Towards realising PRISM based muon to electron conversion experiment

J. Pasternak,

Imperial College London/RAL STFC

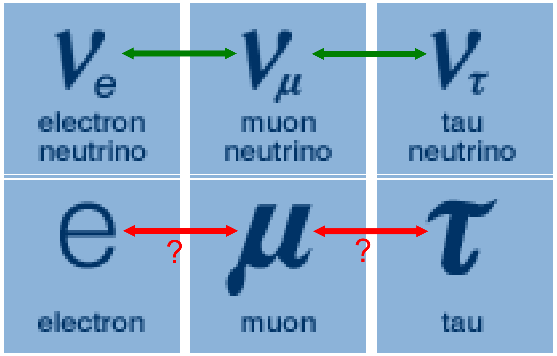
25 September 2017,
Nufact'17, Uppsala

Outline

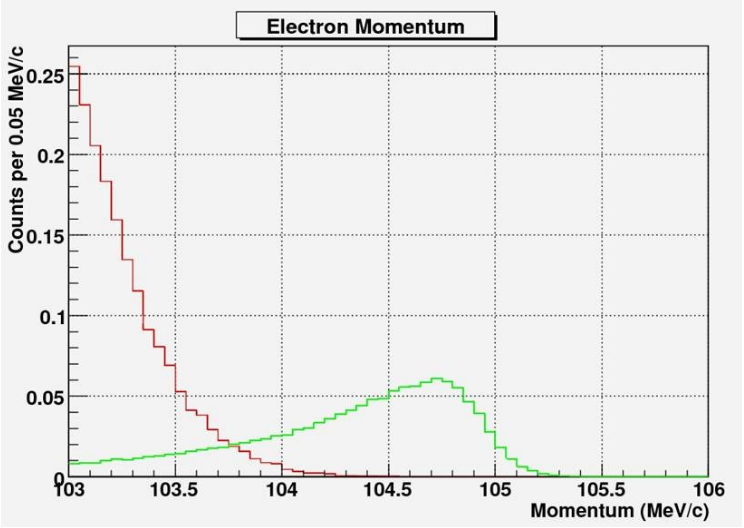
- PRISM Parameters
- Challenges of PRISM
- PRISM Task Force initiative.
- Muon beam matching into FFAG ring.
- Injection/extraction hardware.
- Injection issues
- New ring design
- Way forward
- Conclusions

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 path to COMET).

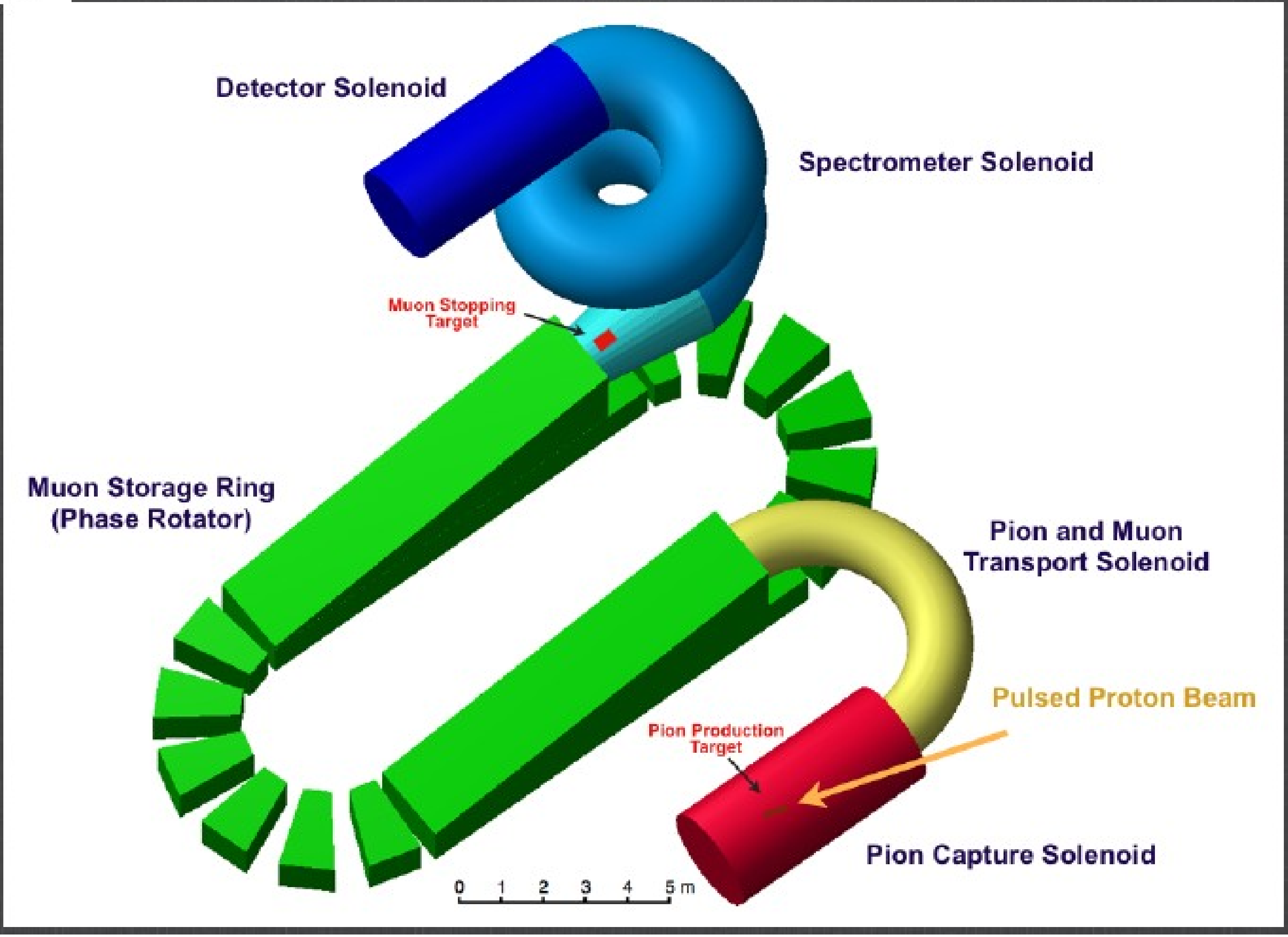


Does cLFV exists?



Simulations of the expected electron signal (green).

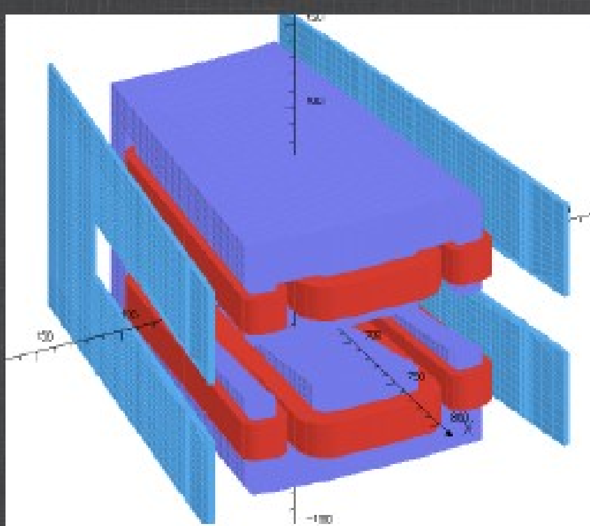
PRISM overview

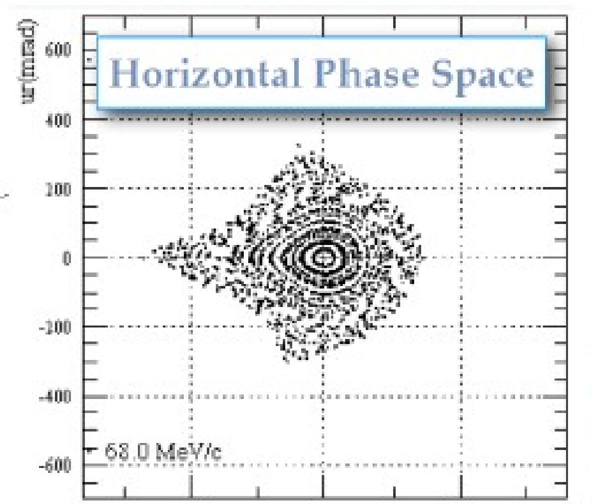


J. Pasternak

Phase rotator (1)

- 10-cell DFD FFAG ring designed at RCNP, Osaka University.
- FFAG magnet designed, manufactured and tested.
- Phase rotation principle demonstrated with α particles.
- Problems of injection / extraction.





PRISM parameters

Parameter	Value
Target type	solid or liquid (powder)
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

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).

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.

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:

J. Pasternak, Imperial College London, UK/RAL STFC, UK
(contact: j.pasternak@imperial.ac.uk)
L. J. Jenner, A. Kurup, J-B. Lagrange, Imperial College London, UK/Fermilab, USA
A. Alekou, M. Aslaninejad, R. Chudzinski,Y. Shi, Y. Uchida, Imperial College London, UK
B. Muratori, S. L. Smith, Cockcroft Institute, Warrington, UK/STFC-DL-ASTeC, Warrington, UK
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.

J. Pasternak

PRISM Task Force Design Strategy

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

We should think how to efficiently use existing PRISM magnets:

- demonstration of the concept (?)
- longitudinal cooling experiment (?)

Option 2:
Find a new design

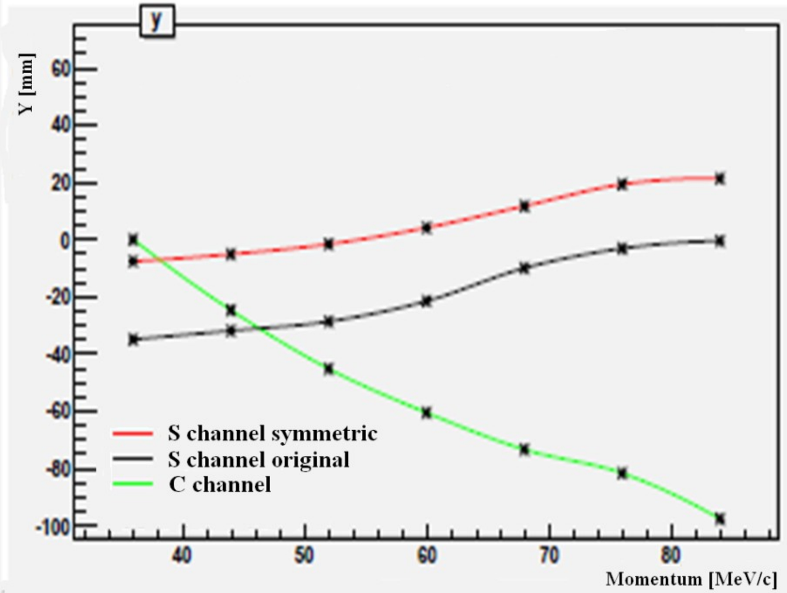
There are indications a new design with very good properties is possible (see later)

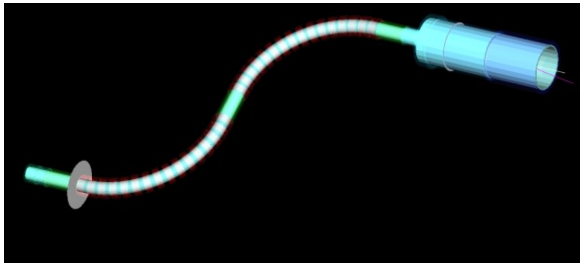
Main challenges before TF started working:

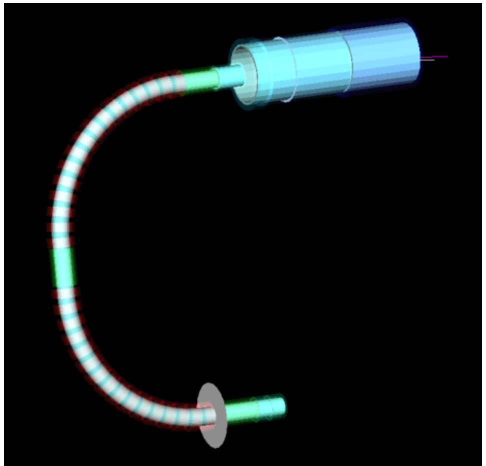
- Matching from the solenoid into FFAG
- Injection/Extraction geometries
- Kicker hardware
- Septum magnet
- RF system
- Beam dynamics in FFAG

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.



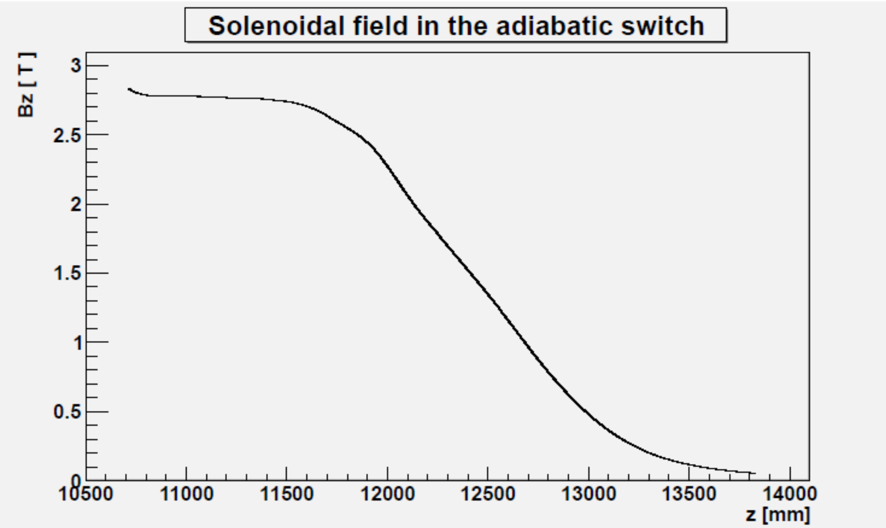




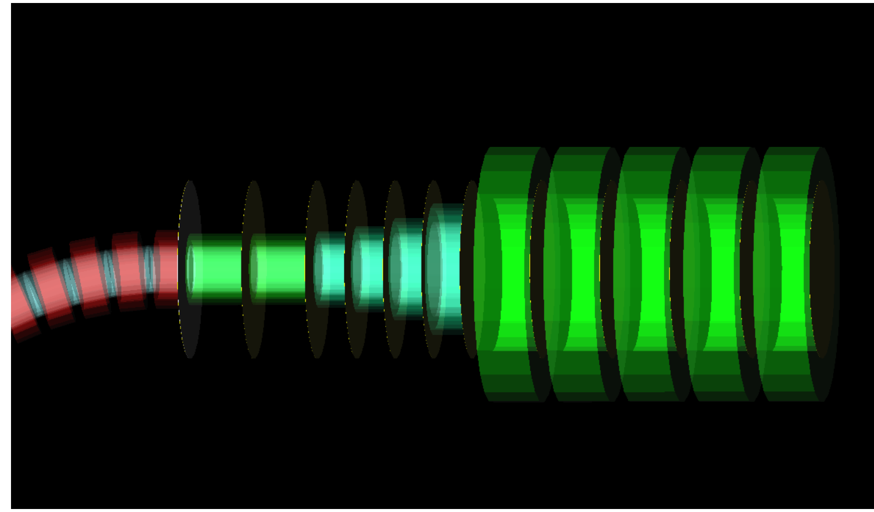
The mean vertical beam position versus momentum at the end of bend solenoid channel for various configurations.

Main conclusion from this study is: both S and C geometries could be used although S is performing a bit better.

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:

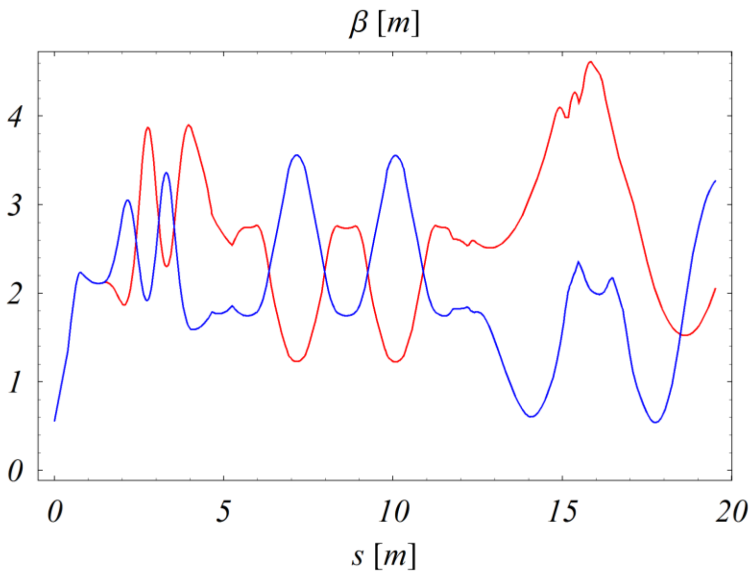
• adiabatic switch from 2.8 to 0.5 T (to increase the beam size),

• additional solenoidal lens to match α=0 (not shown in the pictures above),

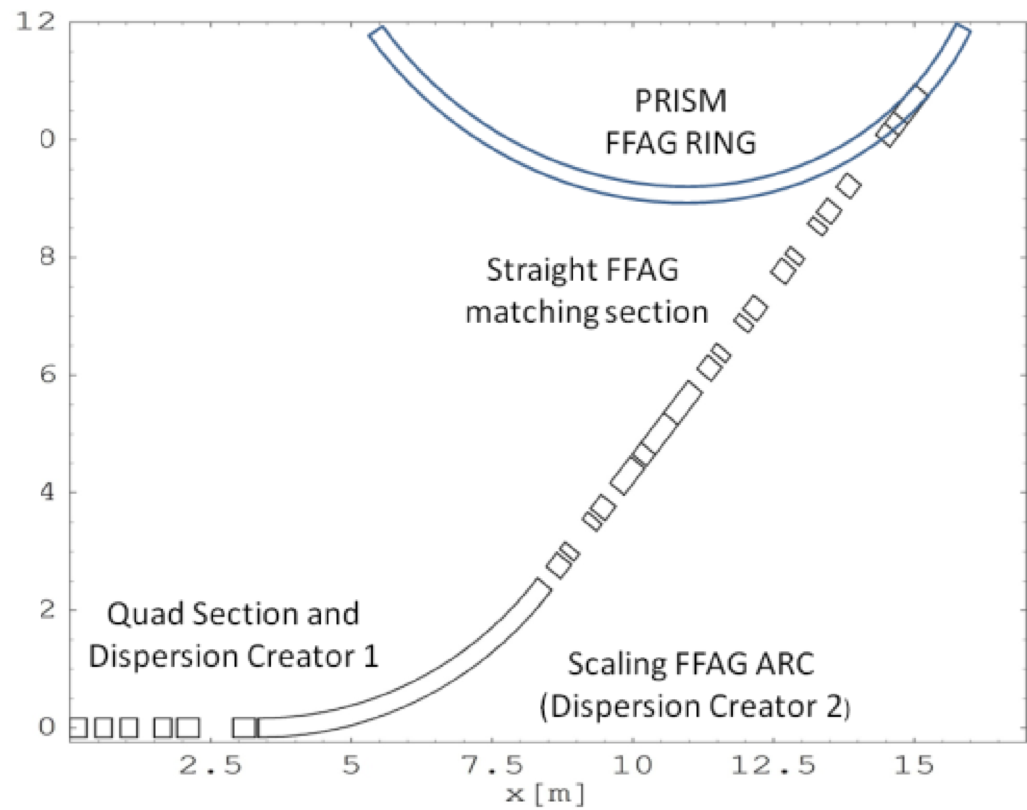
•5 quad lenses,

Matching to the FFAG III

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



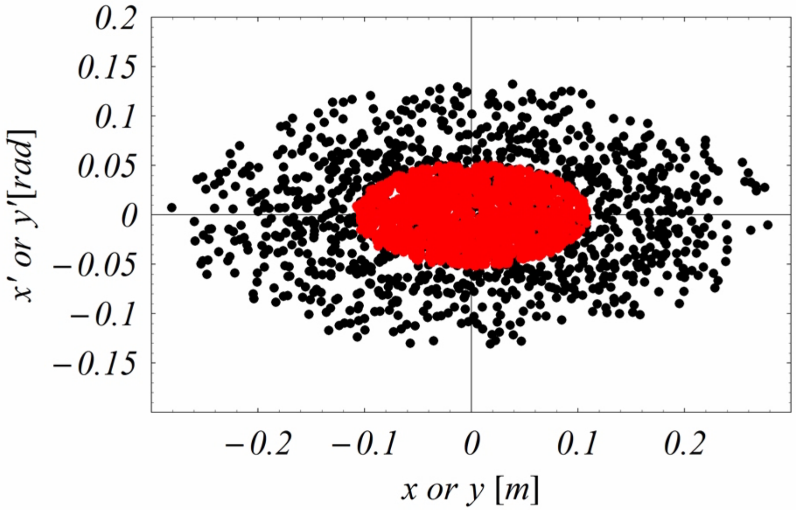
Horizontal (red) and vertical (blue) betatron functions in the PRISM front end.



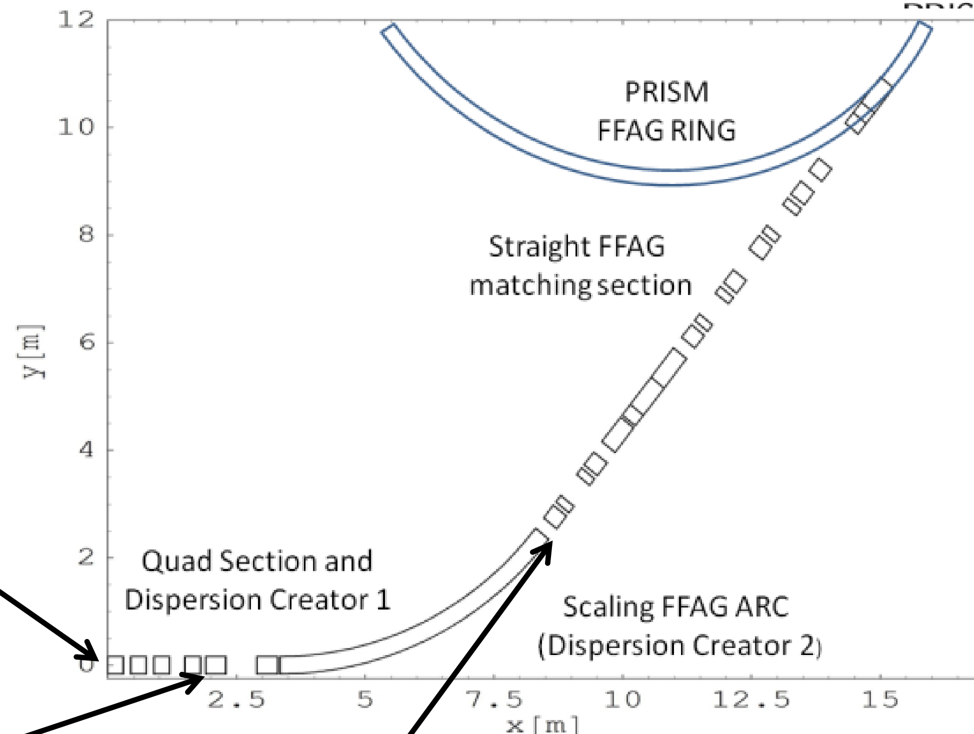
Layout of the matching section seen from the above.

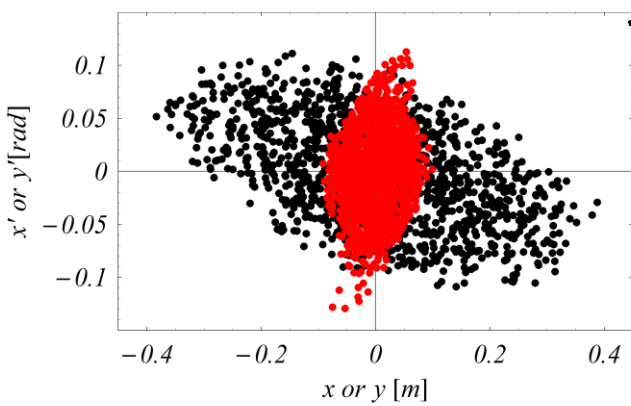
Matching to the FFAG IV

- Tracking status
  (work in progress)

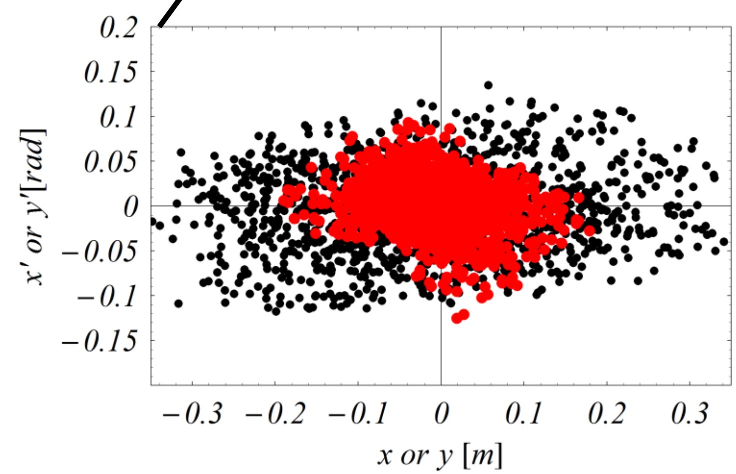


Horizontal (black) and vertical (red) phase spaces at the input to the AG part of the PRISM muon front end.





At the end of the quad Channel



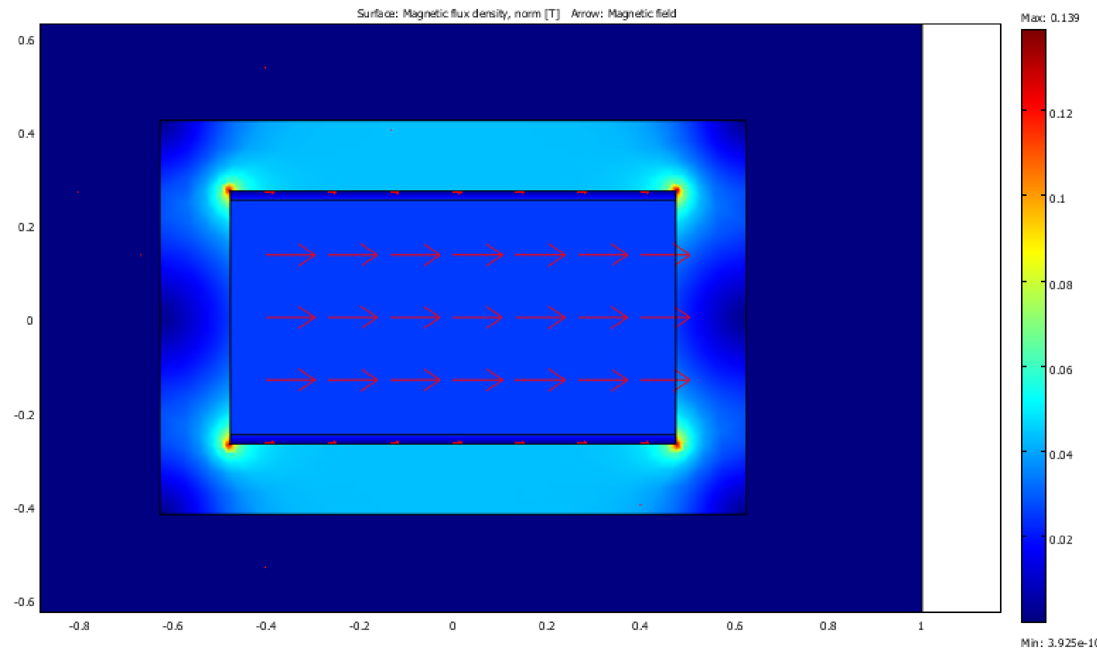
At the end of the horizontal dispersion creator (transmission 97%)

Main conclusion from this study is: matching from the solenoid and dispersion creation can be done without big losses within the FFAG acceptances.

Further optimization and full tracking studies are still required!

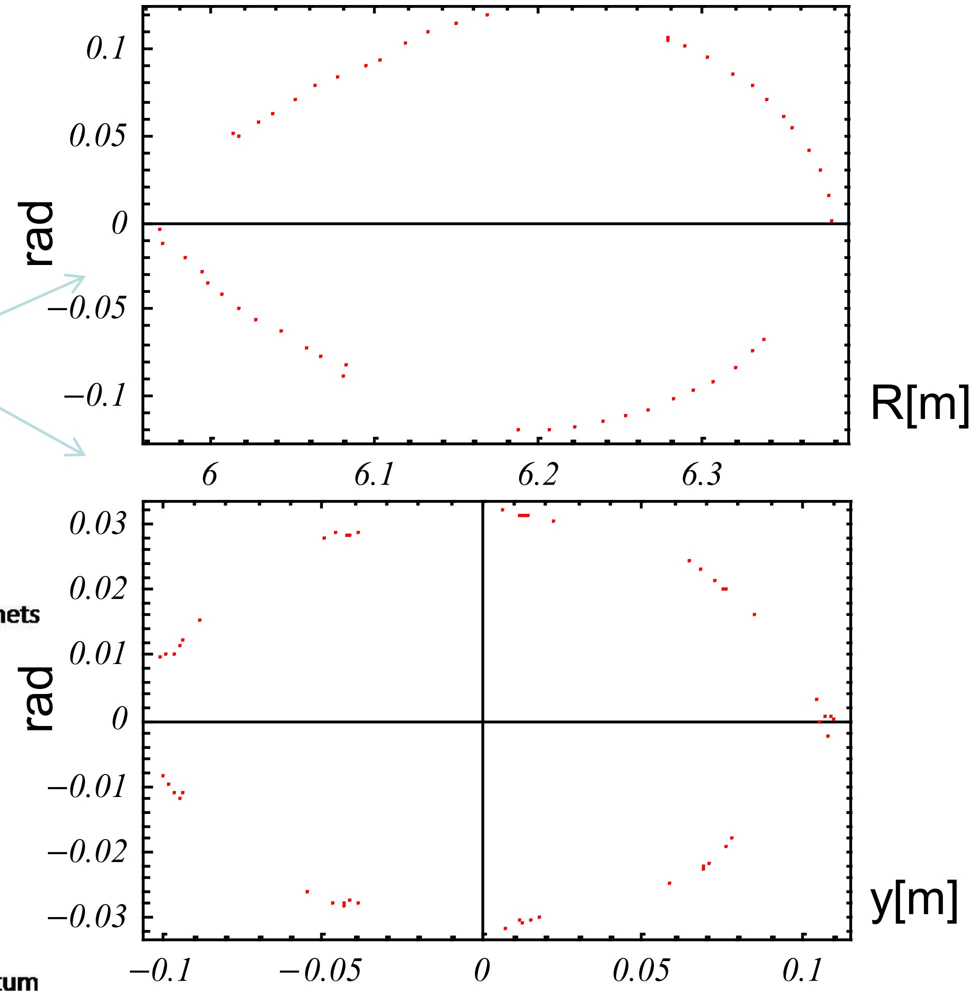
Preliminary PRISM kicker studies

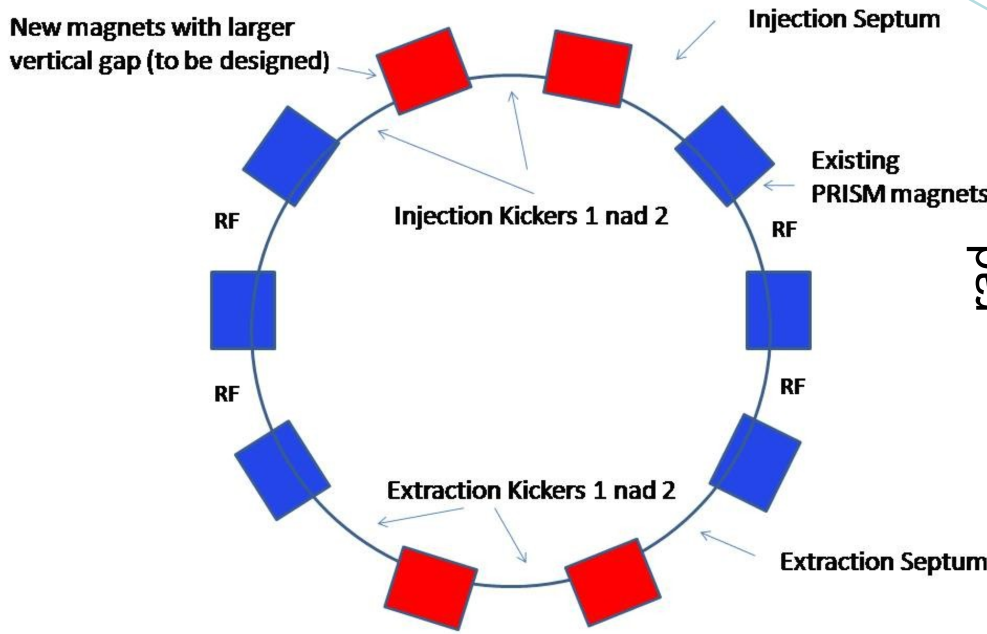
- length 1.6 m
- B 0.02 T
- Aperture: 0.95 m x 0.5
- Flat top 40 /210 ns (injection / extraction)
- rise time 80 ns (for extraction)
- fall time ~200 ns (for injection)
- W_{mag}=186 J
- L = 3 uH (preliminary)
- I_{max}=16 kA



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!



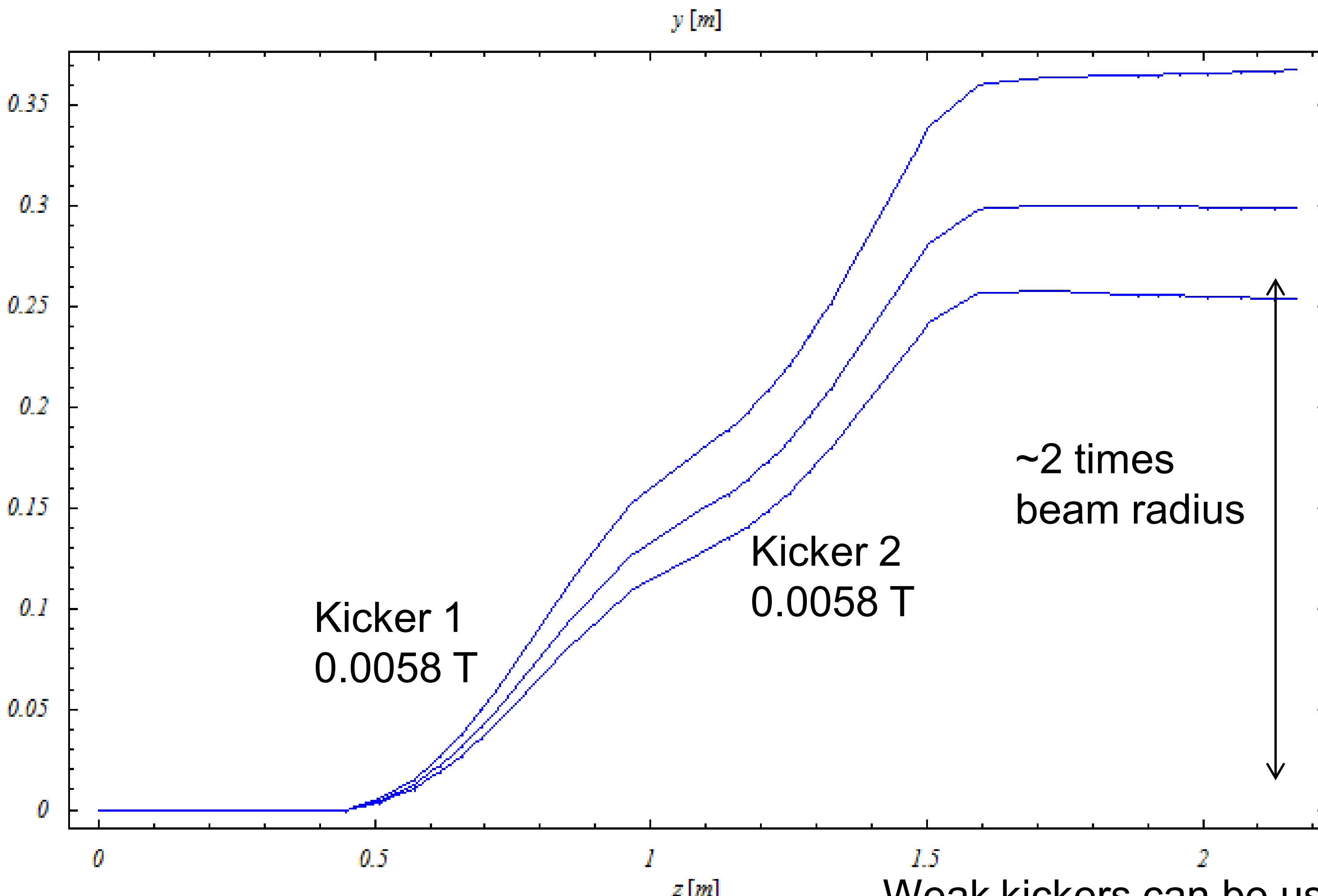


We can re-use existing magnets!

J. Pasternak

Vertical injection

Orbit separation with 2 kickers

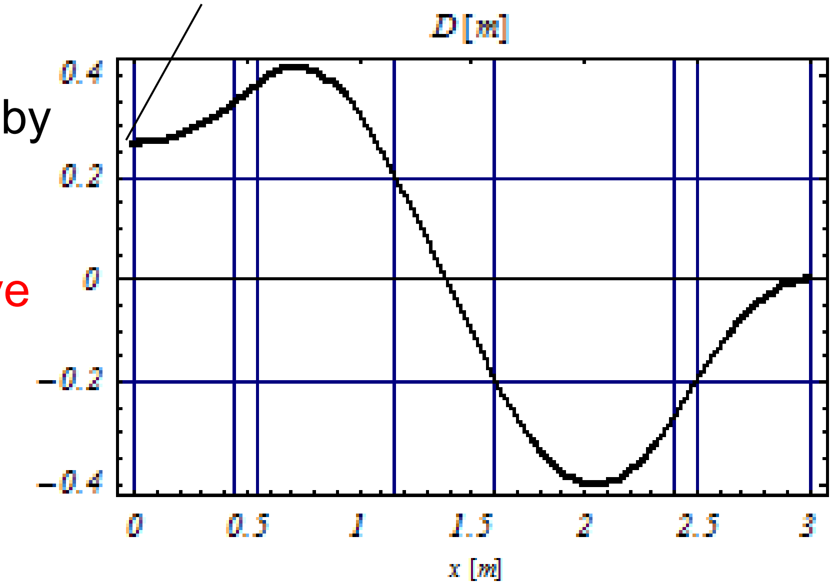


Weak kickers can be used!

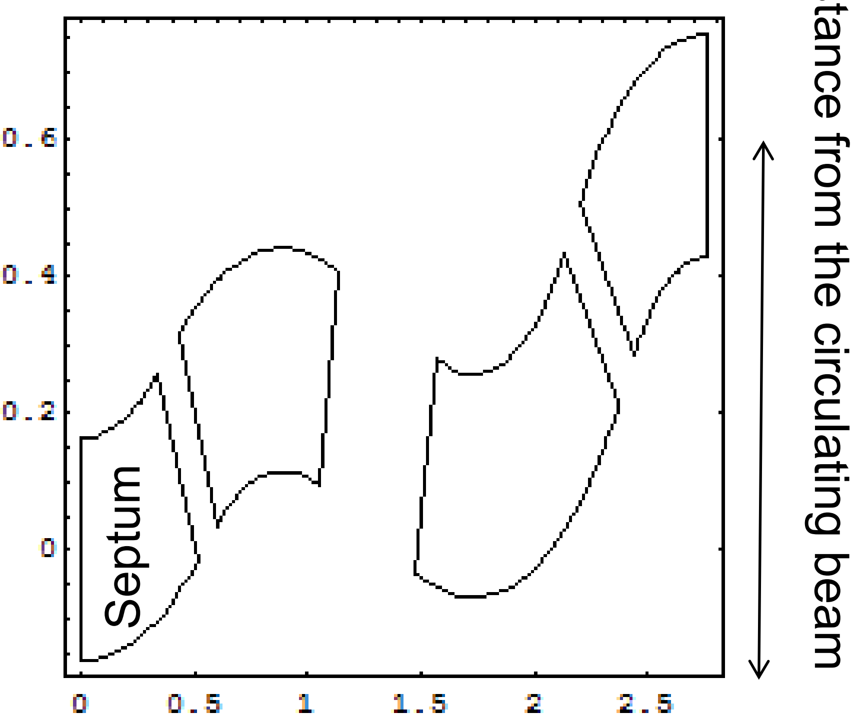
J. Pasternak

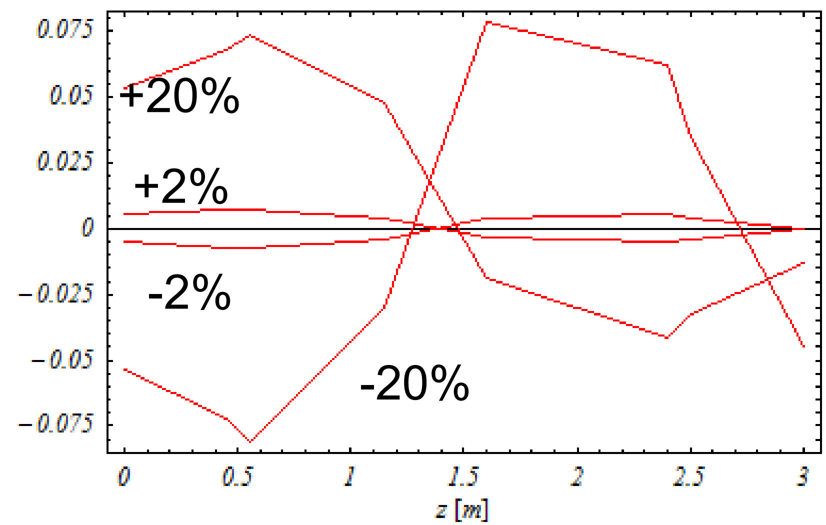
Vertical injection – vertical dispersion suppression

Dispersion created by the kicker



- 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.





Difficult matching!

J. Pasternak

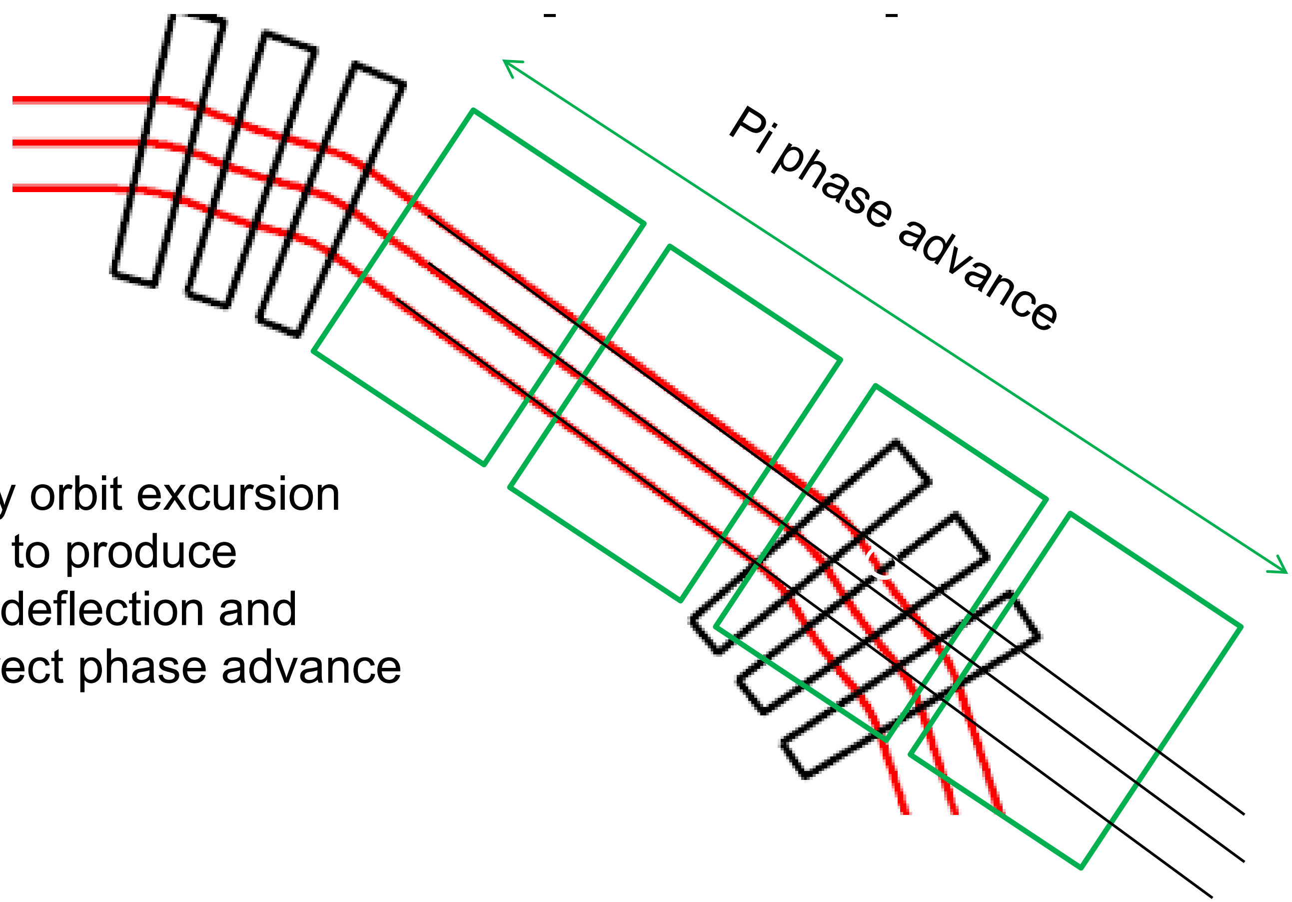
HFFAG with V bending

- Conventional horizontal FFAG bends in horizontal plane and have horizontal orbit excursion
    - For straight case: $B_y = B_{y0}\,Exp[mx]$
- VFFAG bends in horizontal plane and have vertical orbit excursion
    - For straight case: $B_y = B_{y0}\,Exp[my]$
- We need vertical septum, which keeps the horizontal orbit excursion
    - Straight case would mean
    $B_x = B_{x0}\,Exp[mx]$

HFFAG with V bending (2)

$$B_x = B_{x0}\,\mathrm{Exp}[mx] = \underbrace{B_{x0}}_{\text{Vertical dipole}} + \underbrace{B_{x0}mx}_{\text{Skew quad}} + \underbrace{1/2B_{x0}m^2x^2}_{\text{Skew sextupole}} + \ldots$$

HFFAG with V bending (3)



- m is fixed by orbit excursion
- Bx is aimed to produce
both enough deflection and
to obtain correct phase advance

HFFAG with V bending (4)

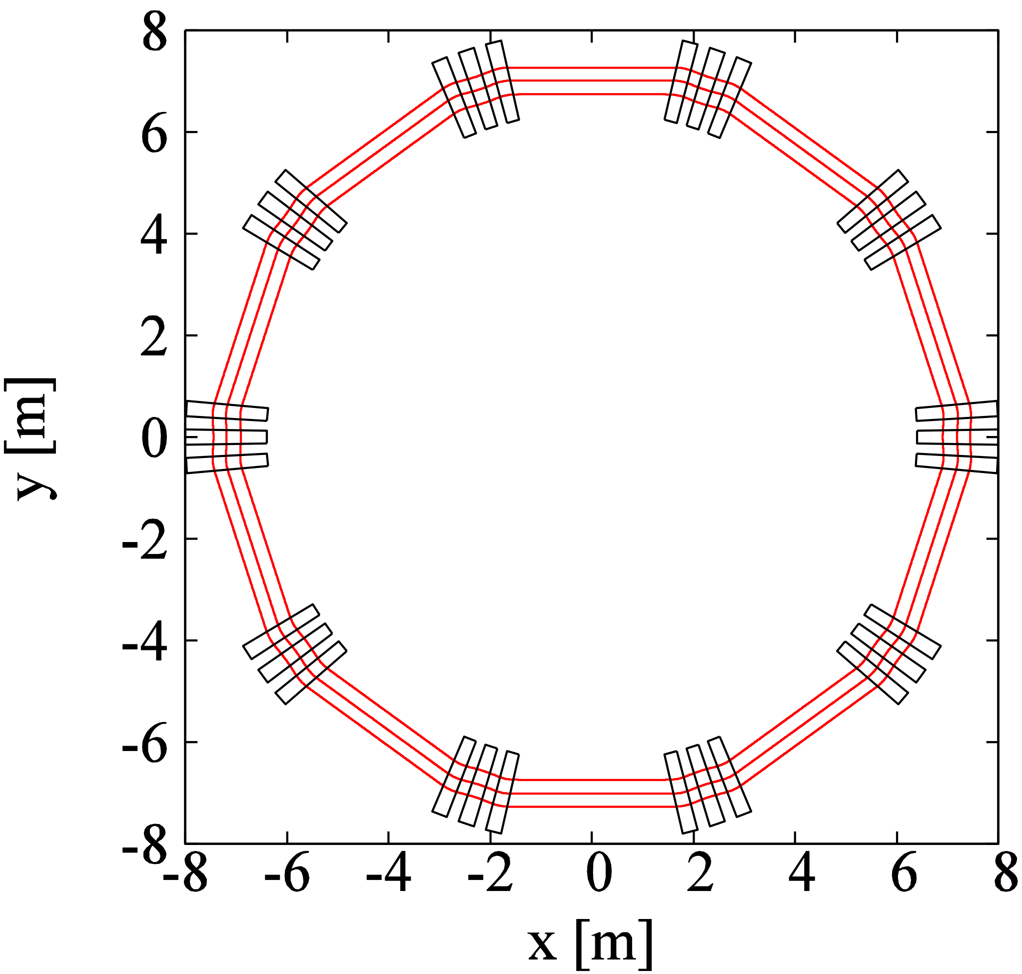
- Preliminary studies confirm the conservation of the orbit excursion
    - ❑Particles with momentum spread but zero betatron amplitude are all deflected by the same angle and reach the same vertical distance even for large $\Delta p/p$
- They also show strong transverse coupling in H/V planes
    - ❑...probably the desired phase advance was not achieved, which can be improved
    - ❑ However strong H/V coupling in the PRISM system with highly asymmetric emittances is rather challenging!

Main conclusion from this study is:
Full vertical injection is very difficult!

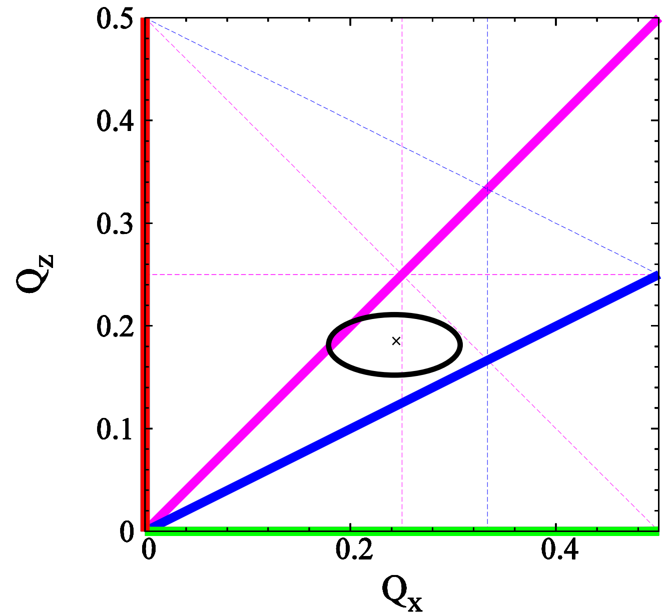
We most likely agree:
Full horizontal injection is impossible!

We need a new idea!

New FDF scaling FFAG design

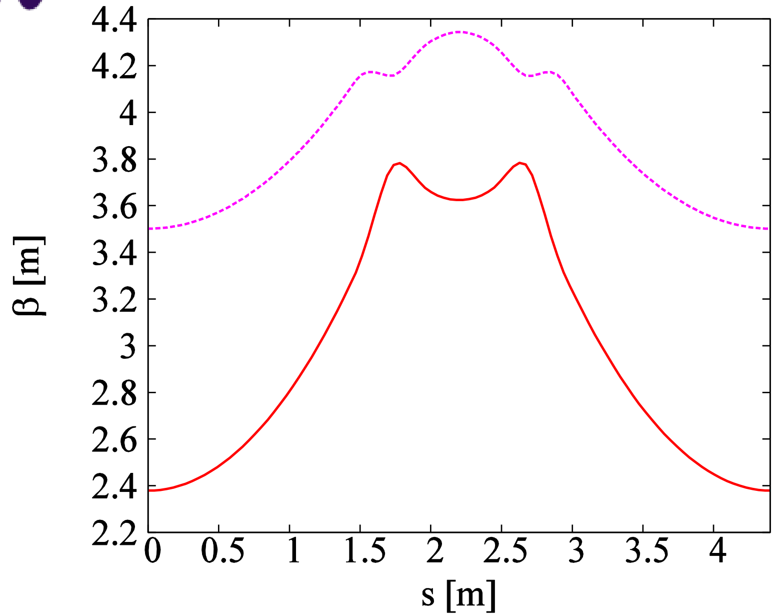


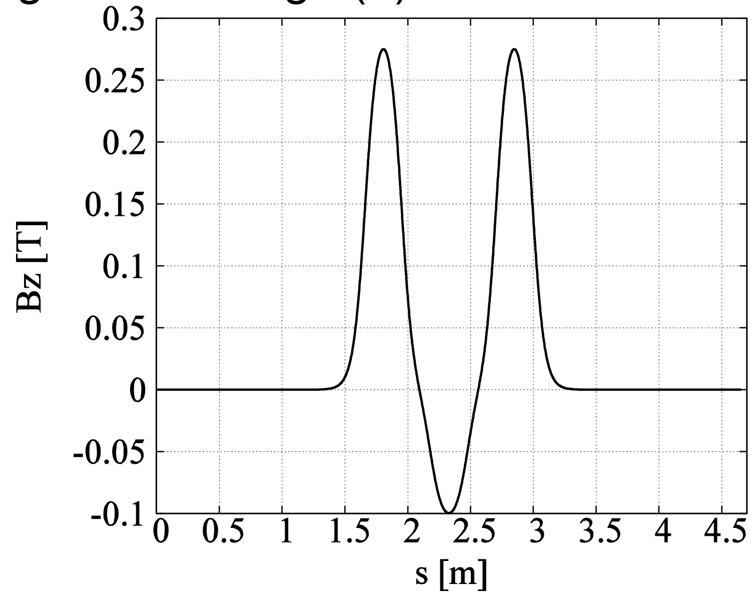
- FDF symmetry motivated by the success of ERIT at KURRI
- 10 cells
- k 4.3
- R_0 7.3 m
- (Q_H, Q_V) (2.45, 1.85)
- Minimal drift length 3m

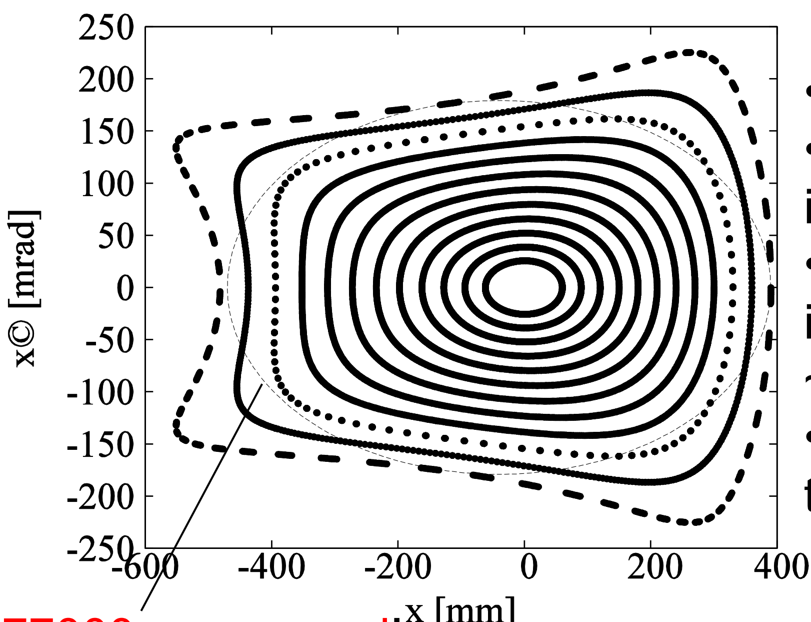


J. Pasternak

New FDF scaling FFAG design (2)







77000 π.mm.mrad!

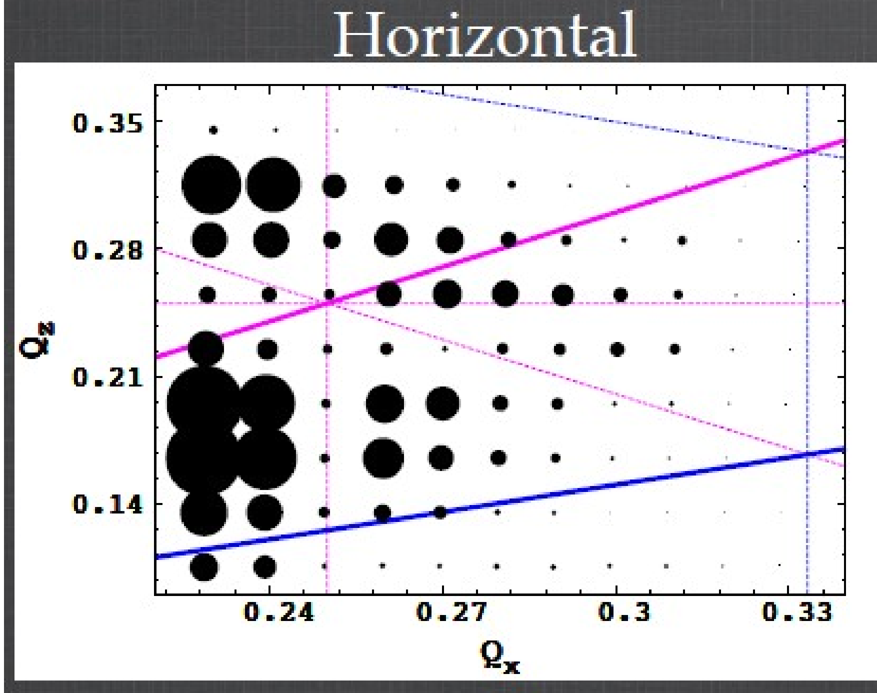
- Enge field fall-off used to study fringe fields
- Enormous horizontal acceptance is achieved in simulations
- Vertical long term stability of ~3000 π.mm.mrad is achieved, however with some optimization ~5000 π.mm.mrad should be stable for a few turns.
- 5000 π.mm.mrad is what we currently aim for due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

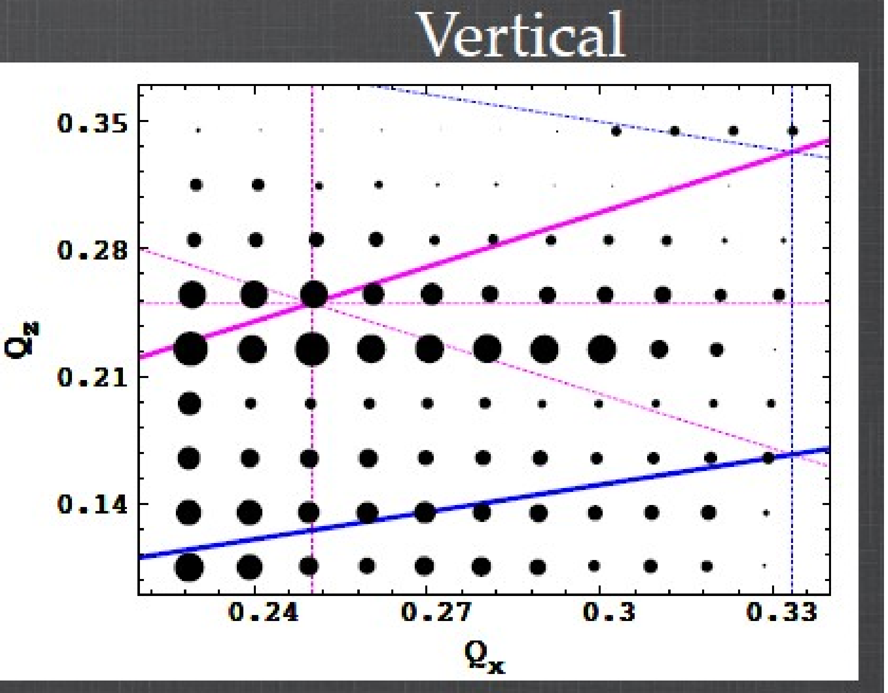
J. Pasternak

Phase rotator (3)

Study of DA for new design

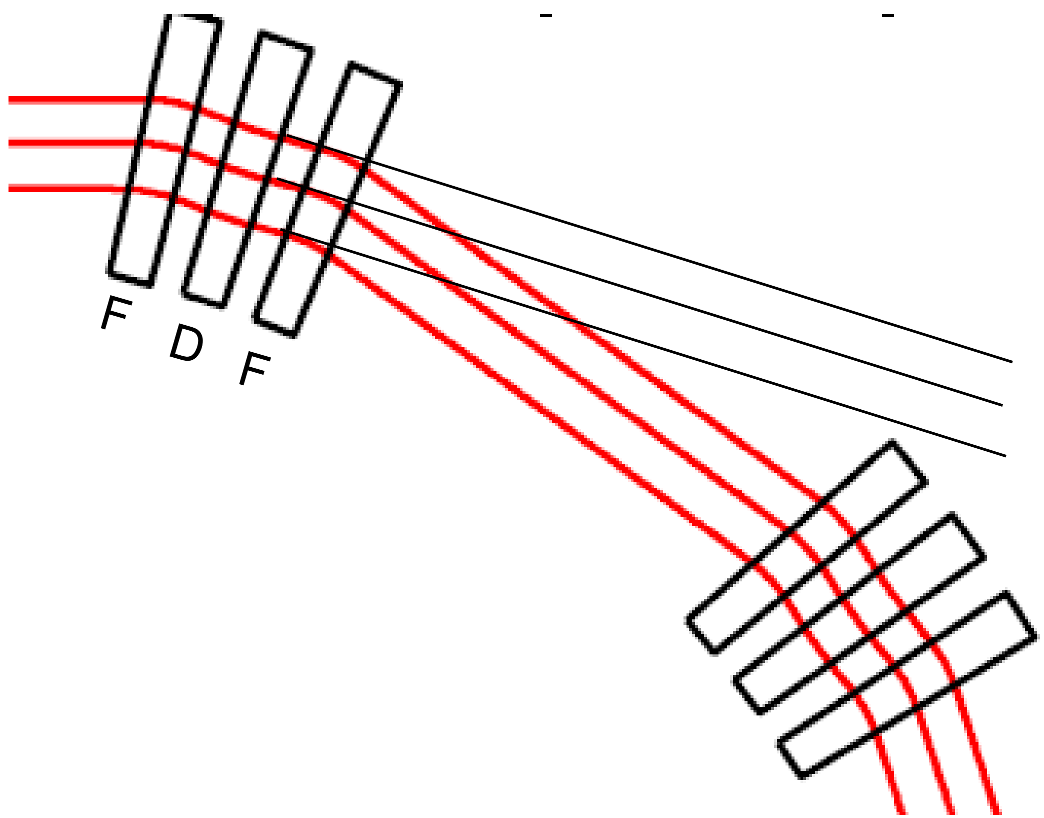
10-cell FDF FFAG





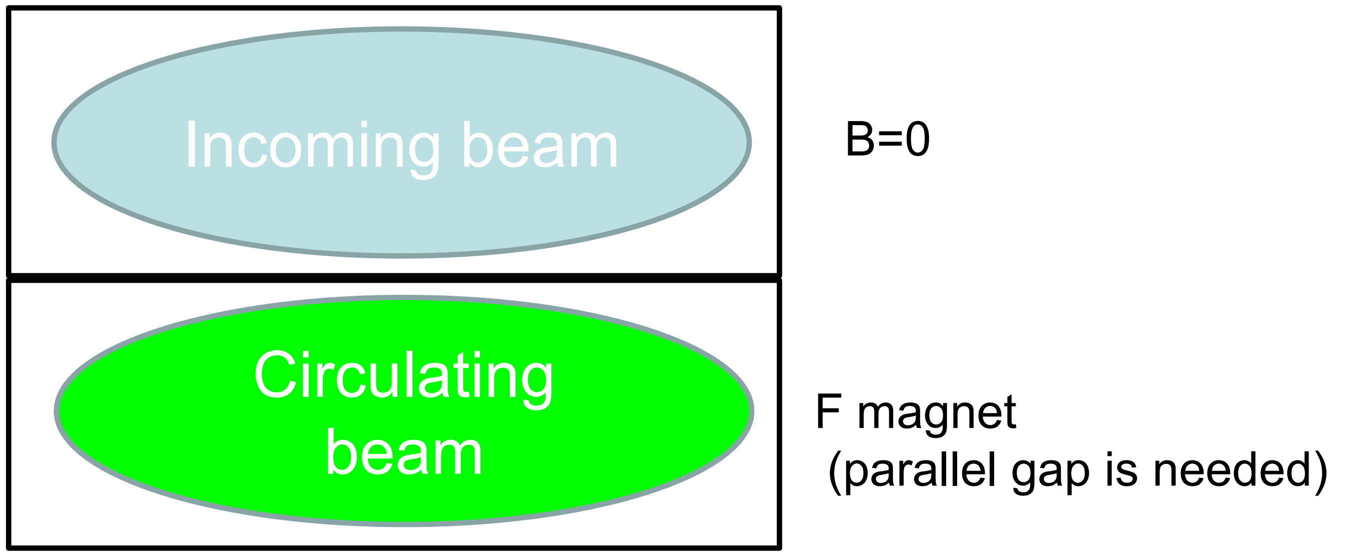
>50 / >3 mm.mrad (H/V) achieved.

New injection concept (1)



If one could switch off the F magnet...

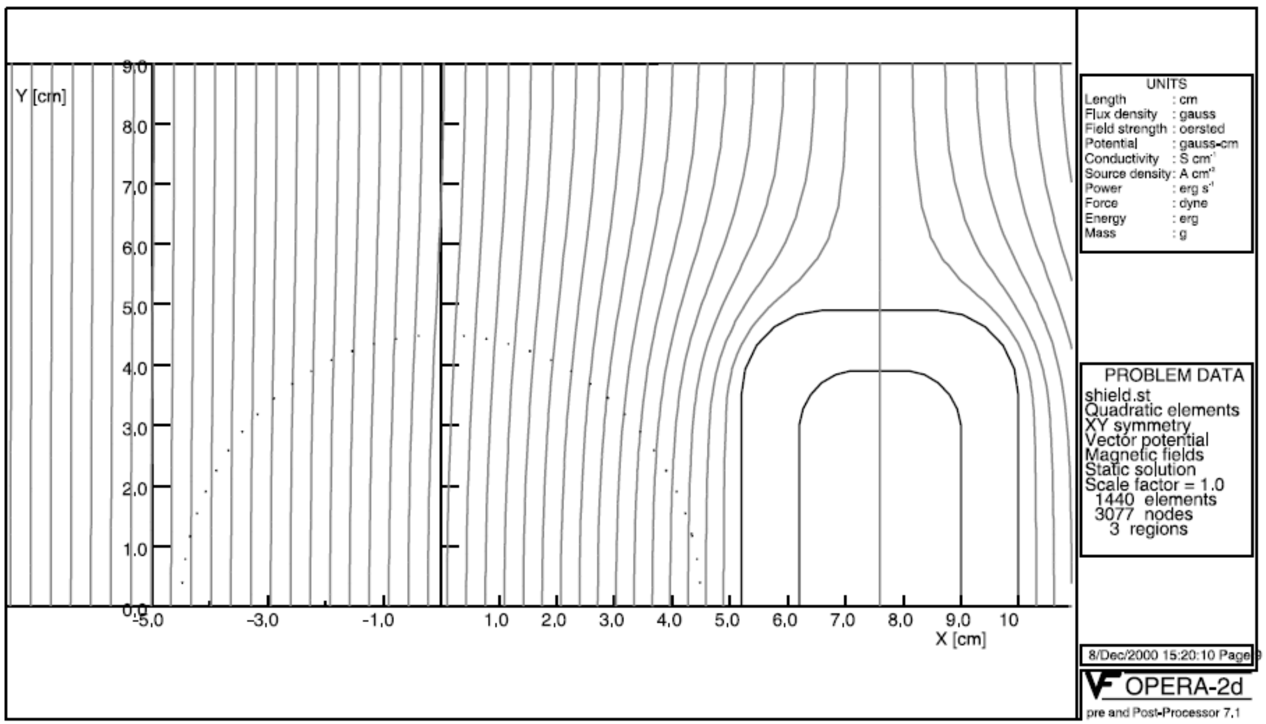
Inflector, flux shielding channel



Injected beam can be put on orbit using vertical kicker(s).

Similar ideas have been studied for g-2 experiment

A. Yamamoto et al. / Nuclear Instruments and Methods in Physics Research A 491 (2002) 23–40



Main challenges at present:

- Matching from the solenoid into FFAG
- Injection/Extraction geometries
- Kicker hardware
- Septum magnet
- RF system
- Beam dynamics in FFAG -> we believe we have now improved ring design.

Conclusions

• Vertical injection is proven to be very challenging due to huge perturbation caused by the septum magnet(s).

• Concept of the inflector effectively “switching off” one of the magnets followed by vertical kicker looks promising.

•The new FDF ring seems to be performing very well, further optimisation studies are needed.

•PRISM is becoming a serious choice for the next generation cLFV experiment.