Report of Activities in Japan

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FFAG-based Scheme

Advantages

- Large acceptance (trans. and vert.)
- Quick Acceleration
- Cooling is not a must. (better if available)

Muon Acceleration based on a series of FFAGs
Japanese Activities
R&D Overview

- International Collaboration
  - MUCCOL
    - LH2 Absorber
  - MICE
    - Scintillating Fiber (SciFi) Trackers
    - LH2 Absorber
  - MERIT
- International Scoping Study
- FFAG R&D in Japan
  - Proton FFAG
  - PRISM
Two types of LH2 absorbers
- Forced flow type
- Convection-driven type

Japanese group (KEK-Osaka U.) started Convection-type R&D.

Advantage of Convection-type:
- less LH2 needed, simple structure

Disadvantage:
- less cooling power ??
- need tests of cooling power with prototype!

MICE a uses convection-type.
The 1st test of LH2 filling test was done at MTA in 2004. showed that 2.4K temperature rise for 20 W. LH2 has 9 K range (Tmin=14K, Tmax=23K). expect 70 W can be take.
Purpose:
- demonstration of 70 W or more cooling power
- measurement of temp. and LH2 level
- forced convection improvements
  - electric heaters (instead of gas heaters)
  - a shorter He transfer line
  - more thermometers
  - liquid-level meter
- wait for safety approval (2006)

2nd LH2 Filling Test

Aims: demonstrate feasibility and performance of a section of cooling channel

Main challenges:
RF in magnetic field!
$10^{-3}$ meas. of emittance
Safety issues

Status:
Approved at RAL(UK)
First beam: 04-2007
Funded in: UK, CH, JP, NL, US
Requests: Be, CH, IT, JP, US

Single-µ beam
~200 MeV/c
**Aims:** demonstrate feasibility and performance of a section of cooling channel

**Main challenges:**
- RF in magnetic field!
- $10^{-3}$ meas. of emittance
- Safety issues

**Cooling cell (~10%)**
- $\beta=5-45\text{cm}$, liquid $H_2$, RF

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**Single-$\mu$ beam**
- ~200 MeV/c

**Japanese Contributions**

Design and construction of Scintillating Fiber (SciFi) trackers
- with FNAL and UK
- fiber supply

VLPC cryostat construction
- with FNAL and UK
- cryo-cooler cooling
SciFi Tests at KEK

Beam test at KEK-PS was done in fall, 2005.
- 4 SciFi stations
- VLPC cryostat with a cryo-cooler.
- solenoid mag. field (1T)
- TOF&ACC for PID

Super JACEE Magnet
### ISS Contribution

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<th>Physics Working Group</th>
<th>Convener</th>
<th>Y. Nagashima</th>
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<td>Phenomenology subgroup</td>
<td>O. Yasuda</td>
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<td>Detector Working Group</td>
<td>Megaton water cherenkov</td>
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<td>Accelerator Working Group</td>
<td>Driver, Acceleration</td>
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- **Physics Cases of a Neutrino Factory**
  - Best case for $\theta_{13}$ and CP violation
  - why Precision measurements
  - new interactions
So, the Flavour Problem may well be related to the GUT problem.

A window into flavour + GUTs
FFAG R&D
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

Original idea  ---> Ohkawa (1953)

"Zero chromaticity"

Radial-sector

Spiral

Scaling FFAG

\[ B(r, \theta) = B_i \left( \frac{r}{r_i} \right)^k F \left( \theta - \eta \ln \frac{r}{r_i} \right) \]

Fig. 2. Plan view of radial-sector magnets.

Fig. 3. Spiral-sector configuration.
FFAGs in the World

FFAG Workshop at KURRI, December, 2005

5 Dec.
ADS project at KURRI, Mishima(KURRI)
Workshop addressing, Mori(KURRI)
BNCT at KURRI, Ono(KURRI)
Limits of MA cavity, Ohmori(KEK)
PRISM status report, Sato(Osaka Univ.)
Correct tracking in FFAG, Berg(BNL)

6 Dec.
Status of 150MeV FFAG, Aiba(KEK)
Movie file
Proton FFAG Accelerator Work at Brookhaven National Laboratory, Ruggiero (BNL)
FFAG studies at RAL, Rees(RAL)
Non-scaling FFAGs in UK, Johnstone(instead of Edgecock)
Status of 6D transmission simulation in FFAGs, Meot(DAPANIA/LPSC)
Tracking study of muon acceleration with FFAG, Machida (RAL)

7 Dec.
Design of FFAG-ERIT, Okabe(KEK), Answers Mori(KURRI)
Diagnostics for FFAG accelerators, Itahashi (Osaka Univ.)
Fermilab, Proton Driver, PRISM/PRIME, Neuffer (FNAL)
FFAG Accelerator For Ibaraki Proton Therapy Facility, Yokoi (Ibaraki Pref.)
Development of PRISM-FFAG Magnet, Arimoto (Osaka Univ.)
Status of FFAG Complex at KURRI, Tanigaki (KURRI)
Deep Underground and Sea Nuclear Park Accelerator Facility, Takahashi(BNL)

8 Dec.
Projects in the near and far future:
Beijing Spallation Neutron Source / Antiproton Generation & Storage Facility, Wei (IHEP / BNL)
ICOOL, Simulation of Berg Doublet Lattice, Palmer (BNL)
Neutrino Factory International Scoping Study, Chris Prior (RAL)
Crossing 3Nx=11 in KEK 150MeV FFAG, Aiba (KEK)
FIXED FIELD SYNCHROTRON --APPLICATION: SECOND GENERATION MEDICAL SYNCHROTRON
Meot (DAPANIA/LPSC)

9 Dec.
Tracking study of muon acceleration with FFAG (follow-up 1), Machida (RAL)
Summary talk, Berg (BNL)
FFAG R&D in Japan

Past
- POP FFAG machine - 500 keV

On-going Projects
- 150-MeV Proton FFAG (KEK)
- FFAG for ADS (Kyoto U., KURRI)
- PRISM (Osaka U.)

Planned Projects
- Neutron source for Boron-captured neutron therapy (Kyoto U., KURRI)
FFAG for ADS

- at Kyoto University Research Reactor Institute (KURRI)
- feasibility study (2002-2006) for accelerator-driven (Reactor) system
- accelerator, reactor, reactor physics

FFAG - KUCA ADSR system schematic diagram
ion source
injector
main ring
KUCA
subcritical reactor
booster
100keV 2.5MeV 20MeV 150MeV
PRISM

for Charged Lepton Mixing
High muon intensity
$10^{11-12}$/sec
High luminosity
phase rotation
High muon purity
no pions
Low energy
68 MeV/c
primarily, for a search for charged-lepton mixing (a muon-to-electron conversion process).
use a FFAG ring to store muons.
- phase rotation to make narrow energy spread
- eliminate pions.
- a scaling FFAG
- large acceptance

Phase Rotated Intense Slow Muon source

PRISM FFAG ring construction has been started in 2003.
PRISM-FFAG Ring Parameters

- **N** = 10
- **k** = 5 (4.6-5.2)
- **F/D(BL)** = 8
- **r_0** = 6.5m for 68MeV/c
- half gap = 15cm
- mag. size 110cm @ F center

**Triplet**
- \( \theta_F = 4.40^\circ \)
- \( \theta_D = 1.86^\circ \)

**Tune**
- \( h : 2.86 \)
- \( v : 1.44 \)

**Acceptance**
- \( h : 40000 \pi \text{ mm mrad} \)
- \( v : 6500 \pi \text{ mm mrad} \)
PRISM-FFAG Acceptance

N=10
F/D=8
k=5
r0=6.5m
H:2.86
V:144

Geant tracking with TOSCA field.

h : 40000 \( \pi \) mm mrad
v : 6500 \( \pi \) mm mrad

a la Akira Sato (Osaka)
PRISM FFAG Magnets

- radial sector with C-type yoke
- D-F-D triplet
- 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
- Construction underway at Toshiba Co.
All the Coils are done.
Iron yokes of PRISM-FFAG ring are underway at Toshiba Co.
NC machining
First magnet will come on March 25th, 2006.
Mag. field measurements will be done.

as of March 11, 2006
86kV/p-p @5MHz achieved with dummy RF cavity. It corresponds to 150 kV/m.
Injection/Extraction

Vertical injection/extraction scheme proposed by R. Palmer.

FFAGの4D Acc. : 1.0G(mm mrad)^2

FFAG-Kickerの4D Acc. : 0.64G(mm mrad)^2

64% of the PRISM-FFAG maximum acceptance. Further study is going on.
Charged Lepton Mixing and Muons

Mixing of Elementary Particles

Charged Leptons are Next!

One type of elementary particles may be transformed into another type. The transformation can be understood by “mixing” of relevant elementary particles. Quark mixing, which is presented in the famous Kobayashi-Maskawa quark mixing theory, has been known for a long time. In addition, neutrino mixing has been recently discovered and the Super-Kamiokande and KamiKland experiments have provided experimental evidence of neutrino oscillations. Now, “charged leptons” are the only elementary particles for which mixing has yet to be observed.

GUT and Neutrino Seesaw Theory

What Can We Learn From Charged Lepton Mixing?

If charged lepton mixing is discovered, it may be possible to study physics phenomena, which occurred before about $10^{-25}$ seconds after the big bang. Current accelerator technology cannot directly achieve the corresponding energy scales (much higher than $10^{6}$ electron-volts). In particular, if the supersymmetric theory, which predicts supersymmetric particles come in pairs, is correct, such a study would become more interesting. If the supersymmetric theory is correct, then possible physics scenarios include supersymmetric grand unified theory or supersymmetric seesaw theory. Such physics cases could happen on an energy scale, which corresponds to about $10^{10}$ seconds after the big bang. We are optimistic that a study of charged lepton mixing will lead to the understanding of GUT or right-handed neutrinos and their mass in the seesaw models.

Our Search!

Charged Lepton Mixing

Charged lepton mixing is a phenomenon where one type of charged lepton (such as electrons, muons, and tau) changes into another type, has yet to be observed. However, PRISM would have the world’s highest sensitivity to detect a muon-to-electron conversion process.

Search for Charged Lepton Mixing with Muons

Why Are Muons Used?

Thus far, various elementary particles such as muons and taus have been used to search for charged lepton mixing. Among these particles, muons are best suited for this search because many particles are needed to achieve high sensitivity and only muons can be produced in large quantities. PRISM uses advanced technology to conduct muon research.

Is the Discovery of Charged Lepton Mixing Possible?

Great improvements in neutrino detectors enabled neutrino oscillations to be observed. Thus, it is conceivable that charged lepton mixing will be discovered when the experimental sensitivity is drastically improved. In fact, PRISM may be the perfect opportunity for discovery of charged lepton mixing. In addition, new theoretical models such as supersymmetric theory or extra dimension models predict that charged lepton mixing could be observed with the experimental sensitivity achieved in the future, such as by PRISM.

Muon to Electron Conversion

What Is the Muon-To-Electron Conversion Process?

There are many processes of charged lepton mixing with muons, but two are especially suited for searches for charged lepton mixing. One is a rare decay of a positive muon to a positron and photon, $\mu^+ \rightarrow e^+\gamma$ and the other is a muon-electron conversion process in which a negative muon is captured by a nucleus and then only a single electron is emitted ($\mu^- + N \rightarrow e^- + N$). Compared to the former, the latter has a better sensitivity with more muons in the future. Experimentally, many negative muons are stopped in a target material and a single electron emitted with a definite energy is searched. PRISM aims to have the experimental sensitivity in which one conversion event out of $10^{11}$ muons can be identified, namely a sensitivity of $10^{-11}$. 
Creation of the Universe and Elementary Particles

Elementary Particles in a Microscopic World

Quarks, Leptons, and Fundamental Forces

Elementary particles are building blocks of matter. They consist of six quarks and six leptons. Quarks are comprised of three electrically-charged leptons (an electron, a muon, and a tau) and three neutrinos with neutral charge. Furthermore, there are four fundamental forces, which are "strong force", "electromagnetic force", "weak force", and "gravity". Particle physics is a fundamental science that studies elementary particles and the four fundamental forces acting between them. However, it was recently realized that elementary particles play an important role in understanding the creation of the Universe.

Big Bang Universe and Elementary Particles Physics

About 14 billion years ago, the Universe was created from a big bang through a gigantic explosion called inflation. The big bang created numerous photons, quarks, and leptons, which formed a plasma state. Since then, the Universe continues to expand and is simultaneously cooling down. As the Universe cooled, quarks bonded together into protons (about a hundred seconds after the big bang). These nuclei bonded with electrons to create atoms (four hundred thousand years after the big bang) and then stars were formed. To study the creation of the Universe, we can not recreate the big bang. However, with particle physics topics, which are related to the early Universe, are presented. Their relationships with charged lepton mixing and PRISM will be shown later.

Where is the Anti-matter?

Each elementary particle has a partner called an anti-particle, which has the same mass as the particle, but has the opposite electric charge. Scientists believe that at the big bang an equal number of particles (ordinary matter) and anti-particles (anti-matter) were created through the pair creation. However, in the present Universe, only particles (matter) exist, and anti-particles (anti-matter) have yet to be found. Why does the Universe have only particles (matter)? A Russian scientist, Andrei Sakharov, proposed that due to some mechanism, the number of particles exceeded that of anti-particles, and after pair annihilation, only the excess of particles survived. This excess is tiny, and the ratio of that excess to the original number of particles is about one to billion. This phenomenon is called baryogenesis. The most acceptable theory to explain baryogenesis is the "leptogenesis theory".

Unification of the Fundamental Forces

Four fundamental forces exist in the present Universe. Scientists believe that only one unified force could exist in the early Universe, which then split into four different forces as the Universe cooled. In his later years, Einstein worked on the unification of the forces, but failed to complete his theory. The problem of unification of the forces is referred to as "Einstein's dream". Recent studies have confirmed that "electromagnetic force" and "weak force" can be unified into one force, the "electroweak force". The electroweak force is on an energy scale of 10^16 electron-volts, which corresponds to about 10^16 seconds after the Universe was created. It is expected that the "strong force" and the "electroweak force" might be unified into one force on the energy scale of 10^19 electron-volts, which corresponds to about 10^19 seconds after the big bang. This theory is called the Grand Unified Theory (GUT). If GUT is confirmed, then we should be able to understand the fundamental forces governing nature, which will aid in the understanding of the Theory of Everything.

Seesaw Theory and Leptogenesis

Are We a Descendant From Neutrinos?

Recently it was discovered from neutrino oscillations and cosmological observations that neutrinos have very small masses. Why do only neutrinos have small masses compared to other elementary particles? The neutrino seesaw theory has been considered as a solution to this. In this theory, neutrinos, which presently exist (left-handed neutrinos), have a partner neutrino, which does not exist today (right-handed neutrinos). However, it is believed that the right-handed neutrinos may have existed in the early Universe at high temperature. In the leptogenesis theory, the right-handed neutrinos decayed into left-handed neutrinos in about 10^13 seconds after the big bang and produced the associated particles over anti-particles. If this is correct, we exist thanks to neutrinos.
PRISM Public Ad. (3)

PRISM Phase Rotated Intense Slow Muon Source

PRISM, A Next-Generation Muon Source

An Accelerator-based Muon Source

How Are Muons Produced?
Muons are naturally unstable, and do not exist in nature. Thus, muons are artificially produced by an energetic proton beam from a proton accelerator, which is bunched on a target to produce pions. During their flight, pions decay into muons, which are collected. To date, conventional muon sources have problems with a low muon beam intensity due to poor collection efficiencies of pions and muons, and too broad energy spread, and pion contamination.

Plan-Capture Section
A section to capture pions with large solid angle under a high solenoidal magnetic field by superconducting magnets.

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

Requirements of a Search for a Muon-to-Electron Conversion

New Muon Source?
To search for a muon-to-electron conversion, a highly intense muon source is needed. Furthermore, several additional requirements are necessary to eliminate the background. These requirements are a narrow beam energy spread (high luminosity) and less pion contamination in the beam (high purity). Using advanced accelerator technology, PRISM can achieve both a high luminosity and a high purity.

In PRISM, the pion capture system, which consists of a large solid angle pion capture under a high solenoidal magnetic field produced by superconducting magnets, is adopted. Compared to current conventional muon sources, the efficiency of the pion collection can be improved by about 1,000 to 10,000 times. When this improved efficiency is combined with a highly intense proton beam of about Mega watt beam power, PRISM can produce about $10^{16} - 10^{17}$ muons per second.

In PRISM, the high intensity, high luminosity, and high purity, and in PRISM, the beam energy spread is narrowed by a phase rotation technique, which results in a high luminosity. The phase rotation technique is a novel method to accelerate slow muons and to deaccelerate fast muons by a rectilinear electric field. In the phase rotation section, a fixed field alternating gradient (FFAG) ring is adopted. Using a FFAG ring for the phase rotation of muons is a unique idea.

In PRISM, a beam will circulate for several turns in the FFAG ring of the phase rotation section. Therefore, a total flight length of the beam is about 150 m or longer. Thus, all the pions, which contaminate the muon beam, decay in their flight, and the survival rate of pions of about less than $10^{-10}$ can be achieved.
World Collaboration

- MICE
- MERIT
- PRISM
- MUCOOL
Summary

- The Japanese group participates in various international collaborations on neutrino factory such as, 
  - MUCOOL/MICE/MERIT, and 
  - ISS
- FFAG-based muon acceleration was originally proposed by us in 2001.
- Constructions and studies of various scaling-FFAGs are going, in particular in Japan.
- A highly intense muon source project, called PRISM, is highly promoted. It could be regarded as prototype of the NF front end.