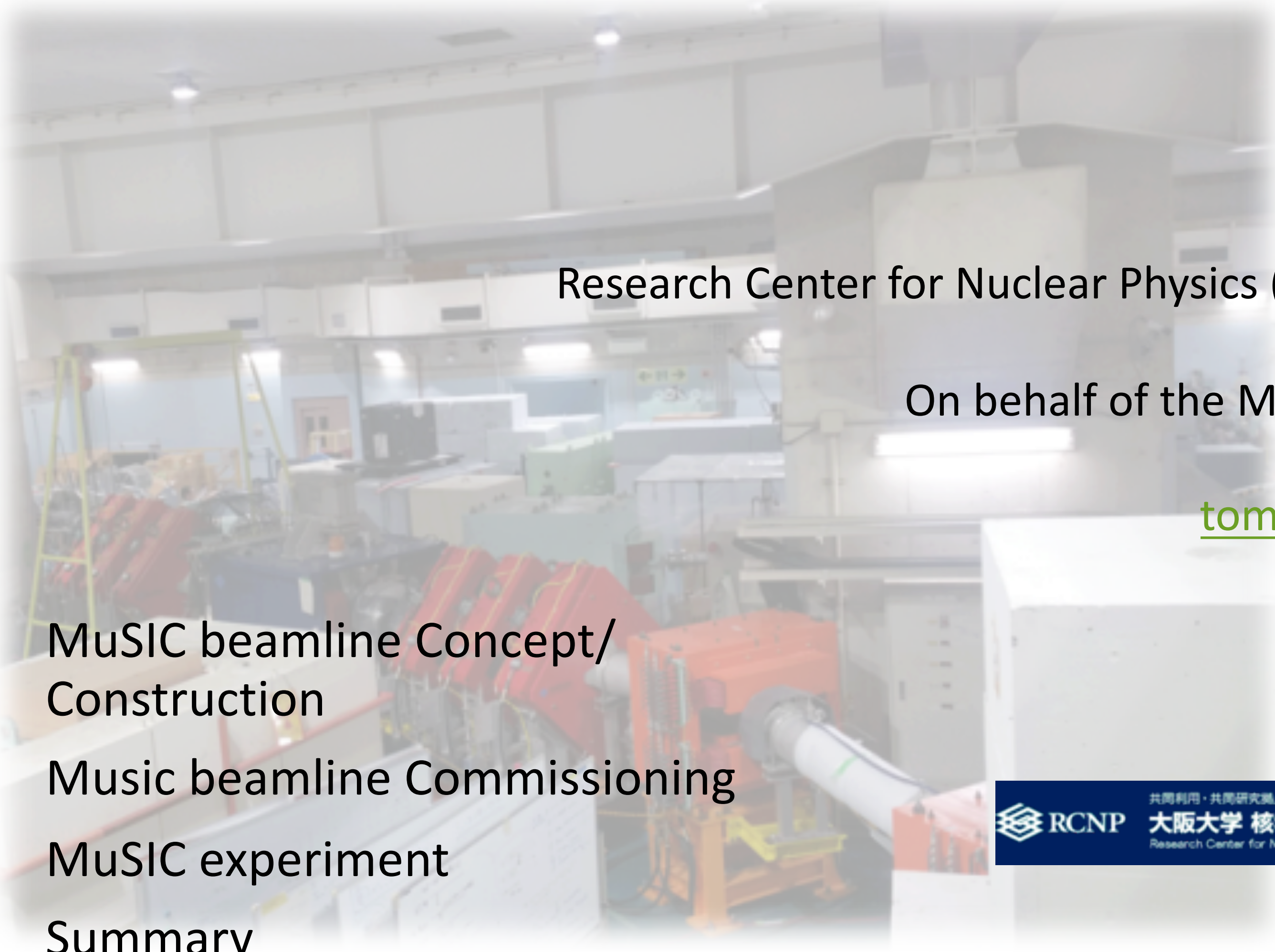
Construction of new DC muon beamline, MuSIC-RCNP, for muon applied science



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NuFact2017, 26th Sep. 2017

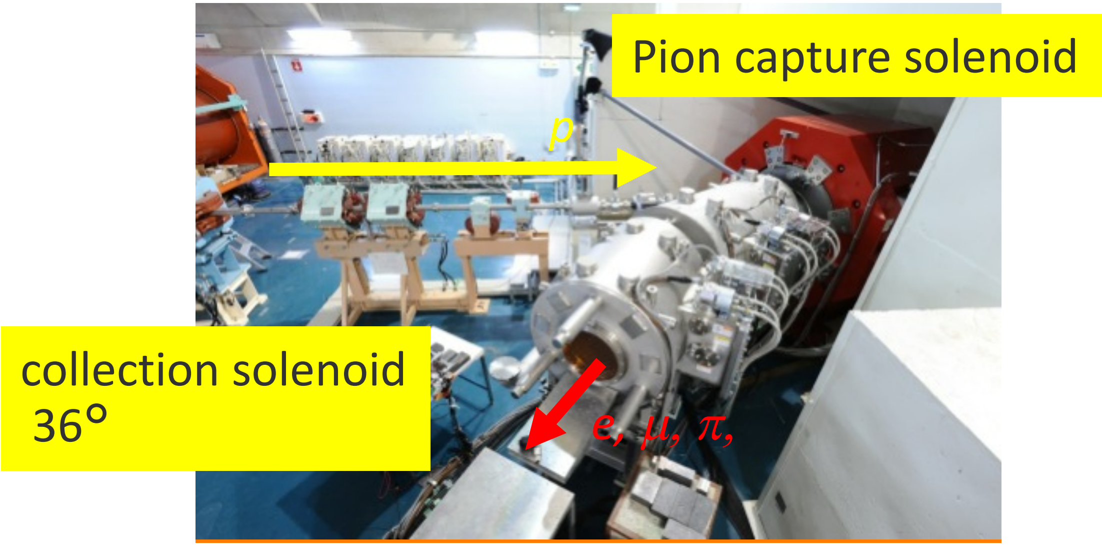
1. MuSIC beamline Concept/ Construction
2. Music beamline Commissioning
3. MuSIC experiment
4. Summary

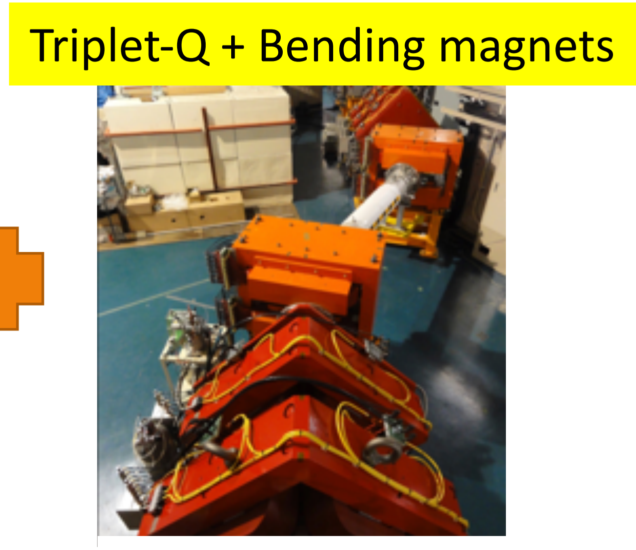
MuSIC Beamline

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)





pion capture solenoid :

- realize large pion / muon collection efficiency
- Radiation issues (coil cooling for the heat load)

muon collection solenoid :

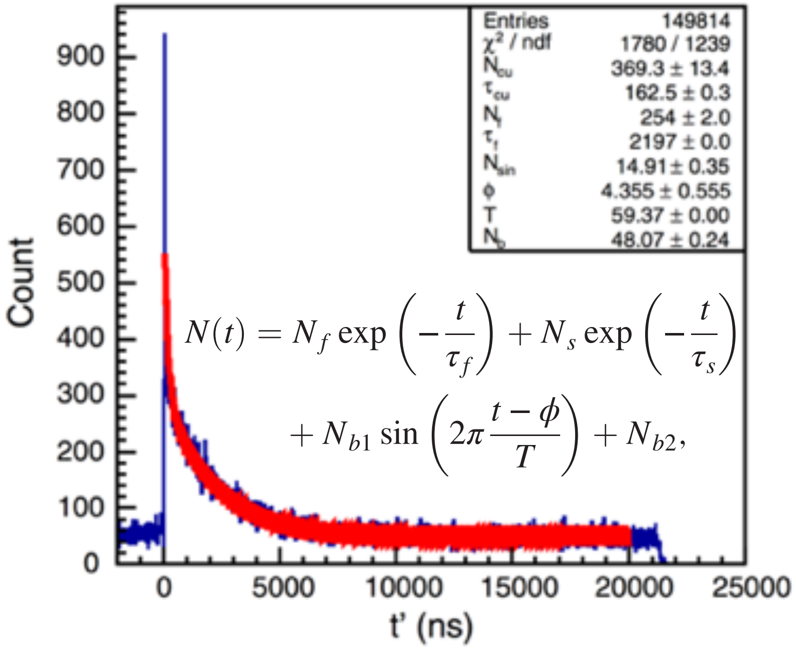
- transport and focus with dipole field

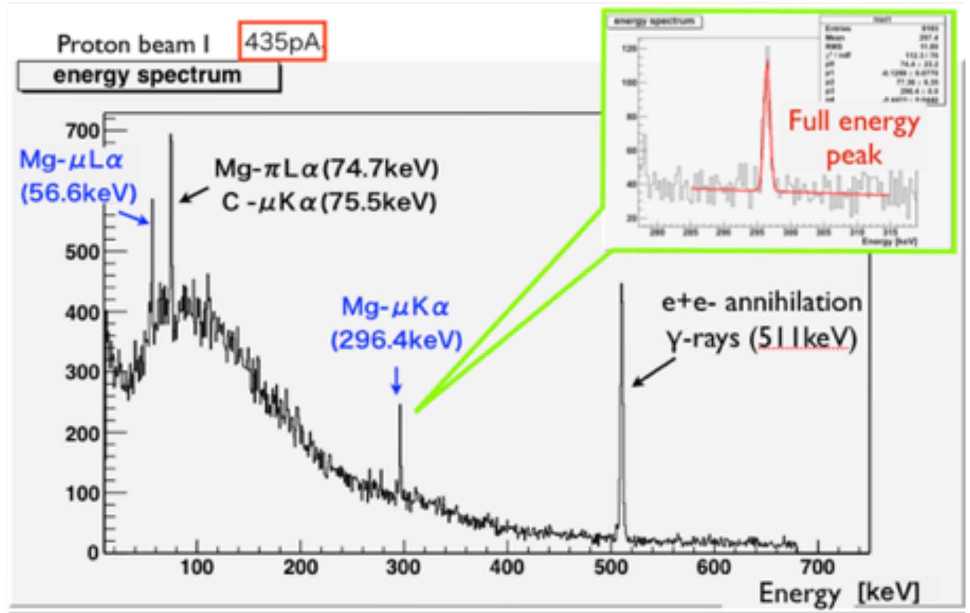
Beam transport:

- Muon beam transport to the experimental port
- Electron separation
- Start experiments

First experiment : Muon yield measurement at the solenoid exit (2011)

Prior experiments to measure muon beams at the solenoid exit.





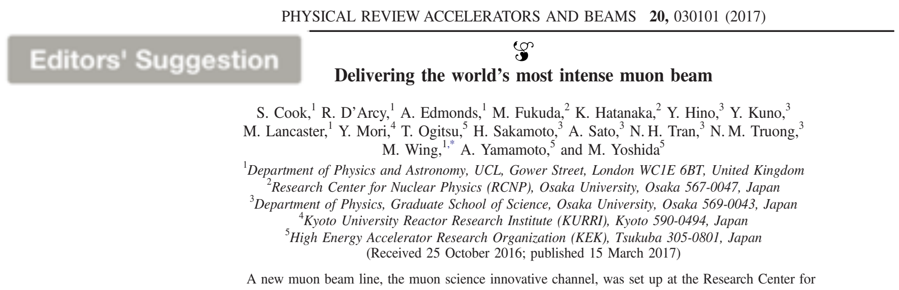
muon lifetime fitting

$$\boxed{N_{\mu+} = (4.2 \pm 1.1)\times 10^{8}}$$

muon X-ray counting

$$\boxed{N_{\mu-} = (3.6 \pm 0.4)\times 10^{7}}$$

published
Phys. Rev. Accel. Beams 20 (2017)030101.


PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 030101 (2017)

Editors' Suggestion

Delivering the world's most intense muon beam

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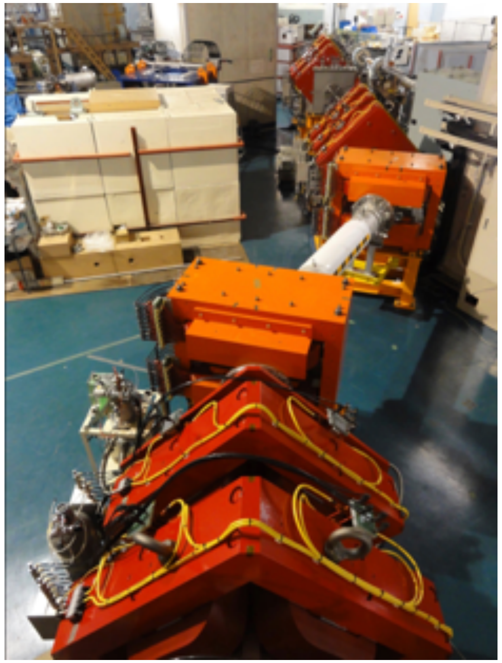
A new muon beam line, the muon science innovative channel, was set up at the Research Center for

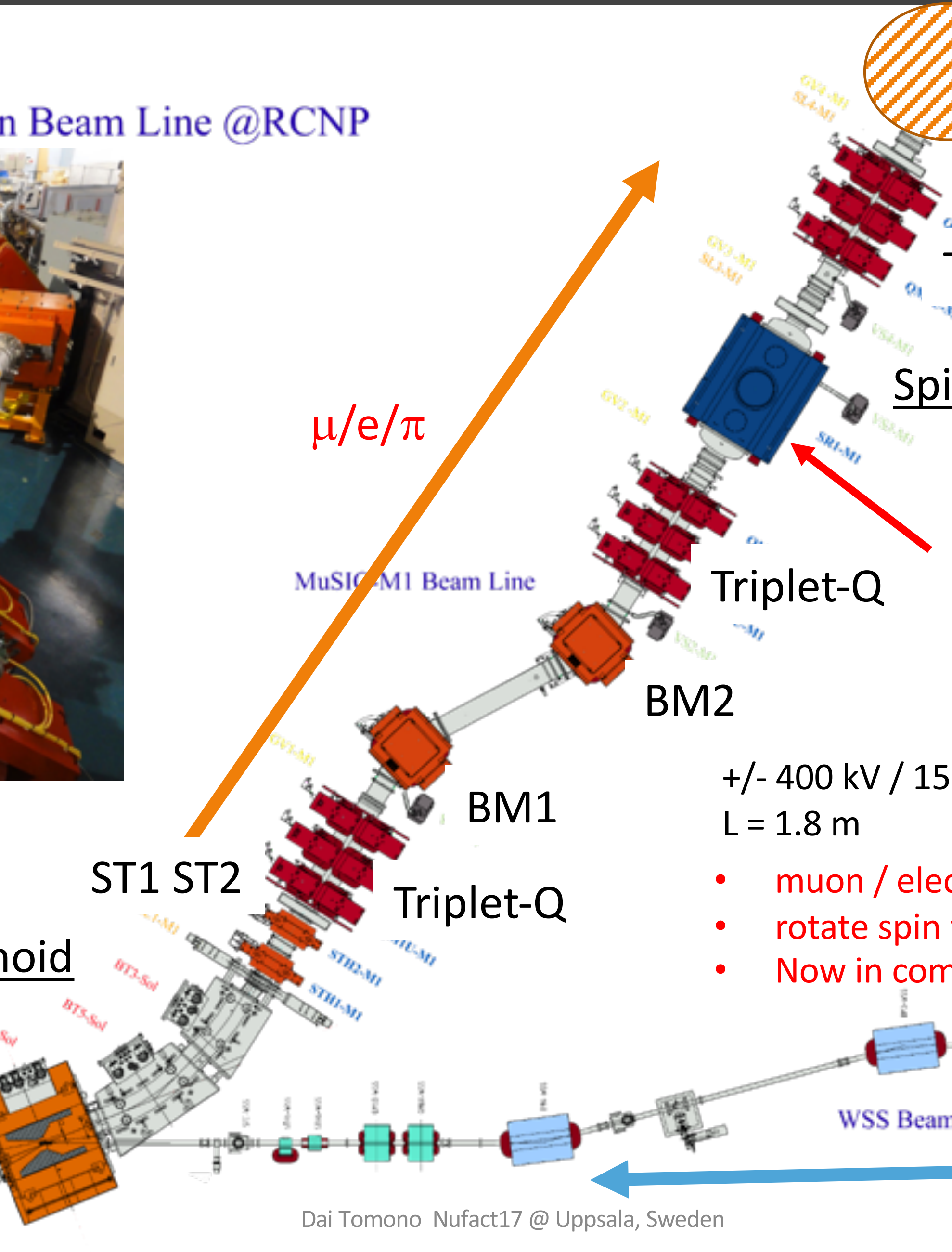
Research Center for Nuclear Physics (RCNP) , Osaka University

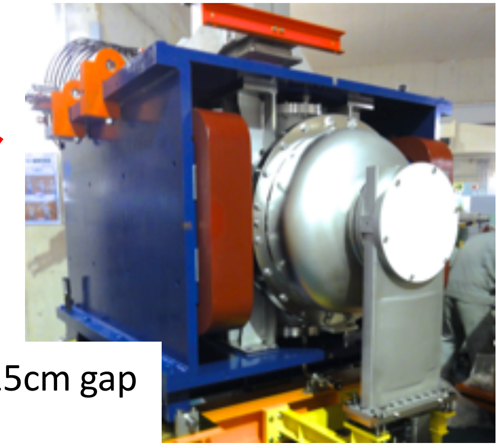
- proton beam energy is only 100 MeV above pion production threshold ($\sim 2m_{\pi}$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

Layout of Music M1 Beamline

DC Muon Beam Line @RCNP





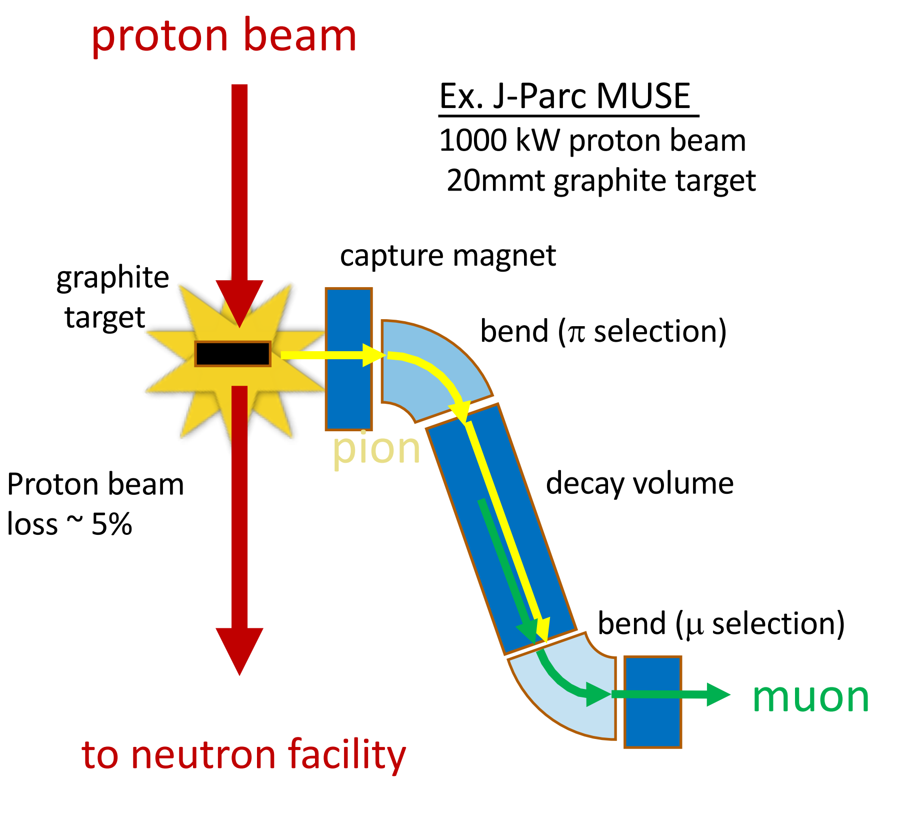


+/- 400 kV / 15cm gap
L = 1.8 m

- muon / electron separation
- rotate spin with 80 degree for surface muon
- Now in commissioning

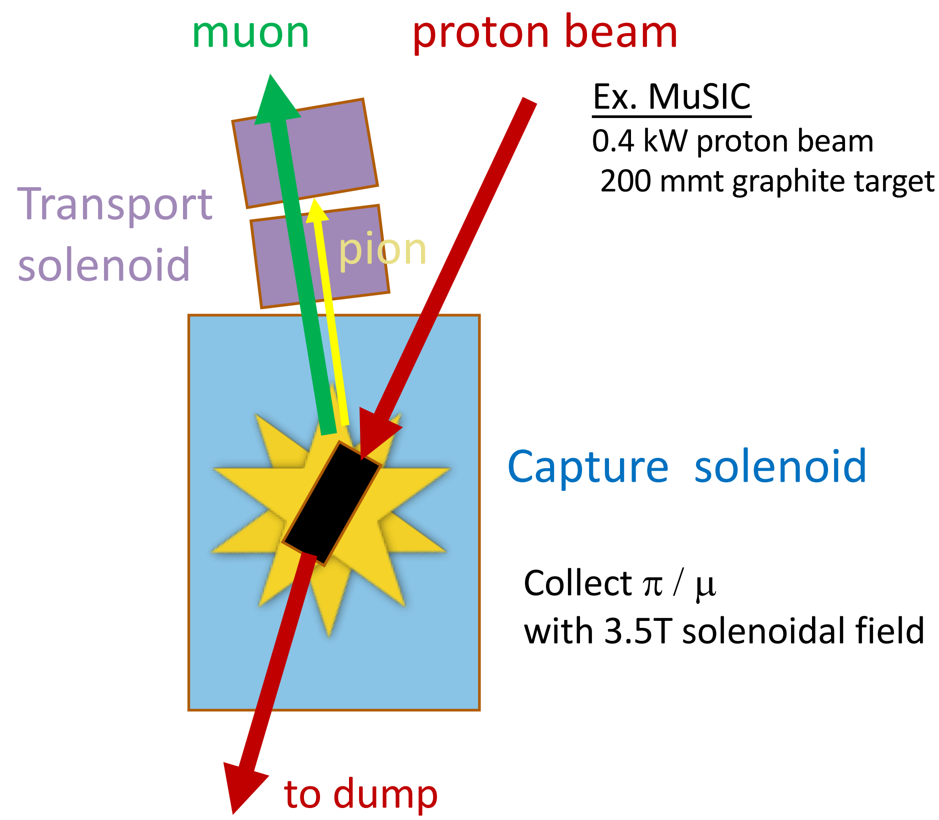
Comparison of pion production methods

Conventional muon beamline



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

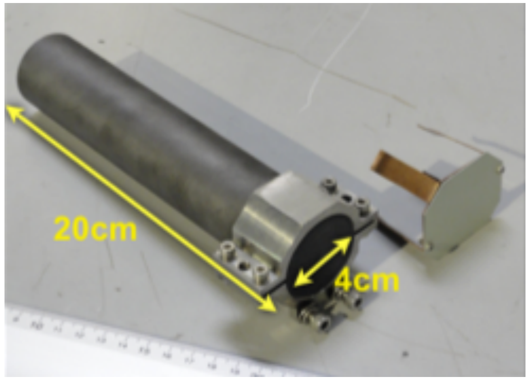
MuSIC beamline

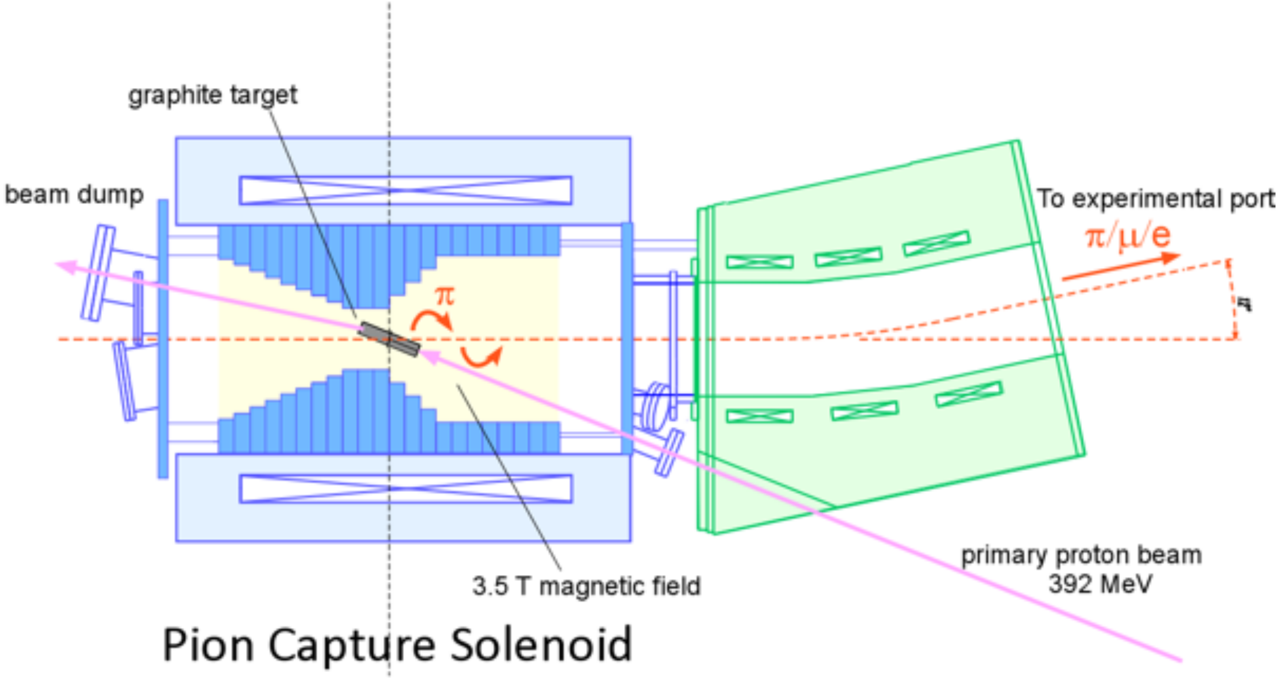


- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

Pion capture solenoid & Pion transport solenoid

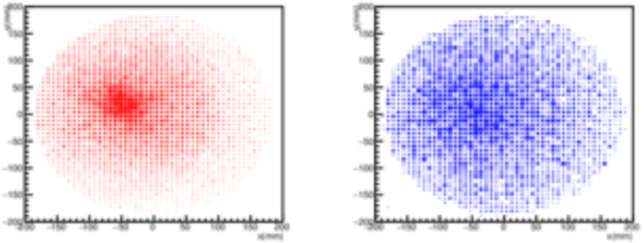
- Pion capture solenoid (3.5T)
  - — pion production target inside (1.5 interaction length)
  - — pion collection with large solid angles
- Pion transport solenoid (2.0T)
  - —Curved solenoid to capture and transport pion/muon
  - — Momentum selection with dipole collection field





Pion Capture Solenoid

Beam Profile by G4beamline simulation



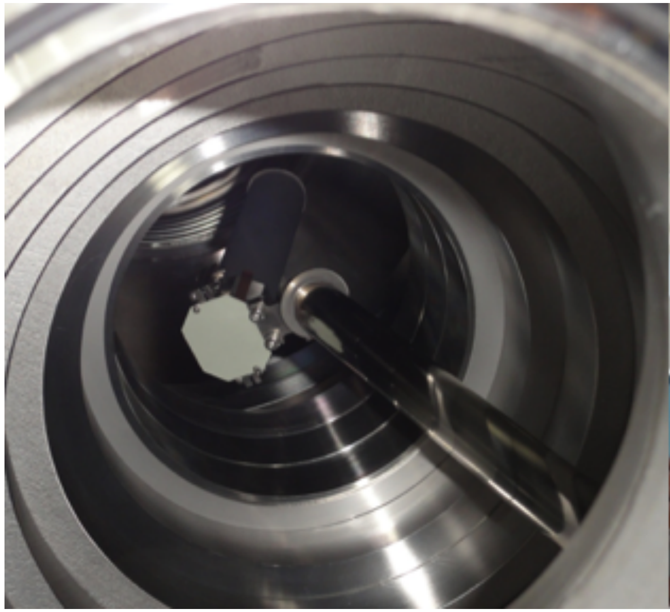
exit of the 36° curved solenoid

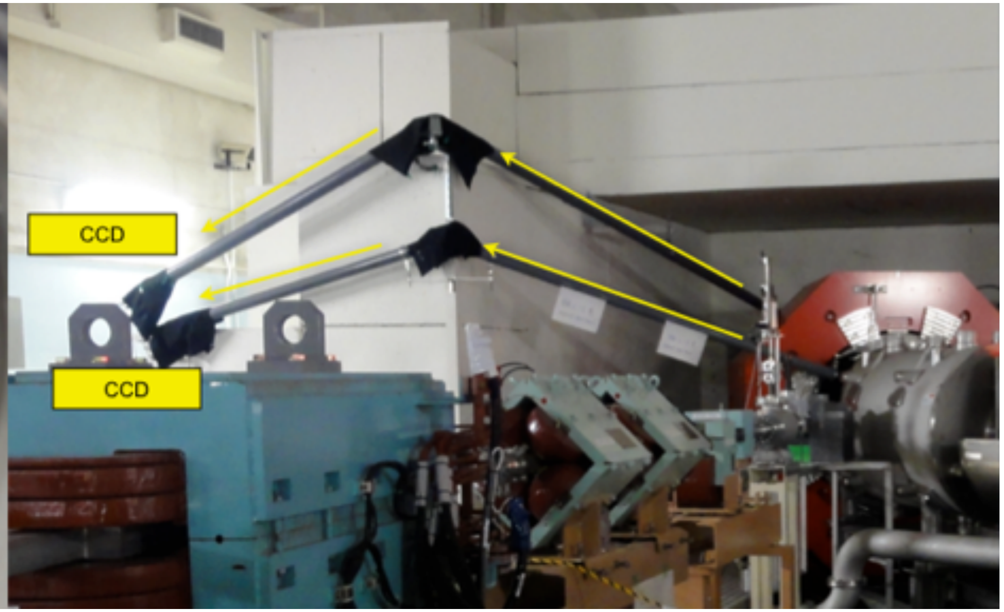
~ 3×10^8 positive muons

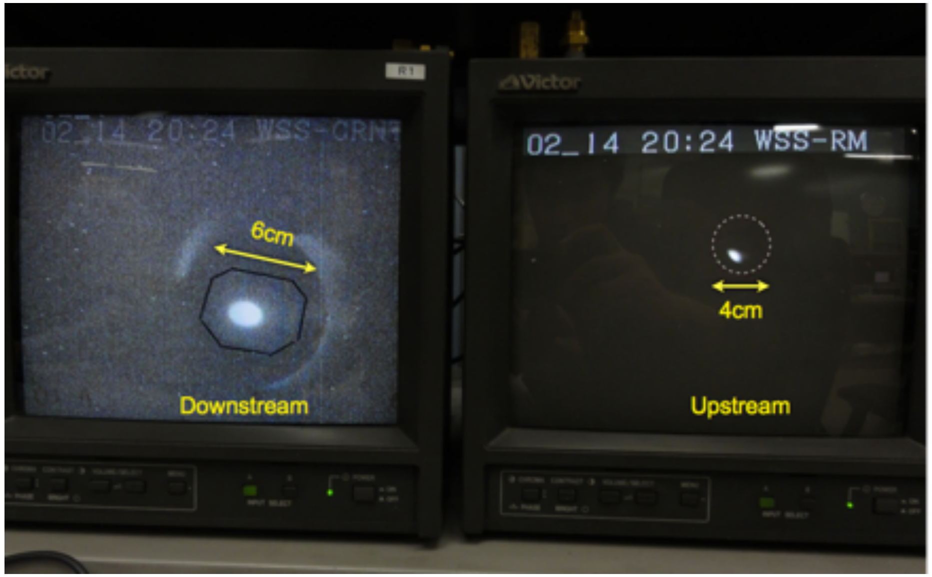
~ 1×10^8 negative muons

~ 10^3 pion production efficiency

Proton beam monitoring

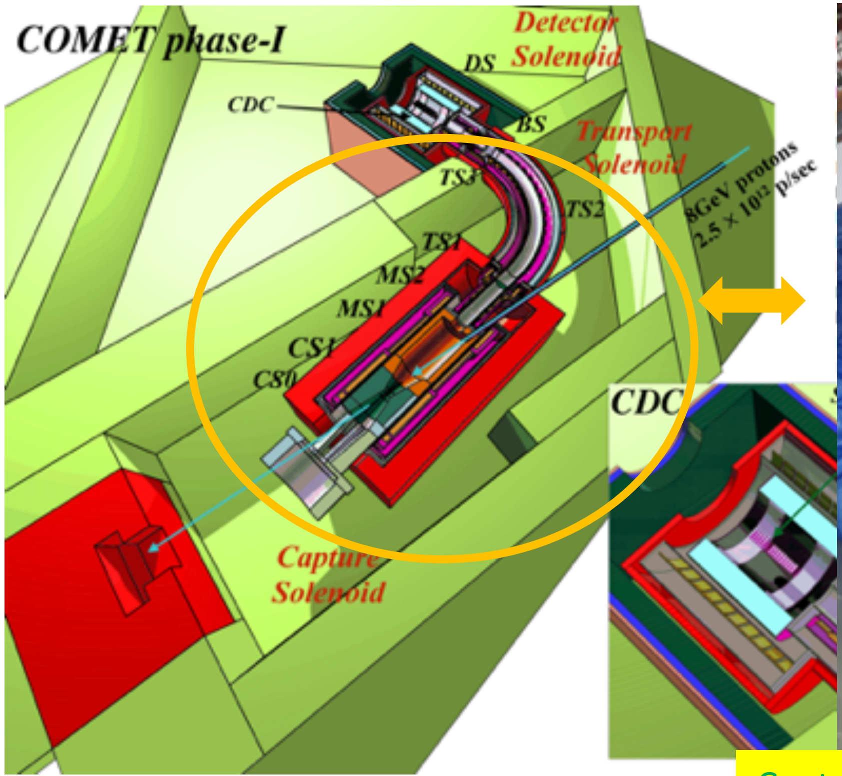






proton beam is tuned
to penetrate and focus
at the center of graphite taeget

Prototype beamline for COMET experiment but …



ref from COMET experiment, TDR2016

COMET for μ-e conversion

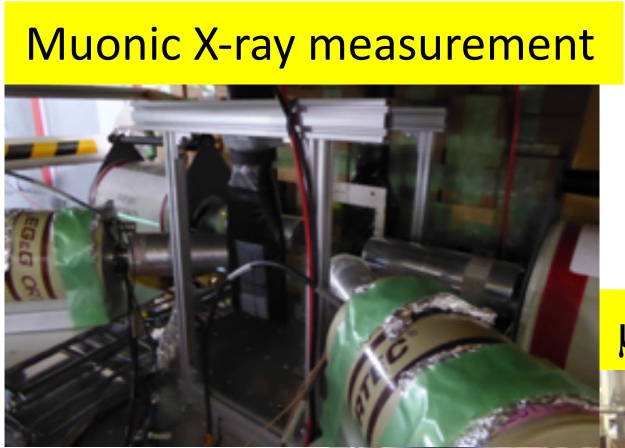
392 MeV,
1.1 uA
DC proton

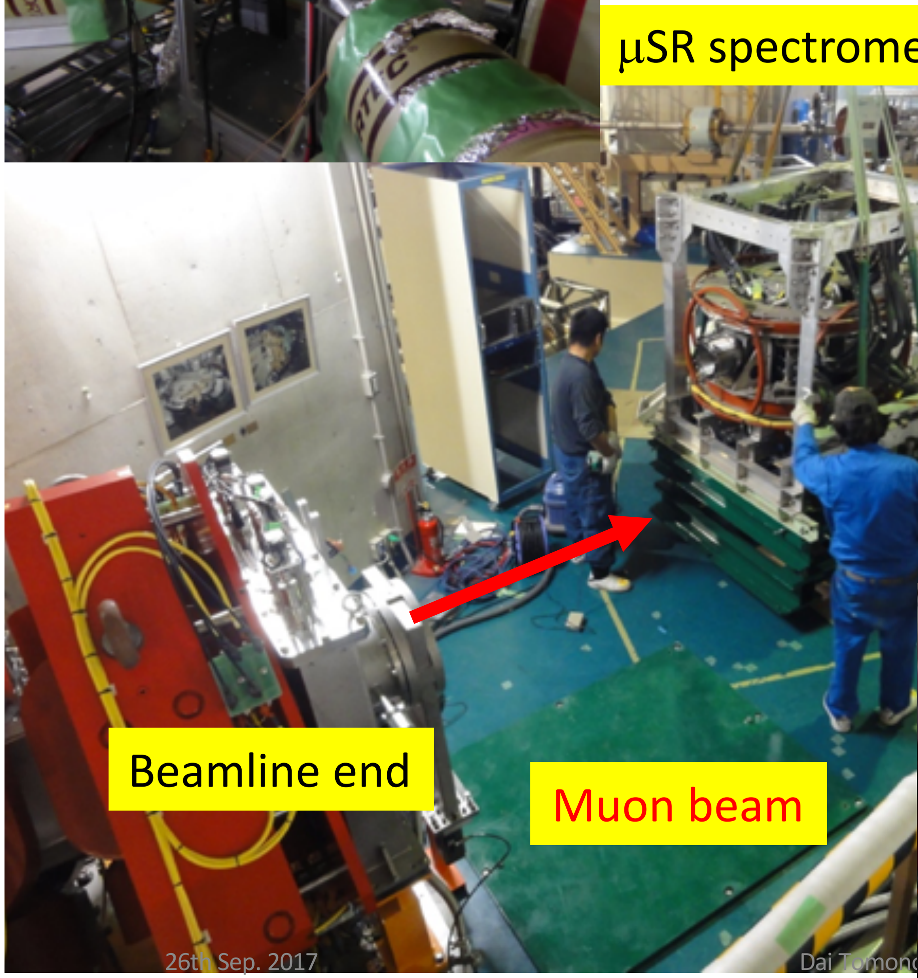
MuSIC
Beamline

- demonstrated proof-of-principle for muon production with the solenoid system using 392 MeV/1uA DC proton beam
- The MuSIC is aiming for a versatile beamline for muon experiments with variety of science.

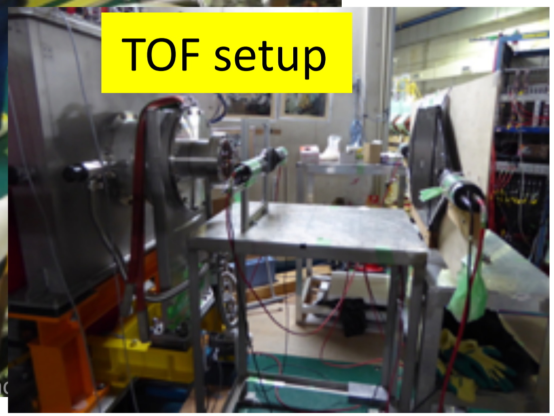
Beamline Commissioning & Experiments

Experimental port (at the M1 beamline end)



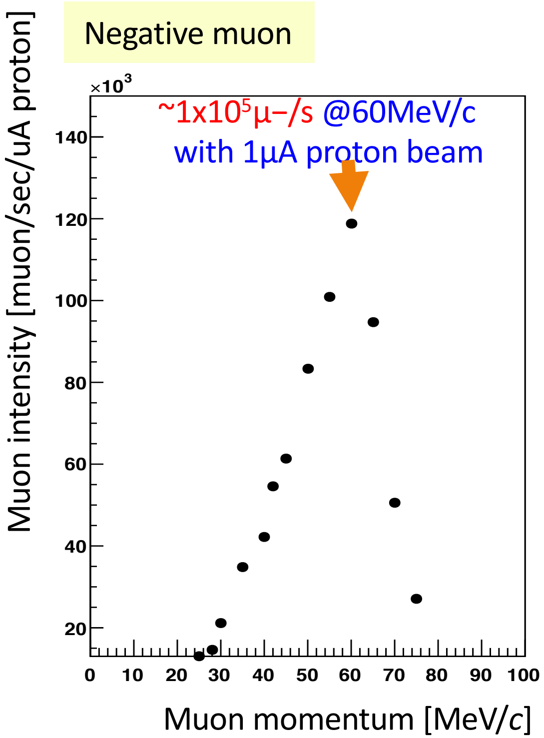


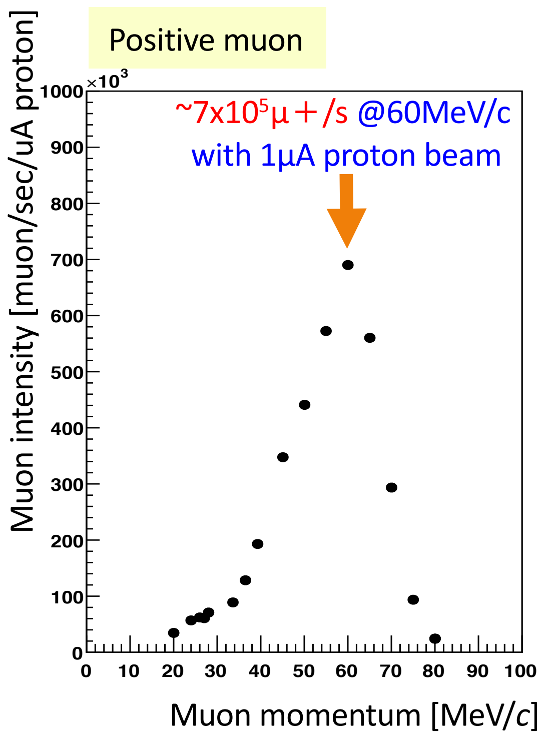
- In Feb 2017, proton beam current increases 20 nA to 1.1 uA owing to the shielding blocks
- Test of the beamline components (steering magnets, Qs, Bends and DC separator)
- Muon yield measurement
- Beam size
- Slit & Background
- Spin polarization



Muon yield measurement

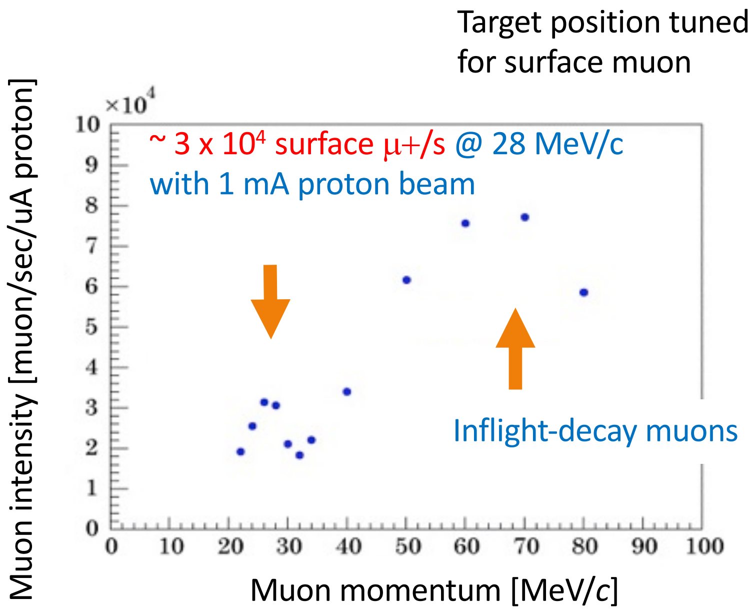
Inflight-decay muons ($\mu^{\pm}$)





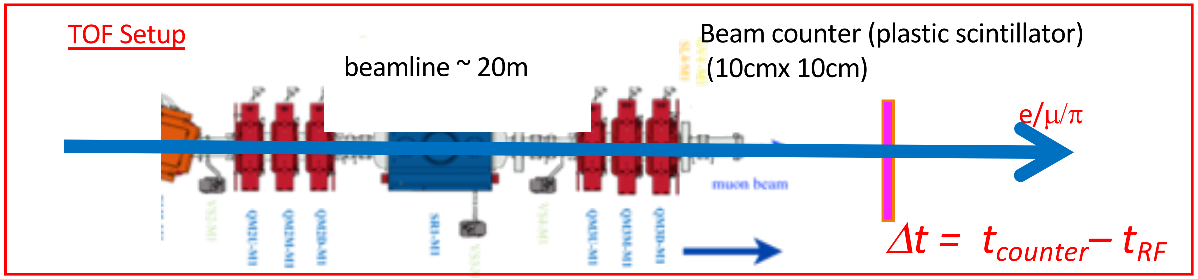
Surface muon (μ^{+})

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



** note that muon yield (vertical axis) is scaled for 1uA proton beam operation

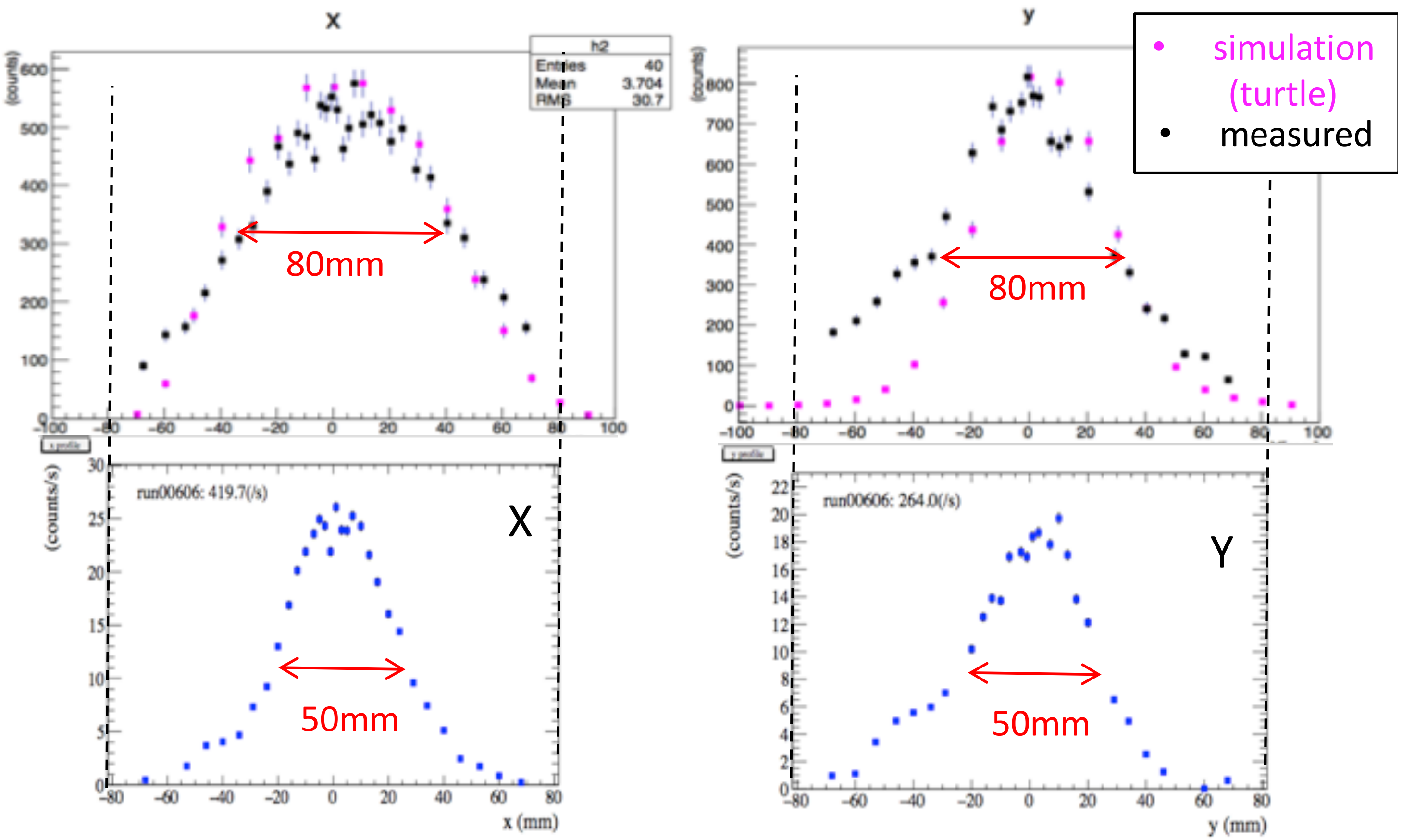
20nA (2016 run) -> 1.1uA (2017 run)



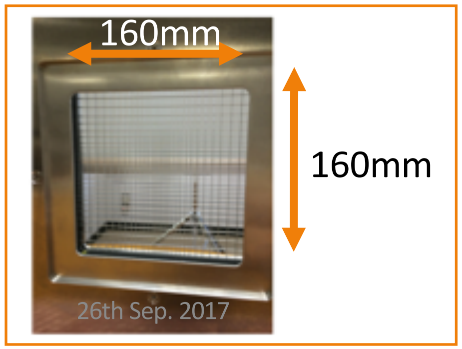
Beam profile measurement

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

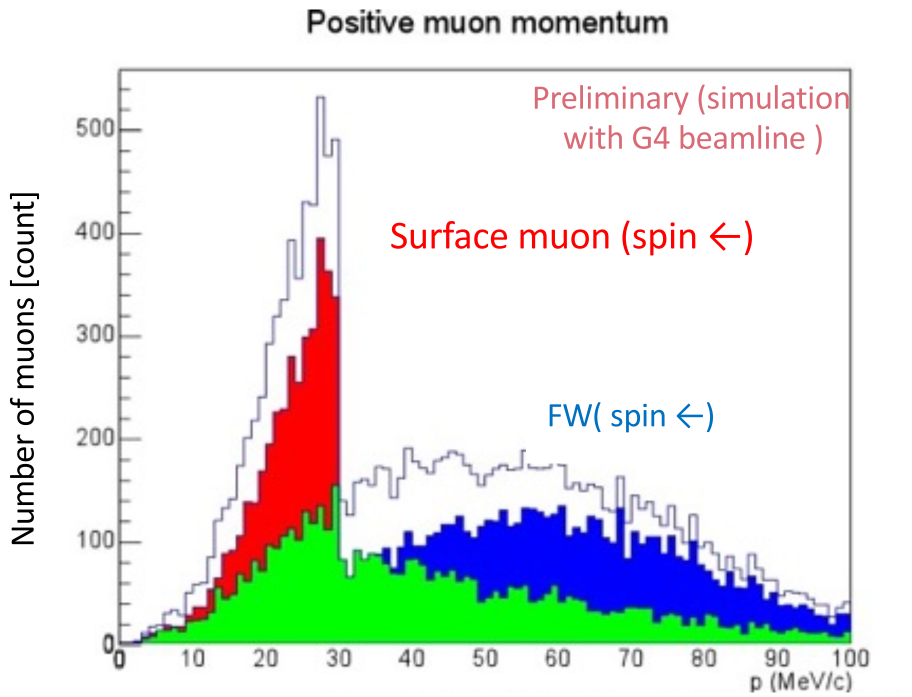


Profile monitor



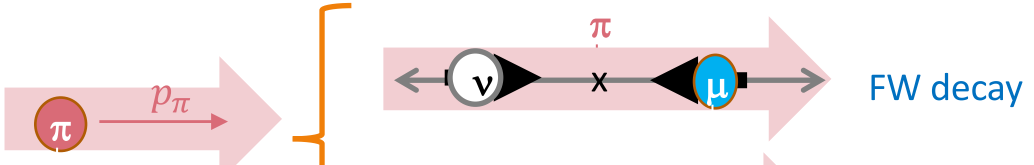
- 1mmϕ thin scintillation fiber + MPPC readout
- Separate e / μ by their energy deposit difference
- 8mm~2mm interval（dense around the center）

Spin measurement



BW(spin →) Muon momentum @ solenoid exit [MeV/c]

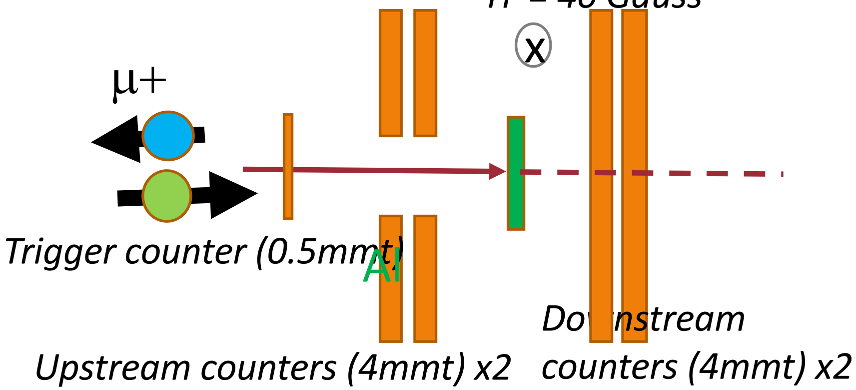
- Muon beam at the solenoid end (G4 beamline output)
- Separate forward and backward decay muons to investigate beam polarization
- Calculate the expected polarization geometrically and compare the experimental results



collect π with sc solenoid

FW and BW decay muons are mixed in the beamline

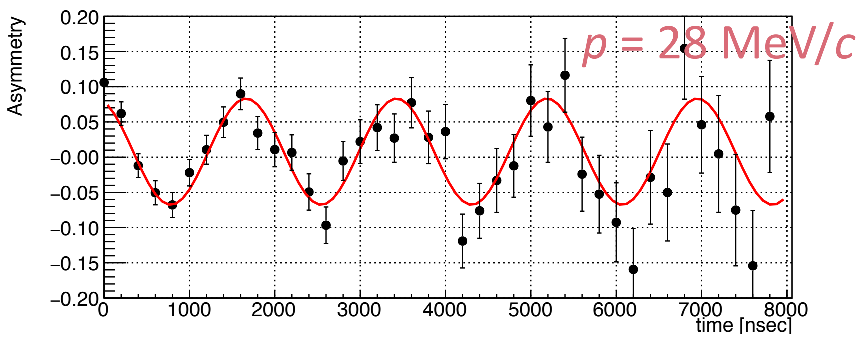
Setup

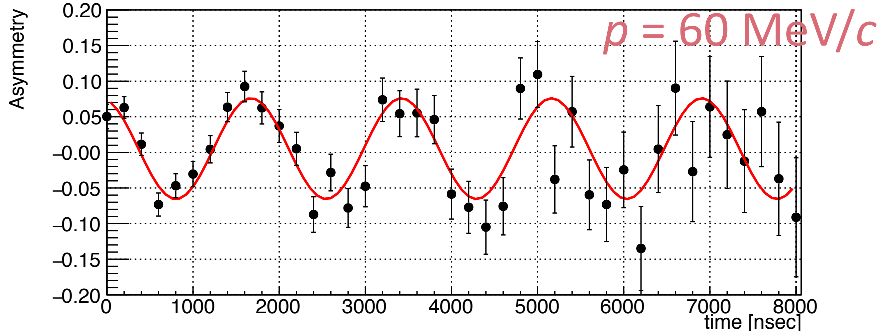


spin asymmetry $A_{asy}(t) \equiv \dfrac{N_u(t) - \alpha N_d(t)}{N_u(t) + \alpha N_d(t)}$

Spin precession measurement results

Typical observed asymmetry spectra

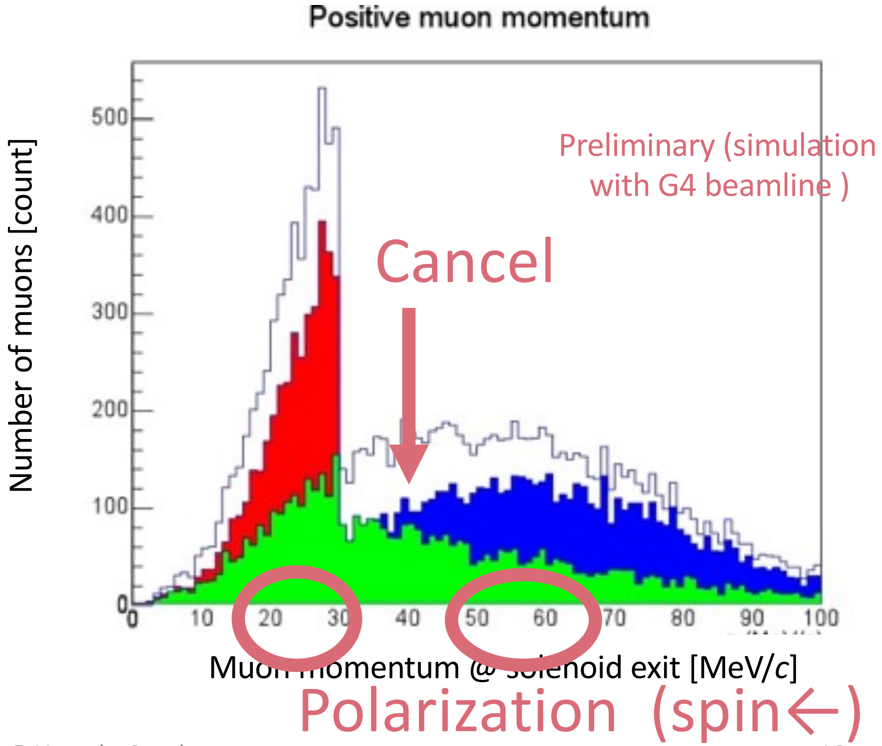




$\propto \mathrm{A}\cos(\gamma_\mu Bt + \delta_0)$ γ_μ : Lamor frequency

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

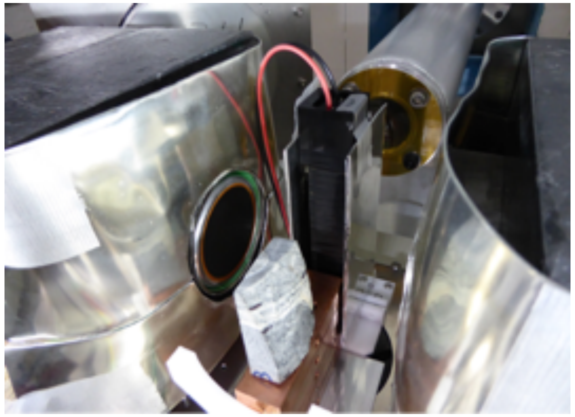
- Stage 0
  - proof-of-principle for muon capture and transport solenoid (also for COMET experiment)
  - high efficiency (~ 10^3) muon production was achieved (measured at the capture solenoid end), paper published in 2017
- Stage 1(2012-16)
  - Conventional triplet-Q and bend magnets were installed successively to the collection solenoid.
  - Beam commissioning is performed
  - 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 in progress
  - beam intensity increased by 50 times larger (proton beam upgrade : 20 nA to 1.1 uA)
- present
  - Start experiments with negative and positive muons
  - Muon capture and X-ray elemental analysis are in progress
  - DC-μSR study (still in commissioning for user experiments)

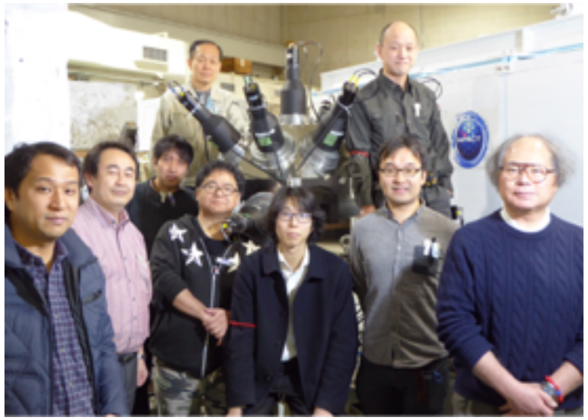
We are now in this stage (2017)

- future
  - Nuclear physics
    - Nuclear muon capture for 0νββ study (for nuclear matrix element determination, assigned beam in 2018)
    - 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 to obtain further intense muon beam (around the solenoid and triplet-Q)
  - new physics programs

Experiments at MuSIC

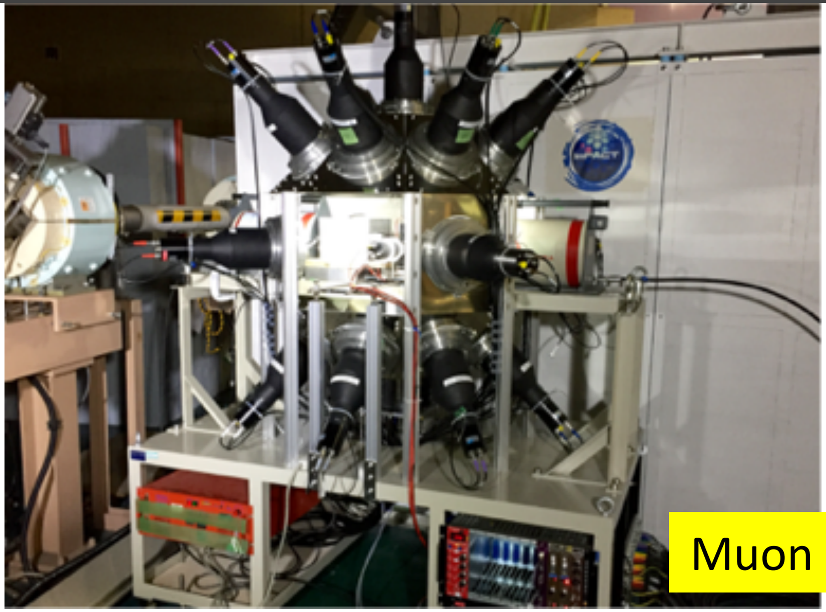
Exp #	spokespersion	Title	Beam time date	Beam current	status
E411	K. Terada (Osaka U)	Development on non-destructive elemental analysis of planetary materials by using high intensity μ- beam	Nov 2015	20 nA	Done
G02/E475	H. Sakurai (RIKEN)	(Impact project) Reaction Mechanism of Muon Nuclear Capture on Pd Isotopes	May 2016	20 nA	Done
G02/E475	T. Matsuzaki (RIKEN)	Reaction Mechanism of Muon Nuclear Capture on Pd Isotopes	Feb 2017	1.1 uA	Done
E467	K. Takahisa (RCNP)	Measurement of the muon capture on 3He by using of the high intensity continuous μ- beam	Jun 2017	1.1 uA	
E490	K. Terada (Osaka U)	Muonic X-ray analysis of planetary materials: Development on Isotopic measurement and Muonic X-ray imaging	Jun 2017	1.1 uA	
E489	Izyan Hashim (Universiti Teknologi Malaysia)	Muon-gamma spectroscopy for neutrino nuclear responses	Jan 2018	1.1 uA	

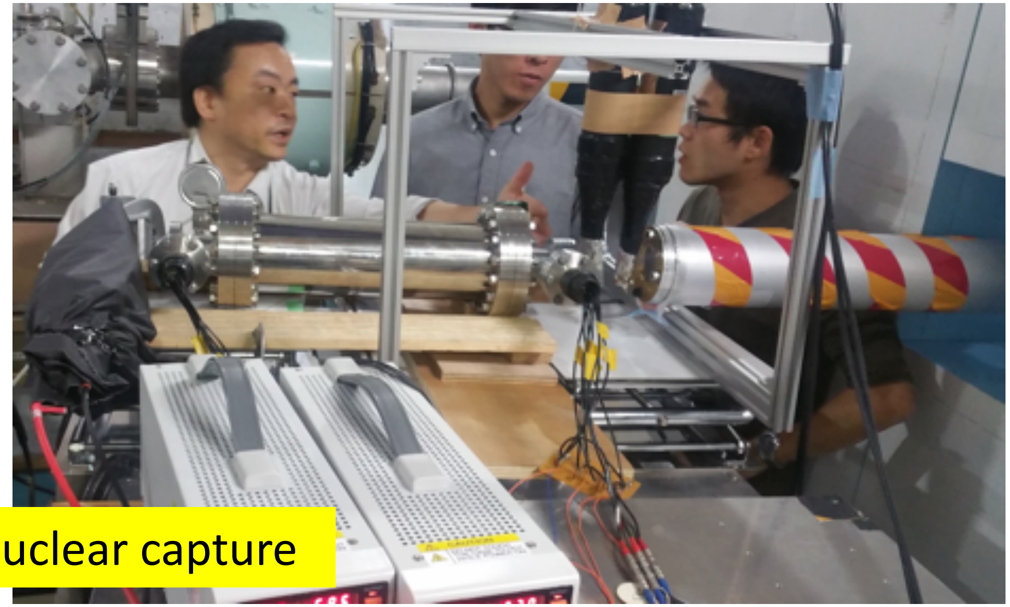




- All experiments (approve) are the negative muon experiments.
- Now we start the feasibility study of the positive muon experiments

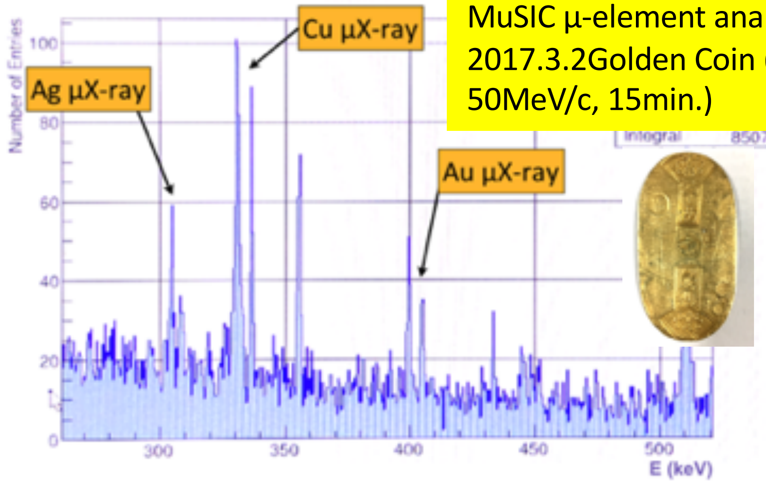
negative muon experiments





Muon nuclear capture

Non-destructive element analysis



MuSIC µ-element analysis：
2017.3.2Golden Coin (1.1µA, 50MeV/c, 15min.)

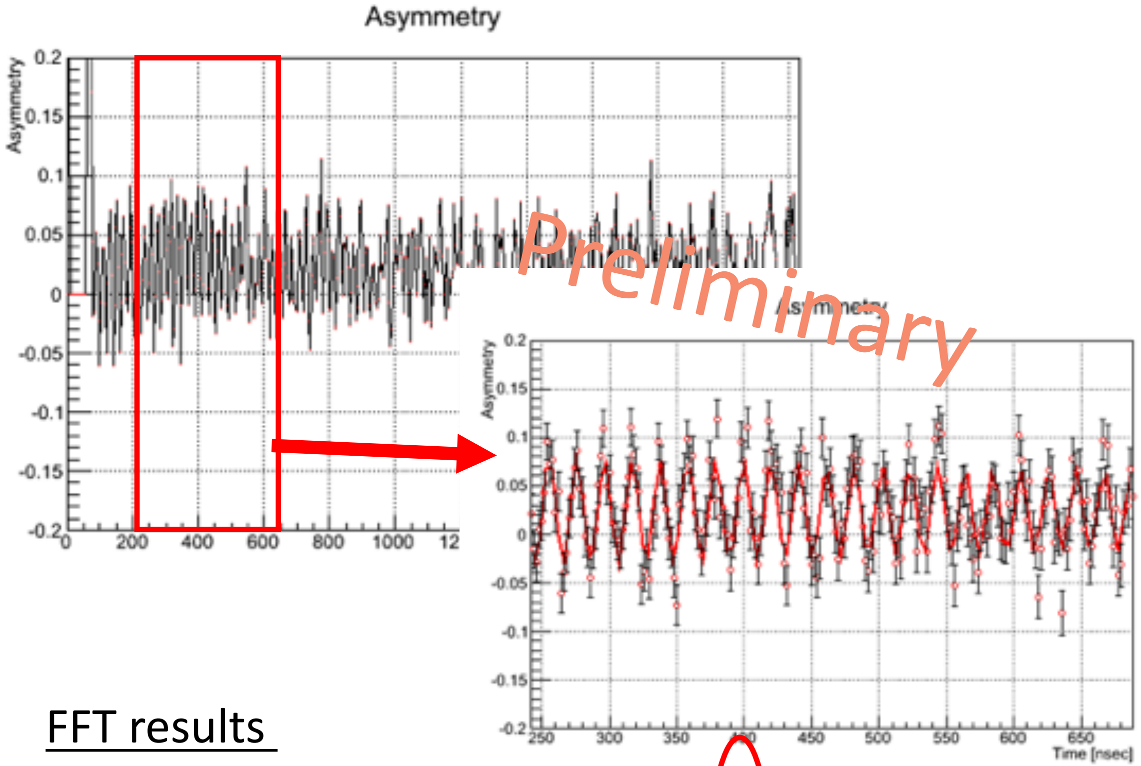
Now analyzng data

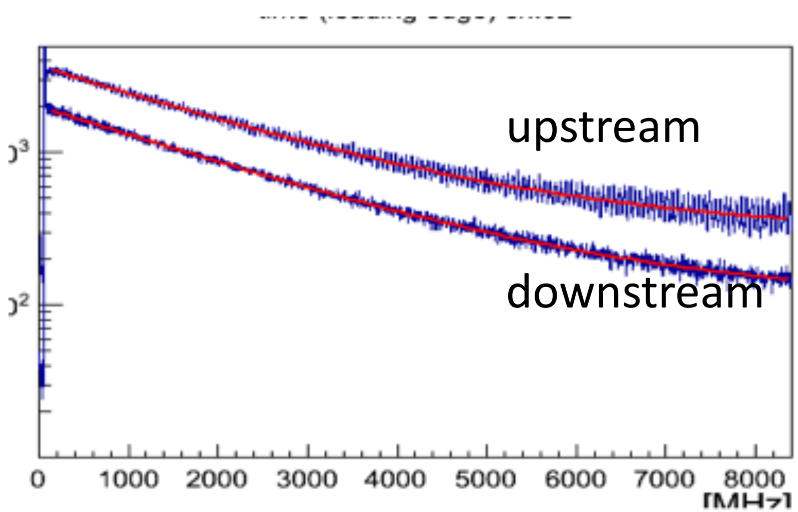
μSR for condensed matter physics

- μSR (Muon Spin Rotation/Relaxation/Resonance) for condensed matter physics
- Large number of users for condensed matter physics
- In Japan, intense pulsed beam at JPARC and DC beam at MuSIC become available
- DC beam has a merit for good time-resolution measurement

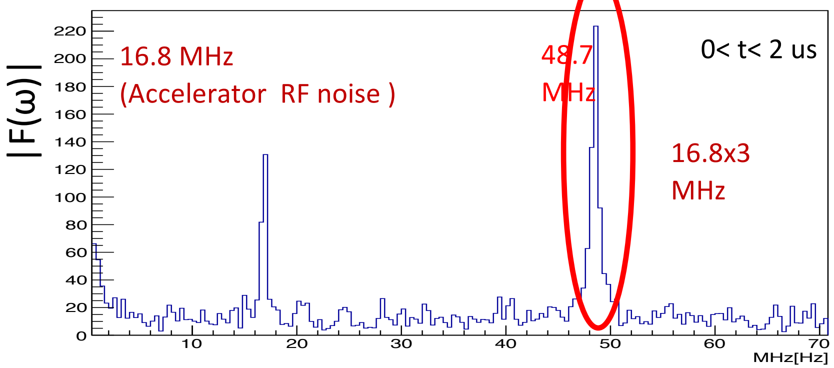
Observation fast precession in Fe

μSR experiment : sample Fe (ferromagnet) at room temperature
observe the internal field of Fe (expect ! 48 MHz precession)





FFT results



Succeeded to observe fast precession
f = 48.58 ±0.01 [MHz]

Summary

- New innovative DC muon source with solenoid system has been developed.
  - — good pion production & collection efficiency of ~ 10^3
  - — pion capture & transport solenoid + triplet-Q and bend magnets beamline for various muon science experiments
- Beamline commissioning is in progress
  - —inflight-decay μ^+ 10^5-10^6 μ^- 10^5-10^6 surface μ^+ 3 x 10^4 [count/sec/1uA proton beam]
  - —Improvement of muon beam (especially, solenoid and triplet-Q connection)
- Start physics program in MuSIC
  - —nuclear physics (muon capture)
  - —radio-chemistry and non-destructive evaluation of elements
  - —positive muon for μSR measurement (feasibility study in progress)
  - — MuSIC has possibility to perform experiments of muon applied science

collaboration photo (2016/2017)