FFAGs for High Intensity Accumulator

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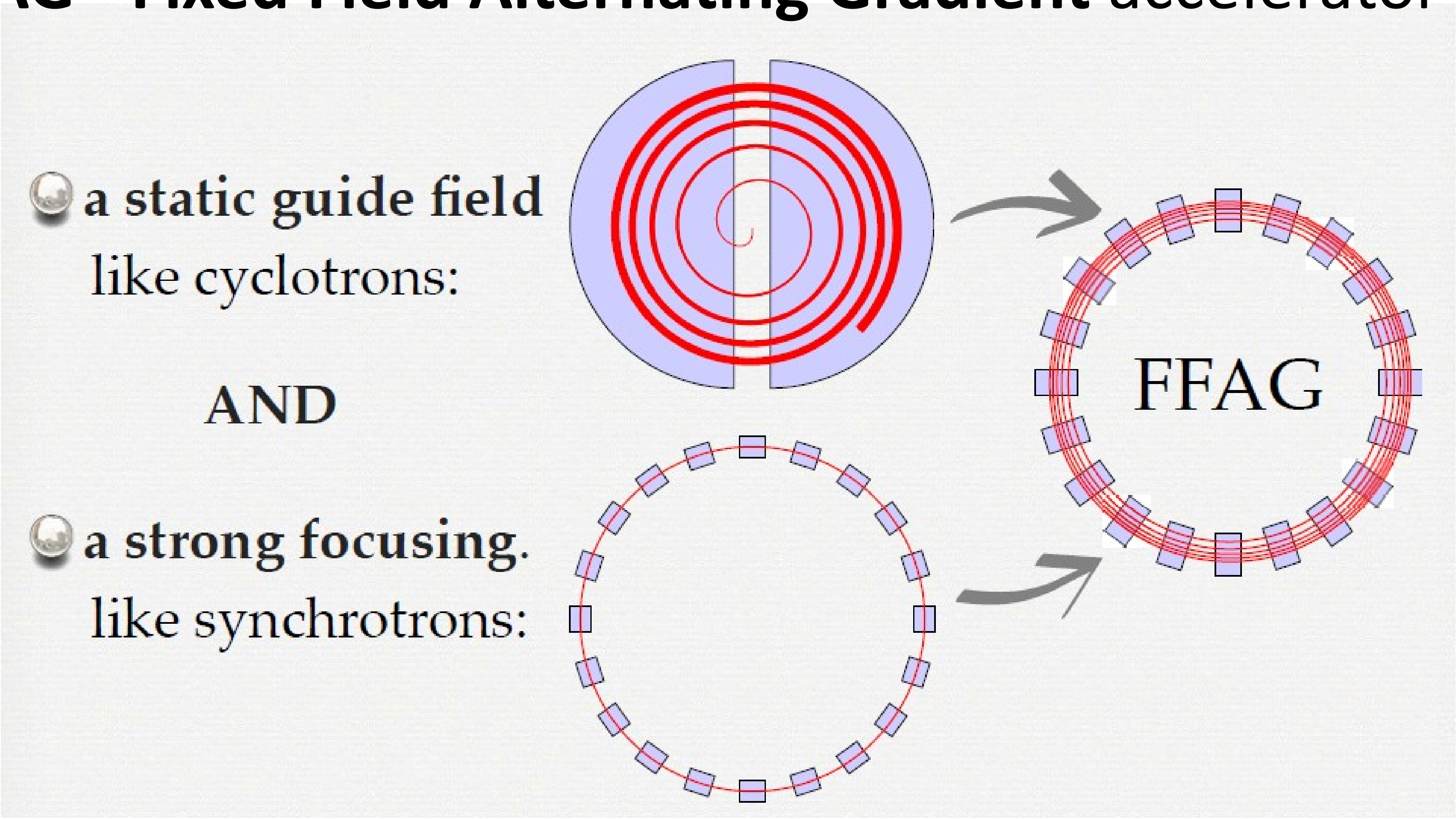
Outline

- Introduction
- FFAG storage rings
- Advantages and disadvantages
- Advanced FFAG concept
- nuSTORM FFAG design
- nuPIL
- Summary

Introduction

FFAG - Fixed Field Alternating Gradient accelerator



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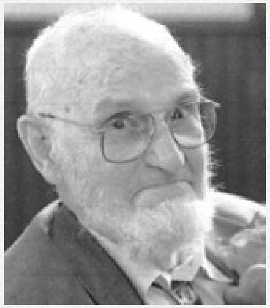
Birth of the FFAGs

FFAGs invented in the 1950s independently

- in Japan (T. Ohkawa, 1953),

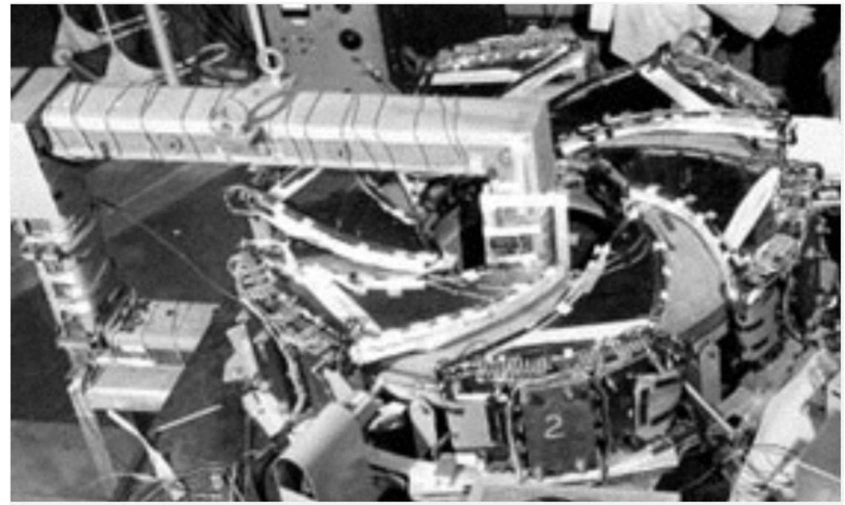
- in the USSR (A. Kolomensky, 1956),

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

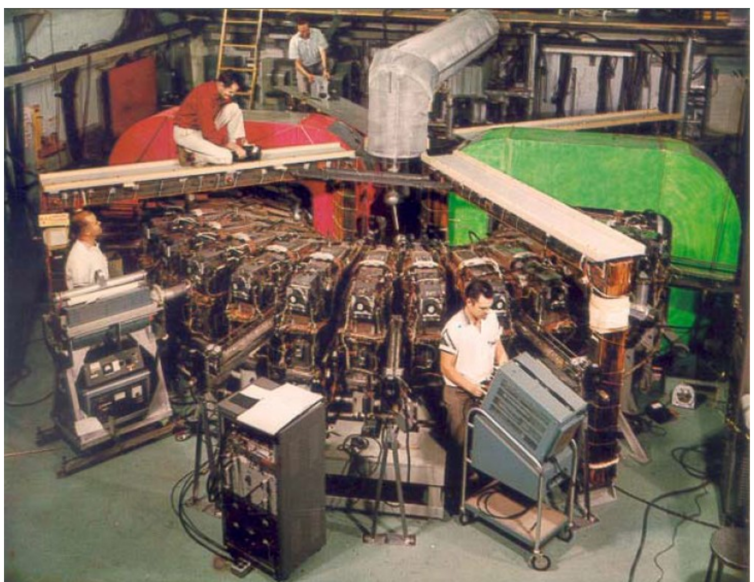


Early developments - MURA

Mark II at MURA



Spiral sector ring



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

Two beam accelerator

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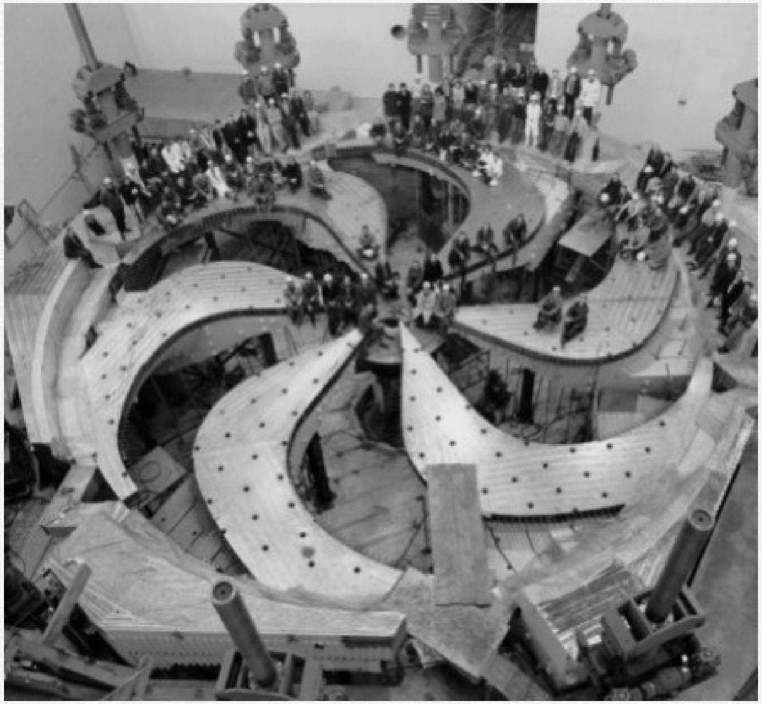
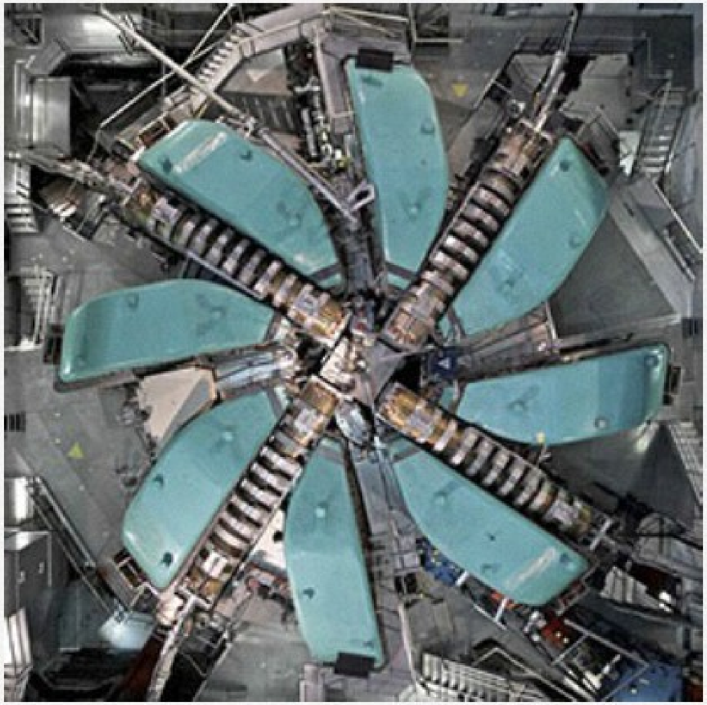
FFAG cyclotrons

Cyclotrons benefitted from spiral sectors to go to higher energies.



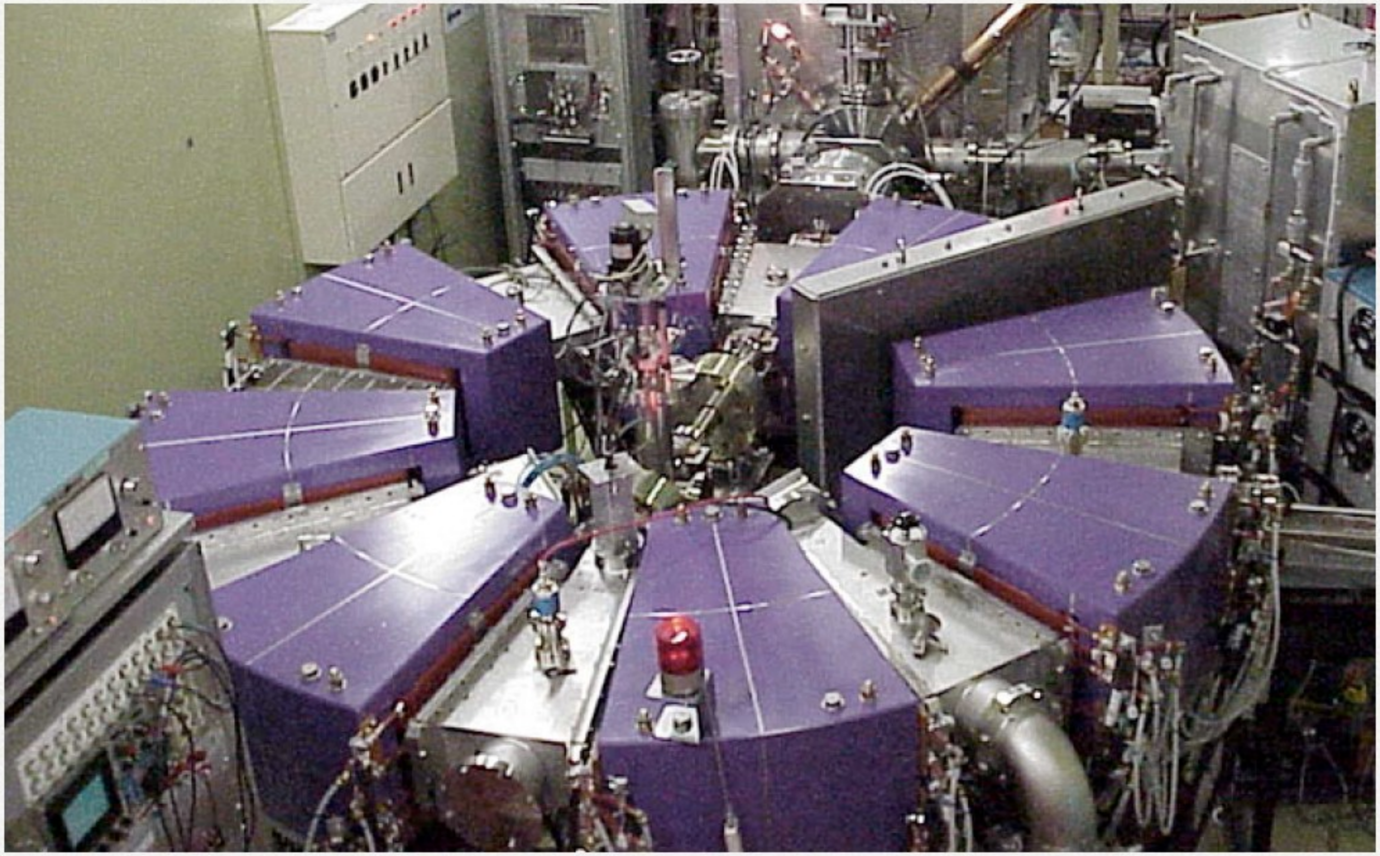
TRIUMF cyclotron
520 MeV H-



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)

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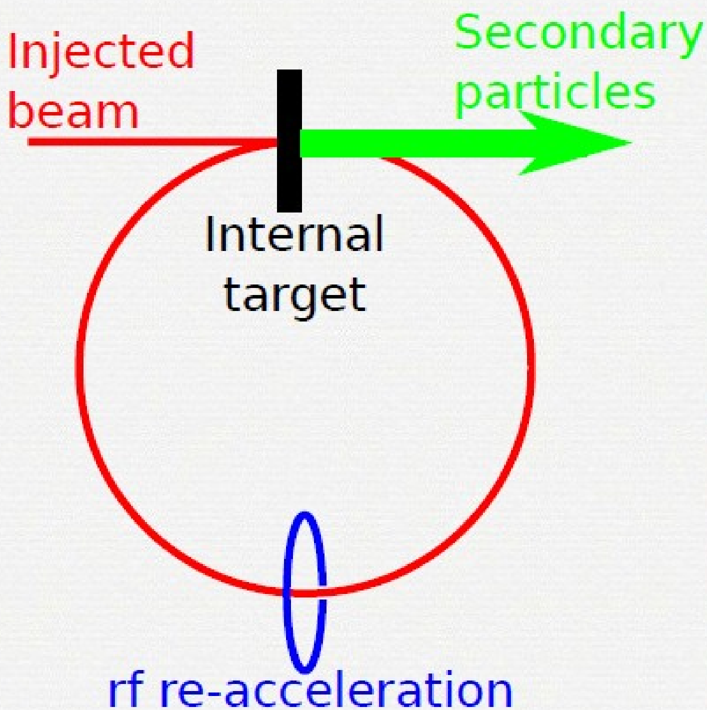
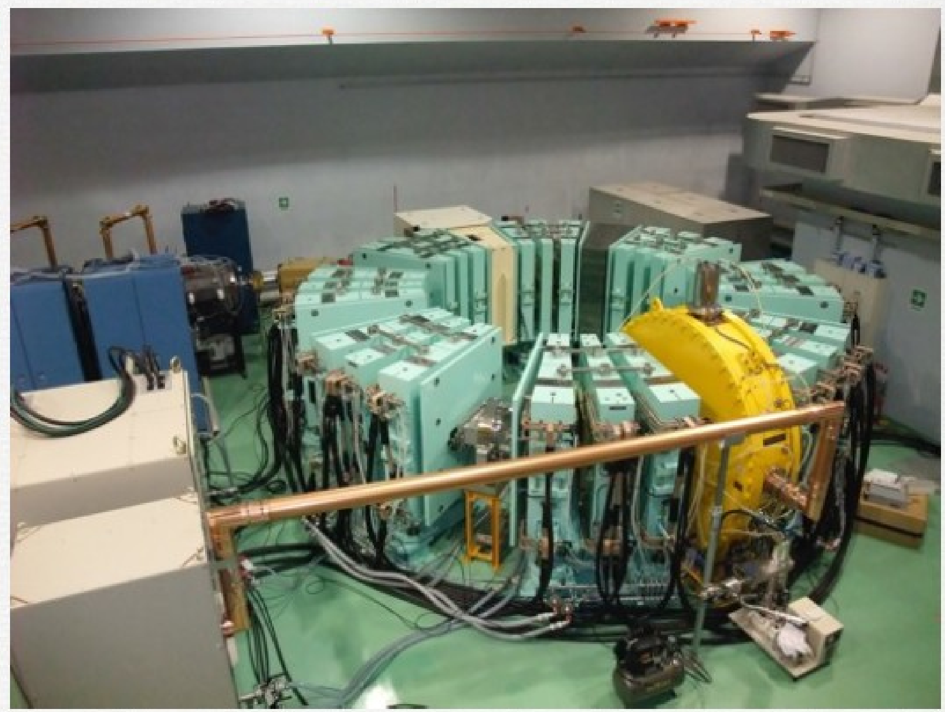
FFAG Storage Ring (1)

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



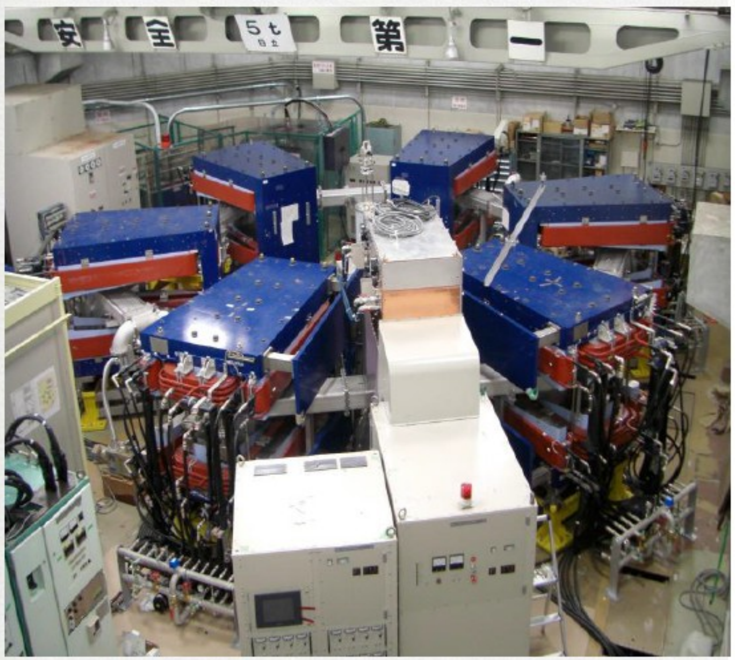


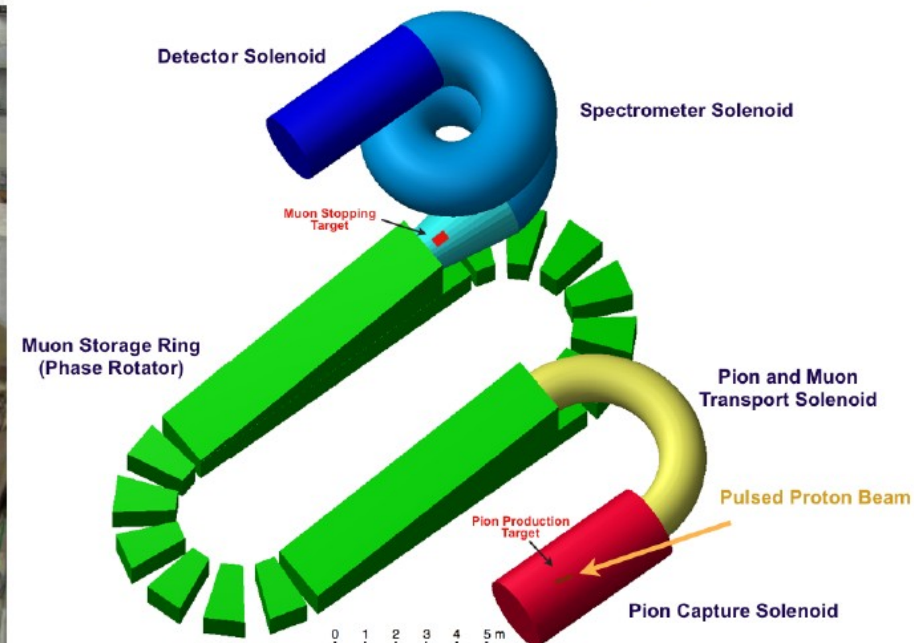
ERIT ring at KURRI

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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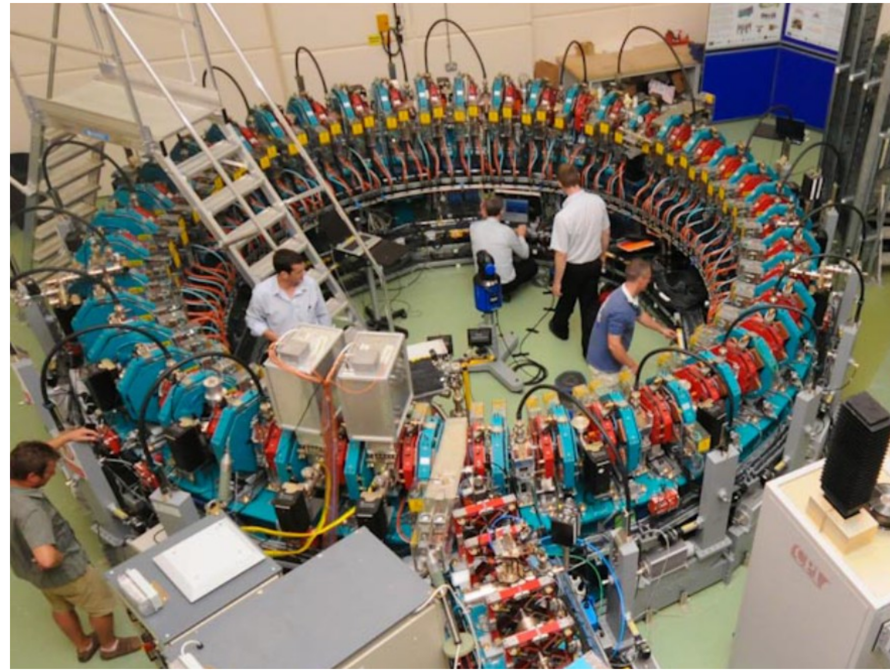
Progress on FFAGs

- EMMA (DL, UK)
- RACCAM (Recherche en ACCe ́le ́rateurs et Applications Me ́dicales)
- eRHIC FFAG design
- CBETA (recently approved)
- .....

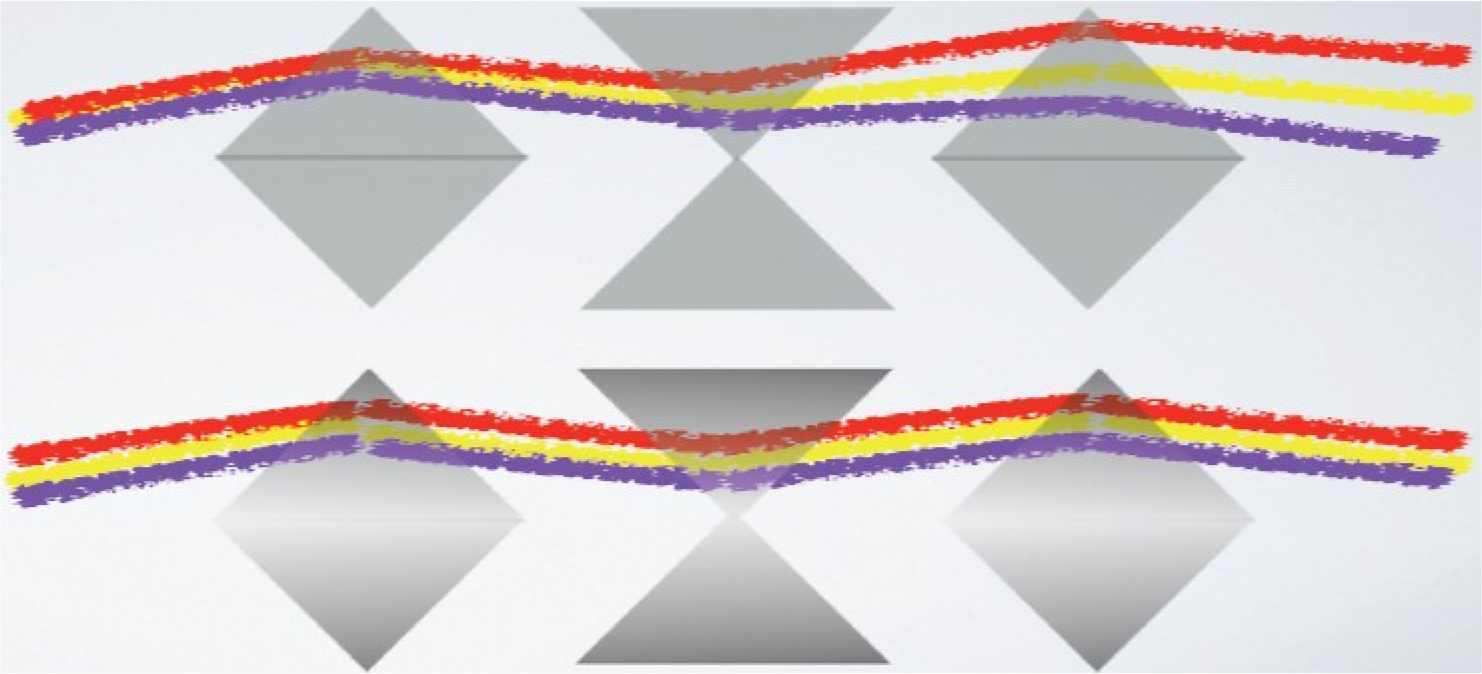


EMMA

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!

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Advantages (2)

- Space charge tune spread is an issue for high intensity machines
- FFAGs allow for large horizontal emittance (large aperture is needed in any case), which facilitates the horizontal spread
- Even for the vertical one it helps, as a large ratio of horizontal/vertical emittances helps too:

$$\Delta Q_v = -\frac{n_t r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h/\epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}$$

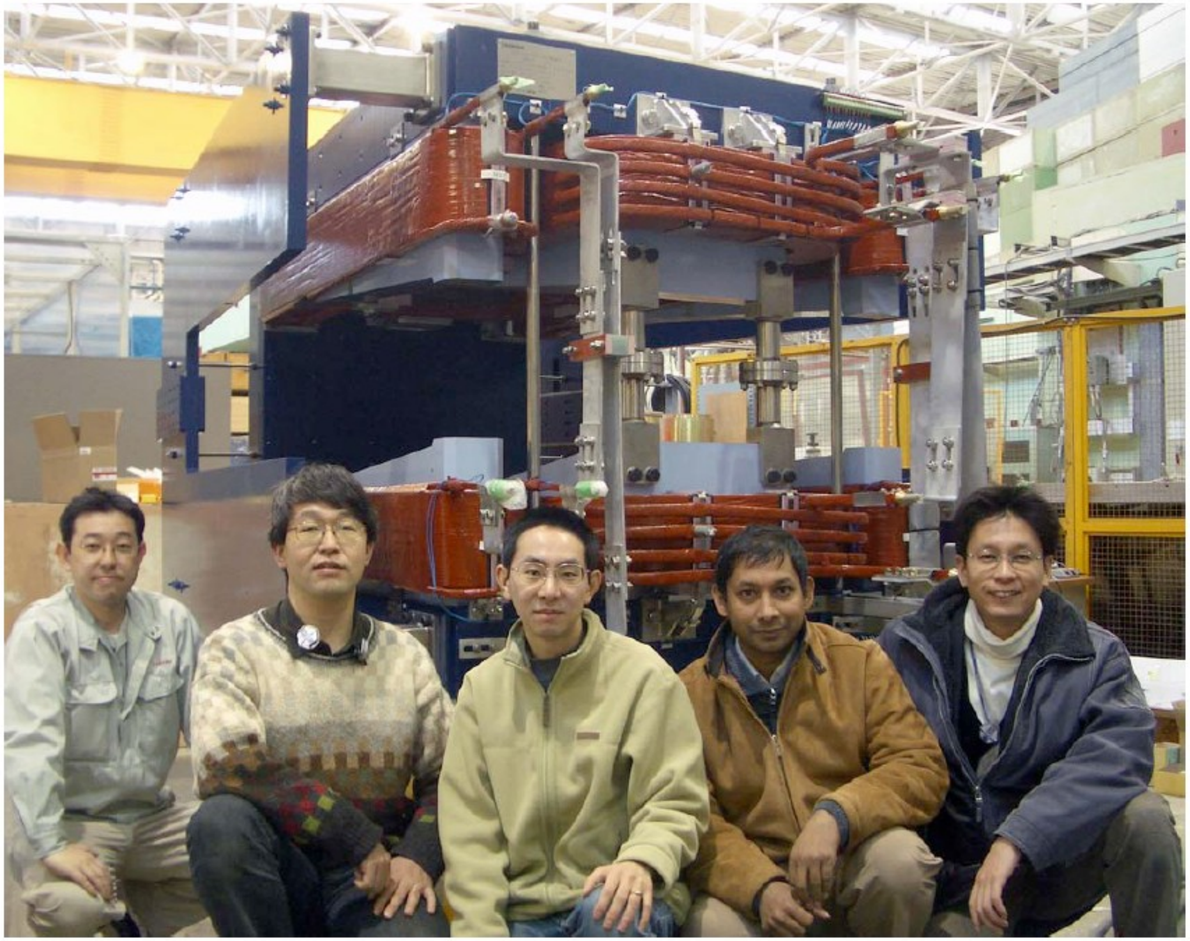
Discussed by S. Machida at FFAG'15

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



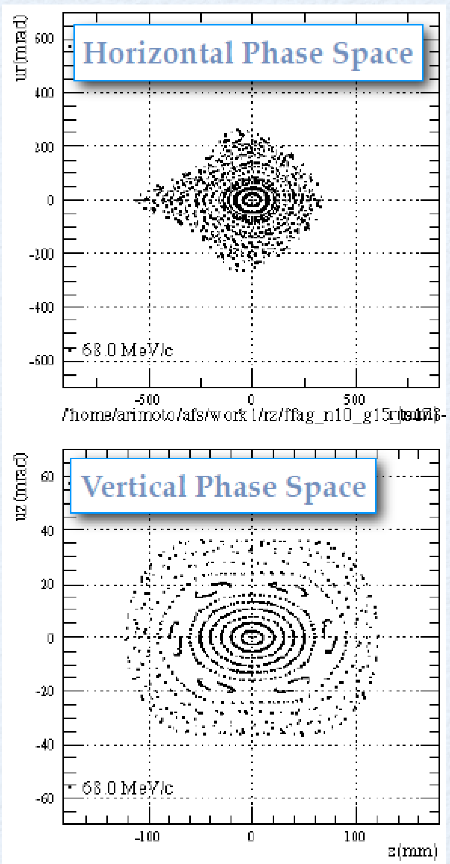
PRISM magnet designed by Osaka University

Very large FFAG magnets were successfully designed and constructed!

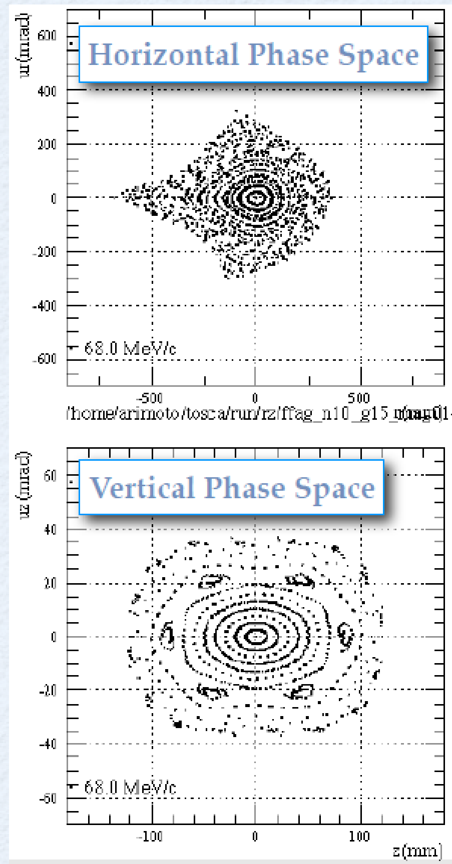
FFAG magnets performance

Field Measurements : Acceptance

PRISM



With TOSCA Map



With Measured Map

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

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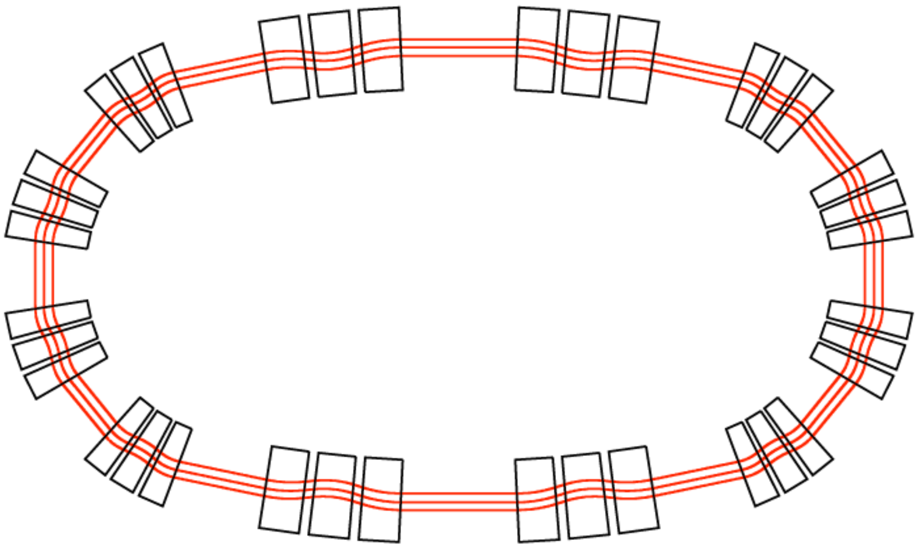
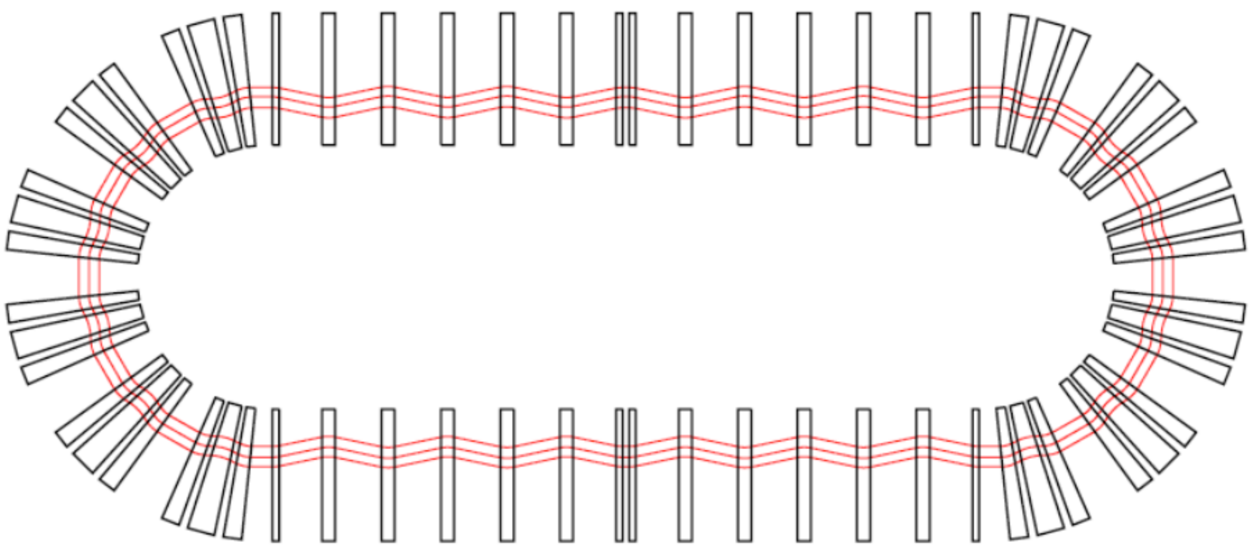
Advanced FFAG



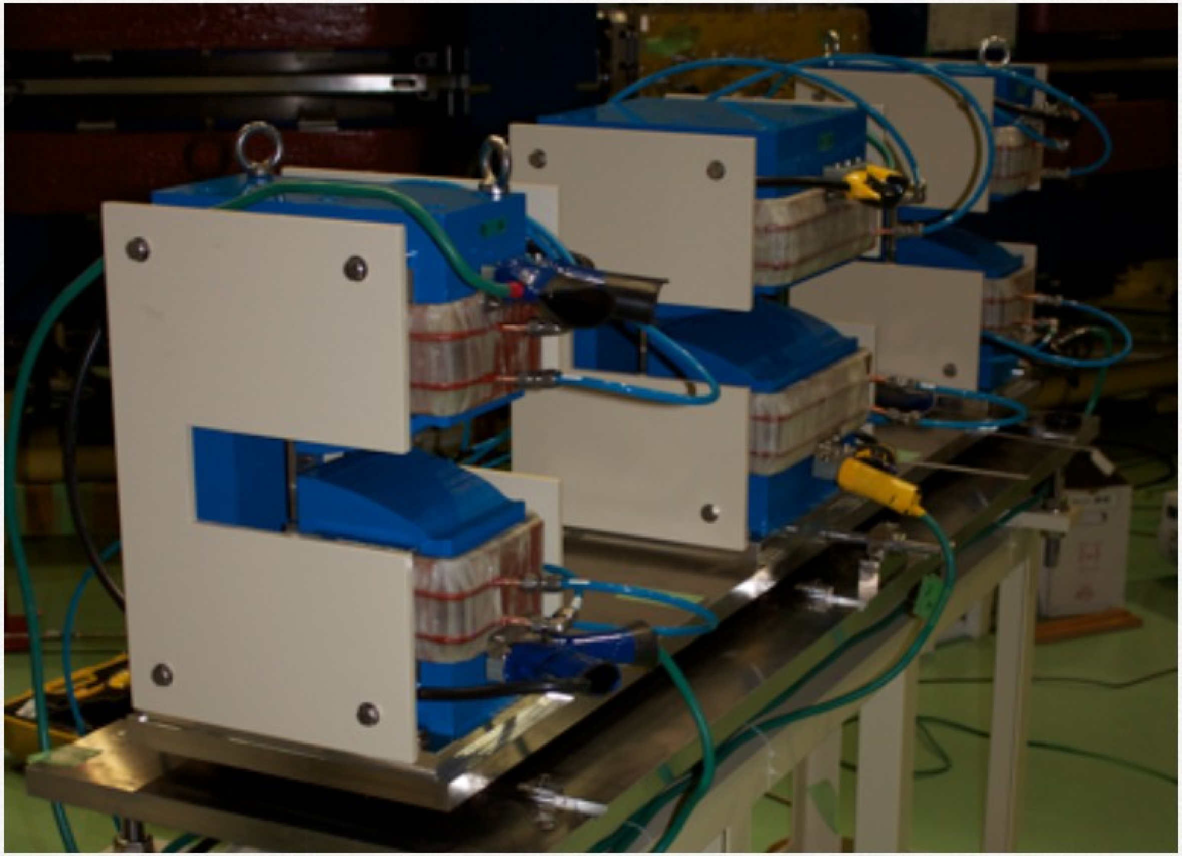
By combining cells with different radius
or arcs with straight cells,
space issue
may be overcome.



How to make straight cell?

Straight scaling FFAG:

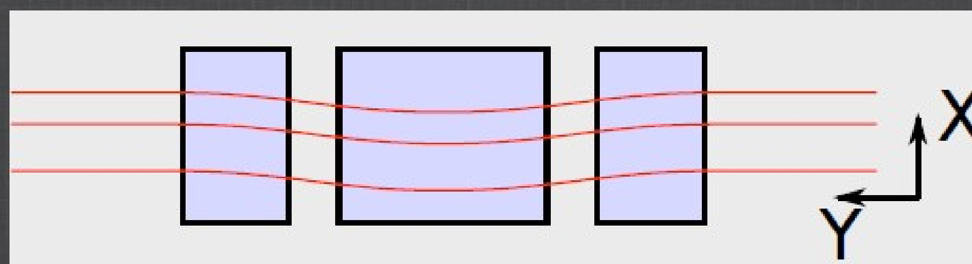
FFAG cell with no overall bend.



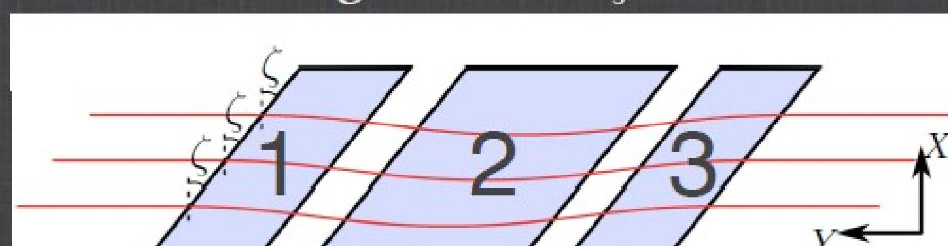
Straight FFAG (principles)

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: $\zeta = 0$

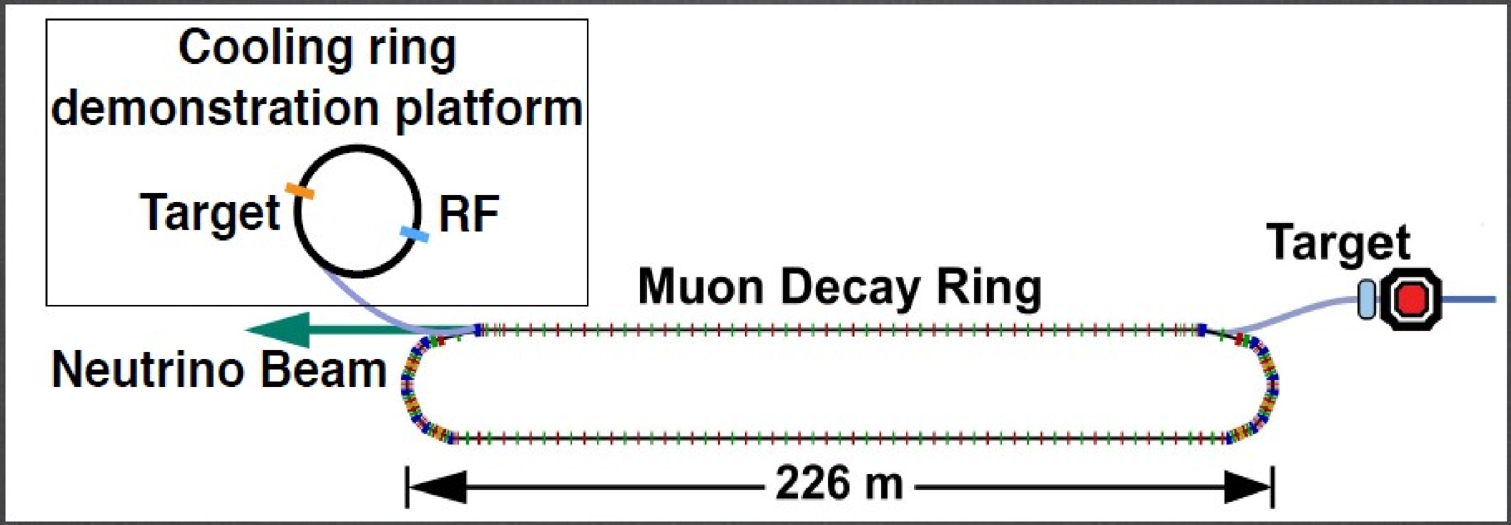


Tilted straight case: $\zeta = const.$

nuSTORM FFAG storage ring

- Let’s see more details, how advanced FFAG storage ring design may look like...

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

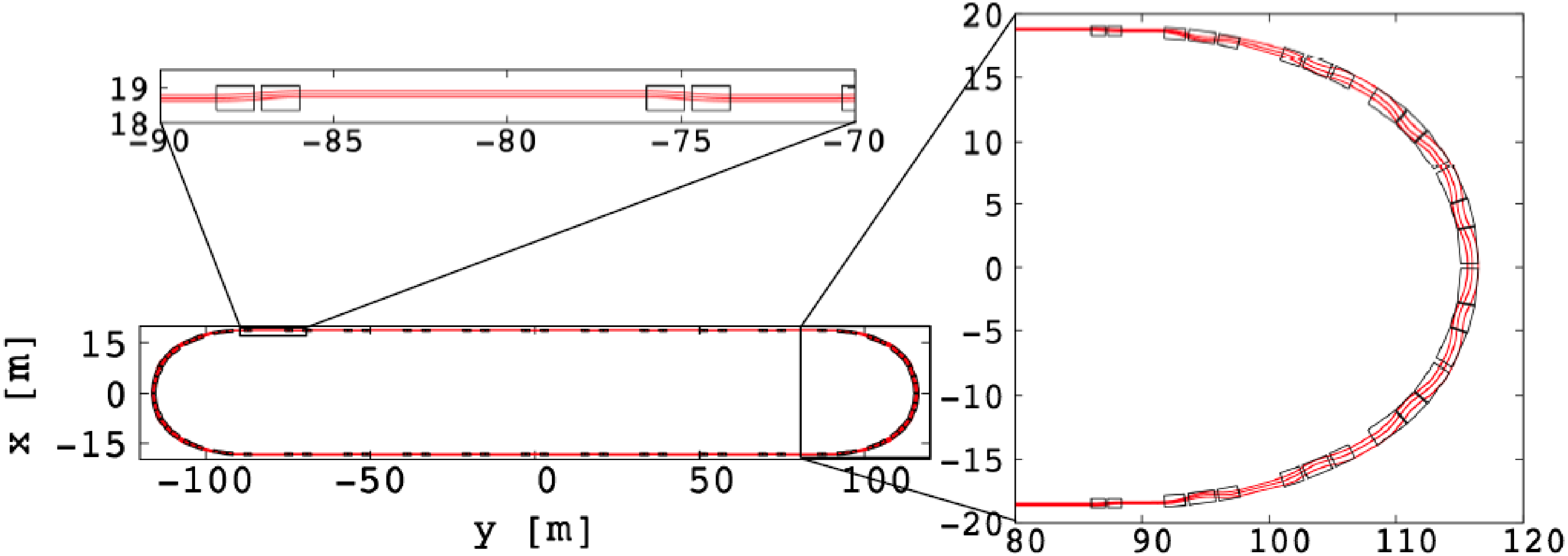
$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

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

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

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

FFAG design for nuSTORM (J-B. Lagrange, JP)



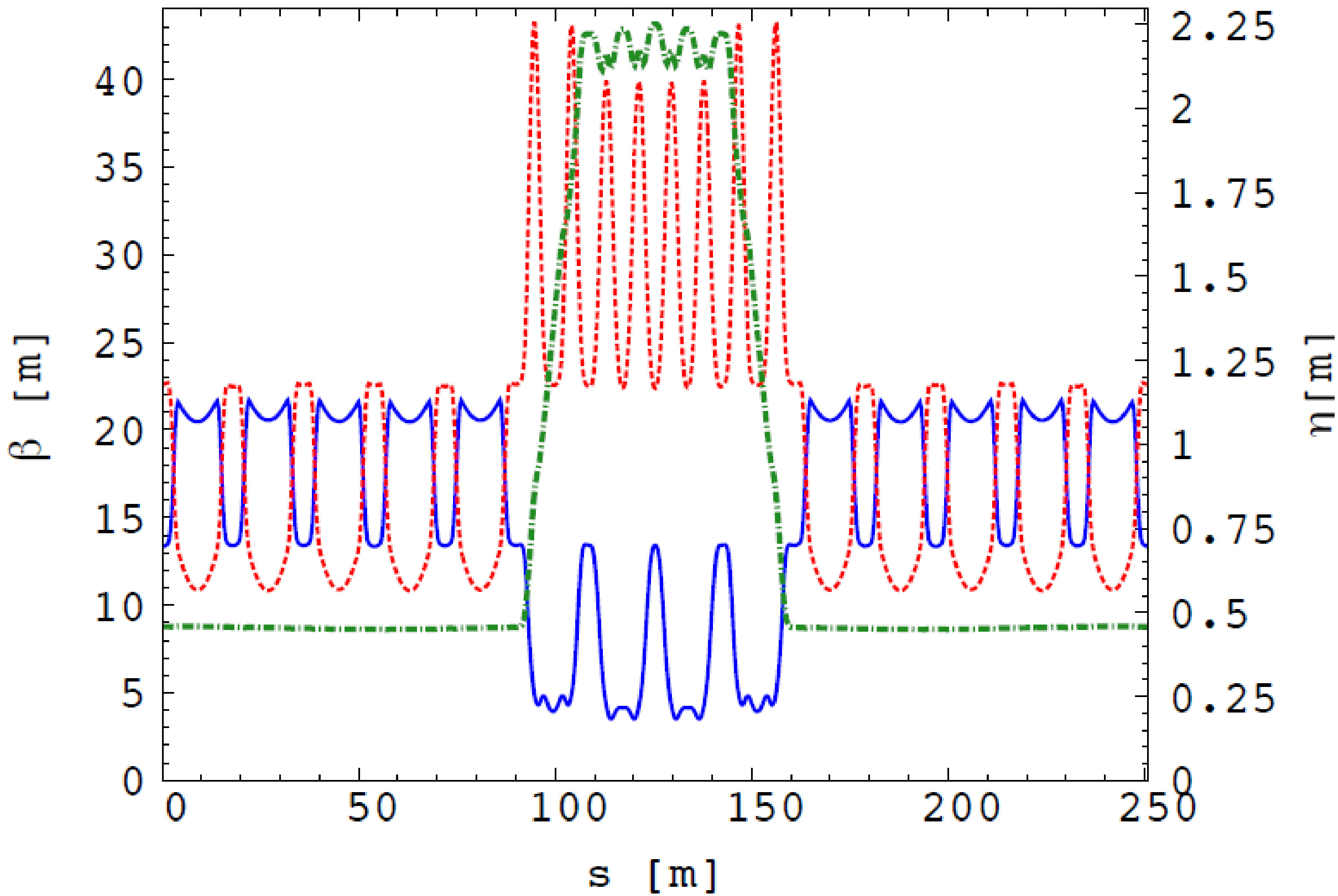
Lattice design includes three cell types
(dens arc, matching and straight ones)

nuSTORM FFAG parameters

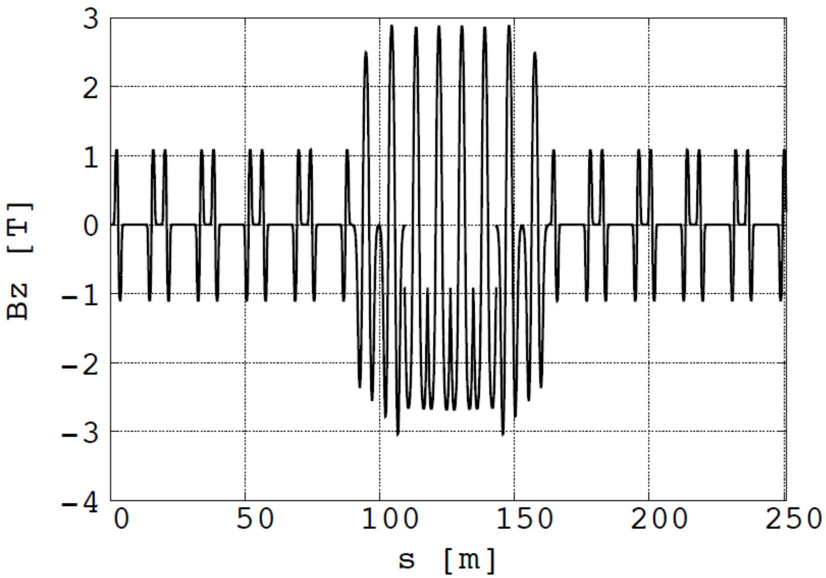
Cell parameters

	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

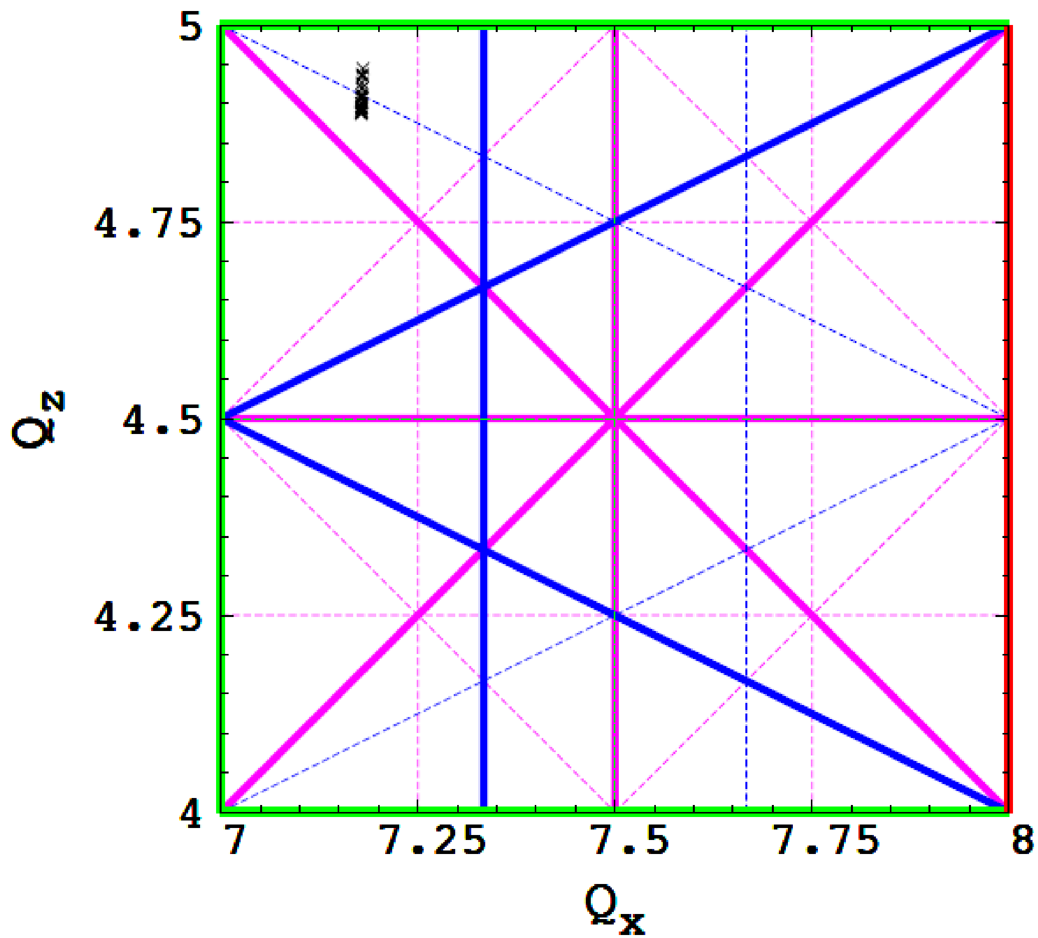
nuSTORM FFAG, lattice functions



nuSTORM, lattice design



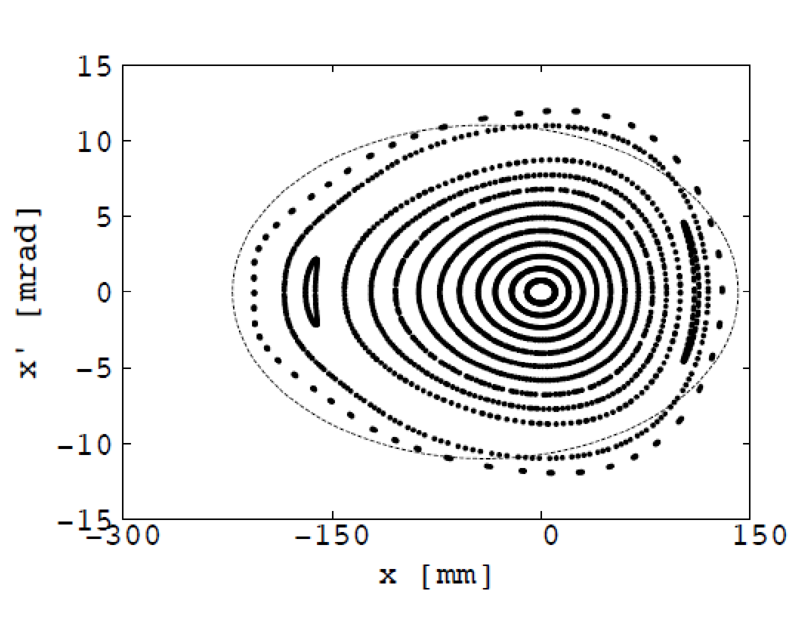
Magnetic field at the top momentum particle



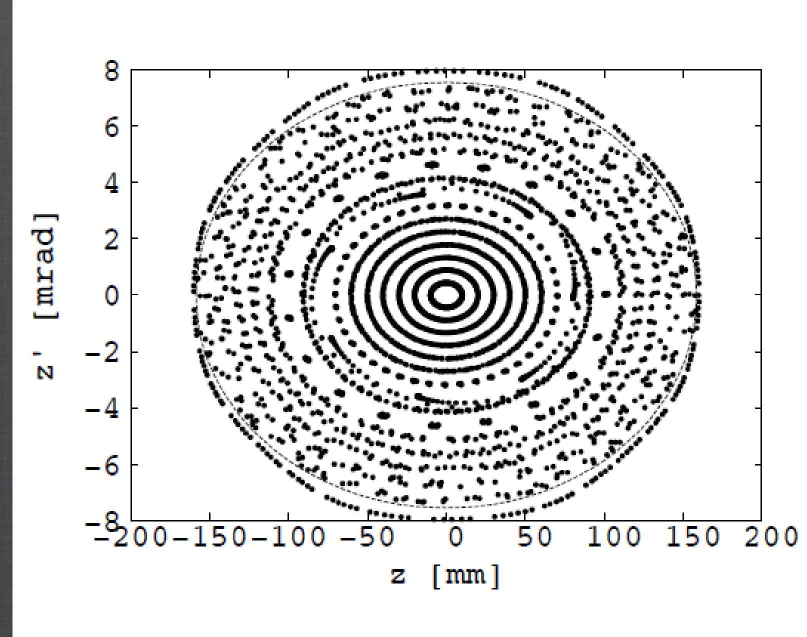
Chromatic tune spread for 19% momentum spread

nuSTORM, DA studies

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns
(Dotted ellipse represents 2 π.mm.rad)



Maximum vertical stable amplitude over 100 turns
(Dotted ellipse represents 1.2 π.mm.rad)

Lessons from nuSTORM study

- By combining lattices with different properties the problem of space in the lattice can be solved
- While doing so the zero-chromaticity can be maintained
- Very large dynamical acceptance can be achieved
- Matching between different optical modules is possible
- Automatic design toolkit was created.

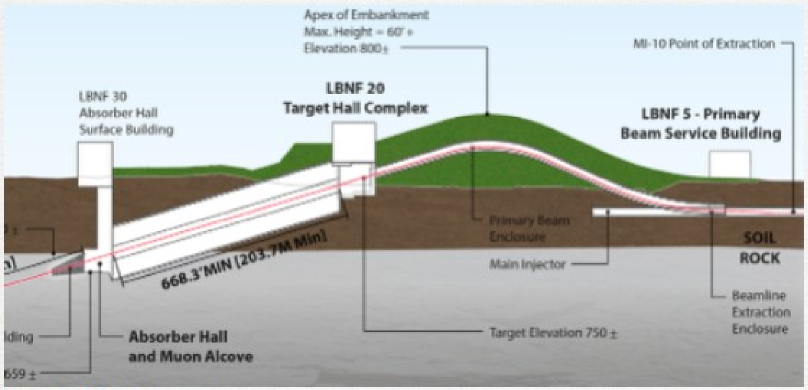
Potential important issue...

- What if the limit comes from the extraction line?

Let’s use an FFAG one

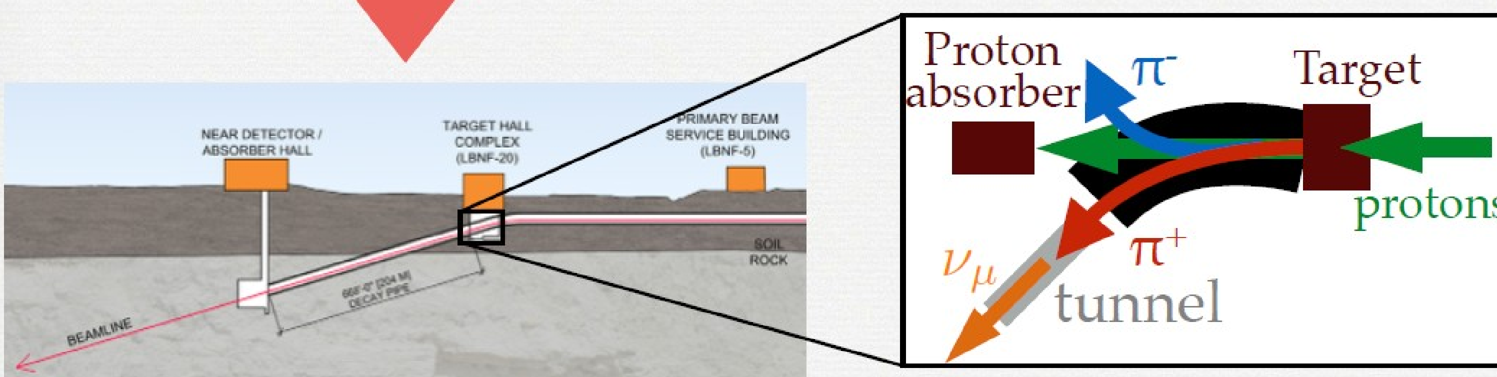
Recent developments

nuPIL (neutrinos from Pion beam Line)



LBNF baseline

zero-chromatic pion beam line with large momentum acceptance



nuPIL

A. Bross, J-B. Lagrange, A. Liu, JP and others

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Summary

- A very interesting FFAG research is still ongoing
  - You can google for FFAG'16 workshop
- A potential FFAG storage ring option for ESS would allow to benefit from a very good chromaticity control and a large acceptance (both dynamical and physical)
  - By reducing the tune spread and control the beam loss in the ring
    - However energy spread is very small so chromatic tune spread is not an issue
  - Sufficient space in the lattice should be achievable with modern advanced FFAG design techniques
- Conventional AG ring seems to be sufficient unless not only accumulation is needed but also acceleration/bunch compression
  - Than an FFAG may be an interesting option.