Commissioning of new DC muon beam line, MuSIC-RCNP at Osaka University

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Outline

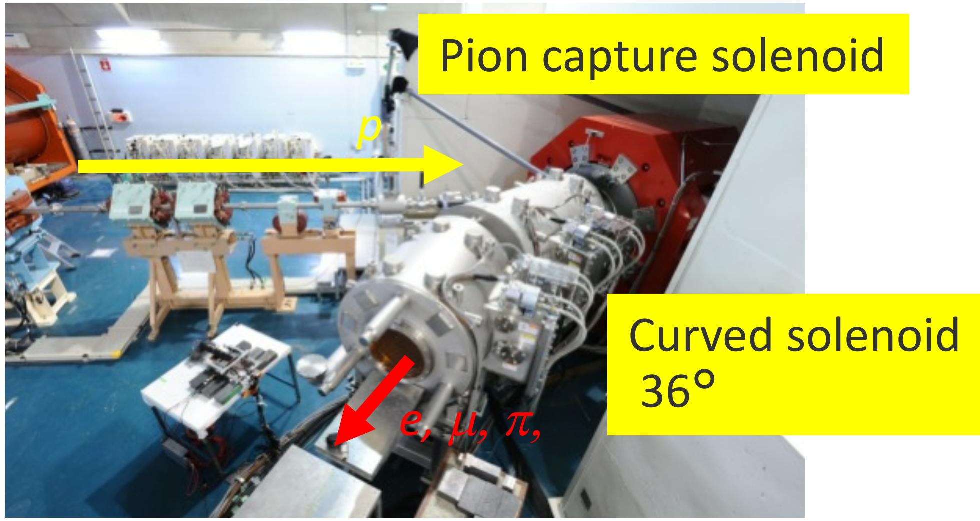
1. MuSIC beamline
2. Beam commissioning (yield and spin measurement)
3. MuSIC status
4. Summary

MuSIC-RCNP Collaboration (Jun, 2016)

MuSIC beamline at RCNP, Osaka University

MuSIC (Muon Science Innovative muon beam Channel) beamline ?

- pion capture solenoid + pion collection solenoid + conventional triplet-Q & bends beamline
- world's most efficient DC muon beam source (~ 10^3)



Large pion/muon collection efficiency ~ 10^3

Triplet-Q + Bending magnets

Beam transport

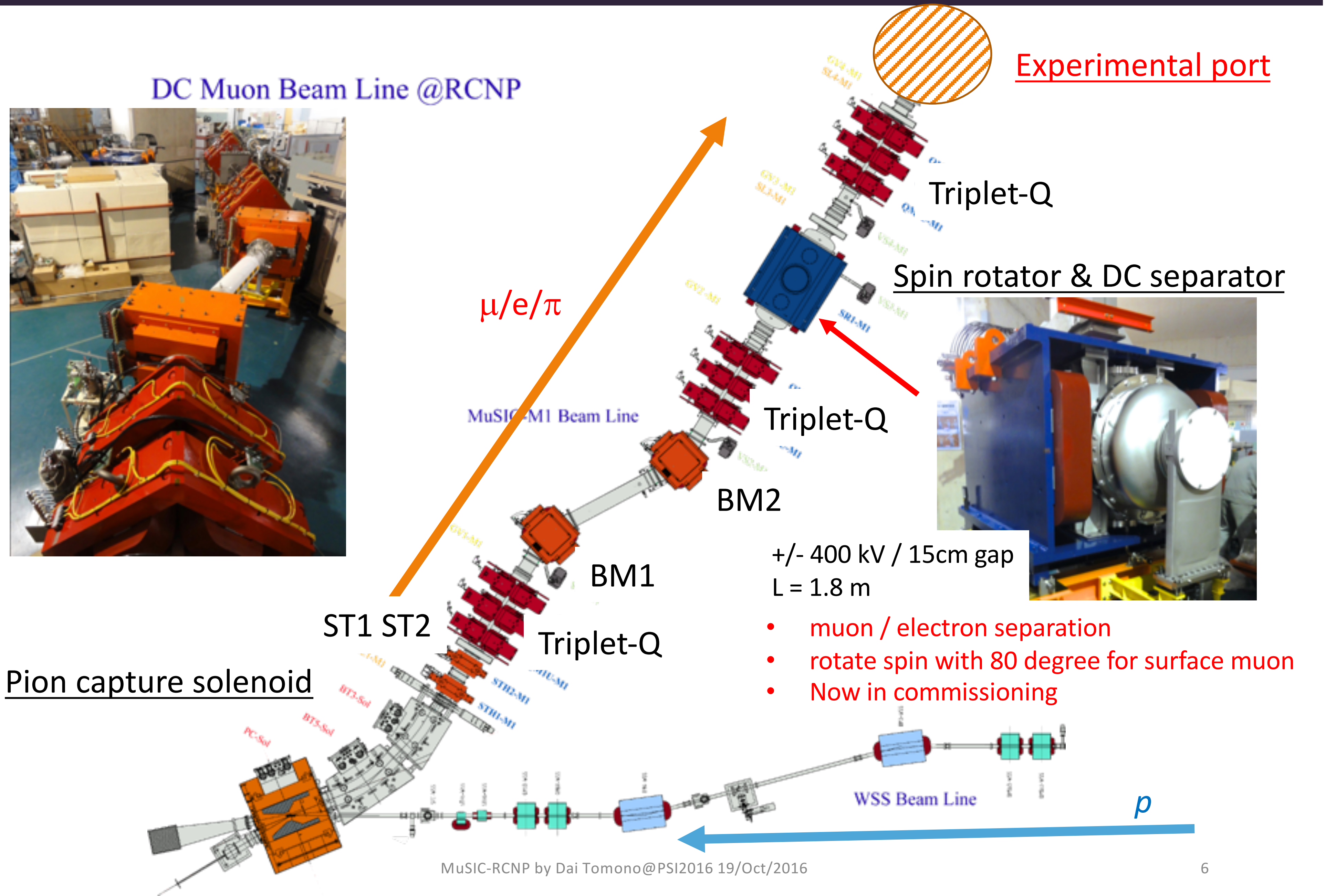
- Present status
  - 10^8 muons are obtained at the curved solenoid end
  - construction of whole beamline is almost completed
  - beam commissioning with 20nA proton beam
  - prepare experimental port and apparatus

MuSIC Beamline

Research Center for Nuclear Physics (RCNP) , Osaka University

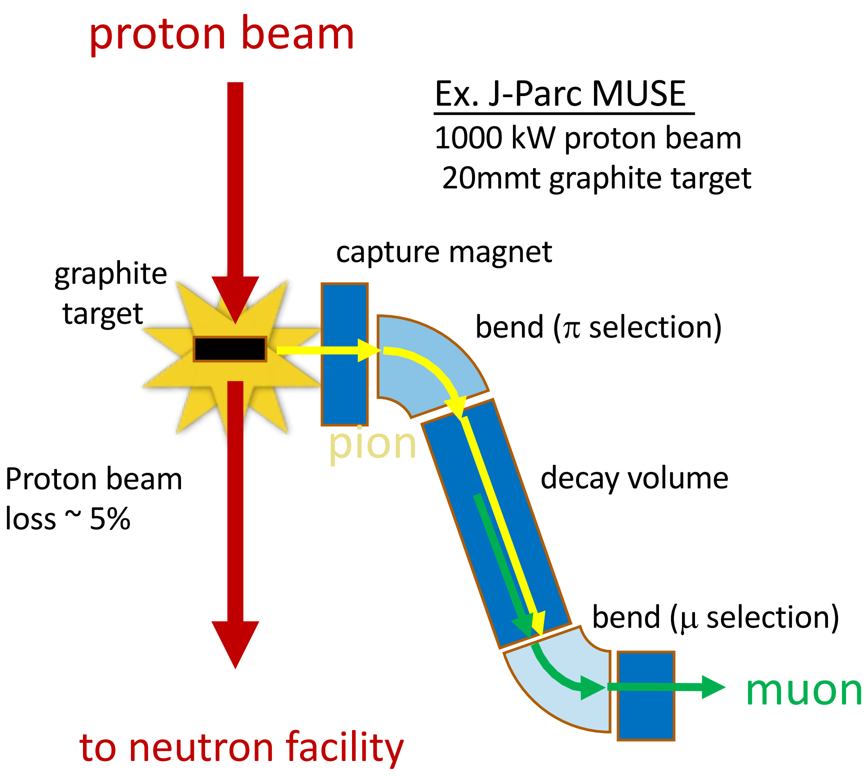
- only 100 MeV above pion production threshold (～$2m_{\pi}$)
- muon source with low proton power (1uA 0.4kW, 5 uA in future)

Layout of Music M1 Beamline



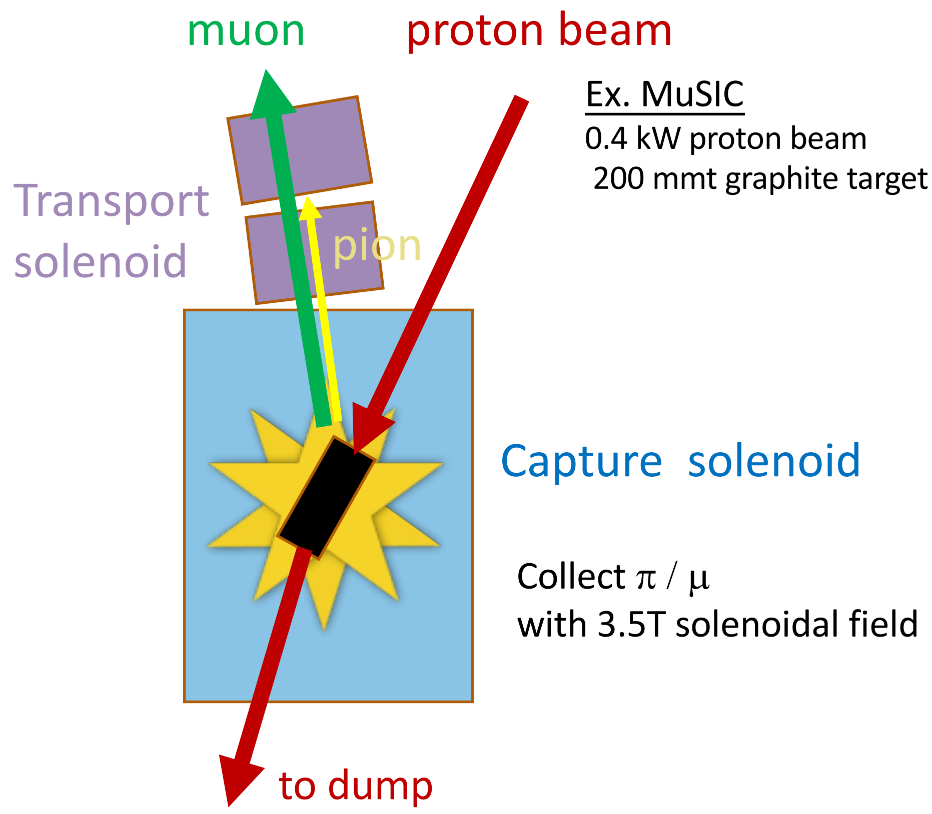
Comparison of pion production methods

Conventional muon beamline



- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

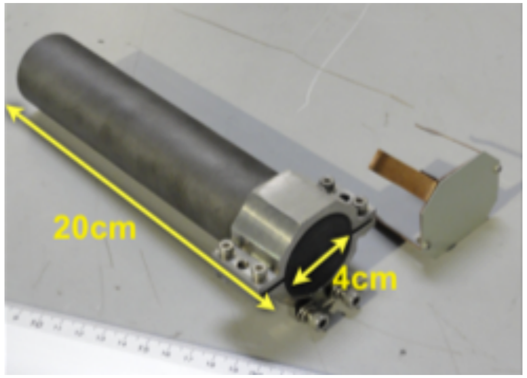
MuSIC beamline

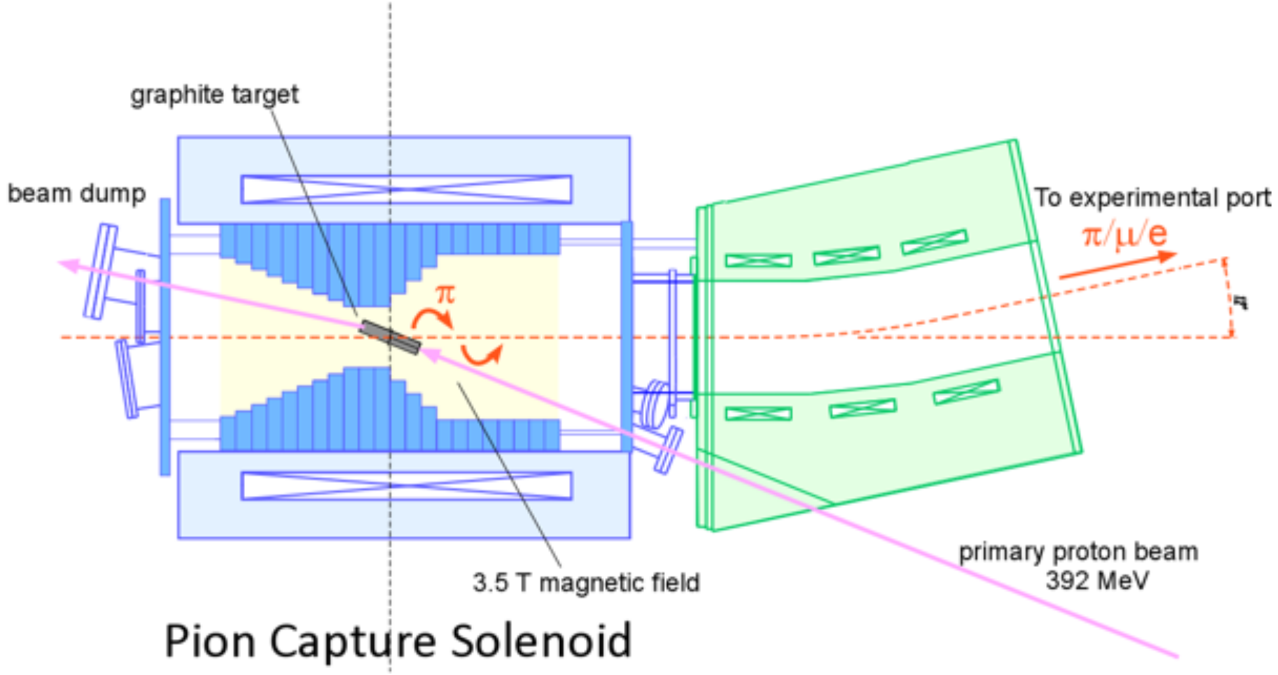


- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

Pion capture solenoid & Pion transport solenoid

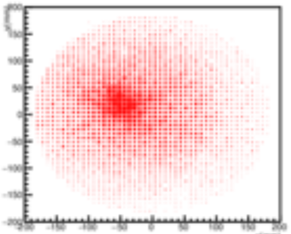
- Pion capture solenoid (3.5T)
  - pion production target inside (1.5 interaction length)
  - pion collection with large solid angles
- Pion transport solenoid (2.0T)
  - Curved solenoid to capture and transport pion/muon
  - Momentum selection with dipole collection field



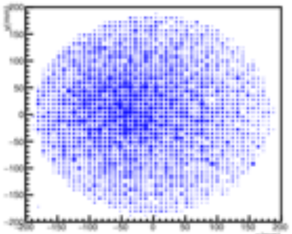


Pion Capture Solenoid

Beam Profile by G4beamline simulation



Surface muon



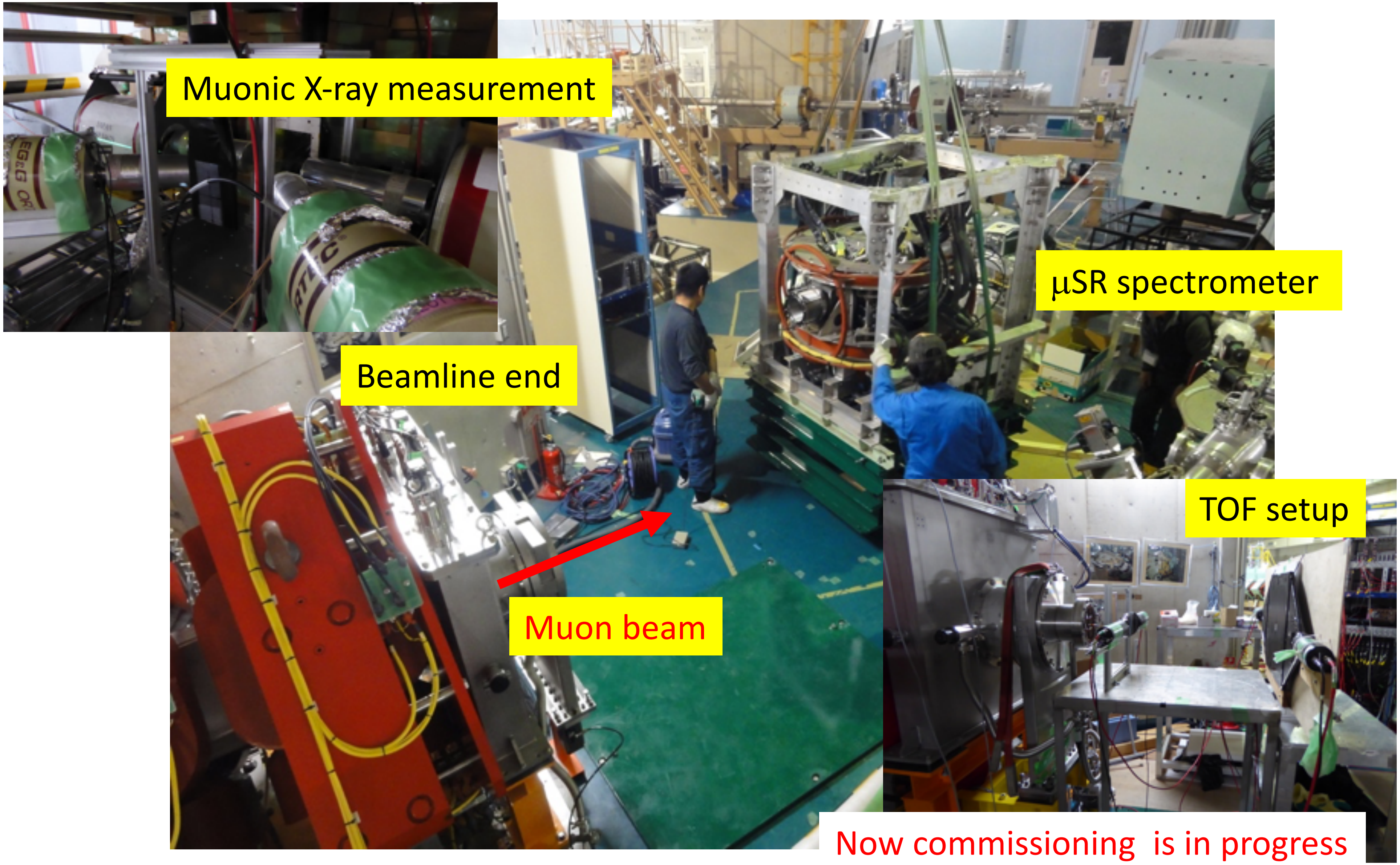
Inflight-decay muon

exit of the 36° curved solenoid
~ 3×10^{8} positive muons
~ 1×10^{8} negative muons

~ 10^{3} pion production efficiency

Beamline Commissioning

Experimental port (at the beamline end)

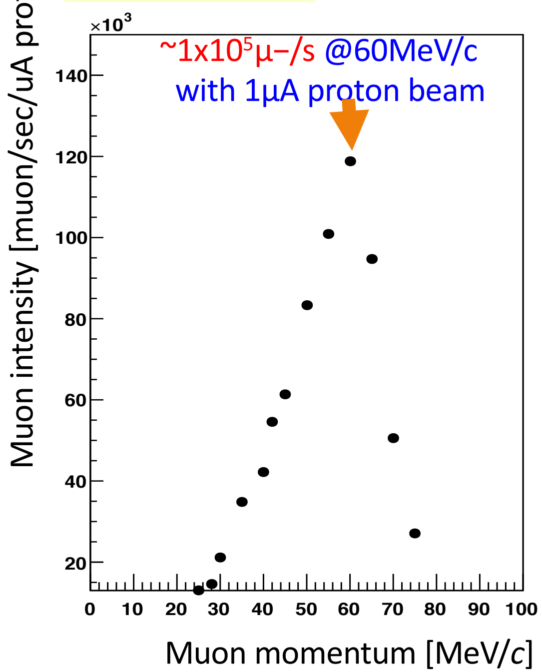


Muon yield measurement

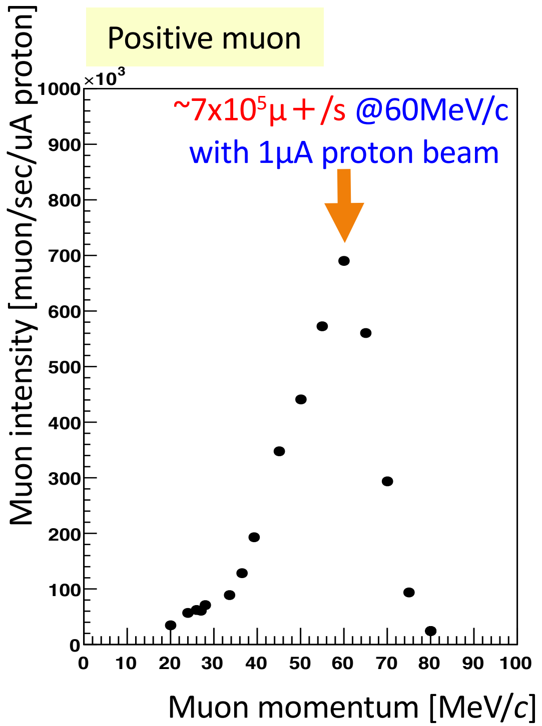
Inflight-decay muons ($\mu^{\pm}$)

Surface muon (μ^{+})

Negative muon

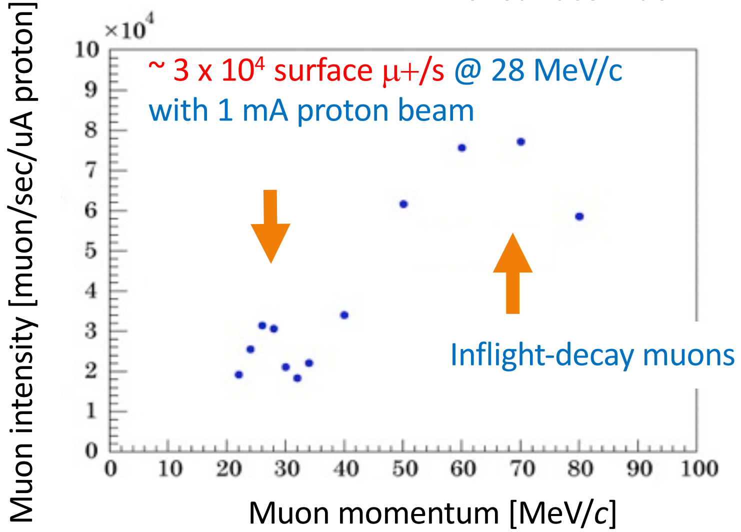


Positive muon

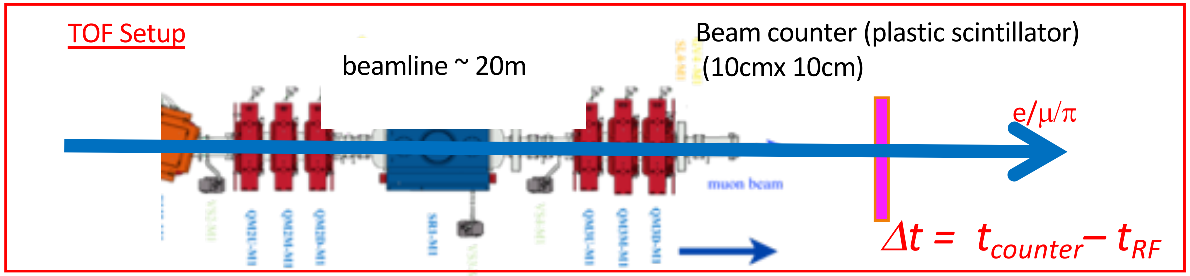


Succeed in observing surface muons (~28 MeV/c)

Target position tuned for surface muon



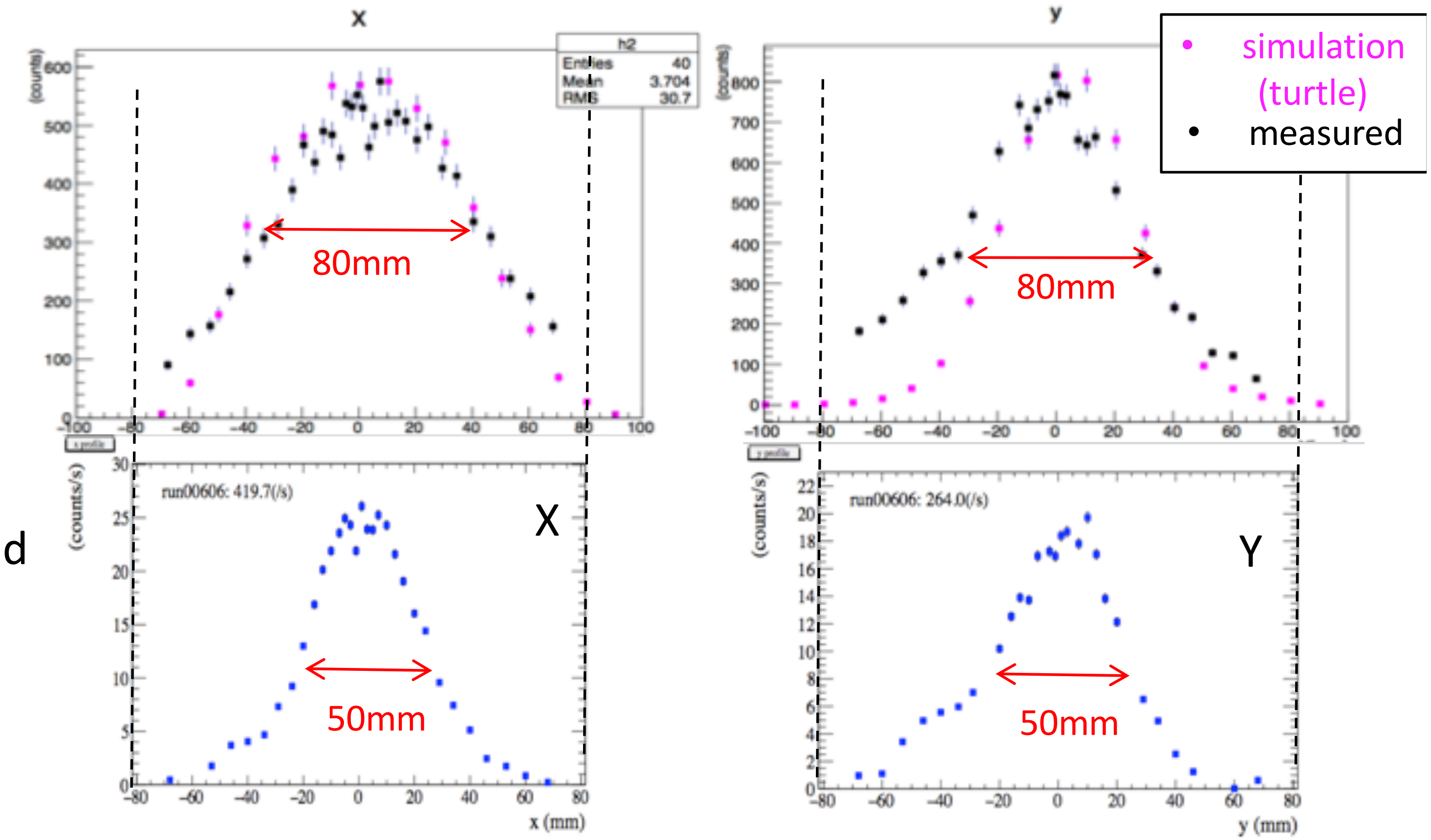
** note that muon yield (vertical axis) is scaled for 1uA proton beam operation
20nA (2016 run) -> 1uA (2017 run)



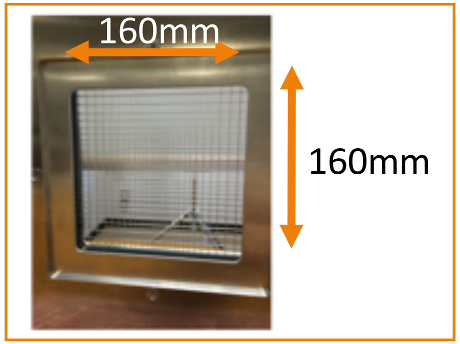
Beam profile measurement

Beam profile at the beamline end (beam focusing position) p =28 MeV/*c*

- slit fully opened
  80 mm x 80 mm
- slit ±30mm opened
  50 mm x 50 mm

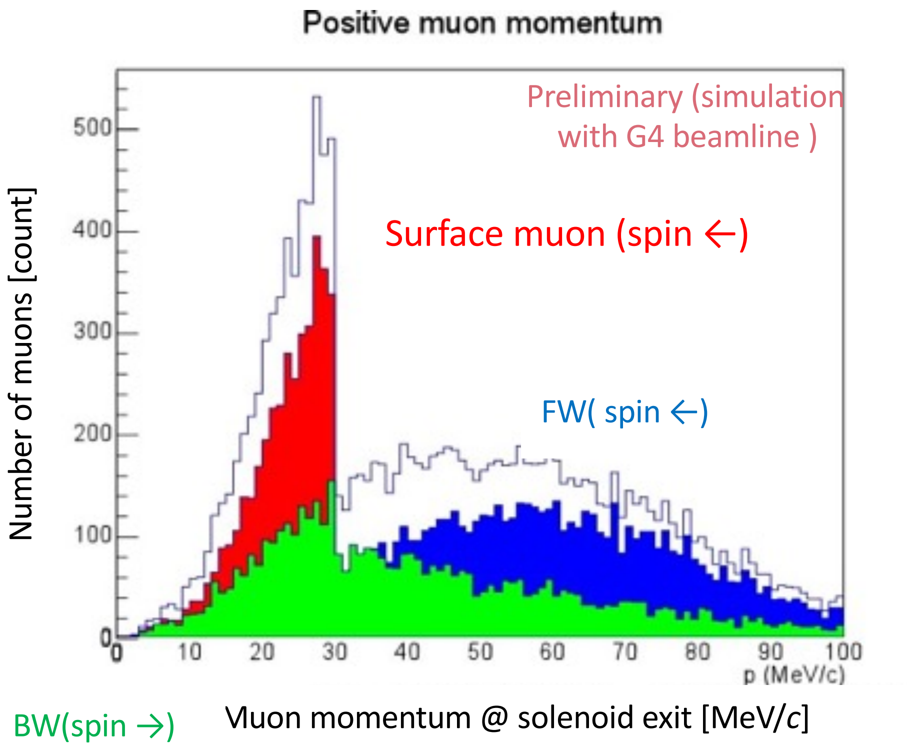


Profile monitor



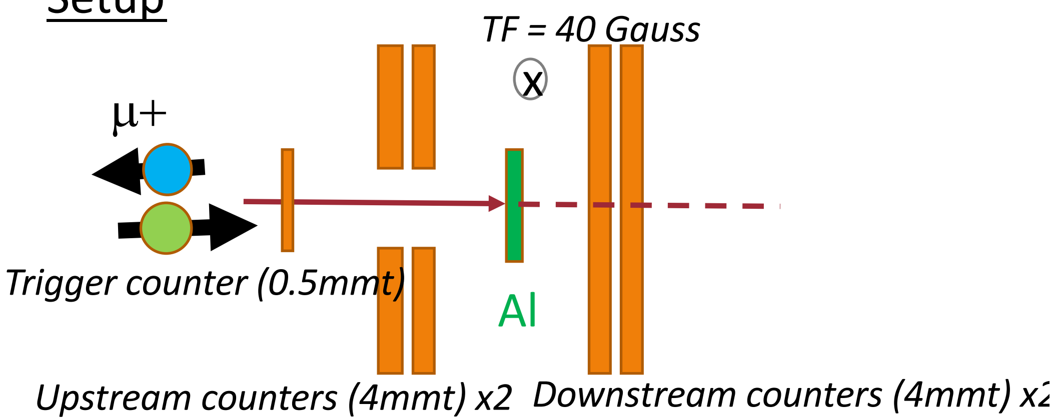
- 1mmϕ thin scintillation fiber + MPPC readout
- Separate e / μ by their energy deposit difference
- 8mm~2mm interval（dense around the center）

Spin measurement



- Muon beam at the solenoid end (G4 beamline output)
- Separate forward and backward decay muons to investigate beam polarization
- Calculate the expected polarization geometrically and compare the experimental results

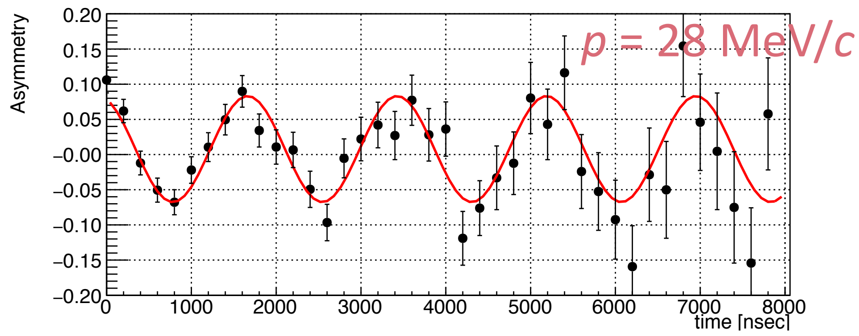
<u>Setup</u>

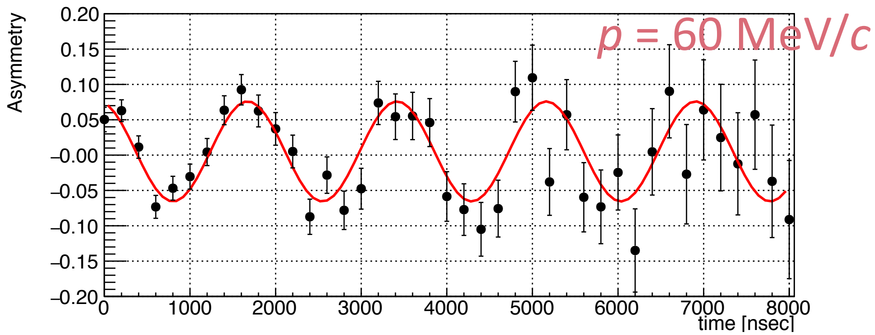


spin asymmetry $$A_{asy}(t) \equiv \frac{N_u(t) - \alpha N_d(t)}{N_u(t) + \alpha N_d(t)}$$

Spin precession results

Typical observed asymmetry spectra

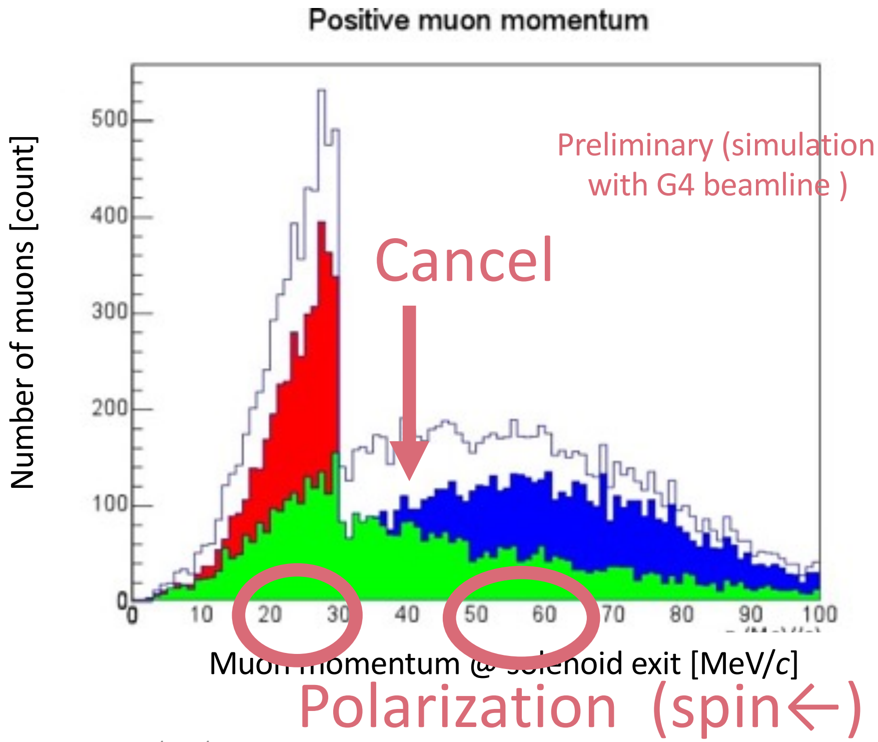




$\propto \mathrm{A}\cos(\gamma_\mu Bt + \delta_0)$ γ_μ : Lamor frequency

Measured polarization

Momentum [MeV/c]	Polarization (G4 simulation)	Polarization (measured)
28 (surface μ)	48	57
40	10	16
50	45	59
60	55	57



Muon Science at MuSIC

- <u>Stage 0</u>
  - — proof-of-principle for muon capture and transport solenoid (also for COMET experiment)
  - — high efficiency (~ 10^3) muon production was achieved (measured at the capture solenoid end)

- <u>Stage 1(2012-16)</u>
  - —Conventional triplet-Q and bend magnets were installed successively to the collection solenoid.
  - —Beam commissioning is now in progress
  - — Physics programs start
    - Muonic X-ray analysis and non-destructive analysis
      - Chemistry on muonic and pionic atoms
      - non-destructive element analysis (ex, from asteroid explorer, Hayabusa-II)
    - Probes for condensed matter physics (DC-μSR), Feasibility tests are now in progress

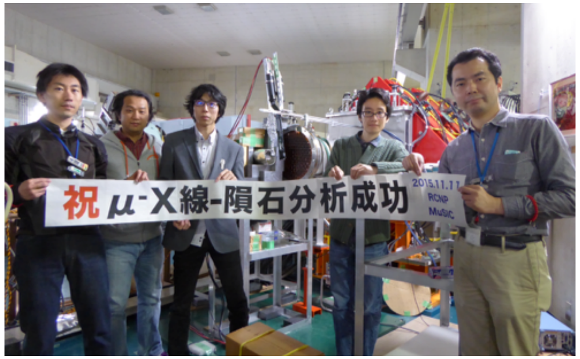
We are now in this stage (2016)

- <u>Next stage and future</u>
  - —Muonic X-ray analysis
  - —DC-μSR study for users
  - — Nuclear physics
    - Nuclear muon capture for 0νββ study (for nuclear matrix element determination, proposed)
    - Gamma-ray measurement from nuclear capture with heavy nuclei
    - Nuclear physics combined with the high resolution / acceptance spectrometer in RCNP (prospects)
  - —Improvement of the beamline
  - —new physics programs

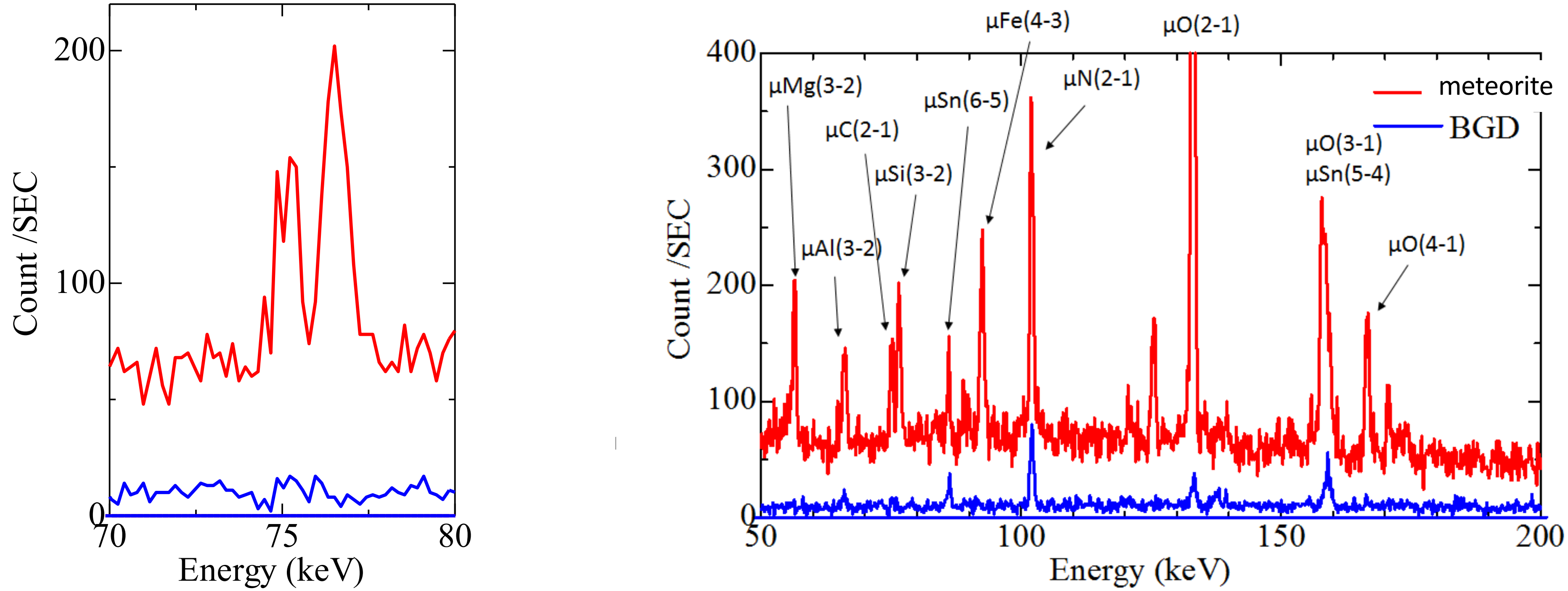
First experiment (μ⁻) : muonic X-ray & gamma-ray measurement

First MuSIC beamline experiment for users (E411)

9th – 11th Nov. , 2015



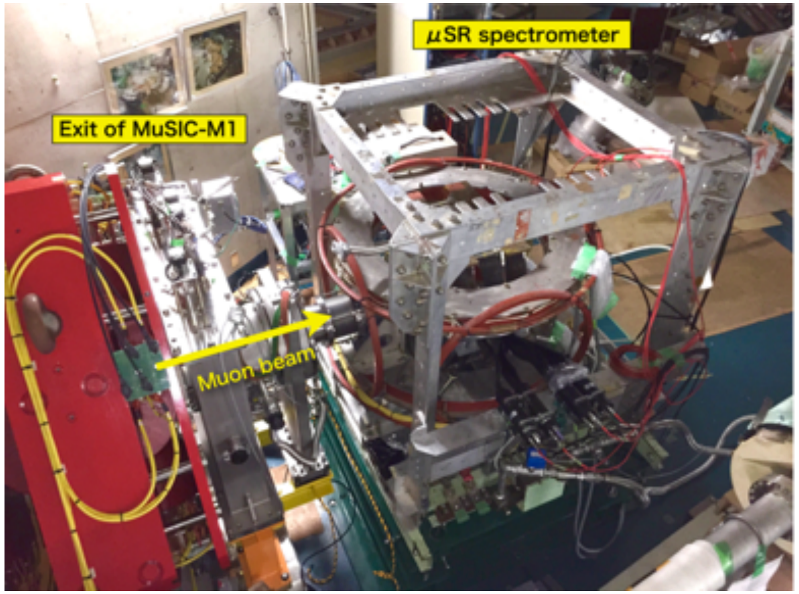
Fundamental study for non-destructive elemental analysis with muon for analyzing planetary materials brought by ”Hayabusa2”

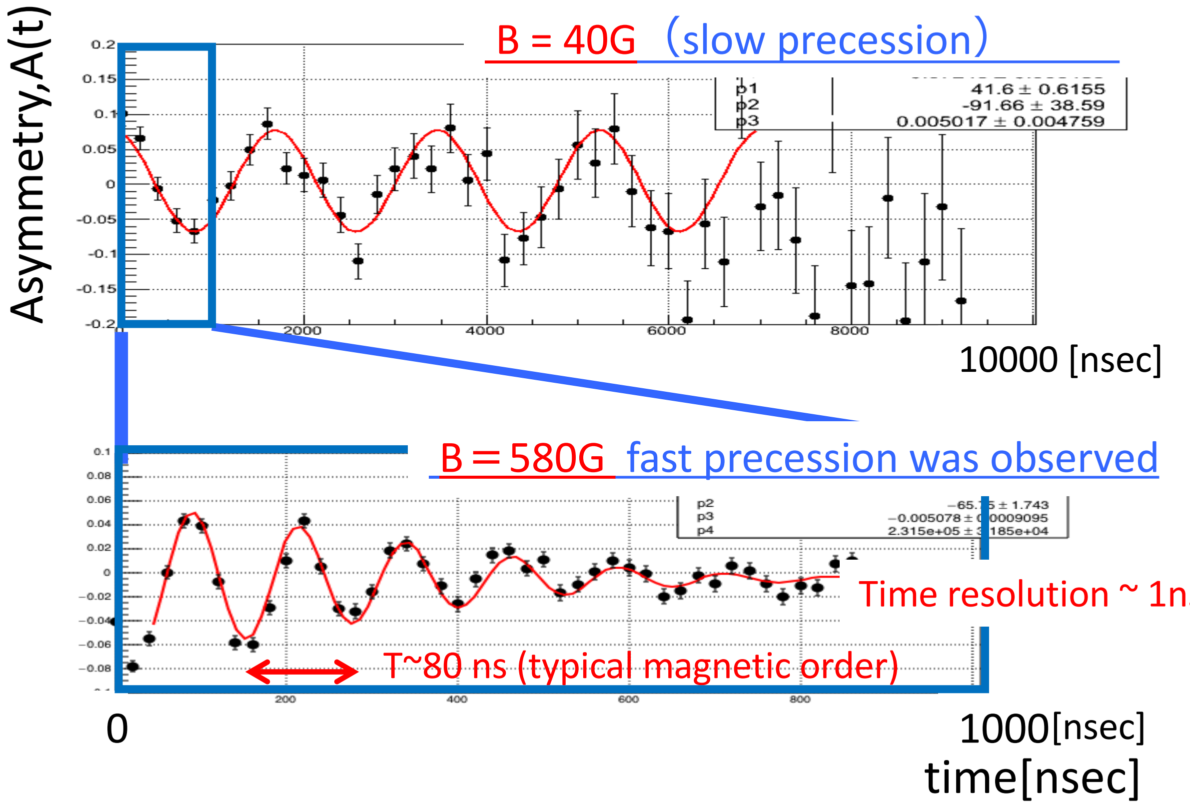


From : K .Terada (Osaka U.) MXG16 slide

Demonstration of fast spin precession with DC muon beam

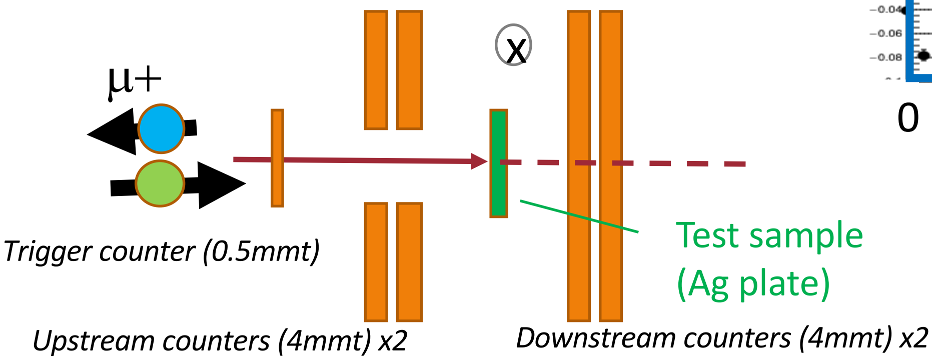
- muon spin precession spectra





<u>Setup</u>

TF = 40 , 580 Gauss



spin asymmetry $A_{asy}(t) \equiv \frac{N_u(t) - \alpha N_d(t)}{N_u(t) + \alpha N_d(t)}$

→ possibility of DC μSR
(proof for high time resolution precession)

Summary

- New innovative DC muon source with solenoid system has been developed at RCNP, Osaka University
  - good pion production efficiency of ~ 10^3
  - pion capture & transport solenoid + triplet-Q and bend magnets beamline

- Beamline commissioning is now in progress
  - 28 MeV/c – 110 MeV/c muon beam
  - inflight-decay μ^+ 10^5-10^6 μ^- 10^5-10^6 surface μ^+ 3 x 10^4 [count/sec/1uA proton beam]
  - beam size (<80mmϕ), momentum bite (<10%) and polarization (~ 60%) were measured
  - start feasibility study
  - Improvement of muon beam (especially, solenoid and triplet-Q connection)

- Physics program in MuSIC
  - nuclear physics (muon capture)
  - radio-chemistry and non-destructive evaluation of elements
  - positive muon for μSR measurement (feasibility study to practical physics program)
  - MuSIC beamline will be a highly intense DC muon source. has possibility to perform DC muon source