nuSTORM: design of FFAG-based storage ring

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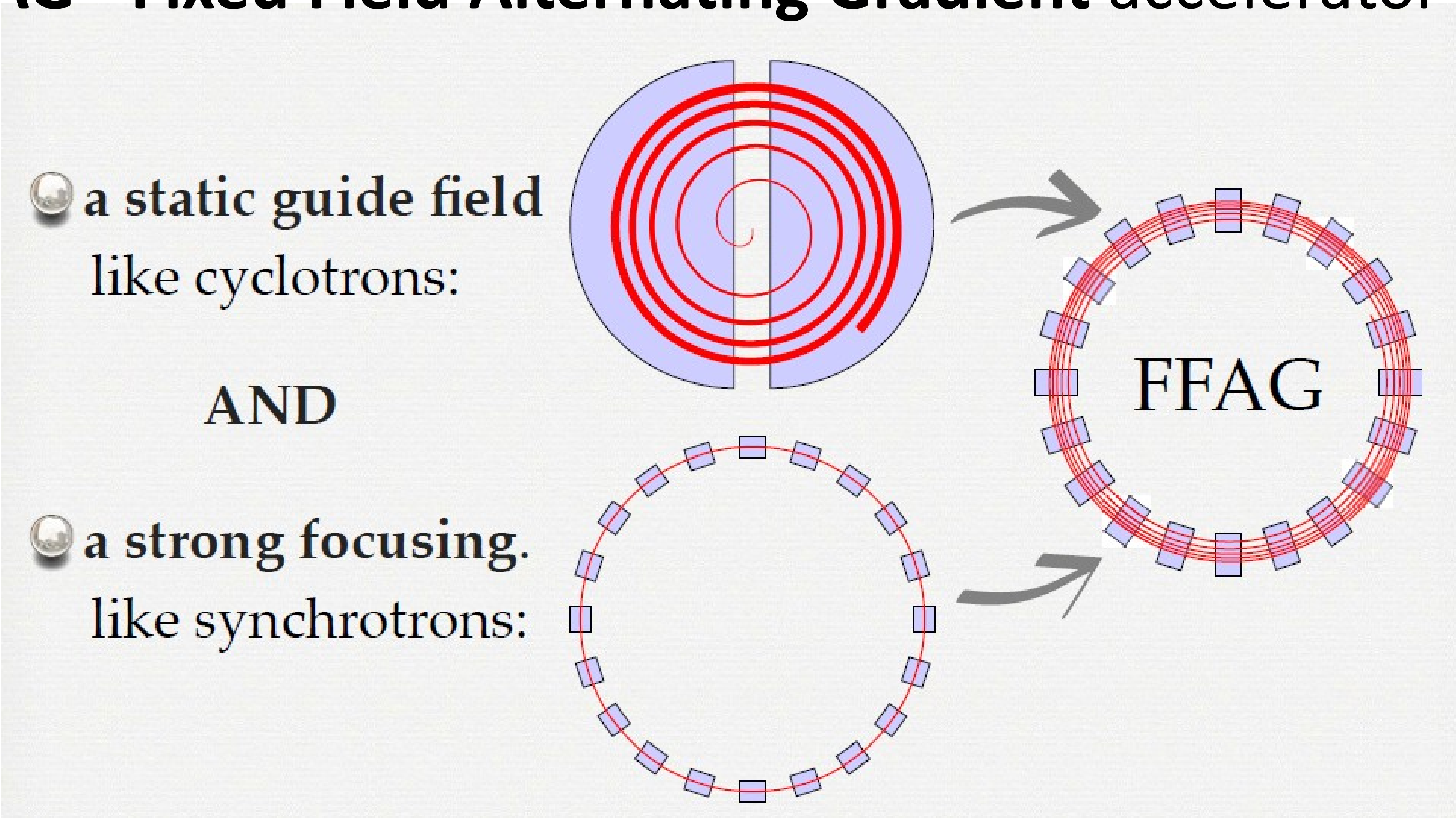
IC 16/02/17

Outline

- Introduction to FFAG accelerators
- Advanced FFAG concept
- Triplet FFAG design for nuSTORM
- Quadruplet FFAG design for nuSTORM
- Issues with FFAG design
- Summary and future plans

Introduction

FFAG - Fixed Field Alternating Gradient accelerator



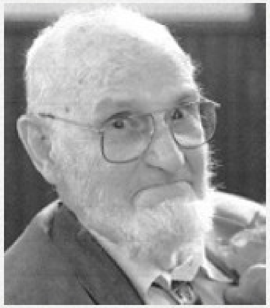
Birth of the FFAGs

FFAGs invented in the 1950s independently

- in Japan (T. Ohkawa, 1953),

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

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



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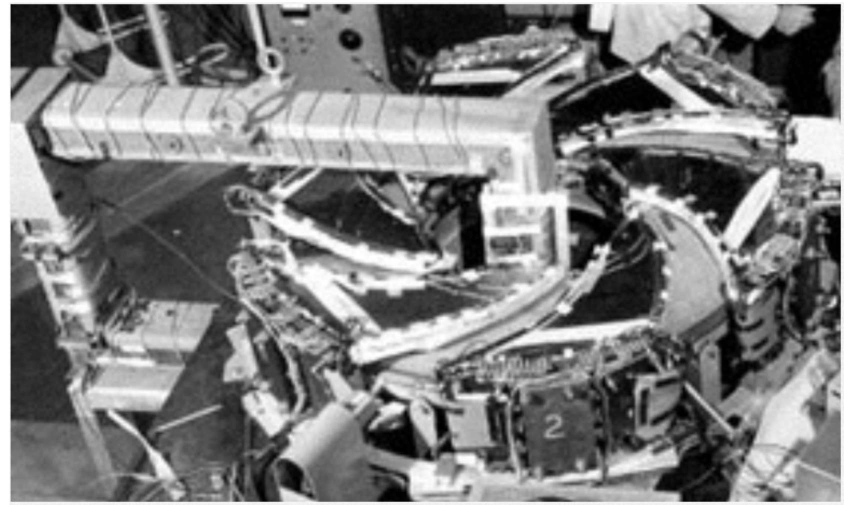
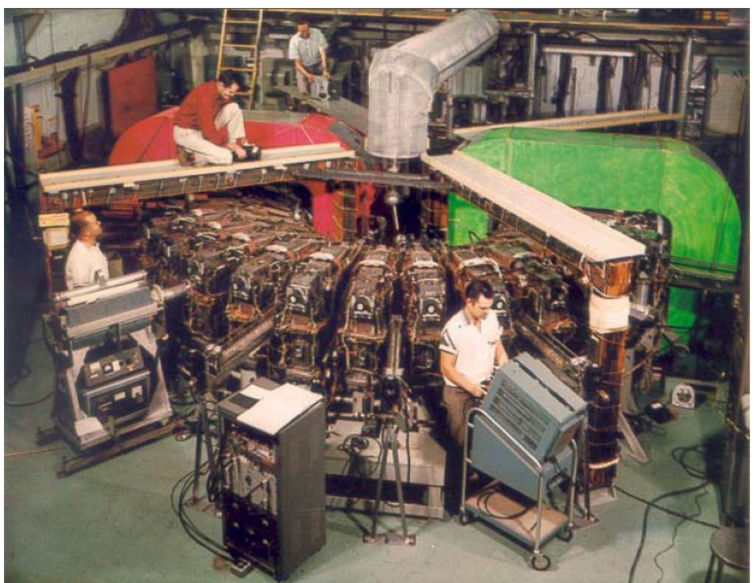
Early developments - MURA

Mark II at MURA



Spiral sector ring



Two beam accelerator

- MURA (Midwestern Universities Research Association) built first prototypes
- All were electron models and used betatron core for acceleration

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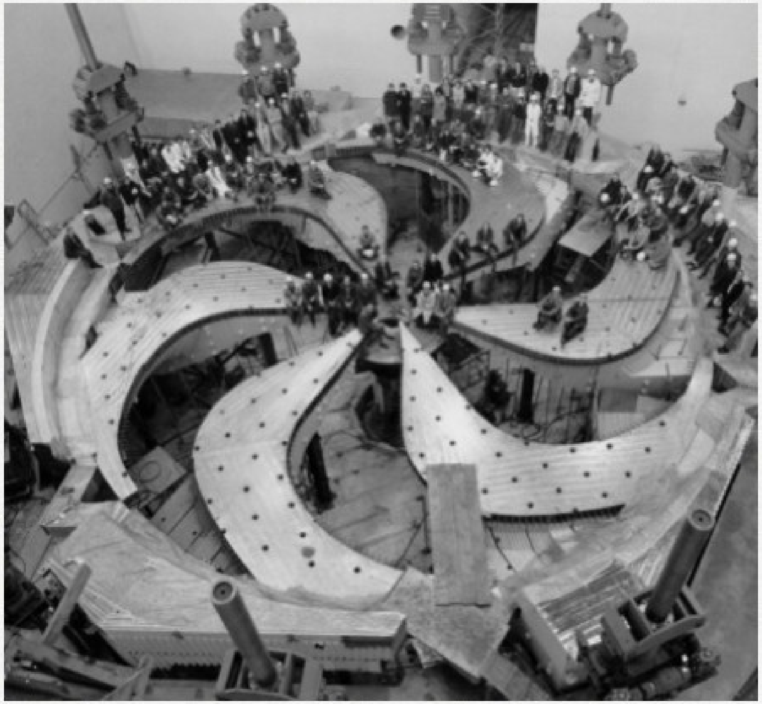
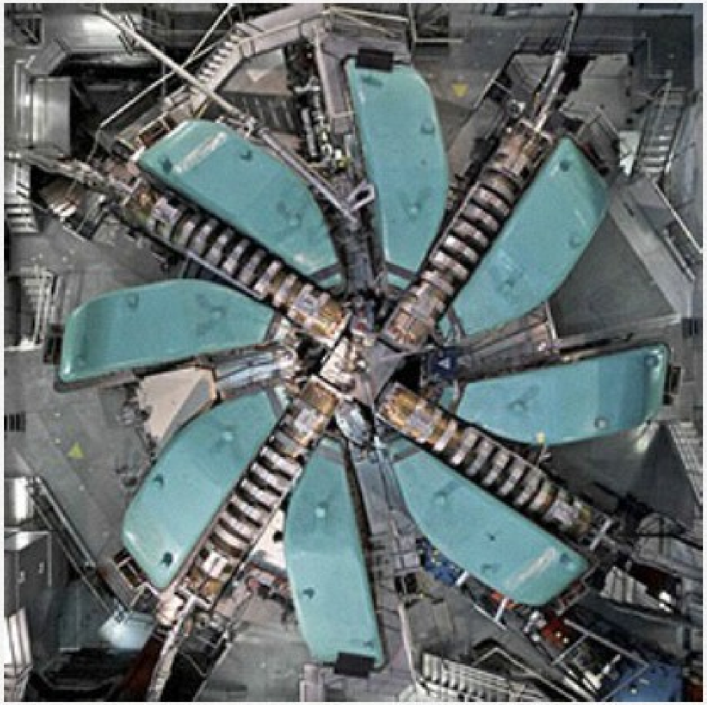
FFAG cyclotrons

Cyclotrons benefitted from spiral sectors to go to higher energies.



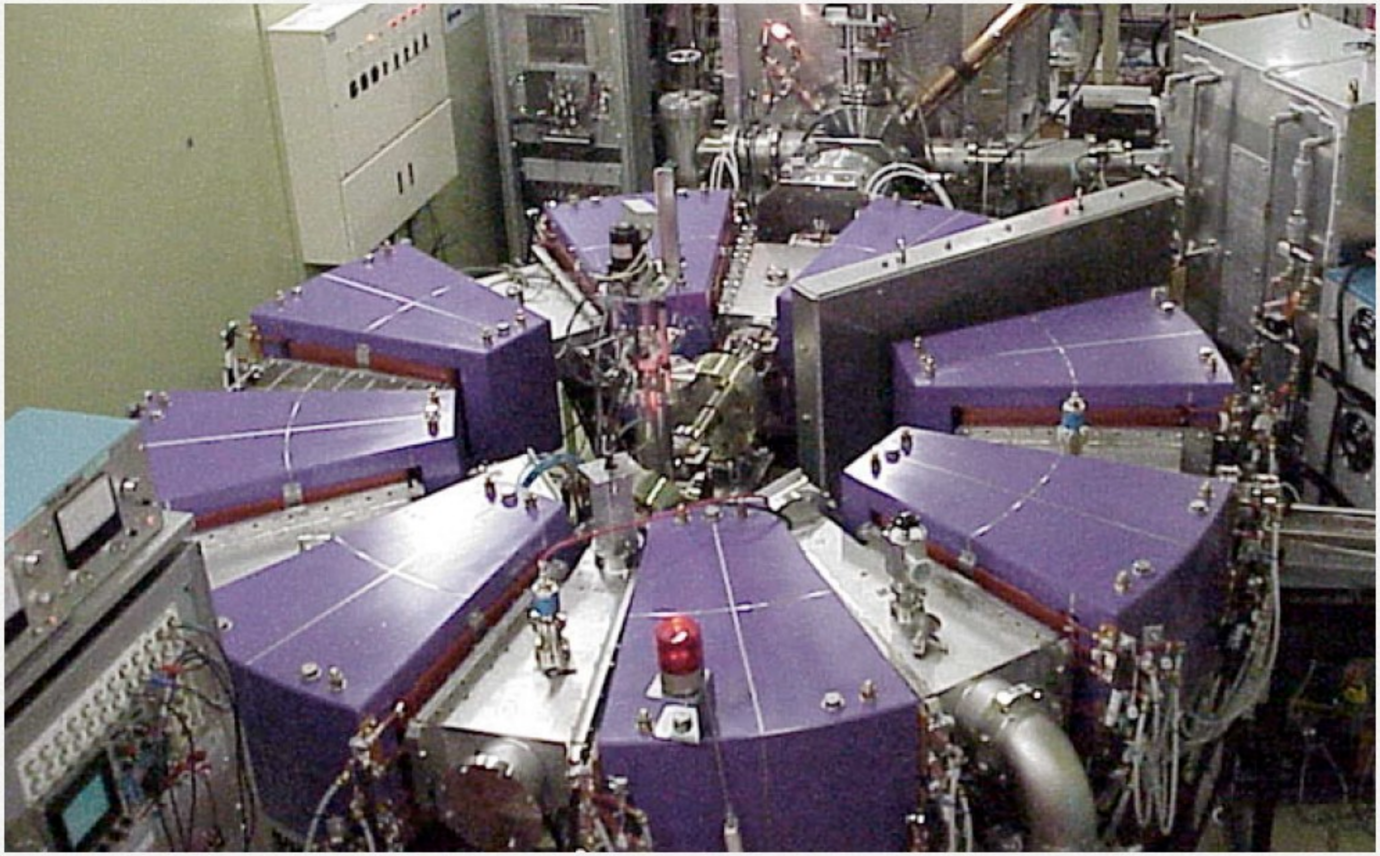
TRIUMF cyclotron
520 MeV H^-



PSI cyclotron
590 MeV proton

FFAG synchrotrons

Revival in 2000s. First proton FFAG synchrotron (POP) in KEK, Japan (Y. Mori and his collaborators)



RF cavity was used for acceleration for the first time in the FFAG

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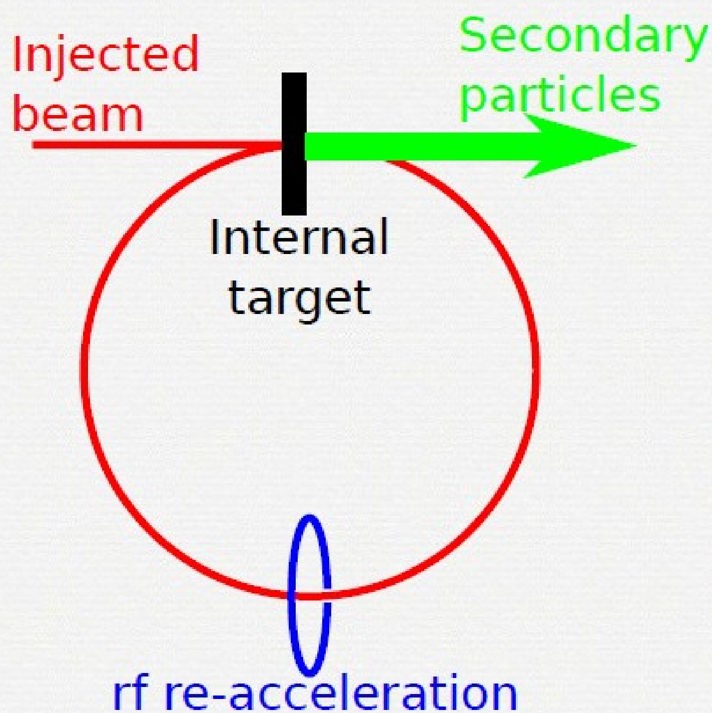
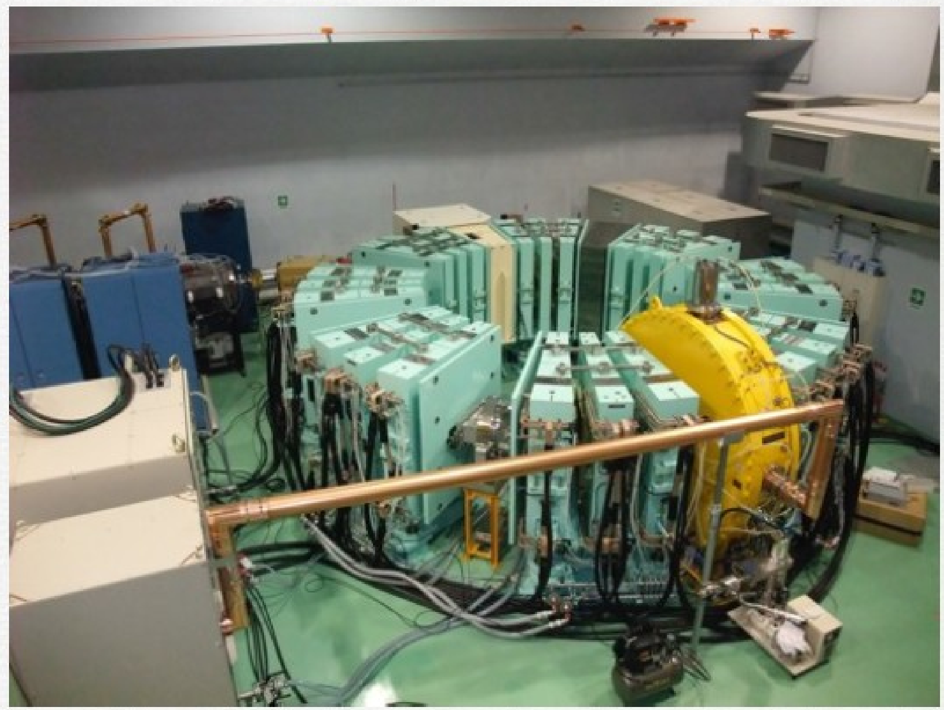
FFAG synchrotrons(2)

FFAG accelerator complex at KURRI
(Kyoto University Research Reactor Institute)

FFAG Storage Ring (1)

ERIT (Energy Recovering Internal Target) for an efficient secondary particle source.





ERIT ring at KURRI

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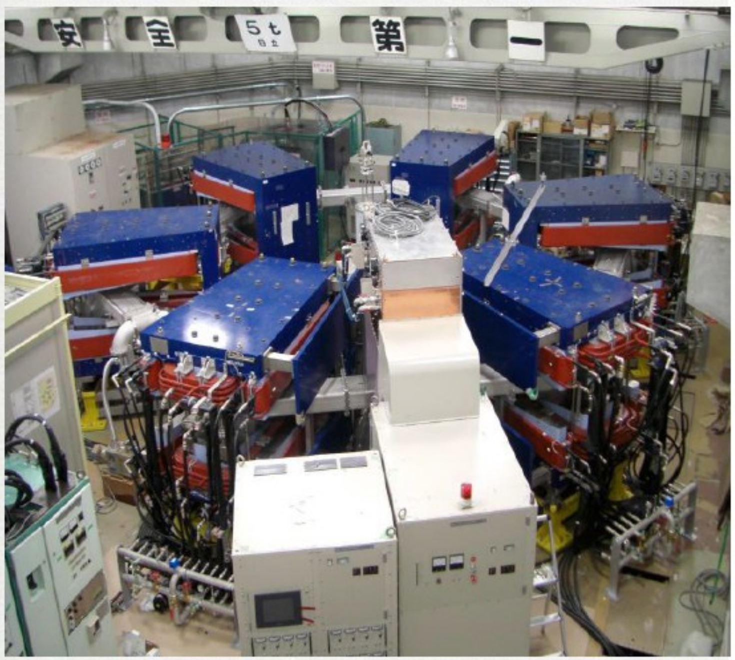
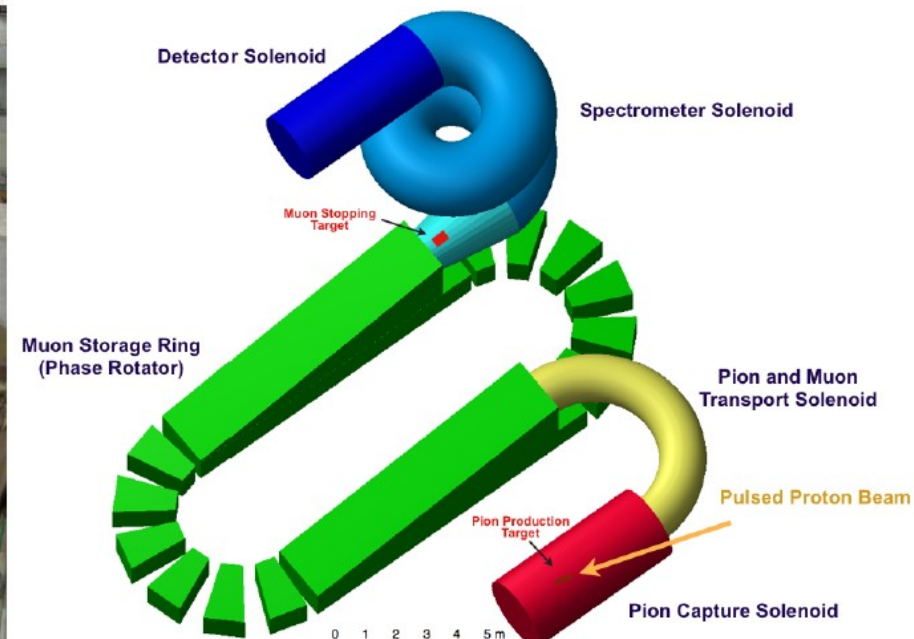
FFAG Storage Ring (2)

PRISM (Phase Rotated Intense Slow Muon source)

Large 6D acceptance for low energy pure muon source





Test PRISM ring, RCNP, Osaka, Japan

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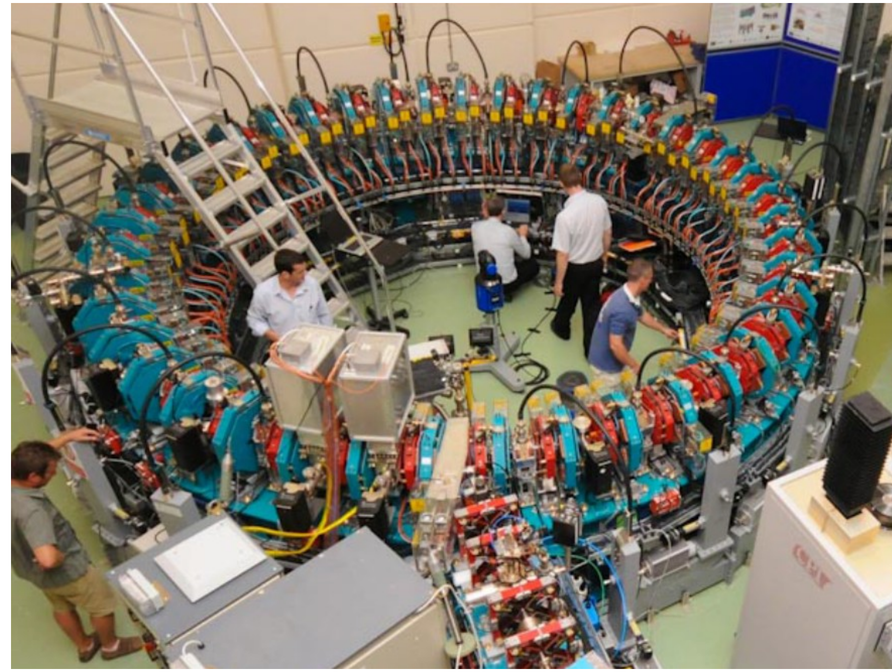
Progress on FFAGs

- EMMA (DL, UK)
- RACCAM (Recherche en ACCélérateurs et Applications Médicales)
- eRHIC FFAG design
- CBETA (recently approved)
- .....

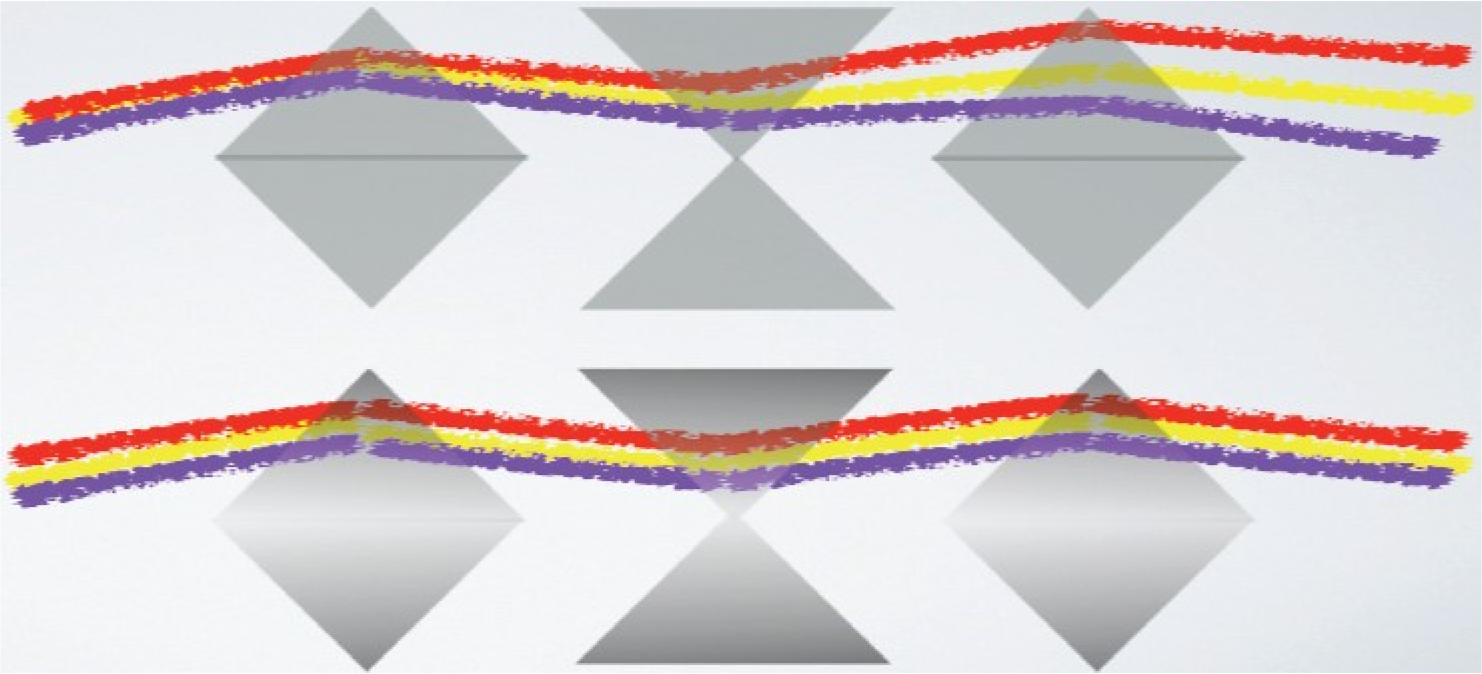


EMMA

RACCAM
spiral magnet

Advantages, zero chromaticity

- FFAGs allows for a natural chromaticity suppression (scaling version).
- This allows to reduce dramatically the chromatic tune spread.



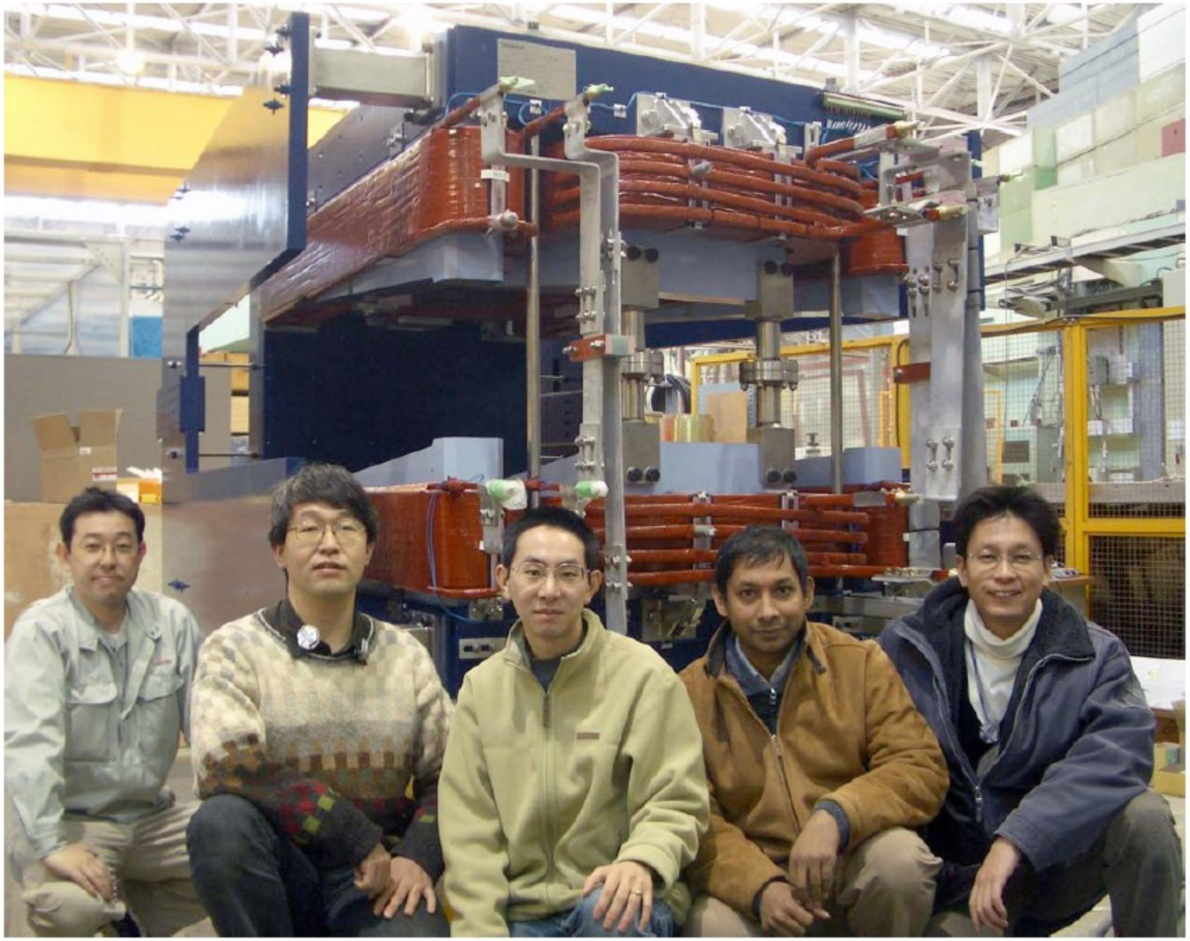
Low beam loss with large momentum spread!

Disadvantages

- Large and difficult to construct magnets
- Small amount of space due to a very packed lattice (for injection/extraction, RF, collimation, etc.)

Magnets

The First PRISM-FFAG Magnet



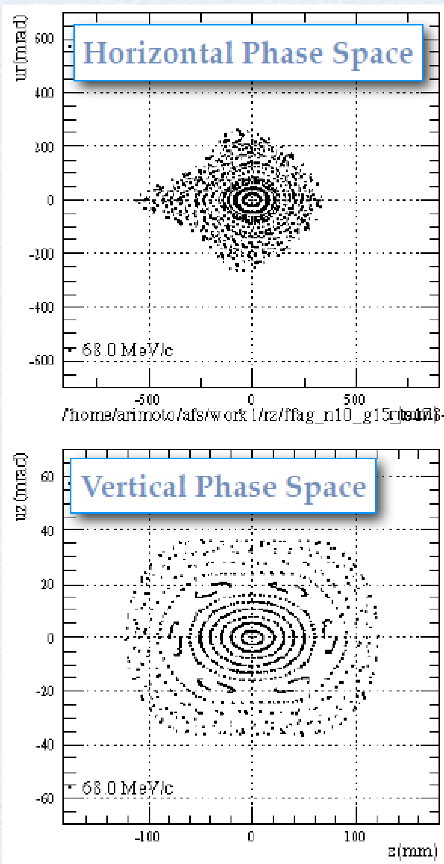
PRISM magnet designed by Osaka University

Very large FFAG magnets were successfully designed and constructed! For SC magnets J-PARC is the closest example.

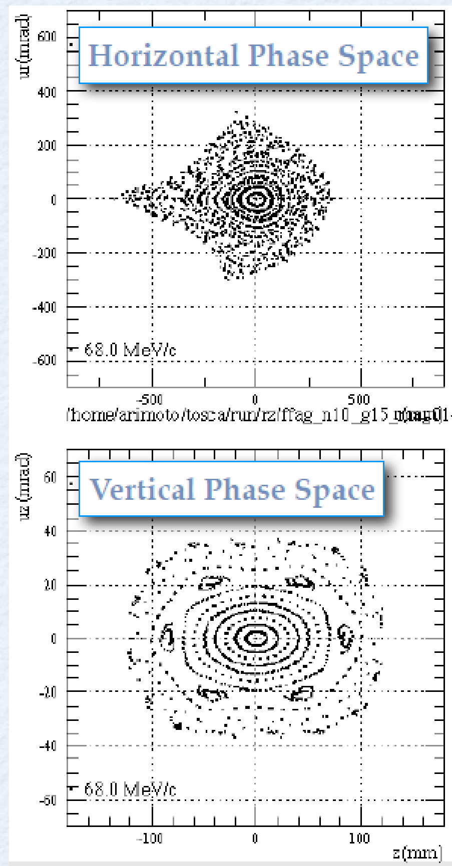
FFAG magnets performance

Field Measurements : Acceptance

PRISM



With TOSCA Map



With Measured Map

- by Geant3
- Both of phase-space distribution is almost same.

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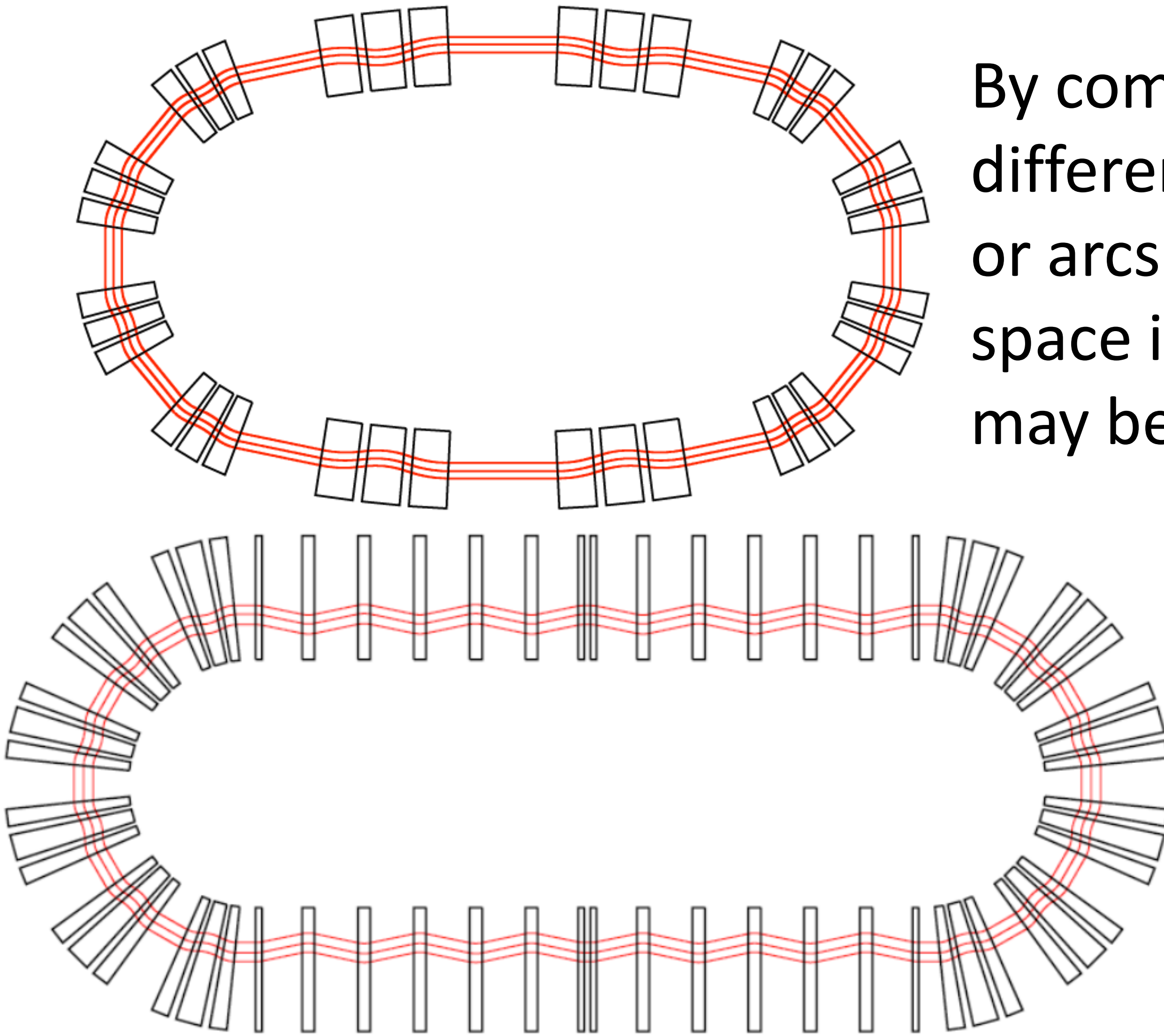
Advanced FFAG



By combining cells with different radius
or arcs with straight cells,
space issue
may be overcome.

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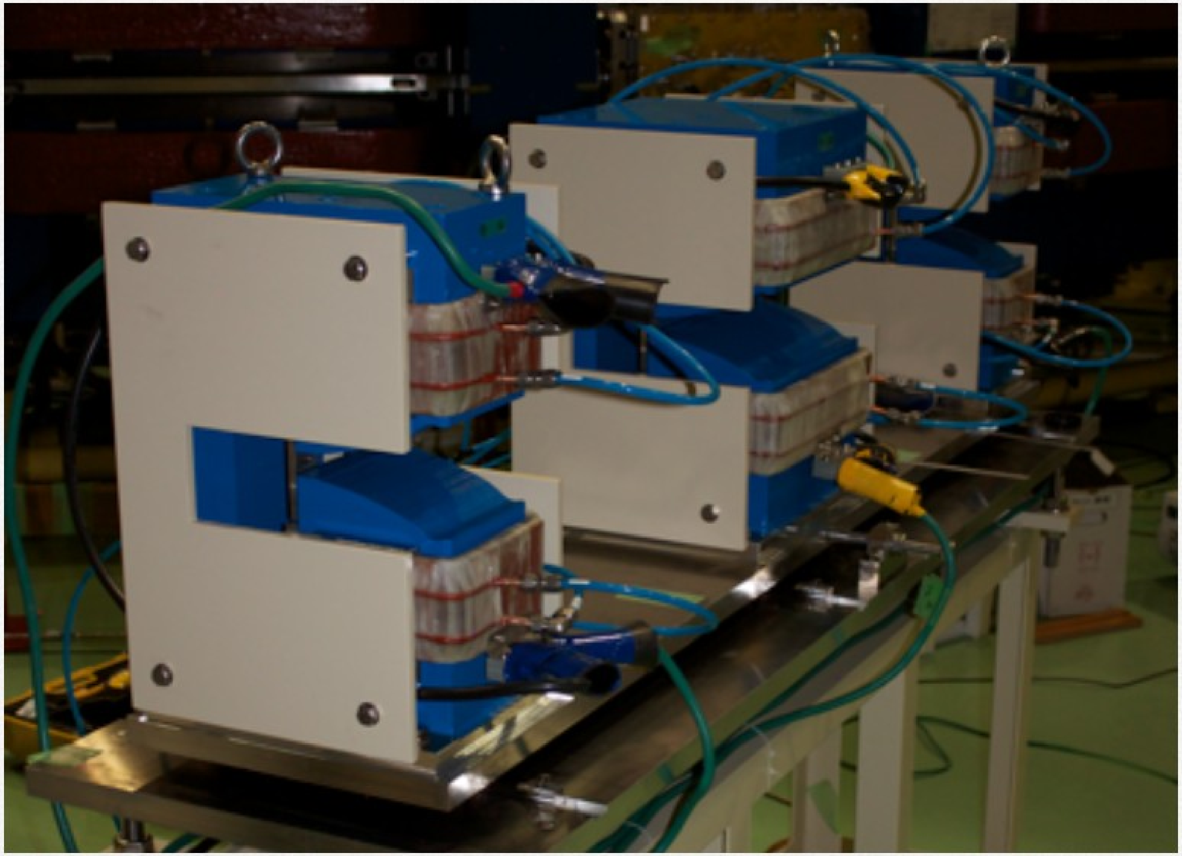
How to make straight cell?

Straight scaling FFAG:

FFAG cell with no overall bend.



J-B. Lagrange's thesis

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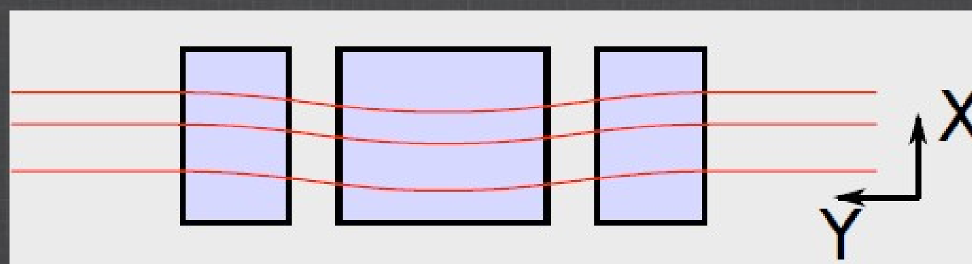
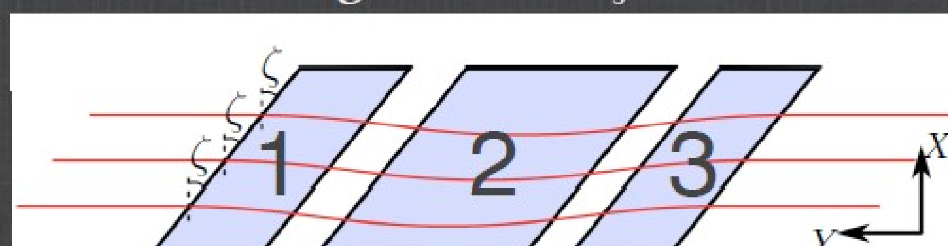
Straight FFAG (principles)

Constant normalized field gradient: $m = \frac{1}{B_y}\frac{dB_y}{dx}$

$$\boxed{B(X,Y) = B_0 e^{m(X-X_0)}\mathcal{F}\left(Y-(X-X_0)\tan\zeta\right)}$$

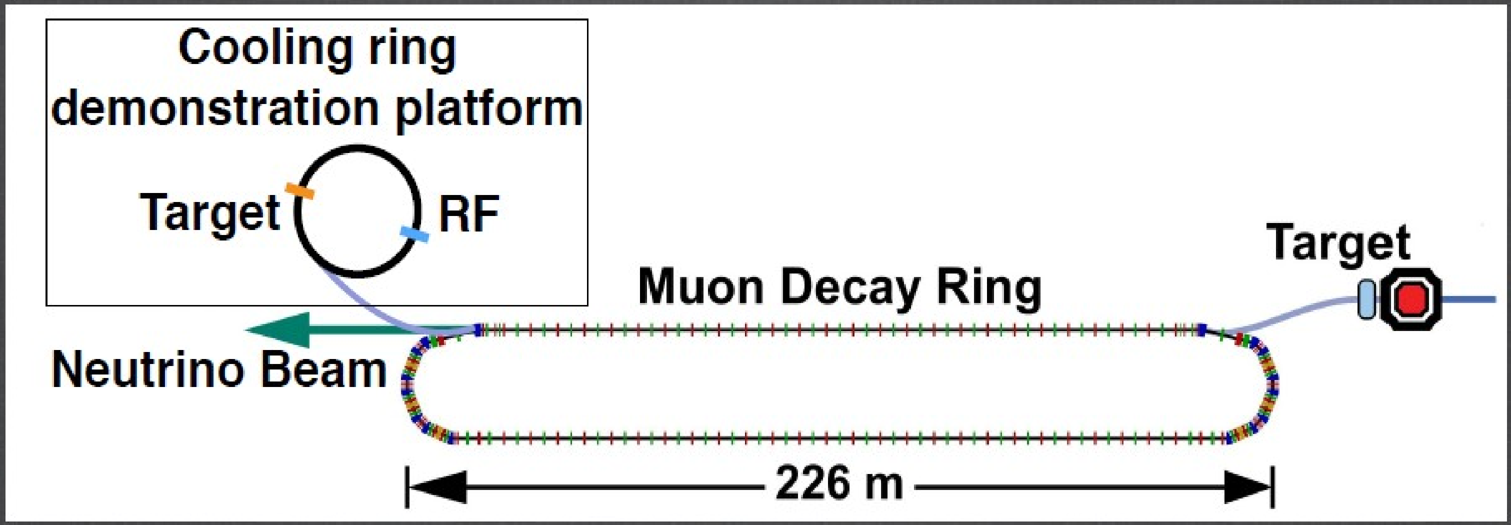


Rectangular case: $\zeta = 0$



Tilted straight case: $\zeta = const.$

nuSTORM Overview



1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
3. Accelerator & Detector technology test bed
   - Potential for intense low energy muon beam
   - Enables μ decay ring R&D (instrumentation) & technology demonstration platform
   - Provides a neutrino Detector Test Facility
   - Test bed for a new type of conventional neutrino beam

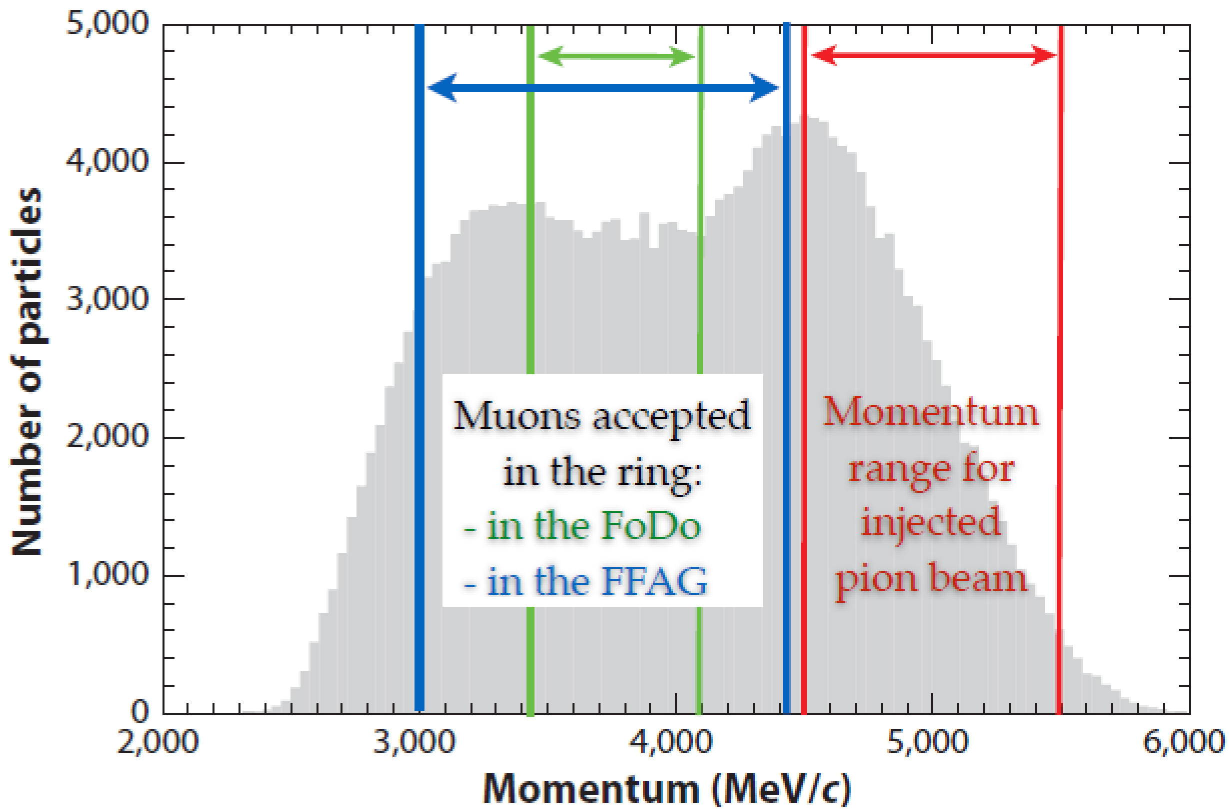
$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

Advantage of FFAG: large momentum acceptance



We have solutions for ±16% (triplet) and ±19% total momentum spread.

νSTORM Racetrack FFAG

Constraints:

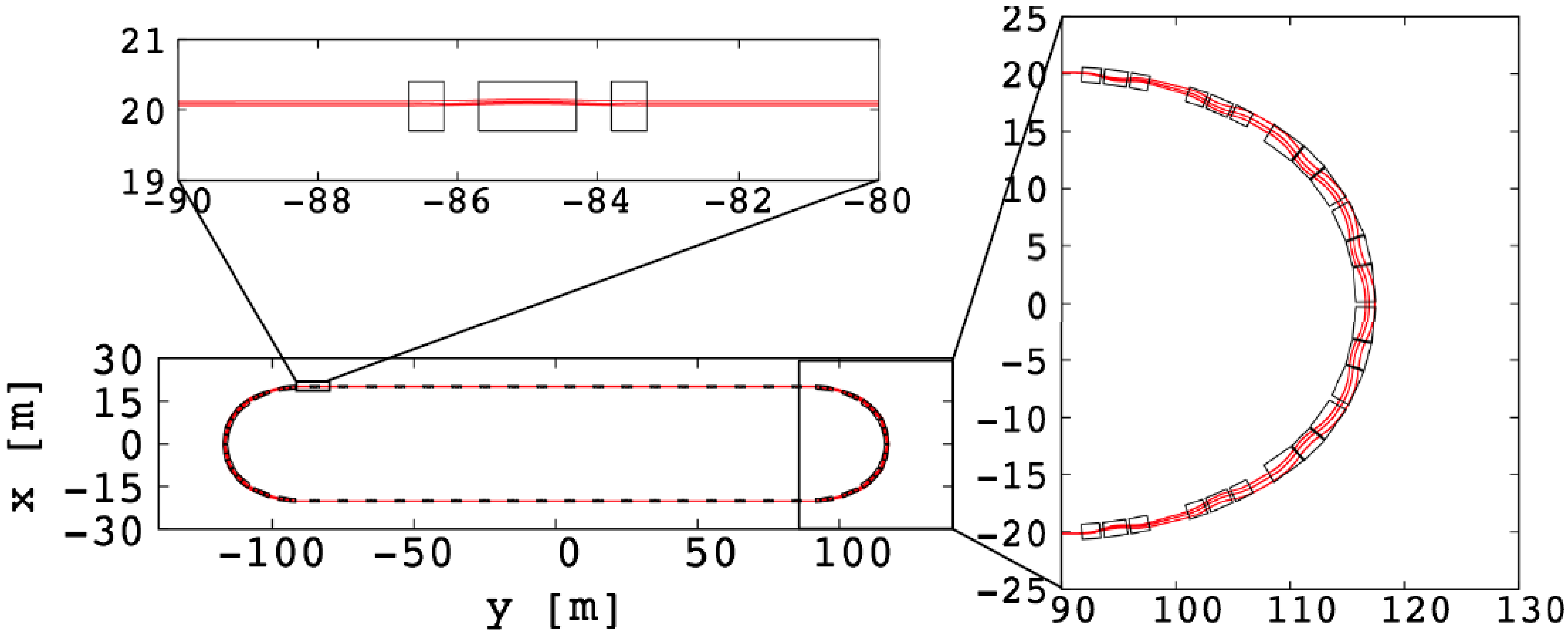
- in the straight part, the **scallop effect** must be as small as possible to collect the maximum number of neutrinos at the far detector.

- **Stochastic injection**: in the dispersion matching section, a drift length of 2.6 m is necessary to install a septum.

- to keep the ring as small as possible, **SC magnets in the arcs** are considered. **Normal conducting magnets in the straight part** are used.

- **large transverse acceptance** is needed in both planes: 1 (2) π mm.rad.

Triplet solution layout (J-B. Lagrange, JP)

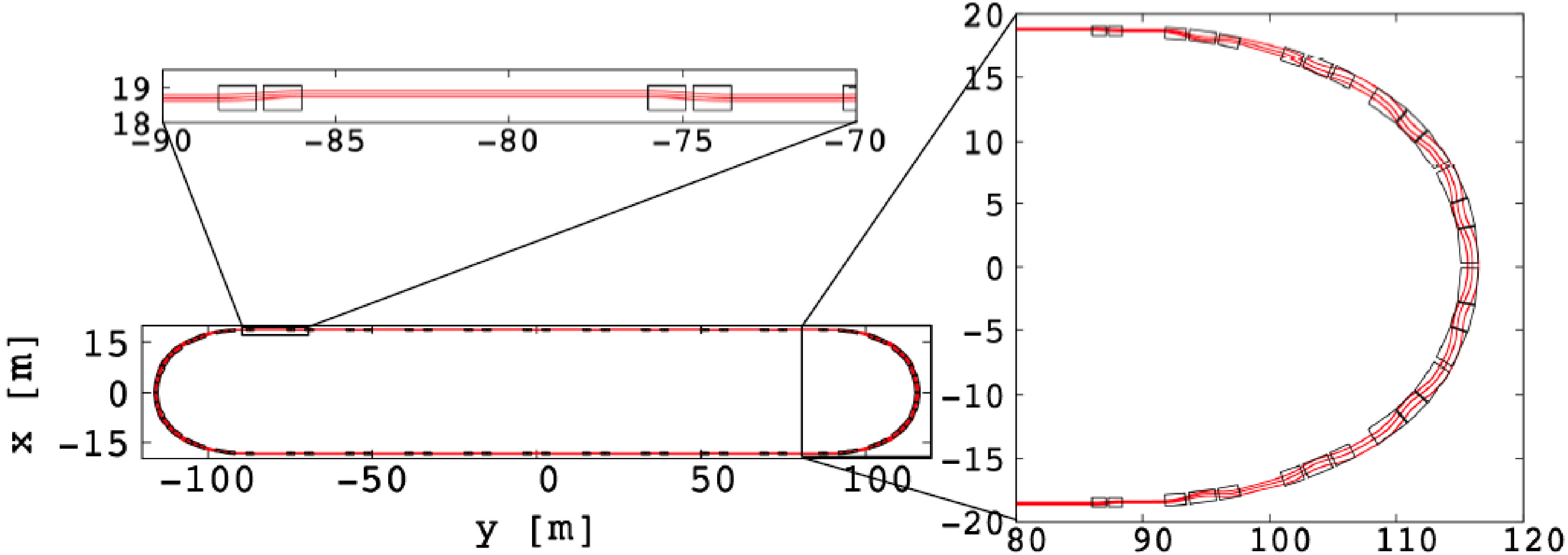


Triplet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.6	36.2	10
Opening angle [deg]	30	15	
k-value/m-value	6.057	26.	5.5 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.5	3.3	1.5
horizontal excursion [m]	1.3	1.1	0.6
Full gap height [m]	0.45	0.45	0.45
Average dispersion /cell [m]	2.5	1.3	0.18
Number of cells /ring	4×2	4×2	36×2

Quadruplet solution (J-B. Lagrange, JP)



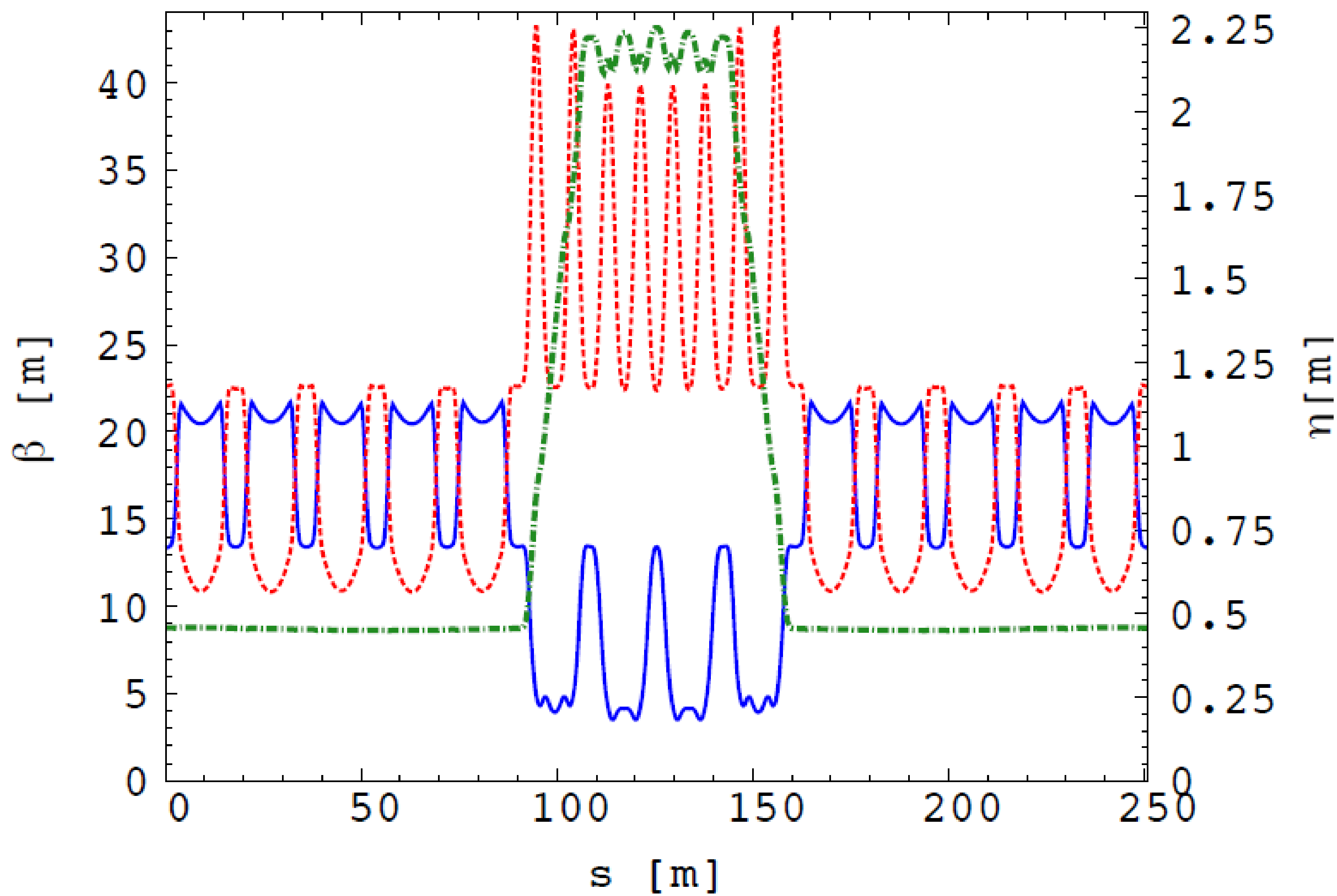
Lattice design includes three cell types (dens arc, matching and straight ones)

Quadruplet Ring FFAG parameters

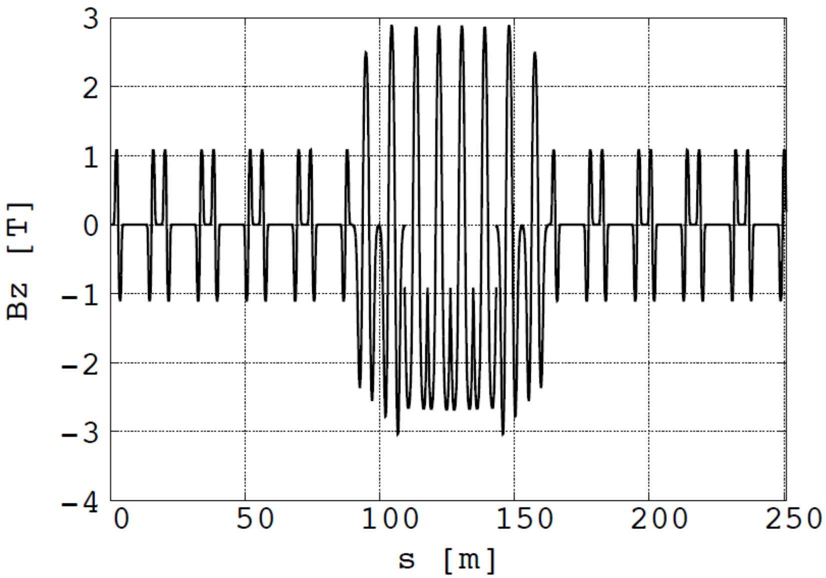
Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFFD
Cell radius/length [m]	15.8	36.1	18
Opening angle [deg]	30	15	
k-value/m-value	6.056	26.	2.2 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.9	3.3	1.7
horizontal excursion [m]	1.4	0.9/1.3	0.7
Full gap height [m]	0.5	0.5	0.25
Average dispersion /cell [m]	2.23	1.34	0.45
Number of cells /ring	4×2	4×2	10×2

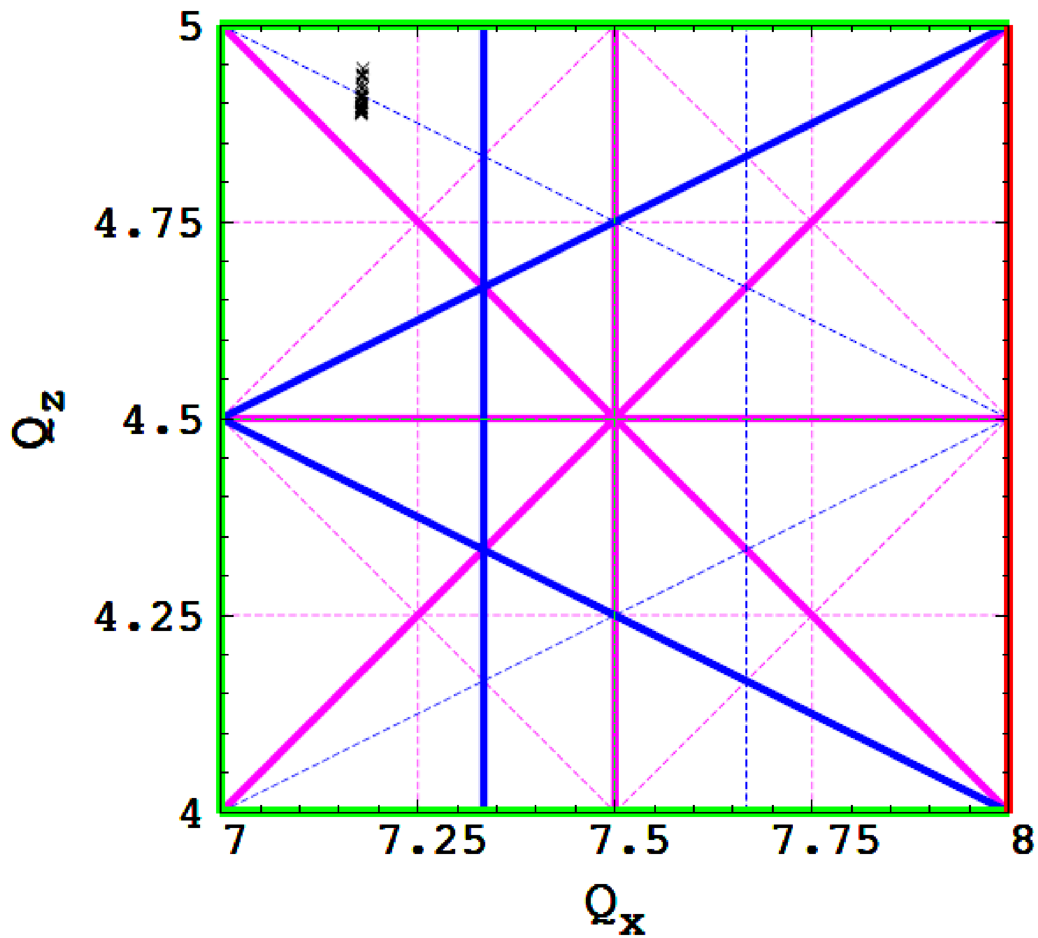
Quadruplet FFAG, lattice functions



Quadruplet, lattice design

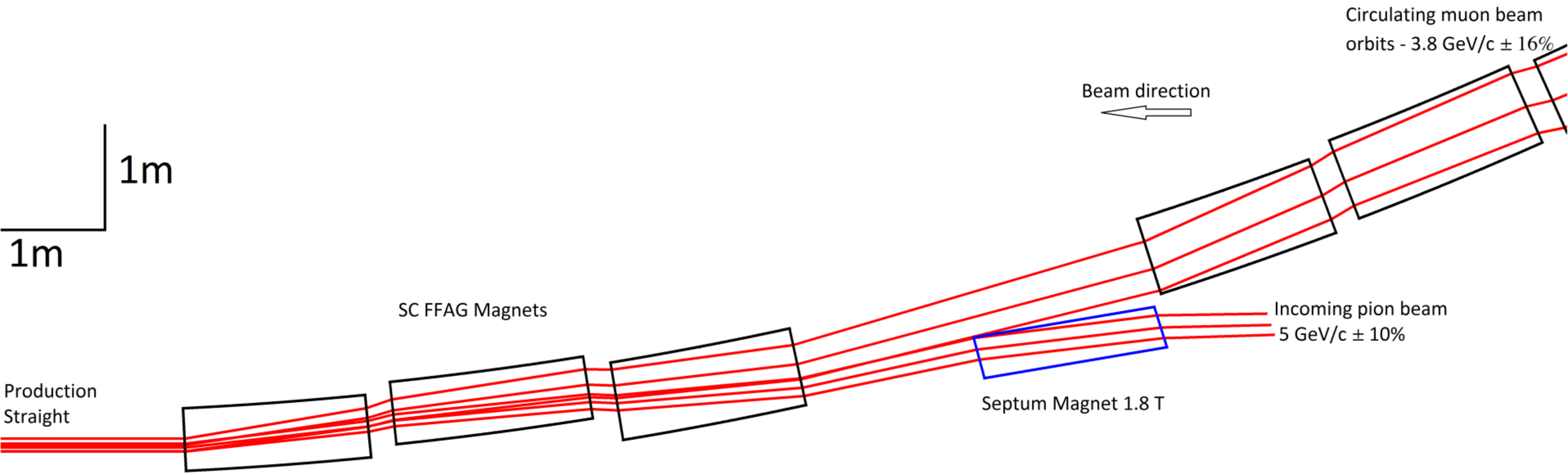


Magnetic field at the top momentum particle



Chromatic tune spread for 19% momentum spread

Injection section



- Injection system will use septum magnet and NO kicker (stochastic injection)
- Special optics allows to introduce a sufficient straight section length

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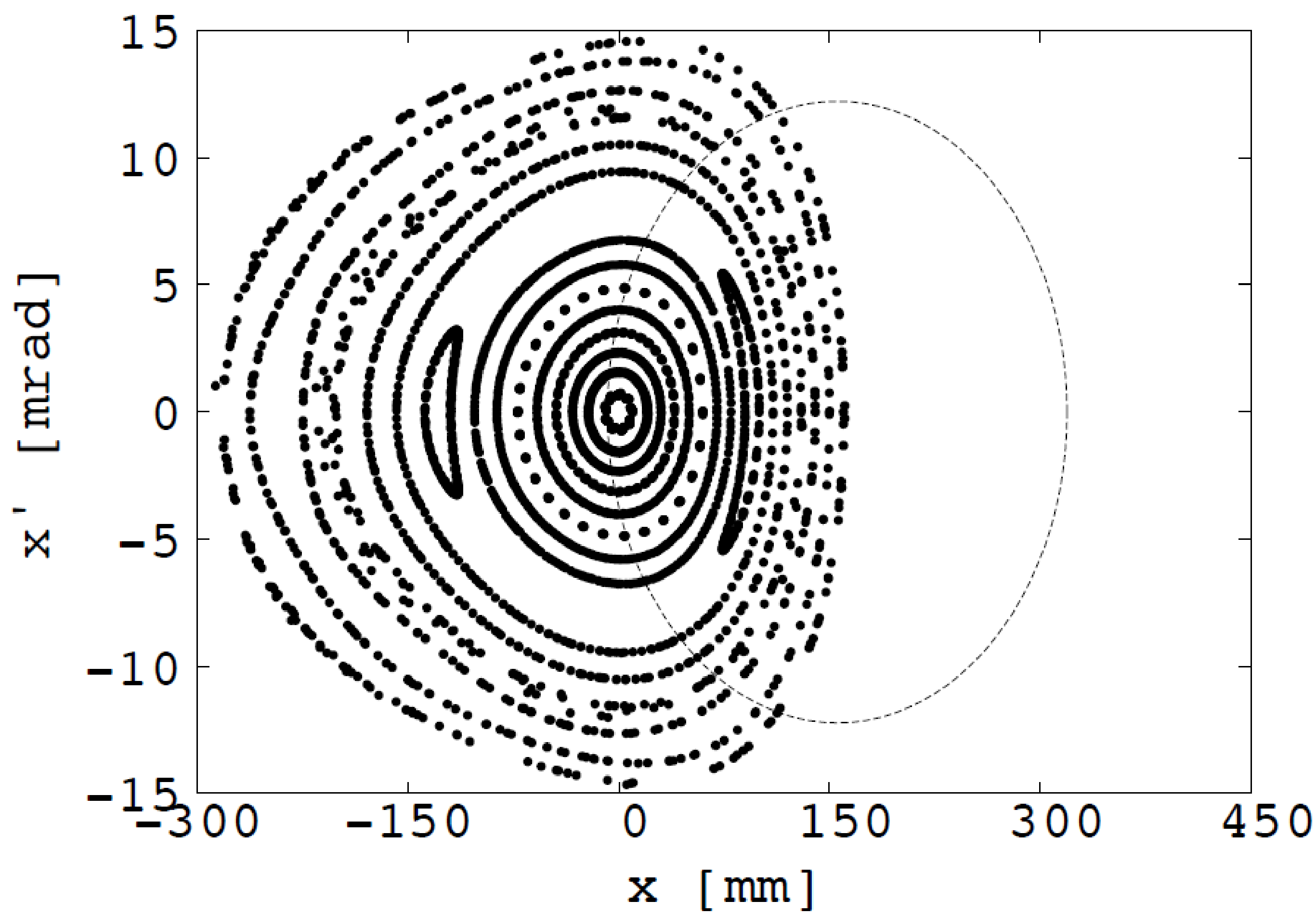
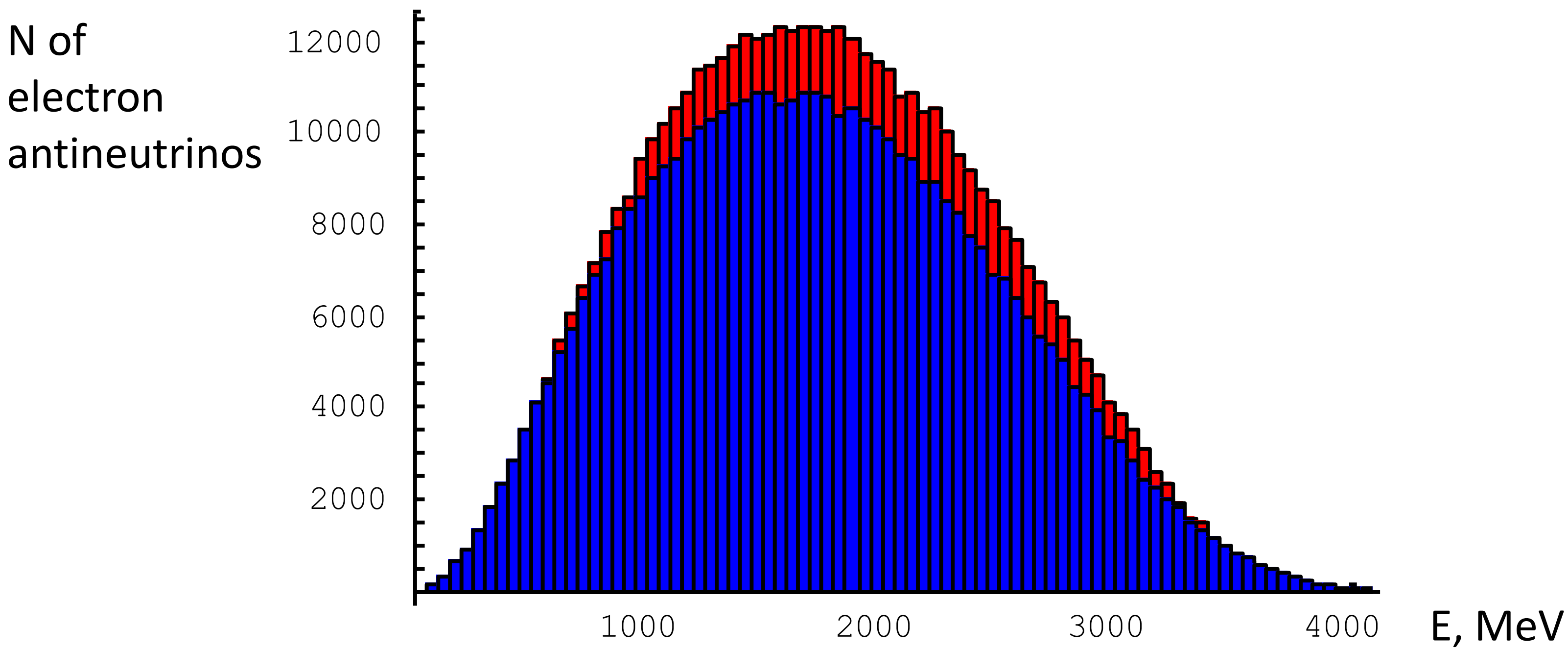
Issues with FFAG design



- Muon beam capture efficiency is reduced due to dispersion present in the decay straight

Issues (2): Effect of scallop on the neutrino spectrum

- Near detector distance: 50m, 5m diameter, simulation for 4000000 stored muons



nuSTORM FODO (red) versus triplet FFAG (blue)

Conclusions

- FFAG design allows to substantially increase the ring's momentum acceptance (and so the neutrino flux), while maintaining a very large transverse acceptance (see the next talk by S. Tygier)
- Modular FFAG design by combining straight FFAG cells with a very compact circular FFAG arcs has been successfully accomplished allowing for a sufficient space for injection. While doing so the zero-chromaticity can be maintained.
- Matching between different optical modules is possible
  - Automatic design toolkit was created.

Future plans

- The design needs to be revisited focusing on the goals of scattering experiment(s)
  - Energy (range) needs to be redefined
- Further improvement into the design should be investigated:
  - Compact Arc
  - Accommodation of zero dispersion and no scallop section (Hybrid design)
- Further details concerning the injection and magnet systems need to be studied.
- Error study needs to be performed.