Studies of PRISM/PRIME - the next generation muon to electron conversion experiment

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on behalf of PRISM Task Force

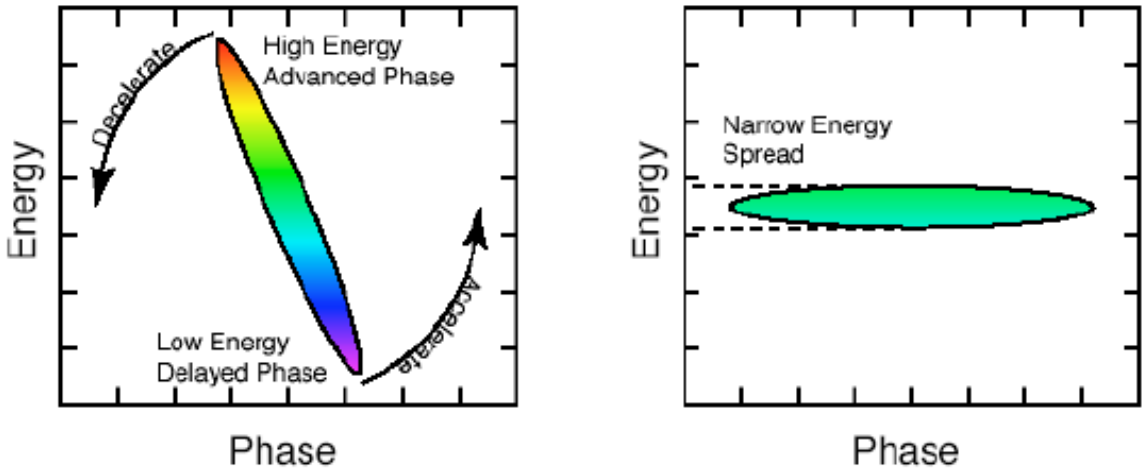
Outline

- Introduction
- Challenges of PRISM
- PRISM Task Force initiative.
- Solving injection…
- New ring design
- Further questions and new ideas
- Conclusions

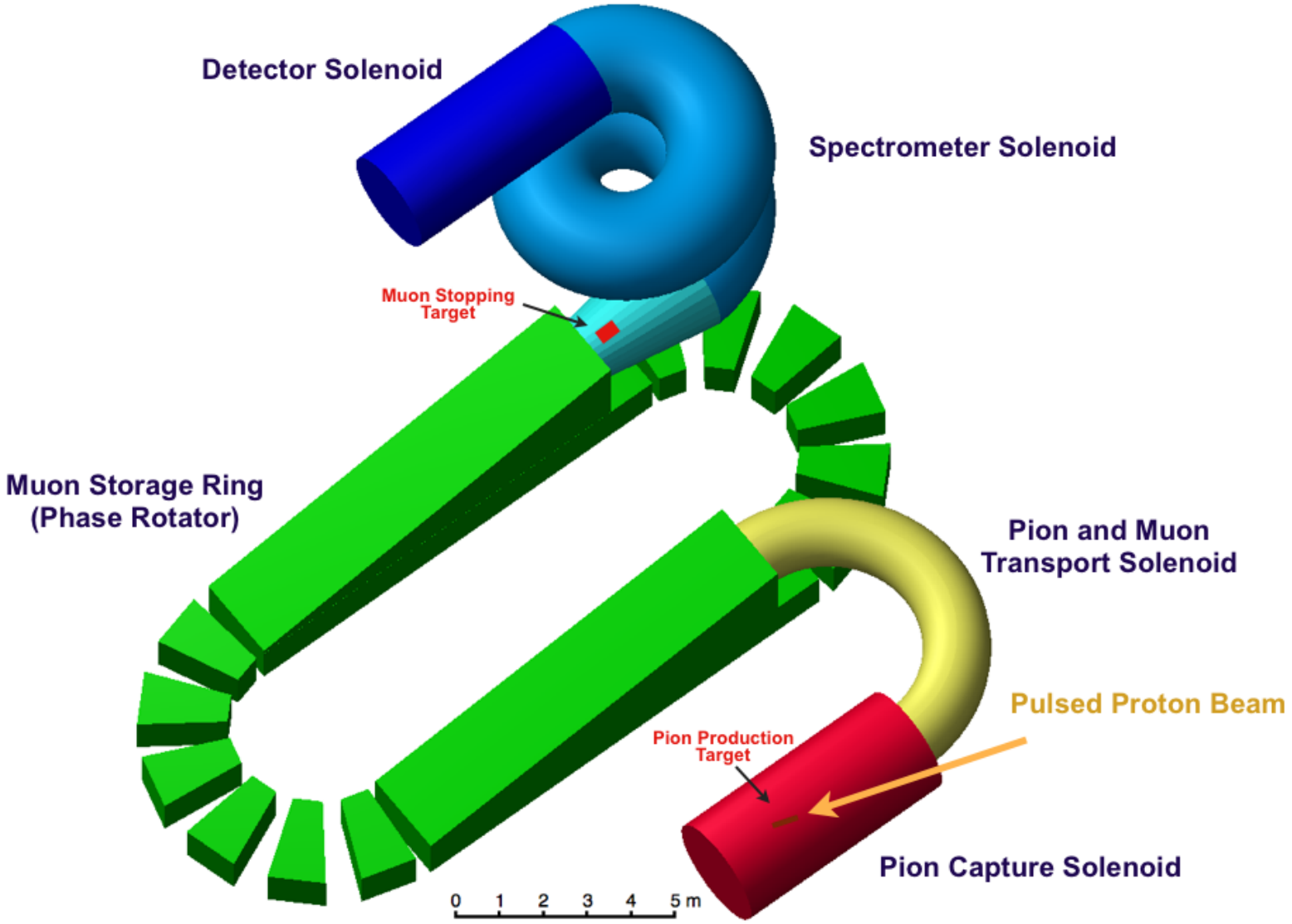
Introduction

PRISM - Phase Rotated Intense Slow Muon beam

- Charge lepton flavor violation (cLFV) is strongly suppressed in the Standard Model, its detection would be a clear signal for new physics!
- The $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$ seems to be the best laboratory for cLFV.
- The PRISM/PRIME experiment based on was proposed(Y. Kuno, Y. Mori) for a next generation cLFV searches in order to (potential upgare to COMET):
  - 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

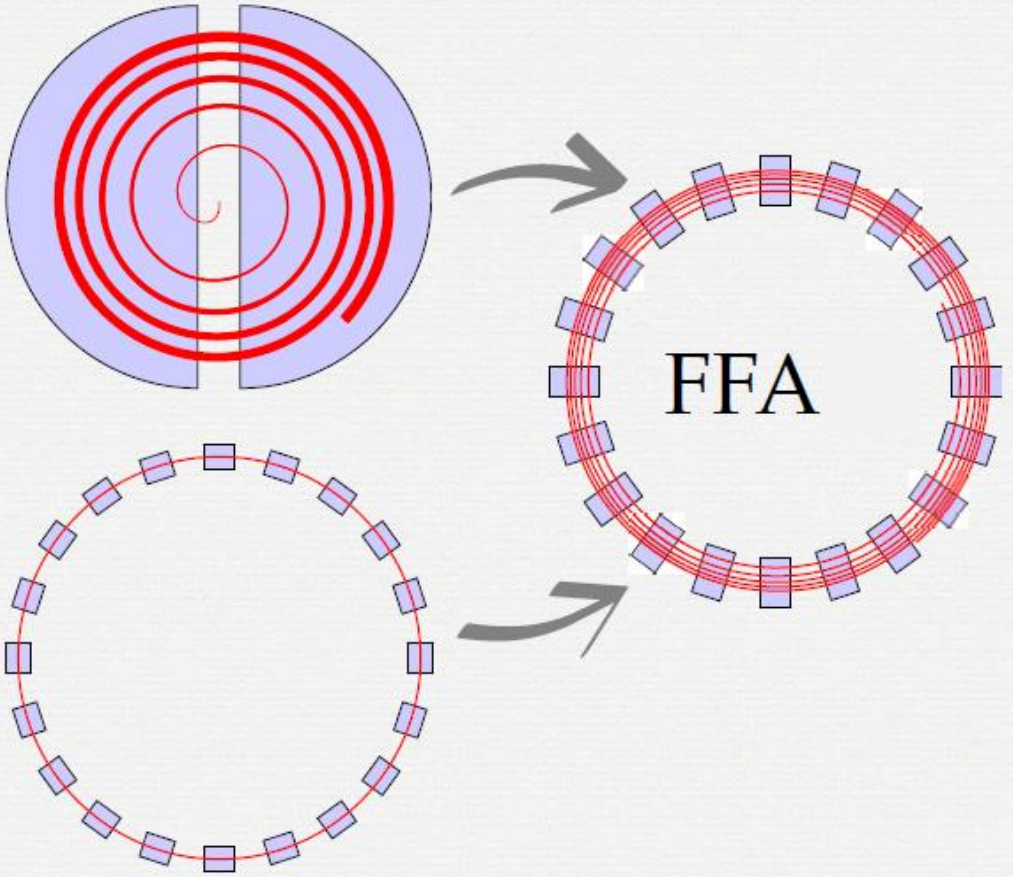


Fixed Field Alternating gradient (FFA) – can read Fixed Field Accelerator

- **a static guide field** like cyclotrons:

AND

- **a strong focusing.** like synchrotrons:



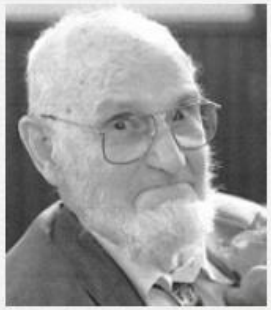
Birth of the FFA

FFA invented in the 1950s independently

- in Japan (T. Ohkawa, 1953),

- in the USSR (A. Kolomensky, 1956),

- and in the USA (K. Symon, 1954).

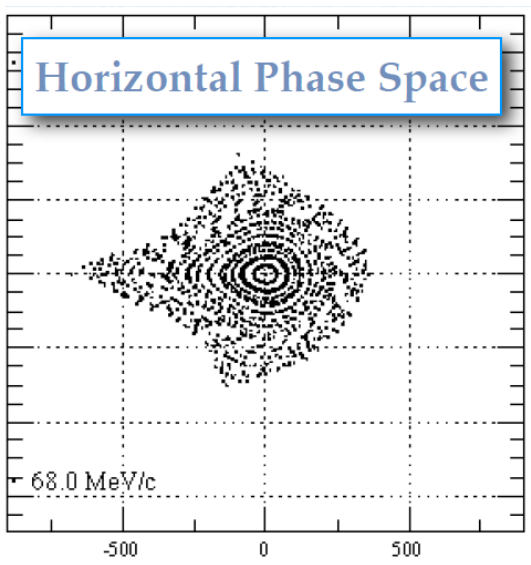


R&D work in Osaka

- 10 cell DFD ring has been designed
- FFA 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.

6 cell FFA ring at RCNP

Magnet for FFA cell - design



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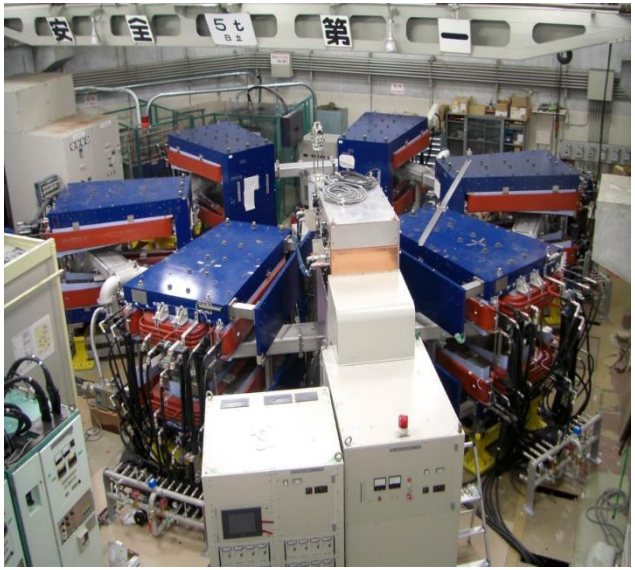
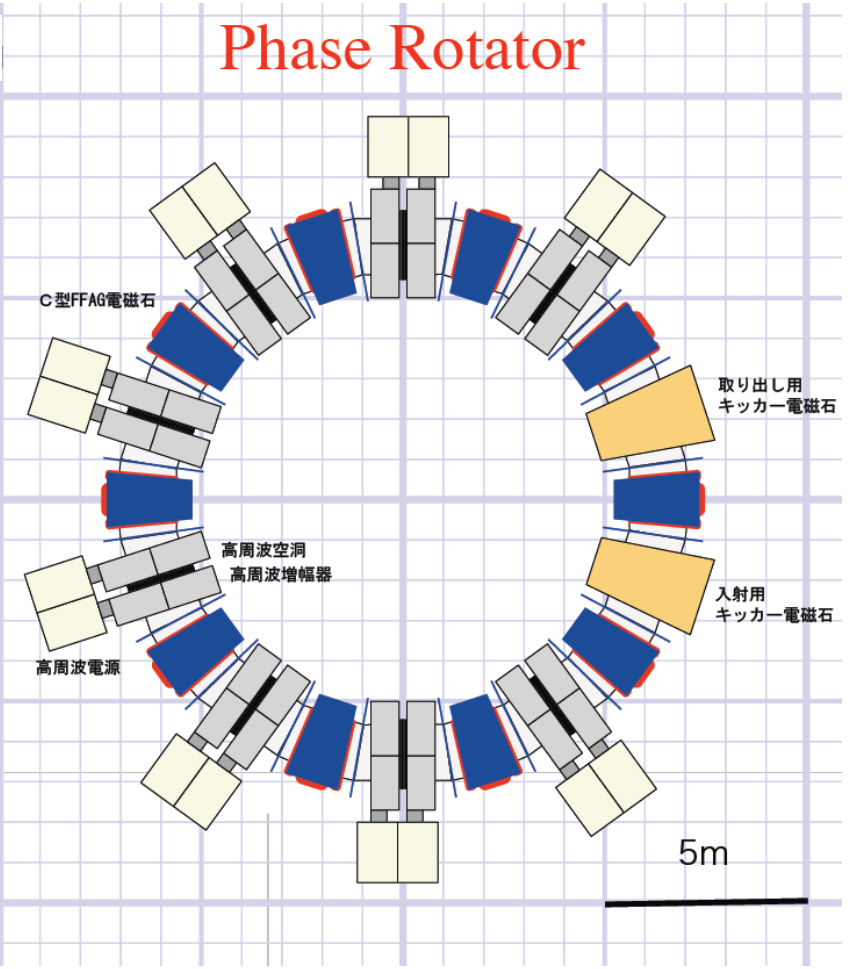


First Design Parameters, A. Sato

PRISM-FFA

- 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

PRISM parameters

Parameter	Value
Target type	solid or liquid (powder)
Proton beam power	multi MW
Proton beam energy	multi-GeV
Proton bunch duration	~10 ns total (in synergy with the NF)
Pion capture field	10 -20 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 or more…
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 transport from the solenoidal capture to the PRISM FFA ring.
-very different beam dynamics conditions.
-very large beam emittances and the momentum spread.

• Muon beam injection/extraction into/from the FFA 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

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The aim of the PRISM Task Force:

• Address the technological challenges in realising an FFA 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-FFA ring,
- FFA ring design including the search for a new improved version,
- FFA hardware systems R&D.

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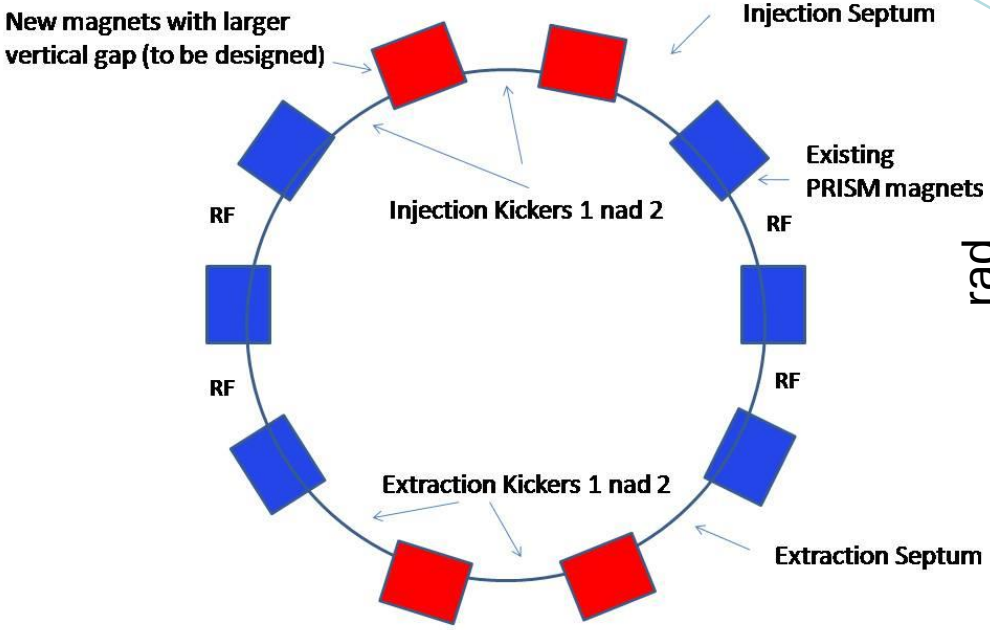
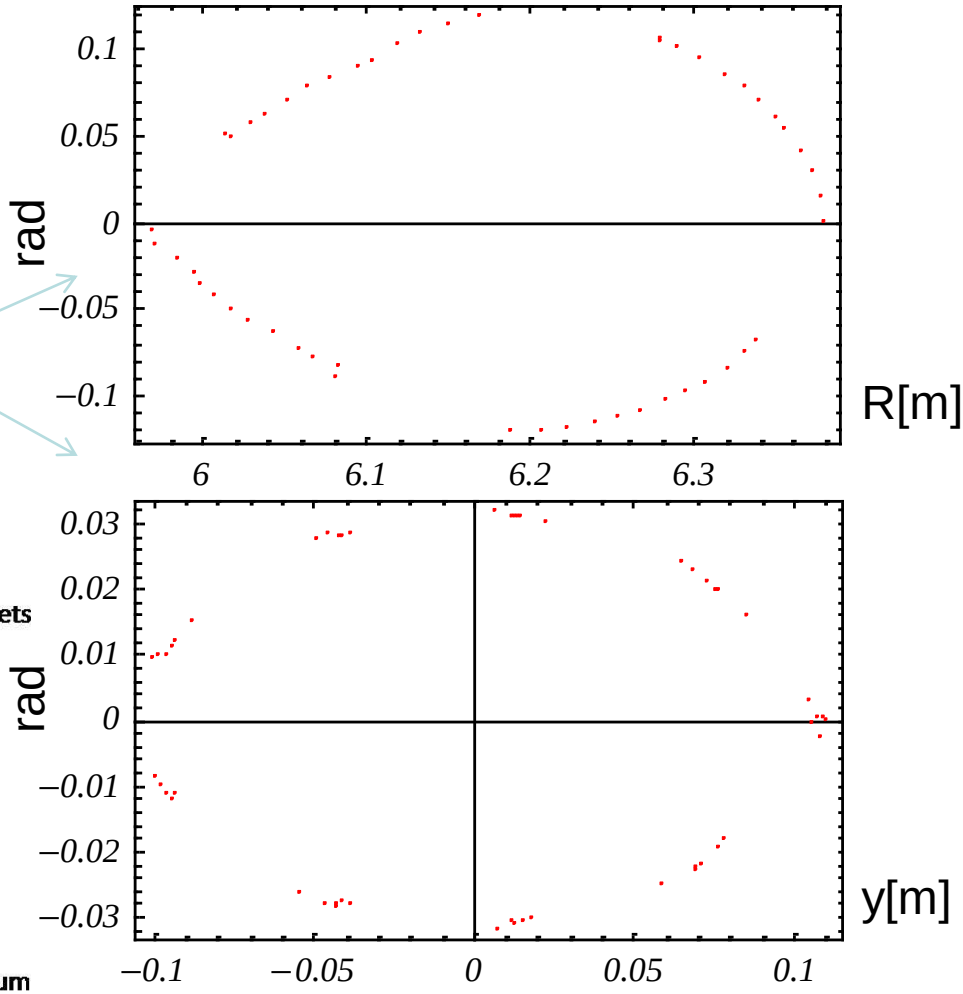
J. Pasternak **You are welcome to join us!**

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!

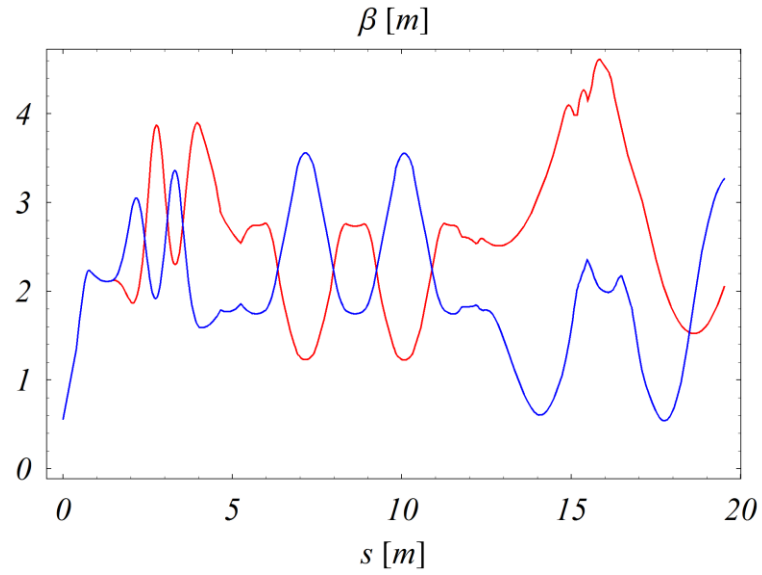




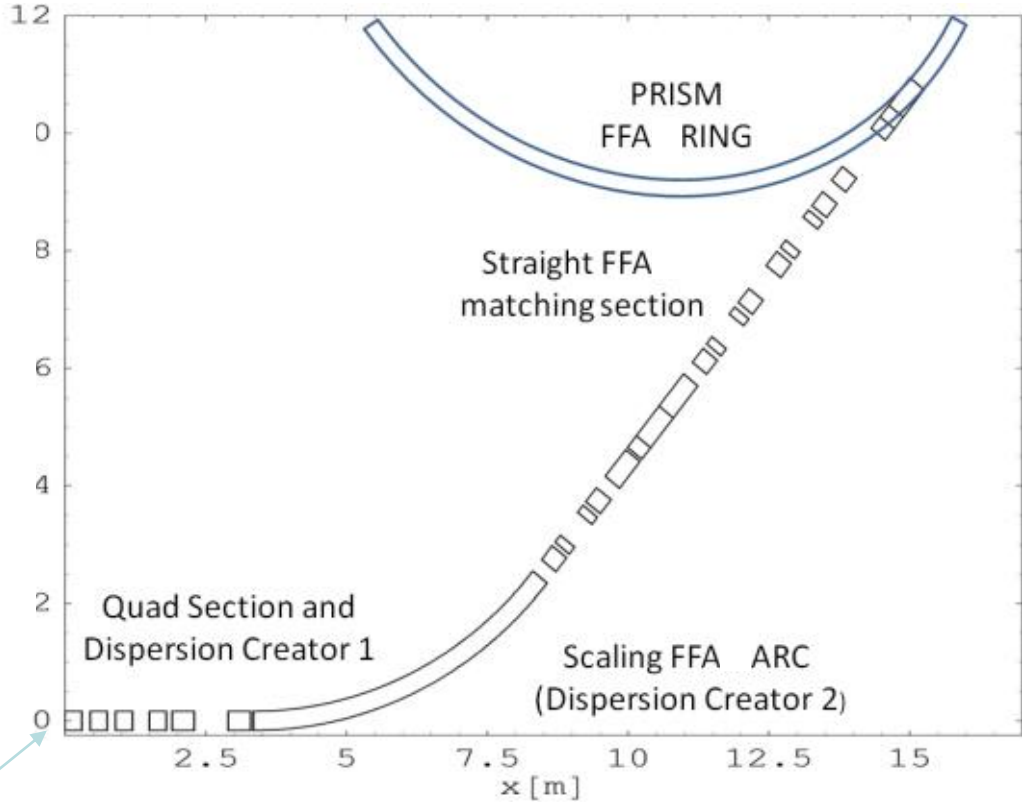
We could re-use existing magnets!

Matching to the FFA

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



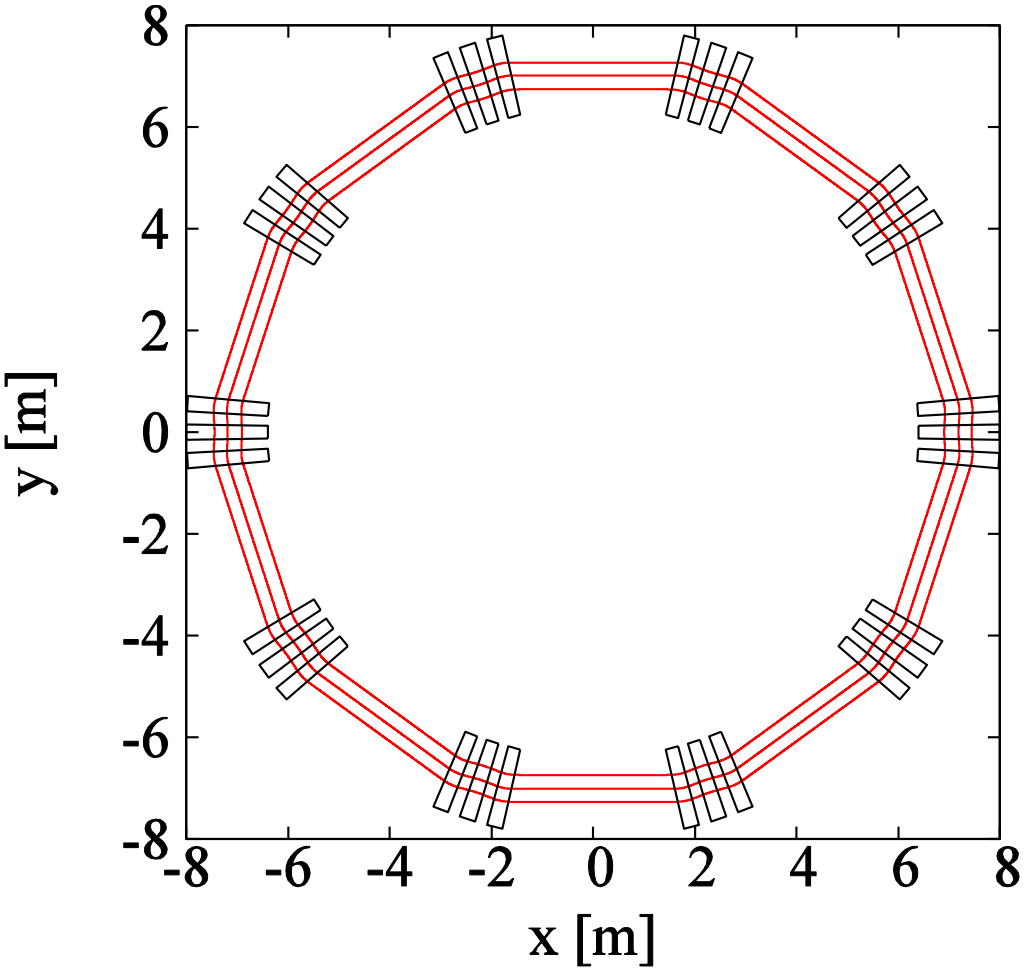
Horizontal (red) and vertical (blue) betatron functions in the PRISM front end.



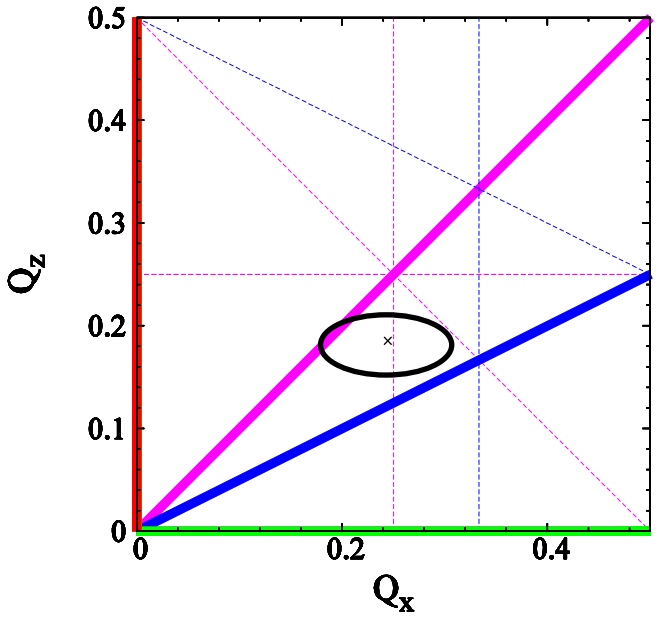
Output of solenoidal channel

Layout of the matching section seen from the above.

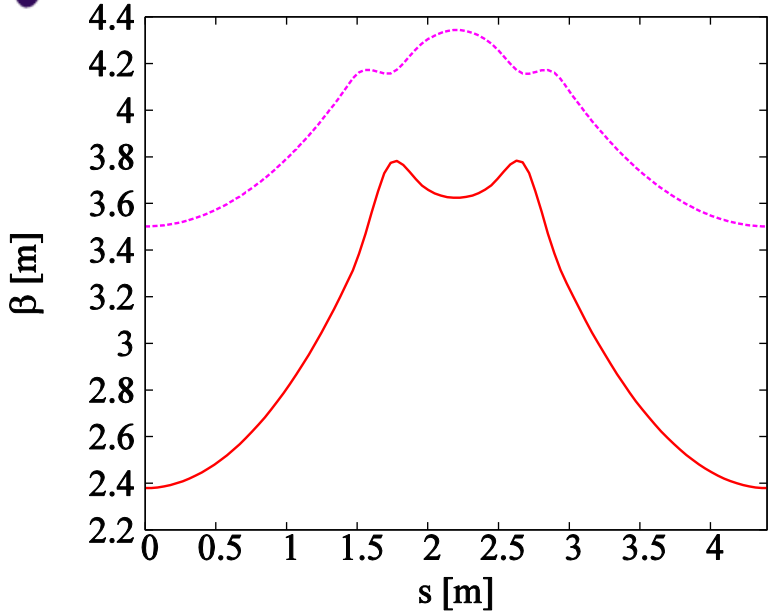
New FDF scaling FFA design

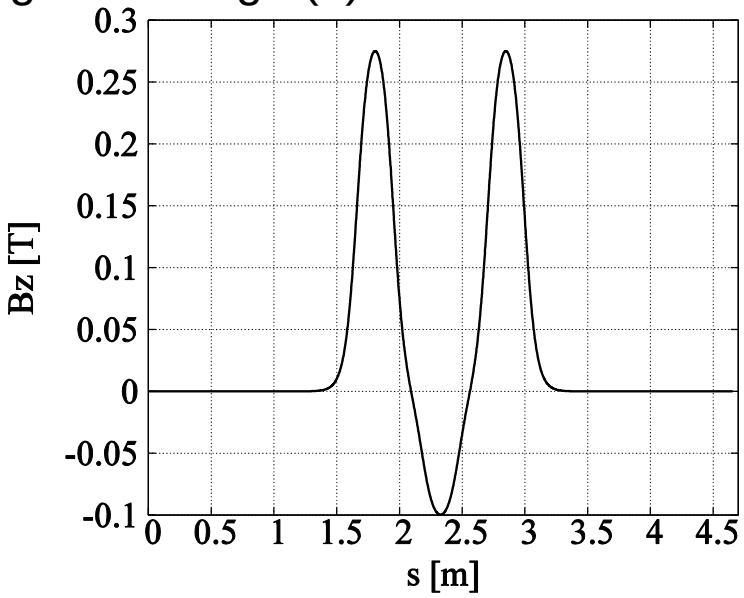


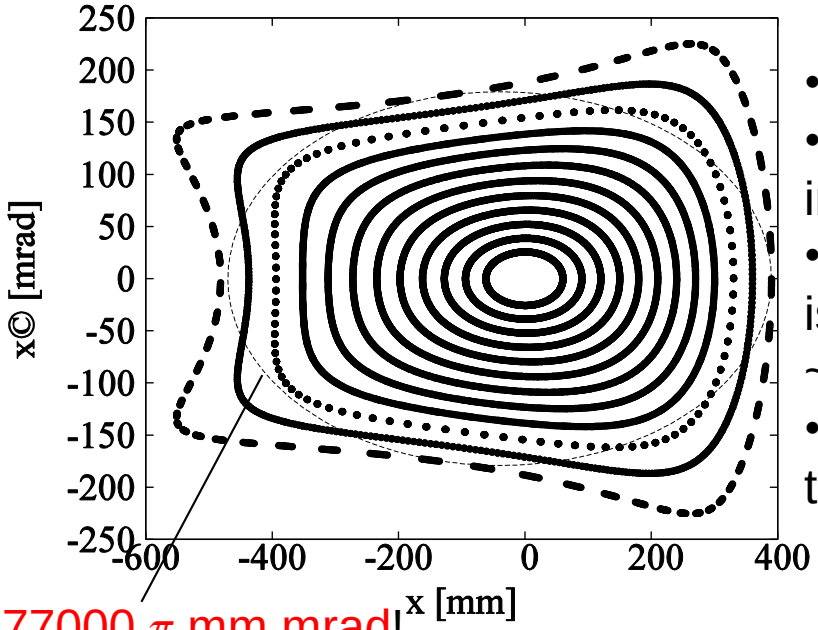
- FDF symmetry motivated by the success of ERIT at KURRI
- 10 cells
- k 4.3
- R_0 7.3 m
- (Q_H, Q_V) (2.45, 1.85)
- Minimal drift length 3m



New FDF scaling FFA design (2)





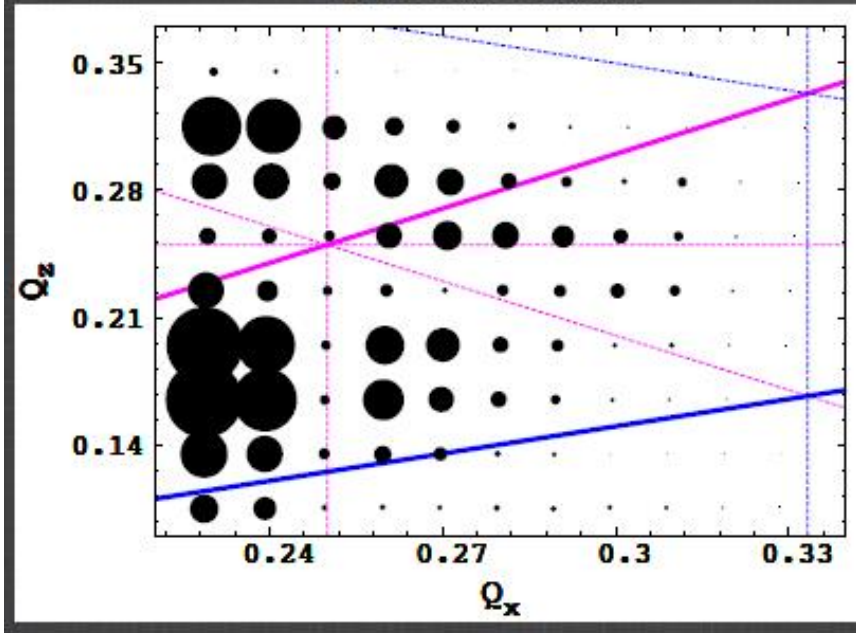


- Enge field fall-off used to study fringe fields
- Enormous horizontal acceptance is achieved in simulations
- Vertical long term stability of ~3000 π.mm.mrad is achieved, however with some optimization ~5000 π.mm.mrad should be stable for a few turns.
- 5000 π.mm.mrad is what we currently aim for due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

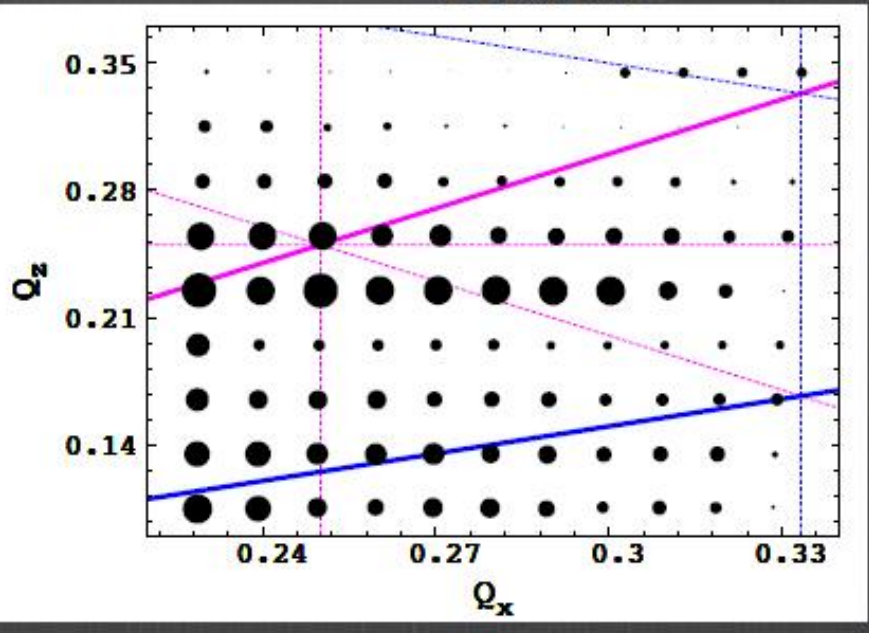
Study of DA for new design

10-cell FDF FFA

Horizontal

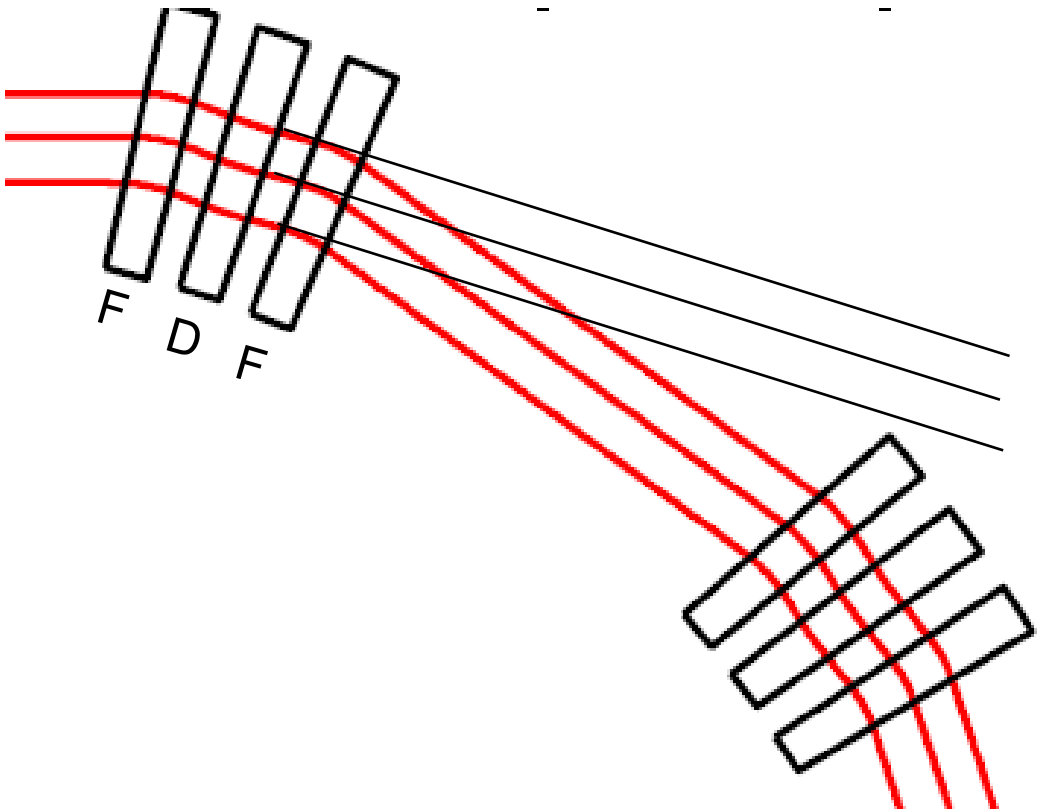


Vertical



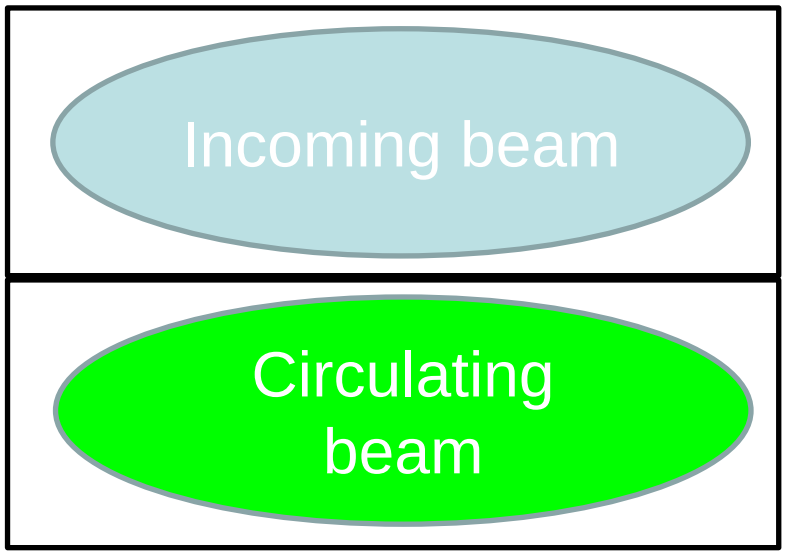
>50/>3 mm.mrad (H/V) achieved.

New injection concept



If one could switch off the F magnet...

Inflector, flux shielding channel



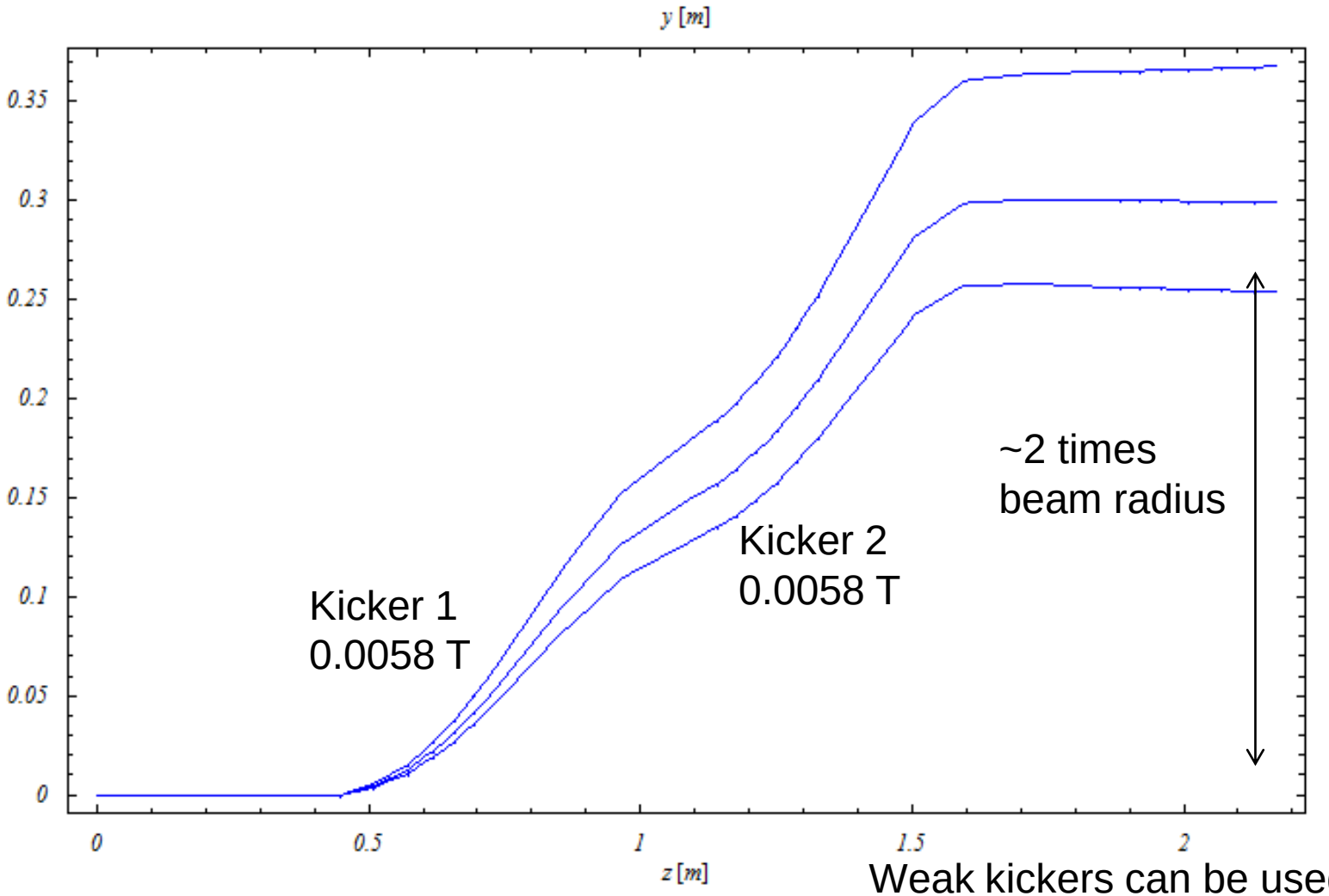
B=0

F magnet
(parallel gap is needed)

- Injected beam can be put on orbit using vertical kicker(s).
- It requires a special septum superimposed with the main focusing FFA magnet (extrapolation of the existing concept used in g-2 ring at FNAL).

Vertical injection

Orbit separation with 2 kickers



Weak kickers can be used!

Main challenges at present:

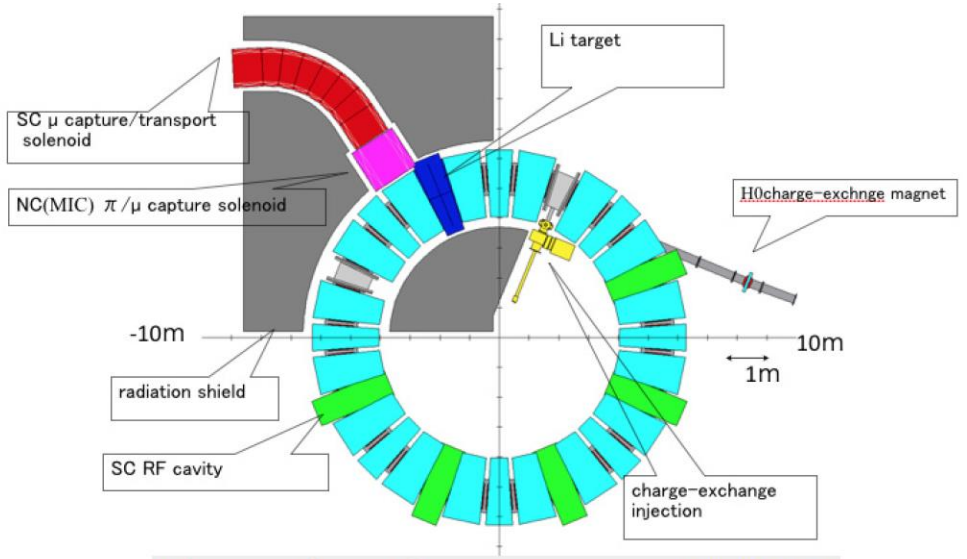
- Matching from the solenoid into FFAG
- Injection/Extraction geometries
- Kicker hardware
- Septum magnet
- RF system
- Beam dynamics in FFAG -> we believe we have now improved the ring design.

Further questions

- Can we increase vertical acceptance?
  - Ring vertical DA needs to be improved
  - Injection would be even more difficult (kicker of ~0.12T – 20 times stronger than assumed presently)
  - Can we use ring with insertions (racetrack)?
- Can we use muon cooling to improve beam quality?
  - Small betatron function at the absorber position would be needed!
- Can we benefit from novel developments on muon sources (see Muon Collider workshop in Padova, July 2018)

MERIT – novel muon source

- MERIT muon production concept (Yoshi Mori, KURNS)
- Extend vertical aperture
  - Splitting coils further
  - Modify pole-tip profile
  - Very large DA
- Accelerate to top energy and hold
  - Wedge shaped liquid Li target
  - Serpentine (fixed frequency) acceleration
- Yields very long beam lifetime

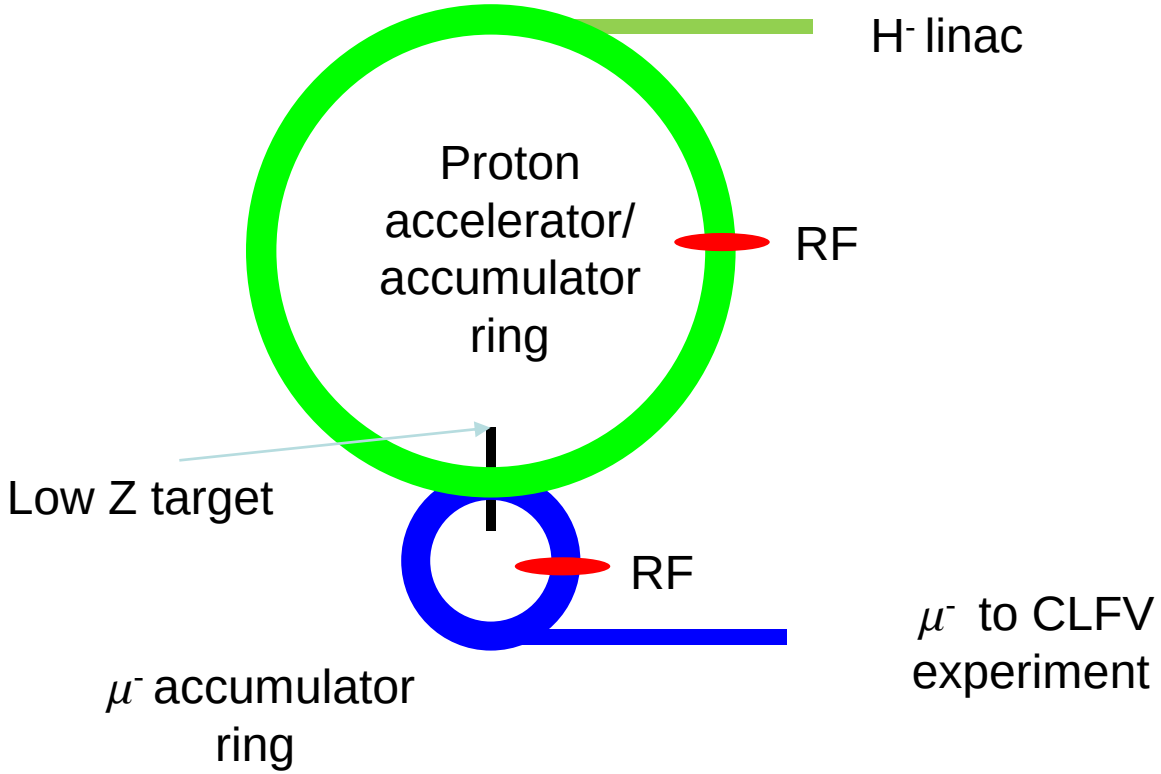


Ring configuration	H−FFAG
Energy Range [MeV]	500-800
Magnetic Rigidity [Tm]	3.633-4.877
Lattice	FDF
Average Radius [m]	5.044-5.5
Magnetic Field [T]: F	1.96-2.41
Magnetic Field [T]: D	1.71-2.11
Number of Cells	8
Field Index	2.43
Cell Tune: H	0.212
Cell Tune: V	0.18
Horiz. Beta Function [m]	2.5
Vert. Beta Function [m]	2.8
Dispersion function [m]	1.5

Y.Mori et al., “Intense Negative Muon Facility with MERIT ring for Nuclear Transmutation”; Proc, 14th Conf. On Muon Spin Rotation,Relaxation and Resonanc(μSR2017), JPS Conf. Proc. 21, 011063(2018). https://journals.jps.jp/doi/book/10.7566/musr2017

Intense Muon Source with Energy Recovery Internal Target (ERIT) Ring Using Deuterium Gas Target, Yoshiharu MORI, Hidefumi OKITA,Yoshihiro ISHI, Yujiro YONEMURA and Hidehiko ARIMA pp.1-9, Vol.77, No.1, September 28, 2017 http://kenkyo.eng.kyushu-u.ac.jp/memoirs-eng/top.php

MERIT-type source for muon-to-electron conversion experiment



- The H^- source could be CW or pulsed. Max theoretical muon repetition rate ~0.6 MHz.
- Concept could also be applicable for a Muon Collider (C. Rogers, Muon Collider workshop in Padova)

Conclusions

• Vertical injection is preferred due to the presence of horizontal dispersion in the ring.

• Concept of the inflector effectively “switching off” one of the magnets followed by vertical kickers offers a potential solution for injection.

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

- ❑ In particular further improvements in the vertical acceptance could be beneficial

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

•Novel ideas in generating muon beams may open new horizons.

Additional material

Background rejection and sensitivity

Background rejection by PRISM

(1) Long muon flight length (eliminating pions in a muon beam)
(2) Narrow muon beam energy spread
(3) Muon beam energy selection
(4) Beam extinction at muons

Rough Estimation on Experimental Sensitivity

- x(1/2) from reduced beam acceptance from solenoid to FFAG
- x3 from removing detection time window (no pion)
- x3 from pion capture improvement
- x20 from 56 kW→1MW

$O(10^{13})$ stopped μ^-/sec for O(1) MW protons