The COherent Muon to Electron Transition (COMET) Experiment

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The 7th UK Neutrino Network Meeting

29th September 2010

Imperial College London

COMET

Introduction

- Brief introduction to the aims of COMET Experiment.
- Experimental overview.
- R&D projects.
- Summary and future plans.

COMET Collaboration

COMET Collaboration List

49 people from 14 institutes (April 2010)

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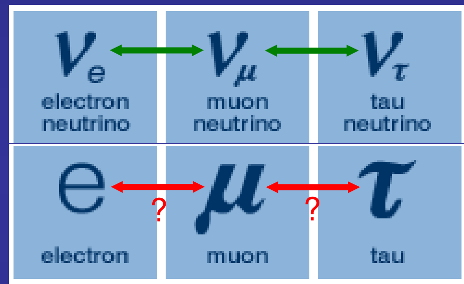
Why Charged Lepton Flavour Violation?

- We know the SM is at best incomplete.
  - Does not include gravity.
  - Certain predictions diverge with increasing energy.
- Neutrinos in the SM are massless but observation of neutrino oscillations is direct evidence that neutrinos have mass.
  - First observation from Super Kamiokande.

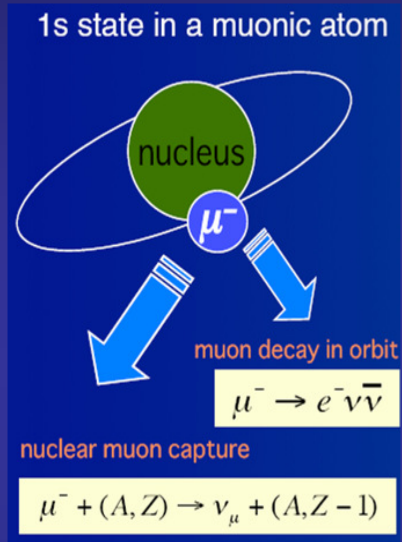
  → Possibility of Charged Lepton Flavour Violation.



- Larger numbers of muons are easier to produce than taus.
  - ~10^{11} μ/sec compared to ~10^{10} τ/yr.
- Some muon processes that could be studied
  - $\mu^- \to e^- \gamma$
  - $\mu^- \to e^- e^+ e^-$
  - μ^- (A,Z) $\to e^-$ (A,Z).
- Single particle final state can make best use of high intensity muon beams.

Muon to Electron Conversion

- Neutrino-less conversion of a muon into an electron in the presence of a nucleus.

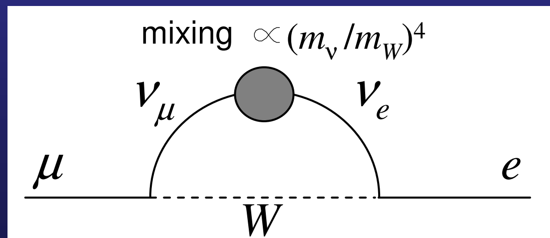


- Look at muonic atoms.
  - muon decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$
  - nuclear capture $\mu^- (A,Z) \to \nu_\mu (A,Z\text{-}1)$

  } SM processes

- Muon to electron conversion $\mu^- (A,Z) \to e^- (A,Z)$
  - Electron energy depends on Z (for Al, E_e = 105 MeV)
  - Nucleus coherently recoils off outgoing electron, no breakup.

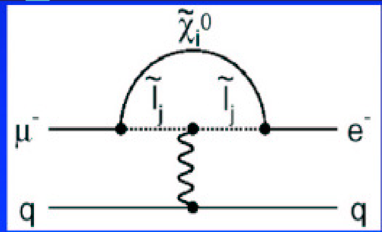
- If we include neutrino mixing in the SM, the probability for muon to electron conversion is $<10^{-52}$
  - Sensitive to physics beyond the SM.

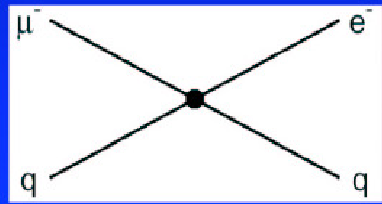


Sensitivity to Different Mechanisms

Supersymmetry

Predictions at 10^{-15}





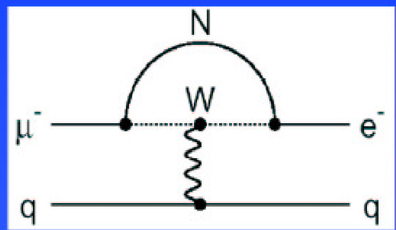
Compositeness

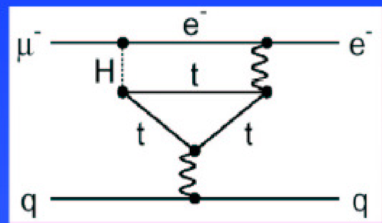
Λ_c = 3000 TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2$ =

8×10^{-13}





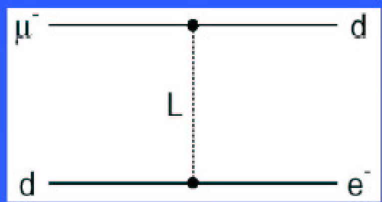
Second Higgs doublet

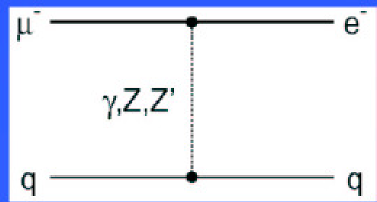
$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

Leptoquarks

M_L =

$3000 (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2





Heavy Z', Anomalous Z coupling

$M_{Z'}$ = 3000 TeV/c^2

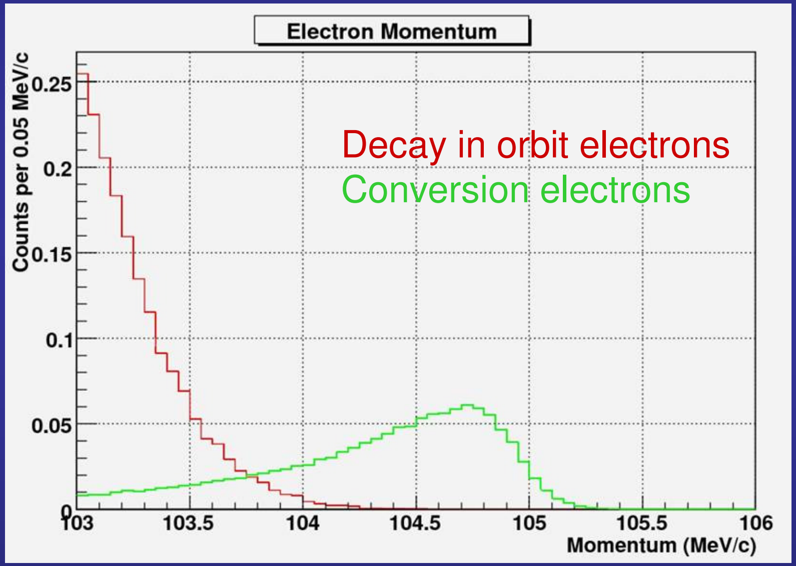
$B(Z \rightarrow \mu e) < 10^{-17}$

After W. Marciano

W. Molzon, UC Irvine The MECO Experiment to Search for Coherent Conversion of Muons to Electrons September 27, 2002 3

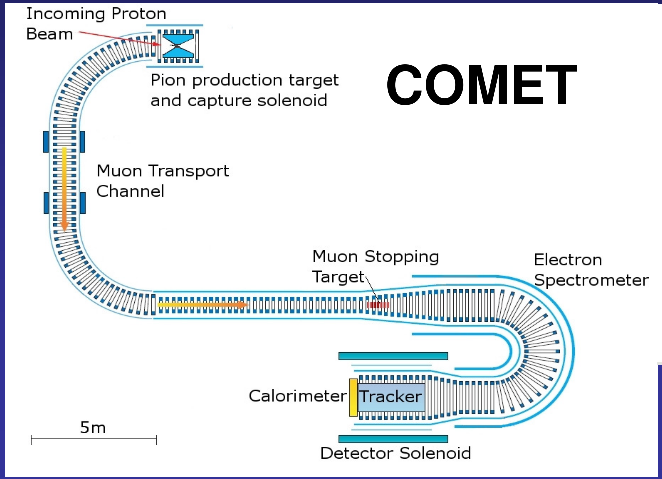
Measuring Muon to Electron Conversion

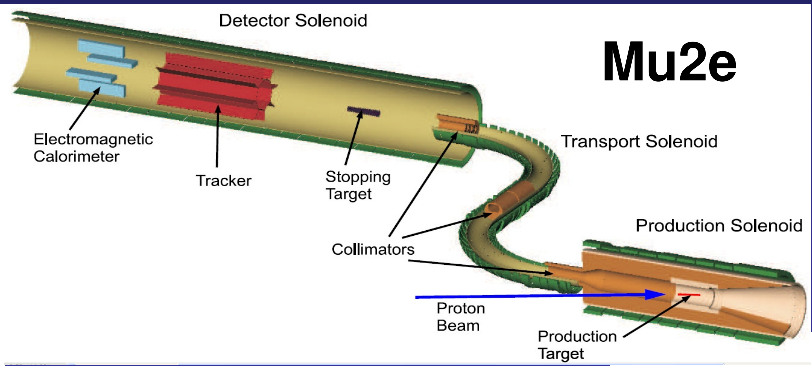
- Current best limit is < 7×10^{-13} by SINDRUM II using a gold target.
- Stop muons in a thin aluminium foil
  - The Bohr radius is ~20fm and the nuclear charge radius 4fm, so the muon sees the nucleus.
- Signal is a monoenergetic electron
  - E = ~105 MeV = m_μ - BE (BE=0.5MeV for Al)
- Prompt beam related backgrounds.
  - Muon decay in flight.
    - If P>75MeV/c can yield signal like electron.
  - Radiative muon capture
    - μ^- (A,Z) $\rightarrow$ (A,Z-1) $\nu\,\gamma$, $\gamma \rightarrow e^+e^-$
  - Radiative pion capture
    - π^- (A,Z) $\rightarrow$ (A,Z-1) γ , $\gamma \rightarrow e^+e^-$
- Muon decay in orbit.
  - Electron recoil off nucleus → endpoint is near 105MeV.
- Scattered electrons, cosmic rays and neutron induced backgrounds.

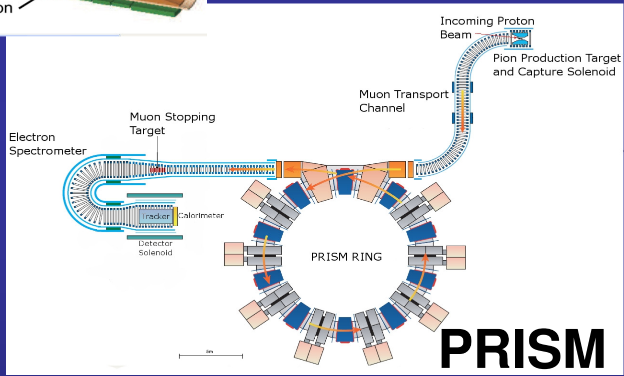


Relative signal and background spectra for a branching ratio of 10^{-16} (including energy loss and tracker resolution). The statistics are 100 times more than the expected 3.8 signal events for 2×10^7s data taking.

Future Muon to Electron Conversion Experiments

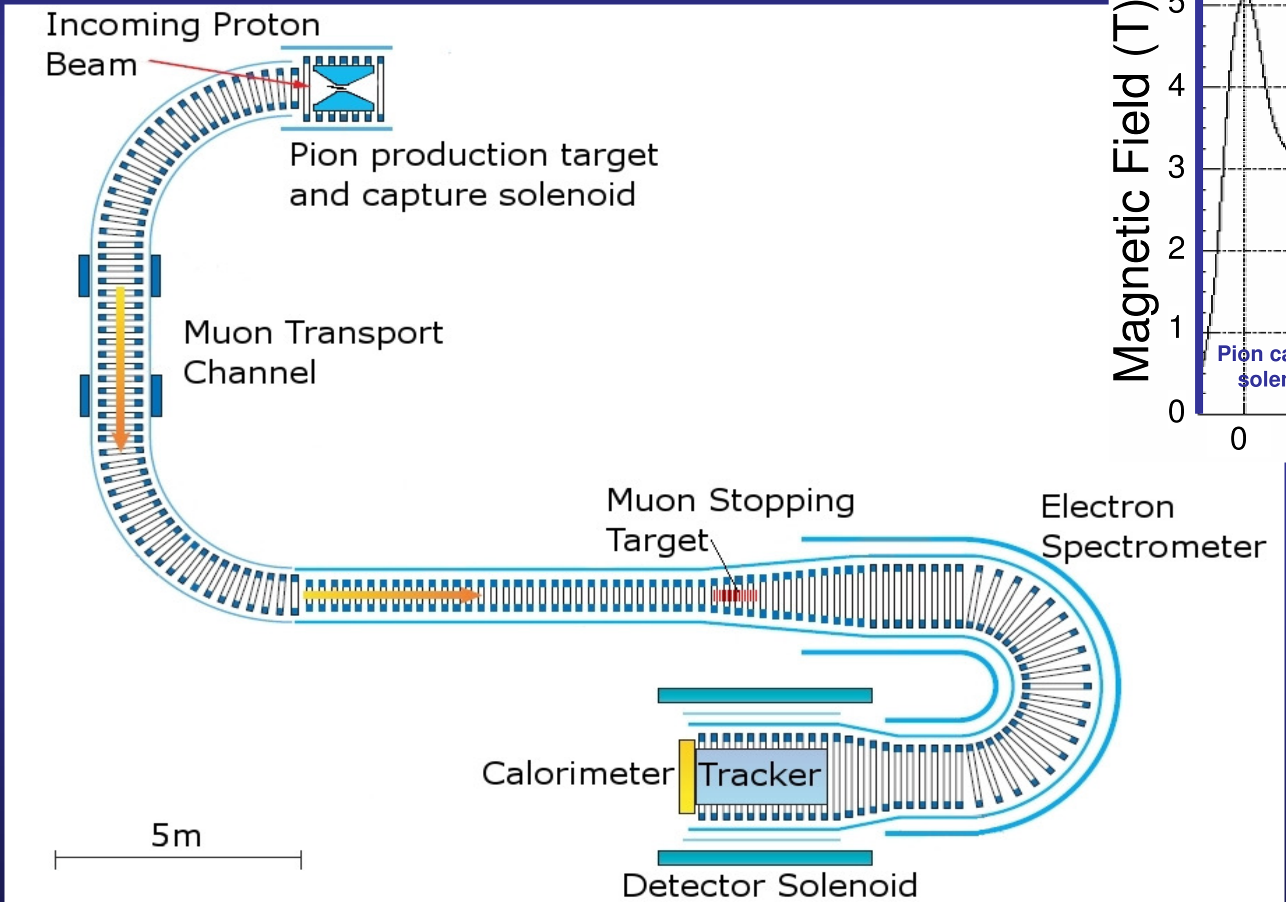


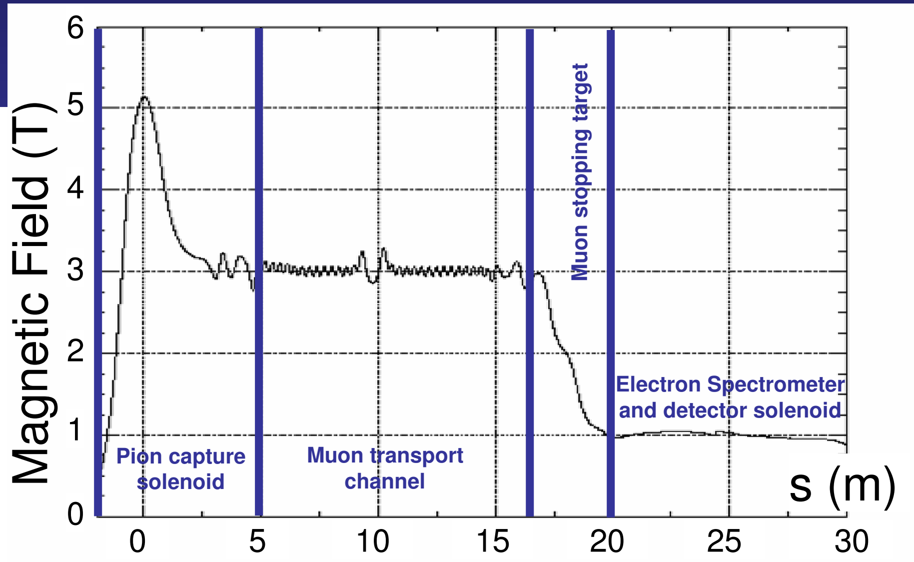




- The COherent Muon to Electron Transition (COMET) experiment will be based at J-PARC and aims to have a sensitivity $<10^{-16}$.
- The Phase Rotated Intense Slow Muon (PRISM) experiment will improve this measurement by a factor of 100 and can be the second phase of COMET.
- Mu2e aims to have a sensitivity of $<10^{-16}$ and will be based at FERMILAB.

COMET Overview





- Aim for factor **10,000** improvement on SINDRUM II.
  - i.e. single event sensitivity of <10-16.

Signal Sensitivity

The single event sensitivity is given by:

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{CAP} \cdot A_e} = \frac{1}{2\times10^{18} \cdot 0.6 \cdot 0.04}$$

$$= 2.6\times10^{-17}$$

$$< 6\times10^{-17} \text{ (90\% C.L.)}$$

where N_μ is the number of stopped muons for a running time of 2×10^7s, f_{CAP} is the fraction of muons captured and A_e is the detector acceptance.

N_μ is given by:

$$N_\mu = N_p \cdot \varepsilon_{MTC} \cdot \varepsilon_{ST} = 8.5\times10^{20} \cdot 0.008 \cdot 0.3$$

where N_p is the total number of protons produced, ε_{MTC} is the muon transport efficiency and ε_{ST} is the stopping efficiency.

Challenges for COMET

- Need for high intensity muon beam
  - $\rightarrow$ Many challenges from an accelerator physics perspective.
  - – Intense proton beams.
  - – Very cleanly pulsed proton beam (extinction $<10^{-9}$).
    - AC Dipole or other technology.
  - – Pion production.
    - Superconducting solenoid in high radiation environment.
  - – Transportation and momentum selection of large emittance pion/muon beams.
- Detector systems.
  - – Extinction measurement device.
  - – 0.4% momentum resolution for ~105MeV/c electrons.
  - – Fast, highly-segmented calorimeter.

COMET at J-PARC

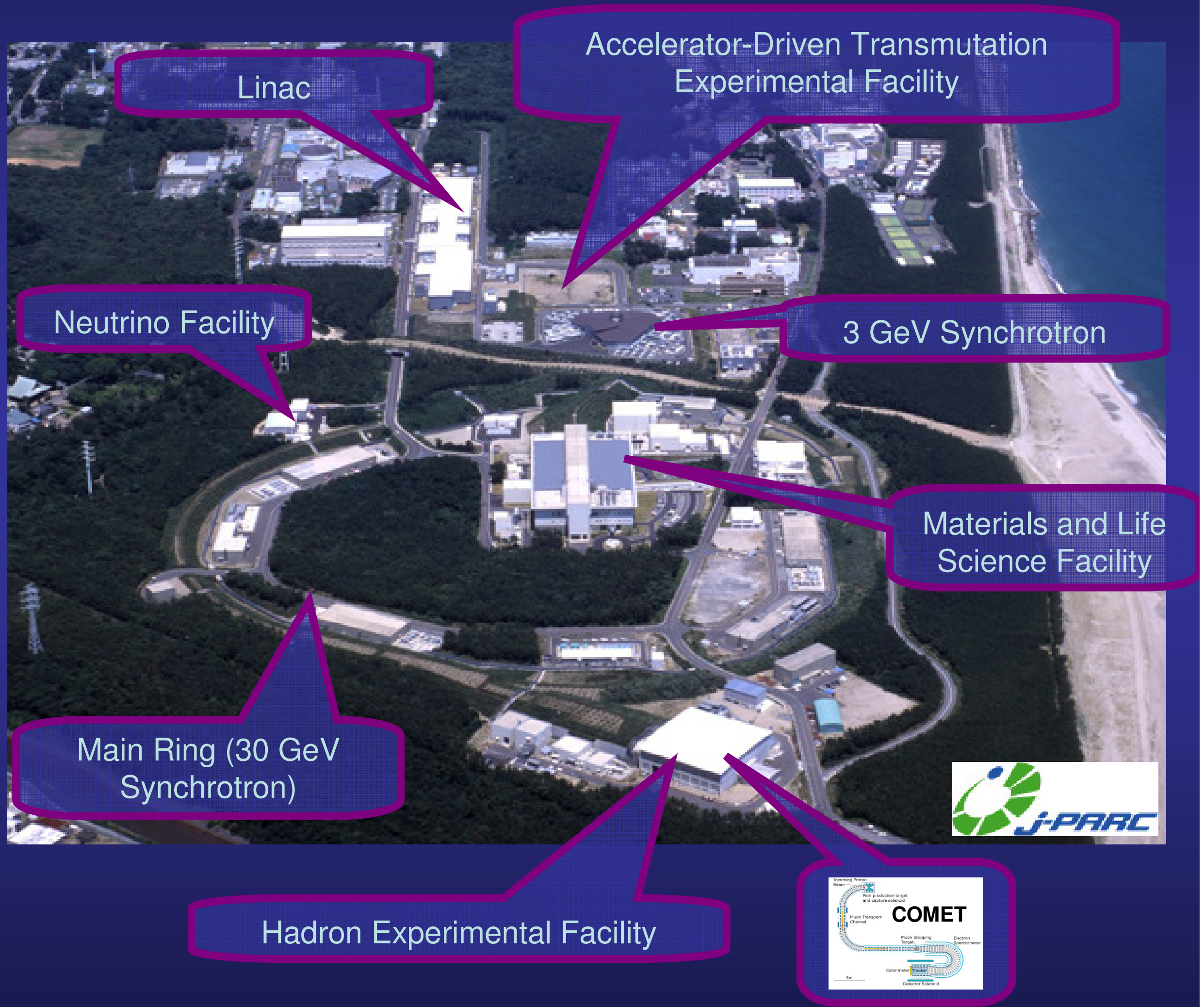
Proton beam design parameters

Beam Power	750 kW
Beam Energy	30 GeV
Average Current	25µA

COMET beam requirements

Beam Power	56 kW
Beam Energy	8 GeV
Average Current	7µA

- Slow-extracted proton beam.
- 8 GeV to suppress anti-proton production.

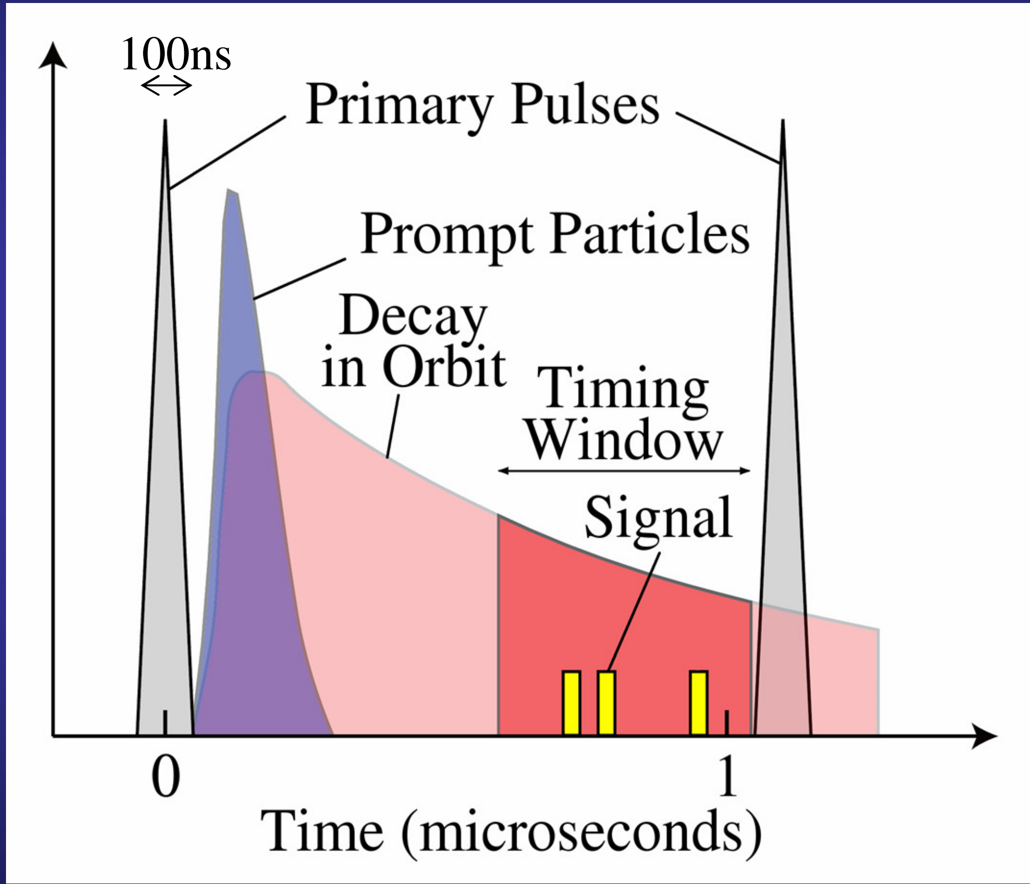


Proton Beam for COMET

- Muonic lifetime is dependent on target Z. For Al lifetime is 880ns.

Bunch Structure

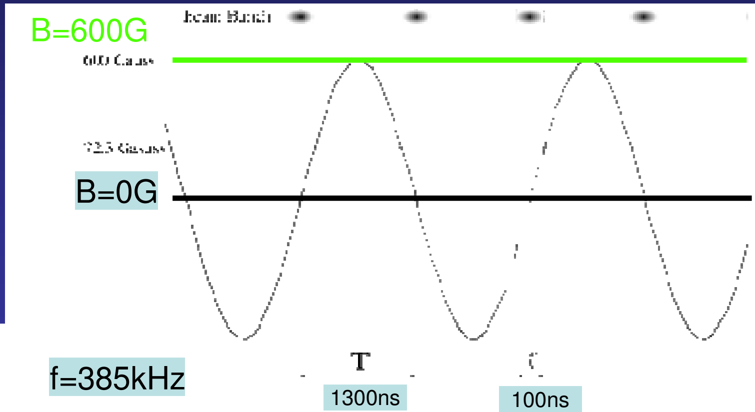
Bunch Separation	1.3 μs
Bunch Length	100ns
Protons per Bunch	1.2×10^{8}
Bunches per Spill	5.3×10^{5}
Spill time	0.7s
Extinction	10^{-9}



- Background rate needs to be low in order to achieve sensitivity of $<10^{-16}$.
- Extinction is very important.
  - Without sufficient extinction, all processes in prompt background category could become a problem.

Proton Extinction

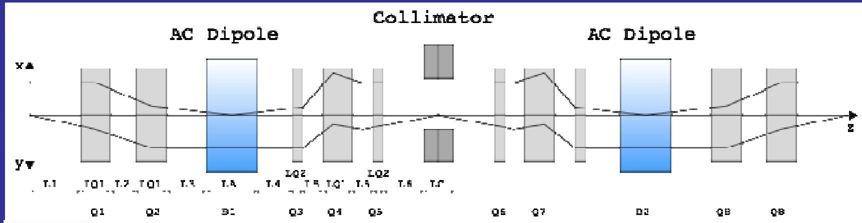
- Intrinsic extinction from the J-PARC main ring is expected to be around 10^{-7}.
  - Need additional extinction device to give additional factor 10^{-2}.
- One possible solution is to use an AC dipole
  - Collaboration between COMET and Mu2e

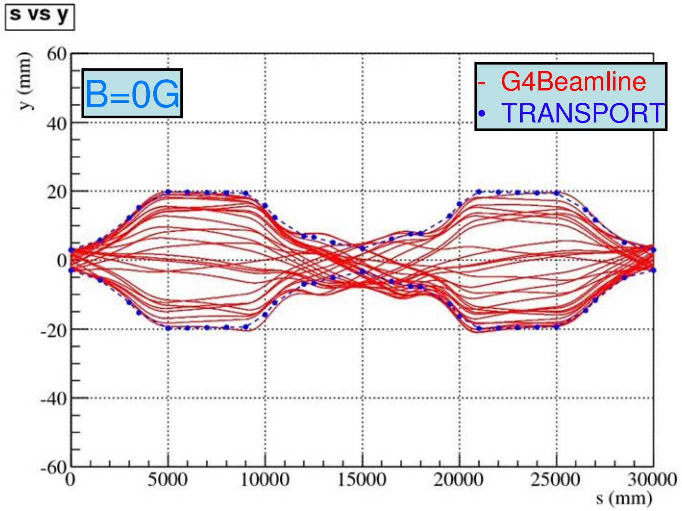


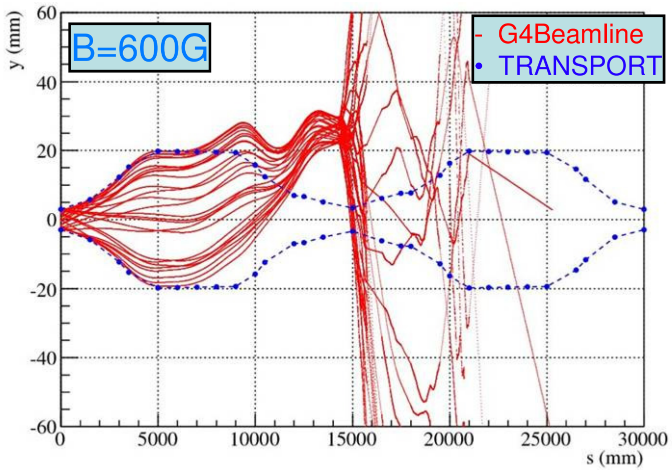
Transmission [-100:100ns] = 100%

$R_{extinction}$ [<-300ns, >300ns] < 1/1000

$R_{extinction}$ [<-200ns, >200ns] < 1/100

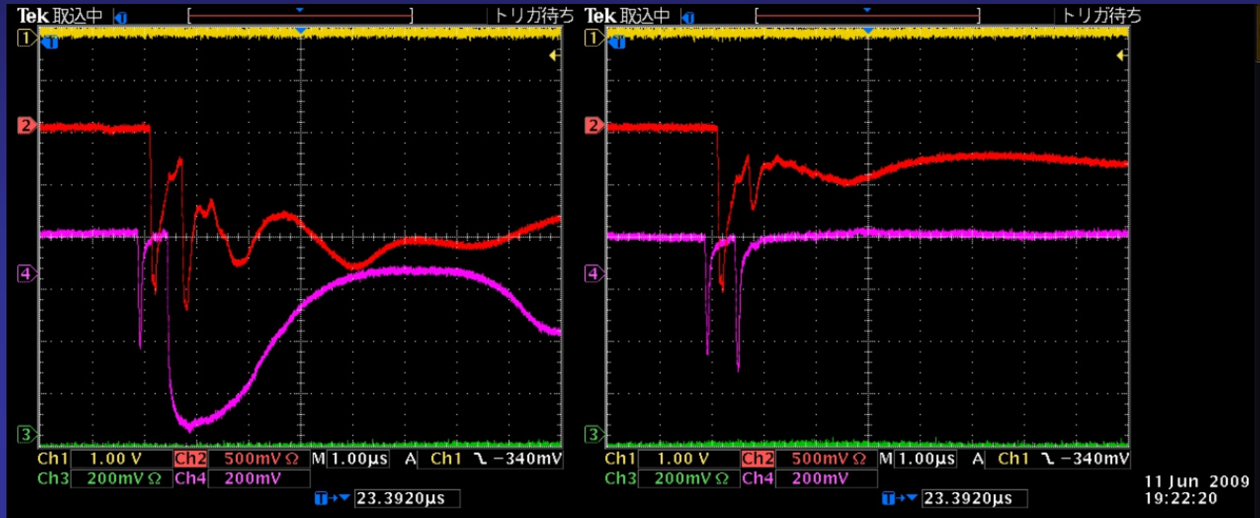




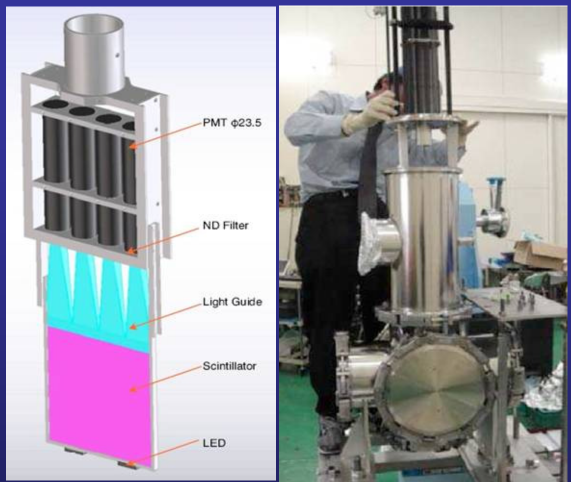


Proton Extinction Measurement

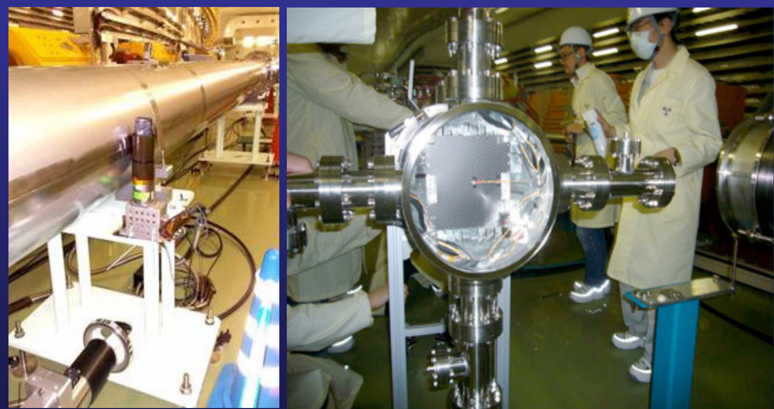
- Need to measure extinction level.
- Requires 10^9 dynamic range and timing resolution of ~10ns.
- R&D at JPARC main ring.
  - Scintillator hodoscope placed in main ring abort line.
- Gating PMT development.
- Paper at IPAC'10.



Residual beam measurement with one filled, one empty bucket (left) and both buckets empty (right).

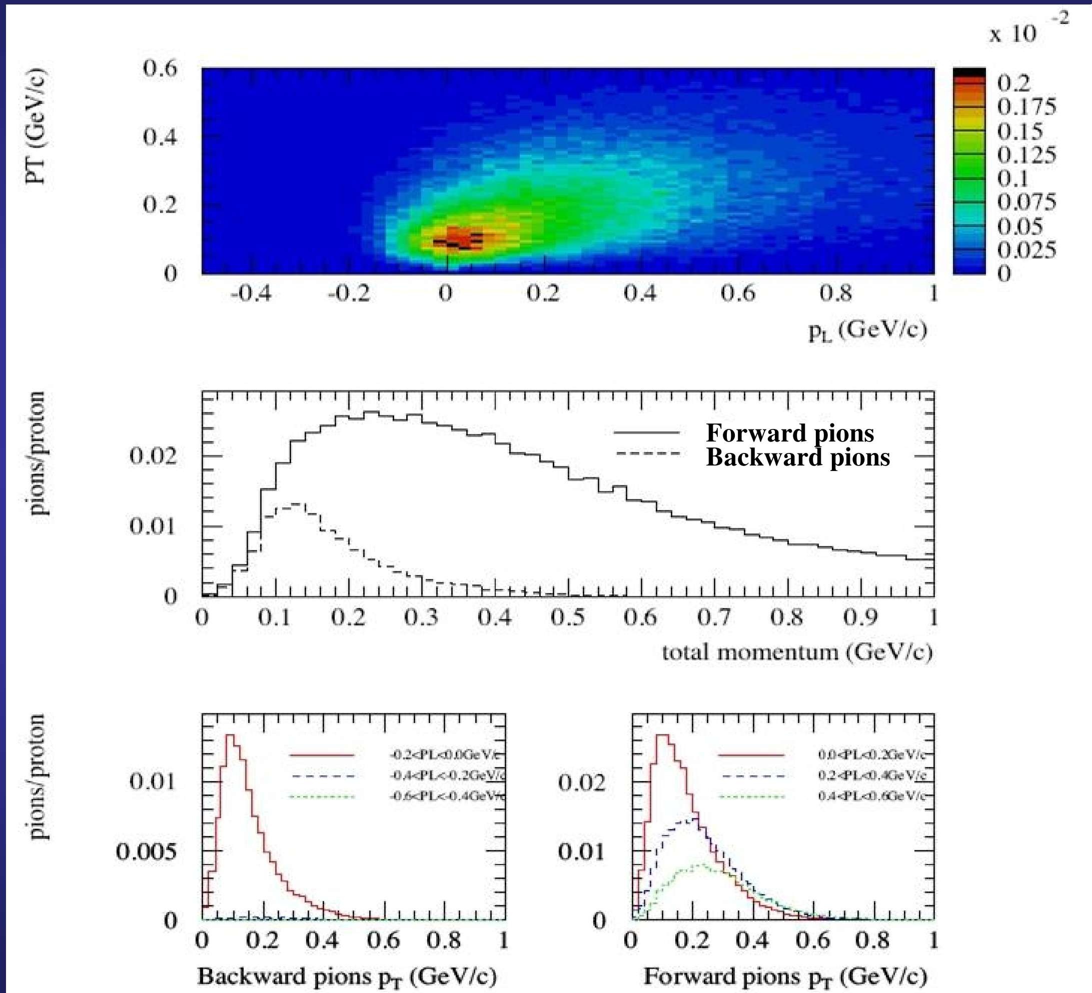


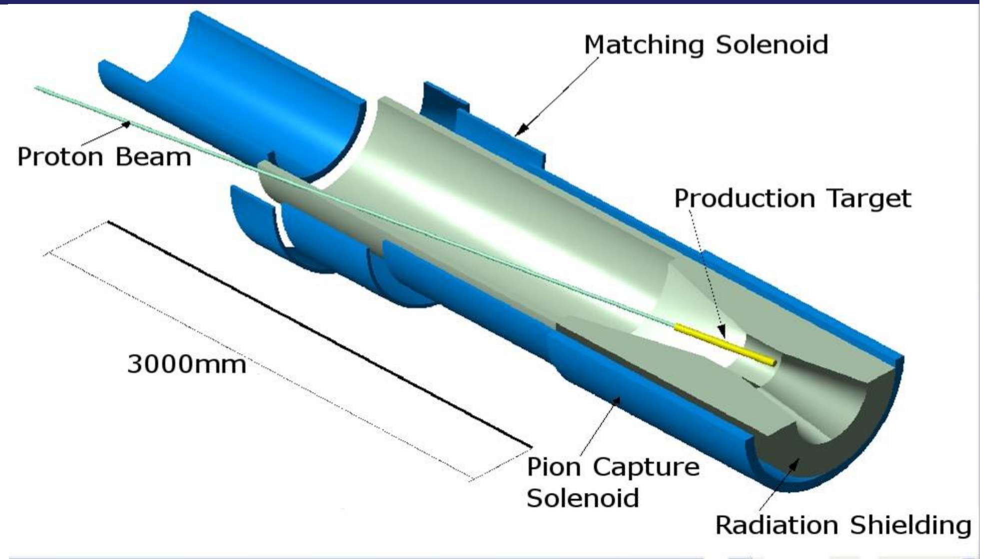
New monitor with moving stage and gate valve.



Extinction monitor installed in the J-PARC main ring abort line

Pion Production

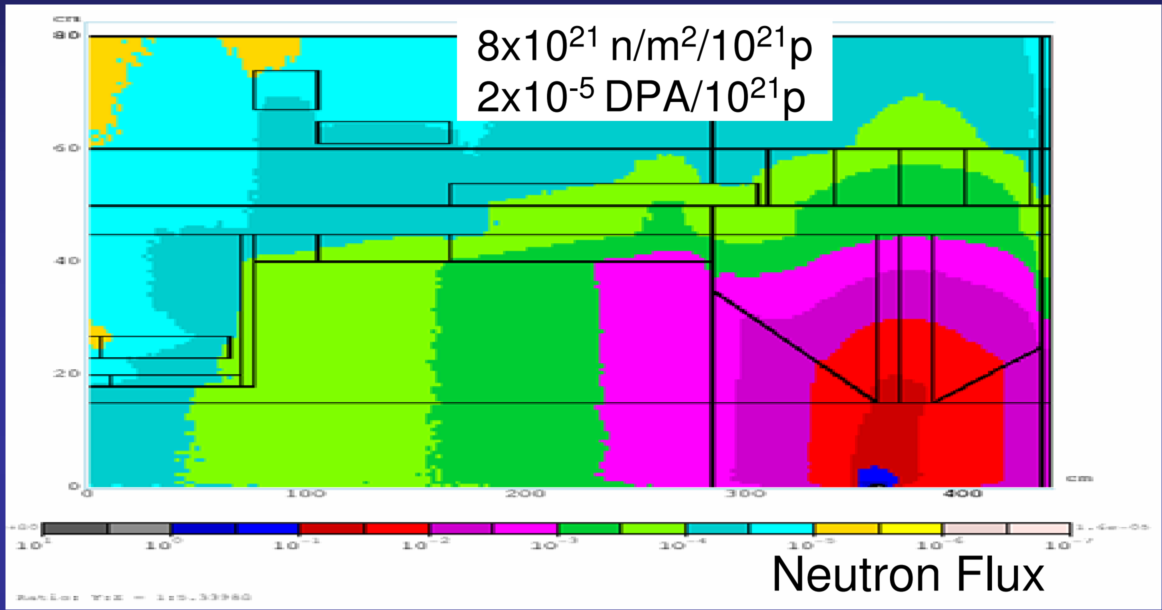




- Heavy metal (W, Au, Pt....) target
- 5 Tesla superconducting pion capture solenoid
- Keep only backward going pions.

Gold target simulations using MARS

Solenoid Design

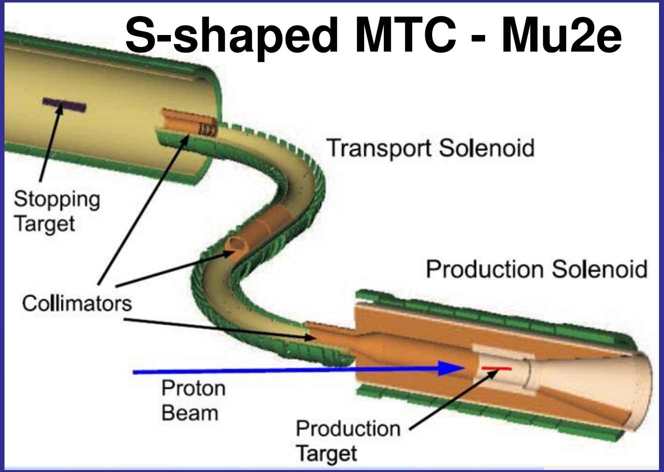


- Neutron Flux:
  - ~10^{22} n/m^2 for 10^{21}p
    - Same criteria as for ITER
  - ~2×10^{-5} DPA for 10^{21}p
    - Conductor degradation
- Inner bore of solenoid increased to 1300mm.

- Copper stabilised conductors are thick.
  - Refrigeration load over 1kW.
- Aluminium stabilised superconducting coil R&D.
  - Better radiation damage performance.
- Prototype being wound at Fermilab.
- Conductor manufactured by Hitachi

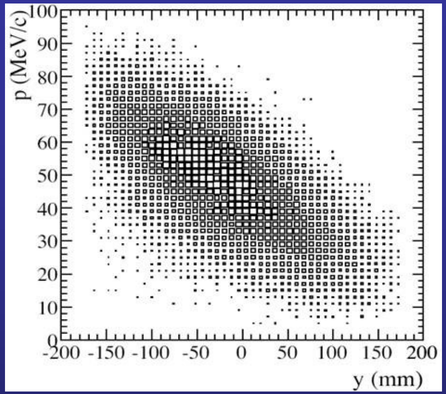
Muon Transport Channel

- Requirements
  - Needs to be long enough so pion survival rate is low, $<10^{-3}$.
  - High transport efficiency for muons with momentum around 40 MeV/c.
  - Eliminate muons with momentum > 75 MeV/c.
  - Select muons with negative charge.

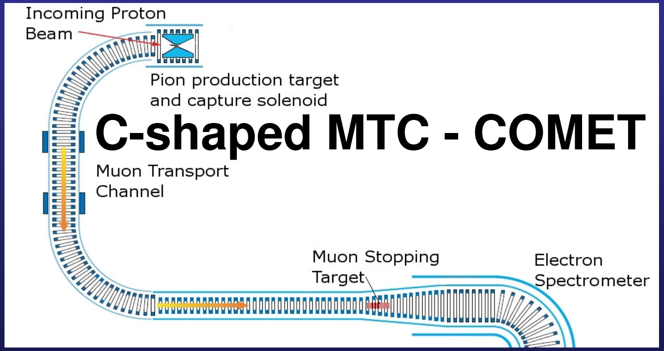


- Use toroidal magnetic field.
  - Particles drift in direction perpendicular to curvature.

$$drift = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + \frac{1}{2}p_T^2}{p_L}$$

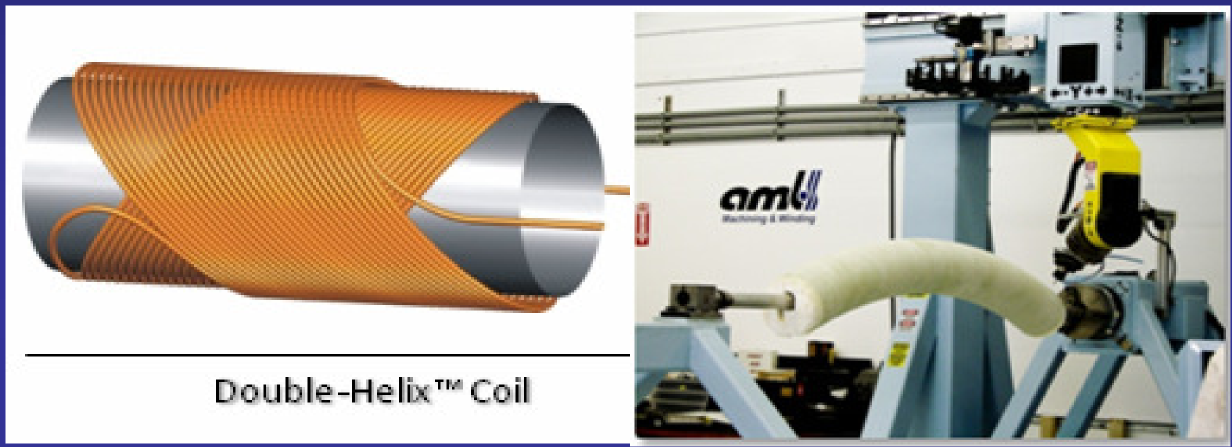


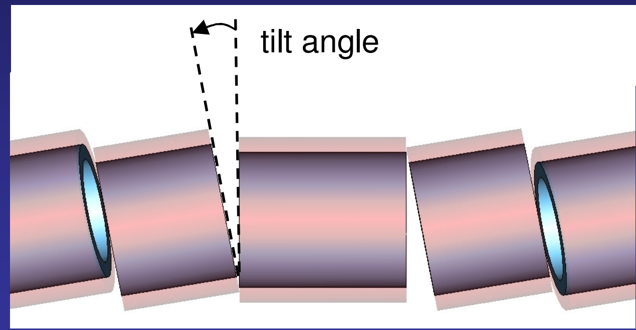
Vertical dispersion at the end of the muon transport channel



- Need compensating dipole field so central momentum muons have no net drift.

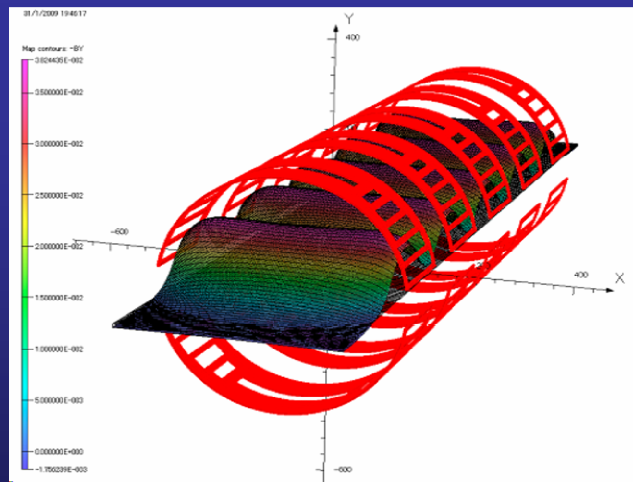
Muon Transport Magnet Designs





Tilted solenoid coils.
Actual tilt angle is 1.43deg.

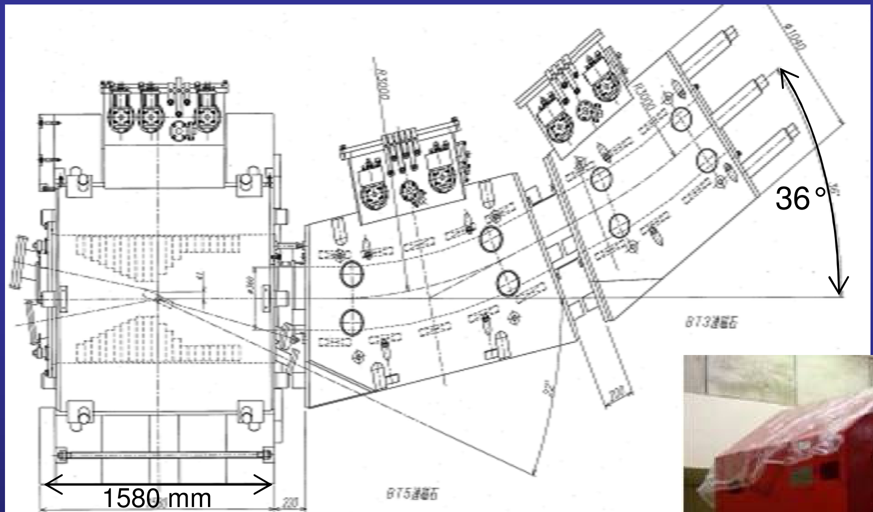
Double Helix from Advanced Magnet Labs.
Additional dipole field windings on top of solenoid winding.
Windings can be formed on a bent substrate.



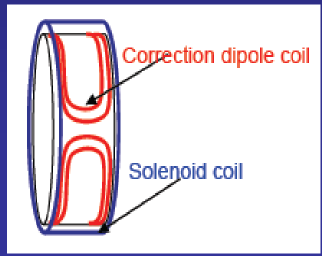
Additional cosine theta coils to give dipole field.

Magnet Prototype

- Muon Science Innovative Commission (MUSIC) at Osaka University.
- Similar to pion capture section in COMET but at lower intensity and momentum.
- 400MeV,1μA protons → 10^9 μ/s
  - World's most intense muon source.



Magnet design done in collaboration with Toshiba



Solenoid Coil

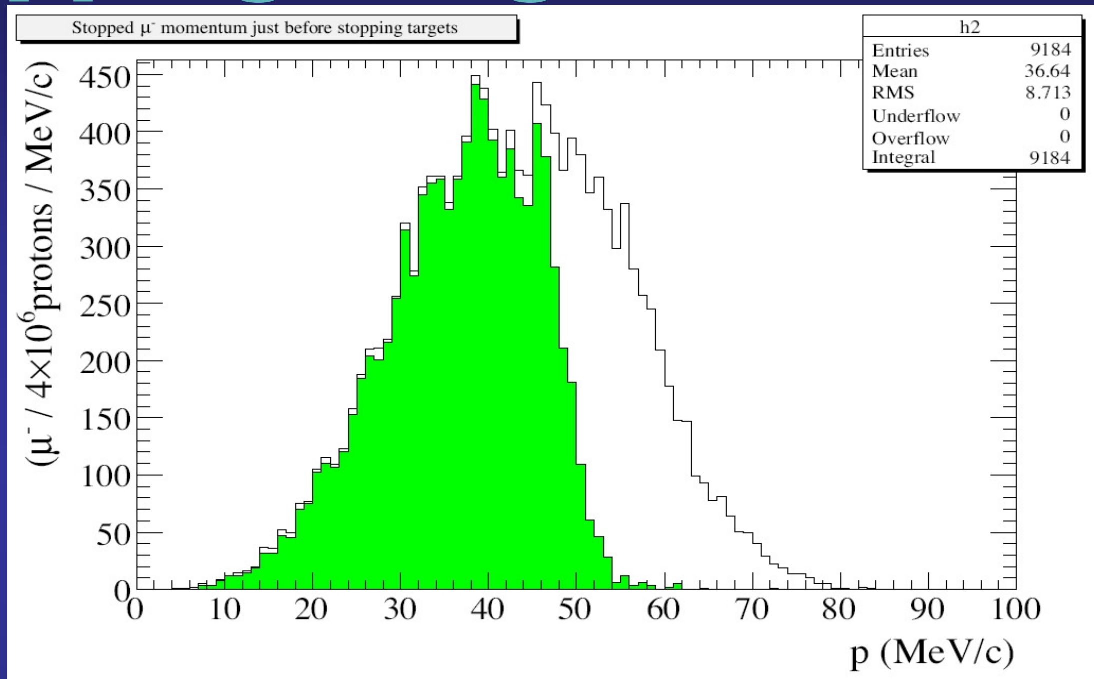
Field on axis	2 T
Bore Diameter	480mm
Length	200mm

Dipole Coil

Field on axis	0.04 T
Aperture	420mm
Length	200mm
No. of Layers	6

Muon Stopping Target

10^6 muons arrive at stopping target per bunch.



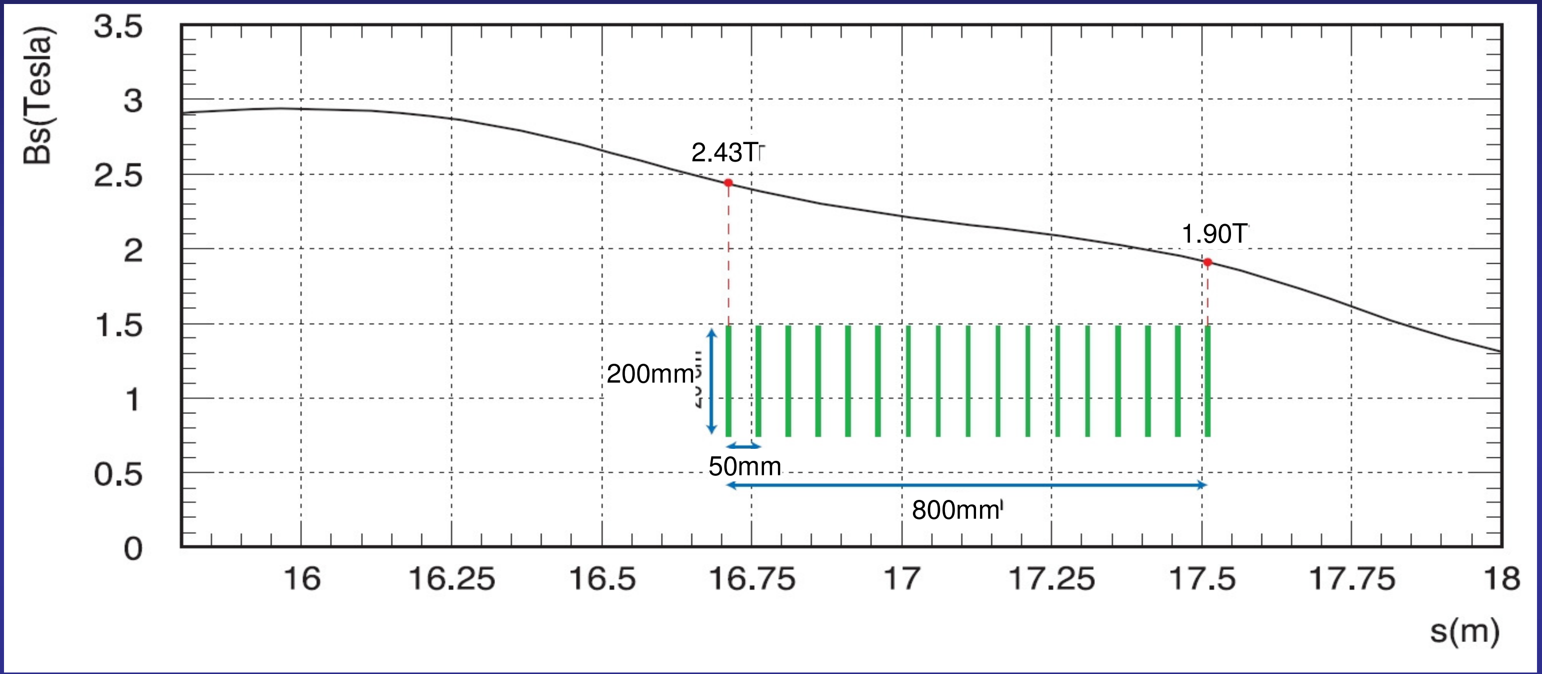
Properties of stopping target

Material	aluminium
Shape	flat disk
Disk radius	100 mm
Disk thickness	0.2 mm
Number of disks	17
Disk spacing	50 mm

Comparison of different target materials

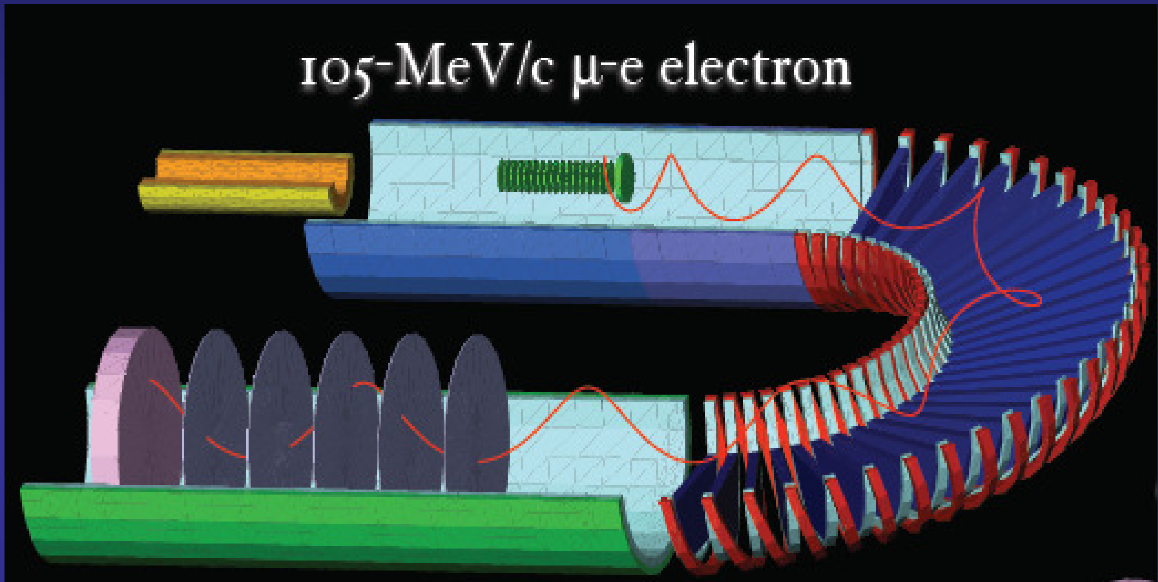
	aluminium	titanium	lead
Atomic number	13	22	82
Lifetime of muonic atoms(μs)	0.88	0.33	0.082
Relative $\mu^- \rightarrow e^-$ conversion branching ratio	1	1.7	1.15

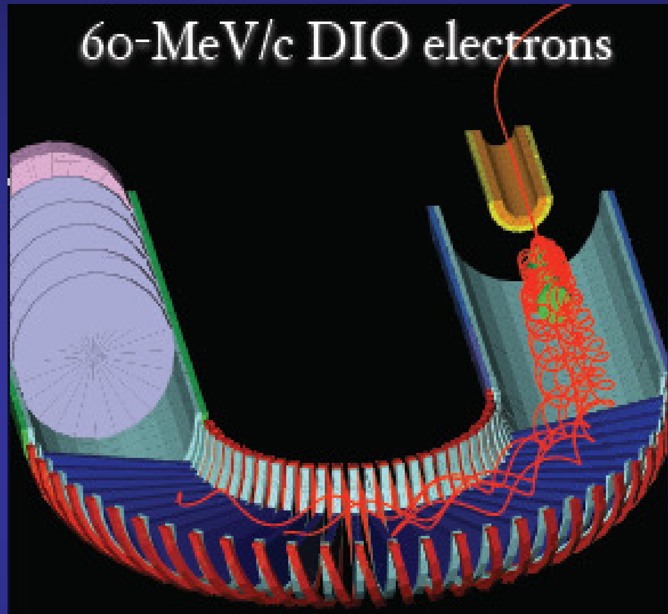
Muon Stopping Target Field



- Graded magnetic field from 3T to 1T
  - Reflect backward going conversion electrons.
  - Maximise acceptance for conversion electrons.
- Stopping efficiency of this design is 0.66
- Optimisation of geometry is one of the areas being studied in the UK.

Electron Spectrometer

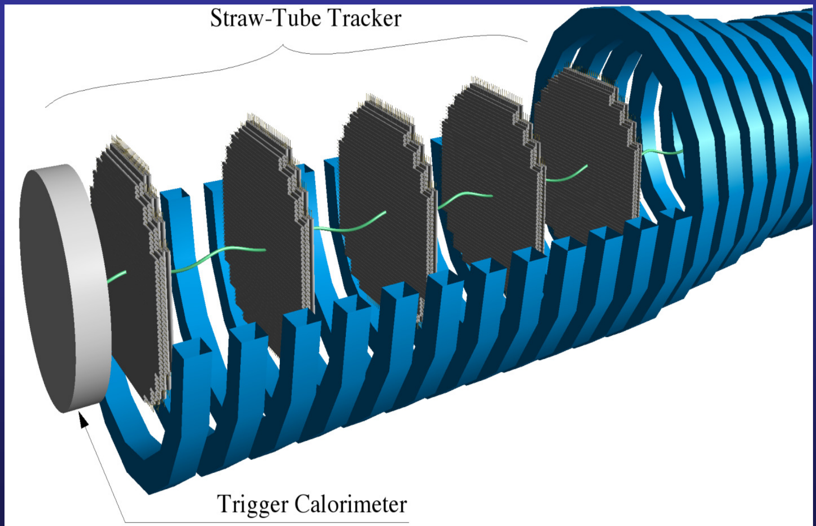


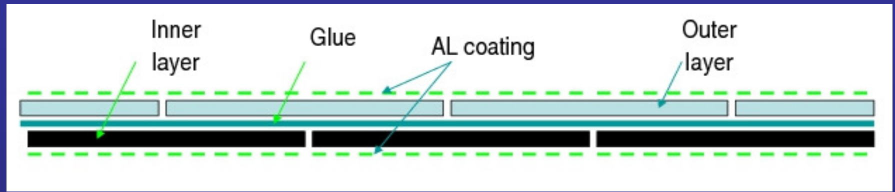


- One component that is not included in the Mu2e design.
- 1T solenoid with additional 0.17T dipole field.
- Vertical dispersion of toroidal field allows electrons with P<60MeV/c to be removed.
  - reduces rate in tracker to ~1kHz.

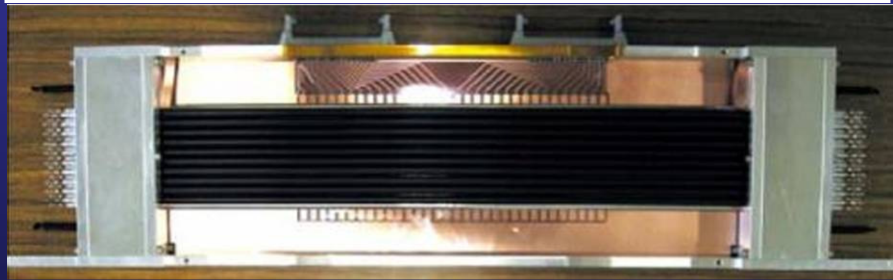
Tracker

- Requirements
  - operate in a 1T solenoid field.
  - operate in vacuum (to reduce multiple scattering of electrons).
  - 800kHz charged particle rate and 8MHz gamma rates
  - 0.4% momentum and 700μm spatial resolution.
- Current design utilises straw tube chambers
  - Straw tubes 5mm in diameter. Wall composed of two layers of 12μm thick metalized Kapton glued together.
- 5 planes 48cm apart with 2 views (x and y) per plane and 2 layers per view (rotated by 45° to each other).





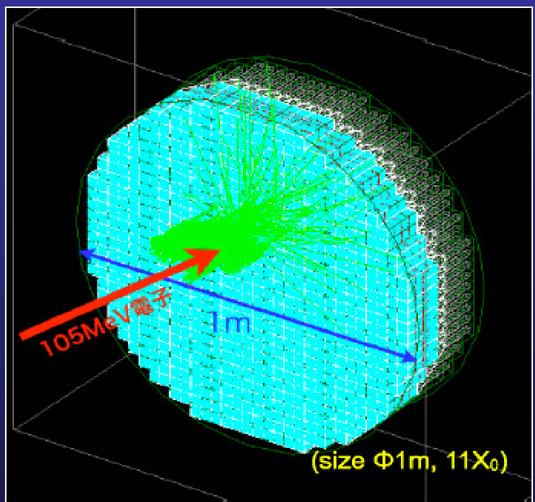
Straw wall cross-section.

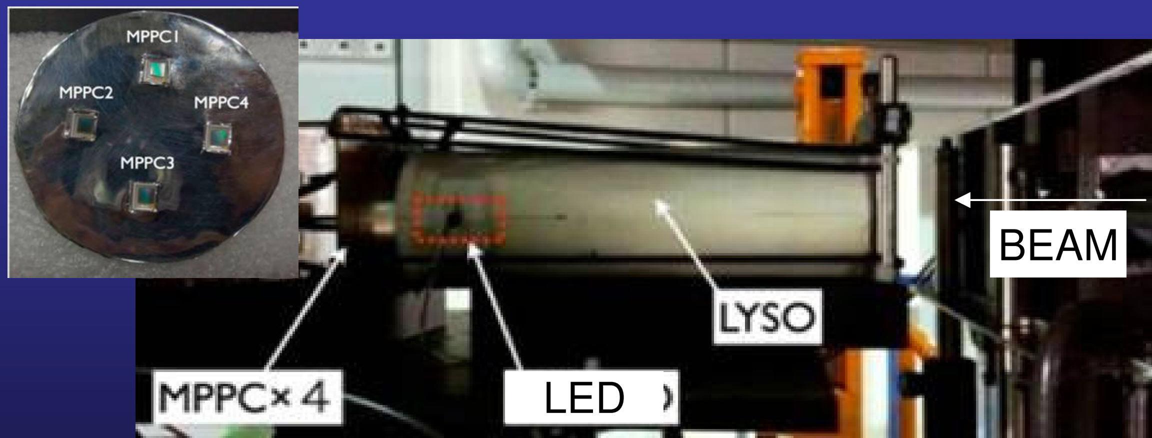


350mm long seamless straw tube prototype.

Calorimeter

- Measure energy, PID and give additional position information. Can be used to make a trigger decision.
- 5% energy and 1cm spatial resolution at 100MeV
  - High segmentation (3x3x15 cm^3 crystals)
- Candidate inorganic scintillator materials are Cerium-doped Lutetium Yttrium Orthosilicate (LYSO) or Cerium-doped Gd_2SiO_5 (GSO).
- Favoured read out technology is multi–pixel photon counters (MPPC).
  - high gains, fast response times and can operate in magnetic fields.
- R&D by Osaka group. Further beam tests planned for November.





100 MeV electron beam tests at Tohoku University

Other Detectors

- Cosmic ray veto counters.
  - Needs to cover a large area.
  - Efficiency 99.99%.
- Muon intensity monitor.
  - X-rays from stopped muons.
- Calibration system for electron momentum.
  - Use pions?
  - Electron linac?
- Late-arriving particle tagger in muon beamline.
  - Only active after main beam pulse.
  - Momentum? PID?
  - Silicon pixels or diamond pixels?
  - Design being done in the UK.

Summary and Future Plans

- COMET is an exciting project to work on!
  - Promises factor 10,000 improvement on current best limit.
- Accelerator is intimately linked to the detector systems.
  - Challenges for the design and simulation of the experiment.
- To achieve sensitivity requires the development of accelerator and detector technology
  - Intense, cleanly pulsed, proton beams.
  - Superconducting solenoid technology.
  - Transport channels for large emittance beams.
  - Tracker technology, cost-effective calorimeter technology, late-arriving particle tagger.
- COMET has Stage-1 approval from J-PARC. Technical Design Report planned to be submitted by end of 2010.