DeeMe

Search for Muon-Electron Conversion in Nuclear Field by using High-Purity High-Power Pulsed Proton Beam from J-PARC RCS

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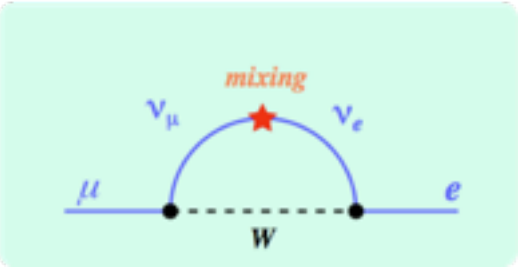
Osaka University

NuFact2015, 10-15 Aug. 2015, Rio de Janeiro

Charge Lepton Flavor Violation

- Charged Lepton Flavor Violation (CLFV)
  - Forbidden in the Standard Model of particle physics.
  - $\underline{\mu^- + A \to e^- + A}$, $\mu \to e\gamma$, $\mu \to eee$, $\tau \to e(\mu)\gamma$, $\tau \to e(\mu)h$ ...
- Neutron Oscillation may induce the effective CLFV, but it is very small due to the combination of GIM-like mechanism and smallness of the neutrino masses.



$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{ei}^* \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \simeq 10^{-60} \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}} \right)^4$$

A. de Gouvea

- CLFV →

  Clear evidence of the physics beyond the Standard Model with neutrino-oscillation extension.

μ−e Conversion in Nuclear Field

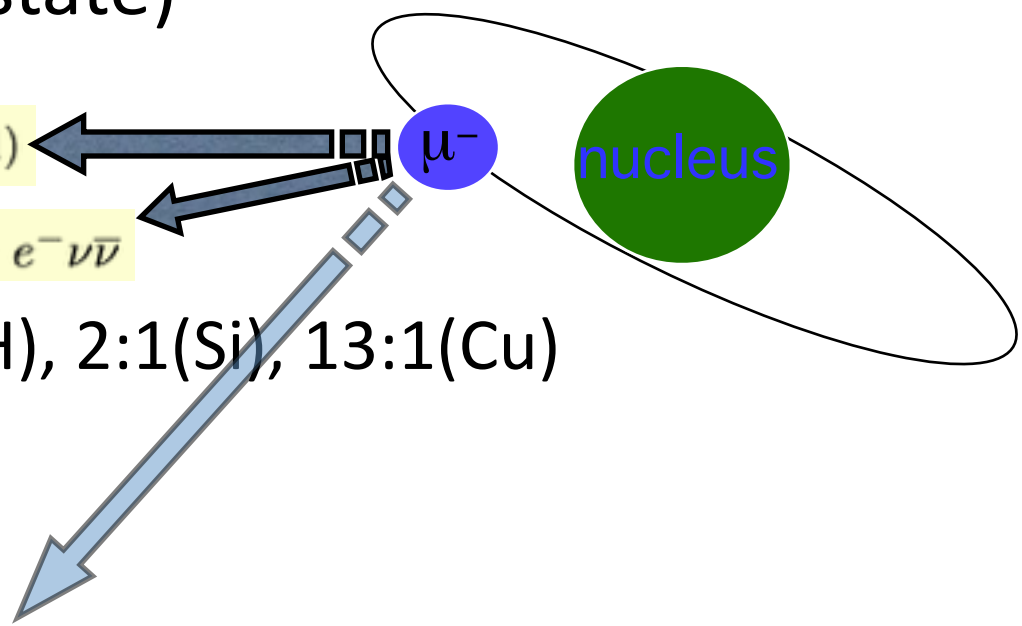
- Muonic Atom (1S state)

Muon Capture(MC)

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

Muon Decay in Orbit (DIO)

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



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

  – τ(free μ-) = 2.2 μs

  – τ(μ⁻;Si) = 0.76 μs

- Charged Lepton Flavor Violation (CLFV)

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

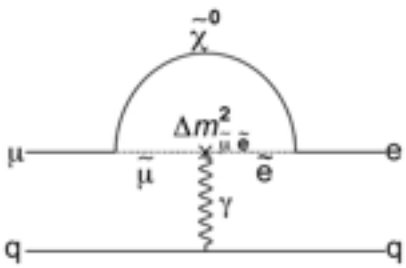
μ-e Conversion in Nuclear Field

$$\mathrm{BR}[\mu^- + (A, Z) \rightarrow e^- + (A, Z)] \equiv \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)]}$$

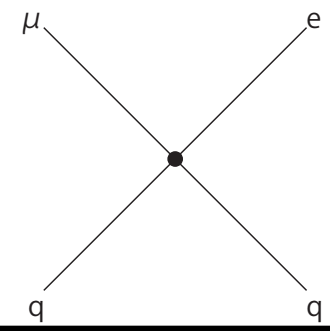
Clear evidence of the new physics

Photonic and Non-photonic

$$\mathcal{L} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \frac{\kappa}{(1+\kappa)\Lambda_F^2}\bar{e}\mu(\bar{q}q+\bar{e}e)$$

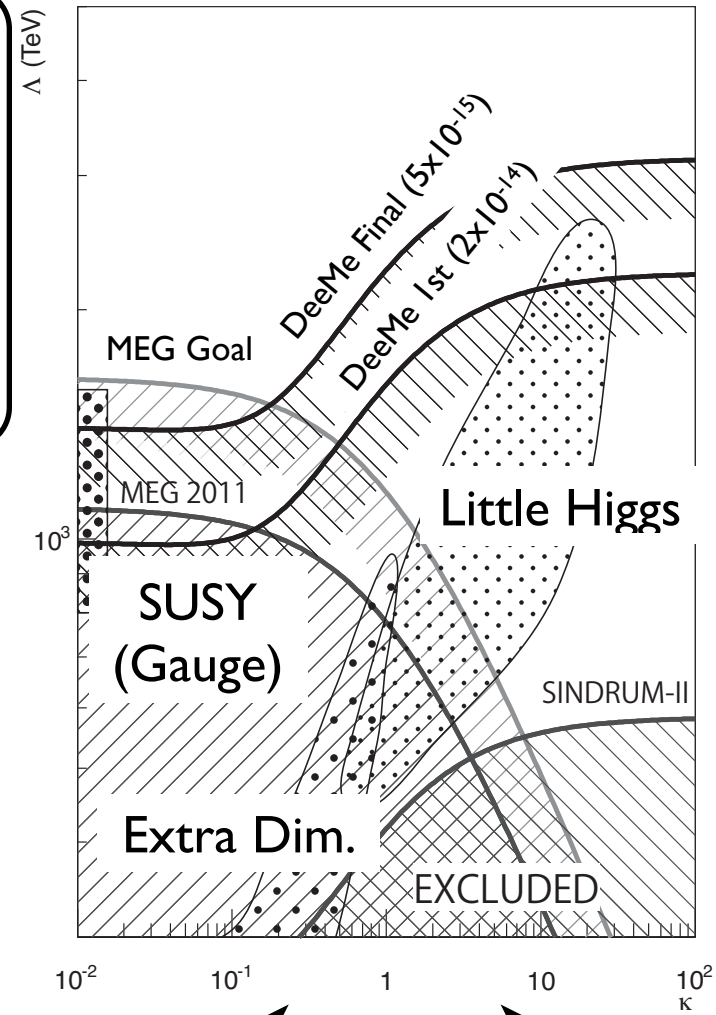


photonic



non-photonic

- SUSY-GUT, SUSY-seesaw
  - higgs mediated processes
- Doubly Charged Higgs Boson (LRS *etc.*)
- Little Higgs Models
- Randall-Sundrum Models
- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Multi-Higgs Models



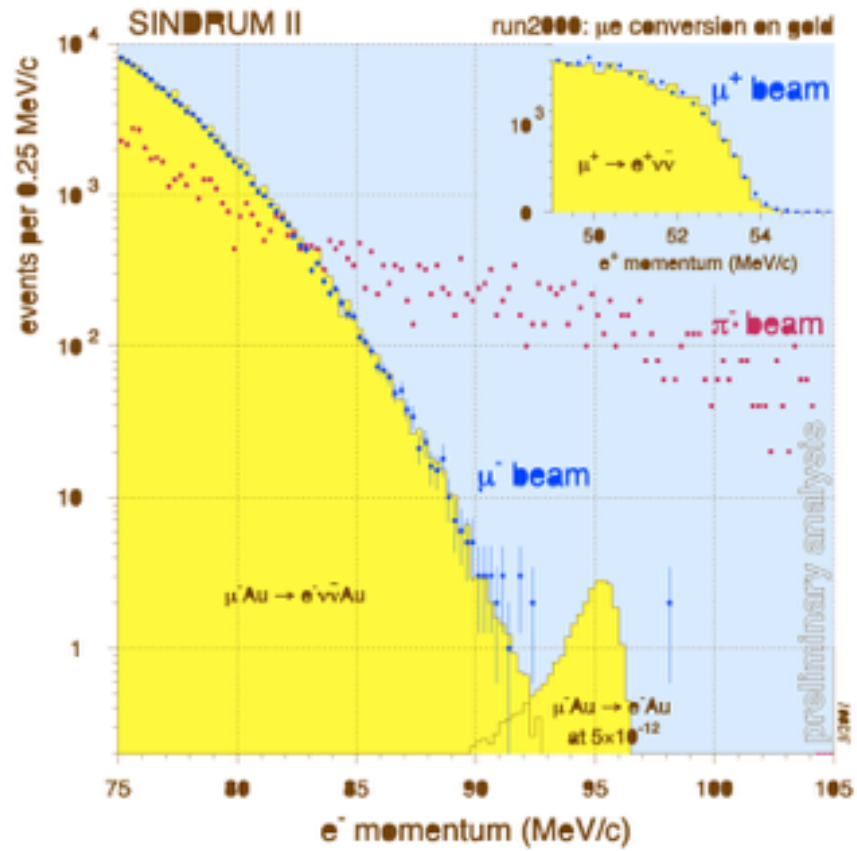
photonic-like ⟷ nonphotonic-like

original plot by Andre de Gouvea

Principle of Measurement

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed ： ~1μS
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Prompt timing

SINDRUM II



Recent Upper Limits

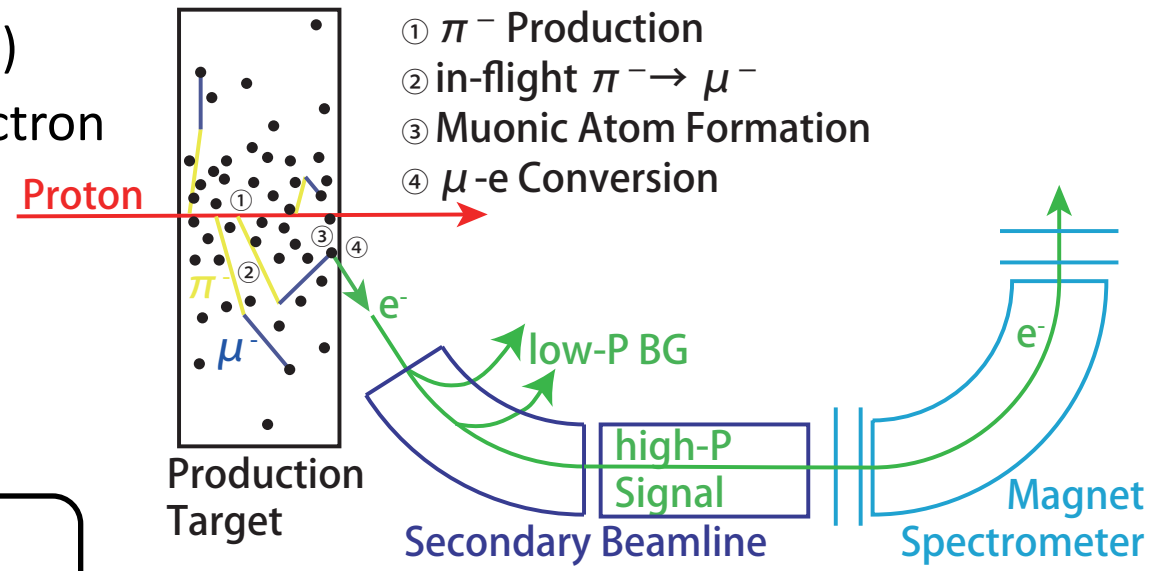
SINDRUM-II: BR[$\mu^- + Au \rightarrow e^- + Au$] < 7×10^{-13}

SINDRUM-II: BR[$\mu^- + Ti \rightarrow e^- + Ti$] < 4.3×10^{-12}

TRIUMF: BR[$\mu^- + Ti \rightarrow e^- + Ti$] < 4.6×10^{-12}

DeeMe

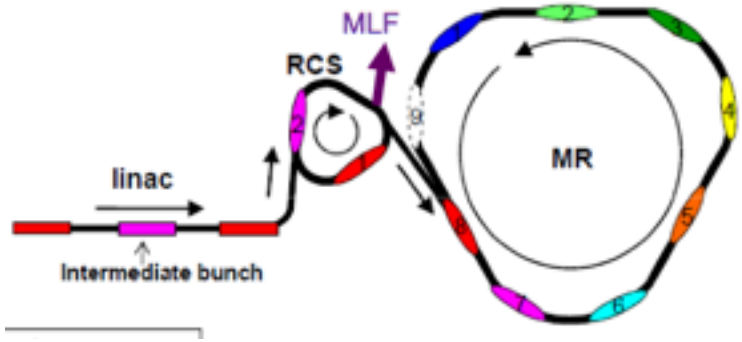
- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed ： ~1μS
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Prompt timing

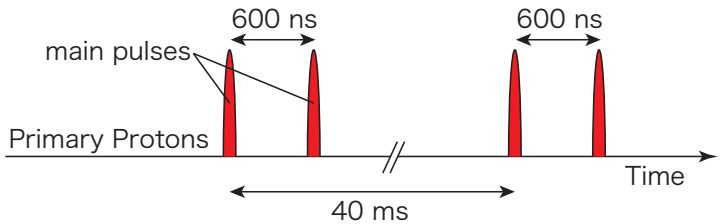


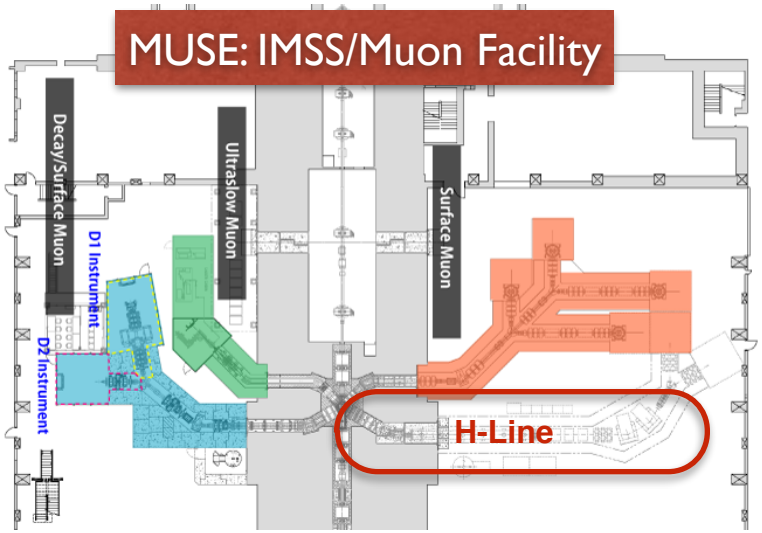
- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer ($\Delta p < 0.5\%$)
- Main pulse burst: State-of-the-art MWPC that becomes operational quickly after a burst.
- After-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{AP} << 10^{-17}$.

J-PARC MLF

- LINAC
  - H^-, 400 MeV, 50 mA
  - 50 Hz
- RCS
  - 3 GeV, 333 μA, 1MW: **High Power**
  - 25 Hz, **Fast Extraction: High Purity**
  - Material and Life-science Facility (MLF)
- MR
  - 30 GeV, 15 μA
  - Fast and Slow EX







DeeMe Collaboration

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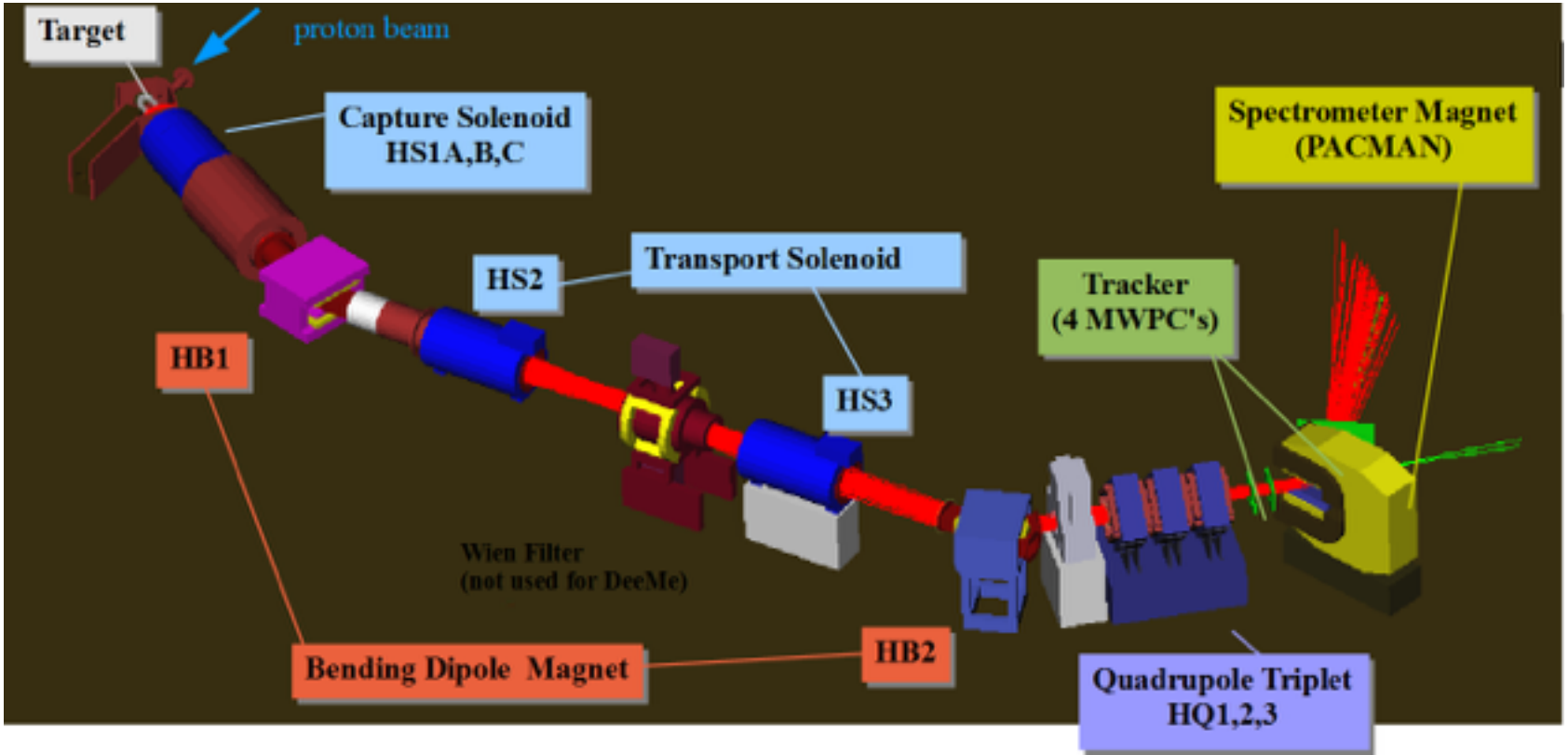
(1) Osaka University, (2) UBC, (3) Osaka City University,
(4) KEK Accelerator, (5) KEK MUSE, (6) JAEA, (7) KEK IPNS, (8) TRIUMF,
(9) Okayama University, (10) PSI

DeeMe Project

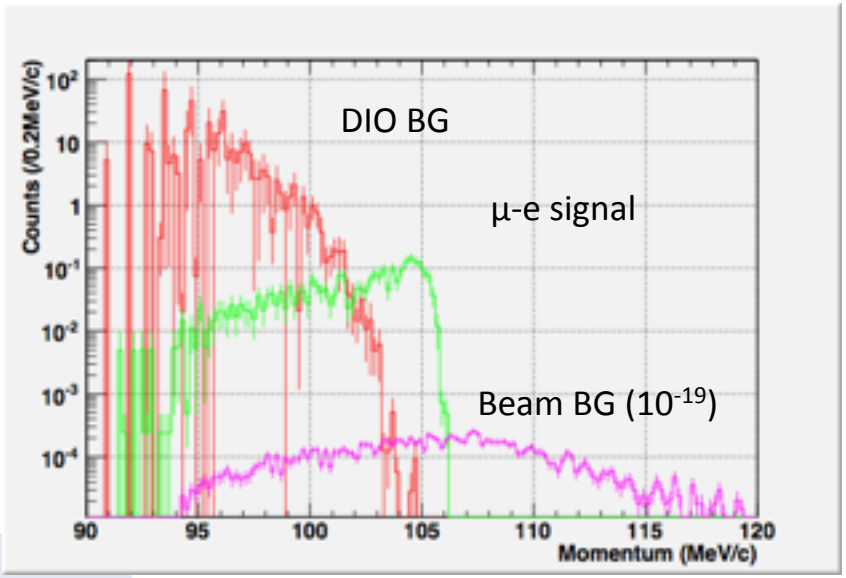
- High-Power High-Purity Pulsed Proton from J-PARC RCS
- Start with Graphite Target
  - Upgrade to a SiC Target
- Large-Acceptance Beam line (H-Line)
- State-of-the-Art HV-Switching MWPC
- Single Event Sensitivity
  - 1×10^{-13} (Graphite, 2×10^{7}sec)
  - 2×10^{-14}(SiC)、5×10^{-15}(8×10^{7}sec)

- Schedule
  - Stage-2 Approved from Muon PAC IMSS
  - Grant-in-Aid for detector construction
    - detector completed in 2015
  - H-Line under construction
    - upstream-half completed
    - beamline shield under a bid
    - downstream at 2016 summer
  - Aiming to start in 2016.



Sensitivity and Backgrounds

- Signal Sensitivity (SiC)
  - S.E.S.: 2×10^{-14} (1 MW, 2×10^{7}sec)
- Backgrounds
  - $R_{AP} < 10^{-18}$
  - Detector live-time Duty = 1/20000 that suppresses cosmic-ray BG
  - no anti-protons (E_p = 3 GeV << 5.6 GeV)



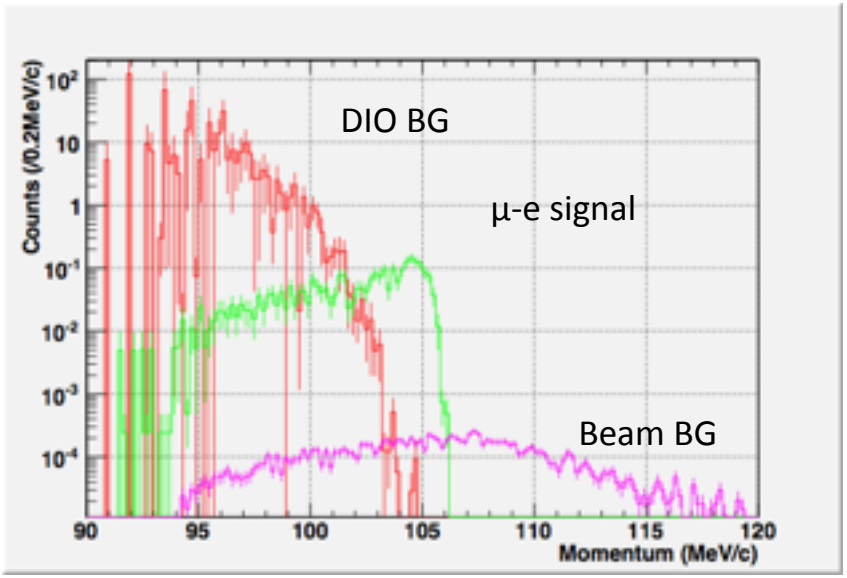
Signal Region: 102.0 -- 105.6 MeV/*c*

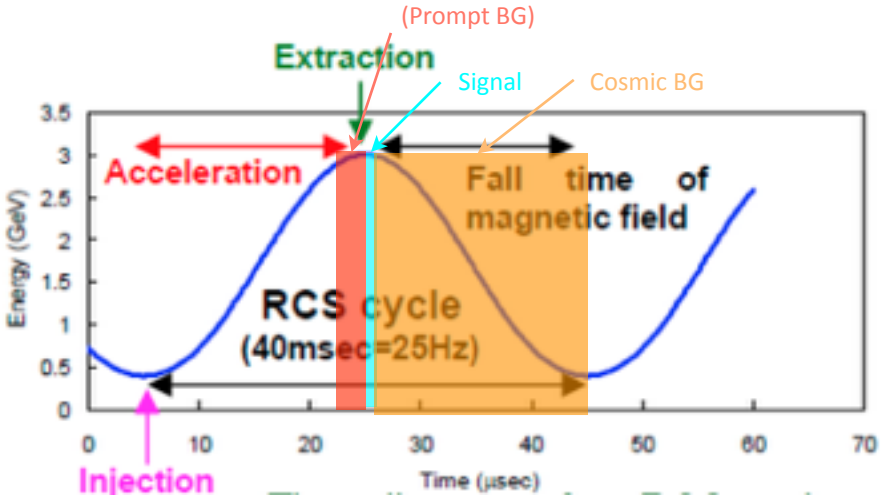
DIO Background	0.09
After-Proton Background	< 0.027 (<0.05 90%CL)
Cosmic-Muon Induced	<0.018 (MC limited)
Cosmic-Muon Induced Muon	<0.001
Radiative Muon Capture BG	<0.0009

- If we could extend the running-time up to 8×10^{7} sec
  - Standard Cut: S.E.S.= 0.5×10^{-14} (N_{BG}<0.64)
  - Tighter Cut: S.E.S.= 0.6×10^{-14} (N_{BG}<0.17)
    N_{BG} could be much less with improved BLM system.

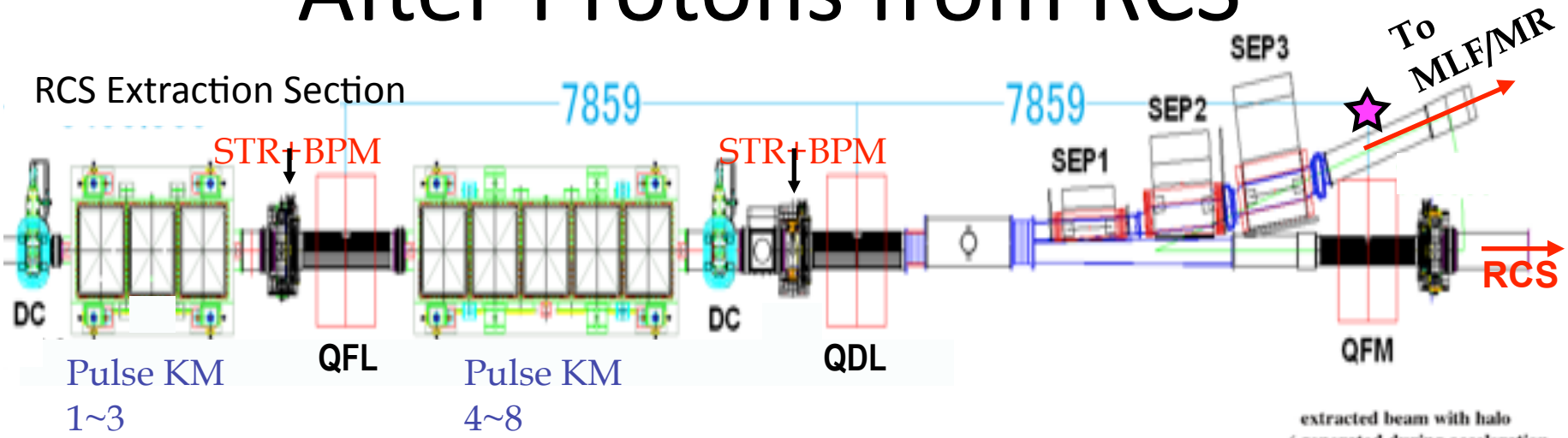
In-situ Monitoring of Backgrounds

- Momentum Domain
  - Moderate Δp of H-line makes it possible to monitor backgrounds in-situ:
    - DIO (p < 102.5 MeV/c)
    - Beam Backgrounds (p > 105.6 MeV/c)
  - Number-of-muon Calibration by using DIO.
- Time Domain
  - Monitor Off-Timing Protons
    - Beam-Loss Monitor @ RCS
    - Spectrometer Activities
  - Cosmic-Ray Background
    - Duty-factor 1/20000

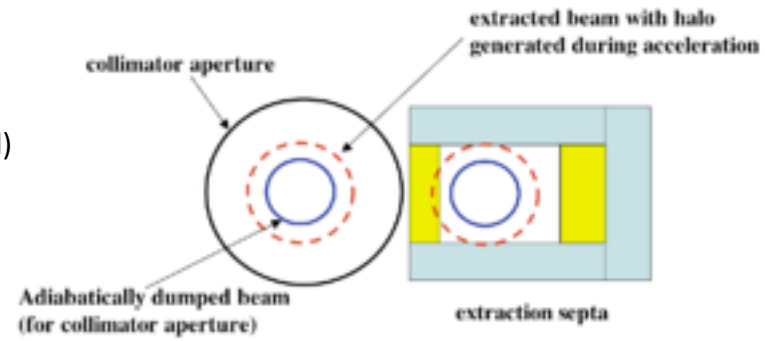


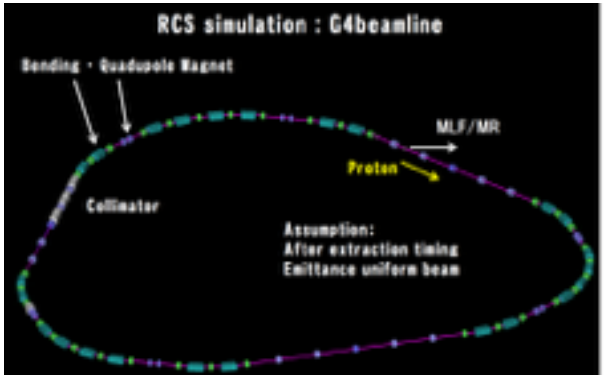


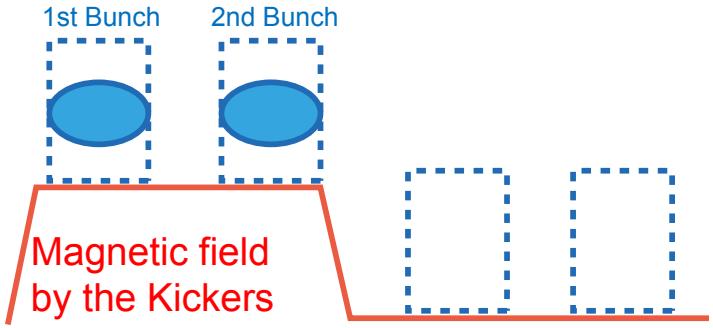
After-Protons from RCS



- RCS has a very large aperture (to reduce the beam loss).
  - Vacuum Duct = 486π mm.mrad (Collimator: 350π mm.mrad)
  - Transport to MLF = 324π mm.mrad
  - Kick Angle = 17 mrad --- > 2000π mm.mrad
- Fast Extraction --- No residual protons in a ring.
- <u>High-Purity High-Power Pulsed Proton Beam</u>



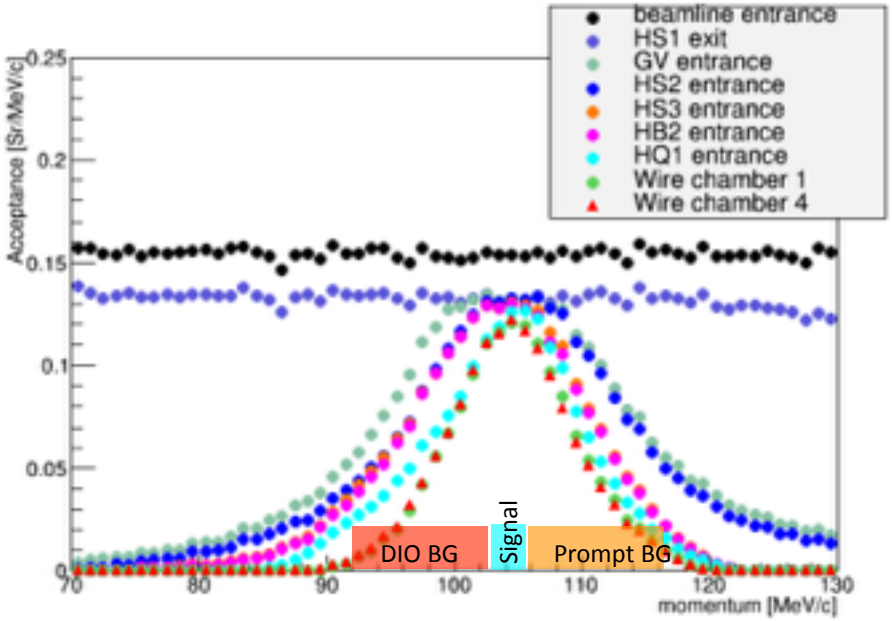


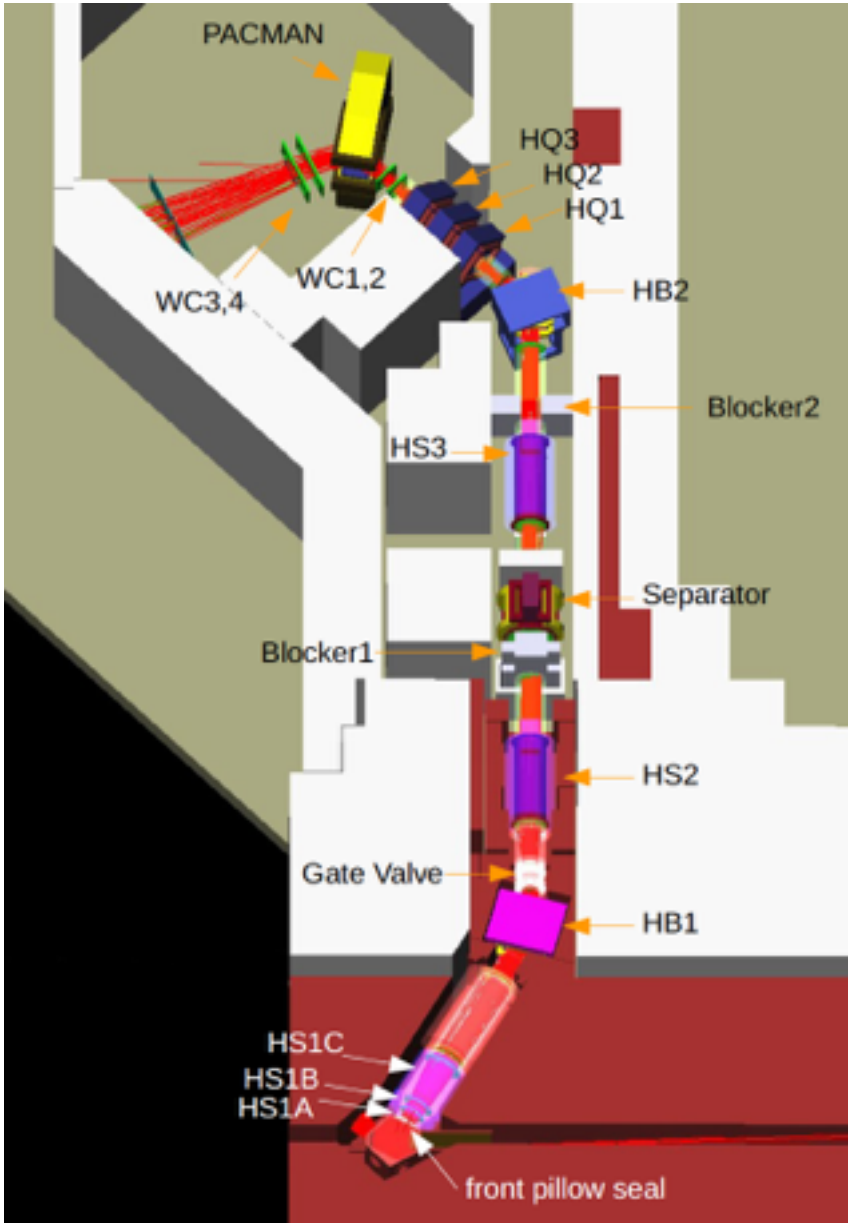


Time structure of RCS extraction scheme

Beamline: H-line

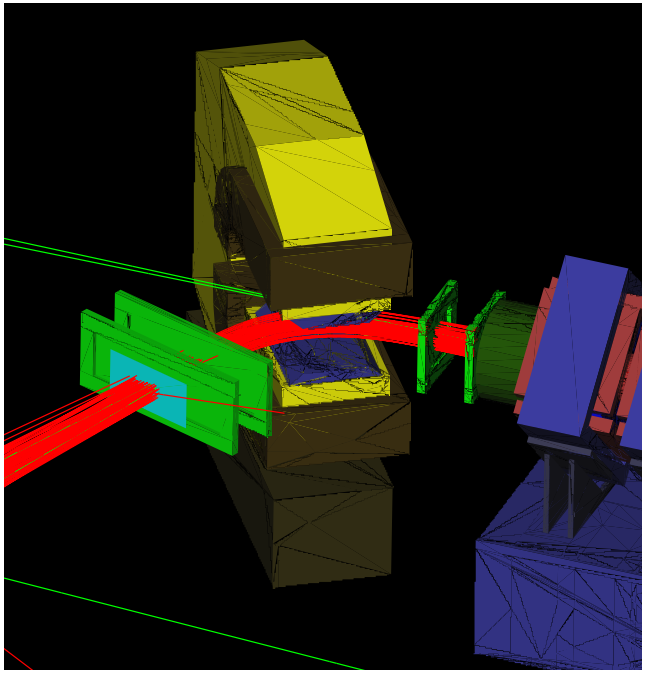
- Concept: Jaap Doornbos (TRIUMF)
  Leader: Naritoshi Kawamura (KEK)
  - Multiple purpose: DeeMe + g-2 + muon-HFS
  - Large Acceptance: > 110 msr
  - Large Momentum Acceptance: BG monitor
    - DIO backgrounds (p < 102.5 MeV/c)
    - Prompt backgrounds (p > 105.0 MeV/c)
- Upstream; already installed in the summer of 2012.
- Downstream; Engineering Design finished;
  - radiation shielding under a bid;
  - is going to be constructed in 2016 summer.

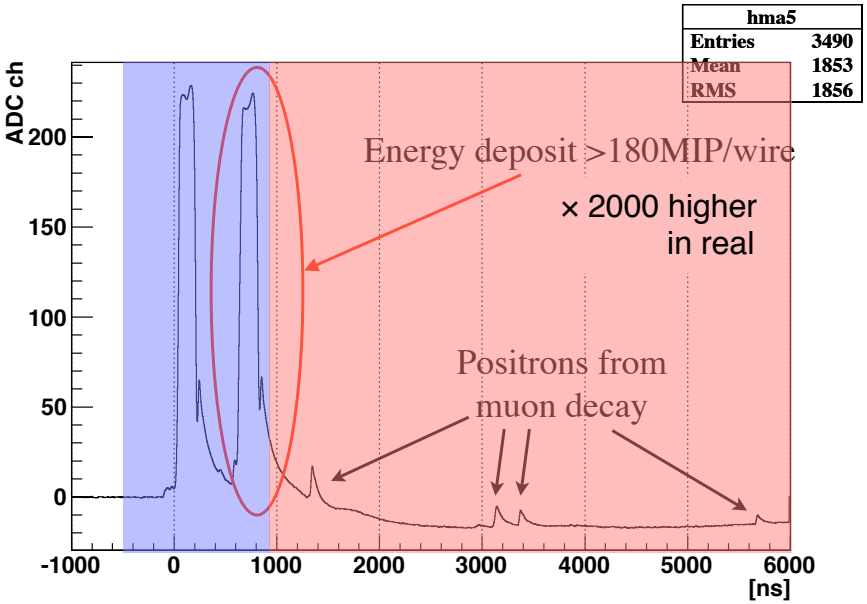




Spectrometer

- Orthodox Dipole Spectrometer
  - $\Delta p < 0.5$ MeV/*c*
  - **<u>A magnet has been borrowing from TRIUMF</u>**
- Prompt Burst: ~10^8/200-ns
  - Need to reduce the drop of gas-gain coming from space-charge effect of ions.

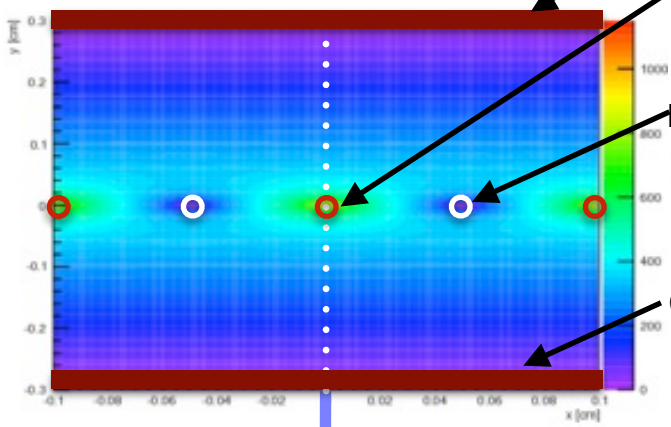




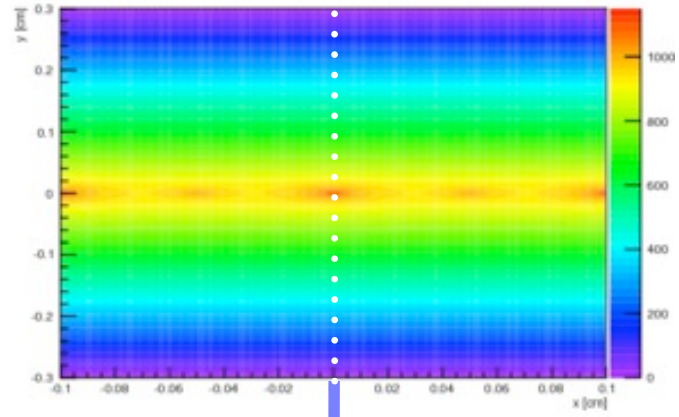
Potential-Wire Voltage Switching MWPC

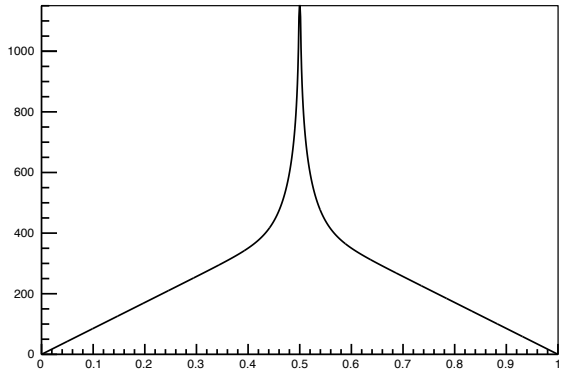
Anode wire: 1150V
Potential wire: 0V
Expected gas gain:~10^4

Anode wire: 1150V
Potential wire: 1000V
Expected gas gain:~7

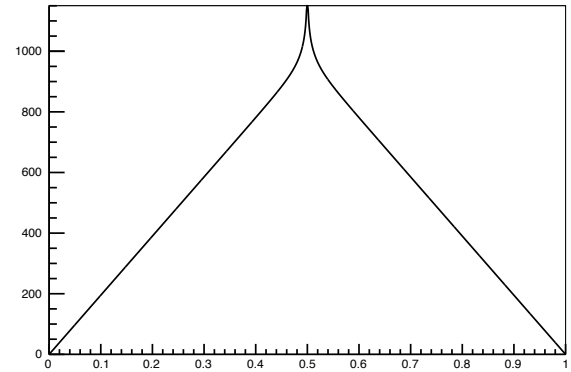


Electric field contour

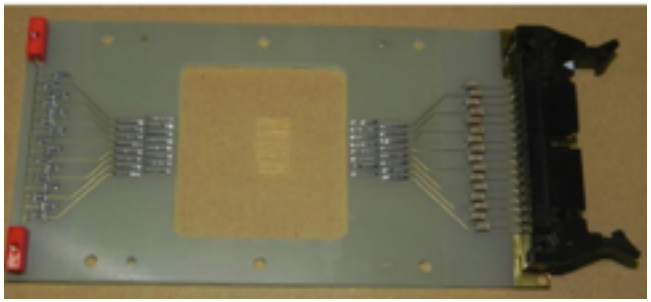




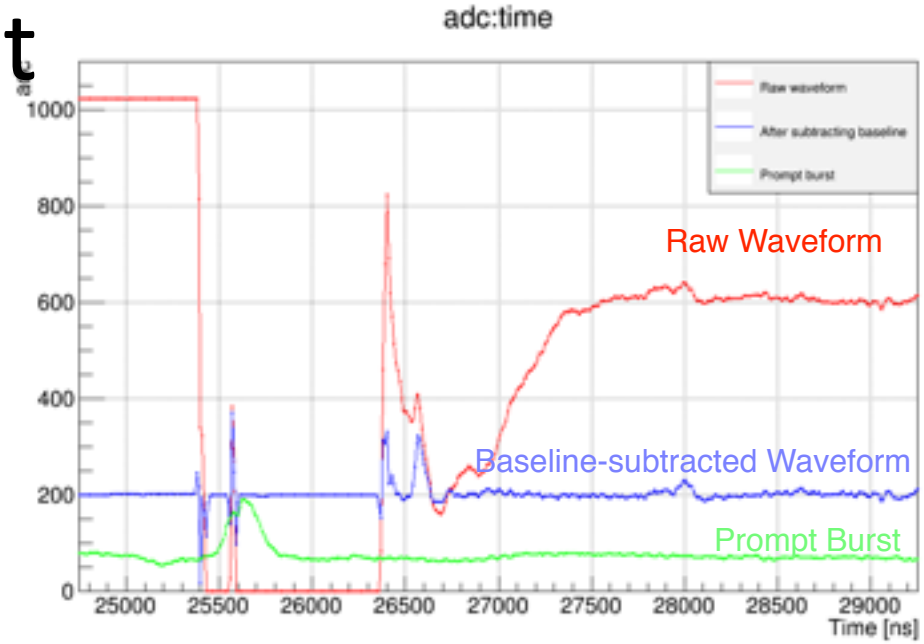
Electric field Profile

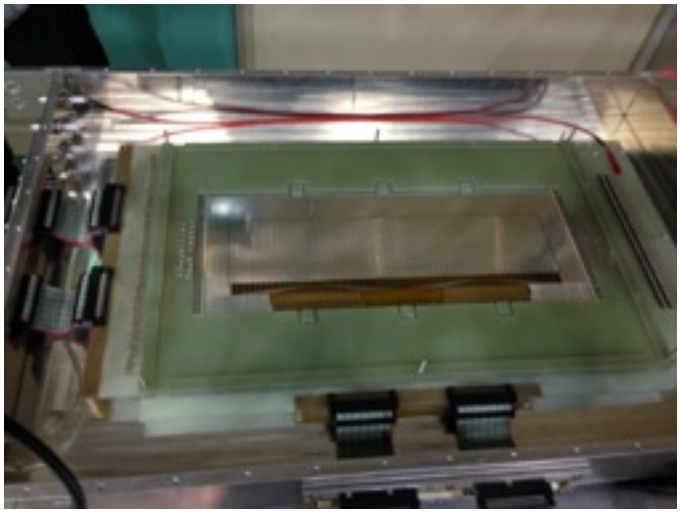


MWPC Development

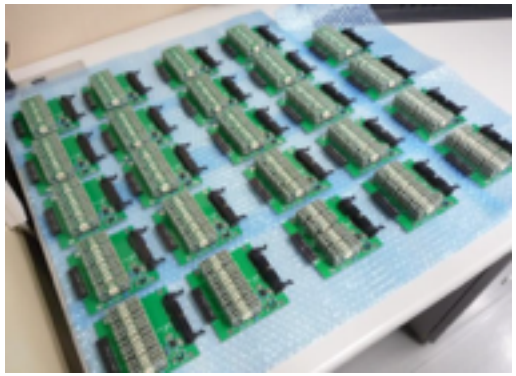


Prototype 1 @2012

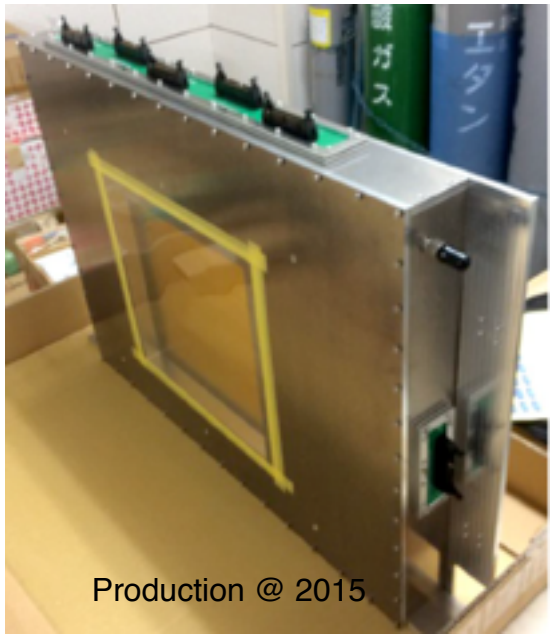




Prototype 2 @2014

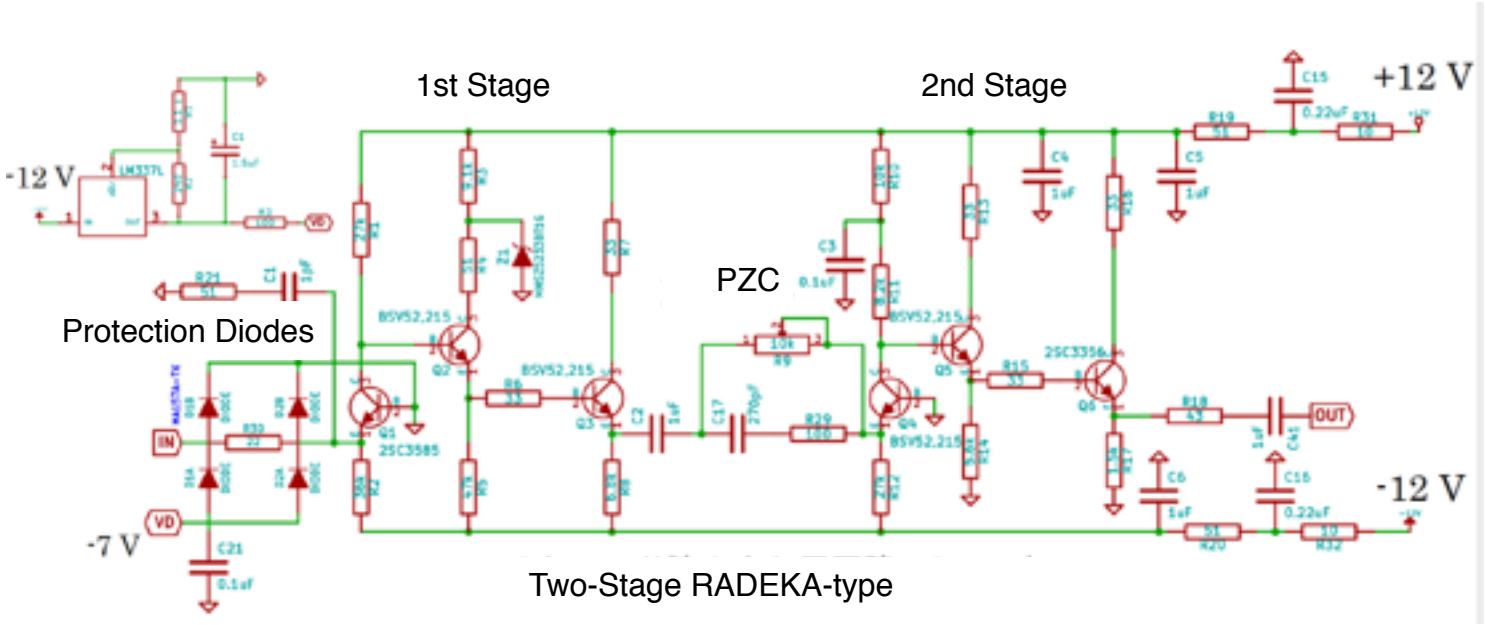


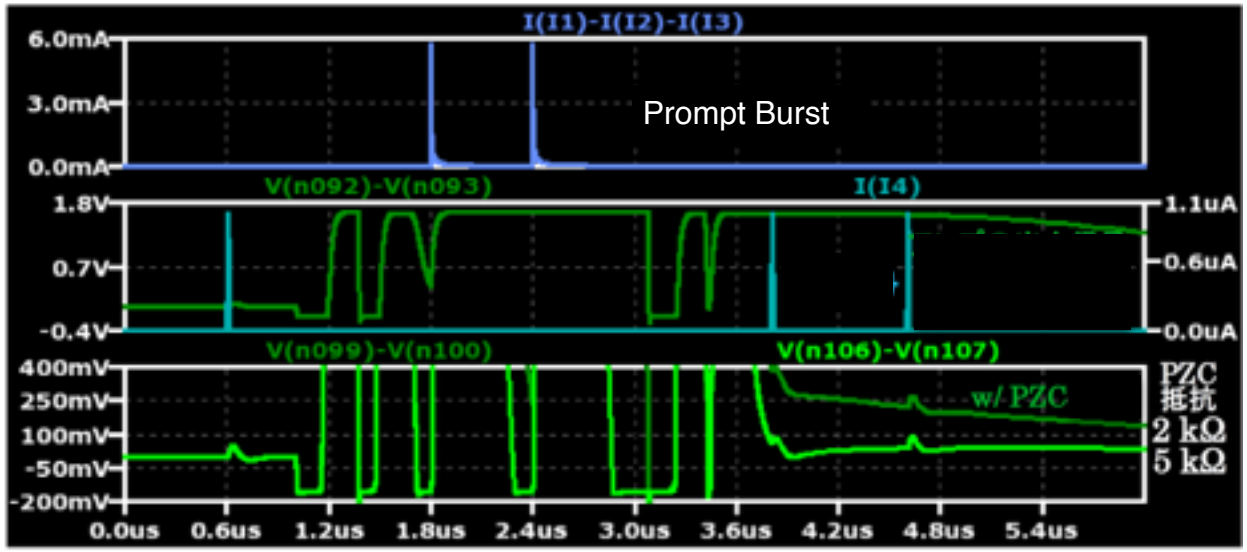
Preamps @ 2015



Production @ 2015

Preamp w/PZC

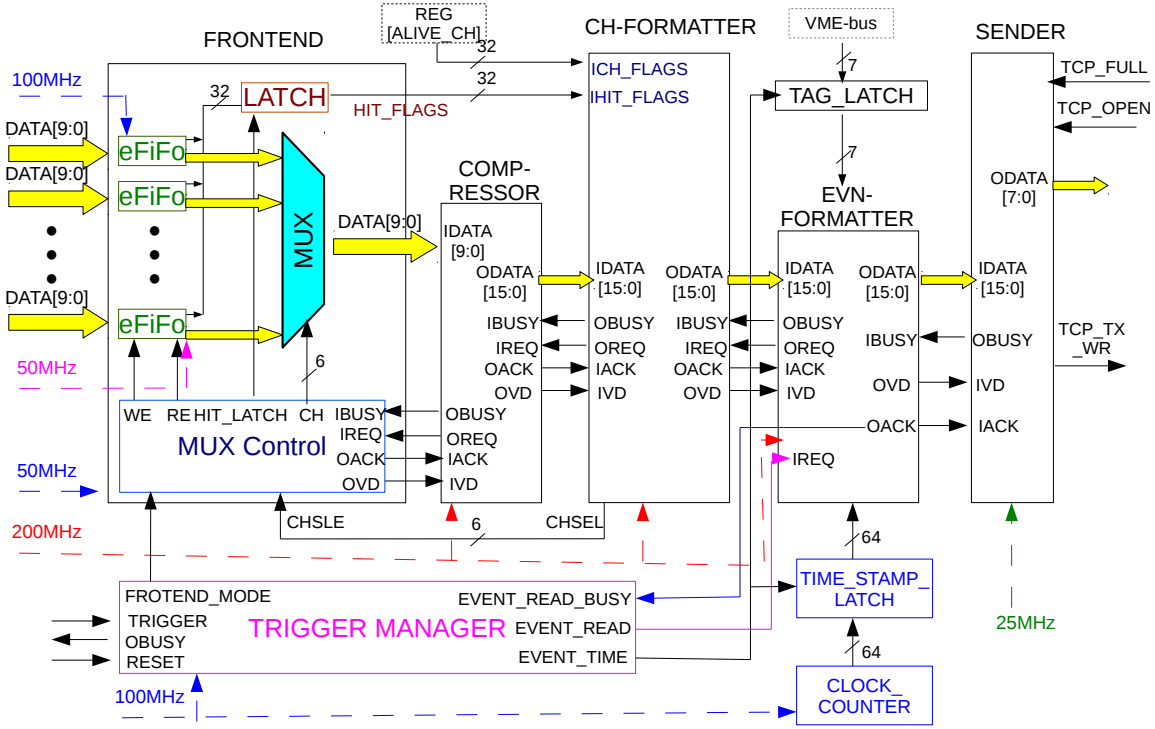




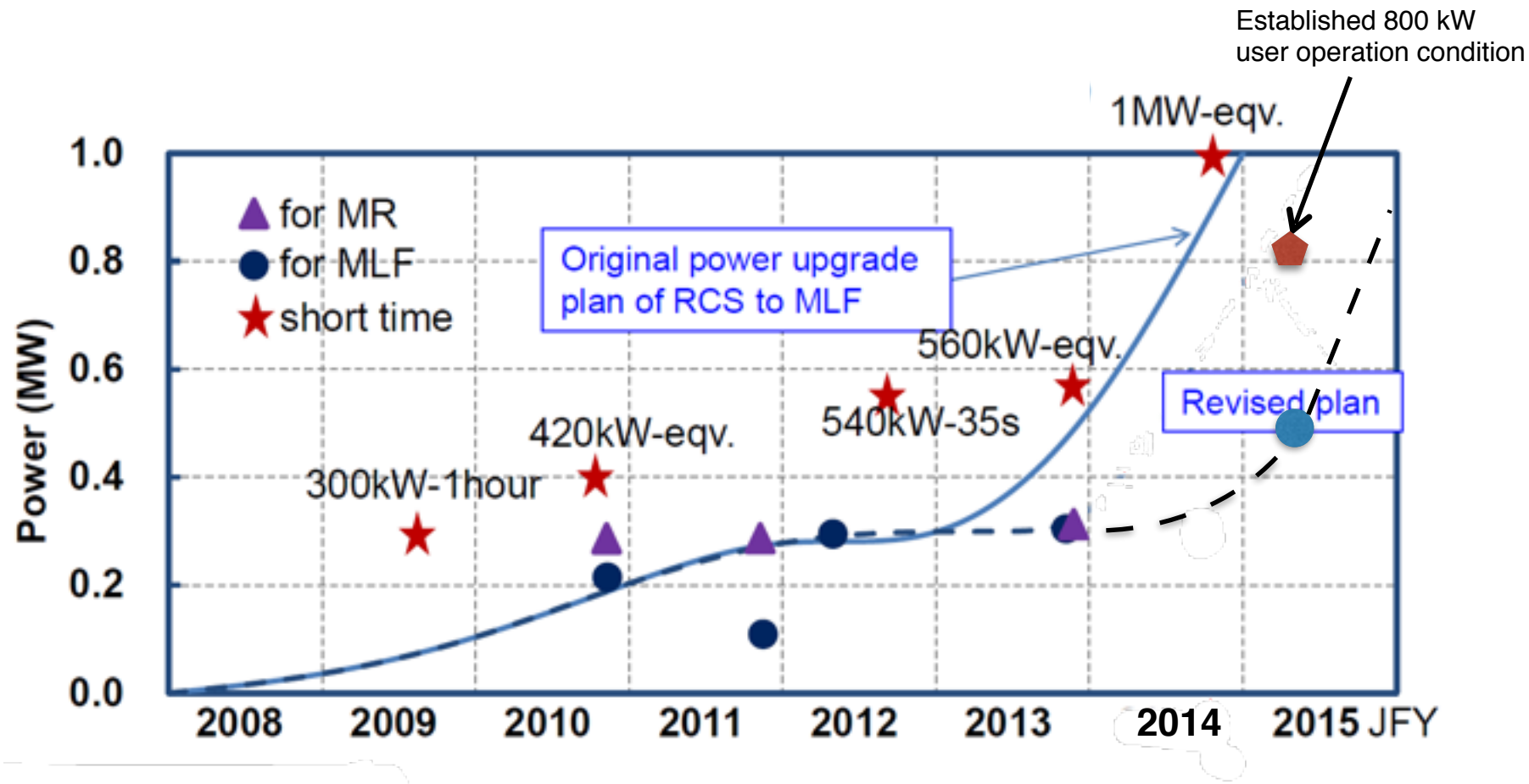
A single-stage PZC right after the 1st transistor to cancel 1/t tail that comes from slow ion movement.

Lowe-cost FADC

- Originally developed for J-PARC/E36 by Y. Igarashi
- Firmware completely replaced by N.M.Truong
- Lossless data reduction
- $70 / channel.



RCS Power Scenario



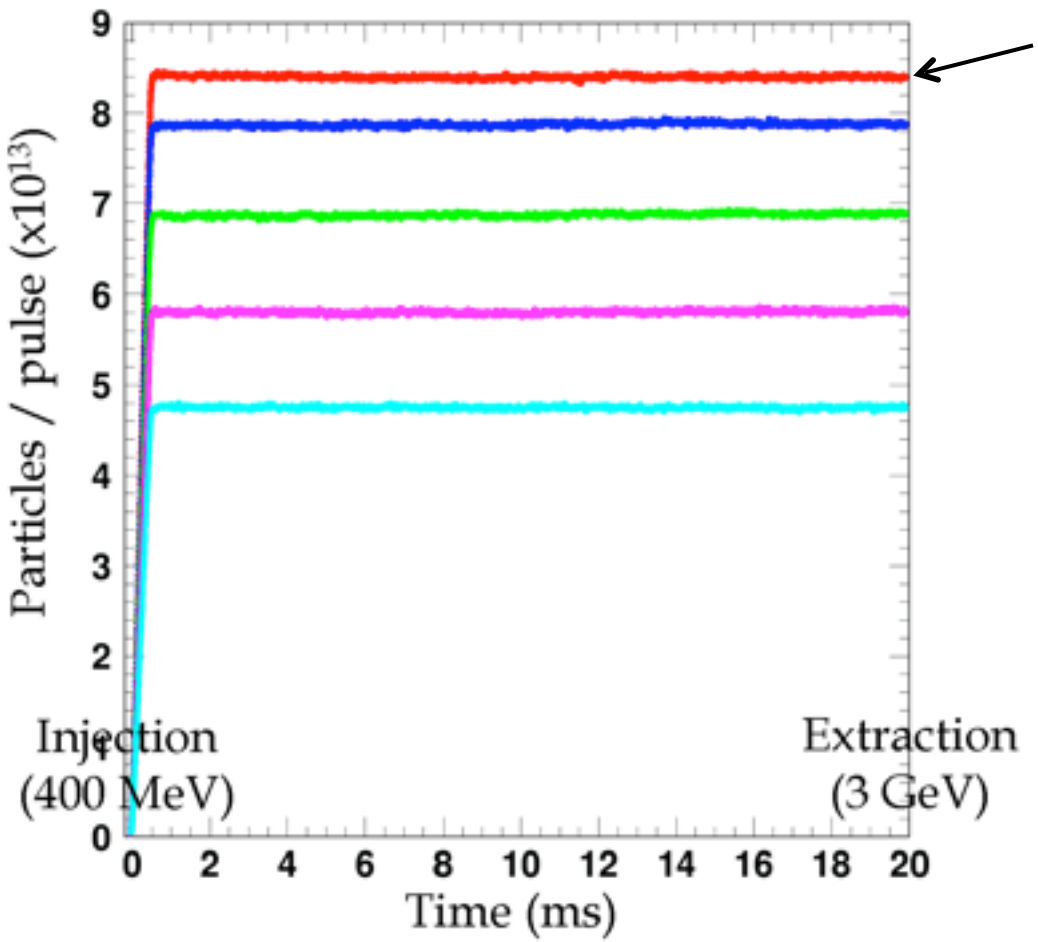
RCS will be ready to start 1-MW user-operation before 2016 JFY.

Summary

- There is a competitive merit of physics in searching for μ-e conversion at sensitivity of 10^{-14} in timely manner.
- It is important to maximize the potential of major discovery at J-PARC.
- DeeMe, yet another mu-e conversion search with totally different method from COMET and Mu2e, creates harmonious diversity for J-PARC.
- DeeMe has already acquired **Stage-2 Approval from muon-PAC of KEK/IMSS**.
- Construction of detector system is ongoing with Grant-in-Aid for Scientific Research of Japan (Basic Science S, 2012–2016).
- It is necessary to build a large-acceptance beamline (H-line) for the best result of DeeMe. The H-line can be used for other experiments, such as g-2.
- We can start the physics measurement with a Graphite target. The development of SiC target will be continued and installed in timely manner for the ultimate sensitivity.
- We are aiming to start the engineering run in 2016. No beam-time conflicts with T2K, KOTO or whatever the physics programs with the main ring of J-PARC.

End of Slides

Demonstration of the high power operation



1 MW-eq.

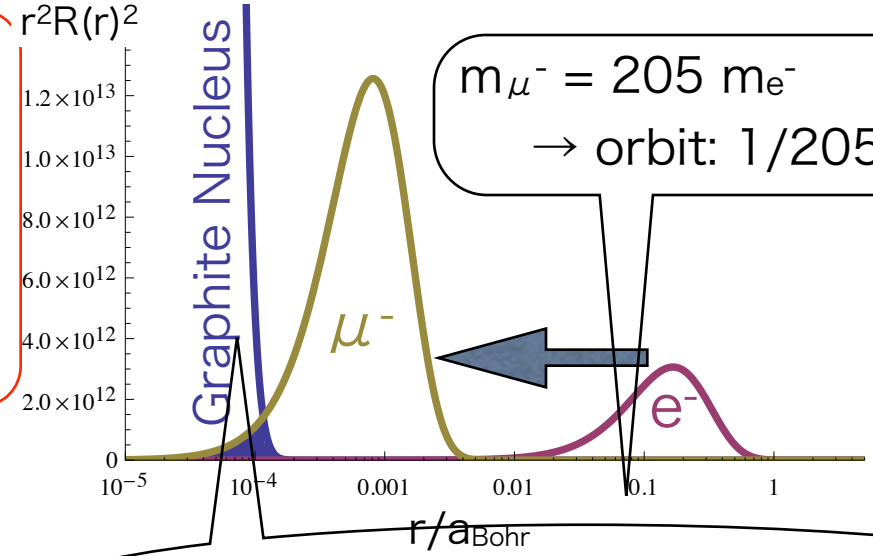
There were no significant loss even if we accelerated 1 MW-eq. beam current.

We established condition of more than 800 kW output beam.

But small loss occurred at the arc sections when we accelerate 900 kW-eq beam. We need further fine tuning.

Beam Survival rate from 0.5 to 1 MW operation measured by the DCCT

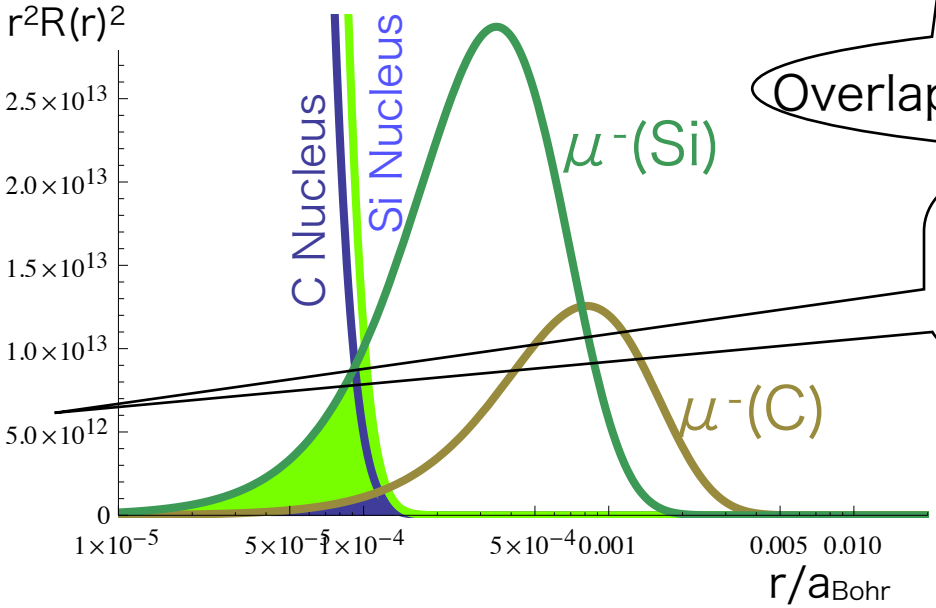
Improvement of Physics Sensitivity by using SiC



$m_{\mu^-} = 205\ m_{e^-}$

→ orbit: 1/205

Overlap of wave function → mu-e conversion



Si → C: wave-function overlap ×11

μ^- reaction: 8%(C)→67%(Si)

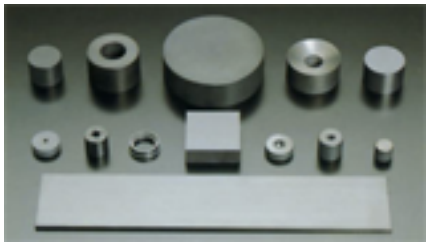
SiC: C also captures μ^-

Effective Reaction Probability 47%

SiC: 6-times improvement of the reaction probability.

2-times improvement of surface muon yield

Evaluation of the influence to other experiments ongoing



Site: J-PARC @ Tokai, Japan