FFAG Accelerators and Their Applications

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Introduction

- Features
- History of development

FFAG: Fixed Field Alternating Gradient

- Strong focusing (AG focusing, phase focusing)

  It is like synchrotron.
- Orbit excursion

  It is like cynclotron, but not much.
- Free from betatron resonances
  - Fixed tunes(constant phase advance/turn) :*Scaling FFAG*

    Zero-chromaticity -fields are non-linear-
  - Fast resonance crossing : *Non-scaling FFAG*

    Linear optics
- Beam acceleration
  - Variable frequency : like synchrotron
  - Fixed frequency : like cyclotron

Advantages of FFAG

- Fast acceleration
  - DC magnetic field allows the beam acceleration only by RF pattern. No needs of synchronization between RF and magnets.
- High intensity with large repetition rate and modest number of particles in the ring
  - Space charge and collective effects are below threshold.
- Large acceptance
  - Transverse (hor.)>10,000mm.mrad
  - Longitudinal dp/p>10%

FFAG Accelerators Hisotry

- *Ohkawa (1953), Kerst & Symon, Kolomenski*
  - *MURA project e-model, induction acceleration ~'60s*
- *No practical machine for 50years!*
  - *Complicated magetic field configuration : 3D design*
  - *RF cavity :Variable Frequency & High Gradient.*
  - **Proton FFAG!** (world first)

-----> PoP FFAG @KEK,1999

History of FFAG Proton Accelerator

- 1953: Basic concept by Ohkawa

  Proton FFAG accelerator was not successful until recent

  →difficulty in fabricating RF cavity with variable frequency & high gradient field

- 1998: Development of RF cavity using Magnetic Alloy

  Grant-in-Aid for Scientific Res. by MEXT: Y. Mori, KEK

- 2000: Demonstration of Proton FFAG Accelerator -POP FFAG-

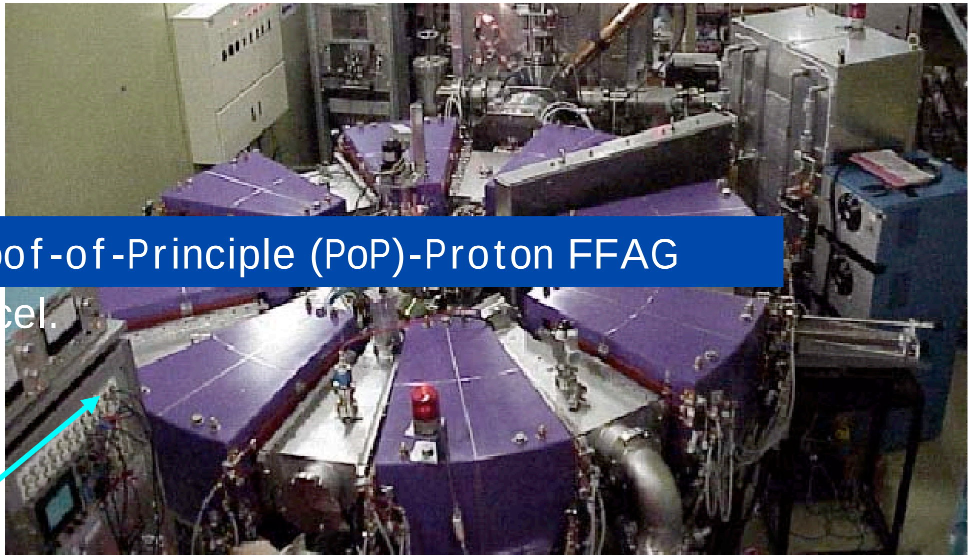
  Grant-in-Aid for Scientific Res. by MEXT: Y. Mori, KEK

  WORLD's FIRST PROTON FFAG!

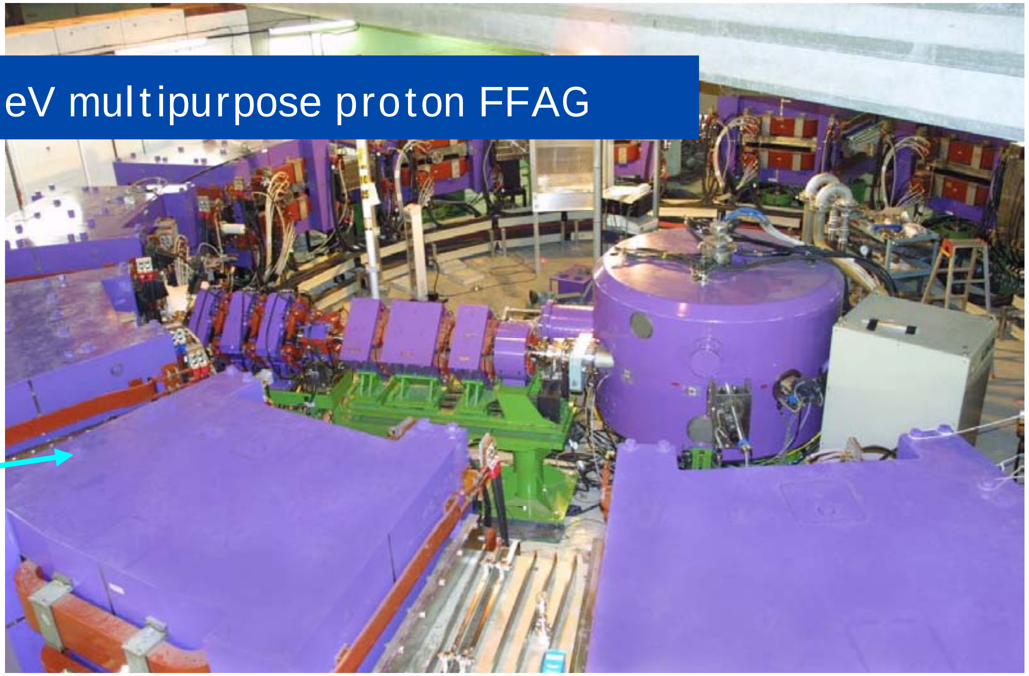
- 2004: Development of 150MeV multipurpose FFAG accelerator

  100Hz Operation!

  Grant-in-Aid for Creative Basic Res.: Y.Mori



Proof-of-Principle (PoP)-Proton FFAG



150MeV multipurpose proton FFAG

International Workshop on FFAG Accelerator

- WORKSHOP
  - 1st FFAG99 (Dec. 1999) KEK PoP-FFAG first beam!
  - 2nd FFAG workshop (July 2000) CERN
  - 3rd FFAG00 (Oct. 2000) KEK
  - 4th FFAG02 (Feb. 2002) KEK 150MeV FFAG approved
  - 5th FFAG workshop (Sept. 2002) LBL
  - 6th FFAG03 (July 2003) KEK
  - 7th FFAG workshop (Sept. 2003) BNL
  - 8th FFAG workshop (Mar. 2004) TRIUMF
  - 9th FFAG04 (Oct. 2004) KEK 150MeV FFAG acceleration
  - 10th FFAG workshop(Apr. 2005) FNAL 150MeV FFAG extraction
  - 11th FFAG05 (Dec. 2005) KURRI 150MeV FFAG 100Hz
  - 12th FFAG2006 (May 2006) BNL
  - 13th FFAG06 (Nov. 2006) KURRI

Almost twice per year! One the most active fields in accelerator physics and technology.

Transverse Beam Focusing

- Scaling FFAG
  - Fixed tunes : non-linear magnetic fields

    Zero-chromaticity

    demonstrated - PoP-FFAG(KEK).
- Non-scaling FFAG
  - Unfixed tunes : linear beam optics

    Fast resonance crossing

    not demonstrated.

Scaling FFAG

Original idea ---> Ohkawa (1953)

"Zero chromaticity"

betatron eq.

$$x'' + g_x x = 0\ ;\quad g_x = \frac{K^2}{K_0^2}(1-n)$$

$$z'' + g_z z = 0\ ;\quad g_z = \frac{K^2}{K_0^2}\,n$$

geometrical field index

$$\left.\frac{\partial}{\partial p}\left(\frac{K}{K_0}\right)\right|_{\theta=const.} = 0 \qquad \left.\frac{\partial n}{\partial p}\right|_{\theta=const.} = 0$$

orbit similarity *no p-dependence*

$$B(r,\theta) = B_i\left(\frac{r_i}{r}\right)^{n_0} F\left(\theta - \varsigma \ln\frac{r}{r_i}\right)$$

radial sector

negative bend

FODO(DFDO)

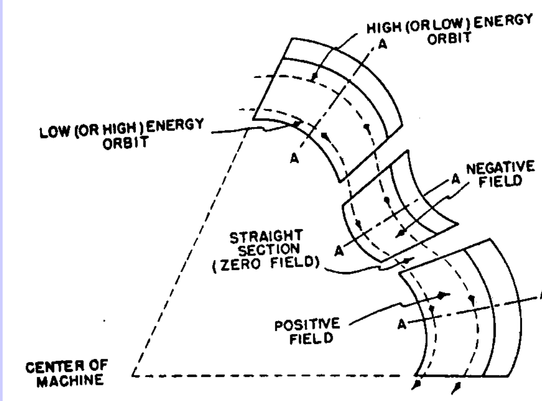


FIG. 2. Plan view of radial-sector magnets.

spiral sector

edge focus

FFDO

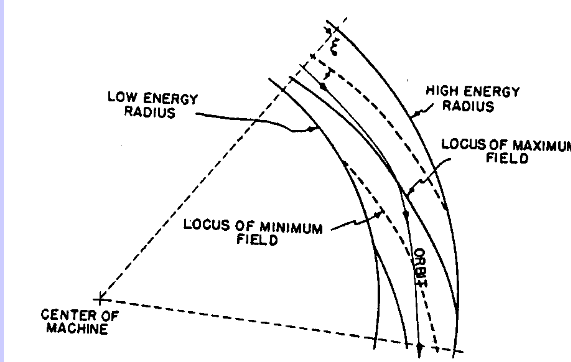
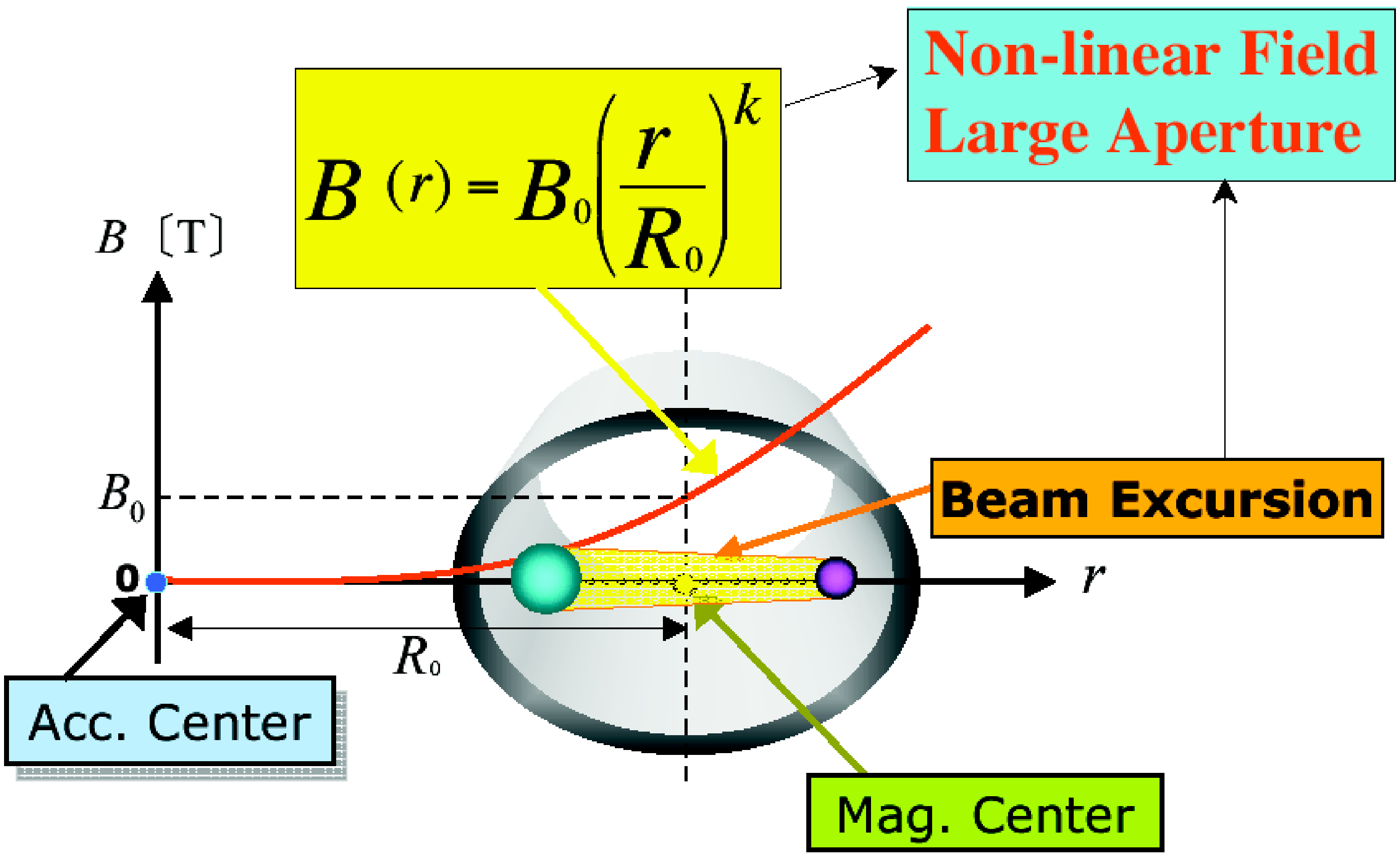


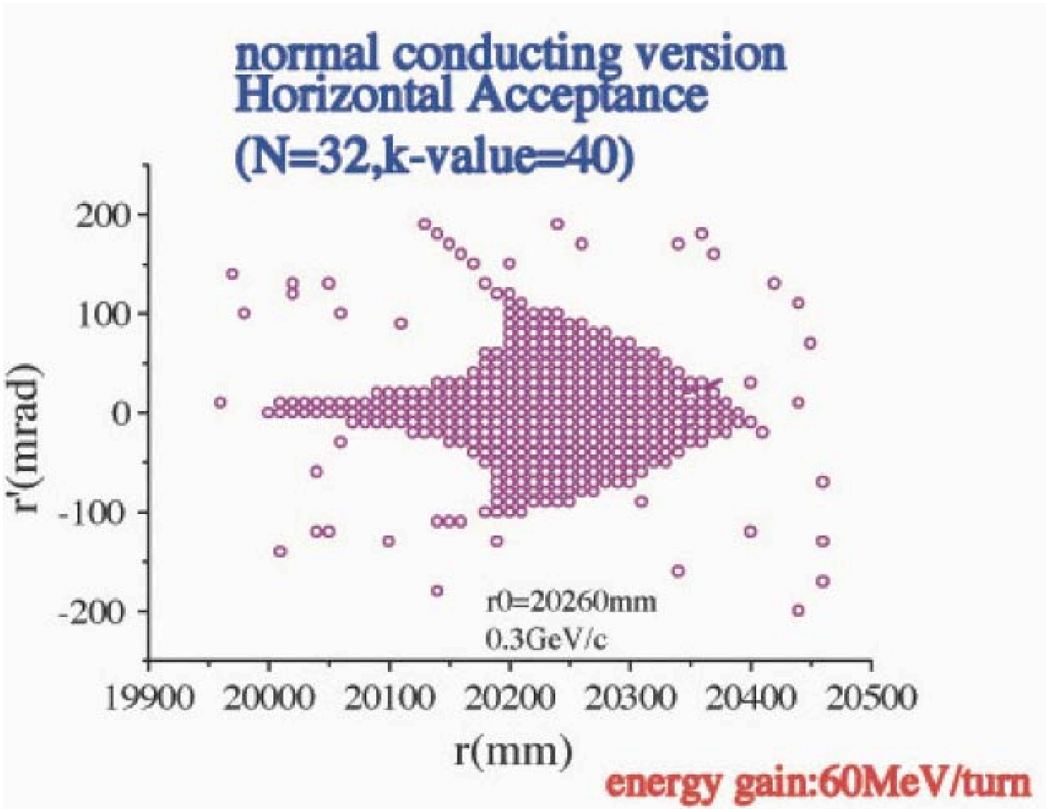
FIG. 3. Spiral-sector configuration.

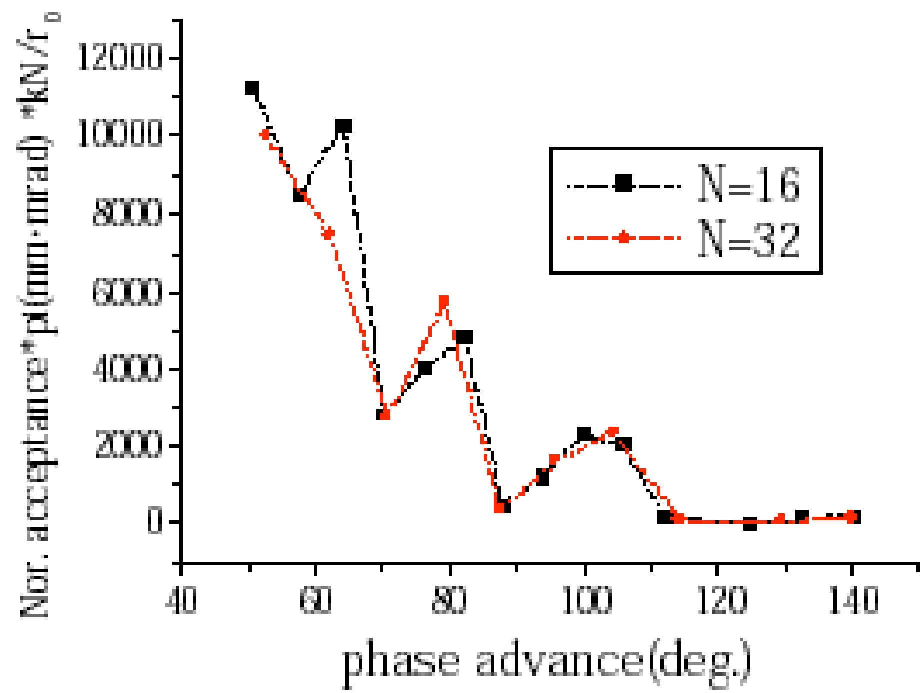
AG focusing

Magnetic Field in scaling FFAG



Dynamic Aperture of Scaling FFAG





Quite large!

cf. A>10,000mm.mrad for phase advance of ~90degree/cell

$$\alpha = \frac{1}{k+1} \quad : \text{ momentum compaction factor}$$

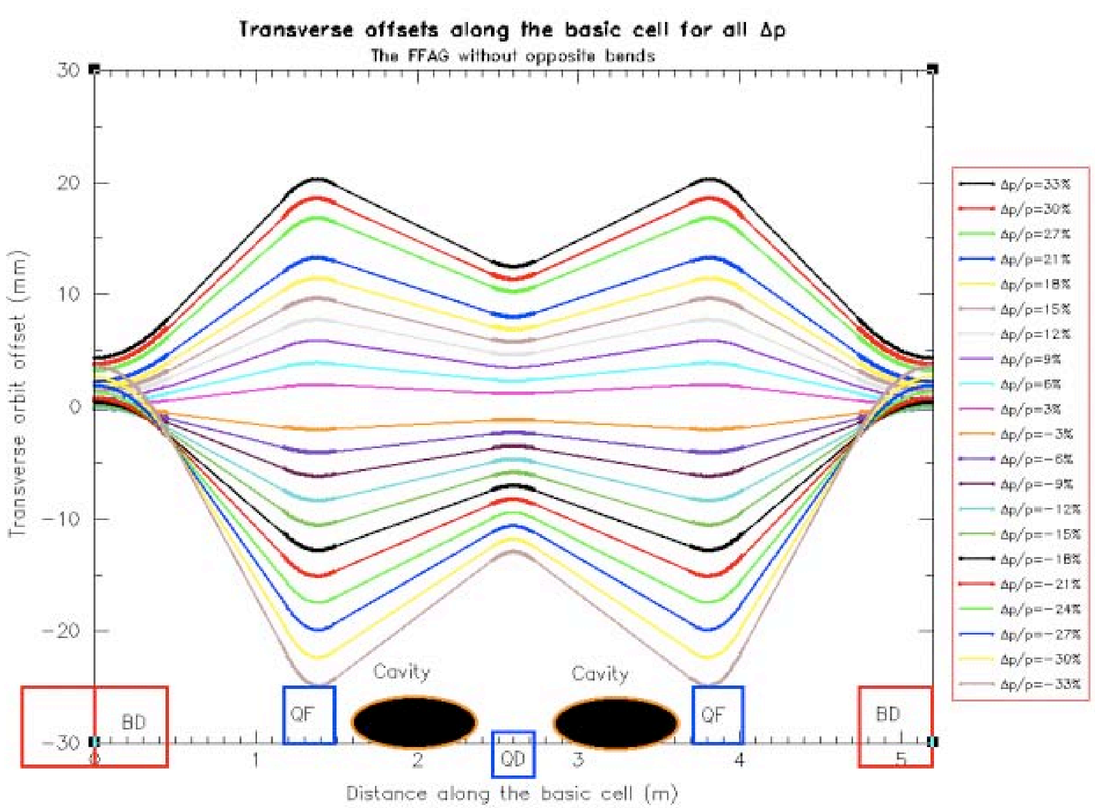
Momentum Comapction: no higher orders

-------- momentum acceptance : large

-------- kinematic effects : small enough

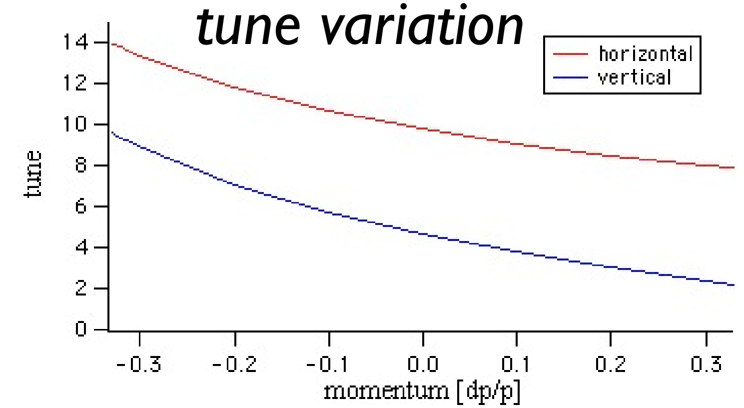
Non-scaling FFAG

- Fields are linear: B,Q fields.
  - momentum compaction: small enough ~parabolic $\alpha = C_1 \xi^2$
- Tunes are varied: Fast resonance crossing

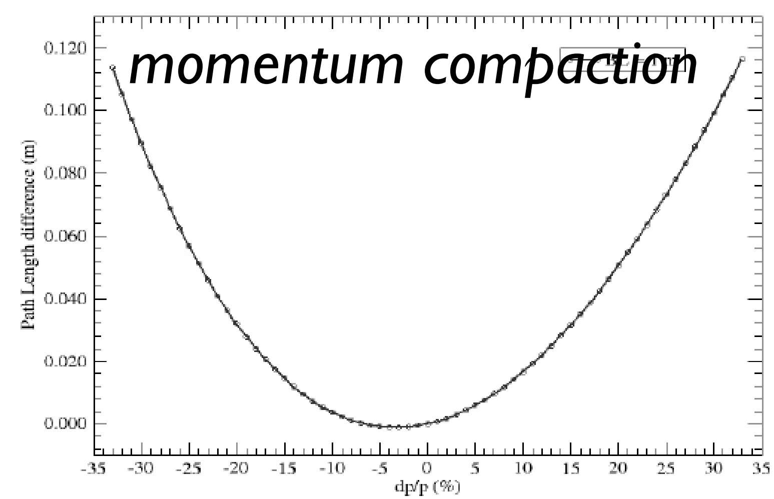


transverse offset for all momentum

tune variation



momentum compaction



Acceleration

- Variable frequency
- Constant frequency

Acceleration(RF)

- Variable frequency RF
  - Broad-band RF cavity : Scaling & Non-scaling

    MA(magnetic alloy) cavity   Q~1
- Fixed frequency RF
  - Stationary RF bucket acceleration : Scaling

    relativistic beam & constant MC
  - Gutter RF acceleration : Non-scaling

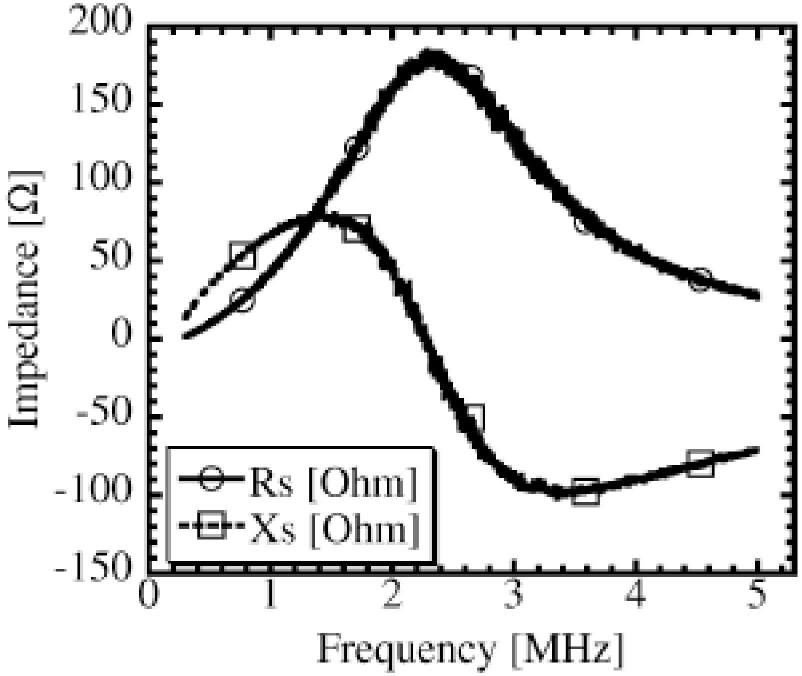
    relativisitc beam & small MC(parabolic) :semi-isochronous
  - Harmonic number jump acceleration : Scaling (non-scaling)

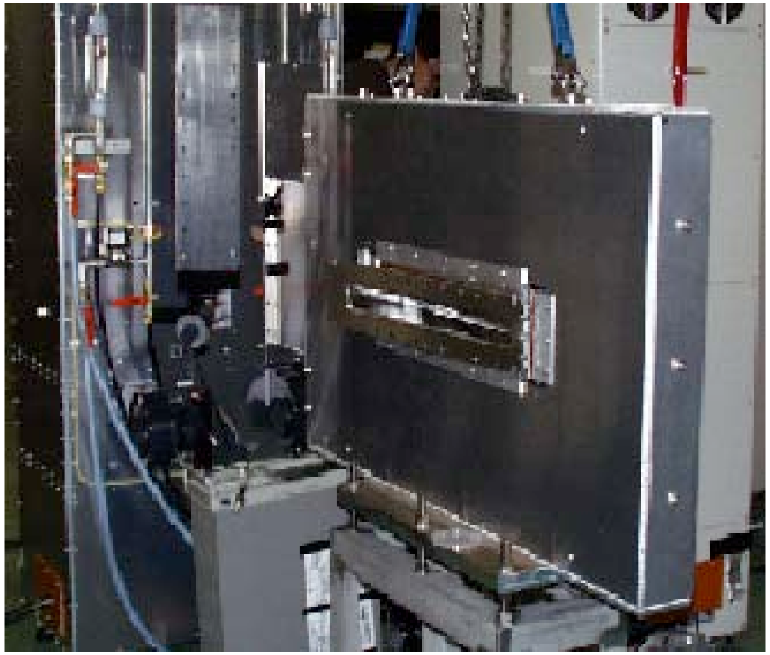
    non-zero slippage factor

Variable RF frequency

- Broad-band RF cavity : MA(magnetic alloy) cavity
  - Fast acceleration requires fast frequency(phase) change.

    Low Q is essentianl !
  - Adequate both for scaling and non-scaling FFAGs.



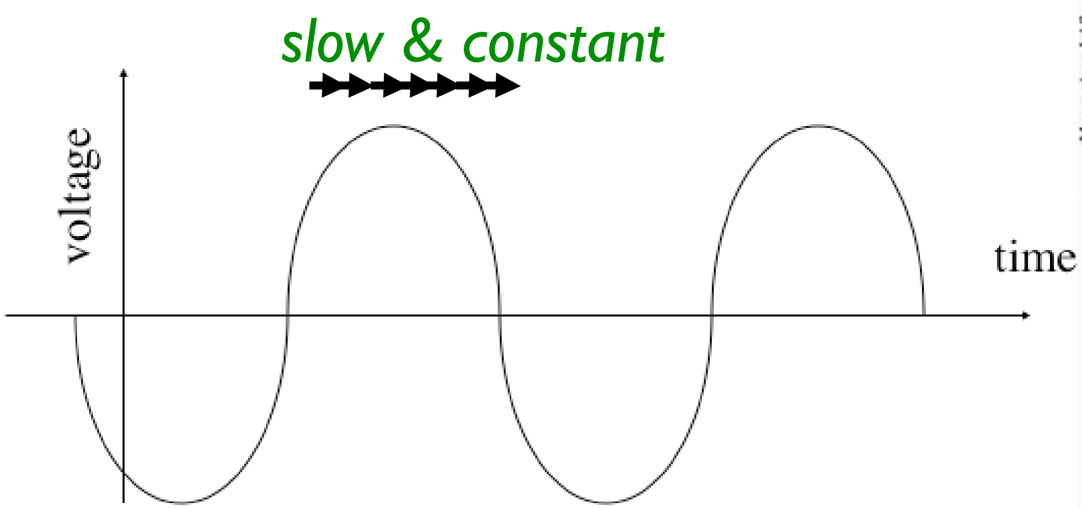


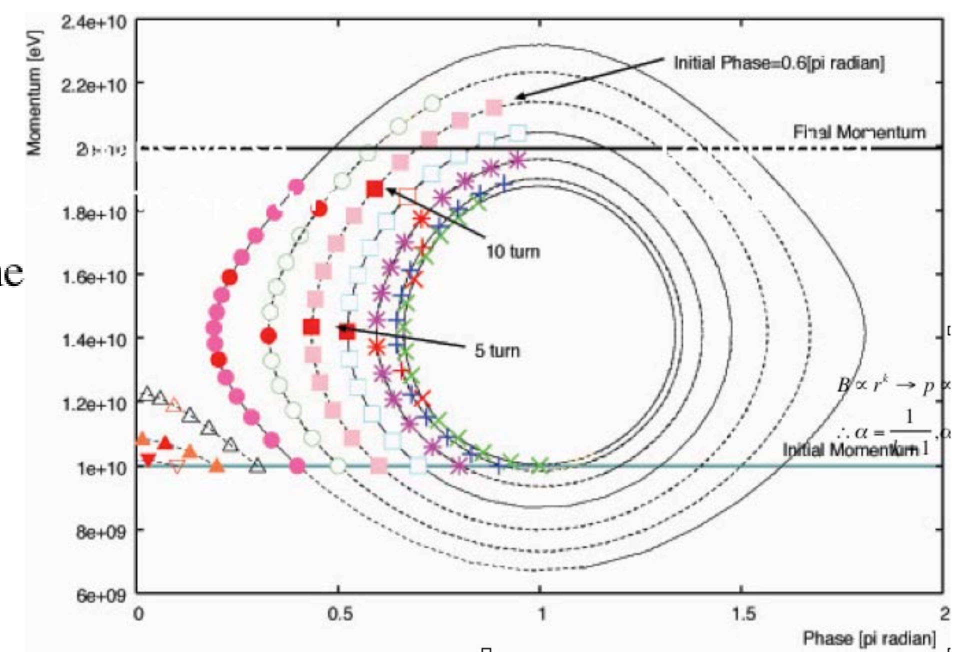
Fixed RF frequency(1)

- Stationary RF bucket acceleration
  - Constant & small enough phase slip --- Large energy gain
    - *relativistic beam*
    - *constant Momentum Compaction*

$$\eta = \frac{1}{\gamma^2} - \alpha \cong -\alpha = -\frac{1}{k+1}$$

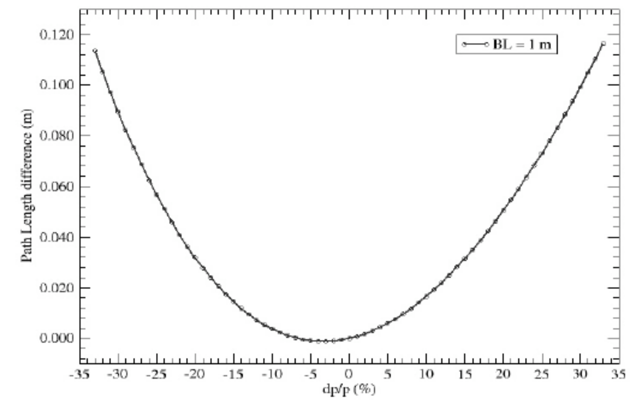
  - Adequate for scaling FFAG

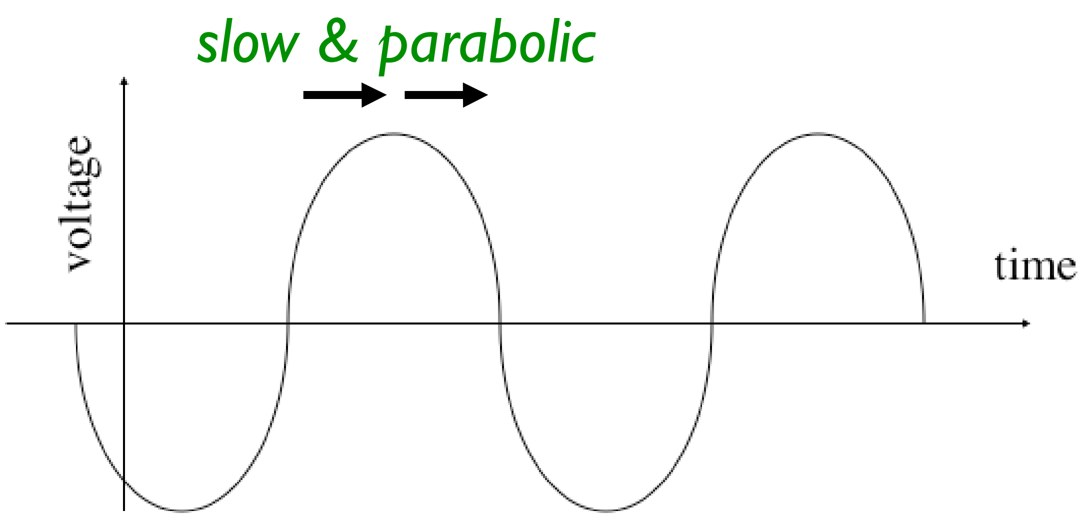




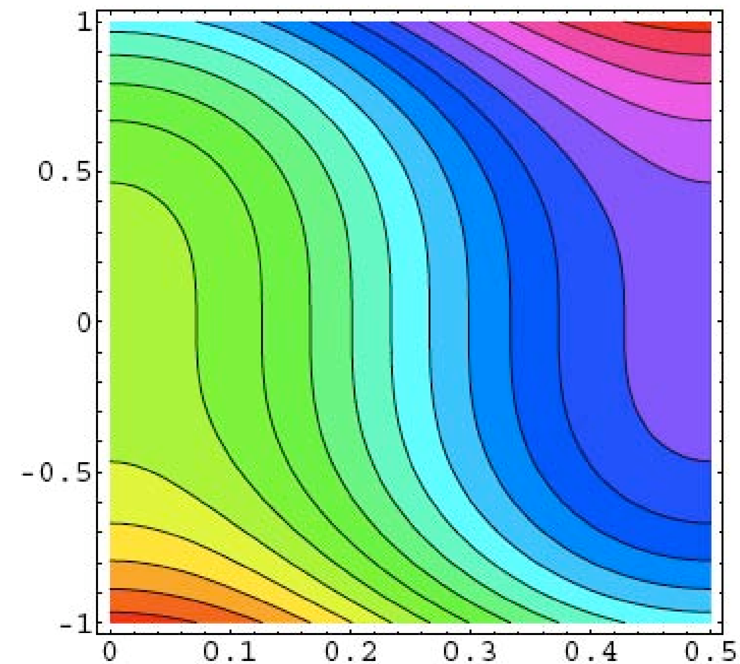
Fixed RF frequency(2)

- ## Gutter RF acceleration
  - Parabolic & small enough phase slip
    - *relativistic beam*
    - *small parabolic Momentum Compaction*
  - Adequate for non-scaling FFAG





cf. S.Machida

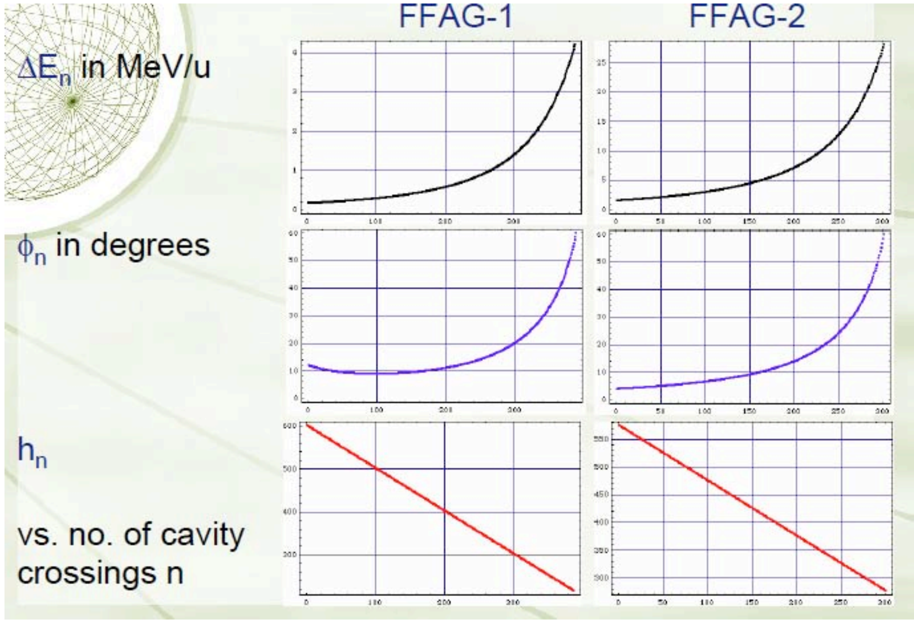


Fixed RF frequency(3)

- Harmoic number jump acceleration
  - Time slip/turn: m x Trf

    m:integer, m<0: before transition, m>0: after transition
  - Energy gain/turn should be tuned.

$$h(E) = \frac{mE\beta^3 \Delta E}{\eta}$$



cf. A.Ruggiero(BNL)

Applications

- Proton driver
- Muon accelerator
- Medical application

Proton driver

- Neutrino factory
  - Muon source (pulsed)
  - Energy:5-20GeV, Power: 4MW, Rep.rate:10Hz, Bunch width:1nsec
- Accelerator driven nuclear system (ADS)
  - Neutron source (cw/semi-cw)
  - Energy:1-2GeV, Power:>10MW, cw/semi-cw(kHz)

Proton driver for neutrino factory

- Intensive design works
  - Non-scaling FFAG by A.G.Ruggiero (BNL)

    E=11.6GeV (two rings)

    Lattice: O-BF-BD-BF-O, MC=linear for momentum

    Harmonic number jump acceleration
  - Semi-scaling(achromatic) FFAG by G.Rees(Rutherford Lab.)

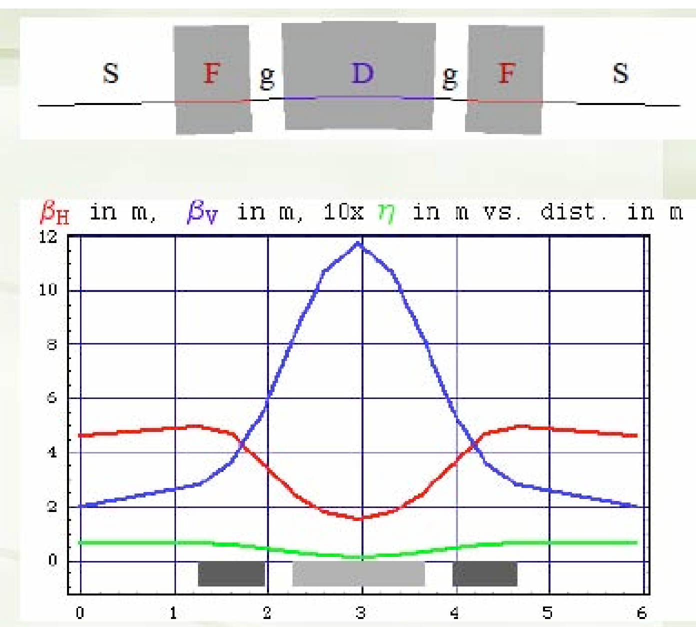
    E=10GeV, 50Hz

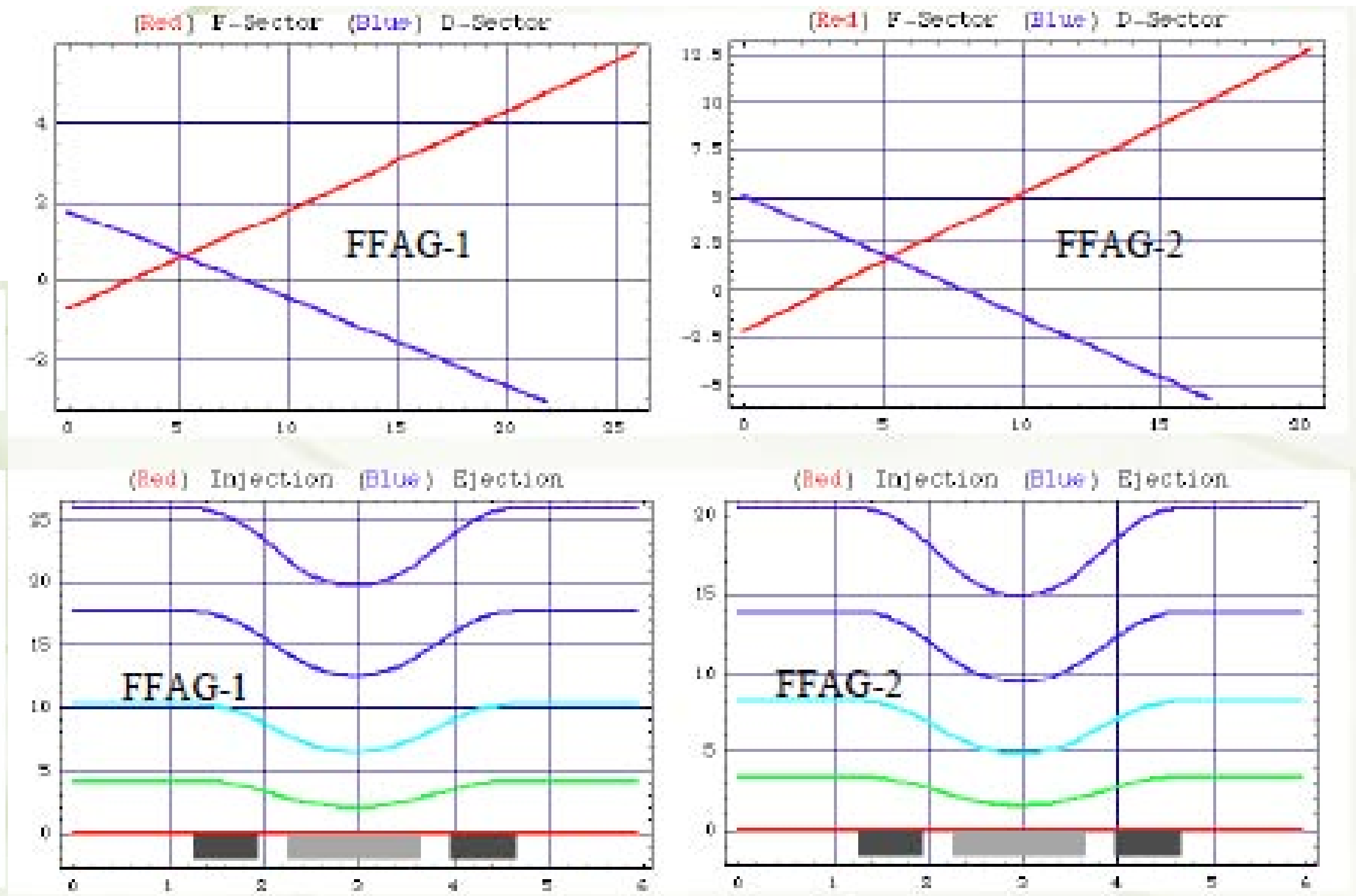
    Lattice:O-bd-BF-BD-BF-bd-Q including non-linear bd

    variable frequency RF acceleration

Non-scaling FFAG by A.G.Ruggiero (BNL)

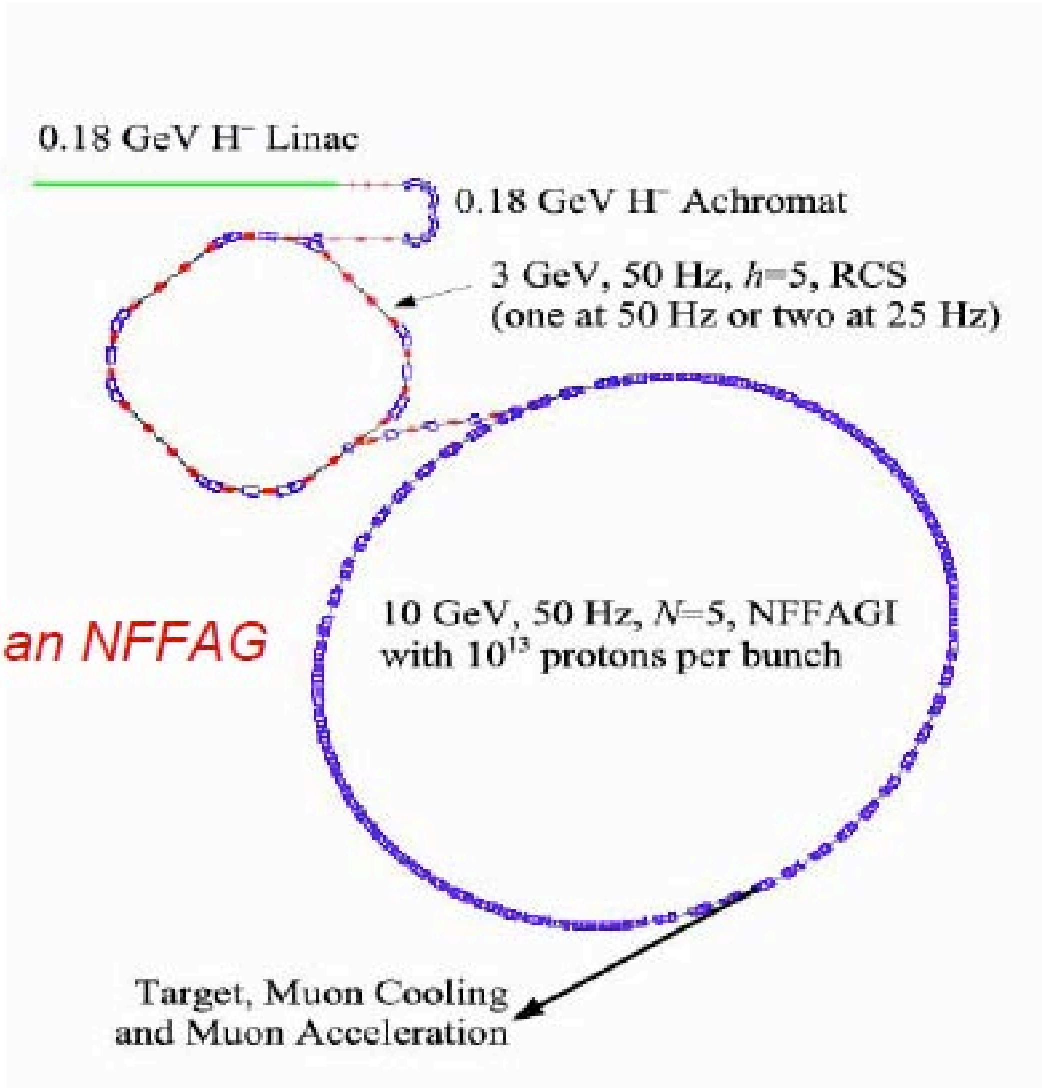
Beam Parameters





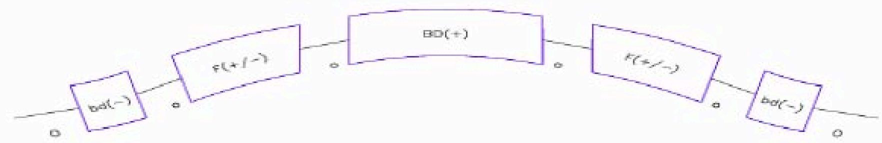
Tune variations & orbit excursion

Semi-scaling(achromatic) FFAG by G.Rees(Rutherford Lab.)



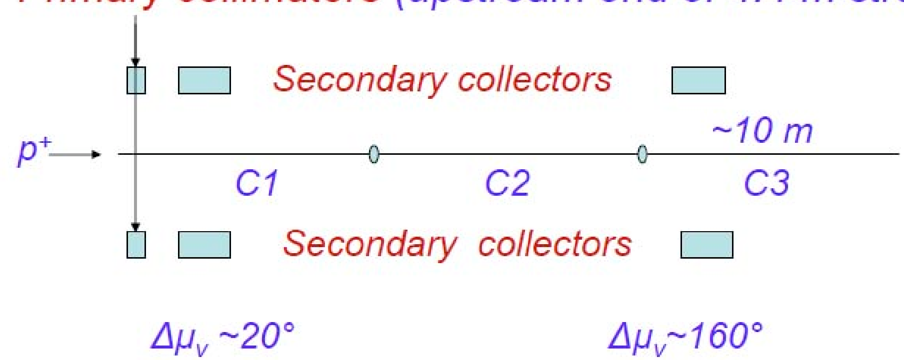
r an NFFAG

NFFAG and IFFAG Lattice Cells



- Cells have the arrangement: O-bd-BF-BD-BF-bd-O.
- NFFAG: non-isochronous ; $\xi_v = 0$, $\xi_h = 0$.
- IFFAG: isochronous ($\gamma_t = \gamma$) ; $\xi_v = 0$, $\xi_h = +ve$.
- NFFAGI and IFFAGI have normal & insertion cells.
- Different length straights in normal & insertion cells.
- There is closed orbit matching between single cells.

Primary collimators (upstream end of 4.4 m straigh



Proton driver for ADS

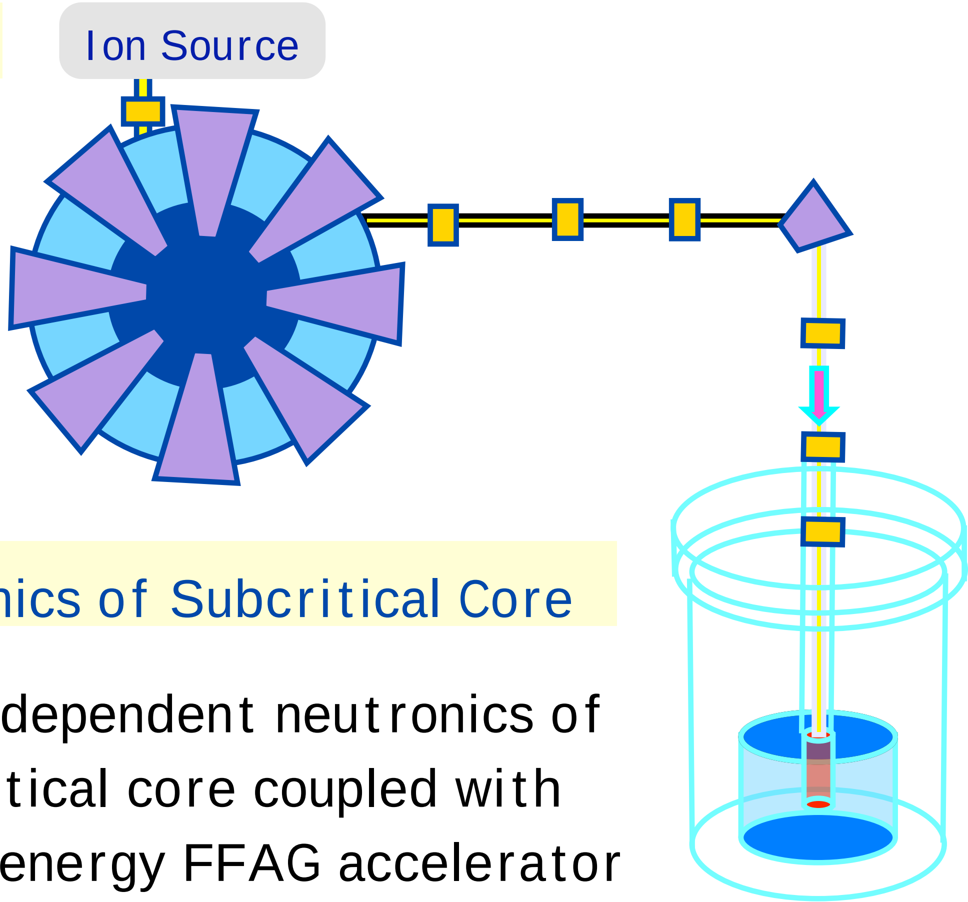
- Design work
  - Non-scaling FFAG: A.G.Ruggiero (BNL)
  - 1GeV, 10MW (single ring)
- Development for basic ADS study
  - Scaling FFAGs at Kyoto University(KURRI)
  - 150MeV, 1(100)micro-A (two rings)
  - Combined experiment with KUCA(sub-critical reactor)

Feasibility Study on ADSR Using FFAG Accelerator

Five-year project (US$~10M in total)
supported by
MEXT Technology Development Project for Innovative Nuclear Energy System

Accelerator Development

Development of variable energy FFAG accelerator with high acceleration efficiency

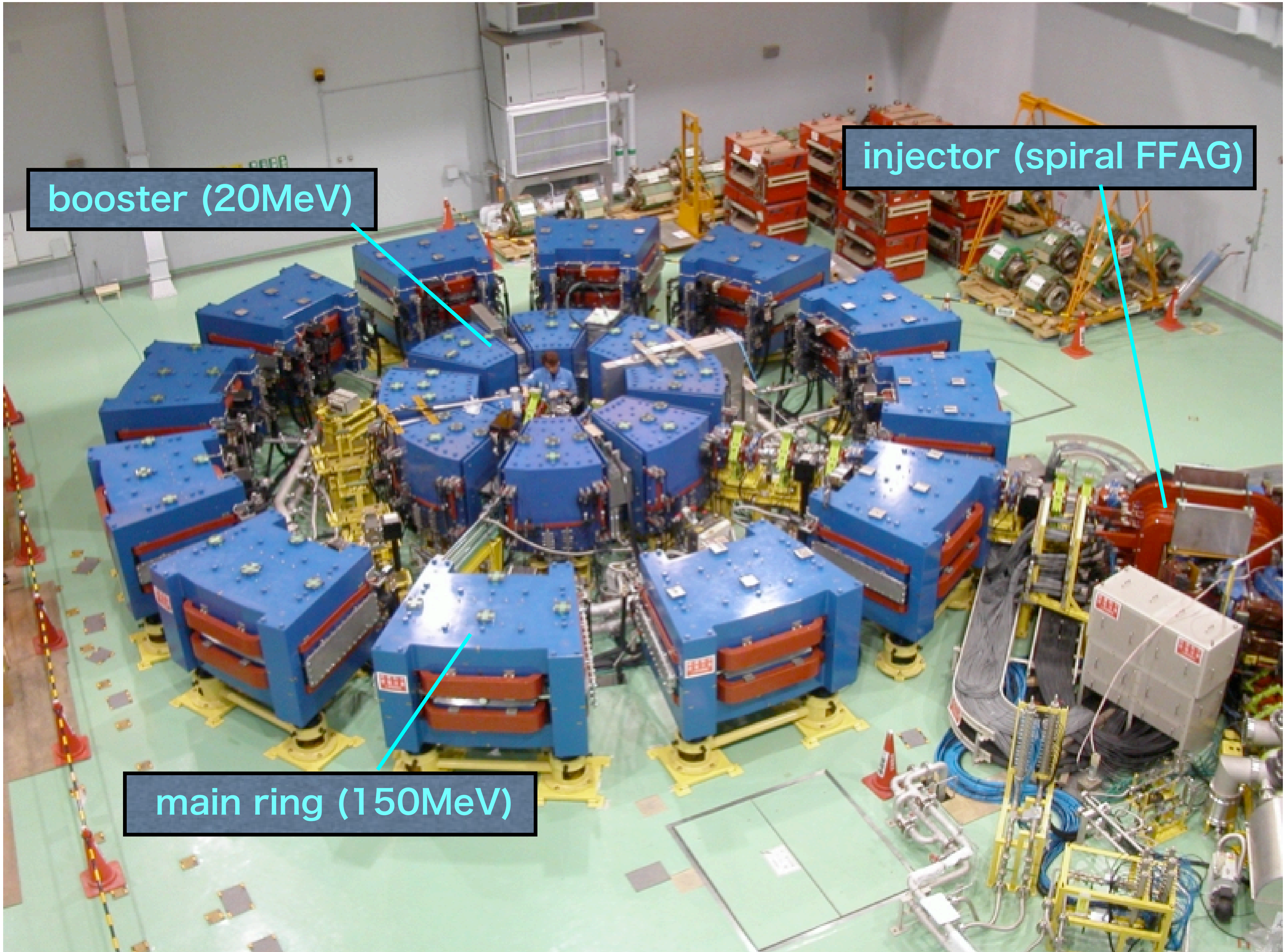


Neutronics of Subcritical Core

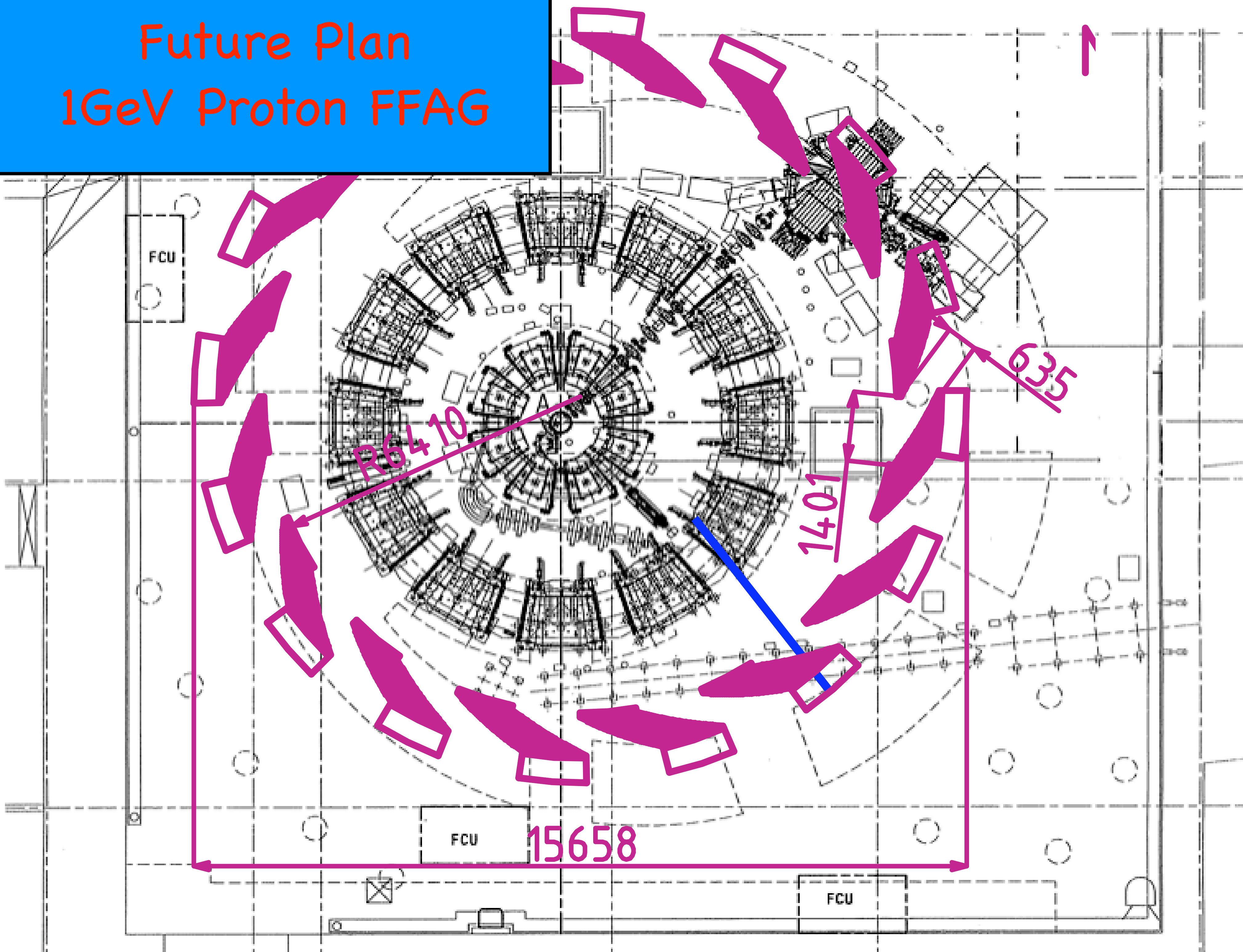
Energy-dependent neutronics of subcritical core coupled with variable energy FFAG accelerator

Research Reactor Institute Kyoto University

FFAG complex at KURRI



Future Plan
1GeV Proton FFAG



Muon accelerator

- PRISM project
  - Logitudinal phase space rotation to obtain small energy spread

    p~20MeV/c, Energy spread <2%
  - Scaling FFAG & MA RF cavity(250kV/m)
- Muon accelerator for neutrino factory
  - Scaling FFAG(NuFact-J) ~ 20(50GeV)

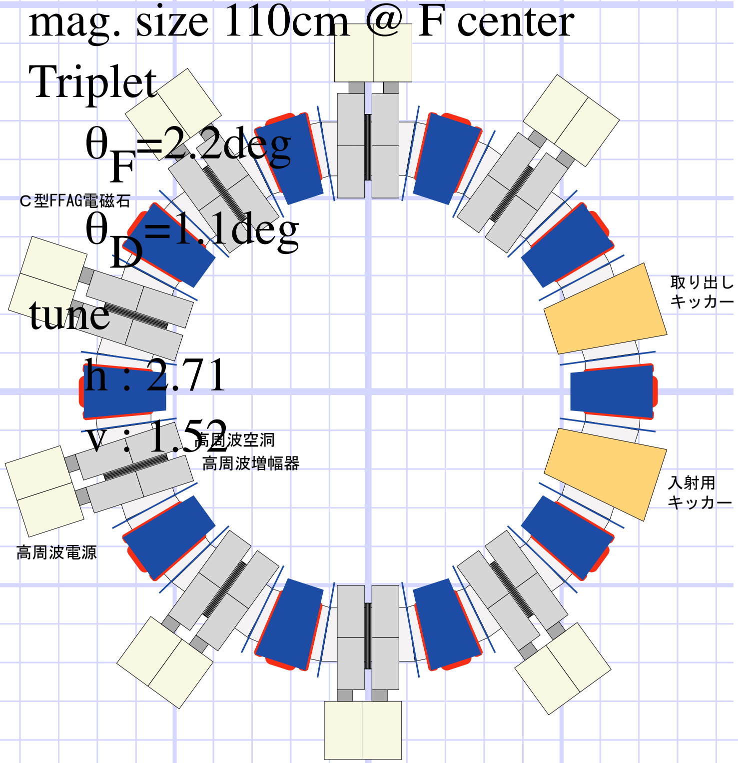
    Stationary RF bucket acceleration
  - Non-scaling FFAG

    Gutter RF acceleration cf. Electron model :EMMA

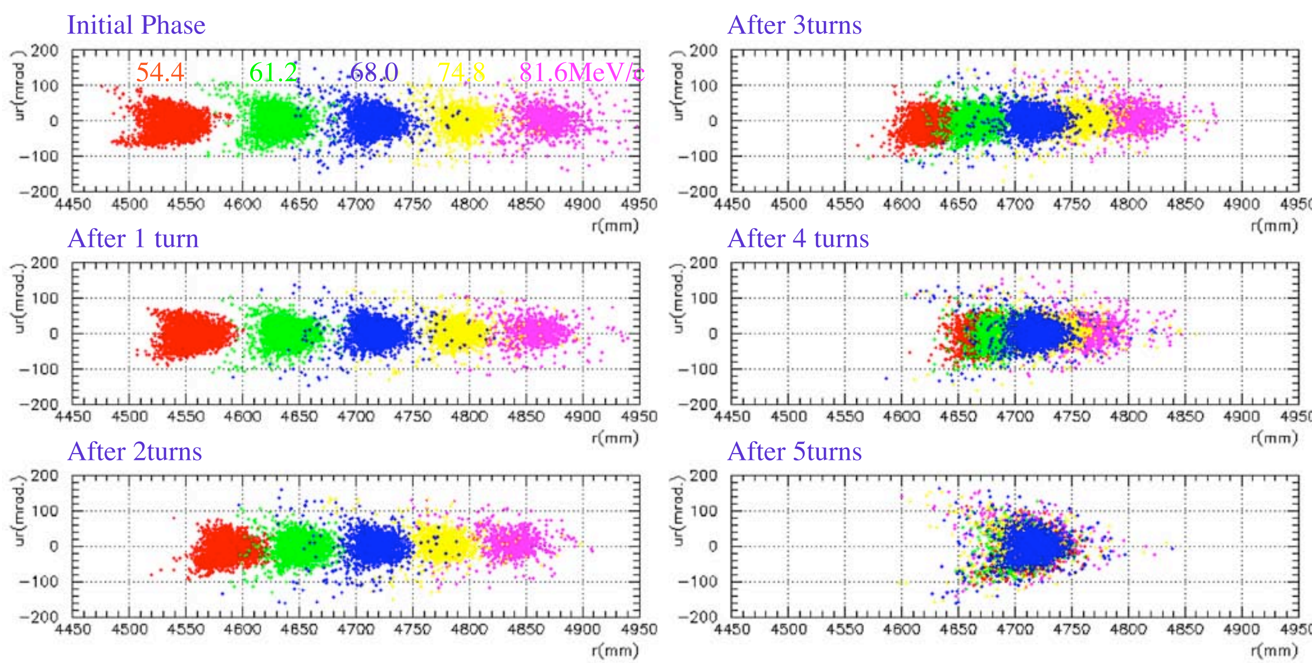
PRISM project

Development at Osaka Univ. (2003-2007)

N=10
k=5(4.6-5.2)
F/D(BL)=6
r0=6.5m for 68MeV/c
half gap = 17cm
mag. size 110cm @ F center
Triplet
θ_F=2.2deg
θ_D=1.1deg
tune
h : 2.71
v : 1.52



Phase Rotation Simulation: Horizontal Phase Space



2003/7/7 FFAG03@KEK

PRISM Phase-Rotation Intense Slow Muon
High-Intensity Low-Energy

Medical application

- Hadron beam therapy
  - Development of multipurpose FFAG (KEK) 2001-2005

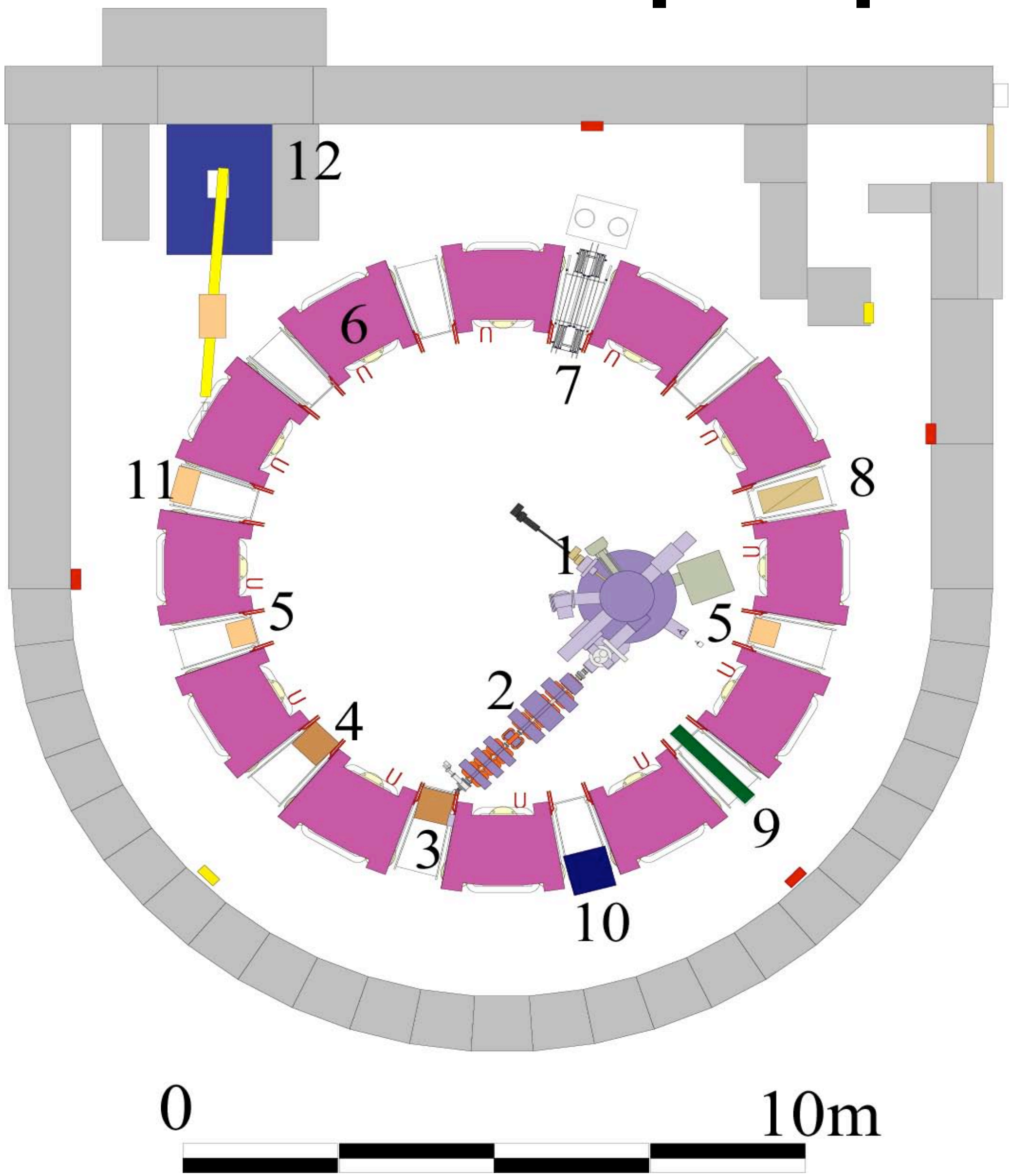
    Scaling FFAG & MA RF cavity
  - Fast spot scanning synchronized respiration

    100Hz operation demonstrated !
- BNCT(boron neutron capture therapy)
  - Intense low energy(epi-thermal) neutron source

    flux at patient >10E09 n/cm2/sec
  - FFAG-ERIT(energy/emittance recovery internal target)

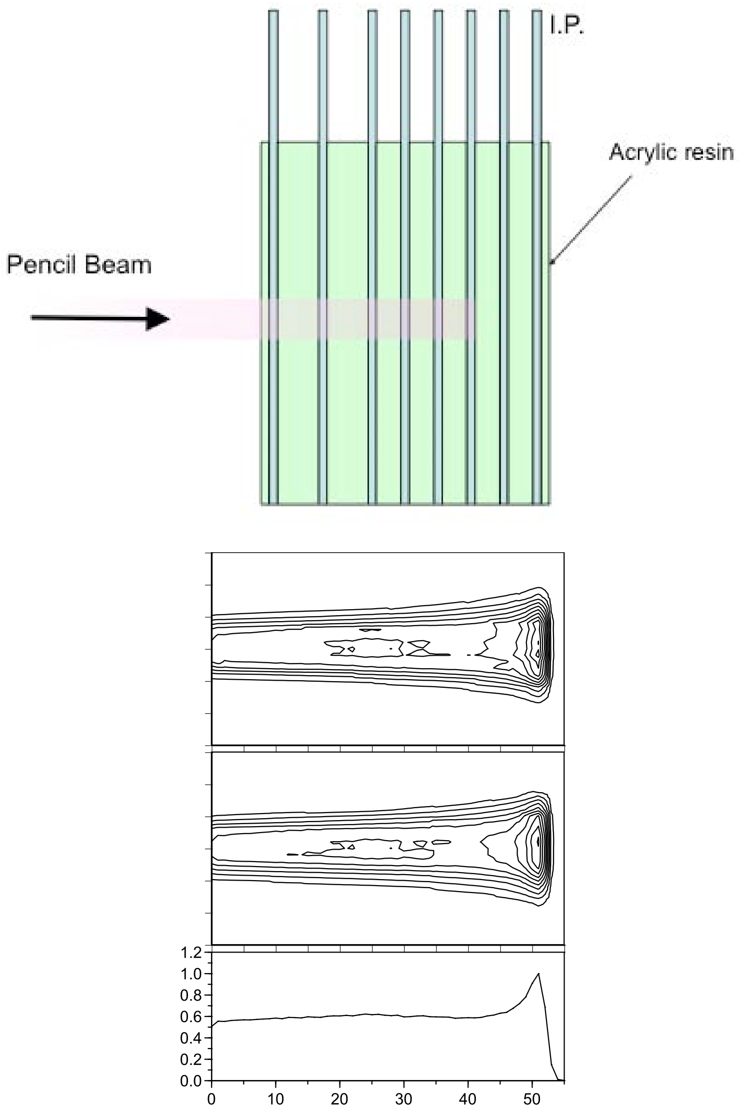
    ionization cooling

Schematic view mulitpurpose FFAG

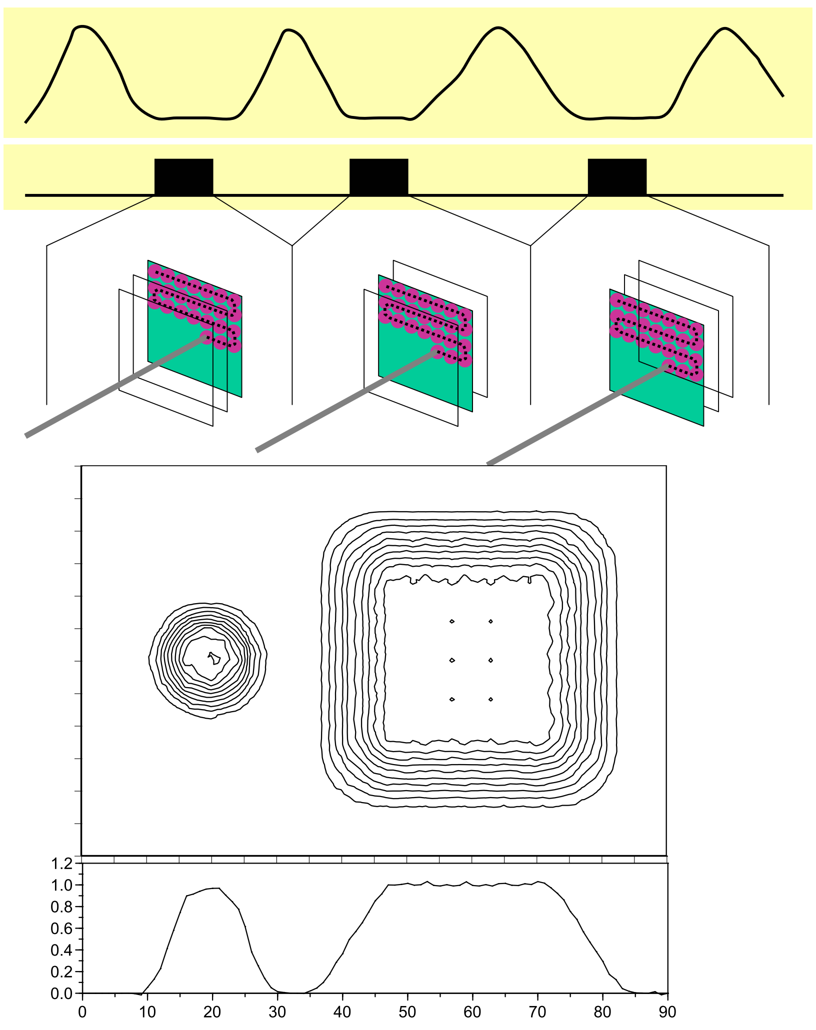


No. of sectors	12
Field index(k -value)	7.5
Energy	12MeV - 150MeV
Repetition rate	250Hz
Max. Magnetic field	
Focus-mag.	1.63 Tesla
Defocus-mag.	0.13 Tesla
Closed orbit radius	4.4m -5.3m
Betatron tune	
Horizontal :	3.7
Vertical :	1.2
rf frequency	1.5 -4.6MHz

Fast spot scanning exeriments & simulations



呼吸同期に対応するスキャンニング照射

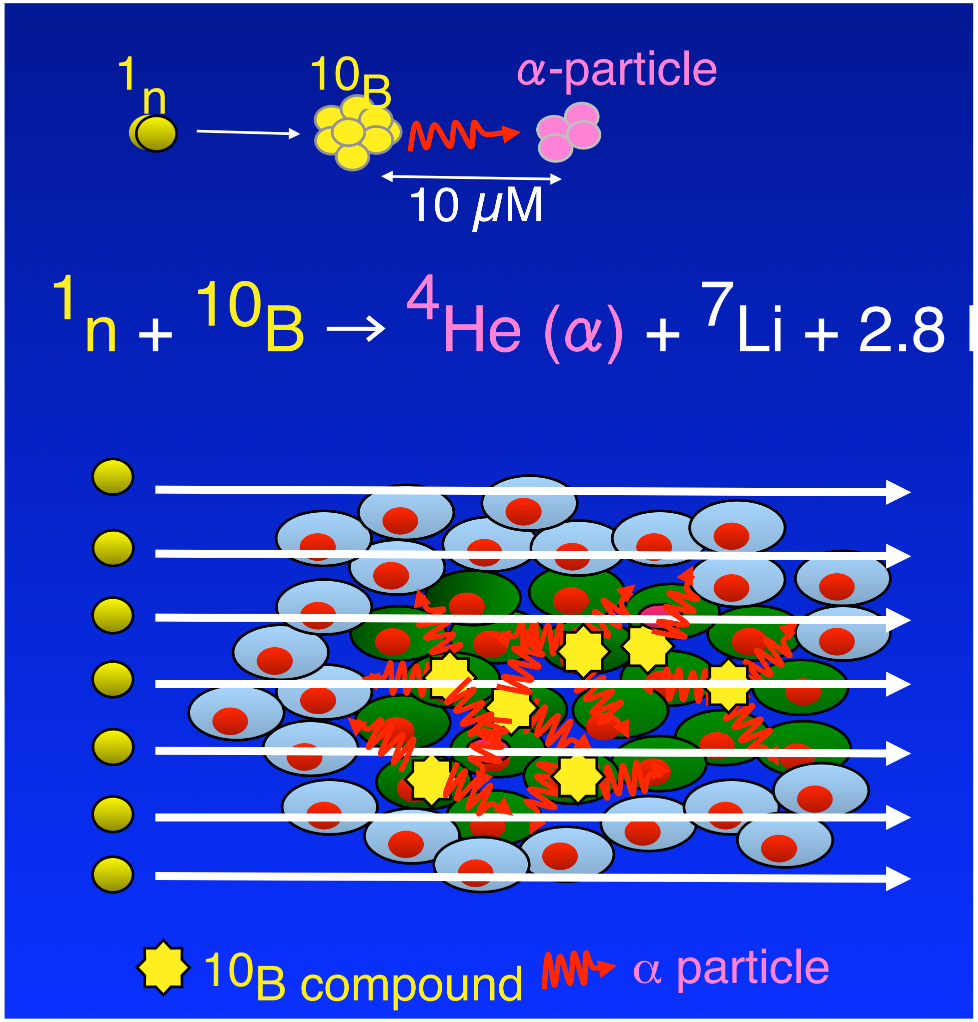


multipurpose FFAG with 100Hz operation

Neutron Source for BNCT

- ***Requirements***
  - *Large neutron flux*
    > 1x10^9 n/cm^2/sec at patient
  - *Low energy spectrum*
    thermal/epi-thermal neutron

Nuclear reactor only can provide these neutrons.



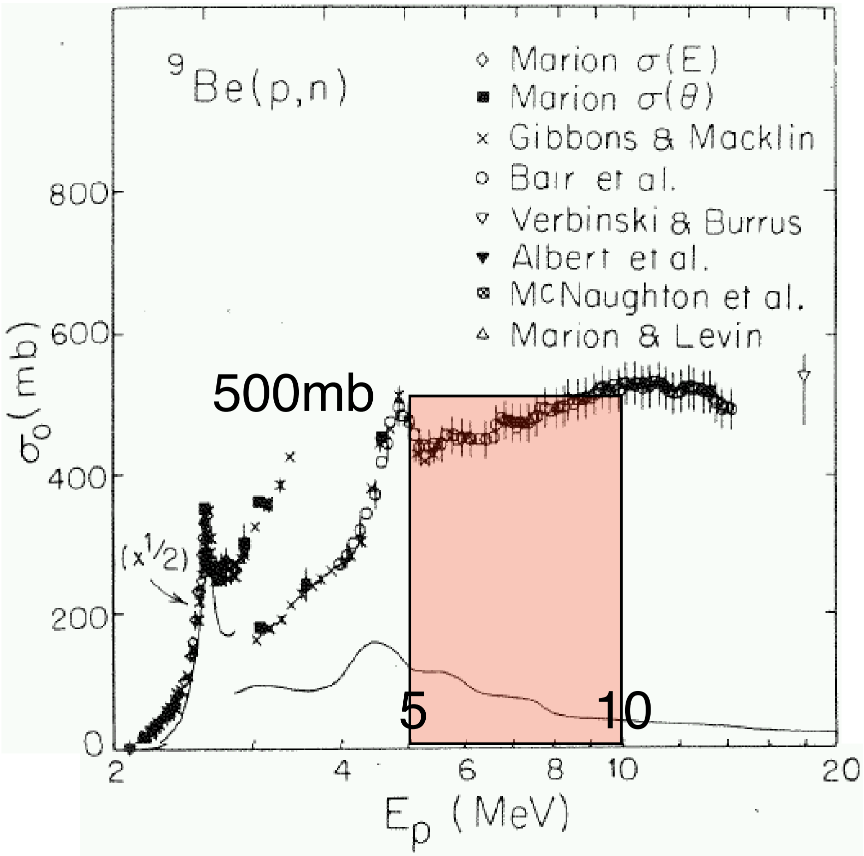
Limited to extend the use of BNCT widely in society.

Accelerator based Neutron Source

In order to obatin

$\varphi > 10^9$ n/cm2/s

- Neutron production
  - Reaction 9Be(p,n)B, 7Li(p,n)Be
  - energy ~10MeV
  - target thickness ~10micron
  - Neutron yield ~1/10000 n/p
- Proton beam current ~40mA



Accelerator based neutron source : Difficluties

- Accelerator
  - energy is low, but required beam current is very large

    I >10mA (CW)

    technically hard and expensive
- Target
  - thin target t<0.1mm ∵dE/dx~50MeV/g/cm2

    beam power is relatively large > 100kW

    difficult cooling and shorter lifetime
- Radiation
  - full beam dumping for 100kW beam

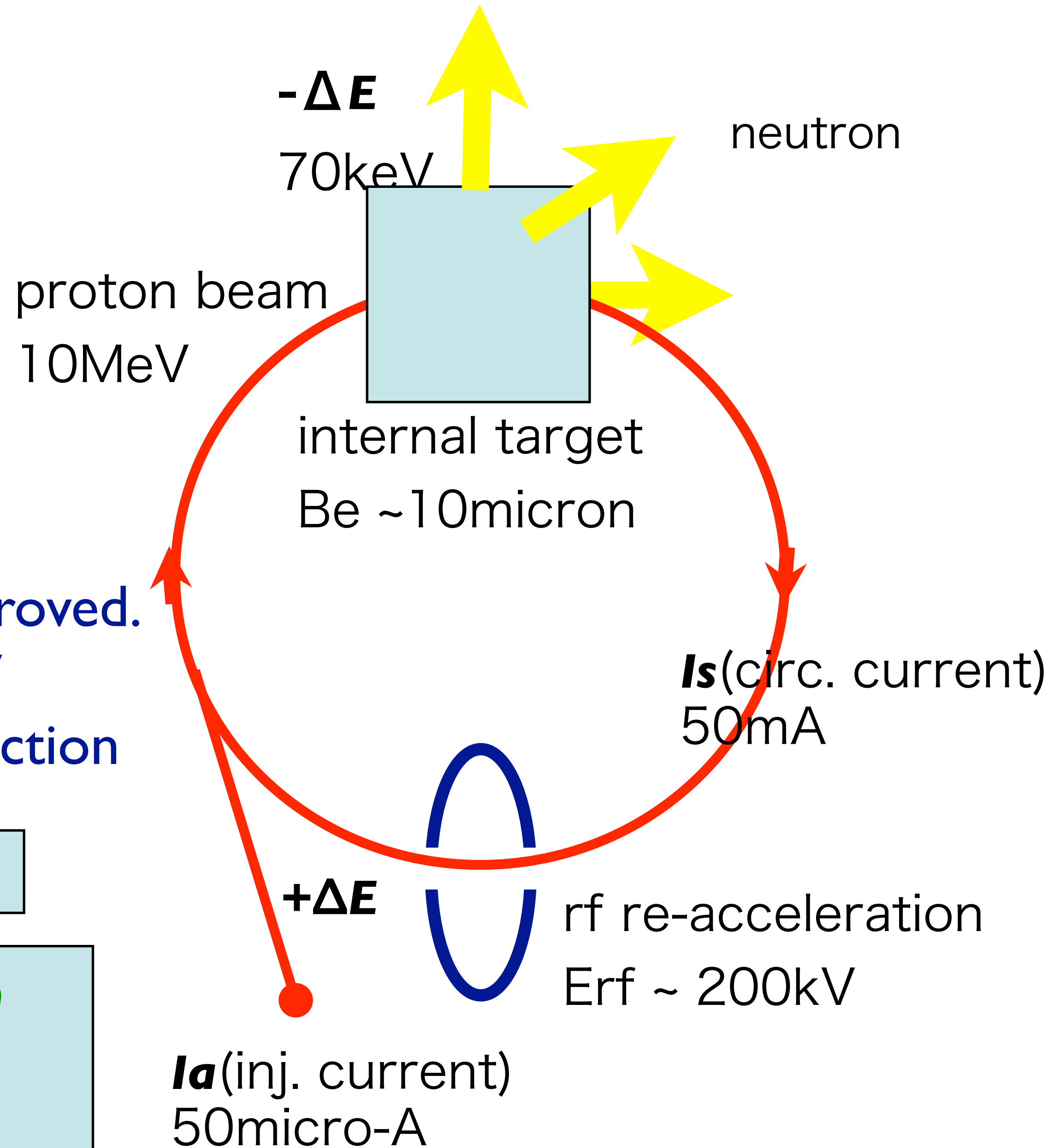
    huge shielding and large gamma-ray contamination

Neutron Source with FFAG-ERIT

Emittance-energy Recovery Internal Target *(ref. Nucl. Instr. Meth.)*

- FFAG-ERIT scheme
  - internal target
  - energy loss
    recovered by rf
  - emittance growth
    ionization cooling
  - large acceptance
    FFAG(scaling)
  - target
    heat loss 1-2kW

Project was approved.
2005-2007
Under Construction



Ia=Is/Nt, Nt=1000turns

Need large momentum acceptance! -> FFAG

Ionization Cooling

$$\frac{d\varepsilon}{ds} = A\varepsilon + B$$

ε : beam emittance

transverse

$$A = -\frac{1}{\beta^2 E}\left\{\frac{dE}{ds}\right\} \qquad B = \frac{\beta\gamma}{2}\beta_T \frac{(13.6MeV)^2}{(\beta cp)^2 L_s}$$

Ratherford mulitple scattering

longitudinal

$$A = 2\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} \qquad B = 4\pi\left(r_e m_e c^2\right)^2 n_e \gamma\left[1 - \frac{\beta^2}{2}\right]$$

straggling

cf. proton beam 10MeV
Be target

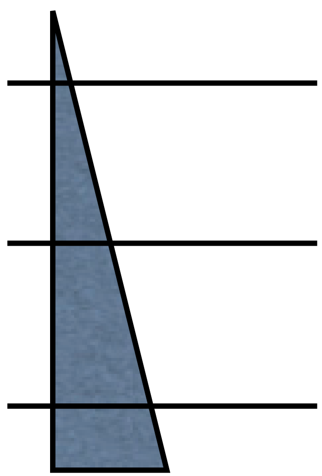
3D beam cooling becomes possible if transverse and longitudinal motions are coupled.

Transverse→Cooling
Longitudinal→Heating

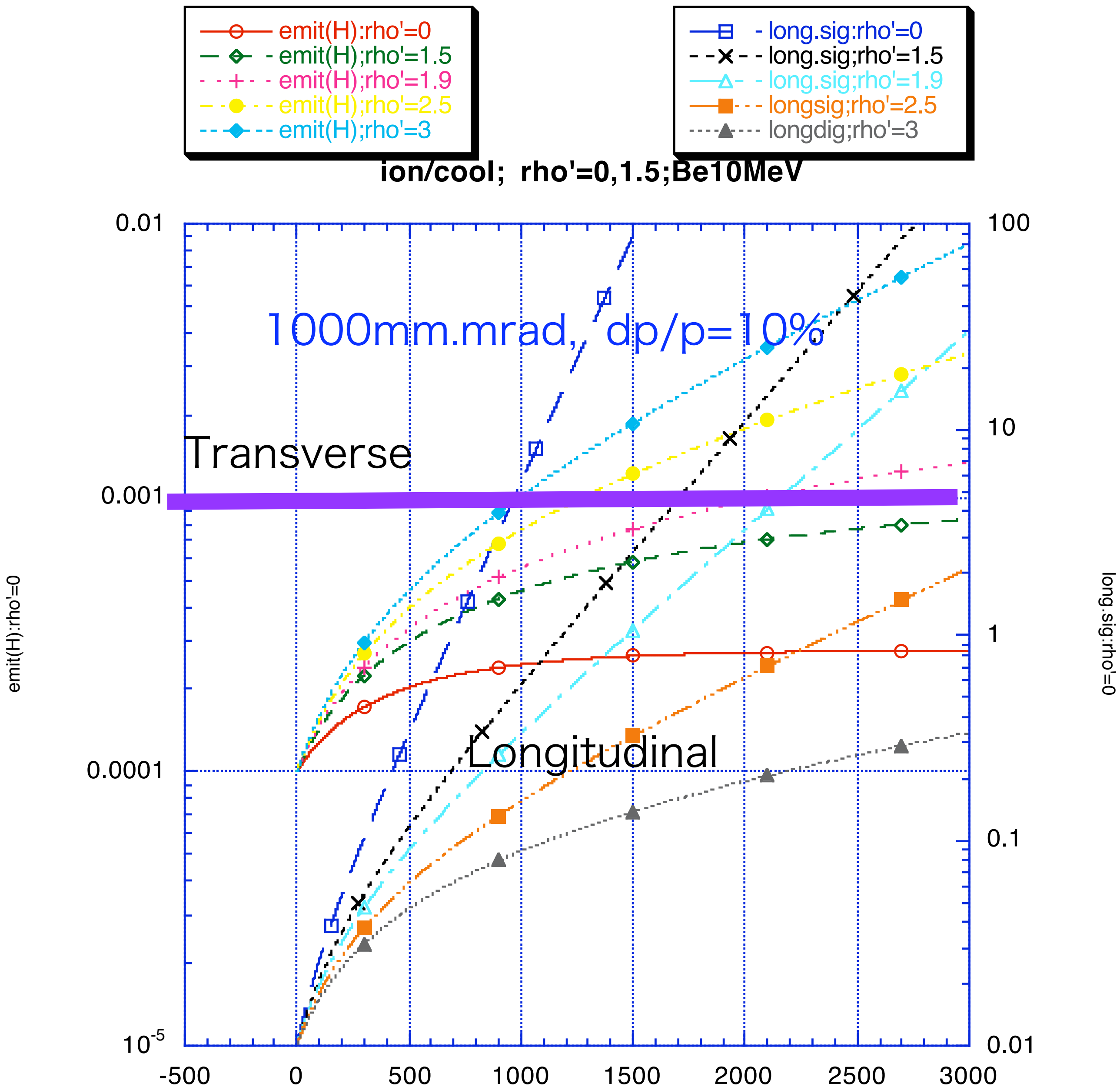
分配関数の和＞０ $\sum_1^3 g_i > 0$

ERIT ionization cooling

wedge target



$$\frac{d\varepsilon}{ds} = A\varepsilon + B$$



Temperature rise of Be target

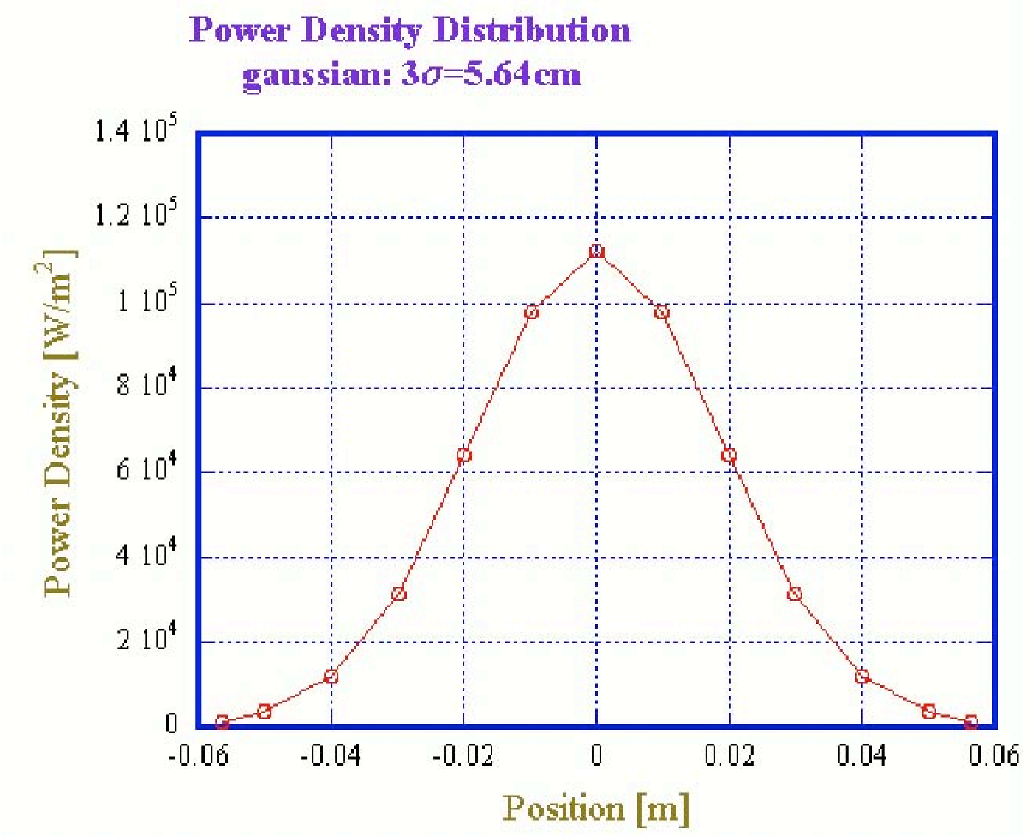
heat load **500W**

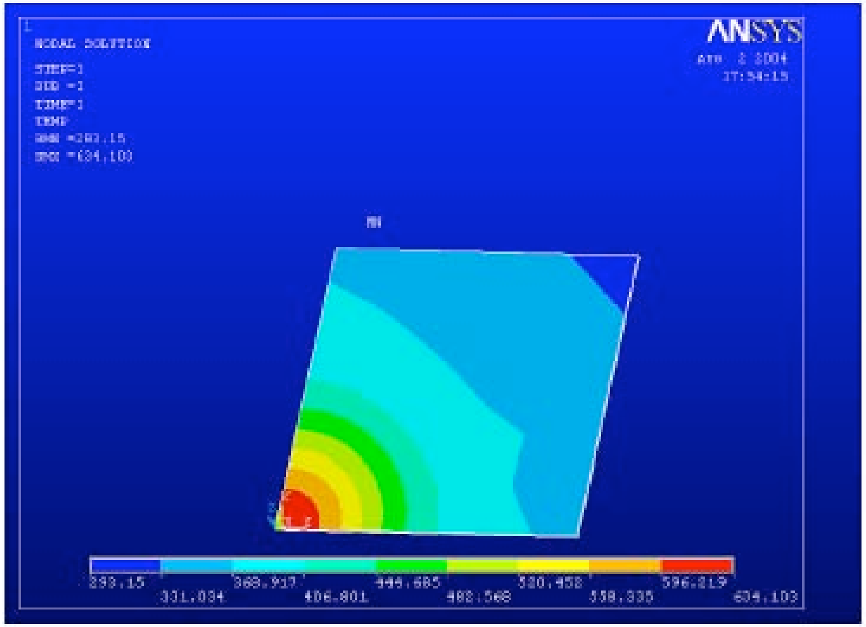
beam distr. **Gauss (3 σ: 5.64cm)**

radiation $\propto T^4$

ANSYS

max. temperature ~634°K





BNT with FFAG-ERIT

Injector(RFQ + IHDTL)

Full energy injection

H^- kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]
Repetition	>1 [kHz]

FFAG ring

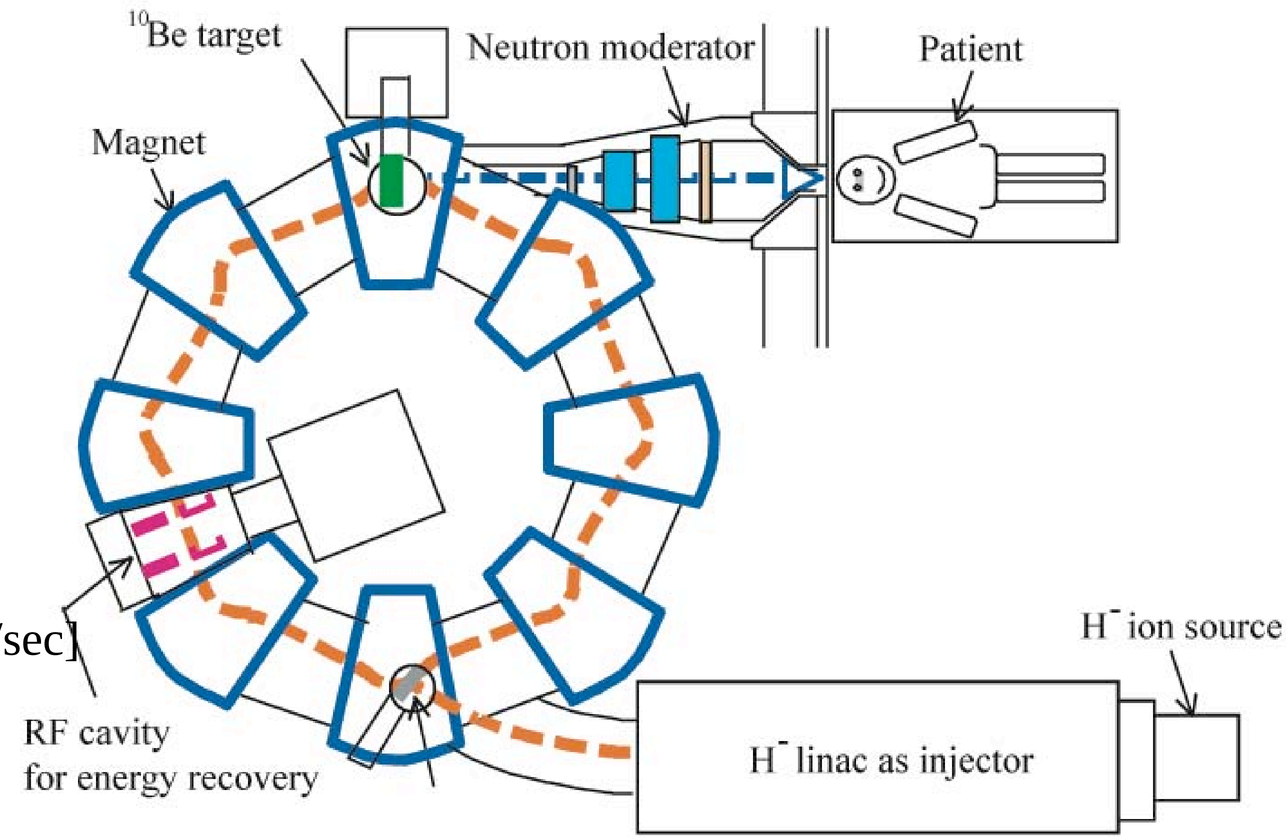
H^- injection	
proton kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]

ERIT system

Turn number	> 1000 turn
Internal target thickness	~ 5 [mm]
Neutron beam intensity	> 10^9 [n/cm^2/sec]

RF cavity

RF voltage	> 200 [kV]
Harmonic num.	~ 5



Summary

- Basic Features and their applications of FFAG accelerators are presented.
  - Types of FFAG
    - *Scaling*
    - *Non-scaling*
  - Acceleration
  - Applications
    - *Proton driver*
    - *Muon accelerator*
    - *Medical applications* *ERIT for BNCT*
- FFAG has large potentials for various applications !