Progress on PRISM designs: injection line and new ring concepts

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on behalf of

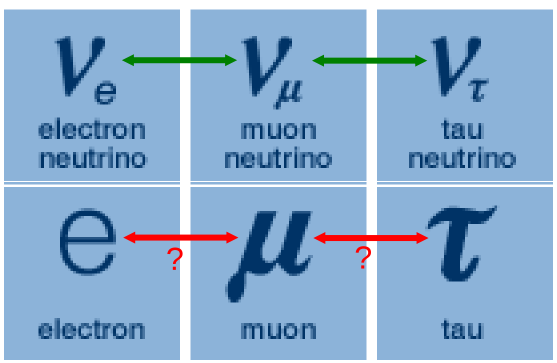
the PRISM Task Force

Outline

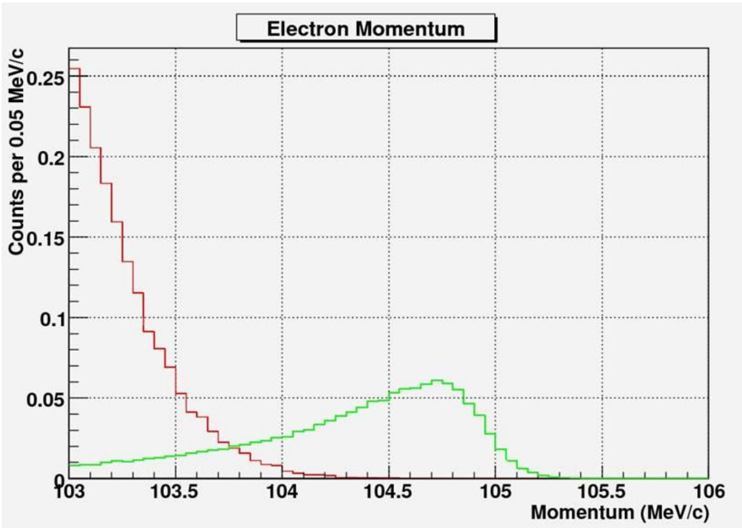
- Introduction.
- PRISM/PRIME experiment.
- Reference PRISM FFAG ring.
- PRISM Task Force initiative.
- Proton beam
- Pion production and capture.
- Muon beam matching into FFAG ring.
- Injection/extraction hardware.
- RF development.
- Reference PRISM FFAG ring modifications.
- Alternative ring designs.
- Conclusions 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.
- The COMET and Mu2e were proposed and PRISM/PRIME is the next generation experiment.



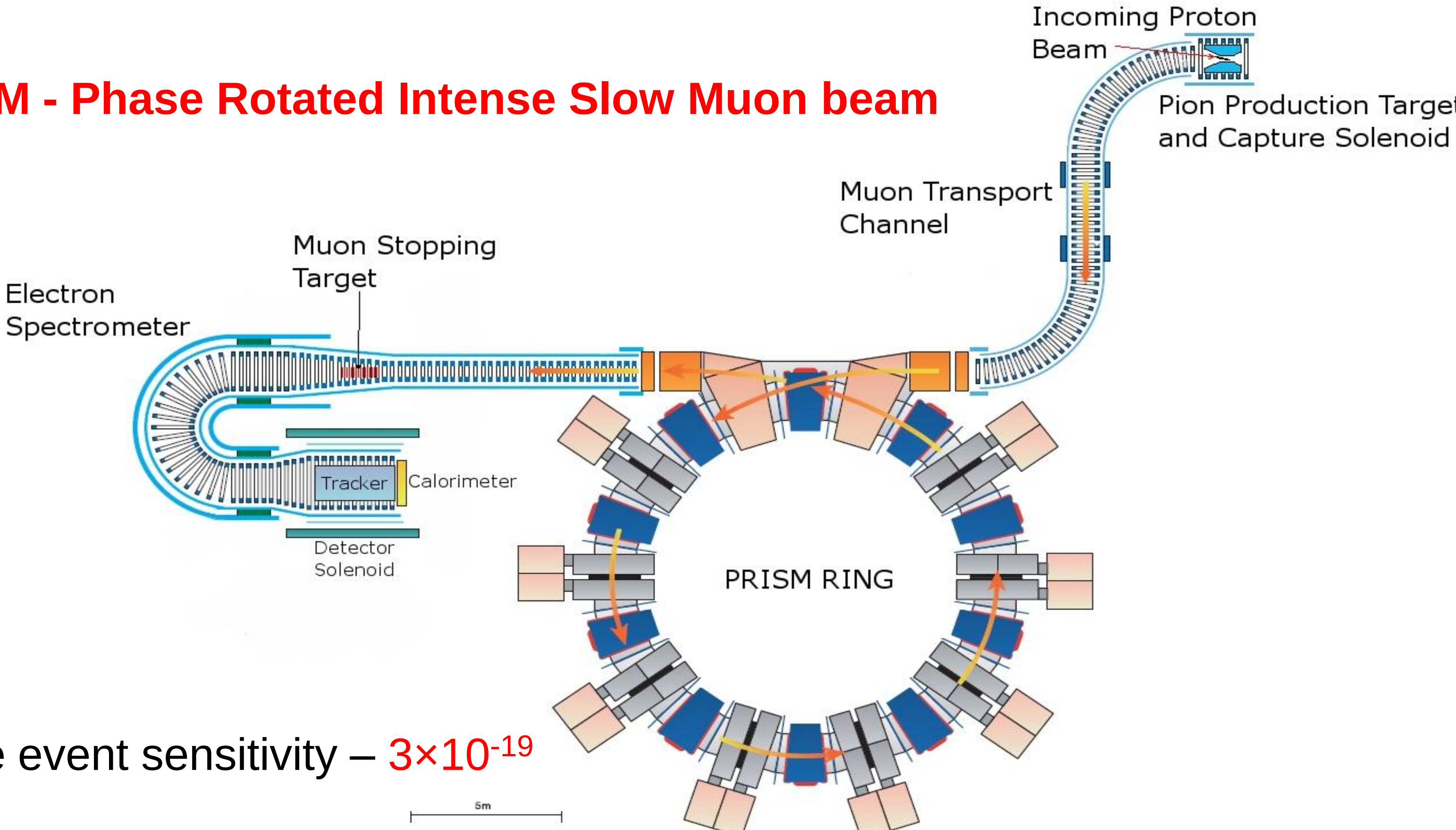
Does cLFV exists?



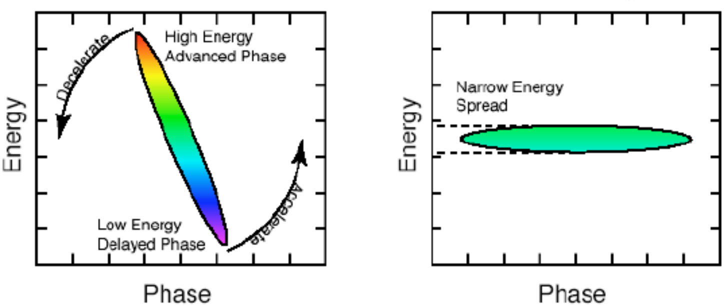
Simulations of the expected electron signal (green).

Layout of the PRISM/PRIME

PRISM - Phase Rotated Intense Slow Muon beam



Single event sensitivity – 3×10^{-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.

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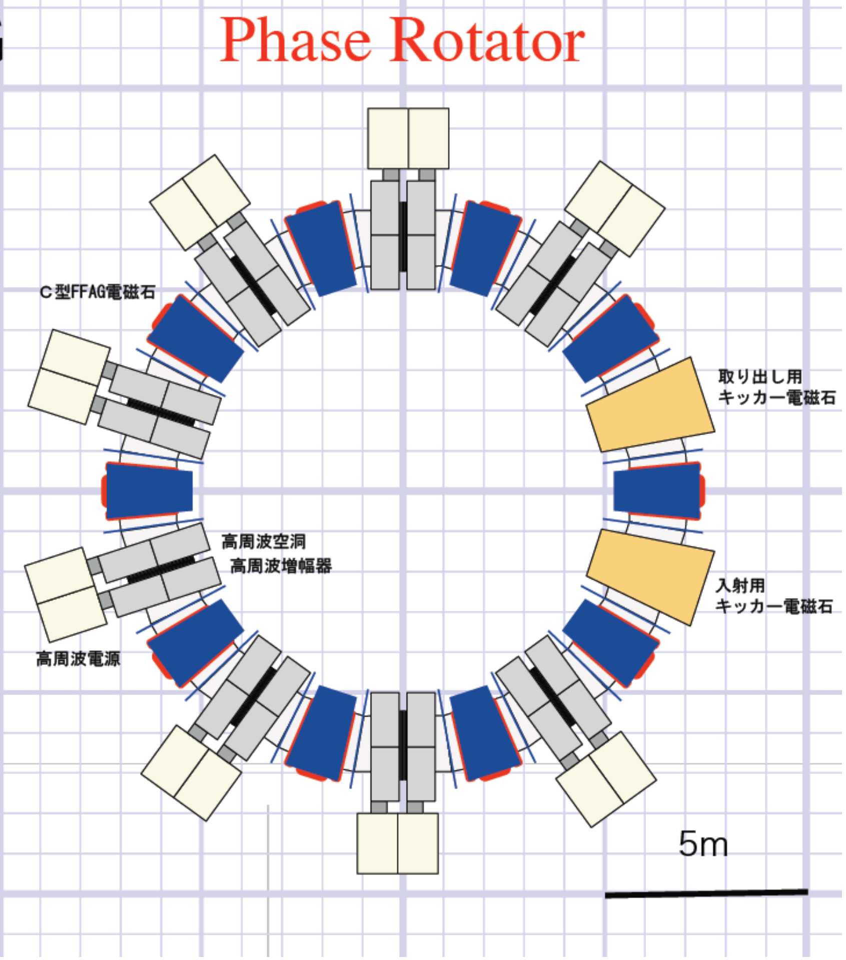
PRISM parameters

Parameter	**Value**
Target type	solid
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

Reference Design Parameters, A. Sato

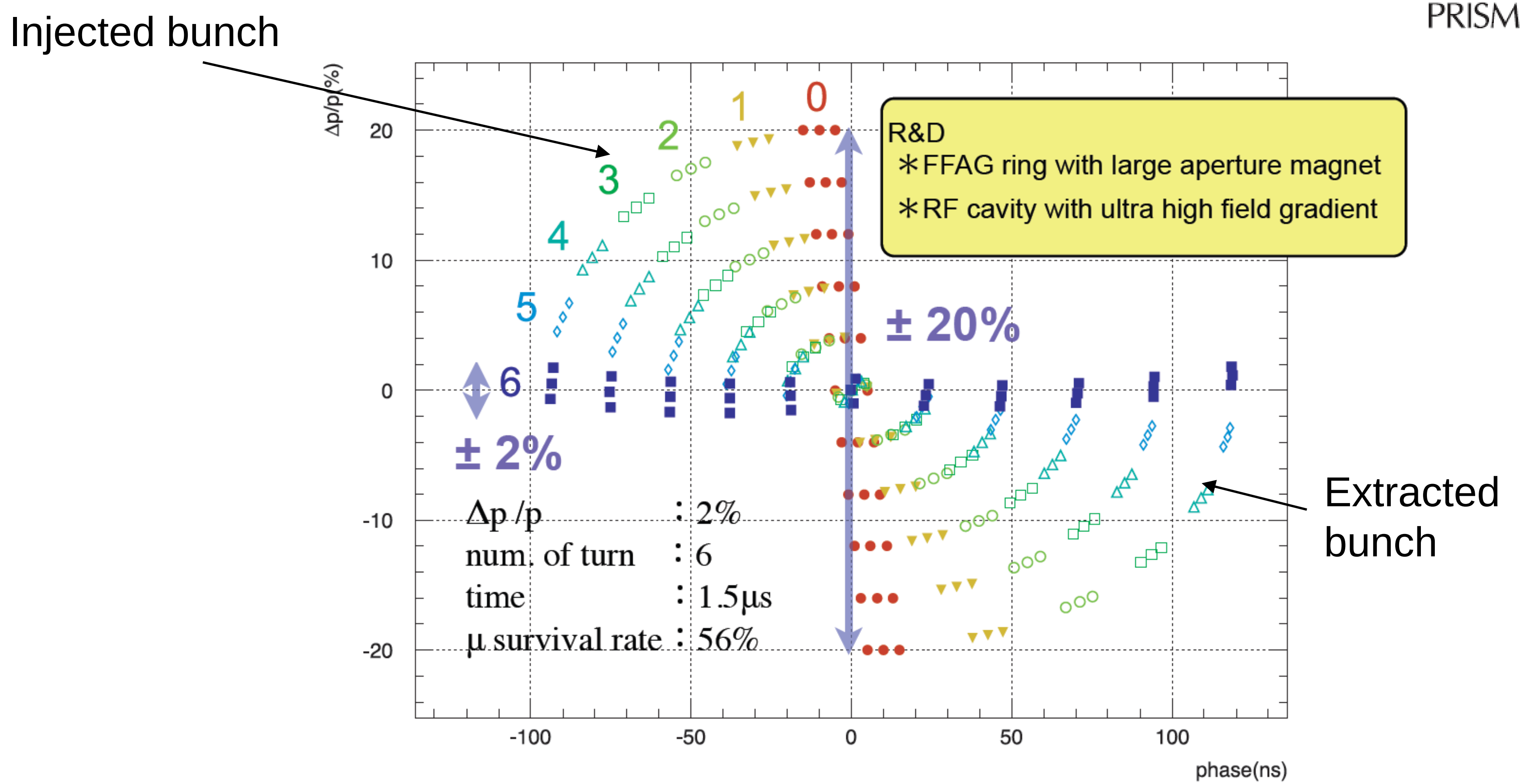
PRISM-FFAG

- 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
- $\theta_F/2$=2.2deg
- θ_D=1.1deg
- Max. field
- F : 0.4T
- D : 0.065T
- tune
- h : 2.73
- v : 1.58



V per turn ~2-3 MV
Δp/p at injection = ± 20%
Δp/p at extraction = ± 2% (after 6 turns ~ 1.5 us)
h=1

Phase rotation calculations in PRISM ring



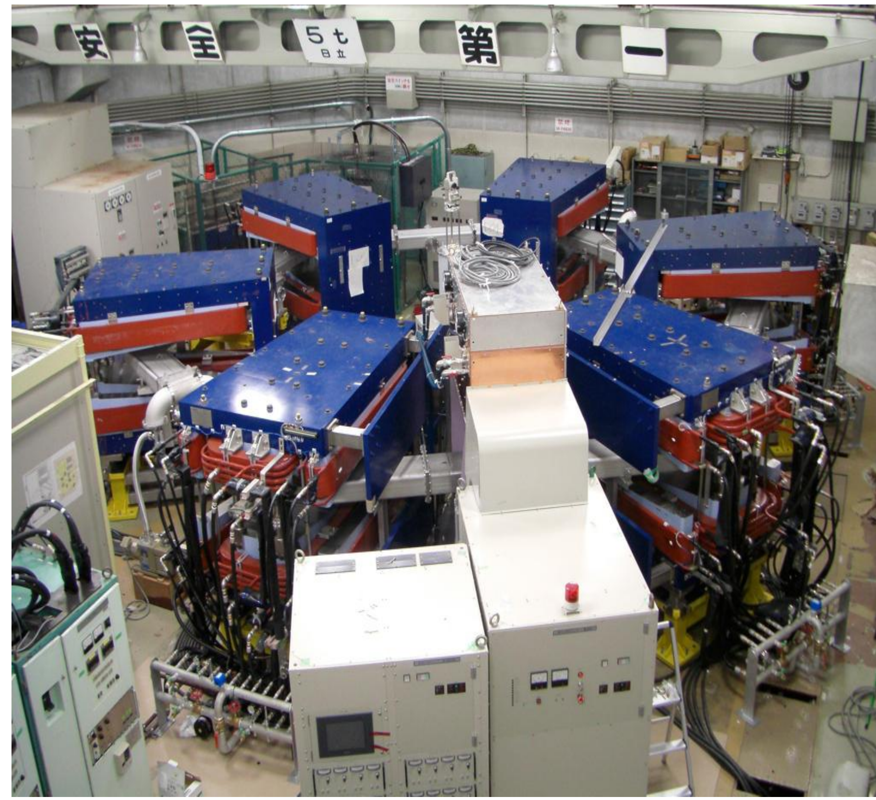
Phase rotation for 68 MeV/c reference muon

- 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

Demonstration Experiment at Osaka

- Original design uses 10 cells. Demonstration experiment used 6 cells.
- Use ^{241}Am alpha source (200 MeV/c degraded to 100 MeV/c with Al foil).
- Can locate position and angle of source.
- Study closed orbits, dynamic aperture and tune.

	10-cell Ring	6-cell Ring
Particle	muon	alpha
Momentum (MeV/c)	68	100
Radius (m)	6.5	3.5
Number of cavities	8	1
Number of field clamps	20	2



PRISM Task Force

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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.

Members:

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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

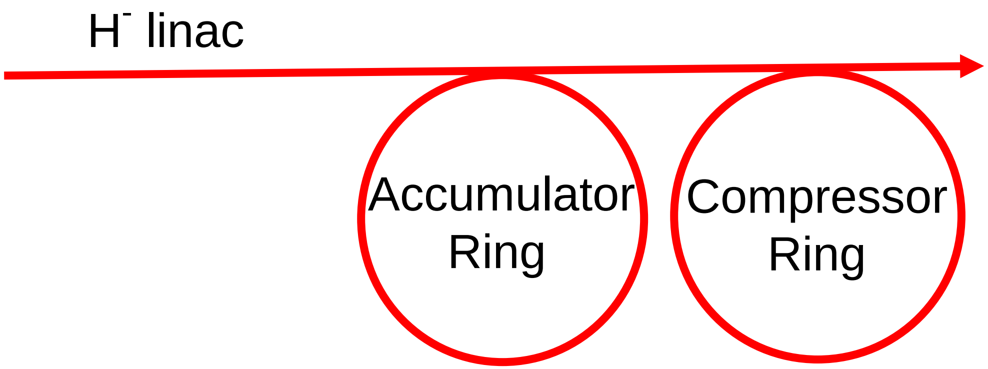
They should be evaluated in parallel and finaly confronted with the figure of merit (FOM) (number of muons delivered to target/cost).

Requirements for a new design:

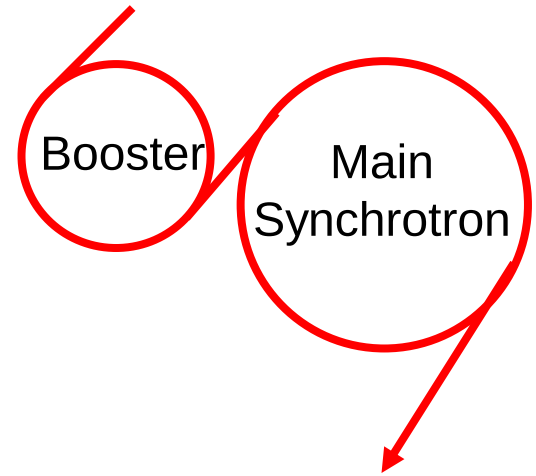
- High transverse acceptance (at least 38h/5.7v [Pi mm] or more).
- High momentum acceptance (at least ± 20% or more).
- Small orbit excursion.
- Compact ring size (this needs to be discussed).
- Relaxed or at least conserved the level of technical difficulties. for hardware (kickers, RF) with respect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

Proton Beam for PRISM/PRIME

Two methods established – BASED on LINAC or SYNCHROTRON acceleration.



H^- linac followed by the accumulator and compressor



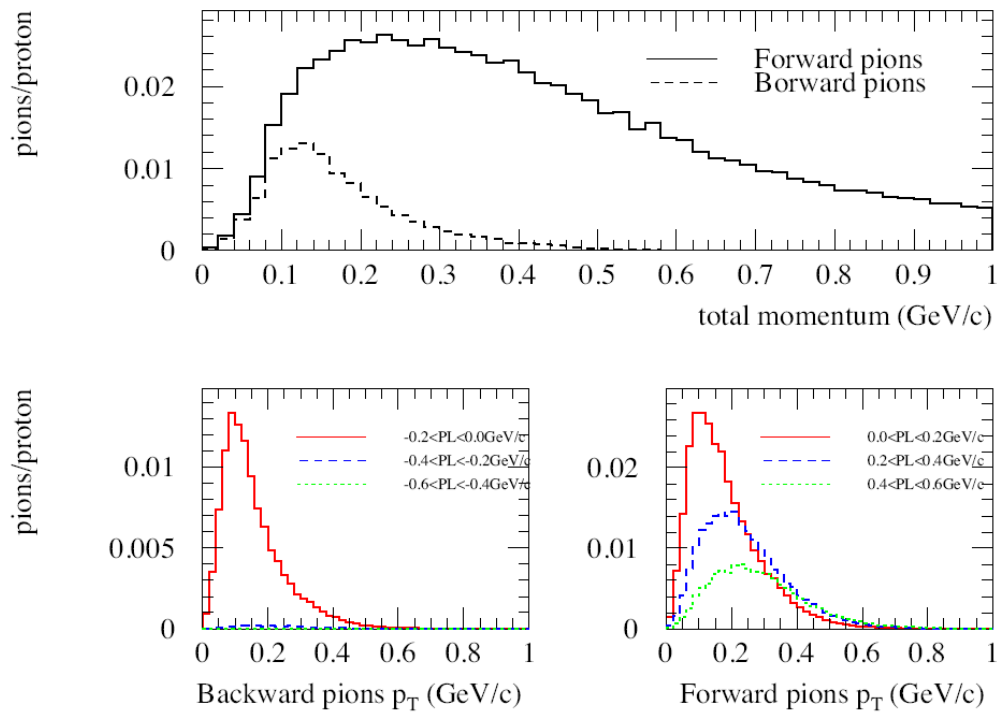
High power synchrotrons produce many bunches and extract one by one (proposed at J-PARC).

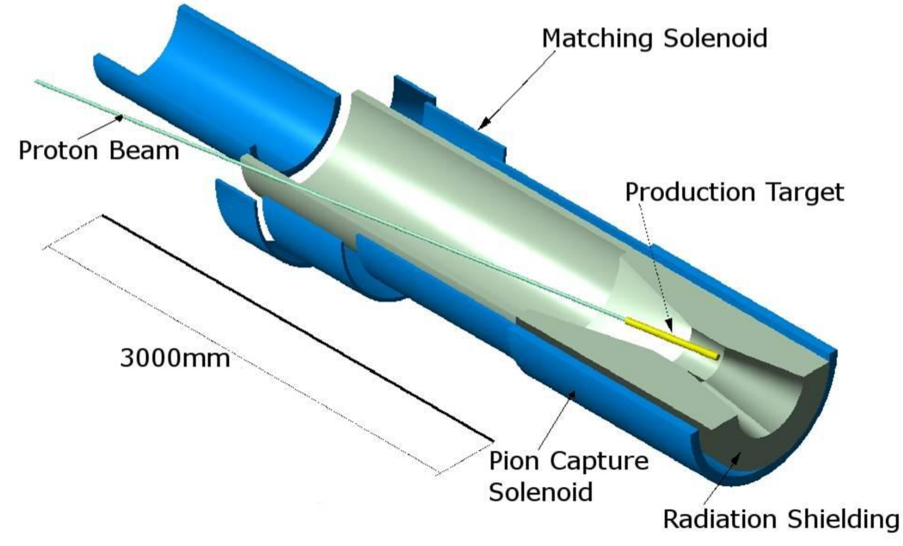
PRISM/PRIME needs a short bunch (~10 ns)!
Where could it be done ?:

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

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

Pion Production





Au target simulations using MARS

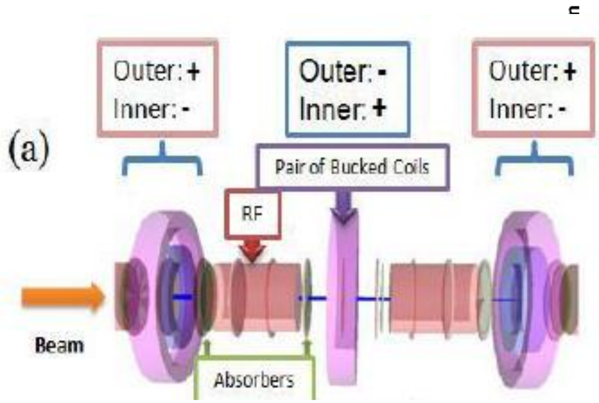
- 2 (4) MW proton beam power.
- Beam energy 3-8 GeV.
- Proton bunch length at the target ~10 ns.
- Heavy metal (W, Au, Pt, Hg) target.
- 12 (20) T SC pion capture solenoid.
- Backward pion collection.

Alternative Front-End

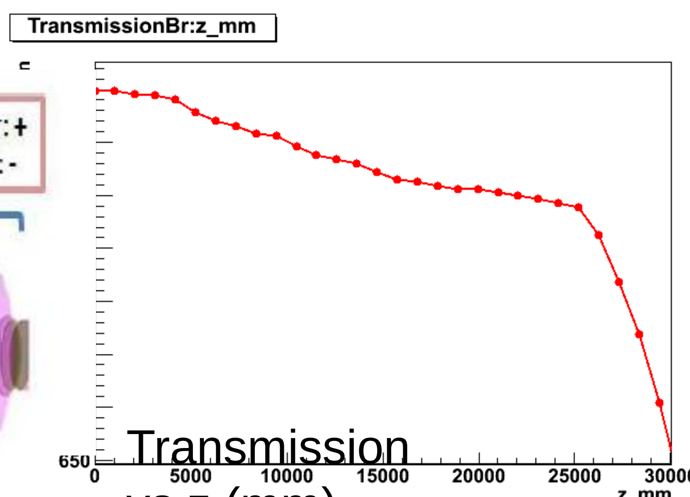
- Capture forward going particles.
  - ✓ Increased particle rate.
  - ✗ Higher momentum particles can lead to more backgrounds.

Y Use a cooling channel like in the Neutrino Factory

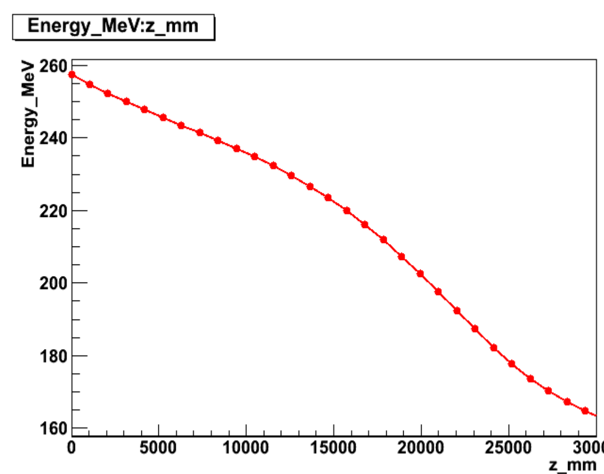
Y with 100 MHz RF to keep the beam bunched (~10 ns) and decelerate/cool using absorbers (LiH).



Bucked coil cooling lattice

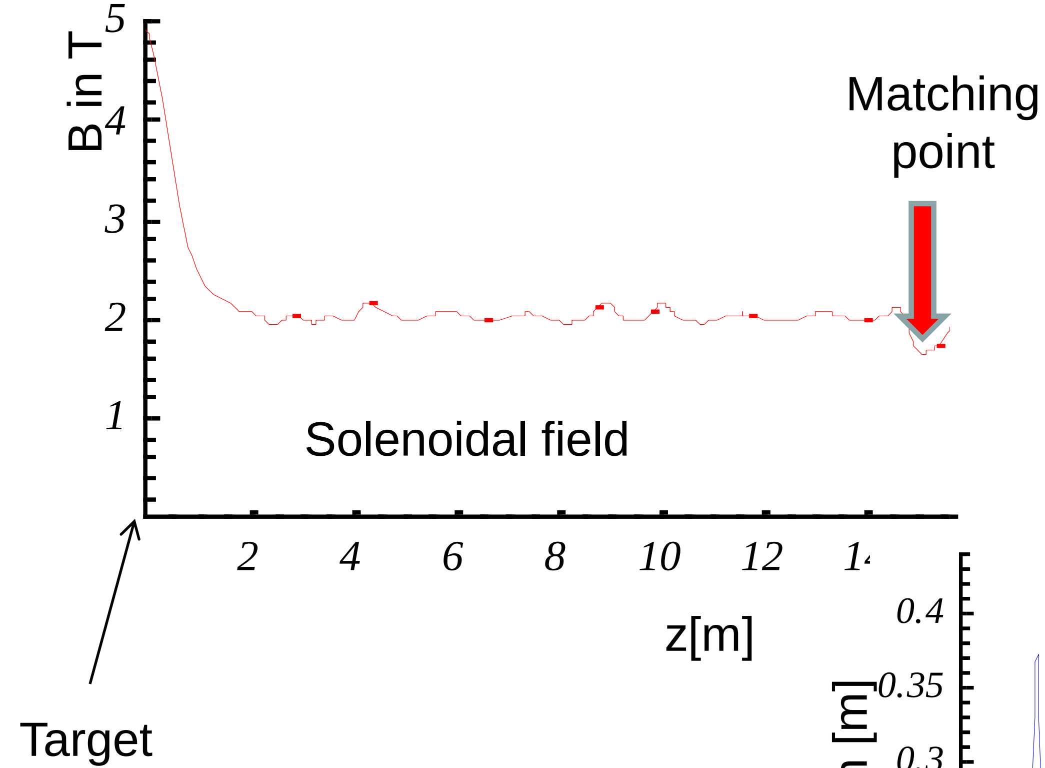


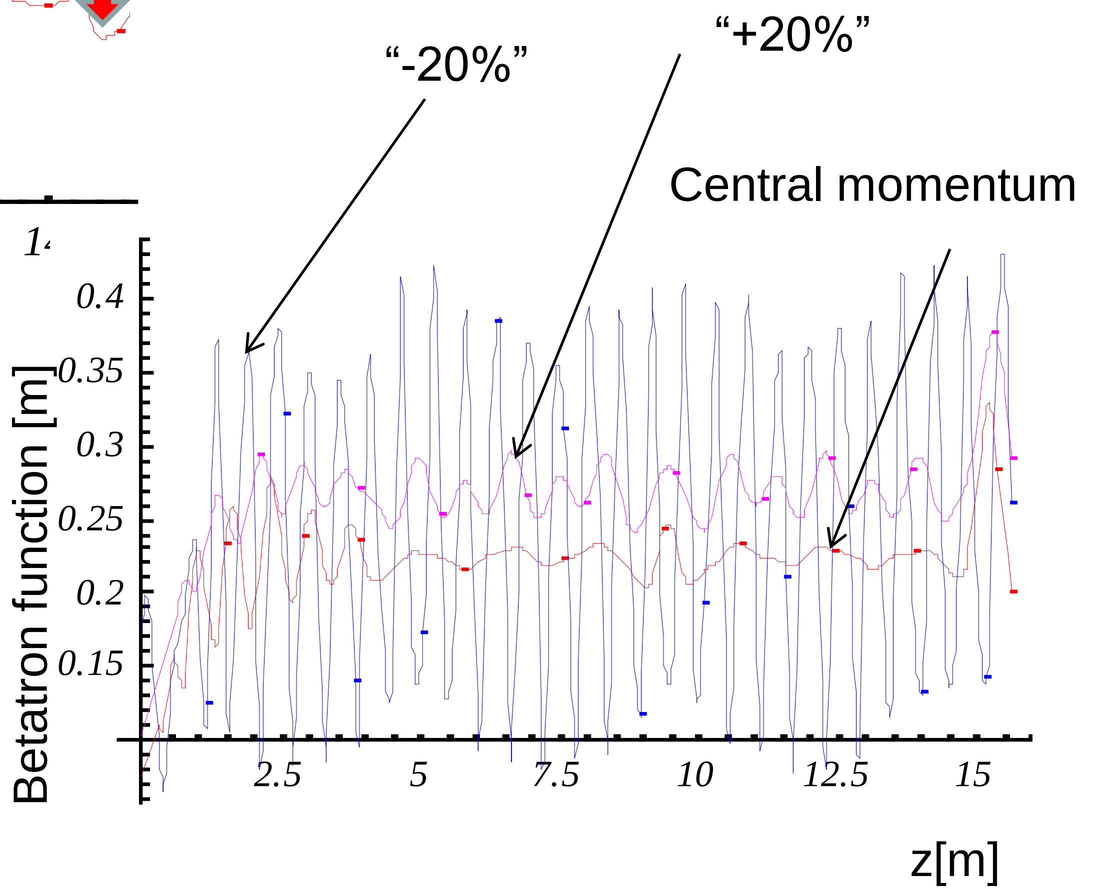
Transmission vs z (mm)



(MeV) vs z (mm)

Optics and B field in solenoidal muon transport





- 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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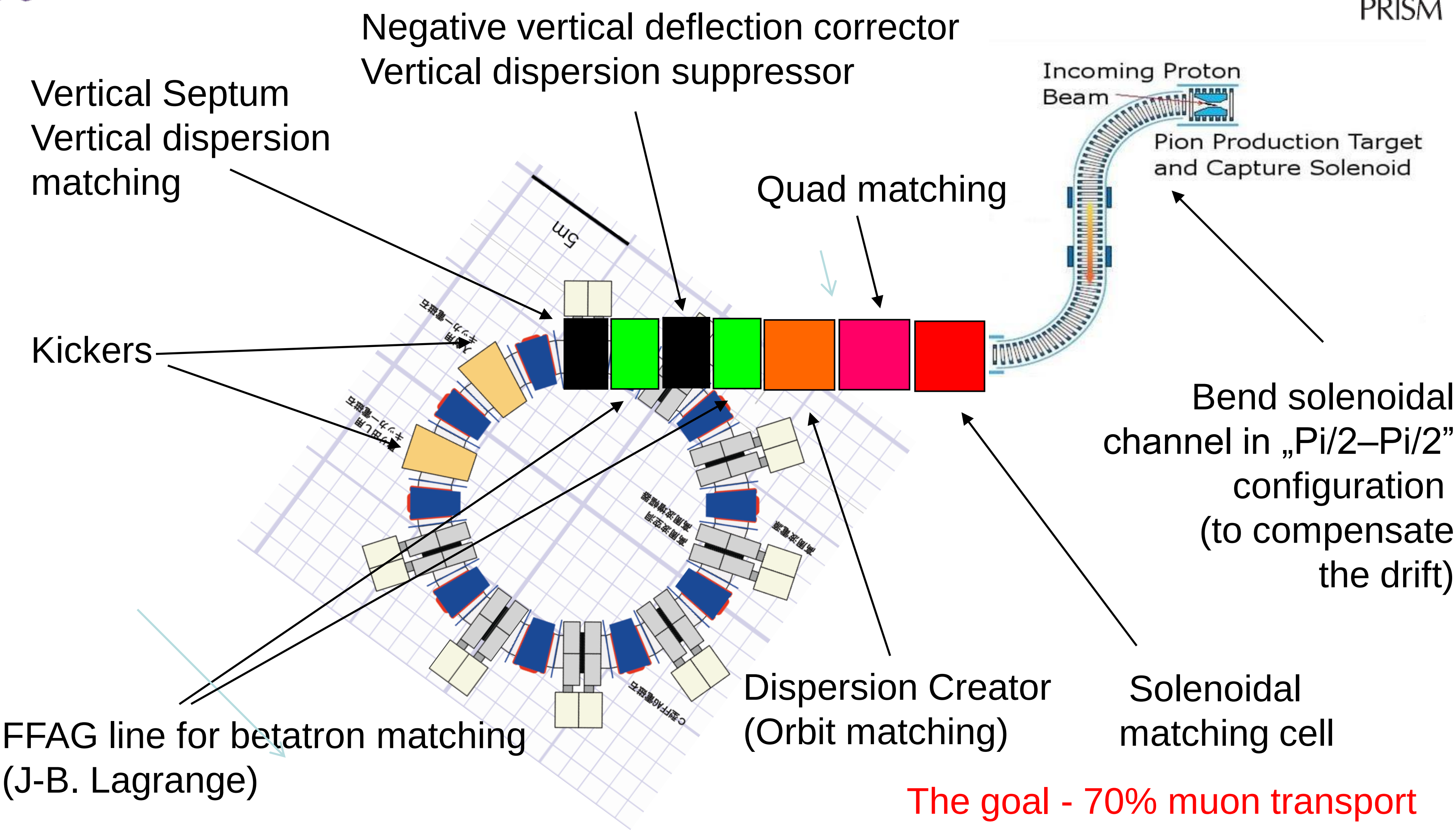
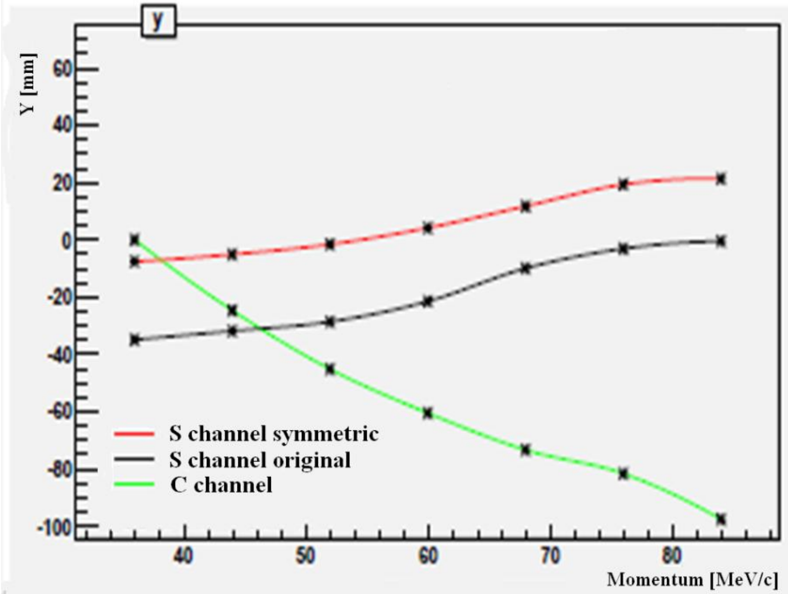
Pion/Muon Transport

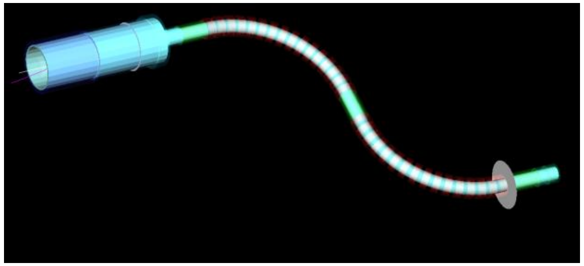


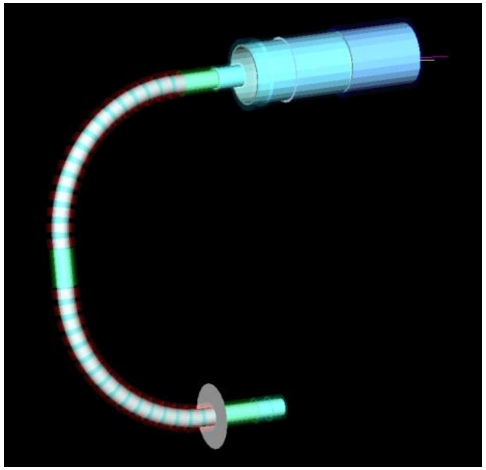
The goal - 70% muon transport efficiency!

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.

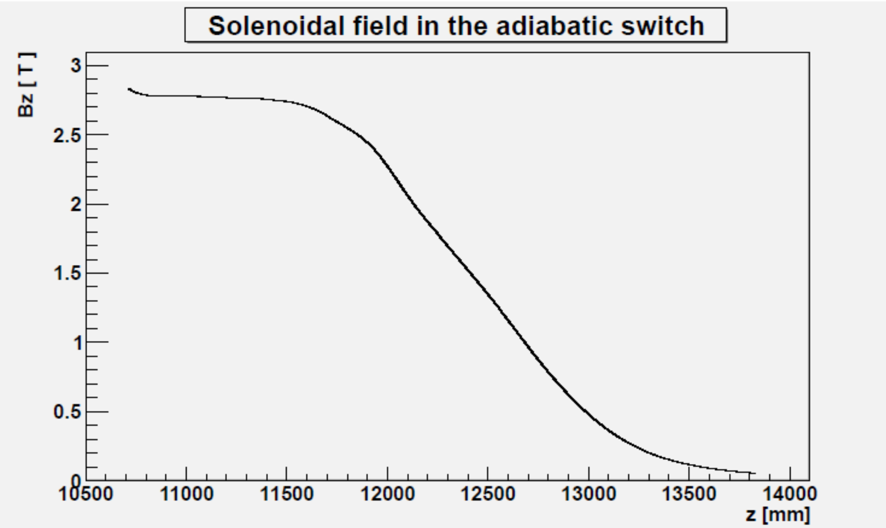


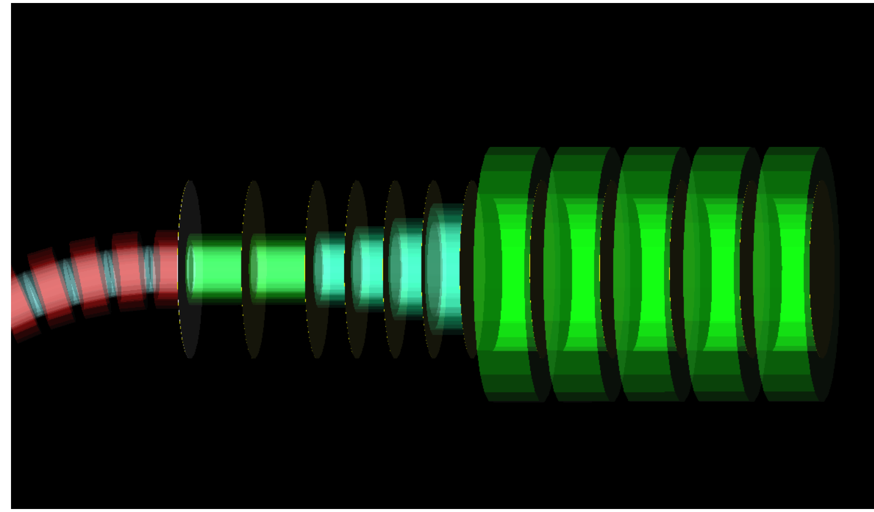




The mean vertical beam position versus momentum at the end of bent solenoid channel for various configurations.

Matching to the FFAG II





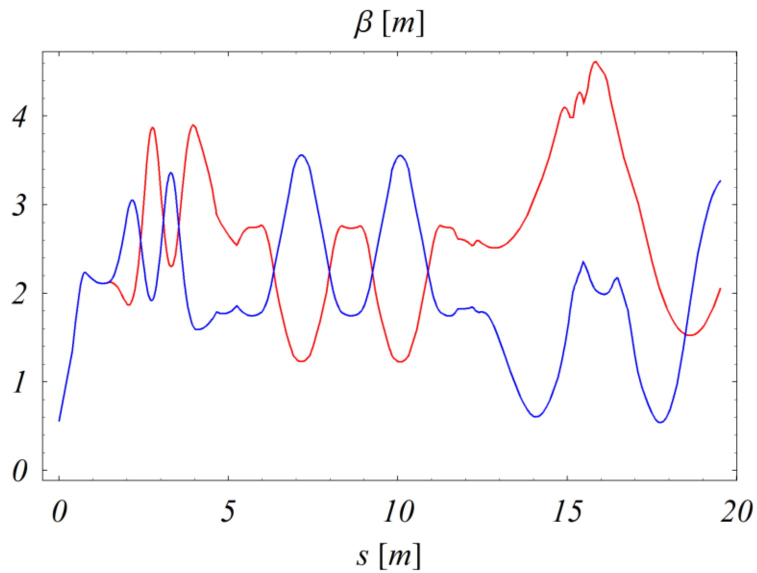
Initial version of the adiabatic switch

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

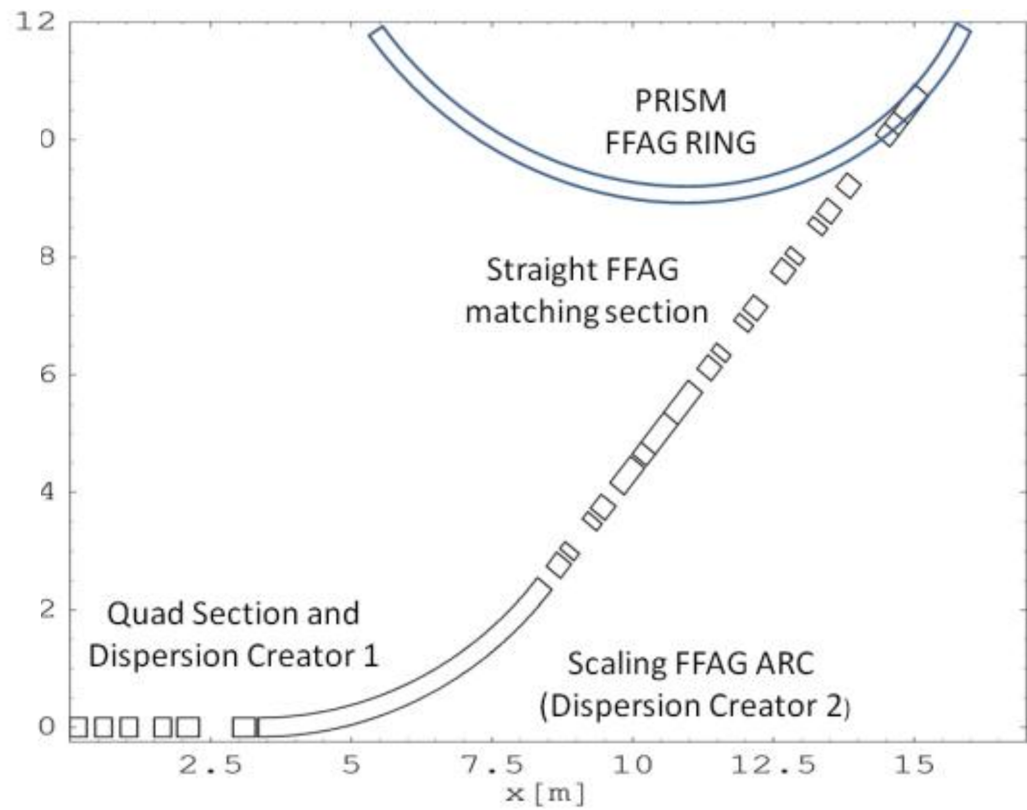
Current best version includes:
• adiabatic switch from 2.8 to 0.5 T (to increase the beam size),
• additional solenoidal lense to match α=0 (not shown in the pictures above),
•5 quad lenses,

Matching to the FFAG III

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

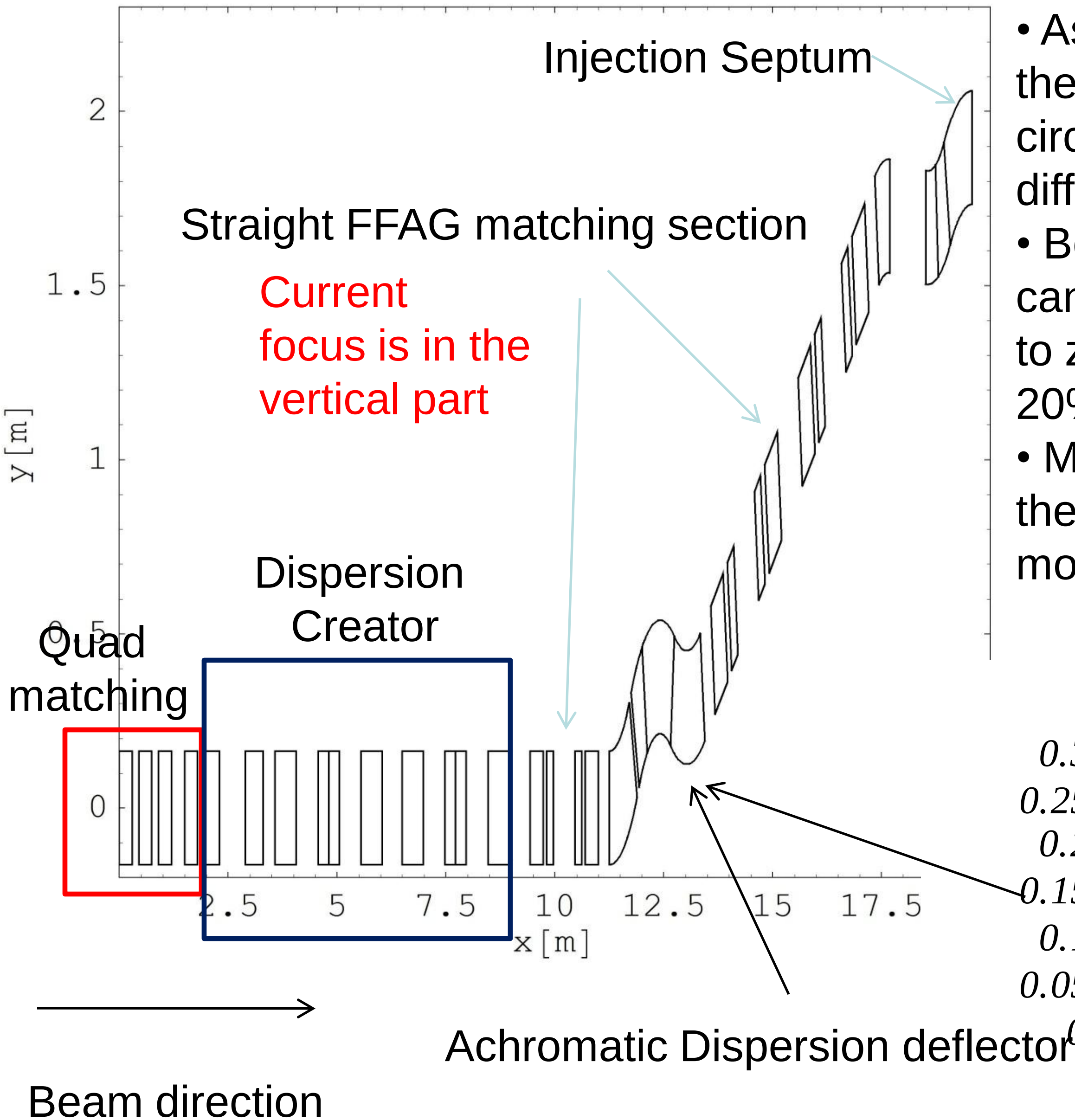


Horizontal (red) and vertical (blue) betatron functions in the PRISM front end.

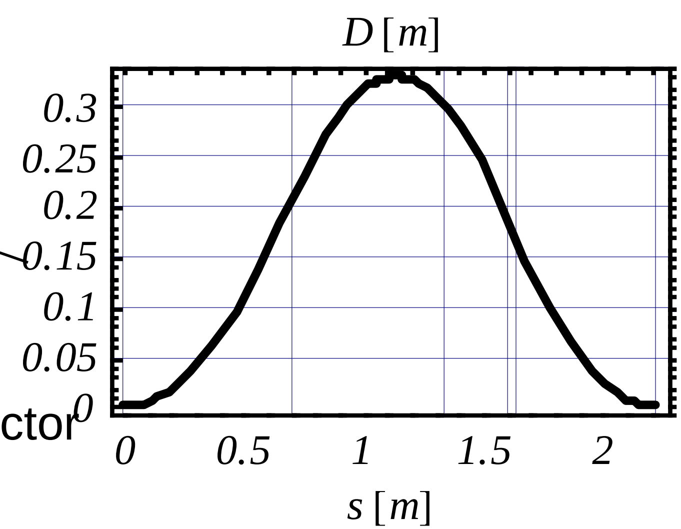


Layout of the matching section seen from the above.

Matching to the FFAG IV



- 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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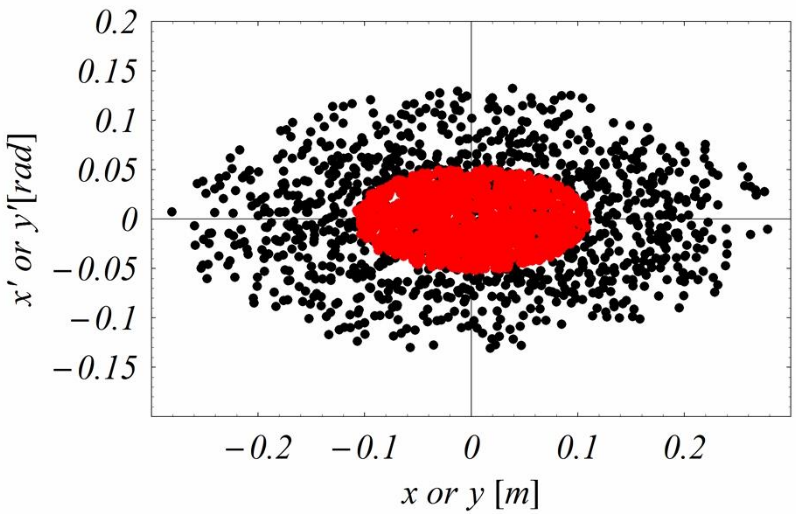
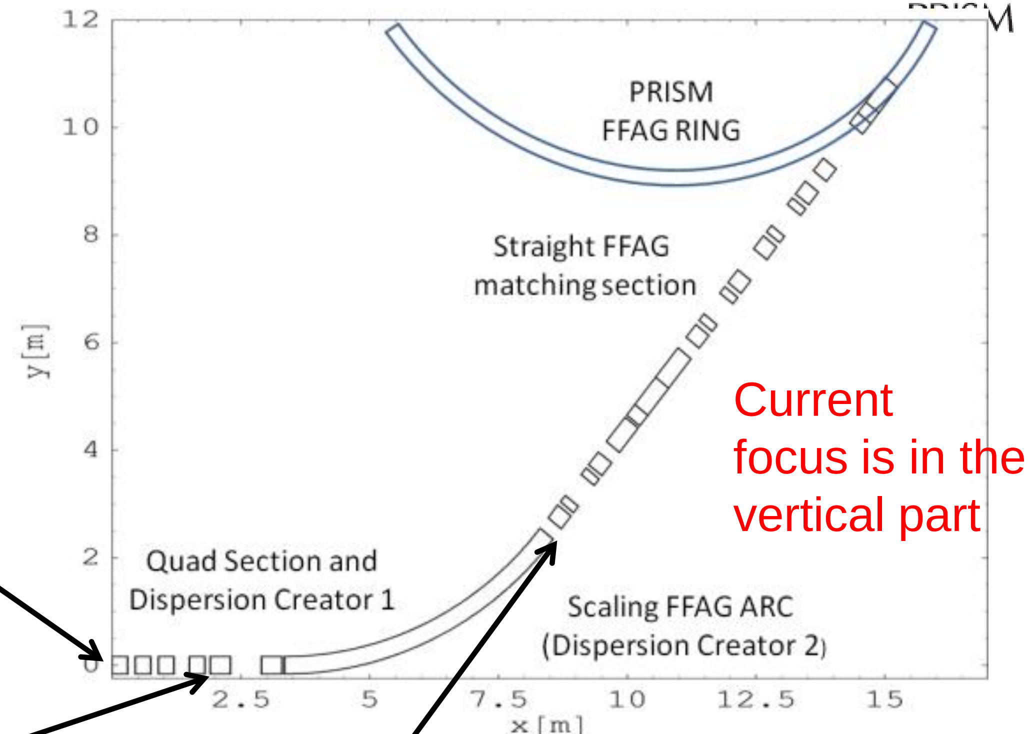
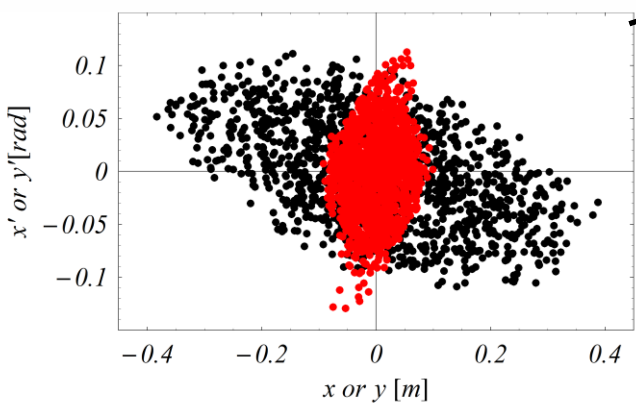
Matching to the FFAG V

- Tracking status (work in progress)

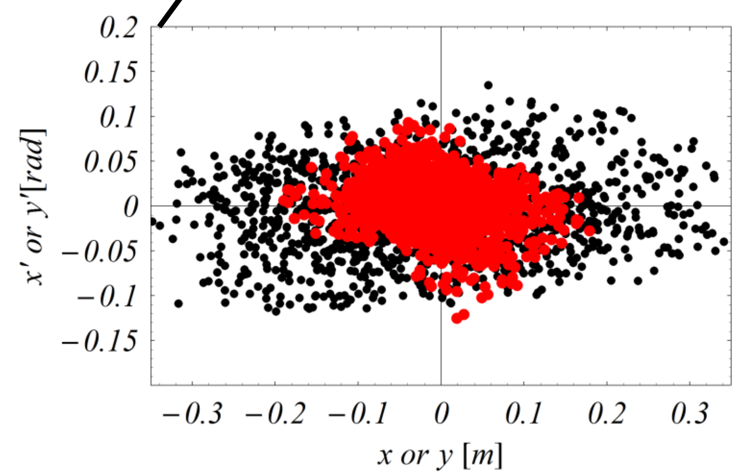


Horizontal (black) and vertical (red) phase spaces at the input to the AG part of the PRISM muon front end.





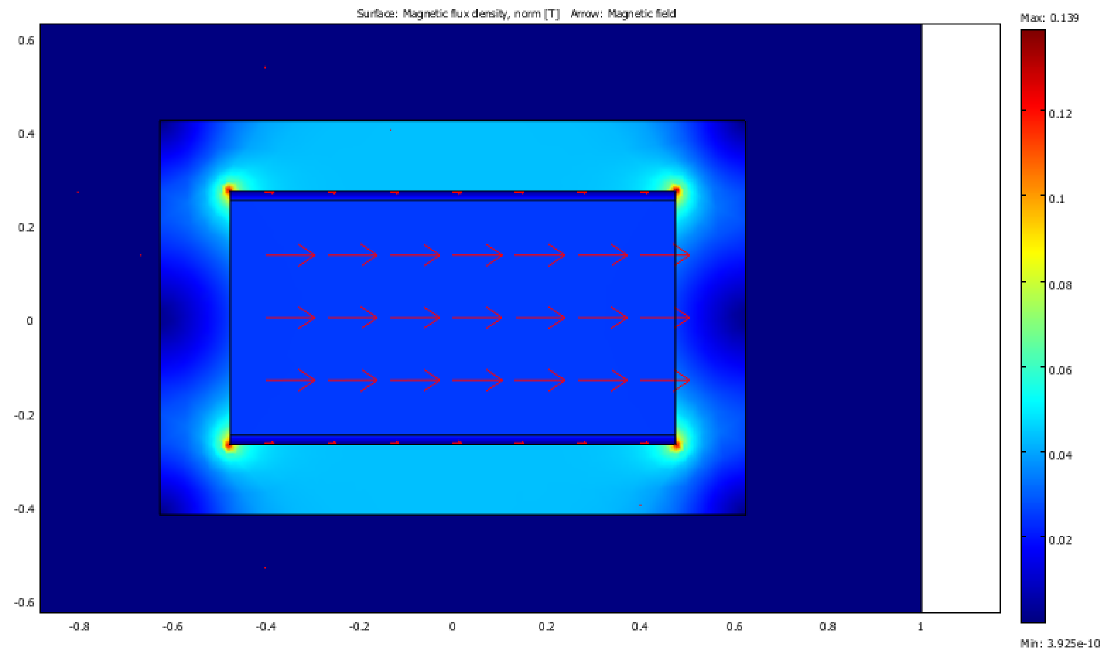
At the end of the quad Channel



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

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



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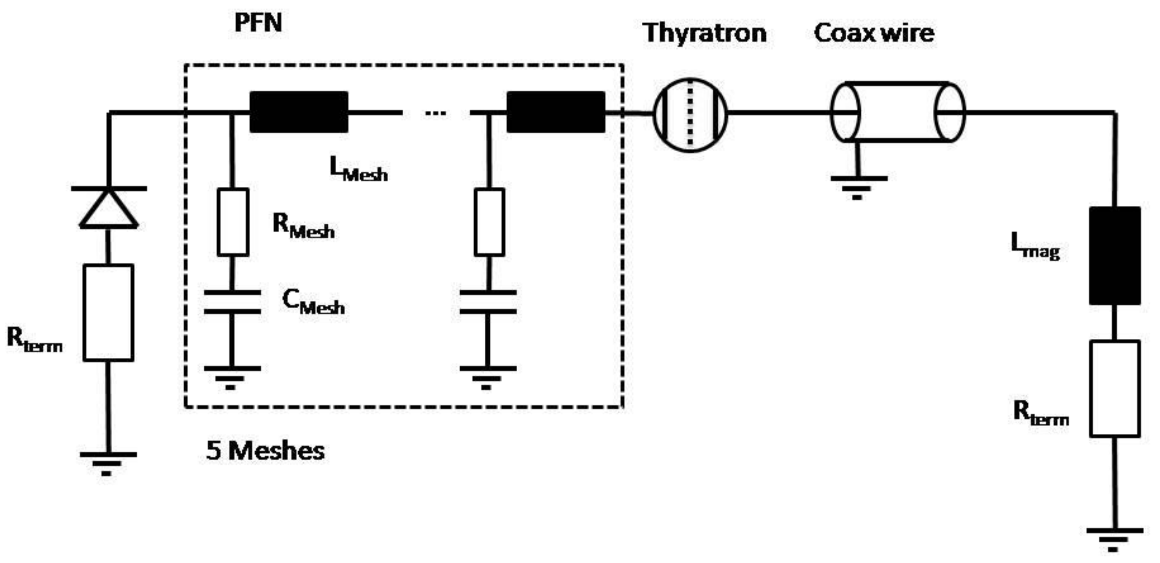
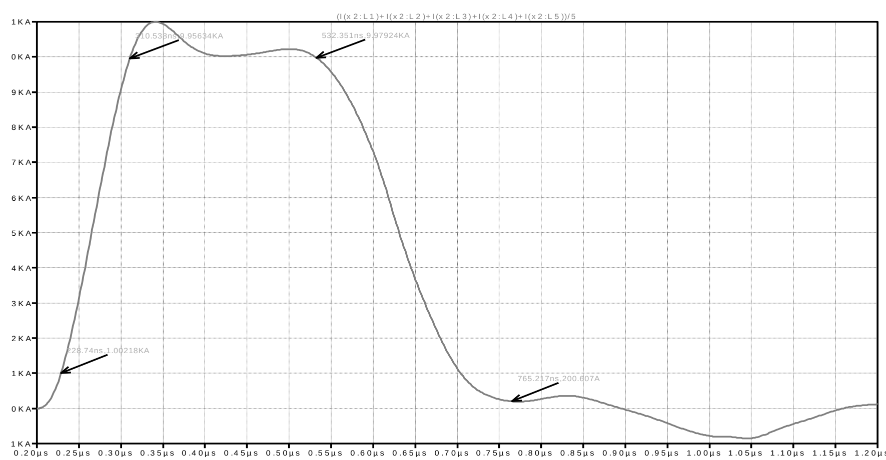
PRISM Pulse Formation



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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RF development

•Substantial progress has been achieved in the design of MA cavities using a new FT3L.

• Large-size MA cores have been successfully fabricated at J-PARC. Those cores have two times higher impedance than ordinary FT3M MA cores.

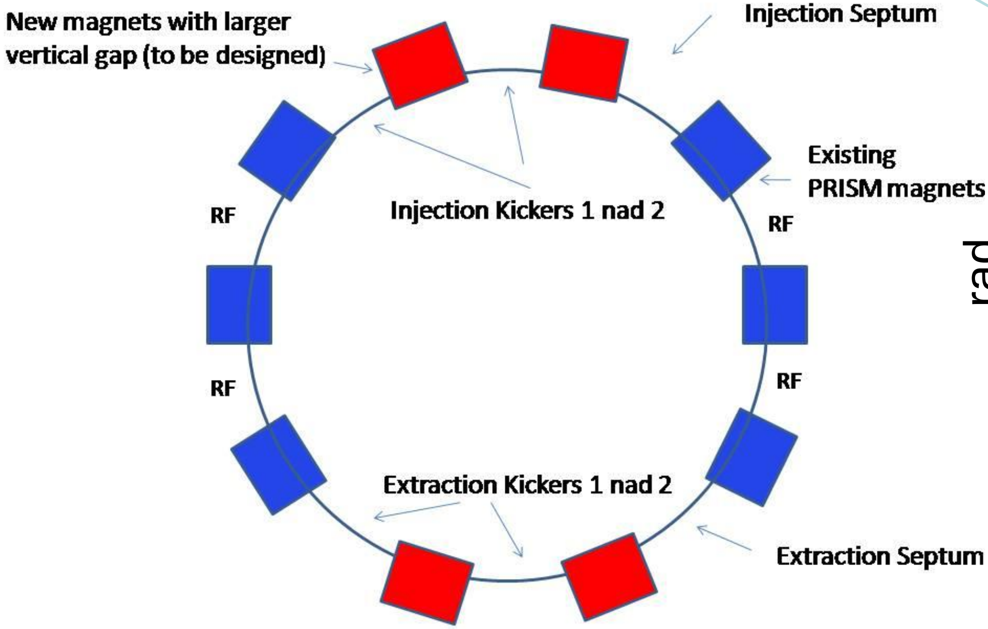
• For the PRISM RF system in order to either reduce the core volume cutting the cost by a factor of 3 or to increase the field gradient.

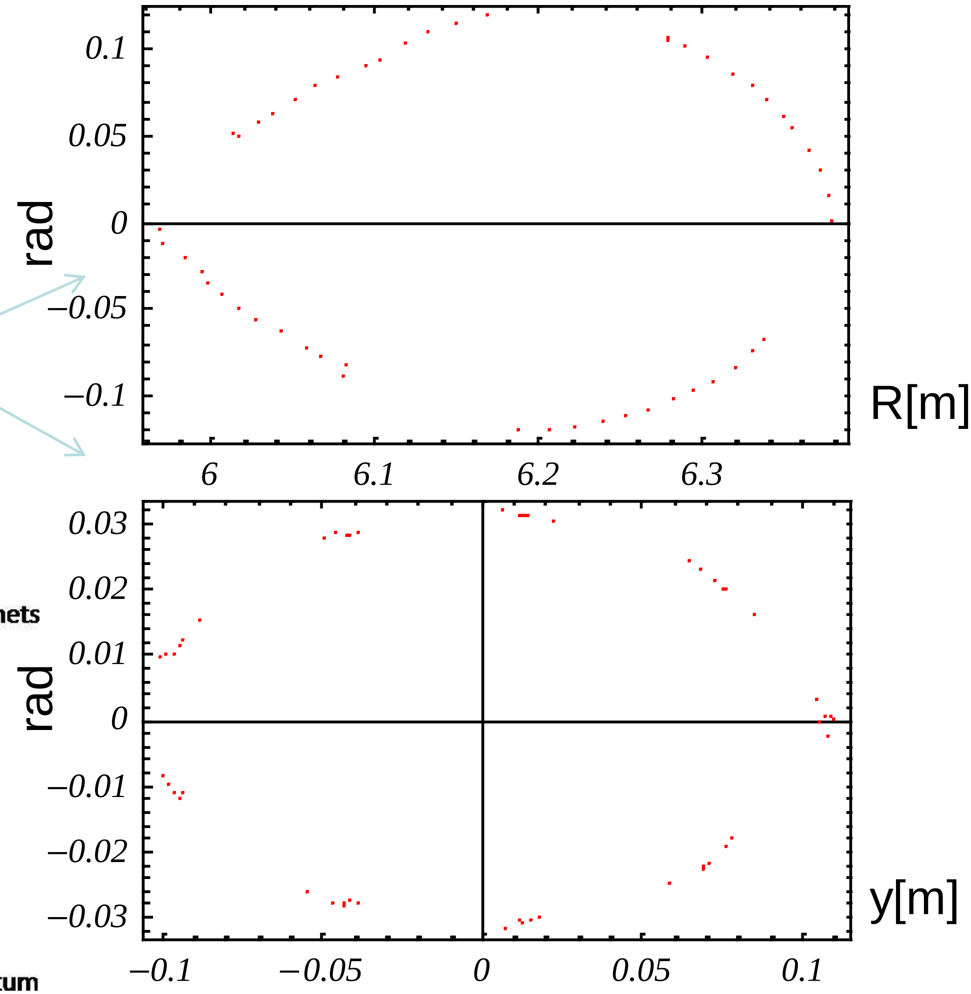
•Both options should be considered.

The first high impedance core annealed at J-PARC

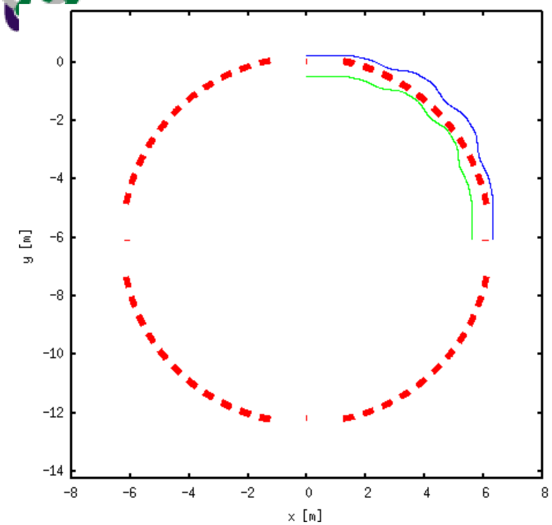
Reference design modifications for Injection/Extraction

•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 limits the dynamical acceptance, if properly done!

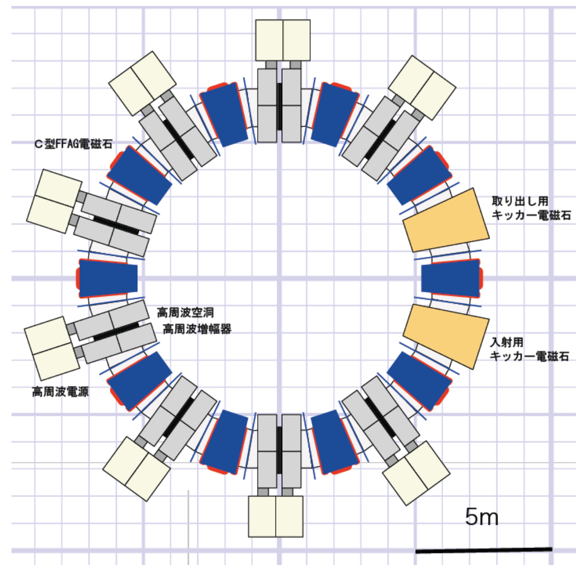




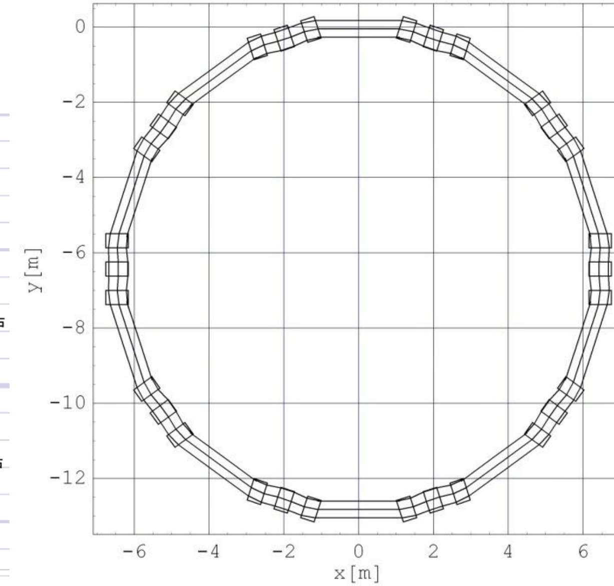
FFAG Ring Choice



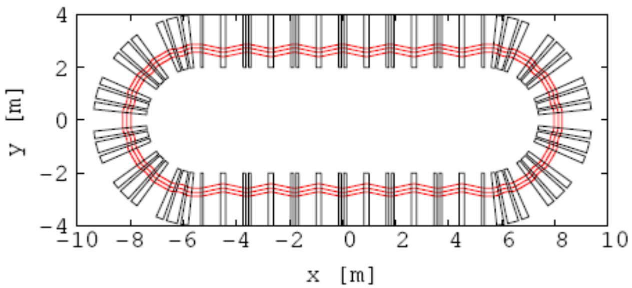
Scaling Superperiodic



Reference design

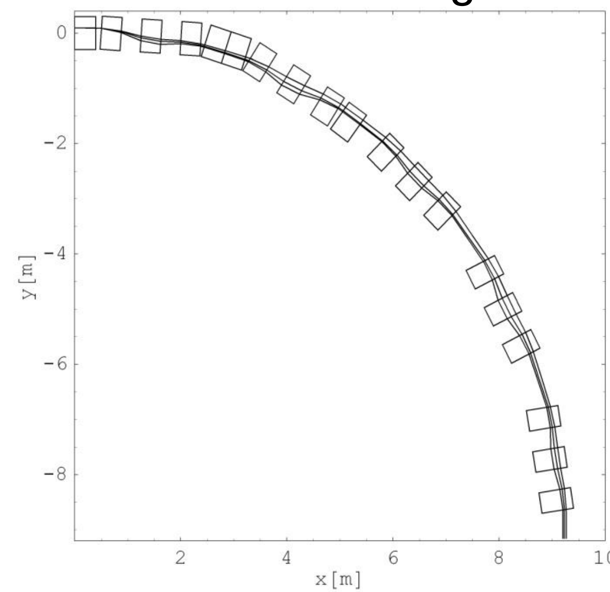


Non-Scaling



Advanced scaling FFAG

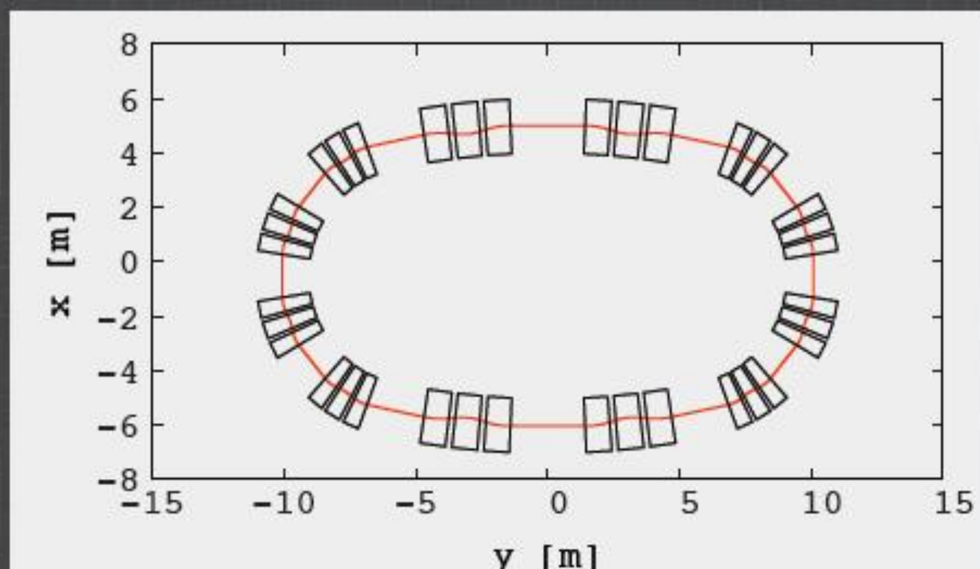
- We need to decide about the possible baseline update very soon.
- The choice is dictated by the performance.



Advanced NS-FFAG

Egg-shape design

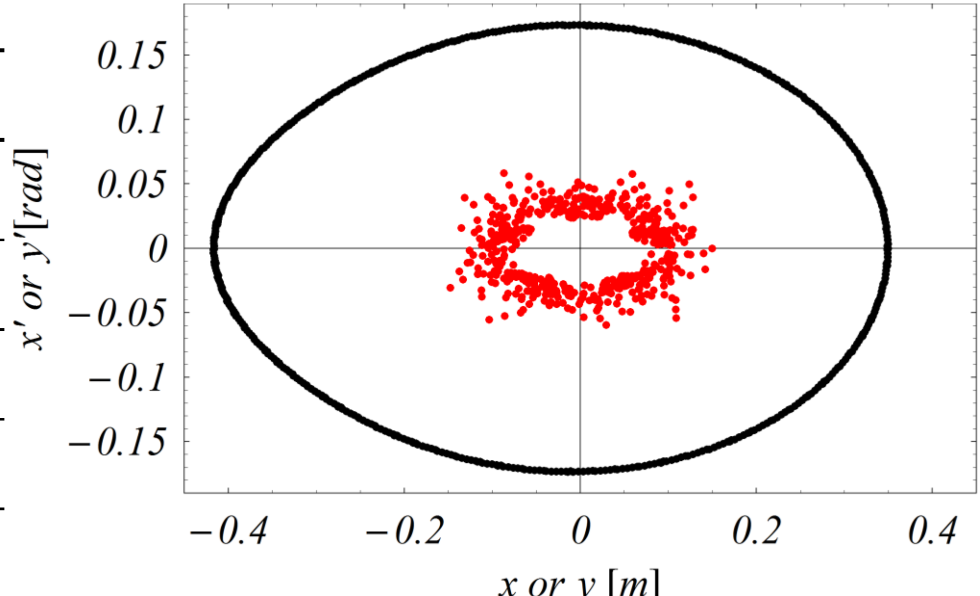
Small Bending cell FDF triplet		Large Bending cell FDF triplet	
k-value	3.82	k-value	28.9503
total bending angle	39.15 deg.	total bending angle	11.7 deg.
Average radius	5 m	Average radius	30 m
Phase advances:		Phase advances:	
Horizontal μ_x	90 deg.	Horizontal μ	75 deg.
Vertical μ_z	60 deg.	Vertical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



Please, see next talk by JB Lagrange!

Alternative symmetric FDF Scaling Ring Design

Parameter	Value
Number of cells	10
k	5.1
(Q_H, Q_V)	(2.62, 1.91)
Lattice type	Symmetric FDF triplet
R	6.5 m
Acceptance (H, V) to be confirmed	(5.55, 0.78) π cm rad
B_F/B_D at R	0.2397/-0.1745 T
$\Theta_F/\ \Theta_D/\ \Theta_S$	0.0607/0.0607/0.3394 rad



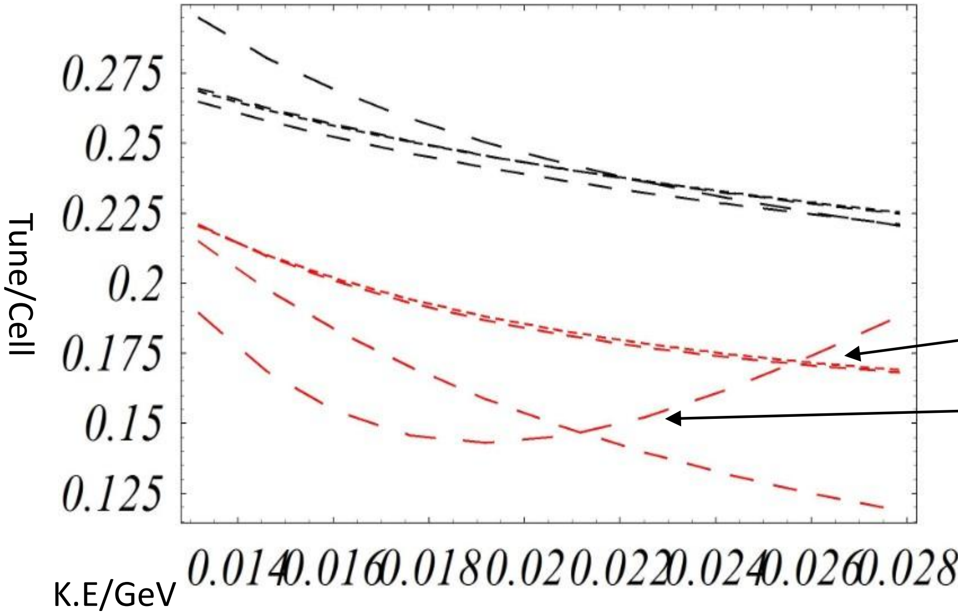
Dynamical acceptance of the new FDF scaling FFAG ring for PRISM in horizontal (black) and vertical (red) planes respectively. Horizontal position is presented subtracting the mean closed orbit.

NS-FFAG ring parameters

Lattice type	“FDF”	“FDF”	“FDF”	FD
F gradient (T/m)	0.1035	0.0545	0.0446	0.6
D gradient (T/m)	0.0997	0.0989	0.1184	-0.14
F field (T)	0.2307	0.0019	0.1756	0.18
D field (T)	-0.0833	0.2500	-0.0685	0.1756
Long drift length (m)	1.1	1.1	1.1	1.1
Short drift length (m)	0.377	0.3	0.3	0.3
Length of F (m)	0.377	0.5	0.5	0.3
Length of D (m)	0.377	0.5	0.5	0.75
N	10	10	10	10

Orbits and tunes

- Chromaticity are relatively flat in both vertical and horizontal plane
- All nicely separated.

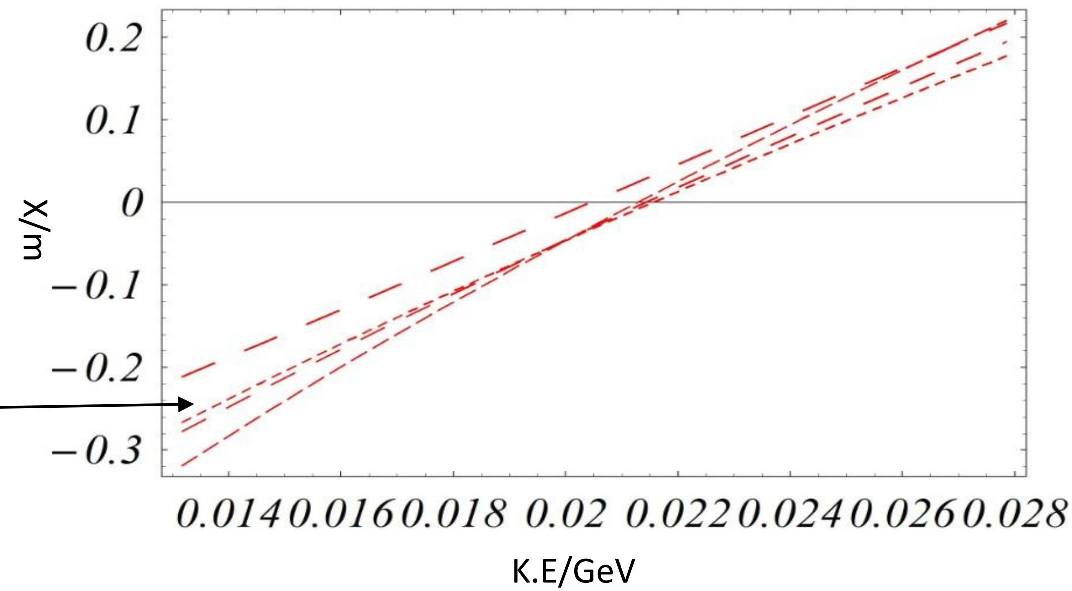


Triplet

Doublet

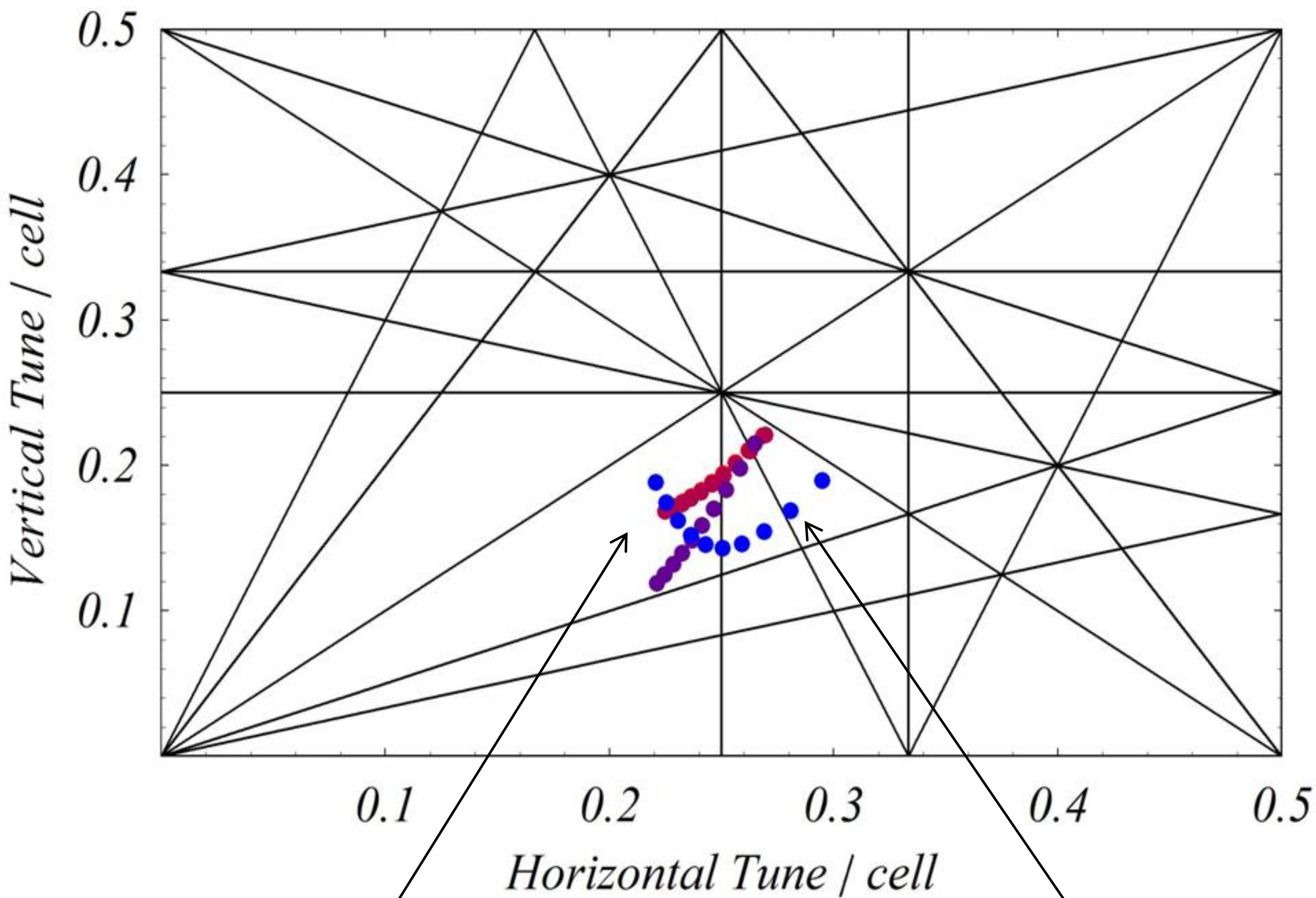
Red-vertical tune
Black-horizontal tune

- Orbit excursion
- Orbits are very linear with momentum



Doublet orbit is the most compacted

Resonance diagram

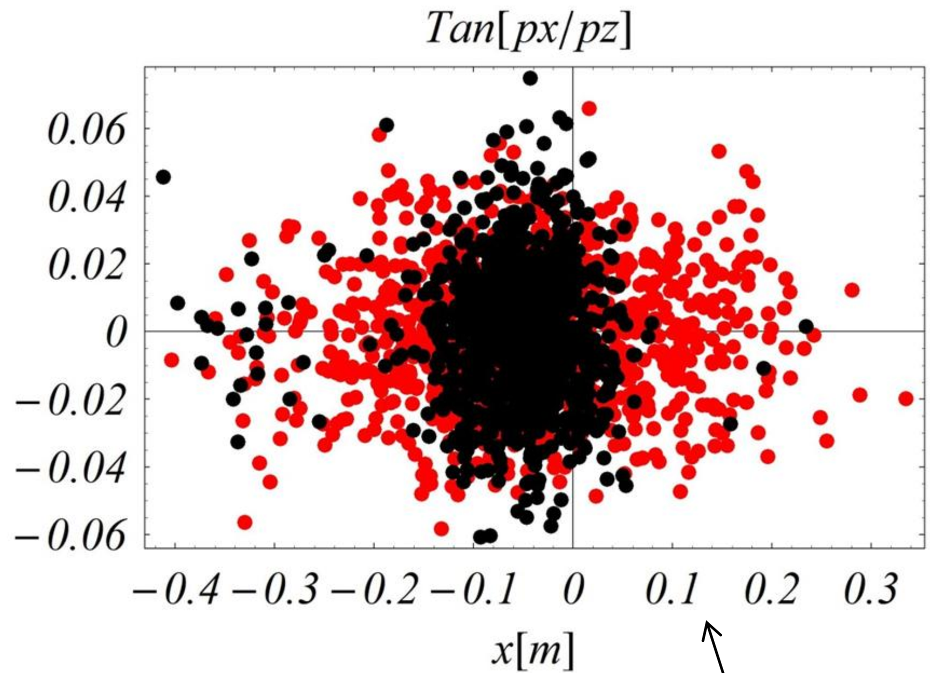


This region gives large dynamical acceptance (DA).

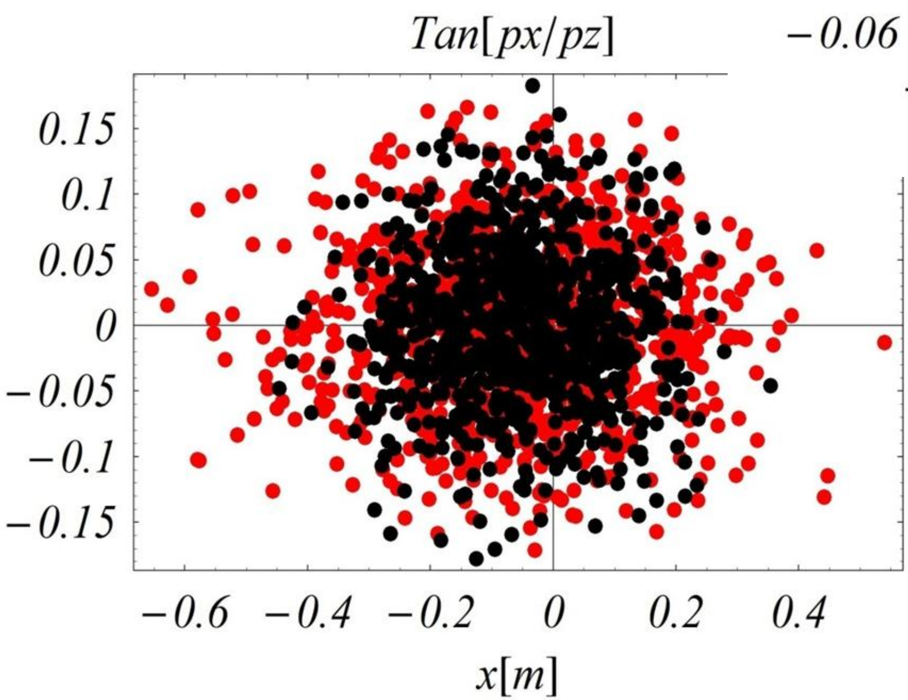
Parabolic *Operation Point* for doublet

Tracking simulations for different emittance (differ by a factor of 10)

- The initial distributions are Gaussian in all 6D for 1000 particles,
- 3.75 MV per turn,
- 6.5 turns,
- Matching is done at the central momentum (68MeV/c)



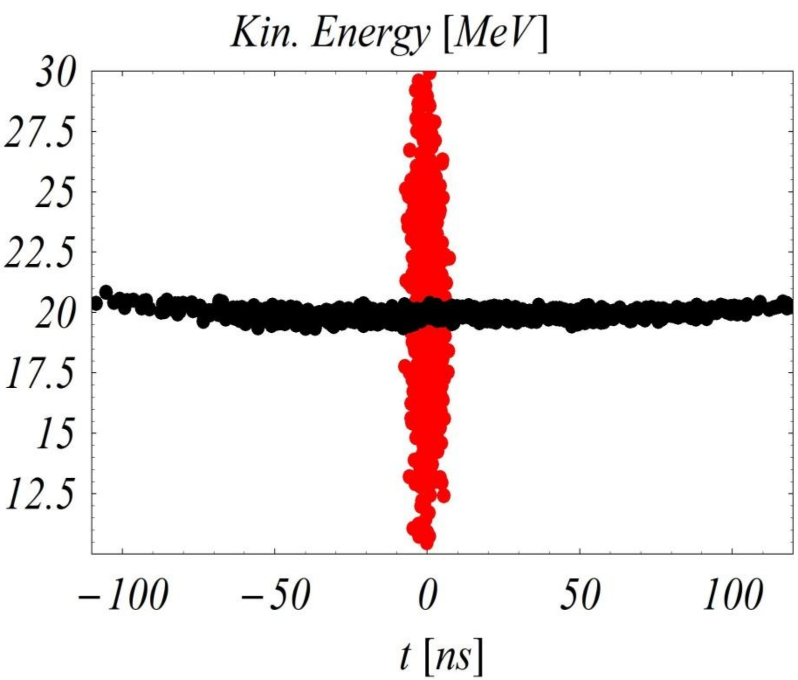
Small emittance



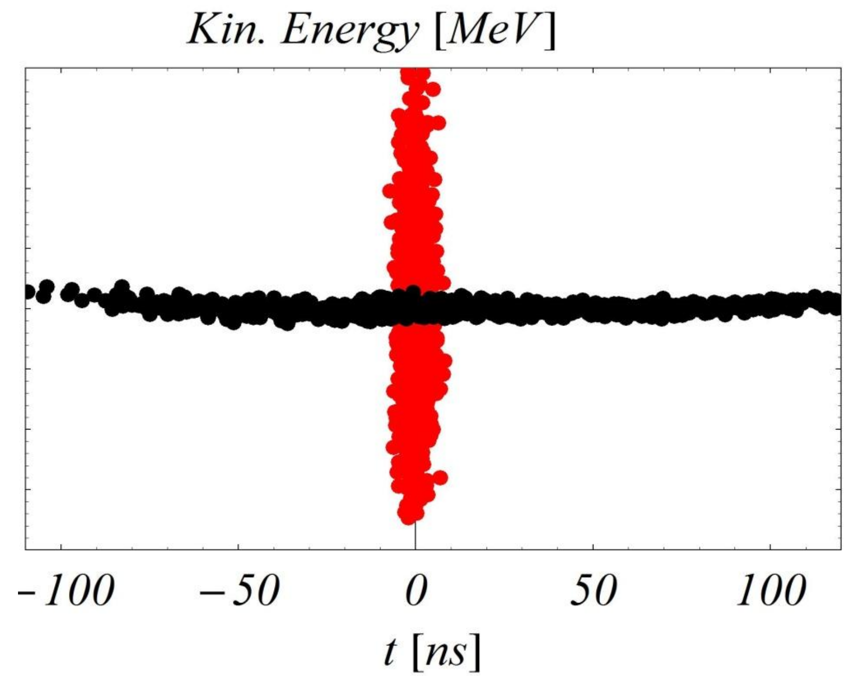
Transverse plane x' vs x

Red-injection
Black-final

Tracking simulations_longitudinal



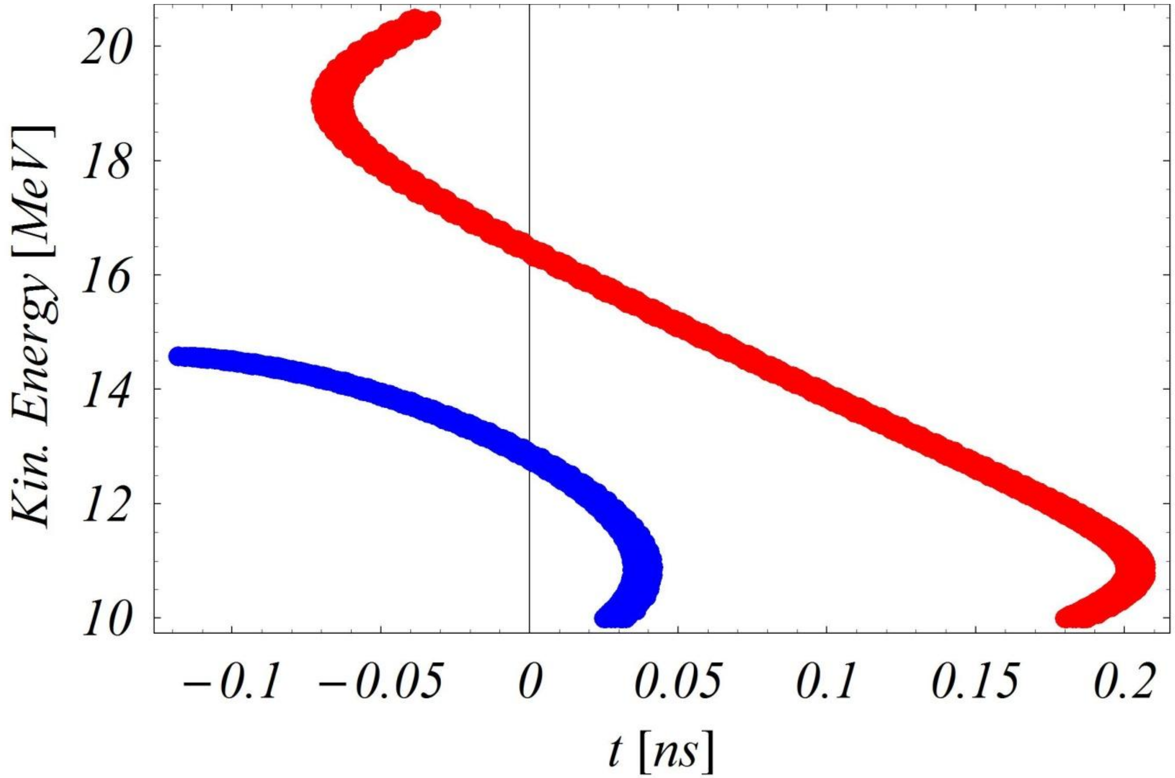
Small emittance



Large emittance

•Phase rotation performed with ideal „sawtooth” RF voltage.

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

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.
- PRISM Task Force aims to demonstrate the feasibility via Conceptual Design Report (to be published at end of 2013).
- PRISM/PRIME and nuSTORM will be the first next generation muon projects and the first muon FFAGs. It may be worth to investigate synergies between the two projects.

Future work

•Finish the tracking of the injection line.

•Optimisation of the injection system (simplification?).

•Review of the alternative ring designs and evaluation of their performance.

•Optimisation of alternative ring options or more alternatives?

•Further development of the injection hardware (kicker and septum magnets).

•Design of the extraction system and matching to the MST (NS-FFAG type?).

•Baseline design of the PRIME detector system,
including the solenoidal magnet system(?).

•Full G4 physics simulation of the best option.