# Search for muon to electron conversion at J-PARC MLF

## - Recent status of DeeMe -

Yohei Nakatsugawa
KEK

NUFACT2014
University of Glasgow
2014 Aug 25-30

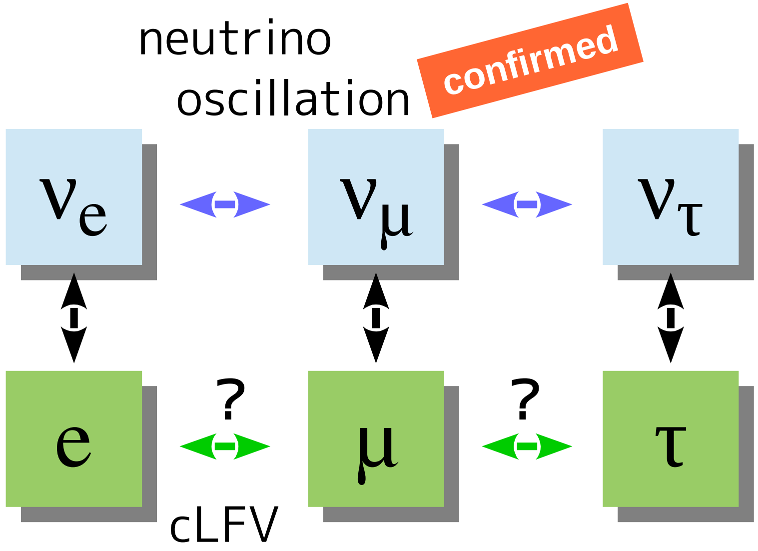
# Collaborators

M. Aoki[1], D. Bryman[2], M. Ikegami[3], Y. Irie[3,4], S. Ito[1], N. Kawamura[4,5], M. Kinsho[6], H. Kobayashi[3], S. Makimura[4,5], H. Matsumoto[3], S. Meigo[6], T. Mibe[7], S. Mihara[7], Y. Miyake[4,5], H. Natori[7], H. Nishiguchi[7], T. Numao[8], C. Ohomori[3], S. Ritt[9], P.K. Saha[6], N. Saito[5,7], Y. Seiya[10], K. Shimizu[10], K. Shimomura[4,5], P. Strasser[4,5], Y. Takezaki[10], N. Teshima[10], N.D. Thong[1], N.M. Truong[1], K. Yamamoto[6], K. Yamamoto[10], M. Yoshii[3], K. Yoshimura[11]

[1] Osaka University
[2] University of British Colombia
[3] Accelerator Laboratory, KEK
[4] Institute of Materials Structure Science, KEK
[5] J-PARC Center
[6] JAEA
[7] Institute of Particle and Nuclear Studies, KEK
[8] TRIUMF, Vancouver
[9] PSI
[10] Osaka City University
[11] Okayama University

# Contents

# Charged Lepton Flavor Violation

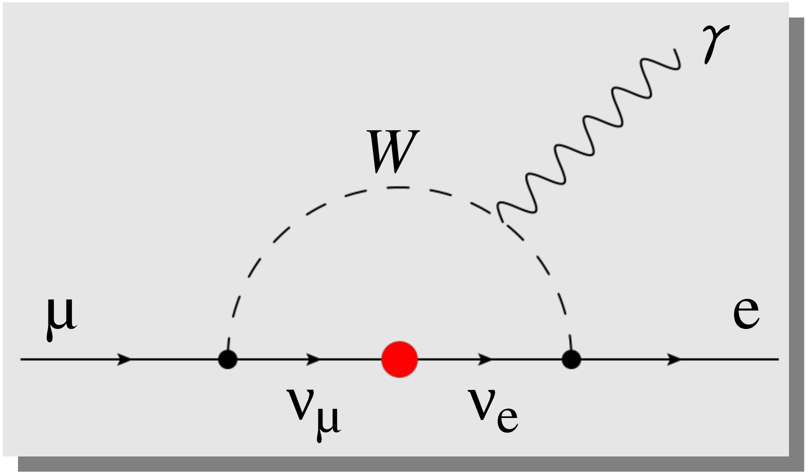



- Lepton Flavor Violation is forbidden in the original Standard Model.
- Neutrino oscillation = Flavor Violation of neutral lepton
- Charged Lepton Flavor Violation ( cLFV )
  - process : $\mu \to e\gamma$ , $\mu \to eee$ , $\mu N \to eN$
  
  … **not observed yet**

- cLFV induced by neutrino flavor mixing

$$BR(\mu \to e \gamma) = (\Delta m_{vij}^{2} / M_{W}^{2})^{2} \sim 10^{-50}$$

**too small to be observed experimentally**
**<u>in the framework of the Standard Model</u>**



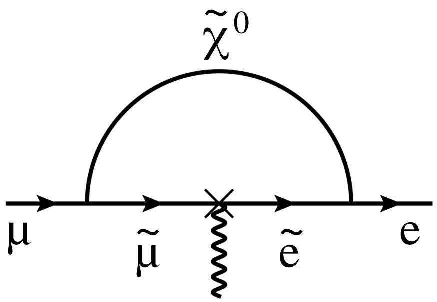

**experimental observation of cLFV process**

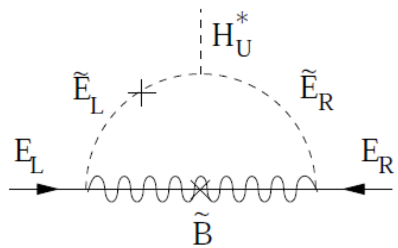
**=**

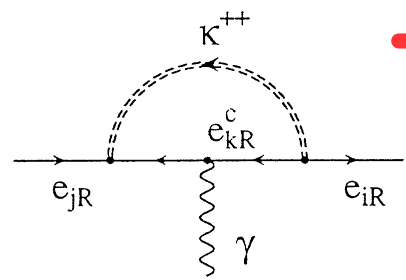
**clear evidence of the new physics beyond the Standard Model**

# Charged Lepton Flavor Violation

- Theoretical models beyond the Standard Model
  ( SUSY-GUT, SUSY-seesaw, Doubly Charged Higgs , etc.. )




**sizable BR of cLFV processes**

- predicted branching ratio = $\mathbf{10^{-14} \sim 10^{-18}}$ (ex. SUSY-GUT)

- current upper limit from experiments

$\mu^- N \rightarrow e^- N$

SINDRUM-II : $BR(\mu^- Au \rightarrow e^- Au) < \mathbf{7 \times 10^{-13}}$
SINDRUM-II : $BR(\mu^- Ti \rightarrow e^- Ti) < \mathbf{4.3 \times 10^{-12}}$
TRIUMF : $BR(\mu^- Ti \rightarrow e^- Ti) < \mathbf{4.6 \times 10^{-12}}$

$\mu^+ \rightarrow e^+ \gamma$

MEG : $BR(\mu^+ \rightarrow e^+ \gamma) < \mathbf{5.7 \times 10^{-13}}$

- The discovery is right around the corner.

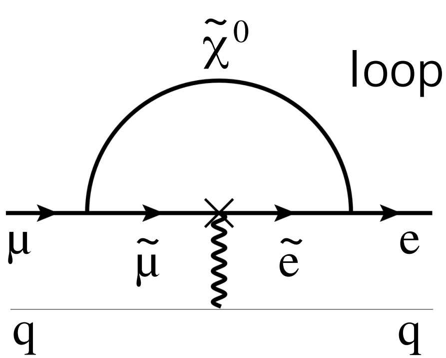
⇒ **A new experimental search with sensitivity under $10^{-13}$ should be started in a timely manner.**

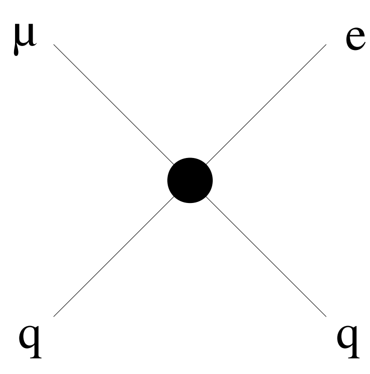
# Photonic and Non-photonic Process

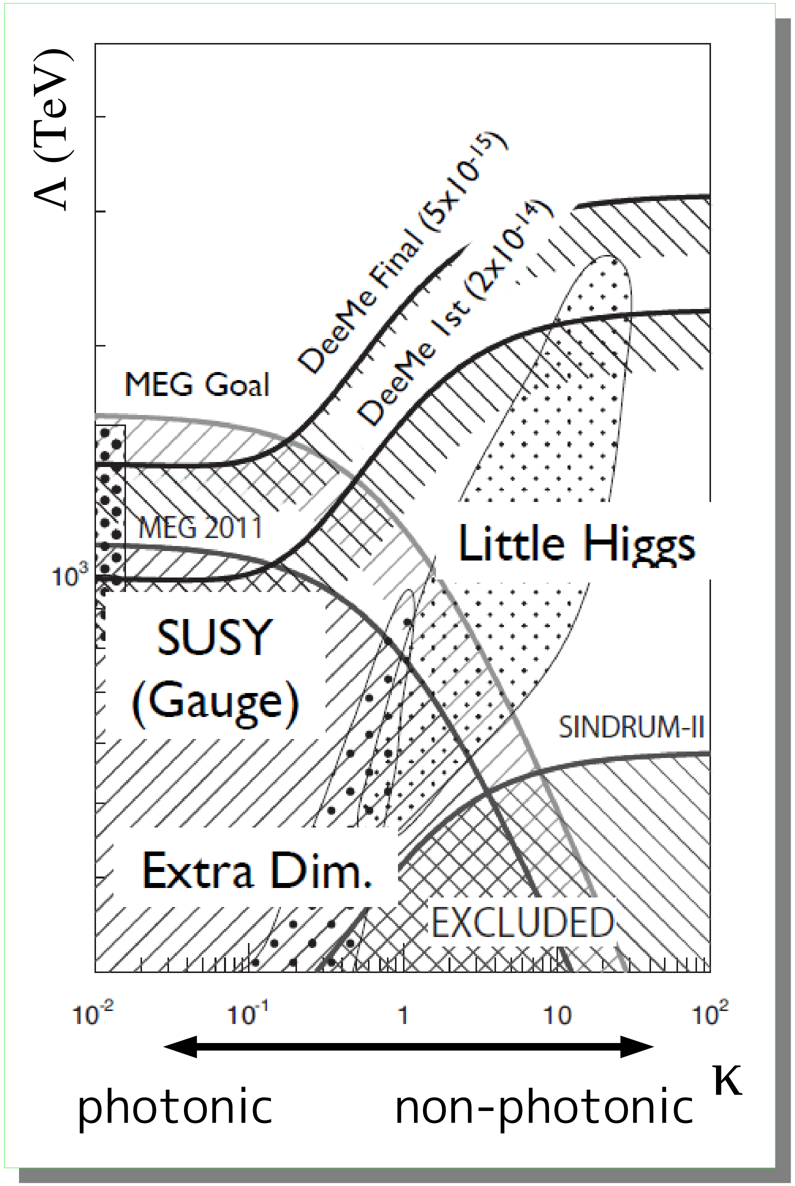
- Effective Lagrangian

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\overline{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{q}_L\gamma_\mu q_L)$$

photonic non-photonic



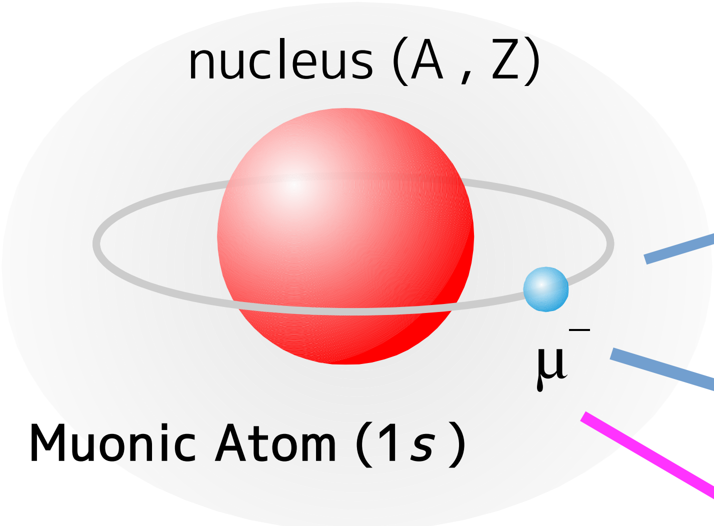




- μ − e conversion in the nuclear field

**... sensitive to both photonic**

**and non-photonic processes**

# Muon to Electron Conversion in the Nuclear Field




## Decay In Orbit (DIO)

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

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

## Muon Capture

nucleus (A, Z-1), $\nu_\mu$

$$\mu^- + N(A, Z) \rightarrow \nu_\mu + N(A, Z-1)$$

## μ – e conversion

$e^-$, nucleus (A , Z)

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

- ▶ charged lepton flavor violation process
- ▶ monochromatic signal electron ( **105 MeV/c** )
- ▶ no accidental backgrounds
- ▶ main backgrounds
  - Muon Decay In Orit
  - Radiative Pion Capture ← **prompt timing**

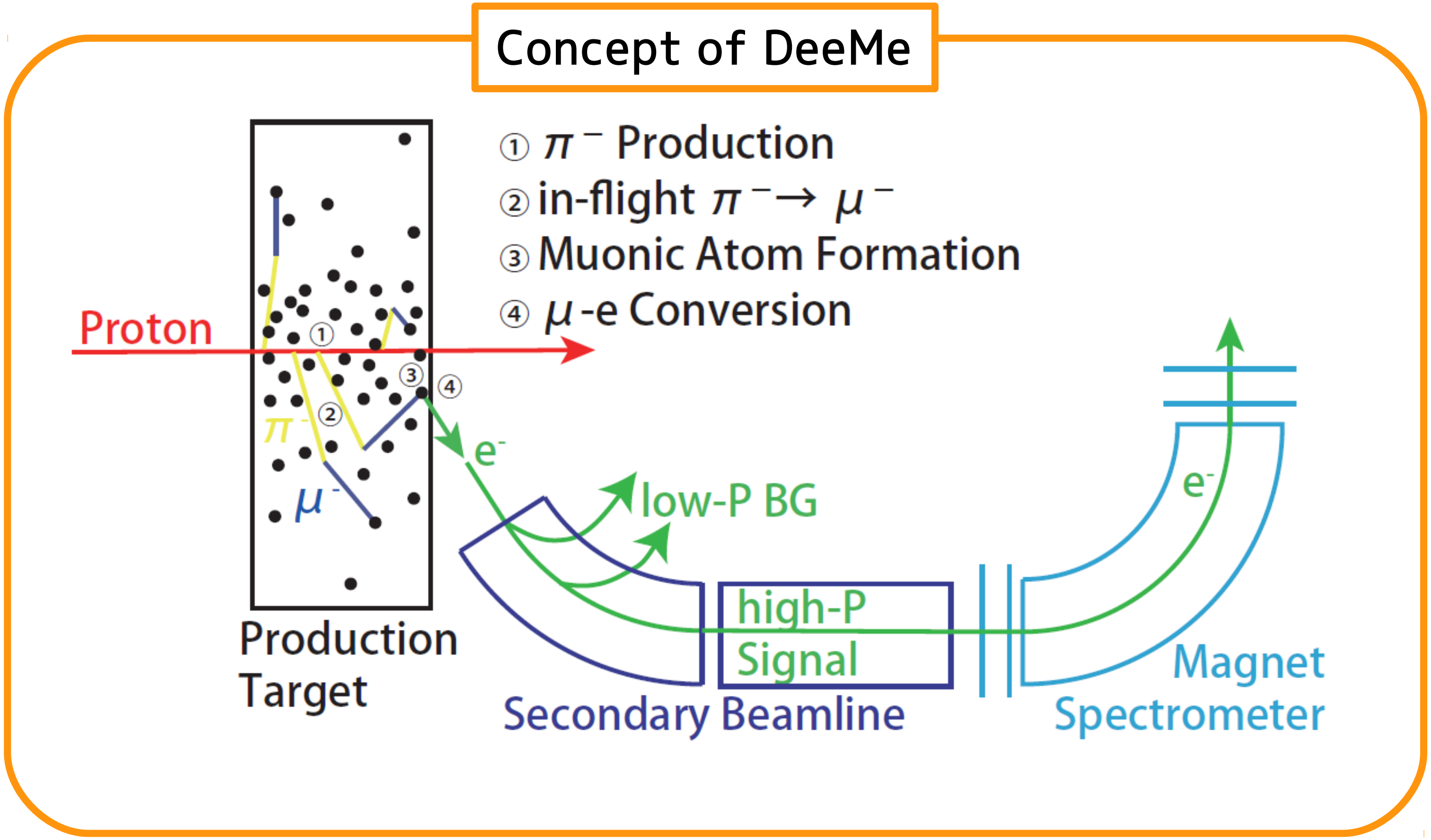
    $\pi^- + N(A,Z) \rightarrow N(A,Z-1)^*$

    $\rightarrow \gamma + N(A,Z-1)$ , $\gamma \rightarrow e^+ e^-$
  - After proton induced background

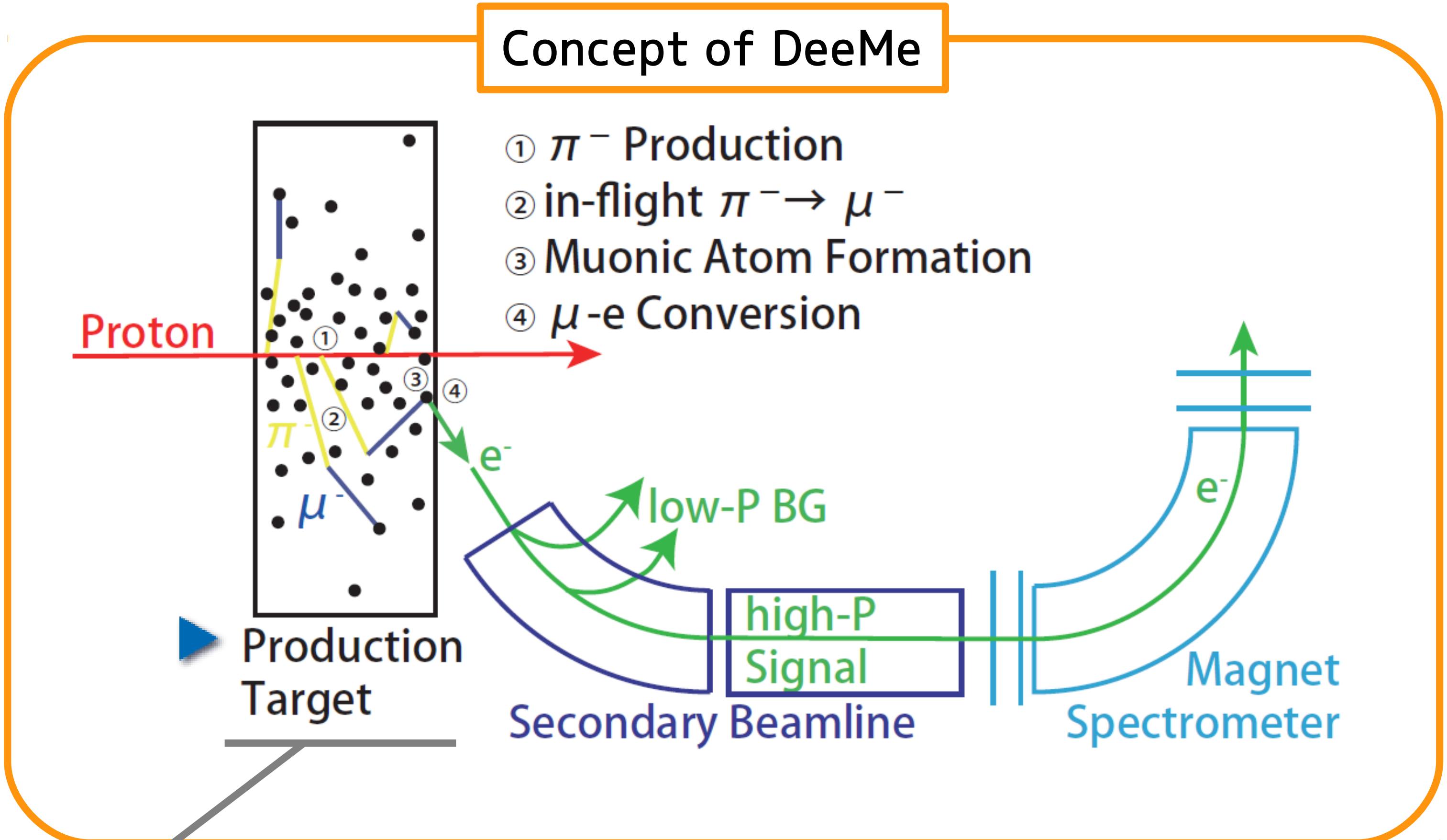
•Definition of the branching ratio

$$BR(\mu - e \text{ conv.}) = \frac{\Gamma(\mu - e \text{ conv.})}{\Gamma(\text{Muon Capture})}$$

# DeeMe Experiment



# DeeMe Experiment

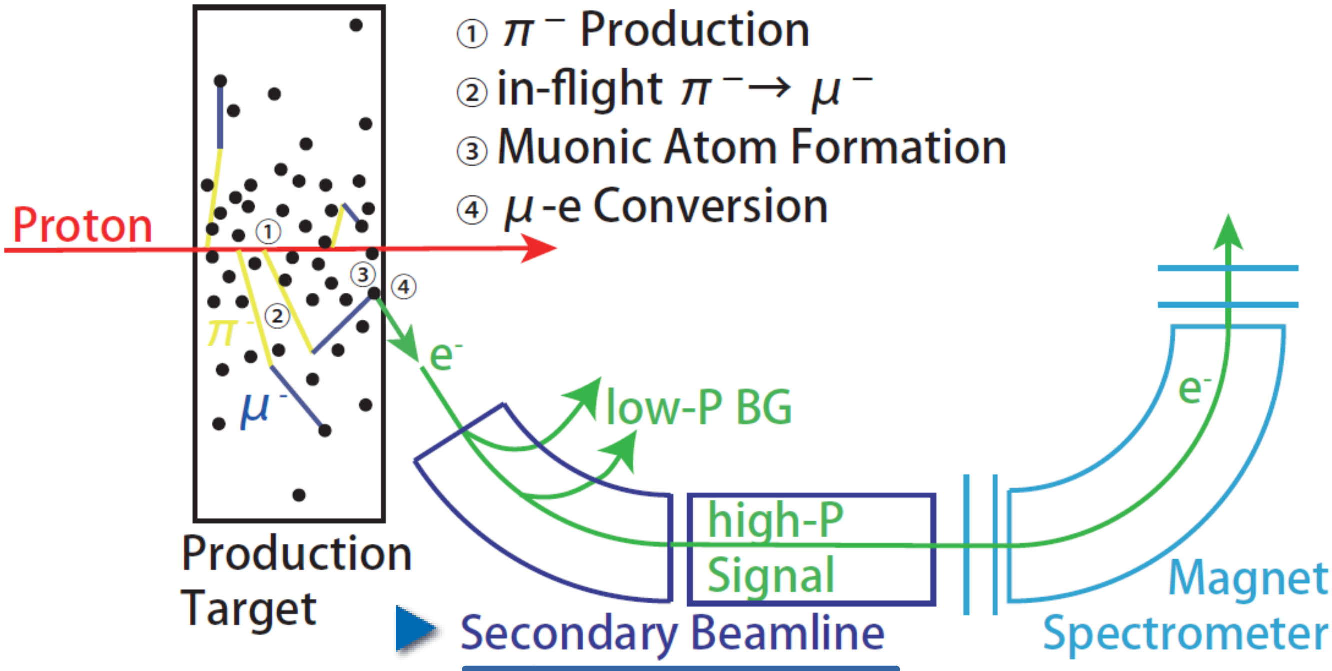



- = $\mu^-$ stopping target
- utilize muonic atoms formed in the production target → NO $\pi^-$ decay volume, NO additional stopping target ⇔ conventional μ–e search

⇒ **unique technique of DeeMe experiment**
- low cost
- early realization

# DeeMe Experiment

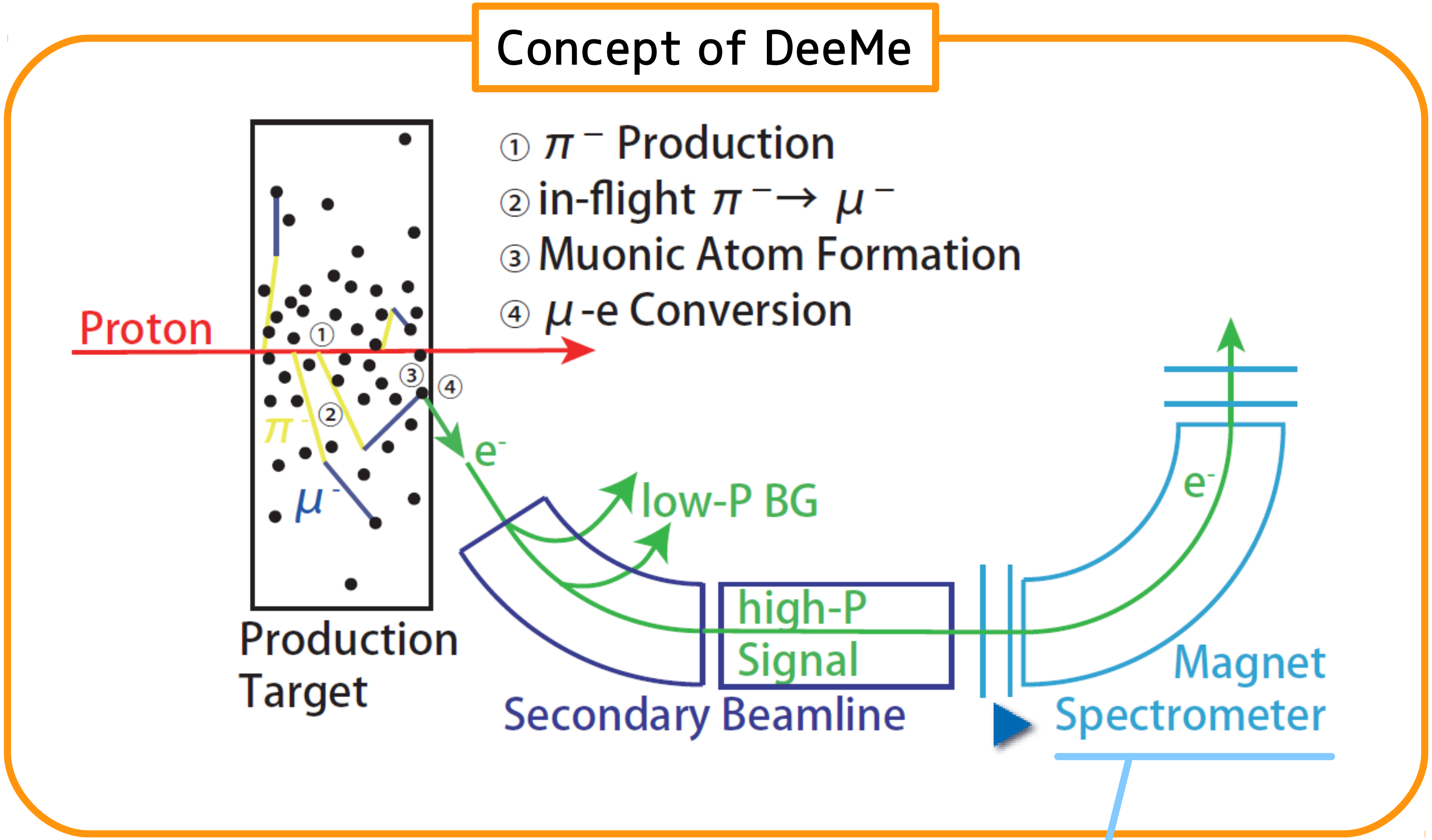
## Concept of DeeMe




- transport signal electrons (105 MeV/c)
- Beam optics is optimized for signal electrons.

  ⇒ ・momentum selection
  
  ・suppress low momentum backgrounds

# DeeMe Experiment

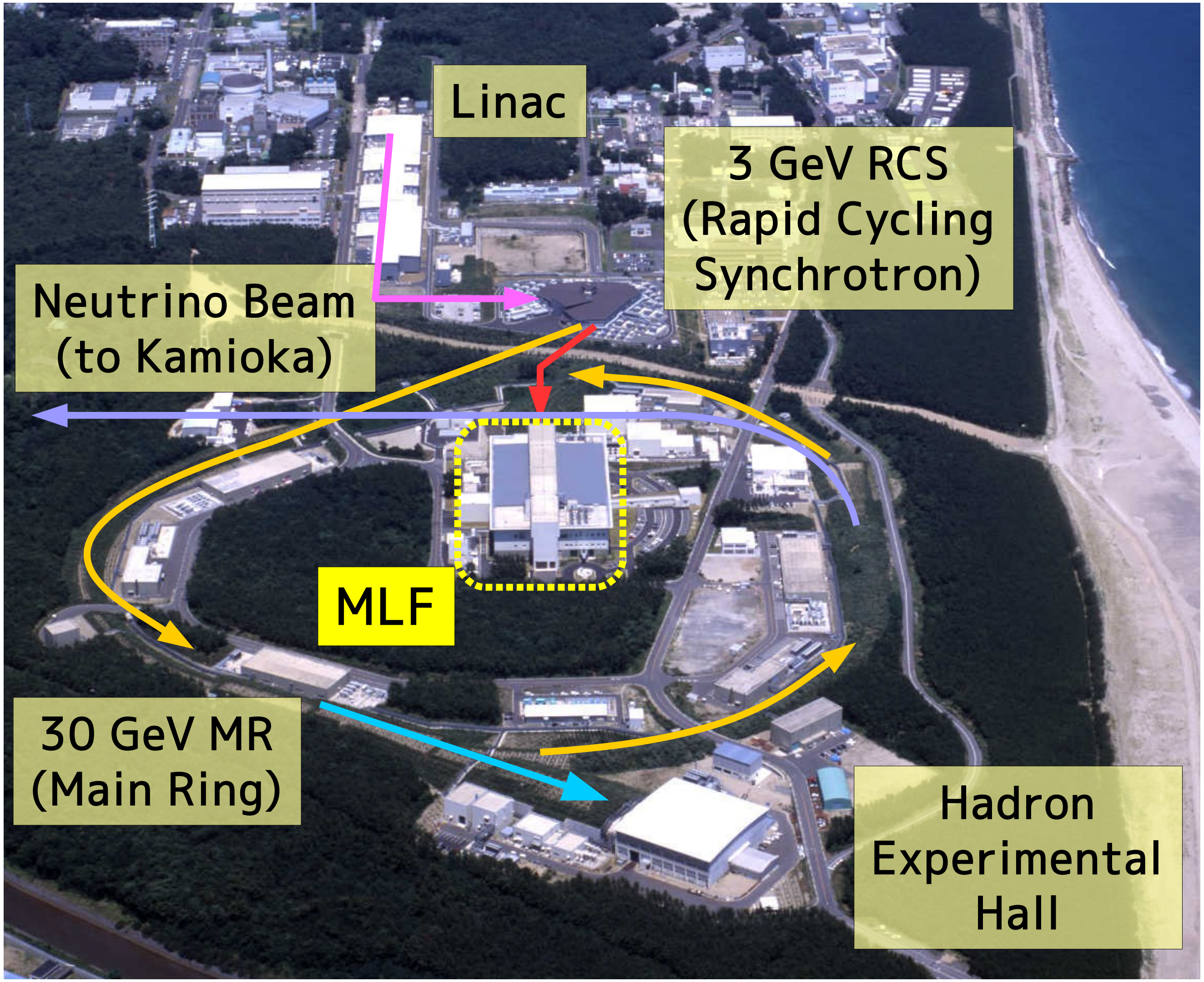



- momentum analysis
- identify signal electrons
- DIO spectrum

- spectrometer magnet & tracking device (MWPC)

# J-PARC MLF

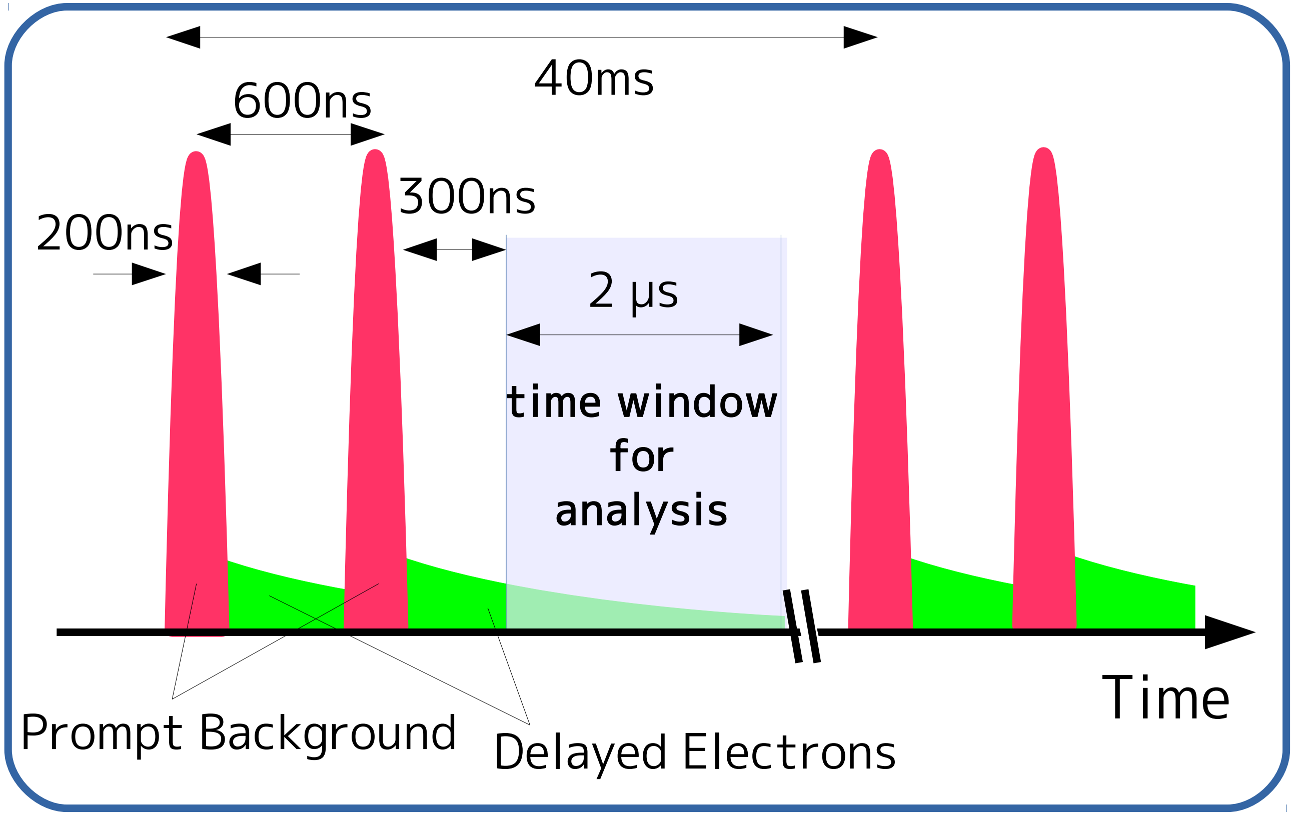
- DeeMe experiment is planned at
  **J-PARC Material and Life Science Experimental Facility (MLF)** .




- MLF
  - primary proton beam
    - **3 GeV, 300 kW**
      → will be upgraded to **<u>1 MW</u>** .
    - **Fast-Extracted pulse** beam
    - 25 Hz, double pulse
  - muon production target
    → 4 beamlines (MUSE)
  - neutron production target
    → more than 20 beamlines

# Beam Structure , Time Window

- pulsed proton beam
  - 25 Hz   double pulse: 200nsec width, 600nsec interval
  - **Time window for analysis at <u>300nsec</u> after the second pulse**
    **⇒ reject the prompt burst**

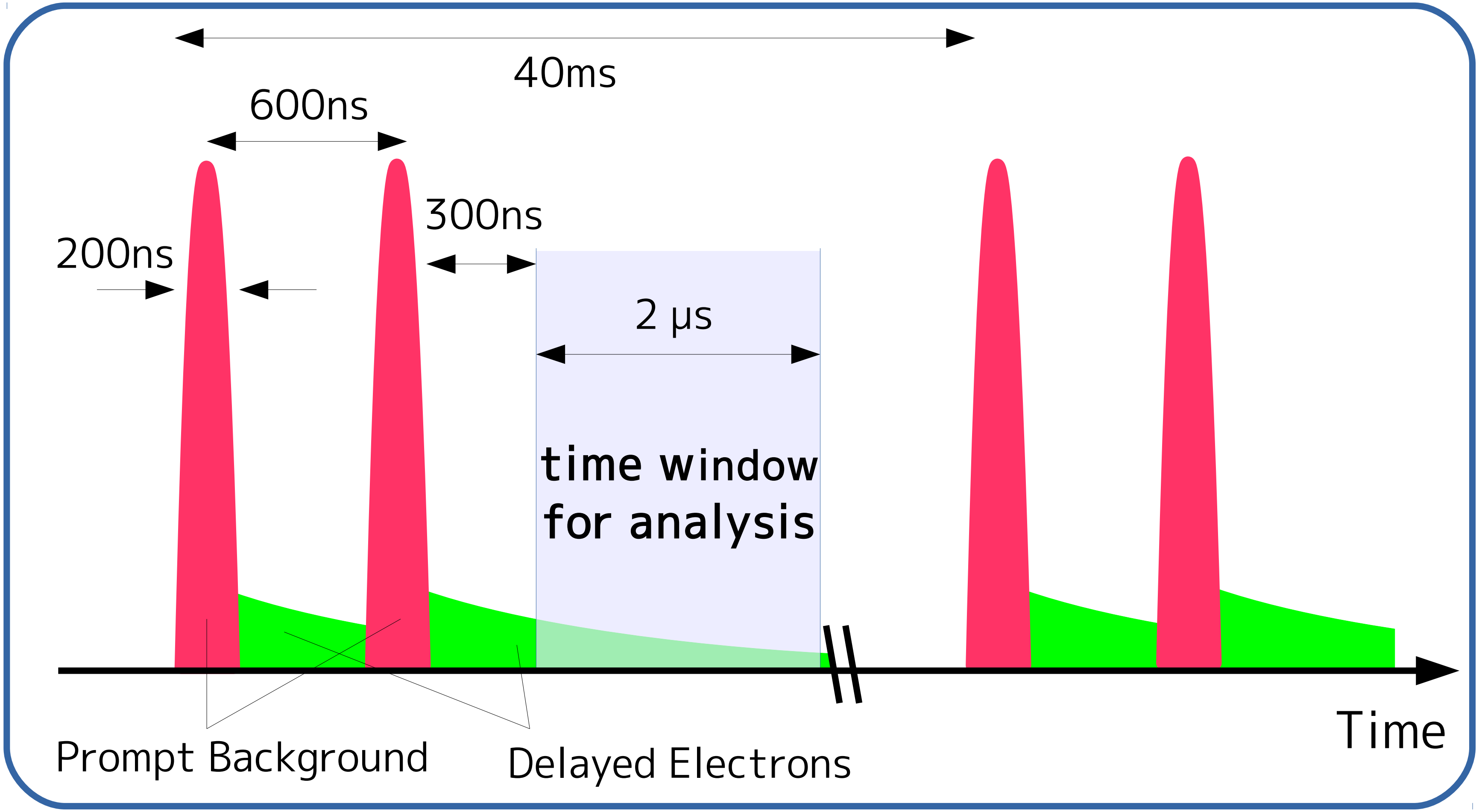



- beam energy = 3 GeV
  - < $\bar{p}$ production threshold
     no $\bar{p}$ induced backgrounds
- fast extraction
  - no off-timing proton
     no prompt background at time window

# Time Window for Delayed Electrons

- pulsed proton beam
  25 Hz  double pulse: 200nsec width, 600nsec interval

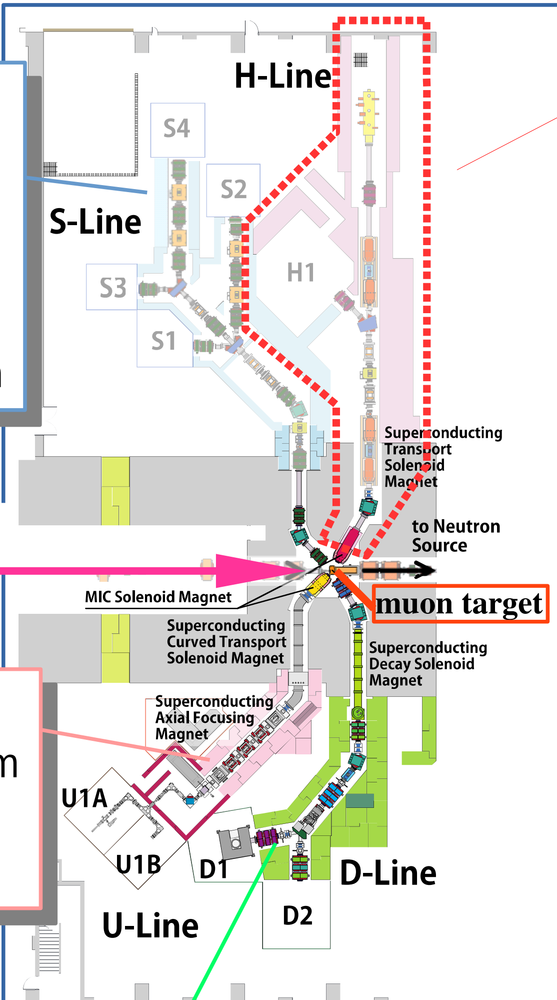
⇒ **Time window for analysis is set at <u>300nsec</u> after the second pulse.**



## J-PARC MLF Muon Science Establishment (MUSE)

S Line
surface μ⁺ beam (30 MeV/c)
material science
under construction

3GeV proton beam




U Line
ultra slow μ⁺ beam
(0.05-60 keV)
material science

D Line
surface μ⁺ beam (30 MeV/c)
decay μ⁺/μ⁻ beam (5-120 MeV/c)
material science
in operation for users' experiment

**H Line** <u>for fundamental physics</u>

- multipurpose beamline
  - μ-e conversion search (DeeMe)
  - muonium hyperfine splitting
  - g-2/EDM
  - muon microscopy
- conceptual design by Jaap Doornbos (TRIUMF)
- under construction

MUSE related talk:

- WG4 Aug, 26 P. Strasser
  "Status of the New Muonium HFS Experiment at J-PARC/MUSE"
- WG4 Aug, 27 Y. Miyake
  "J-PARC MUSE"
- WG4 Aug, 27 T. Adachi
  "Tuning of the ultra slow muon beamline by utilizing ionized hydrogen."

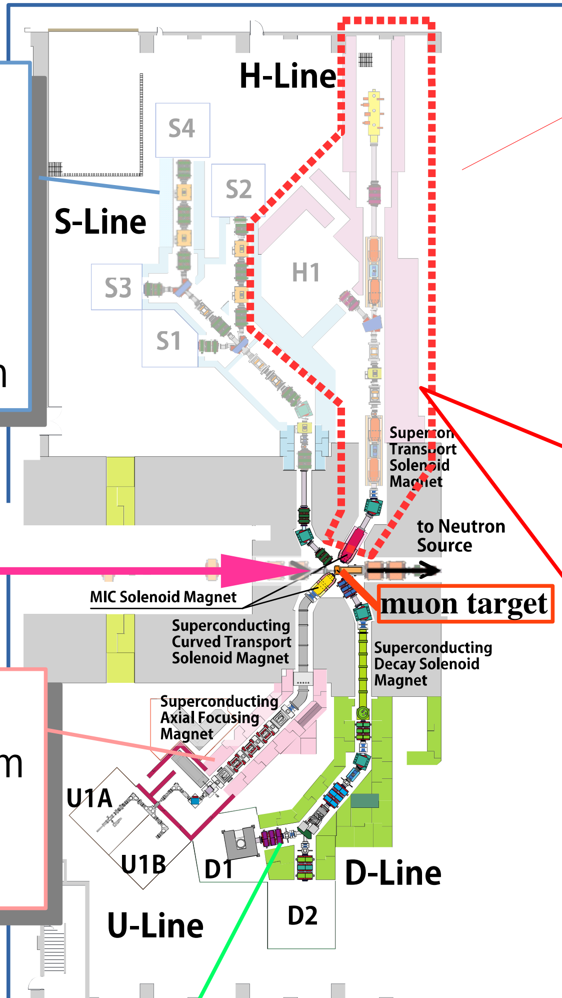
# MLF MUSE H Line

## ▶ J-PARC MLF Muon Science Establishment (MUSE)

S Line
surface μ⁺ beam
(30 MeV/c)
material science
under
construction

U Line
ultra slow μ⁺ beam
(0.05-60 keV)
material science

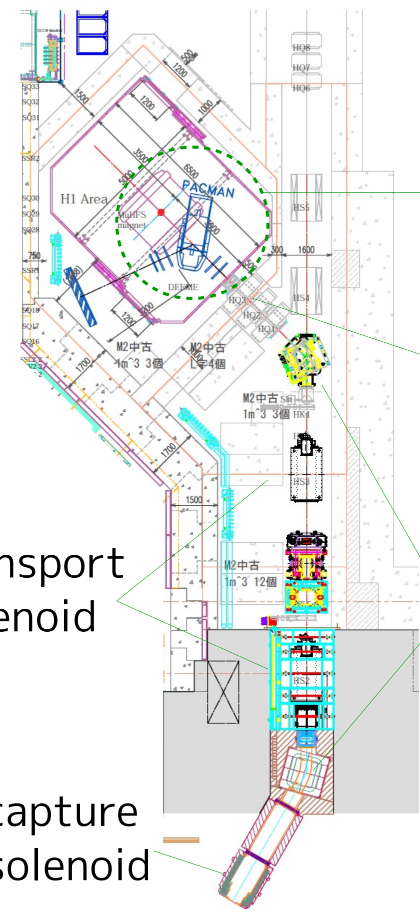
3GeV proton beam




D Line
surface μ⁺ beam (30 MeV/c)
decay μ⁺/μ⁻ beam (5-120 MeV/c)
material science
in operation for users' experiment

**H Line** <u>for fundamental physics</u>

- multipurpose beamline
  - μ-e conversion search (DeeMe)
  - muonium hyperfine splitting
  - g-2/EDM
  - muon microscopy
- co




DeeMe spectrometer

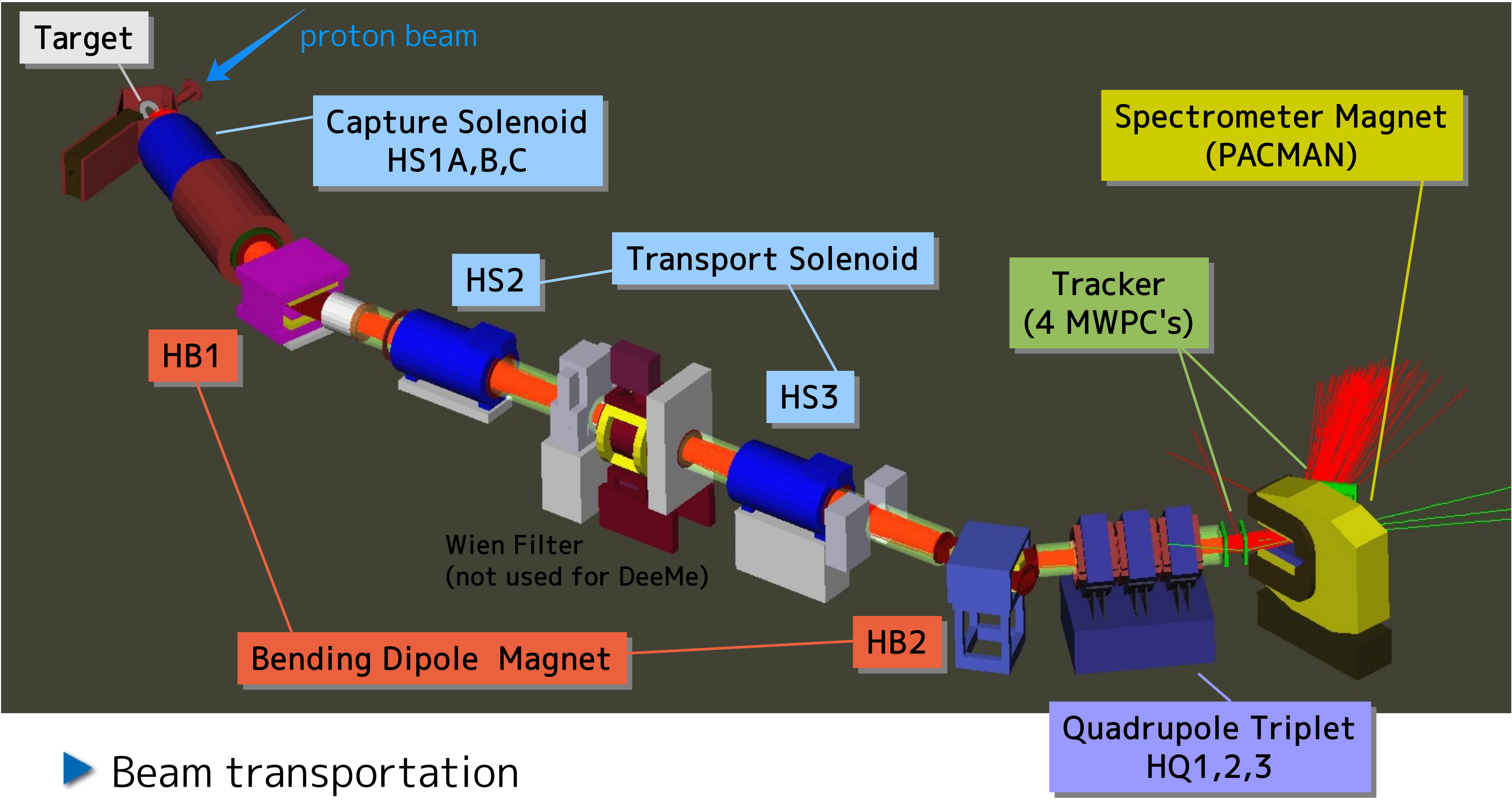
quadrupole

transport solenoid

bending magnet

capture solenoid

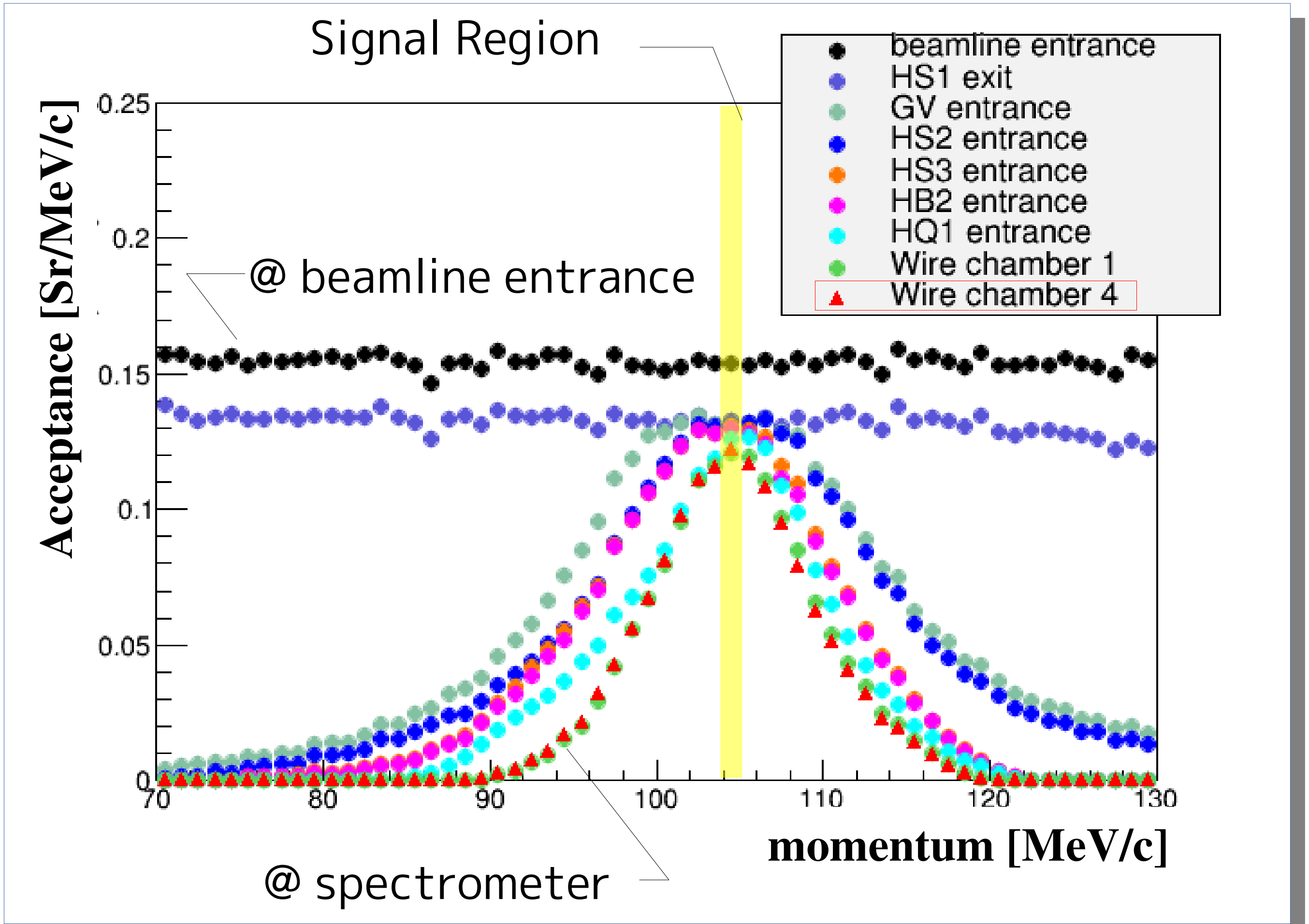
# H Line & DeeMe Spectrometer




- Beam transportation
  simulated by **G4Beamline**

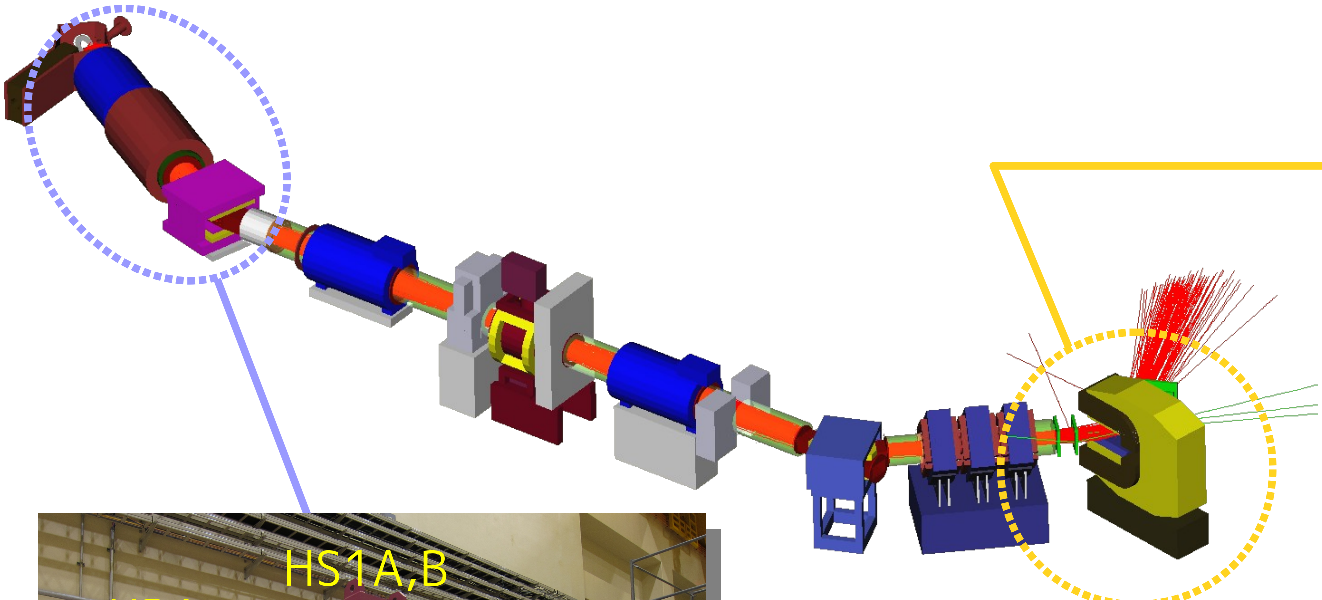
# Performance of H Line

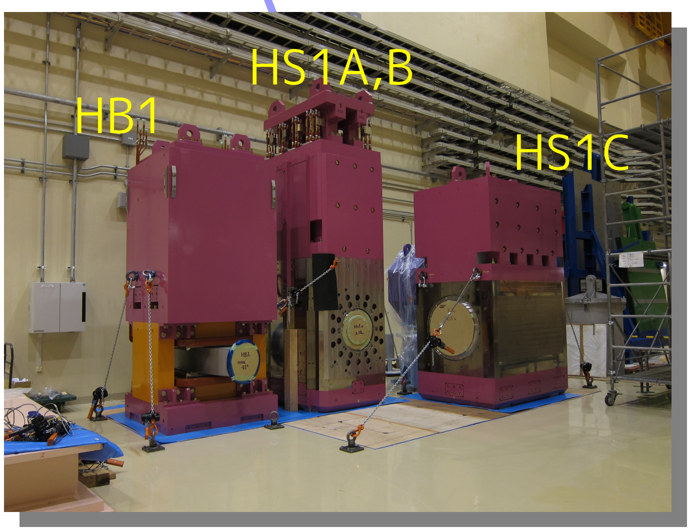
- simulated by G4Beamline
- Beam Optics
  optimized for signal electrons from μ−e conversion ( **105 MeV/c** )
- Acceptance of H Line ( transmission efficiency )
  … obtained as a function of momentum




- > **120 mSr/(MeV/c)**
  @ signal region
- moderate Δp
  ( **90 – 120 MeV/c** )
- **Backgrounds can be monitored simultaneously.**
  - low momentum:
    Decay In Orbit spectrum
  - high momentum:
    prompt background
    (after proton)

# Magnets of H Line





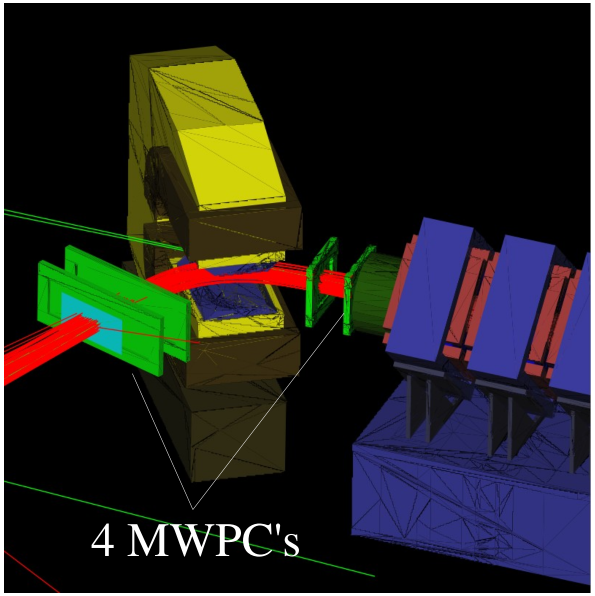

- **PACMAN Magnet**
  - used for PIENU exp.
    @ **TRIUMF** M13 area
  - **just moved to J-PARC MFL**
  - dipole , rectangular type
  - bending angle = **70 degree**

- **Upstream Magnets**
  **HS1A, B, C and HB1**
  ... already installed

# PACMAN Magnet

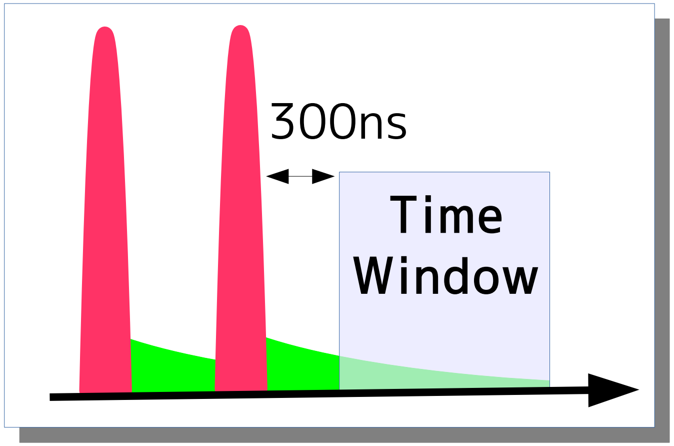
- PACMAN has just been transported from TRIUMF to MLF.
  - shipped from Vancouver
  - arrived at Tokyo Bay on Aug 14
  - brought in MLF on Aug 19

# Tracker




- Spectrometer
  - momentum analysis
  - identify signal electrons (105 MeV/c)
- Tracking Device
  - Thin **Multi Wire Proportional Chamber (MWPC)**
    - 2 upstream + 2 downstream of the magnet = totally **4 chambers**

- Requirements
  - ▷ position resolution = **0.3 mm**, thickness = **0.1% $X_0$** ⇒ δP < **0.5 MeV/c** (RMS)
  - ▶ tolerate to beam bunch of **$10^8$ MIP** ( **prompt burst** )
    instantaneous hit rate ~ **10 GHz/$mm^2$**
  - ▶ return to operational **300 nsec** after beam pulse to detect delayed electrons

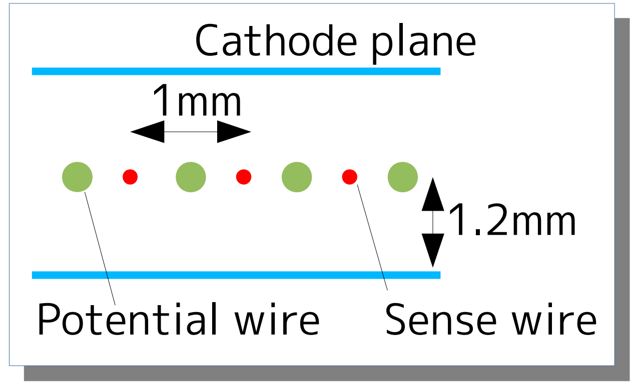


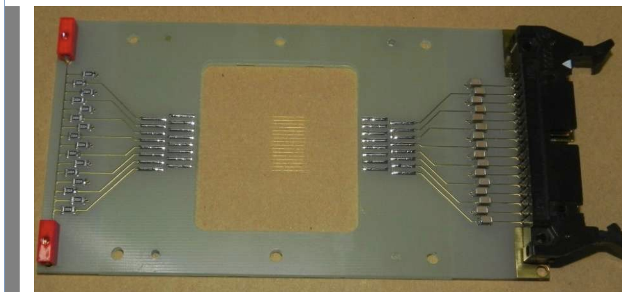



- Performance tests of the prototype have been done.

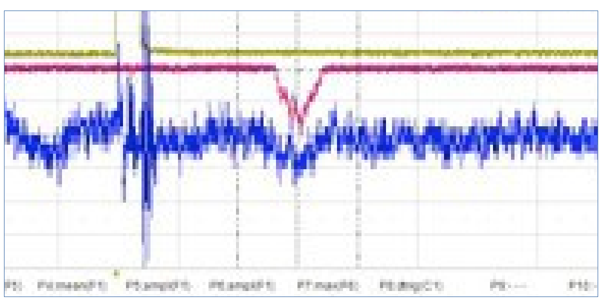
# Beam Tests of Prototype Chamber

- Prototype Chamber
  - sense wire : Ø 10μm
    potential wire: Ø 30μm
  - anode-cathode gap : 1.2 mm
  - gas mixture : Ar 50%, $C_2H_6$ 50%
  - anode : 1100 V
    potential, cathode: 0 V

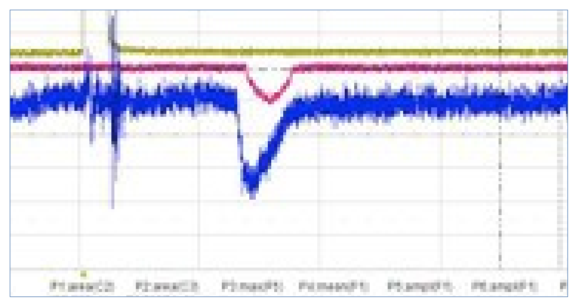


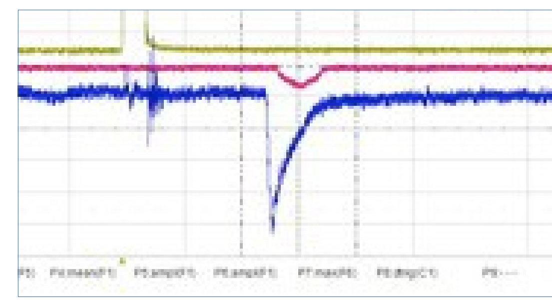
- Beam Test @ KURRI (Kyoto University Research Reactor Institute)
  electron beam 200ns width bunch, 6μsec cycle, controllable intensity



intensity = 1/100 of DeeMe condition



= 1/10 of DeeMe condition



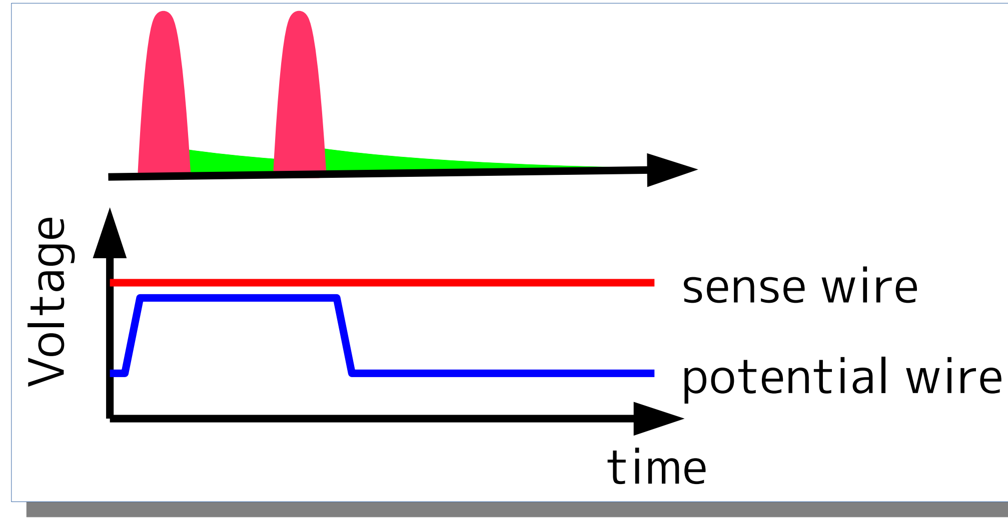
= DeeMe condition

- MWPC survived severer condition than DeeMe experiment without trip
  ⇒ **Good Tolerability**
- Raw waveform of MWPC is strongly distorted at higher intensity.
  ⇒ **Space Charge Effect**
  - not ready to detect delayed electrons
  - need to make chamber insensitive at beam timing ⇒ **HV Switching**

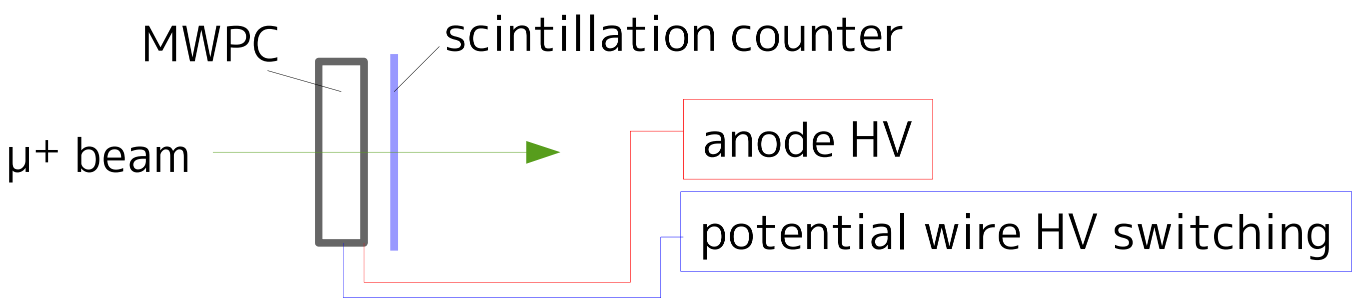
# Beam Tests of Prototype Chamber

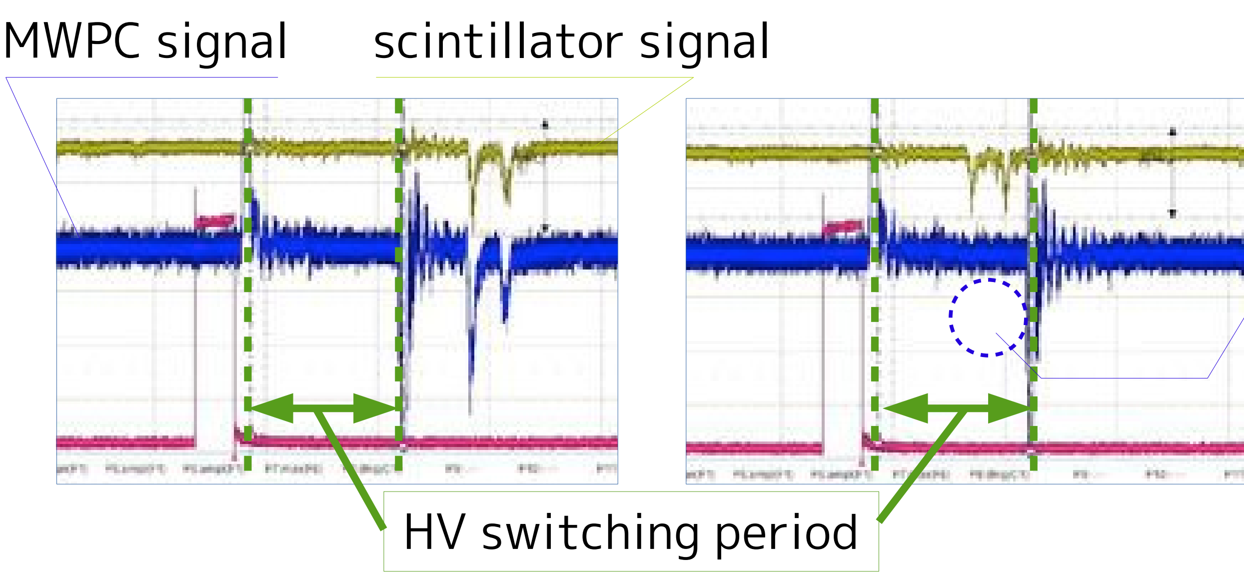
- HV Switching
  - switch the voltage for potential wire
  - smaller electric field gradient

  ⇒ reduce space charge created by prompt burst




- Beam Test @ J-PARC MLF D Line
  - surface μ+ beam (30 MeV/c)

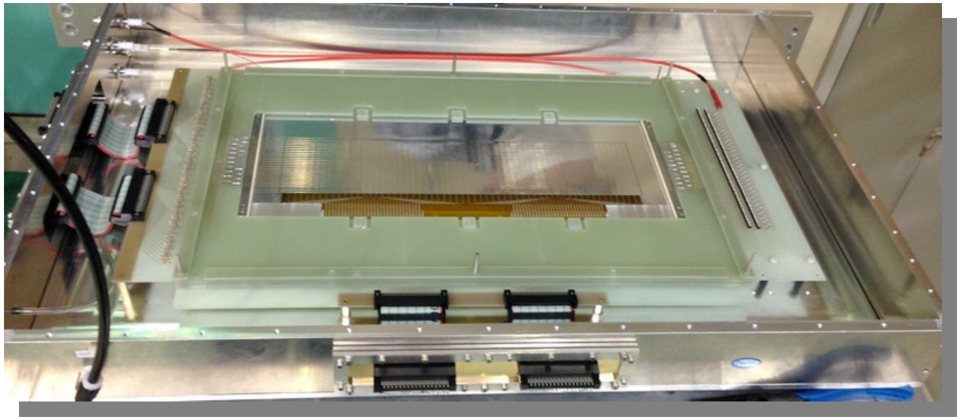



- MWPC signal disappeared during switching period
- confirmed **HV switching module works**

# Beam Tests of Prototype Chamber

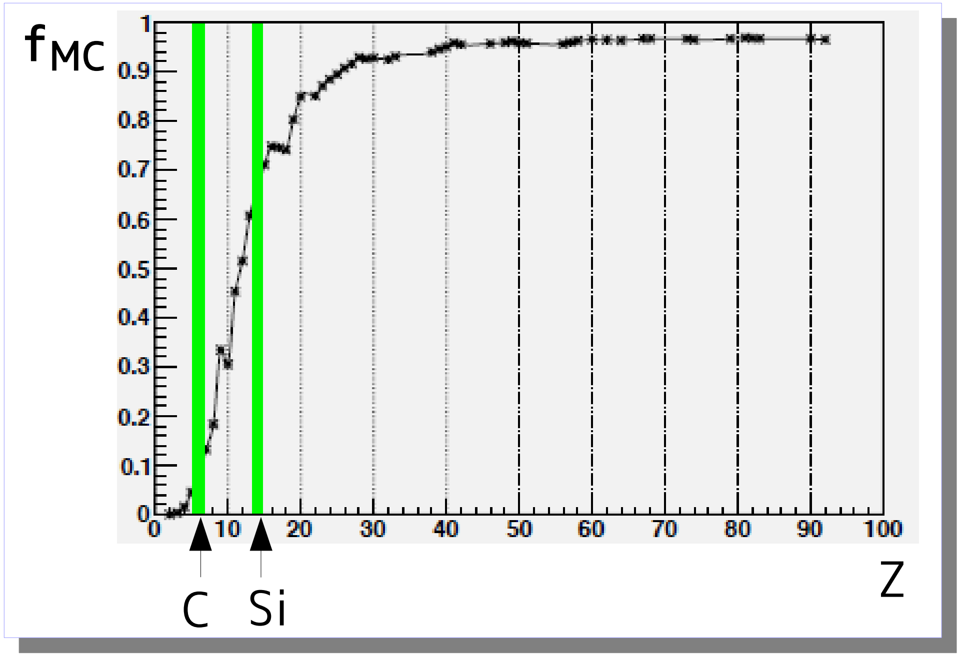
- The second prototype chamber



  - the same wire length as MWPC
    used for physics run ( 300mm )
  - ringing noise at HV switching timing
    ⇒ some modifications for HV line
  - cathode strip readout
  - **Beam test at KURRI is going now ( Aug 25 – 29 ).**

# Silicon Carbide Muon Production Target

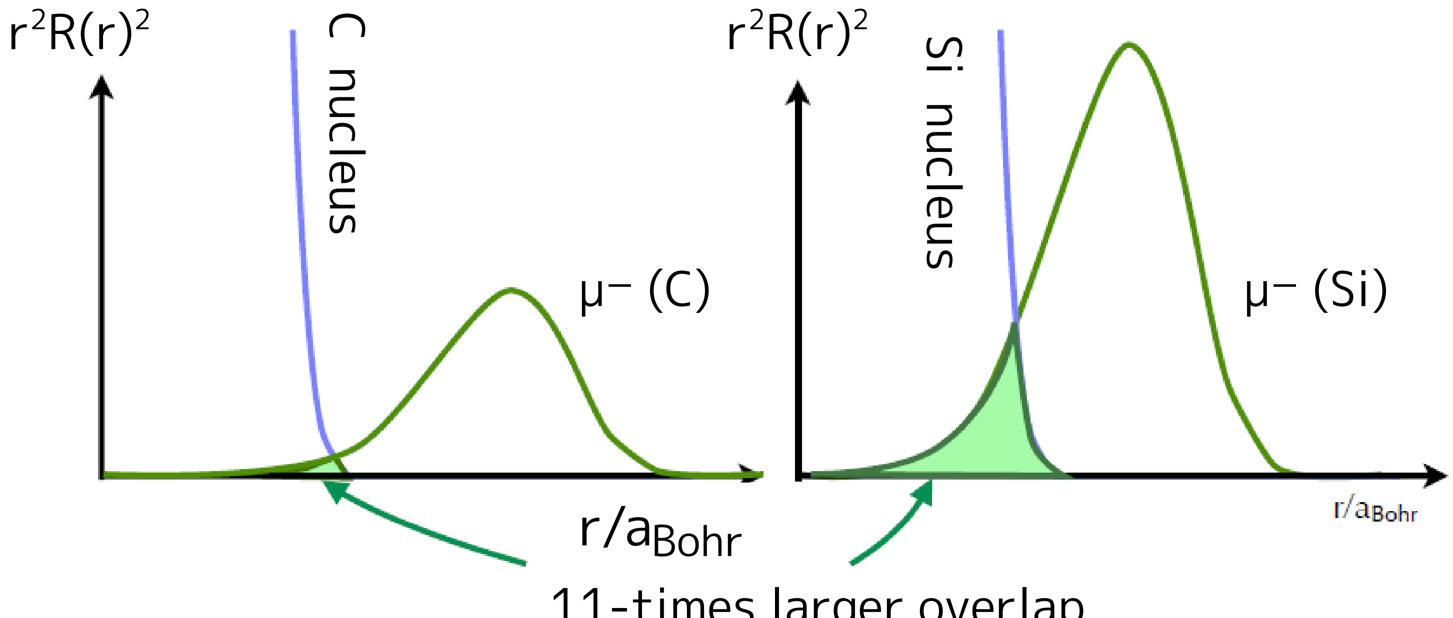
- current muon production target of MLF
  = **graphite ( C )**
- Larger muonic nuclear-capure rate ( $f_{MC}$ )
  is desirable for more sensitive experiment.
- $\tau_{\mu-}$ > **300 nsec** (light Z)
  to avoid the prompt background
  - $\tau_{\mu-}$ (in **silicon**) = **0.76 μsec**




- $f_C$ : Fraction of the atomic capture
  of muon to the atom of interest

  - single-element material : $f_C = 1$
  - composite materia proportional to Z (Fermi-Teller Z law)

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

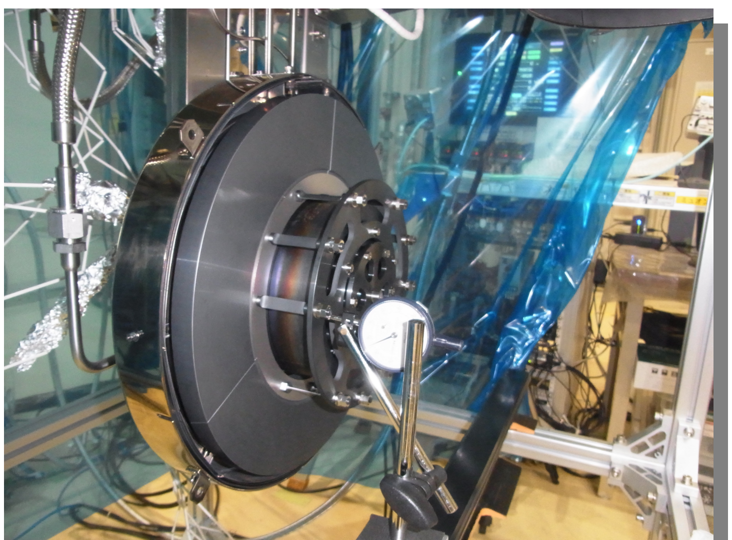


# Silicon Carbide Muon Production Target

- SiC target　　~ **6 times higher physics sensitivity** than current carbide target

| Material | fc x $f_{MC}$ |
|---|---|
| Graphite (C) | 0.08 |
| Silicon Carbide (SiC) | 0.46 |

- Rotating SiC target



prototype of SiC rotating target

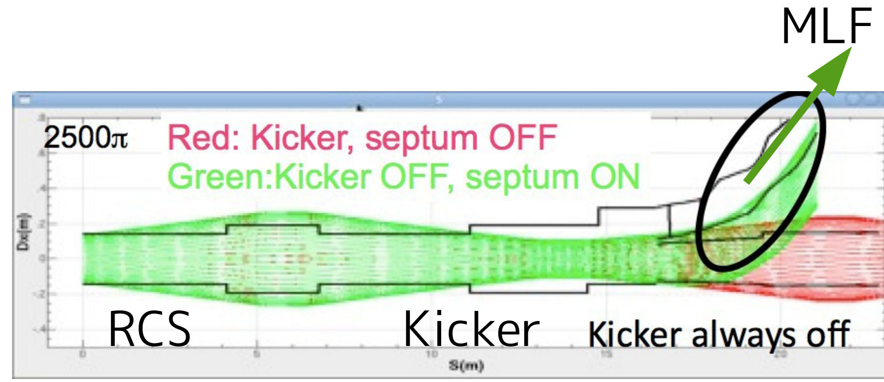
- Rotation … heat diffusion for higher beam power (300 kW → 1 MW)
  - Rotating graphite target will be installed in this September.
- R&D is ongoing.

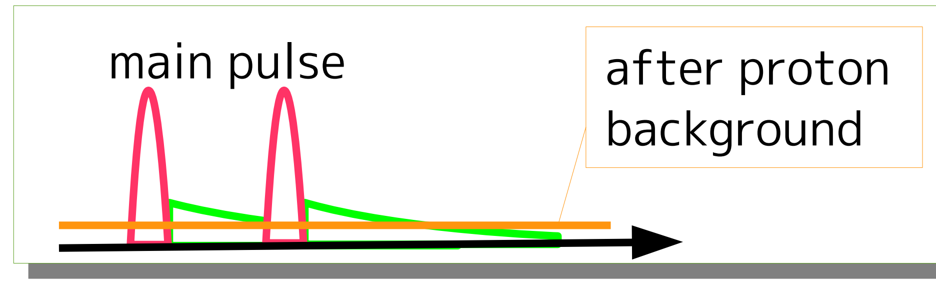
heating & rotating test

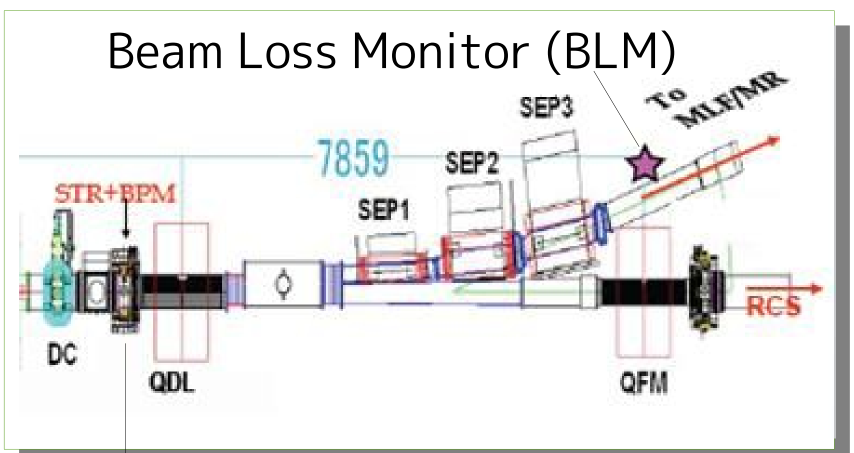
- estimation of dose in experimental area and effect of increased heat at other beamline → ongoing

# After Proton Background

- After proton
  - proton off timing of pulse
  - **in principle no after proton** because of **Fast Extraction**
  - may be created by beam halo and extracted to MLF when kicker is off
  - induce prompt background **in analysis time window**



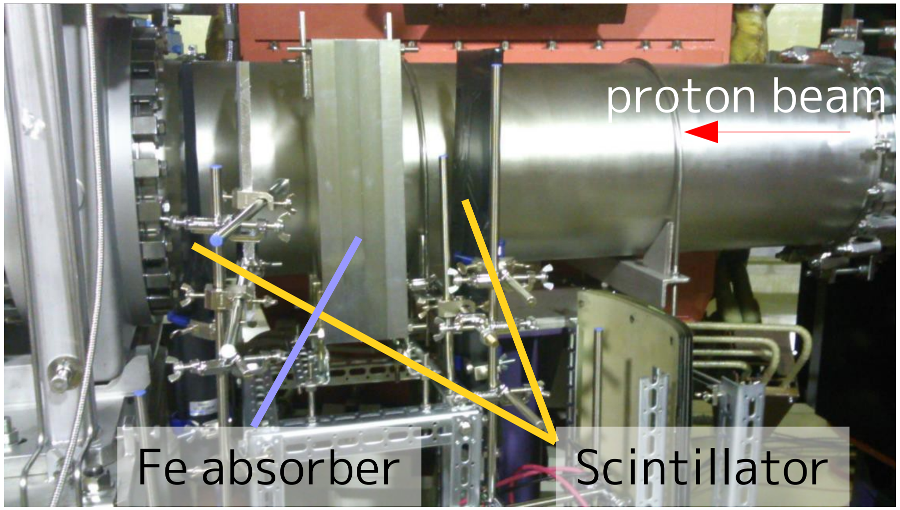

Beam Position Monitor (BPM)

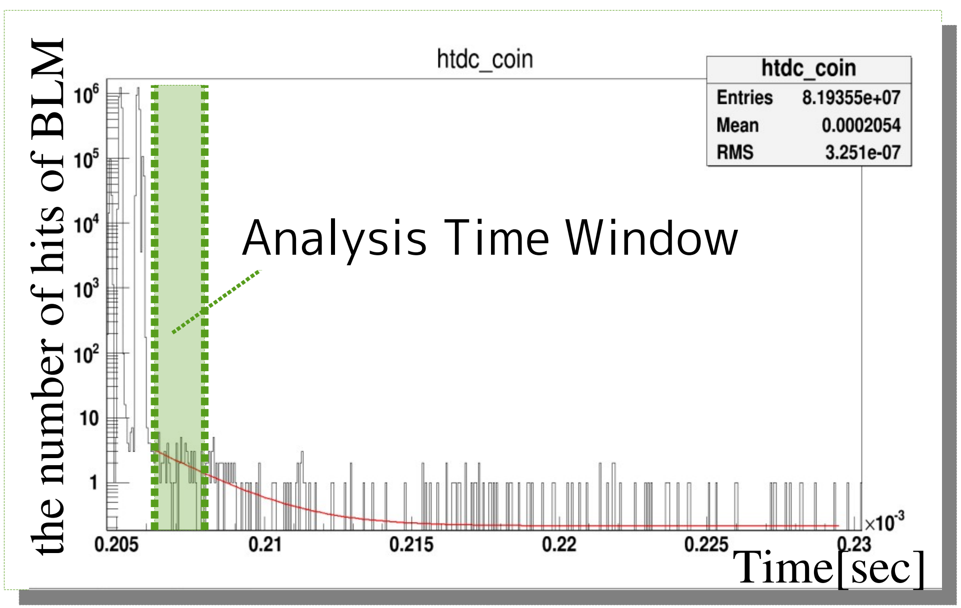
- After proton measurement
  - count protons by Beam Loss Monitor (BLM)
    - plastic scintillators
  - rate of BLM proton to After proton ... estimated by Monte Carlo simulation

$$f = \frac{\text{After proton}}{\text{BLM proton}} = 40$$

  - number of total proton in RCS ... recorded by Accelerator Group

# After Proton Background




- Beam Loss Monitor
  - 2 scintillation counter
    150 × 200 mm$^2$, 500mm gap
    → coincidence
  - Fe absorber
    10 cm thickness
    reject low energy background
- After Proton Rate $R_{AP}$
  - measurement : 2013 March 7 ~ 2013 May 25 @ J-PARC RCS
  - total proton at BLM in the time window = **87**
  - total proton in RCS = **$3.1 \times 10^{21}$**

$$R_{AP} = \frac{BLM \times f}{BPM} = 1.1 \times 10^{-18}$$

- PID is necessary
  for more precise measurement.
  → new BLM calorimeter

# Single Event Sensitivity

- **Single Event Sensitivity (S.E.S)**

$$S = \frac{1}{R_{\pi^-} \times f_{\pi^- \to \mu^- \mathrm{stop}} \times f_{\mathrm{C}} \times f_{\mathrm{MC}} \times A_{\mu-e} \times T}$$

$R_{\pi^-} \times f_{\pi^- \to \mu^- \mathrm{stop}} = \mu^-$ stopping rate per second

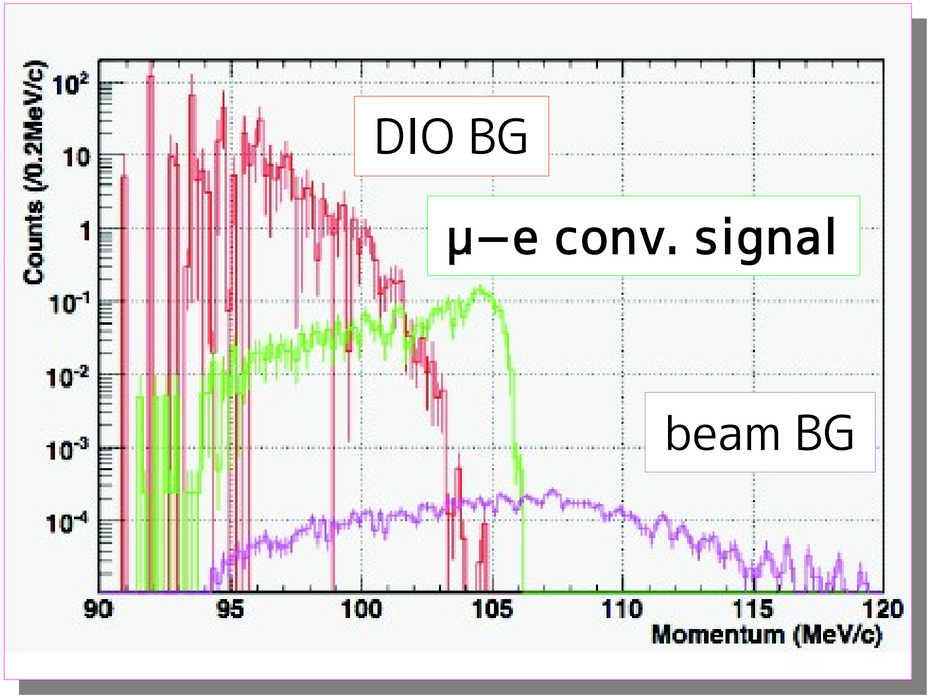
$f_{\mathrm{C}} =$ atomic captur rate

$f_{\mathrm{MC}} =$ muon nuclear capturefraction

$A_{\mu-e} =$ total acceptance for $\mu$-$e$ electrons

$T =$ time length of the measurement

- Running time = **2 × 10⁷ sec** (1 year run)
- Background (MC estimated)
  - Decay in Oribit **0.09**
  - After proton rate ($R_{AP}$) < $10^{-18}$
    - →After proton < **0.027** (0.05 90% C.L.)
  - Cosmic induced
    - e < **0.018** , μ < **0.001**
    - →Detector live-time duty = **1/20000**
    - ⇒ Cosmic ray backgrounds are well suppressed.




- **S.E.S estimated by Monte Carlo study**
- **$2.1 \times 10^{-14}$ for <u>SiC</u> target**
- **$1.2 \times 10^{-13}$ for <u>C</u> target**

current upper limit

BR($\mu^-$ Au → $e^-$ Au) < **$7 \times 10^{-13}$** (SINDRUM-II)

# Summary & Prospects

- Muon to electron conversion search experiment, **DeeMe**, is planned at **J-PARC MLF MUSE**.

- A new beamline ( **H Line** ) is under construction.
  - Upstream magnets are already installed.
  - **Spectrometer magnet ( PACMAN ) has just been moved to J-PARC MLF** from TRIUMF on **Aug 19**.

- Beam optics study by G4Beamline simulation
  - optimized for **105 MeV/c signal electrons**
  - Acceptance for signal electron … ~ **120 mSr/MeV/c**
  - Moderate $\Delta p$ … **90 ~ 120 MeV/c** (**simultaneous monitoring of backgrounds**)

- After proton background measurement
  - $R_{AP} \sim 10^{-18}$

- Single Event Sensitivity
  - **$2.1 \times 10^{-14}$ for SiC target**
  - **$1.2 \times 10^{-13}$ for C target**

# Summary & Prospects

- Tracking device
  - MWPC
  - beam test of prototype
    - Good tolerability against prompt burst
    - Gain drop after prompt burst due to Space Charge

      → HV switching test
        - HV switching module works
        - switching noise with new prototype chamber → testing now

- Silicon carbide production target
  - 6 times higher sensitivity than current graphite production target
  - Development is in progress.
  - Estimation of dose at experimental area

    Effect at other beamline (heat deposit)

- DeeMe already has **Stage-2 approval** from PAC under KEK-IMSS (Institute of Materials Structure Science).
  - start with graphite production target

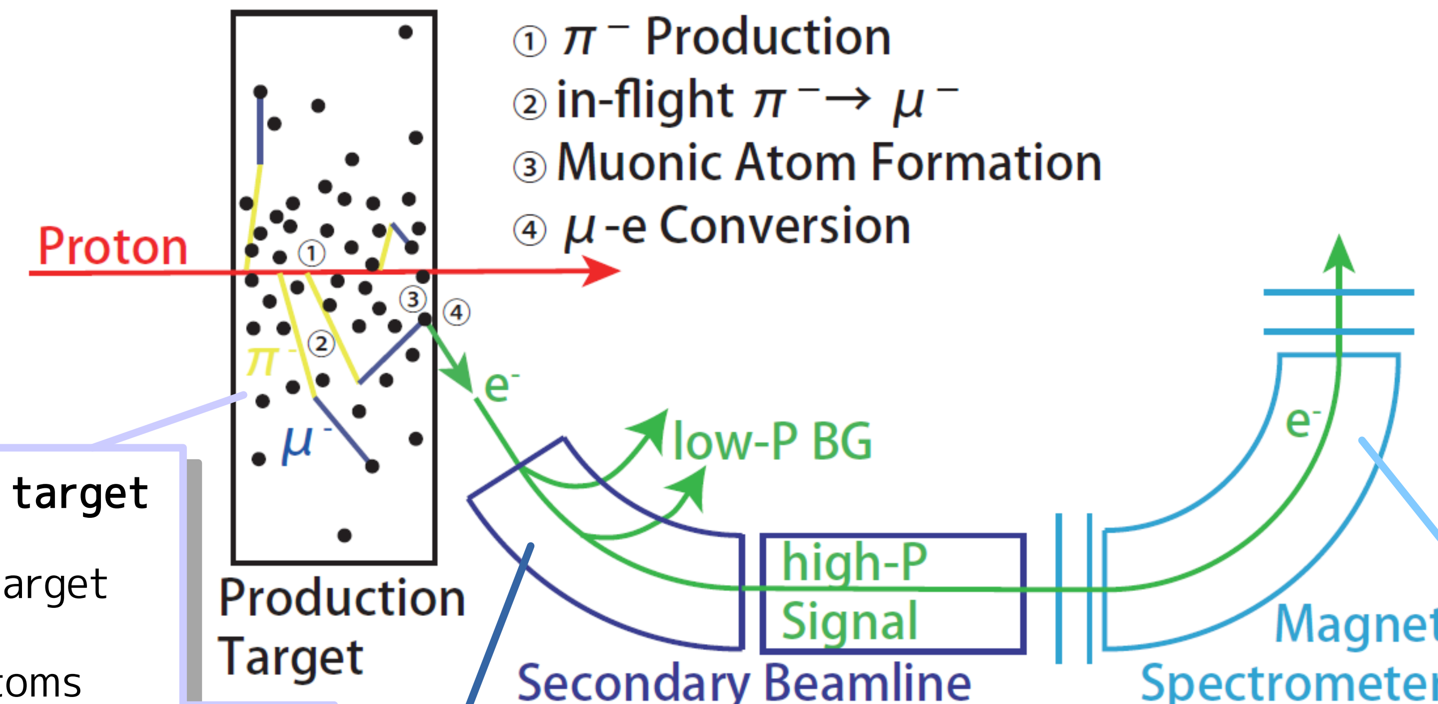
    → will be replaced with silicon carbide target

- The preparation of the experiment is in progress in an effort to start data taking in **2015**.

# Backup

# DeeMe Experiment

## Concept of DeeMe




### ▶ μ⁻ production target

= μ⁻ stopping target

・utilize muonic atoms formed in the production target

→ NO π⁻ decay volume
NO additional stopping target
◀▶ conventional μ−e search

⇒ unique technique of DeeMe experiment

・low cost
・early realization

### ▶ Transport Beamline

Beam optics is optimized for signal electrons.

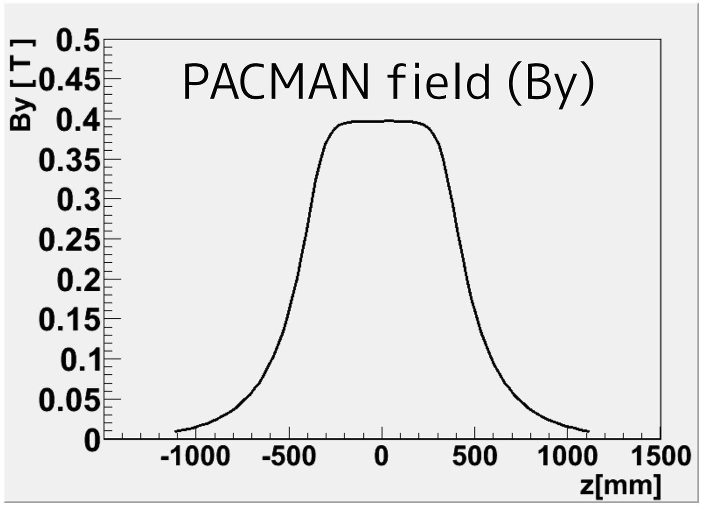
⇒ ・momentum selection
・suppress low momentum backgrounds

### ▶ Spectrometer

・momentum analysis
・identify signal electrons (105 MeV/c)

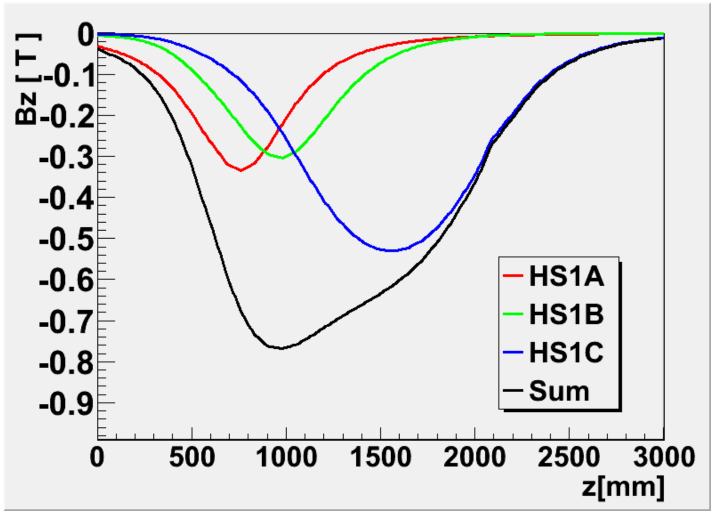
# Magnets PACMAN, HS1A.B.C , HB1

- Spectrometer magnet PACMAN
  - field map based on measurement

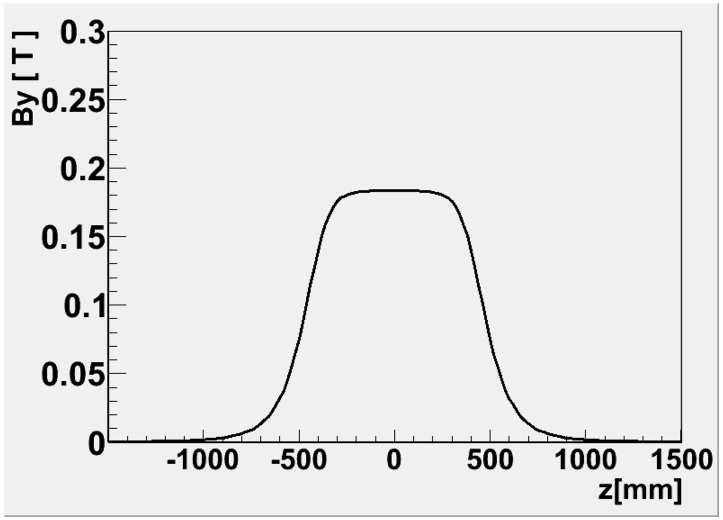



PACMAN@TRIUMF

- capture solenoid **HS1A,B,C ,** bending magnet **HB1**
  - already installed into beamline
  - field map based on measurement

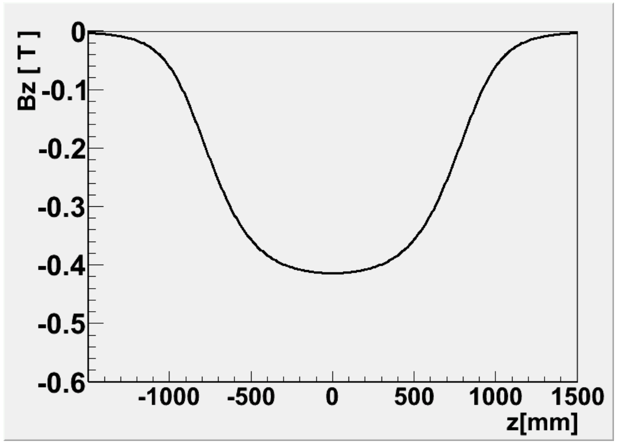

HS1A~C field (Bz)



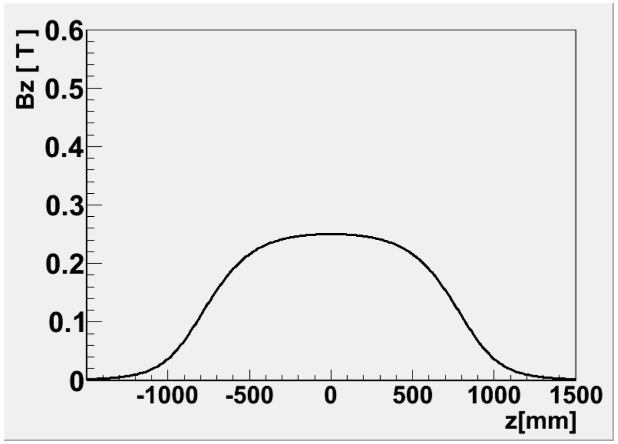

HB1 field (By)

# Magnets HS2, HS3, HB2

- in designing
- field map
  calculated by OPERA
- HS2, HS3
  - Transport solenoid
  - superconduting
- HB2
  - Sector type
  - bending angle 45°

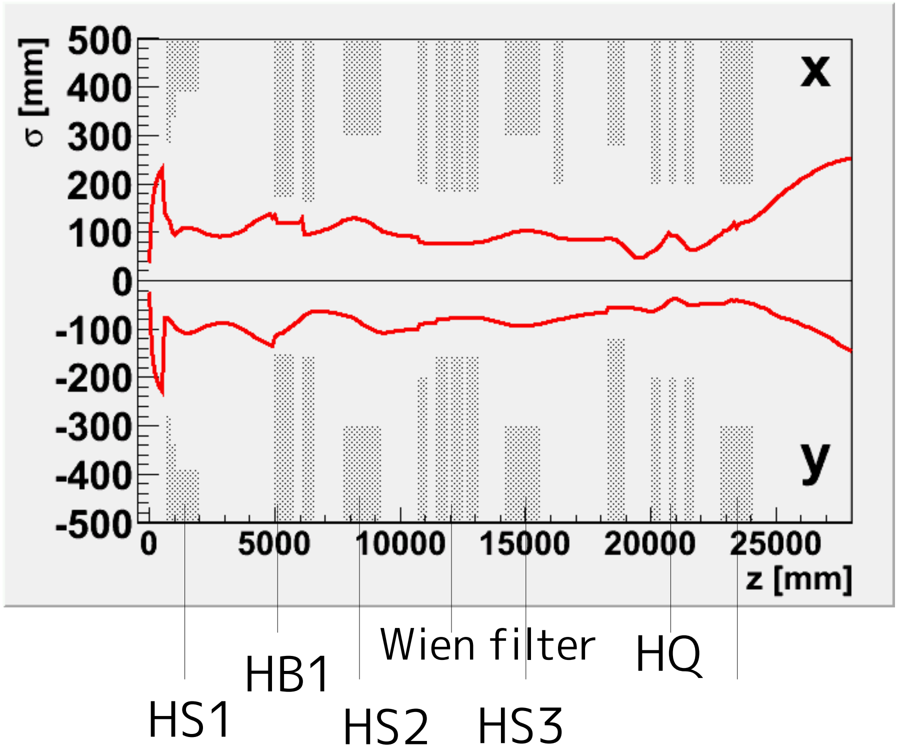


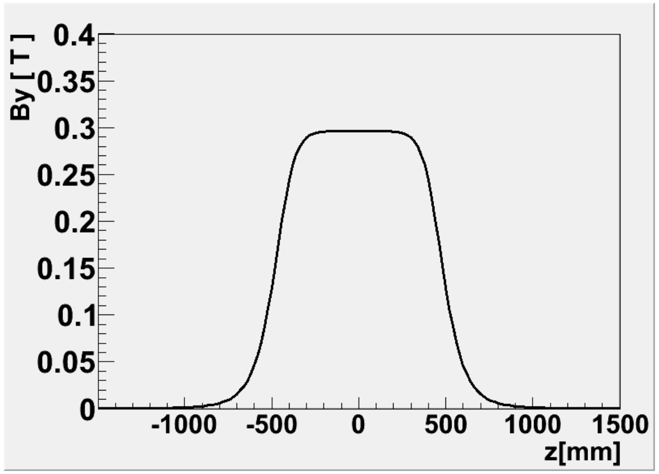

HS2 field (Bz)




HS3 field (Bz)

- beam profile (electron 70~130 MeV/c)



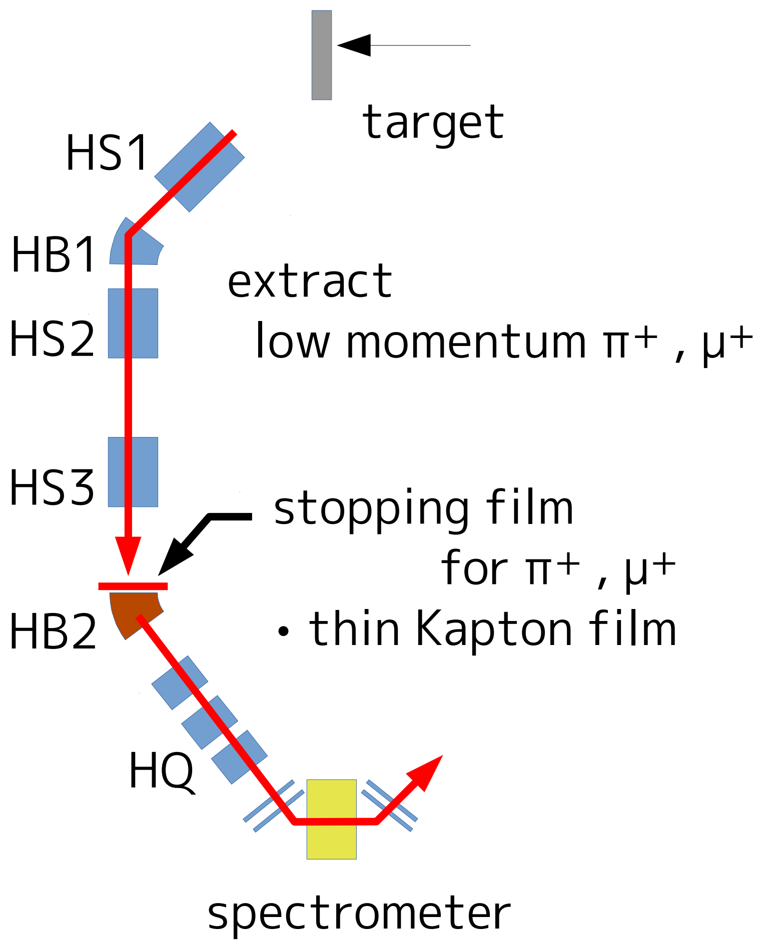

HB2 field (By)

# Spectrometer Calibration

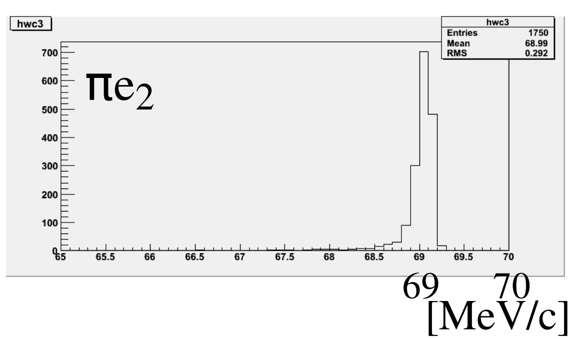
- Reactions for spectrometer calibration

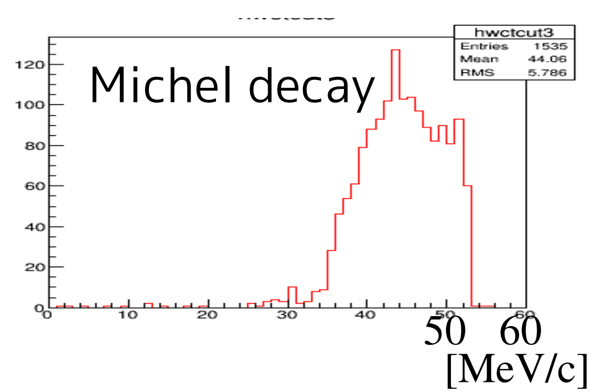
$\pi^+ \rightarrow e^+ \nu_e$ $\pi e_2$ decay, **$Pe^+$ = 69.3 MeV/c**

$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$ Michel decay, **$Pe^+$ = 52.8 MeV/c at Michel edge**




- momentum analysis of positron from stopping film in front of HB2
  → calibration of the spectrometer




- simulated momentum spectrum of positron

- Yield
  - $\pi e2$
    **1.1 x 10²** positron for **1 hour**
  - Michel decay
    **1.1 × 10⁵** positrons for **1 hour**