Recent Studies on the PRISM FFAG Ring

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on behalf of
the PRISM Task Force

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Outline

• Introduction.
• PRISM/PRIME experiment.
• PRISM Task Force initiative.
• Proton beam
• Pion production and capture.
• Muon transport.
• Injection/extraction.
• Reference PRISM FFAG ring design.
• Alternative ring designs.
• PRIME detector.
• Conclusions and future plans.
• Charge lepton flavor violation (cLFV) is strongly suppressed in the Standard Model, its detection would be a clear signal for new physics!
• Search for cLFV is complementary to LHC.
• The $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$ seems to be the best laboratory for cLFV.
• The background is dominated by beam, which can be improved.
• The COMET and Mu2e were proposed and PRISM/PRIME is the next generation experiment.

Does cLFV exists?

Simulations of the expected electron signal (green).

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The PRISM/PRIME experiment based on FFAG ring was proposed (Y. Kuno, Y. Mori) for a next generation cLFV searches in order to:
- reduce the muon beam energy spread by phase rotation,
- purify the muon beam in the storage ring.

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The aim of the PRISM Task Force:
• Address the technological challenges in realising an FFAG based muon-to-electron conversion experiment,
• Strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.

The Task Force areas of activity:
- the 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 systems R&D.

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You are welcome to join us!

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PRISM Task Force Design Strategy

Option 1:
Adopt current design and work out injection/extraction, and hardware

Option 2:
Find a new design

They should be evaluated in parallel and finally confronted with the figure of merit (FOM) (number of muons delivered to target/cost).

Requirements for a new design:
• High transverse acceptance (at least 38h/5.7v [Pi mm] or more).
• High momentum acceptance (at least ± 20% or more).
• Small orbit excursion.
• Compact ring size (this needs to be discussed).
• Relaxed or at least conserved the level of technical difficulties for hardware (kickers, RF) with respect to the current design.

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Proton Beam for PRISM/PRIME

Two methods established – BASED on LINAC or SYNCHROTRON acceleration.

H⁻ linac

Accumulator Ring

Compressor Ring

H⁻ linac followed by the accumulator and compressor

PRISM/PRIME needs a short bunch (~10 ns)!
Where could it be done?:
• at Fermilab (possibly at the Projext-X muon line)?
• at J-PARC,
• at CERN (using SPL),
• at RAL (MW ISIS upgrade could be adopted).

In general any Neutrino Factory Proton Driver would work for PRISM!

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Pion Production

- 2 (4) MW proton beam power.
- Beam energy 3-8 GeV.
- Proton bunch length at the target ~10 ns.
- Heavy metal (W, Au, Pt, Hg) target.
- 12 (20) T SC pion capture solenoid.
- Backward pion collection.

Au target simulations using MARS

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Pion/Muon Transport

Vertical Septum
Vertical dispersion matching

Kickers

Incoming Proton Beam
Pion Production Target and Capture Solenoid

Negative vertical deflection corrector
Vertical dispersion suppressor

Quad matching

Dispersion Creator (Orbit matching)

Bend solenoidal channel in „Pi/2–Pi/2” configuration (to compensate the drift)

Solenoidal matching cell

The goal - 70% muon transport efficiency!

This design is under studies within the PRISM Task Force.

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Status of matching section

- Optics in solenoidal matching section has been designed.

- It needs to be followed by the quad channel (in preparation).

- Preliminary design for the dispersion creator based on 4 spectrometer magnets has been achieved, but more studies are needed (mismatch at extreme momentum).

- The vertical dispersion creation and suppression is based on the “immediate method”. Optics has been design (the mismatch at extreme momentum is ~1 cm – acceptable).

- The design of betatron matching (including the FFAG section) is advancing.

- The optics design will be followed by the tracking studies to evaluate the performance.

- The final optimisation is the study on itself (could be based on the genetic algorithms).

- The challenge is the fact that the beam with a very large emittance needs to be matched into the injection conditions of the FFAG ring simultaneously for all momenta!

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Optics and B field in solenoidal muon transport and matching
From the target to adiabatic matching

Capture and decay channel will use the solenoidal transport system.
The matching of the solenoidal system with the FFAG is an interesting, but challenging problem.

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• Betatron functions needs to be matched to AG channel (~ 1-4 m).
• Solenoidal field needs to be smoothly switched off.
Optics and layout of the vertical correction sections (to be upgraded)

FFAG RING LEVEL

This is where the FFAG matching cell will be located

Beam direction

Injection Beam Level

- As the injection will be vertical, the incoming beam and the circulating beam will be on two different levels.
- Bending angle needs to be cancelled and dispersion matched to zero in the FFAG ring (for ± 20% momentum deviation).
- Mismatch of vertical orbits is of the order of 1 cm at extreme momentum (acceptable).

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Pion/Muon Transport (hardware)

- Bend solenoids create drift of charged particles in the vertical plane.

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

- In order to compensate for this effect, the dipole field needs to be introduced.
- Muon beam transport is similar to COMET and the NF.
- Similar muon transport system is under construction for Muon Science Innovative Commission (MUSIC) at RCNP, Osaka University.
- Combined function – SC solenoid and dipole magnet design was done in collaboration with Toshiba.
Preliminary PRISM kicker studies

- length 1.6 m
- B 0.02 T
- Aperture: 0.95 m x 0.5
- Flat top 40 /210 ns (injection / extraction)
- rise time 80 ns (for extraction)
- fall time ~200 ns (for injection)
- $W_{mag} = 186$ J
- $L = 3$ uH (preliminary)
- $I_{max} = 16$ kA

H. Witte, M. Aslaninejad, J. Pasternak

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PRISM Pulse Formation

80 kV
Impedance 3 Ohm
Kicker subdivided into 8 smaller kickers
Travelling wave kicker
Each sub-kicker has 5 sections
1 plate capacitor per section

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Reference Design Parameters – A. Sato

PRISM-FFAG

- N=10
- k=4.6
- F/D(BL)=6.2
- r0=6.5m for 68MeV/c
- half gap = 17cm
- mag. size 110cm @ F center
- Radial sector DFD Triplet
- $\theta_F/2=2.2\text{deg}$
- $\theta_D=1.1\text{deg}$
- Max. field
  - F : 0.4T
  - D : 0.065T
- tune
  - h : 2.73
  - v : 1.58
- V per turn \(~2-3\text{ MV})
- $\Delta p/p$ at injection = ±20%
- $\Delta p/p$ at extraction = ±2% (after 6 turns ~ 1.5 us)
- h=1

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In order to inject/extract the beam into the reference design, special magnets with larger vertical gap are needed.

This may be realised as an insertion (shown in red below).

The introduction of the insertion breaks the symmetry but this does not limit the dynamical acceptance, if properly done!
Phase rotation calculations in PRISM ring

Injected bunch

Extracted bunch

Phase rotation for 68 MeV/c reference muon

- An RF system has been constructed and tested.
- Very large (~1.7 m X 1.0 m) magnetic alloy cores were loaded in the cavity
- An independent work on development of a new material, FT3L, is undergoing.

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We need to decide about the possible baseline update very soon.

The choice is dictated by the performance.

Under study within the PRISM TF.

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Observation of the serpentine acceleration is the main goal of the EMMA commissioning. Phase rotation experiment can also be performed in EMMA Non-Scaling FFAG ring. It will test the phase space motion for large amplitude particles in this novel accelerator. The applicability of the Non-Scaling optics for PRISM and similar applications can be tested. 

¼ of the synchrotron oscillation takes ~3 turns in EMMA and ~6 turns in PRISM. Similar or even larger momentum spread can be tested.

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PRIME Detector

- Thin Stopping Targets
  - due to mono-energetic muons
- Graded Field at Muon Target
  - Solenoid
  - To maximize transmission efficiency of the curved solenoid.
- Curved Solenoid
  - To suppress low momentum electrons.
- Low Mass Tracker
  - to be transparent to γ’s.
  - f < 1 MHz
- Electron Calorimeter
  - Trigger
  - Cosmic Muon suppression
  - f < 1 MHz
- No Time Window
  - pure muon beam
  - + curved solenoid


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Conclusions and future plans

• PRISM/PRIME aims to probe cLFV with unprecedented sensitivity (single event - $3 \times 10^{-19}$).
• The reference design was proven in many aspects (phase rotation, magnet design, RF system, etc.) in the accelerator R&D at RCNP, Osaka University.
• PRISM Task Force continues the study addressing the remaining feasibility issues.
• PRISM Task Force aims to demonstrate the feasibility via Conceptual Design Report (to be published next year).
• PRISM/PRIME will be very likely the first next generation muon project and the first muon FFAG.