mu-e conversion
COMET at J-PARC

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Outline

- Introduction
- COMET at J-PARC
  - Muon beam at J-PARC
  - Detector
  - Sensitivity and Background
  - R&D Status
  - Schedule and Cost
- Summary

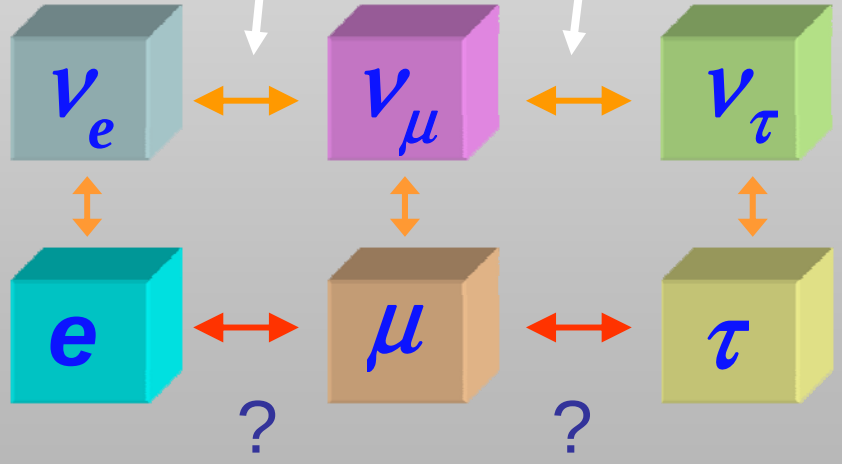
Introduction

Introduction

Lepton Flavour Violation of Charged Leptons

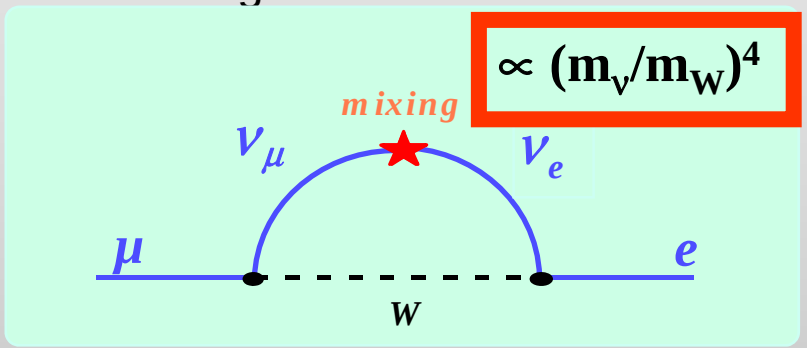
Neutrino Mixing (confirmed)

Soon!



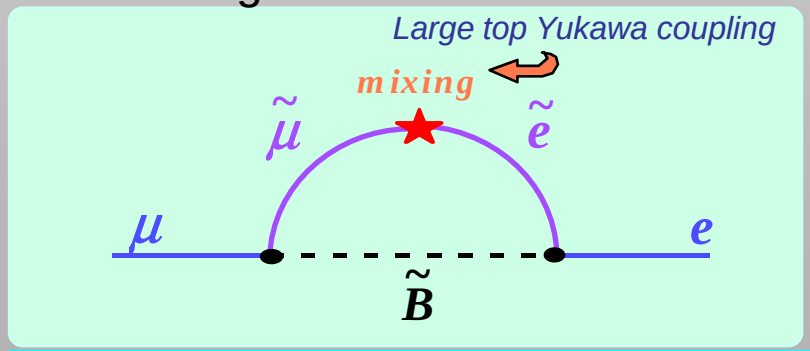
Charged Lepton Mixing (not observed yet)

LFV diagram in Standard Model



Very Small (10^{-52})

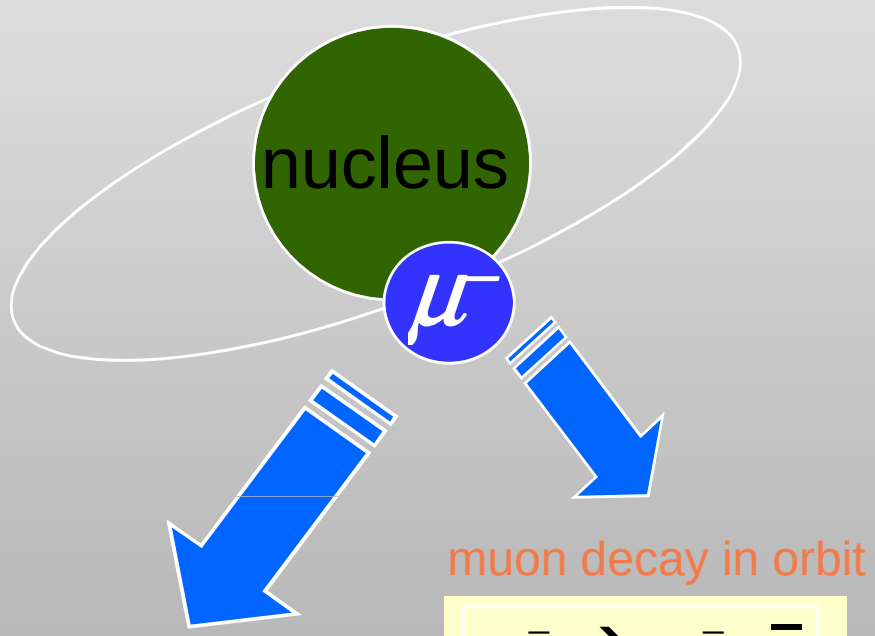
LFV diagram in SUSY



Sensitive to new Physics beyond the Standard Model

What is a μ-e Conversion ?

1s state in a muonic atom



Neutrino-less muon nuclear capture (=μ-e conversion)

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

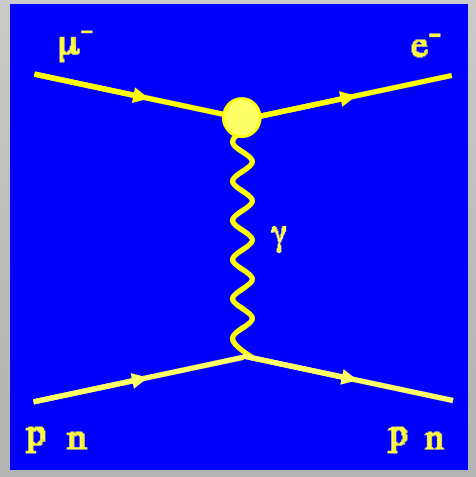
lepton flavors changes by one unit

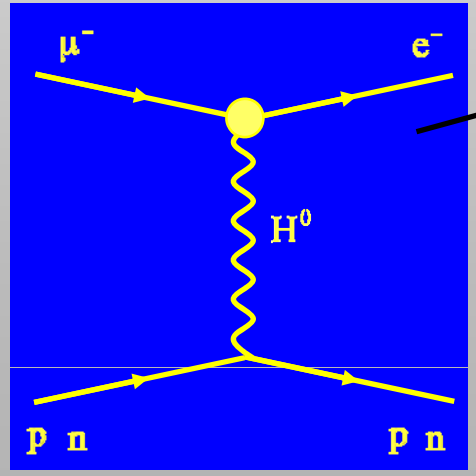
$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Comparison between $\mu \rightarrow e\gamma$ and μ-e Conversion (Physics Sensitivity)

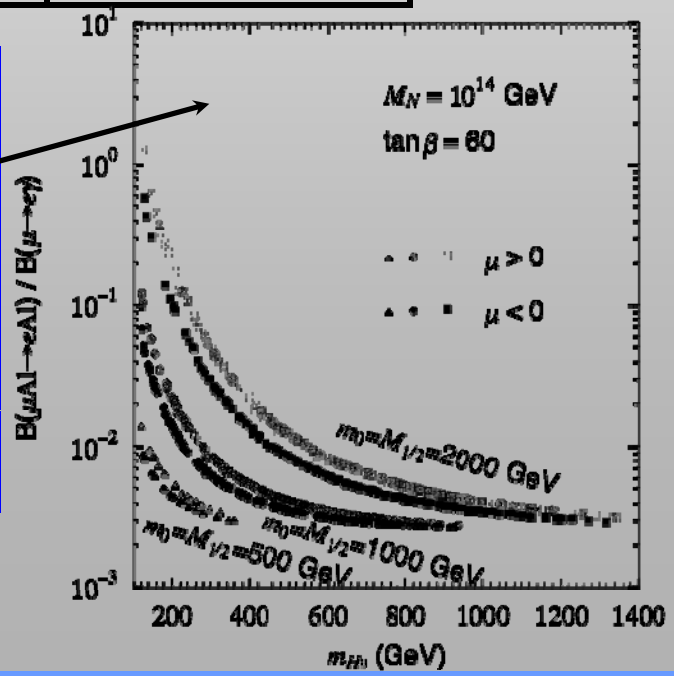
- Photonic and non-photonic (SUSY) diagrams

	photonic	non-photonic
• $\mu \rightarrow e\gamma$	yes (on-shell)	no
• μ-e conversion	yes (off-shell)	yes





$$\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \sim \frac{1}{100}$$

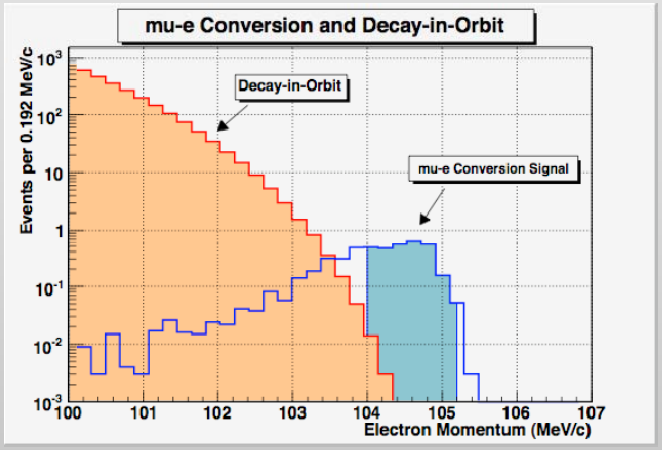


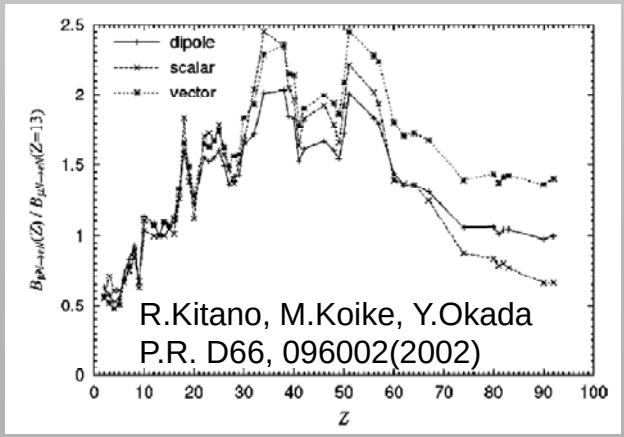
μ-e conversion Signal

- $E_{\mu e} \sim m_{\mu} - B_{\mu}$
  - B_{μ}: binding energy of the 1s muonic atom
- Comparison with μ→eγ (and μ→3e) from the view point of experimental technique

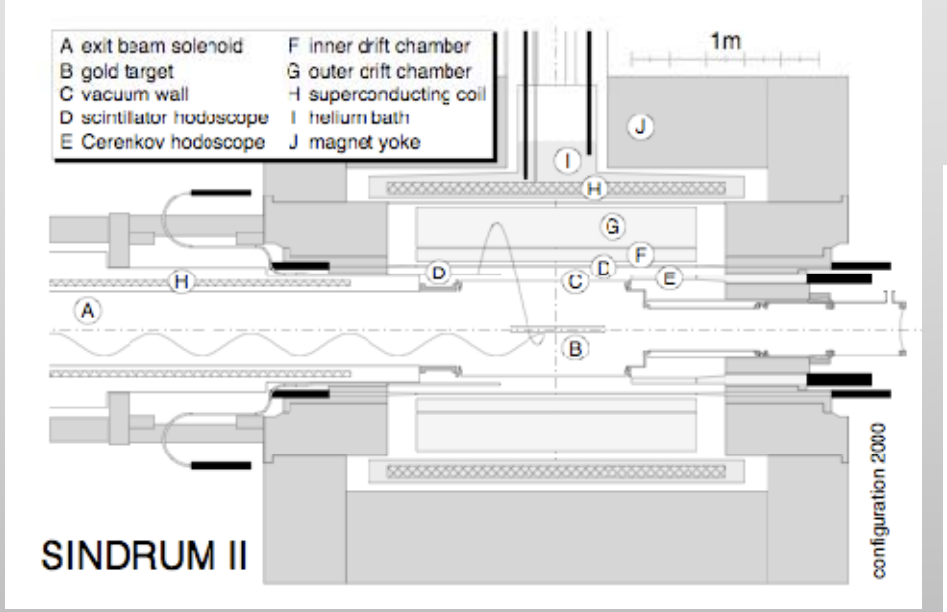
	Background	Challenge
μ→eγ and μ→3e	Accidental	Detector performance resolution, high rate
μ-e conversion	Beam	Beam background

- Improvement of a muon beam can be possible, both in purity (no pions) and in intensity (***thanks to muon collider R&D***). A higher beam intensity can be taken because of no accidentals.
- Potential to discriminate different models through studying the Z dependence



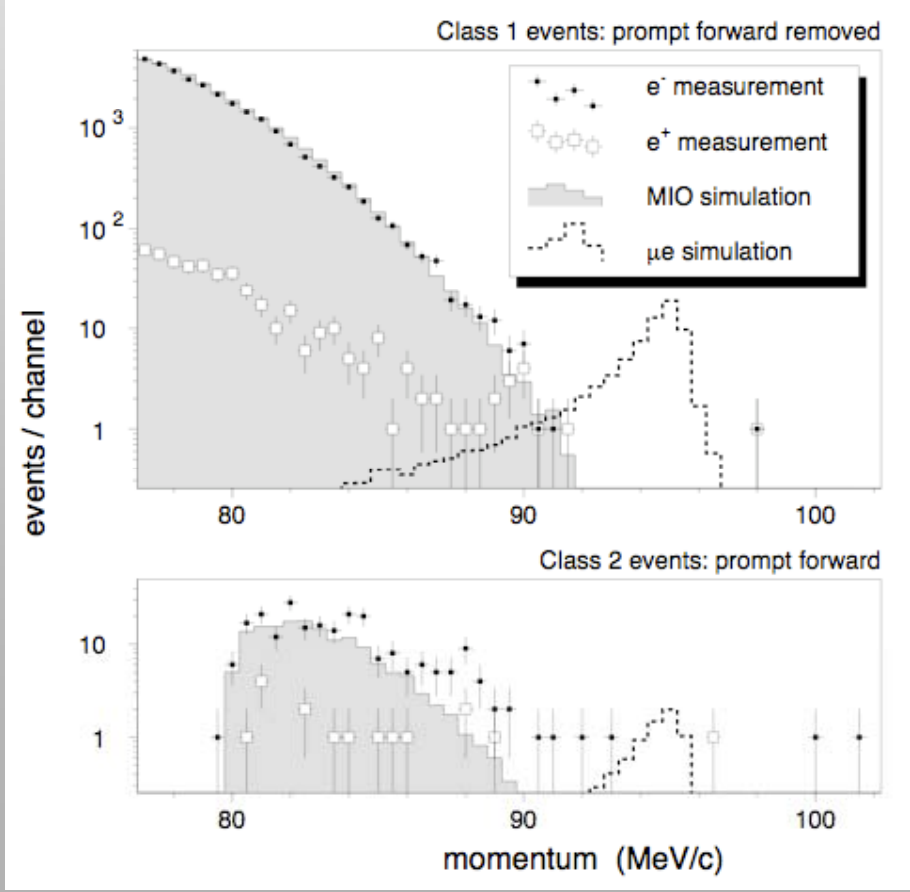


The SINDRUM-II Experiment (at PSI)



Published Results

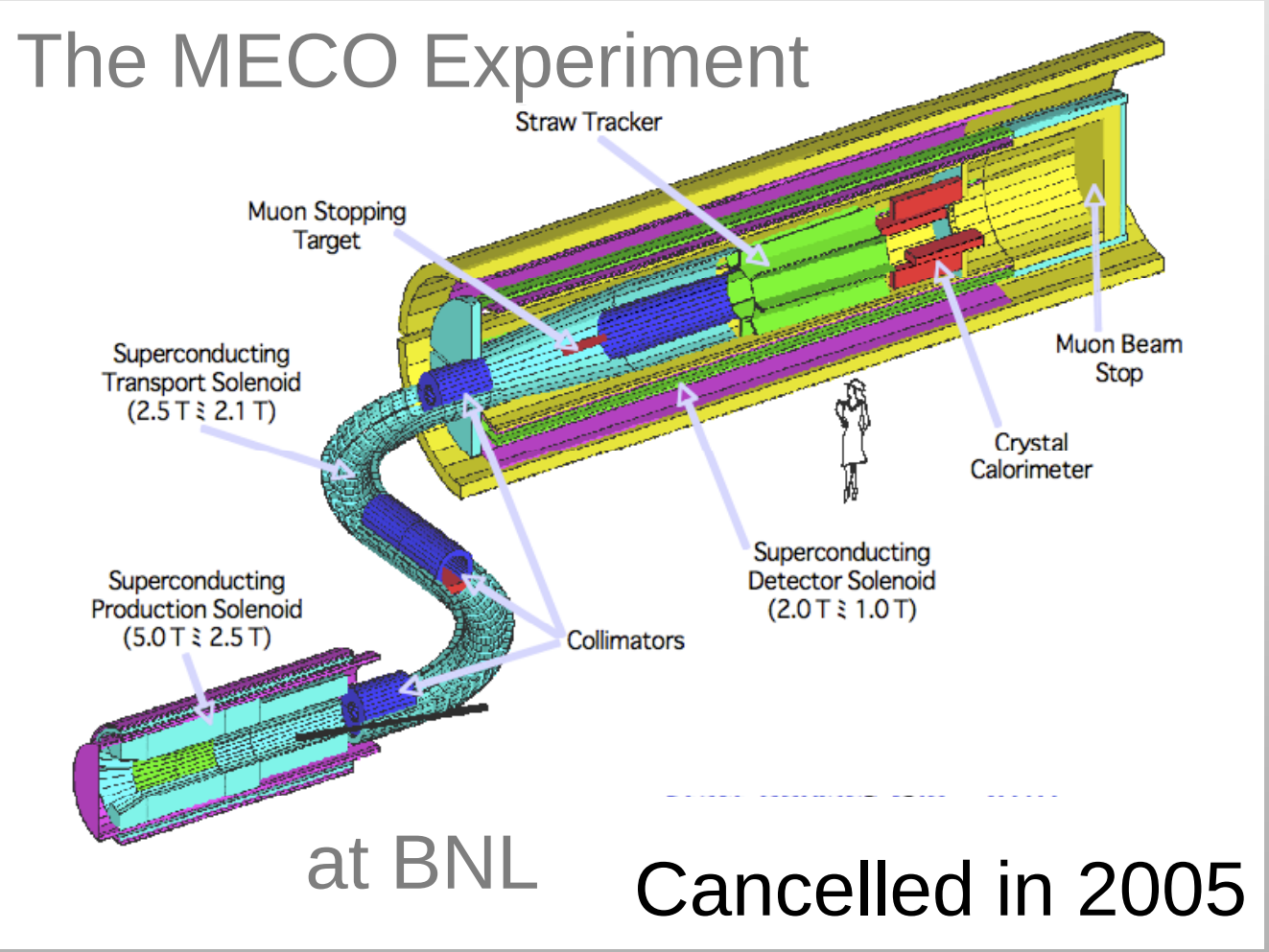
$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



SINDRUM-II used a continuous muon beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed.

The MELC and MECO Proposals

- MELC (Russia) and then MECO (the US)
- To eliminate beam related background, beam pulsing was adopted (with delayed measurement)
- To increase a number of muons available, pion capture with a high solenoidal field was adopted
- For momentum selection, curved solenoid was adopted

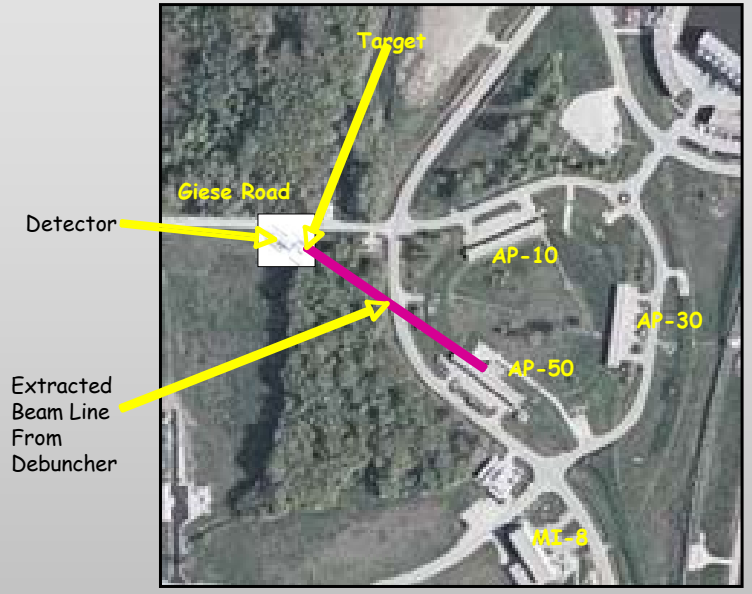


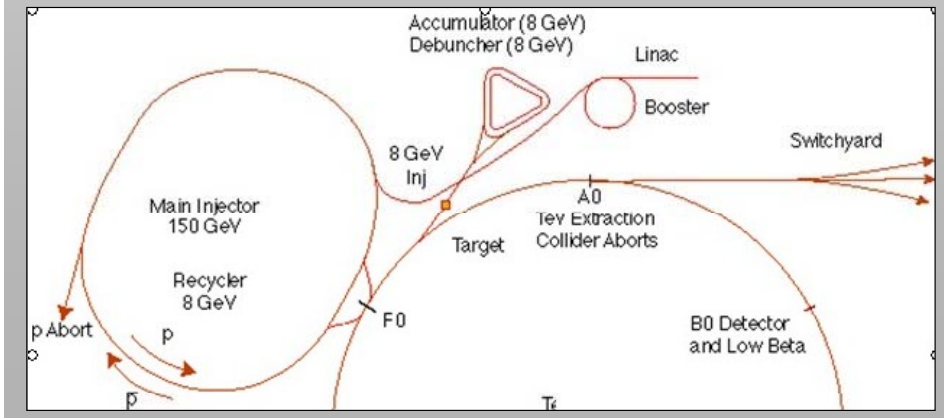
→ mu2e @ Fermilab

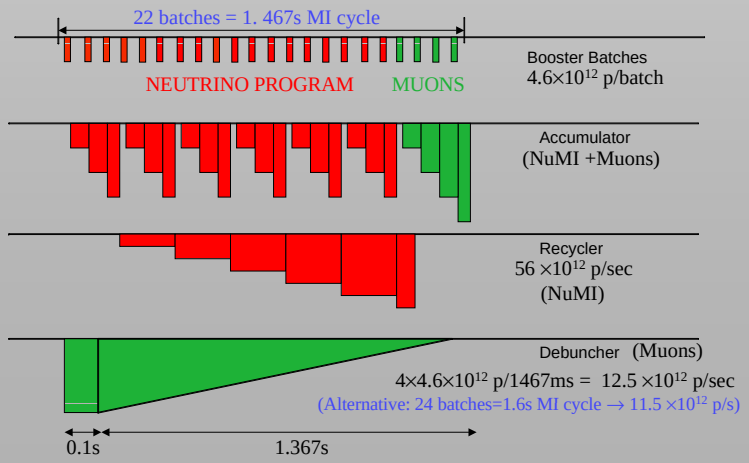
Mu2E @ Fermilab

- The mu2e Experiment at Fermilab.
  - Proposal has been submitted.
  - After the Tevatron shut-down
    - uses the antiproton accumulator ring
    - the debuncher ring to manipulate proton beam bunches

Fermilab Accelerators







cLFV Search Experiment

- cLFV search is as important as ν oscillation measurements to find a clue to understand
  - SUSY-GUT
  - Neutrino See-saw
- MEG result is expected to appear pretty soon
- Need other experiment(s) to confirm it
  - Using “different” physics process (with better sensitivity)!
- COMET (COherent Muon Electron Transittion) submitted a proposal to J-PARC in 2008
  - http://comet.phys.sci.osaka-u.ac.jp/internal/publications/main.pdf

COMET

An Experimental Search For Lepton Flavor Violating

$\mu^- - e^-$ Conversion at Sensitivity of $\mathbf{10^{-16}}$

Collaboration
as of Oct/2008

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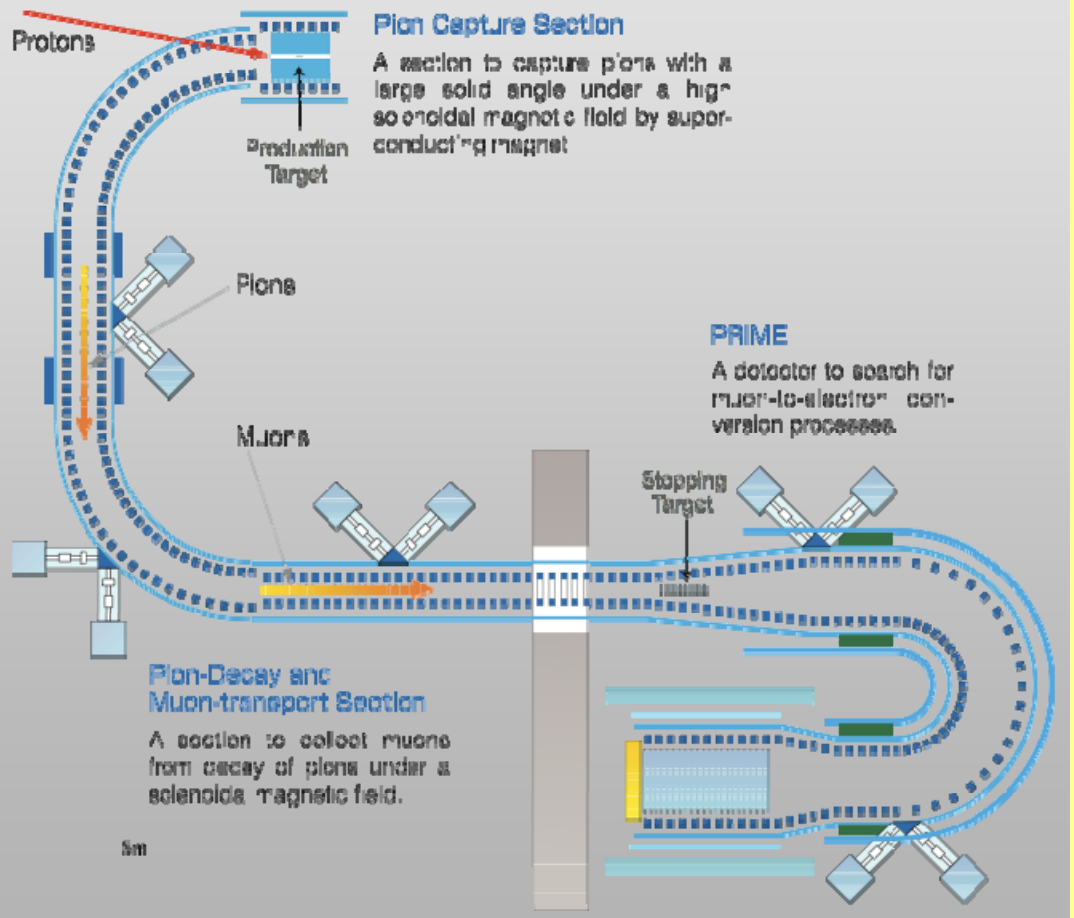
T. Numao
TRIUMF, Canada

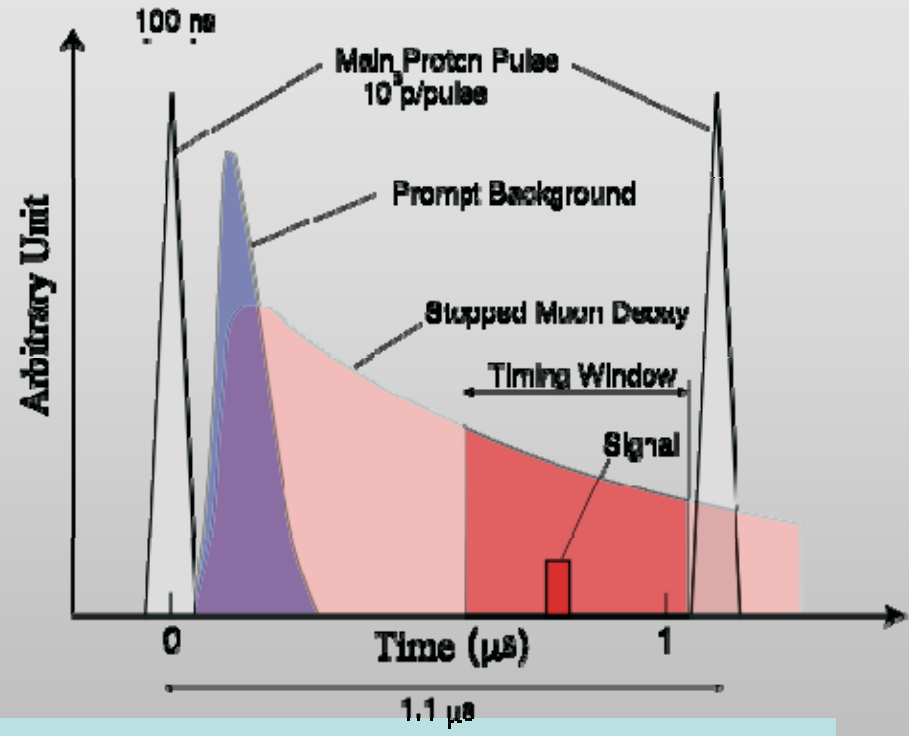
Overview of the COMET Experiment



- Proton Beam
  - $p \rightarrow \pi \rightarrow \mu$
- The Muon Source
  - Proton Target
  - Pion Capture
  - Muon Transport
- The Detector
  - Muon Stopping Target
  - Electron Transport
  - Electron Detection

Requirements for the Muon Beam

- Backgrounds
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - ***Prompt timing → good Extinction!***
  - μ^- decay-in-flight, e^- scattering, neutron streaming
- Requirements from the experiment
  - Pulsed
  - High purity
  - Intense and high repetition rate



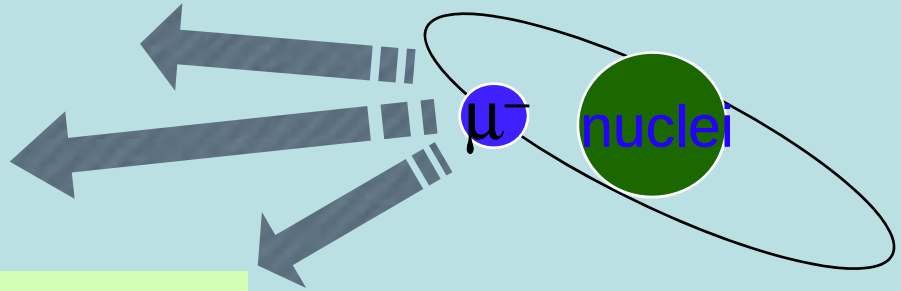
Muon Capture(MC)

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

Muon Decay in Orbit (MDO)

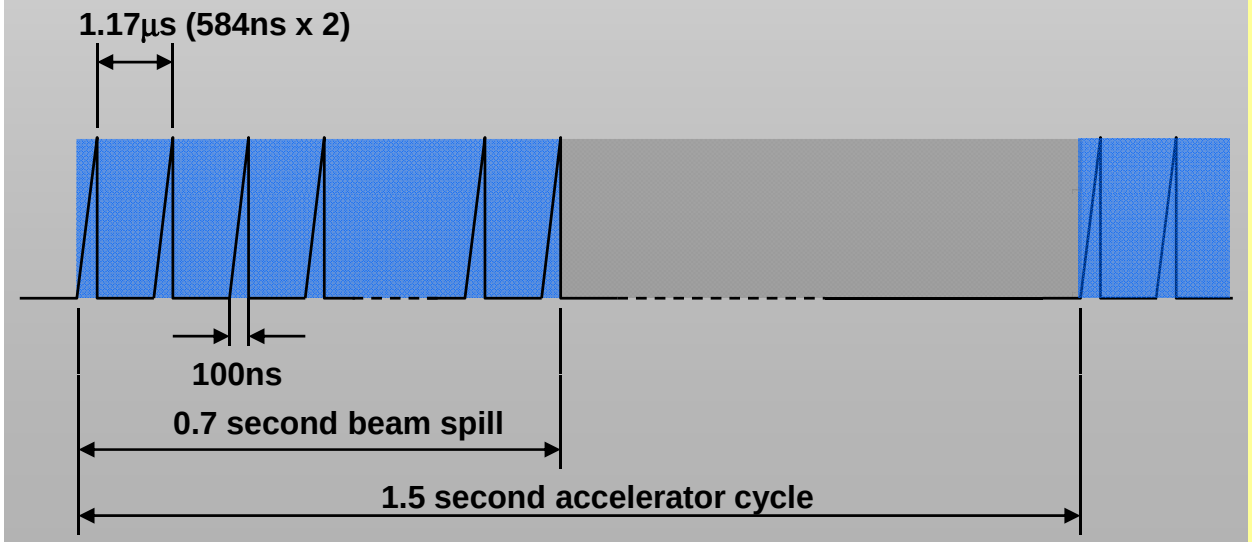
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

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



Requirements for the Proton Beam

- Proton beam structure for the mu-e conversion search
  - 100nsec bunch width, 1.1μsec bunch-bunch spacing
  - 8GeV to suppress anti-proton background
  - < 10^{11} proton/bunch, limited by the detector performance
  - Repetition rate as high as possible within tolerable CR background
- Extinction
  - Residual protons in between the pulses should be < 10^{-9}



N_{bg} =
$NP \times R_{ext} \times Y_\pi/P \times A_\pi \times P_\gamma \times A$

NP : total # of protons (~10^{21})
R_{ext} : Extinction Ratio (10^{-9})
Y_π/P : π yield per proton (0.015)
A_π : π acceptance (1.5×10^{-6})
P_γ : Probability of γ from π (3.5×10^{-5})
A : detector acceptance (0.18)

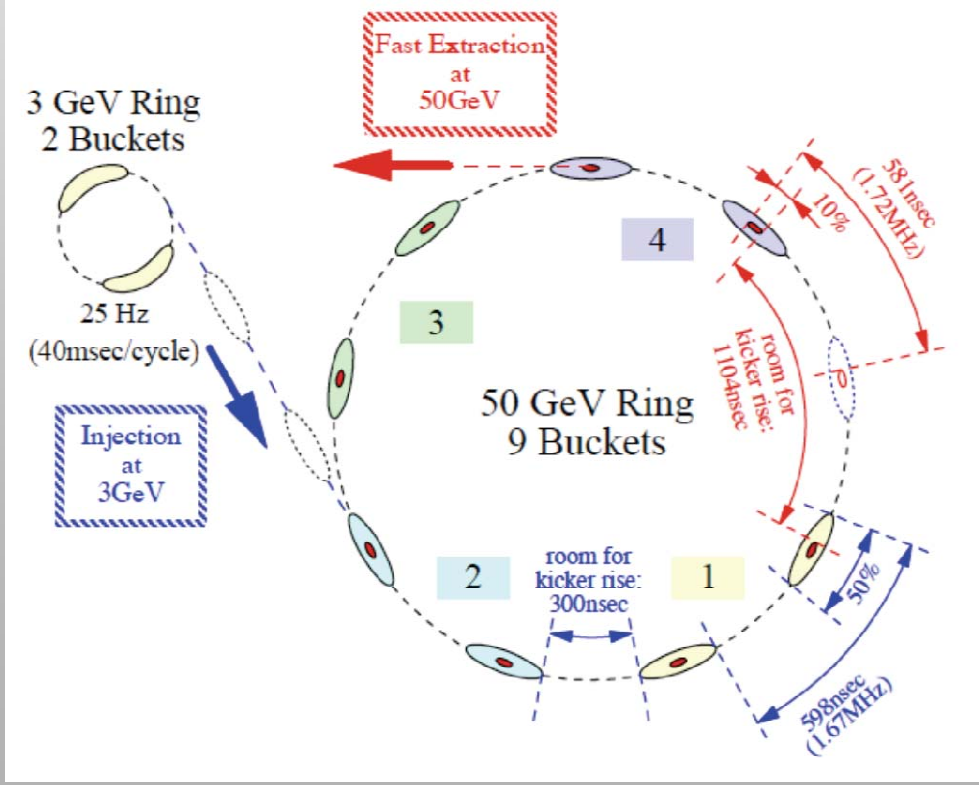
BR=10^{-16}, N_{bg} < 0.12 →

Extinction < 10^{-9}

Proton Acceleration at J-PARC

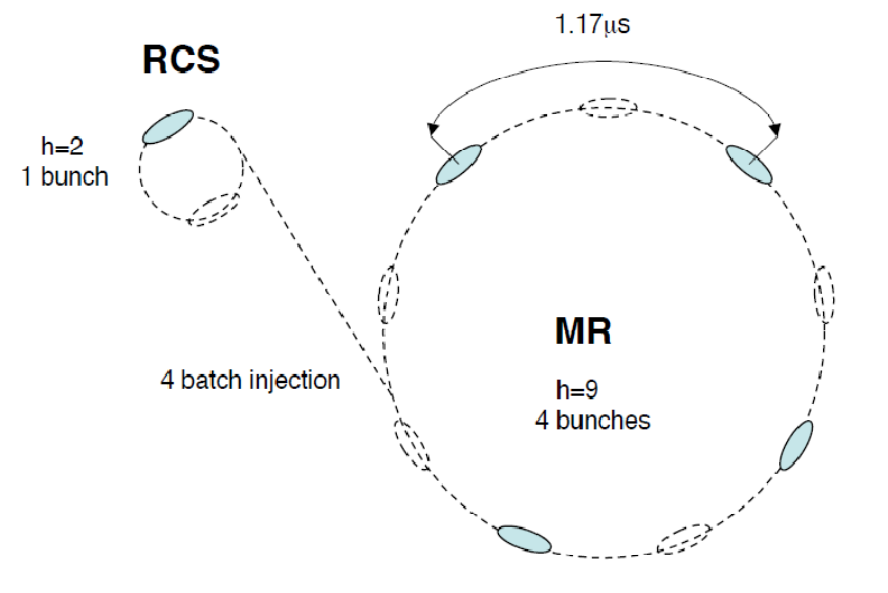
- Proton acceleration in
  - LINAC
  - Booster (RCS)
  - Main Ring
- Nominal scheme
  - RCS: h=2
  - MR:h=9
    - 8 buckets filled
    - 1 empty bucket, used for kicker excitation
- MR RF cavities are designed for this scheme
  - h=18 optional by removing capacitors on cavities
  - Need long shutdown to change the configuration

8 filled buckets out of 9 buckets

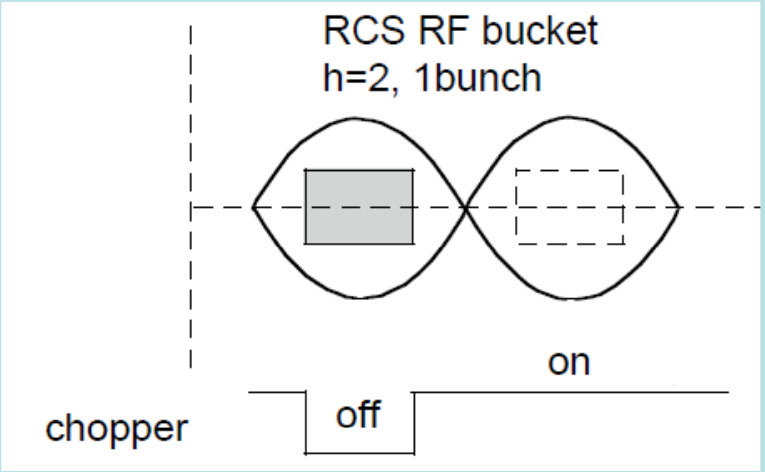


Proton Acceleration for COMET
Proposed Scheme (I)

- RCS: h=2 with one empty bucket
- MR:h=9 with 5 empty buckets
- Bunched slow extraction
  - Slow extraction with RF cavity ON, 210kV



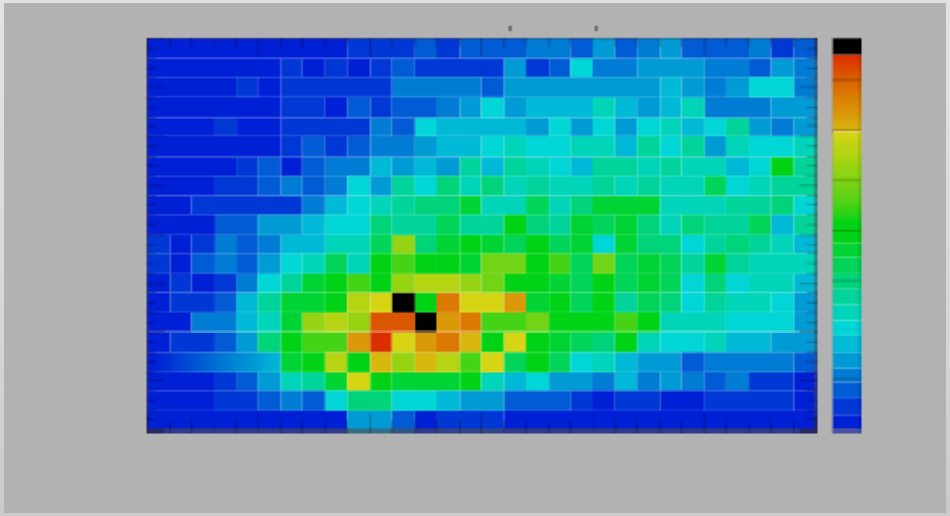
Realization of an empty bucket in RCS by using the chopper in Linac

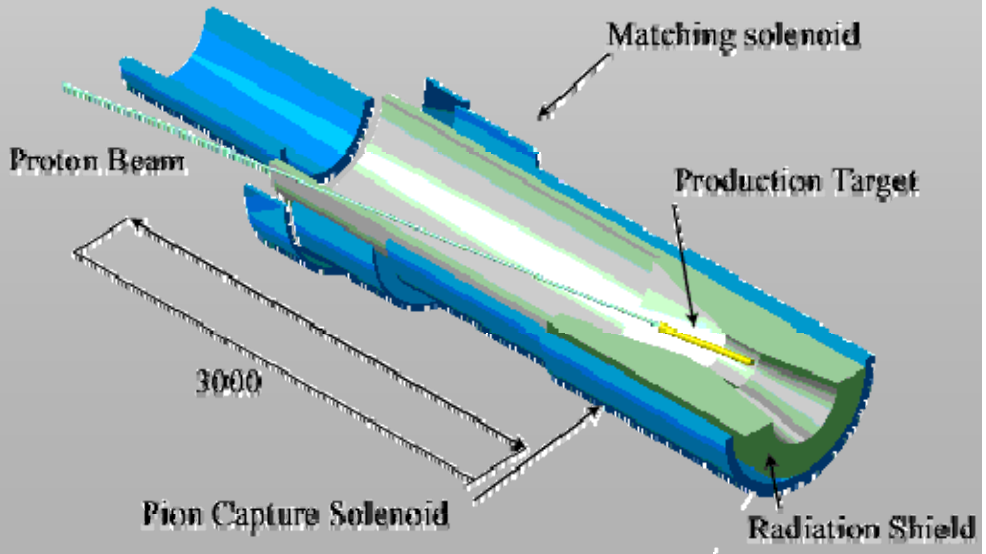


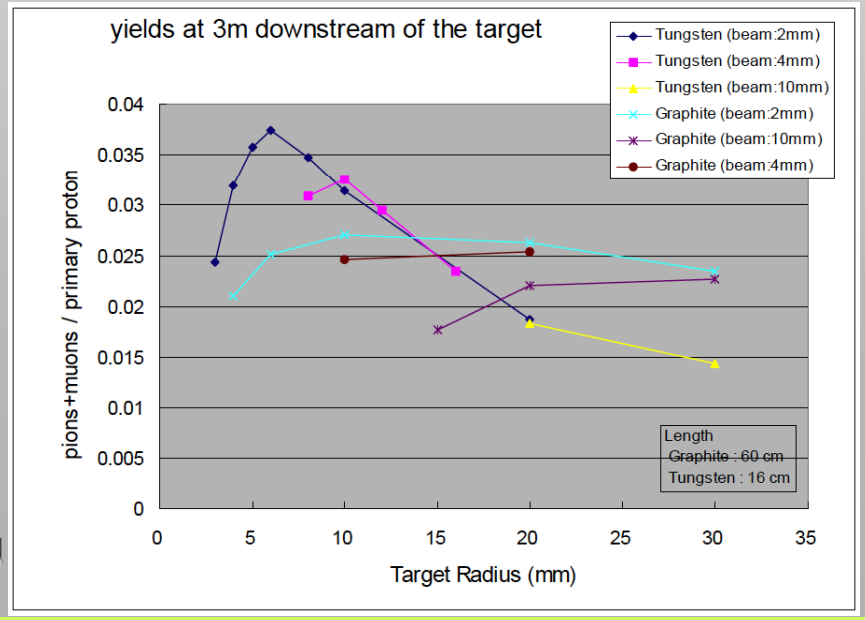
- Simple solution
  - No need of hardware modification
- Heavier heat load in the scraper
- Possible leakage of chopped beam in empty buckets

Pion Production Target

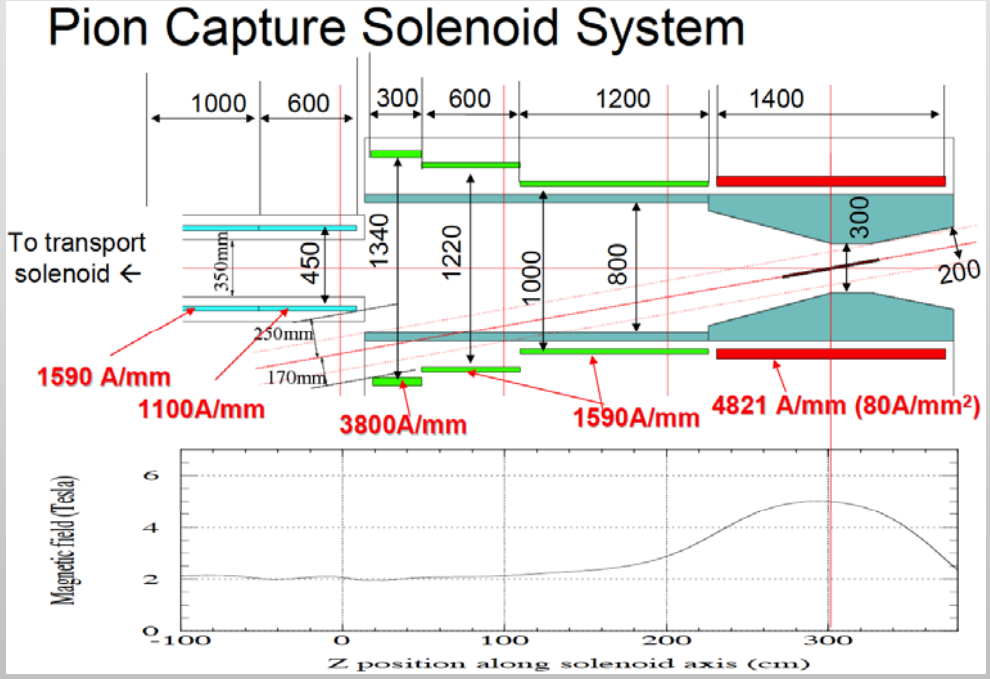
- **low-E pions**
  - **for low-E muons to stop**
  - **Backward extraction**
- **pion yield is proportional to T_{proton}**
  - **pion yld is proportional to Beam Power**
- **High-Z Metal Rod**
  - **12-mmϕ x 16-cm**
  - **3-4 kW on the target**
  - **Water cooling or Radiation cooling**

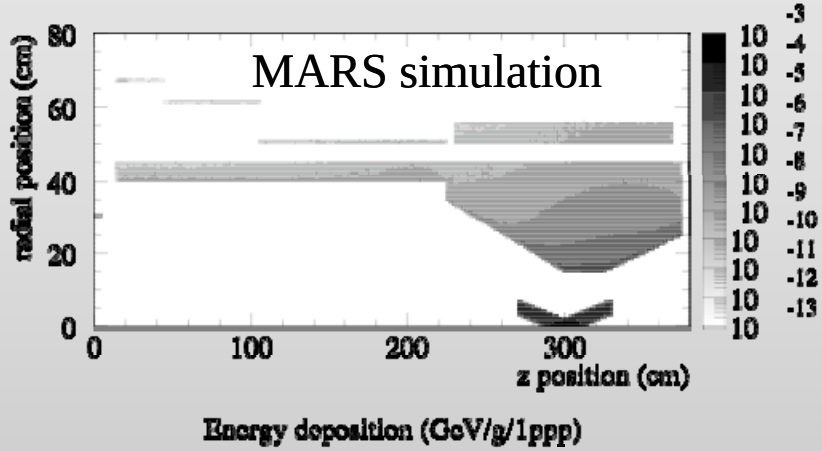


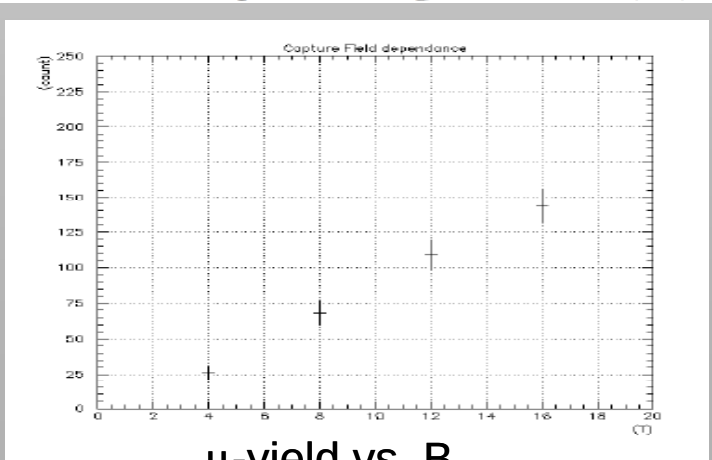




Pion Capture





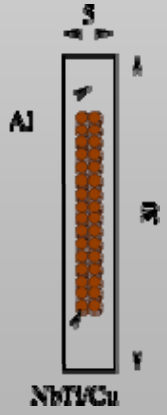


μ-yield vs. B_{max}

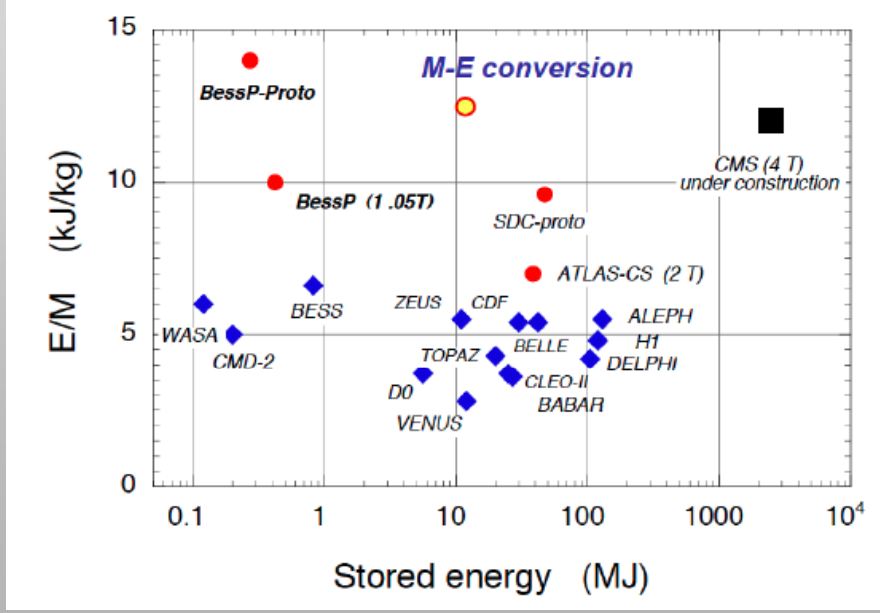
- 5 T at the target position
  - capture p_t < 120 MeV/c
- Radiation Shield
  < 100 W on SC coil
  - 3-4 kW @ target
  - 35 kW @ W Shield
  - 2×10^{-5} W/g @ coil
- Yields
  - 0.05(π+μ)/8-GeV-proton

π-Capture Solenoid

- Heat-load density : 2 x 10^{-5} W/g behind W shield
- Utilize Al stabilized SC cable to reduce a heat load to the cold mass.
  - 2-layers x 3-cm^t Al SC coil : 10 W
    »(20cm-Cu SC coil : 1 kW)
    - B = 5T
    - 80 A/mm^2
    - load line ratio: 0.63
  - 12.3 MJ, 12.5 kJ/kg

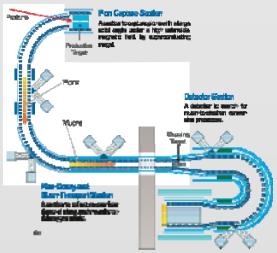


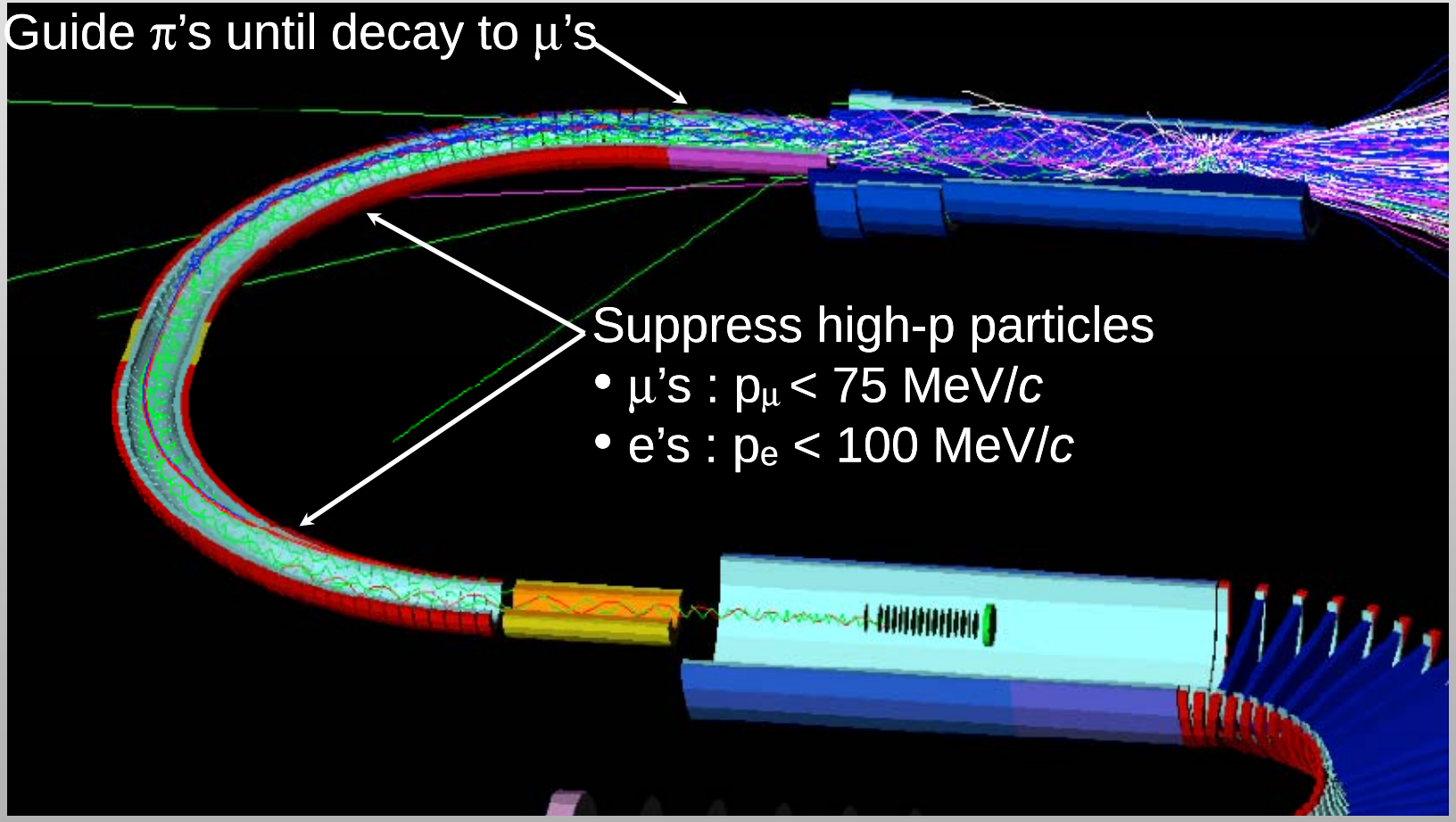
30 mm x 5 mm
NbTi
1.28 mm diameter
32 strands
NbTi: Cu: Al = 19%: 34%: 46%
density: 4.0 g/cm^3



Al-SC: one of world leading expertise of KEK

Muon Transport



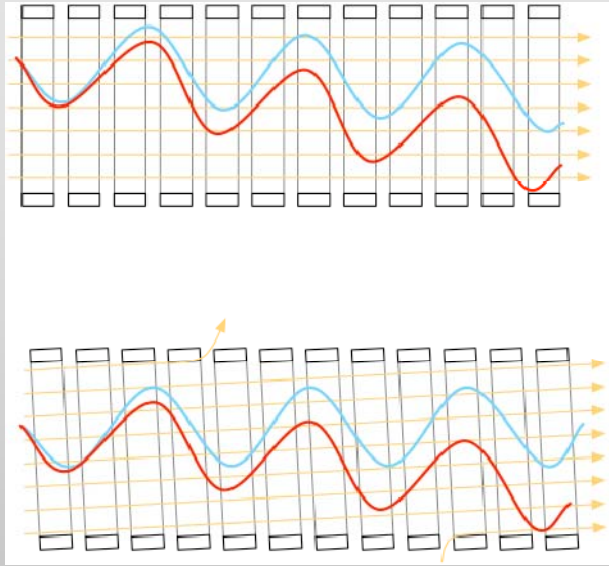


High-p Suppression

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

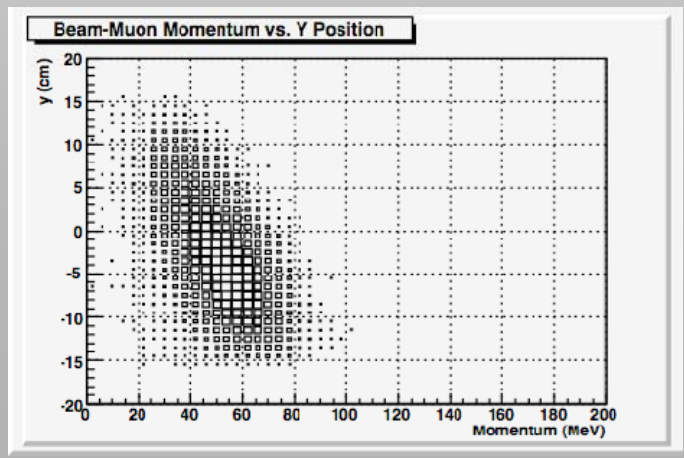
$$D[m] = \frac{1}{0.3 \times B[T]} \times \frac{s}{R} \times \frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}$$

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



See “Classical Electrodynamics”, J.D.Jackson Ch.12-Sec.4

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



$\delta p/\delta x$ = 1 MeV/c/cm

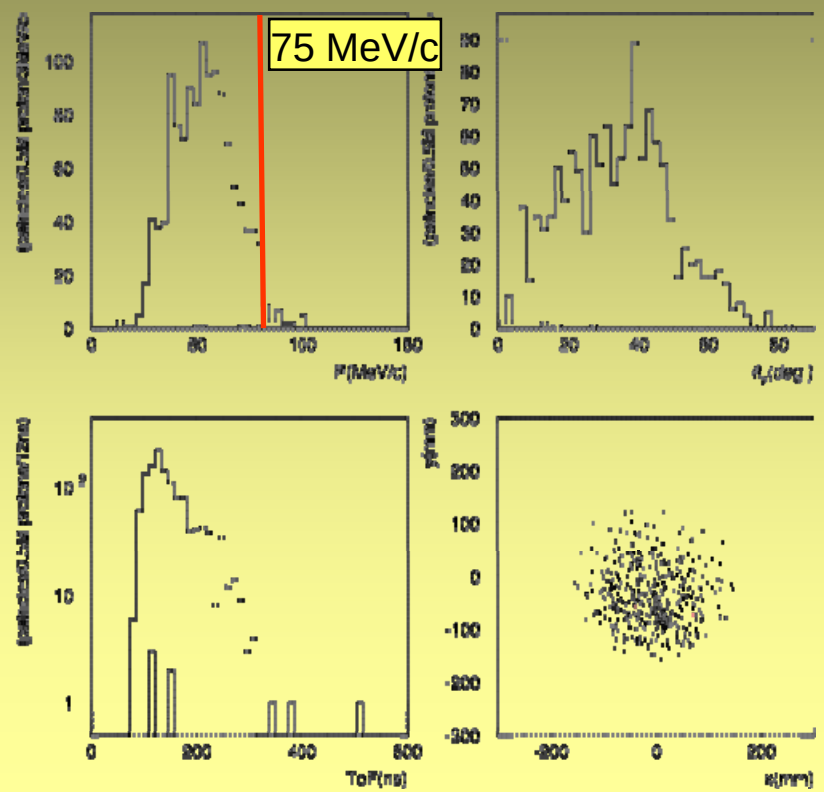
Spectra at the End of the Muon Transport

- Preliminary beamline design
  - main magnetic field
  - compensation field
  - radius of magnets (200 mm)
- Transport Efficiency

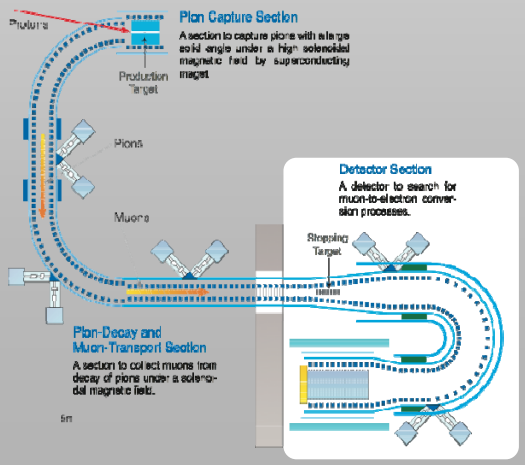
# of μ /proton	0.0071
# of stopped muons/proton	0.0018
# of μ of p_μ >75 MeV/c /proton	2×10^{-4}

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.



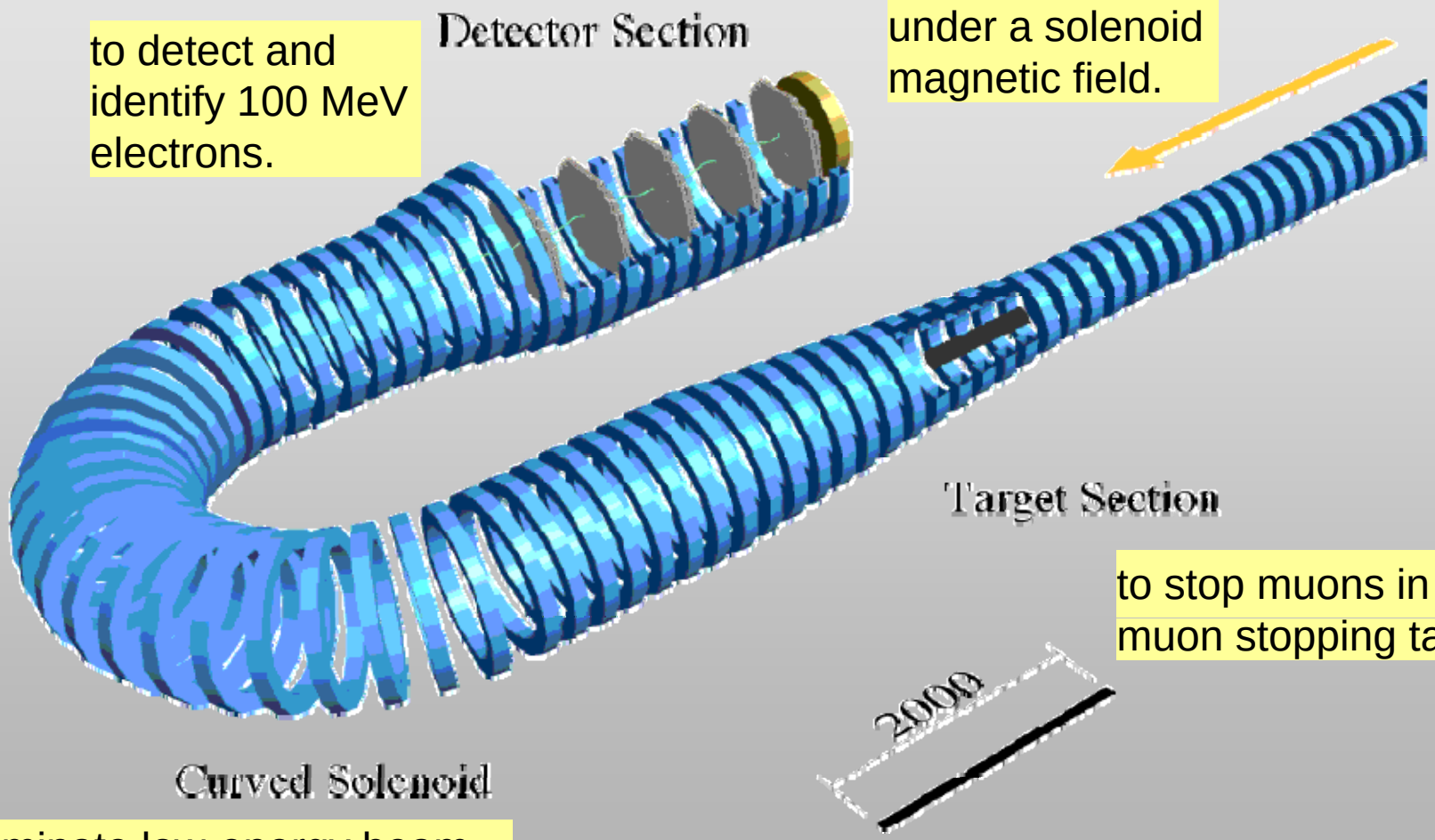
The COMET Detector



The COMET Detector

to detect and identify 100 MeV electrons.

under a solenoid magnetic field.

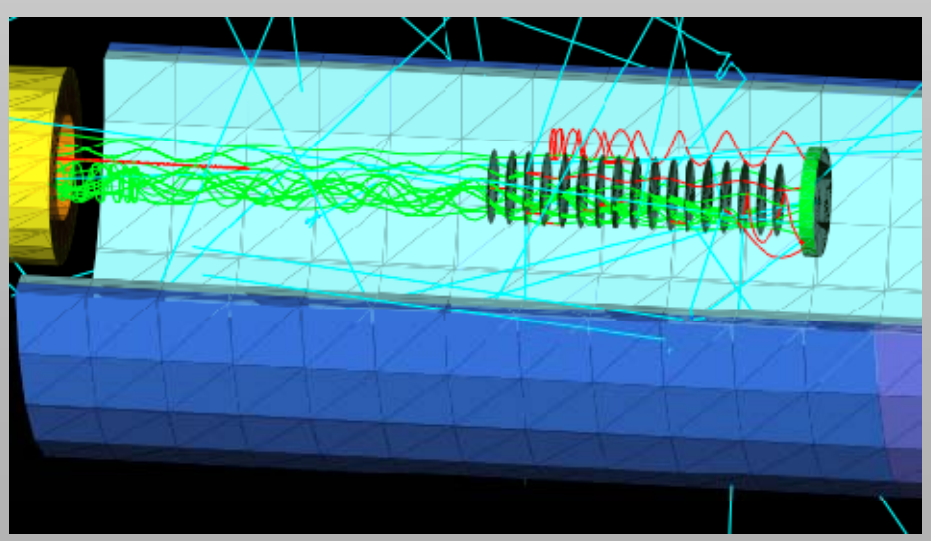


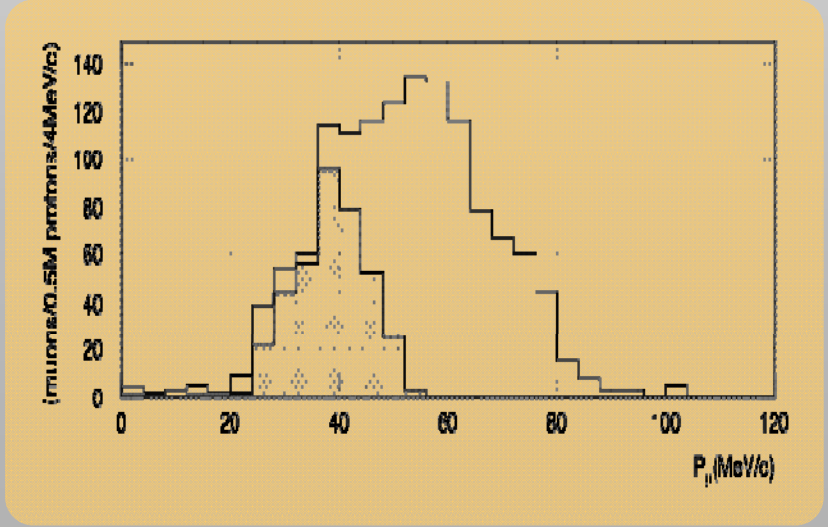
to stop muons in the muon stopping target

to eliminate low-energy beam particles and to transport only ~100 MeV electrons.

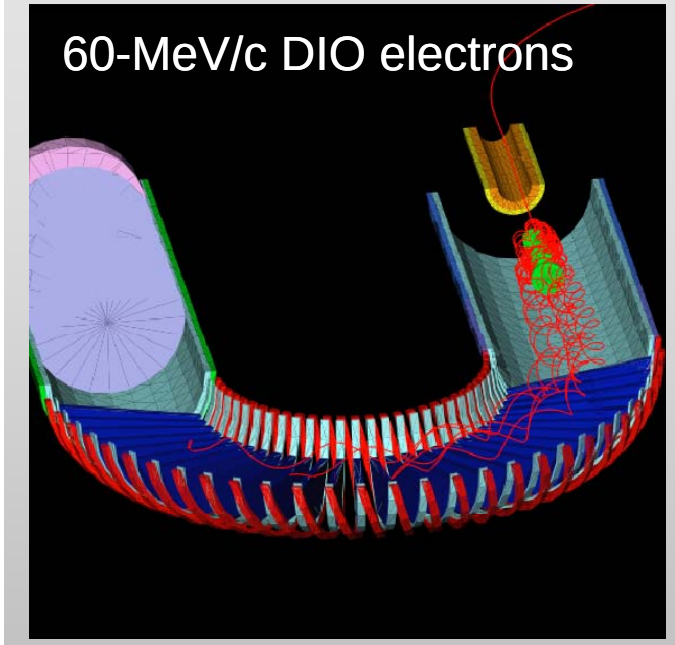
Muon Stopping Target

- Light material for delayed measurement
  - Aluminum : τ_{μ^-} = 0.88 μs
- Thin disks to minimize electron energy loss in the target
  - R = 100 mm, 200μm^t, 17 disks, 50 mm spacing
- Graded B field for a good transmission in the downstream curved section.
- Good μ-Stopping efficiency: ε=0.3
  - stopped-muon yields:~0.002 μ's/proton





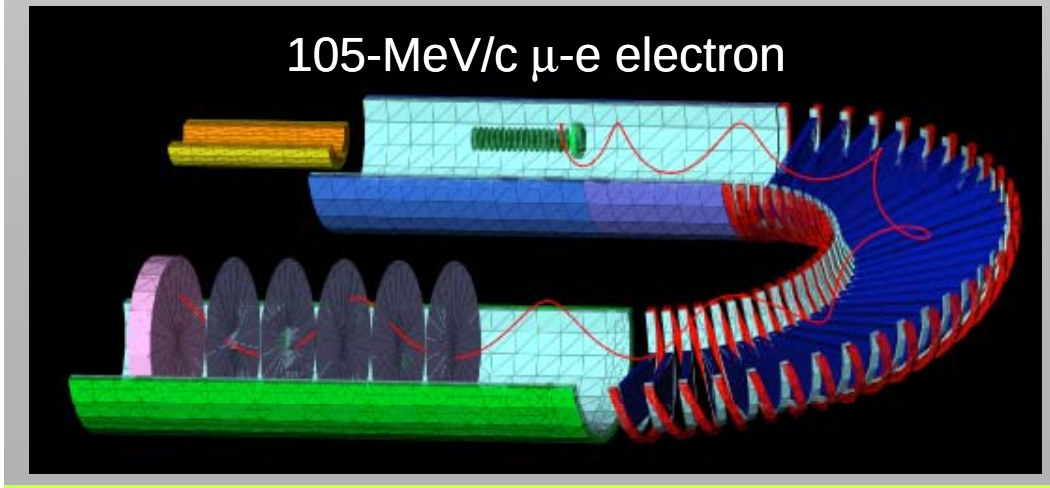
Curved Solenoid Spectrometer

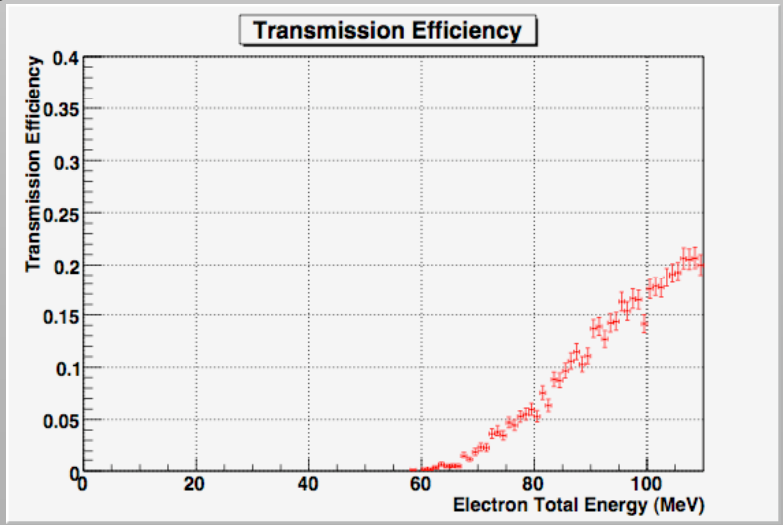


- Torus drift for rejecting low energy DIO electrons.

$$D[m] = \frac{1}{0.3 \times B[T]} \times \frac{s}{R} \times \frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}$$

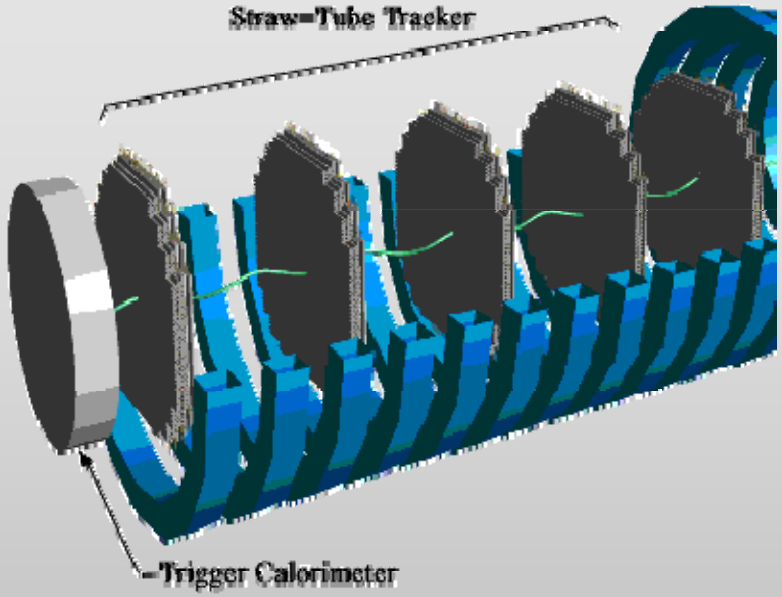
  – rejection ~10^{-6}: < 10kHz
- Good acceptance for signal electrons
  – 20%

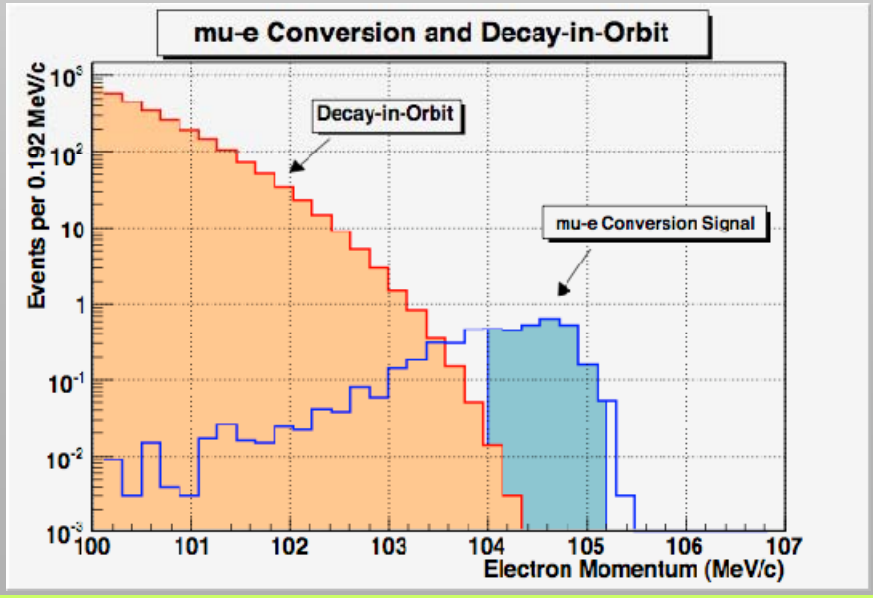


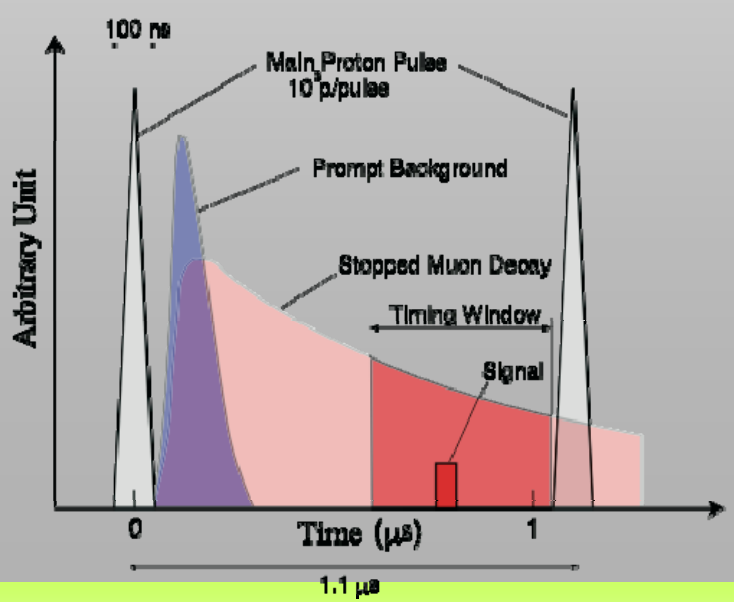


Electron Detectors

- Rate < 10-100 kHz
- Straw-tube tracker to measure electron momentum
  - 5 Planes with 48cm distance, σ_p = 230 keV/c
    - One plane has 2 views (x and y) with 2 layers per view.
    - A straw tube has 25mm thick, 5 mm diameter.
  - should work in vacuum and under a magnetic field.
  - 250μm position resolution.
- Crystal calorimeter for Trigger
  - GSO or PWO

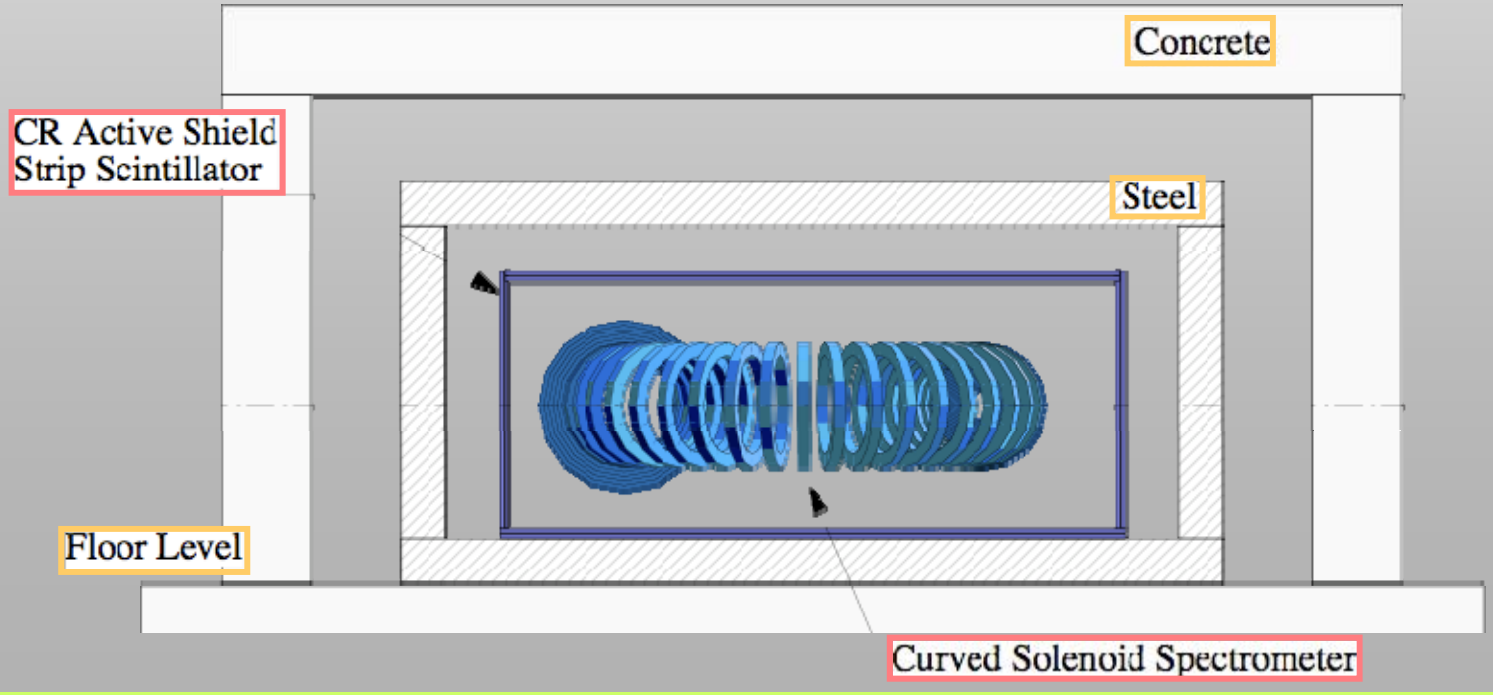






Cosmic Ray Shields

- Both passive and active shields are used
- Passive shields
  - 2 meter of concrete and 0.5 m thick of steel
- Active shields
  - layers of scintillator veto counters (~1% inefficiency)



Signal Sensitivity

2×10^7 sec running

- Single event sensitivity

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

  - N_μ is a number of stopping muons in the muon stopping target. It is 1.5×10^{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	8×10^{20}
muon transport efficiency	0.0071
muon stopping efficiency	0.26
# of stopped muons	1.5×10^{18}

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

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

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)

Intrinsic Background (from muons)

- Muon Decay in Orbit
  - Electron spectrum from muon decay in orbit
  - Response function of the spectrometer included.
  - 0.05 events in the signal region of 104.0 - 105.2 MeV (uncorrected).

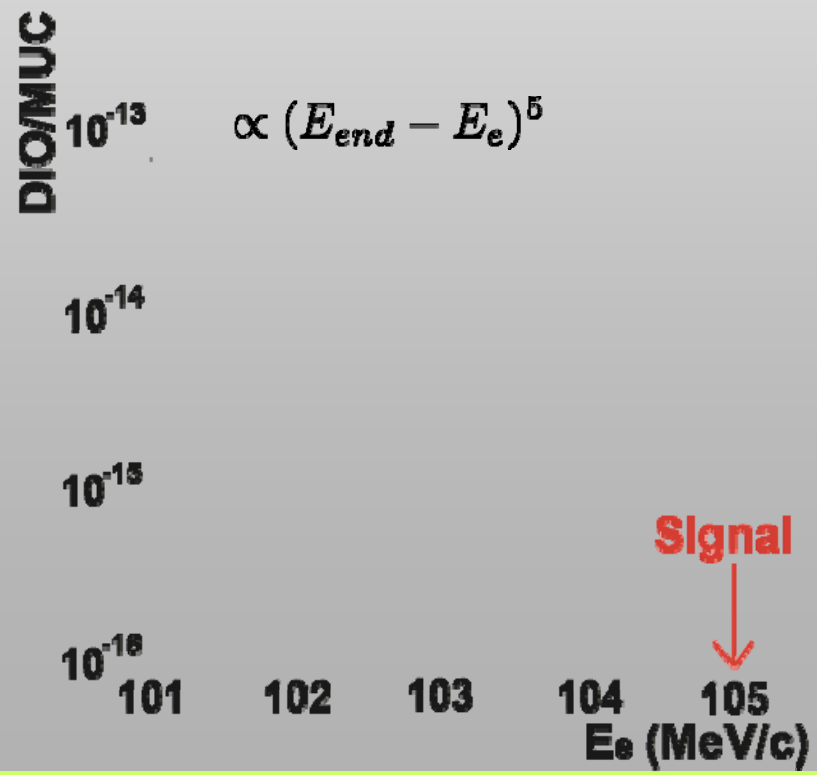
- Radiative Muon Capture with Photon Conversion

$$\mu^- + Al \rightarrow \nu_\mu + Mg + \gamma$$

  - Max photon energy 102.5 MeV
  - < 0.001 events

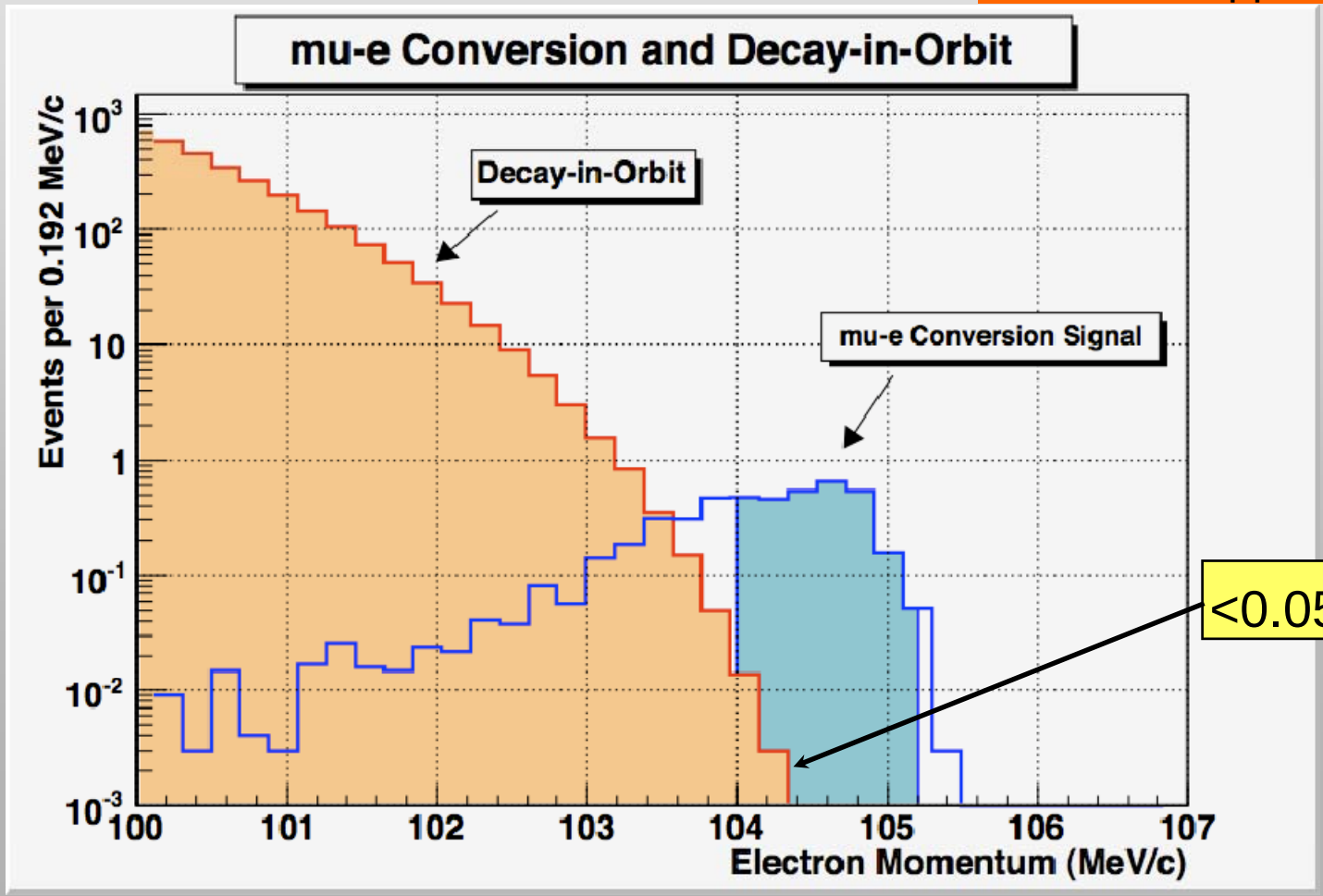
- Muon Capture with Neutron Emission
- Muon Capture with Charged Particle Emission
  - <0.001 events for both.

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.



DIO Background

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



<0.05 events

Beam Related Background Rejection

Rejection of beam related (prompt) backgrounds can be done by a combination of the following components.

Momentum Selection at the Muon Transport
(p_μ < 75 MeV/c)

Electron Energy Cut
(104.0 - 105.2 MeV uncorrected)

Electron Transverse Momentum Cut
(p_T> 52 MeV/c)

Timing Cut and Beam Extinction
(10^{-9})

Beam Channel Length
(pion decay)

Beam Related Backgrounds (and CR)

$8x10^{20}$ protons

- Radiative Pion Capture
  - pion prod. rate : $1x10^{-5}$
  - pion survival : $2x10^{-3}$
  - E_e>104 MeV with conversion : $6.3x10^{-6}$
  - beam extinction : 10^{-9}
  - 0.12 events at 10^{-16}.
- Muon Decay in Flight
  - p_μ>77 MeV/c : $2x10^{-4}$/proton
  - muon decay prob. : $3x10^{-2}$
  - E_e>104 MeV & p_t> 52MeV/c : <10^{-8}
  - beam extinction : 10^{-9}
  - total is 0.02 events at 10^{-16}.
- Pion Decay in Flight
  - $\pi \rightarrow e\nu$ branching ratio : 10^{-4}
  - p_π>60MeV/c to make E_e>104MeV:$5x10^{-6}$ /proton
  - E_e>104 MeV & p_t> 52MeV/c : $5x10^{-6}$
  - beam extinction : 10^{-9}
  - <0.001 events at 10^{-16}
- Beam Electrons
  - p_e>100 MeV/c : 10^{-8}/proton
  - scat. prob. : 10^{-5}
  - beam extinction : 10^{-9}
  - 0.08 events at 10^{-16}

- Neutron induced
  - neutrons through beamline.
  - E_n>100 MeV : $3x10^{-7}$/proton
  - E_e>100 MeV : 10^{-7}
  - beam extinction : 10^{-9}
  - 0.024 events at 10^{-16}.
- Antiproton induced
  - eliminate high-energy antiprotons by curved solenoid.
  - absorb low-energy antiprotons by 120 μm beryllium foil placed in the middle of beamline.
  - eliminate backgrounds from antiproton annihilation above.
  - 0.007 events at 10^{-16}.

- Cosmic ray Background
  - eliminate by passive and active shields.
  - 10^{-4} veto inefficiency assumed.
  - 0.04 events for $2x10^{7}$ sec (a duty factor 0.2)

Background Rejection Summary

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV/c 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	

BG with asterisk needs beam extinction.

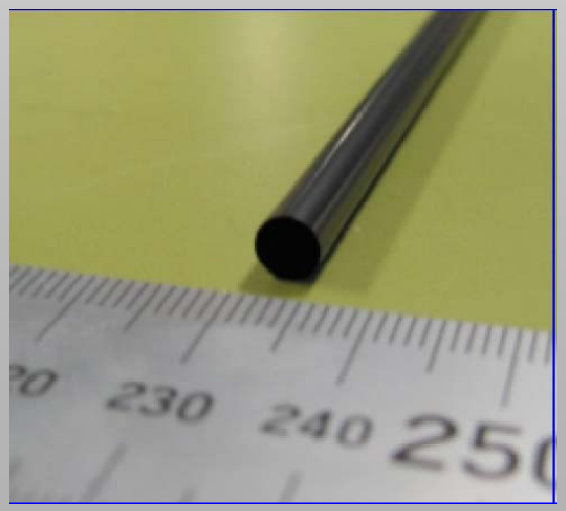
R&D Status

R&D Status

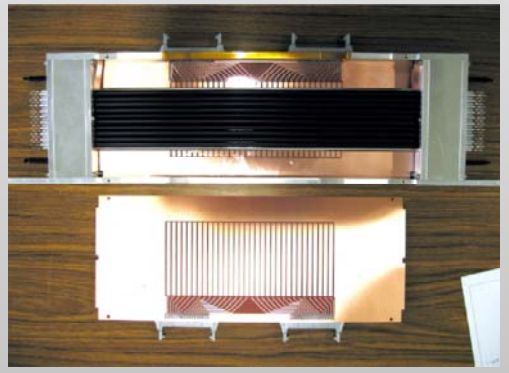
- Straw-tube tracker
  - Done by Osaka group for MECO
- Crystal calorimeter
- Transport Solenoid
- Extinction Measuring Device R&D
  - Gas Cherenkov + Gated PMT
- Extinction measurement at J-PARC MR

Straw-tube Tracker R&D

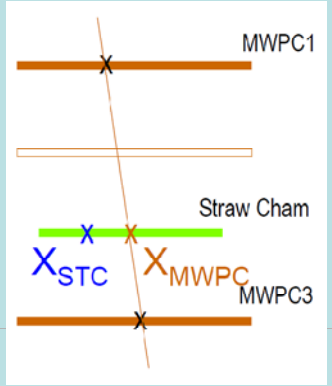
- ***Seamless type tube (I.S.T.)***
  - **Thickness : 25 μm**
  - **Diameter : 5mm**
  - **Material : polyimide+carbon**
  - **Resistance : 6MΩ/sq**

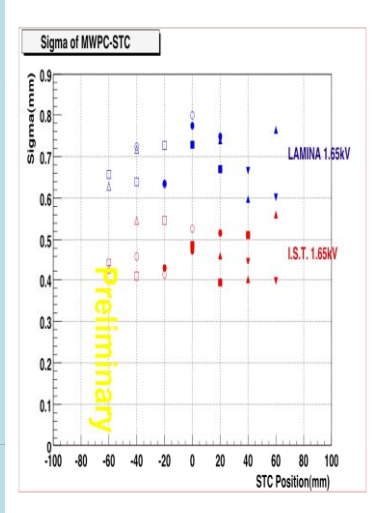


- ***Prototype Straw-tube chamber***



Beam test using 2.0GeV/c pion beam in 2002

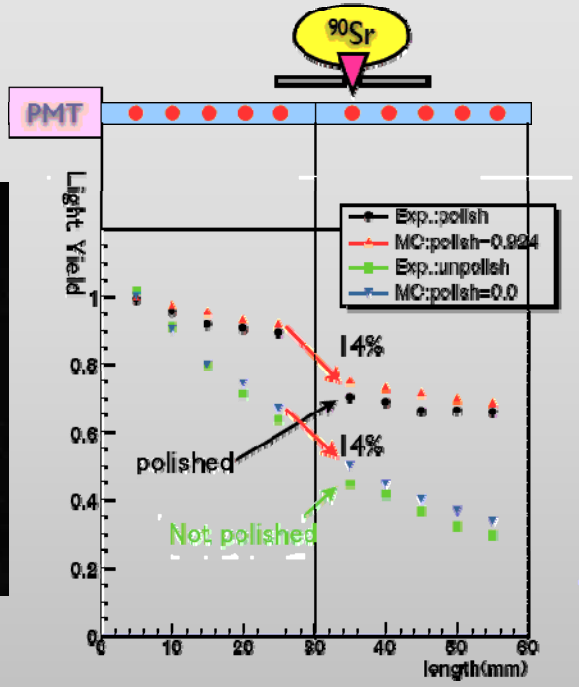


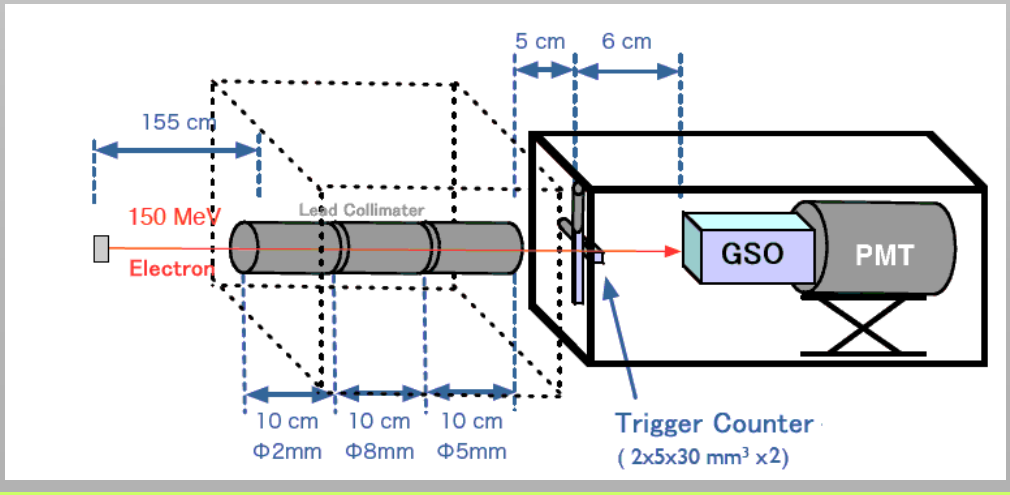


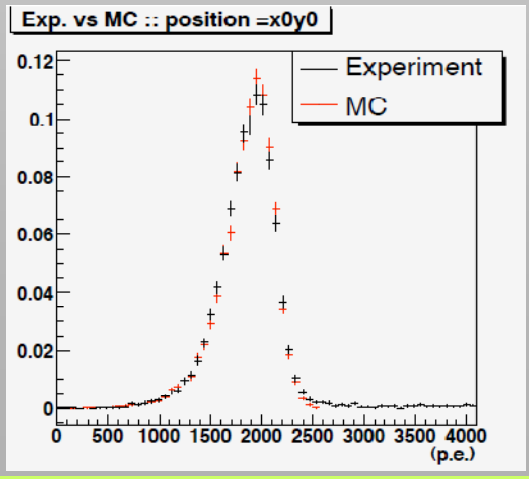
Calorimeter R&D

- GSO crystal for PET use
  - Stack in 3D
  - Light loss across the connection
- Agreement btw data & MC
- Need further study
  - Stacking method
  - Readout
  - Radiation hardness?

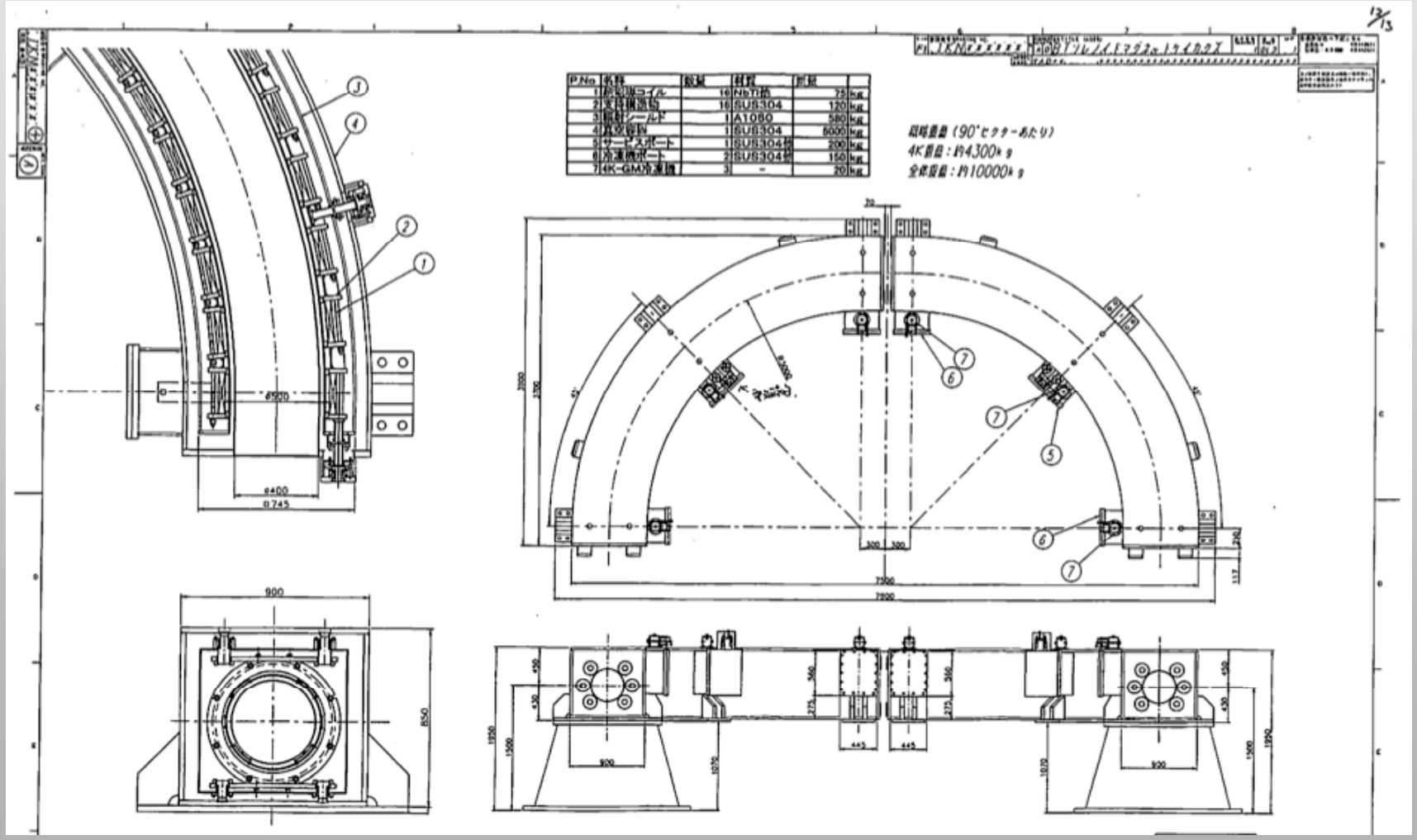
30mm x 32mm x 120mm
Stack of 5 x 8 x 4 crystals





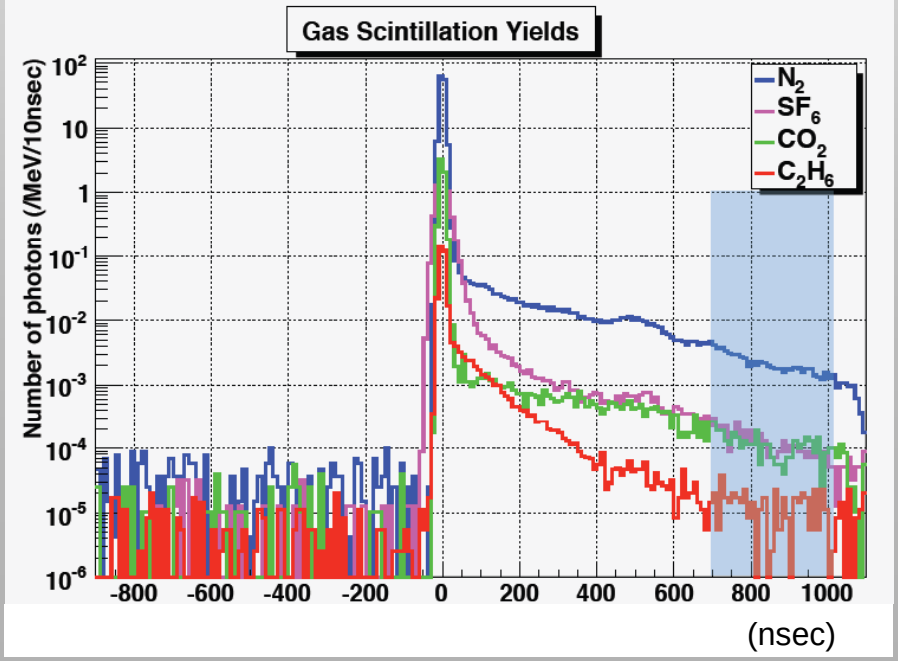


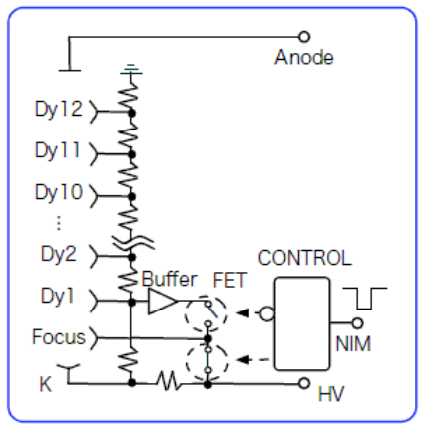
Transport Solenoid Design

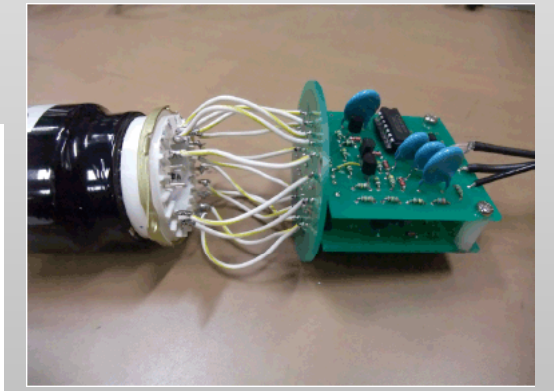


Extinction Measuring Device

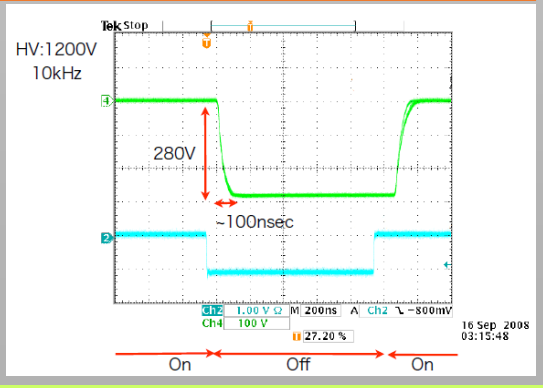
- Monitor extinction level online by using a Gas Cherenkov detector with gating PMTs
  - Blind to proton beam core, active only in between proton pulses







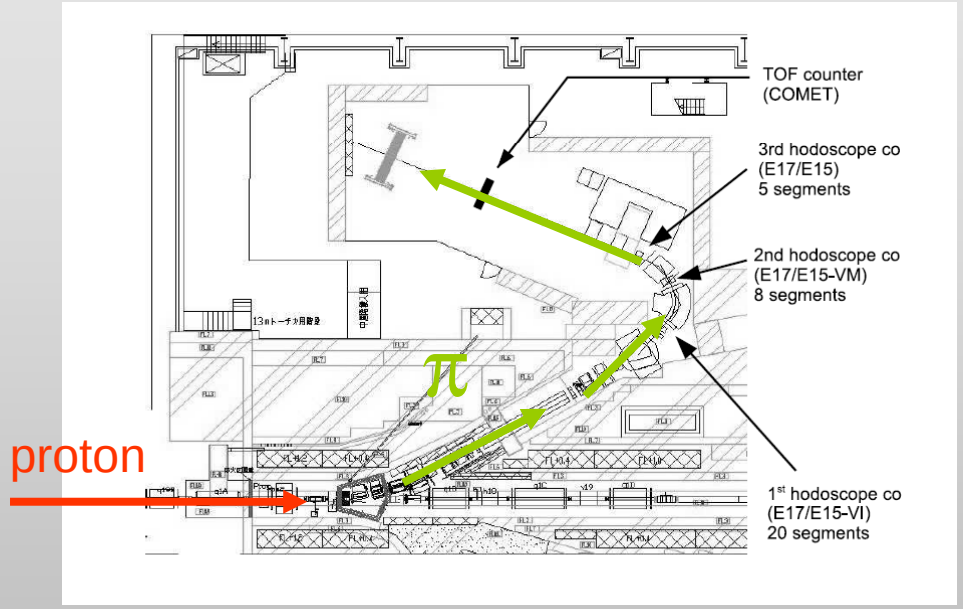
280V, 10kHz, fall t ~100nsec

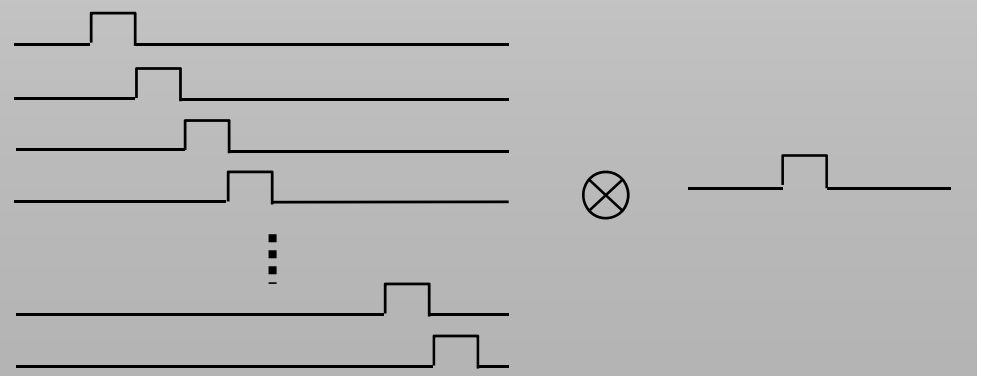


Aiming at
- Repetition ~1MHz
- On/off ratio <10^{-6}
- Long-term operation

Extinction Measurement using Secondary Beam

- Measure secondary particle time structure relative to a reference signal from the MR
  - MR RF signal in the experimental area
  - Beam line hodoscope counters at the K1.8BR line
    - Support by E15/E17 group
  - MR operation with empty buckets
  - Bunched slow extraction
  - Count the number of secondary particles as a function of time
    - Particle identification
      - TOF
    - Integration for ~10^3 seconds supposing 1MHz counting rate



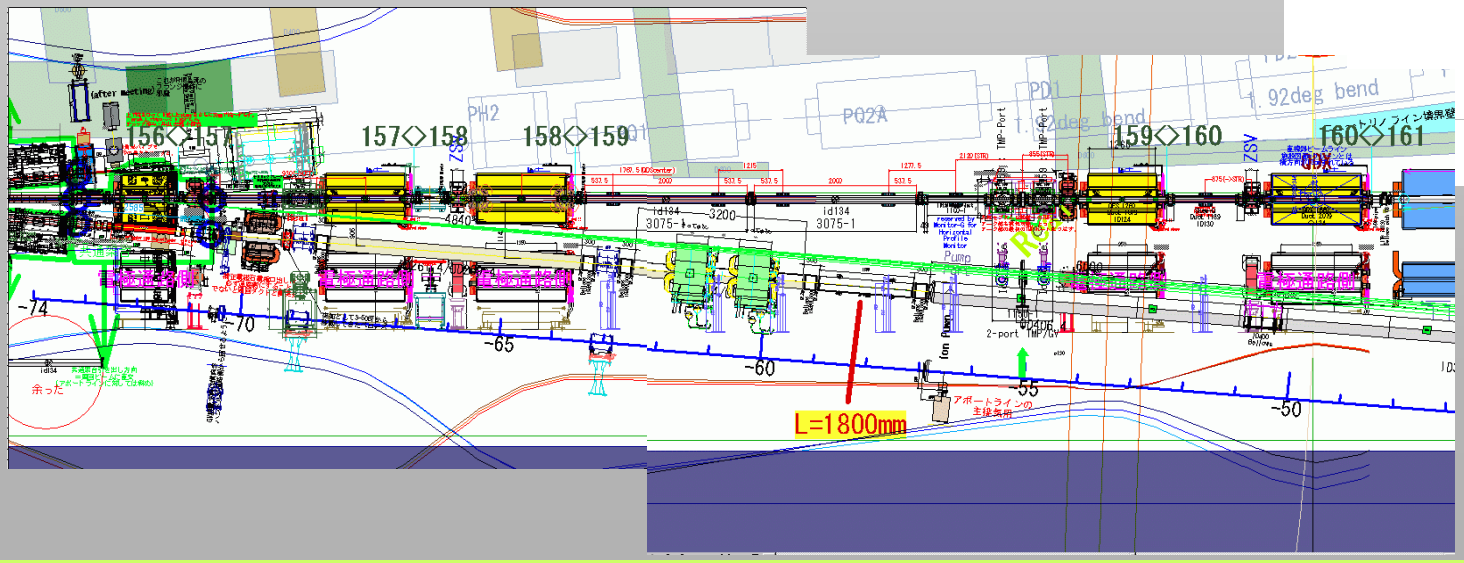


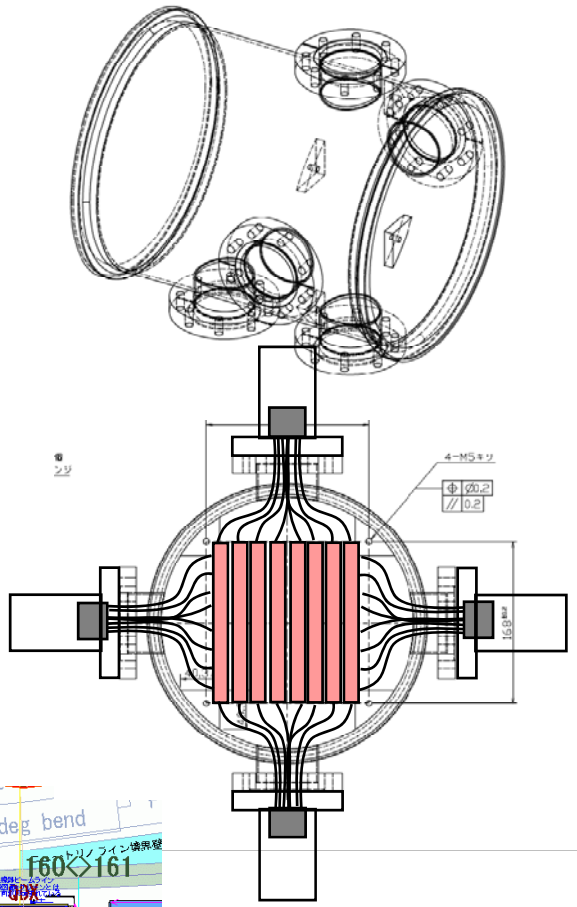
Delayed reference signals Counter signal

Extinction Measurement

- Utilize beam monitor in the abort line
- Single bunch operation of the MR
  - Look at the empty bucket before the filled one
  - Detector that can count the number of protons

- Two layers of 2mmt scintillator hodoscopes
  - Support by thin carbon fiber plates
  - Read by Multi-anode PMT through optical fibers
  - Operated in the beam line vacuum





Schedule and Construction Cost

Funding starting

1st year	design & order of SC wires
2nd year	construction
3rd year	
4th year	
5th year	engineering run
6th year	physics run

Item	Cost (MJPY)
MR modification[1)]	130
External Extinction Device	230
Production Target & Shield	190
Superconducting Solenoid[2)]	2,420
Pion Capture Solenoid	(870)
Curved Muon Transport Solenoid	(360)
Muon-Stopping Target Solenoid	(530)
Curved Solenoid Spectrometer	(370)
Detector Solenoid	(290)
SC Solenoid Extension (20 m)[3)]	380
Tracking Detector	110
Electron Calorimeter	160
Cosmic Ray Shield	570
Data Acquisition and Trigger	50
Installation and Integration	200
Total	4,440

100 JPY =1.23CHF as of 15/Nov/2008

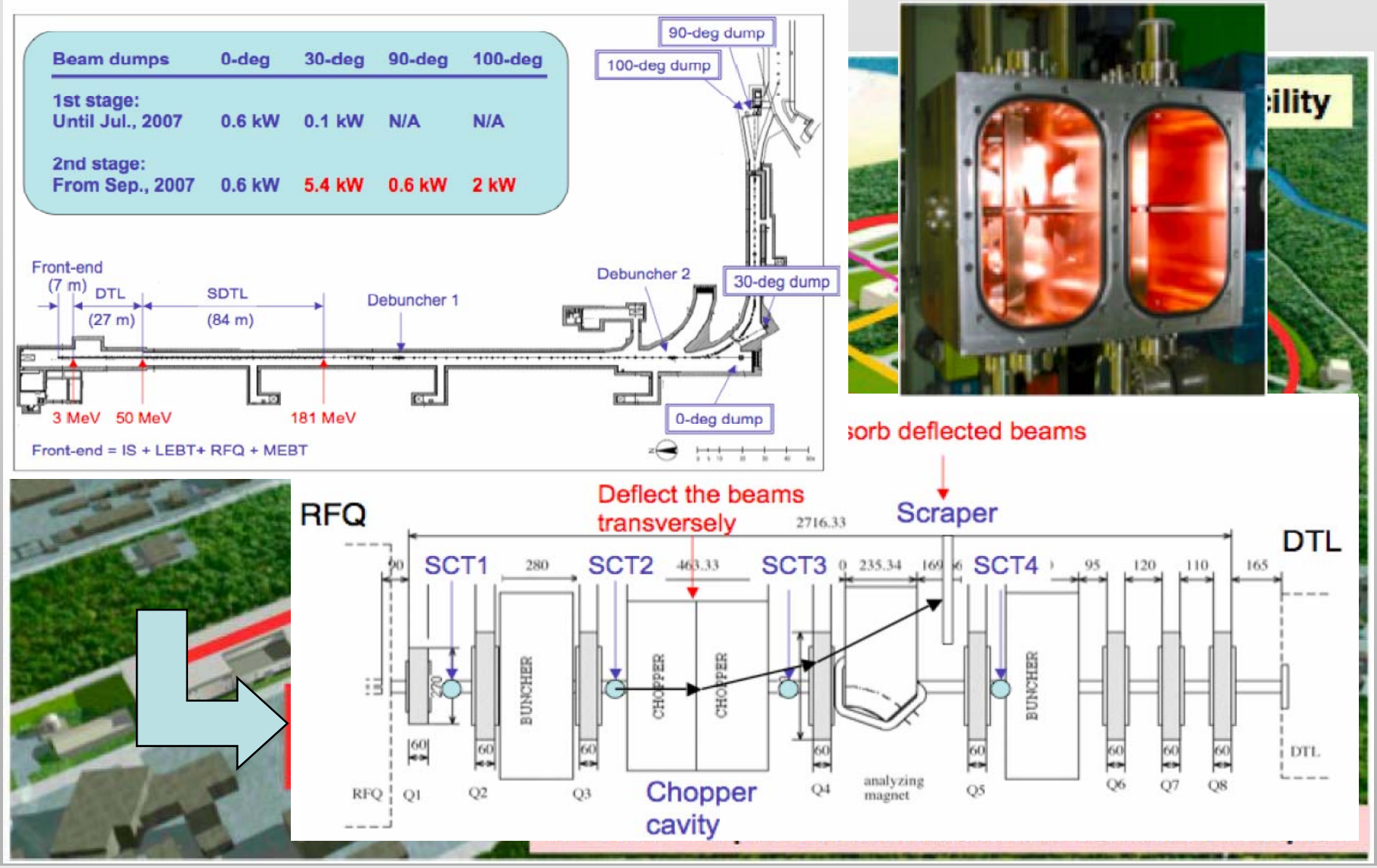
Summary

- New experiment (COMET) to search for mu-e conversion at J-PARC
- COMET aims at achieving a sensitivity of 10^{-16}
  - High-intensity, high-purity pulsed proton beam at J-PARC
  - Curved solenoid muon transport/spectrometer to suppress backgrounds efficiently
- R&D work in progress
  - Detector
  - Magnet
  - Proton beam
    - Beam structure
    - Extinction

Do Join COMET Now!

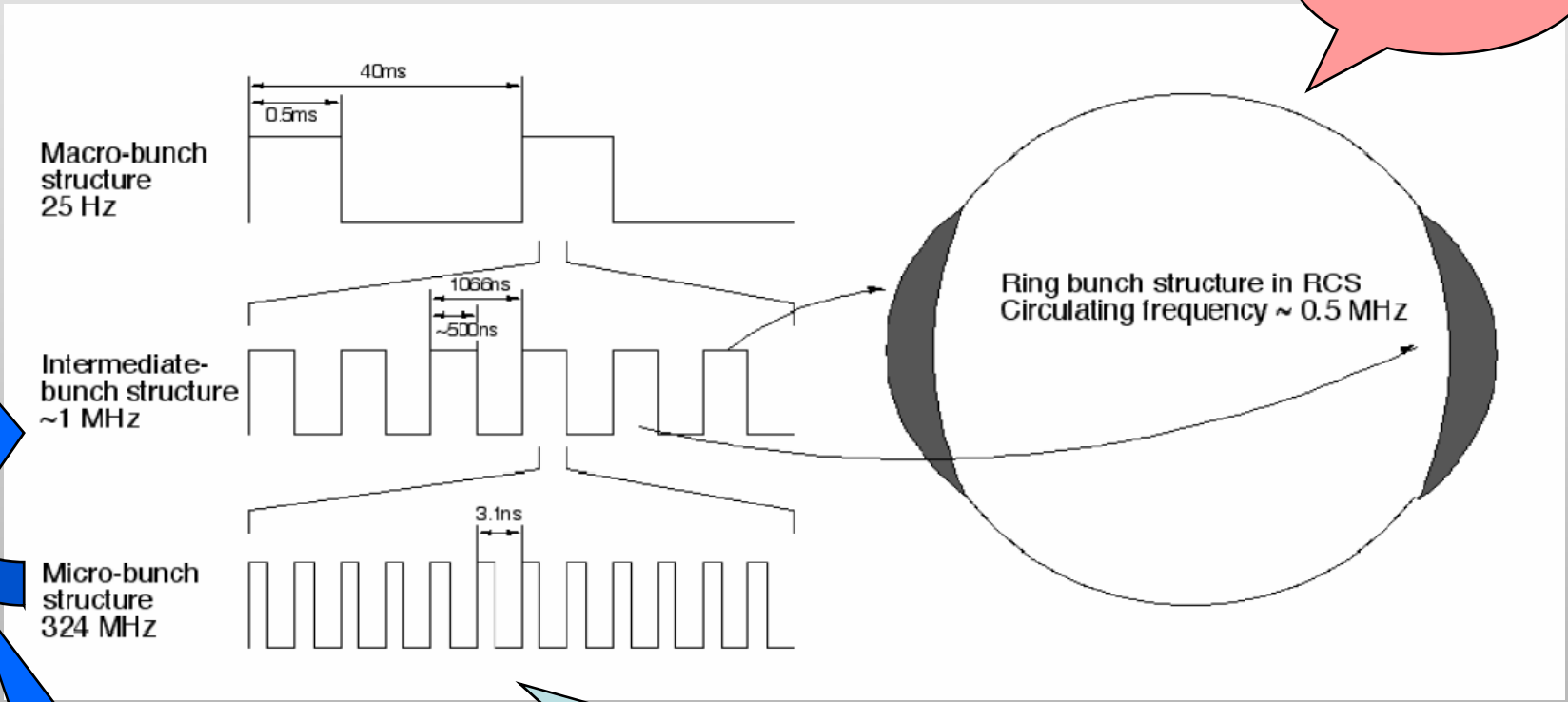
Backup

High-frequency Chopper



RCS Bunch Structure

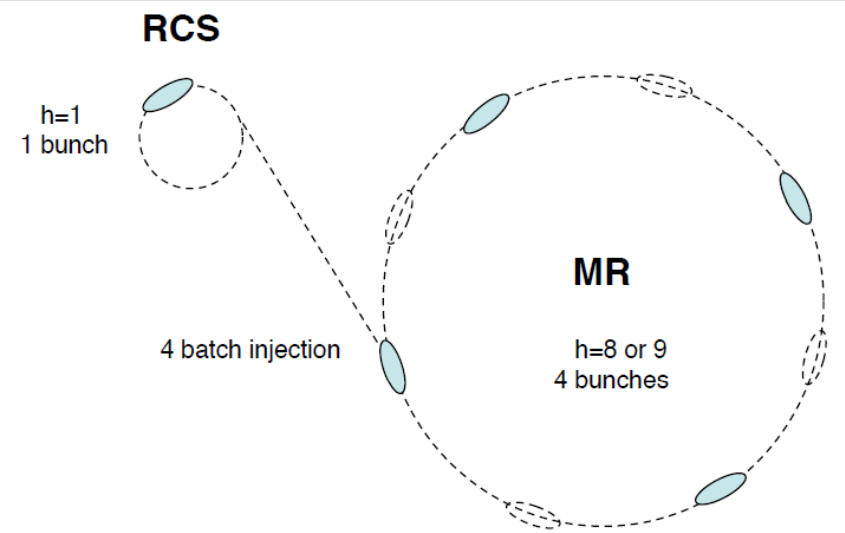
RCS

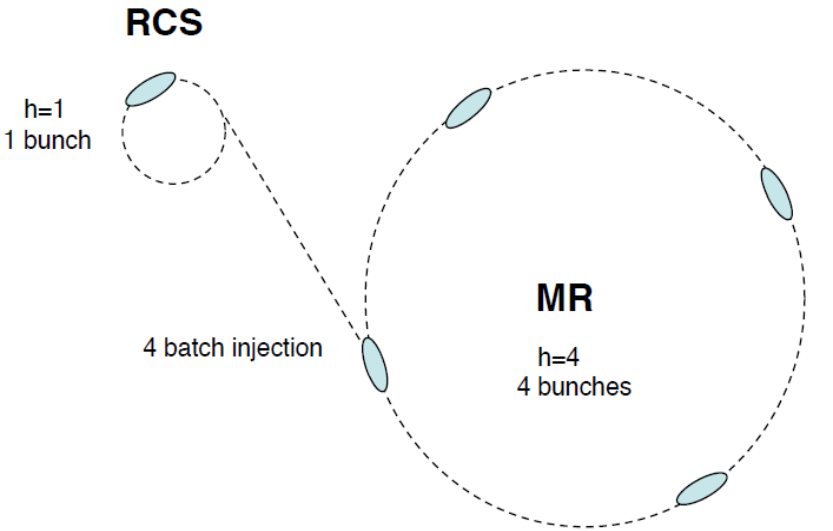


Chop!

RFQ
Bunch structure

Proposed Scheme (II) & (III)





- Space charge tune shift is half of (1)
- Longitudinal emittance is twice of (1)
- NO EMPTY BUCKET IN RCS
- RCS RF system needs minor modification (low level RF)

- NO EMPTY BUCKET BOTH IN RCS AND MR
- Space charge tune shift is half of (1)
- **LARGE MODIFICATION OF MR RF SYSTEM IS NECESSARY**
- Long bunch

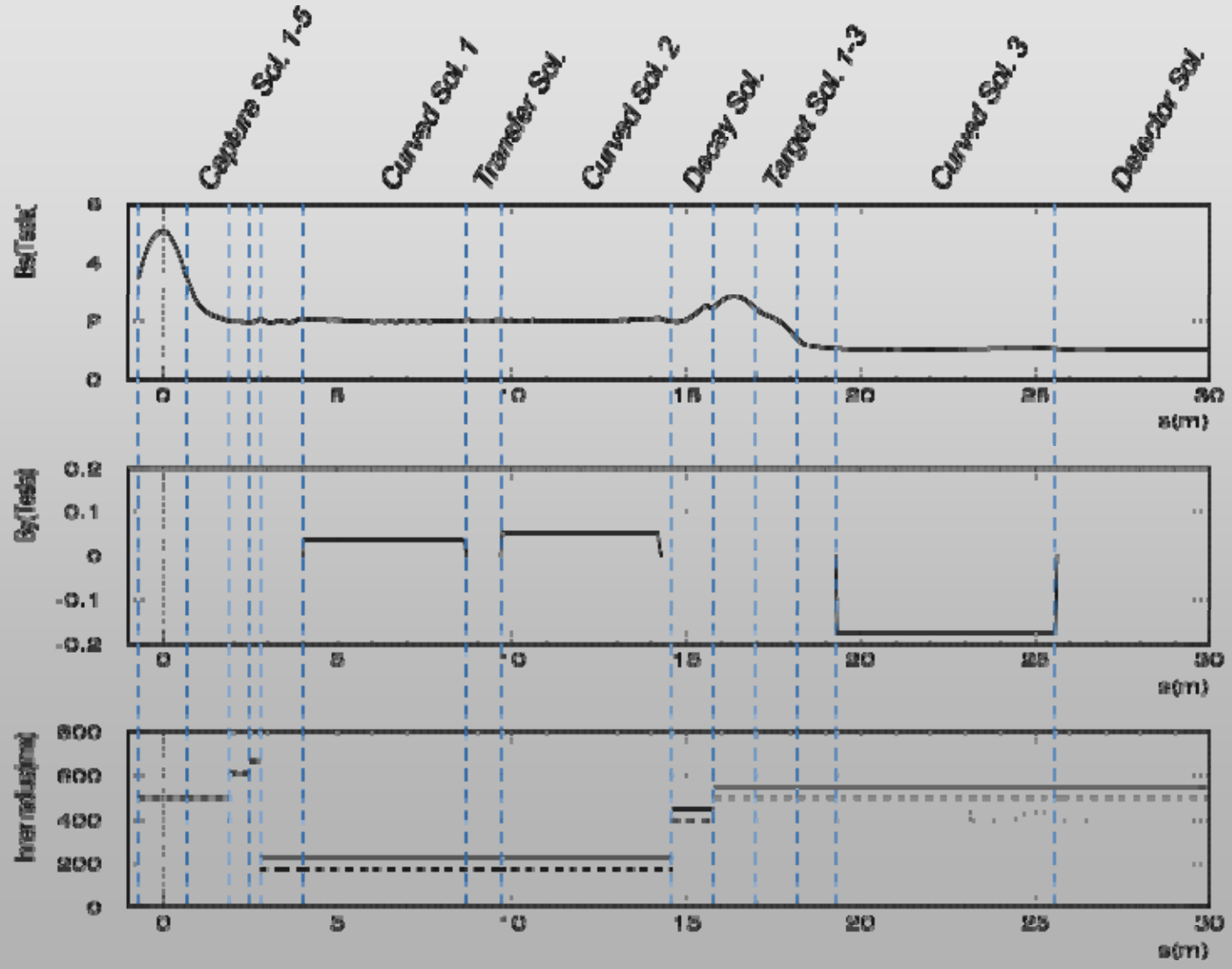
Design of Muon Transport Beamline

(preliminary)

Solenoid field

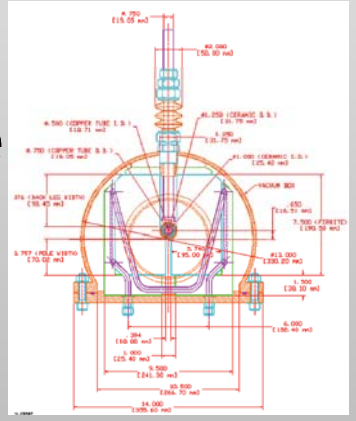
Compensation field

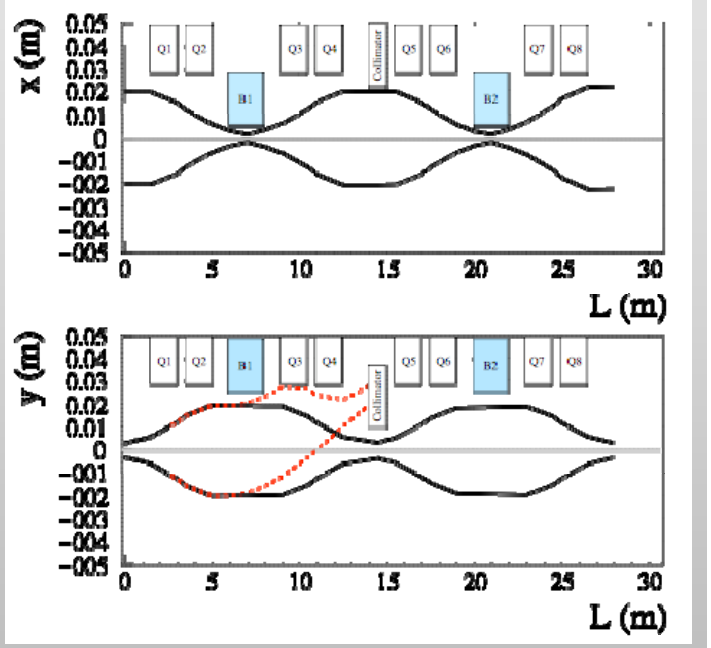
Inner radius



Additional Extinction Means

- AC-dipole
- @ primary beamline
- $f_{extinction}$ ~ 1/100
- collaboration with mu2e





- Bunch Cleaner
  - in MR
  - tested at AGS for MECO