Experimental Search for μ-e Conversion in Nuclear Field at J-PARC MLF H-Line

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DeeMe Collaboration

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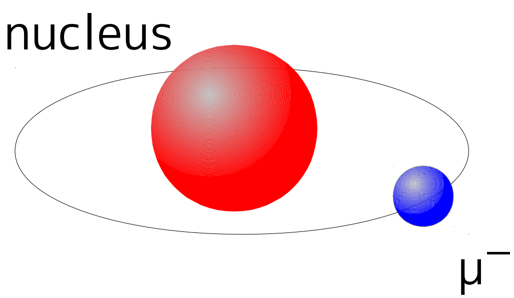
2: UBC
3: KEK Accelerator
4: KEK IMSS MUSE
5: JAEA
6: KEK IPNS
7; TRIUMF
8: Osaka City University

Contents

μ-e Conversion in Nuclear Field

Muonic atom (1S state)



● **Muon Decay in Orbit (DIO)**

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

● **Muon Capture (MC)**

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z\text{-}1)$$

- MC:DIO = 1:1000 (H), 2:1 (Si), 13:1 (Cu)

- μ^- life time
  τ (in free space)= 2.2 μsec
  τ (in Si) = 0.76 μsec

● **μ-e conversion in nuclear field**

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

- Charged Lepton Flavor Violation (cLFV)
- Forbidden in the Standard Model (SM)
- Clear evidence of the new physics

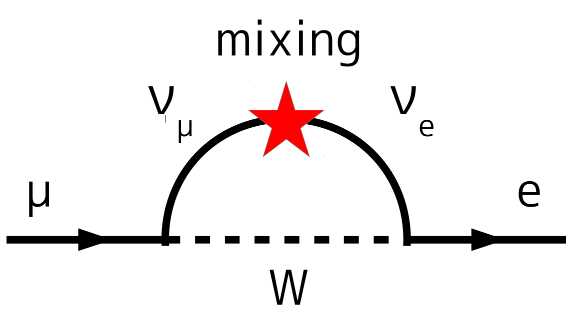
<u>Branching ratio definition</u>

$$\mathrm{BR}(\mu\text{-}e \text{ conversion}) = \frac{\Gamma(\mu\text{-}e \text{ conversion})}{\Gamma(\text{muon capture})}$$

charged Lepton Flavor Violation

- Forbidden in the Standard Model
- cLFV process
  $\mu^- + N \rightarrow e^- N$, $\mu \rightarrow e\gamma$, $\mu \rightarrow e\,e\,e$, ...
- Neutrino-mixing predicts very small amount of cLFV via higher order diagram.
  However..
  It is too small to be observed experimentally.

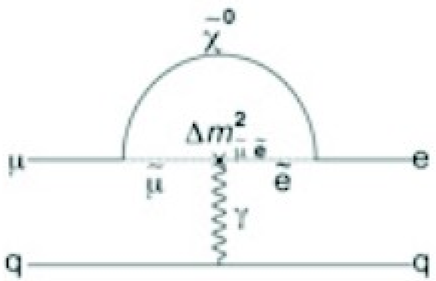
$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha}{2\pi} \left| \sum_k U_{ek} U^*_{\mu k} \frac{m^2_{\nu_k}}{m^2_W} \right|^2 \simeq \frac{\alpha}{2\pi} \left| U_{e3} U^*_{\mu 3} \frac{\Delta m^2_{\mathrm{atm}}}{m^2_W} \right|^2 < 10^{-54}$$

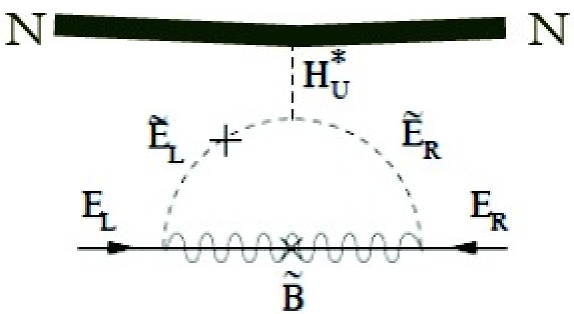


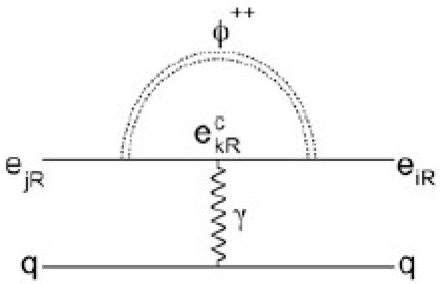
cLFV = Physics beyond the Standard Model with neutrino oscillation

Theoretical Prediction for μ-e Conversion

Many theoretical models predict large branching ratio of μ-e conversion.
- SUSY-GUT, SUSY-seesaw, Doubly Charged Higgs, Little-Higgs, etc...







Process	SUSY-GUT level	Current Limit
μ + N → e + N	$10^{-14} \sim 10^{-17}$	10^{-13}
μ → eγ	10^{-14}	10^{-11}

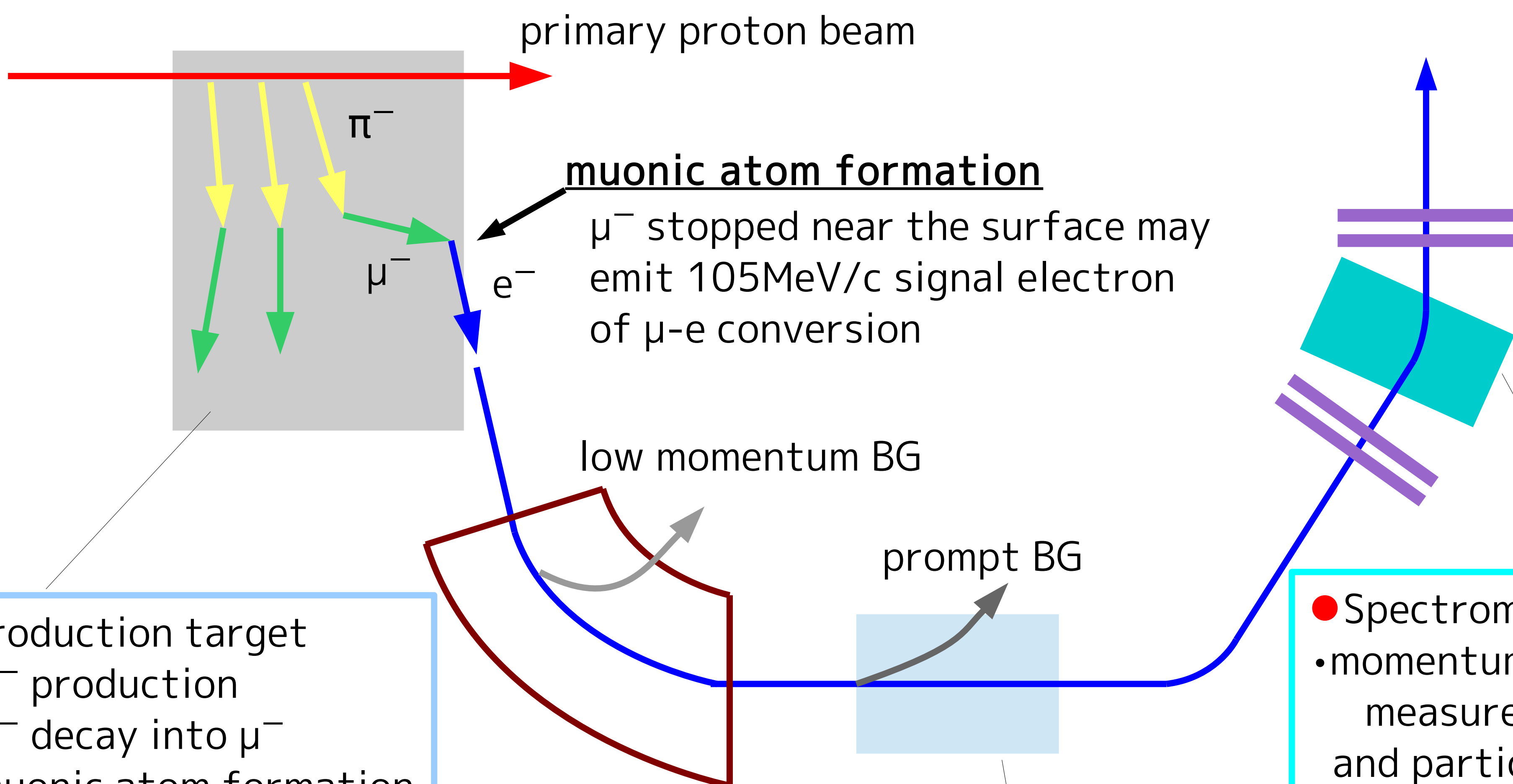
The discovery is right around the corner.

Principle of Measurement

- target process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - signal electron ... • monochromatic (105 MeV/c)
    • ~ 1 μsec delayed
  - No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
  - Beam Pion Capture
    • $\pi^- + (A,Z) \rightarrow (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)\ ,\ \gamma \rightarrow e^+e^-$
  - Radiative muon capture
    • $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)\ ,\ \gamma \rightarrow e^+e^-$

prompt timing

DeeMe Experiment



- **Production target**
  - π^- production
  - π^- decay into μ^-
  - muonic atom formation inside the production target

- **Spectrometer**
  - momentum measurement and particle ID
  - measure delayed electrons

- **Beamline**
  Low momentum electron
  → suppressed by the beamline

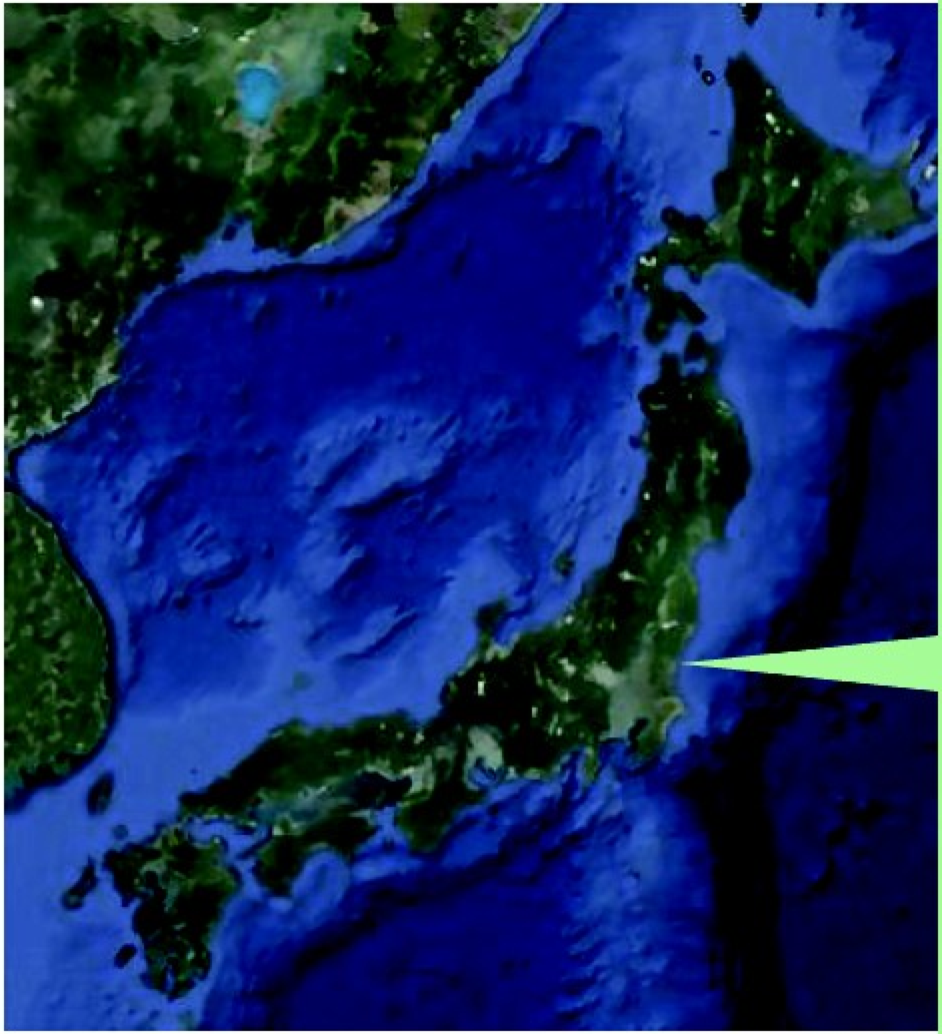
- **Prompt kicker**
  reduce the backgrounds from main pulse
  → protect detectors at spectrometer

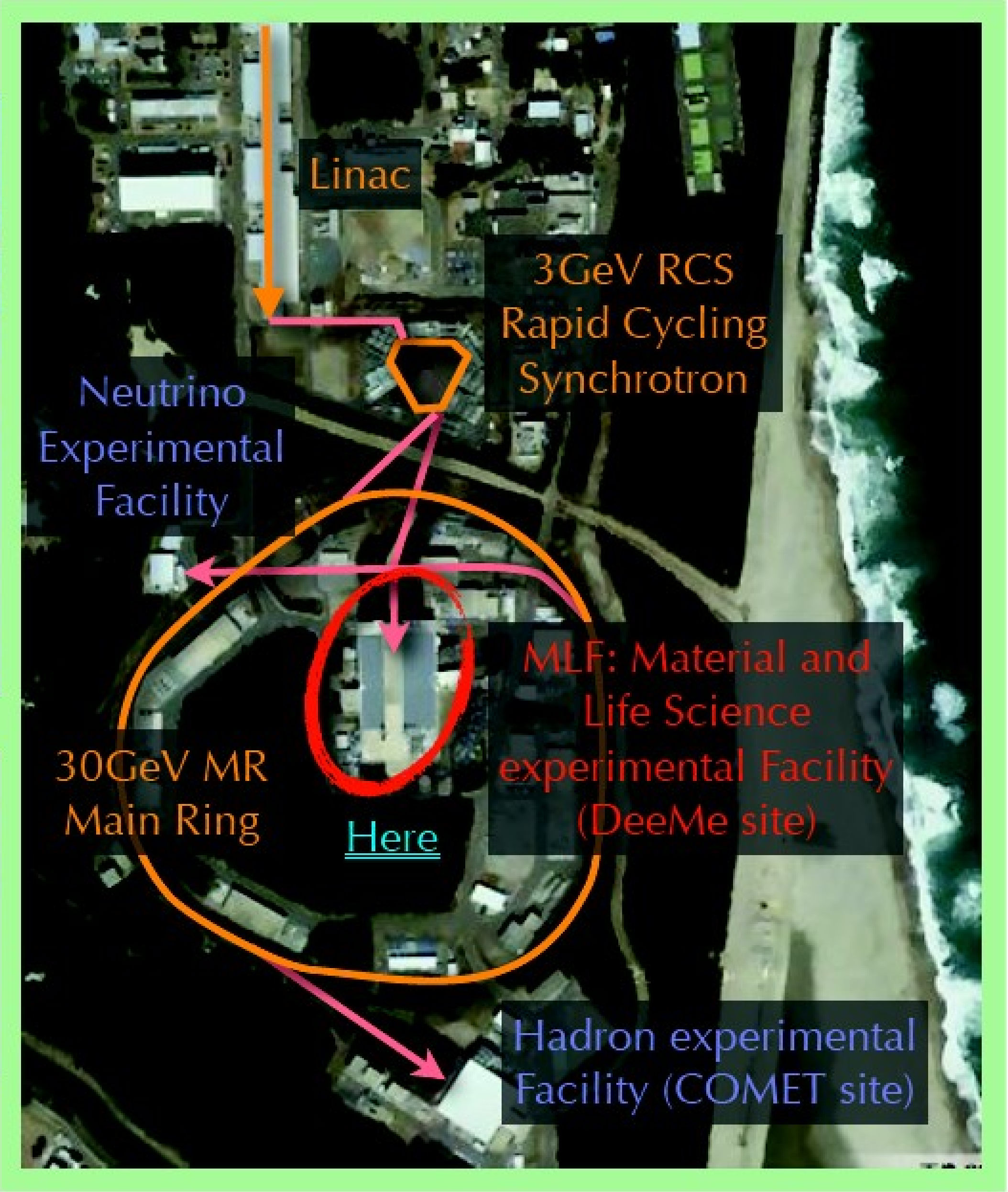
DeeMe Experiment

- Search for μ-e conversion in nuclear field
  at single event sensitivity of 10^{-14}
  - Recent Upper Limits
    SINDRUM-II : $BR(\mu^{-} + Au \rightarrow e^{-} + Au) < 7 \times 10^{-13}$
    SINDRUM-II : $BR(\mu^{-} + Ti \rightarrow e^{-} + Ti) < 4.3 \times 10^{-12}$
    TRIUMF : $BR(\mu^{-} + Ti \rightarrow e^{-} + Ti) < 4.6 \times 10^{-12}$
- Planned at J-PARC MLF MUSE (muon facility)
  - H-Line (brand new beam line)
- SiC muon production and stopping target
  - $\mu^{-} + Si \rightarrow e^{-} + Si$
- Momentum analysis using spectrometer
  - 105 MeV/c signal electron

J-PARC MLF

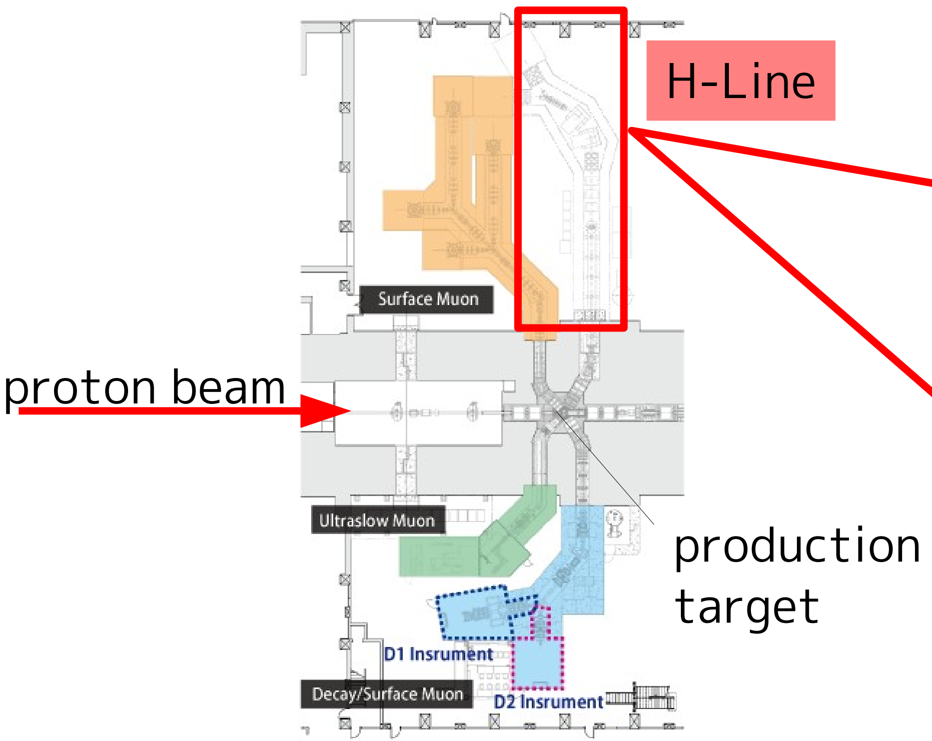
- DeeMe experiment is planned at J-PARC MLF MUSE (muon facility).

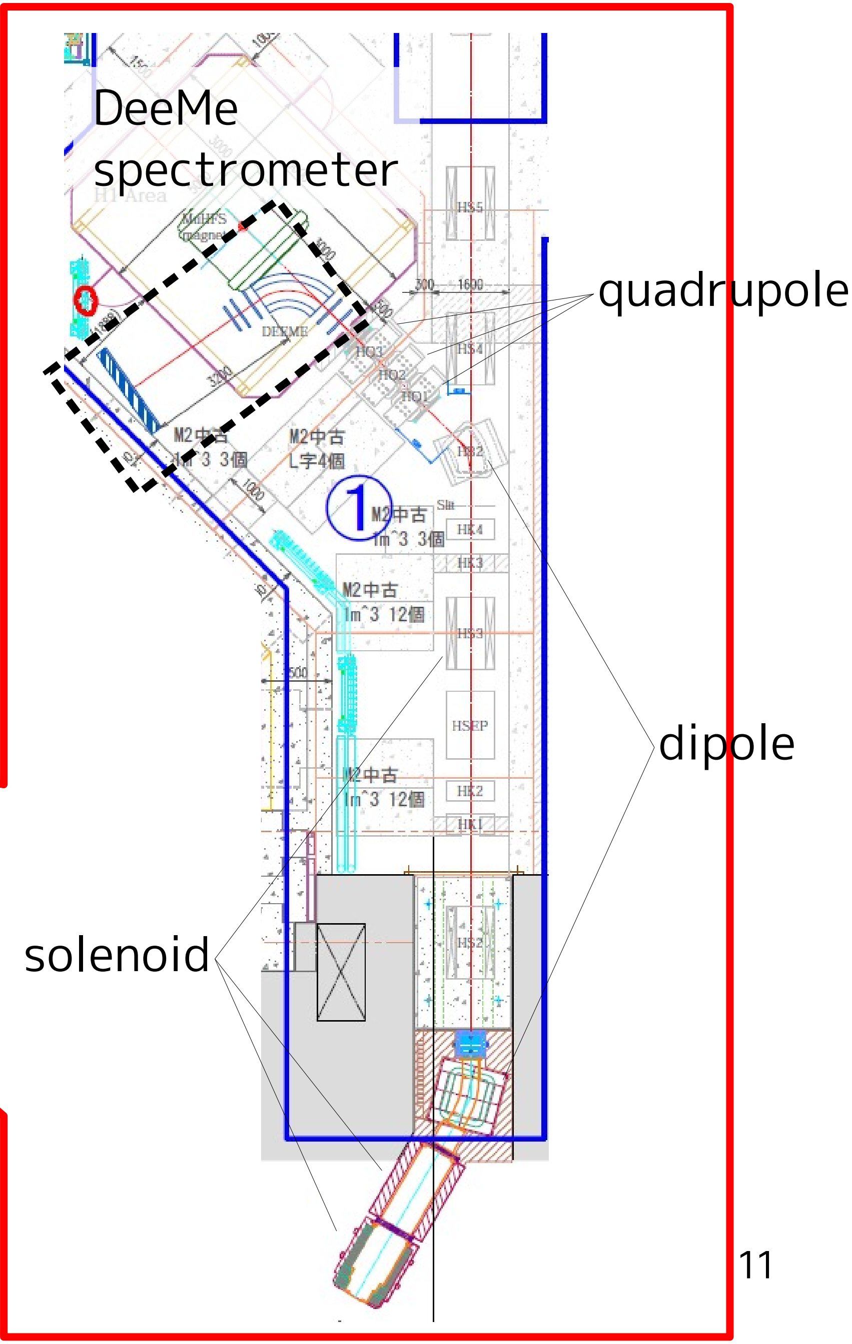




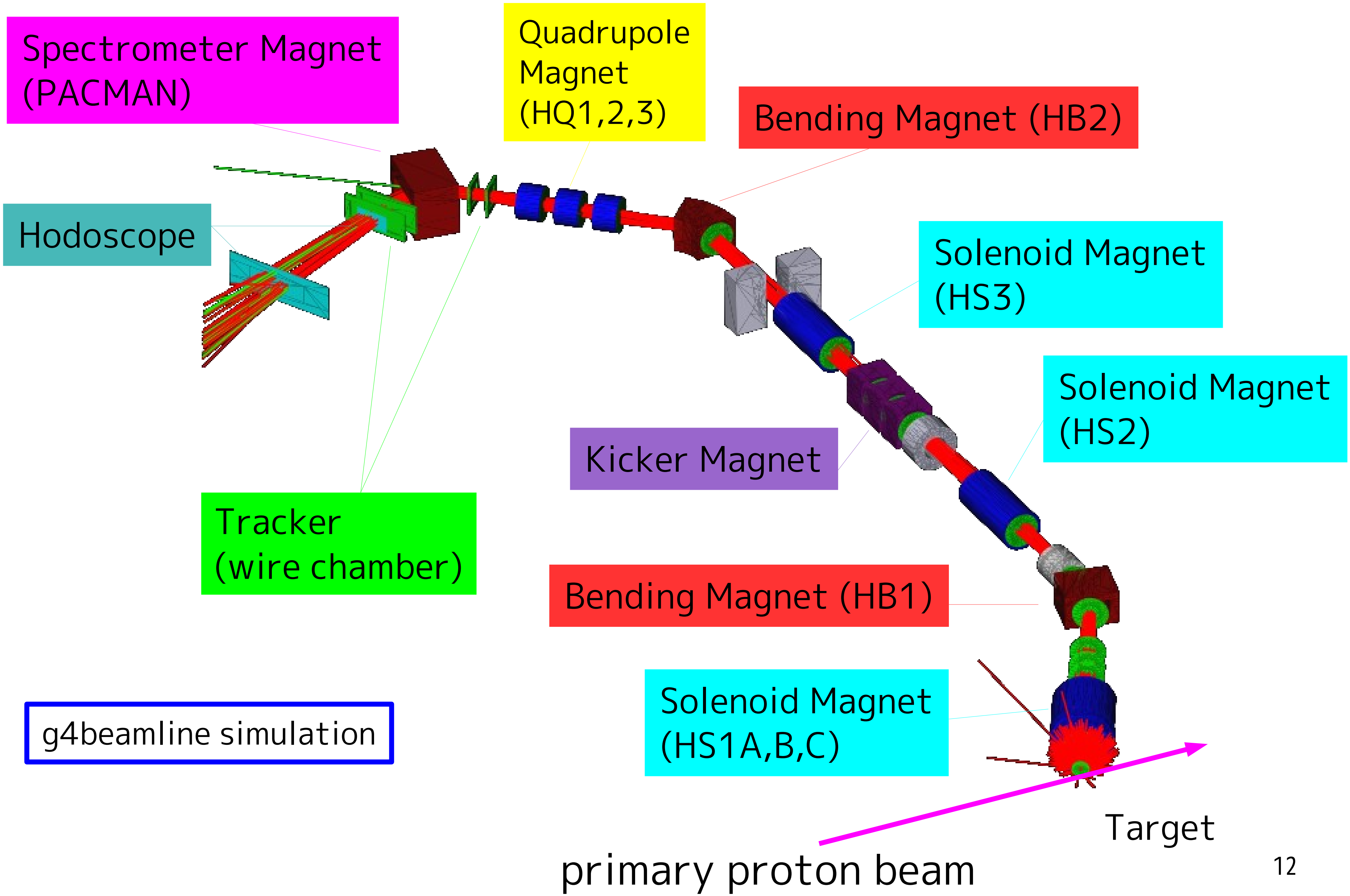
H-Line @ MLF MUSE

- proton beam
  3GeV, 1MW, 333μA
  Fast-Extracted pulse beam: 25Hz, double pulse
- H-Line is multipurpose beamline
  Conceptual Design by J.Doornbos
  - DeeMe
  - g-2/EDM
  - muonium HFS
  - μCF and other muon program





H-Line and DeeMe spectrometer

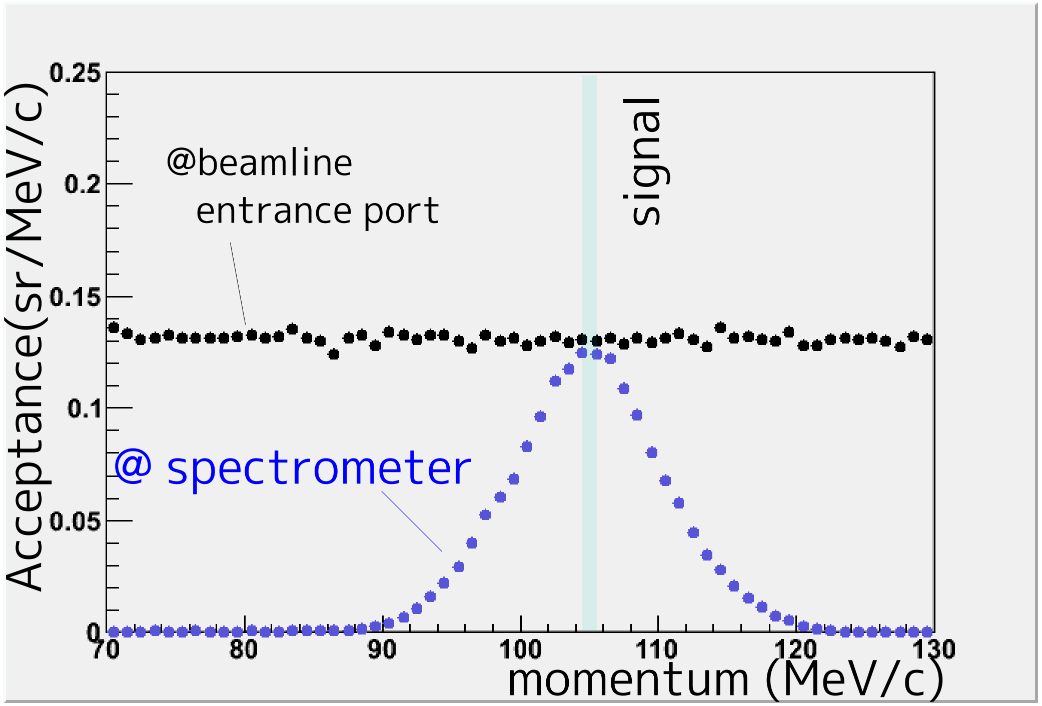


g4beamline simulation

H-Line

- Large acceptance
  - > 120 msr
    for signal electron(105MeV/c)
- moderate Δp
  →The backgrounds
    can be monitored simultaneously.
  - DIO backgrounds (p<102.5 Mev/c)
  - Prompt backgrounds (p>105 MeV/c)
- Detailed design is ongoing.
- HS1A,B, C and HB1 are already installed.

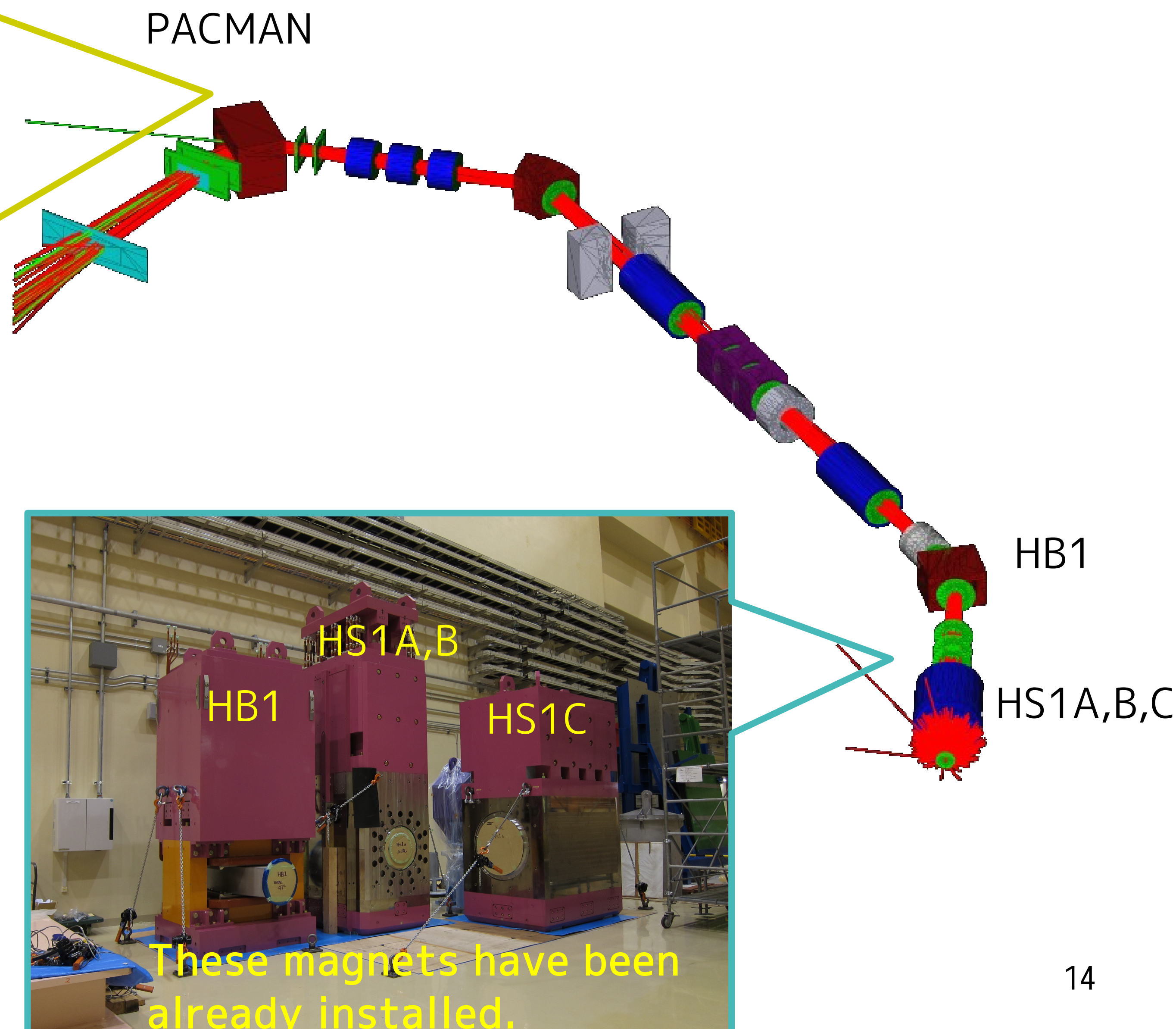
Momentum Acceptance



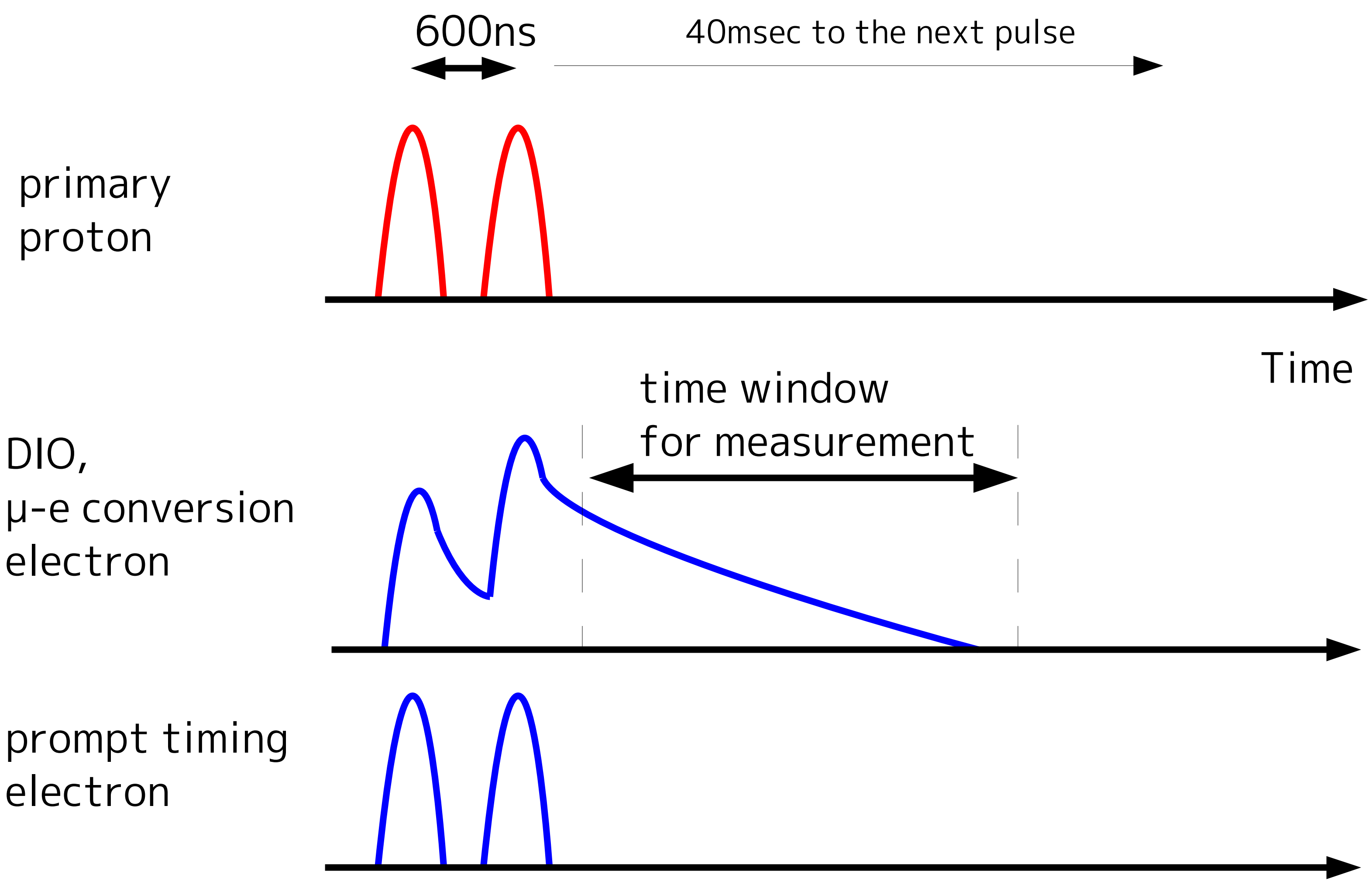
- PACMAN dipole magnet in TRIUMF is going to be borrowed for spectrometer bending magnet. Transportation procedures and examination of the performance with MC study are in preparation.

H-Line @ MLF MUSE

PACMAN @ TRIUMF

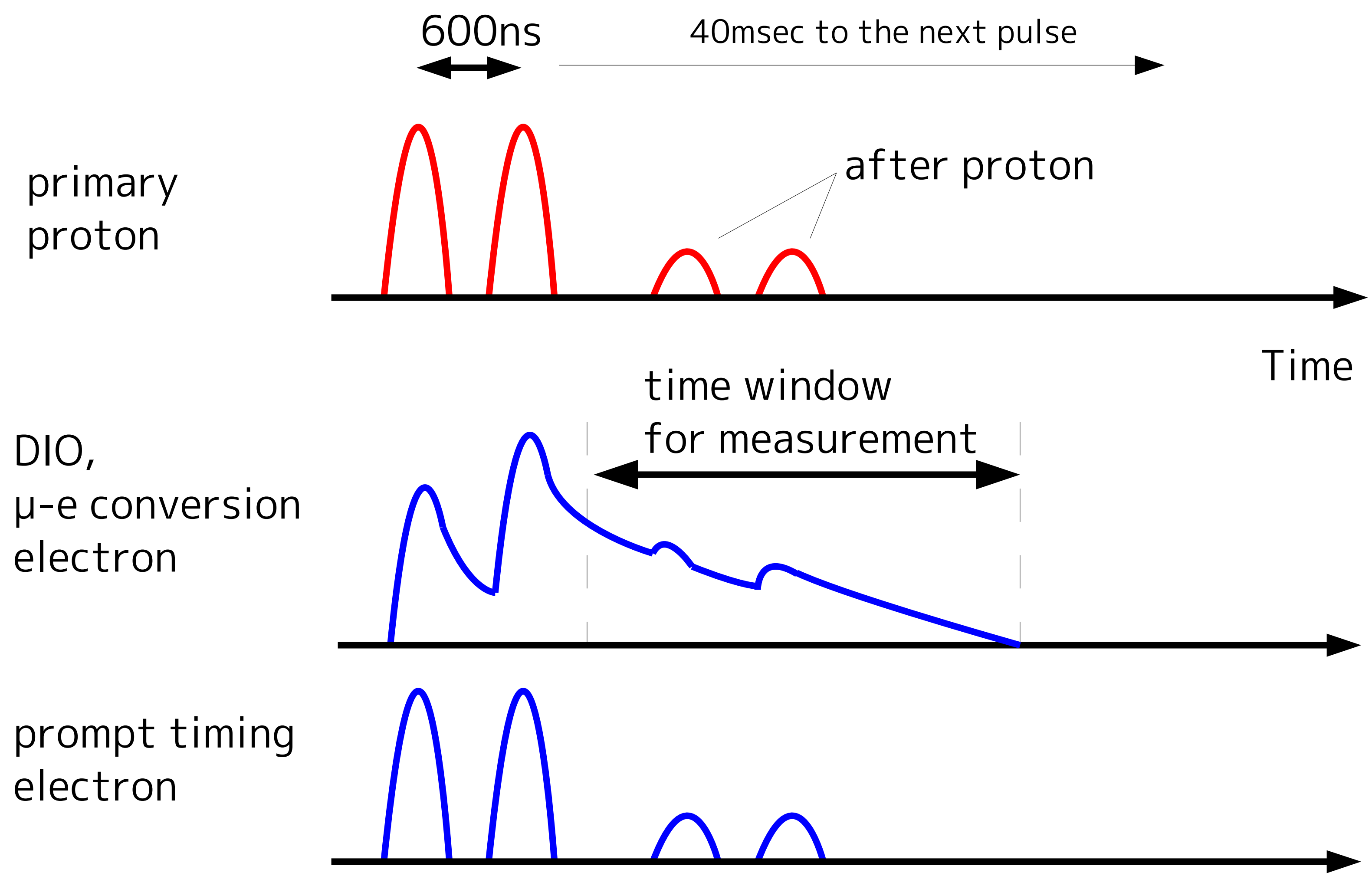


Time window



- To avoid the prompt timing backgrouds,
  the time window for measurement is delayed from
  the beam timing.

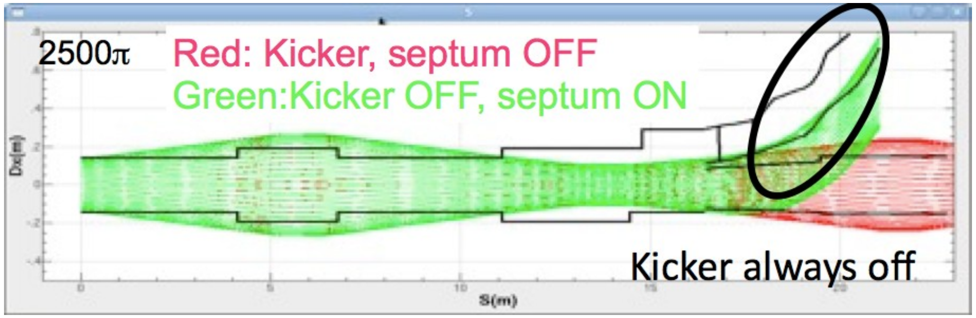
After Proton Background



- If off-timing protons exist, they create the prompt backgrounds in the time window for measurement.

After Proton Background

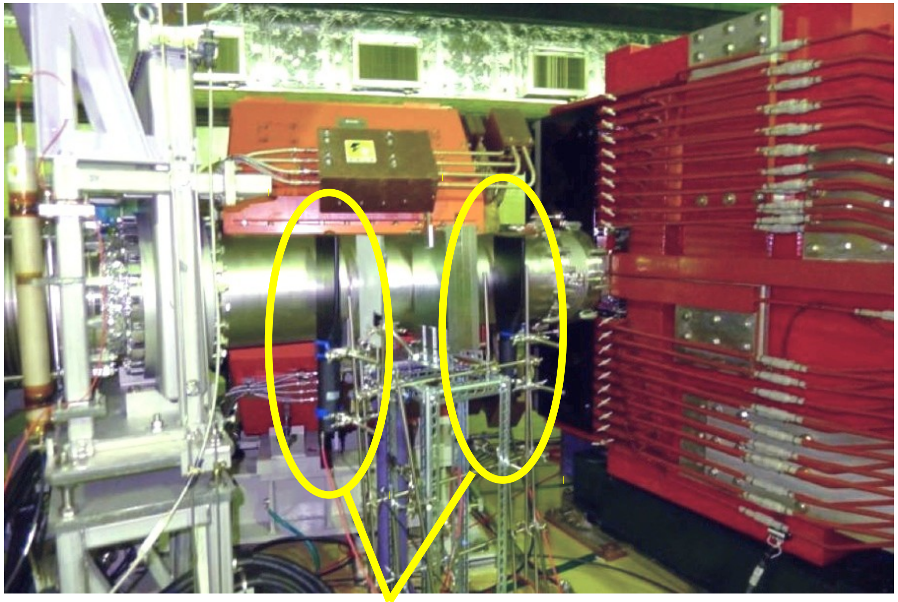
- Beam halo (2500π ~5xPhysical aperture) may produce after proton pulse.



- Measurement of after proton rate is ongoing.

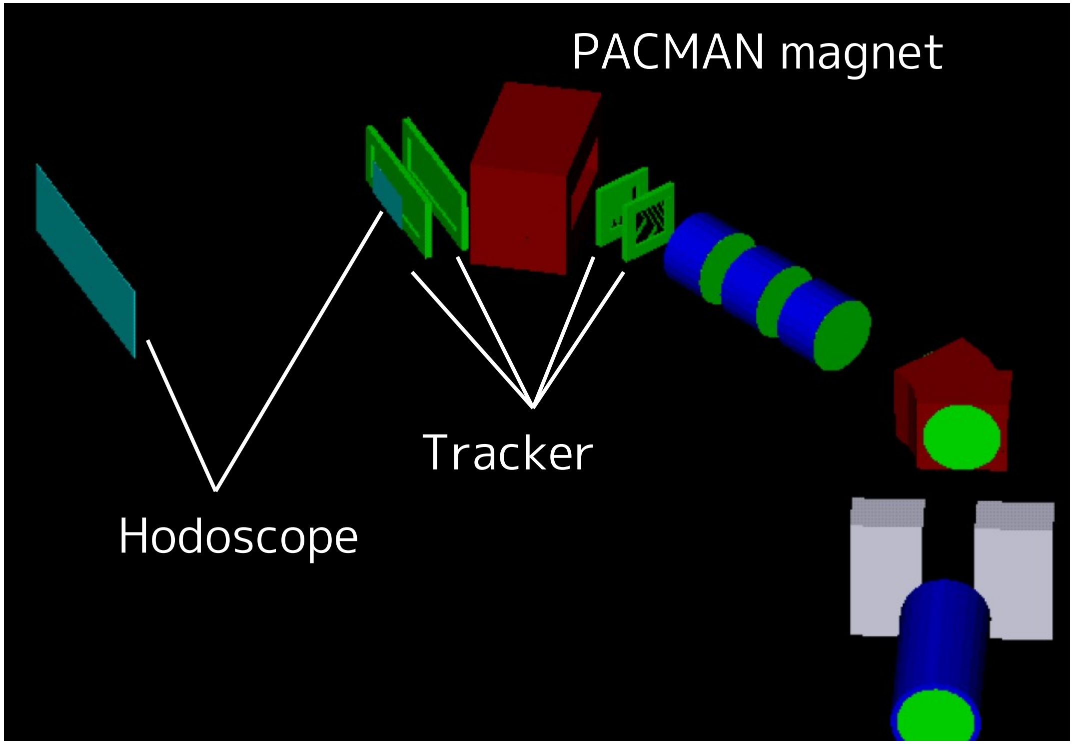
- After proton monitoring system will be established for physics run.

- Currently, after proton rate (R_{AP}) is estimated to be < 9×10^{-19} (ratio of After Proton to the main pulse)



scintillation counters

Tracker

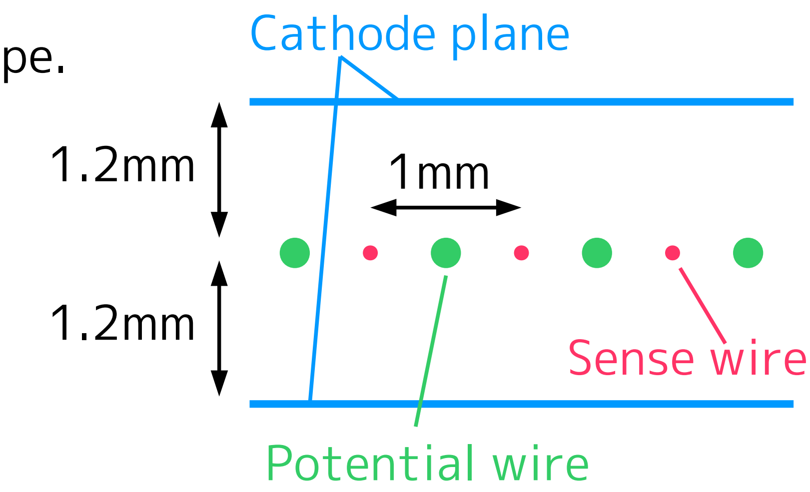


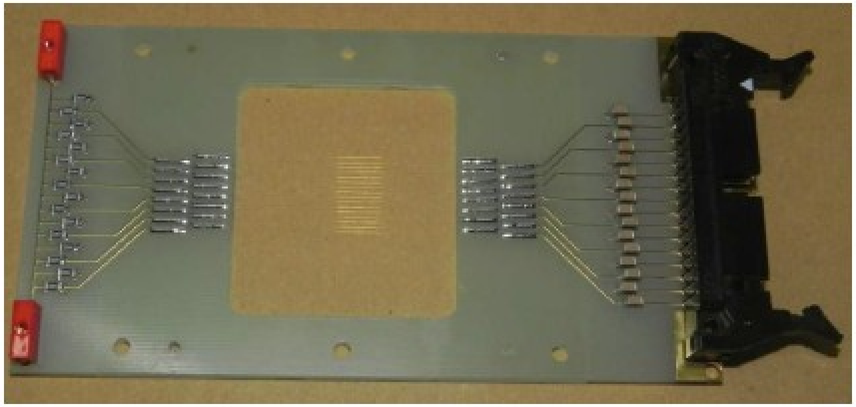
- Required resolution :
  $\delta P < 0.5$ MeV/c (RMS)
- According to prior MC study, this can be achieved when
  - tracker position resolution = 0.3 mm
  - 50 degree bending
  - 0.1% X_0
- Bending magnet (PACMAN, rectangular) will be operated with 70 degree bending.
  → Updated MC study is on going.

- Tracker should be operational 300ns after prompt electrons.
  (33k per pulse with reduction by kicker)
- Tracker currently planed : 300 mm x 300 mm thin MWPC
  1mm wire spacing

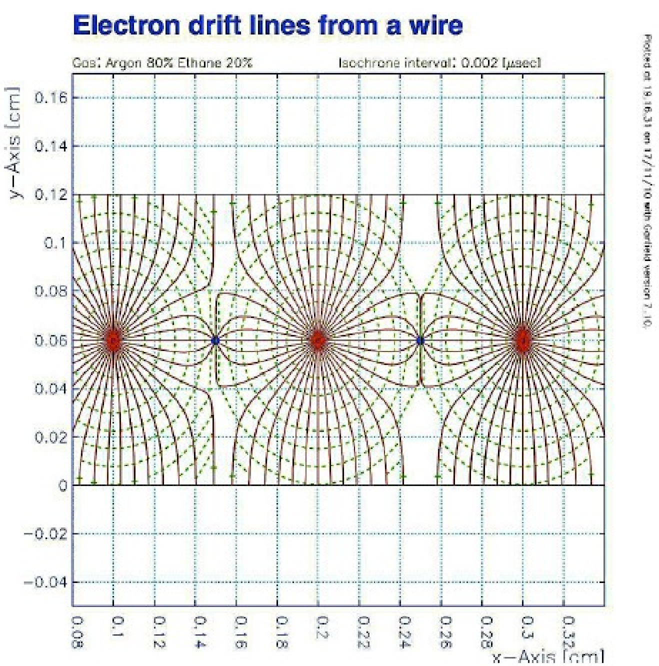
Prototype MWPC

- MWPC performance was studied using prototype.
  - Active area : 16 mm x 16 mm
  - 0.5 mm pitch
    16 sense wires (Φ 10μm)
    17 potential wires (Φ 30μm)
  - Anode-Cathode gap is adjustable
    (0.6 mm or 1.2 mm)





Anode wire frame



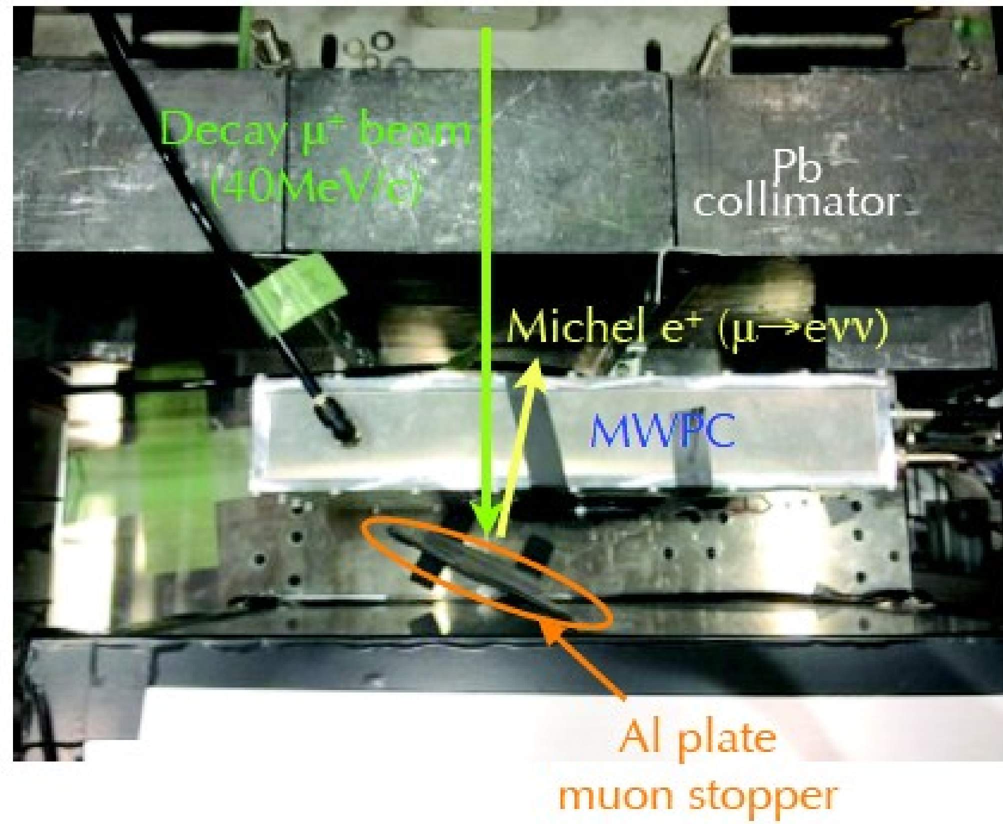
Drift line for gap=0.6mm
(calculated by GARFIELD)

Prototype beam test

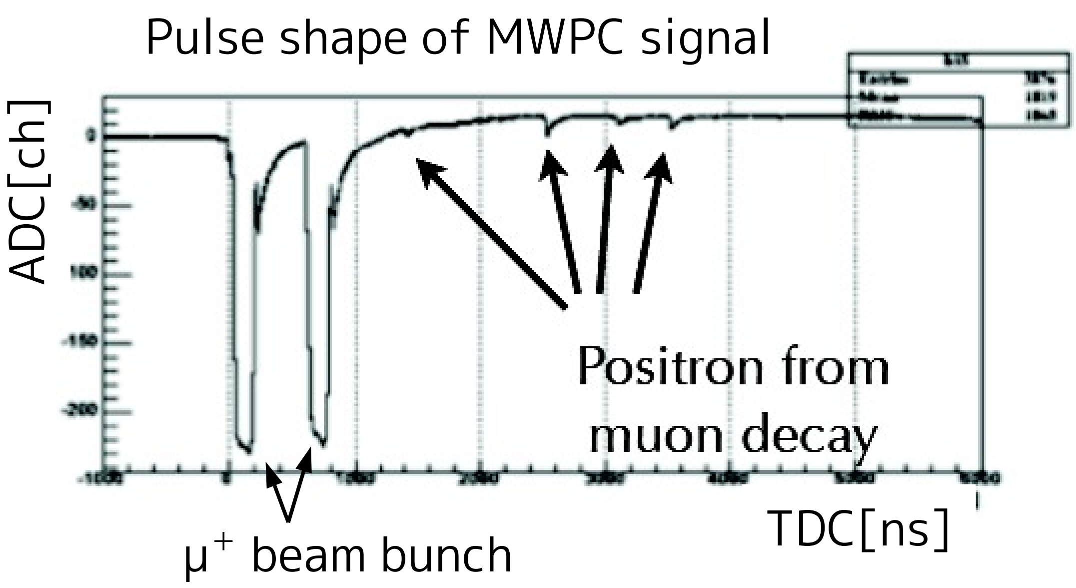
- Beam test of prototype was carried out at J-PARC MLF MUSE D2 beamline. (2013 Feb)
  - Same bunch structure
  - Muon beam 40MeV/c
  - Gas mixture : Ar/CO_2 90/10
  - MWPC HV : 950 V

- Tolerability was checked
  required...
  - 33k/ (300mm x 300mm) = 0.37 / mm2
  - 33k/ 300 wires = 110/wire

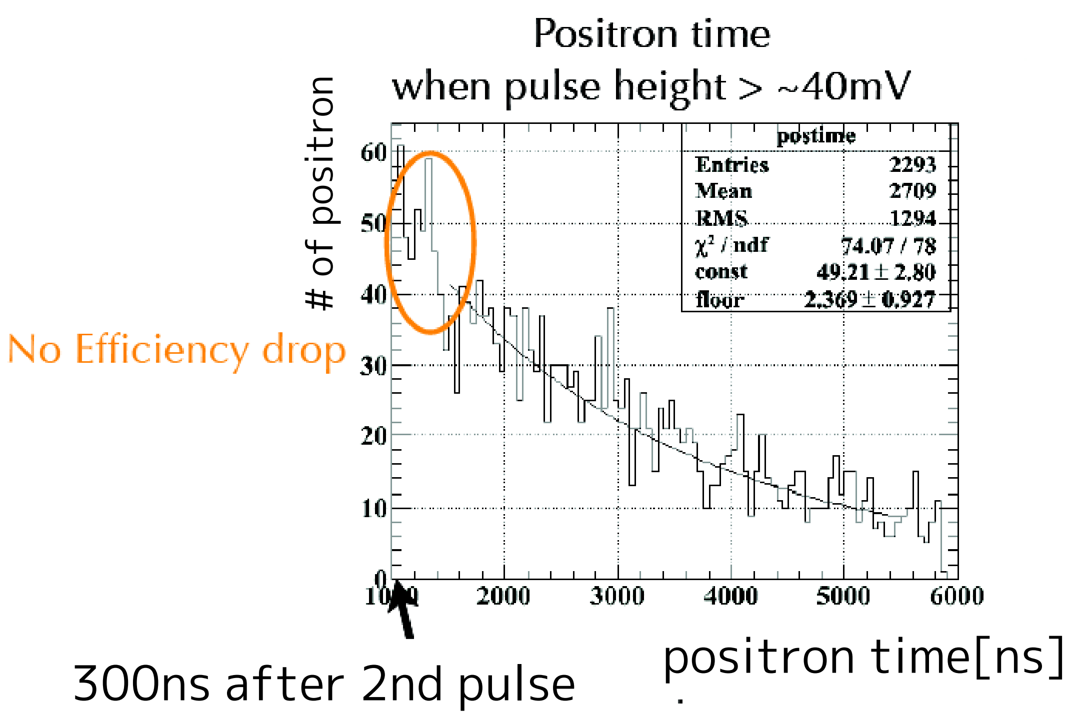
- Al muon stopper place was placed downstream of the chamber.
  →Delayed positrons were measured.



Prototype beam test result



- **No trip during beam test**
  - Deposit/ area (by μ^+ bunch) > 30 times of DeeMe condition
  - Also survived with electron beam ... 90 times of DeeMe condition
    → Prototype survived much severer condition than DeeMe.
  - Delayed positrons from μ^+ decay were measured.



- **No significant gain drop**
  - Time distribution of positrons was fitted by exponential. (const x exp(-time/2.2μsec) + floor)
  - No significant efficiency drop at early timing.

MWPC

- The 2nd prototype was constructed.
  (300mm x 300mm, the same size as the chamber used
  in the physics experiment)
- Beam test will be carried out in this September.

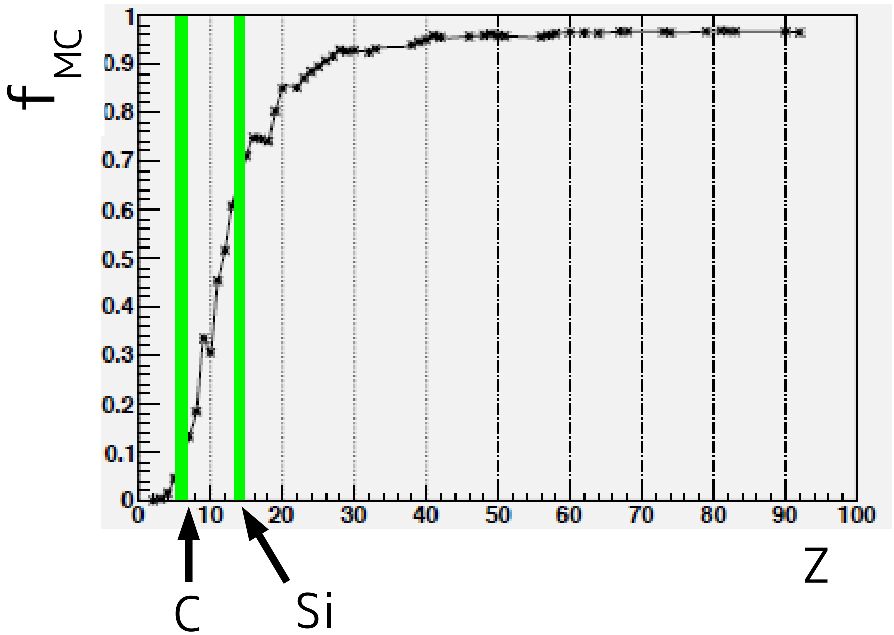
- If MWPC can survive the beam intensity,
  → •no kicker magnets , or
  •the number of kickers can be reduced.

↓

Development of MWPC is very important issue.

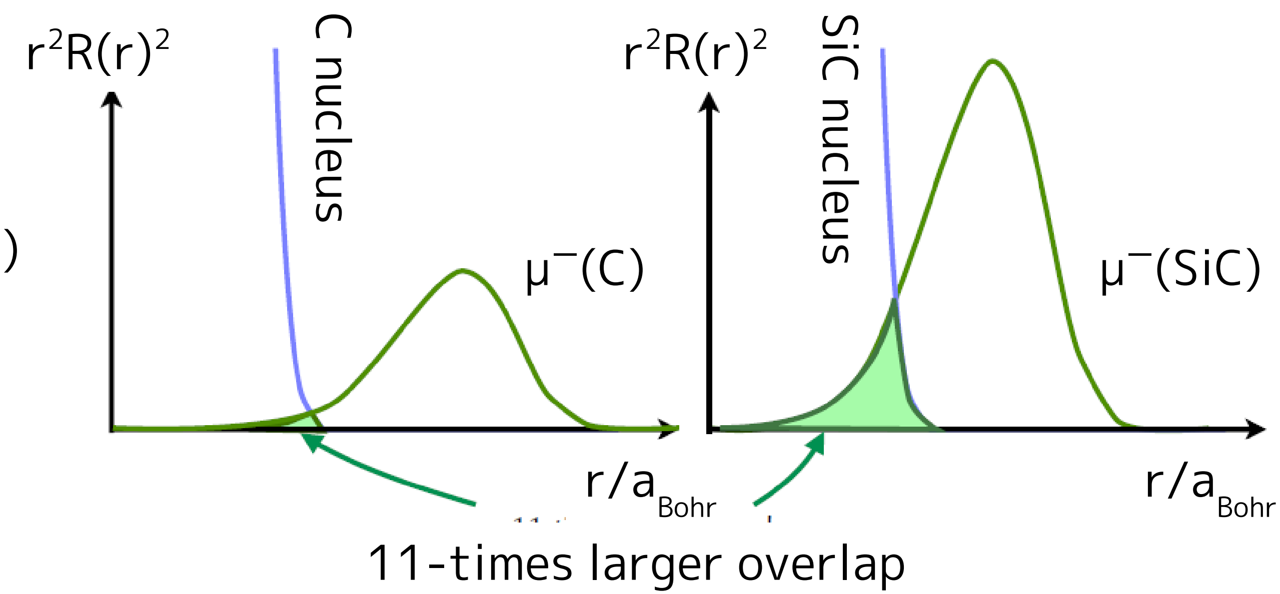
SiC target

- Currently, Carbide is used for muon production target at MLF MUSE.
- Larger muonic nuclear-capture rate(f_{MC}) is desirable.
- $\tau_{\mu-}$ > 300nsec (light Z) to avoid the prompt background
  - $\tau_{\mu-}$(in Si) = 0.76 μsec



- f_C : Fraction of the atomic capture of muon to the atom of interest
  - single-element material : f_C = 1
  - composite material: proportional to Z (Fermi-Teller Z law)

Silicon-Carbide (SiC)
→ Si : C = 7 : 3



SiC target

- SiC target :
  ~**6 times higher physics sensitivity** than Carbide target

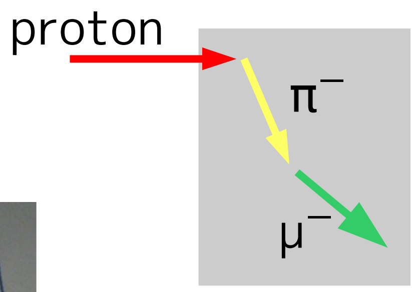
Material	f_C x f_{MC}
Graphite (C)	0.08
Silicon-carbide (SiC)	0.46

- Radiation and heat effect on other beamline at MUSE and downstream of SiC target
  → ongoing study

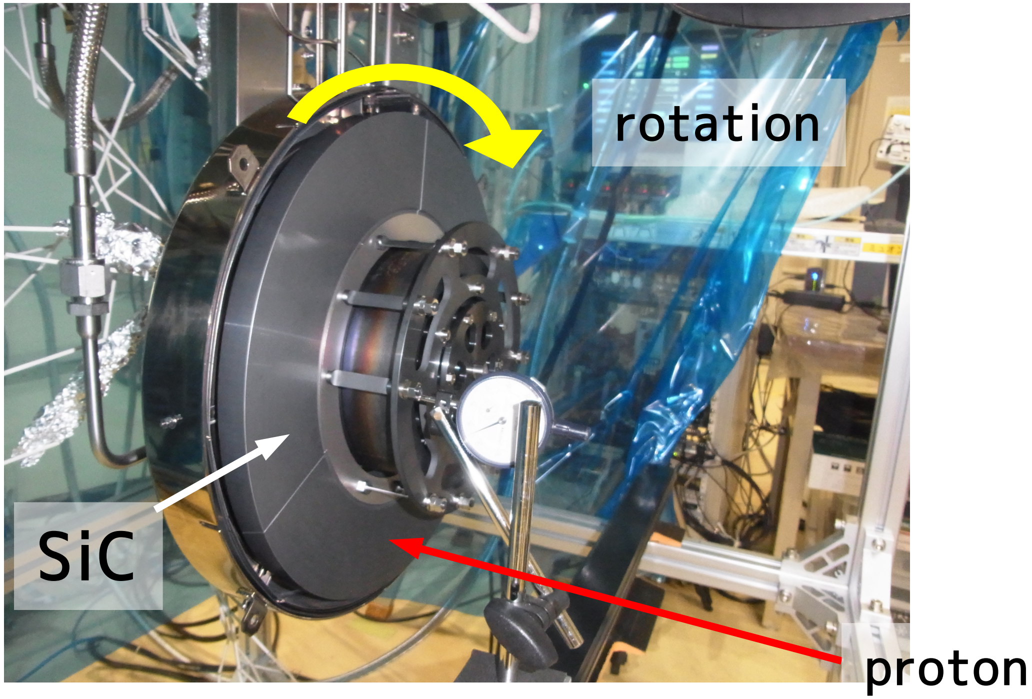
SiC target

- Technological benefit
  - good thermal shock resistance: ΔT = 450℃
  - high melting point: > 1450℃
  - good radiation resistance: 10dpa @ 1000℃ or more
- In DeeMe experiment ...

  SiC = muon production and muon stopping target



- Rotating SiC target R&D is ongoing.
  - rotation for heat diffusion

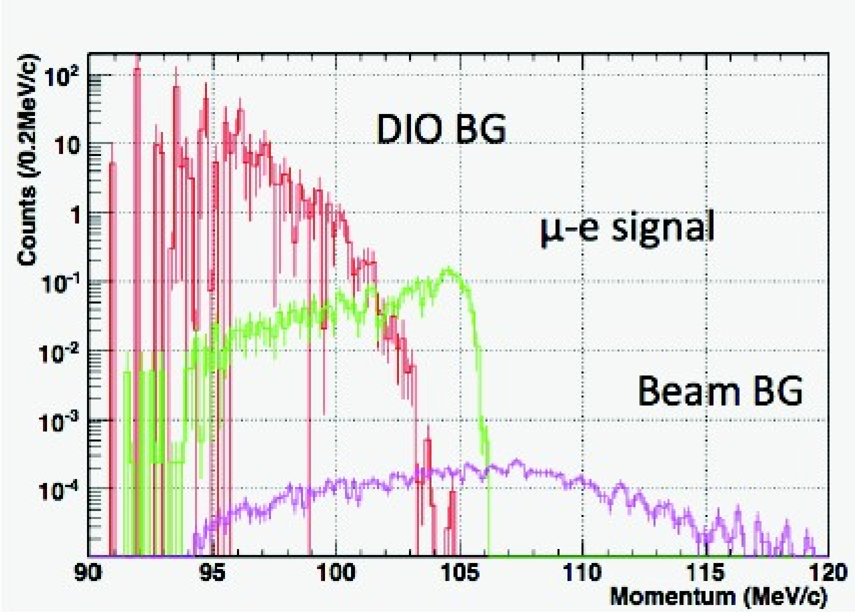


prototype SiC rotating target

rotating target assembly (for C target)

Sensitivity and Backgrounds

- **Signal Sensitivity**
  S.E.S (single event sensitivity) = $\mathbf{2 \times 10^{-14}}$
  (1MW proton beam, 2×10^{7}sec)



- **Backgrounds**
  - After proton rate (R_{AP}) < 9×10^{-19}
  - Detector live-time duty = 1/20000
    → Cosmic ray backgrounds are suppressed.
  - No anti-protons

Decay in Oribit	0.09
After proton	< 0.027 (0.05 90% C.L.)
Cosmic induced e	< 0.018 (MC stat. limited)
Cosmic induced μ	< 0.001
Radiative muon capture	< 0.0009

Current Status & Summary

- Experimental search for μ-e conversion in nuclear field is planned at J-PARC/MLF/MUSE (DeeMe) .
  - single event sensitivity = 2×10^{-14}
- DeeMe already has Stage-1 approval from KEK/IMSS/MUSE PAC.
- Beamline is under construction.
  - J-PARC/MLF/MUSE H-Line
  - beamline design
  - Magnets at entrance port has been installed.
- Production target R&D is ongoing.
  - rotating SiC target
- Preparations of detectors at spectrometer are in progress.
  - MWPC
    final design, prototype beam test
- Updated Monte Carlo simulation study is under way.
- Physics data taking is planned to start from 2015.