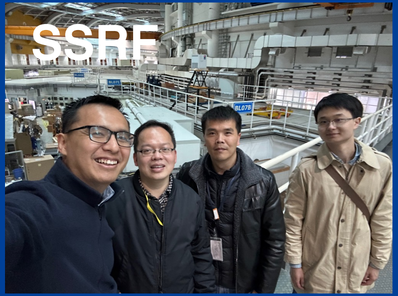
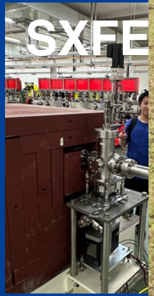
SHINE
SHANGHAI HIGH REPETITION RATE XFEL
AND EXTREME LIGHT FACILITY
硬X射线自由电子激光装置

Prospects ... rate pulsed muon b ... E facility





This project is supported by
Shanghai Pilot Program for

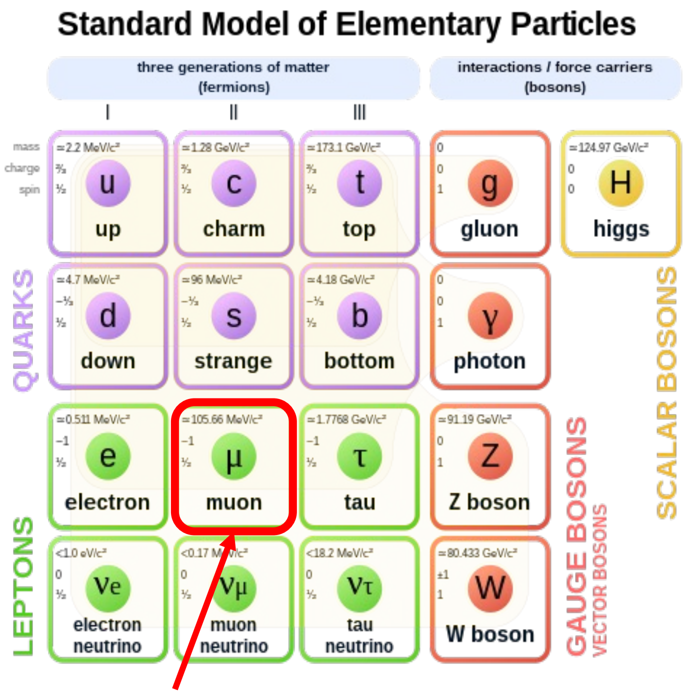
李政道研究所
TSUNG-DAO LEE INSTITUTE

Outline

- Overview of Muon Physics
  - Condensed matter physics, particle physics, tomography, etc
- Overview of Muon Facilities
  - In operations, under constructions/study
- Muon Source Drivers
  - Proton, electron, positron, laser, and gamma
- The SHINE Muon Source
  - Expected performance, potential locations and physics program
- Future Plan
  - Test beams at SXFEL, low-energy surface muons, high-energy surface muons

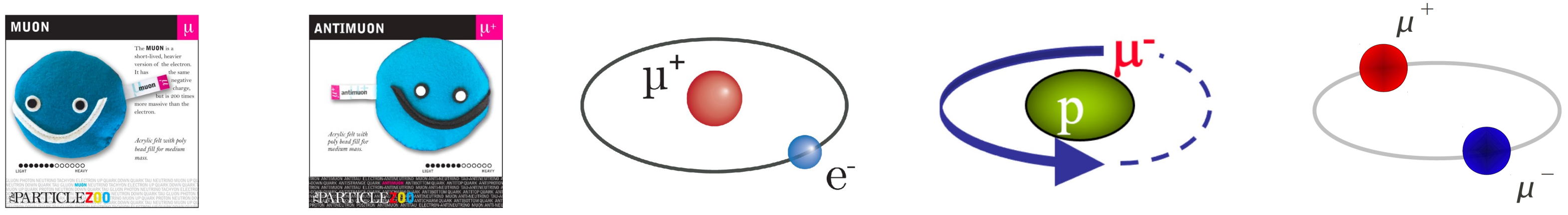
Overview of muon physics

Tsung-Dao Lee Institute



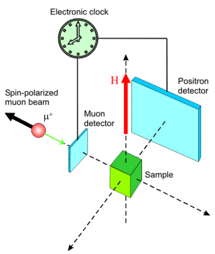
- Muon is a second generation charged lepton in the SM
- Charge +-, spin ½, $m_\mu \sim 206\ m_e$, $m_\mu \sim 1/9\ m_p$
- Discovered in 1936, "Who ordered that?!" by Isidor Rabi.

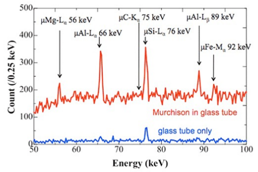
Muon can exist in various forms



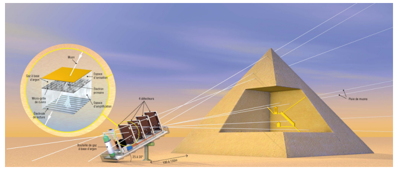
negative muon | positive muon | muonium | muonic atom | dimuonium

- **Condensed Matter Physics & Chemistry**
  - Using muon as a sensitive magnetic probe
    - μSR technique developed for studying magnetism and superconductivity
  - Muon mass in between electron and proton ~ an isotope of e or p
    - Can study mobility of e or p in material
  - X-ray emitted in the process of forming muonic atoms
    - Can be used to characterize material: elemental analysis in archeology





- **Tomography (Large object imaging)**
  - Muons produced from cosmic ray bombarding earth atmosphere are highly penetrating
    - Imaging of pyramids, volcanos, Xi'an City Wall, Qin emperor's tomb
- **Particle Physics**
  - High-precision test of the Standard Model prediction
    - Anomalous magnetic moment, weak interaction V-A structure, etc
  - Using muon as a probe to search for new physics beyond SM
    - Electric dipole moment, lepton number violation, new muonphilic scalar/vector particles, etc



Overview of Muon Facilities

Tsung-Dao Lee Institute

★ TRIUMF

TWIST, Mu studies

Fermilab

Muon g-2, Mu2e

★ Paul Scherrer Institut (PSI)

muEDM, MEG II, Mu3e, MUSE, CREMA, etc

★ ISIS

muSR, elemental analysis

★ RCNP

muSR, elemental analysis

RAON

muSR

★ J-PARC

Muon g-2/EDM, COMET, DeeMe, Mu HFS/1S-2S, etc

ORNL

muSR

SHINE

muSR, EDM, tomography, etc

★ in operation (for users)

HIAF/CiADS

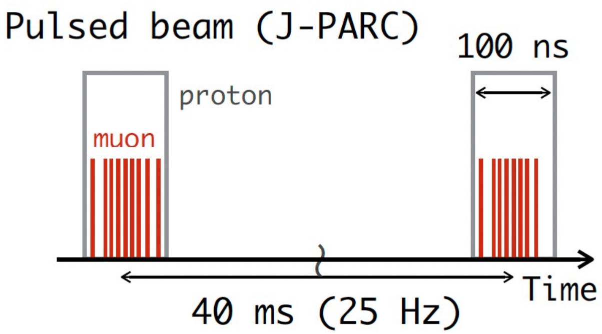
Next generation muon g-2/EDM?

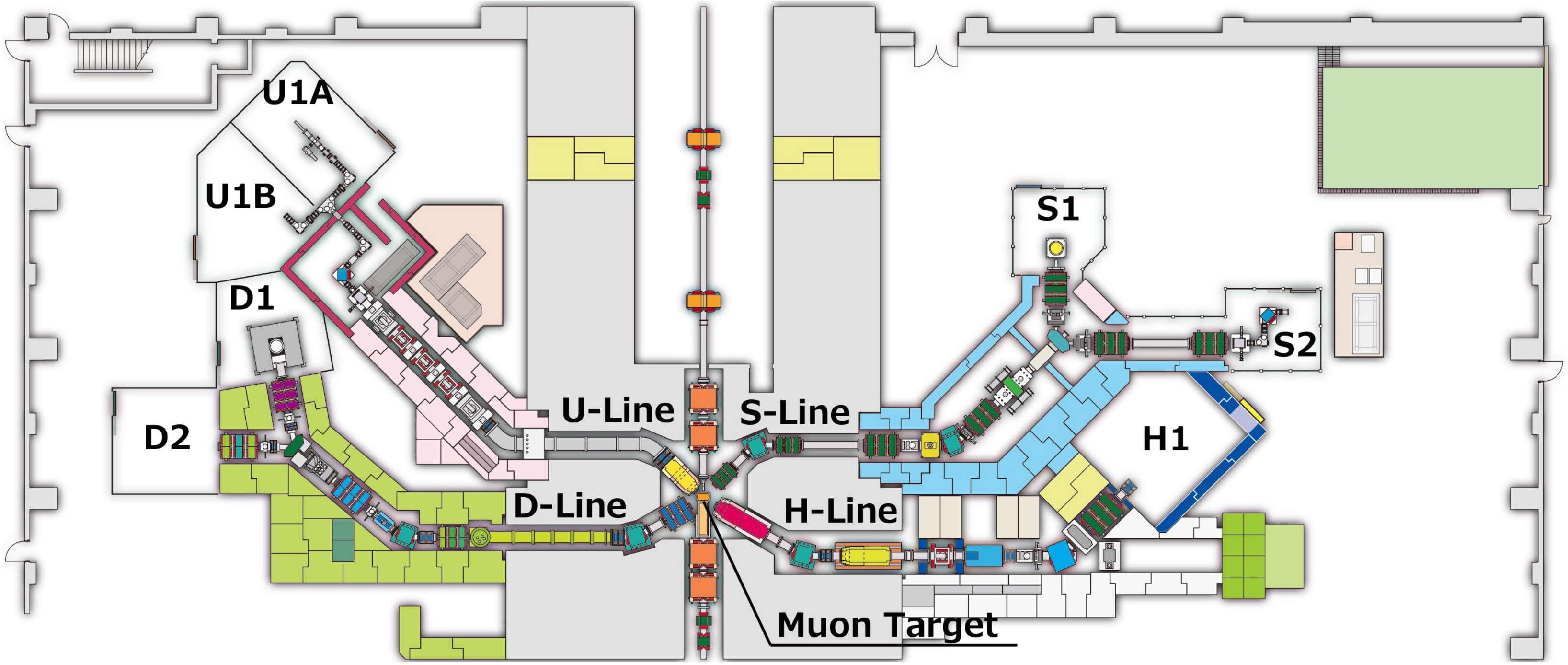
CSNS

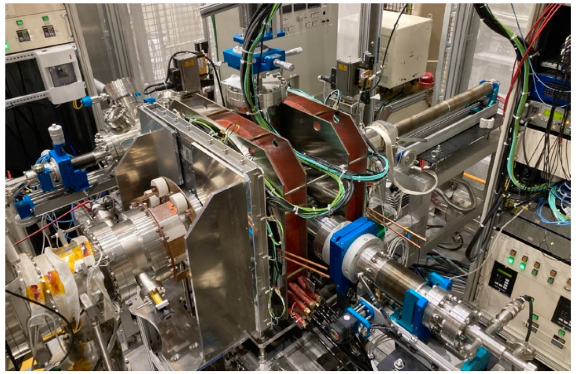
Applications, MACE

Pulsed muon source

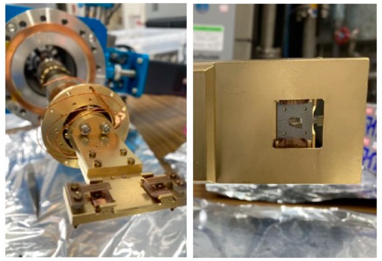
- Example: J-PARC in Japan
- Pulse frequency: 25 Hz (double bunch)
- Experiments: μSR, Muon g-2/EDM, etc



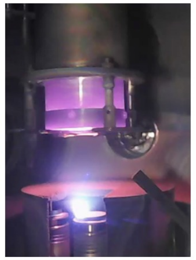




Muon spin spectrometer on the high-voltage platform in U1A



Thin film sample mounted on the cryostat for USM-μSR

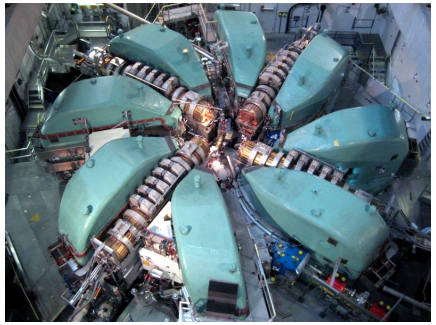


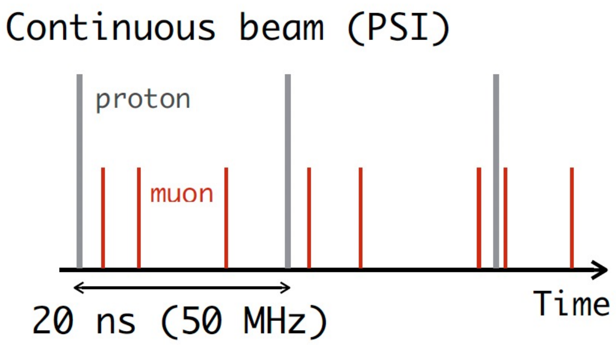
Sample fabrication by PLD

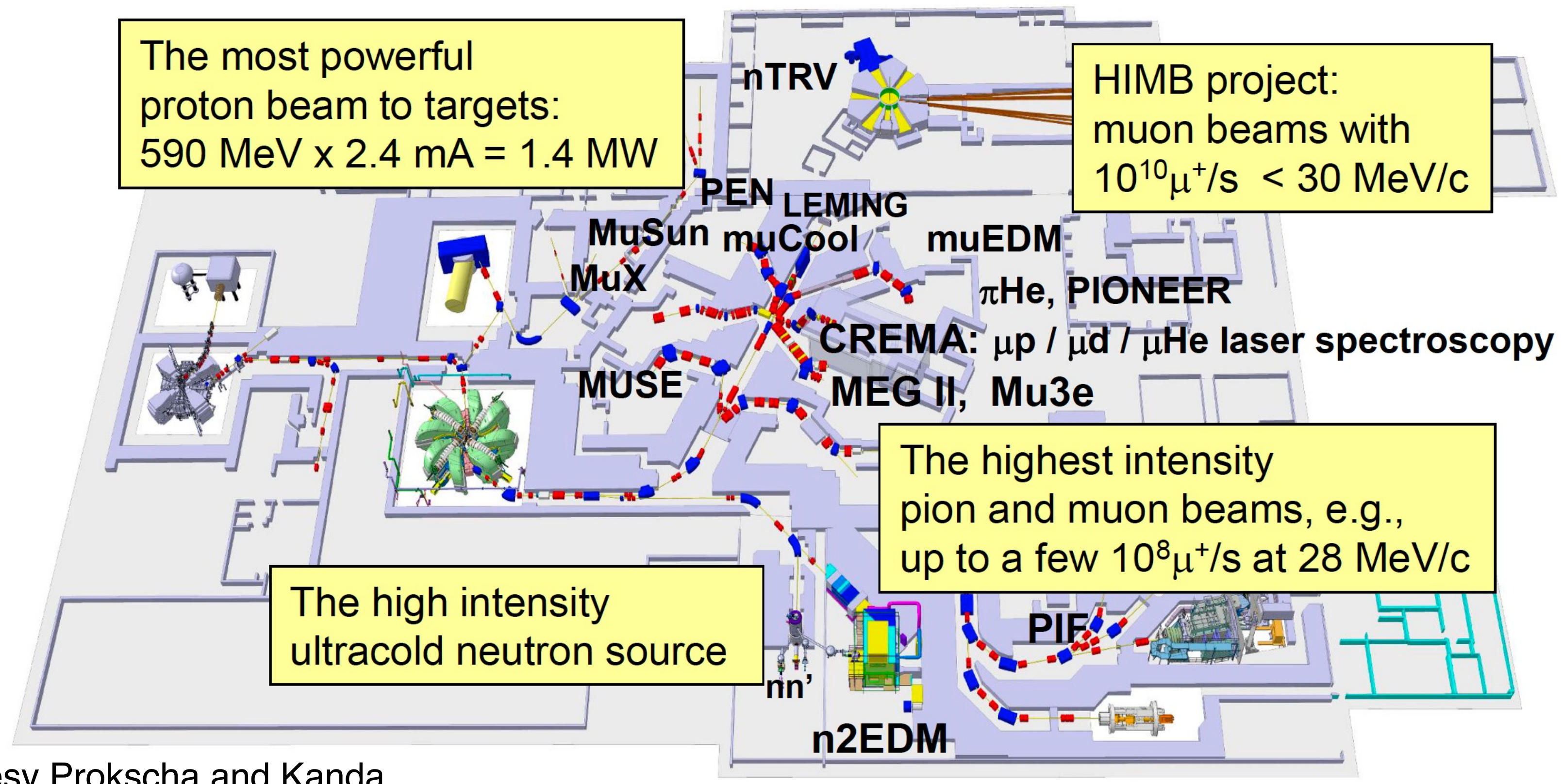
Courtesy Kanda and Shimomura, JoP: Conference Series 2462 (2023) 012033

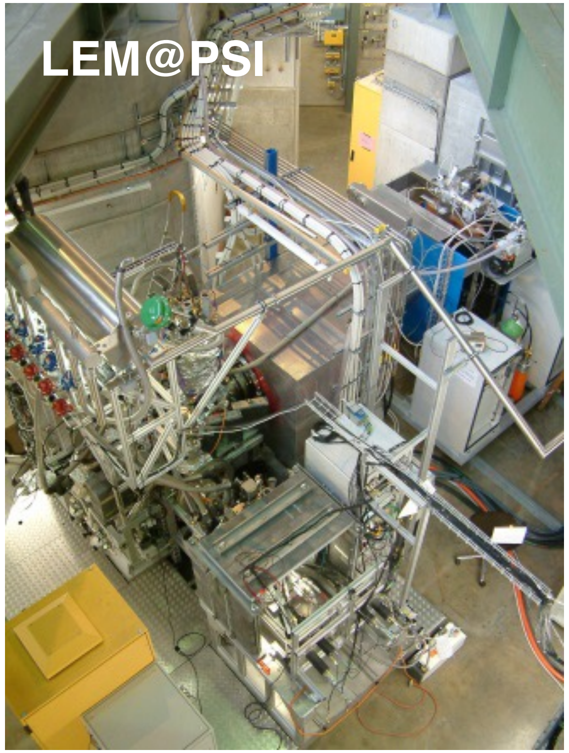
Continuous (DC) muon source

- Example: PSI in Switzerland
- Cyclotron frequency: 50 MHz
- Experiments: μSR, MEG, Mu3e, etc



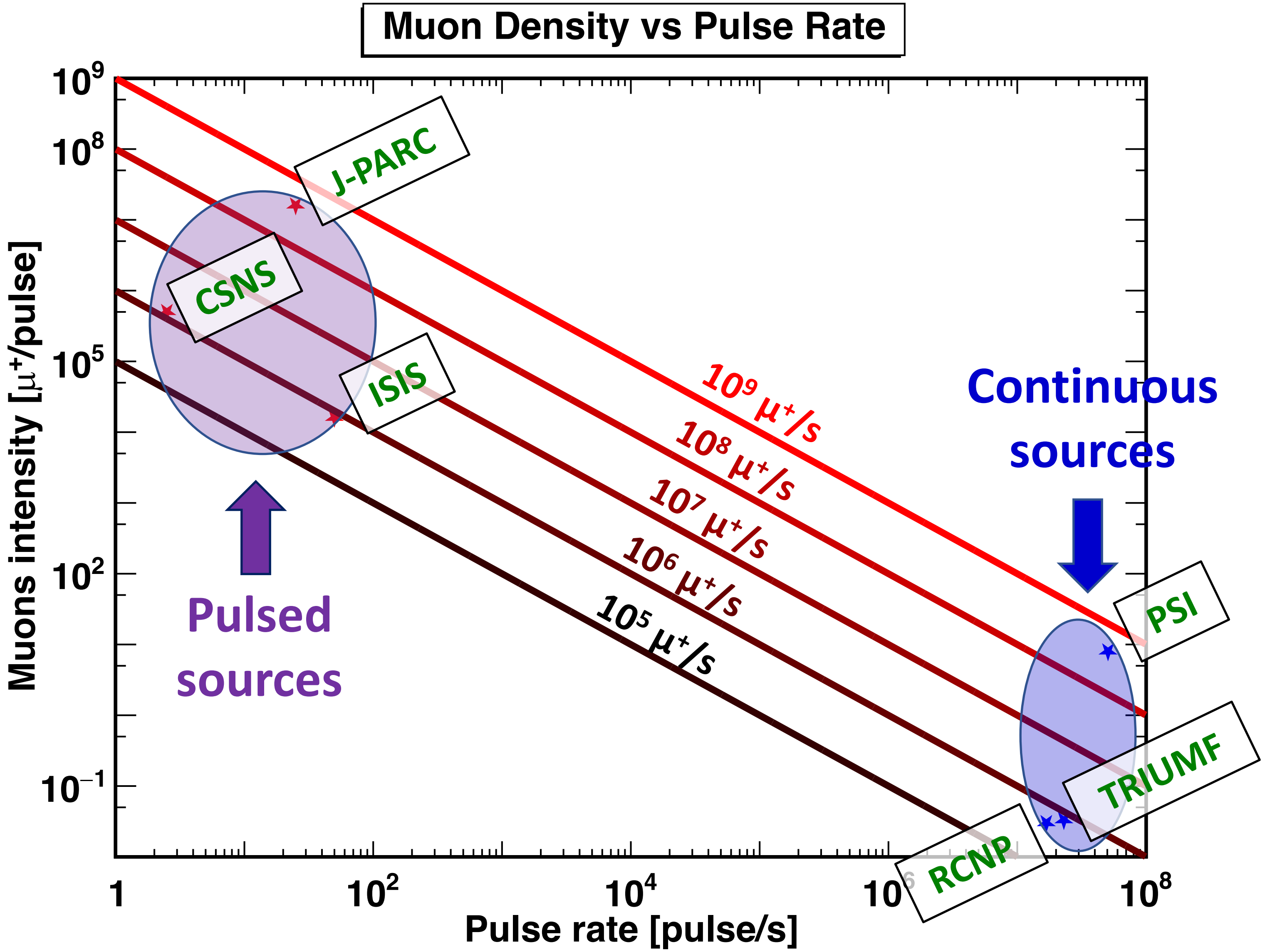






Courtesy Prokscha and Kanda

Muon density vs pulse rate



Muon physics program vs beam type

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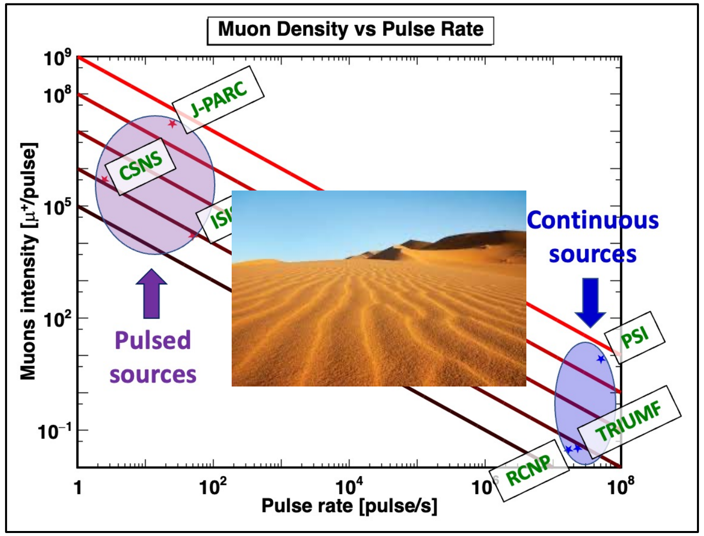


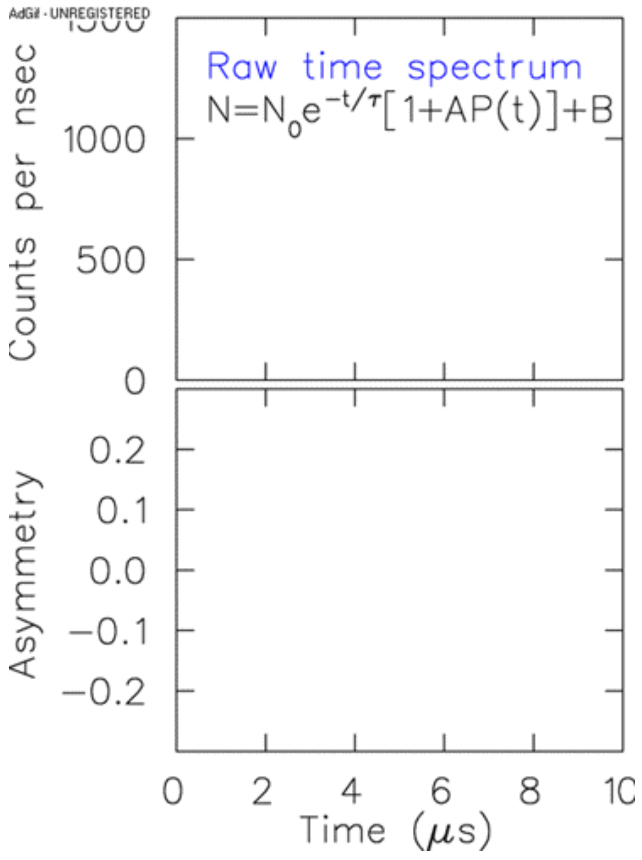
54 Y. Kuno / Nuclear Physics B (Proc. Suppl.) 155 (2006) 53–57

Table 1
Overview list of slow muon physics programs.

Categories	Topics	Comments	Beam
Precision measurements	muon lifetime	G_F determination	pulsed
	muon capture rates	nuclear physics	pulsed or DC
	muonic X-ray	nuclear physics	pulsed or DC
	muon $g-2$	SM allowed, new physics	pulsed
Rare processes	**muon EDM**	SM suppressed, new physics	pulsed
	charged lepton mixing	SM forbidden, new physics	pulsed or DC
Application	catalyzed fusion	aim break-even	pulsed
	materials science	μSR	DC

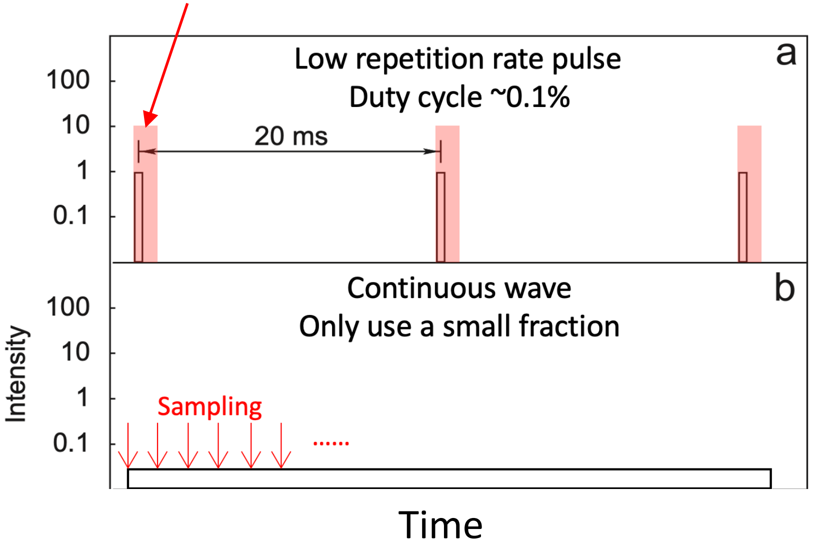
Limitation of current muon sources

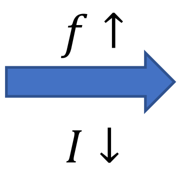
μSR



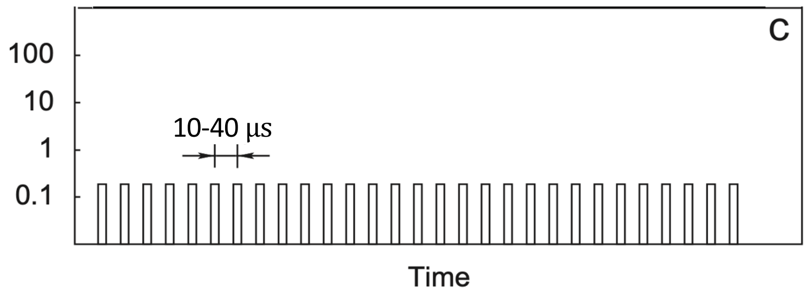
Typical measurement period:
a few muon lifetimes ~ 10-20 μs

Duty cycle





An ideal muon source



- Pulsed muon source
  - Detector dead time limitation
  - Low duty cycle
- DC muon source
  - Allows 1 muon every 10-20 μs
  - Most of the muons are kicked away

- Less muon per bunch, less pileup ($\sim 10^3$ μ^+/pulse)
- Higher pulse frequency: Higher duty cycle

Calls for high rep-rate muon sources

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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

MuMuBar

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

Muonium-antimuonium conversion

Lorenz Willmann* and Klaus Jungmann

Van Swinderen Institute, University of Groningen, 9747 AA, Groningen, The Netherlands

* L.Willmann@rug.nl

PAUL SCHERRER INSTITUT PSI — *Review of Particle Physics at PSI*
doi:10.21468/SciPostPhysProc.5

muSR

Physica B 404 (2009) 1024–1027
Contents lists available at ScienceDirect
Physica B
journal homepage: www.elsevier.com/locate/physb
ELSEVIER

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

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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.

$\overline{M}$ 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 $\approx \mu$s 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].

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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

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

Sohtaro Kanda

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1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan

E-mail: kanda@post.kek.jp

Muon Lifetime

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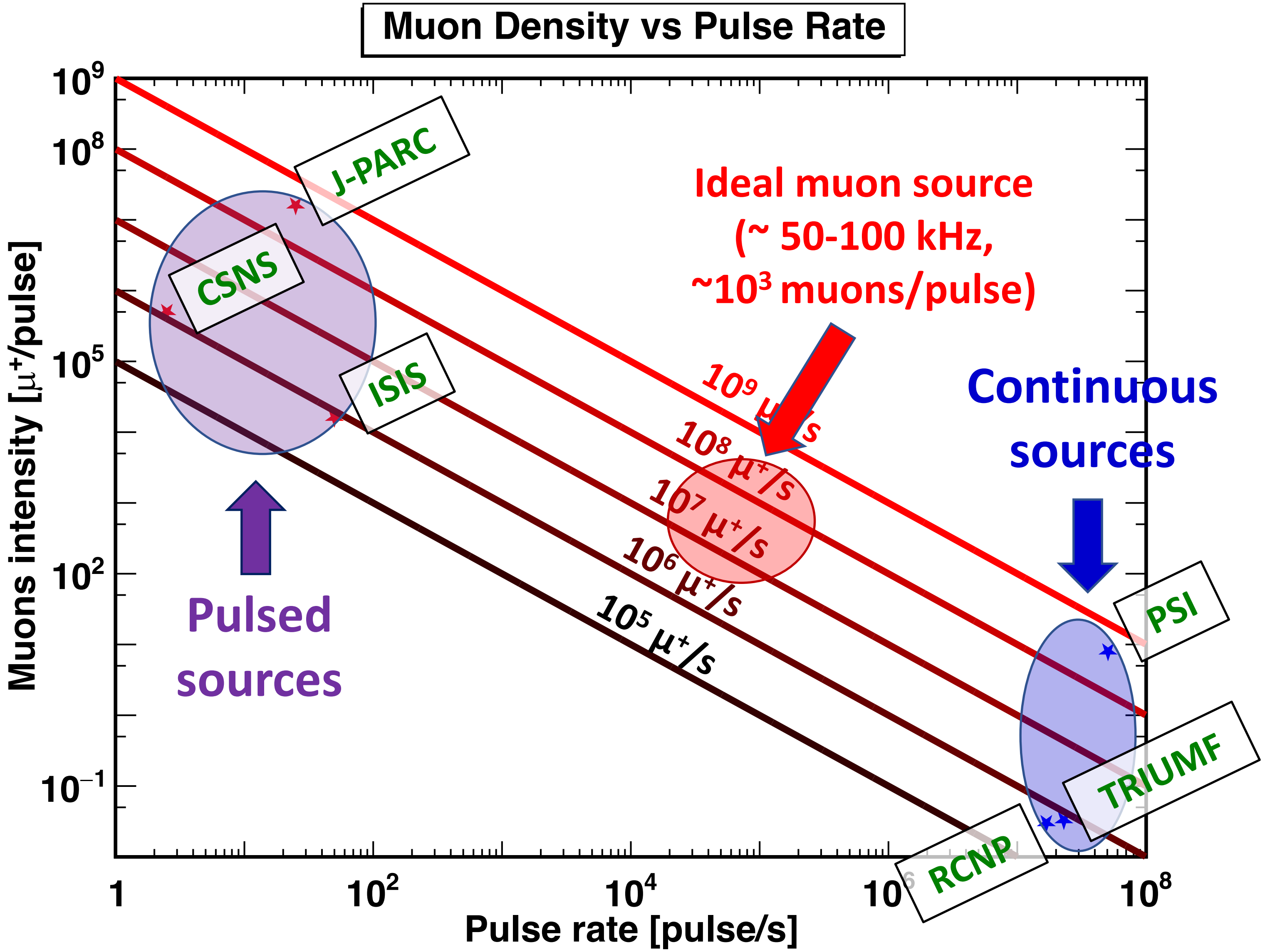
lifetime with an intense pulsed muon beam at Rutherford Appleton Laboratory (RAL) [9].

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.

Muon density vs pulse rate



Towards high-repetition-rate driver

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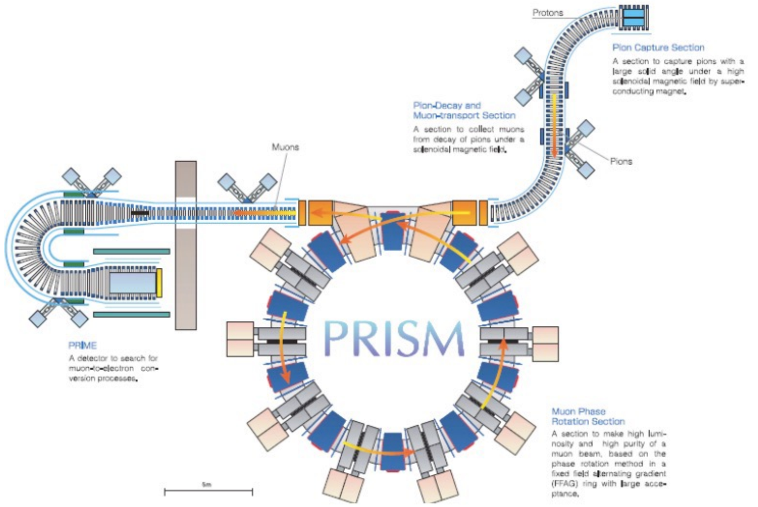
Proton

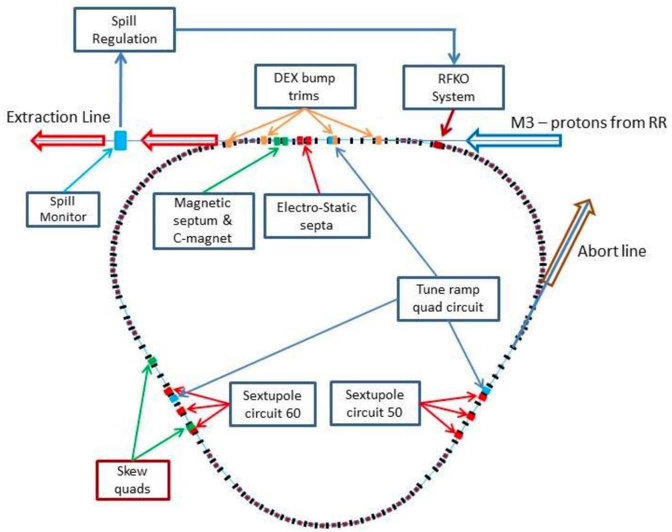
Fixed Field Alternating Gradient @ J-PARC



- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}

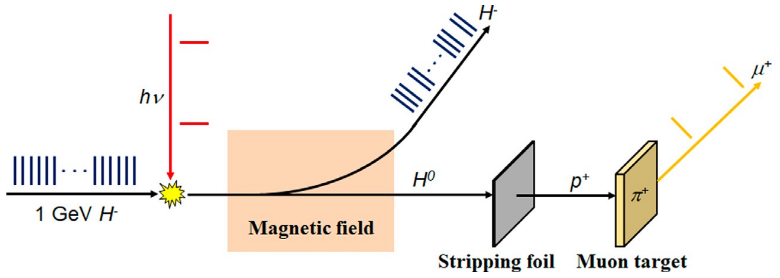
Research in progress

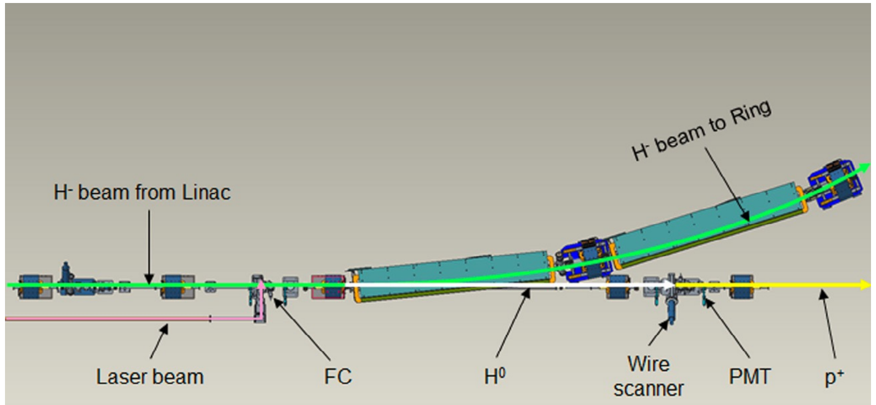
Resonant extraction Mu2e@FNAL



Effectively achieve 0.59 MHz!
(same idea for COMET@J-PARC)

Laser neutralization @ ORNL





Successfully demonstrated 30 ns/50 kHz proton pulses in 2019

NIM A 962 (2020) 163706

Alternative drivers: Electron

Electron

Physica B 404 (2009) 1020–1023

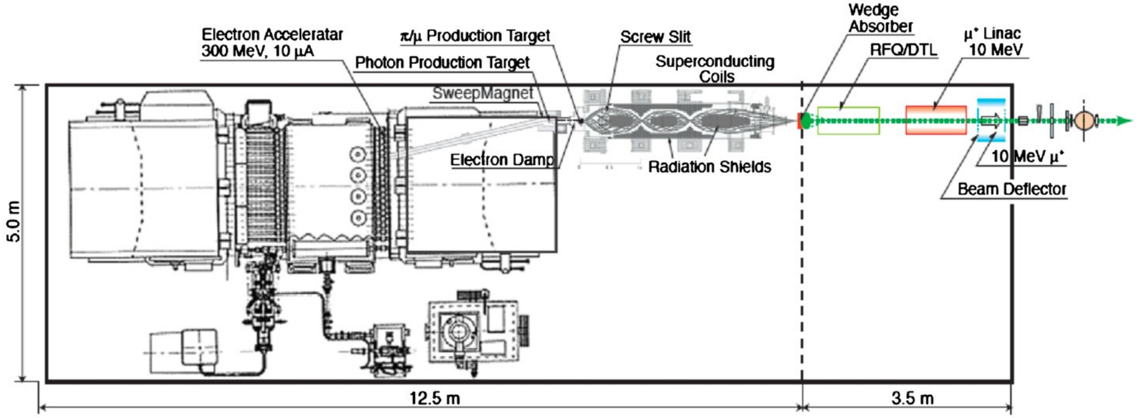
Contents lists available at ScienceDirect

Physica B

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

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 and 10 μA electron microtron
→ 8 x 10^3 μ^+/s

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

Dimuon production by laser-wakefield accelerated electrons

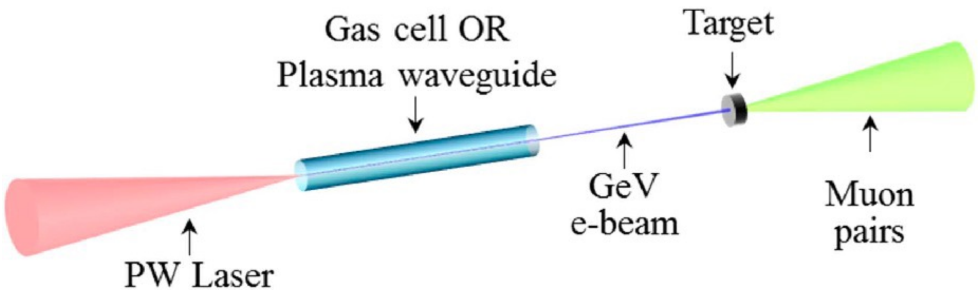
A. I. Titov,[1,2,3] B. Kämpfer,[1,4] and H. Takabe[3]

IOP Publishing — Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **60** (2018) 095002 (8pp) https://doi.org/10.1088/1361-6587/aacdea

Bright muon source driven by GeV electron beams from a compact laser wakefield accelerator

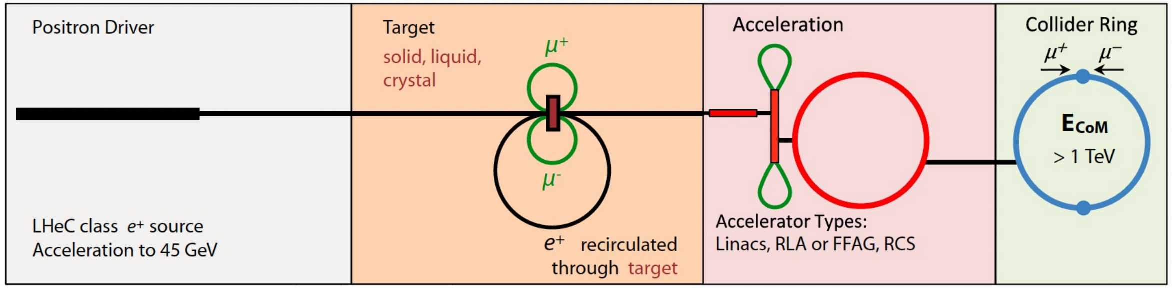
Bobbili Sanyasi Rao[1,4], Jong Ho Jeon[1], Hyung Taek Kim[1,2,4] and Chang Hee Nam[1,3]

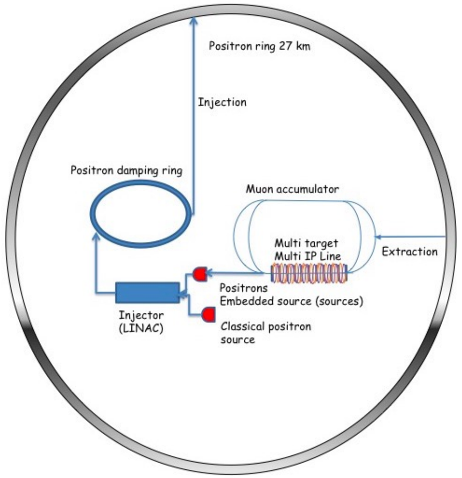


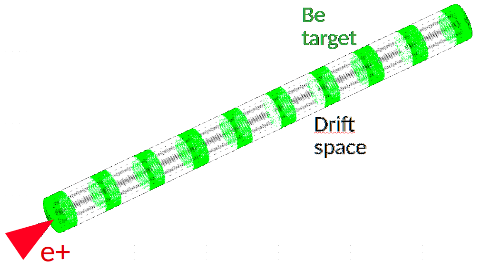
100 pC, 10 GeV electron
→ 8 x 10^3 $\mu^\pm$/s

Alternative drivers: Positron/Gamma

Positron







Material	Density	Length		eff
	[g/cm^3]	[m]	[X_0]	[$10^{-6}\mu/e^+$]
Be	1.85	0.106	0.3	1.3
C	2.27	0.057	0.3	1.0
C A412	1.7	0.075	0.3	1.0
H_2	0.07	2.664	0.3	2.9

LEMMA: arXiV:1905.05747

45 GeV, 5 x 10^{11} e^+ on Be
→ 6.5 x 10^5 μ^+/s

Gamma

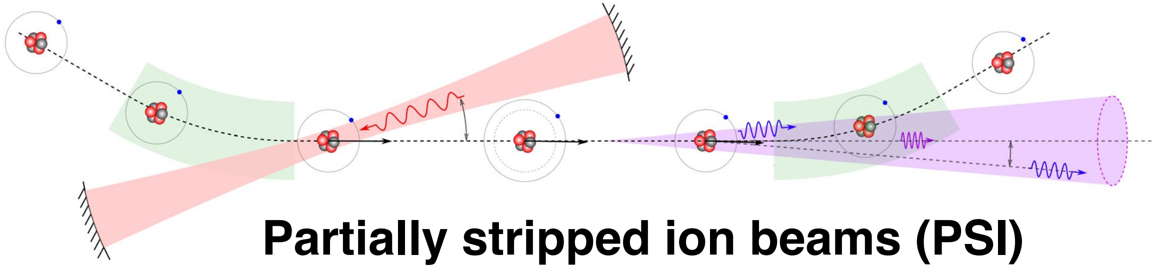
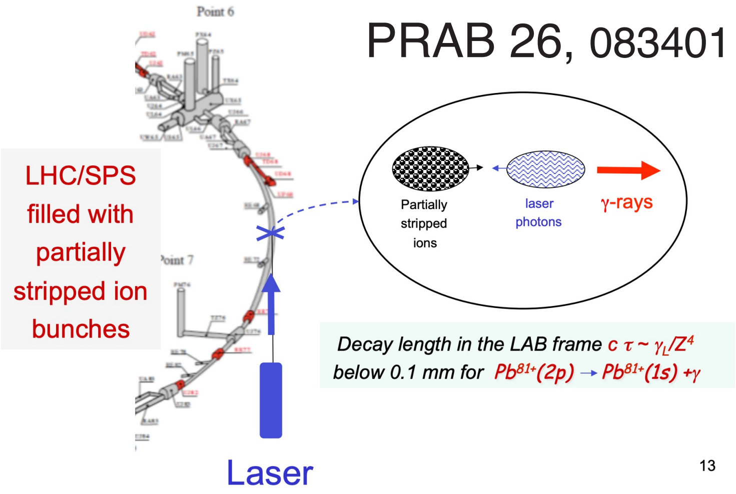


FIG. 20. The Gamma Factory concept: laser photons with momentum k collide with ultrarelativistic partially stripped ions (with relativistic Lorentz factor γ_L, mass m, velocity $v = \beta c$, where c is the velocity of light) circulating in a storage ring; resonantly scattered photons with momentum $k_1 \gg k$ are emitted in a narrow cone with an opening angle $\theta \approx 1/\gamma_L$ in the direction of motion of the ion beam.

PRAB 26, 083401 (2023)



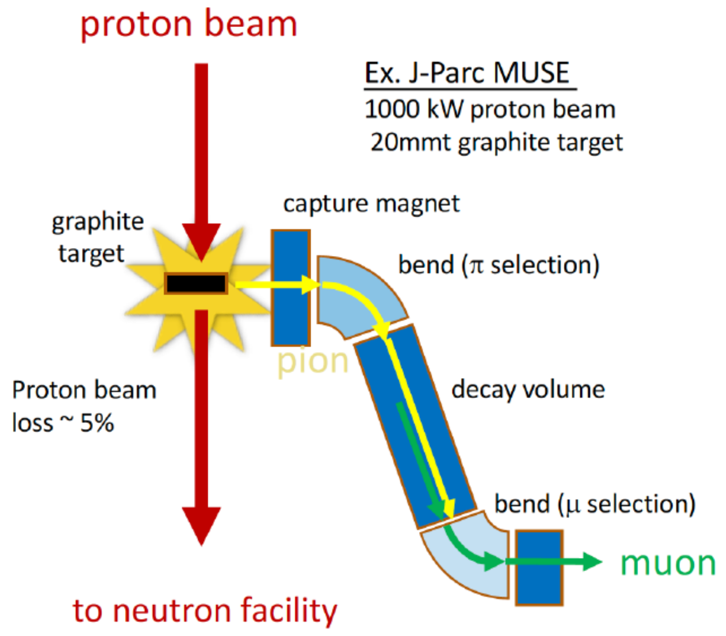
1 MW Gamma beam (20 MHz!)
→ ~10^{13} μ^+/s

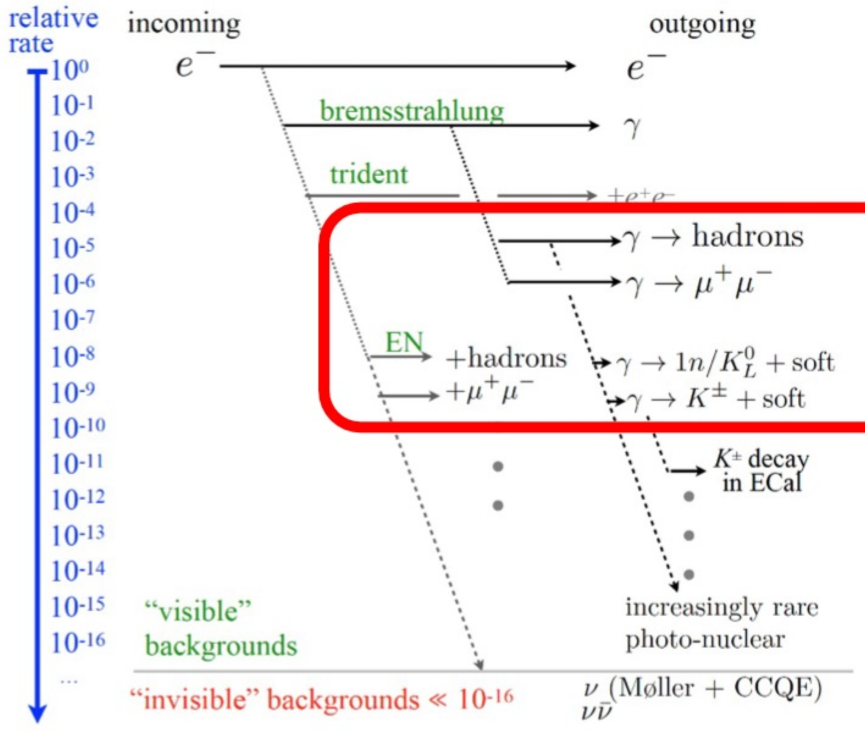
Proton-on-target vs electron/gamma-on-target

Proton on target

pp Collision

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





Is such an electron accelerator (high-repetition-rate) available?

Electron on target

Photo-nuclear process

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

Electro-nuclear process

$$e^- + Z_1 \to$$
$$(e^-)' + Z_1 + \pi^\pm + Z_2$$

Bethe-Heitler process
(Dimuon production)

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

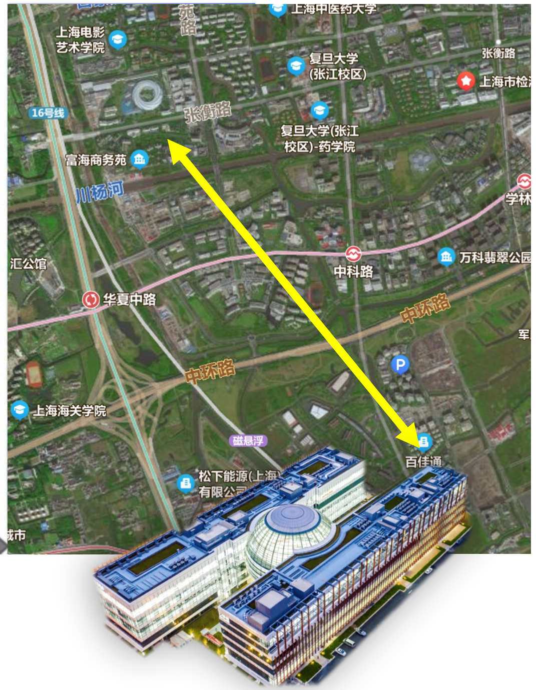
without pion production!

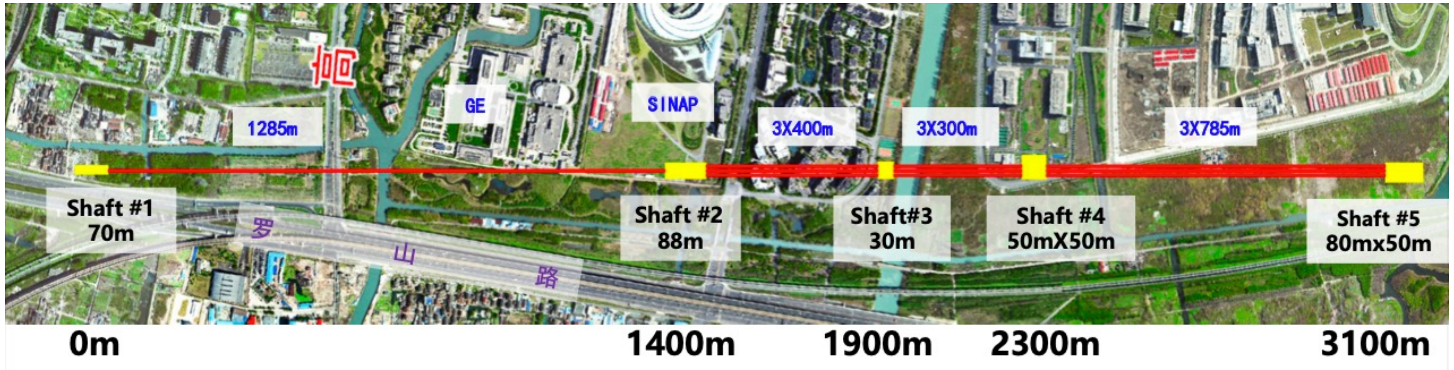
SHINE: an introduction

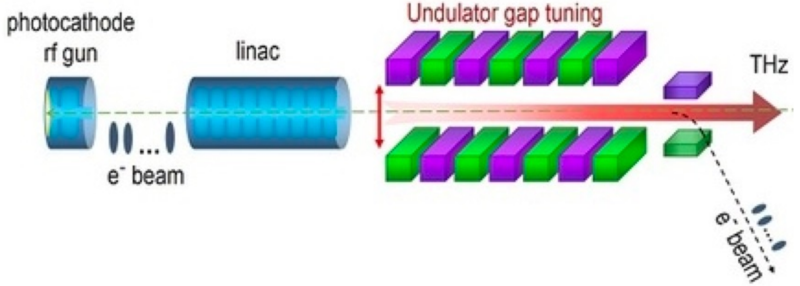
Tsung-Dao Lee Institute

Only 4 km from TDLI!

- Located in Zhangjiang, Shanghai
- To be commissioned in 2025
- Electron accelerator:
  - 8 GeV energy
  - 1 MHz bunch frequency
  - 100 pC charge (6.25 x 10^8 electrons) per bunch







MC simulation: simple setup

- Simulation setup: 8 GeV, 100 pC (SHINE), 30-mm thick, 6-mm radius, tungsten target
- $\gamma \to \mu^+\mu^-$ process: High energy, low emittance, low cross-section
- Photo-nuclear process: Low energy, high emittance, high cross-section
- Two-material target study is in progress (motivated by Nagamine's proposal)

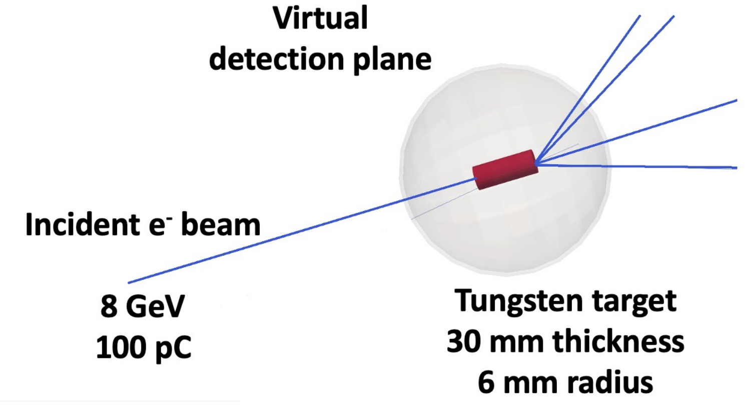
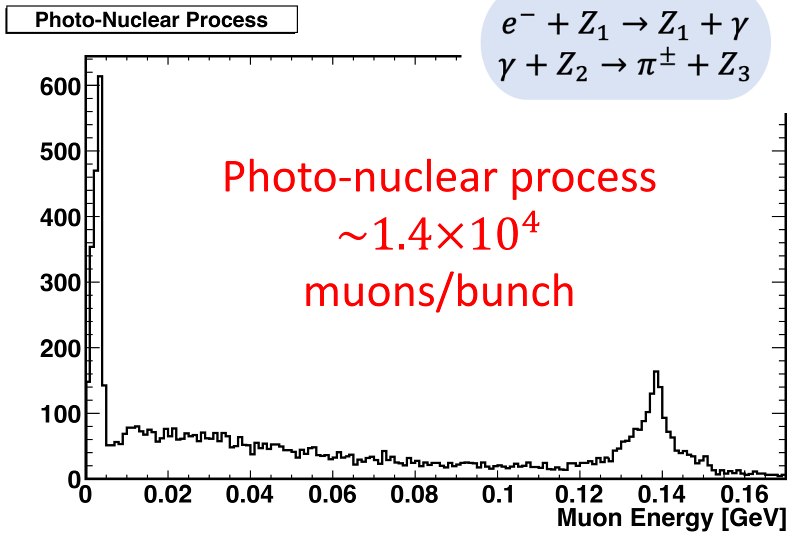


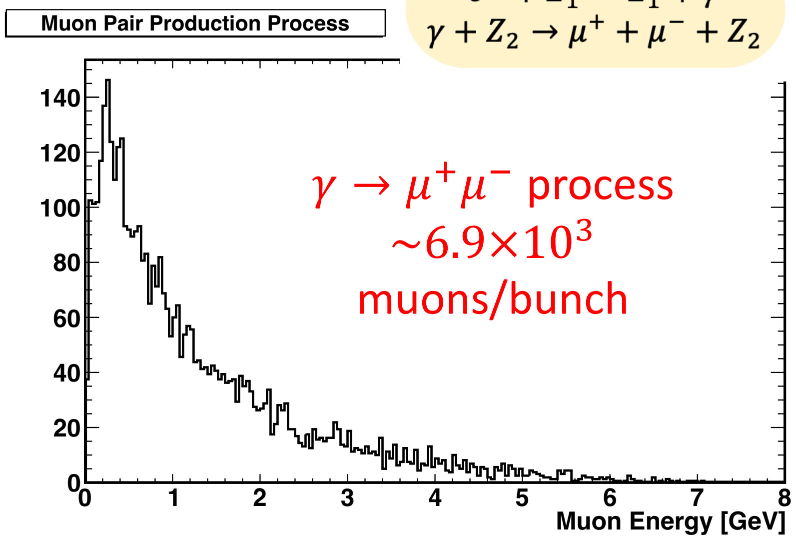
Photo-nuclear process

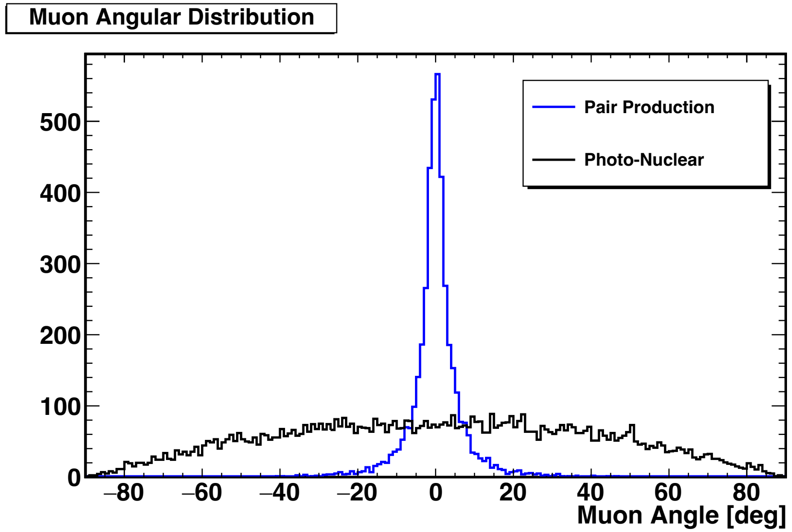
$e^- + Z_1 \to Z_1 + \gamma$
$\gamma + Z_2 \to \pi^\pm + Z_3$

Bethe-Heitler process

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

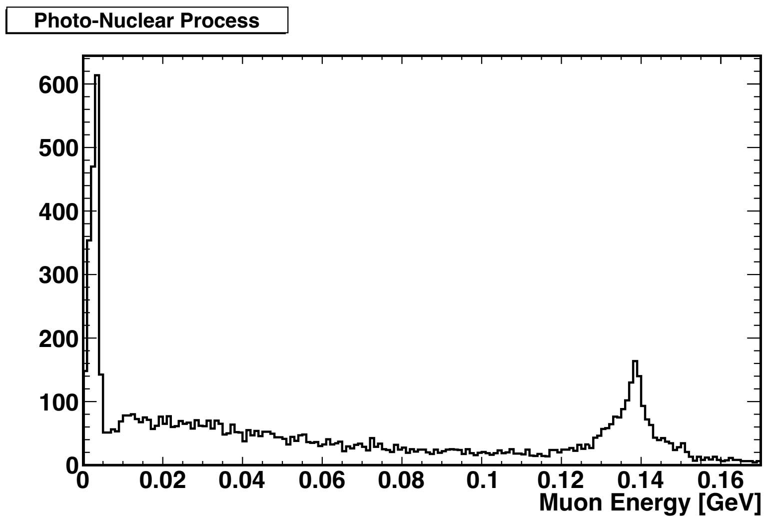


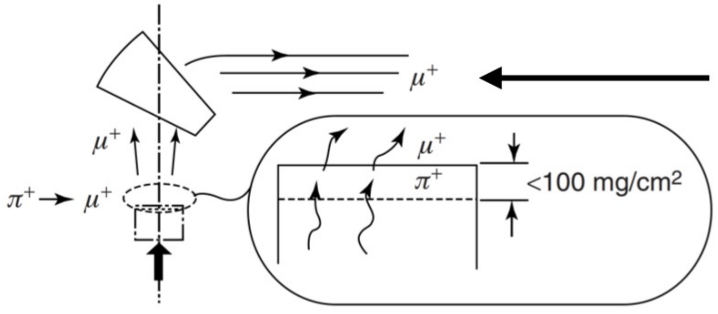




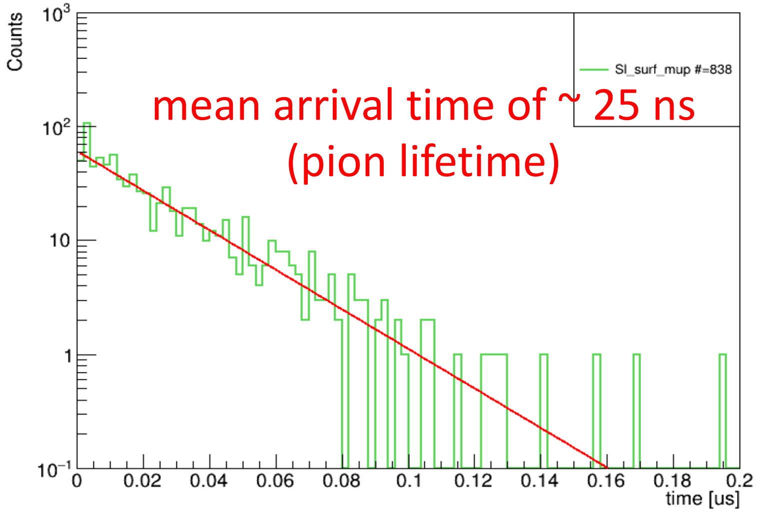
Surface muon production

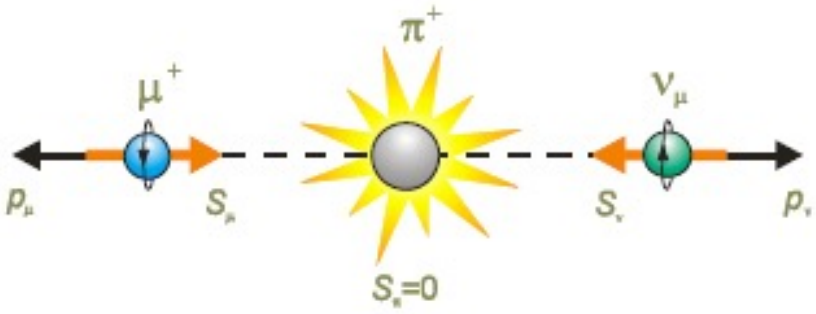
- Surface muon: $\pi^{\pm}/K^{\pm}$ decay near target surface
- Nearly 100% polarization
- Monoenergetic:
  - 4 MeV for $\pi^{\pm}$ decay, 140 MeV for $K^{\pm}$ decay
  - Expected to reach $1.4\times10^{3}\ \mu^{+}/\mathrm{bunch}$ (simple target)
  - Good for high-pressure μSR (K-surface muon)





Introductory Muon Science, Nagamine





Parity violation weak decay

Muon beam from SHINE beam dump?

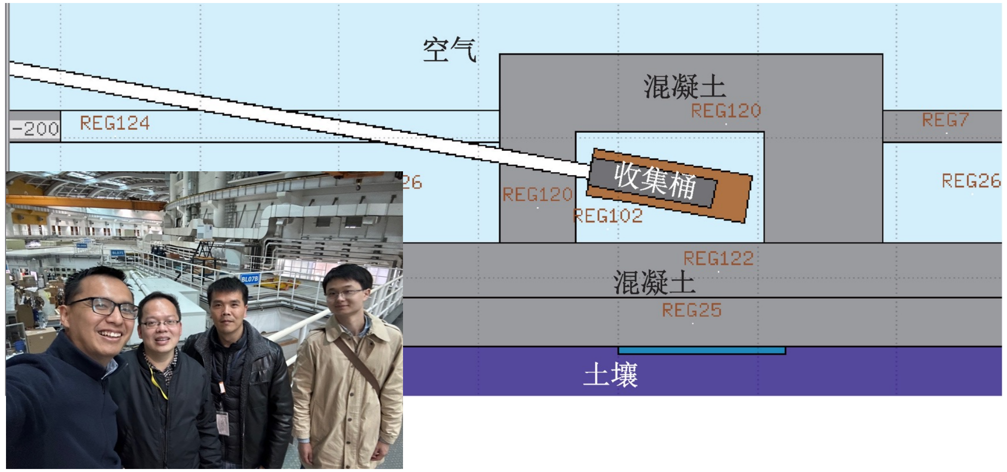
第 40 卷 第 6 期 辐 射 防 护 Vol. 40 No. 6
2020 年 11 月 Radiation Protection Nov. 2020

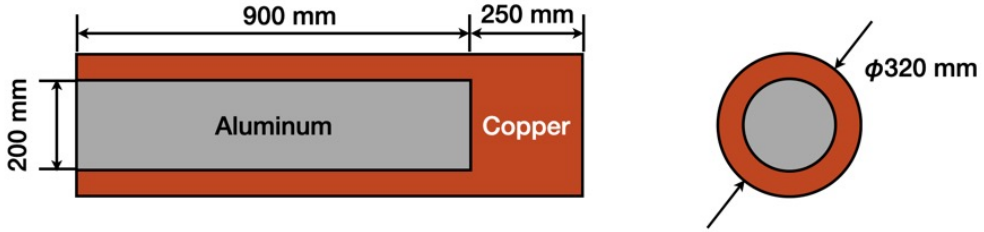
· 辐射传输与屏蔽 ·

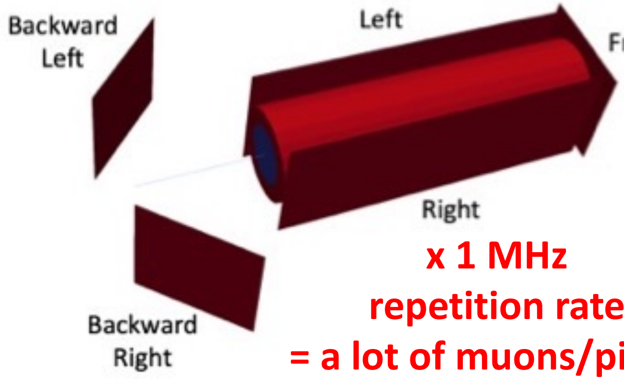
上海硬 X 射线自由电子激光装置调试用束流收集桶的设计

徐玉海[1], 王光宏[1], 李哲夫[1], 许文贞[1], 张斌团[1], 吕炯军[1], 杨夫彬[1], 夏晓彬[2]

(1. 中国科学院上海高等研究院张江实验室 上海 201204; 2. 中国科学院上海应用物理研究所, 上海 201800)



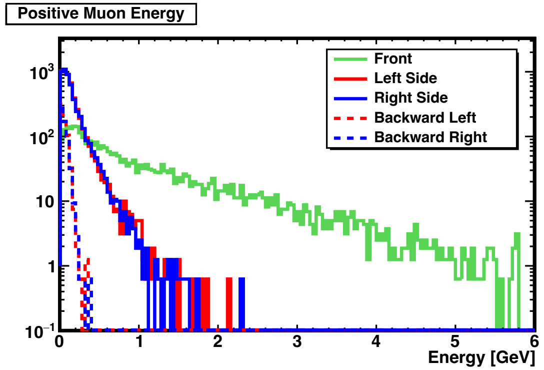


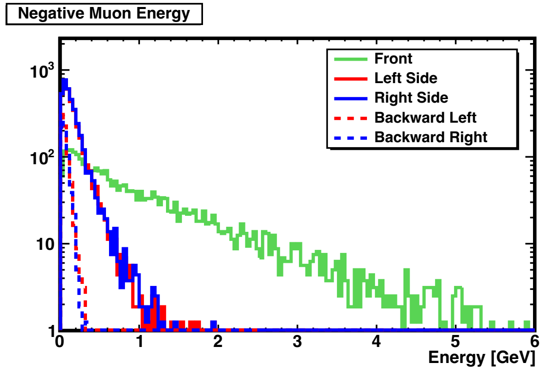


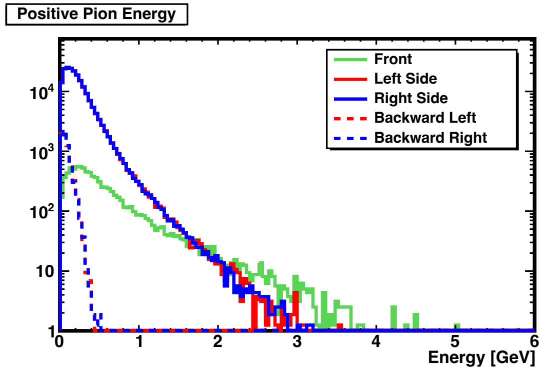
x 1 MHz repetition rate = a lot of muons/pions!

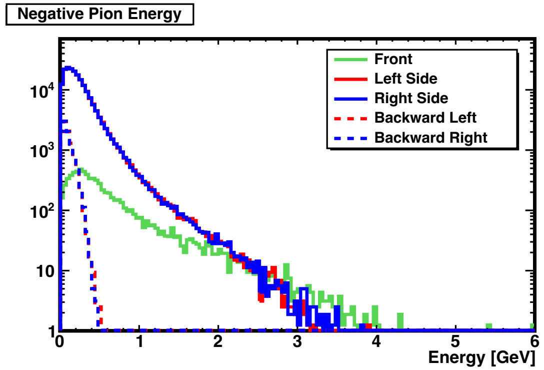
Table 1: Intensity of leptons and mesons produced from 8 GeV electrons-on-target. The numbers here are normalized to the bunch charge of 100 pC for SHINE.

Location	μ^+/bunch	μ^-/bunch	π^+/bunch	π^-/bunch
Front	3.1×10^3	2.9×10^3	8.9×10^3	7.6×10^3
Side (L)	5.1×10^3	3.6×10^3	2.0×10^5	1.9×10^5
Side (R)	5.0×10^3	3.6×10^3	2.0×10^5	1.9×10^5
Back (L)	6.6×10^2	7.5×10^2	6.8×10^3	1.0×10^4
Back (R)	6.5×10^2	7.1×10^2	6.6×10^3	1.0×10^4









Potential locations for beam line

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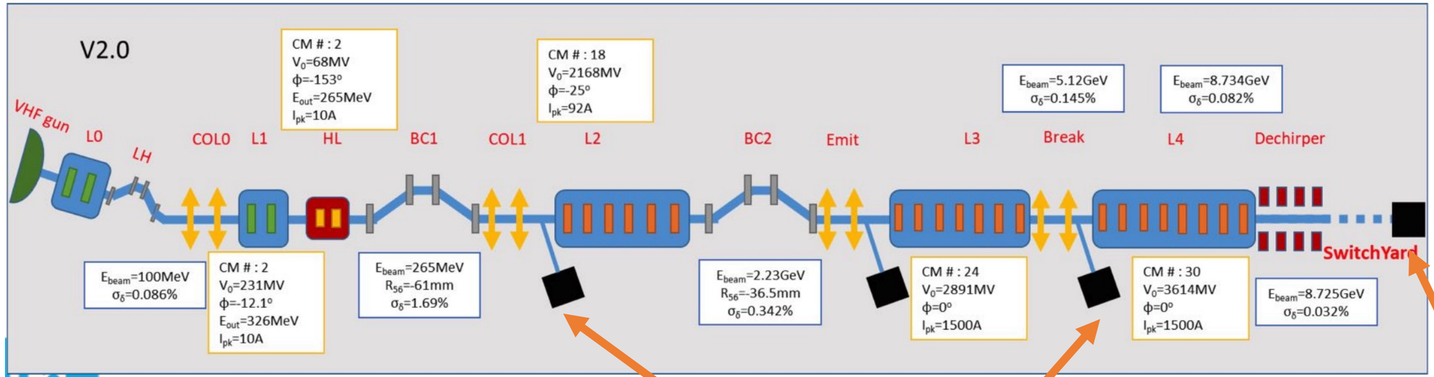
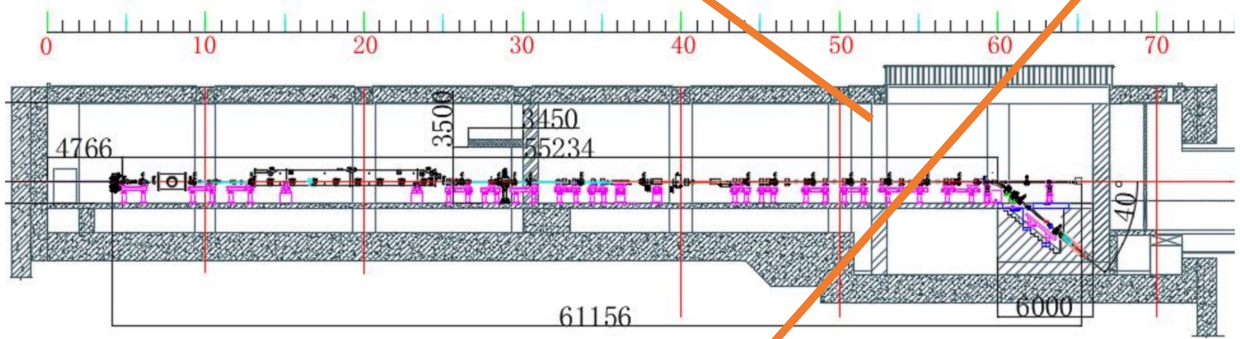
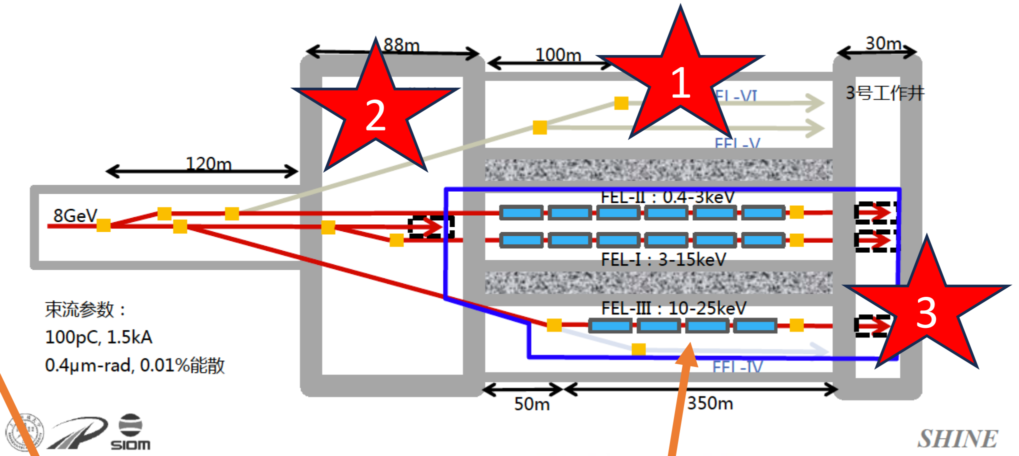
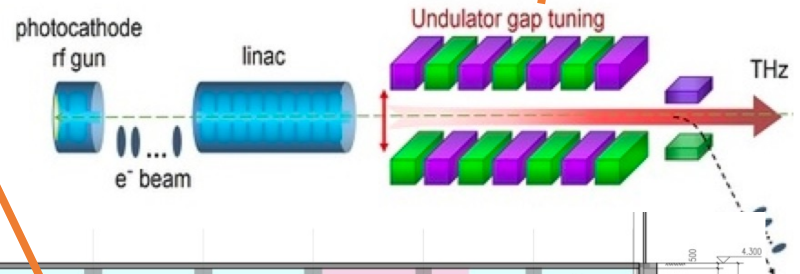
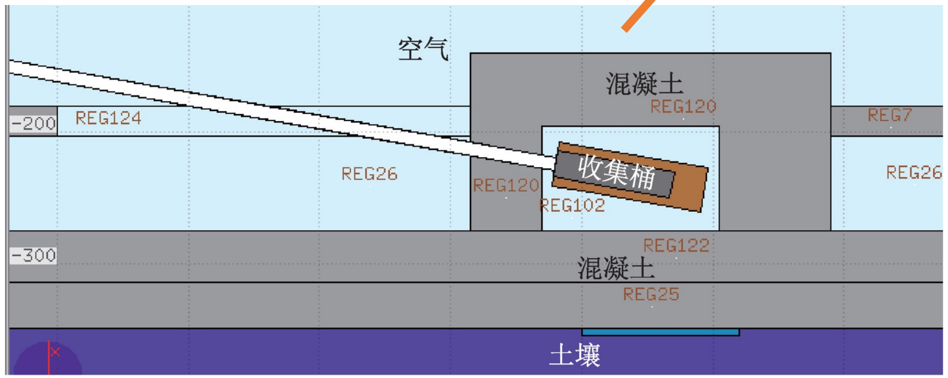
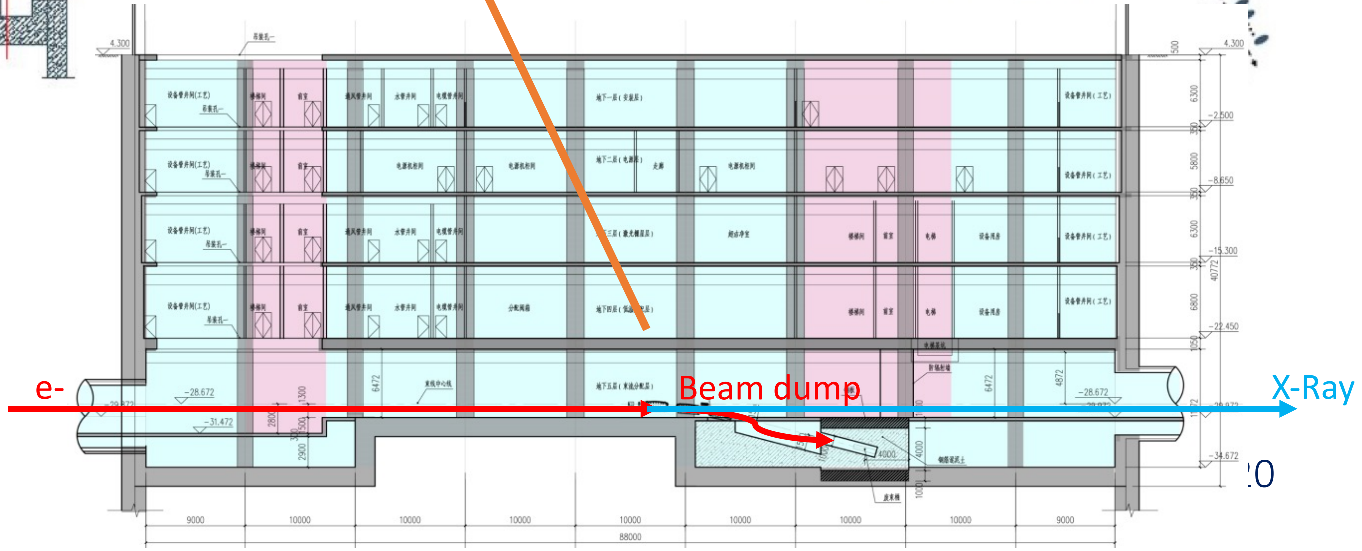






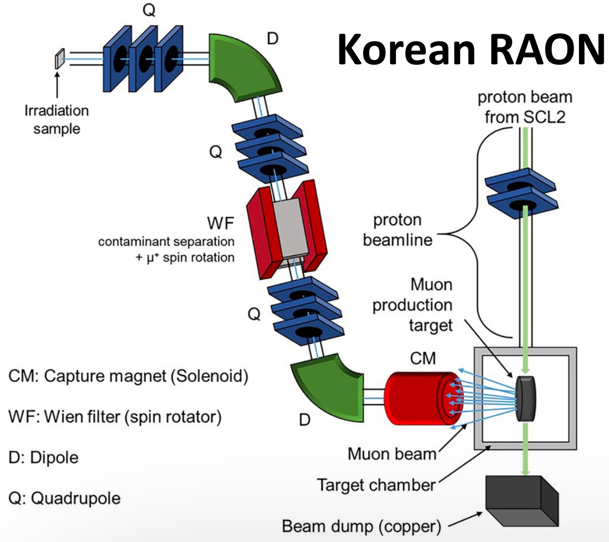


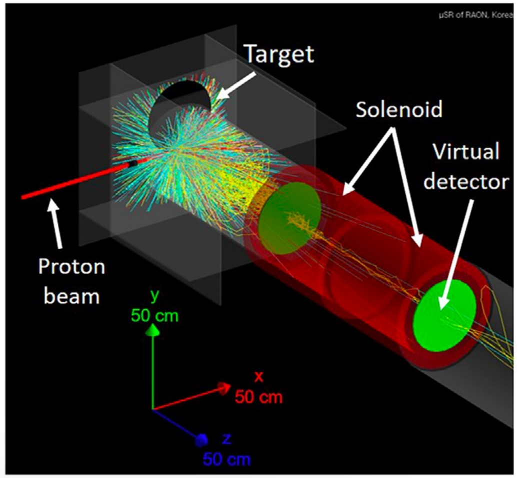




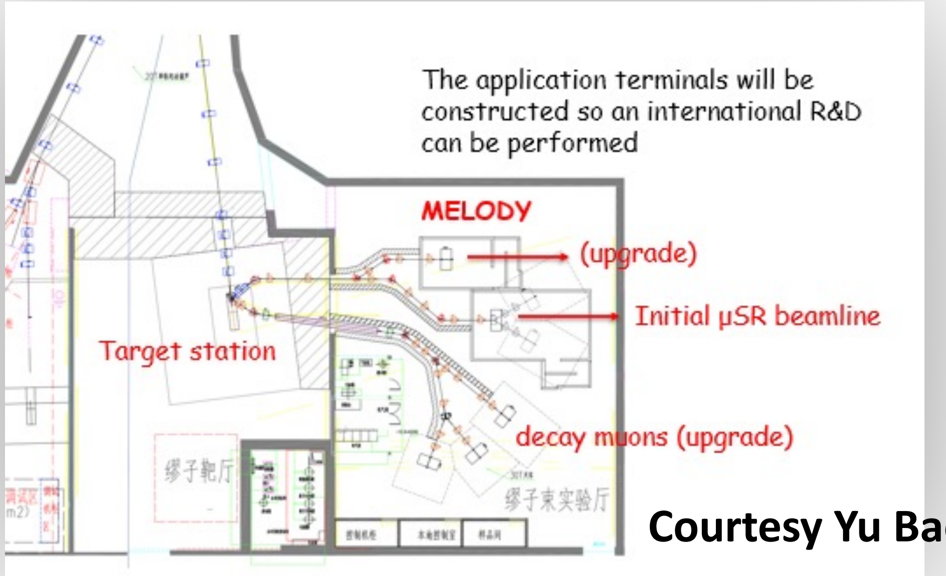
Possible schemes for muon extraction

Korean RAON



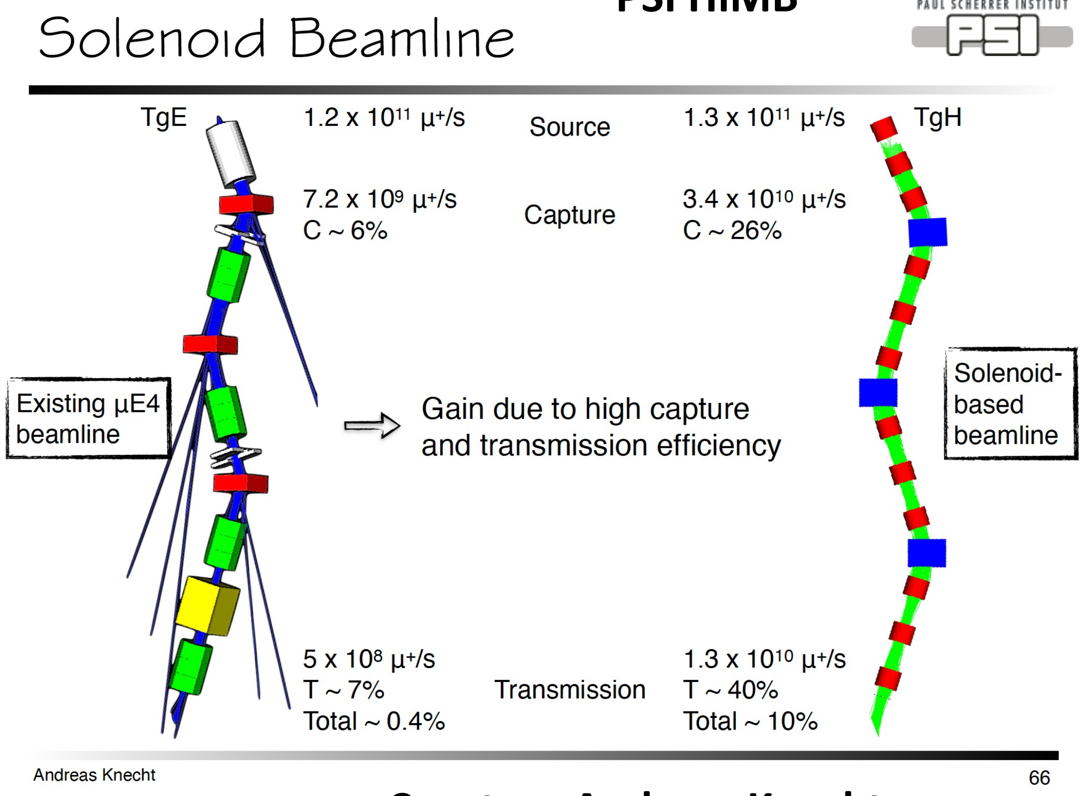


Nuclear Engineering and Technology 53 (2021) 3344-3351



Courtesy Yu Bao

PSI HiMB



Courtesy Andreas Knecht

We are studying various beam extraction schemes. Once the site is selected at SHINE, a dedicated study will be performed.

Beam Test at SXFEL (2023/2024)

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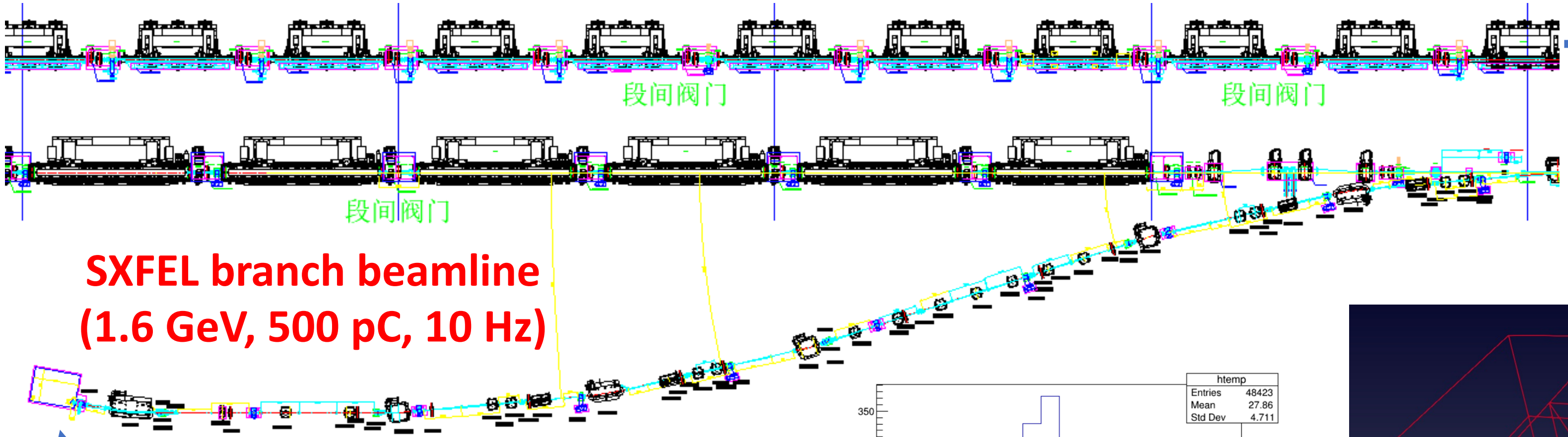
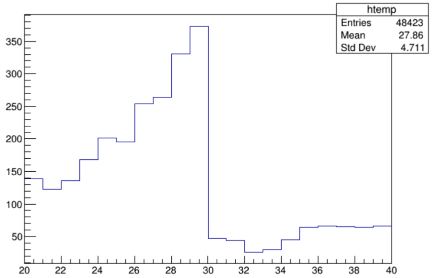
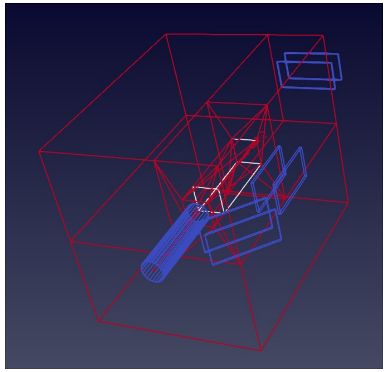
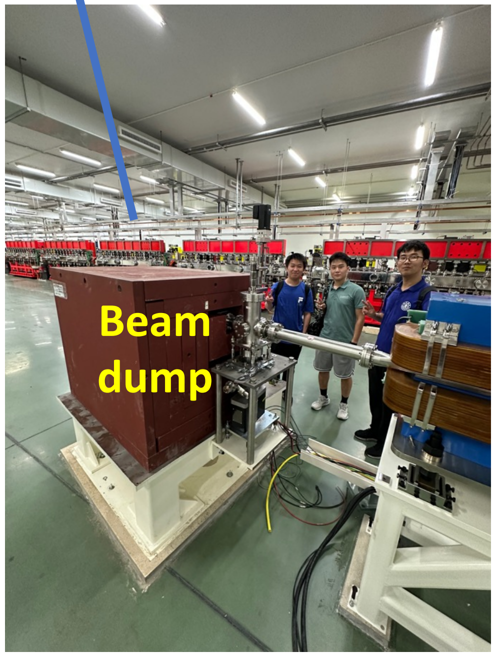
SXFEL



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

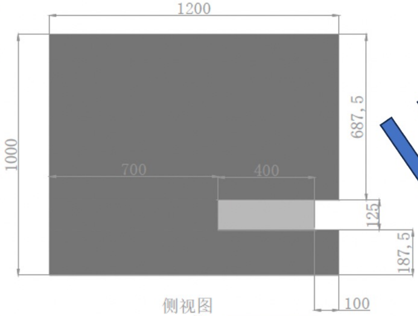






muon pair production t ~ 0

Plastic Scint.

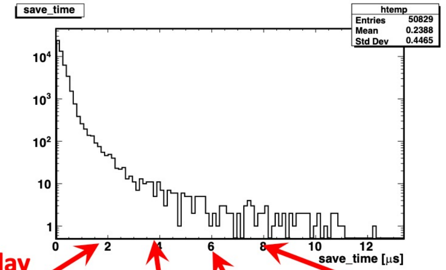


Plastic Scint.

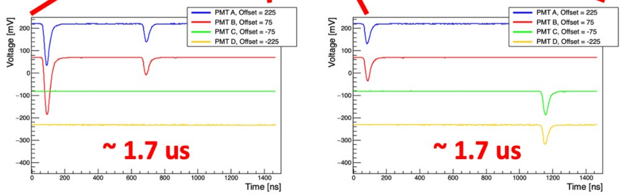
absorber

Photo-nuclear t ~ 26 ns/2.2 us

Plastic Scint.



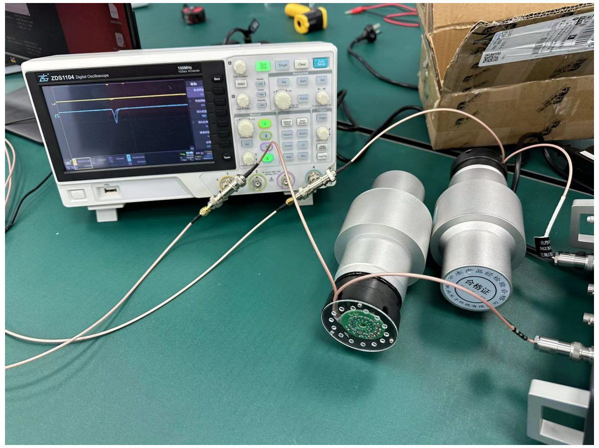
trigger and delay



~ 1.7 us

~ 1.7 us

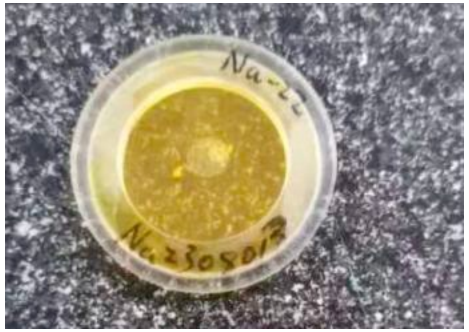
Gearing up for SXFEL beam test



LaBr$_3$ for muonic X-ray (cheaper than the Ge detector)

LESBER
— 莱 斯 博 —
服 务 能 源 产 业　专 注 核 能 领 域

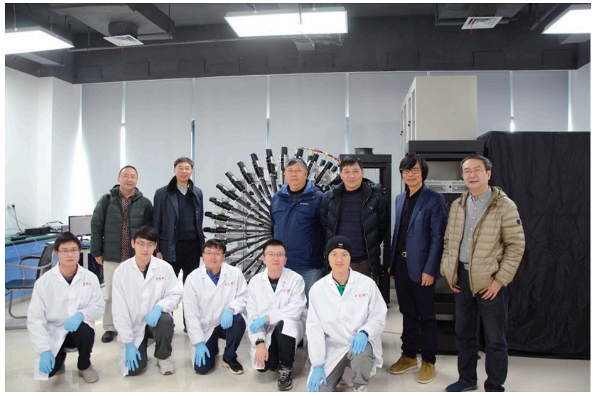
Plastic Scintillators for muon/electron/positron detection

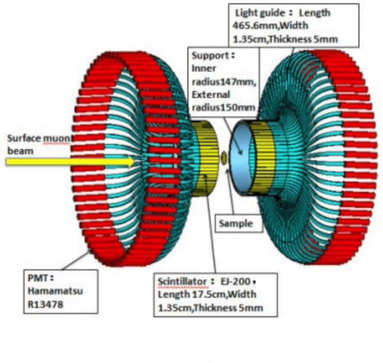


Various calibration sources

Potential collaborations within China

Muon Spin Spectroscopy

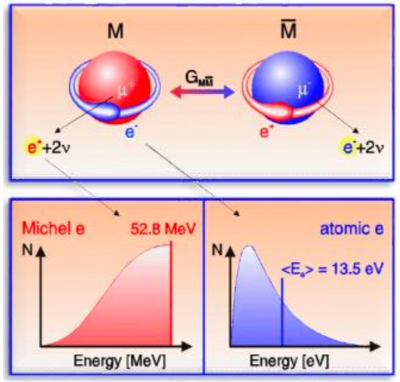


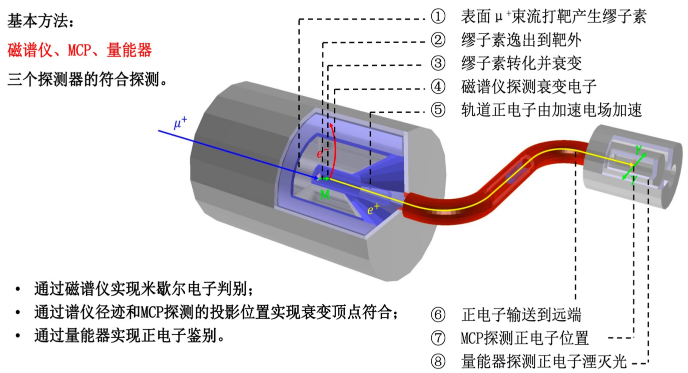


128路μSR谱仪整体设计图

China's first muSR prototype has been built in USTC (led by Prof. Bangjiao Ye)

Muonium-to-antimuonium conversion



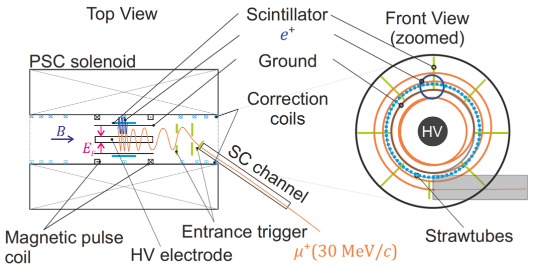


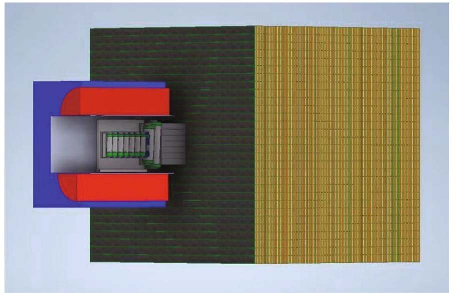
Prof. Jian Tang (SYSU) is leading the R&D of this experiment (MACE)

Muon beam line technology, muon cooling, etc

CSNS and IMP (HIAF, CiADS)

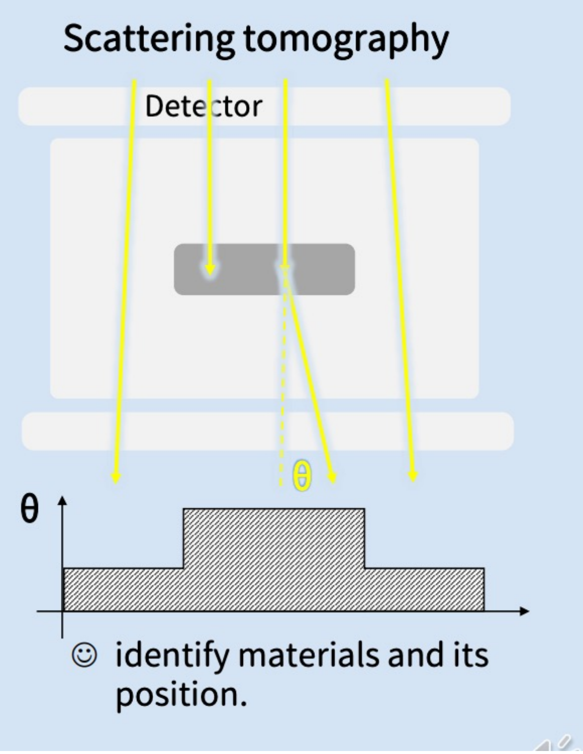
Muon EDM, EOT process study for DarkSHINE

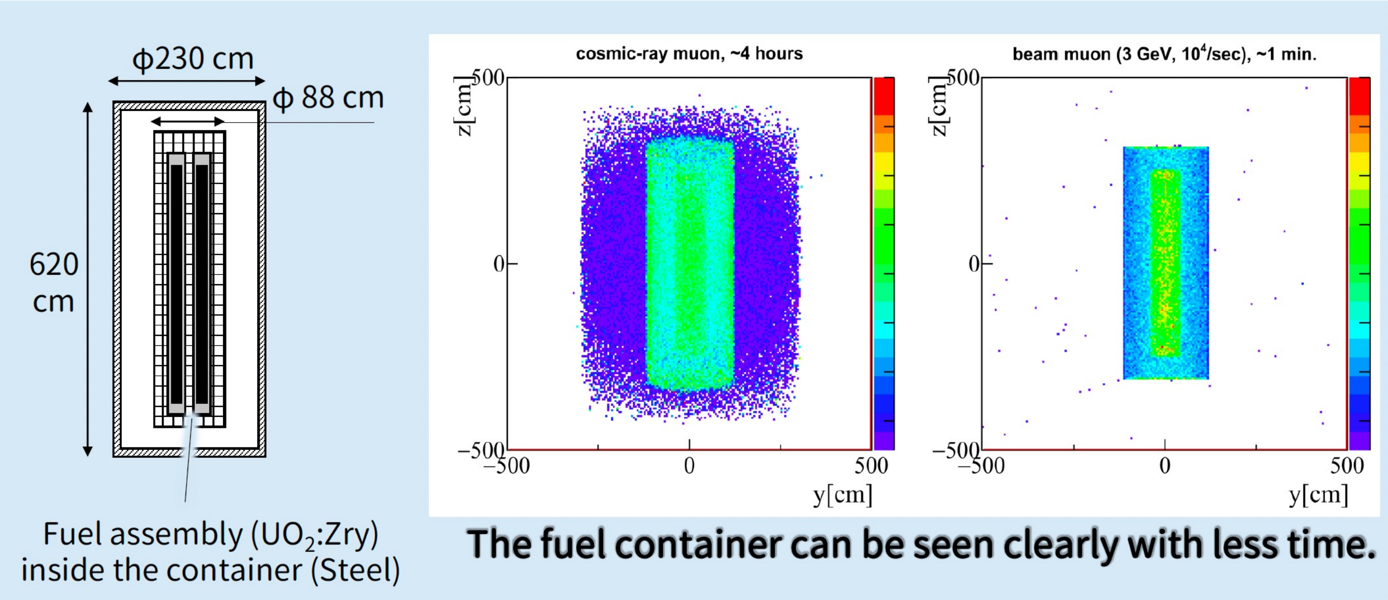




Team within SJTU

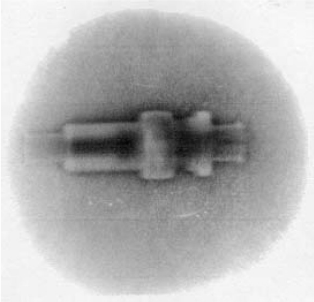
Accelerator muon tomography





faster than the cosmic muon approach

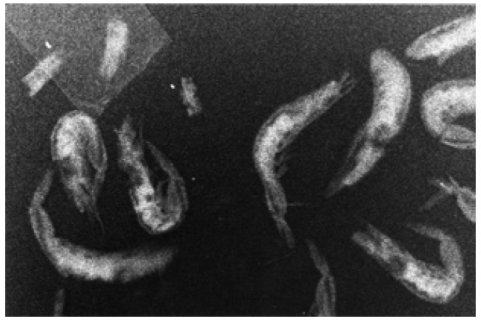
M. Ootani, JACoW-IPAC2021-THXC05



I-------------------------I
5 cm
(a)

(b)

I--------------------------I
5 cm
(a)



I-----------------I
5 cm
(b)

better resolution than the positron approach

M. Doyama et al, Phys. Status Solidi C 6, No. 11, 2471–2475 (2009)

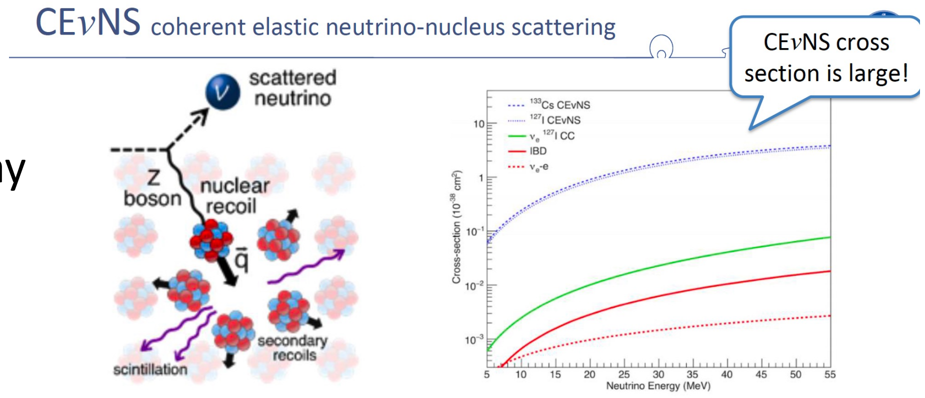
Neutrino experiments

- CEvNS

~10^{18} ν year/m^2 at 10 m away

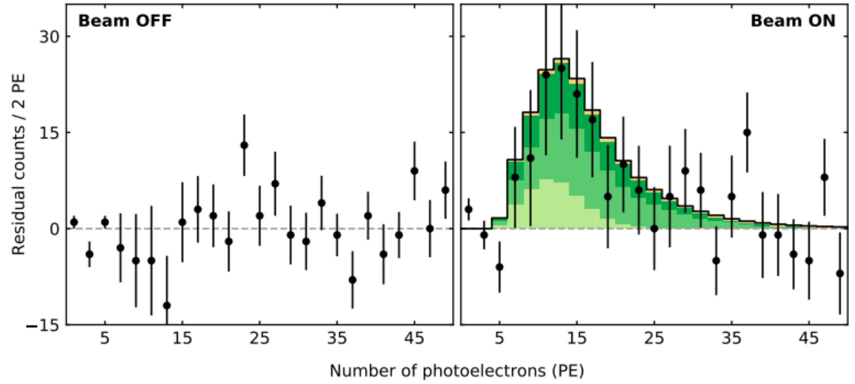
- Inspect SM at low momentum transfer
- Background of WIMP detection

Courtesy: Chenguang Su (CSNS)



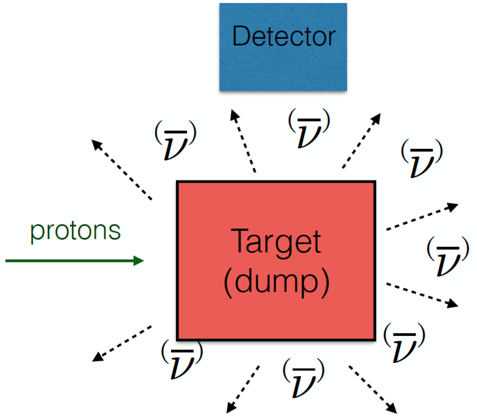
- CEνNS cross section is well calculable in the SM

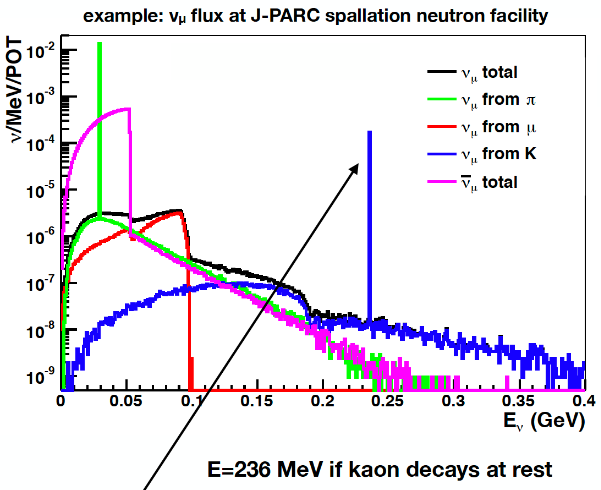
$$\frac{d\sigma_0}{dE_r} = \frac{G_f^2}{4\pi} m_a [Z(4\sin^2\Theta_W - 1) + N]^2 \left(1 - \frac{m_a E_r}{2E_\nu^2}\right) \propto N^2$$



Independent cross-check for COHERENT

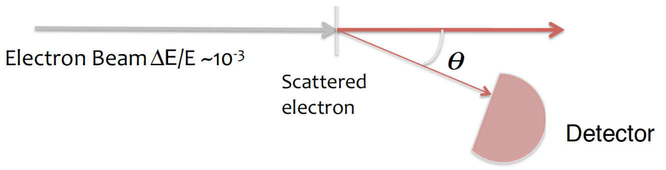
- Kaon Decay at Rest (KDAR)

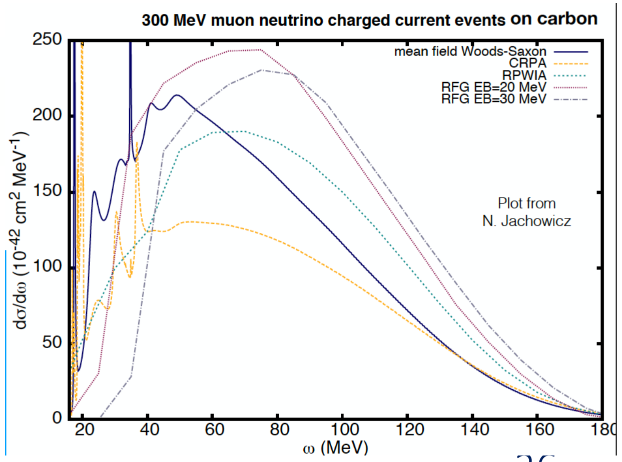




$K^+ \to \mu^+ \nu_\mu$ (branching ratio=64%)

A probe of the nucleus



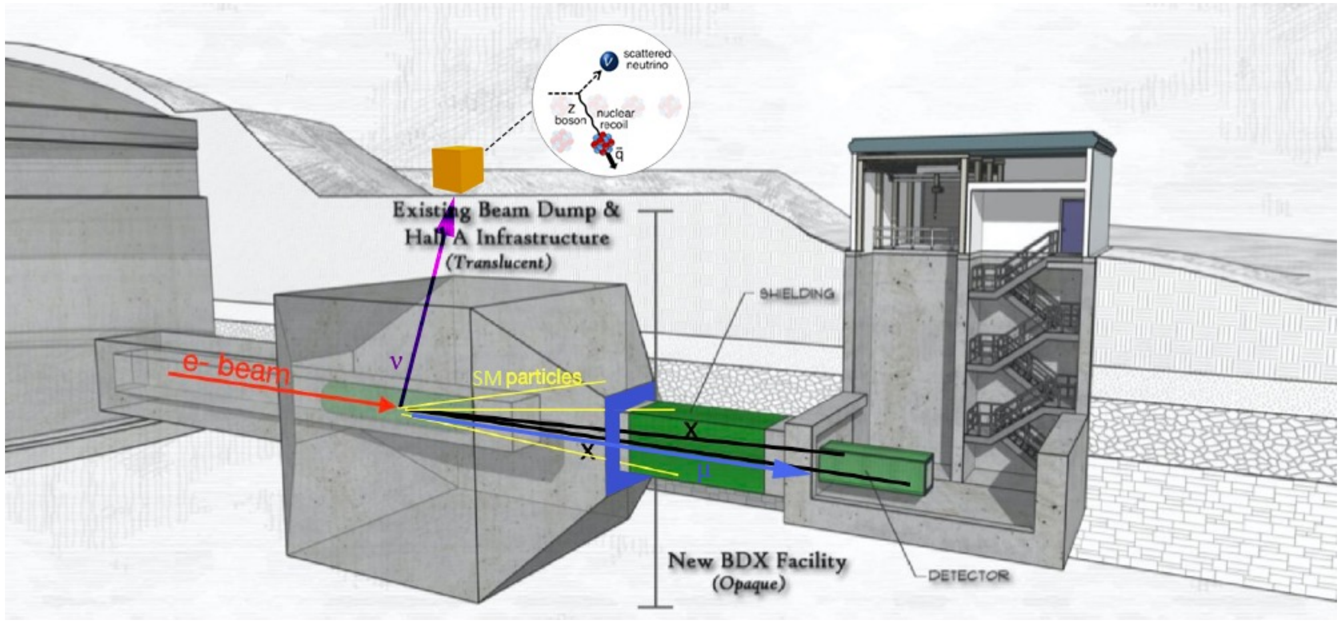


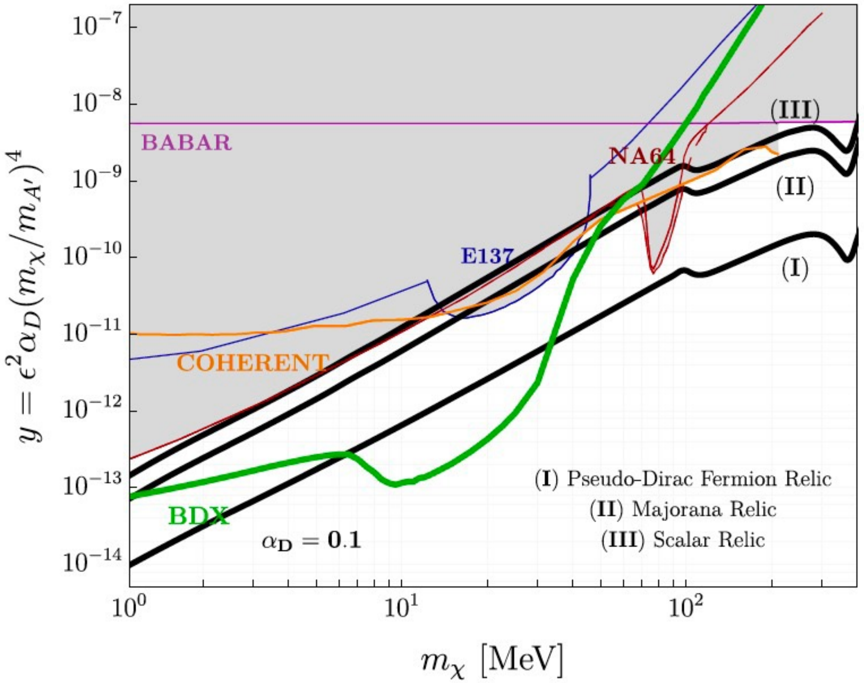
MiniBooNE

Phys. Rev. Lett. 120 (2018) 14, 141802

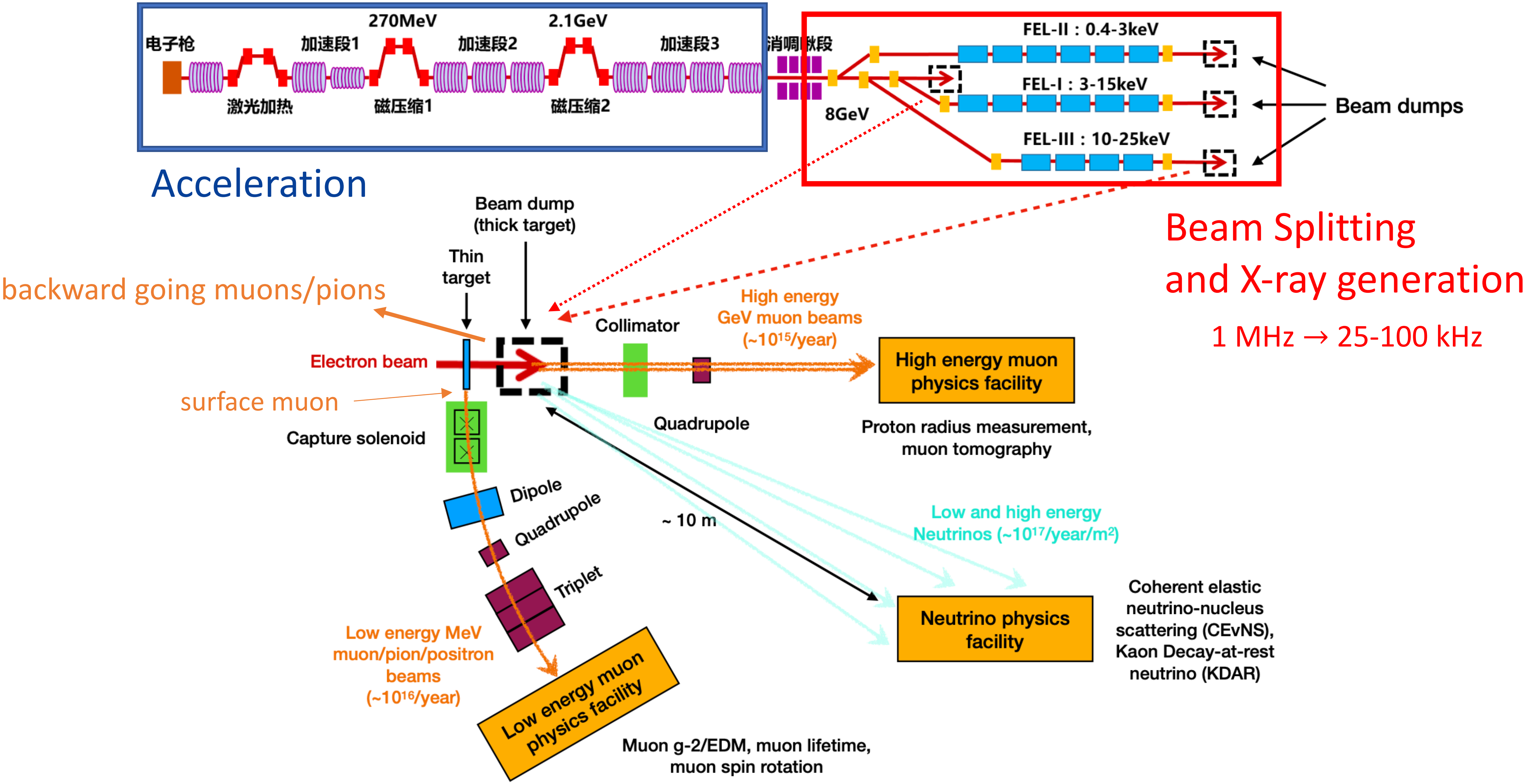
Dark matter experiments

- BDX-style experiment
  - Similar electron beam as the CEBAF at JLab (12 GeV, 100 µA)
  - Expected annual EOT ~ 10^{22}
  - Can provide high sensitivity search for visibly decay dark photons





Very rich physics SHINE-based program



Summary

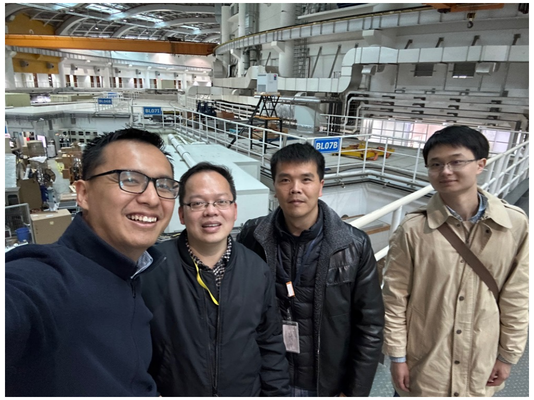
- Current proton-driven muon sources are either low-repetition-rate pulsed sources or DC sources, which are not optimal for many muon experiments

- An ideal high-repetition pulsed muon can be built based on pulsed electron beam in the SHINE facility
  - Bunch rate: kHz – MHz (tunable)
  - ~10^3 muons per bunch (assuming ~10% efficiency, target to be further optimized!)
  - will benefit particle physics (μ, *v*, DM), condensed matter physics, tomography, etc

- The Shanghai Muon Source will (hopefully) be developed in 3 stages
  - Beam test at SXFEL with the 1.6 GeV electron beam (next 1-2 years)
  - Phase 1 surface muon beam line at 4 MeV (next 5 years)
  - Phase 2 surface muon beam line at 140 MeV (next 10 years)

Thank you for your attention!

李政道研究所 TSUNG-DAO LEE INSTITUTE



A new lab for muon beamline and detector R&D

Would not be possible without the support/suggestions from Dong Wang, Jianhui Chen, Guanghong Wang, Wenzhen Xu, Vadim Grinenko, Hong Ding, Dao Xiang, and more …

New collaborators and ideas utilizing the SHINE muon source are very welcome!