Design studies for PRISM

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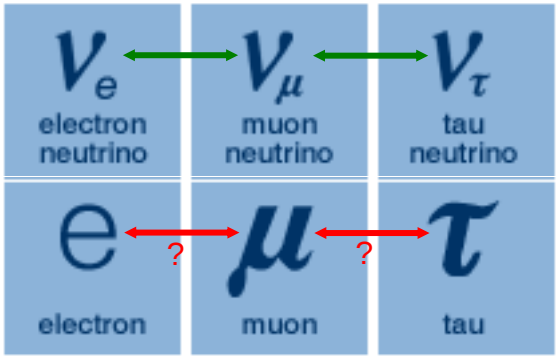
on behalf of
the PRISM Task Force

Outline

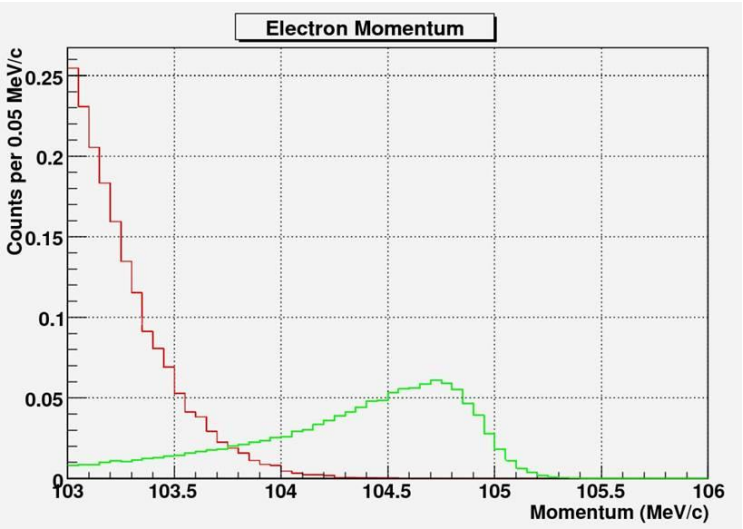
- Introduction
- Main challenges
- Task Force and status of its achievements
- Summary and future plans.

Introduction

- 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 μ- + N(A,Z)→e- + N(A,Z) seems to be the best laboratory for cLFV.
- The background is dominated by beam, which can be improved.
- PRISM/PRIME is the next generation experiment (possible upgrade pathe to COMET).



Does cLFV exists?

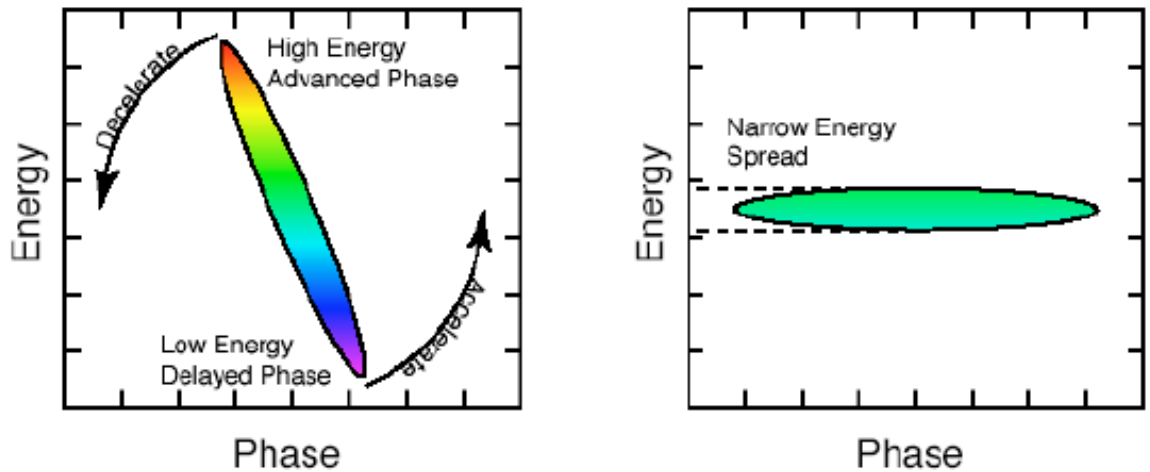


Simulations of the expected electron signal (green).

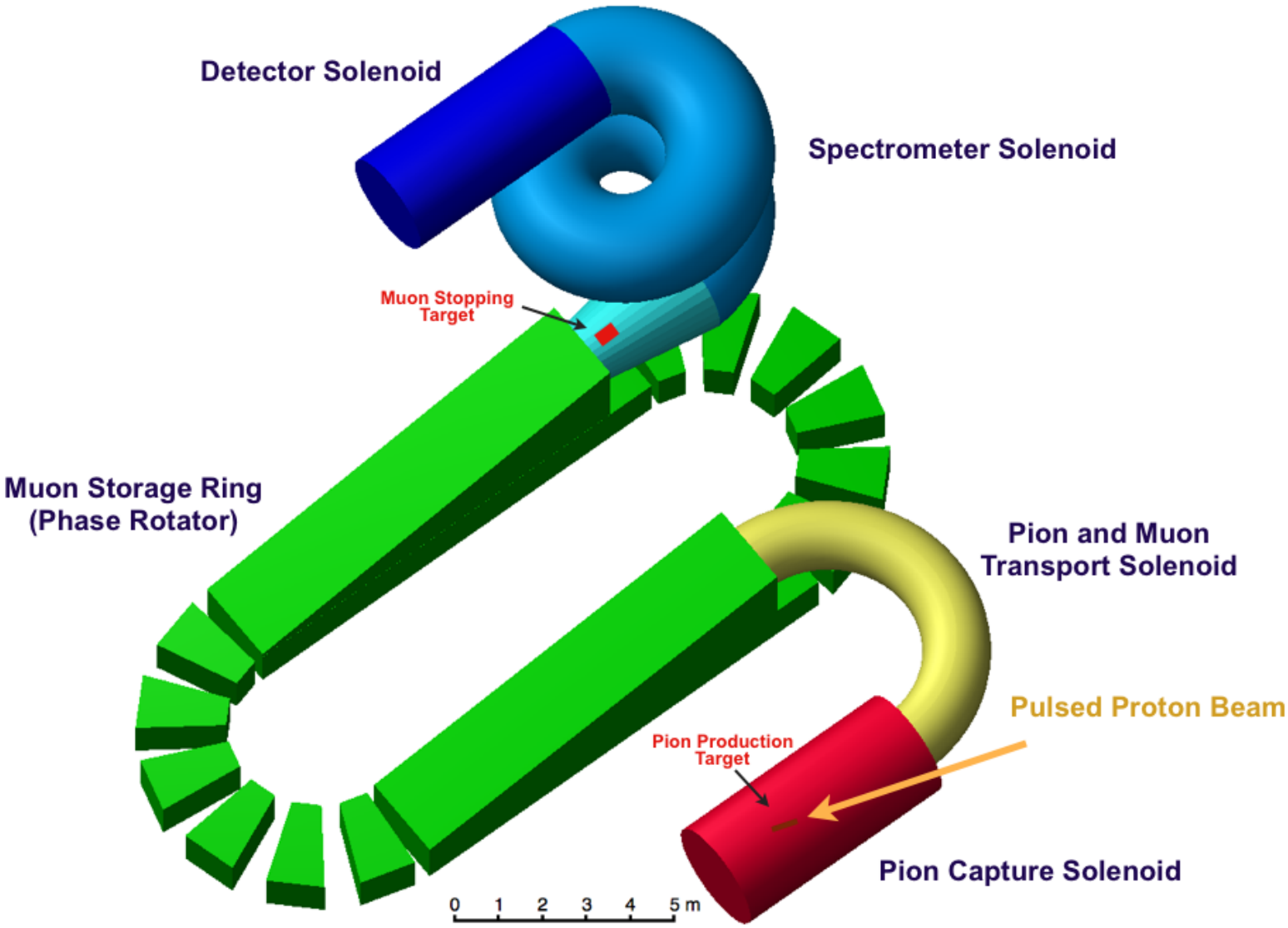
PRISM System Concept

PRISM - Phase Rotated Intense Slow Muon beam

- 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.
- PRISM requires a compressed proton bunch and high power proton beam
  - It needs a new proton driver!
- This will allow for a single event sensitivity of 3×10^{-19}



Conceptual Layout of PRISM/PRIME



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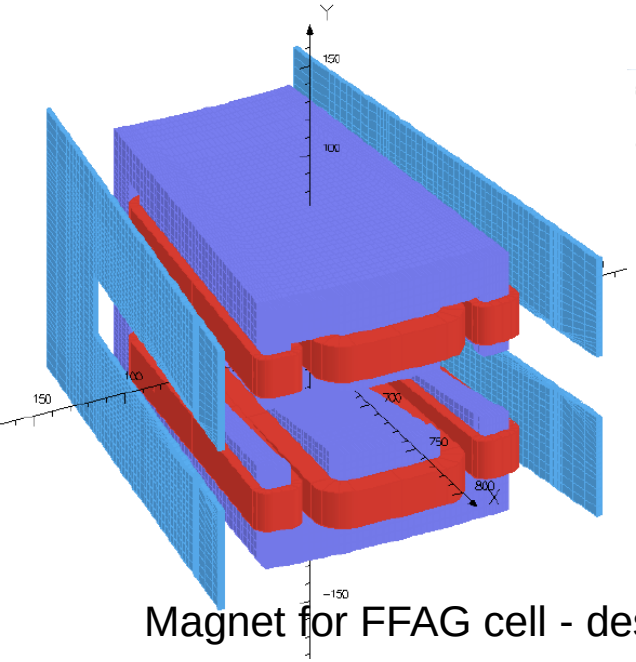
PRISM parameters

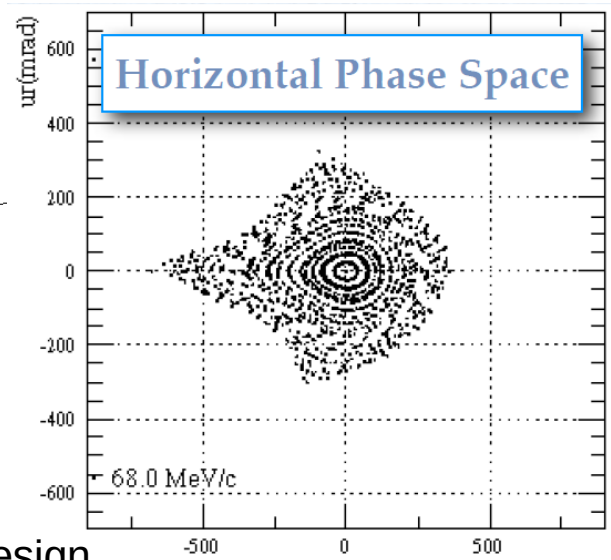
Parameter	Value
Target type	solid
Proton beam power	1-4 MW
Proton beam energy	multi-GeV
Proton bunch duration	~10 ns total (in synergy with the NF)
Pion capture field	4-10 T
Momentum acceptance	±20 %
Reference μ^-momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

R&D work in Osaka

- 10 cell DFD ring has been designed
- FFAG magnet-cell has been designed, constructed and verified.
- RF system has been designed, tested and assembled.
- 6 cell ring was assembled and its optics was verified using α particles.
- Phase rotation was demonstrated for α particles.



Magnet for FFAG cell - design



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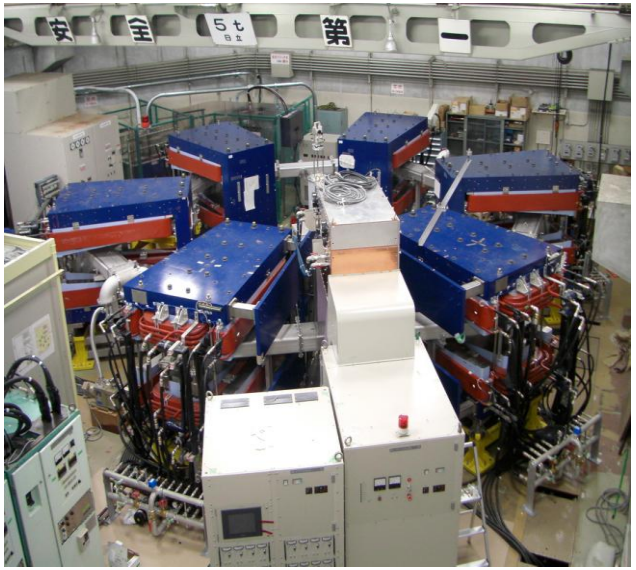
6 cell FFAG ring at RCNP



PRISM Task Force

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.

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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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K. M. Hock, Cockcroft Institute, Warrington, UK/University of Liverpool, UK
R. J. Barlow, Cockcroft Institute, Warrington, UK/University of Manchester, UK
R. Appleby, J. Garland, H. Owen, S. Tygier, Cockcroft Institute, Warrington, UK/University of Manchester,UK
C. Ohmori, KEK/JAEA, Ibaraki-ken, Japan
H. Witte, T. Yokoi, JAI, Oxford University , UK
,Y. Mori, Kyoto University, KURRI, Osaka, Japan
Y. Kuno, A. Sato, Osaka University, Osaka, Japan
D. Kelliher, S. Machida, C. Prior, STFC-RAL-ASTeC, Harwell, UK
M. Lancaster, UCL, London, UK

 You are welcome to join us!

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 finaly 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.

Challenges for the PRISM accelerator system

• The need for the compressed proton bunch:
- is in full synergy with the Neutrino Factory and a Muon Collider.
- puts PRISM in a position to be one of the incremental steps of the muon programme.

• Target and capture system:
-is in full synergy with the Neutrino Factory and a Muon Collider studies.
-requires a detailed study of the effect of the energy deposition induced by the beam

• Design of the muon beam matching from the solenoidal capture to the PRISM FFAG ring.
-very different beam dynamics conditions.
-very large beam emittances and the momentum spread.

• Muon beam injection/extraction into/from the FFAG ring.
-very large beam emittances and the momentum spread.
-affects the ring design in order to provide the space and the aperture.

• RF system
-large gradient at the relatively low frequency and multiple harmonics (the “sawtooth” in shape).

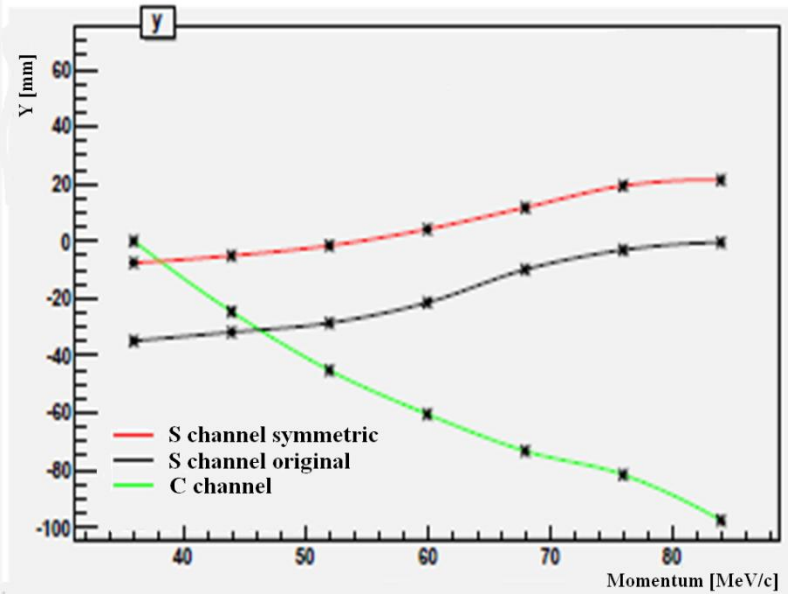
Progress achieved by the Task Force

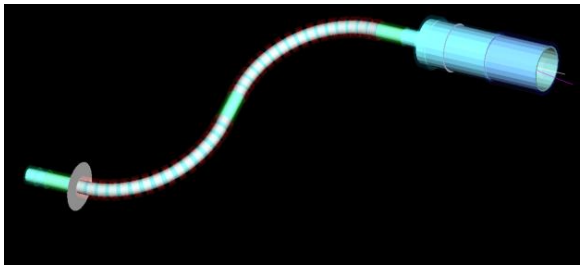
- Several new ring designs has been proposed including scaling and non-scaling options.
- New material for RF cores has been developed (at J-PARC for RCS), which offers higher gradient (or cost reduction).
- Preliminary design of the kicker system has been studied.
- Matching from the solenoidal channel to the FFAG was studied and shows promising results.
- Injection options have been reviewed.
- Effects related to non-zero chromaticity in non-scaling designs have been addressed experimentally at EMMA (DL, UK) and analysis is ongoing.

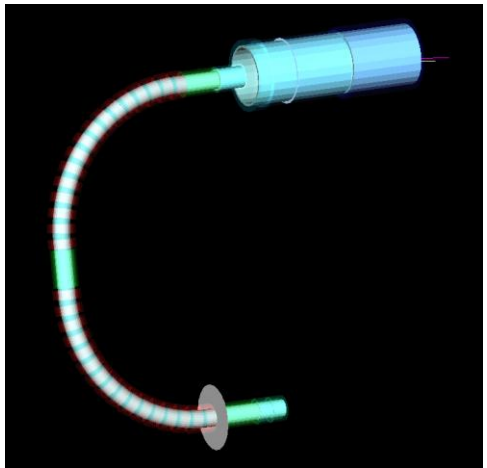
I can cover only part of this in this talk...

Matching to the FFAG I

- Muon beam must be transported from the pion production solenoid to the Alternating Gradient channel.
- Two scenarios considered, S-shaped and C-shaped.
  - S-shaped with correcting dipole field has the best transmission and the smallest dispersion.

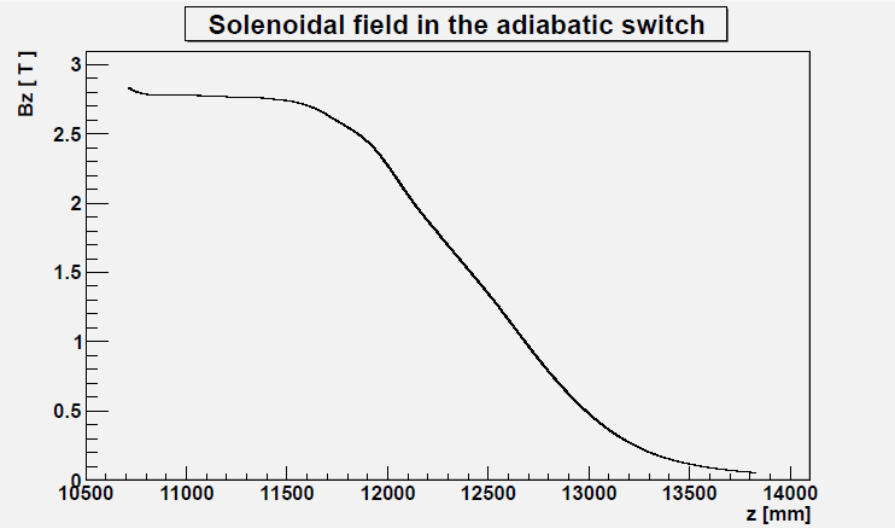


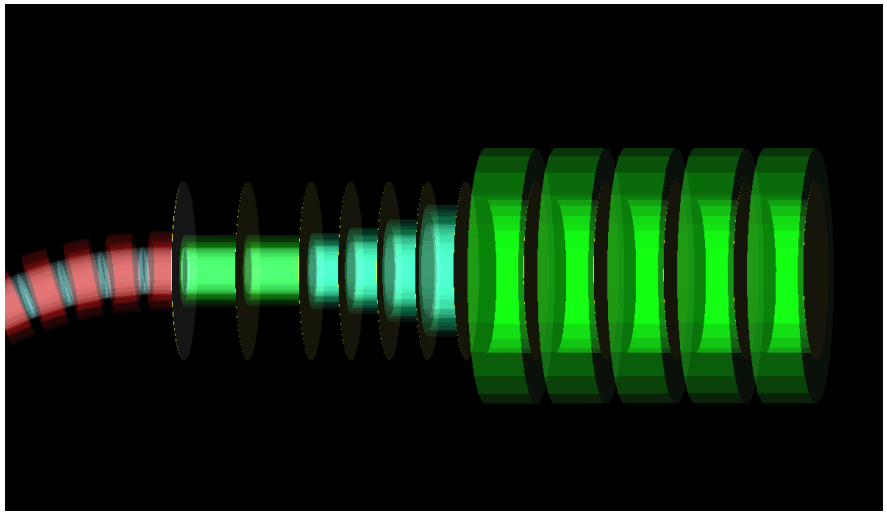




The mean vertical beam position versus momentum at the end of bend solenoid channel for various configurations.

Matching to the FFAG II





Initial version of the adiabatic switch

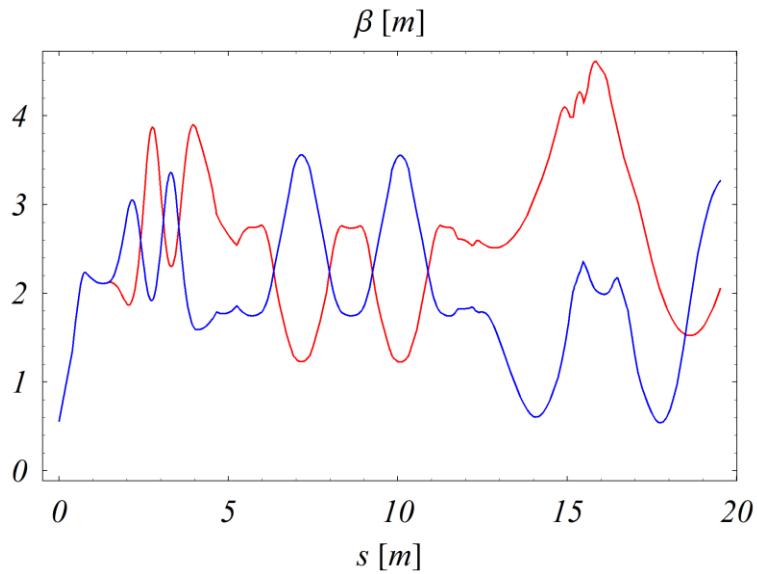
Preliminary geometry: the end of the S-channel together with matching solenoids, adiabatic switch and 5 quad lenses.

Current best version includes:

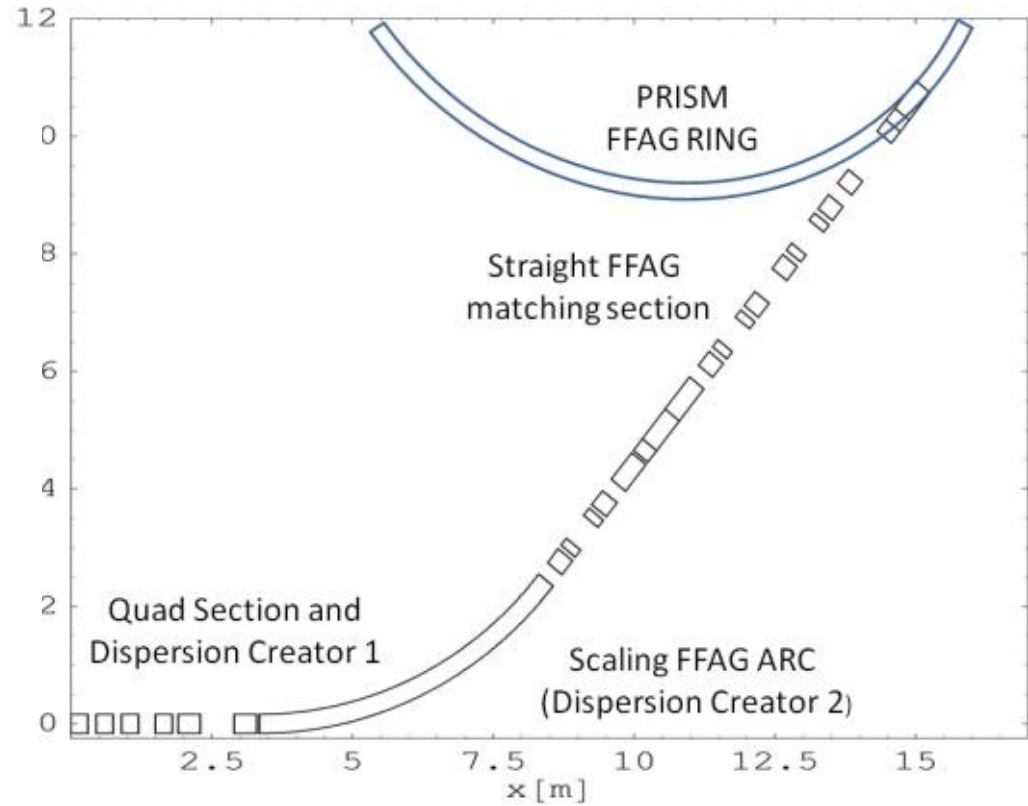
- adiabatic switch from 2.8 to 0.5 T (to increase the beam size),
- additional solenoidal lense to match α=0 (not shown in the pictures above),
- 5 quad lenses,

Matching to the FFAG III

- A dedicated transport channel has been designed to match dispersions and betatron functions.



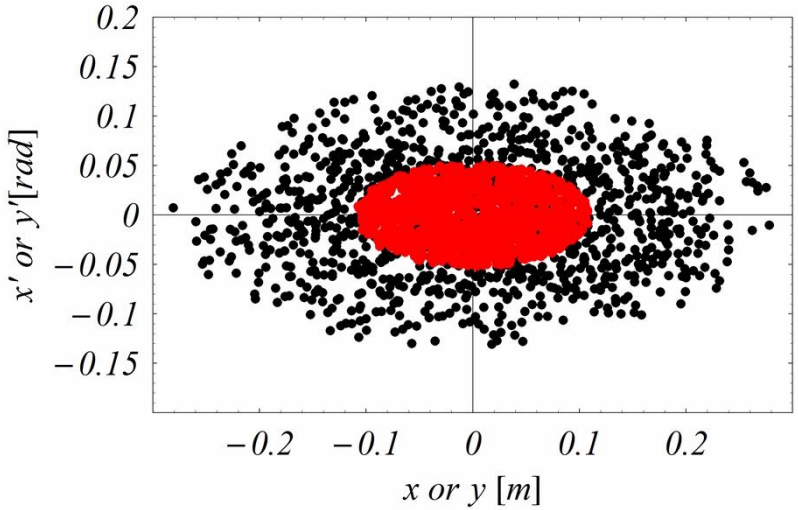
Horizontal (red) and vertical (blue) betatron functions in the PRISM front end.



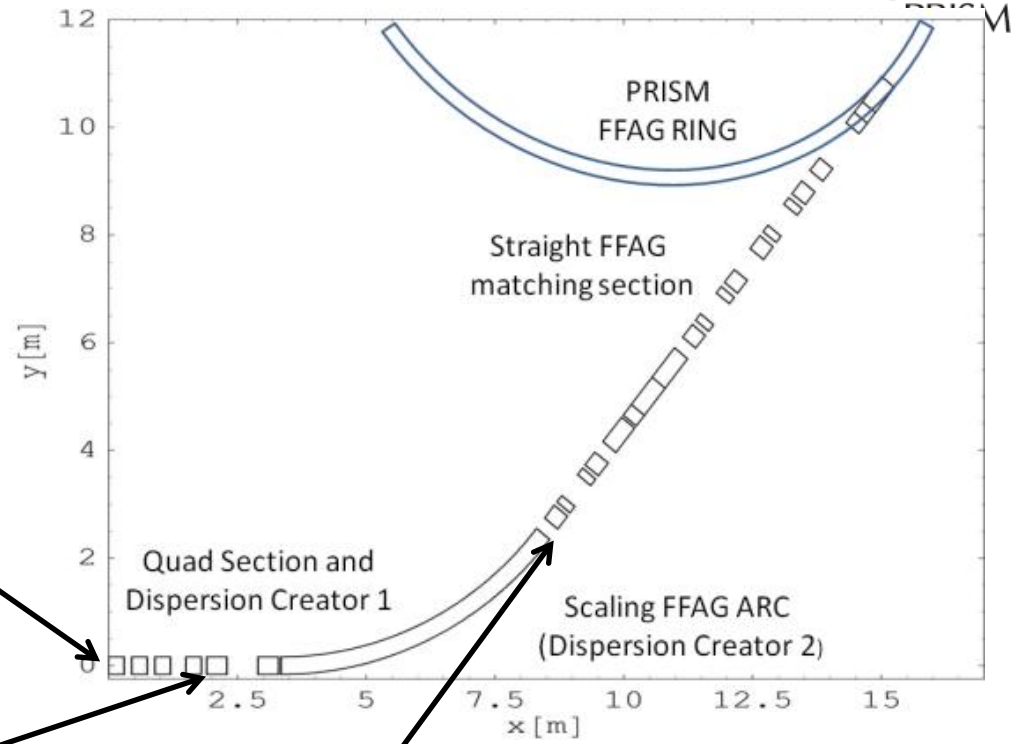
Layout of the matching section seen from the above.

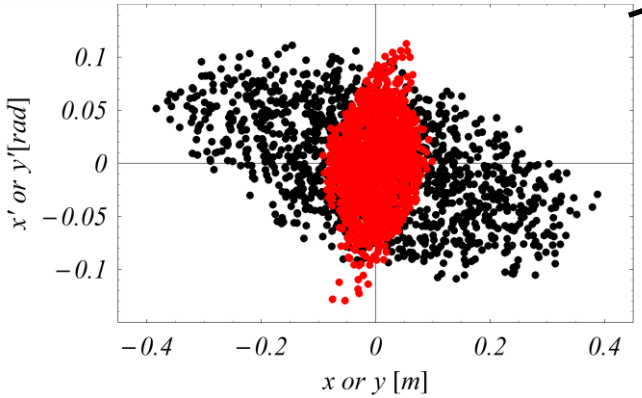
Matching to the FFAG IV

- Tracking status (work in progress)

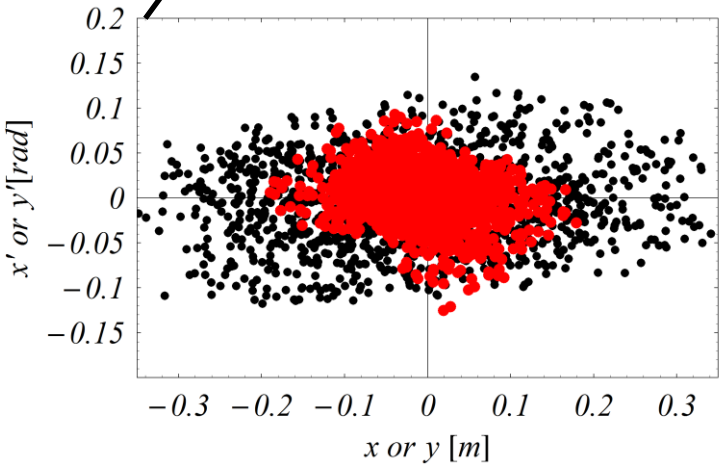


Horizontal (black) and vertical (red) phase spaces at the input to the AG part of the PRISM muon front end.





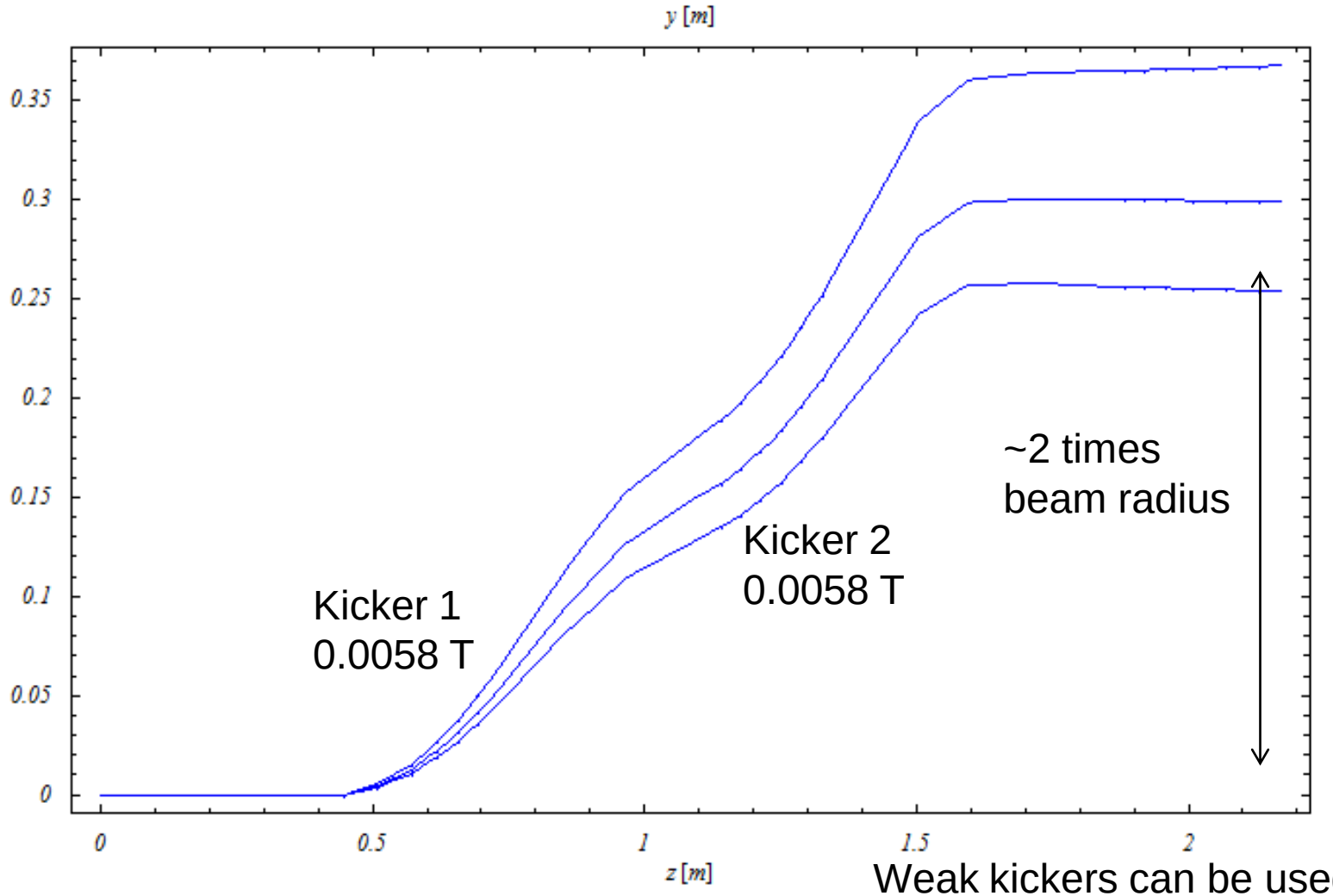
At the end of the quad Channel



At the end of the horizontal dispersion creator (transmission 97%)

Vertical injection

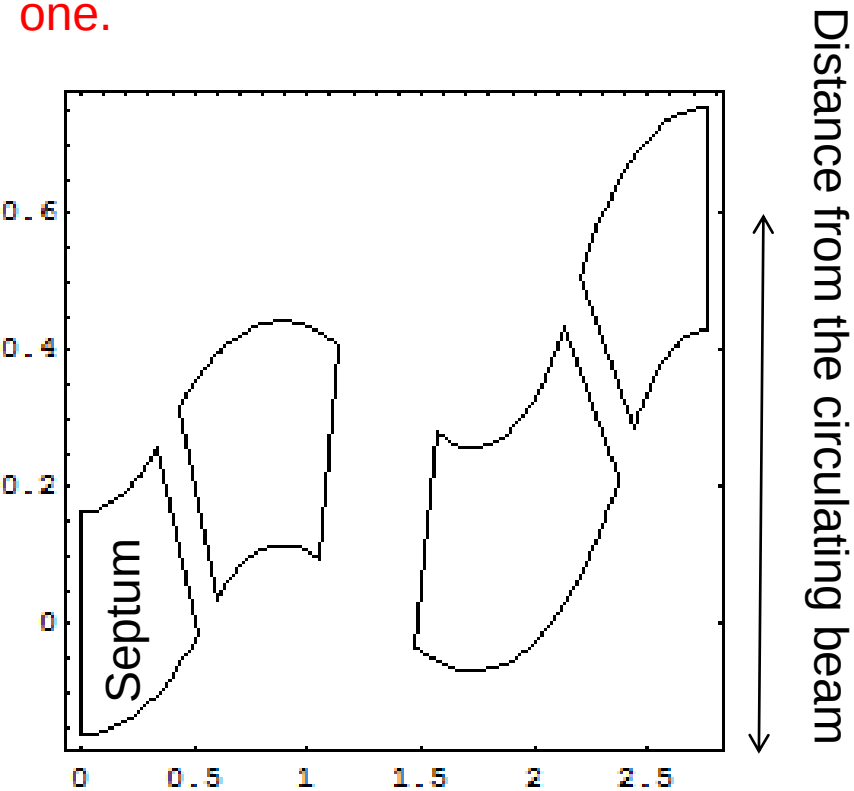
Orbit separation with 2 kickers



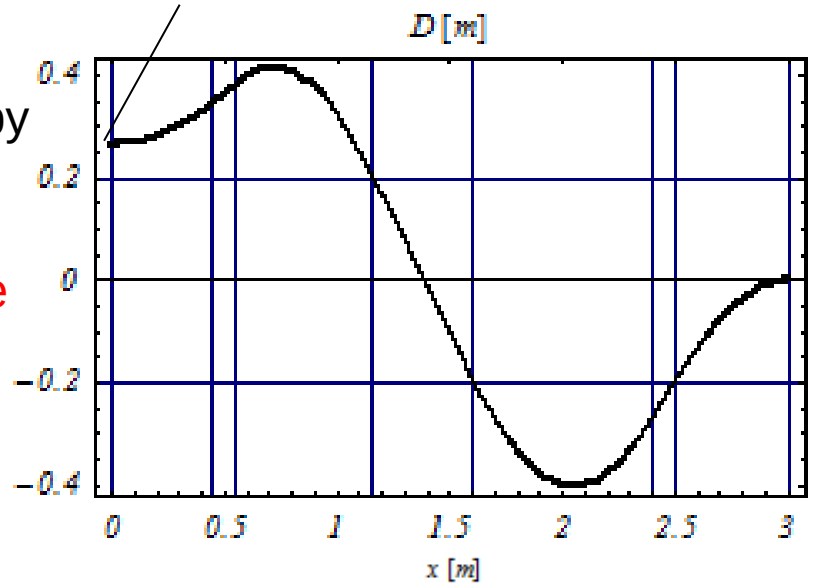
Weak kickers can be used!

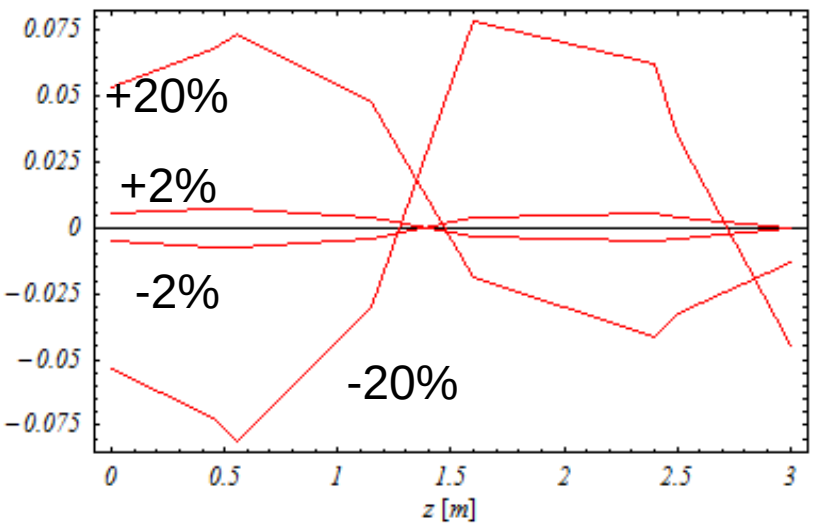
Vertical injection – vertical dispersion suppression

- System of vertical deflectors is proposed to suppress the vertical dispersion produced by the kicker and septum.
- It works for small and large positive Δp/p, however there are problems for large negative one.



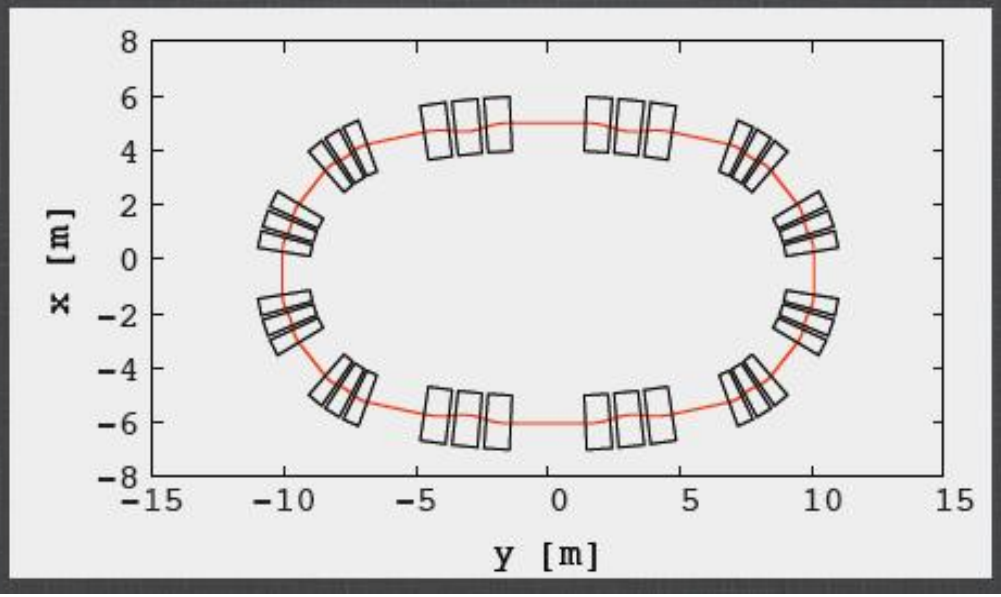
Dispersion created by the kicker





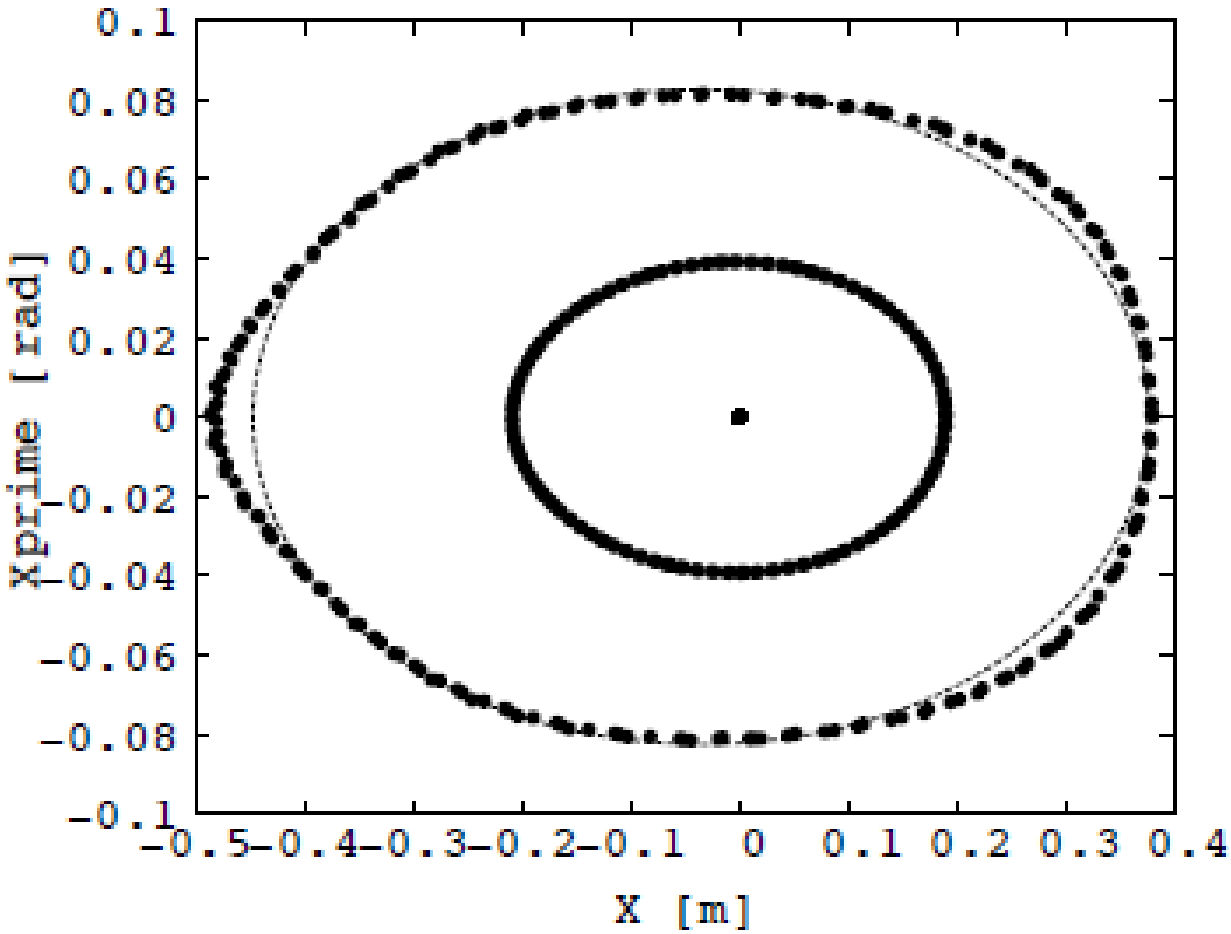
Egg-shape design

Small Bending cell FDF triplet		Large Bending cell FDF triplet	
k-value	3.82	k-value	28.9503
total bending angle	39.15 deg.	total bending angle	11.7 deg.
Average radius	5 m	Average radius	30 m
Phase advances:		Phase advances:	
Horizontal μ_x	90 deg.	Horizontal μ	75 deg.
Vertical μ_z	60 deg.	Vertical μ	81 deg.
Dispersion	1 m	Dispersion	1 m



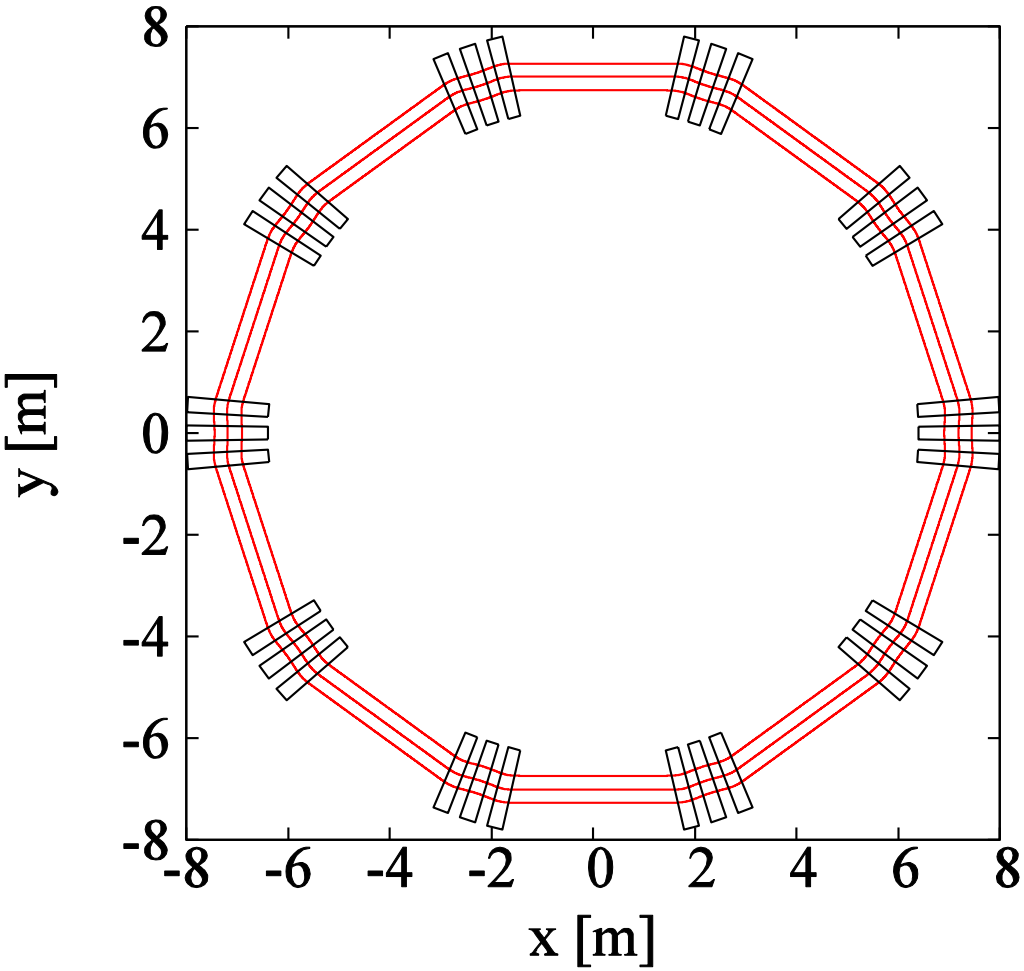
The most promising concept, work in collaboration with JB Lagrange.
This work triggered the progress on the nuSTORM FFAG design.

Egg-shape ring horizontal acceptance

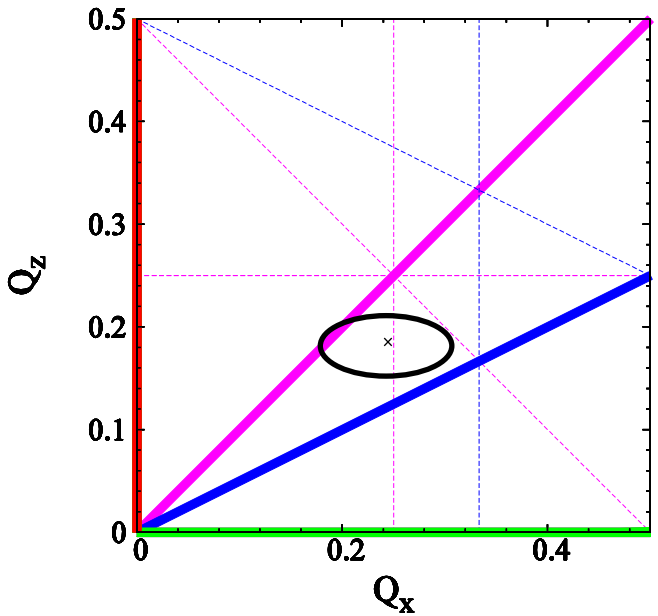


~40000 π.mm.mrad!

New FDF scaling FFAG design



- FDF symmetry motivated by the success of ERIT at KURRI
- 10 cells
- k 4.3
- R_0 7.3 m
- (Q_H, Q_V) (2.45, 1.85)
- Minimal drift length 3m



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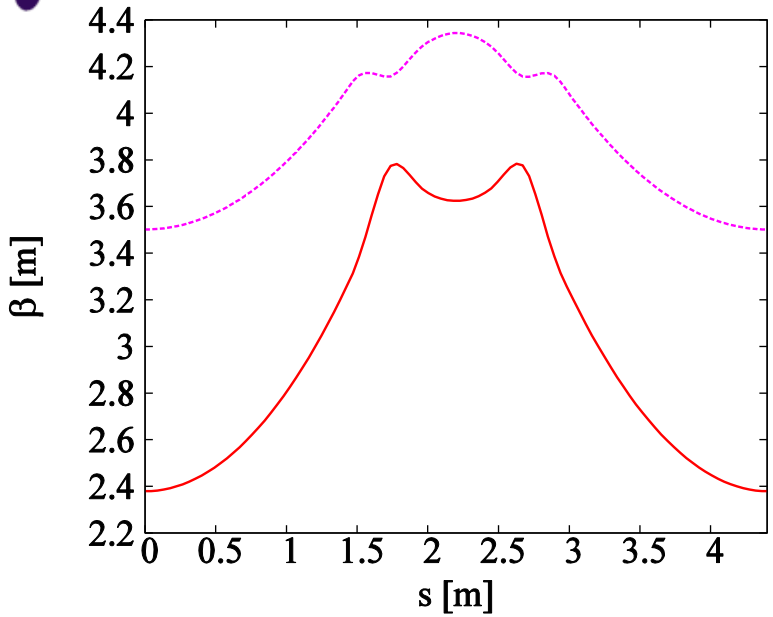
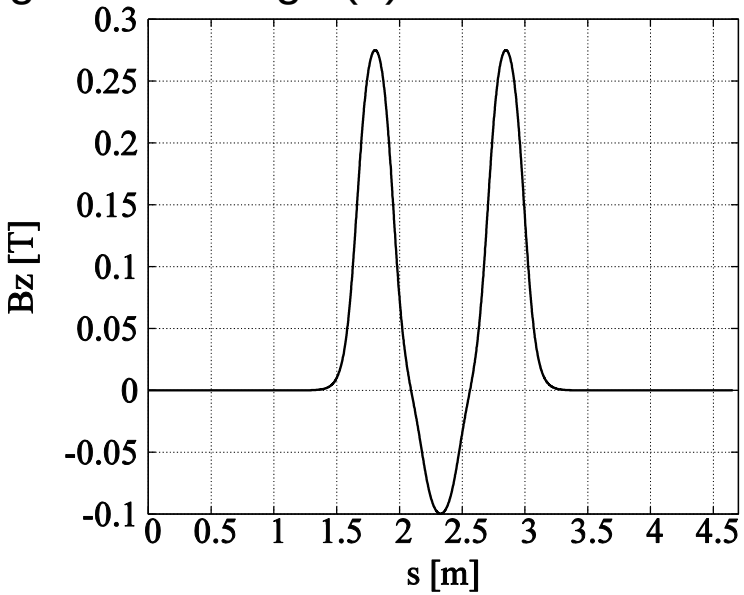
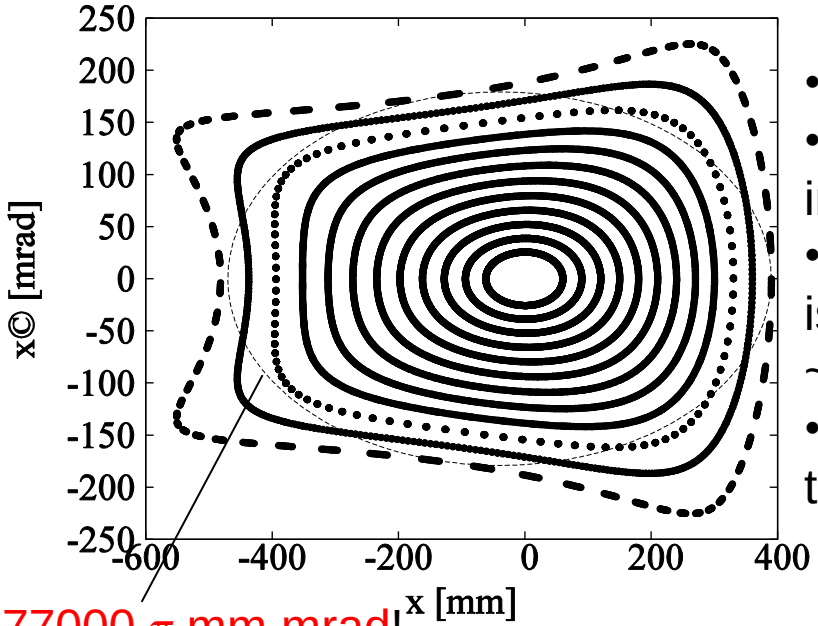
New FDF scaling FFAG design (2)







77000 π.mm.mrad!

- Enge field fall-off used to study fringe fields
- Enormous horizontal acceptance is achieved in simulations
- Vertical long term stability of ~3000 π.mm.mrad is achieved, however with some optimization ~5000 π.mm.mrad should be stable for a few turns.
- 5000 π.mm.mrad is what we currently aim for due to injection limitations.

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Conclusions and future plans

- PRISM/PRIME aims to probe cLFV with unprecedented sensitivity (single event - 3×10^{-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 and a substantial progress has been achieved.
- We are approaching the demonstration of feasibility of the PRISM system...

Future work

- **Further work on the injection/extraction systems.**

- **Review of the alternative ring designs and evaluation of their performance.**

- **Further optimisation of the best current FDF ring option.**

We also need:

- Baseline design of the PRIME detector system.

- Full G4 physics simulation of the best option.