PRISM and PRIME

Measuring $\mu^- \rightarrow e^-$ conversion at the 10^{-18} level and beyond

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Contents

- The Challenge: 10^{-18}

- PRISM: Phase Rotated Intense Slow Muon source
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  - FFAGs
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- The PRISM task force

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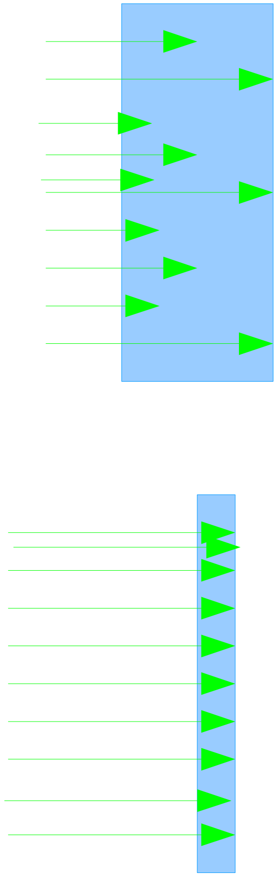
μ-e conversion

Rate down by factor ~200 from μ→eγ BUT probes different BSM physics AND has very clean signature of monochromatic105 MeV electron, beyond decay spectrum.

To go beyond COMET we will need:
1) More muons
    For statistics
2) No pion contamination
    Pions can decay to electrons with energies up to 140 MeV
3) Extra beam extinction
    As discussed
4) No muons above 76 MeV/c
    As these can decay in flight to 105 MeV electrons
5) Very small muon energy/momentum spread

This can achieve an experiment essentially free of any background

Muon Beam Requirements



Want very narrow energy spread so muons all stop in same foil thickness (just 1 foil). Reduces electron energy straggling, and improves spectrometer accuracy as z known.

<u>But</u>

Muons are produced with wide spread in energy/momentum.
Just selecting a narrow momentum bite is too inefficient

<u>Solution</u> (preserving Liouville's theorem)

Generate muons in very short pulses.
Trade certainty in time for certainty in energy

Phase Rotation

All muons in a bunch start together

Muons with higher energy travel faster and arrive earlier at the RF

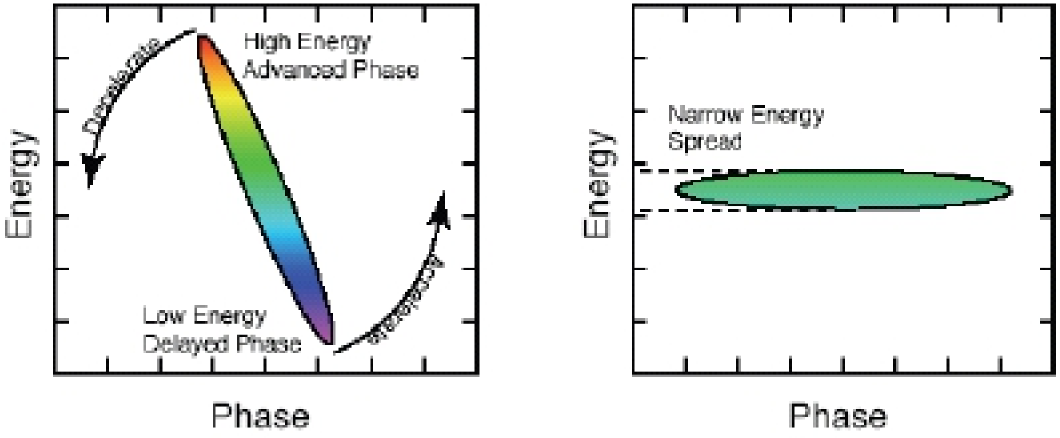
Arrange RF phase so that they are decelerated

Muons with lower energy travel slower and arrive later at the RF

Arrange RF phase so that they are accelerated

Reduce momentum spread from 20% to 2% in a few turns (~1.5 μs)

Pulse timespread increases from ~10 ns to 220 ns



The complete package

Proton Accelerator   2-8 GeV ~1 MW with bunch compression

Solid target, pions captured by 4-10T solenoid and allowed to decay

Storage ring:Comprising
- Magnets
- RF (~40 gaps as acceleration must be fast)
- Injection and extraction systems

Has to operate at ~1000 Hz
Acceptance 3.8 π cm rad horizontally, 0.57 π cm rad vertically
Momentum 68 MeV/c (below 75 MeV/c)
Momentum spread 20% → 2%

Stopping foil

Electron spectrometer.

The system

One suggested layout (baseline)

FFAG storage ring

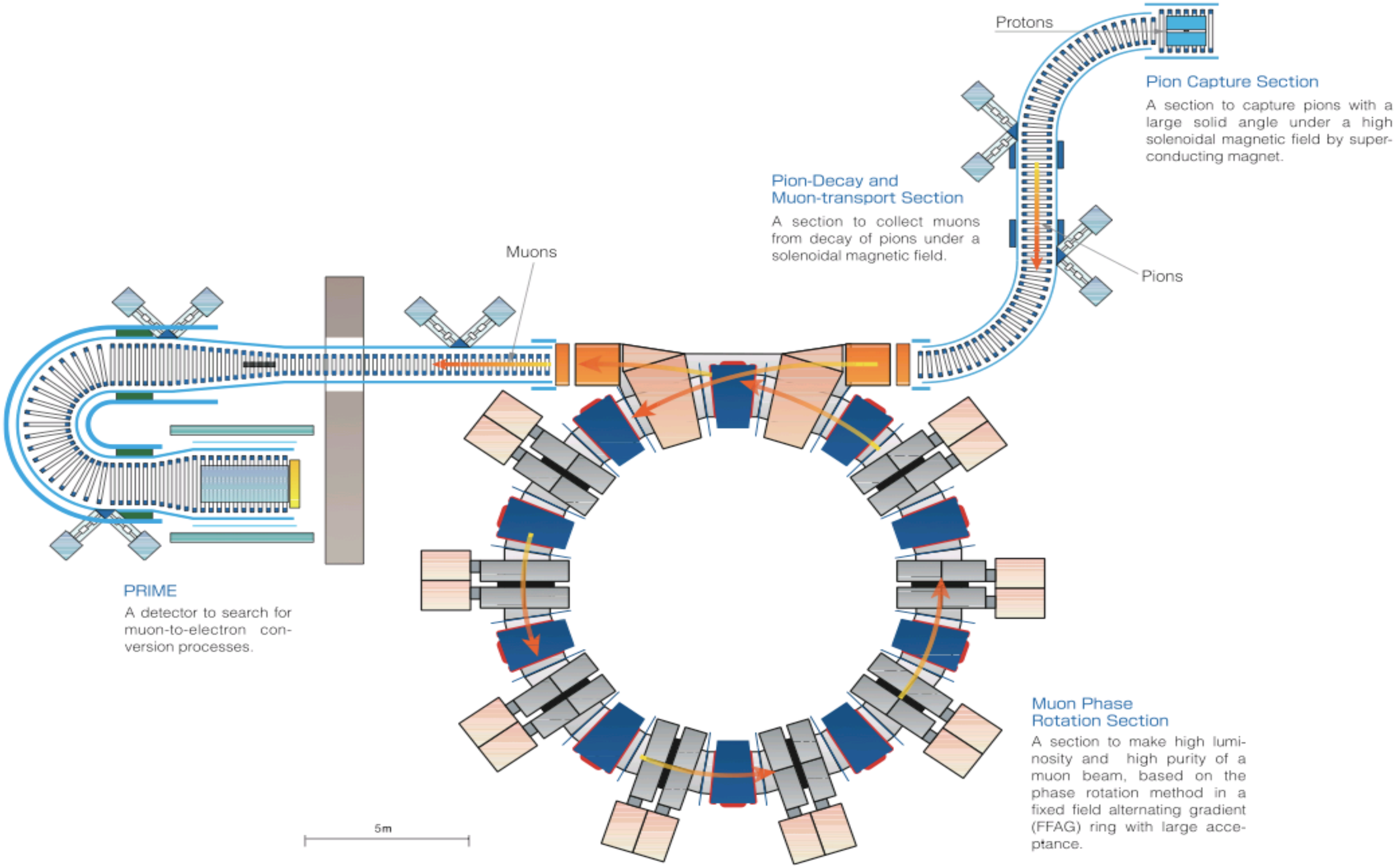
~6 turns, ~1.5 μsec

Pions all decay

Extinction: No transmission outside duty cycle

High acceptance- lots of muons

Phase rotation – monochromatic muons



Pion Capture Section

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

Pion-Decay and Muon-transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

PRIME

A detector to search for muon-to-electron conversion processes.

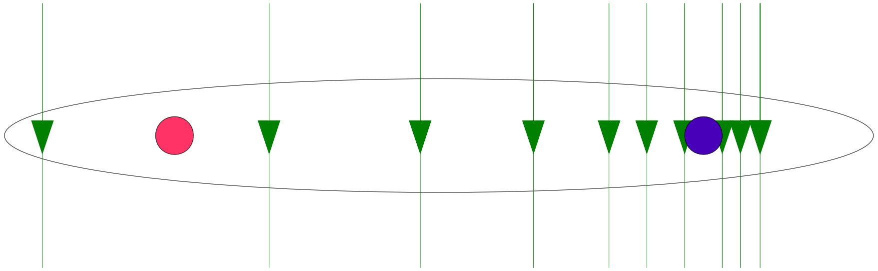
Muon Phase Rotation Section

A section to make high luminosity and high purity of a muon beam, based on the phase rotation method in a fixed field alternating gradient (FFAG) ring with large acceptance.

Why an FFAG?

What is an FFAG?

Cyclic accelerator in which particle moves from low-field to high-field region



Changes in dipole field provide quadrupole field for strong focussing

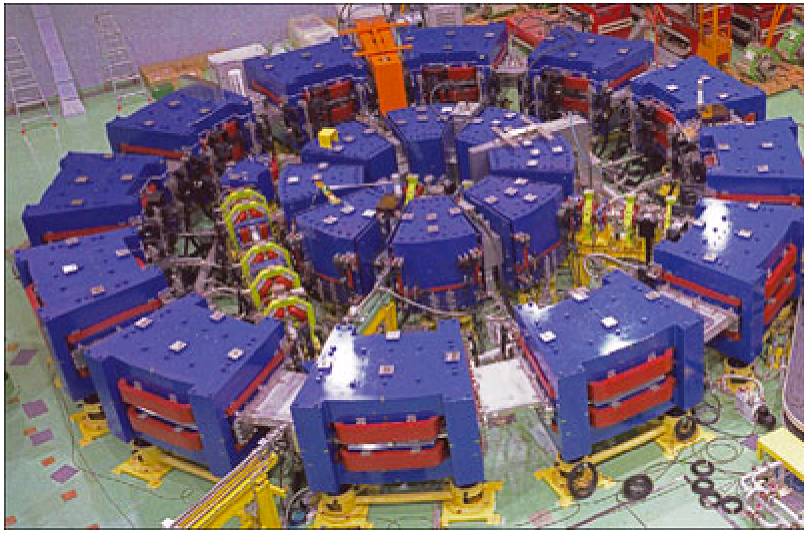
What are the advantages?

Acceleration not limited by ramping magnets. So can be rapid.

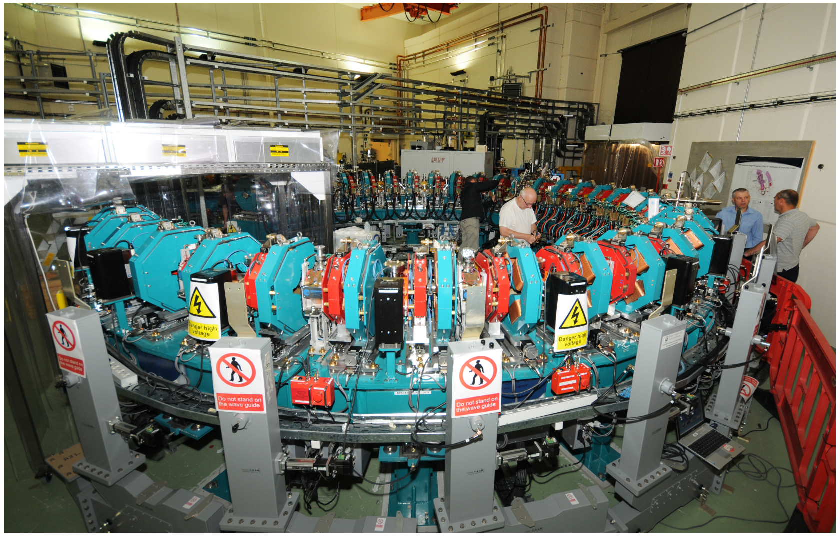
Very large acceptance

Simplicity, robustness...

FFAG prototypes



Nested proton FFAGs at KURRI



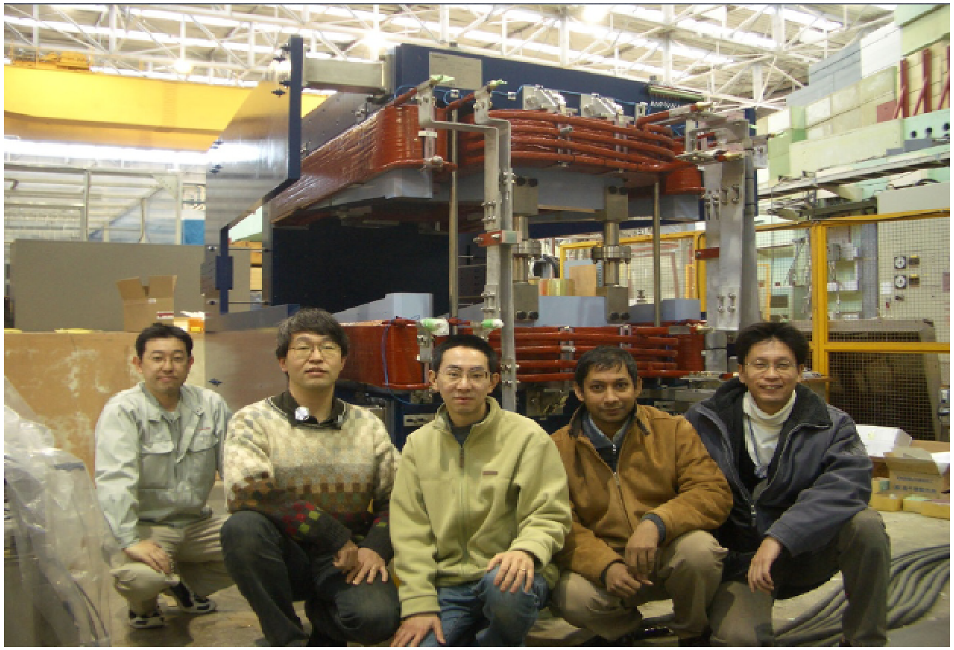
A prototype electron nsFFAG has been built in Daresbury and is now being tested.

EMMA stands for...

The Magnets

Wide aperture, complicated field shape

Prototype built, and magnetic fields measured at KEK to be as predicted/required

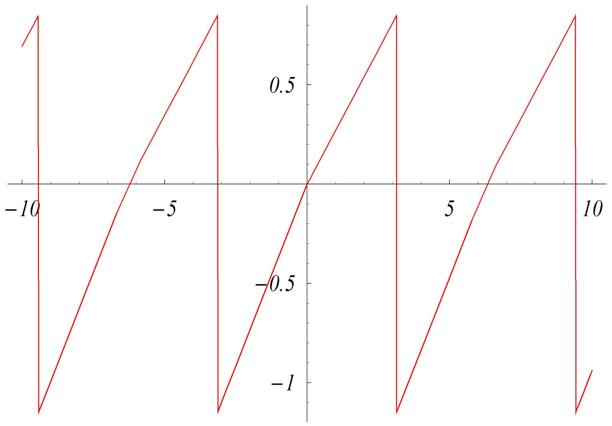


The RF

Require high gradient – 200 kV/m – to give 2-3 MV/turn

At low frequency – 4 MHz

In a magnetic field



With triangular shape: add harmonics
(Asymmetric sawtooth is even better)

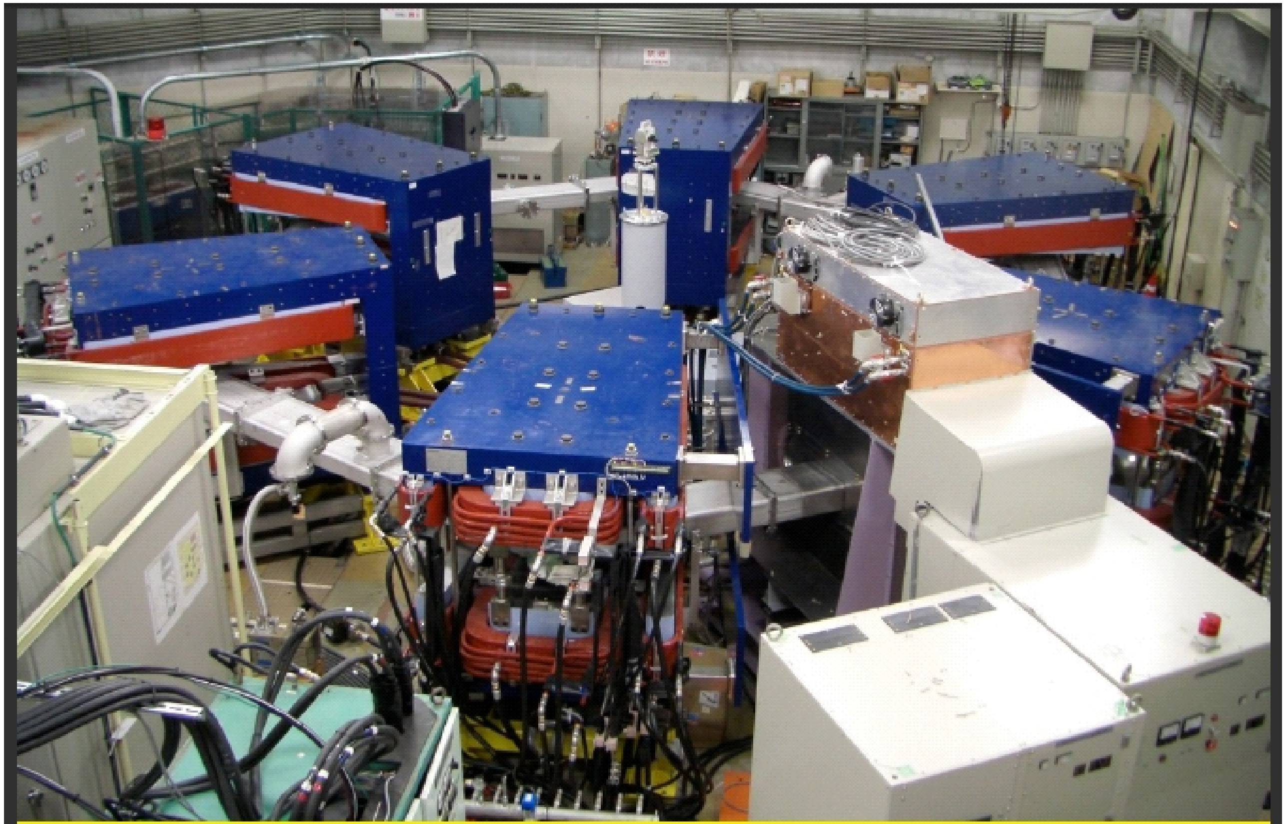
Low duty factor (0.1%) so cooling not a problem

Prototype using (expensive) magnetic alloy with very large cores (~1.7 m X 1.0 m) successfully constructed

Experiments with beam have been performed to simulate the bunch rotation.

Development of a new (cheaper!) material, FT3L, is underway

Prototype tested with alpha particles



6-sector PRISM-FFAG at RCNP, Osaka Univ.

PRIME: the detector

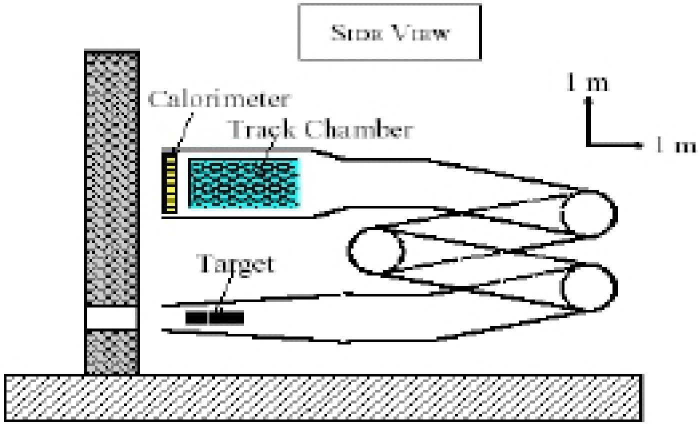
Magnetic spectrometer – curved solenoid

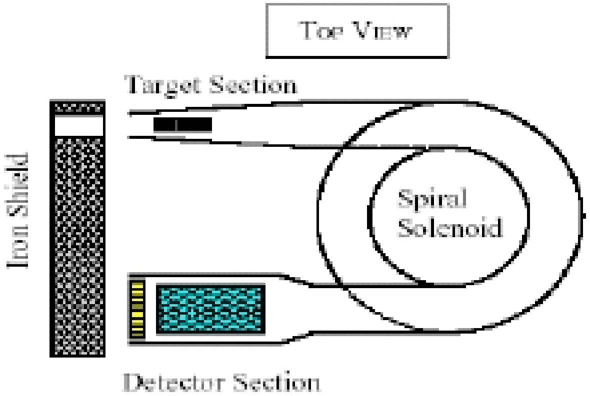
Resolution ~ 150 keV

Rate is very high. Off energy particles must be lost. They never make it to the tracking chambers.

With 10^9 muons/pulse, about 10 electrons/pulse will reach the spectrometer

Calorimeter is for triggering/calibration/checking





Peformance

10^9 muons per pulse
10^3 pulses per second
10^{12} muons per second
~20x more than COMET

10^7 seconds per year
0.4 detector (PRIME) efficiency
~ 5x more than COMET due to better beam quality

Expect ~0.06 background events

Branching ratios of 10^{-18} and below will be observable with a few years' running

The PRISM Task Force

Aim: to address the technological challenges in realising an FFAG based muon-to-electron conversion experiment, and strengthen R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments, especially

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

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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

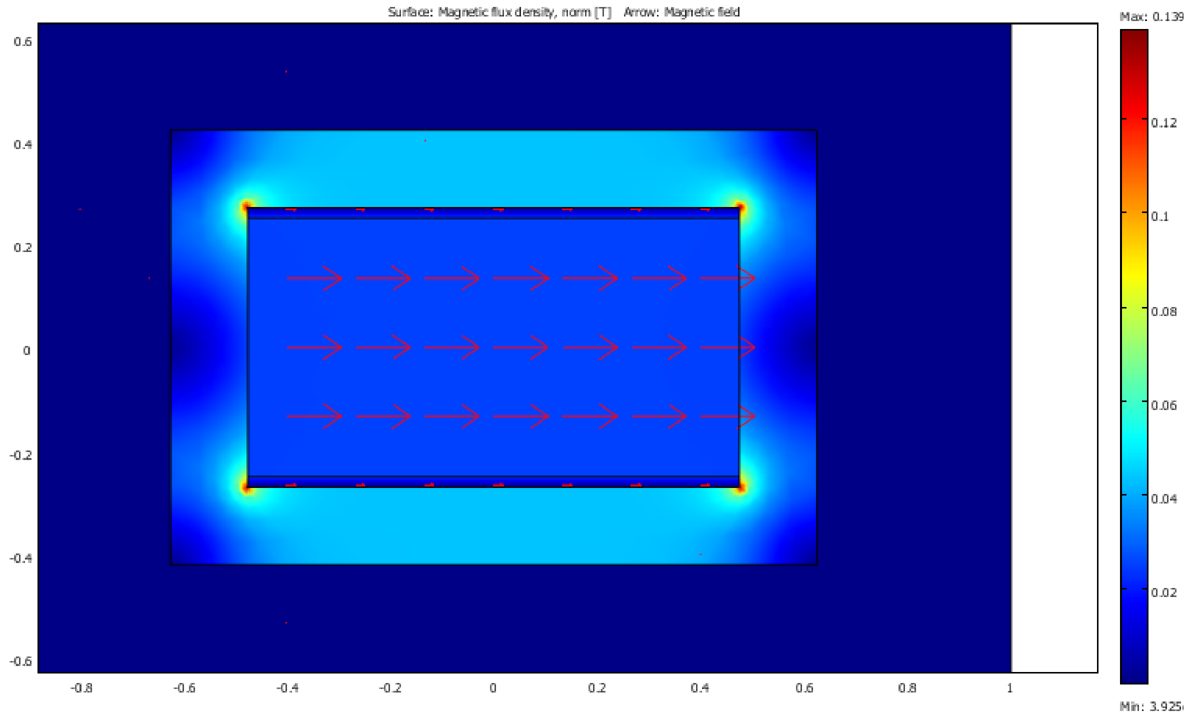
They should be evaluated in parallel and confronted with the number of muons delivered to target/cost

Requirements for a new design:

- High transverse acceptance (at least 38h/5.7v [Pi mm]).
- High momentum acceptance (at least ± 20% or more).
- Small orbit excursion.
- Compact ring size
- Relax or at least conserve the level of technical difficulties. for hardware (kickers, RF) with respect to the current design.

Task force activity: PRISM kicker studies

- length 1.6 m
- B 0.02 T
- Aperture: 0.95 m x 0.5 m
- 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



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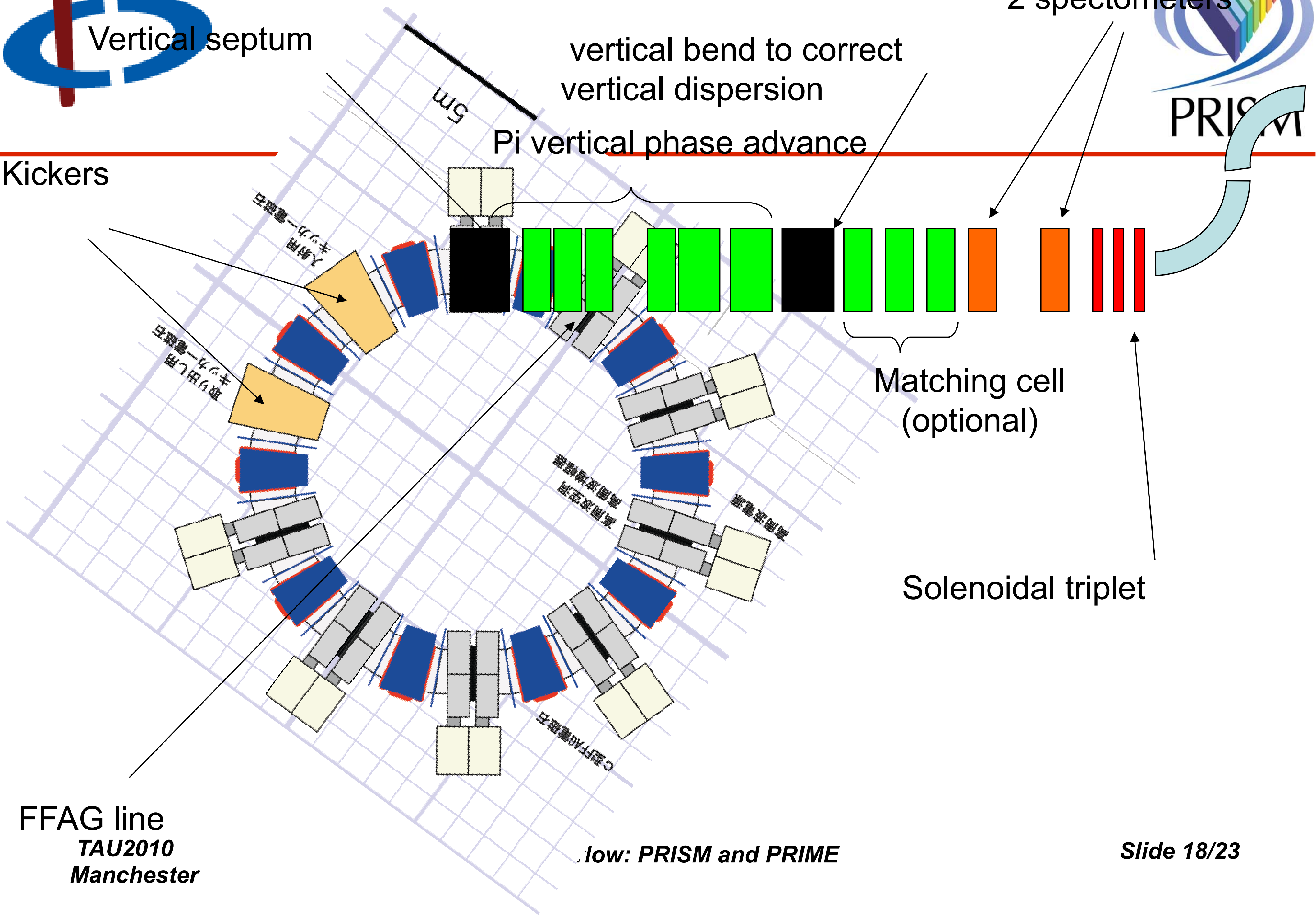
New ideas for matching



Vertical septum

vertical bend to correct
vertical dispersion

2 spectometers

Pi vertical phase advance

Kickers

Matching cell
(optional)

Solenoidal triplet

FFAG line

New solutions

Scaling FFAG

Options:,
- periodic with extended cell (for example 5 magnets per cell),
- superperiodic (proposed by S. Machida)
- advanced (proposed by Y. Mori and collaborators, see J-P.Lagrange’s lattice)

Non-Scaling FFAG

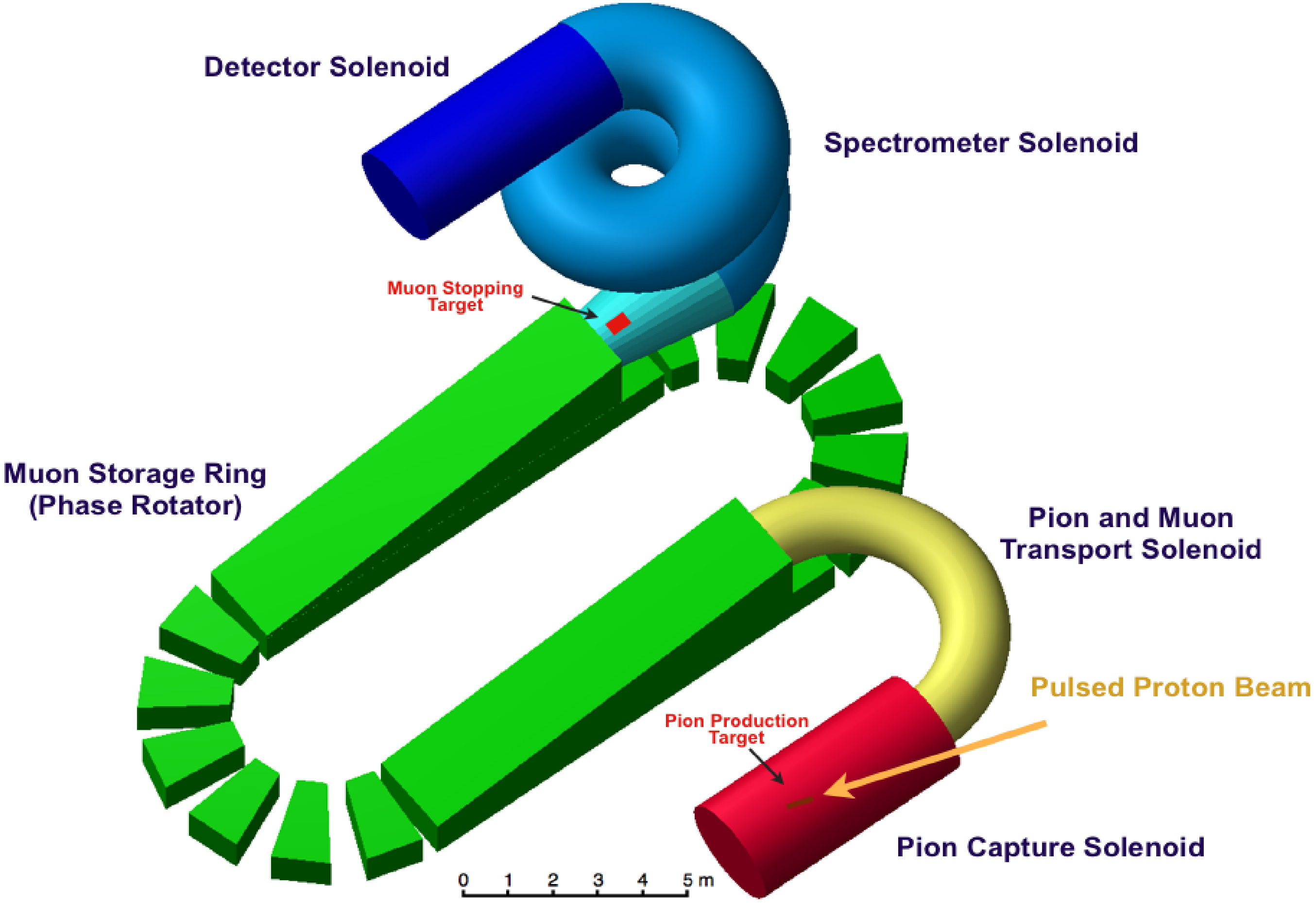
Main motivation for Non-Scaling design is a possibility to obtain ”infinite” acceptance

•Problems to be addressed:
- currently no insertion scheme,
- very difficult injection
- TOF varies with amplitude

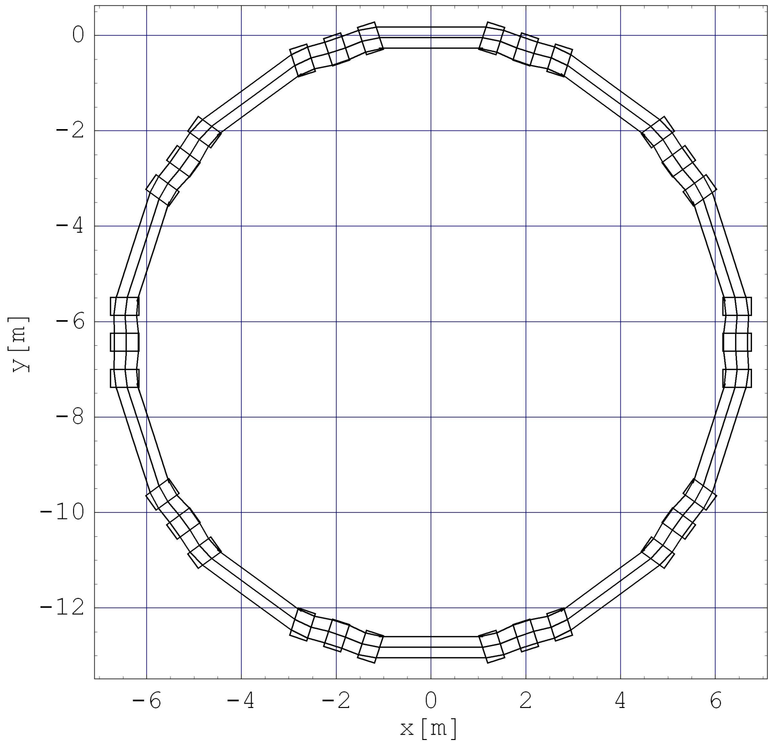
Alternative system

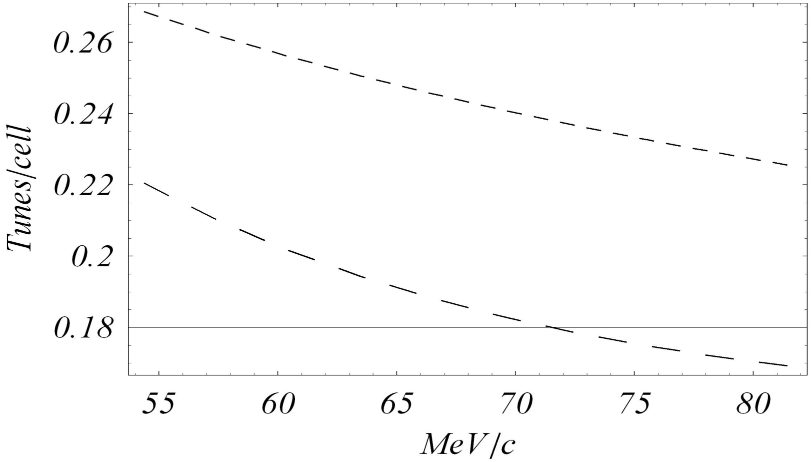
Another suggested layout. Racetrack rather than circle allows easier injection and extraction

(J-B Lagrange et al)



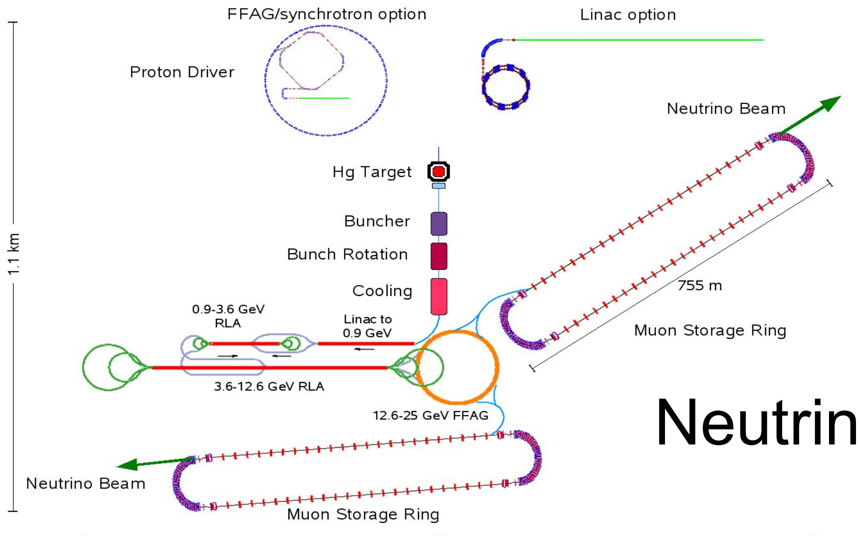
Non-scaling FFAG design

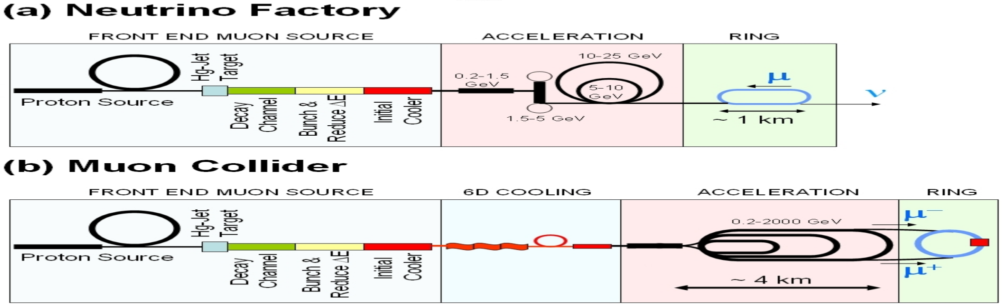




- Simple linear and rectangular magnet design.
- Tunes vary with momentum, but large acceptance is expacted for ~6 turns.
- TOF variation with amplitude affects the final energy spread, but seems to be acceptable.
- Injection/extraction and matching seem difficult, but not imposible.
- More cells (20) could reduce the orbit excursion (magnet size), but assuming constant drift length in the symmetric ring, more RF would be required!
- This difficulty may be overcome by the design with insertions for the injection/extraction.

PRISM and beyond?





Neutrino Factory

•Muon Collider

Synergies include:

- high power proton driver
- short proton bunch length
- pion production and capture
- muon beam transport
- need for high acceptances
- requirements for kickers
  and RF (for proton driver)
- techiniques in machine design and beam dynamics studies
- etc …

Outlook

PRISM task force

Aim: a CDR in 2011 showing how to measure μ→e conversion at BR<10^{-18}

PRISM could be built at JPARC, or as part of Project X, or...

Lots of work to do – help welcome - contact Jarloslaw Pasternak (J.Pasternak@imperial.ac.uk) to get involved