Search for Lepton Flavor Violating Muon to Electron Conversion at J-PARC

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Outline

• Physics Motivation of Low Energy Muon Particle Physics
  • Why Precision Frontier ?
  • Why Lepton Flavor Violation (LFV) ?
  • Why Muons ?
• Phenomenology of LFV of Charged Leptons
  • LFV and Supersymmetry (SUSY)
  • Search for muon to electron conversion process
• New Experimental Proposals at J-PARC
  • COMET
  • PRISM
• R&D for PRISM Muon Storage Ring (FFAG Ring)
• Summary
Physics Motivation
Goal of Particle Physics

• The Standard Model of Particle Physics is known to be incomplete. It is considered to be a low-energy approximation of a more-complete theory.

• To understand a more-complete theory, search for New Physics at High Energy Scales.
Electroweak Epoch
- Higgs particles
- Supersymmetry

Unification Epoch
- Grand unification of fundamental forces
- Origin of Neutrino mass (RH neutrino)
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch
- Superstrings

Time scale:
- $10^{13}$ sec
- $10^{2}$ sec
- $10^{-10}$ sec
- $10^{-34}$ sec

Energy scale:
- $10^{-9}$ GeV
- $10^{-3}$ GeV
- $10^{2}$ GeV
- $10^{16}$ GeV
- $10^{19}$ GeV

We are here
History of the Universe

- Electroweak Epoch
  - Higgs particles
  - Supersymmetry
- Unification Epoch
  - Grand unification of fundamental forces
  - Origin of Neutrino mass (RH neutrino)
  - Leptogenesis (baryogenesis)
- Quantum Gravity Epoch
  - Superstrings

We are here
How to Study Phenomena at Higher Energy?

(1) High Energy Frontier Measurements
- Direct searches for new physics
- Energy scale to reach is $O(\text{TeV})$
  - LHC (~14 TeV), ILC (0.5 TeV$\rightarrow$), muon collider (multi TeV)

(2) High Precision Frontier Measurements
- Indirect searches for new physics at low energy
  - radiative corrections (renormalization equations)
- Energy scale to reach could be much higher than accelerators.
- Effects are small.
  - High precision measurements
  - High intensity beams
Which Processes for New Physics in Low Energy?

- Processes which are forbidden or highly suppressed in the Standard Model would be the best ones to search for new physics beyond the Standard Model.
- **Flavor Changing Neutral Current Process (FCNC)**
  - **FCNC in the quark sector**
    - $b \to s\gamma$, $K \to \pi\nu\nu$, etc.
    - Allowed in the Standard Model.
    - Need to study deviations from the SM predictions.
      - Uncertainty of more than a few % (from QCD) exists.
  - **FCNC in the lepton sector**
    - $\mu \to e\gamma$, $\mu + N \to e + N$, etc. (*lepton flavor violation* = LFV)
    - Not allowed in the Standard Model ($\sim 10^{-50}$ with neutrino mixing)
    - Need to study deviations from none
      - Clear signature and high sensitivity
Why Muons, not Taus for LFV Search?

- A number of taus available at B factories are about $1-10$ taus/sec. At super-B factories, about $100$ taus/sec are considered. Also some of the decay modes are already background-limited.
  - intensity improvement factor of about $O(10)$.

- The number of muons available now, which is about $10^8$ muons/sec at PSI, is the largest. Next generation experiments aim $10^{11}-10^{12}$ muons/sec. With the technology of the front end of muon colliders and/or neutrino factories, about $10^{13}-10^{14}$ muons/sec are considered.
  - intensity improvement factor of about $O(1,000,000)$

Synergy in Technology between Muon Physics and MCNF
Which Muon Processes for High Intensity Measurements?

- List of typical muon LFV processes
  - $\mu^+ \rightarrow e^+ \gamma$
  - $\mu^+ \rightarrow e^+ e^+ e^-$
  - $\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)$
  - $\mu^- + N(A, Z) \rightarrow e^+ + N(A, Z - 2)$

- When a high intensity beam is used, measurements that need coincidence requirements in detection of daughter particles would suffer from huge accidental backgrounds.
- Only experiments that have single particle detection would make the best use of high intensity of $10^{14}$ muons/sec.
  - muon-to-electron conversion ($\mu + N \rightarrow e + N$)
  - muon g-2, muon EDM ($\mu \rightarrow e \nu \nu$)
# Present Limits and Expectations in Future

<table>
<thead>
<tr>
<th>process</th>
<th>Present limit</th>
<th>Near Future</th>
<th>MC&amp;NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \rightarrow e\gamma$</td>
<td>$1.2 \times 10^{-11}$</td>
<td>$10^{-13}$ (MEG)</td>
<td></td>
</tr>
<tr>
<td>$\mu \rightarrow eee$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>$10^{-13} - 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td>$\mu N \rightarrow eN$ (in Tl)</td>
<td>$4.3 \times 10^{-12}$</td>
<td>$10^{-18}$ (PRISM)</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>$\mu N \rightarrow eN$ (in Al)</td>
<td>none</td>
<td>$10^{-16}$ (mu2e,Pl)</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>$\tau \rightarrow e\gamma$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow eee$</td>
<td>$2.7 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\gamma$</td>
<td>$6.8 \times 10^{-8}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$</td>
<td>$2 \times 10^{-7}$</td>
<td>$10^{-8} - 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>
Lepton Flavor Violation of Charged Leptons
Lepton Flavor Violation of Charged Leptons (Charged Lepton Mixing)

What is The Contribution to Charged Lepton Mixing from Neutrino Mixing?

- Neutrino Mixing (confirmed)
  - $\nu_e$ $\leftrightarrow$ $\nu_\mu$ $\leftrightarrow$ $\nu_\tau$
  - $e$ $\leftrightarrow$ $\mu$ $\leftrightarrow$ $\tau$

- Charged Lepton Mixing (not observed yet)
  - Very Small ($10^{-52}$)
  - Sensitive to new Physics beyond the Standard Model

$\propto \left(\frac{m_\nu}{m_W}\right)^4$
Various Models Predict Charged Lepton Mixing.

Sensitivity to Different Muon Conversion Mechanisms

- **Supersymmetry Predictions at $10^{15}$**
- **Compositeness**
  - $\Lambda_c = 3000$ TeV

- **Heavy Neutrinos**
  - $|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$

- **Leptoquarks**
  - $M_L = 3000 \left(\lambda_{\mu d}^{\lambda_{ed}}\right)^{1/2} \text{TeV/c}^2$
  - After W. Marciano
  - $B(Z \rightarrow \mu e) < 10^{-17}$

- **Second Higgs doublet**
  - $g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu \mu}}$

- **Heavy $Z'$, Anomalous $Z$ coupling**
  - $M_{Z'} = 3000$ TeV/c$^2$
LFV in SUSY Models

\[
\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{200}
\]

(photon being attached to quarks in nucleons)

\[\tilde{W} \tilde{\nu}_\mu \rightarrow e \gamma \tilde{\nu}_e \]

The decay rates is determined by SUSY-mass scale but the dot includes higher energy information.

Through quantum corrections, LFV could access ultra-heavy particles such as $\nu_R$ ($\sim 10^{12}-10^{14}$ GeV/c$^2$) and GUT that cannot be produced directly by any accelerators.

SUSY GUT and SUSY Seesaw
SUSY Predictions for LFV with Muons

\[
\text{Experimental bound, } \tan \beta = 30
\]

\[
\text{MEG, COMET, super-MEG, PRISM}
\]

\[
M_{\tau} = 130 \text{GeV}, m_{\mu} = 170 \text{GeV}, m_{\nu} = 0.07 \text{eV}, m_{\chi} = 0.004 \text{eV}
\]

\[
\text{Experimental bound, } \tan \beta = 3, 10, 30
\]

\[
\text{MEG, COMET, super-MEG, PRISM}
\]

\[
\text{SU(5) SUSY GUT, SUSY Seesaw Model}
\]
Energy Frontier, SUSY, and Charged Lepton Mixing

- In SUSY models, charged lepton mixing is sensitive to slepton mixing.
- LHC would have potentials to see SUSY particles. However, at LHC nor even ILC, slepton mixing would be hard to study in such a high precision as proposed here.

- Slepton mixing is sensitive to either (or both) Grand Unified Theories (SUSY-GUT models) or neutrino seesaw mechanism (SUSY-Seesaw models).
- If LFV sensitivity is extremely high, it might be sensitive to multi-TeV SUSY which LHC cannot reach, in particular SUSY models.
Searches in the Past

- No lepton flavor violation in the Standard Model.
- No lepton flavor violation in the charged lepton sector has been observed, although it in the neutrino sector has been observed.
- Upper limit improved by two orders of magnitude.
1s state in a muonic atom

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

μ^- + (A,Z) → e^- + (A,Z)

B(μ^- N → e^- N) = \frac{\Gamma(μ^- N \rightarrow e^- N)}{\Gamma(μ^- N \rightarrow νN')}

What is a μ-e Conversion?
**μ-e Conversion**

**Signal and Backgrounds**

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

- **Signal**
  - single mono-energetic electron
  - coherent process (the same initial and final nucleus)
    \[ m_\mu - B_\mu \sim 105 \text{MeV} \]
    \[ \propto Z^5 \]

- **Backgrounds**
  - Muon decay in orbit
    - Endpoint comes to the signal region
      \[ \propto (\Delta E)^5 \]
  - Radiative muon capture
  - Radiative pion capture
    - pulsed beam required
    - wait until pions decay.
  - Electrons from muon decays in flight
  - Cosmic rays
  - and many others
Comparison between $\mu \rightarrow e\gamma$ and $\mu$-$e$ Conversion (Physics sensitivity)

<table>
<thead>
<tr>
<th></th>
<th>Photonic</th>
<th>Non-Photonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \rightarrow e\gamma$</td>
<td>yes (on-shell)</td>
<td>no</td>
</tr>
<tr>
<td>$\mu$-$e$ conversion</td>
<td>yes (off-shell)</td>
<td>yes</td>
</tr>
</tbody>
</table>

Photonic and non-photonic (SUSY) diagrams

\[
\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \sim \frac{1}{100}
\]
The SINDRUM-II Experiment (at PSI)

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. But, it could not work at a high rate.

Published Results

\[ B(\mu^- + Ti \rightarrow e^- + Ti) < 4.3 \times 10^{-12} \]
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

Cancelled in 2005
Mu2E @ Fermilab

- The mu2e Experiment at Fermilab.
- EOI and LOI have been submitted. It is well accepted.
- After the Tevatron shut-down.
- use the antiproton accumulator ring and the debuncher ring to manipulate proton beam bunches.
- sNUMI running with Nova.
- with Project-X in future.
New Experimental Proposal at J-PARC
J-PARC at Tokai, Japan
COMET/PRISM Projects in Japan

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

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

PRISM

- 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

\[ B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18} \]
Aiming the World Highest Muon Beam Intensity!

- Highest Muon Beam Intensity
  - $10^{11} - 10^{12}$/sec
  - $10^3 - 10^4$ times the PSI muon beam intensity
- Pion capture with large solid angle by a solenoidal magnetic field
- A superconducting solenoid (SC) magnet surrounding a proton target
- Good matching to muon transport beam line consisting of SC magnets
- Dedicated channel
  - One beam line / target.

![Graph showing normalized muon beam intensity](image)
mSUGRA with right-handed neutrinos will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.

Sensitivity Goal

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

\[ B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18} \]
COMET
Overview of the COMET Experiment (COherent Muon to Electron Transition)

The beamline design is very important.

- **Proton Beam**

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

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

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**Protons**

**Production Target**

A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.

**Pion Capture Section**

**Pion-Decay and Muon-transport Section**

A section to collect muons from decay of pions under a solenoidal magnetic field.
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 $\sim 1\mu\text{sec}$ 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) $\sim 0.7$ sec
  - good to be shorter for cosmic-ray backgrounds.
Proton Beam (2)

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

- Required Protons:
  - $8 \times 10^{20}$ protons of 8 GeV in total for a single event sensitivity of about $0.3 \times 10^{-16}$.
  - For $2 \times 10^7$ sec running, $4 \times 10^{13}$ protons /sec ($= 7 \mu$A).
  - 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 15$\mu$A).

Test of Extinction at BNL-AGS
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.

\[ P_T(\text{GeV/c}) = 0.3 \times B(T) \times \left( \frac{R(m)}{2} \right) \]

- B=5T, R=0.2m, \( P_T = 150\text{MeV/c} \).

- 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
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 ≈ 2x10^{-3}).
  - high transport efficiency ($P_\mu$~40 MeV/c)
  - negative charge selection
  - low momentum selection ($P_\mu$<75 MeV/c)

- Straight + curved solenoid transport system is adopted.
Transport Solenoid Design
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
\( \theta_{bend} \): Bending angle of the solenoid channel
\( p \): Momentum of the particle
\( q \): Charge of the particle
\( \theta \): \( \text{atan}(P_T/P_L) \)

• This 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
\( \theta \): \( \text{atan}(P_T/P_L) \)

Tilt angle=1.43 deg.
Detector Components

- a muon stopping target, curved solenoid, tracking chambers, and a calorimeter/trigger and cosmic-ray shields.
- Curved Solenoid: to eliminate low-energy beam particles and to transport only ~100 MeV electrons.
- Detector Section: under a solenoid magnetic field.
- Target Section: to stop muons in the muon stopping target.

To detect and identify 100 MeV electrons.
Electron Detection (preliminary)

Straw-tube Trackers to measure electron momentum.
• Should work in vacuum and under a magnetic field.
• A straw tube has 25\(\mu\)m 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.
• 250\(\mu\)m position resolution.

Under a solenoidal magnetic field of 1 Tesla.
In vacuum to reduce multiple scattering.

Electron calorimeter to measure electron energy and make triggers.
• Candidate are GSO or PbWO2.
• APD readout (no PMT).
Signal Sensitivity (preliminary) - 2 SSC years

- Single event sensitivity

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

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

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>total protons</td>
<td>( 8 \times 10^{20} )</td>
</tr>
<tr>
<td>muon transport efficiency</td>
<td>0.0071</td>
</tr>
<tr>
<td>muon stopping efficiency</td>
<td>0.26</td>
</tr>
<tr>
<td># of stopped muons</td>
<td>( 1.5 \times 10^{18} )</td>
</tr>
</tbody>
</table>

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

\[ B(\mu^- + Al \rightarrow e^- + Al) < 5 \times 10^{-17} \quad (90\% \text{ C.L.}) \]
# Background Rejection Summary (preliminary)

<table>
<thead>
<tr>
<th></th>
<th>Backgrounds</th>
<th>Events</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Muon decay in orbit</td>
<td>0.05</td>
<td>230 keV resolution</td>
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<tr>
<td></td>
<td>Radiative muon capture</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muon capture with neutron emission</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muon capture with charged particle emission</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>Radiative pion capture</td>
<td>0.12</td>
<td>prompt</td>
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<tr>
<td></td>
<td>Radiative pion capture*</td>
<td>0.002</td>
<td>late arriving pions</td>
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<tr>
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<td>Muon decay in flight*</td>
<td>&lt;0.02</td>
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</tr>
<tr>
<td></td>
<td>Pion decay in flight*</td>
<td>&lt;0.001</td>
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<td>Beam electrons*</td>
<td>0.08</td>
<td>for high energy neutrons</td>
</tr>
<tr>
<td></td>
<td>Neutron induced*</td>
<td>0.024</td>
<td>for 8 GeV protons</td>
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<tr>
<td></td>
<td>Antiproton induced</td>
<td>0.007</td>
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<tr>
<td>(3)</td>
<td>Cosmic-ray induced</td>
<td>0.10</td>
<td>10^{-4} veto &amp; 2x10^7 sec run</td>
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<tr>
<td></td>
<td>Pattern recognition errors</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td>0.4</td>
<td></td>
</tr>
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BG with asterisk needs beam extinction.
Status of the COMET Proposal

• The COMET proposal was submitted to the J-PARC PAC in January, 2009. It is highly evaluated (saying “... would be one of the flagship experiments at J-PARC”), and some requests were made.
  • a more detailed CDR
  • coordination with KEK on a beam line and so on.
  • increase of the collaboration

New Collaborators are welcome to join us.
PRISM Muon Beam

- muon intensity: $10^{11} \sim 10^{12}$ /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination: $10^{-20}$ for 150m

Phase rotation = accelerate slow muons and decelerate fast muons by RF

PRISM = Phase Rotated Intense Slow Muon source
... 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)?
Phase Rotation for a Muon Beam

**Use a muon storage ring?**

1. **Use a muon Storage Ring:**
   - A muon storage ring would be better and realistic than a linac option because of reduction of # of cavities and rf power.

2. **Rejection of pions in a beam:**
   - At the same time, pions in a beam would decay out owing to long flight length.

**Which type of a storage ring?**

1. cannot be cyclotron, because of no synchrotron oscillation.
2. cannot be synchrotron, because of small acceptance and slow acceleration.

**Fixed field Alternating Gradient Ring (FFAG)**
Types of FFAG

- **Scaling type FFAG**
  - betatron tune: constant (zero chromaticity)
  - non-linear field elements

- **Non-scaling type FFAG**
  - betatron tune: not constant
  - linear field elements

Scaling FFAG

\[
B(r, \theta) = B_i \left( \frac{r}{r_i} \right)^k F\left( \theta - \eta \ln \frac{r}{r_i} \right)
\]
A portion of the PRISM-FFAG ring is under construction at Osaka University.
PRISM FFAG Lattice Design

- 10 cells
- $k=5(4.6-5.2)$
- $F/D(BL)=8$
- $r_0=6.5\text{m}$ for $68\text{MeV/c}$
- half gap = 15cm
- mag. size 110cm @ F center
- Triplet
  - $\theta_F=4.40\text{deg}$
  - $\theta_D=1.86\text{deg}$
- tune
  - $h : 2.86$
  - $v : 1.44$
- acceptance
  - $h : 140000 \pi \text{mm mrad}$
  - $v : 6500 \pi \text{mm mrad}$
PRISM-FFAG Acceptance

Horizontal Acceptance
40000 $\pi$ mm mrad

Vertical Acceptance
6500 $\pi$ mm mrad

4D Acc. = 1035.5M(mm.mrad)

N=10
F/D=8
k=5
r0=6.5m
H:2.86
V:144
PRISM FFAG Ring
R&D
PRISM FFAG RF R&D

MA Cavity  Power Supply

PRISM MA Core

1.7m  700cm  3.5cm

156Ω @ 5MHz

(36 kVpp/2) x 2 / 33 x 100 = 108 kV/m

preliminary
PRISM FFAG Magnets

- radial sector with C-type yoke
- D-F-D triplet
  \[ B(r) = B_0 \times \left( \frac{r}{r_0} \right)^k \]
- machined pole shape to create field gradient (k)
- trim coils for variable k values (future)
- vertical tune : F/D
- horizontal tune : k value
- magnetic field design : TOSCA
• Magnetic field measurements for PRISM FFAG magnet has been made in spring, 2006.
• The measured field distribution was compared with TOSCA calculation.
• Differences between them are less than 0.5%. It is within tolerance.
Alpha Particle Tracking with One Magnet Cell

Purpose: study beam dynamics at large amplitudes (non-linearity) by determining a transfer mapping between in and out.

muon 68 MeV/c = alpha particle 2.5 MeV.
One-cell Test Stand under Preparation

- Beam duct
- Injector and detector chamber
- Position detector
- Injector collimator
Transfer Matrix Method with Truncated Taylor Expansion (by Y. Kuriyama)

- The transfer matrix (from one cell boundary to the other) has been experimentally determined by using alpha particles (for different positions, emission angles and energies).
- The transfer matrix is represented by a truncated Taylor expansion of the 5th order.
- By using the transfer matrix thus obtained, the closed orbits and betatron tunes were calculated. They are compared with tracking simulations.
Alpha Particle Tracking with 6 Magnet Cells

Purpose: study demonstration of phase rotation with a 6-cell ring with one RF cavity by single alpha particle tracking. Electric static kicker plus SSD detectors are needed.
PRISM-FFAG 6 Cell Ring Layout
6-Cell PRISM FFAG Magnets at Osaka

PRISM-FFAG (6 sectors) in RCNP, Osaka

Ready to demo. phase rotation
Studies of the 6-cell PRISM FFAG Ring

- Alpha particles from radioactive sources (Am) are used.
- Plastic scintillators and SSD are used for detection.
- Alpha particles that revolve in the ring were observed.
- The closed orbits were determined.
- Betatron tunes are being studied.
- Tests with RF is being prepared.
Muon Source at Osaka University, RCNP

- Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 420 MeV. The energy is above pion threshold.
- A plan is to install the PRISM at RCNP, and inject muons.
  - Test of PRISM FFAG with muons.
  - PRISM front provides high intensity muons.
- Wait for funding in future
Future

Muon Factory

Muon Collider

Neutrino Factory

High Intense Muons
Synergy in Roadmap - Staging Approach

Based on common technologies

Muon Factory
muon LFV, muon g-2, muon EDM, muon application

Neutrino Factory

Energy frontier Muon Collider - 1.5~4 TeV
Summary

• Muon particle physics is important to discover new physics phenomena, in particular lepton flavor violation in muons.
• To carry out muon particle physics, a highly intense muon source of $10^{11}-10^{12}$/sec would be needed.
  • Thanks to neutrino-factory and muon collider R&D, a study of highly intense muon source can be developed.
• The Osaka University group is developing a new highly intense muon source, called PRISM.
• As the first step, a proposal on the COMET experiment, which does not have a muon storage ring, has been submitted to J-PARC MR.
• The muon storage ring R&D (based on FFAG ring) is being done at Osaka University, Research Center for Nuclear Physics (RCNP).
• A muon source at RCNP with PRISM front (~$10^8$) is also planned.
End of My Slides