FFAG EXPERIENCE AND FUTURE PROSPECTS

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CONTENTS

INTRODUCTION

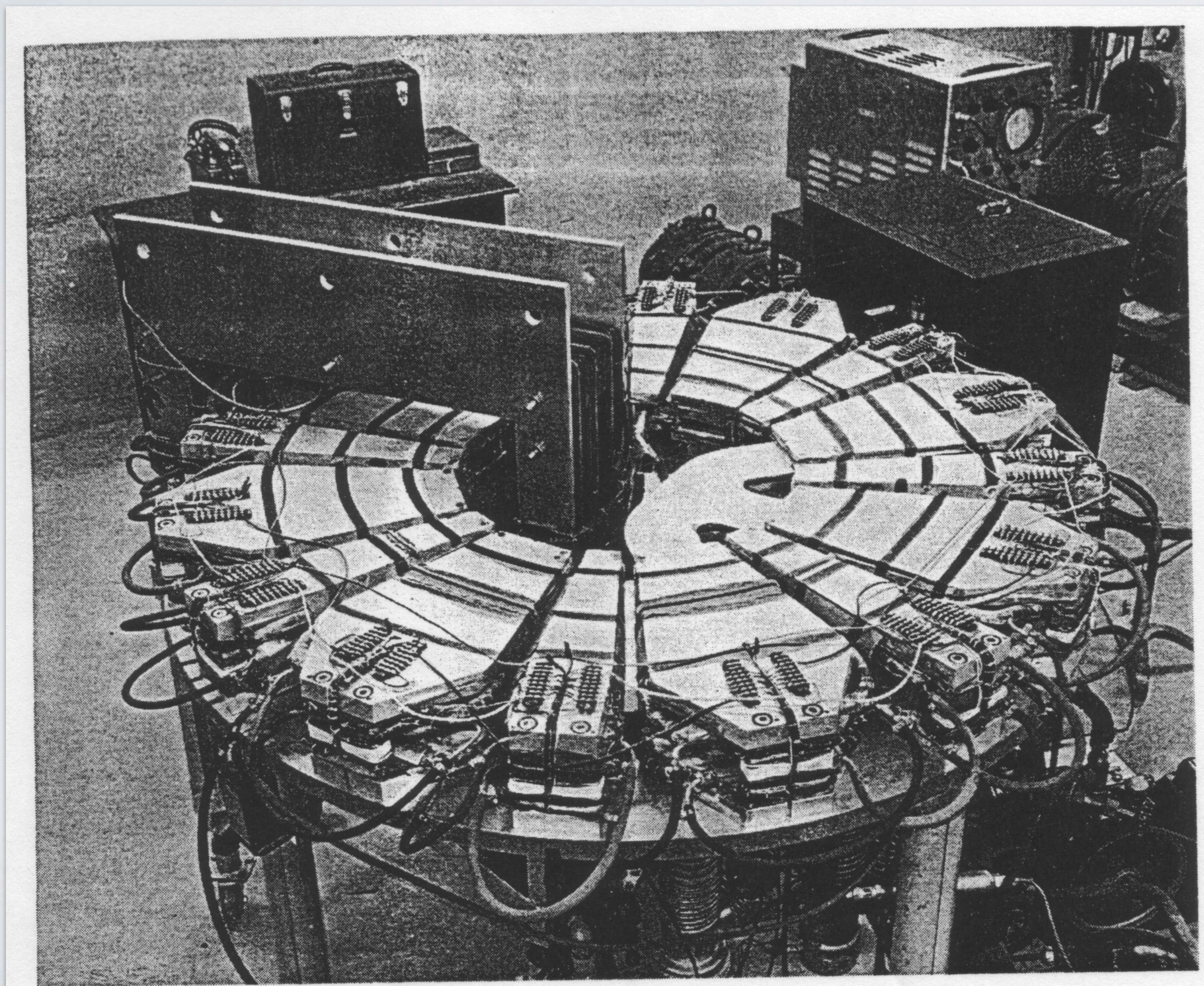
HISTORY

-FFAG: Fixed Field Alternating Gradient-

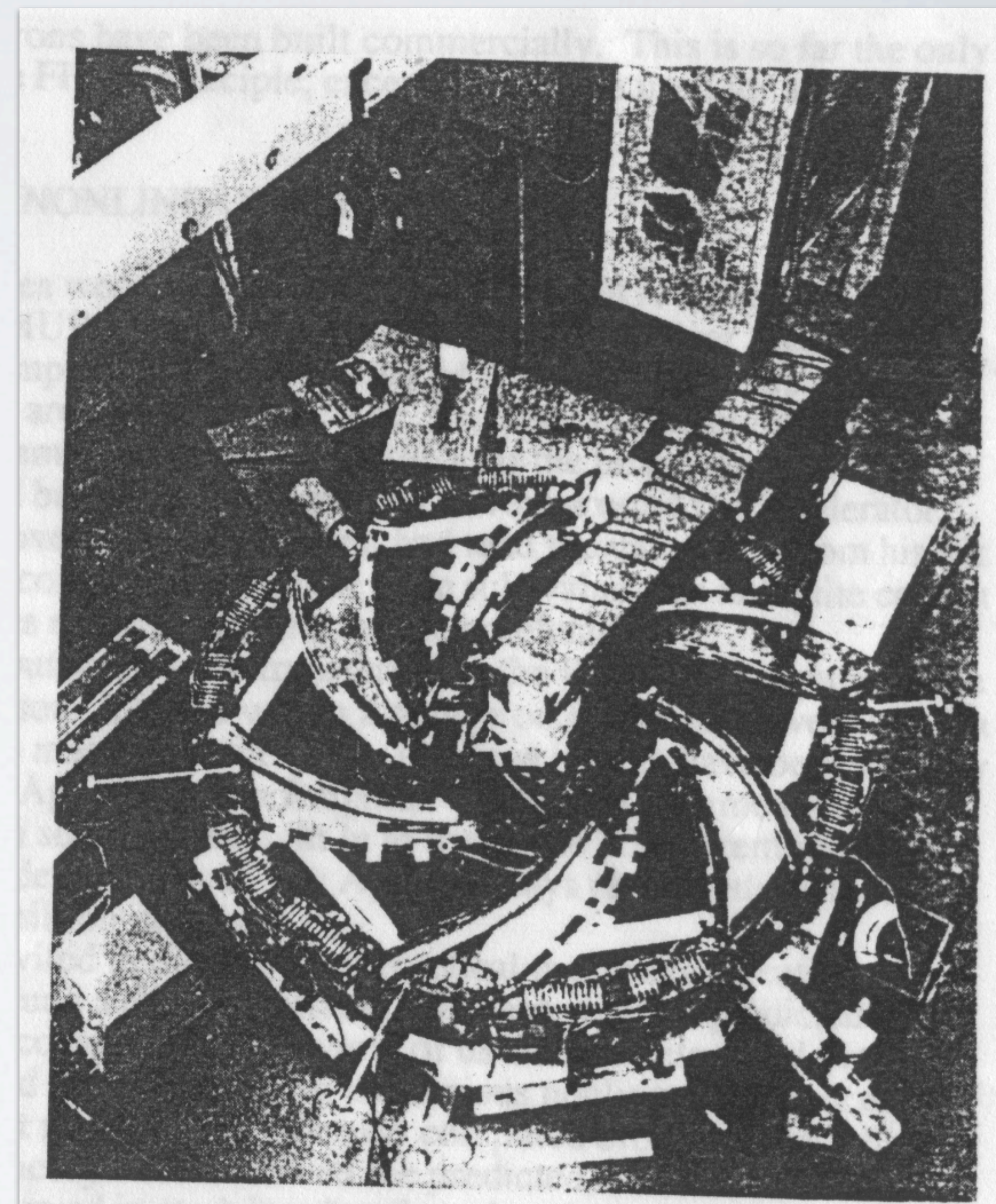
- Invention of FFAG 1950s
  - Okawa (Japan), Symon, (USA), Kolomenskii (USSR)
  - Development of e-models 1960s
    - MURA project (Cole, Symon, Okawa, Meads, Mills et al.)
      - Radial & spiral sector FFAG e-model
      - 2-way FFAG ring
      - Induction acceleration
    - No actual development since then.
      - Complicated 3D magnet design & RF acceleration difficulty (orbit path length change)
- Rebirth of FFAG in 2000
  - World first Proton FFAG (POP) was developed at KEK (2000)
  - SInce then, eleven FFAGs have been built at six institutes in the world.

MURA PROJECT

e-models



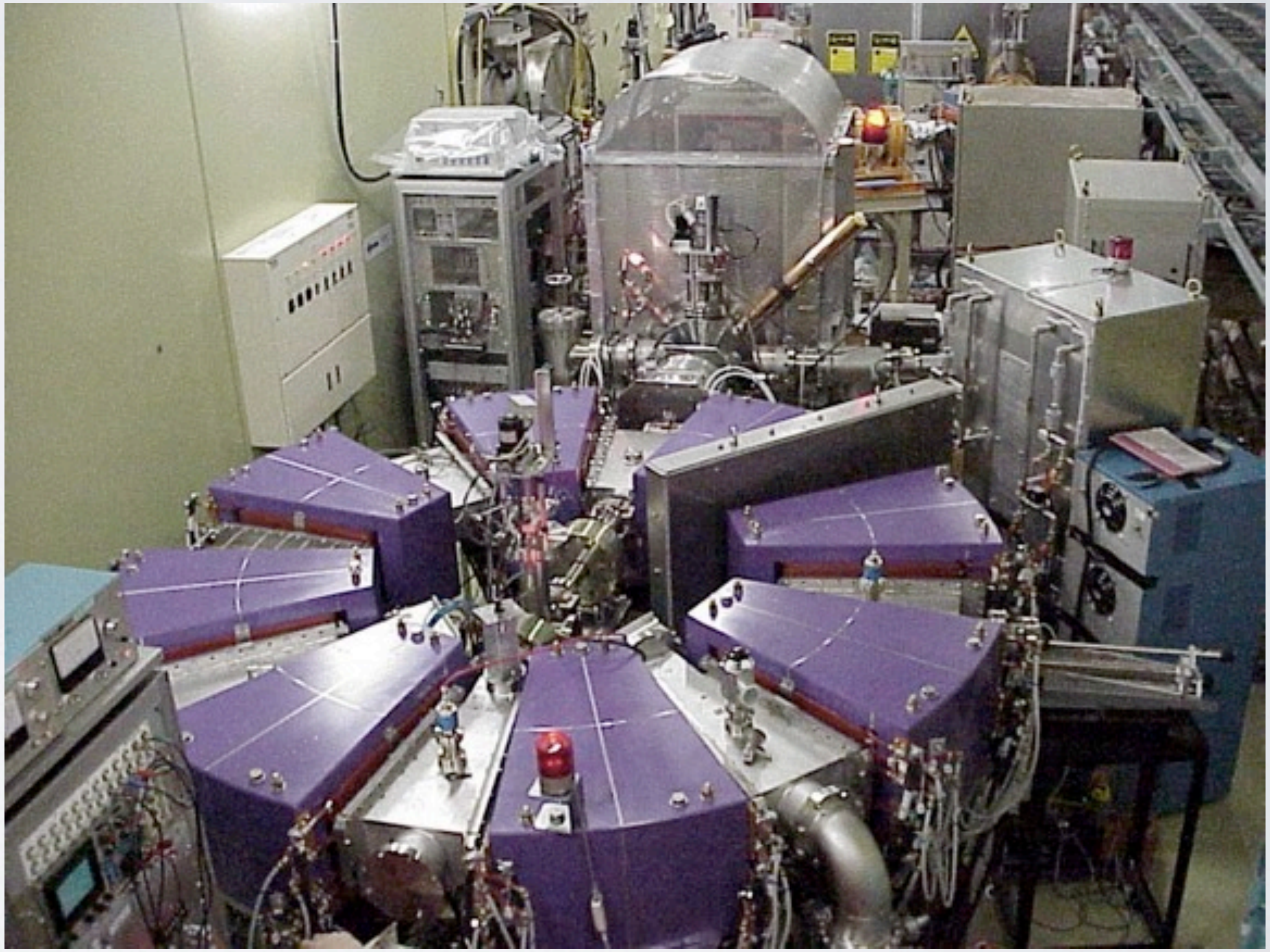
radial sector



spiral sector

REBIRTH OF FFAG

- First proton FFAG (POP) in 2000 developement at KEK
  - Type Scaling
  - Energy 50-500keV(1MeV)
  - Lattice DFD triplet
  - Radius@max. energy 1.2m
  - RF cavity Broad-band MA
  - Repetition 1kHz



- RF acceleration broad-band RF cavity (MA cavity)
- 3D field calculation and tracking

- Since then, world-wide R&D activities on FFAG re-started.

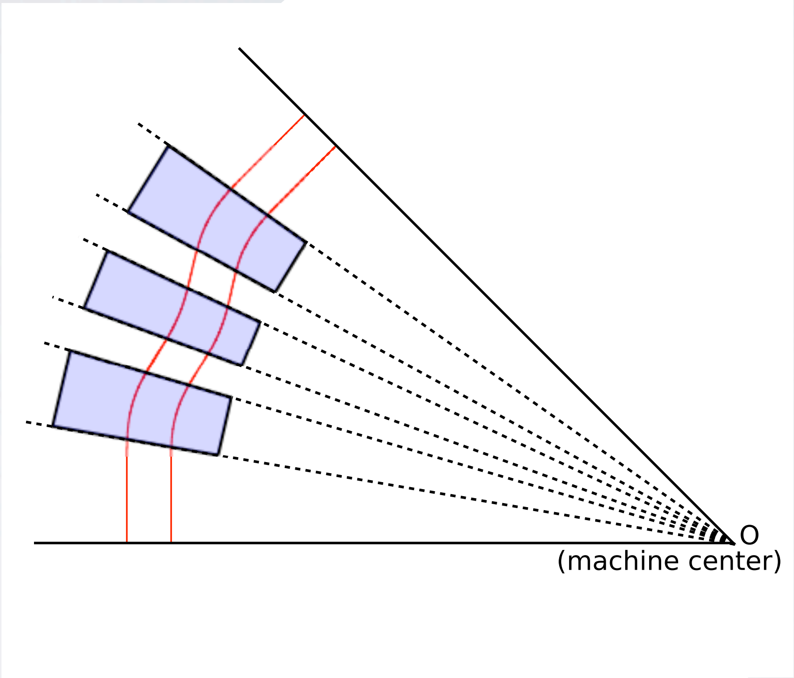
FFAG

FIXED FIELD ALTERNATING GRADIENT

- **Fixed field → Static magnetic field**
- **AG focusing → Strong focusing**
- Problem
  - Tune resonance crossing during beam acceleration
- Solutions
  - (1) Constant betatron tunes : Zero chromaticity → Scaling FFAG
    - Circular orbit (Okawa, Symon) : magnetic field → $B_z = B_0 \left(\frac{r}{r_0} \right)^k f(\theta)$
    - Oribit similarity and momentum independent field gradient.
  - (2) Fast resonance crossing : Quick acceleration → Non-scaling FFAG
    - Demonstrated by EMMA(world first non-scaling FFAG) in UK (2011).

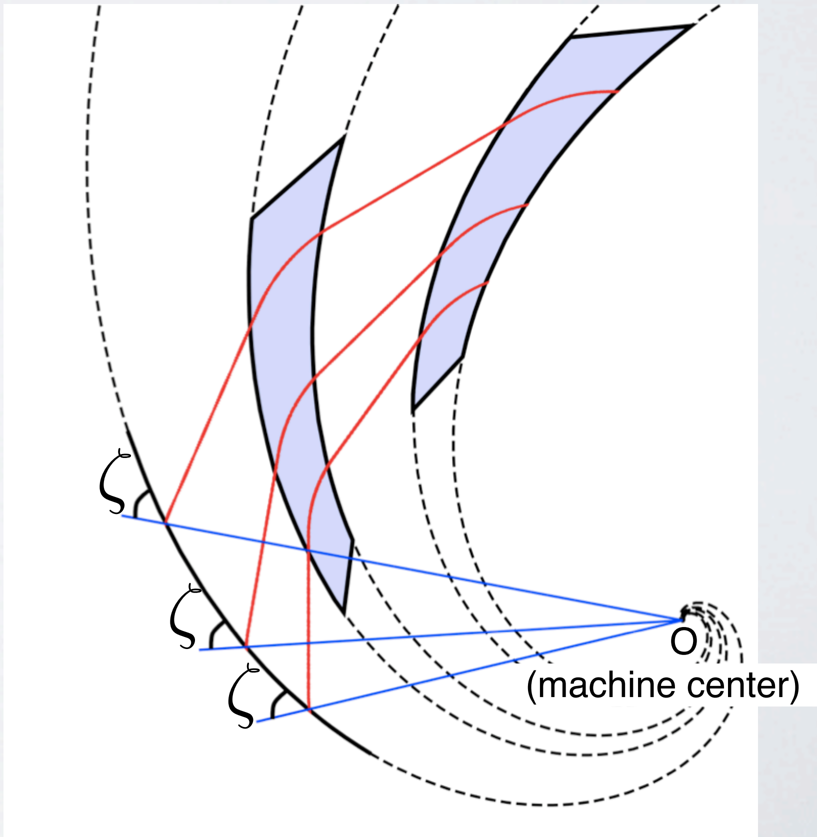
AG FOCUSING LATTICE OF SCALING FFAG RING

- AG focusing : FODO lattice
- Radial sector
  - F: positive bend
  - D:negative bend



$$B_z = B_0 \left(\frac{r}{r_0} \right)^k f(\theta)$$

- Spiral sector
  - F: positive bending
  - D: edge focusing



FEATURES

- Strong focusing in 3-D: AG-focus in transverse and phase focus in longitudinal directions
  - It is like synchrotron.
  - Large acceptance especially in longitudinal space.
  - Various longitudinal RF gymnastics become possible.
    - Bunching, Stacking, Coalescing, etc.
- Static magnetic field: small orbit excursion.
  - It is like cyclotron, but not much orbit excursion
  - Fast acceleration
    - Fixed magnetic field allows the beam acceleration only by RF pattern.
    - No needs of synchronization between RF and magnets.
    - Good for accelerating short-lived particles such as muons.
  - Large repetition rate
    - Space charge and collective effects are below threshold.
    - Good for hight intensity operation

CONSTRUCTION AND DEVELOPMENT

SINCE FFAG REBIRTH IN 2000

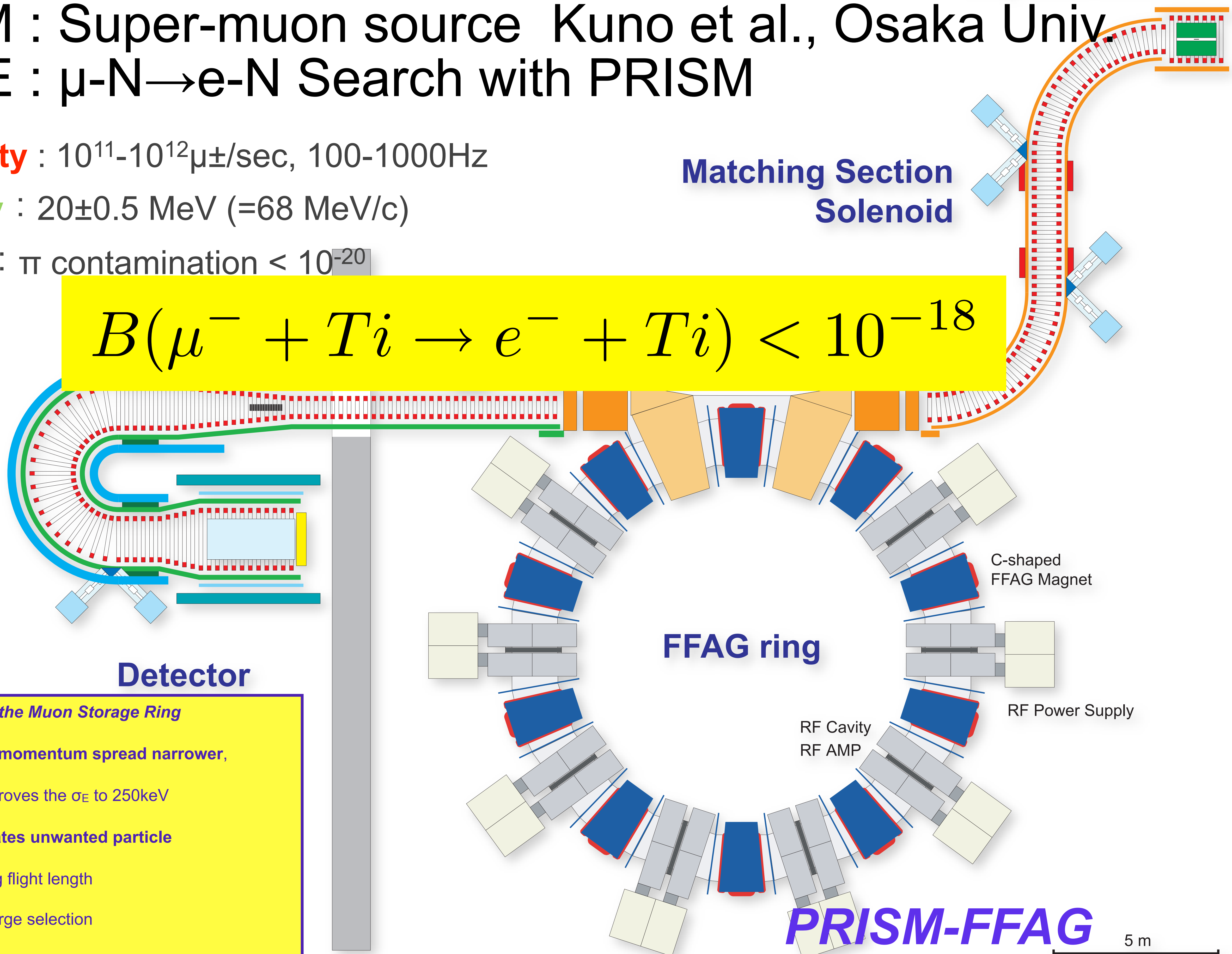
- Eleven operational FFAGs were constructed at six institutes in the world.
- Lepton FFAGs
  - PRISM project :Muon phase rotation ring (Osaka University)
  - Two compact electron machines (Mitsubishi Ele. Co.)
  - Two high current e-FFAGs (NHV Co.)
  - EMMA project : World first non-scaling FFAG (Cockcroft Inst. UK)
- Hadron FFAGs
  - Proton FFAG complex(3-cascade rings) for ADSR experiment (Kyoto Univ., Research Reactor Inst.)
  - Proton FFAG for versatile applications (Kyusyu Univ.)
  - Neutron source with proton storage FFAG with ERIT sheme (Kyoto Univ., Research Reactor Inst.)
- Study
  - Hadron therapy :RACCAM (Grenoble), PAMELA (Oxford), BNL, FNAL
  - Proton driver, ADSR : Isochronous FFAGs : (Rutherford, Lab., FNAL, KURRI,BNL, PAL)
  - Muon accelerator and decay ring : (KURRI, Imp. College, Rutherford, FNAL etc.)

LEPTON FFAGS

PRISM : Super-muon source Kuno et al., Osaka Univ.
PRIME : μ-N→e-N Search with PRISM

- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

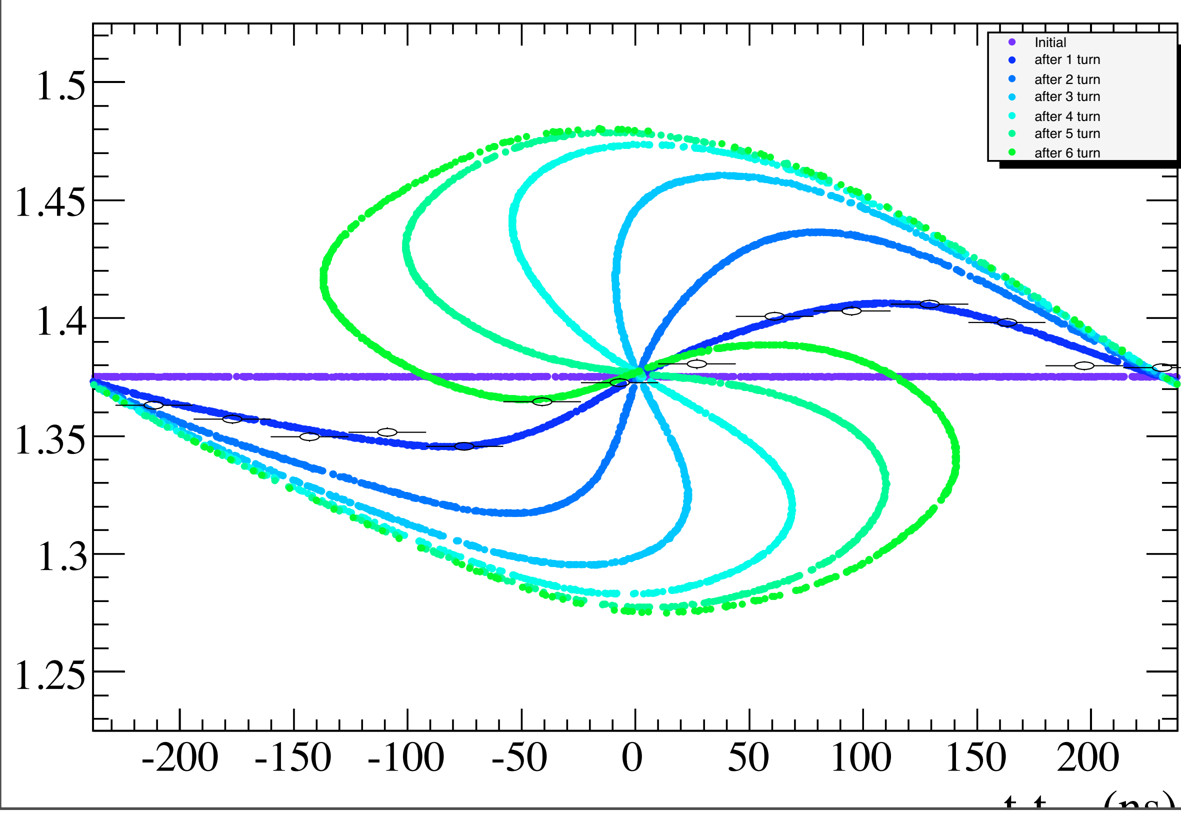


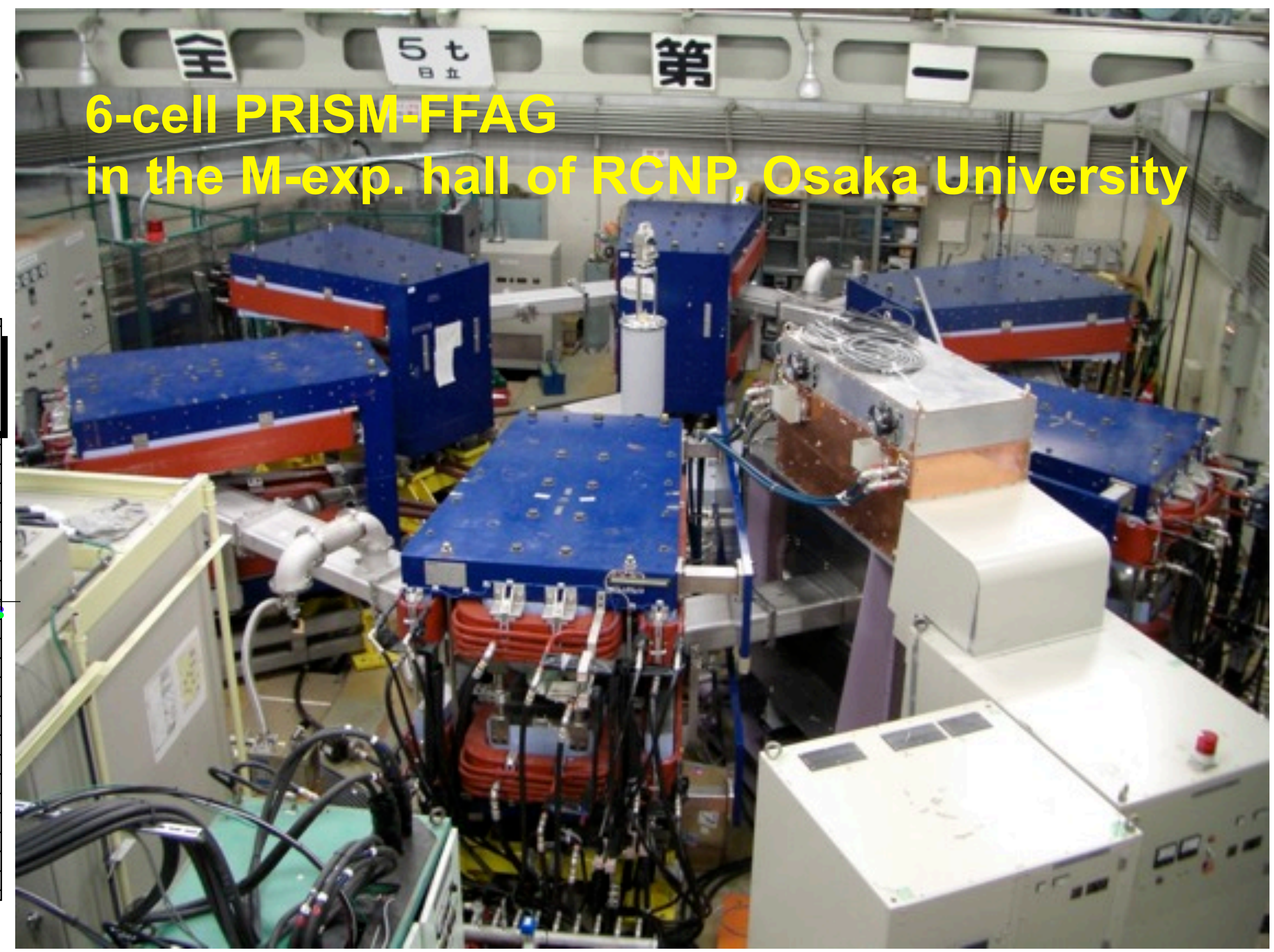
Functions of the Muon Storage Ring

- **Makes momentum spread narrower,**
  - improves the σ_E to 250keV
- **Eliminates unwanted particle**
  - long flight length
  - charge selection
  - momentum selection

Demonstration of Phase Rotation with α-particles

- FFAG-ring
  - PRISM-FFAG Magnet x 6、RF x 1
- Beam : α-particles from radioactive isotopes
  - ^{241}Am 5.48MeV(200MeV/c) → degrade to 100MeV/c
  - small emittance by collimators
  - pulsing by electrostatic kickers
- Detector : Solid state detector
  - energy
  - timing

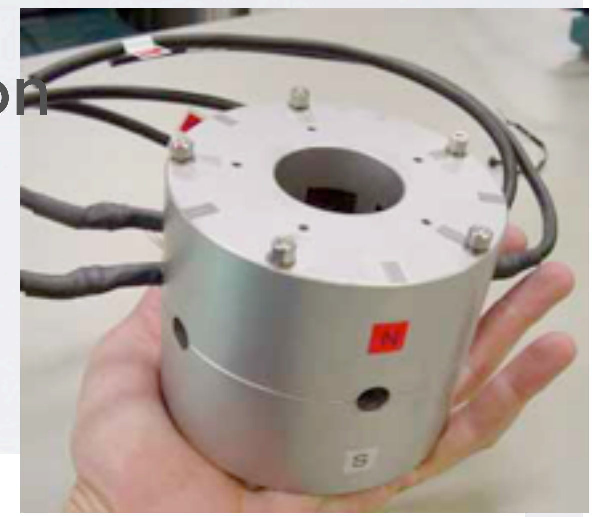


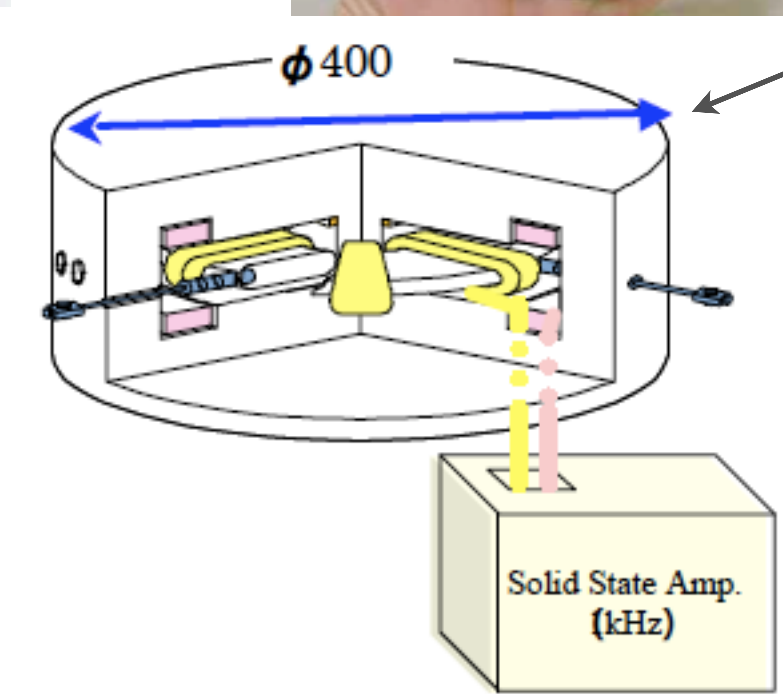


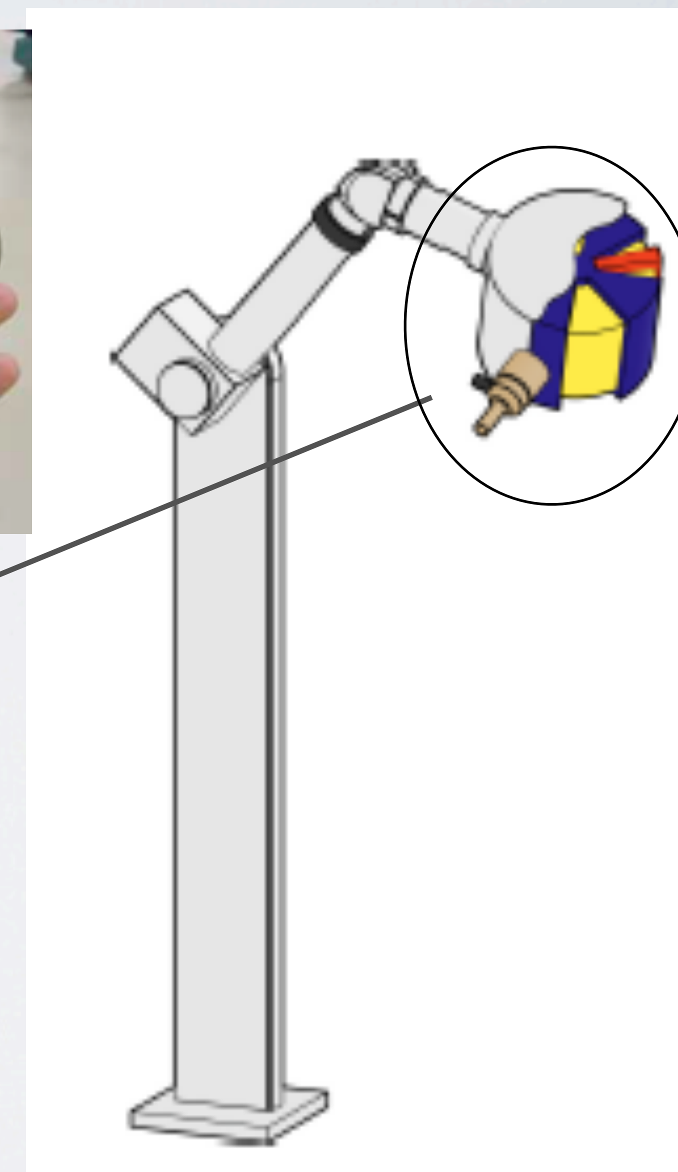
MITSUBISHI ELECTRIC CO.

F.Tanaka-CYCLOTRON 2004

- LAPTOP Electron accelerator: E=1MeV
  - FFAG(injection/acceleration)+Betatron (acceleration)
- E=6MeV , 400mm in diameter







Proto-type Machine

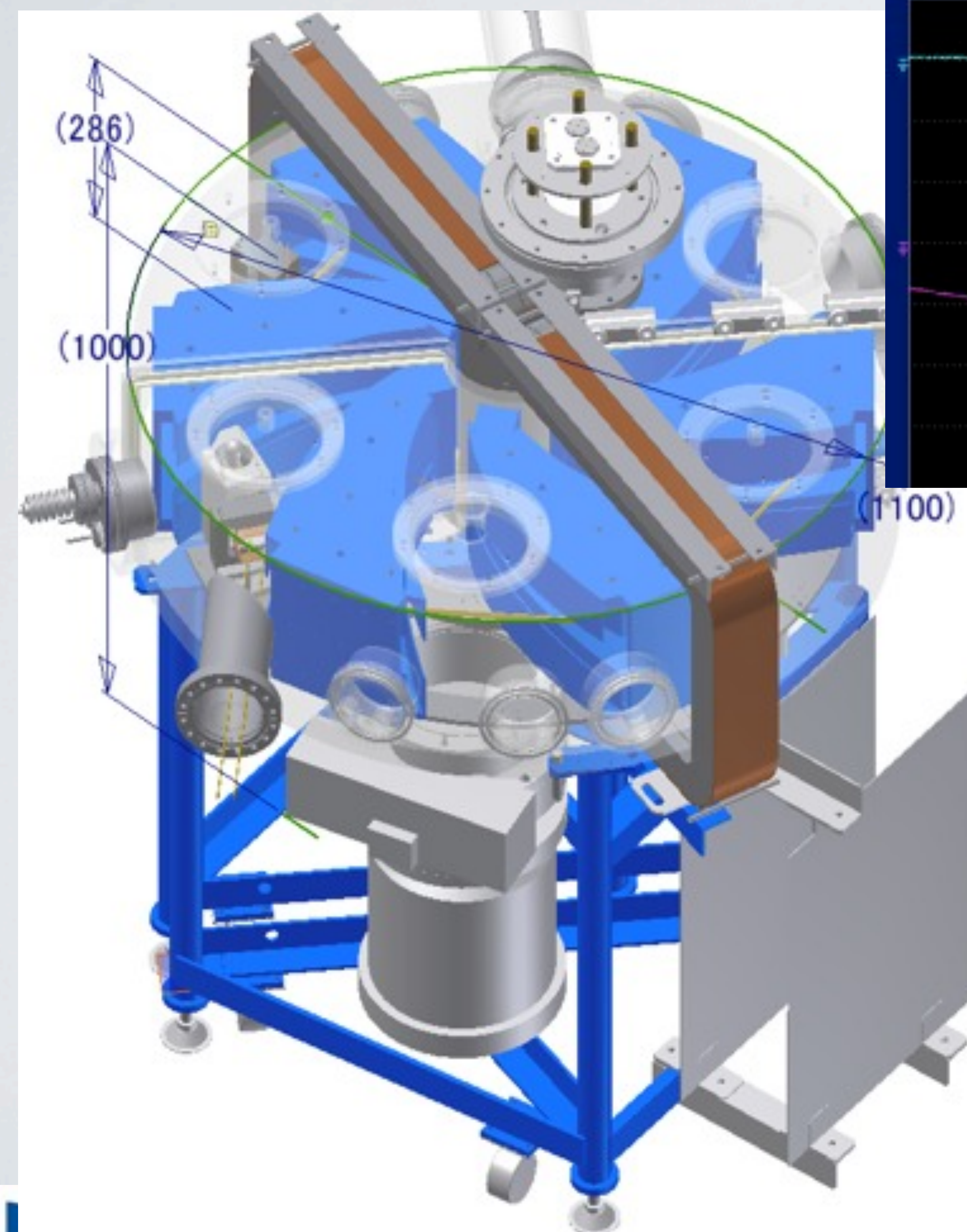
Injection Energy	50 [keV]
Acceleration Energy	6 [MeV]
Injection Radius	0.1 [m]
Extraction Radius	0.125[m]
K value	2~3
Magnet	Spiral Sector Magnet
Repetition	1 [kHz]
Duty	2 [%]
Energy after injection	50~250[keV]

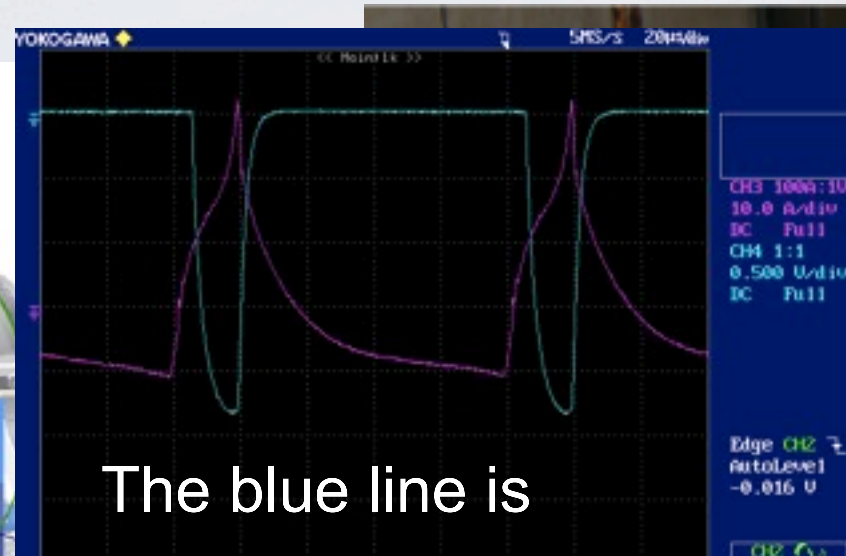
NHV CO.

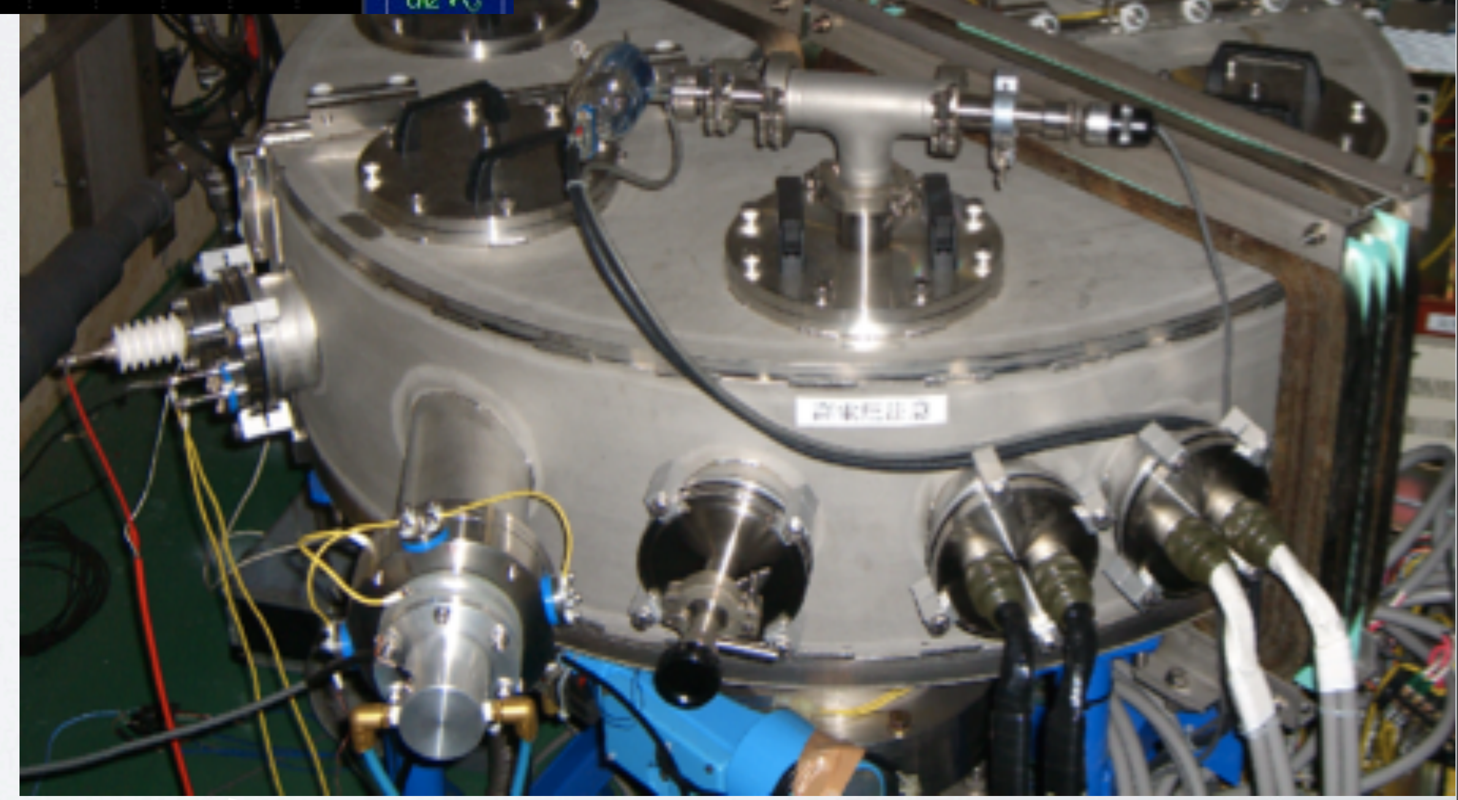
T.Baba, M.Yuasa

E-FFAG: 500keV-20mA

*Scaling FFAG, Induction acceleration

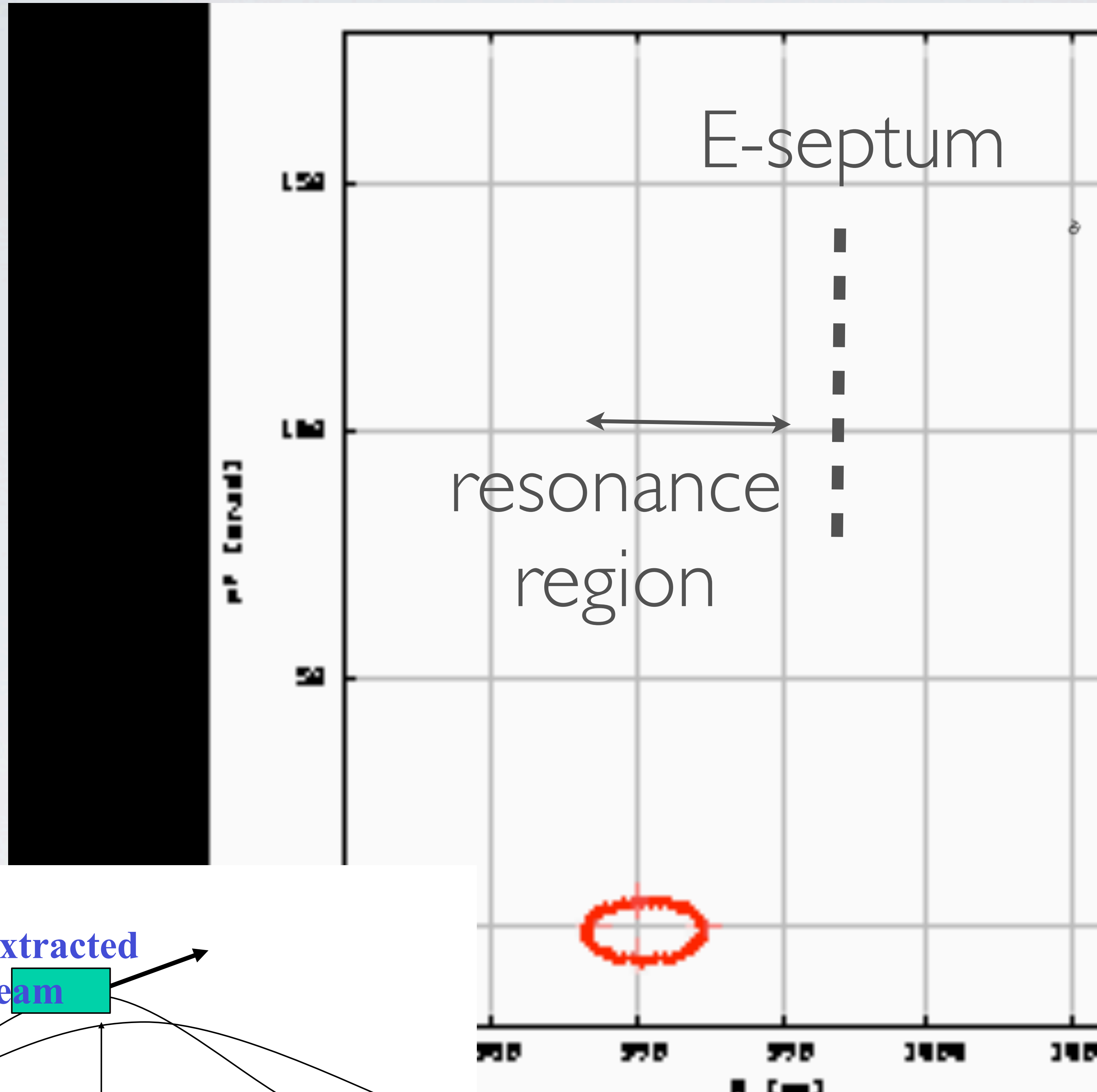


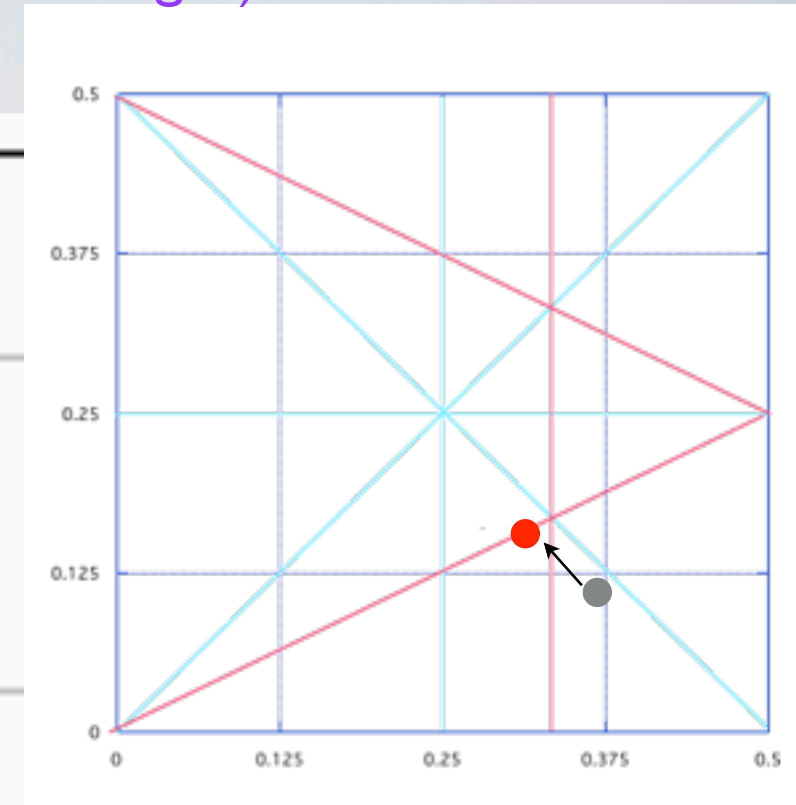


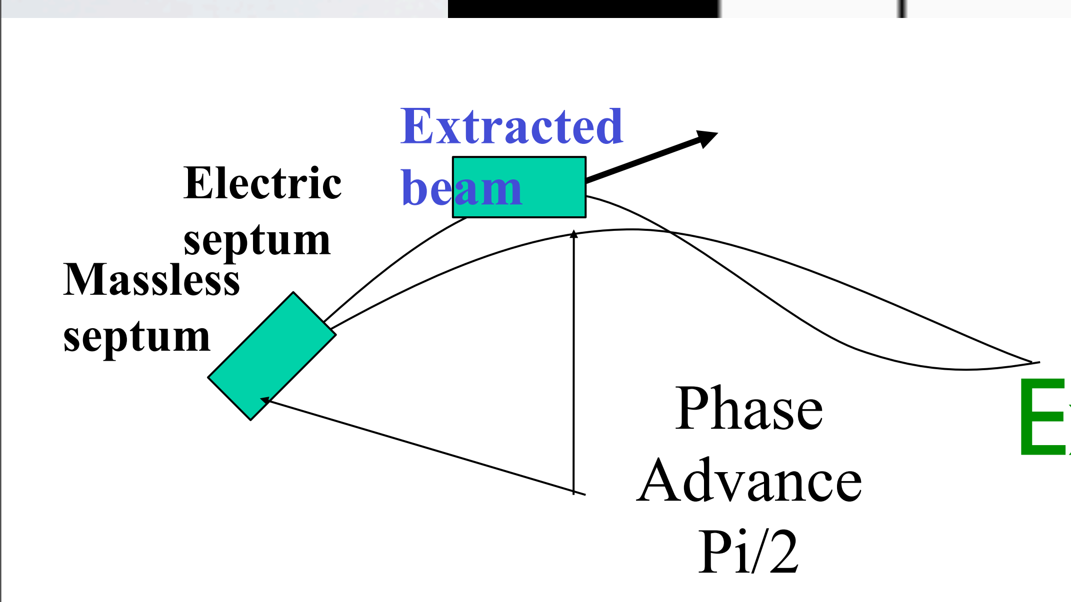


Corporation

RESONANCE BEAM EXTRACTION (3rd-integer)







Extraction efficiency of >90% was achieved.

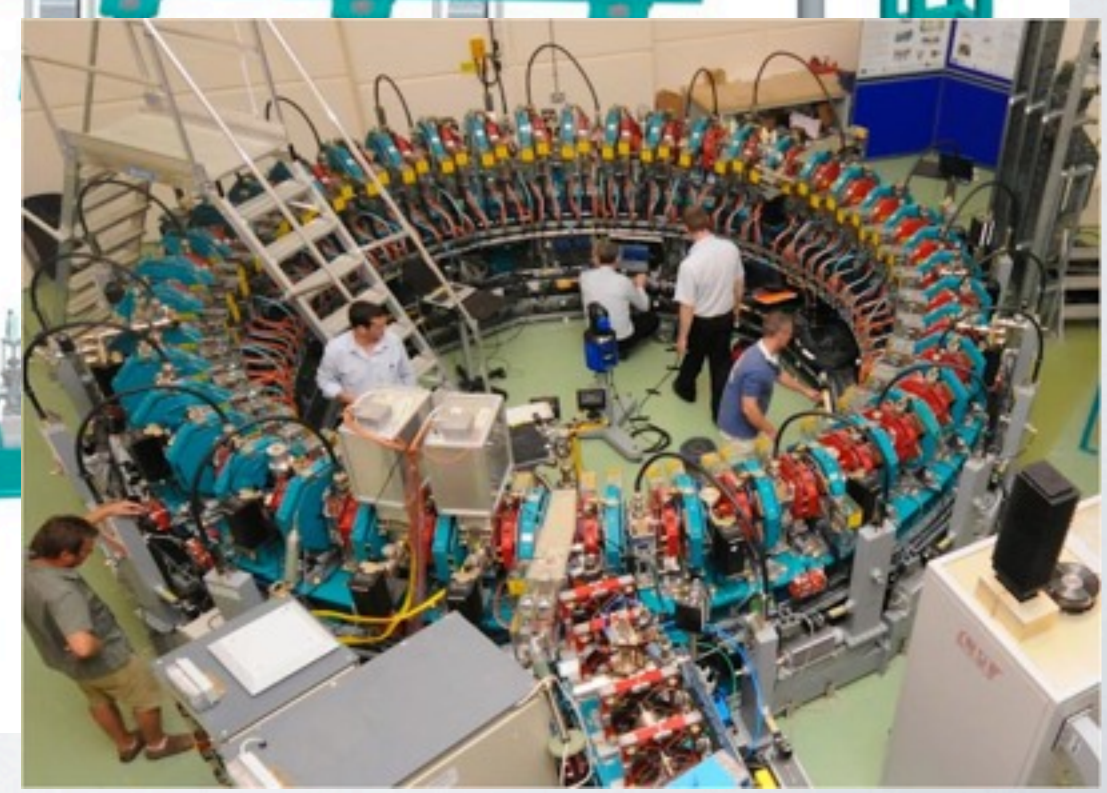
EMMA

- World first non-scaling FFAG: successfully developed in 2011
- Linear magnets
- Fast acceleration 15 turns for E=10→20 MeV
  - Resonance crossing : Tunes are varied largely during acceleration.
  - Serpentine path acceleration : Parabolic variation of time-of-flight with energy

EMMA Parameters & Layout

Energy range	10 – 20 MeV
Lattice	F/D Doublet
Circumference	16.57 m
No of cells	42
Normalised transverse acceptance	3π mm-rad

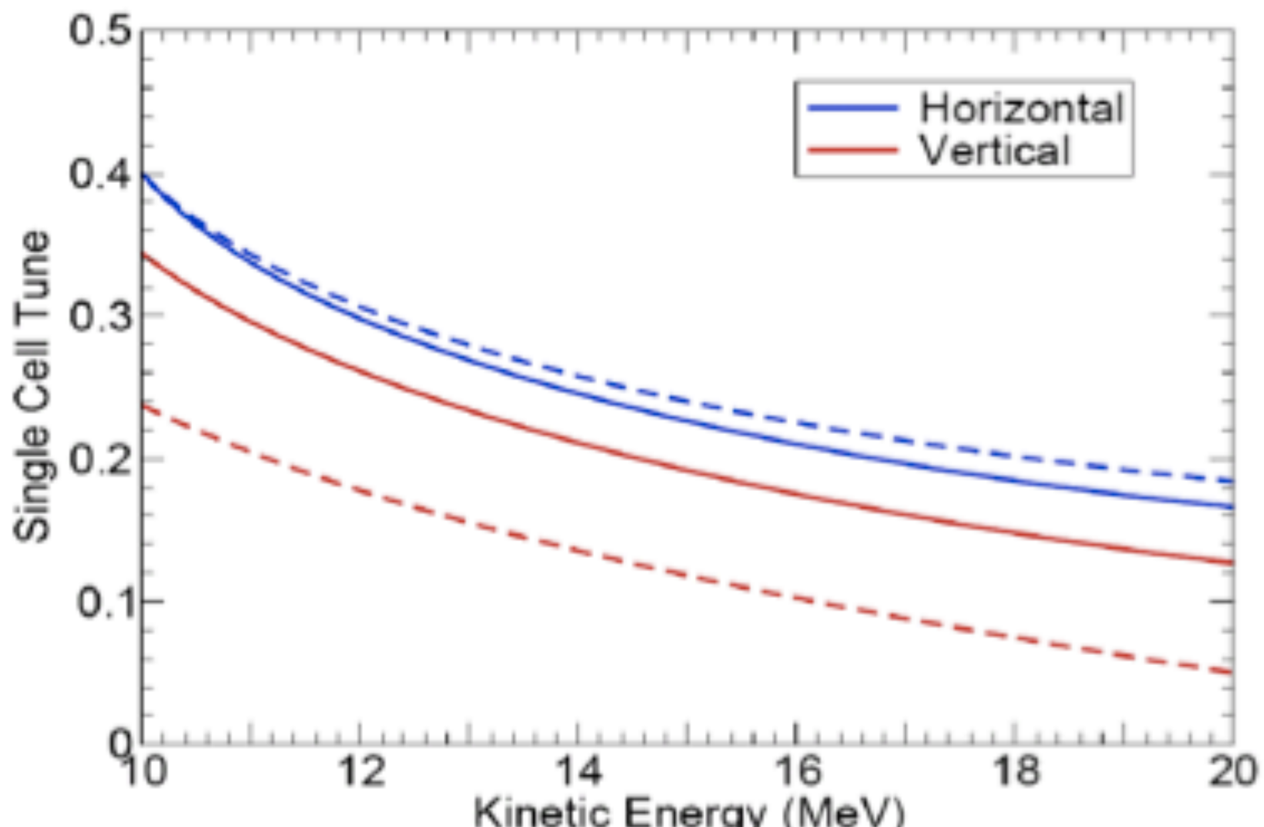
Frequency (nominal)	1.3 GHz
No of RF cavities	19
Repetition rate	1 - 20 Hz
Bunch charge	16-32 pC single bunch



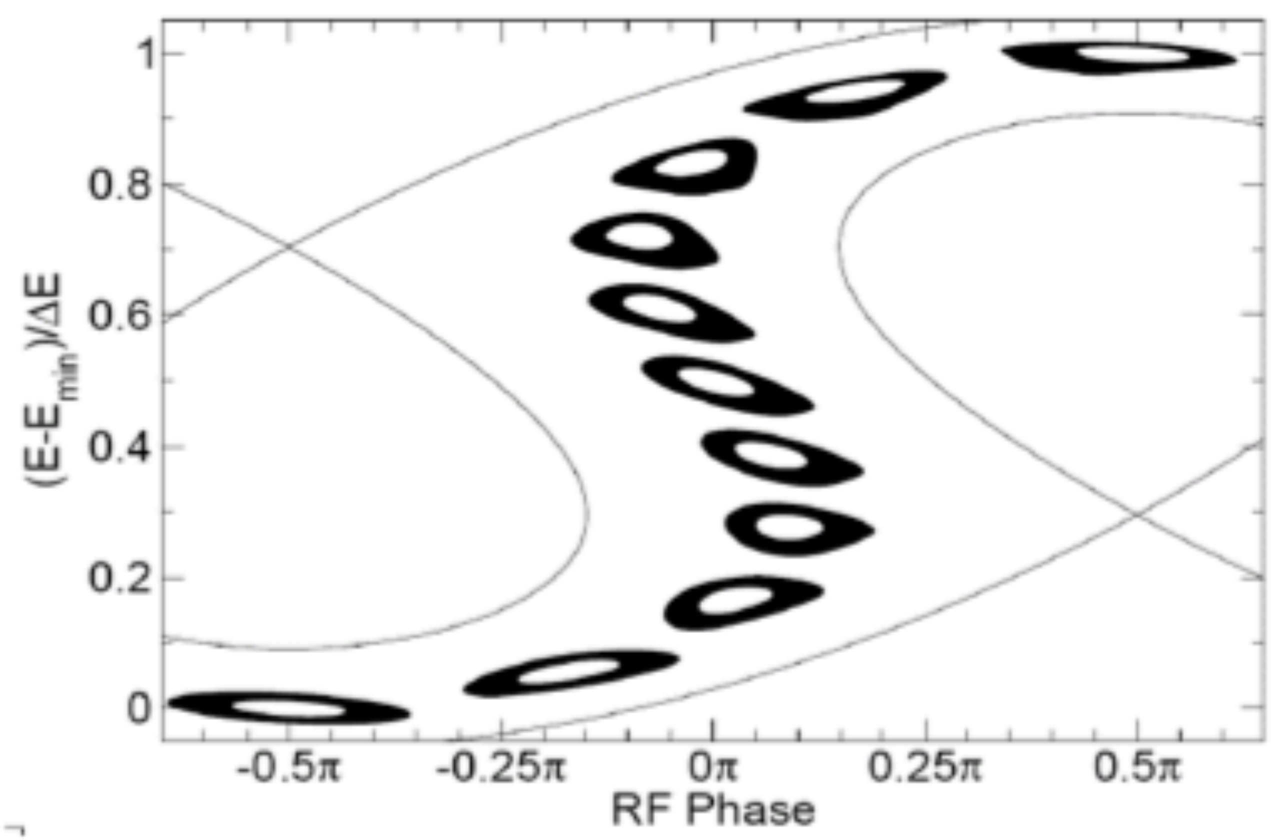
EMMA GOALS

Serpentine path in the longitudinal phase space

(1) Rapid acceleration with large tune variation (natural chromaticity)



(2) Serpentine acceleration (results from parabolic ToF)

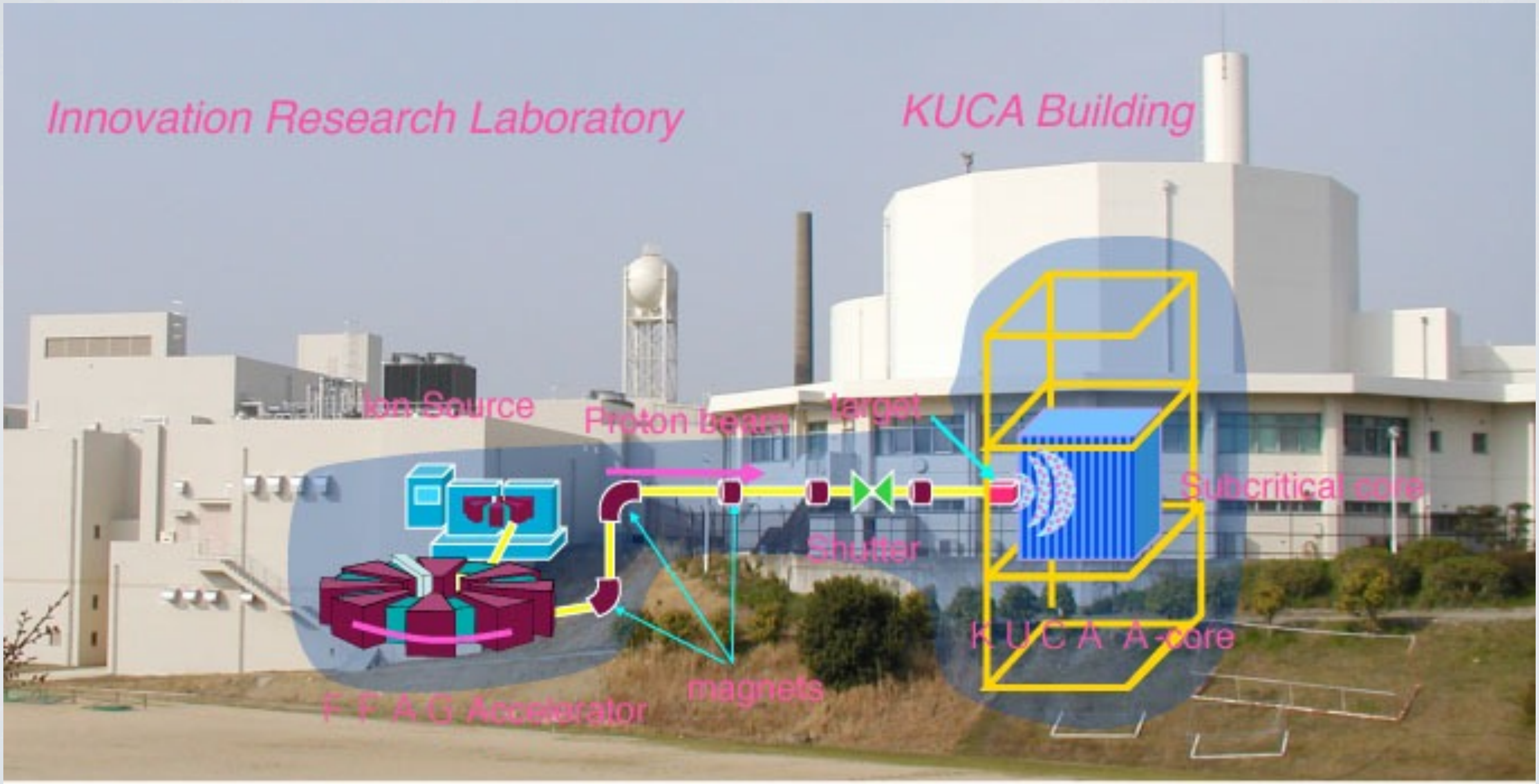


(3) Map the transverse and longitudinal acceptances.

HADRON FFAGS

FFAG-KUCA ADSR PROJECT

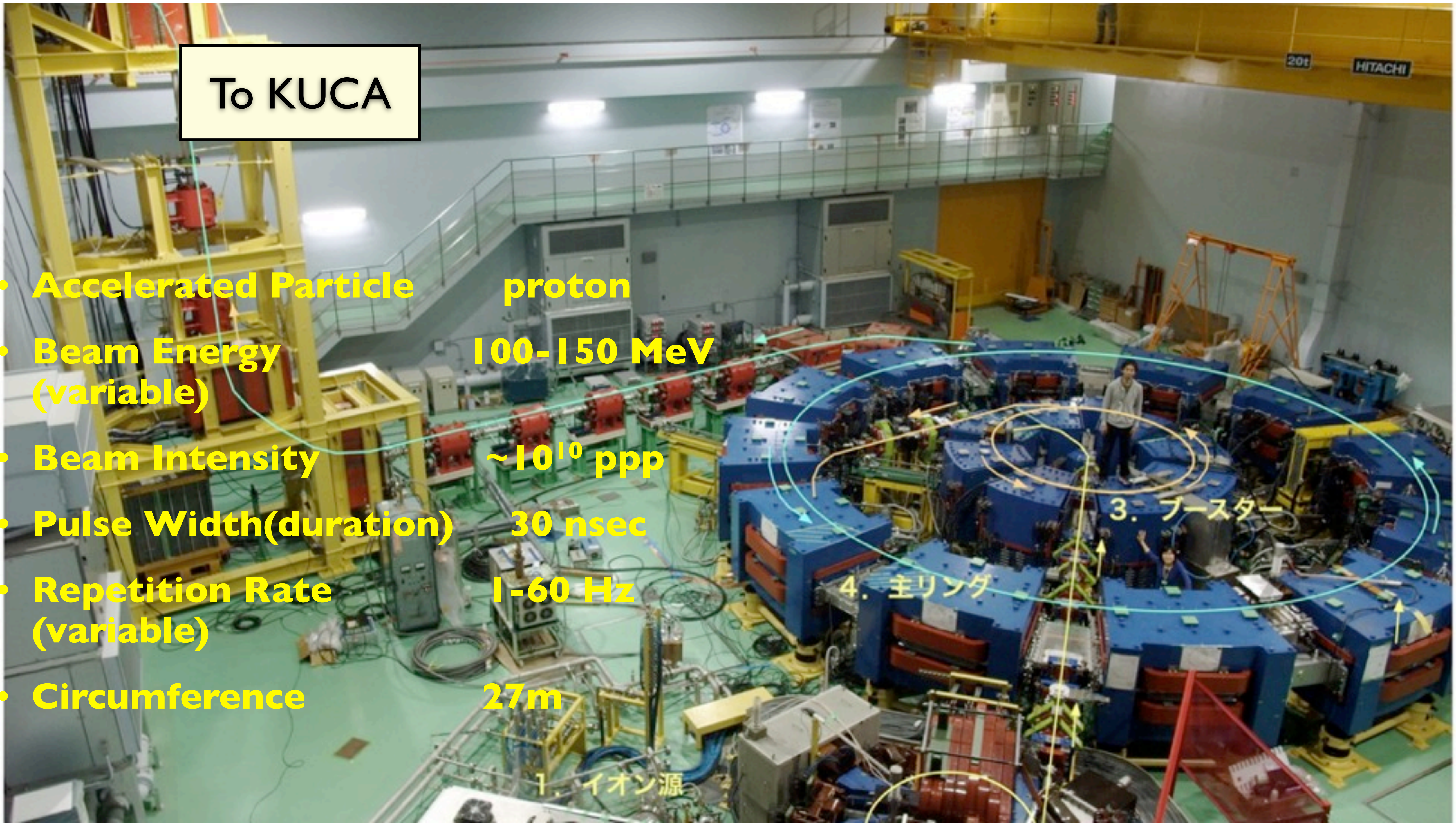
Kyoto University, Research Reactor Institute (KURRI)



FFAG accelerator complex

Intensity was upgraded with a new H- injection system in 2011.

~x100 times increased →reached ~10% level of space charge limit.



- **Accelerated Particle** **proton**
- **Beam Energy (variable)** **100-150 MeV**
- **Beam Intensity** **~10^{10} ppp**
- **Pulse Width(duration)** **30 nsec**
- **Repetition Rate (variable)** **1-60 Hz**
- **Circumference** **27m**

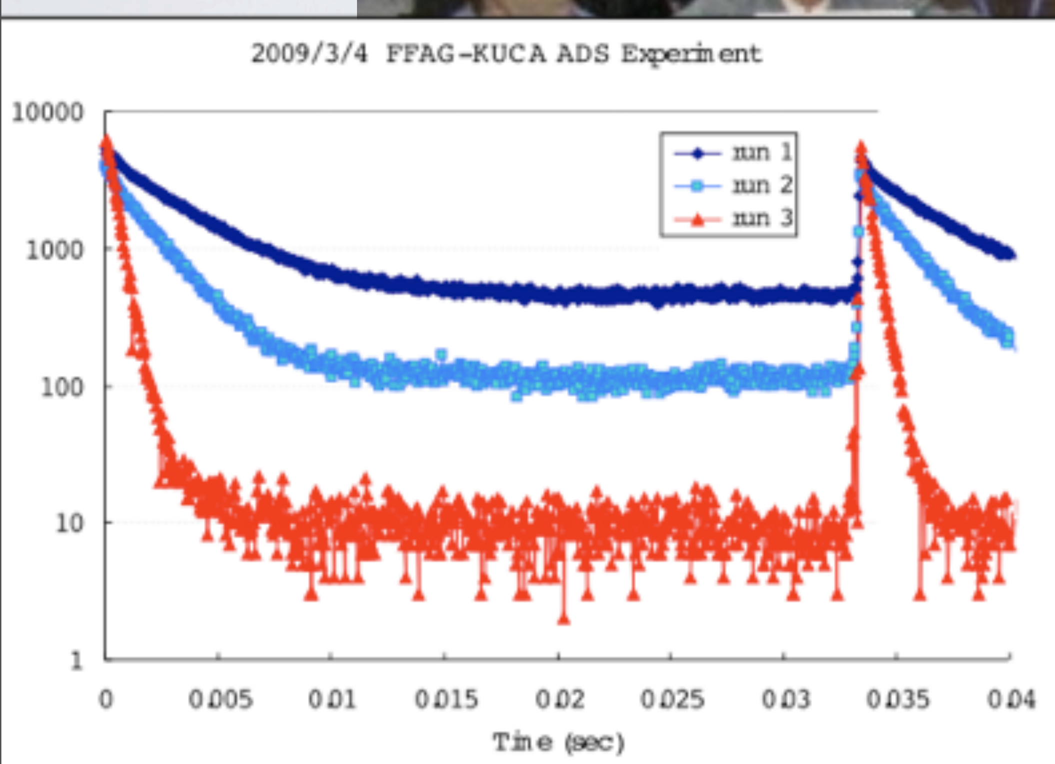
ADSR EXPERIMENT

WORLD FIRST ADSR EXPERIMENT WITH SPALLATION NEUTRONS

The fast FFAG being used for scientific application.

C.H.Pyeon et al.,, J. Nucl. Scie. Tech., Vol.46 No.12, pp.1091-1093(2009).

- *March 4, 2009: The first beam from FFAG was successfully delivered to KUCA.*
- *2010 & 2011:Thorium loaded ADSR experiments were carried out.*

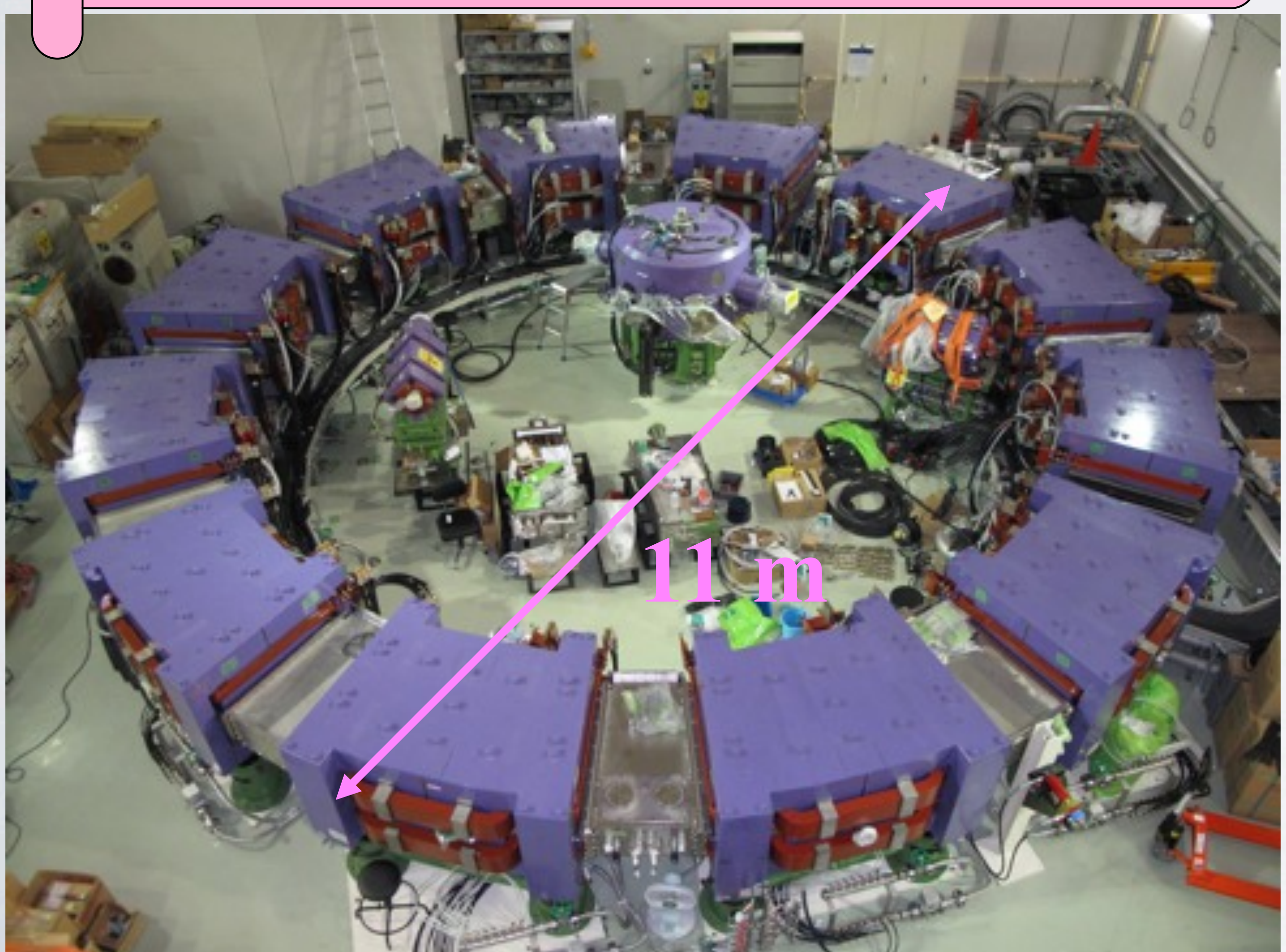


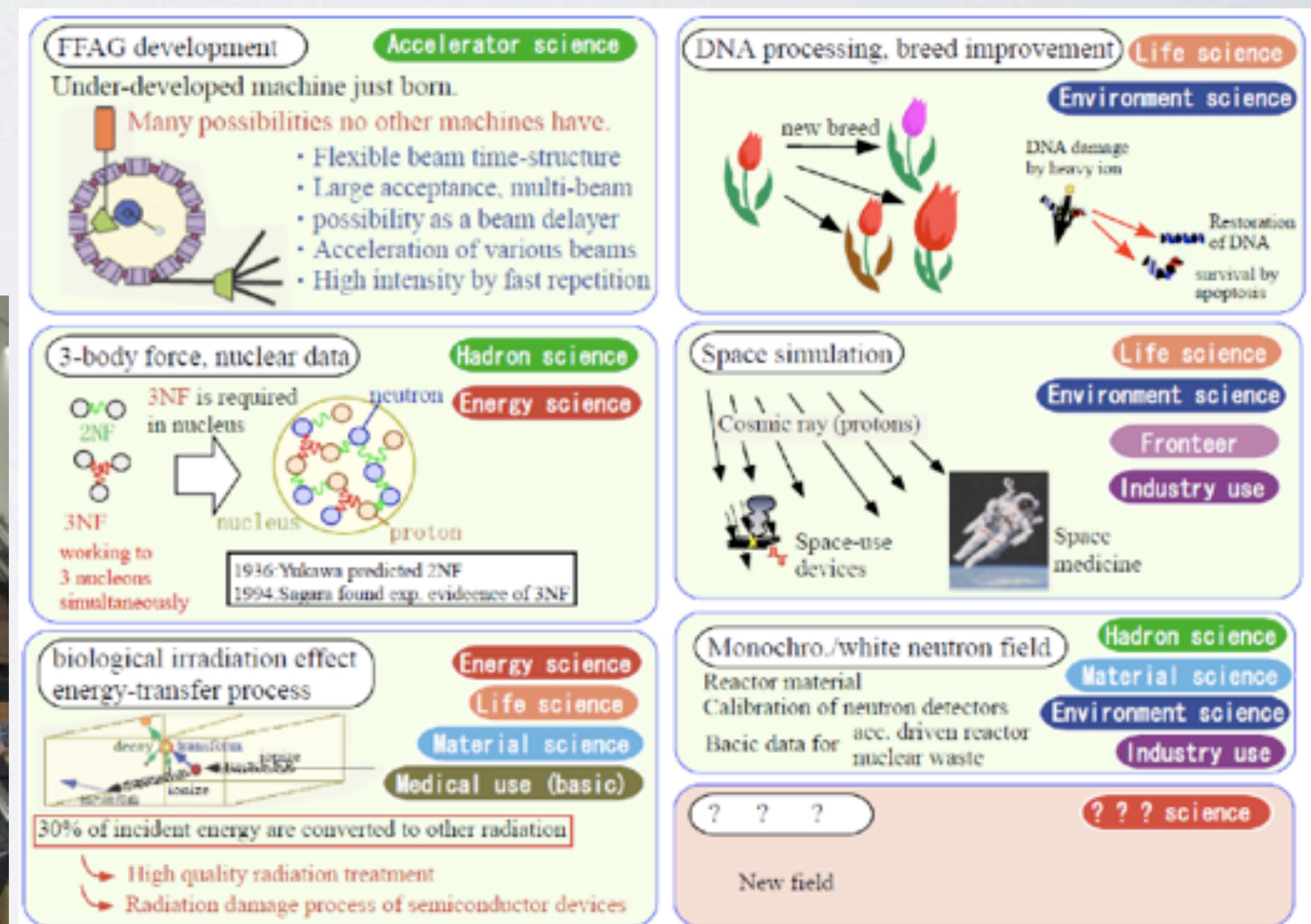
KYUSYU UNIVERSITY

Construction of new accelerator center

Main accelerator : FFAG Synchrotron

The test machine that Mori's group developed is under re-installation.



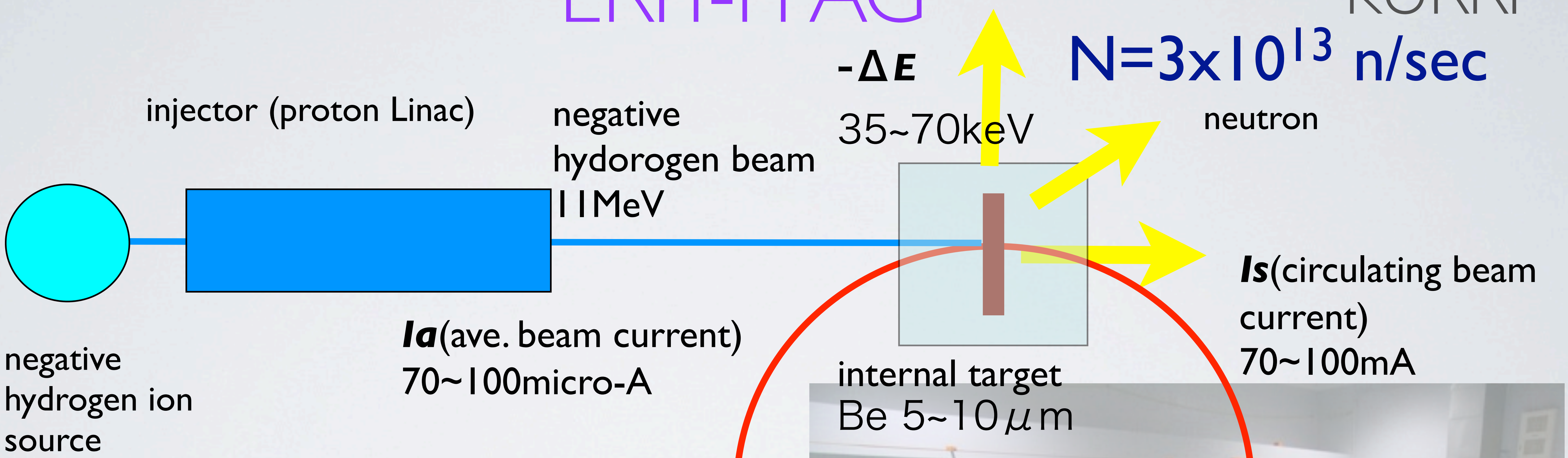


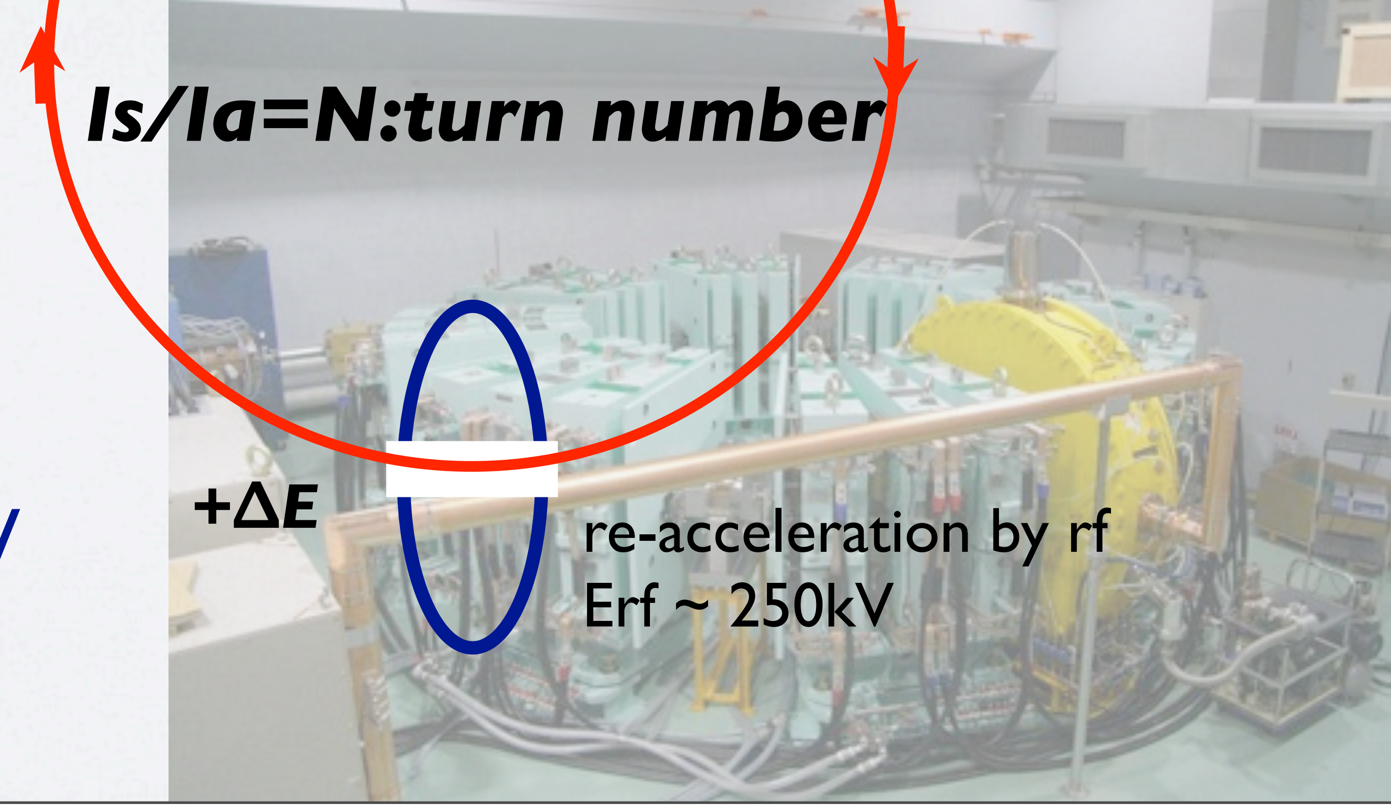
A machine with
various possibilities
Challenges for new usage

NEUTRON SOURCE WITH EMITTANCE RECOVERY INTERNAL TARGET

ERIT-FFAG

KURRI





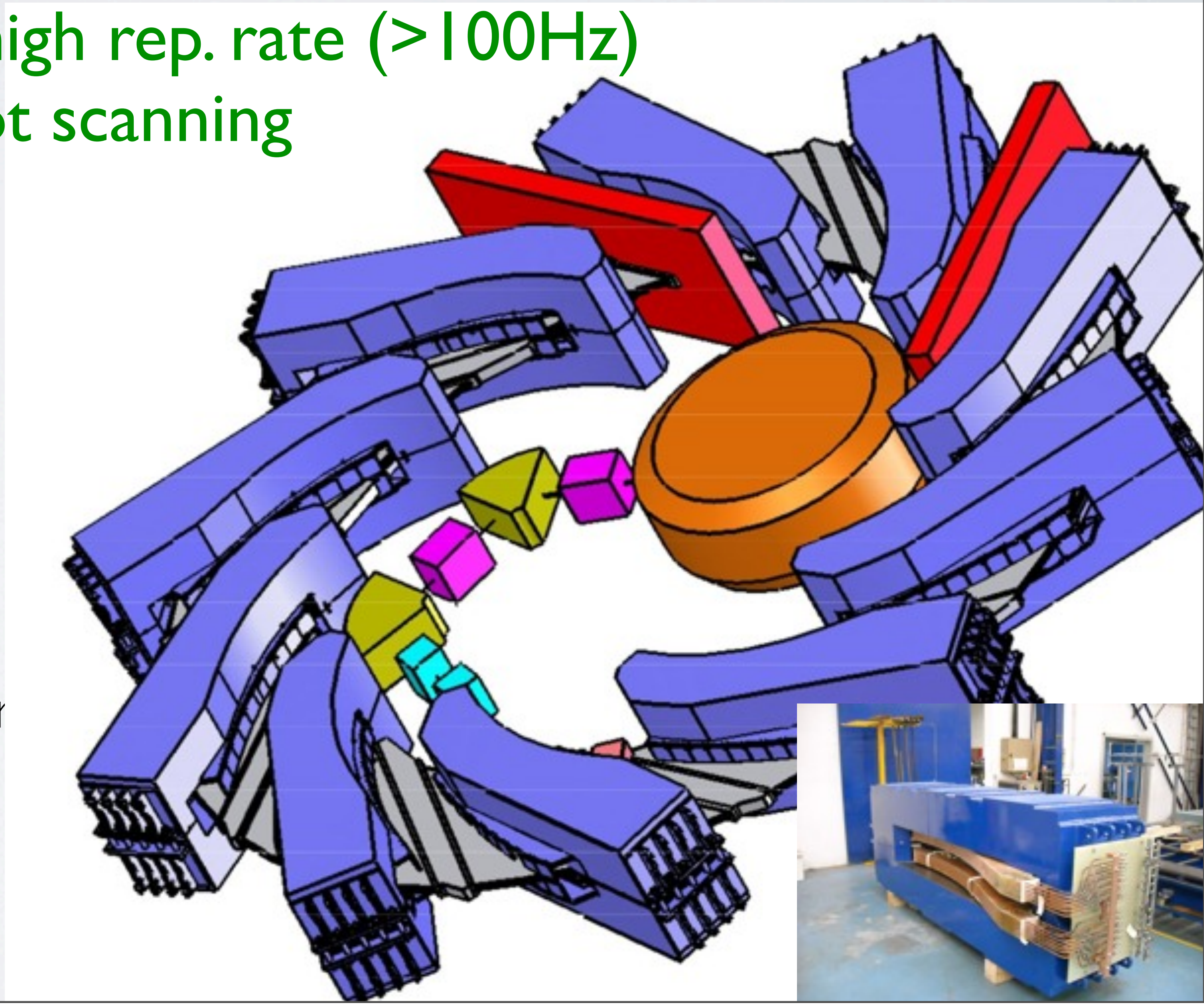
Scheme : Neutron production with internal target placed in the proton storage ring where the beam emittance and energy are cured by ionization cooling.

STUDY FOR HADRON THERAPY -RACCAM PROJECT-

F. Meot et al., Nucl. Instr. Meth., A602(3), pp.293-305(2009).

FFAG has a capability for high rep. rate (>100Hz) operation:suitable 3-D spot scanning

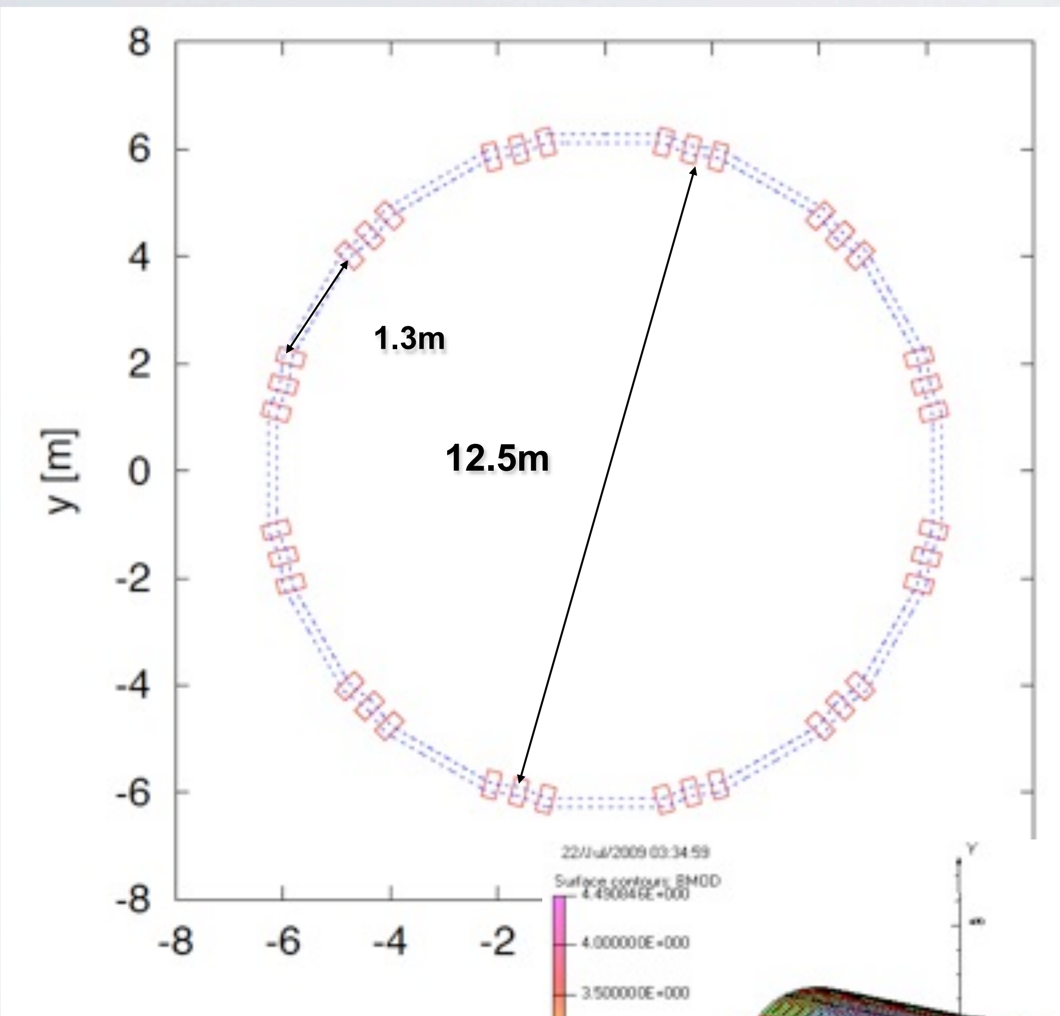
- The project also includes the prototyping of a spiral magnet capable of delivering the required r^k field law.
- Preliminary design study of a variable energy proton installation, based on a variable energy, 5 to 15 MeV H- injector cyclotron followed by a spiral lattice FFAG ring with 70 to 180 MeV extraction energy.

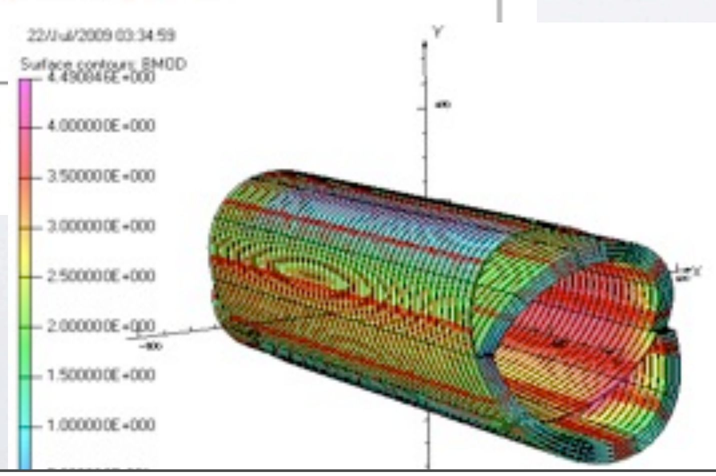


STUDY FOR HADRON THERAPY -PAMELA PROJECT-

T.Yokoi , Proc. of FFAG '09, FNAL

PAMELA Carbon ring





Energy	30~250MeV (for p) 8~70MeV/u (for C)
# of Cell	12
Radius	6.25m
Orbit excursion	18cm
Rev frequency	1.94~4.62MHz
Magnet	Triplet(FDF),SC
Magnet length	57cm
Magnet aperture	25cm
Max field	5T
Straight section	1.3m
Packing factor	0.48
Injection/extraction	1turn inj/ext 2 straight section(each)
RF	Max 8 straight section

ADVANCEMENT : AVAN-GARDE

ADVANCEMENT OF FFAG

- Two ways to overcome the betatron tune resonance-crossings during acceleration in FFAG.
  - Zero-chromatic optics → Scaling
    - Need orbit similarity & momentum independent focusing: Field configuration satisfying the criteria is obtained so far only for symmetric circular ring.
    - How about for others such as straight line, race-track ring, etc.? : NEED MORE GENERAL CONSIDERATION on ZERO CHROMATIC OPTICS.
  - Fast acceleration → Non-scaling, Scaling
    - Need fixed frequency RF acceleration.
    - How overcome a path length(TOF) difference problem? Either for non-scaling or scaling.

ZERO CHROMATICITY

NEW FINDINGS

JB Lagrange, Mori et al., TUPPC022, PhD Thesis

- Betatron oscillation ;local coordinate

$$\frac{d^2X}{ds^2} + \Gamma X = 0. \qquad \begin{cases} \Gamma = \frac{1}{\rho^2}(1-n) \text{: horizontal} \\ \Gamma = \frac{1}{\rho^2}(n) \text{: vertical} \end{cases} \qquad n = -\frac{\rho}{B}\frac{\partial B}{\partial X}$$

- More general criteria for zero chromaticity in circular ring we found.

- For circular ring, $s = R\Theta$, and $\rho = Rf(\Theta)$.

$$\begin{cases} \frac{d\left(R^2/\rho^2\right)}{dp} = 0 \\ \frac{d(n)}{dp} = 0 \end{cases} \rightarrow B(R,\Theta) = B_0\left(\frac{R}{R_0}\right)^k \bullet \exp\left[k_2\int_{R_0}^{R}\frac{\tan\varsigma(R)dR}{R}\right]F(\Theta)$$

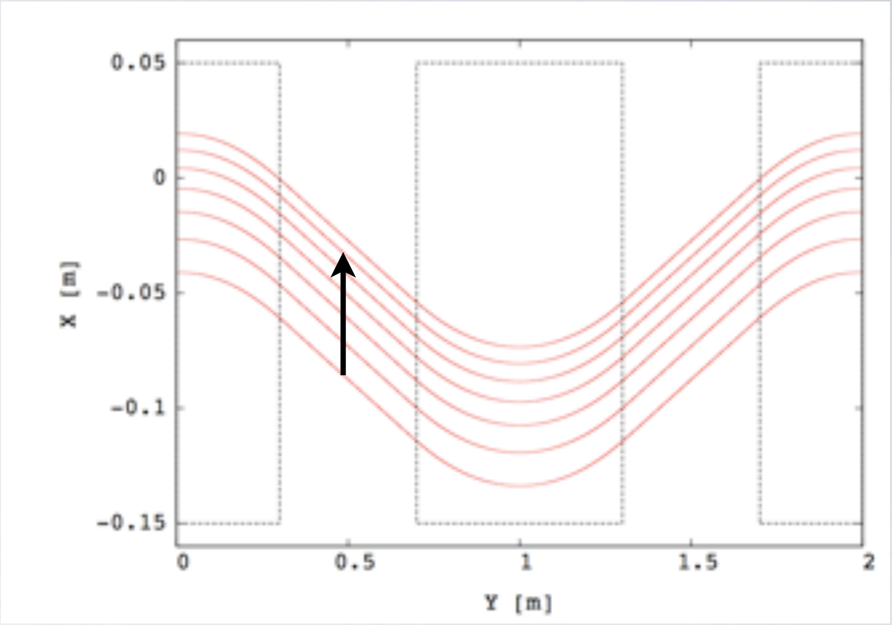
- For straight line,

$$\begin{cases} \frac{d(\rho)}{dp} = 0 \\ \frac{d(n)}{dp} = 0 \end{cases} \rightarrow B(x,s) = B_0 \exp\left[\frac{n}{\rho}x + m_2\int_{R_0}^{R}\tan\varsigma(x)dx\right]F(\Theta)$$

EXPERIMENT OF SCALING FFAG STRAIGHT LINE

Lagrange et al., (TUPPC022, IPAC'12)

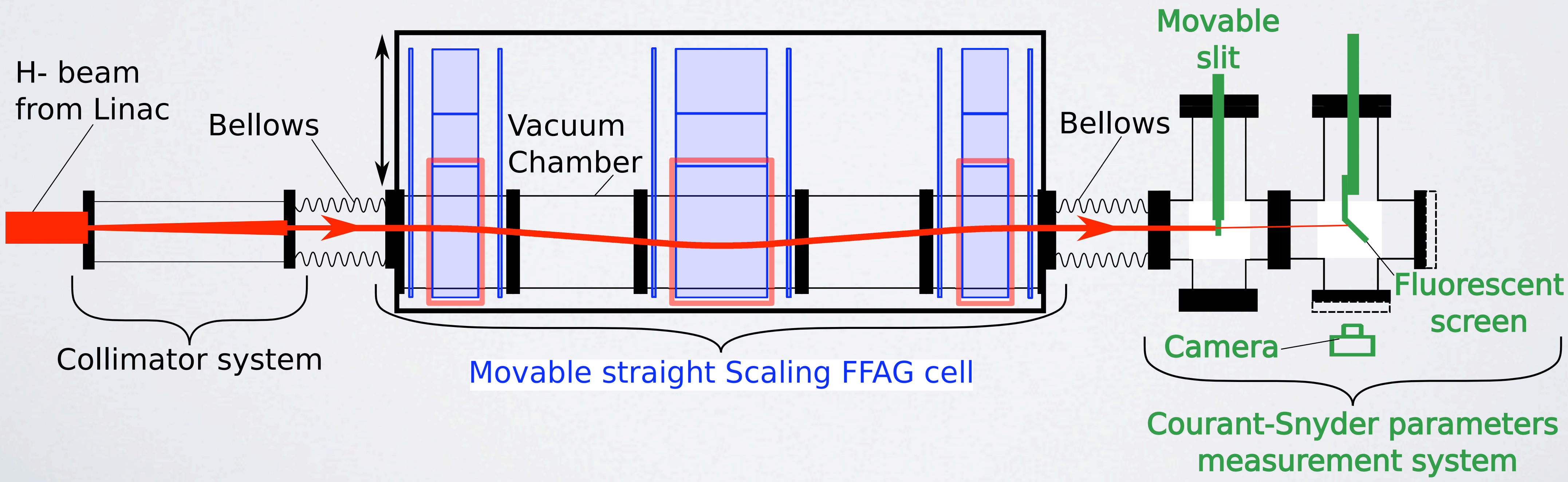
$$B_z = B_0 \exp\left[\frac{n}{\rho}x\right]$$



- Clarify the FFAG straight line experimentally with π-section
  - Dispersion suppressor
  - Insertion matching
- Momentum range
  - 0.0811 - 0.1441 GeV/c
  - H- ion beam

RESULT

	$\bar{x}_1$ (mm)	$\bar{x}'_1$ (mrad)	$\bar{\beta}_1$ (m)	$\bar{\alpha}_1$	$\psi_{exp.}$ (deg)	$\psi_{track.}$ (deg)
11 MeV	**2.0**	**-2.4**	**17.7**	**-1.5**	**87.5** ± 3.3	**87.5**
7 MeV	**1.8**	**-2.1**	**11.7**	**-1.0**	**86.1** ± 9.6	**87.6**



2012年5月22日火曜日

VERTICAL EXCURSION SCALING FFAG

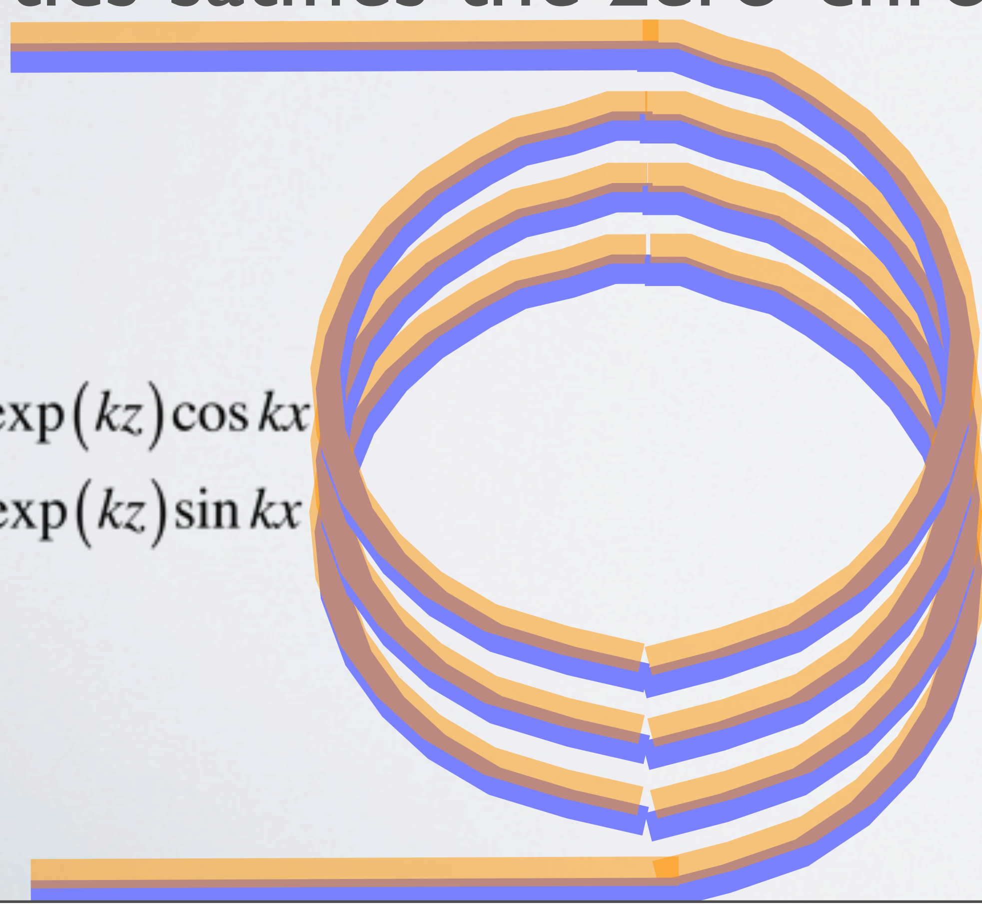
$$\begin{cases} \dfrac{d\left(R^2/\rho^2\right)}{dp} = 0 \rightarrow \begin{cases} R = const. \\ \rho = const. \end{cases} \\ \dfrac{d(n)}{dp} = 0 \end{cases}$$

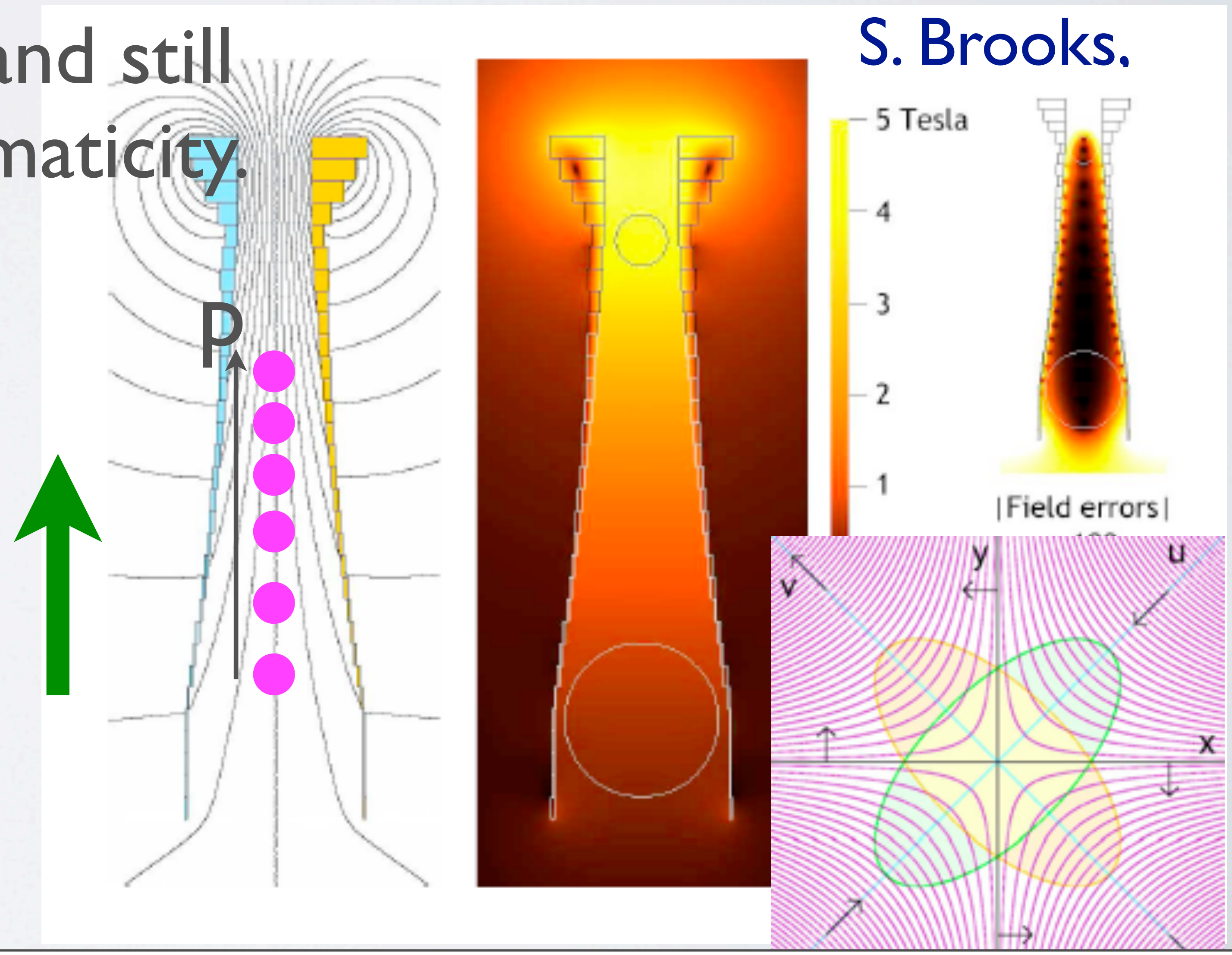
Brooks, IPAC10&11 & MOPPD019(IPAC12)

$$B_{z,x} = B_0 \exp\left(\frac{n}{\rho} z\right) \bullet f(x)$$

The beam moves up vertically and still its optics satifies the zero-chromaticity.

$$B_z = B_0 \exp(kz) \cos kx$$
$$B_x = B_0 \exp(kz) \sin kx$$





RACE-TRACK FFAG RING

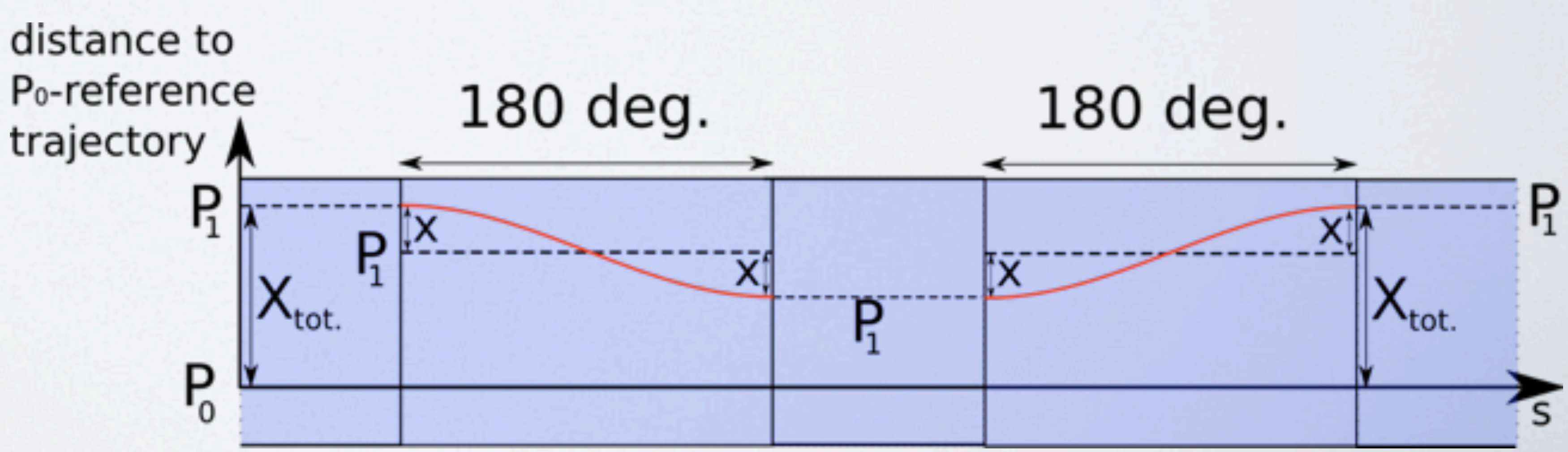
- Matching between circular and linear parts
- Insertion matching
- Matching condition for closed orbit between ring and straight line

ring — linear line

$$\left(1+\frac{x}{r_m}\right)^{k+1} = \exp\left(\frac{n}{\rho}x\right) \Rightarrow \boxed{\frac{k+1}{r_m} = \frac{n}{\rho}}$$

← 1st order

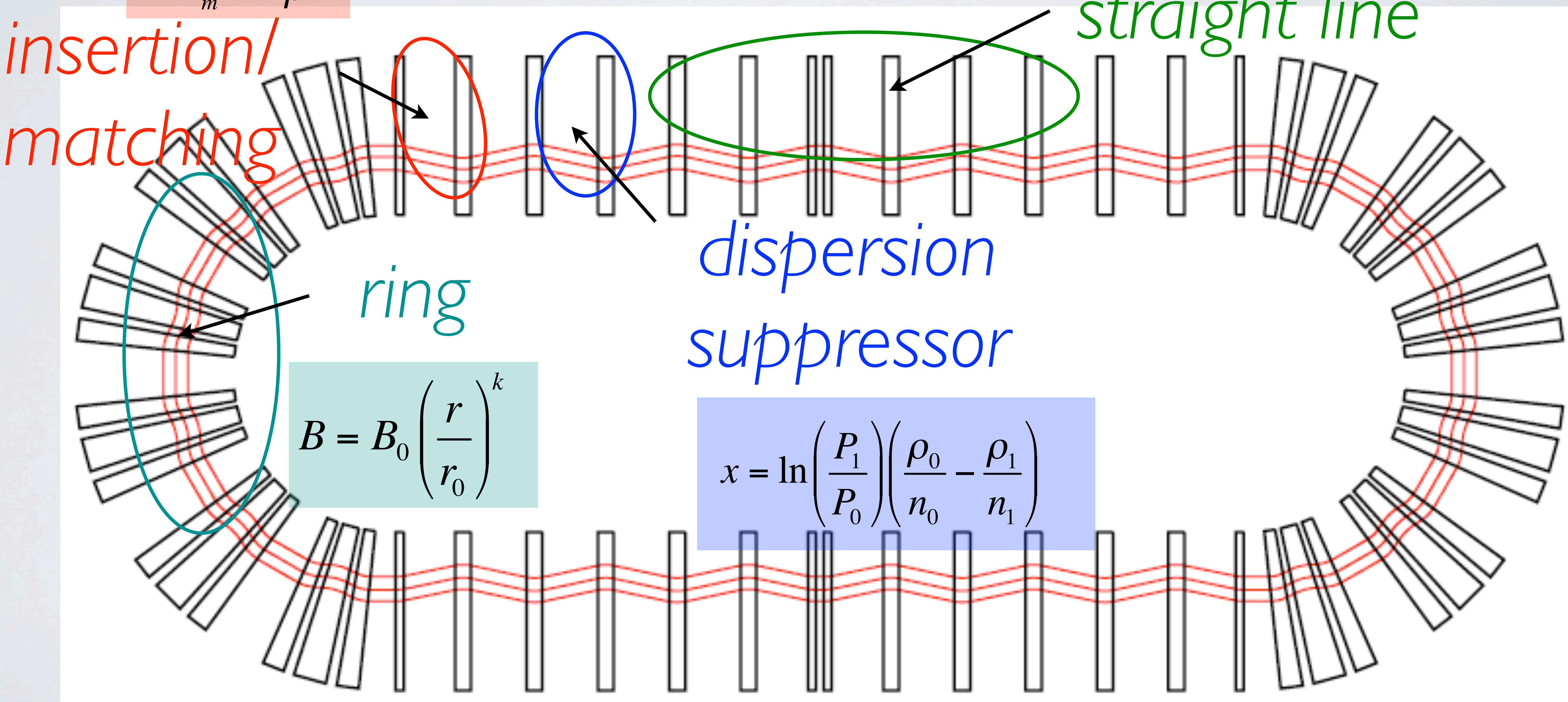
- Dispersion suppressor
- Successive π-cells in the horizontal plane can suppress the dispersion.
- Help to reduce the size of apertures of the magnet and rf cavity.
- $$x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$



ADVANCED SCALING FFAG -RACE TRACK FFAG RING-

$$B_z = B_0 \exp\left[\frac{n}{\rho} x\right]$$

$$\frac{k+1}{r_m} = \frac{n}{\rho}$$



$$B = B_0 \left(\frac{r}{r_0}\right)^k$$

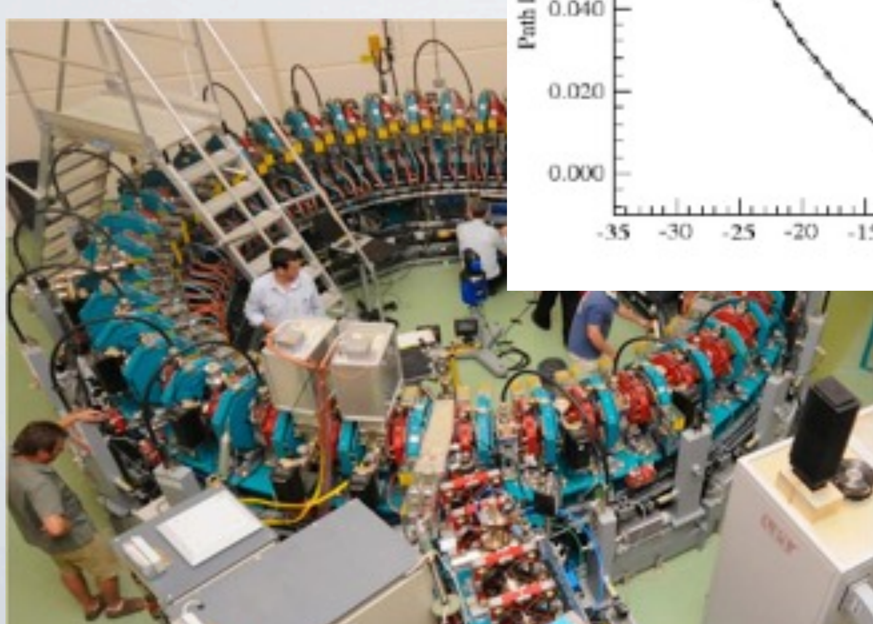
$$x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$

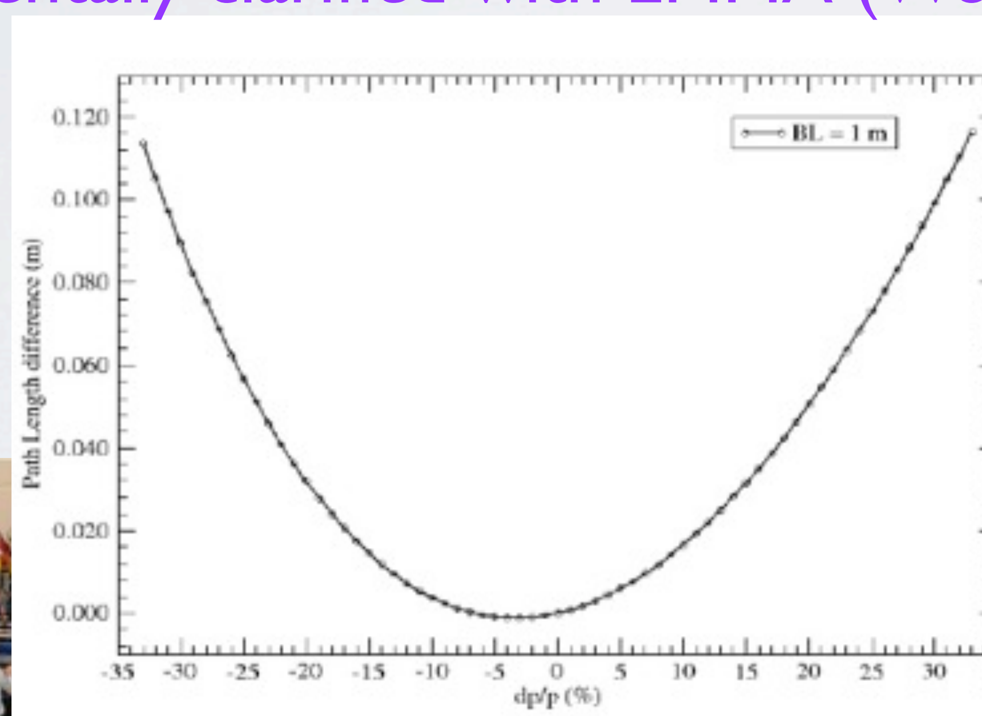
FAST ACCELERATION

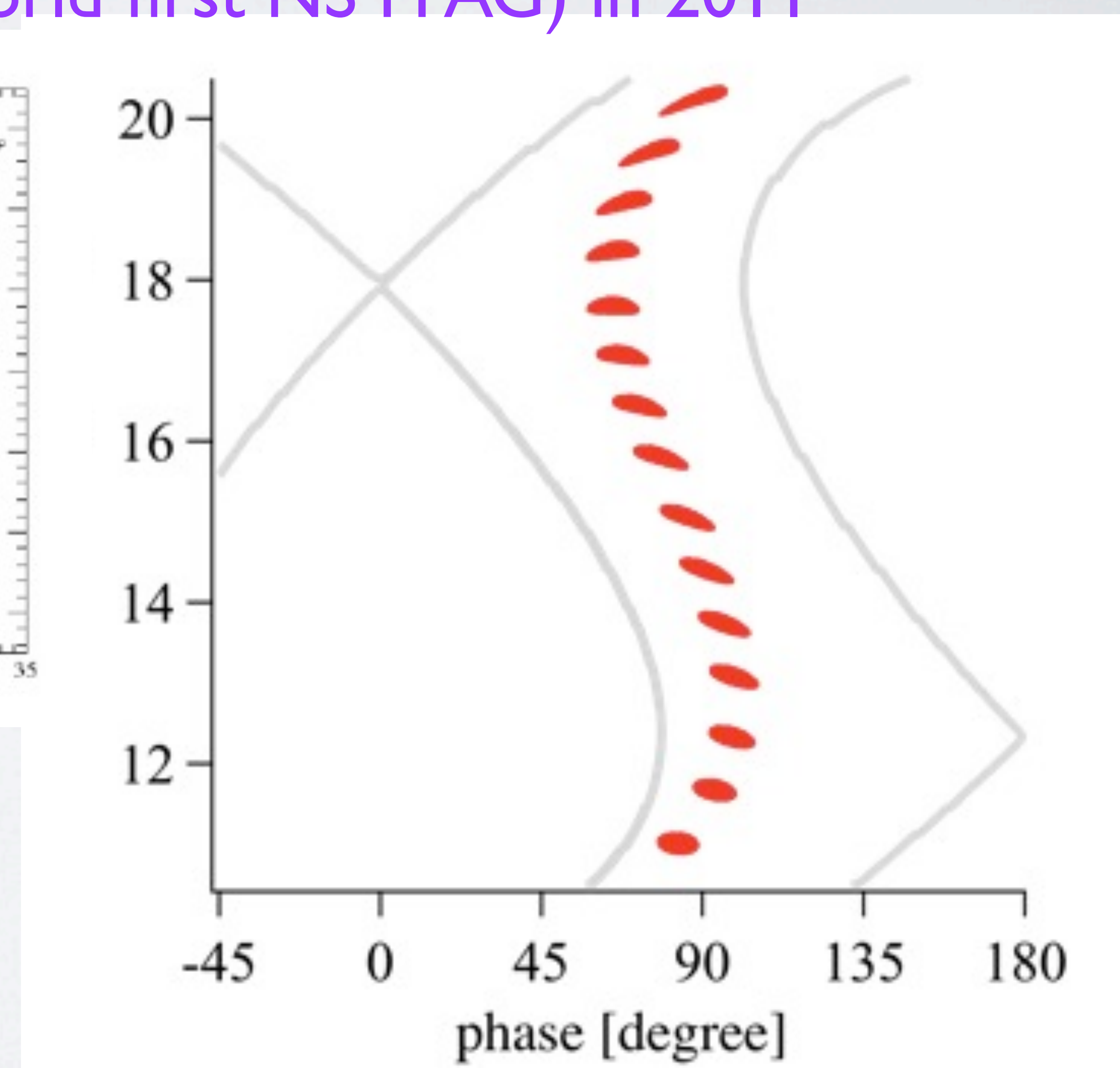
- FIXED FREQUENCY RF ACCELERATION -

SERPENTINE ACCELERATION

- Originally proposed for acceleration of non-scaling FFAG
    - Johnstone & Koschieniak, (Nucl, Instr, Meth., PR A503(2003)445.
    - Dejan et al., FFAG workshop FFAG'04.
- Small and parabolic momentum compaction in NS FFAG leads very small TOF difference for relativistic particle during beam acceleration.
- There is a serpentine path between two buckets in longitudinal phase space.
- Experimentally clarified with EMMA (World first NS FFAG) in 2011







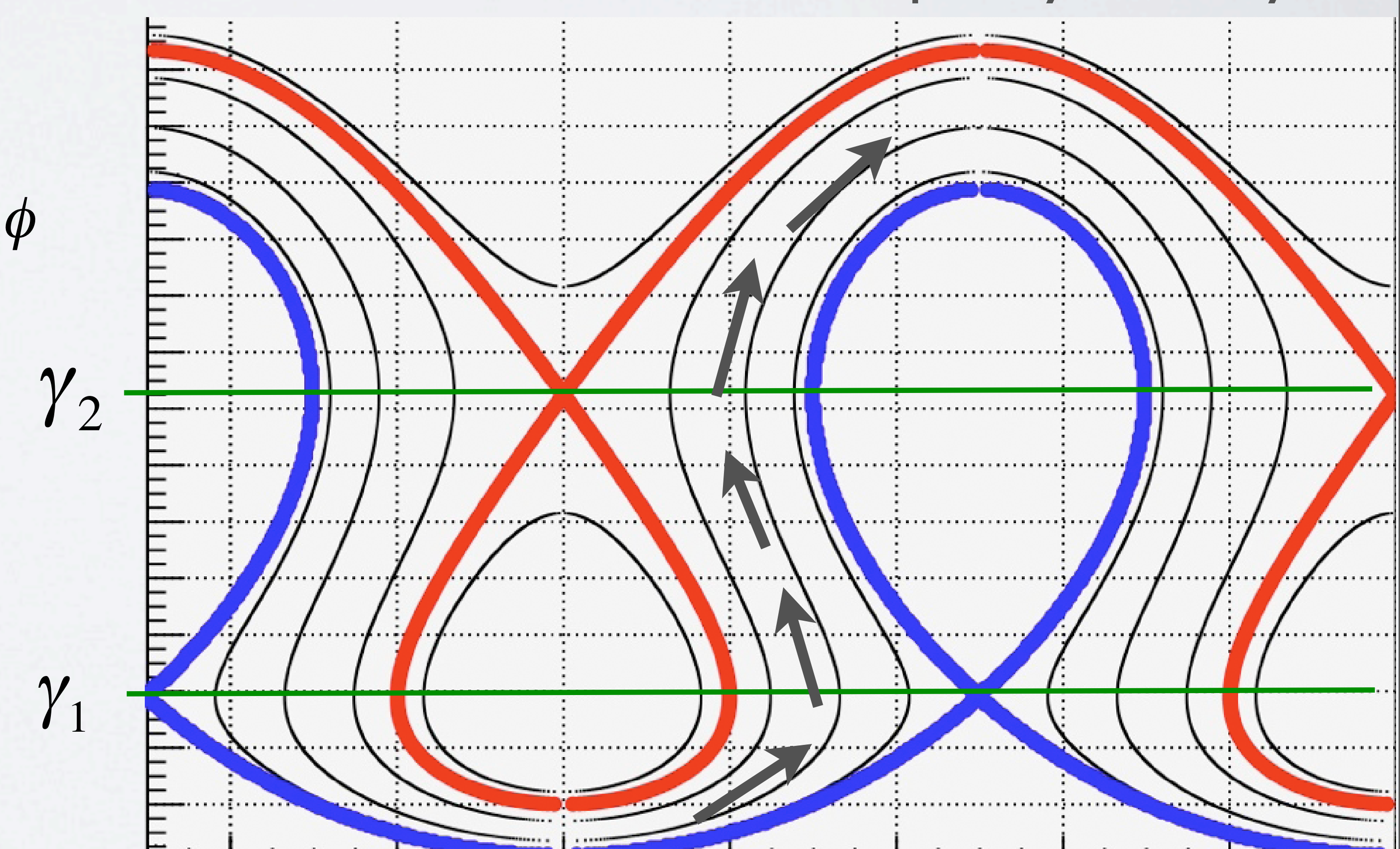
SERPENTINE ACCELERATION IN SCALING FFAG

- Two rf buckets below and above the transition energy are interfered in the strong focusing machine. Serpentine path between two buckets exist. (Sessler, Symon)
- In the scaling FFAG, hamiltonian of longitudinal motion can be obtained analytically. (Yamakawa, et al., cf. WEPPR006, IPAC'12)
  - Either relativistic or non-relativistic beam can be accelerated with fixed frequency rf cavity

$$H = 2\pi m_0 c^2 \left[\frac{\left(\gamma_s^2 - 1\right)^{\lambda}}{2\gamma_s} \frac{\left(\gamma^2 - 1\right)^{-\lambda+1}}{(1-\lambda)} + \gamma \right] + e\frac{V_{rf}}{h} f_0 \cos\phi$$

$$\lambda = \frac{k}{2(k+1)}$$

$$\frac{dp}{dT} = 0 : \quad p = \gamma_1 \text{ and } \gamma_2$$



10MeV Electron Accelerator

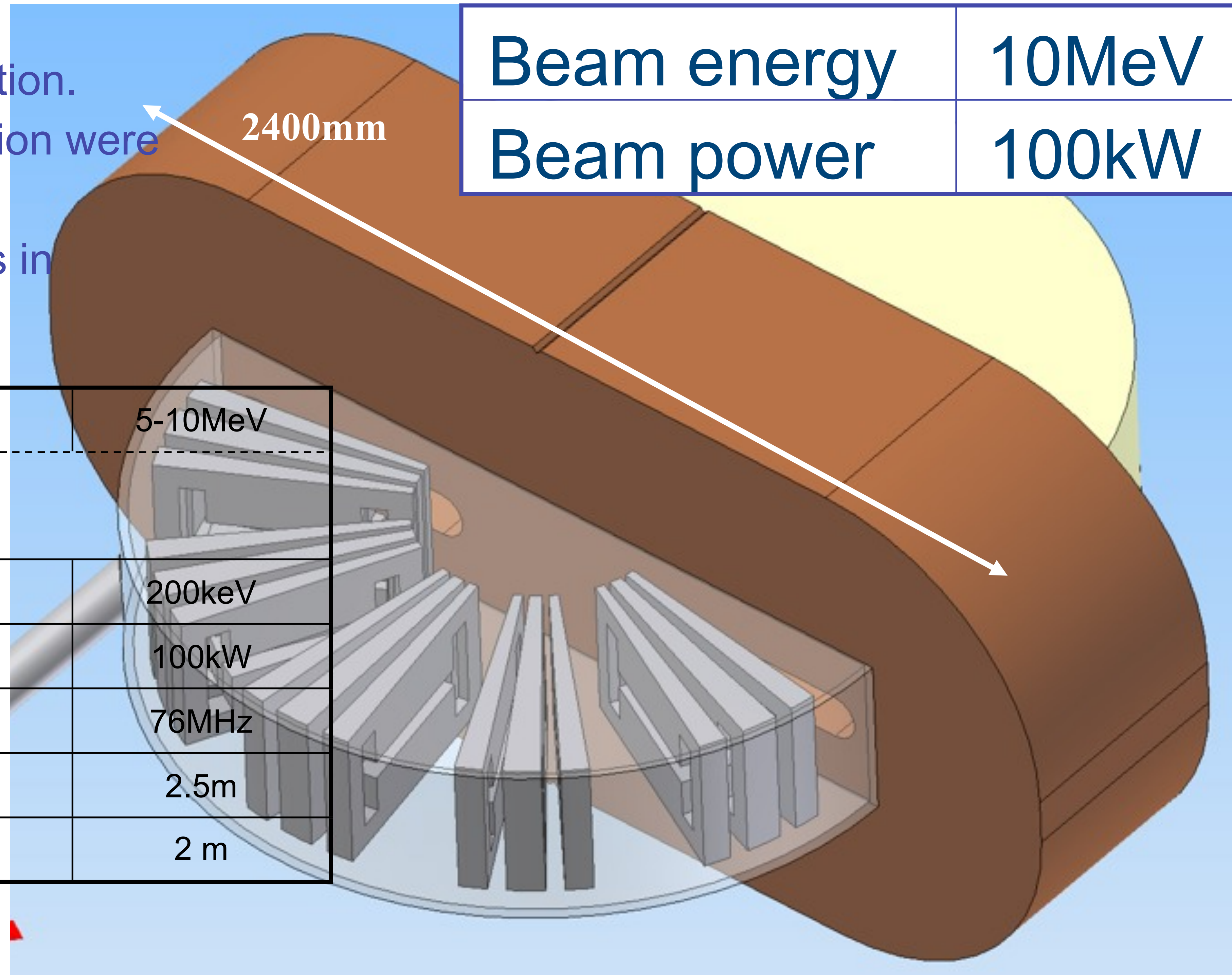
*Scaling FFAG

*Fixed frequency RF acceleration.

*Beam acceleration & extraction were successfully carried out.

*Increasing the beam power is in progress.

Beam energy	10MeV
Beam power	100kW



Energy range of output beam	5-10MeV
Electron beam for all energy range can be used with only one port.	
Injection energy	200keV
Beam power	100kW
Acceleration frequency	76MHz
Diameter of accelerator	2.5m
Height of accelerator	2 m

NHV Corporation

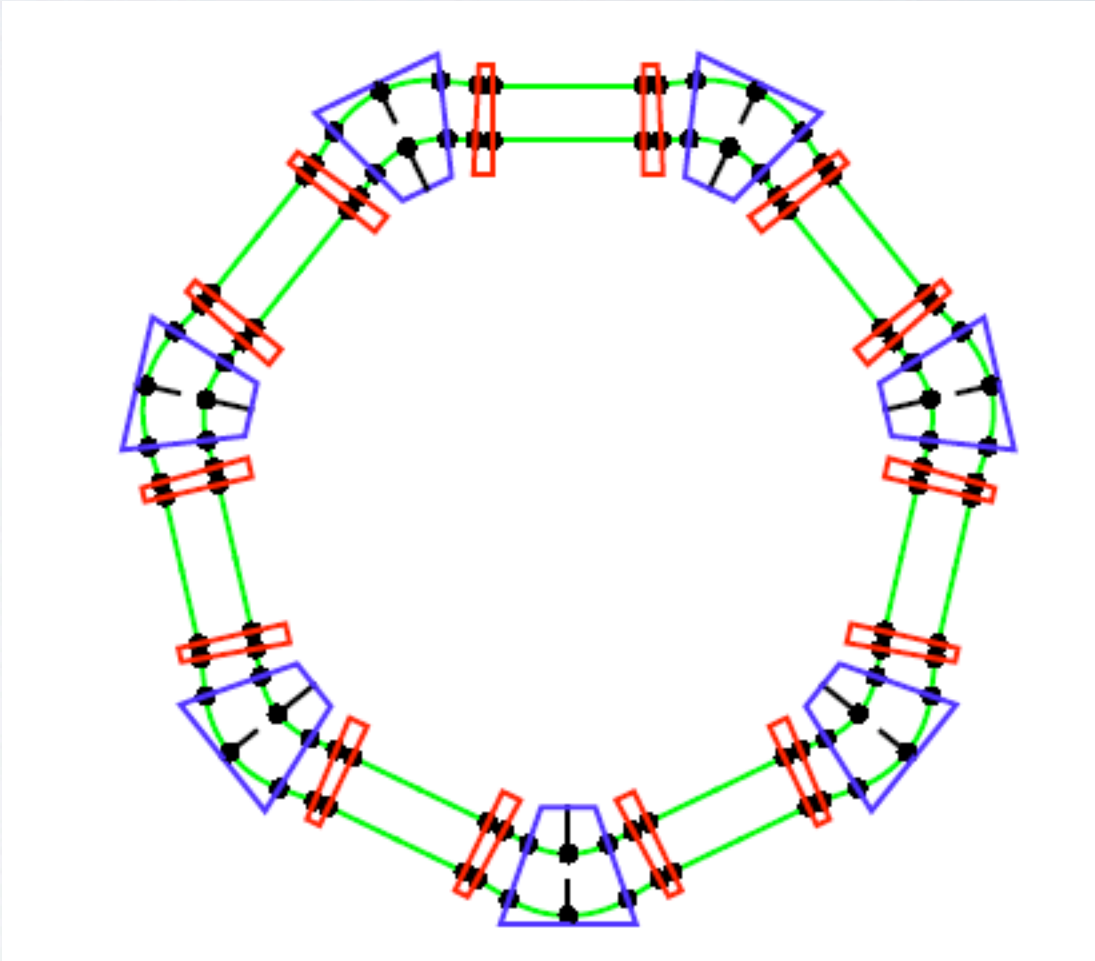
ADVANCED FFAGS FOR APPLICATIONS

FFAGS FOR ADSR

- Johnstone et al., (this conf. THPPR063)
  - (Semi) Isochronous NS(or semi-S) FFAG
  - Fixed frequency RF acceleration
  - CW beam acceleration

Table 3: General parameters, 7-cell 1 GeV FFAG.

Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	4.354	4.816	5.126
ν_x/ν_y (cell)	0.250/0.250	0.243/0.242	0.252/0.251
Field F/D [T]	3.3/−0.07	3.3/−0.7	3.8/−3.0
Magnet Size F/D [m]	0.79/0.25	1.10/0.25	1.67/0.25



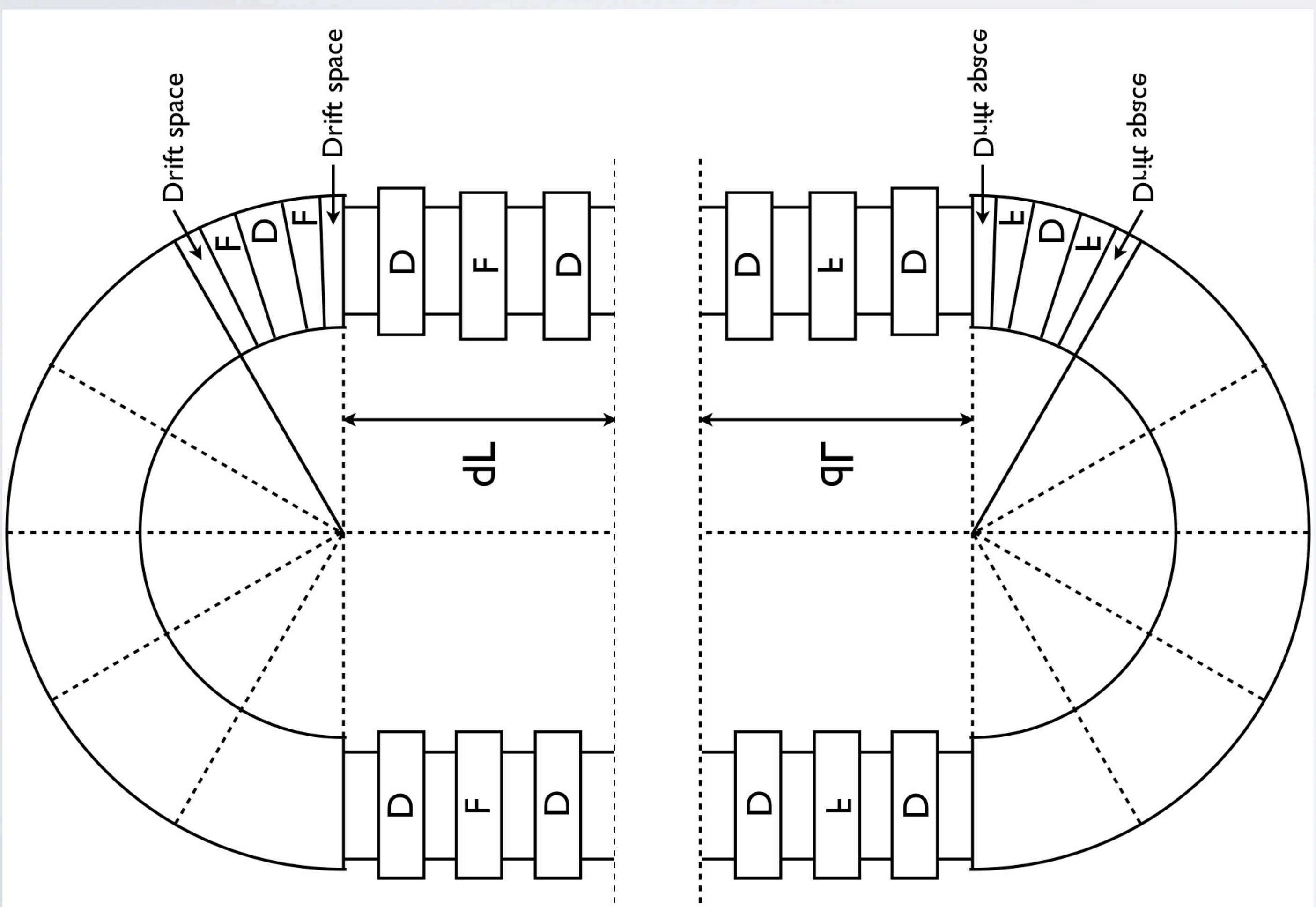
ADVANCED SCALING FFAG FOR ADSR

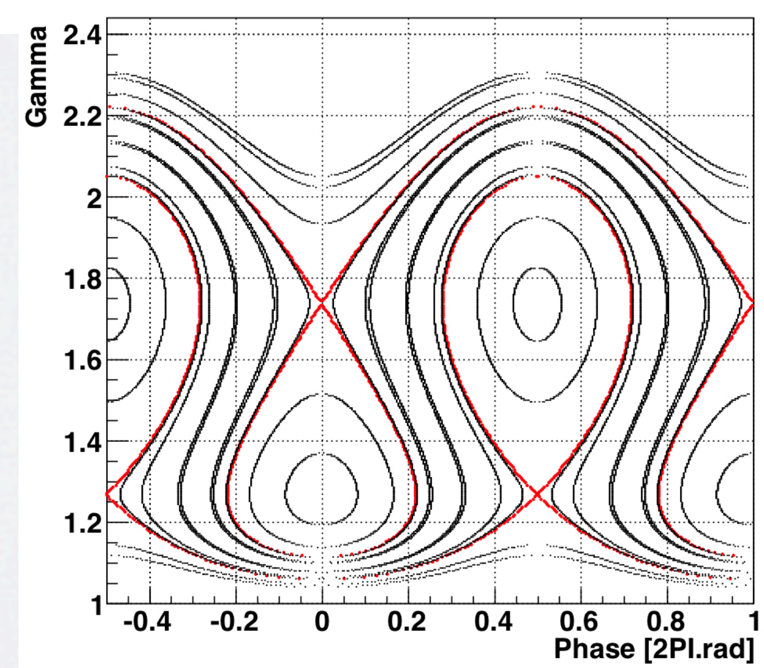
- Yamakawa, WEPPR006, IPAC'12
  - Race-track scaling FFAG
  - Fixed RF frequency acceleraton :CW beam
  - Serpentine acceleration

Fixed-filed & fixed frequency & AG focus
→ F^4AG accelerator

E=2.5GeV proton FFAG

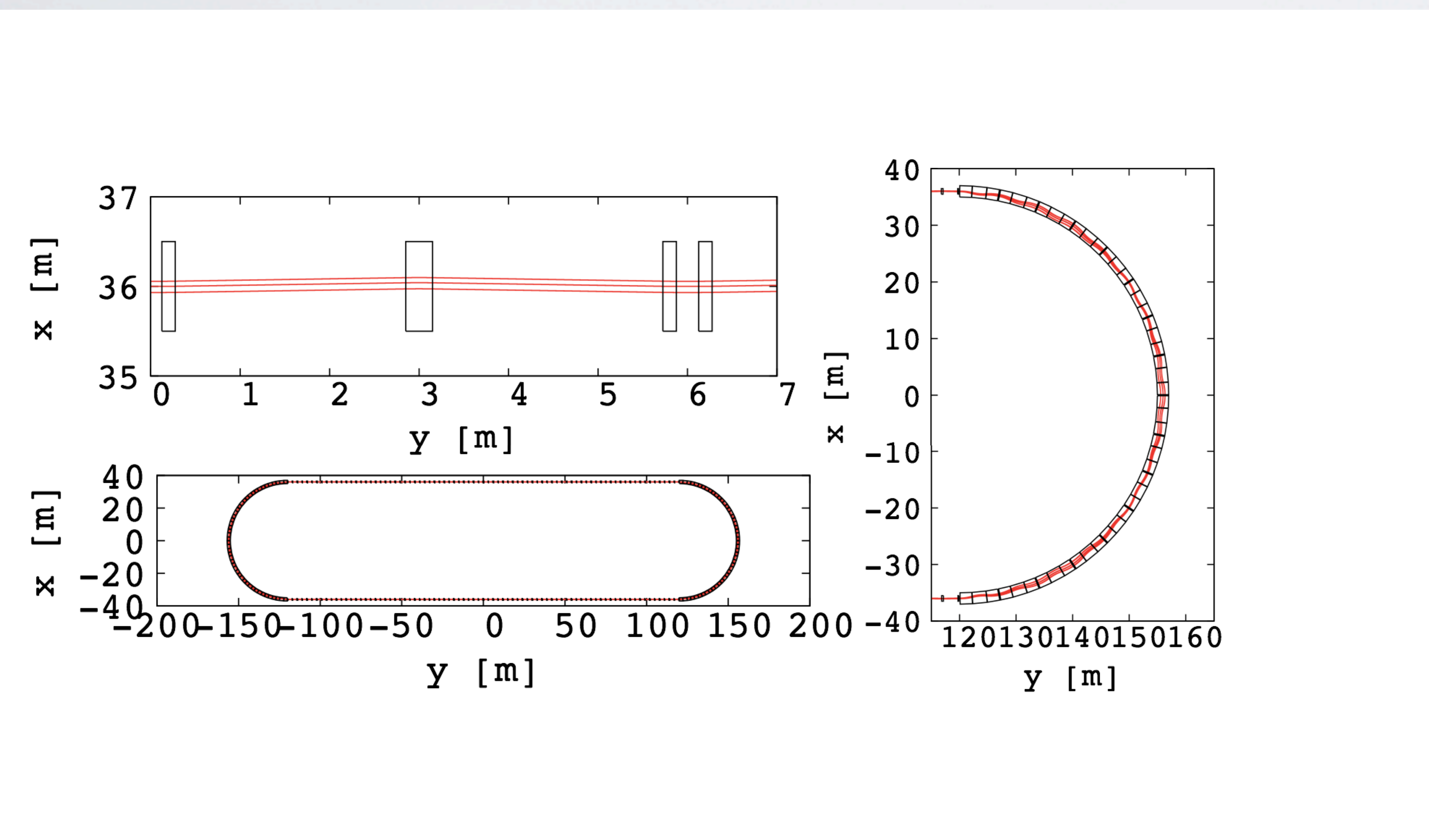
k at circular section	2.8
Mean radius of the arc part (500 MeV) [m]	10
Long straight section [m]	12
Stationary energy below transition[MeV]	820
rf voltage [MV/turn]	23 (h=1)
rf frequency [MHz]	2.75 (h=1)

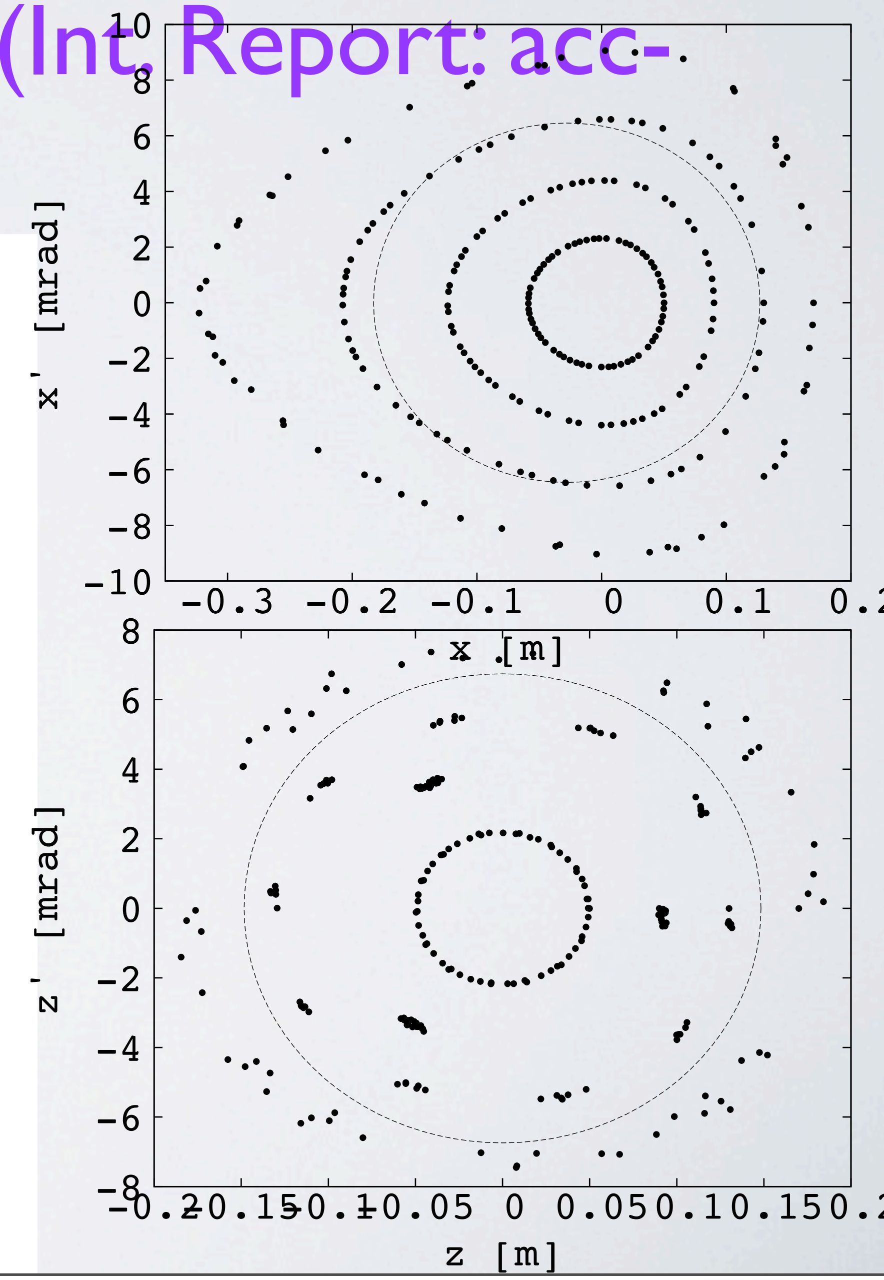




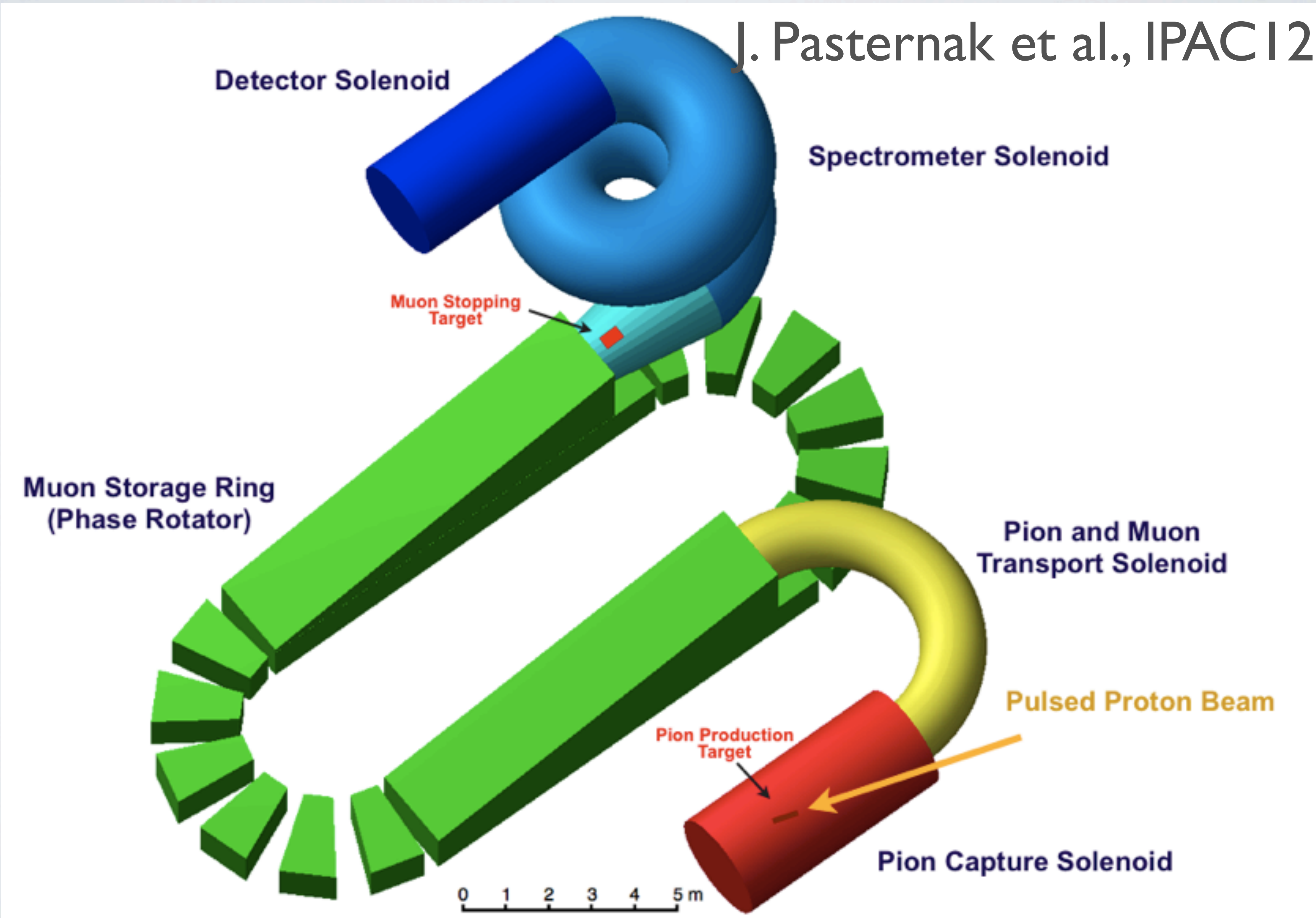
FFAG FOR MUON DECAY RING -LOW ENERGY NEUTRINO FACTORY -

- Muon energy 3.8GeV/c, Δp/p>+-16%, A>30mm.rad
- VLENF project by A. Bross (NuFact'11)
- Race-track FFAG ring : Lagrange & Mori (Int. Report: acc-kurri-0508-01-2012)





SCHEMATIC LAYOUT OF PRISM WITH ADVANCED FFAG



SUMMARY

- Dawn of FFAG 1950-60s
  - Discovery of scaling optics for circular ring : Radial & Spiral lattice , Okawa, Symon, Kolomenskii
  - **e-models in MURA: Induction acceleration**
  - Difficulty in 3-D magnet design
  - Difficulty in RF acceleration
- Rebirth of FFAG 2000s
  - 3-D magnet design & 6-D phase space beam tracking.
  - RF acceleration : MA cavity
  - **Since 2000, 11 operational FFAGs were constructed at 6 institutes in the world.**
- Advancement of FFAGs 2010s,~
  - Scaling FFAG straight line: Race-track ring, Vertical beam excursion FFAG
  - Resonance extraction/injection
  - Fixed frequency acceleration : Serpentine path, Stationary bucket, Harmonic number jump
  - **e-FFAG EMMA, NHV, VLENF, PRISM**
  - **p-FFAG for ADSR**
    - *Advanced FFAG could be the only ring accelerator that can compete with linac for future applications such as ADSR, Muon accelerator.*
    - *→My very personal prospects.*

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FFAG → F^4AG

Fixed Field &
Fixed Frequency
AG focus