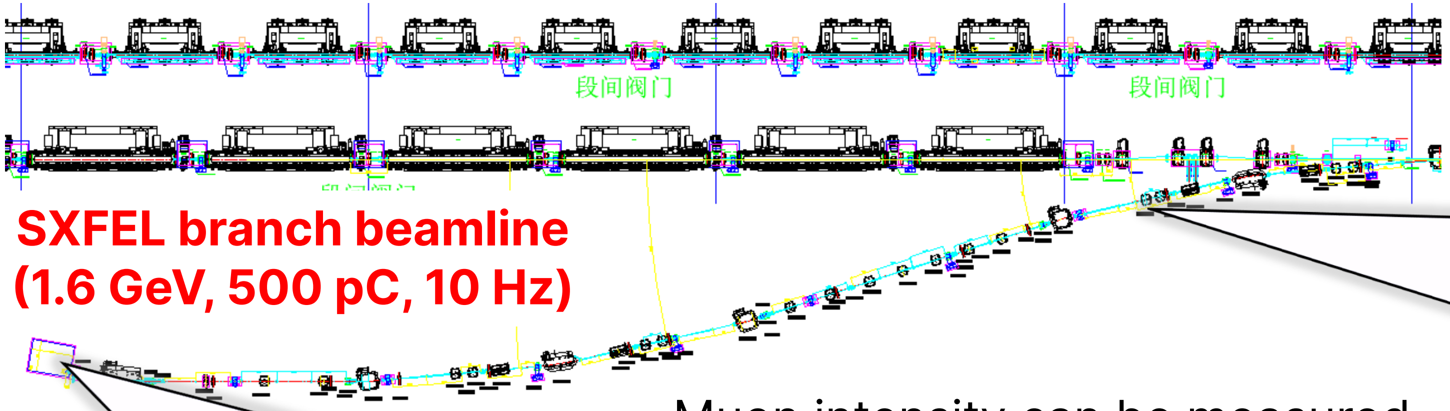
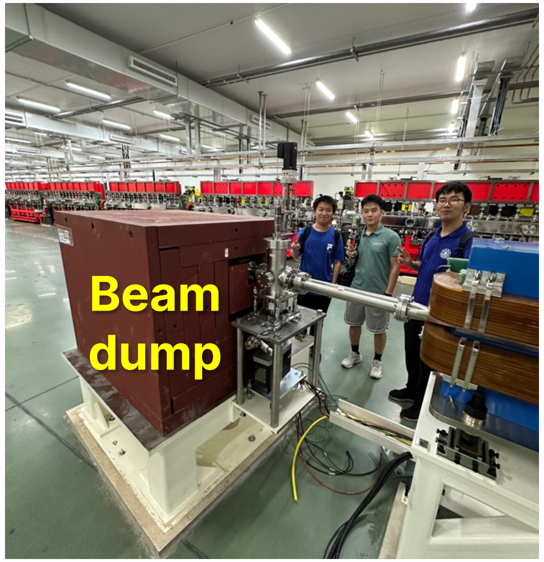
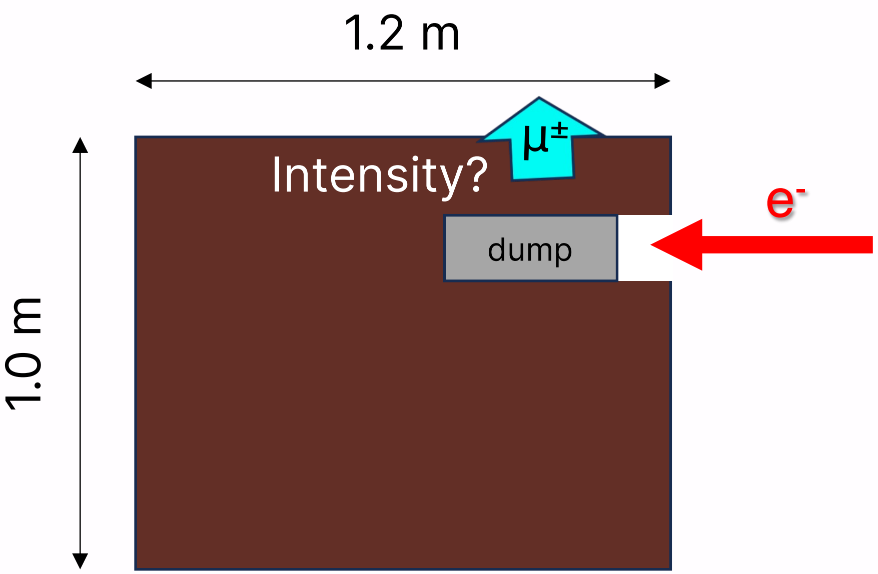


SXFEL branch beamline (1.6 GeV, 500 pC, 10 Hz)

Another beam line is currently available for test beam

Muon intensity can be measured

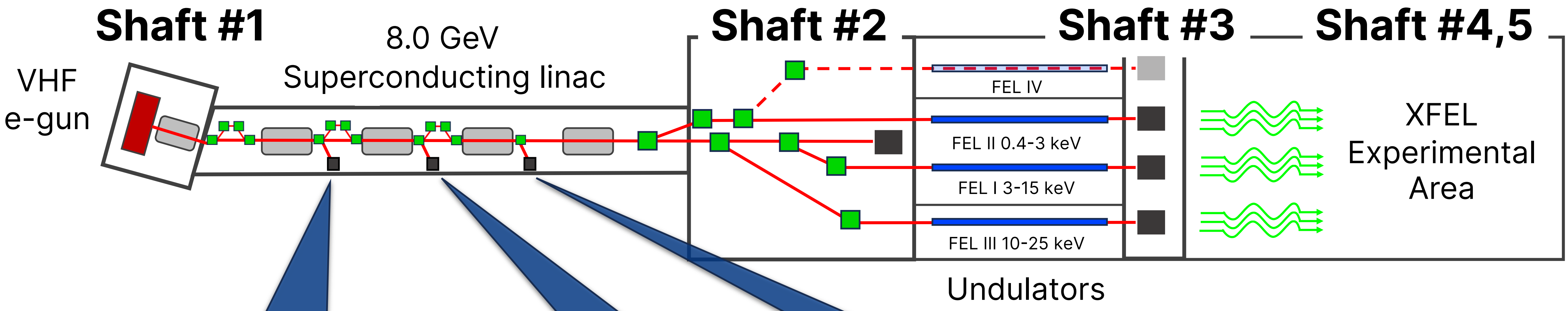




Poster presentation by J. Wang "Muon yield estimation for the Beam Test at the SXFEL beam dump"

Simulation studies and detector preparations are ongoing

Potential beam test



2024/December

BC1 beam dump

- 0.5 GeV
- 100 pC
- 1 kHz

2025

BC2 beam dump

- 3.2 GeV
- 100 pC
- 1 kHz

2025

BREAK beam dump

- 7.7 GeV
- 100 pC
- 1 kHz

Feasibility studies can be performed with actual beam in the next few years

Discussion at SHINE facility

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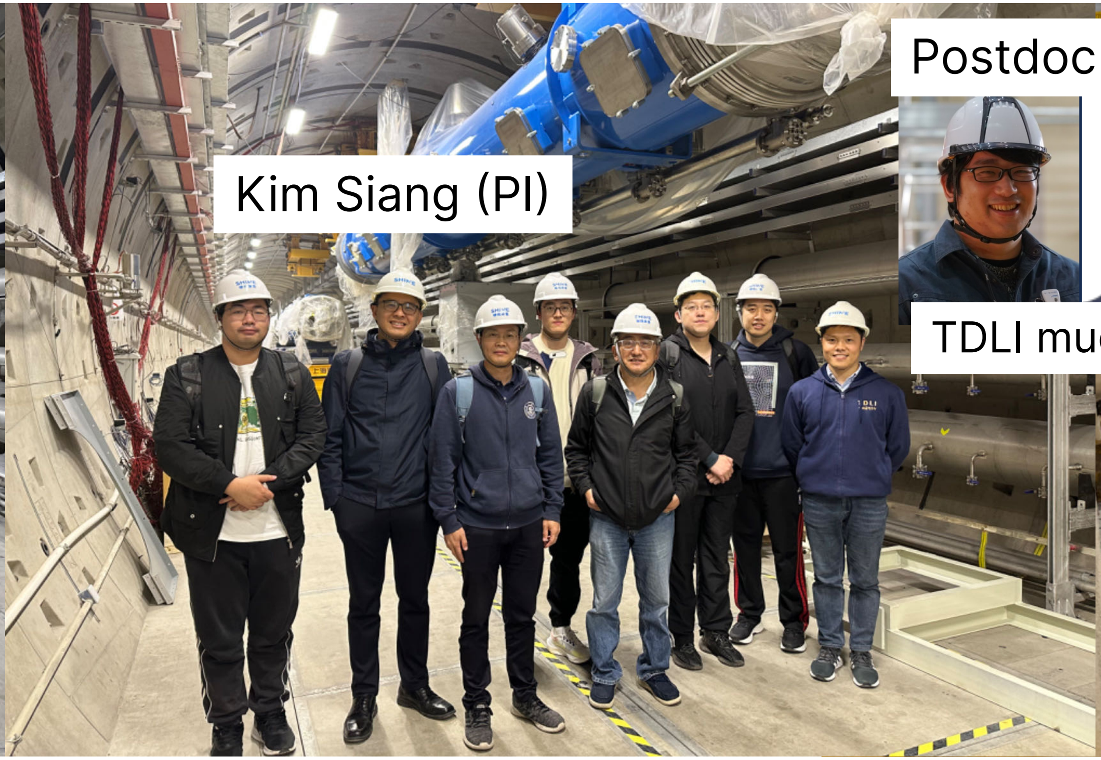
SHINE 电子束流科学应用与关键技术研讨会

2024 年 4 月 1~2 日　上海张江

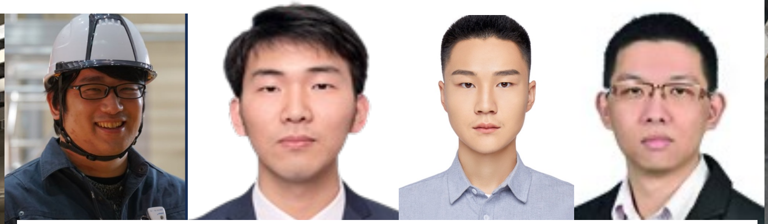
We had a discussion about utilizing SHINE facility ~ 2 weeks ago

Construction is steadily ongoing

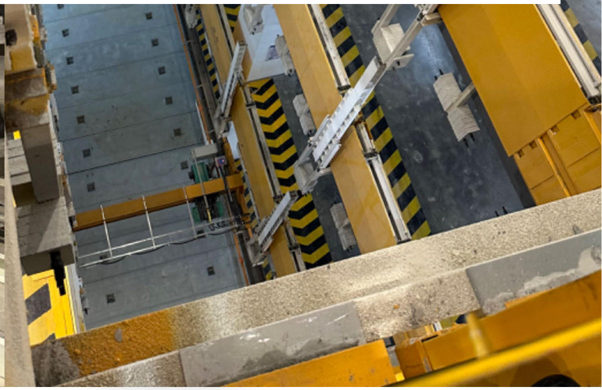


Postdoc

Students



TDLI muon source group members



Summary

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- Current proton-driven muon sources are either low-repetition-rate pulsed sources or DC sources, which are not optimal for typical muon experiments

- A high-repetition pulsed muon source can be built based on pulsed electron beam in the SHINE facility
  - Rep-rate: kHz – MHz (tunable)
  - ~2×10^3 muons per bunch, ~14% efficiency expected, target to be further optimized
  - will benefit particle and nuclear physics, condensed matter physics, tomography, etc

- Muon source project at SHINE is steadily developing
  - Design studies are currently on-going!
  - Beam test at 1.6 GeV and intermediate energy electron beam dump (in 1-2 years)
  - Phase 1 surface muon beam line at 4 MeV (next 5 years, hopefully)
  - Phase 2 surface muon beam line at 140 MeV (next 10 years, hopefully)