Neutrino Factory R&D in Japan

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Outline

- Neutrino Factory in Japan
  - FFAG-based scheme
  - Staging aproach
- R&D activities
- Future Prospect & Summary
NuFactJ
Japanese scenario
FFAG
Pre-FFAG Era

- **Neutrino factory in the linear system (PJK scenario)**
  - High accelerating gradient (> 5 MV/m)
    - Decay loss must be small
    - Accelerator should be short.
  - RF frequency ~ several 100 MHz
    - Phase rotation/ buncher is necessary
    - Beam aperture become small
    - Transverse beam **cooling** is needed.
  - RF and cooling channel are cost drivers.
Alternative - Circular system?

- No. of muons is main concern for neutrino factories.
  - cf. Muon collider requires small emittance beam.
  - Cooling is not mandatory.
- Ring accelerator with large acceptance
  - RF can be used many times
    - Cost saving
  - Low accel. gradient ~ 1MV/m
    - Decay loss
      - 50% efficiency --> still tolerable
    - Low frequency ~ 25 MHz
      - Large longitudinal acceptance
      - Large beam aperture
- Accelerator with large acceptance and quick acceleration cap.
  
  **FFAG**

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**Figure:**

- Survival of muons as a function of energy for different magnetic fields:
  - 5 MeV/m: 3.94 km
  - 2 MeV/m: 9.85 km
  - 1 MeV/m: 19.7 km
  - 0.75 MeV/m: 26.3 km
FFAG was regenerated

- **Fixed Field Alternative Gradient**
- Original idea by Ohkawa (1953)
- Magnetic Field for scaling FFAG

\[ B(r, \theta) = B_i \left( \frac{r_i}{r} \right)^{n_0} F \left( \theta - \xi \ln \frac{r}{r_i} \right) \]

- **Features**
  - Fixed Field
    - quick acceleration
  - Strong focusing
    - Large transverse acceptance
  - Zero chromaticity
    - betatron tune const.
    - Large momentum (longitudinal acceptance)

Radial Sector Type

Spiral Sector Type
FFAG Era has arrived

- Many FFAG’s are now being studied and constructed.
  - POP (KEK)
    - Commissioning done
  - 150 MeV proton FFAG (KEK)
    - commissioned since April 2003
  - FFAG’s for ADSR (Kyoto Univ.)
    - construction from 2003
  - PRISM FFAG (Osaka Univ.)
    - construction from 2003
  - Superconducting FFAG (KEK)
    - Prototype magnet in 2005
  - Non scaling FFAG
    - used in Study IIa for final acceleration
    - electron POP machine in somewhere?
Japanese FFAG Scheme

- FFAG acceleration
  - No ramping field
    - -> fast muon acceleration
    - Superconducting FFAG
  - Large horizontal and longitudinal acceptance
    - $H > 10000\ \pi$, $V > 2000\ \pi$
    - Momentum acceptance $\pm 50\%$
      - Best match for Low freq. RF

- Advantages over Linear scheme
  - Simple and Compact (R~120m)
  - Hardware can be commonly used.
  - Small # of RF with low gradient
    - 1MV/m (cf. > 5MV/m for Linear system)
  - Cooling is not mandatory.
    - but better if available
  - Cost Saving and Early Readiness
Nufact at JPARC

- **50 GeV PS**
  - 15μA -> 0.75 MW
  - $3.3 \times 10^{14}$ proton/spill
  - Rep rate 0.3 Hz
  - Two extraction line so far
    - Fast extraction
    - Slow extraction
  - **New beamline is proposed.**
    - short bunch extraction

Overview of J-PARC facility
Muon yield (muon/proton) = 0.3 for $e_{h,v} = 0.03$ m rad, $e_L = 4.6$ eV s

Brightness $Q = 72.5$ muons/proton/(m rad)$^2$(eV s)
FFAG Ring (10-20 GeV)

- Kinetic Energy 10 --> 20 GeV
- Radius 120 m
- # of cells 100
- Max field 6.04 T (F)
- Orbit excursion 0.18m
- RF & power
  - Field gradient 0.55-0.75 MV/m
  - 150 kW tetrode x 100 sets
Muon beam

\[ I = \phi \quad Q \quad A_h \quad A_v \quad A_L \quad \eta \quad f \quad T \]

- \( \phi \) : proton flux = 1.9 \( \times 10^{14} \) p/sec
- \( Q \) : brightness = 72.5 \( \left( \mu / p / (m.rad)^2 / (eV . sec) \right) \)
- \( A_{h,v,L} \) : normalized value of accelerator acceptance
- \( \eta \) : muon survival rate after acceleration = 0.5@1MeV / m
- \( f \) : fraction of one - straight section per ring = 1 / 3
- \( T \) : total period of experiment / year = 4000 hours

- \( I = 1.2 \times 10^{20} \) muon decays / year @ one s.s
Staging Approach towards Realization

- Staging scenario (with FFAG)
  - Muon Factory (PRISM)
    - For stopped muon experiments
  - Muon Factory-II (PRISM-II)
    - Muon moments (g-2, EDM)
  - Neutrino Factory-I
    - Based on 1 MW proton beam
  - Neutrino Factory-II
    - Based on 4.4 MW proton beam
  - Muon Collider

Physics outcome at each stage
PRISM Project

- **PRISM** (=Phase Rotated Intense Slow Muon source)
  - High power Proton Driver
  - Pion capture with High Field Solenoid
  - Phase rotation
- **Beam characteristic**
  - Intense $\times 1000\sim 10000$
    - 20 MeV (68 MeV/c)
    - $10^{11} \sim 10^{12} \mu/s$
  - Bright
    - $dE/E \sim$ a few %
  - Pure
    - no pion contamination
- **For muon experiment**
  - $m$-$e$ conversion $Br(\mu N \rightarrow eN) < 10^{-18}$
  - Muon EDM $10^{-24} e \cdot cm$
  - Application for material and life science
R&D Activities in Japan
R&D Activities

- FFAG
  - 150 MeV Proton FFAG
  - Phase rotator FFAG
  - Superconducting FFAG
  - New lattice (non-scaling)*

- Cooling
  - Liquid H2 Absorber
    - Convection type for MICE*
    - MUCOOL absorber*
  - Scifi tracker
    - MICE detector*

- Targetry/Collector
  - R&D for high field SC solenoid
    - Prototype magnet of 10.9 T
    - Beam test to measure radiation heat load using 12 GeV proton beam
  - Material Test*
  - Mercury loop for study of conducting target*

*International collaboration
150 MeV Proton FFAG R&D

- **Parameters**
  - 12 sectors
  - Repetition ~ 250Hz
  - 10 MeV to 150 MeV

- **Study on**
  - Yoke-free magnet
  - Beam injection
  - Beam extraction
  - Fast repetition rate

- **Commissioning**
  - since April 2003
  - plenty of outputs
  - final stage

[Diagram showing the components of the FFAG:]

1. Injection cyclotron
2. Injection line
3. Injection septum magnet
4. Injection ES septum
5. Bump magnet
6. Triplet magnet
7. RF cavity
8. Beam position monitor
9. Current monitor
10. Extraction kicker
11. Extraction septum
12. Beam dump
COD compensation

beam position measurement @ ES

current (nA) vs. radius (mm)

injected

septum electrode

1 turn

2 turn

fringing field

lost field

compensation field

bump magnet

iron shield

permanent magnet

Beam Position at MS

- bump uninstalled
- bump with 12 pieces of permanent mag.
- bump with 16 pieces of permanent mag.
- bump with 24 pieces of permanent mag.
Acceleration

adiabatic capture  acceleration  flat top

RF Voltage

synchronous phase

time

Bunch Monitor

adiabatic capture  acceleration  RF input

250 ms
Power Supply for Kicker

- Power supply for kicker magnet
- IGBT module
- RF input signal
- Kicker current

IGBT array
100 Hz Operation
Extraction

The circulating beam shifts to the extraction orbit after excitation of the kicker magnet.
Two pictures above show circulating beam signal before and after kicker excitation.
ADSR FFAG’s KUCA
(Accelerator Driven Subcritical Reactor)

- **Accelerator complex**
  - Kyoto University
  - consist of 3 FFAG’s
- **Injector**
  - Spiral sector
  - 100 keV to 2.5 MeV
- **Booster**
  - DFD Radial sector
  - 2.5 MeV to 20 MeV
- **Main Ring**
  - KEK 150 MeV Design
  - 20 MeV to 150 MeV
PRISM-FFAG

- **FFAG phase rotator**
  - muon accelerator
    - 20 MeV (62 MeV/c)
    - $dE/E \sim$ a few %
    - Very large acceptance
  - **Budget request was approved**
    - construct ring and RF’s
    - demonstrate phase rotation and cooling

- **Simulation**
  - 3D tracking
  - RF kick
    - Higher harmonics to simulate saw tooth shape
Construction of the PRISM-FFAG

- FY2003
  - Lattice design, Magnet design
  - RF R&D
- FY2004
  - RFx1gap construction
  - test Magnetx1 construction & field meas.
- FY2005
  - RF tuning
  - Magnetx9 construction
  - FFAG-ring construction
- FY2006
  - Commissioning
  - Phase rotation
- FY2007
  - Muon acceleration (Ionization cooling)

Phase rotator section will be constructed from Japanese fiscal year (JFY) of 2003 in five years.
Calculated by TOSCA
Beam optics design study

- 3D tracking with 3D magnetic field to study
  - acceptance
  - tune
  - tune shift
  - beam size
  - COD
- Optimization
  - number of cell
  - Cell structure
    - FD, DFD, FDF
  - k value
  - F/D ratio
  - gap size

DFD, N=10, half gap=15cm, w/o field clamps, r0=6.5m for 68MeV/c
Acceptance Study

N=10, F/D=8, k=5, r0=6.5m

35000 $\pi$ mm mrad

140000 $\pi$ mm mrad
Magnetic Alloy Cavity

- A soft magnetic alloy
  - Thin tape
- Broad band
  - small Q-value (Q<1)
- PRISM RF
  - Wide gap (0.74 m x 0.34 m)
  - High field gradient 200kV/m
  - High Q is possible by cut core

*PRISM RF core*
Outer size : 1.4m x 1.0m x 0.35m
Inner size : 0.74m x 34 m
Superconducting FFAG

- FFAG with superconducting (SC) magnet
  - Fixed Field
    - No AC Loss -> suitable for SC
  - High Field w/ SC
    - make orbit small
  - Compact accelerator
    - Medical application
    - Nufact acceleration

Reference Design

\[ B_0 = 6.0T, r_0 = 120m, k = 450, \]

beam excursion 0.18m
Combined Function Magnet

- FFAG Scaling field

\[ B = B_0 \left( \frac{r}{R_0} \right)^k = B_0 \left( \frac{R_0 + x}{R_0} \right)^k = B_0 \left[ 1 + \frac{k}{r_0} \frac{x}{R_0} \frac{r}{r_0} \right] + \frac{k (k+1)}{2!R_0^2} \frac{x}{r_0} + \cdots \]

Multi-Layer coil

Combine

Single Layer

Elliptic-shaped for compact
Future Prospect & Summary
Pulsed proton beam facility

- **Pulsed proton beam**
  - Fast extraction
    - Extract bunch by bunch
    - Fast-risetime kicker is needed
  - Bunch operation
    - 9 bunches -> 90 bunches for PRISM
  - PRISM (for muon-electron conversion), PRISM2 (for muon-electric dipole moment), muon g-2, antiproton
  - A liquid mercury jet target study - LOI was submitted by Nufact/Muon collider group
Summary

- FFAG-based neutrino factory has been proposed and studied.
  - FFAG technology has exhibited no serious flaw so far.
  - More and more FFAG are being built.
- R&D works have been carried out actively.
  - FFAG, Cooling, Targetry
  - Many outputs from FFAG studies are crucial to realize NufactJ
  - A world-wide collaboration is important
- J-PARC 50 GeV PS @ Japan
  - A unique MW-class beam
  - A new **pulsed proton beam facility** is requested:
    - PRISM and PRISM-II (FFAG studies)
    - Suitable for target studies with high intensity proton beam
    - A step toward a neutrino factory