

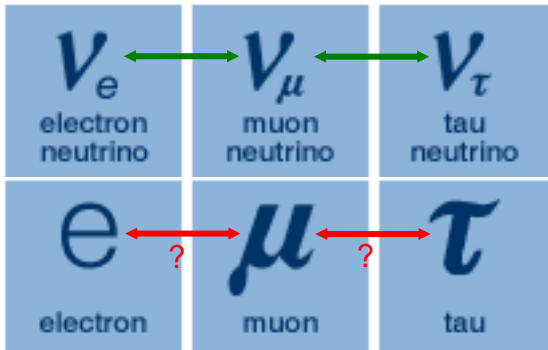
# Recent Studies on the PRISM FFAG Ring

J. Pasternak,  
Imperial College London/RAL STFC  
on behalf of  
the PRISM Task Force

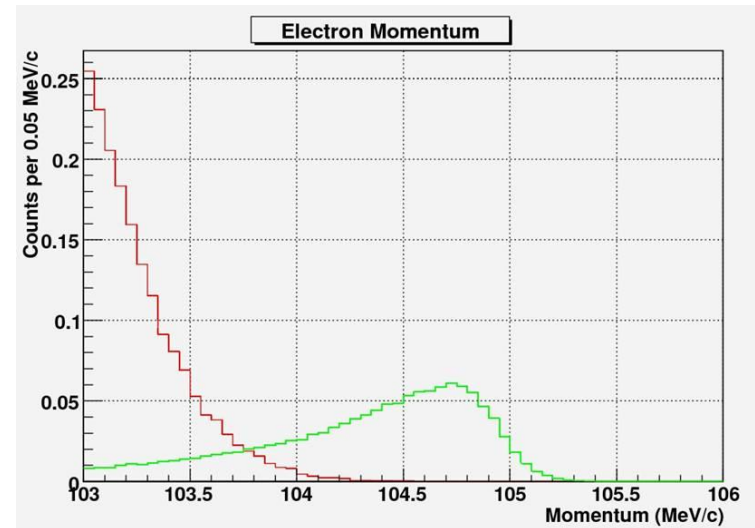
# Outline

- 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.



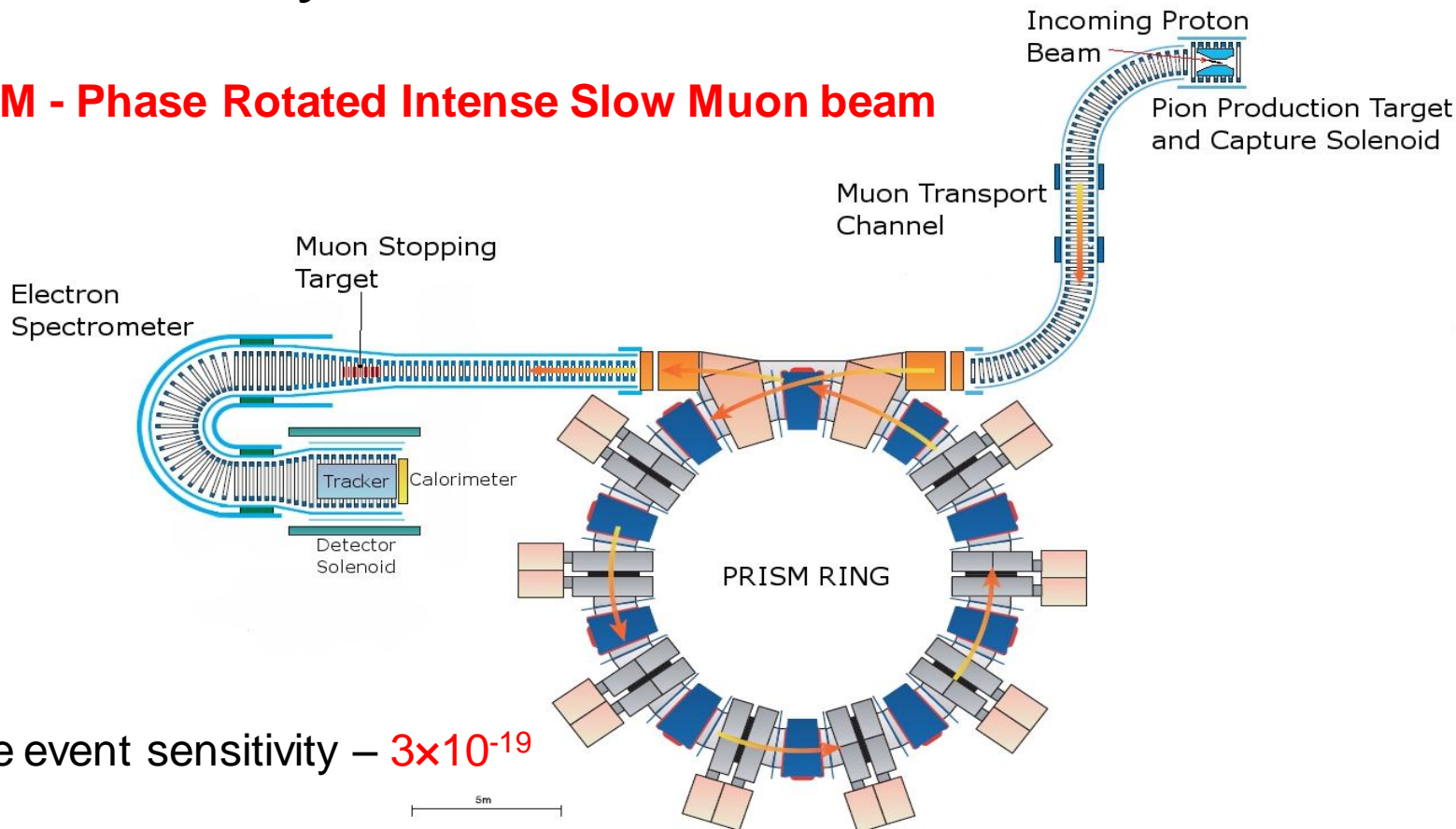
Does cLFV exists?



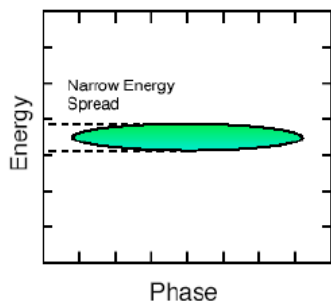
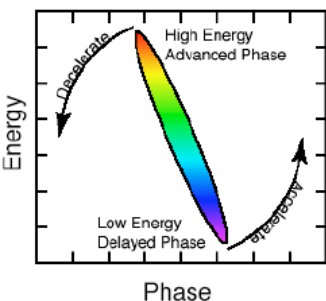
Simulations of the expected electron signal (green).

# Layout of the PRISM/PRIME

## PRISM - Phase Rotated Intense Slow Muon beam



Single event sensitivity –  $3 \times 10^{-19}$



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.

## 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.

## Members:

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 M. Lancaster, UCL, London, UK

## 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).

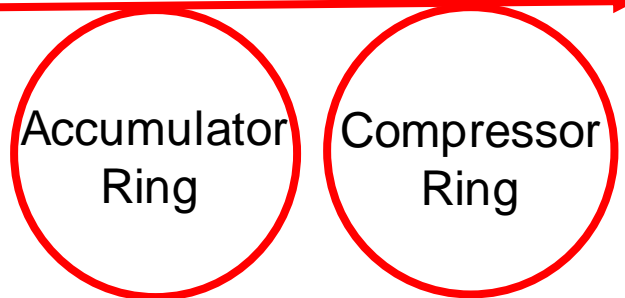
## Requirements for a new design:

- High transverse acceptance (at least  $38h/5.7v$  [Pi mm] or more).
- High momentum acceptance (at least  $\pm 20\%$  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.

# Proton Beam for PRISM/PRIME

Two methods established – BASED on LINAC or SYNCHROTRON acceleration.

H<sup>-</sup> linac

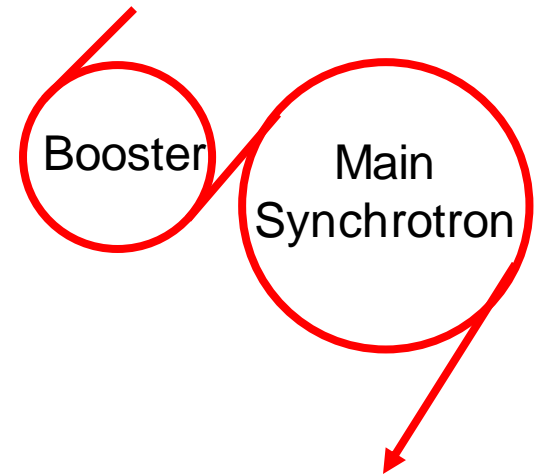


H<sup>-</sup> linac followed by the accumulator and compressor

PRISM/PRIME needs a short bunch (~10 ns)!

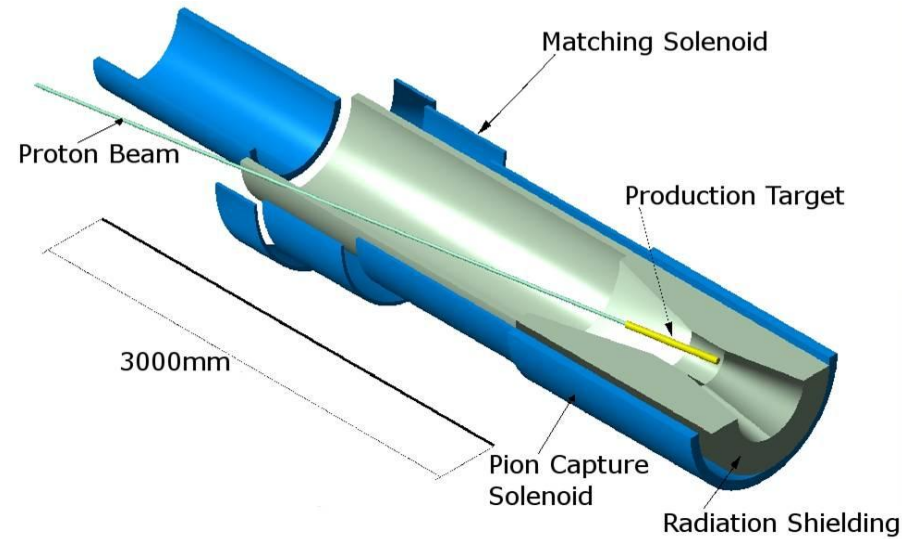
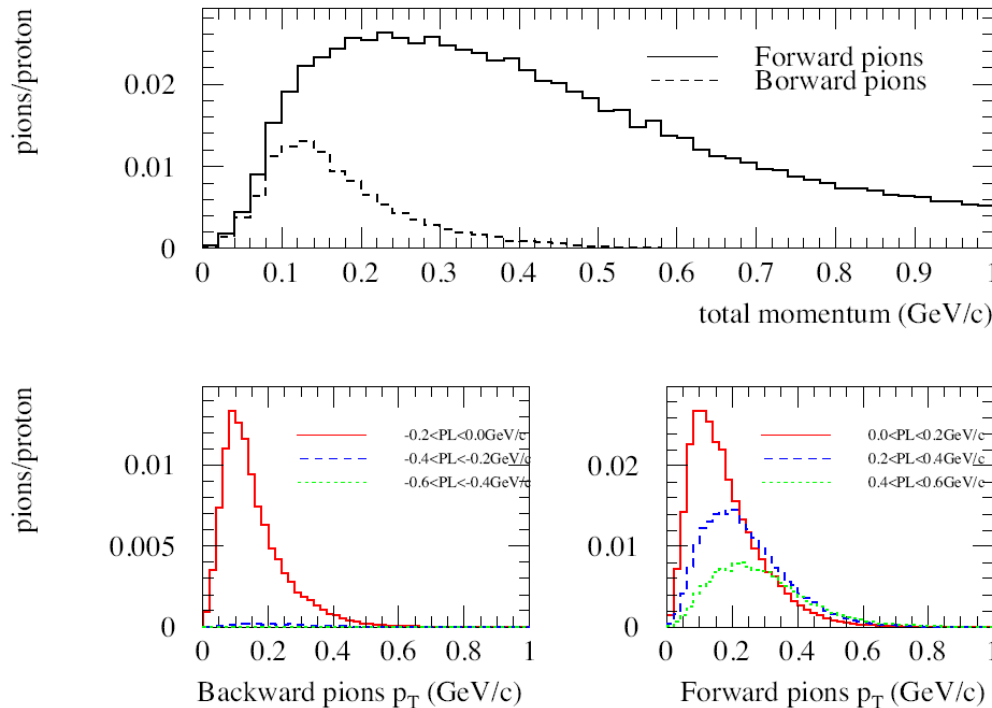
Where could it be done ?:

- at Fermilab (possibly at the Projext-X muon line)?
- at J-PARC,
- at CERN (using SPL),
- at RAL (MW ISIS upgrade could be adopted).



High power synchrotrons produce many bunches and extract one by one (proposed at J-PARC).

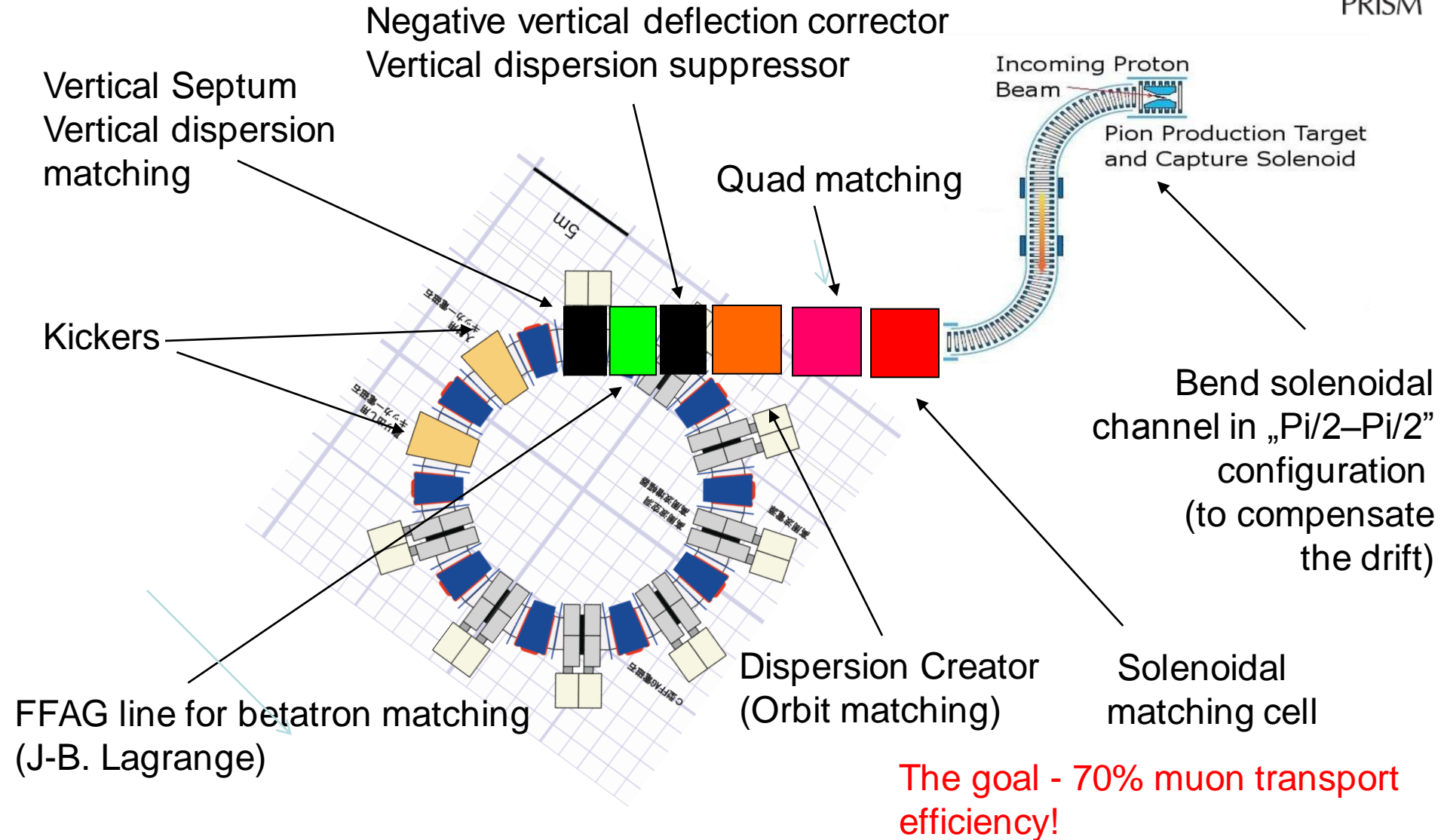
In general any Neutrino Factory Proton Driver would work for PRISM!



Au target simulations using MARS

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

# Pion/Muon Transport



This design is under studies within the PRISM Task Force.

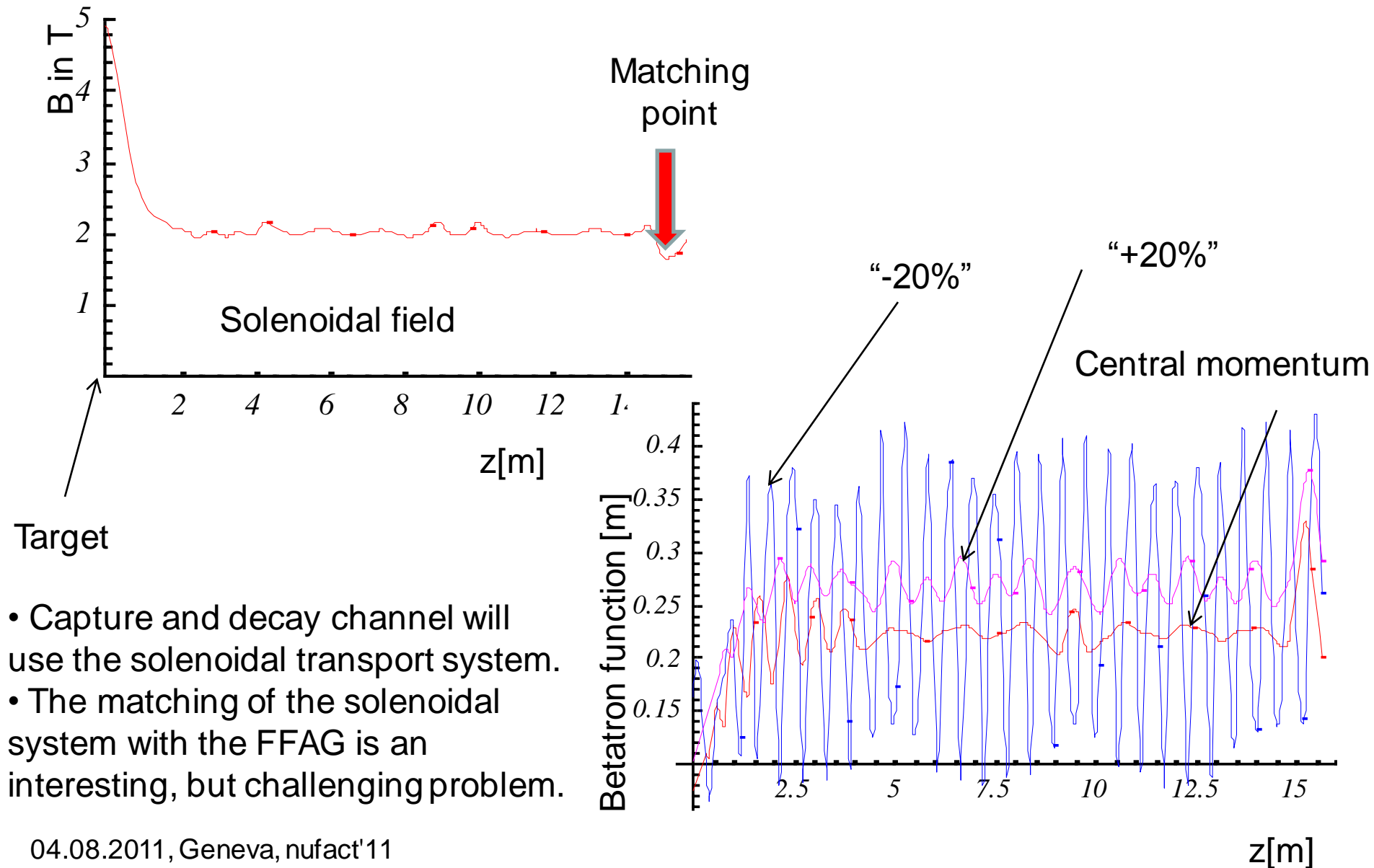
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# Status of matching section

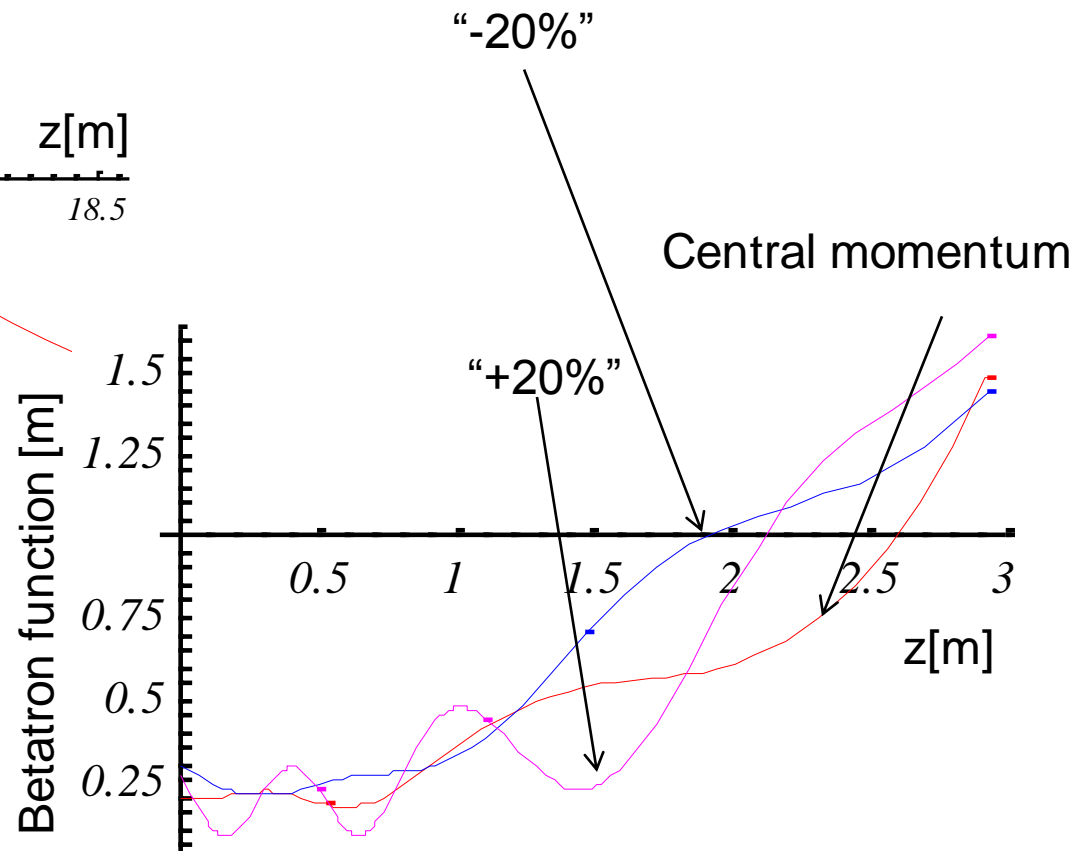
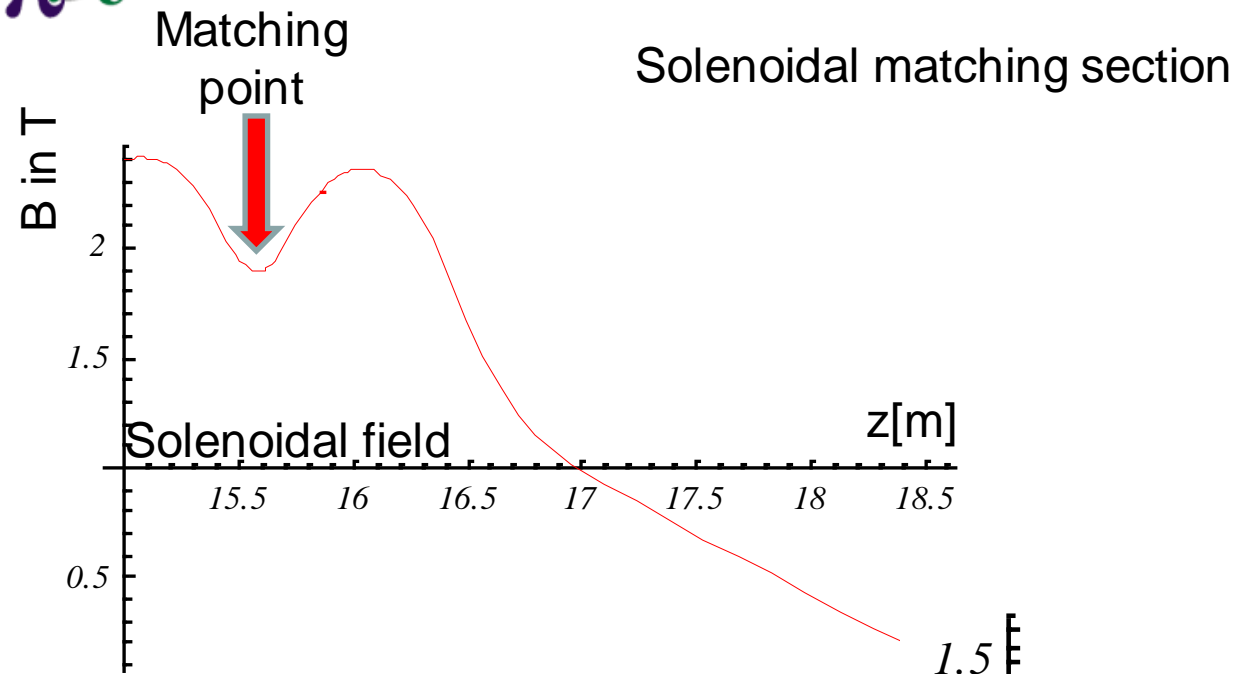
- Optics in solenoidal matching section has been designed.
- It needs to be followed by the quad channel (in preparation).
- Preliminary design for the dispersion creator based on 4 spectrometer magnets has been achieved, but more studies are needed (mismatch at extreme momentum).
- The vertical dispersion 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!

## From the target to adiabatic matching

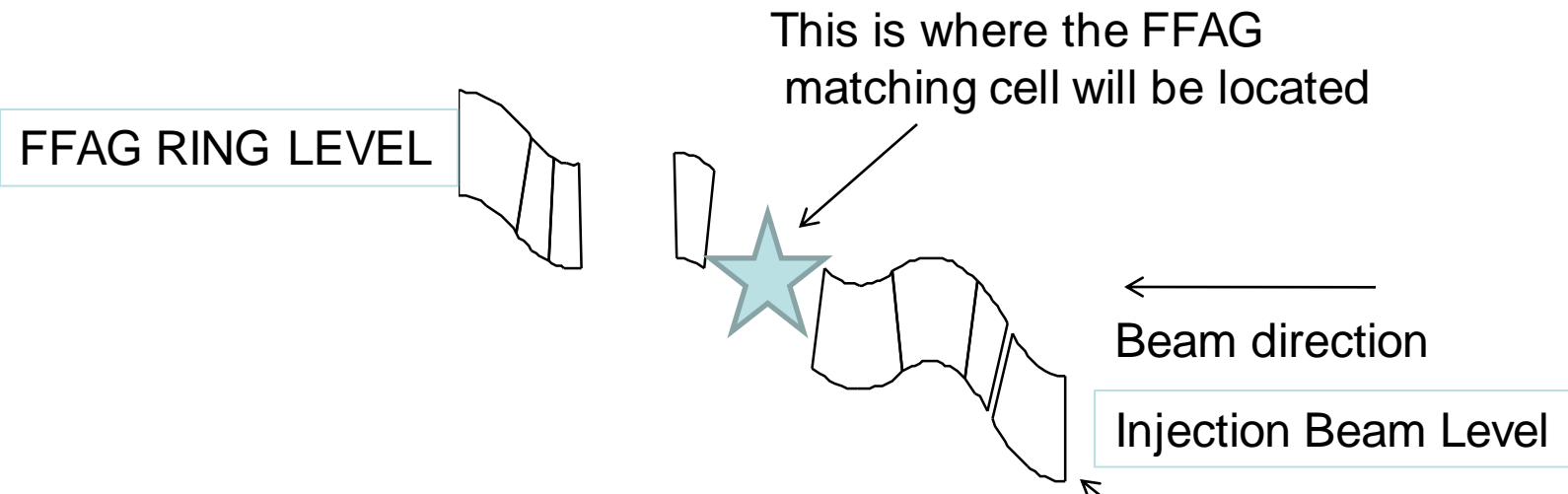


- Capture and decay channel will use the solenoidal transport system.
- The matching of the solenoidal system with the FFAG is an interesting, but challenging problem.

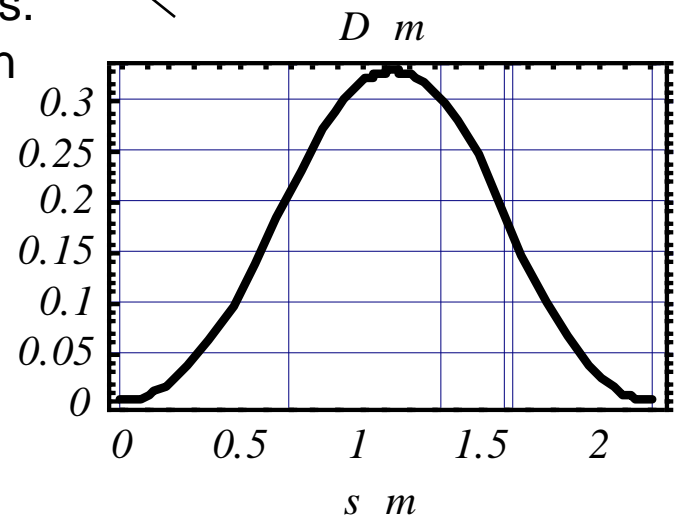
# Optics and B field in solenoidal muon transport and matching (II)



- Betatron functions needs to be matched to AG channel (~ 1-4 m).
- Solenoidal field needs to be smoothly switched off.



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



# Pion/Muon Transport (hardware)

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

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

- 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.

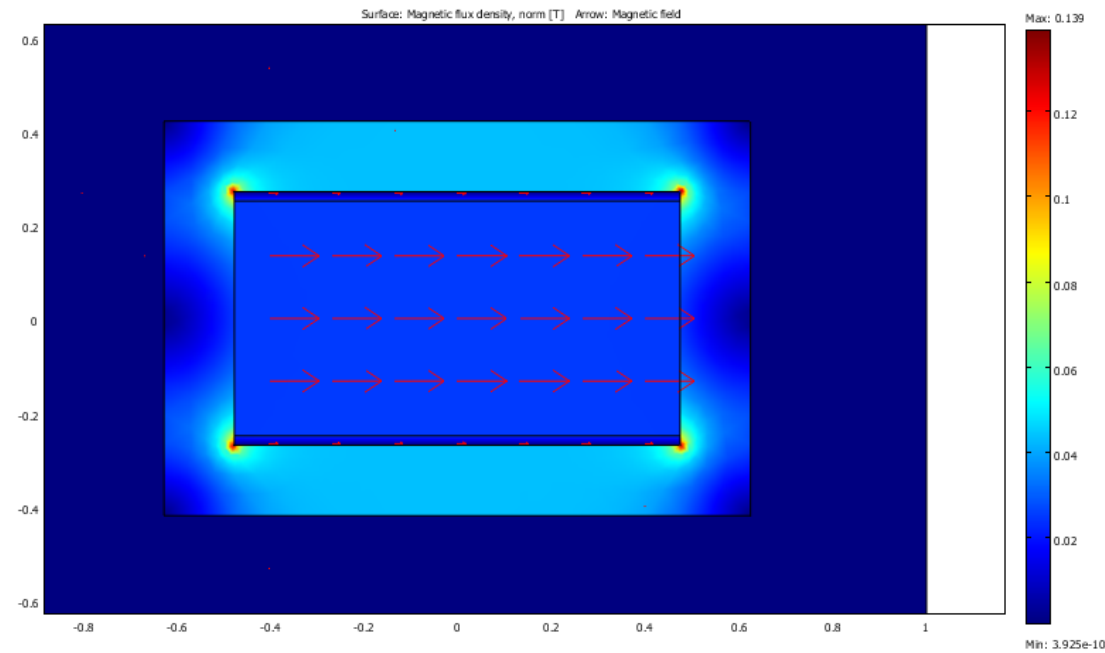


MUSIC bend solenoid under construction



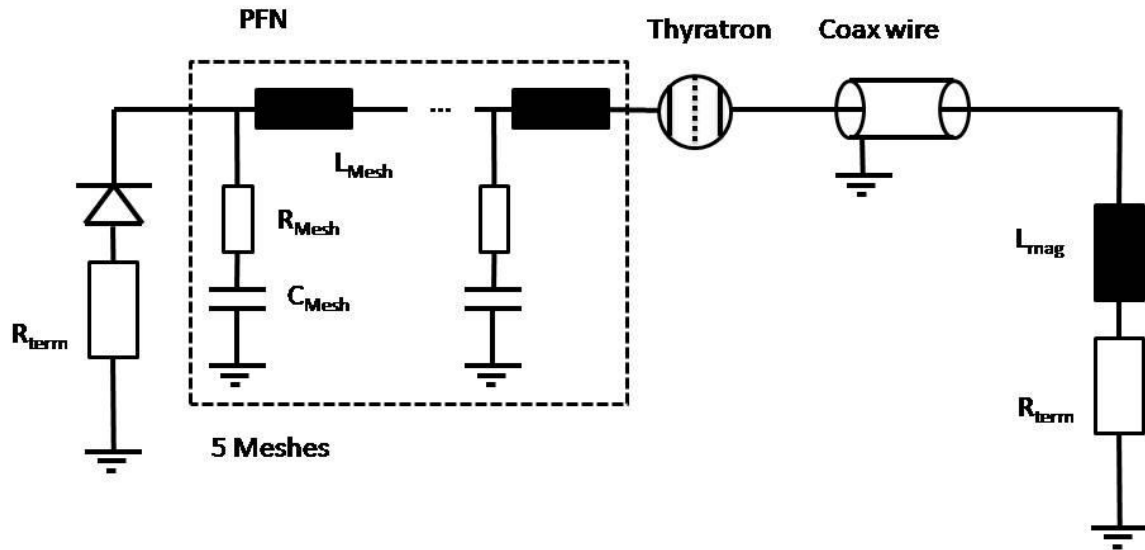
# Preliminary PRISM kicker studies

- 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  $\sim 200$  ns (for injection)
- $W_{\text{mag}} = 186$  J
- $L = 3$   $\mu\text{H}$  (preliminary)
- $I_{\text{max}} = 16$  kA

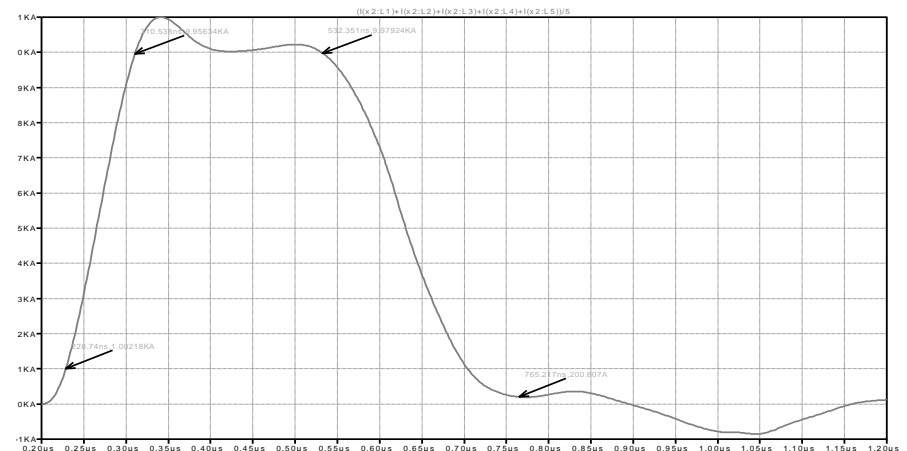


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# PRISM Pulse Formation



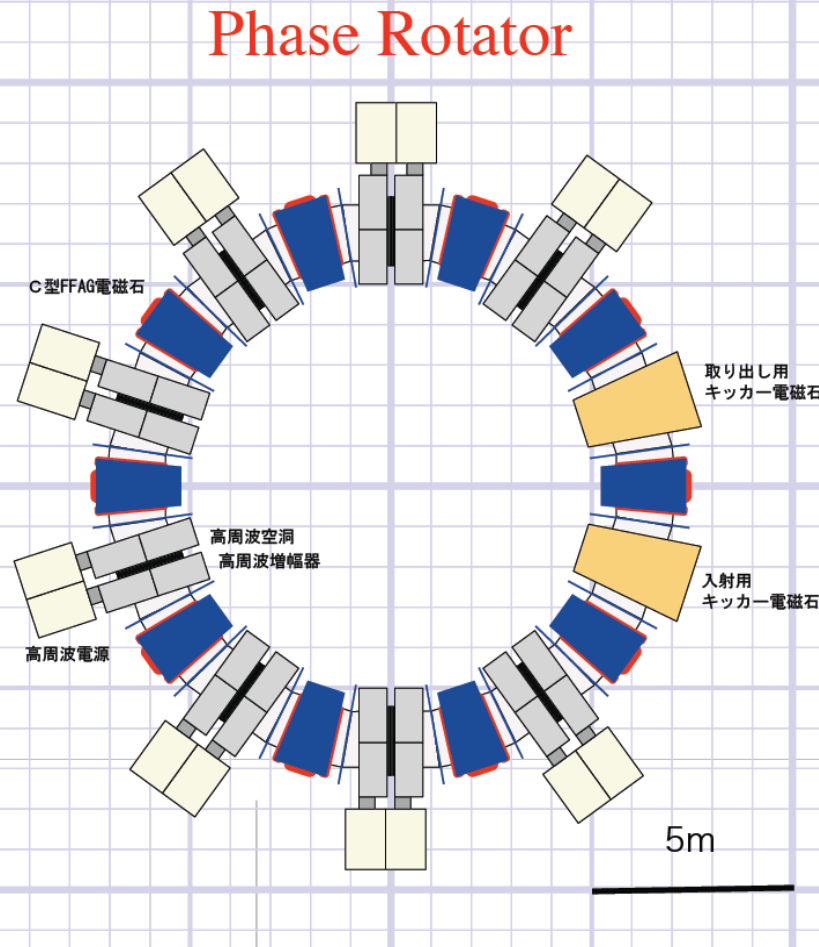
80 kV  
Impedance 3 Ohm  
Kicker subdivided into 8 smaller kickers  
Travelling wave kicker  
Each sub-kicker has 5 sections  
1 plate capacitor per section



# 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 MV

☞ p/p at injection =  $\pm 20\%$

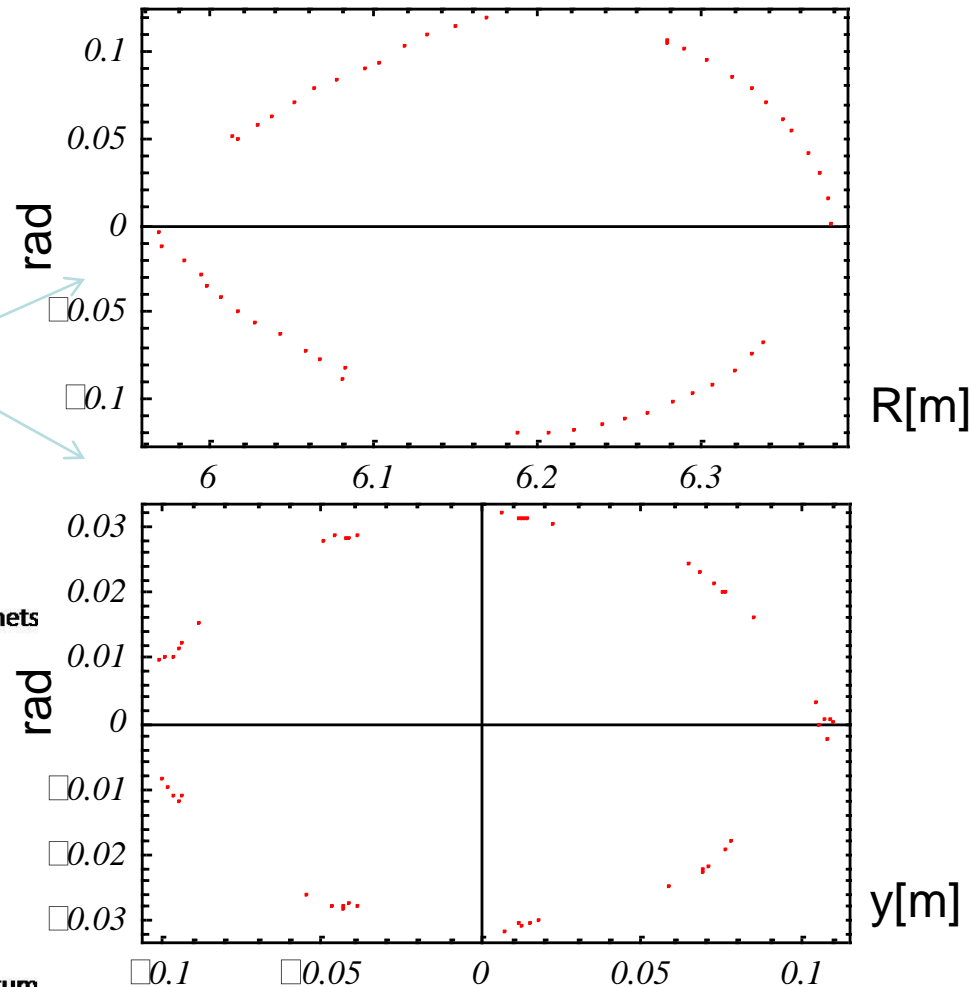
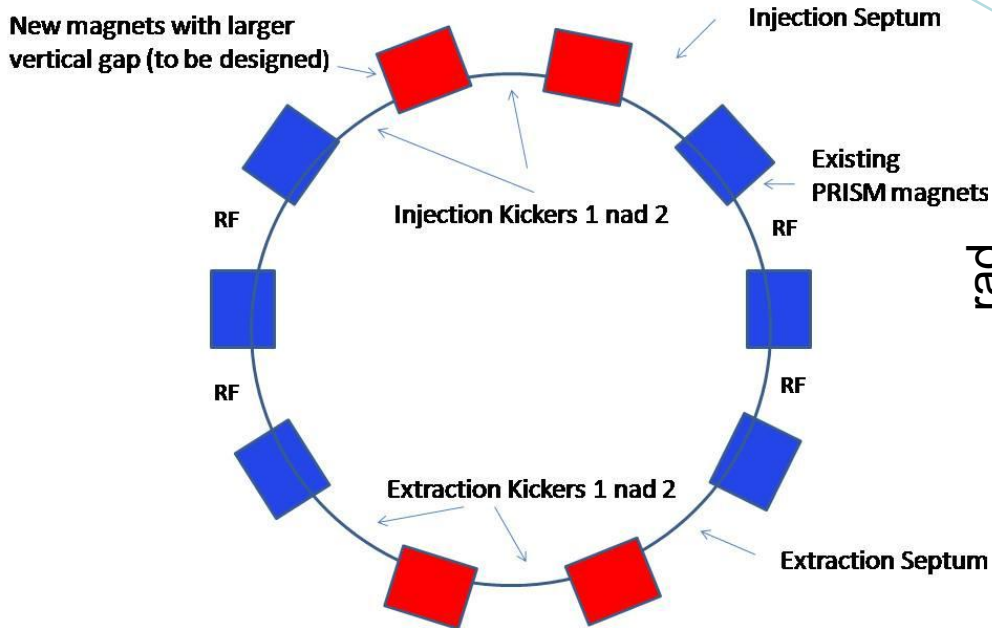
☞ p/p at extraction =  $\pm 2\%$  (after 6 turns ~ 1.5 us)

h=1

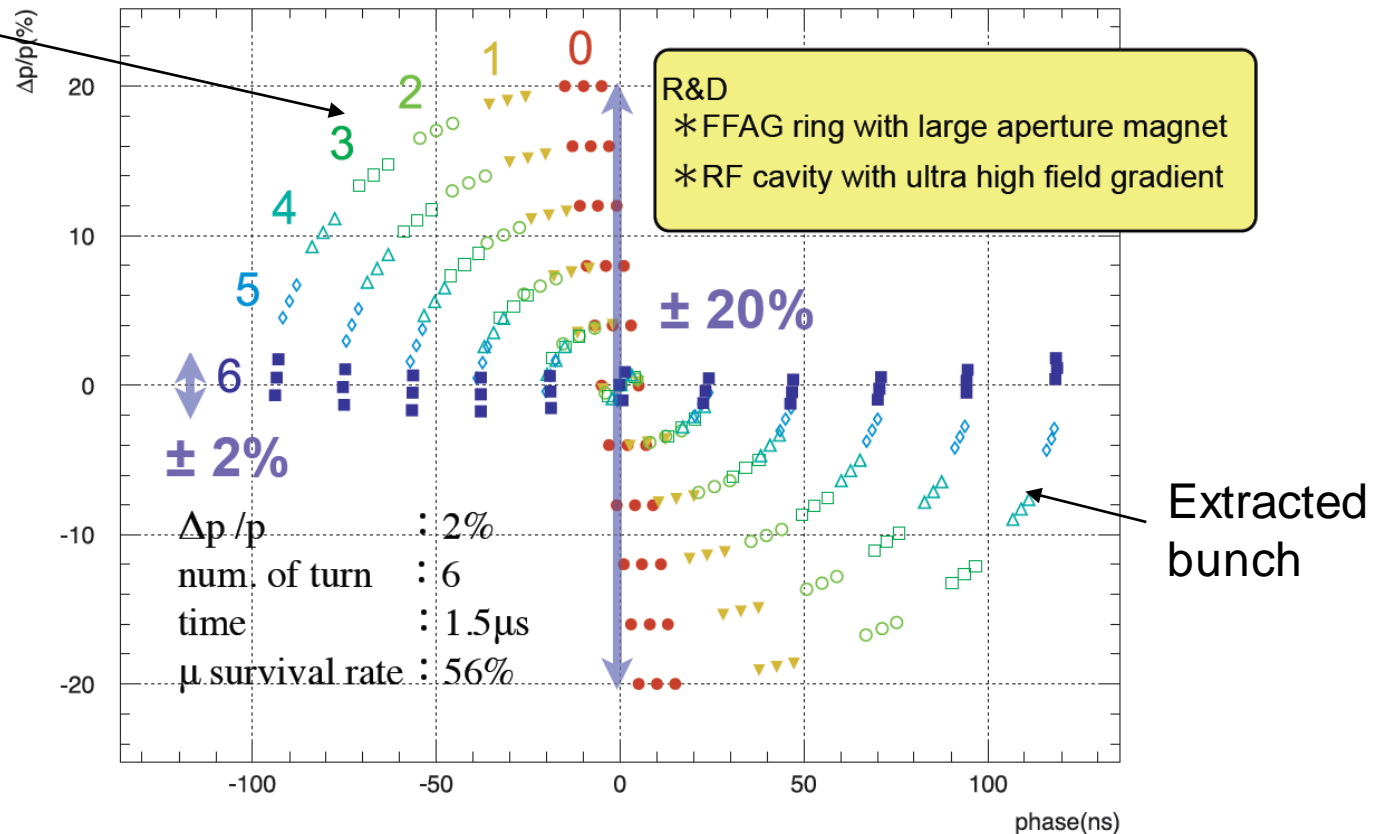
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- In order to inject/extract the beam into the reference design, special magnets with larger vertical gap are needed.
- This may be realised as an insertion (shown in red below).
- The introduction of the insertion breaks the symmetry but this does not limit the dynamical acceptance, if properly done!



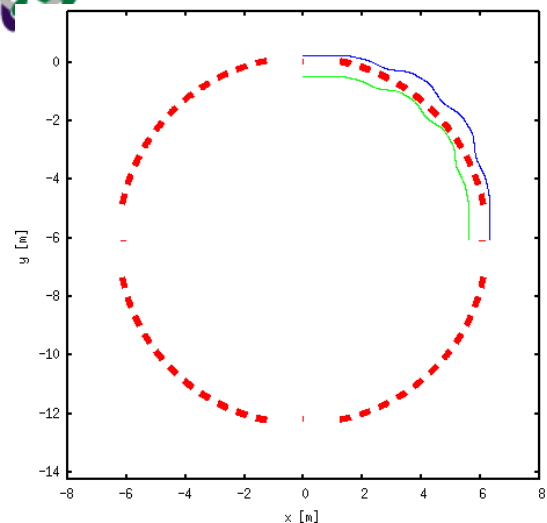
Injected bunch



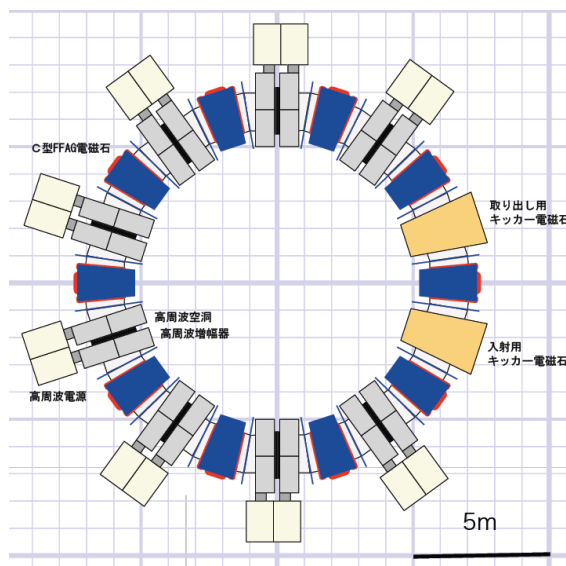
Phase rotation for 68 MeV/c reference muon

- 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.

# FFAG Ring Choice

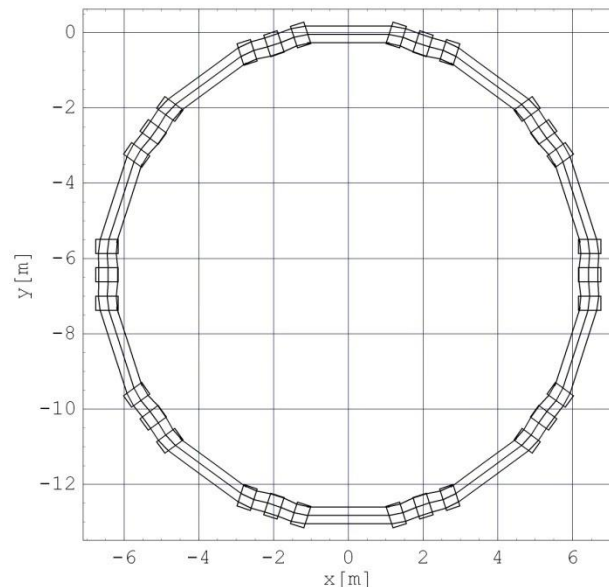


Scaling Superperiodic

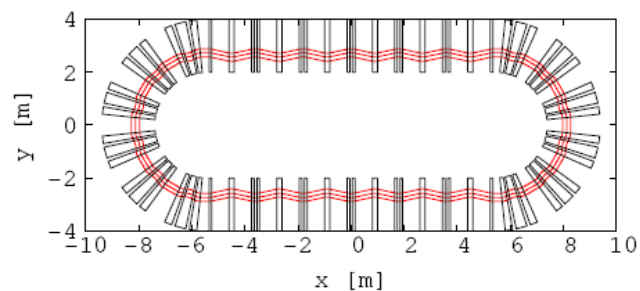


Reference design

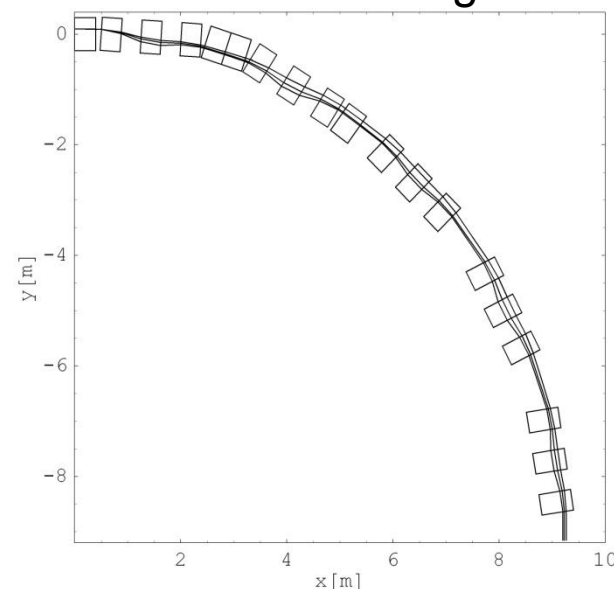
- We need to decide about the possible baseline update very soon.
- The choice is dictated by the performance.



Non-Scaling



Advanced scaling FFAG

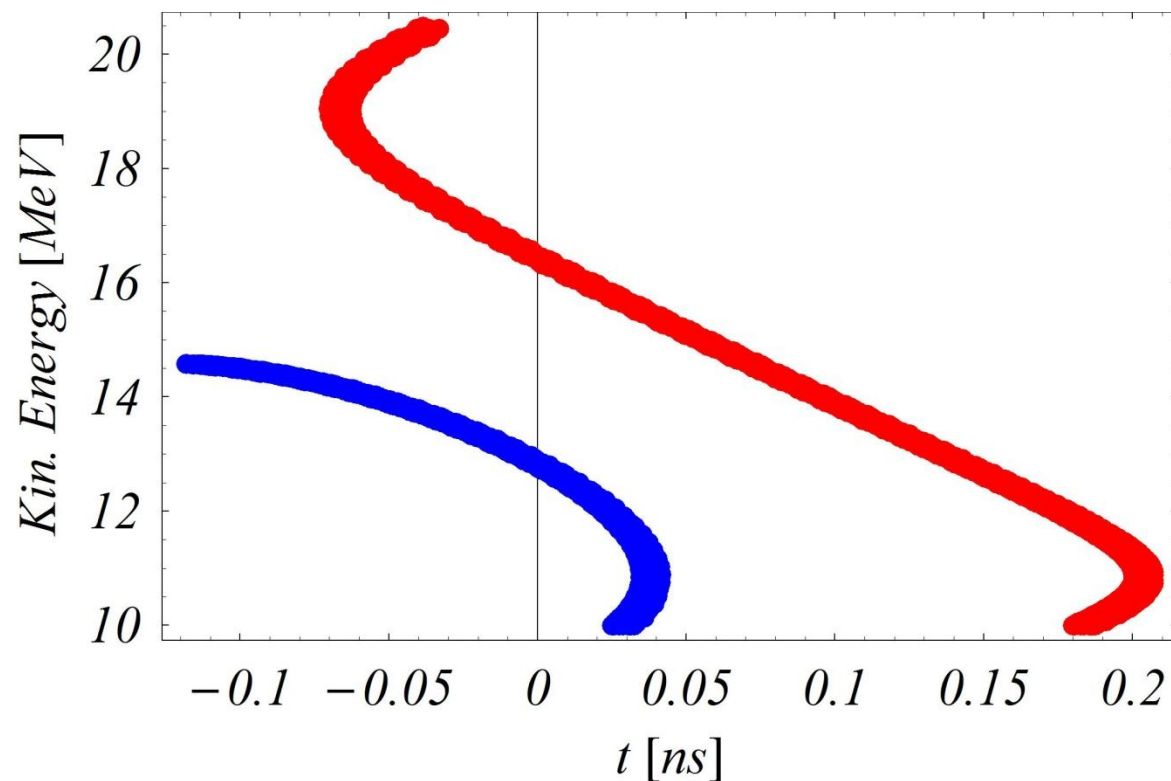


Advanced NS-FFAG

Under study within the PRISM TF.

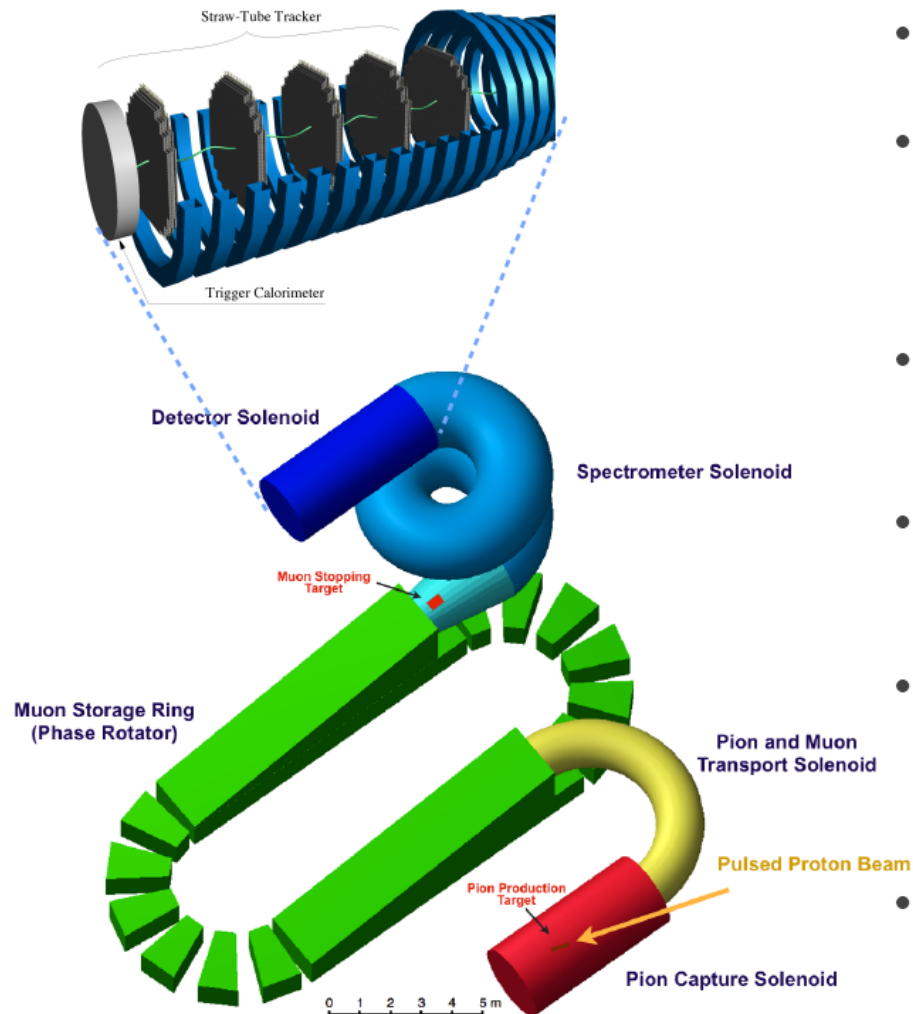
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# Experimental test of the phase rotation in NS-FFAG using EMMA ring (in preparation)



Simulations of the serpentine acceleration (red) and phase rotation (blue) in EMMA FFAG ring

- 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.
- $\frac{1}{4}$  of the synchrotron oscillation takes  $\sim 3$  turns in EMMA and  $\sim 6$  turns in PRISM.
- Similar or even larger momentum spread can be tested.



- **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  $\gamma$ 's.
  - $f < 1$  MHz
- **Electron Calorimeter**
  - Trigger
  - Cosmic Muon suppression
  - $f < 1$  MHz
- **No Time Window**
  - pure muon beam
  - + curved solenoid

Goal: PRIME detector/beam simulations using G4.

# 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.