Wishful Staging Scenario from MuSIC to NF

2009-2016
MuSIC

Proton beam: 0.4kW
DC muon: $10^8$/s

µ-eee search
Solenoid R&D
Accelerator R&D

2017-
COMET/Mu2e

Proton beam: 56kW
pulsed muon: $10^{11}$/s

µ-e conv. search

2020?
PRISM

Proton beam: 1000-4000kW
pulsed muon: $10^{12-13}$/s

The ultimate µ-e conv. study

2019??

Neutrino factory
Muon collider

pulsed muon: $10^{13-14}$/s

MuSIC is a very important step for the future muon programs.
# Staging Programs for the $\mu$-e conversion

<table>
<thead>
<tr>
<th></th>
<th>MuSIC</th>
<th>COMET</th>
<th>PRISM/PRIME</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics</strong></td>
<td>$\mu\rightarrow$eee nuclear physics material science</td>
<td>$\text{BR}(\mu\rightarrow e) &lt; 10^{-16}$</td>
<td>$\text{BR}(\mu\rightarrow e) &lt; 10^{-18}$</td>
</tr>
<tr>
<td><strong>$\mu$ intensity</strong></td>
<td>$10^{8}\mu/s$</td>
<td>$10^{11}\mu/s$</td>
<td>$10^{12}\mu/s$</td>
</tr>
<tr>
<td><strong>DC/Pulse</strong></td>
<td>DC</td>
<td>Pulse width $&lt;100\text{ns}$</td>
<td>Pulse width $&lt;10\text{ns}$</td>
</tr>
<tr>
<td><strong>Phase Potation?</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Proton Beam</strong></td>
<td>400W (400MeV, 1$\mu$A)</td>
<td>56kW (8GeV, 7$\mu$A)</td>
<td>2MW (2-5GeV?)</td>
</tr>
<tr>
<td><strong>$B_{\text{max}}$ of $\pi$ Capture Solenoid</strong></td>
<td>3.5 Tesla</td>
<td>5 Tesla</td>
<td>5 Tesla</td>
</tr>
</tbody>
</table>
Comparison on the pion capture systems

<table>
<thead>
<tr>
<th></th>
<th>MuSIC</th>
<th>COMET</th>
<th>PRISM</th>
<th>NuFact&lt;sup&gt;(1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muon Intensity</strong></td>
<td>$10^8$/sec</td>
<td>$10^{11}$/sec</td>
<td>$10^{12}$/sec</td>
<td>$10^{12-13}$/sec</td>
</tr>
<tr>
<td><strong>Muon Momentum</strong></td>
<td>20-70 MeV/c (Backward)</td>
<td>20-70 MeV/c (Backward)</td>
<td>20-70 MeV/c (Backward)</td>
<td>170-500 MeV/c (Forward)</td>
</tr>
<tr>
<td><strong>Time structure</strong></td>
<td>Continuous</td>
<td>Pulsed</td>
<td>Pulsed</td>
<td>Pulsed</td>
</tr>
<tr>
<td><strong>Proton Beam Power</strong></td>
<td>400W (0.4GeV)</td>
<td>56kW (8GeV)</td>
<td>2-3MW (~8GeV)</td>
<td>4MW (8GeV)</td>
</tr>
<tr>
<td><strong>Production Target</strong></td>
<td>Graphite</td>
<td>Tungsten</td>
<td>Tungsten?</td>
<td>Mercury jet</td>
</tr>
<tr>
<td><strong>Capture Solenoid Max. Field Strength</strong></td>
<td>3.5 T</td>
<td>5.0 T</td>
<td>12-16 T</td>
<td>20 T</td>
</tr>
<tr>
<td><strong>Inner radius of Main SC Coil</strong></td>
<td>0.45 m</td>
<td>0.65 m</td>
<td>?</td>
<td>0.64 m</td>
</tr>
<tr>
<td><strong>Outer radius of Main SC Coil</strong></td>
<td>1.0 m</td>
<td>1.6 m</td>
<td>?</td>
<td>1.78 m</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> Based on The Muon Collider/Neutrino Factory Target System, H.Kirk and K.McDonald (Aug.14,2010) and Study-II report
Backward and Forward Pion/Muon

Figure 4.1: Pion production in a graphite target. (top) correlation between $p_L$ and $p_T$, (middle) Total momentum distributions for forward and backward $\pi^−$, (bottom) $p_T$ distributions for $0.2 < p_L < 0.4$ GeV/c, $0.0 < p_L < 0.2$ GeV/c, and $0.2 < p_L < 0.4$ GeV/c.

- The yield of pions at low energy decreases as the radius of the target increases. This would be explained by the absorption of pions at low energy. The optimum radius is about 0.5 cm.
- One of the disadvantages of heavy metals is their low melting point. They might melt down when a proton beam of 1 MW beam power hits. On the other hand, it has been known that graphite could work with up to beam power of about 1 MW level, with either radiation-cooled or water-cooled configuration, but with the cost of an relatively low pion production yield (which is smaller by a factor of about 3 smaller than in heavier materials). It is however needed to replace frequently due to the radiation damage on the specific heat of graphite.

R&D of the target system has just started. Several options, such as (1) a rotating metal band system, (2) a liquid mercury jet, (3) a tantalum fine particles packed in the titanium casing, and (4) a graphite with radiation or water cooling (as the basic option). All these are studied as the R&D works for the neutrino factory projects in the world-wide. We would like to keep exchange information among various foreign studies.
A lot of radiation to forward direction
MuSIC aims to provide the world intense DC muon beam with the 400W proton beam.
### MuSIC (=MUon Science Innovative Commission)

#### Muon yield estimation

- **0.4 kW (400MeV, 1μA protons)**
- **$10^9$ muons/sec (for MuSIC)**

Nuclear and particle physics, material science chemistry, and accelerator R&Ds will be possible.

#### PRISM-FFAG ring (2014)

- To study the muon phase rotation

This part has been constructed. The first beam time for the MuSIC will be 29-30 July 2010.

Pion capture solenoid and muon transport solenoid

- The first pion capture system, as a prototype of COMET/Mu2E/PRISM
- Neutrino factory

MuSIC final layout plan in 2014
The 1st beam test has been performed at 29-30 July, 2010. The 2nd beam test will be in 13-15 Feb. 2011.
MuSIC in 2010

- GM cryocooler
- SUS radiation shield
- Pion Capture Solenoid (3.5T)
- Iron yoke
- Graphite target
- 1.5Wx2 + 1W
- 1Wx2
- Transport Solenoid (2.0T with 0.04T dipole field)
- Proton beam line

Scale: 1m
Requirements to the superconducting solenoids

- Strong magnetic field on the pion production target
  - Trap pions in 3.5 T
  - Superconducting coils surrounding the target
- Long solenoid transport channel with a big aperture
  - Pions decay out and muons transported in 2T solenoid
  - ~10m long
  - 360mm dia. bore
  - Correction dipole field for momentum and charge selection
- LHe free refrigeration
  - Conduction cooling by GM cryocoolers
    - Heat deposit on the coils < 1W
    - Dose < 1MGy
      - for insulator, glue ...
    - Neutron flux < $10^{20}$n/m²
      - avoid degradation of the stabilizer of SC wires
Pion capture solenoid: radiation issue

- Radiation shields (27cm thick stainless steels) are installed b/w the target and the coils.
- MC simulation by MARS (M. Yoshida)
  - Heat deposit: 0.6W
    - 0.4W in the coils (~1ton)
    - 0.2W in the coil supports
  - Dose on the coils < 10kGy/year
- Heat load
  - 100W on the target
  - 50W on the rad. shields
- Neutron flux: $5 \times 10^{18}$n/m$^2$/year
  - no degradation is expected
## Pion capture solenoid: parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Cu-stabilized NbTi</td>
</tr>
<tr>
<td>Cable diameter</td>
<td>$\phi 1.2$mm</td>
</tr>
<tr>
<td>Cu/NbTi ratio</td>
<td>4</td>
</tr>
<tr>
<td>RRR (R293K/R10K at 0T)</td>
<td>230-300</td>
</tr>
<tr>
<td>Operation current</td>
<td>145A</td>
</tr>
<tr>
<td>Max field on axis</td>
<td>3.5T</td>
</tr>
<tr>
<td>Bore</td>
<td>$\phi 900$mm</td>
</tr>
<tr>
<td>Length</td>
<td>1000mm</td>
</tr>
<tr>
<td>Inductance</td>
<td>400H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>5MJ</td>
</tr>
<tr>
<td>Quench back heater</td>
<td>1.2mm dia.</td>
</tr>
<tr>
<td>Cu wire</td>
<td>$\sim 1\Omega@4K$</td>
</tr>
</tbody>
</table>
Transport solenoids

**Solenoid coils**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation current</td>
<td>145A</td>
</tr>
<tr>
<td>Field on axis</td>
<td>2T</td>
</tr>
<tr>
<td>Bore</td>
<td>φ480mm</td>
</tr>
<tr>
<td>Length</td>
<td>200mm ×8 Coils</td>
</tr>
<tr>
<td>Inductance</td>
<td>124H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>1.4MJ</td>
</tr>
<tr>
<td>Quench back heater Cu wire</td>
<td>~0.05Ω/Coil@4K</td>
</tr>
</tbody>
</table>

**Correction dipole coils**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil layout</td>
<td>Saddle shape dipole</td>
</tr>
<tr>
<td></td>
<td>6 layers</td>
</tr>
<tr>
<td></td>
<td>528 turns (1 set)</td>
</tr>
<tr>
<td>Current</td>
<td>115A (Bipolar)</td>
</tr>
<tr>
<td>Field</td>
<td>0.04T</td>
</tr>
<tr>
<td>Aperture</td>
<td>φ460mm</td>
</tr>
<tr>
<td>Length</td>
<td>200mm</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.04H/Coil</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>280J/Coil</td>
</tr>
</tbody>
</table>

The world first working beam line which adopts \( \cos \theta \) winding dipole coils
Refrigeration

- Conduction cooling by GM cryocoolers
- Can be cooled down within 1 week with pre-cooling by LN2

- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 300K→40K: 50W
    - GM 1st stage
  - 3 x GM cryocooler
    - 1.5Wx2+1Wx1 @4K
    - 45Wx2+44W @40K

- Transport solenoid
  - 4K: 0.8W
  - 300K→40K: 50W
    - GM 1st stage
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K
    - 44Wx2 @40K

- Achievable temperature
  - Pion capture solenoid: 3.7K
  - Transport solenoids: 4.2K-4.5K(BT3), 4.5K-5.8K(BT5)
Expected Muon Yield

- MC simulations were performed from the production target to the end of the transport solenoid (180°).
  - by Dr. M. Yoshida
- **Simulation codes:**
  - Hadron production at the graphite target
    - MARS
  - Tracking in the magnetic field
    - g4beamline
Simulation results for $B_y=\pm 0.04T$

This is just an example. We need to optimize the beam characteristic for various experiments using collimators, DC separators, and so on.

- At the end of the transport solenoid (180 deg.)
- Charge of the muons can be selected by changing the direction of the dipole field.

8x10^8 $\mu^+$/sec for 400MeV, 1 $\mu$A proton beam

2x10^8 $\mu^-$/sec for 400MeV, 1 $\mu$A proton beam
Charged Particle Trajectory in Curved Solenoids

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

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

\( D \) : drift distance
\( B \) : Solenoid field
\( \theta_{\text{bend}} \) : Bending angle of the solenoid channel
\( p \) : Momentum of the particle
\( q \) : Charge of the particle
\( \theta \) : \( \text{atan}(P_T/P_L) \)

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

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

\( p \) : Momentum of the particle
\( q \) : Charge of the particle
\( r \) : Major radius of the solenoid
\( \theta \) : \( \text{atan}(P_T/P_L) \)

• This effect can be used for charge and momentum selection.
COMET and Mu2E: S.E.S. $\approx 10^{-16}$

- To achieve a single event sensitivity (S.E.S.) of $10^{-16}$, we need:
  - High intense muon beam: $\sim 10^{11}$ μ/sec
  - Pulsed muon beam: for the BG rejection
- Two experiments have been proposed to be carried out around 2016.

**COMET at J-PARC**

- **Pion Capture Section**: A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.

- **Detector Section**: A detector to search for muon-to-electron conversion processes.

- **Pion-Decay and Muon-Transport Section**: A section to collect muons from decay of pions under a solenoidal magnetic field.

**Mu2E at Fermilab**

- **Superconducting Target**
- **Muon Stopping**
- **Straw Tracker**
- **Superconducting Transport Solenoid** ($2.5 \ T \pm 2.1 \ T$)
- **Superconducting Production Solenoid** ($5.0 \ T \pm 2.5 \ T$)
- **Collimators**
- **Superconducting Detector Solenoid** ($2.0 \ T \pm 1.0 \ T$)
- **Crystal Calorimeter**

Aim for $10^{-16}$

After the cancellation of the MECO experiment in 2005

- **Stage-1 approval July 2009 at J-PARC**
- **CD0 approval Nov. 2009 by DOE**
The PRISM-FFAG Task Force was proposed and discussed during the last PRISM-FFAG workshop at ICL (1-2 July’09).

The aim of the Task Force is to address the technological challenges in realizing an FFAG based $\mu$-e conversion experiment, but also to strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.

The following key areas of activity were identified and proposed to be covered within the Task Force:

- physics of muon to electron conversion,
- proton source,
- pion capture,
- muon beam transport,
- injection and extraction for PRISM-FFAG ring,
- FFAG ring design including the search for a new improved version,
- FFAG hardware R&D for RF system and injection/extraction kicker and septum magnets.

Studies will continue to obtain a feasible design, aiming on CDR in 2011.

Synergy between PRISM and Neutrino Factory
Members of PRISM Task Force

- J. Pasternak (contact person), Imperial College London / RAL STFC
- L. J. Jenner, A. Kurup, Imperial College London / Fermilab
- Y. Uchida, Imperial College London
- B. Muratori, S. L. Smith, Cockcroft Institute / STFC-DL-ASTeC
- K. M. Hock, Cockcroft Institute / University of Liverpool
- R. J. Barlow, Cockcroft Institute / University of Manchester
- C. Ohmori, KEK/JAEA
- H. Witte, T. Yokoi, JAI, Oxford University
- J-B. Lagrange, Y. Mori, Kyoto University, KURRI
- Y. Kuno, A. Sato, Osaka University
- D. Kelliher, S. Machida, C. Prior, STFC-RAL-ASTeC
- M. Lancaster, University College London

Welcome to join us!

Many young physicists. We are trying to apply our skills, which got thorough the NF related studies, to the muon physics experiment!

as on IPAC’10 paper
Staging Plan of $\mu$-e conv. in Japan

1st Stage: COMET
- 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

2nd Stage: PRISM/PRIME
- 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

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

$B(\mu^- + Ti \to e^- + Ti) < 10^{-18}$
Schematic Layout of New PRISM

- Detector Solenoid
- Spectrometer Solenoid
- Muon Stopping Target
- Muon Storage Ring (Phase Rotator)
- Pion and Muon Transport Solenoid
- Pion Production Target
- Pulsed Proton Beam
- Pion Capture Solenoid

[Diagram of PRISM layout with labeled components]
The first SC pion capture system has been build in Osaka for MuSIC.

Design study for the COMET/PRISM capture solenoid.

- Measurement of radiation heating using a mockup.

- Neutron Irradiation Experiments for Pure Stabilizers at Low Temperature

- MgB$_2$?
Experimental Conditions (KEK 12GeV-PS)

Beam parameters
- 12 GeV proton
- Intensity $\sim 10^{11}$ (protons/sec)
- Slow extraction

Experimental area
- At upstream of EP2-A dump
Experimental setup

- Sensitive measurement of radiation heat load to the mockup with the cryo-calorimeter

12GeV primary protons $10^{11}$ (p/s)

Beam monitors

SEC (Cu foil)

Cryostat

Cryo-calorimeter

Cryo-cooler

Mockup

Thermal shunt

Movable target (0.2 interaction length)

Beam dump
Experimental Installation

12GeV VPS primary protons

12GeV $\sim 10^{11}$ (p/s)

Cryostar

Beam dump

Mockup

Experimental area

Beam Dump

240 mm
How to Measure Radiation Heat Load

Thermal equilibrium state!

Mockup

Heater

$T_{heater}$

$Q_{heater}(W)$

GM cryocooler

Thermal shunt

Mockup temperature

Temperature

Time

$T_{beam} = T_{heater}$

$Q_{beam} = Q_{heater}$
The uncertainty of the beam intensity mainly arises from the copper activation foil data. In the simulation, the cutoff energy of all particles was 10 GeV, while that of neutrons was 2 GeV. Other particles were respectively set to be 80 and 23 MeV. In PHITS183, the default value for the cutoff parameters for protons was 250 MeV. We studied the effect of various input parameters, such as the cutoff energy used in both the target and the absorbers. The results were compared with the experimental data within 35%. The tendency of the position dependence was well reproduced in both simulations.

The radiation heat induced by secondary particles from a production copper target at the beam position dominantly contributes to the heat loads (W) and beam intensities. Finally, normalized heat flux.

**Fig. 12.** Comparison of the simulation results with the experimental data. Both simulation results agree with the experimental data within 35%. The normalized heat flux.

The measured radiation heat is shown in Fig. 12.
Relationship among the programs

towards the ultimate $\mu$-e conversion study

**PRISM-FFAG R&D**
- large FFAG magnets, high field grad. RF system, phase rotation demo. $\alpha$
- FFAG design
- Study results

**MuSIC**
- 2010-
- super-conducting solenoid, $\mu$ phase rotation, tests of new ideas
- Test results of $\pi$ capture and transport solenoid

**PRISM-TF**
- 2009-
- Reconsideration of PRISM design, lattice, matching, inj./ext., kicker ...
- FFAG design

**COMET/Mu2E**
- S.E.S. $<10^{-16}$, for early realization
- Test results of new ideas with muon beam
- Study results

**PRISM**
- The ultimate $\mu$-e Study, S.E.S. $<10^{-18}$, Target dependence
- New design and results of feasibility studies
- Upgrade

**Neutrino Factory and Muon Collider R&Ds**
- Study results

**Technological Synergy**

Akira SATO

NuFact10, 20-25 October 2010, TIFR, Mumbai, India