COMET and PRISM/PRIME

Akira SATO
Dept. of Physics, Osaka University
for the COMET/PRISM working group

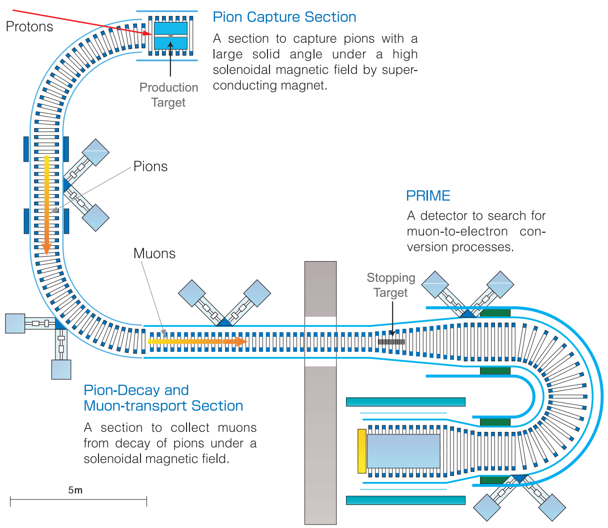
The 4th International Workshop on Nuclear and Particle Physics at J-PARC
(NP08), March.05- 07, 2008 @ Mito, Ibaraki, Japan

Outline

- Staging scenario of μ-e Conv. to BR~10^{-18} at J-PARC
  - COMET : μ-e Conv. for BR~10^{-16}
  - PRISM/PRIME : μ-e Conv. for BR~10^{-18}
    -

Staging scenario of μ-e Conv. to BR~10^{-18}

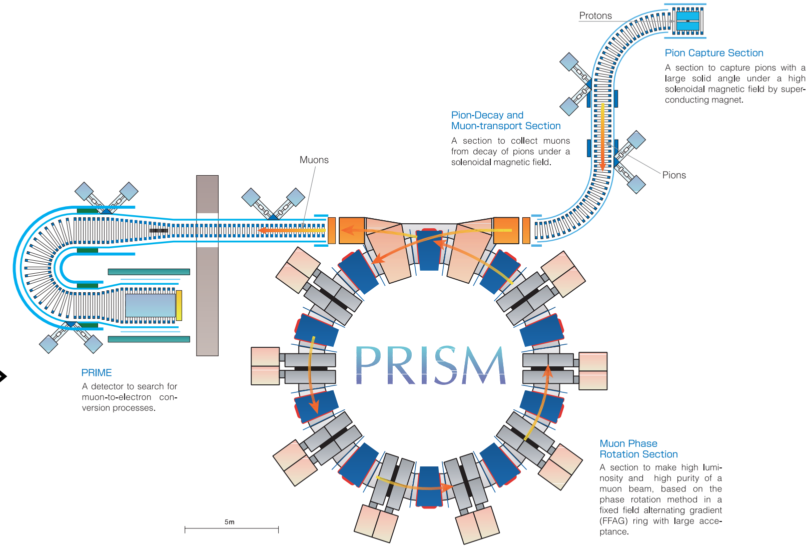
COMET



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

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

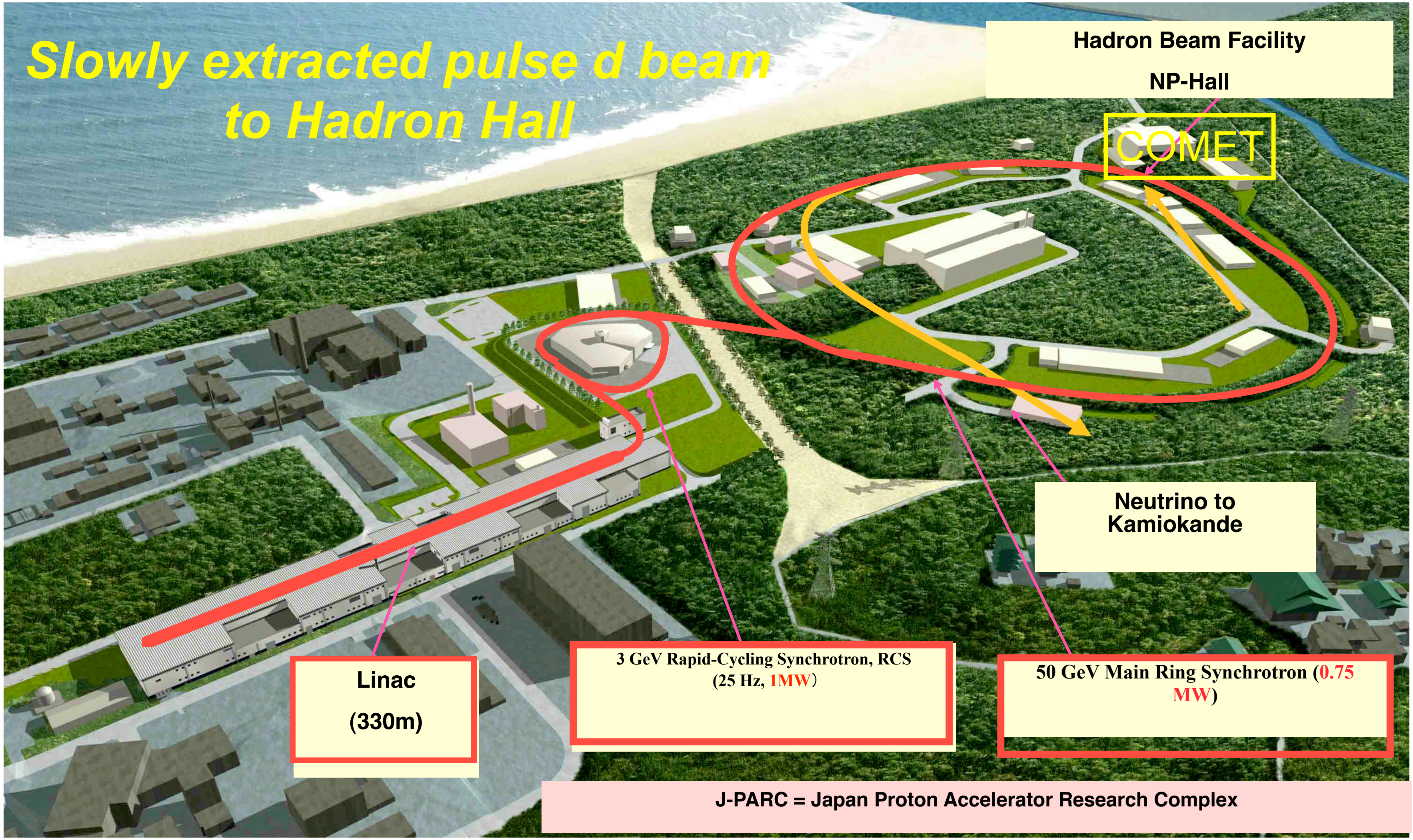
PRISM/PRIME



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

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

COMET at hadran hall of J-PARC



COMET : COherent Muon to Electron Transition

Dec. 2006 : LoI submission to J-PARC
Dec. 2007 : Proposal submission to J-PARC
(http://j-parc.jp/NuclPart/pac_0801/pdf/Kuno.pdf)
The production target was changed to tungsten.
Configuration of the transfer solenoid was optimized again.
Jan. 2008 : 1st PAC presentation

from Minutes of the 4th PAC meeting, Draft (March.01)

5. PROPOSAL EVALUATION

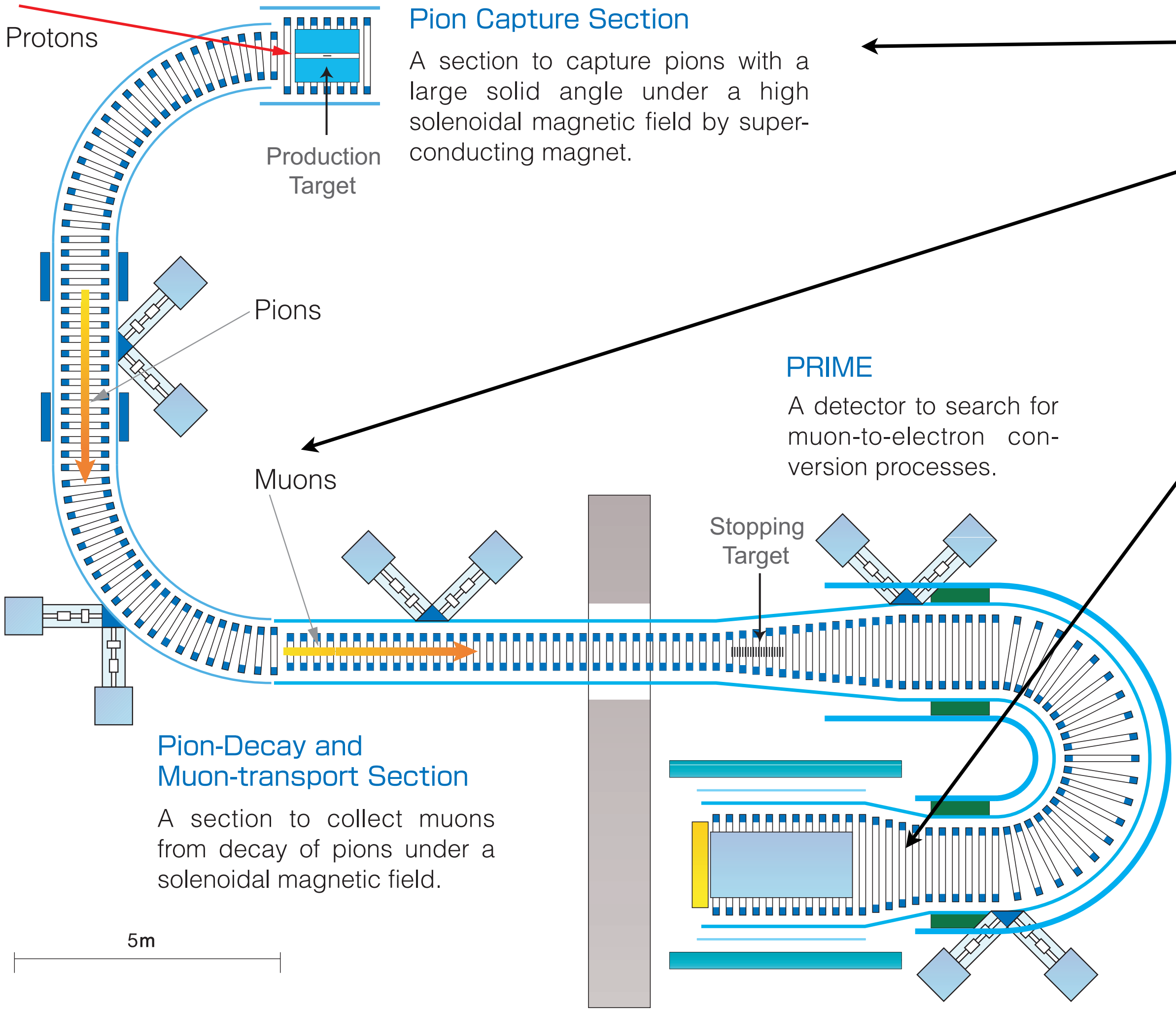
1. **P21:** An experimental Search for Lepton Flavour Violating mu-e conversion

The P21 (COMET) collaboration proposes to search for lepton flavor violation (LFV) in the coherent neutrino-less conversion of a muon to an electron in muonic atoms with a sensitivity less than 10^{-16}. Observable LFV in neutral currents is a process manifestly beyond the standard model. Model predictions based on various beyond the standard model processes have been put forward including supersymmetry, heavy neutrinos, multiple Higgs bosons, leptoquarks, and composite leptons. All the models except the Higgs boson mediated ones can involve photon couplings and so can also be probed through searches for muon to electron + gamma events. An observation of LFV in mu-e conversions would not only be a spectacular discovery but also give important information on, for example, the origin of flavor physics in supersymmetric theories. If LHC discovers supersymmetry, mu-e conversion could be very important in sorting out the physics scenarios of supersymmetry breaking. If LHC does not see new particles in the

from Minutes of the 4th PAC meeting, Draft (March.01) cont.

The PAC is impressed with the physics capabilities of the proposed COMET experiment and believes that this experiment could become one of the flagship experiments in the J-PARC program. On the other hand, this is a very difficult experiment and will demand large resources from the collaboration and the laboratory. A detailed assessment by the PAC and Laboratory of the feasibility for making such a precise measurement will need a more detailed design and simulation of the experiment. For these reasons, the PAC asks for more information to be provided over the next several meetings on the design, capability, and schedule for the experiment. This information and answers to the questions posed below should be given in an addendum to the proposal and presentations should be given at the next meeting if possible. Preliminary interactions should take place with the FIFC as to resources, schedule, location, and beam requirements. If possible a task force should be set up to consider the special demands of the required beam structure, energy, and intensity. Reports from these committees should be made to the PAC in upcoming meetings. The collaboration also needs to develop a Conceptual Design Report for the complete experiment in order to allow realistic assessments of the feasibility, cost, and schedule.

Overview of the New Experiment



Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

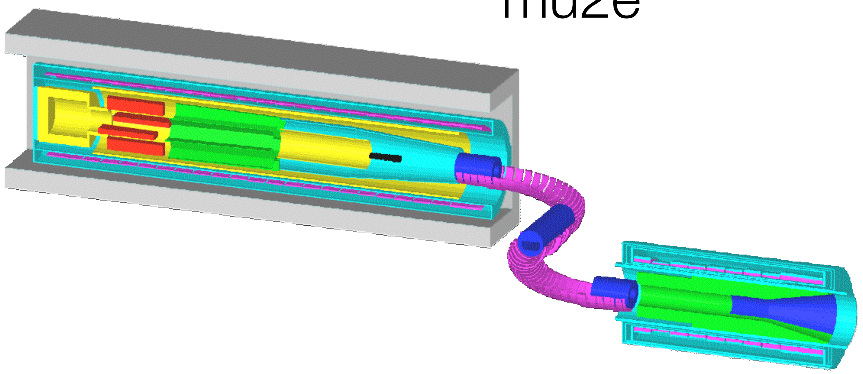
The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

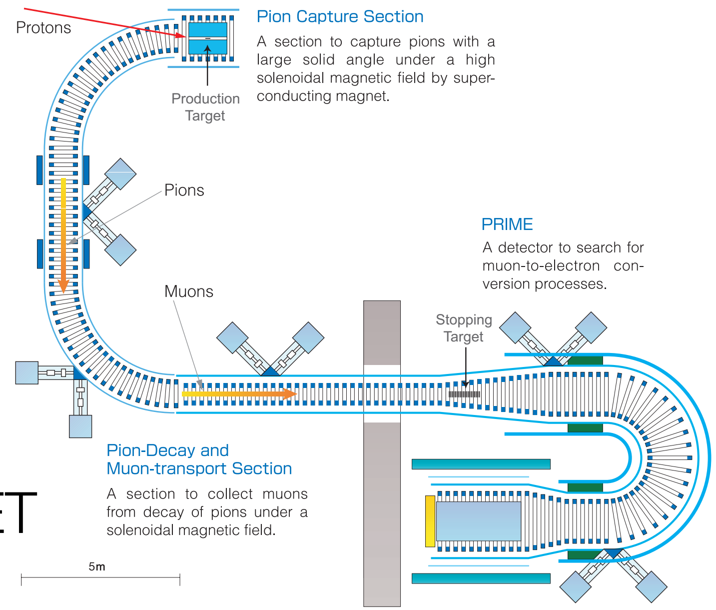
The beamline design is very important.

Comparison with mu2e Experiment

- Proton driver
- Proton Target
  - tungsten (mu2e/COMET)
- Muon Transport
  - Magnetic field distributions are different.
  - Efficiencies of the muon transports are almost the same.
- Spectrometer
  - For 10^{11} stopping muons/sec
  - Straight Solenoid (mu2e)
  - Curved Solenoid (COMET)
    - ~ 300 DIO tracks/sec

mu2e





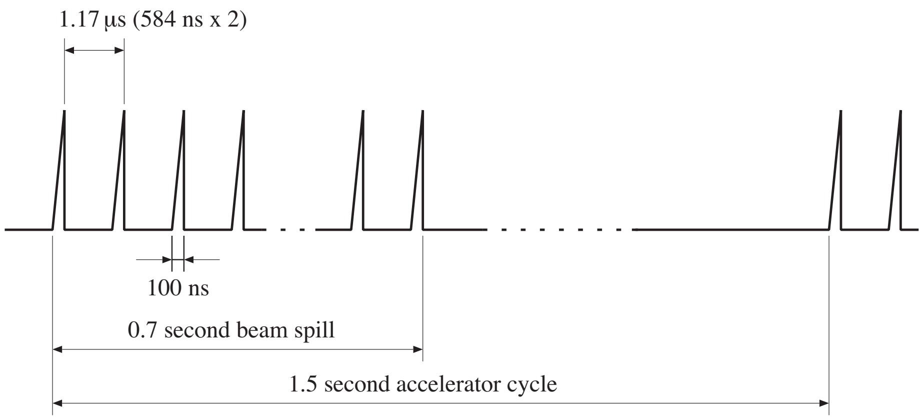
COMET

The Muon Source

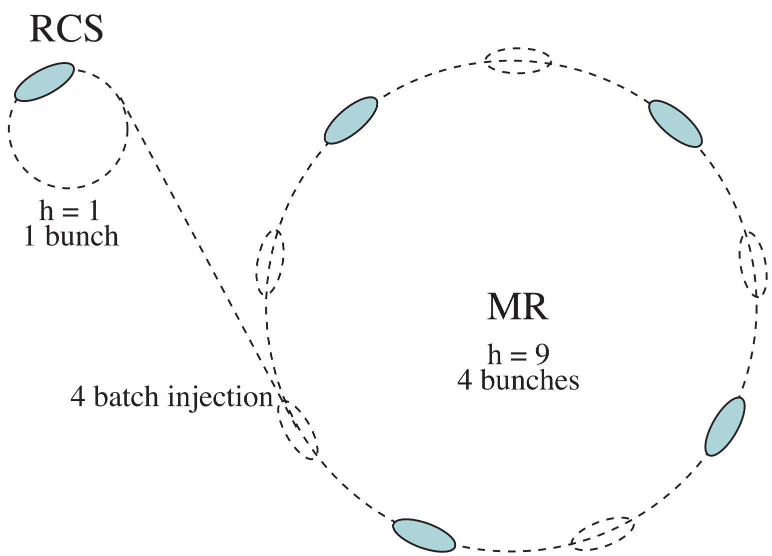
M.Tomizawa in the afternoon session

Proton Beam (1)

- A pulsed proton beam is needed to reject beam-related prompt background.
  - Detection will be made between pulses (delayed measurement).
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)



- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction with keeping bunches
  - spill length (flat top) ~ 0.7 sec
    - good to be shorter for cosmic-ray backgrounds.

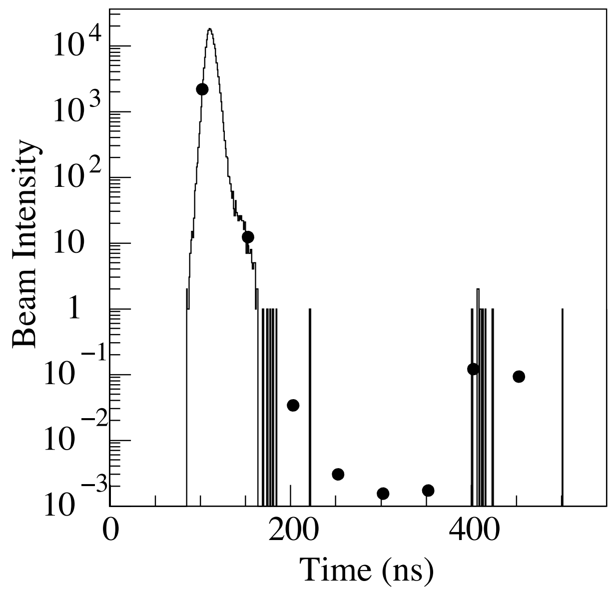


h=8 would be possible.

M.Tomizawa in the afternoon session

Proton Beam (2) - 2 SSC years

- Proton Extinction :
  - (delayed)/(prompt)<10^{-9}
  - Test done at BNL-AGS gave 10^{-7} (shown below).
  - Extra extinction devices are needed.



Test of Extinction at BNL-AGS

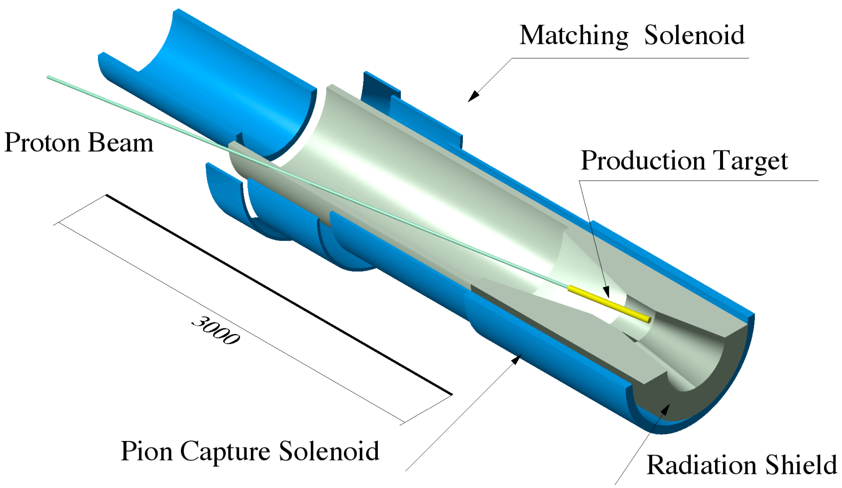
- Required Protons :
  - 8 x 10^{20} protons of 8 GeV in total for a single event sensitivity of about 0.3 x 10^{-16}.
  - For 2 x 10^7 sec running, 4 x 10^{13} protons /sec (= 7 μA).
  - A total beam power is 56 kW, which is about 1/8 of the J-PARC full beam power of 450 kW (30 GeV x 15μA).

R&D on extinction device and monitor is under way by US-JP collaboration.

T.Ogitsu in the afternoon session

Pion Capture

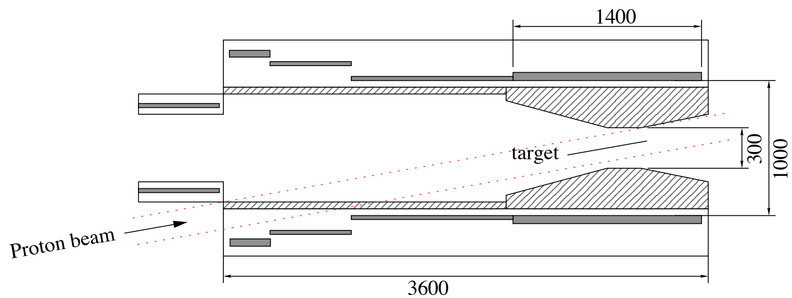
- A large muon yield can be achieved by large solid angle pion capture by a high solenoid field, which is produced by solenoid magnets surrounding the proton target.



$$P_T(GeV/c) = 0.3 \times B(T) \times (\frac{R(m)}{2})$$

- B=5T,R=0.2m, P_T=150MeV/c.

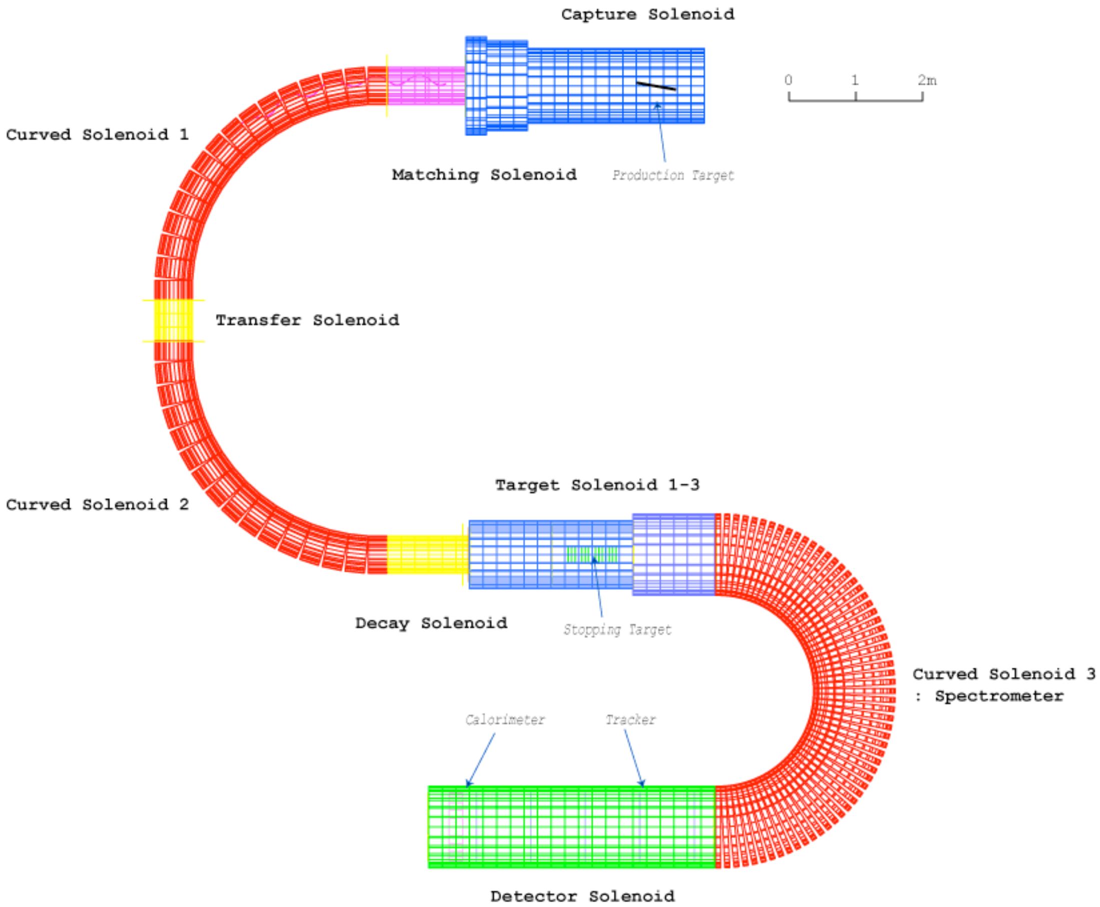
- Superconducting Solenoid Magnet for pion capture
  - 15 cm radius bore
  - a 5 tesla solenoidal field
  - 30 cm thick tungsten radiation shield
  - heat load from radiation
  - a large stored energy



T.Ogitsu and M.Yoshida in the afternoon session

Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- Requirements :
  - long enough for pions to decay to muons (> 20 meters ≈ 2×10^{-3}).
  - high transport efficiency (P_μ~40 MeV/c)
  - negative charge selection
  - low momentum selection (P_μ<75 MeV/c)
- Straight + curved solenoid transport system is adopted.



Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

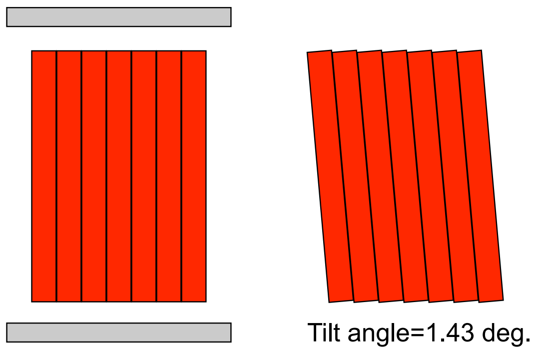
D : *drift distance*
B : *Solenoid field*
θ_{bend} : *Bending angle of the solenoid channel*
p : *Momentum of the particle*
q : *Charge of the particle*
θ : *atan*(P_T/P_L)

  - This effect can be used for charge and momentum selection.

- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : *Momentum of the particle*
q : *Charge of the particle*
r : *Major radius of the solenoid*
θ : *atan*(P_T/P_L)



Spectra at the End of the Muon Transport

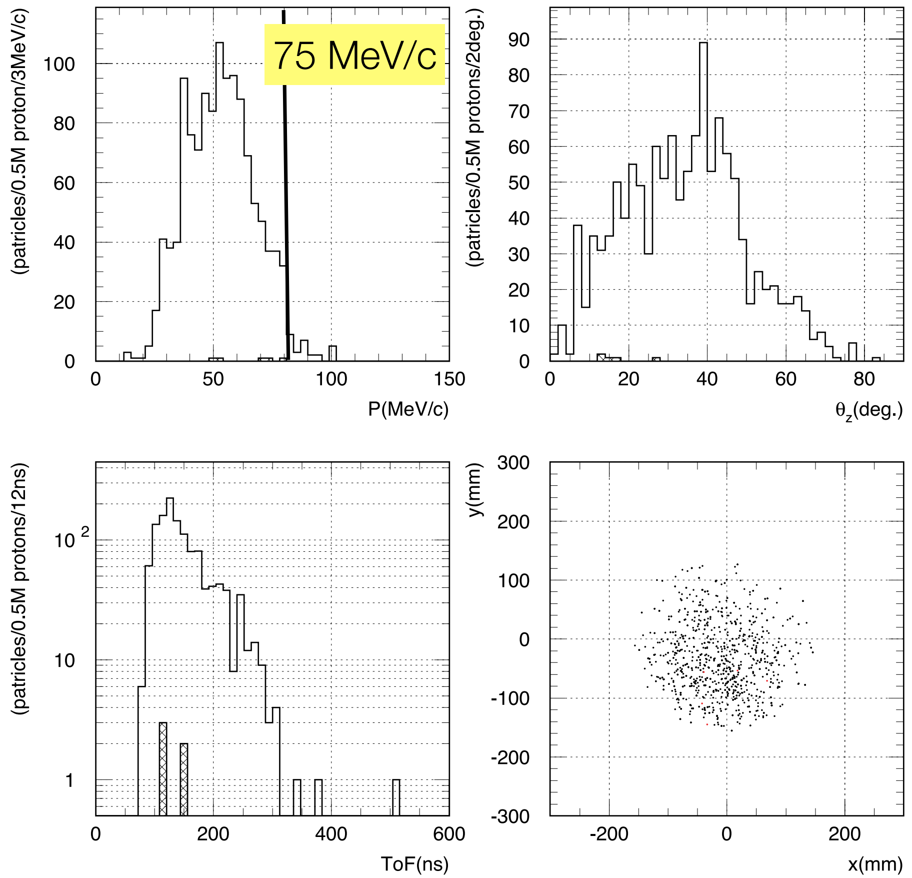
- Preliminary beamline design
  - main magnetic field
  - compensation field
  - radius of magnets (175 mm)

- Transport Efficiency

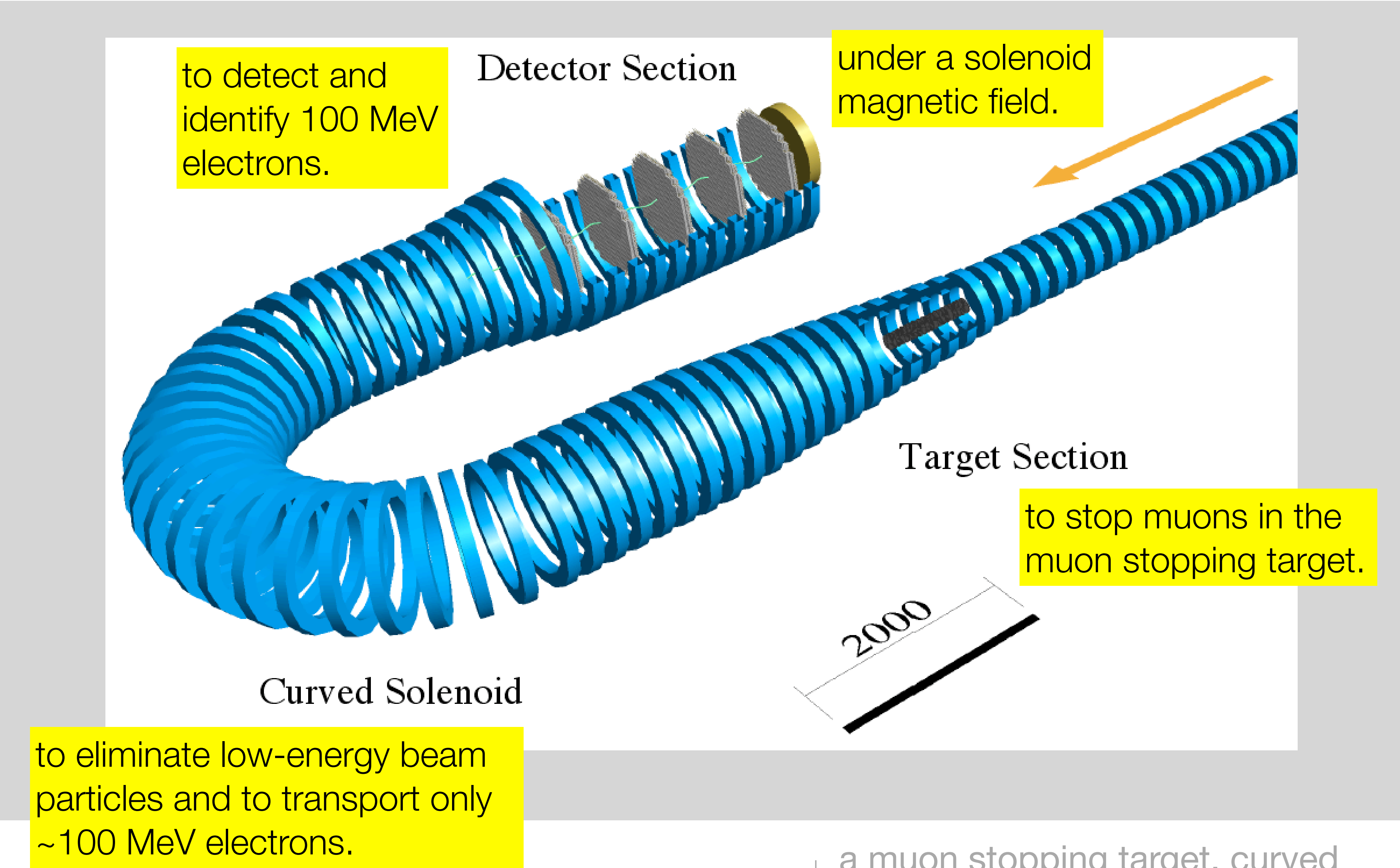
# of muons /proton	0.0071
# of stopped muons /proton	0.0018
# of muons of p_μ >75 MeV/c /proton	$2\text{x}10^{-4}$

Spectra at the end of the beamline

(top left) total momentum
(top right) direction angles to beam axis
(bottom left) time of flight
(bottom right) beam profile
muons for open histograms, pions for hatched histograms.



The Detector



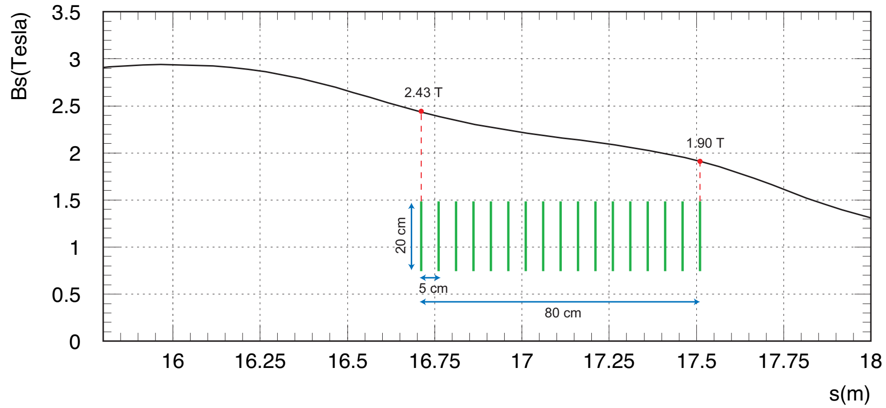
Detector Components

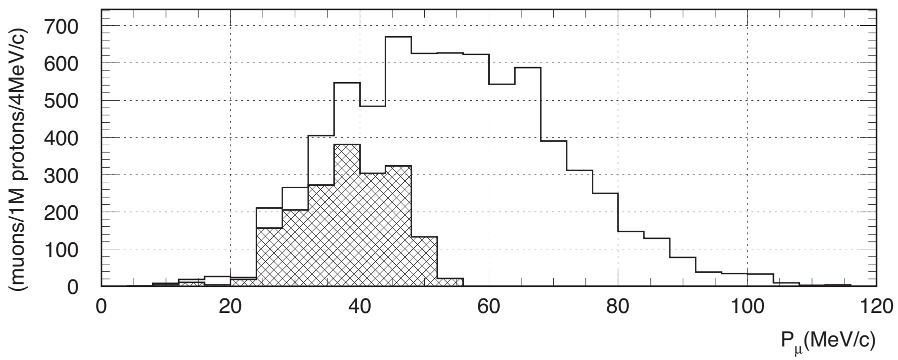
a muon stopping target, curved solenoid,tracking chambers, and a calorimeter/trigger and cosmic-ray shields.

Muon Stopping Target (preliminary)

- Target material
  - First choice : aluminum
- Configuration (preliminary)
  - material : aluminum disk
  - disk radius : 100 mm
  - disk thickness : 200 μm
  - a number of disks : 17
  - disk spacing : 50 mm
  - a graded magnetic field (for mirroring).
- Muon stopping efficiency
  - about 26% is stopped.

	aluminum	titanium	lead
Atomic number	13	22	82
Lifetime of muonic atoms (μsec)	0.88	0.33	0.082
Relative branching ratio	1	1.7	1.15





Detector and Spectrometer

- To identify the genuine mu-e conv. enevts from a huge number of B.G. events.
  - signal : a 105MeV electron from the stopping targets.
  - background : muon decay in orbit etc.
- Muon Decay in Orbit (DIO)
  - Main B.G. source
  - Electron spectrum from muon decay in orbit

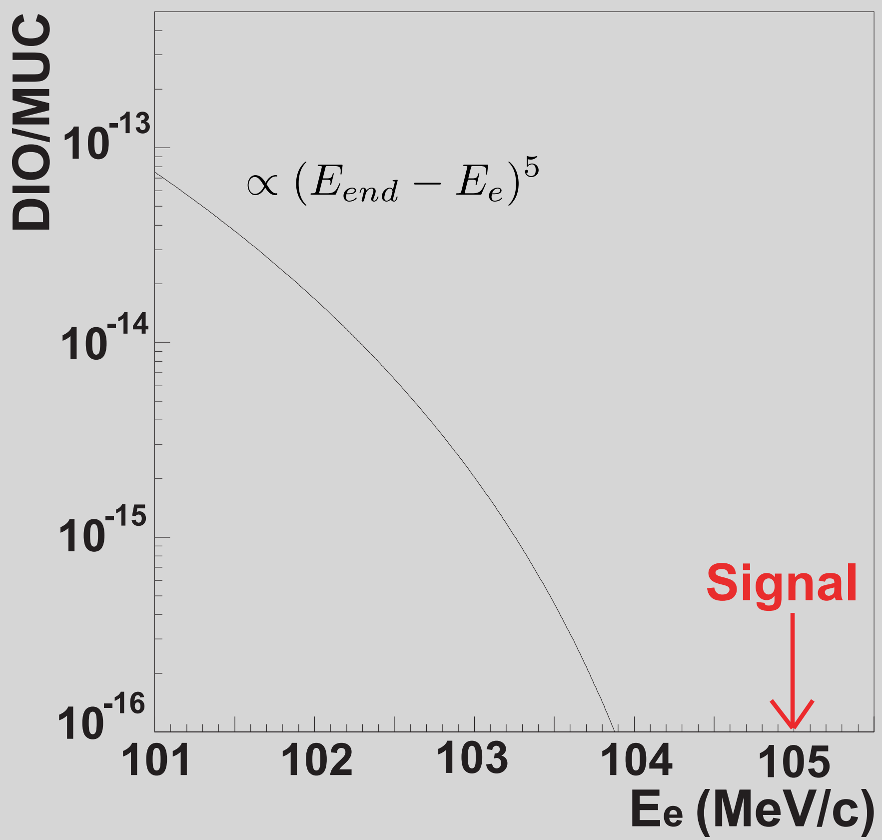
energy

timing

as precisely as possible

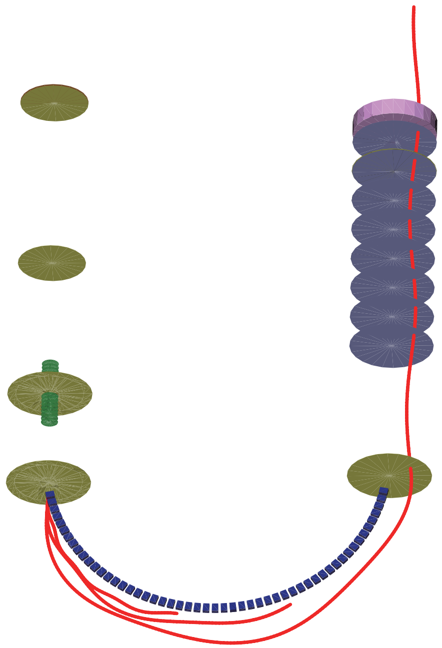
Reject using a curved solenoid spectrometer

Energy spectrum of electrons from decays in orbit in a muonic atom of aluminum, as a function of electron energy. The vertical axis shows the effective branching ratio of μ-e conversion.

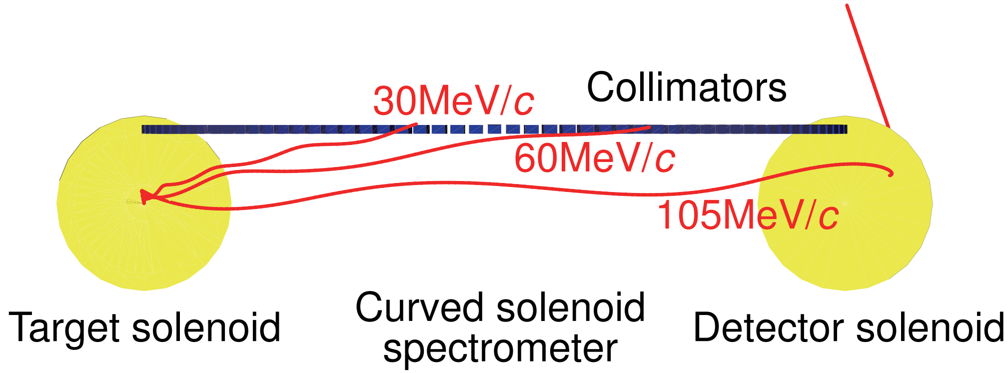


Mom. Selection in a Curved Solenoid

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



Top view

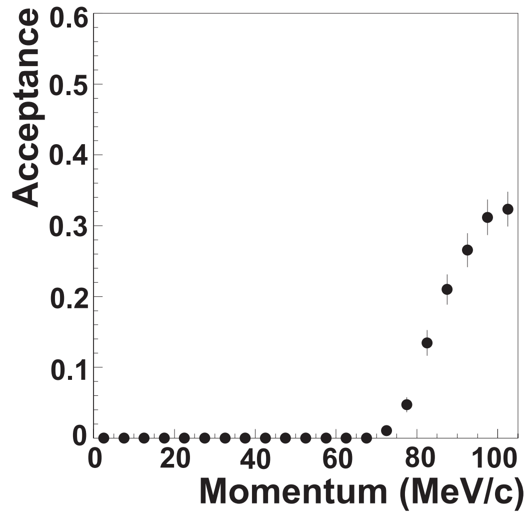


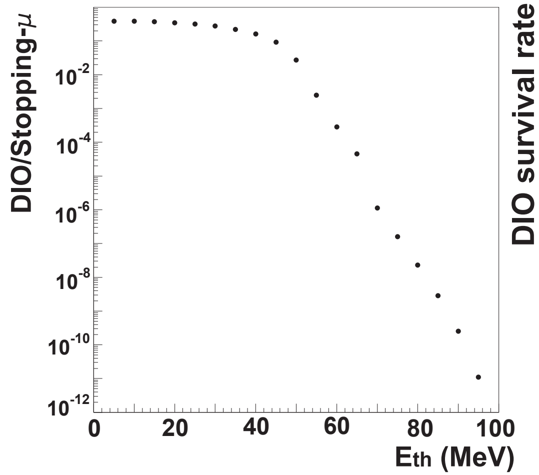
Side view

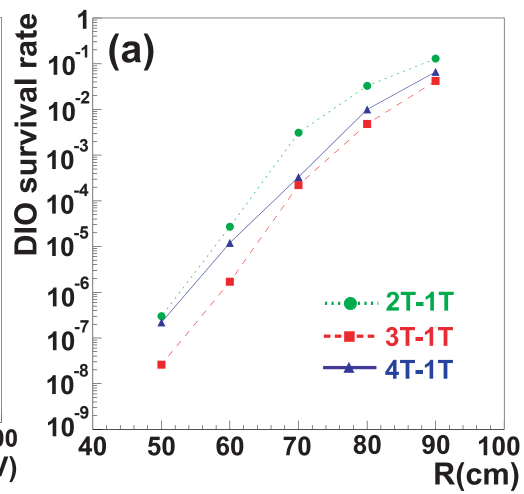
Transmission of the Electron Transport (CS)

- Electron Transport System Parameters (preliminary)
  - Radius : 50 cm
  - Magnetic field : 1 Tesla
  - Bending angle : 180 degrees
- Geometrical Acceptance
  - Solid angel at the target : 0.73
    - mirror effect at a graded field
  - Transport efficiency : 0.44
  - Total : 0.32
- Suppression of electrons from decay in orbit.
  - about 10^{-8} suppression
  - about 1000 tracks / sec for 10^{11} stopping muons.

Ratio of a number of electrons reaching the end of transport to all electrons emitted in 4π.





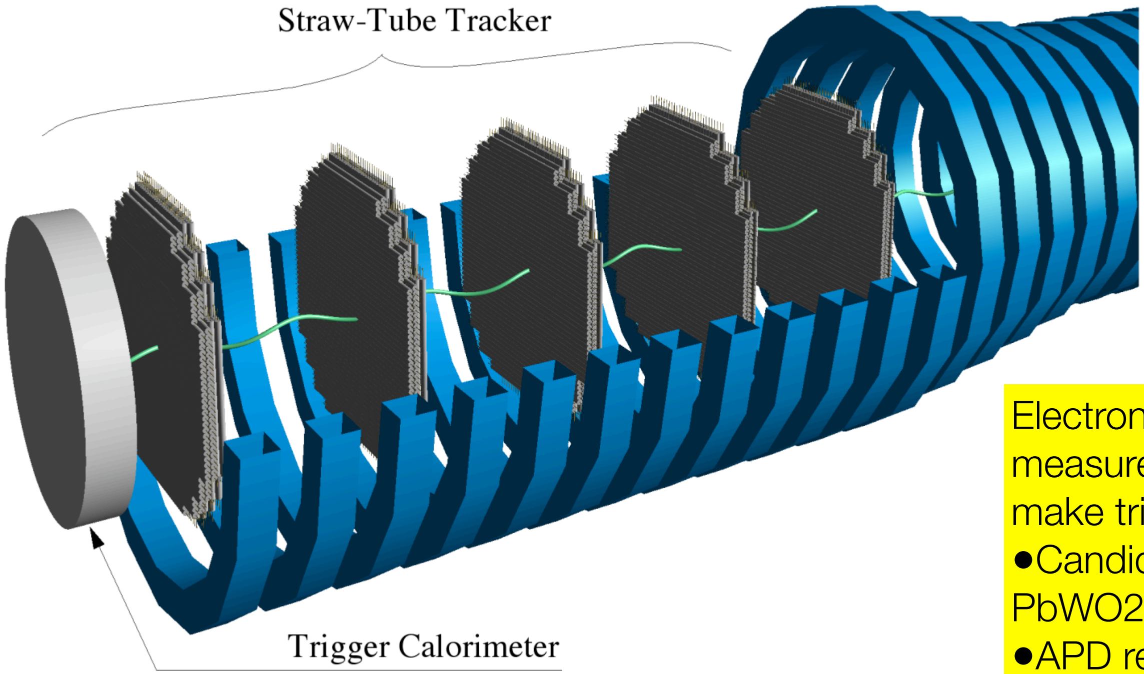


Electron Detection (preliminary)

Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.

Straw-tube Trackers to measure electron momentum.
- should work in vacuum and under a magnetic field.
- A straw tube has 25μm thick, 5 mm diameter.
- One plane has 2 views (x and y) with 2 layers per view.
- Five planes are placed with 48 cm distance.
- 250μm position resolution.
- 230 keV/c in sigma (multiple scattering dominated.)

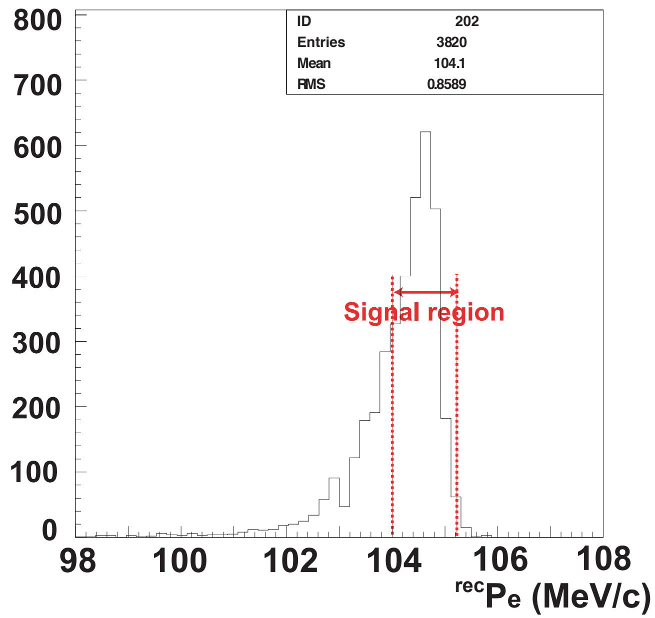


Electron calorimeter to measure electron energy and make triggers.
- Candidate are GSO or PbWO2.
- APD readout (no PMT).

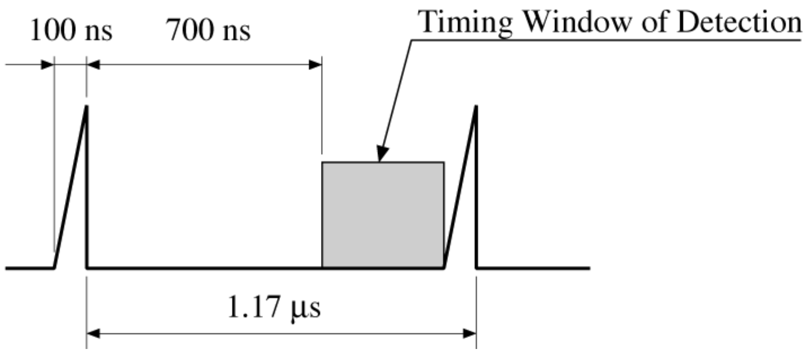
Signal Acceptance

- The signal acceptance is given by the geometrical acceptance of the detector and the analysis (cut) acceptance.

Items	Acceptance
geometrical	
solid angle at target	0.73
transport efficiency	0.44
analysis	
p_t > 52 MeV/c cut	0.67
chi2 cut	0.86
energy cut	0.56
time window cut	0.38
total	0.04



signal energy window (104.0-105.2 MeV in uncorrected energy scale)



Signal Sensitivity (preliminary) - 2 SSC years

Tungsten target & beam line optimzation → improvement of x2.7

- Single event sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- N_μ is a number of stopping muons in the muon stopping target. It is $1.5\text{x}10^{18}$ muons.
- f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
- A_e is the detector acceptance, which is 0.04.

total protons	$8\text{x}10^{20}$
muon transport efficiency	0.0071
muon stopping efficiency	0.26
# of stopped muons	$1.5\text{x}10^{18}$

$$B(\mu^- + Al \to e^- + Al) = \frac{1}{1.5 \times 10^{18} \times 0.6 \times 0.04} = 2.8 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 5 \times 10^{-17} \quad (90\% \text{ C.L.})$$

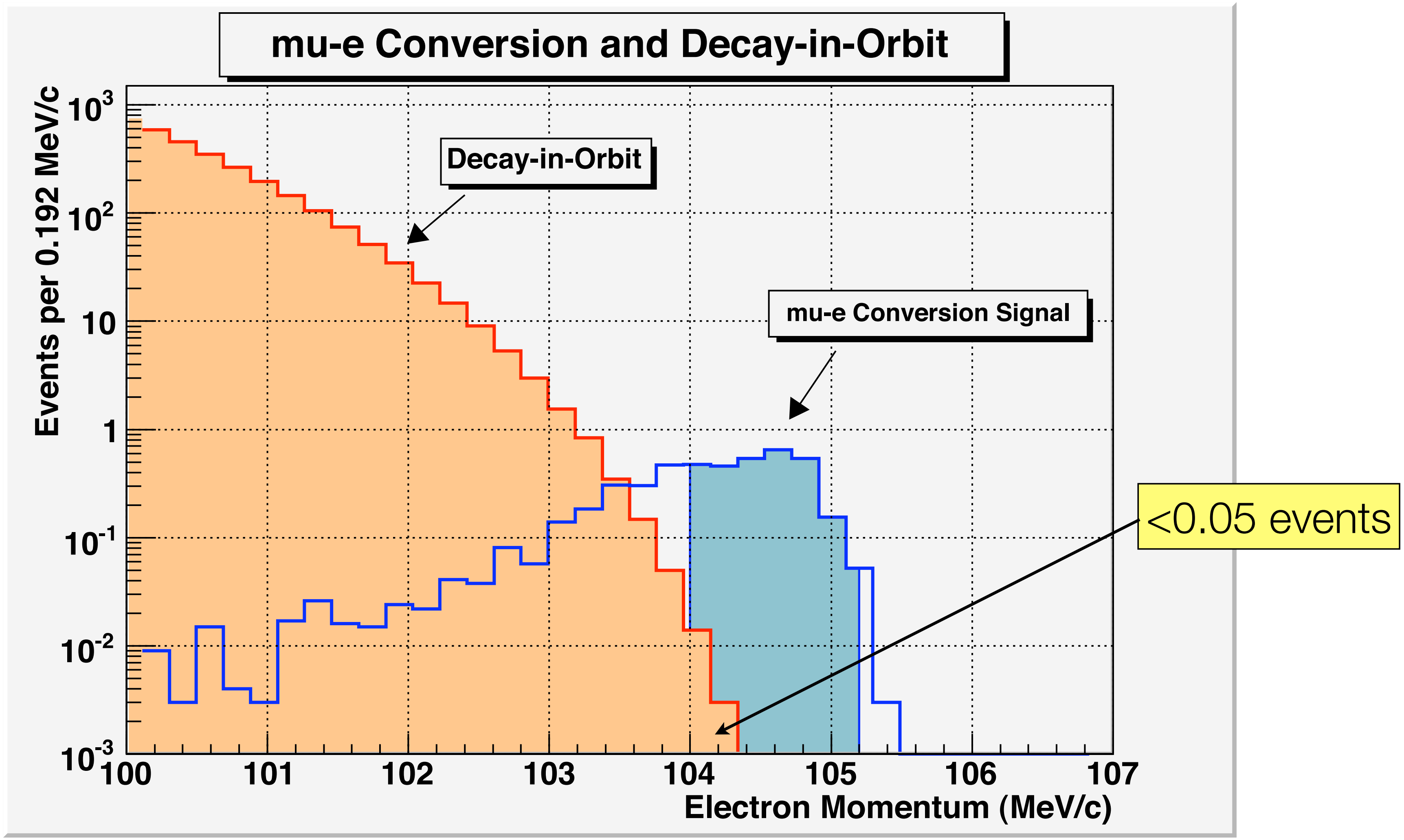
Potential Background Events

- Background rejection is the most important in searches for rare decays.
- Types of backgrounds for $\mu^- + N \rightarrow e^- + N$ are,

Intrinsic backgrounds	originate from muons stopping in the muon stopping target.	•muon decay in orbit •radiative muon capture •muon capture with particle emission
Beam-related backgrounds	caused by beam particles, such as electrons, pions, muons, and anti-protons in a beam	•radiative pion capture •muon decay in flight •pion decay in flight •beam electrons •neutron induced •antiproton induced
Other backgrounds	caused by cosmic rays	•cosmic-ray induced •pattern recognition error

DIO Background

a number of events for
1.1 x10^{18} stopped muons.



BG with asterisk needs beam extinction.

Background Rejection Summary (preliminary)

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.10	10^{-4} veto & 2×10^{7} sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

PRISM/PRIME

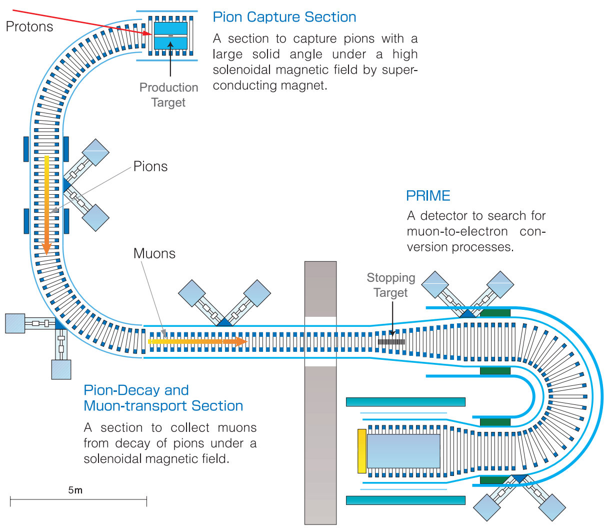
Requirements for BR<10^{-18}

PRISM

- Higher muon intensity
  - > 10^{11}-10^{12} μ/sec
- Less beam related backgrounds
  - Pulsed Beam
  - Beam extinction between pulses
    - to reject b.g. from proton beam
  - no pion contamination
- Better e^- energy resolution
  - Narrow energy spread
    - allow thinner muon-stopping target
- Less detector hit rate

COMET to PRISM/PRIME

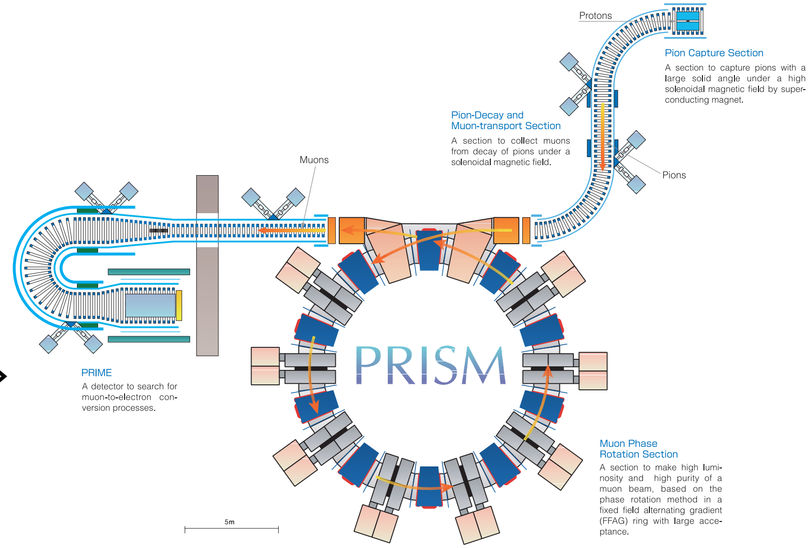
COMET



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

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

PRISM/PRIME



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

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

PRISM : Phase Rotated Intense Slow Muon source

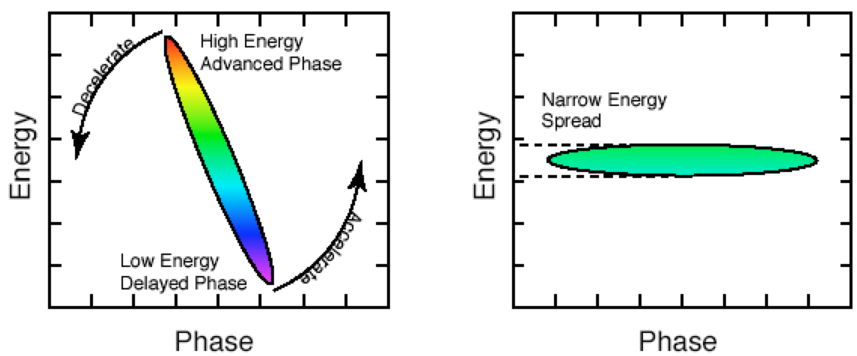
- **High intensity**
  - intensity : 10^{11}-$10^{12}\mu^{\pm}$/sec
  - beam repetition :100-1000Hz
  - kinetic energy : 20MeV(=68MeV/c)
- **Narrow energy spread**
  - kinetic energy spread : ±0.5-1.0MeV
- **Less beam contamination**
  - contamination < 10^{-18}

PRIME : PRIsm Muon to Electron Conv. Experiment

sensitivity of $\mu \rightarrow e \sim 10^{-18}$

... To Make Narrow Beam Energy Spread

- A technique of phase rotation is adopted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles.
- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
  - Fast particle comes earlier and slow particle comes late.
- Proton beam pulse should be narrow (< 10 nsec).
- Phase rotation is a well-established technique, but how to apply a tertiary beam like muons (broad emittance) ?



PRISM-FFAG (6 sectors) in RCNP, Osaka

Ready to demo. phase rotation

Muon Yield Estimation at PRISM

based on the PRISM FFAG acceptance of 40 mm rad in horizontal and 6.5 mm rad in vertical and a muon stopping target of 1/10 thickness of MECO.

Cases	Proton Beam Power	Target Material	Pion Capture Magnetic Field	Muon Yield (/sec)
1	0.6 MW	Graphite	6 T	7×10^{10}
2	0.6 MW	Graphite	16 T	2×10^{11}
3	0.6 MW	Tungsten	6 T	2×10^{11}
4	0.6 MW	Tungsten	16 T	5×10^{11}
5*	4 MW	Mercury	6 T	1×10^{12}
6	4 MW	Mercury	16 T	3×10^{12}

from the PRISM/PRIME LOI (2006)

PRISM

Muon Yield Estimation at PRISM

based on the PRISM FFAG acceptance of 40 mm rad in horizontal and 6.5 mm rad in vertical and a muon stopping target of 1/10 thickness of MECO.

Cases	Proton Beam Power	Target Material	Pion Capture Magnetic Field	Muon Yield (/sec)
1	0.6 MW	Graphite	6 T	7×10^{10}
2	0.6 MW	Graphite	16 T	2×10^{11}
3	0.6 MW	Tungsten	6 T	2×10^{11}
4	0.6 MW	Tungsten	16 T	5×10^{11}
5*	4 MW	Mercury	6 T	1×10^{12}
6	4 MW	Mercury	16 T	3×10^{12}

from the PRISM/PRIME LOI (2006)

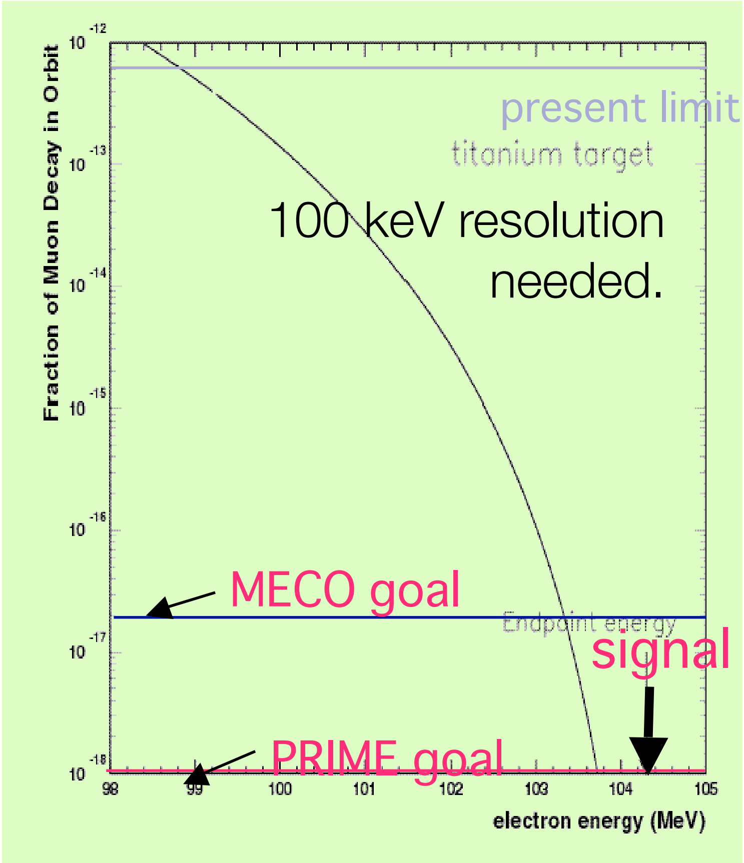
PRISM/PRIME Sensitivity for μ-e conversion

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

preliminary

	PRIME
proton beam power	0.6 MW
muon intensity	2×10^{11}/sec
acceptance	0.22
time window	100%
running period	5 year
Single Event Sensitivity	6×10^{-19}

Work in Progress



from the PRISM/PRIME LOI (2006)

PRISM Features to Reject Backgrounds

- (1) Long muon flight length
  - about 40 m circumference x 5-6 turns at the muon storage ring (PRISM-FFAG)
  - pion survival rate of <10^{-23}
- (2) Narrow muon beam energy spread
  - goal : +- 3 %
  - by phase rotation at the PRISM-FFAG ring
- (3) Muon beam energy selection before the detector
  - momentum slit after the PRISM-FFAG ring
  - 68 MeV/c +- 3% (not 104 MeV)
- (4) Beam extinction at muons
  - Kicker magnets of the PRISM-FFAG ring
  - no proton extinction needed
- (5) Small duty factor of detection
  - ~ 10^{-4} for a detection of 1 μs with 100 Hz repetition

Background Consideration

as simple as possible

Source	How to Eliminate	Comments
muon decays in orbit	(2) energy spread	1/10 of the MECO target
Radiative pion capture	(1) flight	no pions
Beam electrons	(3) momentum cut	
Muon decay in flight	(3) momentum cut	P < 77 MeV/c
Decayed background	(4)	
Cosmic rays	(5)	no active cosmic ray shield needed.

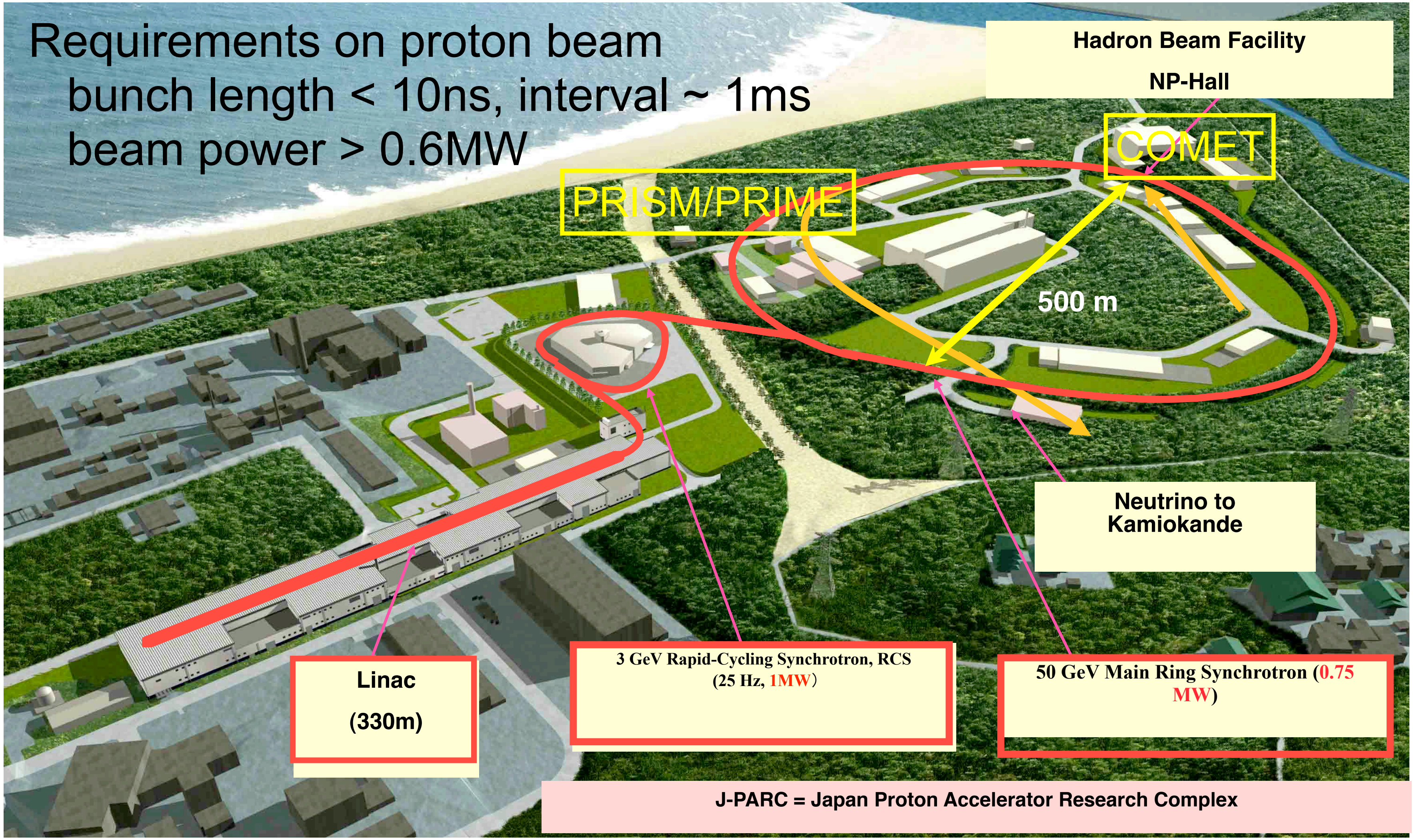
Estimation of Background Rates

preliminary

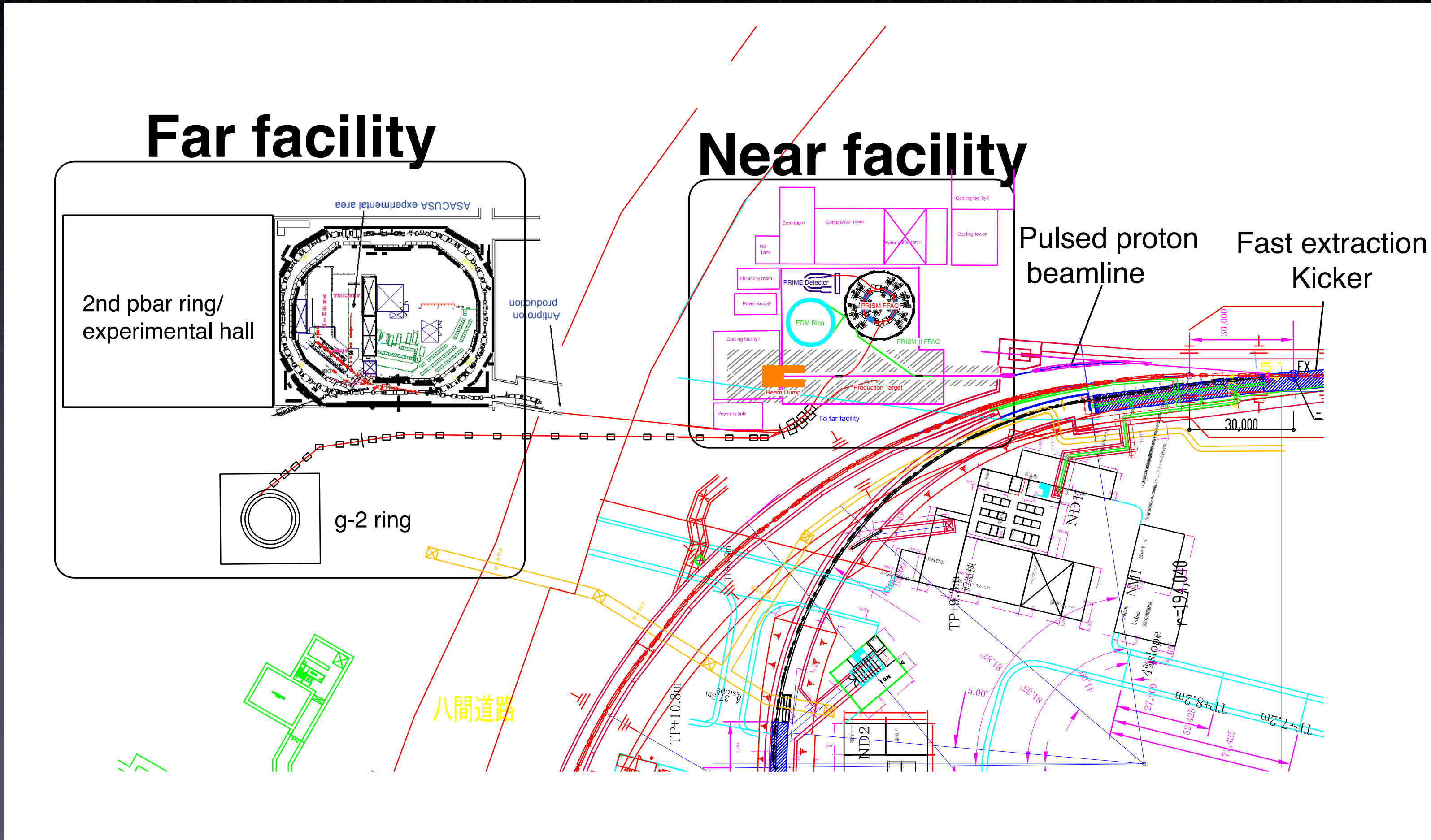
Background	Rate	comment
Muon decay in orbit	0.05	energy reso 350keV(FWHM)
Radiative muon capture	0.01	end point energy for Ti=89.7MeV
Radiative pion capture	0.03	long flight length in FFAG, 2 kicker
Pion decay in flight	0.008	long flight length in FFAG, 2 kicker
Beam electron	negligible	kinematically not allowed
Muon decay in flight	negligible	kinematically not allowed
Antiproton	negligible	absorber at FFAG entrance
Cosmic-ray	< 10^-7 events	low duty factor
Total	0.10	

from the PRISM/PRIME LOI (2006)

Possible halls for PRISM/PRIME



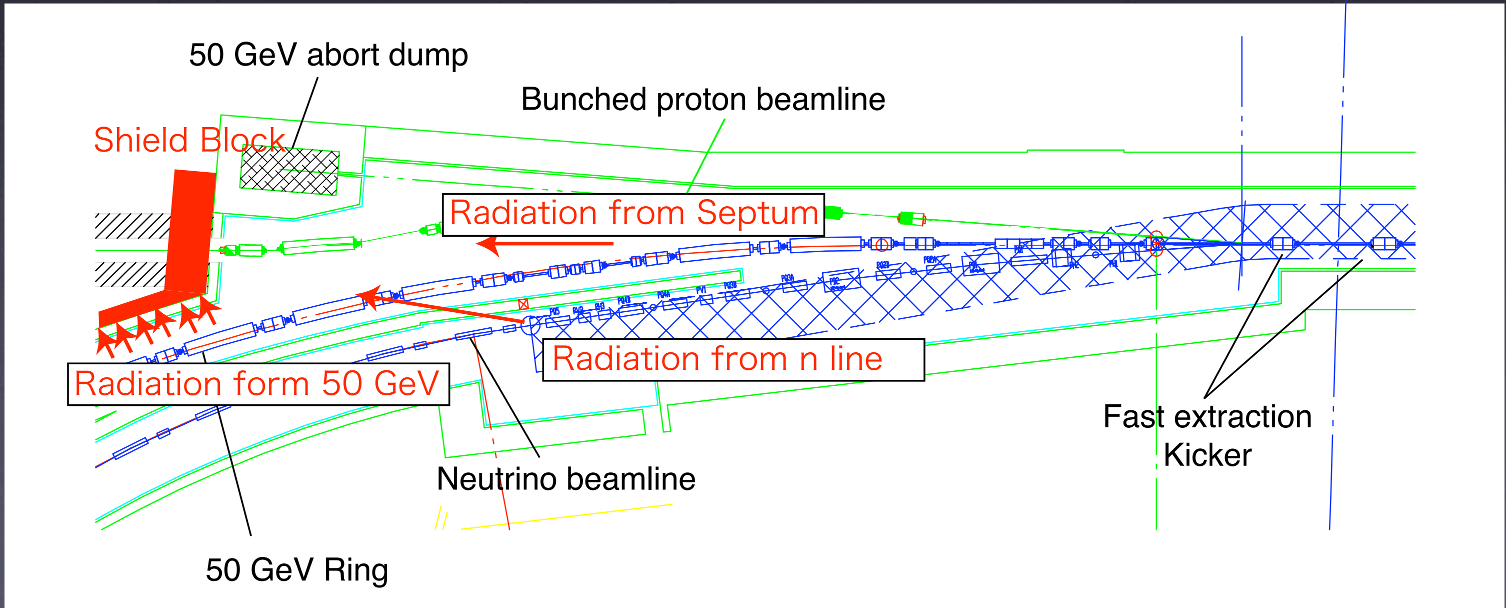
Fast extraction facility
possible layout



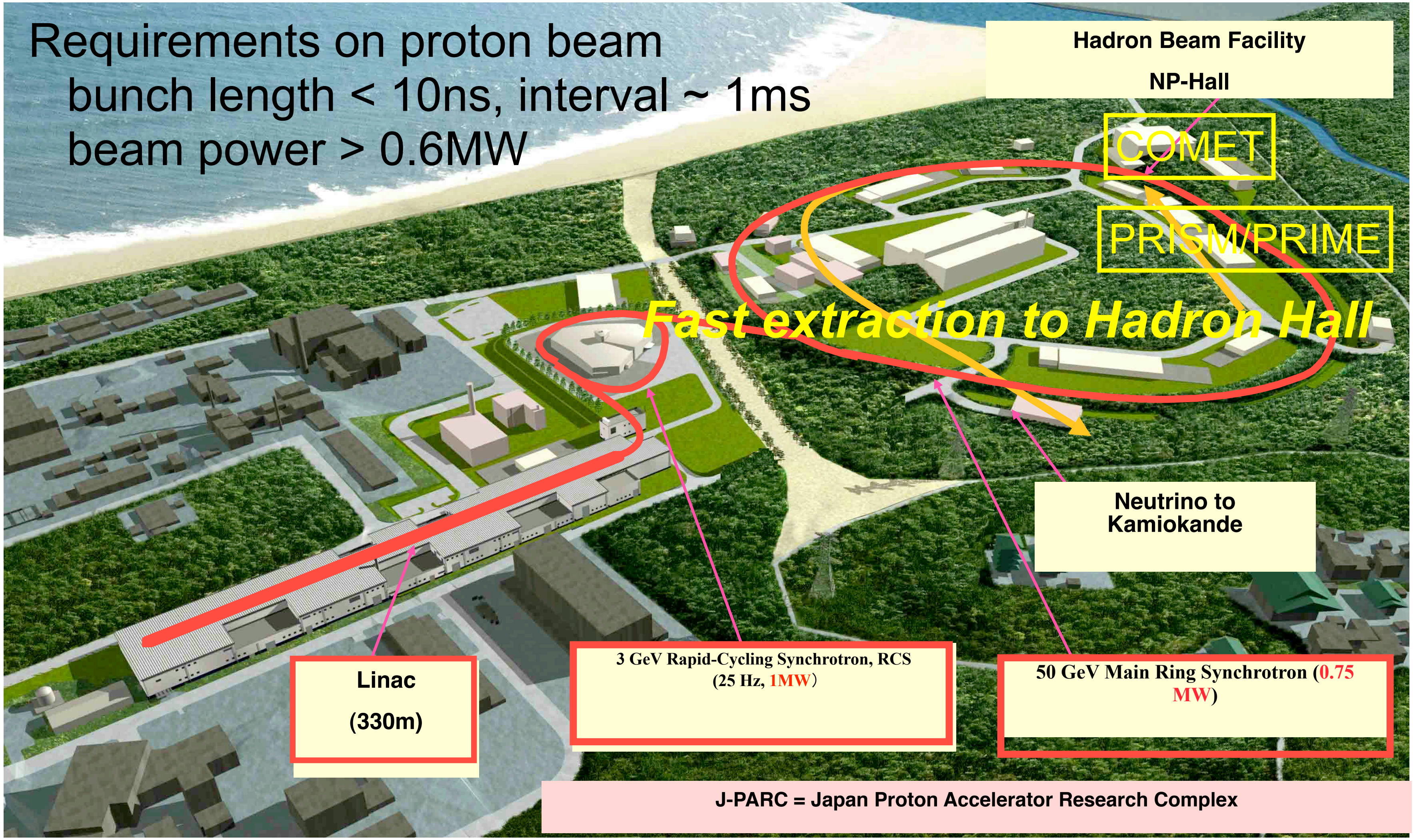
Shielding blocks

- Once soil is activated, future excavation would become almost impossible. To avoid soil activation at the location of proton extraction port to a planned facility. We installed concrete shielding blocks at location of future extraction.

It has been approved!



Possible halls for PRISM/PRIME



Summary

- We have a staging plan of searching for coherent neutrino-less conversion of muons to electron (μ-e conversion) at sensitivity of 10^{-16} (COMET) to 10^{-18} (PRISM/PRIME). The experiments would offer powerful probe for new physics phenomena beyond the Standard Model.
- COMET is planned to carry out in the J-PARC NP Hall by using a bunched proton beam slowly-extracted from the J-PARC main ring. This new initiative has been taken recently to achieve an early and timely start of a series of the searches. It is planned to be as the first step of our staging approach continuing towards the ultimate search and the discovery of μ-e conversion.
- Proposal submitted for COMET. Still under discussion.