Muon Facility
- Low Energy Muon Beam -

Akira SATO
Osaka University

Topical workshop on The Neutrino Factory and Muon Collider,
the physics and the R&D programs

22-24 October 2007
The Cosener's House, Abingdon, Oxfordshire. UK

Introduction

- At the front end of muon collider/neutrino factory, a low energy muon beam with a high intensity will be available. The expected intensity is 3 to 4 orders of magnitude larger than presently available.
- Muon groups made a lot od discussion to carry out muon experiments using such a muon beam and requirements on the beam.
- There some good papers for that;
  - "PHYSICS WITH LOW-ENERGY MUONS AT A NEUTRINO FACTORY COMPLEX"
    - arXiv:hep-ph/0109217 v1 24 Sep 2001
  - Proceedings of NuFact Workshops
  - etc
- I will give a review of the requirements on beam for muon physics.

PHYSICS WITH LOW-ENERGY MUONS AT A NEUTRINO FACTORY COMPLEX

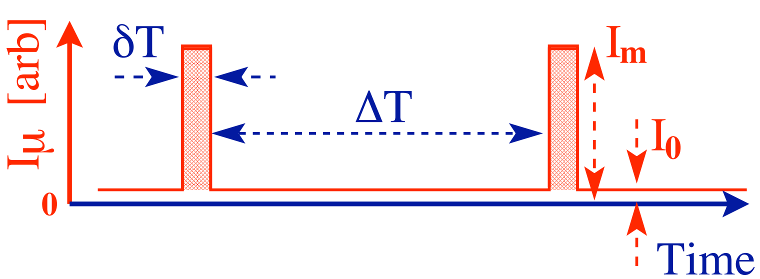
TABLE II. Experiments which could beneficially take advantage of the intense future stopped muon source. The numbers were worked out for scenarios at a future stopped muon source (SMS) of a neutrino factory at CERN [87]. They are based on a muon flux of 10^{21} particles per annum in which beam will be available for 10^7 s. Typical beam requirements are given in Table III.

Type of experiment	Physics issues	Possible experiments	Previously established accuracy	Present activities (proposed accuracy)	Projected for SMS @ CERN
"Classical" rare and forbidden decays	Lepton number violation;	$\mu^- N \rightarrow e^- N$	6.1×10^{-13}	PSI, proposed BNL (5×10^{-17})	$<10^{-18}$
	searches for new physics:	$\mu \rightarrow e\gamma$	1.2×10^{-11}	Proposed PSI (1×10^{-14})	$<10^{-15}$
	SUSY, L-R symmetry,	$\mu \rightarrow eee$	1.0×10^{-12}	Completed 1985 PSI	$<10^{-16}$
	R-parity violation, ...	$\mu^+ e^- \rightarrow \mu^- e^+$	8.1×10^{-11}	Completed 1999 PSI	$<10^{-13}$
Muon decays	G_F; searches for new physics;	τ_μ	18×10^{-6}	PSI ($2\times$), RAL (1×10^{-6})	$<10^{-7}$
	Michel parameters	non $(V-A)$	Typically, few 10^{-3}	PSI, TRIUMF (1×10^{-3})	$<10^{-4}$
Muon moments	Standard model tests; new physics; CPT tests, T, respectively;	$g_\mu - 2$	1.3×10^{-6}	BNL (3.5×10^{-7})	$<10^{-7}$
	CP violation in 2nd lepton generation	edm_μ	$3.4 \times 10^{-19} e$ cm	Proposed BNL ($10^{-24} e$ cm)	$<5 \times 10^{-26} e$ cm
Muonium spectroscopy	Fundamental constants, μ_μ, m_μ, α;	M_{HFS}	12×10^{-9}	Completed 1999 LAMPF	5×10^{-9}
	weak interactions; muon charge	M_{1s2s}	1×10^{-9}	Completed 2000 RAL	$<10^{-11}$
Muonic atoms	Nuclear charge radii; weak interactions	μ^- atoms	Depends	PSI, possible CERN ($\langle r_p \rangle$ to 10^{-3})	New nuclear structure
Condensed matter	Surfaces, catalysis, bio sciences, ...	Surface μSR	n/a	PSI, RAL (n/a)	High rate

PHYSICS WITH LOW-ENERGY MUONS AT A NEUTRINO FACTORY COMPLEX
arXiv:hep-ph/0109217 v1 24 Sep 2001

Beam Requirements for Future Muon Experiments from CERN Neutrino Factory Study (2001)

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	+	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	+	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	+	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	+	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
transvers. polariz.	+	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	$\leq$1000	$\leq 10^{-3}$
M_{HFS}	+	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20	4	1...3
M_{1s2s}	+	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^3$	1...4	1...2
μ^- atoms	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20	1...4	1...5
condensed matter (incl. bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20	1...4	1...5



PHYSICS WITH LOW-ENERGY MUONS AT A NEUTRINO FACTORY COMPLEX
arXiv:hep-ph/0109217 v1 24 Sep 2001

Beam Requirements for Future Muon Experiments from NuFact05

Experiment	Charge	Intensity ($\mu/10^7$sec)	Pulse width (μs)	Pulse interval (μs)	Energy (MeV)	Mom. spread (%)	Polarization n/a	Note
$\mu \to e\gamma$	+	10^{15}	DC	≤1	1	≤10	Depol	e comtami. ≤ 10-2, beam size cm
$\mu N \to eN$ (MECO type)	−	10^{21}	10-100	1-1000	≤20	≤10	n/a	
$\mu N \to eN$ (PRISM type)	−	10^{20}	10-100	1-1000	≤20	3	n/a	π comtami. ≤ 10-15, beam size cm
g-2	±	10^{15}	≤15	≥1000	3100	10^{-2}	Pol ~100%	
edm	±	10^{18}	≤50	≥1000	200-400	10^{-3}	Pol >50%(NP^2)	❖ $d_\mu < 10^{-24}$ e.cm → $NP^2 > 10^{16}$ total
μ lifetime	+	10^{14}	~100	30-100	4	1-10	π beam	
μ lifetime (π)	+	10^{14}	~100	30-100	4	1-10	100%	
Michel parmammeter	+	10^{16}	≤0.5	≥0.02	30-40	1-3	~100%	
Pol param.	+	10^{16}	≤0.5	≥0.02	30-40	1-3	Pol	
μ-atoms	−	10^{16}	≤100	100-1000	1-4	1-5	n/a	e comtami. ≤ 10-2, beam size cm
Life science	−	10^{15}	1	100-1000	1-4	1-5	n/a	beam size mm
μCF	−	10^{19}	1	≥1000	≥100			
μSR	±	10^{9}/s	DC	-	4	1-5	~100%	
μSR	±	10^{10-20}/s	0.001	100	4	1-5	~100%	

Beam Requirements for Future Muon Experiments from NuFact05

Experiment	Charge	Intensity ($\mu/10^7$sec)	Pulse width (μs)	Pulse interval (μs)	Energy (MeV)	Mom. spread (%)	Polarization n/a	Note
$\mu \to e\gamma$	+	10^{15}	DC	≤1	1	≤10	Depol	e comtami. ≤ 10-2, beam size cm
$\mu N \to eN$ (MECO type)	−	10^{21}	10-100	1-1000	≤20	≤10	n/a	
$\mu N \to eN$ (PRISM type)	−	10^{20}	10-100	1-1000	≤20	3	n/a	π comtami. ≤ 10-15, beam size cm
g-2	±	10^{15}	≤15	≥1000	3100	10^{-2}	Pol ~100%	
edm	±	10^{18}	≤50	≥1000	200-400	10^{-3}	Pol >50%(NP^2)	❖ $d_\mu < 10^{-24}$ e.cm → $NP^2 > 10^{16}$ total
μ lifetime	+	10^{14}	~100	30-100	4	1-10	π beam	
μ lifetime (π)	+	10^{14}	~100	30-100	4	1-10	100%	
Michel parmammeter	+	10^{16}	≤0.5	≥0.02	30-40	1-3	~100%	
Pol param.	+	10^{16}	≤0.5	≥0.02	30-40	1-3	Pol	
μ-atoms	−	10^{16}	≤100	100-1000	1-4	1-5	n/a	e comtami. ≤ 10-2, beam size cm
Life science	−	10^{15}	1	100-1000	1-4	1-5	n/a	beam size mm
μCF	−	10^{19}	1	≥1000	≥100			
μSR	±	10^{9}/s	DC	-	4	1-5	~100%	
μSR	±	$10^{10\text{-}20}$/s	0.001	100	4	1-5	~100%	

Muon Trio with the next high power proton driver

New Generation of Muon Trio

	current limit	at NuFact/MC
$\mu N \rightarrow eN$	BR(Ti)<10^{-13}	BR(Ti)<10^{-18}
g-2	0.54 ppm	0.05 ppm
μEDM	10^{-19} e.cm	10^{-24} e.cm

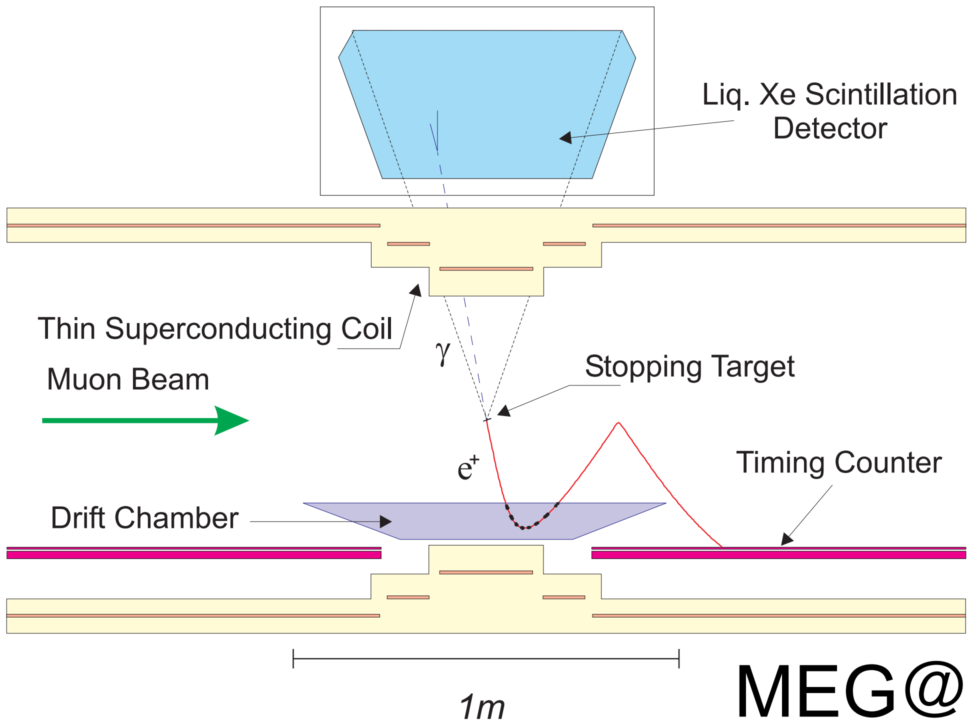
Assuming 4MW proton driver

Among these experiment, the rare decay process, such as $\mu N \rightarrow eN$, has a lot of requirements on the beam.

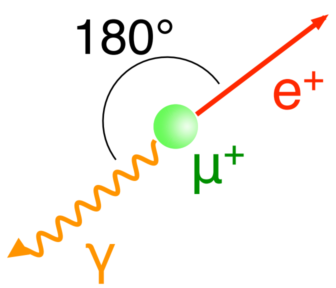
Beam Requirements
from Search for Charged Lepton Flavor Violation

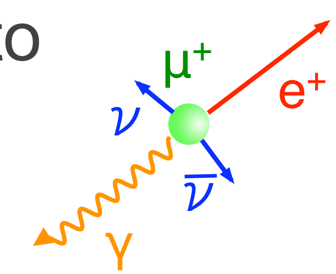
μ→eγ

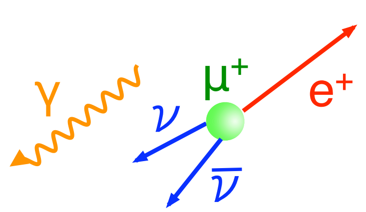
- μ^+ beam is stopped in a thin target.
- Signal Event
  - coincidence of e^+ and γ detection
  - each have energy 52.8MeV
  - originate from a common point
  - have opposite momenta
- Background
  - Prompt background: μ→eγνν
  - "Accidental" overlap: μ→eνν + γ : Predominant
- μ→eγ search requires
  - Precise measurements of energy, timing and angle for positron and gamma
  - High intensity μ+ beam with high duty factor to avoid accidentals.



MEG@PSI







μ→eγ (cont.)

$$\text{Accidental Background} \propto \left(R_\mu\right)^2 \times \Delta E_e \times \left(\Delta E_\gamma\right)^2 \times \Delta t_{e\gamma} \times \left(\Delta\theta_{e\gamma}\right)^2$$

Place	Year	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit
TRIUMF	1977	10%	8.7%	6.7ns	–	$< 3.6 \times 10^{-9}$
SIN	1980	8.7%	9.3%	1.4ns	–	$< 1.0 \times 10^{-9}$
LANL	1982	8.8%	8%	1.9ns	37mrad	$< 1.7 \times 10^{-10}$
LANL	1988	8%	8%	1.8ns	87mrad	$< 4.9 \times 10^{-11}$
LANL	1999	1.2%	4.5%	1.6ns	15mrad	$< 1.2 \times 10^{-11}$
PSI (MEG)	2007	0.9%	5 %	0.1 ns	23mrad	$< 10^{-13}$

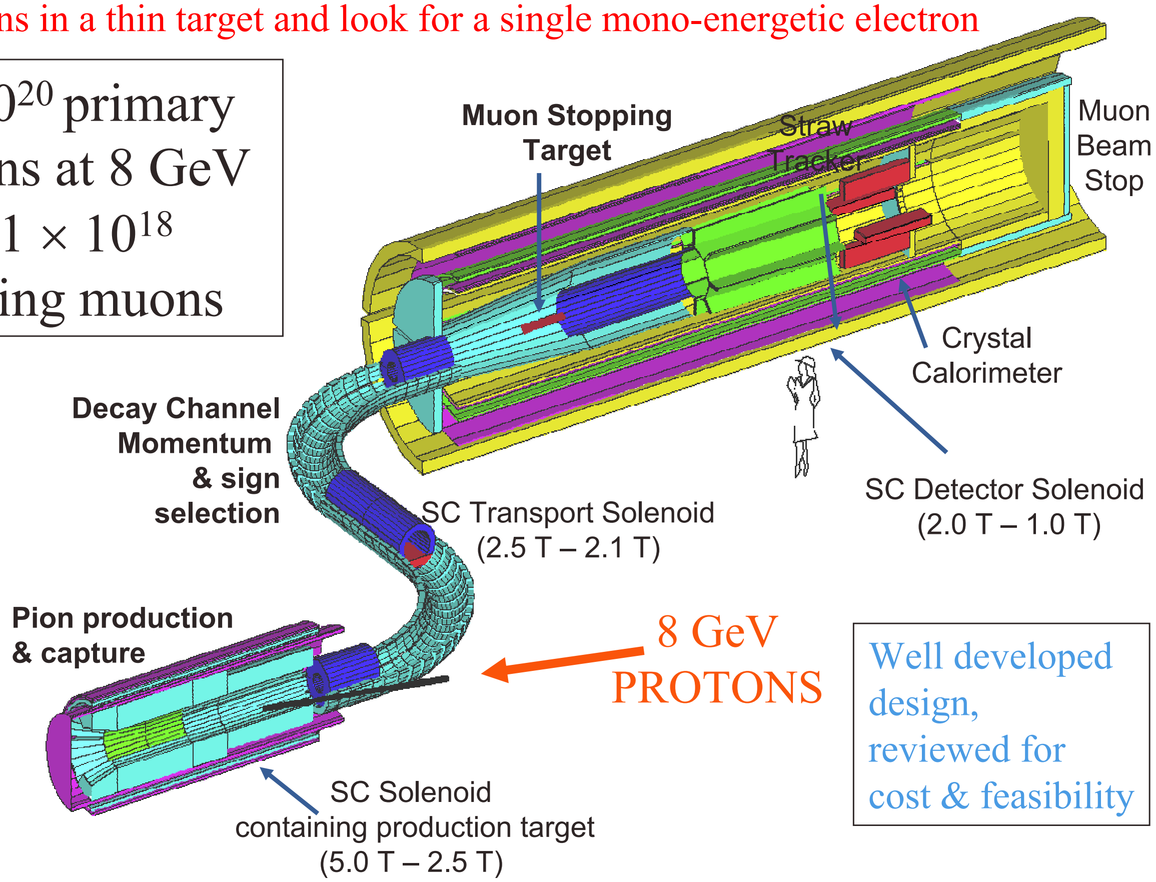
- MEG : N_B=0.5 events at B(μ→eγ)~10^{-13} (T=4×10^{7}s, R_μ=3×10^{7}μ/s)
- At FEMC with the same resolutions,
  - R_μ=10^{10}μ/s → N_B=3×10^{2} events at B(μ→eγ)~10^{-16}
- Better detector resolutions and/or improved detector concepts are required.
- Beam Requirements
  - DC beam
  - Little momentum spread

Proposals of μN→eN (MECO type)

mu2e@FNAL

Stop muons in a thin target and look for a single mono-energetic electron

4×10^{20} primary protons at 8 GeV yield 1×10^{18} stopping muons

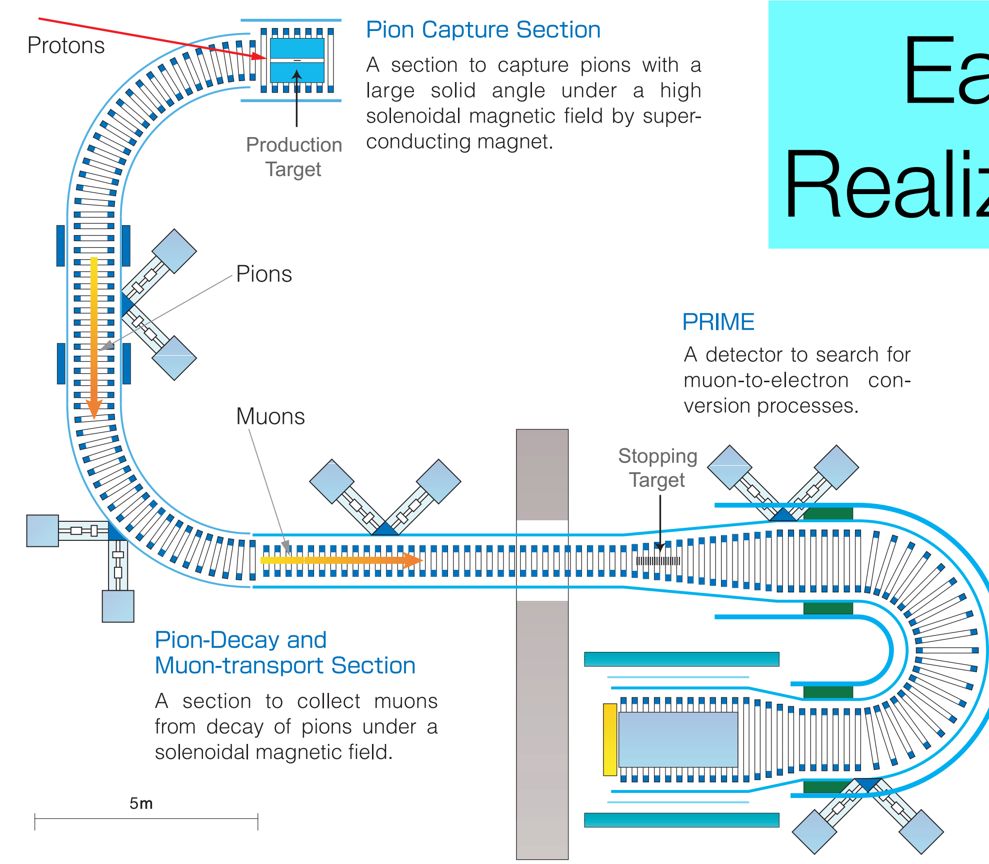


Well developed design, reviewed for cost & feasibility

PRISM-Phase1@J-PARC

New Experiment

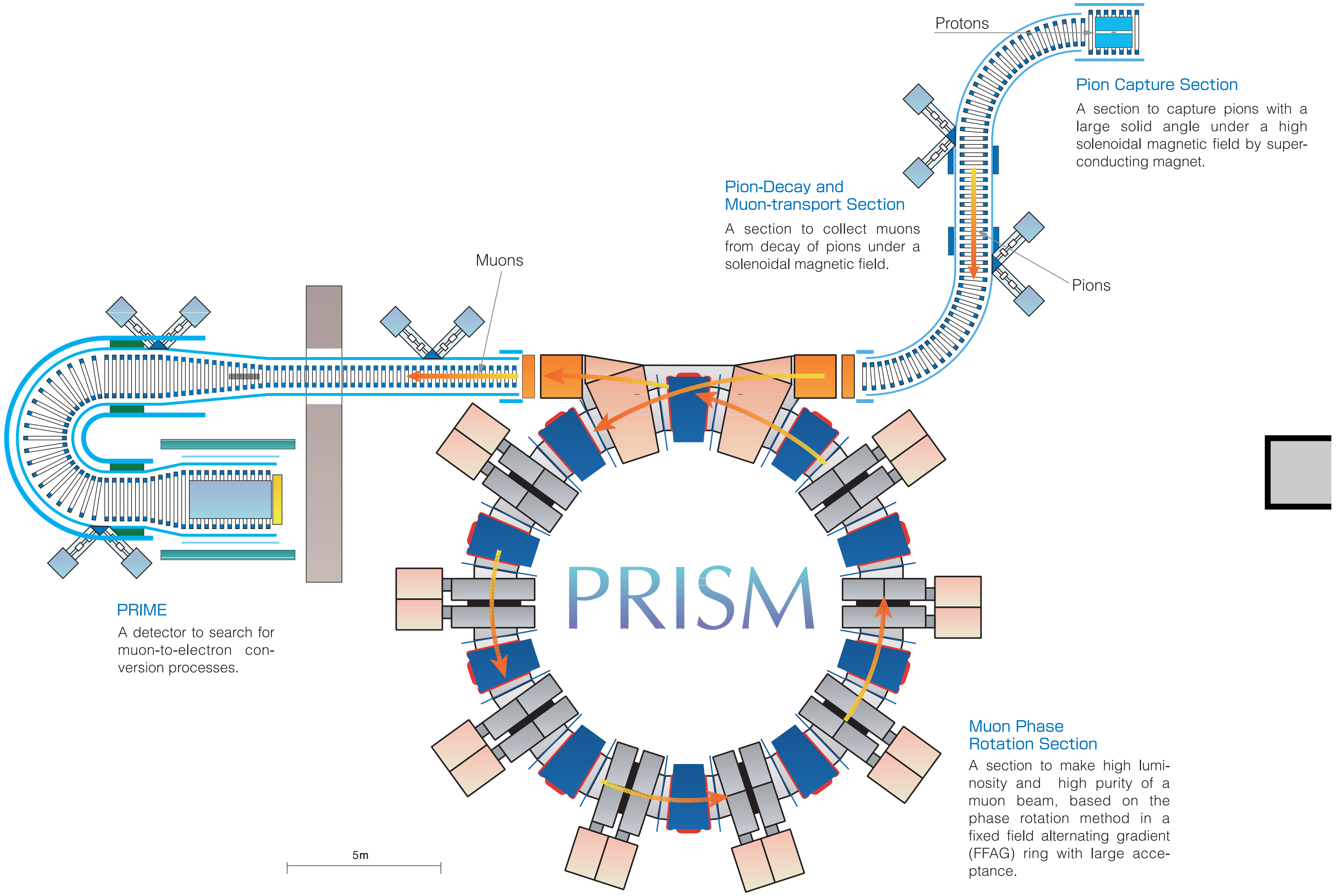
Early Realization



$$B(\mu^- + Al \to e^- + Al) < 10^{-16}$$

Proposals of μN→eN with a Storage Ring

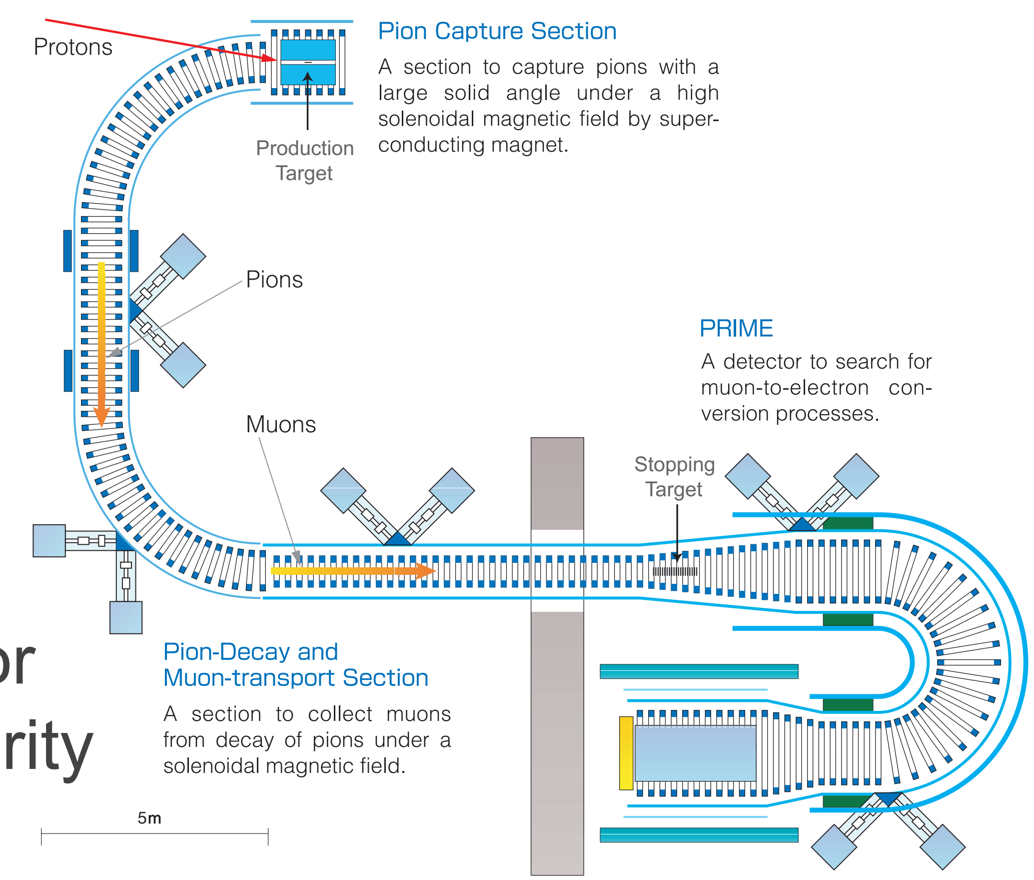
PRISM



$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

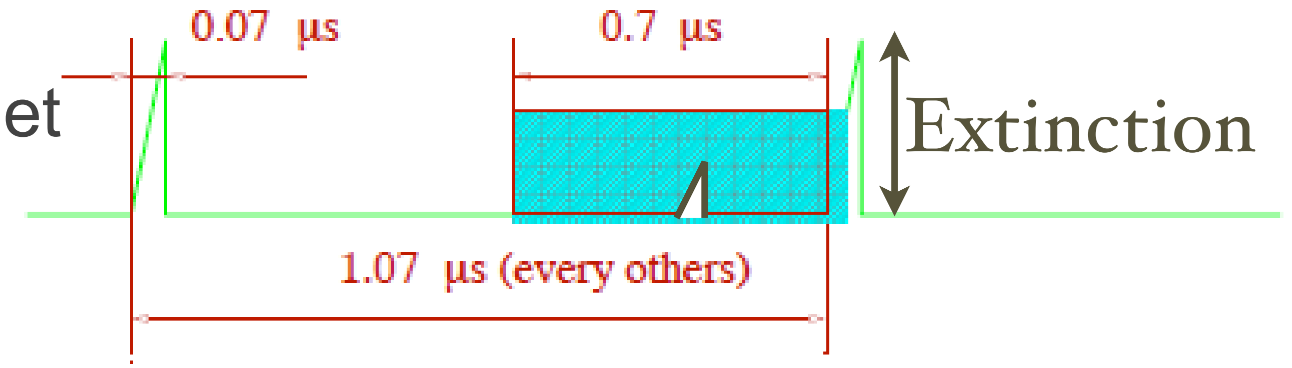
μN→eN

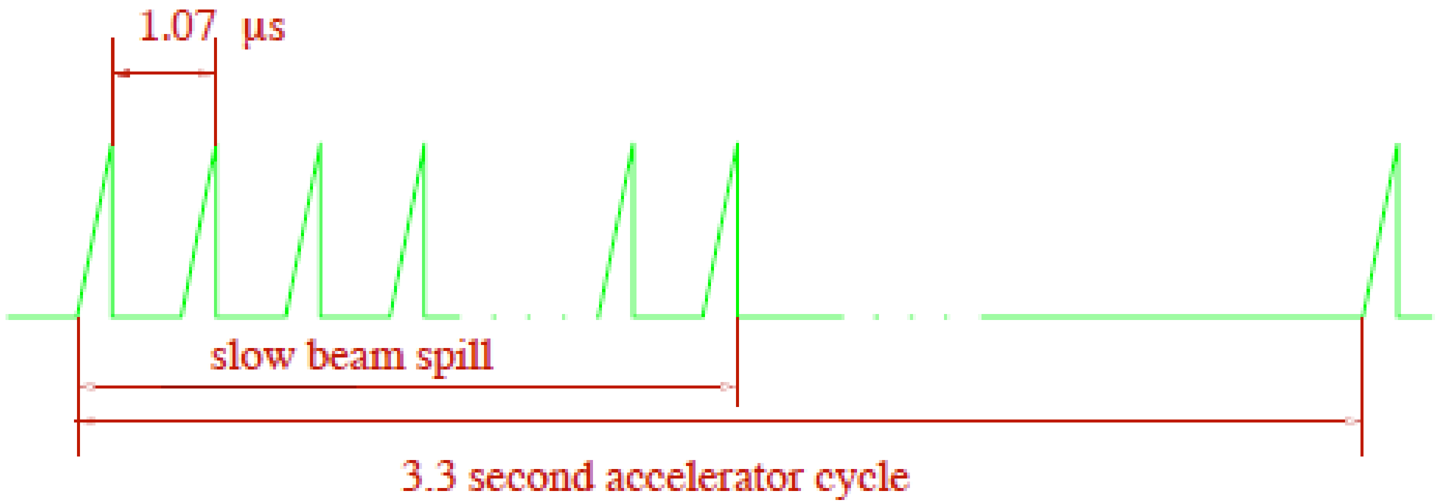
- μ^- beam is stopped in a thin target.
- Signal Event
  - mono-energetic e^- ~105MeV
- Background
  - Intrinsic Physics Background
    - Muon decay in orbit : Endpoint comes to the signal region $\propto (E_{signal}-E_e)^5$
    - Radiative muon capture etc
  - Beam-related Background
    - Radiative pion capture
    - Electrons from muon decays in flight
    - Pion decay in flight
    - Beam electrons
- μN→eN search requires
  - Precise measurement of e- energy
  - Reject the intrinsic background at the detector
  - High intensity pulsed μ- beam and/or high purity
    - to reject the beam-related BG



Pulsed Proton Beam

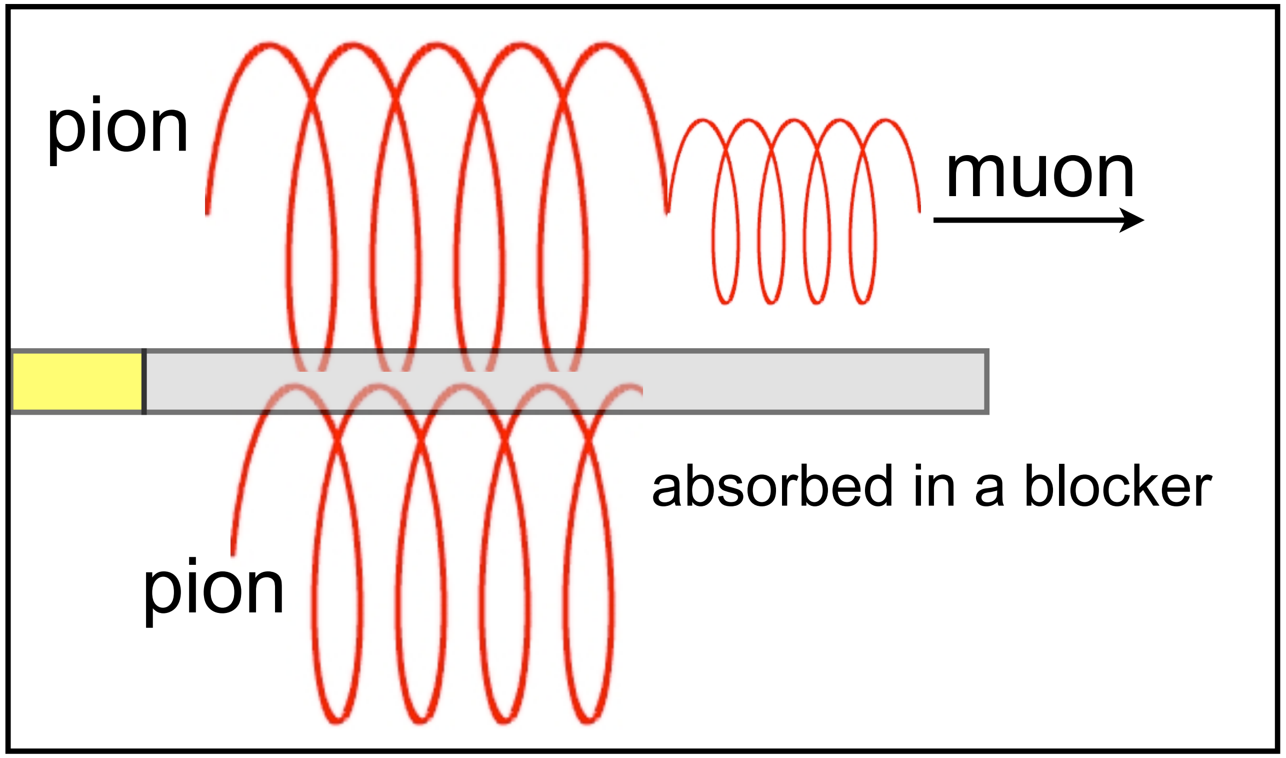
- Beam requirements for MECO type (BR ~10^{-16}) experiments
  - Short pulsed (<100ns)
    - remove prompt backgrounds by measuring in a delayed time window.
  - Time separation (~1μs)
    - lifetime of μ- stopped in the target
  - Extinction < 10^{-9}





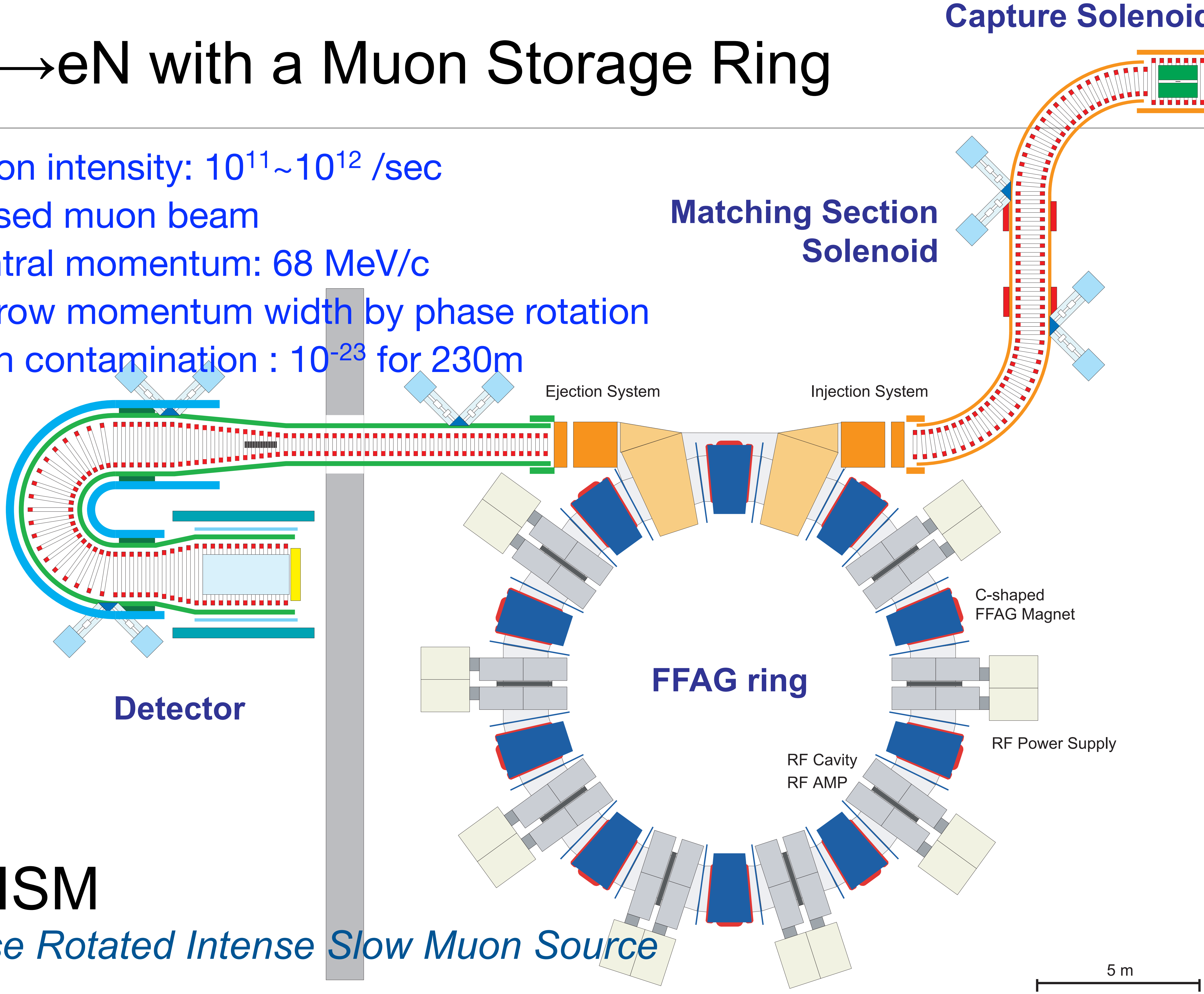
Extremely Pure Muon Beam

- Extremely pure muon beams can reduce the beam related backgrounds.
- In the SIUDRUM-II (BR ~10^{-12})
  - a blocker was located in a solenoid axis to make a novel DC muon beam with high purity.
  - backgrounds from pi- and e- contamination in the beam < 10^{-14} level.
  - But this technic will not work at a sensitivity below 10^{-16}.



μN→eN with a Muon Storage Ring

- muon intensity: 10^{11}~10^{12} /sec
- pulsed muon beam
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-23} for 230m



PRISM

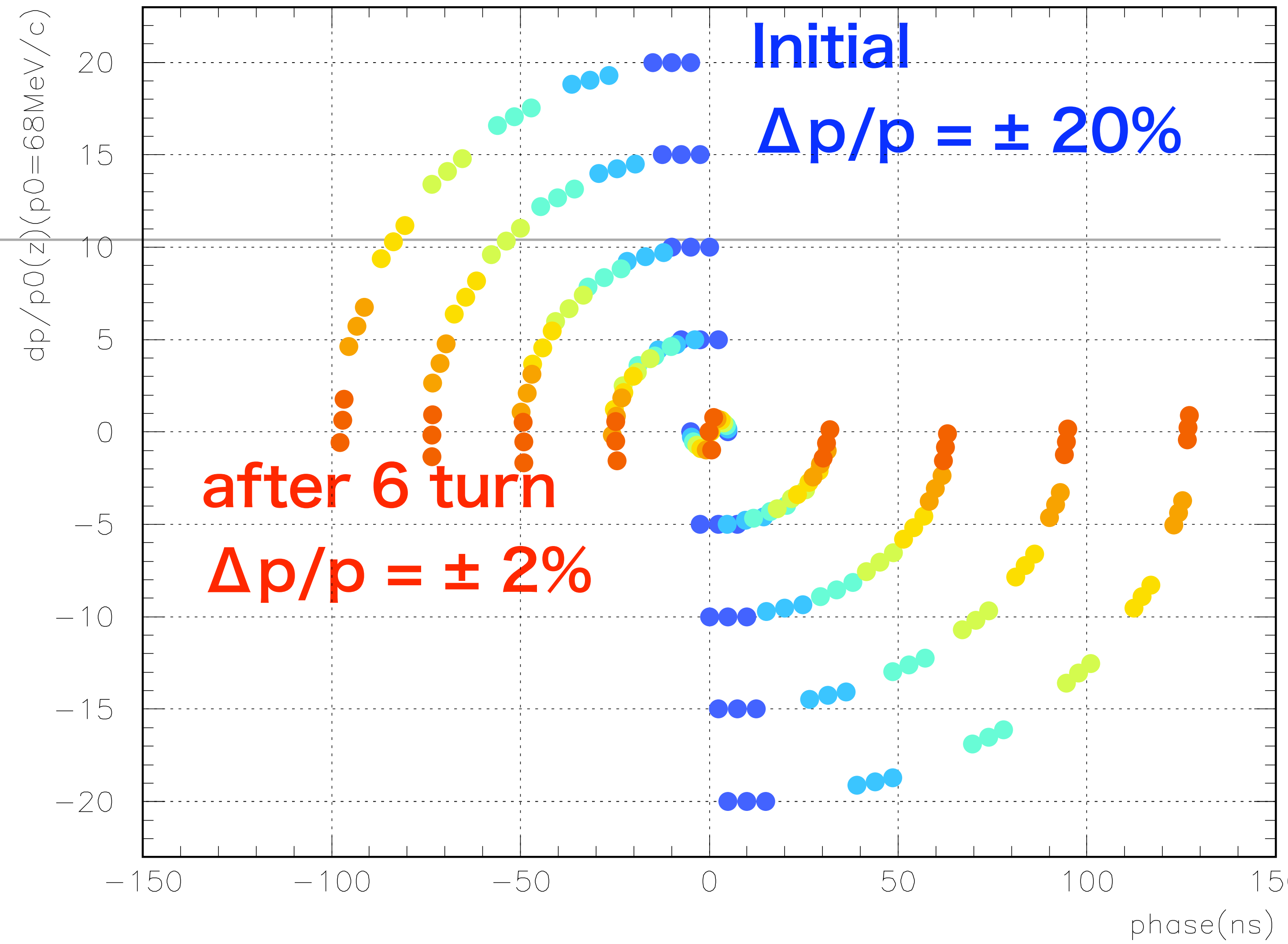
Phase Rotated Intense Slow Muon Source

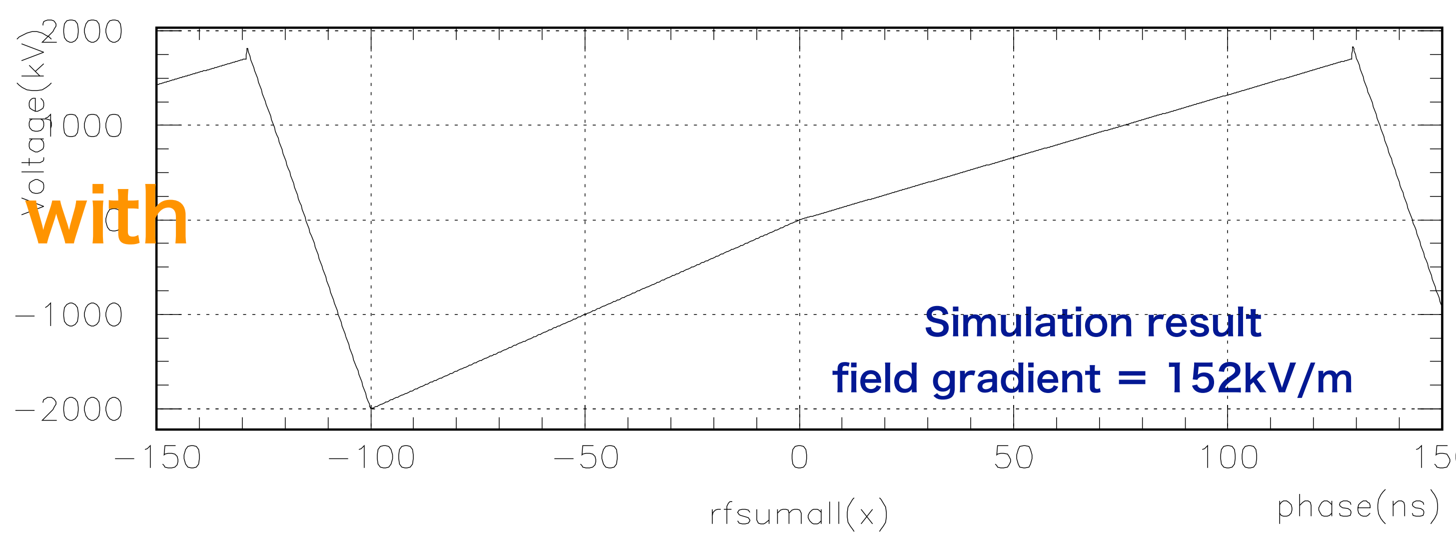
Phase Rotation

momentum spread
$\Delta p/p = \pm 2\%$

needs 6 turns (=1.5 μs)

survival rate (68MeV/c)
μ : 0.56
π : <10^{-23}





a bright pulsed muon beam with no pi- and e- contamination

Shorter pulsed proton (<10ns) is required for phase rotation.

Conclusion

- Muon groups have discussed a number of muon experiment, which have strong physics motivation, using a high power proton driver (~4MW) coming with front end of neutrino factories and/or a muon collider, with a large variety of applications in many fields.
- This new low-energy muon source would provide unprecedented intensity, 3 to 4 orders of magnitude larger than presently available and improve many muon programs. But they have various requirements on the beam. We need discussion from the design stage of muon collider to proceed the muon programs.
- We have many common R&D items between muon collider and Muon Physics, such as target region, high field solenoids, phase rotation and so on. Collaboration on these R&D should be encouraged.

$\mu N \rightarrow eN$ (PRISM type)	−	10^{20}	10-100	1-1000	≤20	3	n/a	π comt
g-2	±	10^{15}	≤15	≥1000	3100	10^{-2}	Pol	~100%
edm	±	10^{18}	≤50	≥1000	200-400	10^{-3}	Pol	>50%(NP^2)