# R&D Activities on FFAG Accelerator

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# FFAG R&D Activities in Japan

- On-going project
  - 150-MeV proton FFAG R&D : KEK
    - Prototype for various applications
  - FFAG for ADS : Kyoto Univ.
    - FFAG + Sub Critical Reactor
  - Muon phase rotation PRISM : Osaka Univ.
    - Muon Rare Decay (Mu-e conversion)
- Future project
  - Hadron therapy @ Ibaraki Prefecture
  - Electron source for sterilization
  - Neutron source for BNCT
  - Neutrino factory (muon accelerator )

# FFAG project

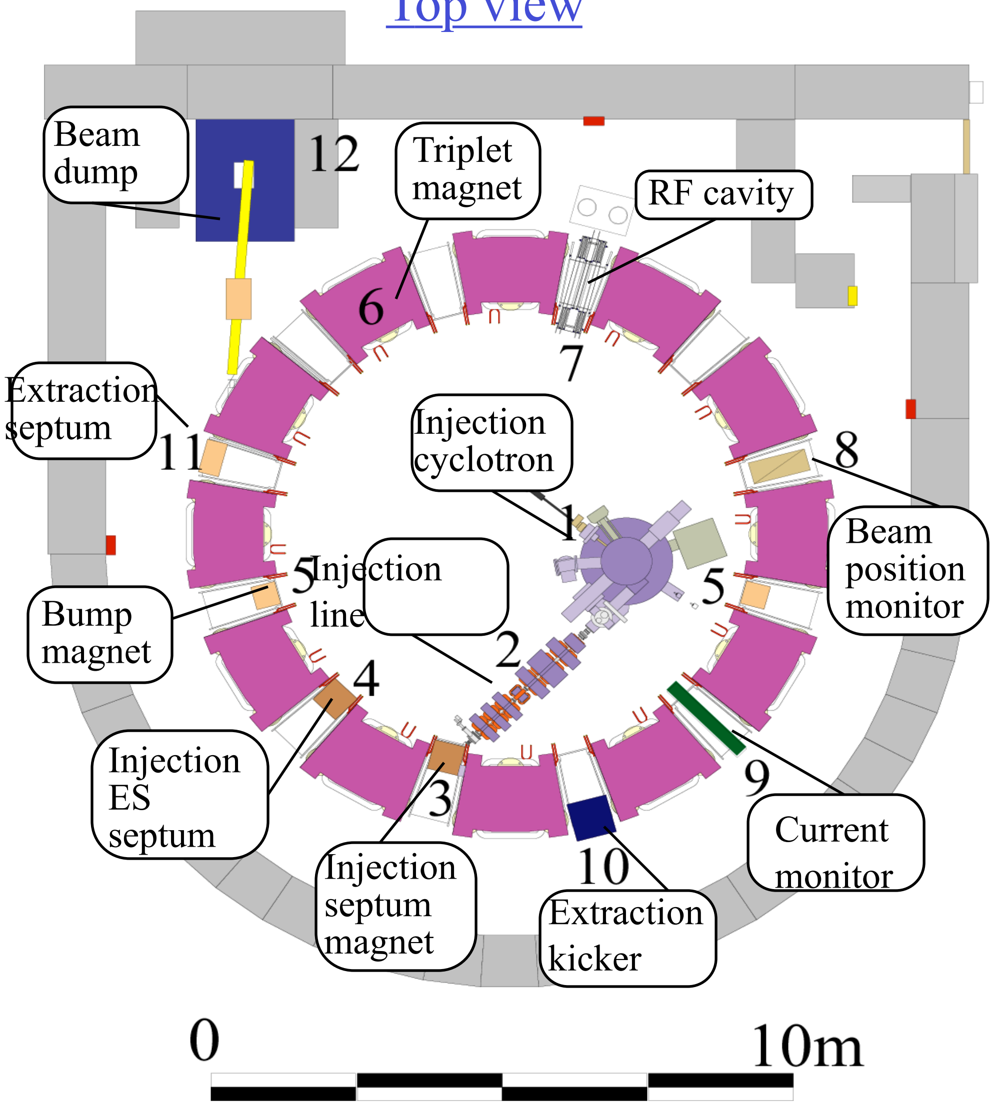
Mori moved from KEK to Kyoto Univeristy

- Kyoto University Reserach Reactor Insitute
  - ADS,Neutron Source,Particle Therapy
- KEK : FFAG project office (officially organized)
  - Particle Therapy, Muon

# Proton FFAG Accelerator

# 150MeV Proton FFAG

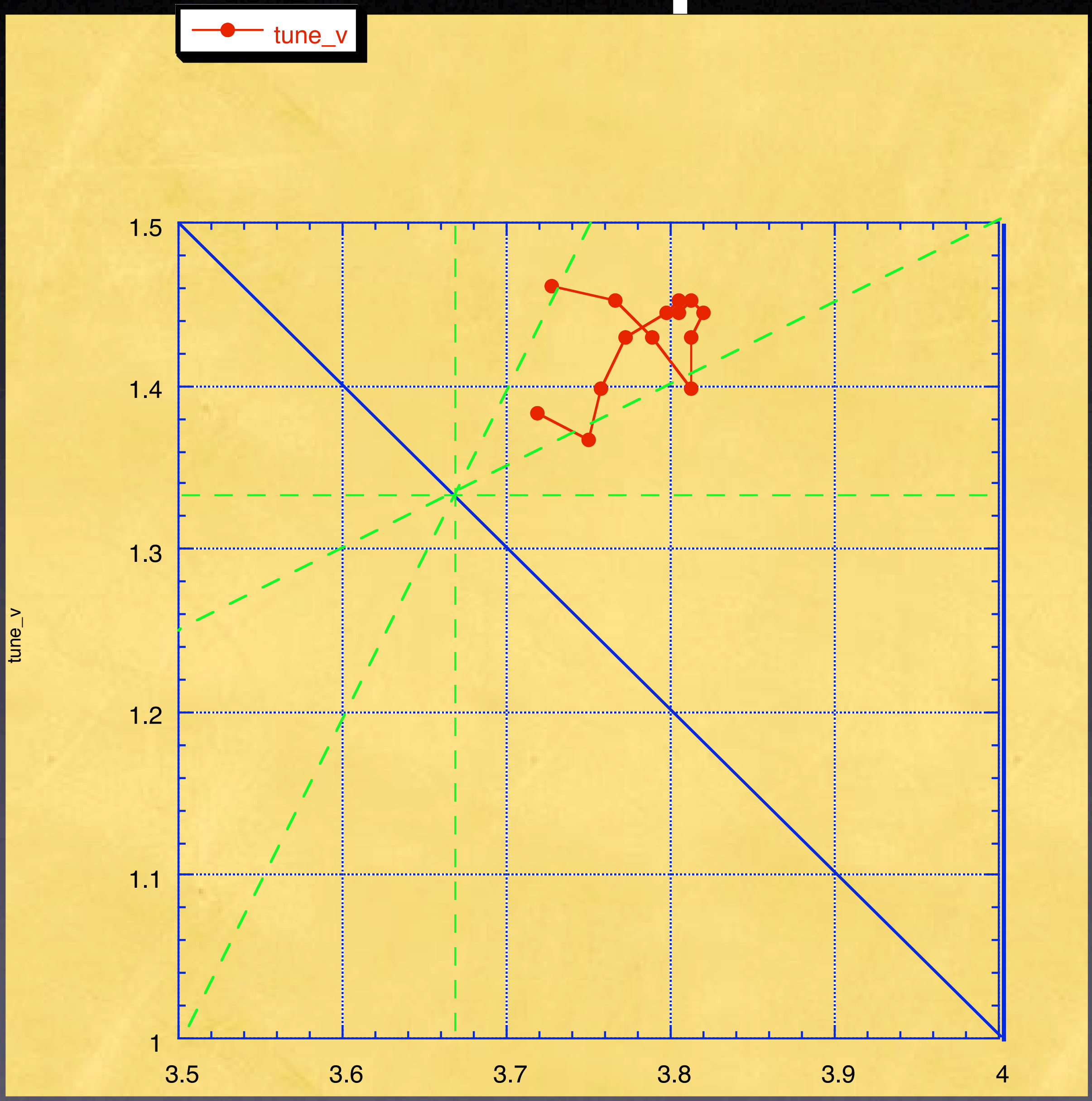
Top view




Design parameter

| | |
|---|---|
| Magnet | radial sector type (DFD triplet) |
| Num. of cell | 12 |
| k-value | 7.6 |
| Ek | 12 => 150MeV (10 => 125MeV) |
| Av. radius | 4.47 => 5.20m |
| betatron tune | hor. : 3.69 ~ 3.80<br>ver. : 1.14 ~ 1.30 |
| Peak Field (@beam orbit) | F-mag. : 1.63T<br>D-mag. : 0.78T |
| revolution | 1.55 ~ 4.56MHz |
| repetition | 250Hz |

# 12-150MeV mode operation

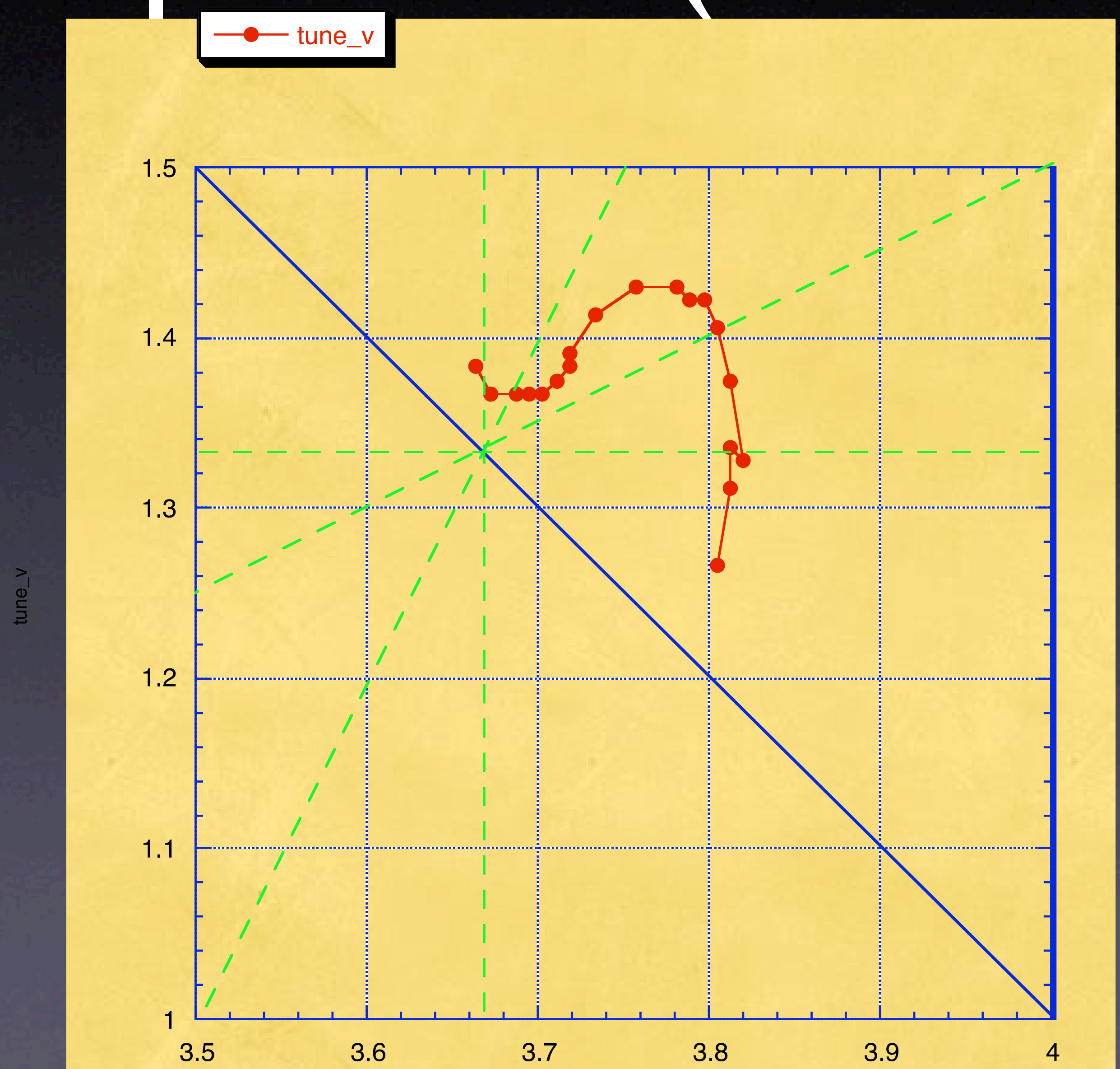



criterion

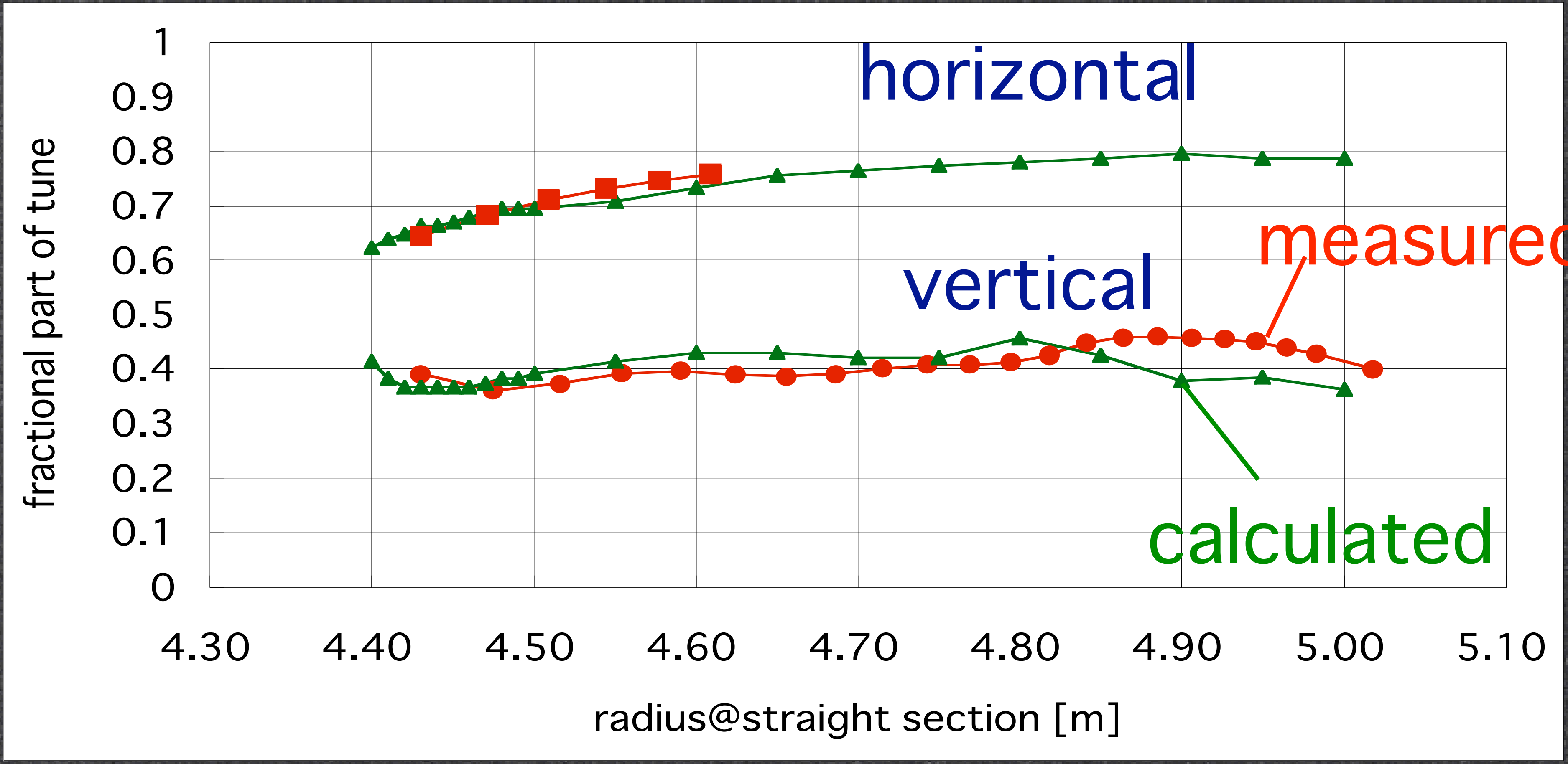
1) Δν<0.1

2)avoid structure & linear resonaces

# 9-100MeV mode operation(B~80%)



# Betatron Tunes

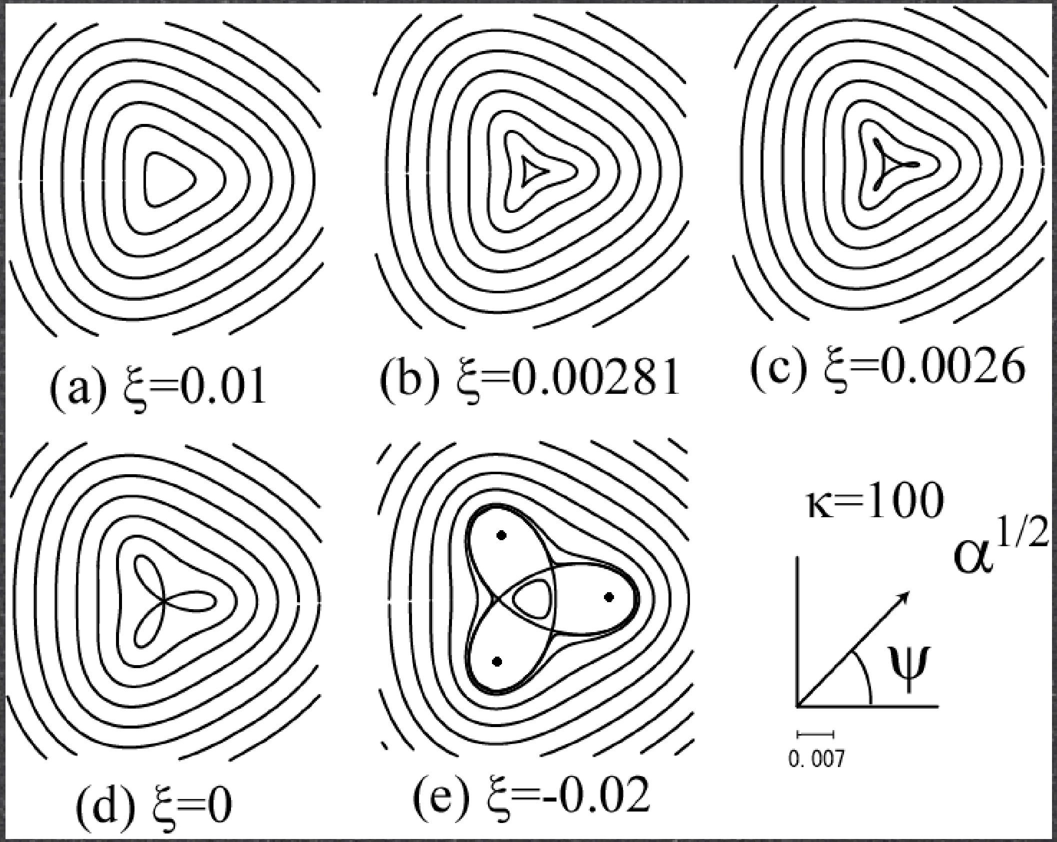


# Resonance Crossing

- $3n_x=11$ : lowest order and normal
  Crossing right after injection
  - Direction of crossing
    - Particle Trapping
      Emittance Growth

# Resonance Crossing

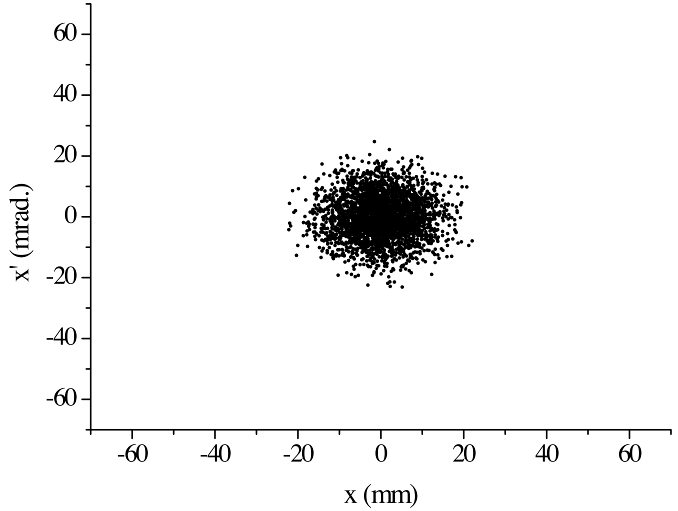
## direction of crossing

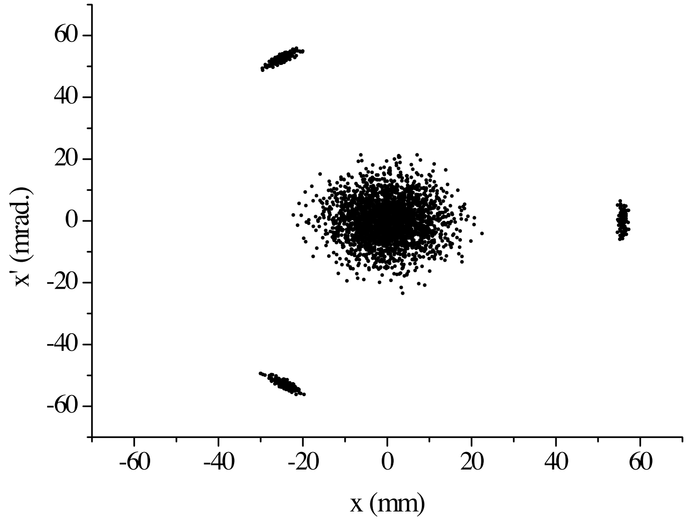



$$\xi \propto \frac{1}{3}p - \nu$$

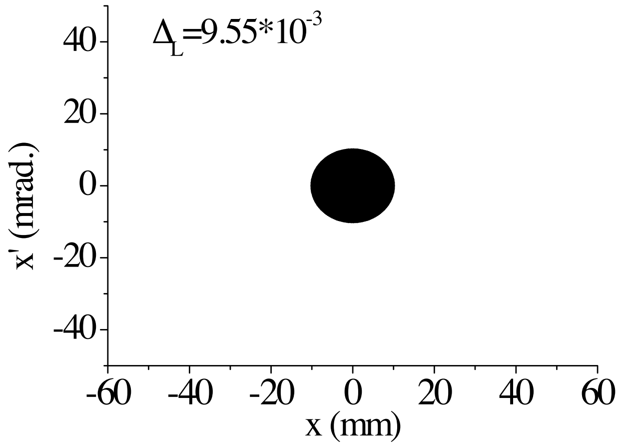
(a)->(e):particle trappin
(e)->(a):emittance grow

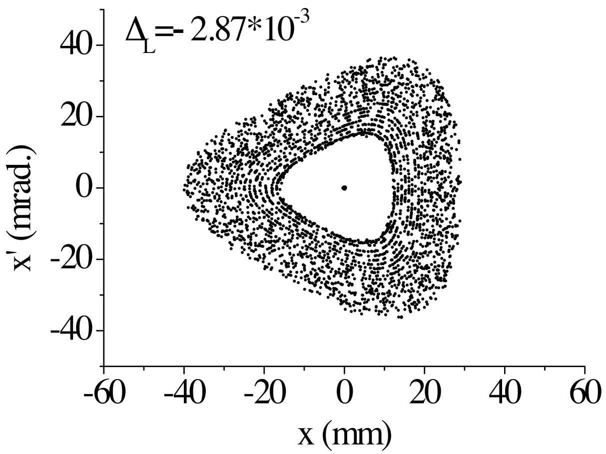
## “Particle trapping”




## “Emittance growth”




エミッタンス増大は有限

※変化を分かりやすくするため
150MeVと無関係なパラメータ

# Resonance Crossing : Emittance Growth

**Max. Emittance Growth Rate**

$$\frac{R + A/\pi}{R} = 1 + \frac{\pi}{\sqrt{2}} \kappa^{-1\ 2} R^{-1\ 4}$$

※仮定：無限に遅い横切り

Crossing speed: $\varepsilon$

Nonlinear detuning: $B_0 = \frac{<\beta>}{16\pi\nu} \int_0^{2\pi} d\theta\, O(\theta)$

Driving term: $A_p = \frac{<\beta>^{\frac{1}{2}}}{8\pi\nu} \int_0^{2\pi} d\theta\, e^{-ip\theta} S(\theta)$

Linear tune shift: $\Delta_L = \frac{1}{3} p - \nu$

Nonlinear tune shift: $\Delta_{NL} = -12 B_0 a_0$

Excitation width: $\Delta_e = -3 A_p a_0^{\frac{1}{2}}$

$\kappa \equiv 3\Delta_{NL}\ \ 4\Delta_e, \quad \xi \equiv 3\Delta_L\ \ 2\Delta_e$

$a_s$ : relative emittance at island

$A \approx \frac{\pi^2}{\sqrt{2}} \kappa^{-\frac{1}{2}} \alpha_s^{\frac{3}{4}}$ : area of island

# Crossing Speed

$$G(\alpha) = 1 + G_m \exp(-\alpha/\tau)$$

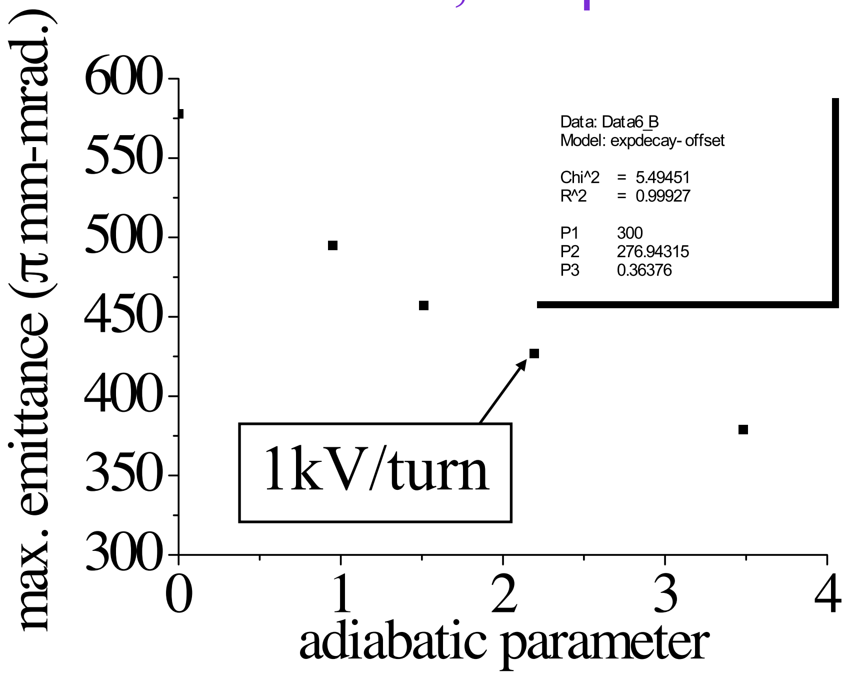
$$\alpha_1 = \left(\frac{\varepsilon}{4\pi\Delta_{NL}\Delta_e}\right)^{-\frac{2}{3}} \quad : \text{ Adiabatic parameter}$$

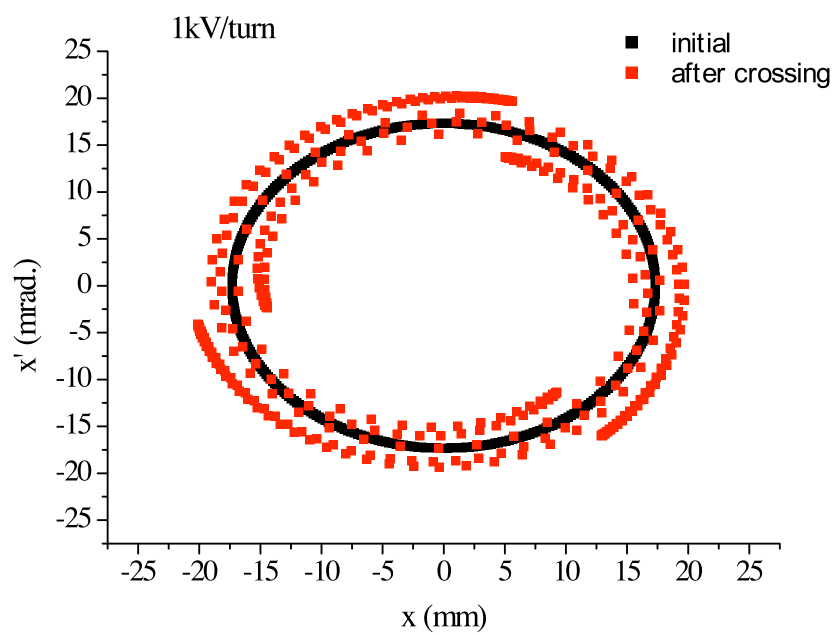
Crossing speed: $\varepsilon$

Nonlinear tune shift: $\Delta_{NL} = -12 B_0 a_0$

Excitation width: $\Delta_e = -3 A_p a_0^{\frac{1}{2}}$

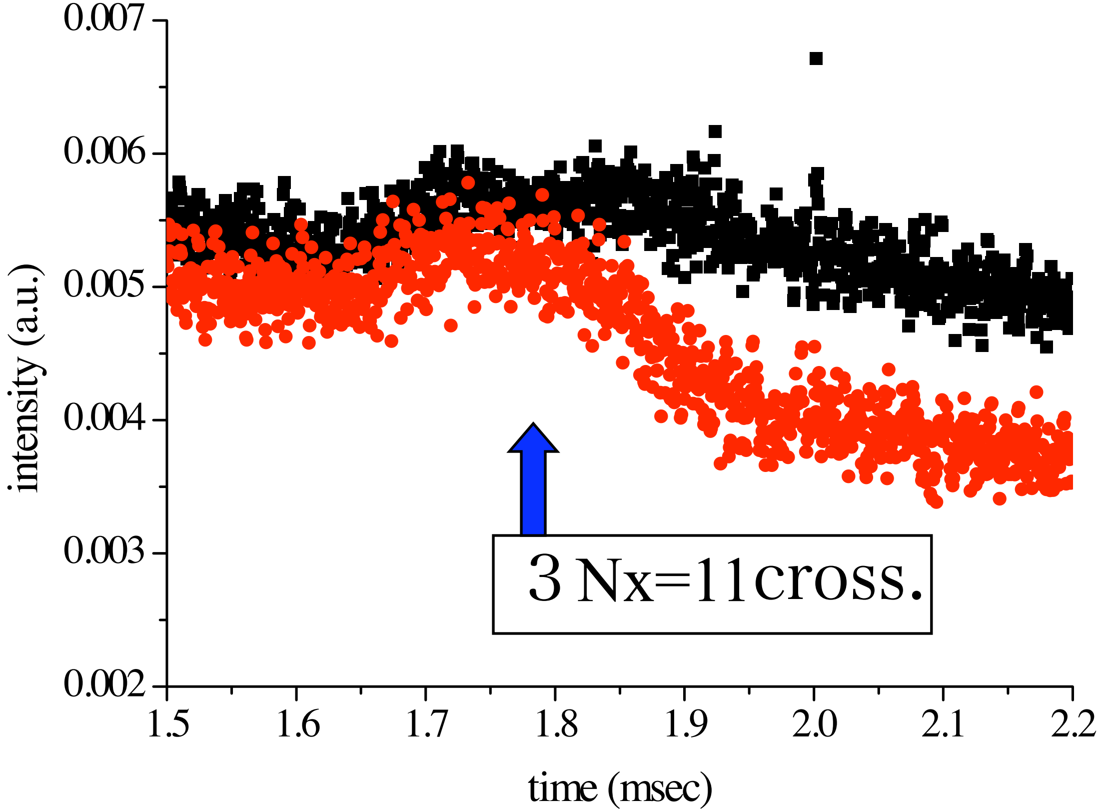
Error: -5mrad., 300p mm-mrad.




Emittance Growth : 300p⇒420p

# Experiment



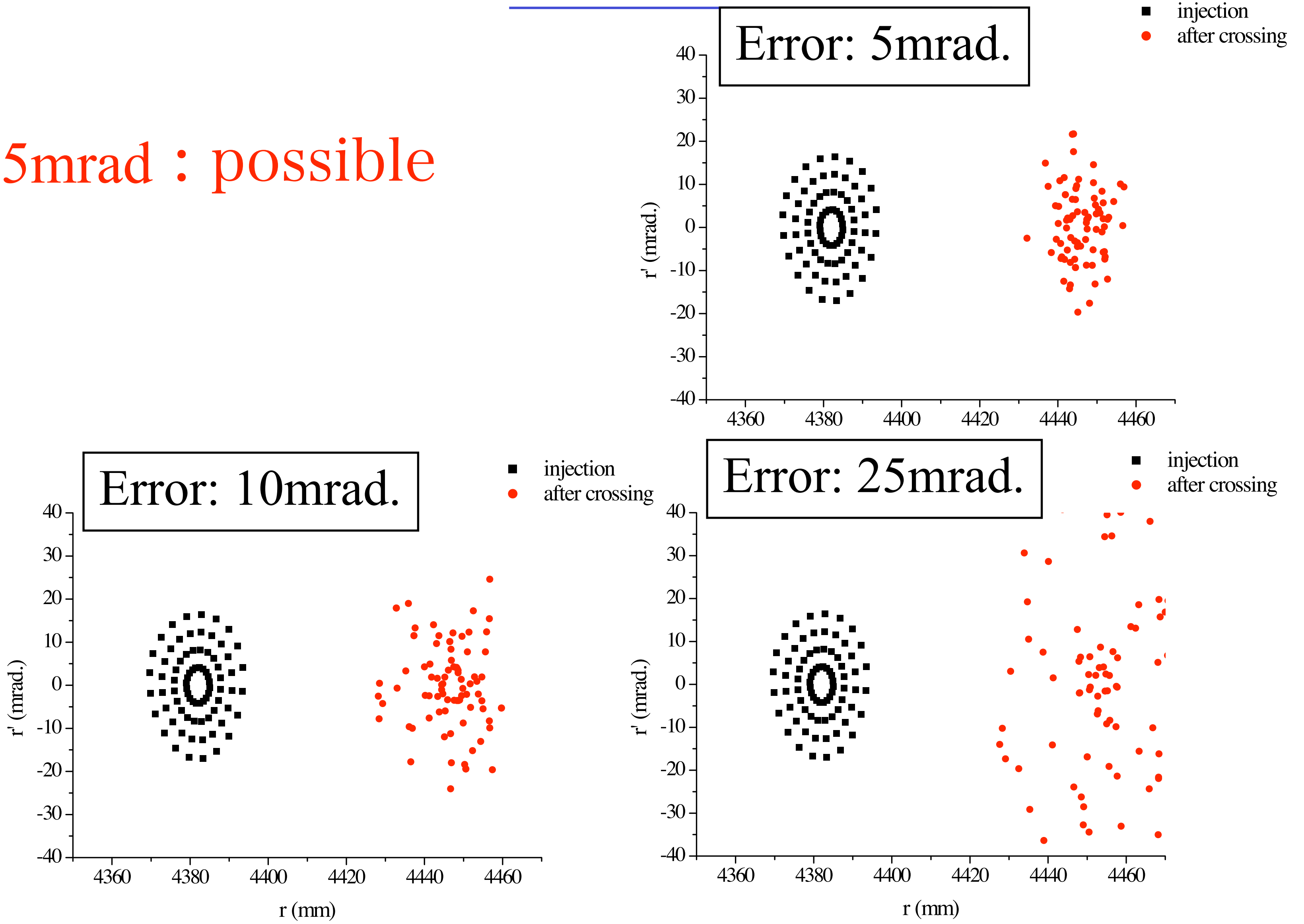

黒：COD corrected

赤：COD uncorrected
～30%

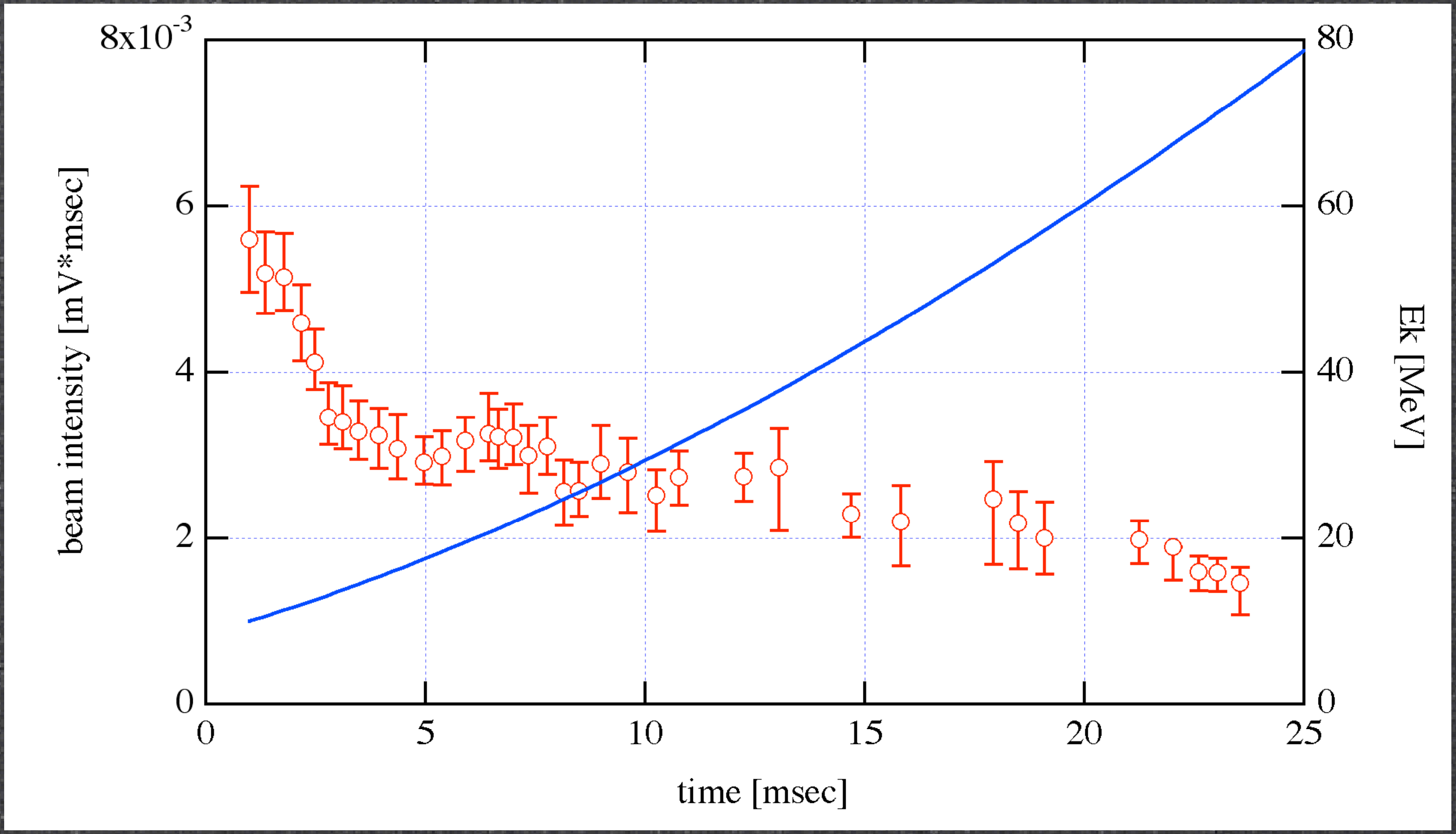
COD corrected → No Beam Loss!

# Error source of COD : dipole kick

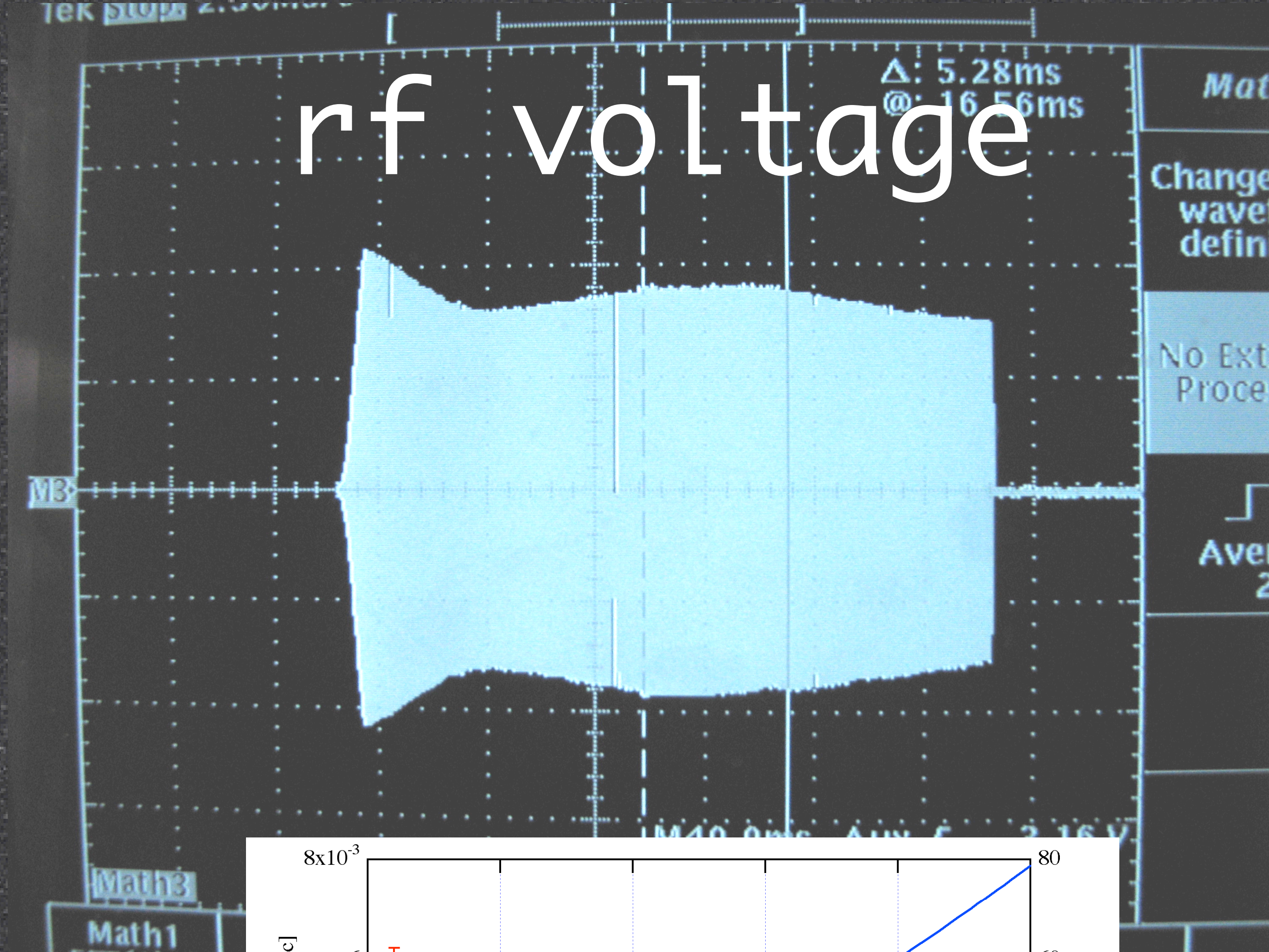
〇<5mrad : possible



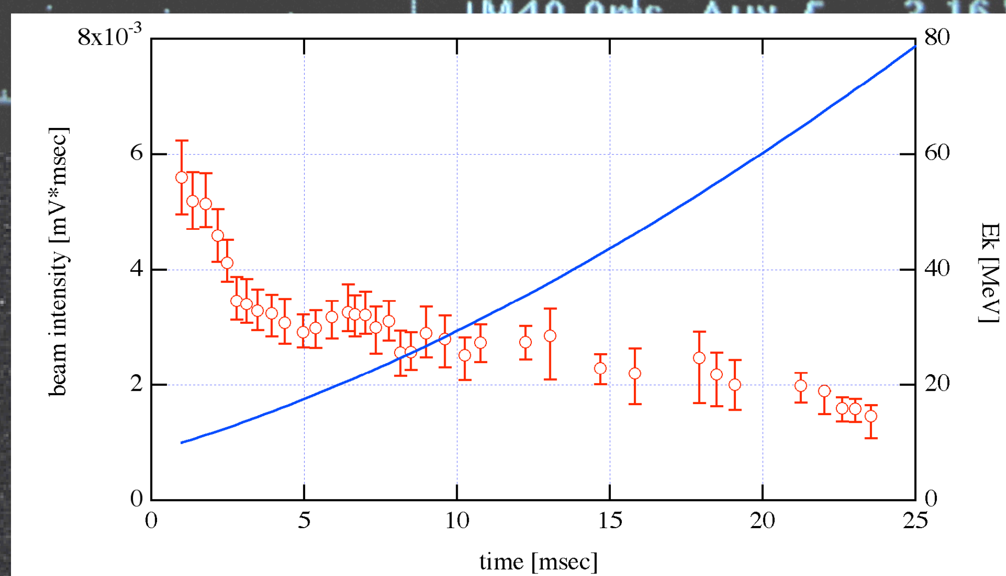
# Beam Intensity



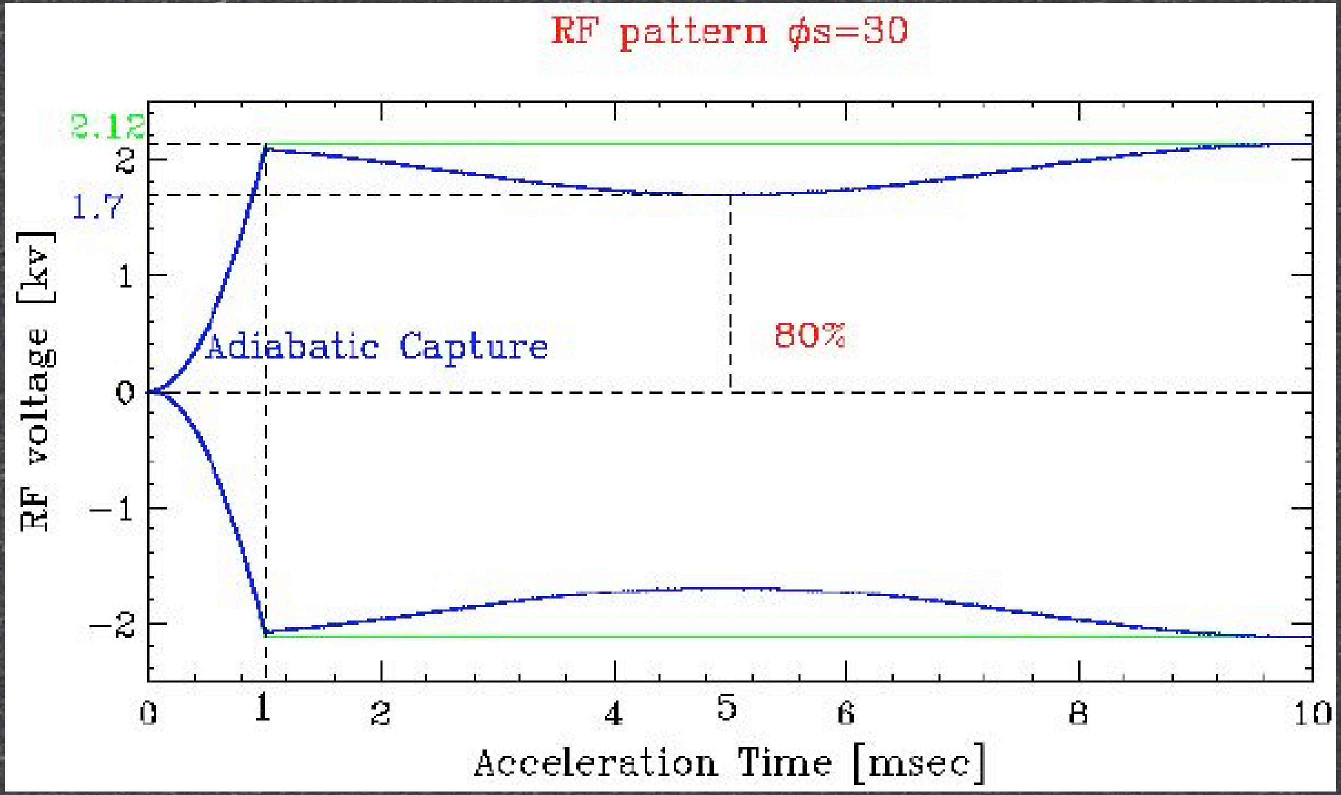
# rf voltage

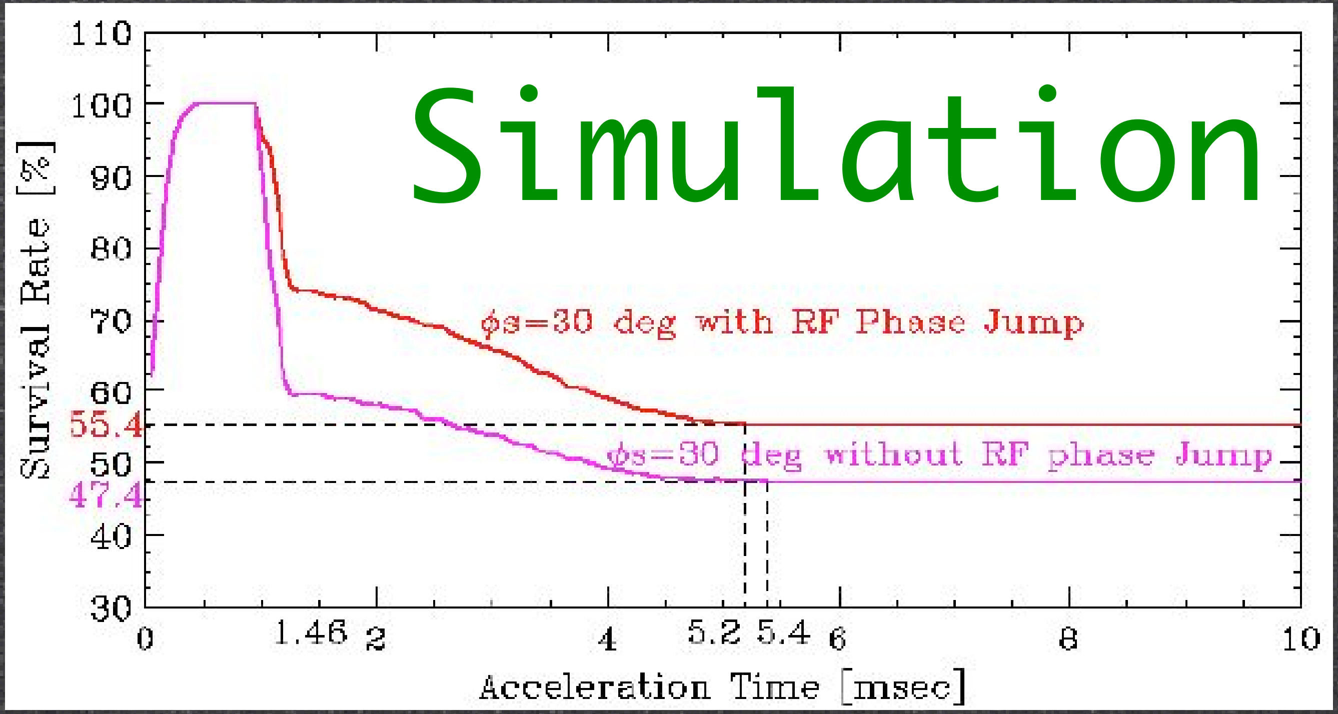


Δ: 5.28ms
@: 16.56ms
M3
Math3
Math1

8x10-3
6
4
2
0
beam intensity [mV*msec]
80
60
40
20
0
Ek [MeV]
0
5
10
15
20
25
time [msec]


RF pattern φs=30
2.12
2
1.7
1
0
−1
−2
RF voltage [kv]
Adiabatic Capture
80%
0
1
2
4
5
6
8
10
Acceleration Time [msec]


Simulation
110
100
90
80
70
60
55.4
50
47.4
40
30
Survival Rate [%]
φs=30 deg with RF Phase Jump
φs=30 deg without RF phase Jump
0
1.46
2
4
5.2
5.4
6
8
10
Acceleration Time [msec]

# FFAG for ADS

## ADSR in Kyoto University Research Reactor Institute (KURRI)

Feasibility study of ADSR
Five-year program 2002 – 2006

Subject
Accelerator technology
-variable energy FFAG
Reactor technology
-basic experiments for energy dependence of the reactor physics

# FFAG for ADS

## ADSR in Kyoto University Research Reactor Institute (KURRI)

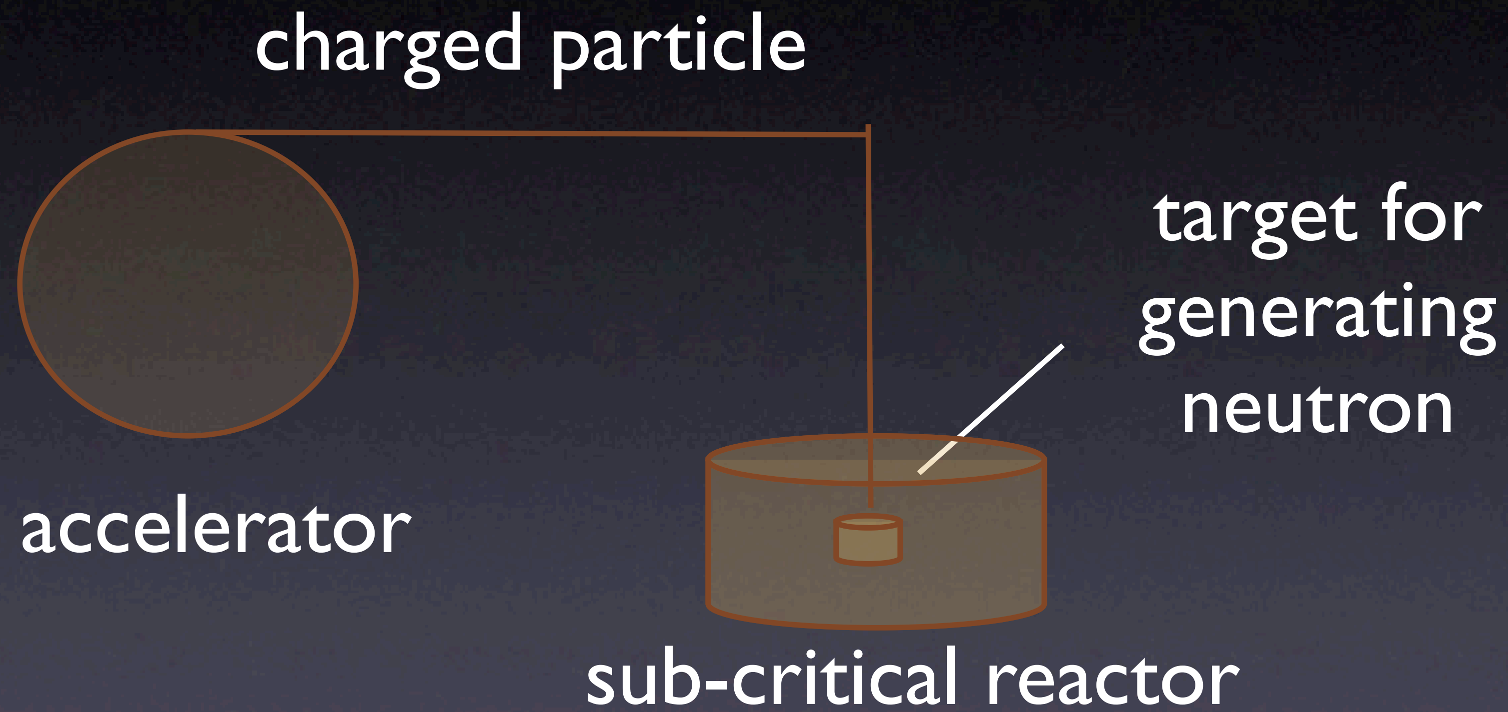
- Feasibility study of ADSR
- Five-year program 2002 – 2006
- Subject
  - Accelerator technology

    -variable energy FFAG
  - Reactor technology

    -basic experiments for energy dependence of the reactor physics

# What is ADSR?

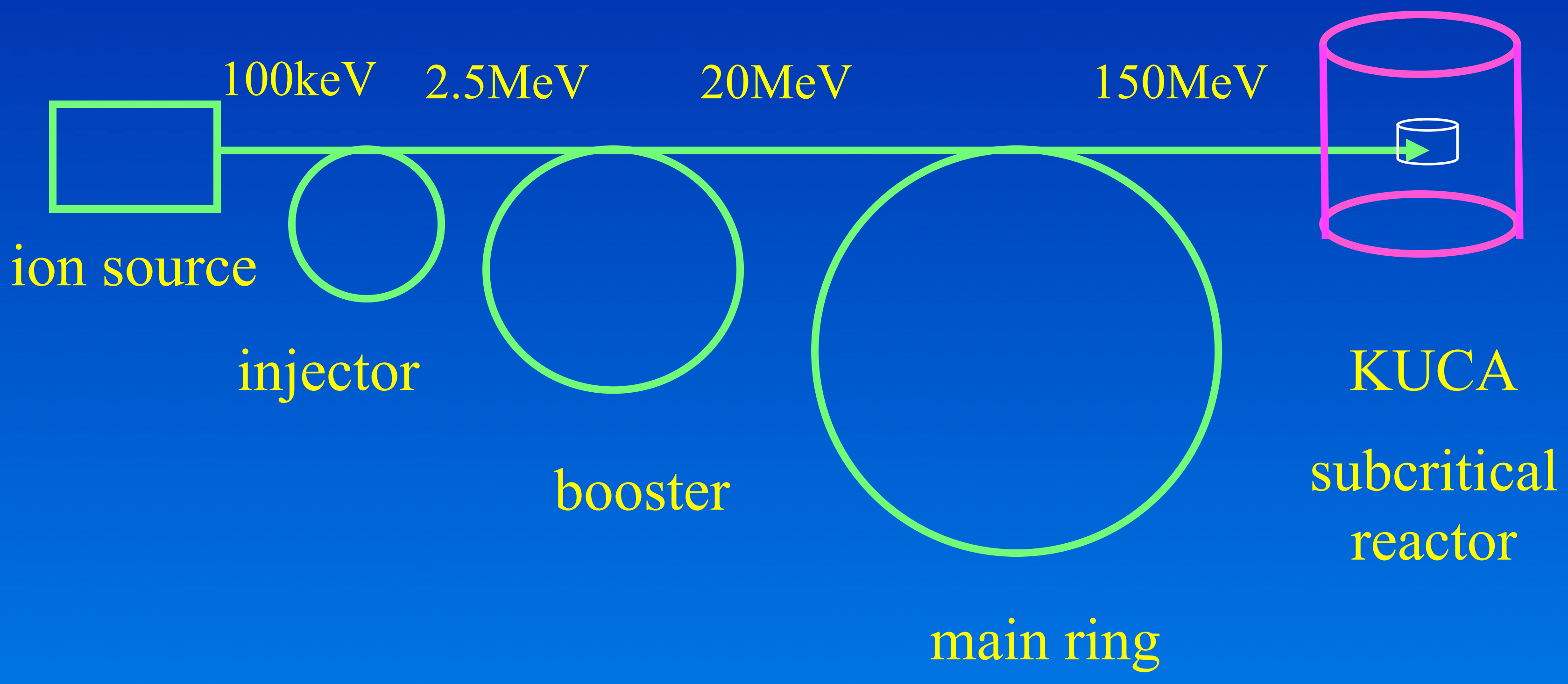
- Accelerator Driven Sub-critical Reactor




Beam off @ chain reaction stops

Safer system !

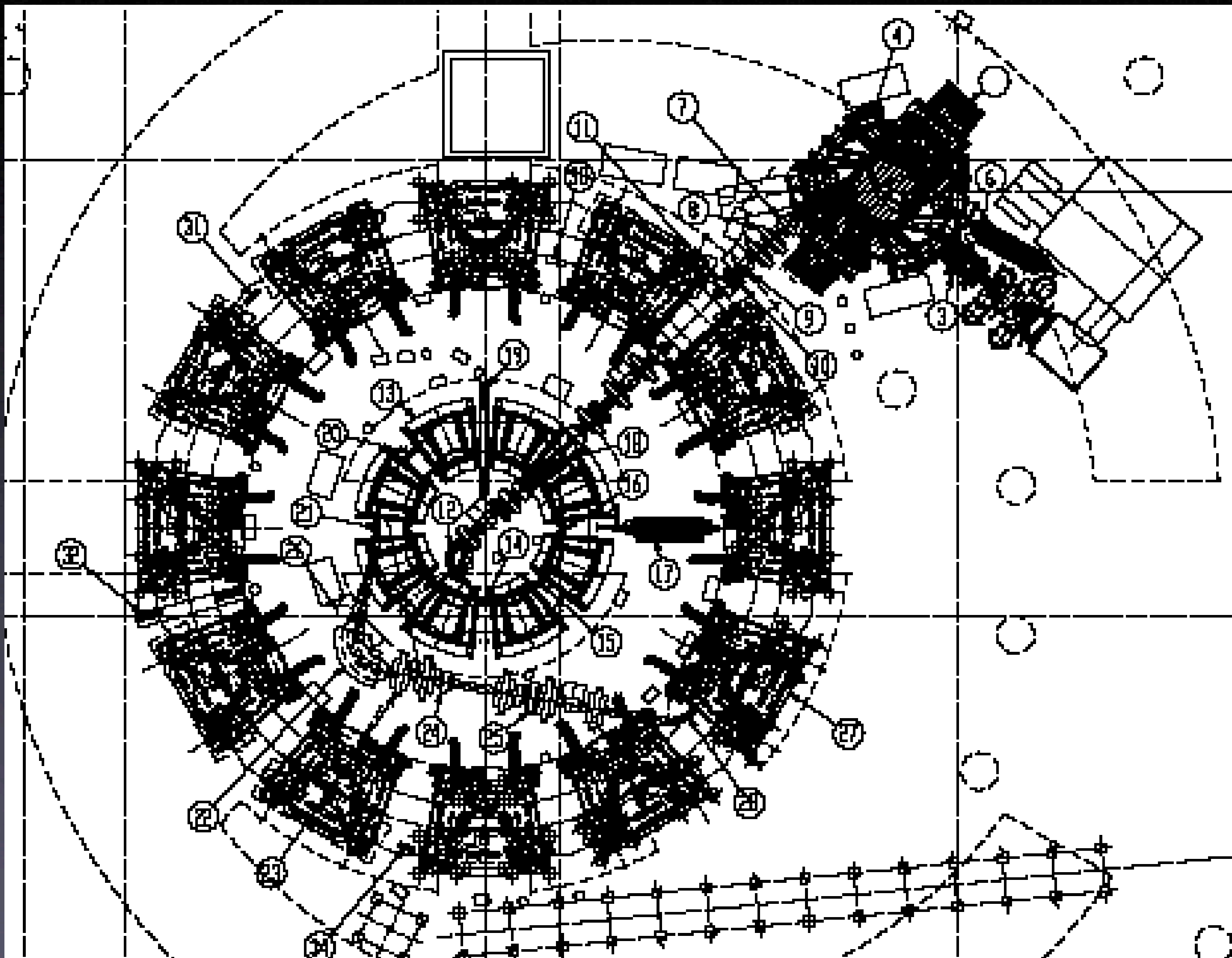
# FFAG – KUCA ADSR system schematic diagram

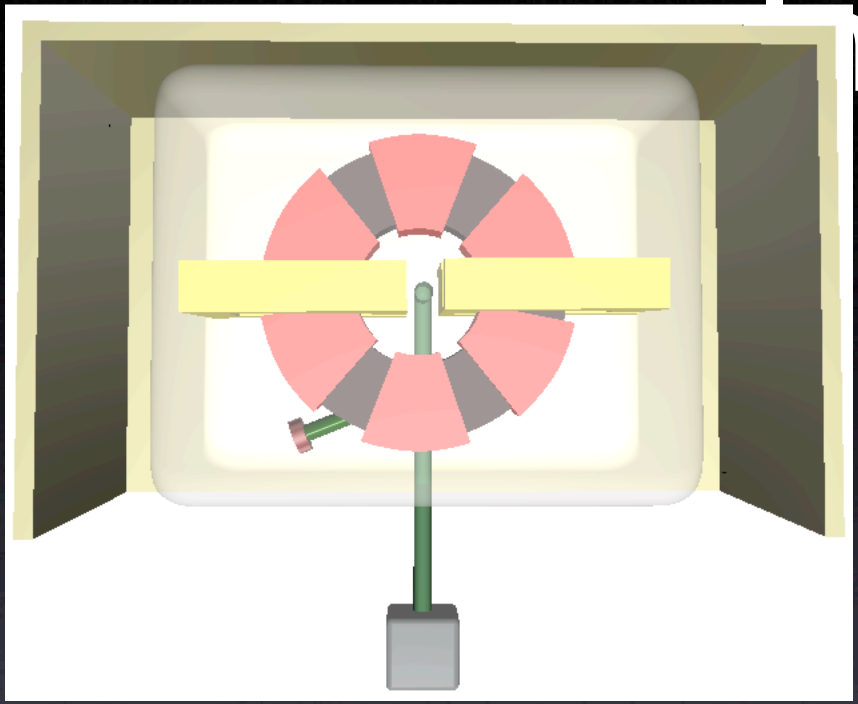
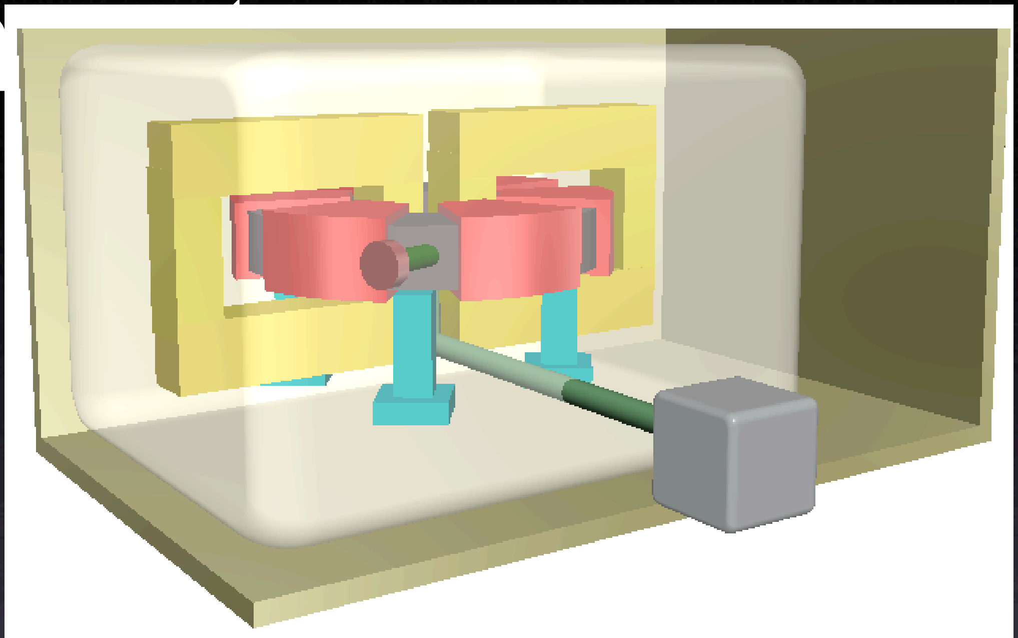
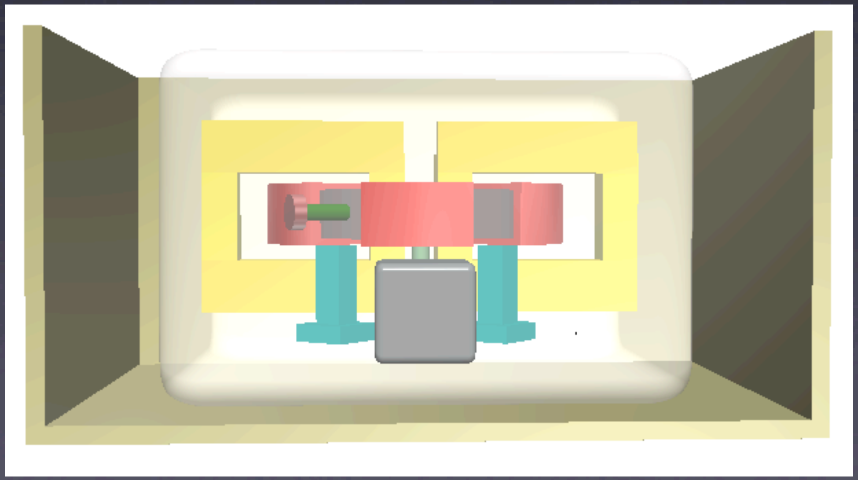


# Parameters of the Accelerator Complex

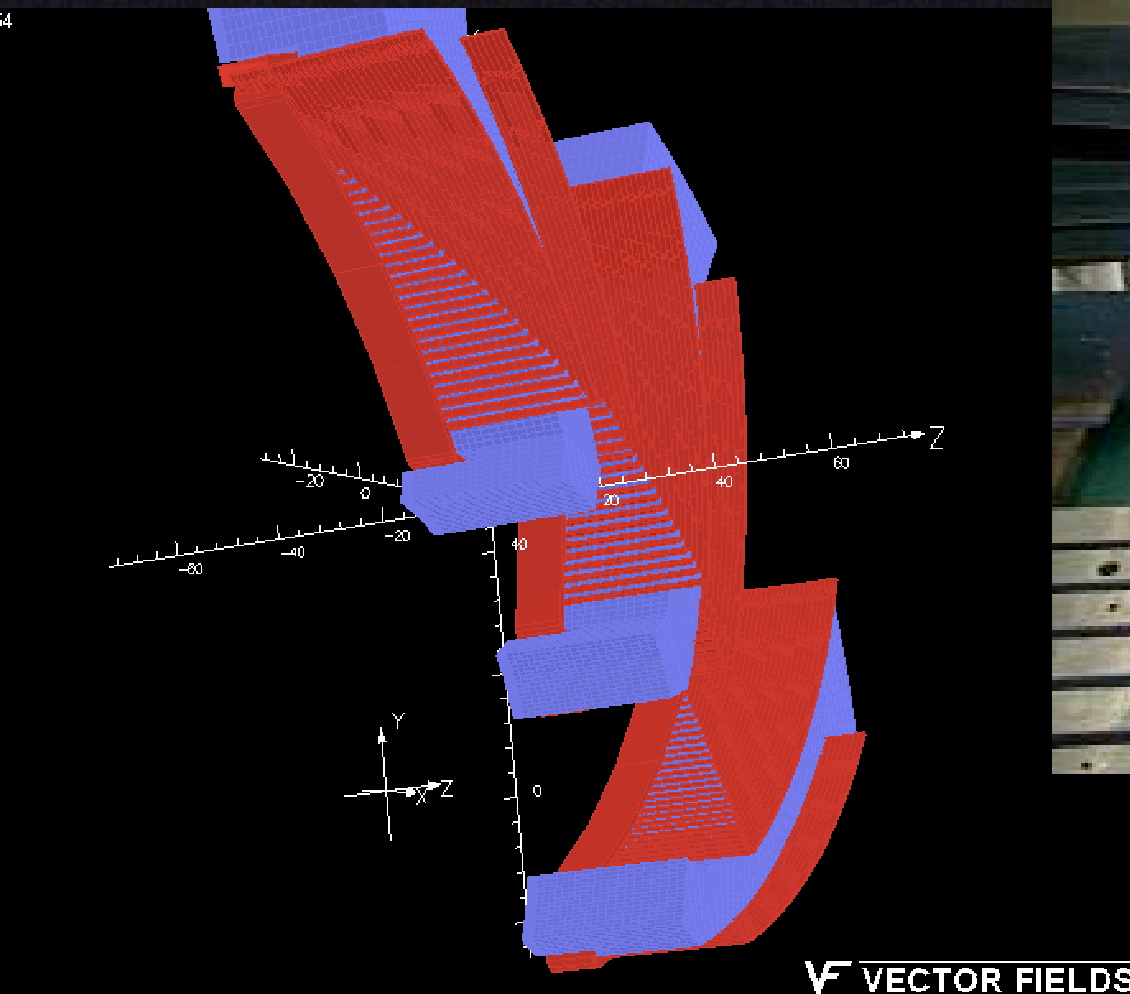
| | Injector | Booster | Main ring |
|---|---|---|---|
| Einj | 100keV | 2.5MeV | 20MeV |
| Eext | 2.5MeV | 20MeV | 150MeV |
| Lattice type | Spiral | Radial DFD | Radial DFD |
| Acc. scheme | Induction | rf | rf |
| # of cells | 8 | 8 | 12 |
| k value | 2.5 | 4.5 | 7.6 |
| coil/pole | coil | coil | pole |
| Pext/Pinj | 5.00 | 2.84 | 2.83 |
| Rinj | 0.60m | 1.42m | 4.54m |
| Rext | 0.99m | 1.71m | 5.12m |

# Layout of the complex



# Model of injector magnet




# Particle Beam Therapy

# Requirements

## To extend the use of Proton Therapy widely in (Japanese)society

- Efficient treatment
  - >500pateints/year
- High dose rate
  - >5Gy/min.
- Flexibility (various types of cancer)
  - Respiration mode
  - Spot scanning
- Easy operation
- High maintenance ability
  - Small residual radio activities
- Small cost
  - Construction and operation

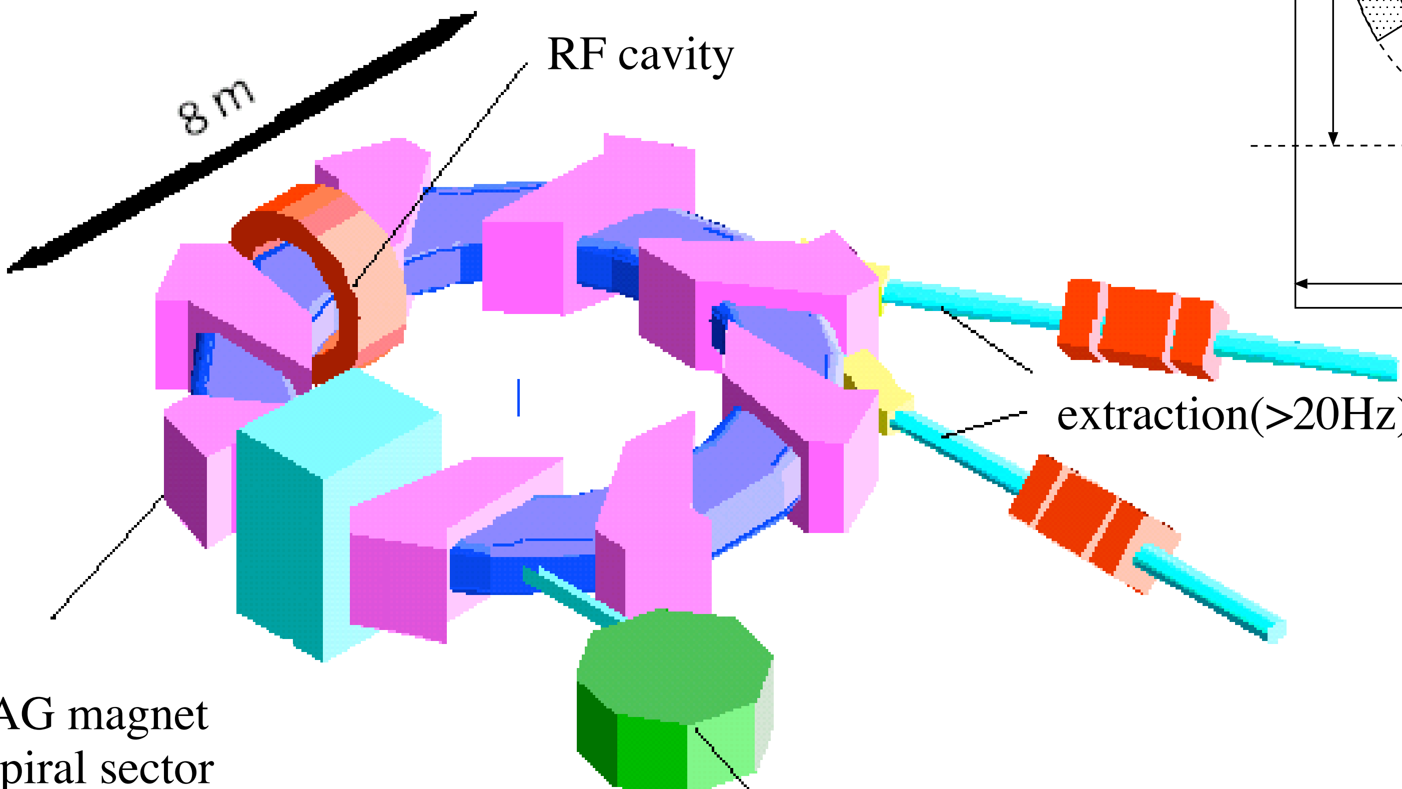
# Features
## proton therapy accelerator

| | Synchrotron | Cyclotron | FFAG |
|---|---|---|---|
| • Intensity | Low | Enough | Enough |
| • Maintenance | Normal | Hard | Normal |
| • Operation | Not easy | Easy | Easy |
| • Multi-extraction | Difficult | No | Yes |

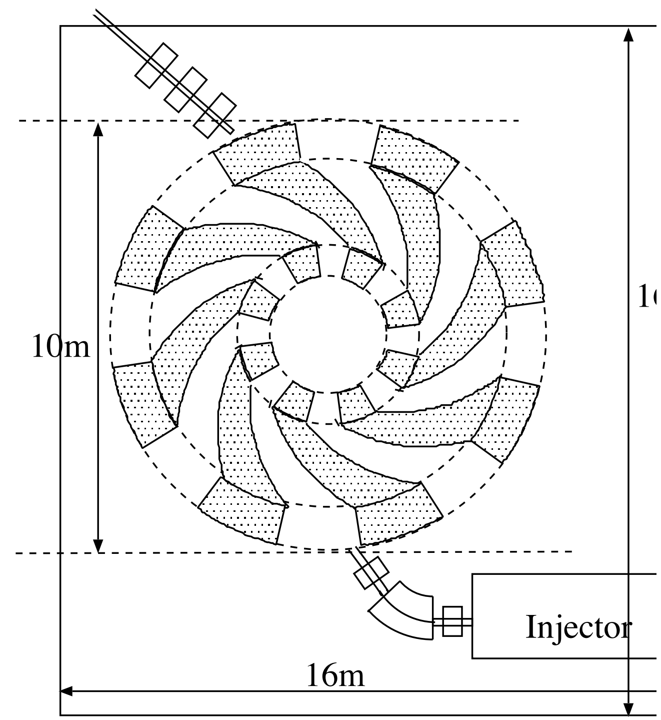
# Accelerator for Hadron(proton) Therapy

- Requirements
  - Proton energy 230MeV (variable)
  - Intensity >100nA : 5Gy/min
  - Beam extraction efficiency >90%
- Synchrotron 1~16nA, not enough
- Cyclotron Extraction efficiency ~<70%
- FFAG 1 > 100nA (100Hz), Extraction >95%

# Proton Beam Therapy FFAG Accelerator



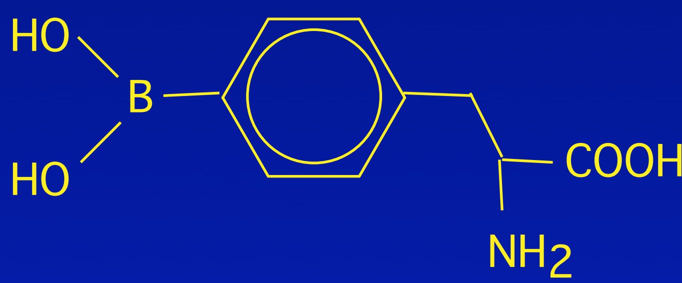

FFAG magnet
- spiral sector
- #sector:8
- k:2
- hybrid magnet



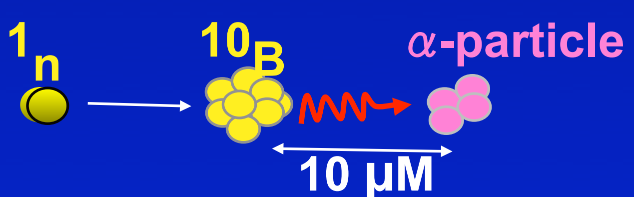
# Neutron Source for Boron Captured Neutron Therapy (BNCT)

# Boron Neutron Capture Therapy (BNCT)


Borocaptate sodium
(BSH)




L-p-Boronophenyl alanine
(BPA)




$$^{1}n + {}^{10}B \rightarrow {}^{4}He\ (\alpha) + {}^{7}Li + 2.8\ MeV$$

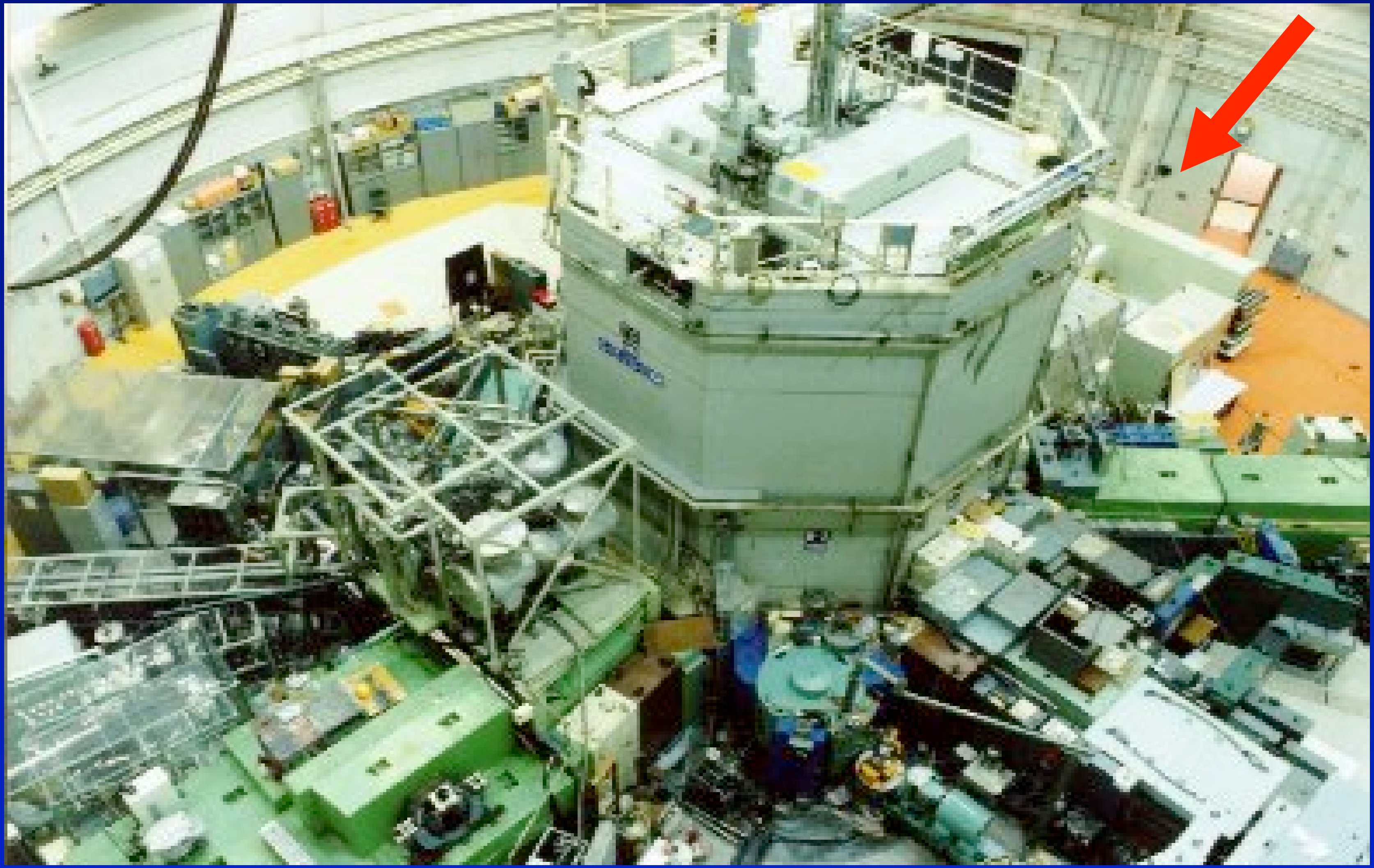

a
b
c

# Neutron source

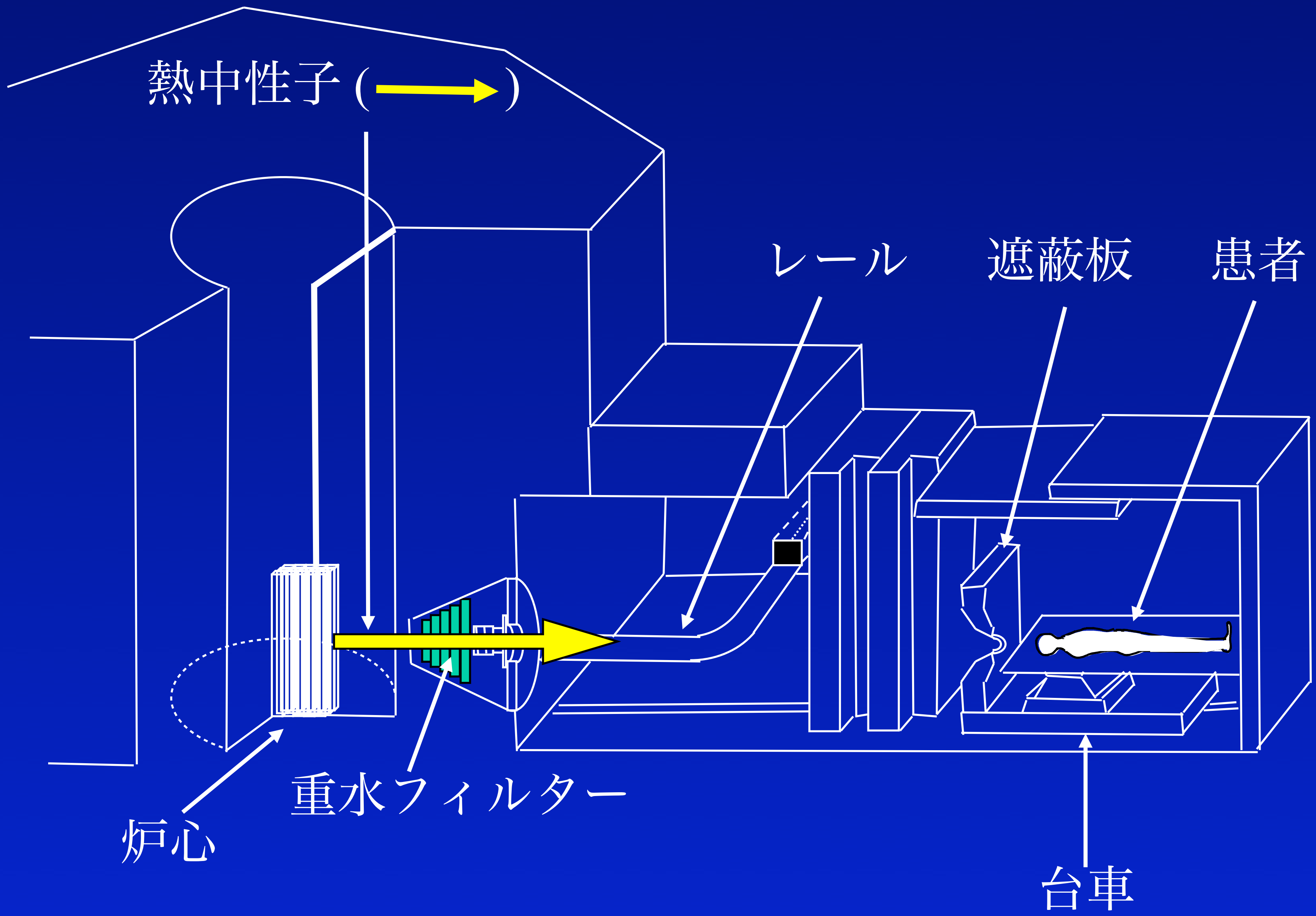
- Large neutron flux
  - **> 1x10E09 n/cm2/sec** at patient for 30 min. treatment.
    - Nuclear reactor only can provide.
- Low energy spectrum :thermal/epi-thermal neutron

Limited to extend the use of BNCT widely in society.

# Kyoto University Research Reactor (KUR)

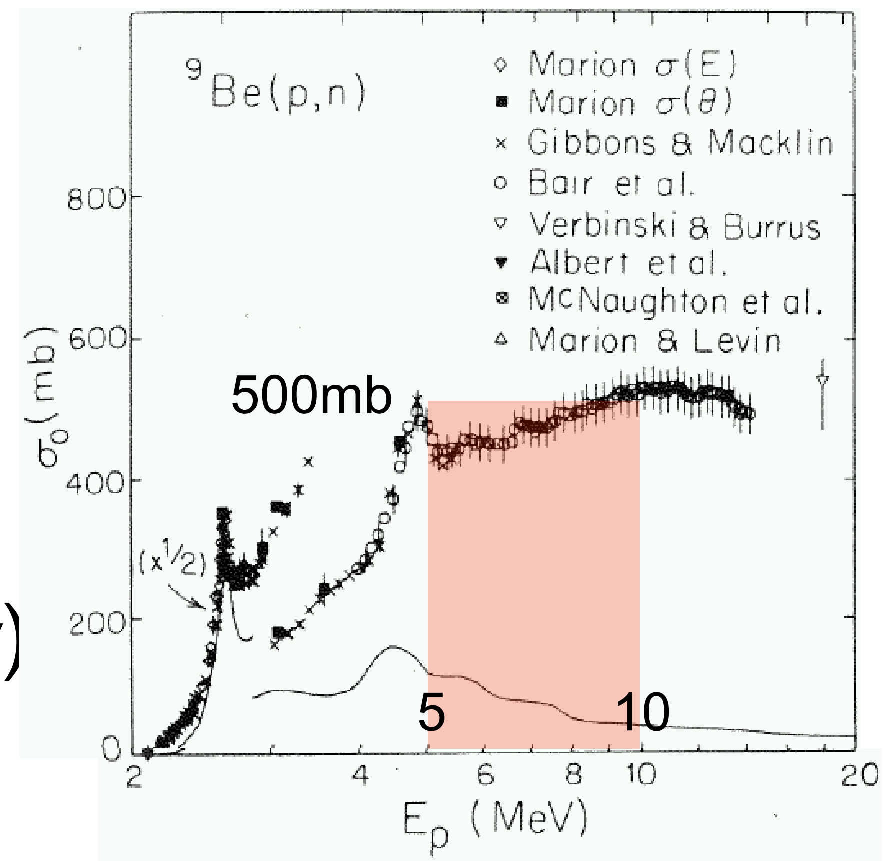


# The rough sketch of $D_2O$-neutron facility in KUR



# Accelerator-based neutron source

- Neutron production reaction
  - 9Be(p,n)B,  8Li(p,n)Be
- proton energy     3-10MeV
  - (Coulomb barrier ~2MeV)
  - Low gamma-ray background
- beam current      >20 mA (cw)



# Difficulties

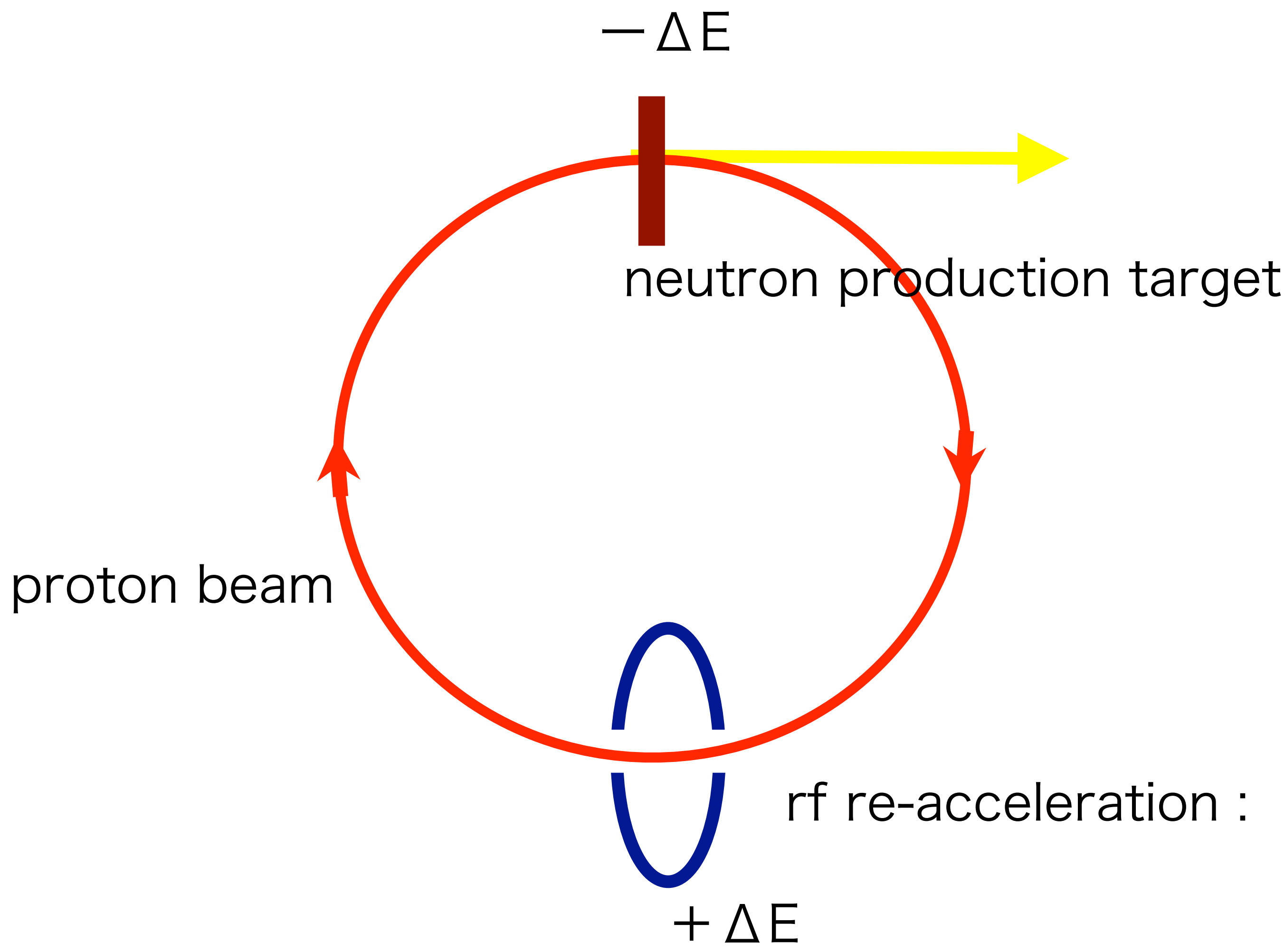
- Beam current : >20mA (CW)
  - Very high duty factor
    - ex. Linac (RFQ, IH, DTL)
    - cw operation : technically not easy & expensive
- Heat load for the target : Beam power ~100kW
  - Stopping power ~100MeV/g/cm2, Range <1mm

## Proton beam power is mostly consumed by ionization in the target, not by neutron production.

- Neutron production/Ionization(energy loss) Efficiency ~ <1/1000
- 
- If the beam energy lost in the target is recovered by re-acceleration, the efficiency of neutron production can be improved.

# ERIT

## Energy Recovering Internal Target



# ERIT for neutron production with FFAG

- Erergy loss
  - recovered by rf re-acceleration
- Emittance growth due to scattering
  - cured by "Ionization Cooling"
- Beam current
  - Required accelerating averaged beam current can be reduced because the ciruculating current in the ring is large.

# Energy loss

- Proton energy 10 MeV dE/dx ~30MeV/g/cm2
- Target : Be 5microns

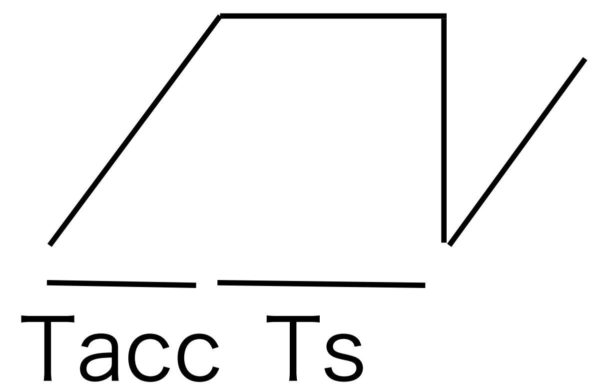
Energy loss/turn ~ 30keV

Power loss in the target ~1.2kW

Heat load becomes modest.

# Beam current

$$I_p = \frac{eN_p f_{rev} T_{st}}{\left(T_{acc} + T_{st}\right)} \qquad \frac{I_p}{I_{ave}} = f_{rev} T_{st}$$



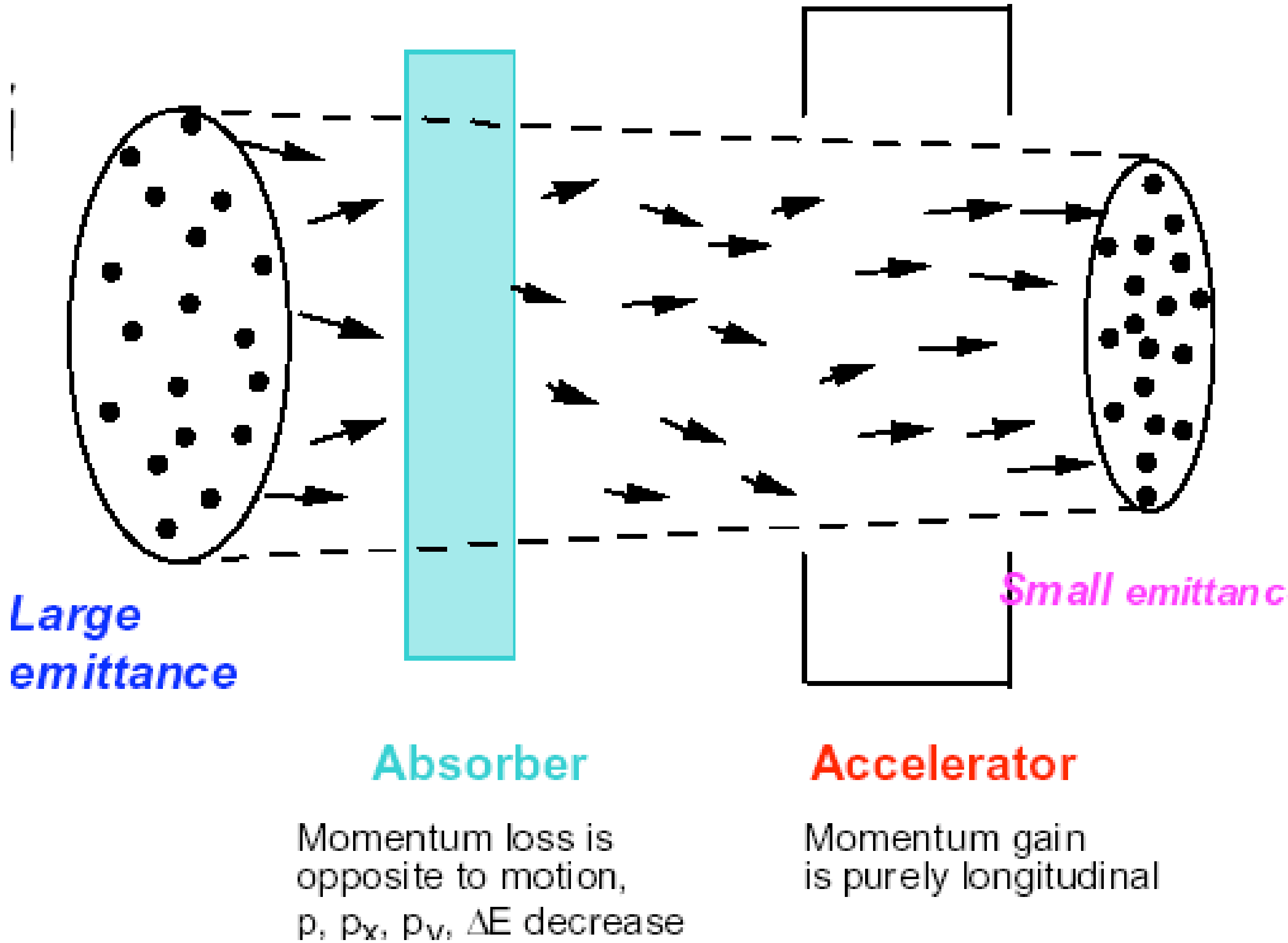

- Revolution frequency ~5MHz
- Storage time ~0.5msec
- Number of turns n=frevTst=2500
- Accelerating time 0.5msec
- Np ~5x10E10
- Ip ~ 40mA, Iave ~ 16micro-A=Ip/2500

# Emittance growth

- Using an internal target, the beam emittance could be increased by the effects of multiple scattering and straggling.
- In ERIT, however, “Ionization Cooling” should help to cure the emittance growth.

ERIT = Ring Ionization Cooling

# Ionization Cooling




Only muon!

How about proton?

$\tau_\mu = 2.2\gamma$ μs or $L_\mu = 660\beta\gamma$ m

# Ionization cooling

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

- Transverse

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

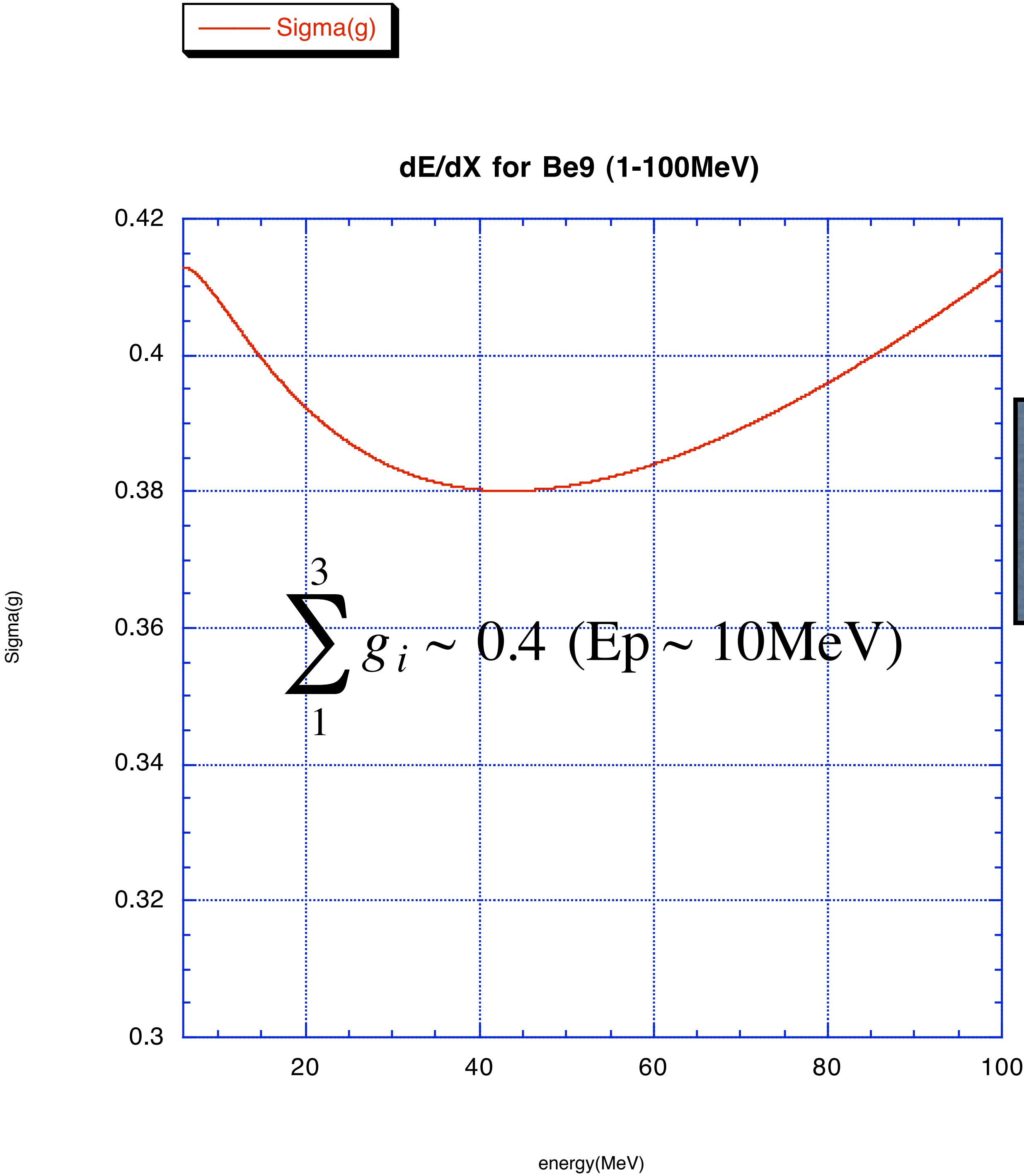
- Longitudinal

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

cf. p:10MeV, Be target
Transverse : Cooling
Longitudinal : Heating
without coupling.

$$\sum_1^3 g_i > 0$$

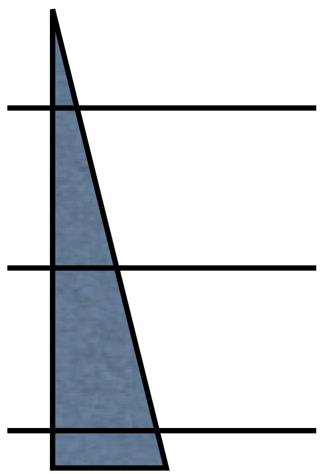
In all of directions (trans. &long.), the beam can be cooled .




$$1.6 < D\,\rho' / \rho_0 < 2$$

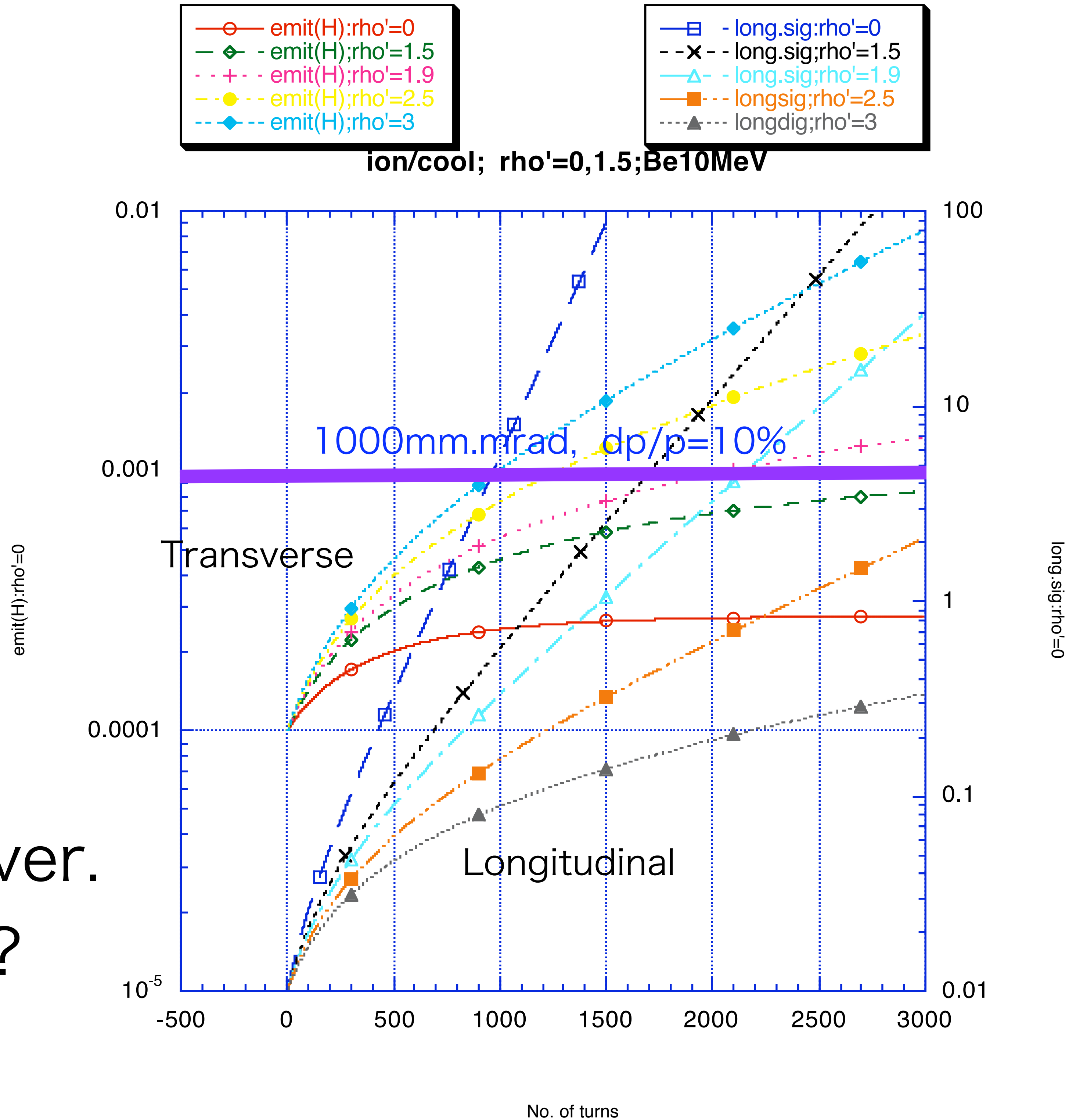
for 3D cooling

# Tran x Long




wedge target

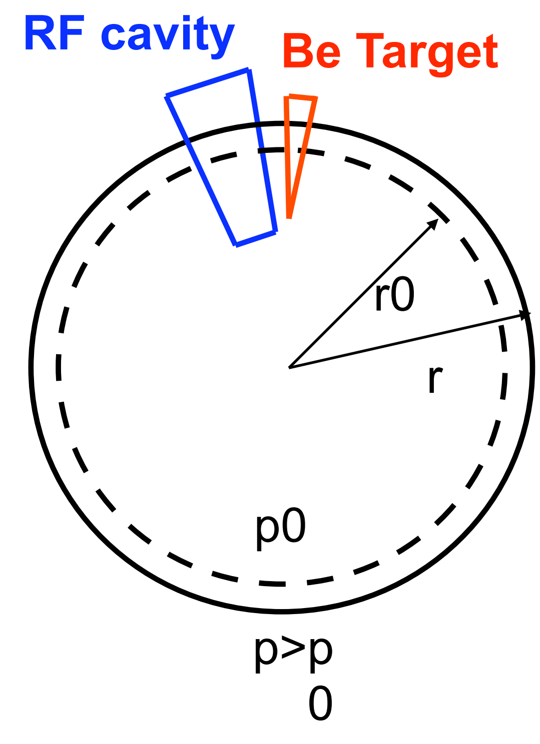
need hor.&ver. coupling?

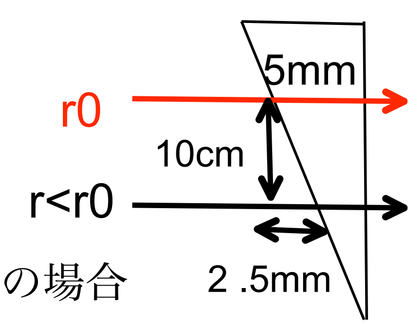


# 縦方向運動のシミュレーション

シミュレーションの条件

| ビームエネルギー : T0 [MeV] | 5 | 10 |
|---|---|---|
| 加速器平均半径 : r0 [m] | 1.1 | 1.5 |
| 周回周波数 : Frev [MHz] | 4.46 | 4.61 |
| Dispersion : D [cm/%] | 25 | 25 |
| ターゲット 厚 @ r0 : G0 [mm] | 5, 8 | 5, 8 |
| ターゲット厚の傾き : r'/r0 [1/cm] | 0.03~0.07 | 0.03~0.07 |
| RF加速電圧 : Vrf [kV] | 2 | 2 |
| ハーモニックナンバー : h | 5 | 5 |
| エネルギーロス @r0 : dEt [keV] | 63, 101 | 36, 57 |
| ストラグリング(s) : dEs [keV] | 8.1, 10.2 | 8.1, 10.2 |
| **Dr'/r0** | **0.75~1.75** | **0.75~1.75** |



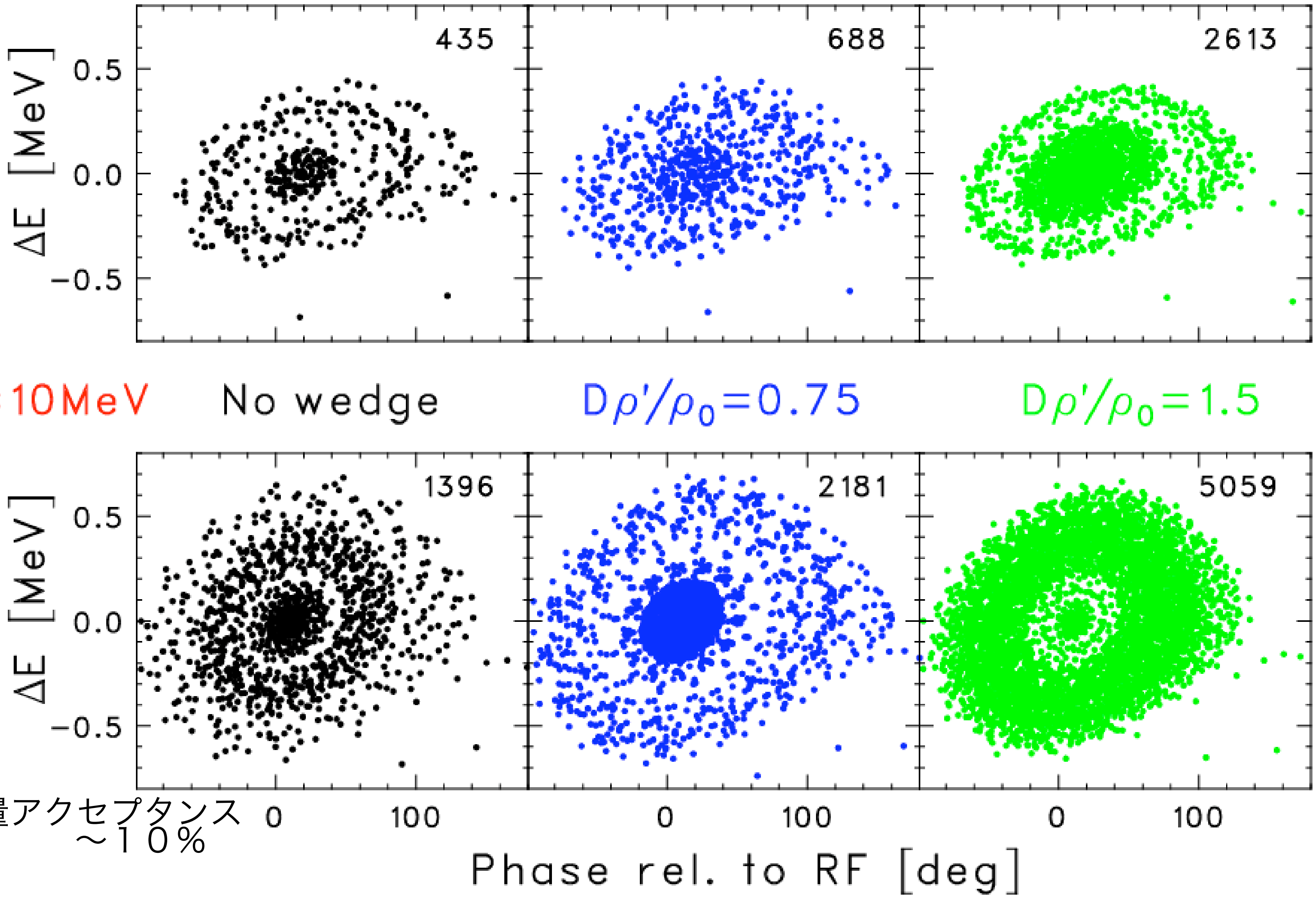




r/r0=0.05の場合

# シミュレーションの結果

$T_0$=5 MeV

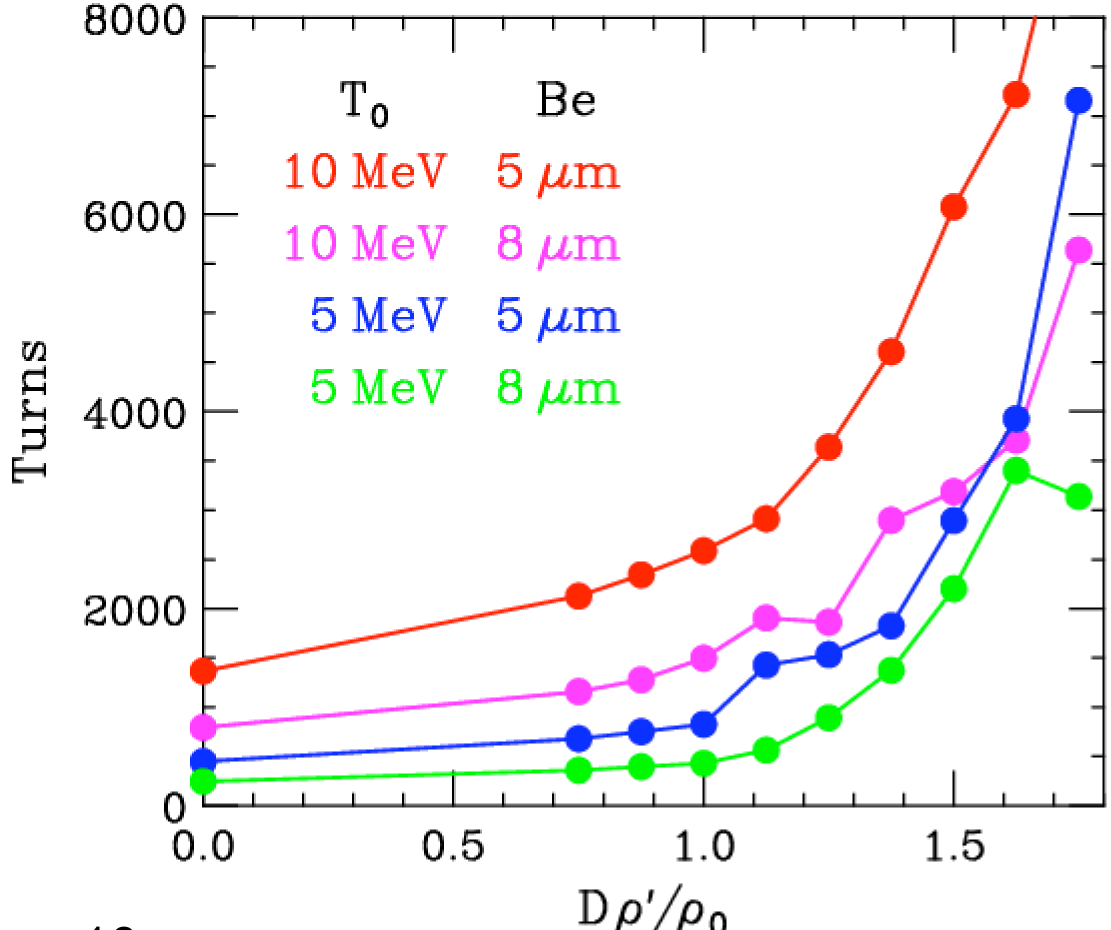
Be 5mm の場合




$T_0$=10MeV

運動量アクセプタンス
～１０％

# シミュレーションのまとめ




アパーチャー ±10 cm
粒子数 100 個の平均

イオン化冷却により2~3000 turn 程度可能

# Heat Load

- Advantages of ERIT
  - dE/dx ~ smallest at maximum beam energy
- Power loss at target
- $P = I_c \times \Delta E$ cf. 50mA x 30keV = 1.5kW

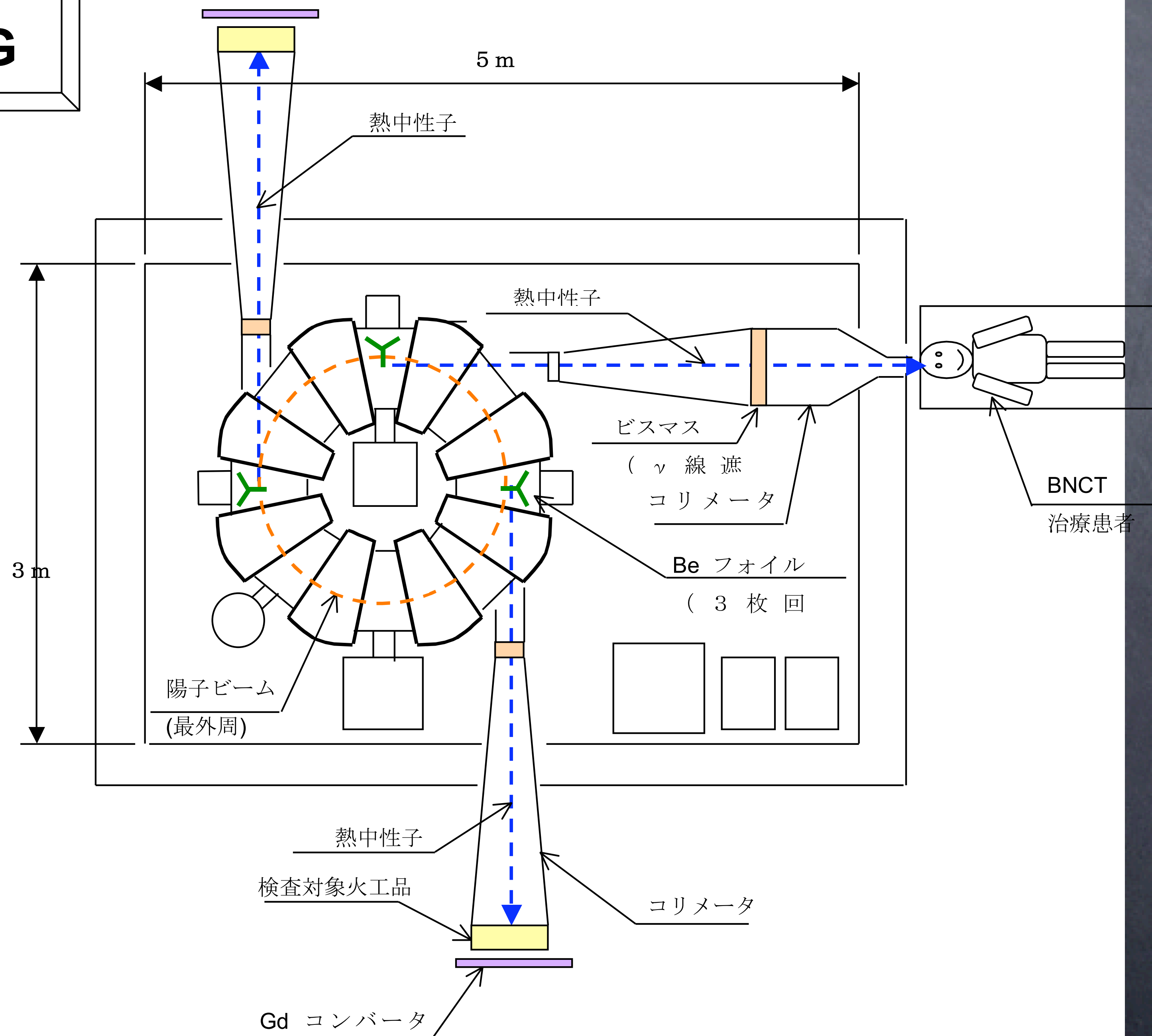
# Requirements for ERIT Ring

- Beam intensity
  - 5x10e10 ppp
- Acceptance
  - trans.:1000mm.mrad, long. : dp/p +-10%
- Repetition rate
  - ~1kHz

FFAG looks the best choice.

# 熱中性子源 FFAG

| | | |
|---|---|---|
| 磁石の形式 | : | Radial sector type |
| セクター数 | : | 8 |
| k 値 | : | 4 |
| ﾋﾞｰﾑｴﾈﾙｷﾞｰ | : | 100keV ～4.7MeV |
| 加速時間 | : | 4 ms 以下 |
| 平均磁場強度 | : | 0.35 ～ 1.63 Tesla |
| 軌道半径 | : | 0.8～1.2 m |
| r f 周波数 | : | 0.87～4 MHz |
| r f 電圧 | : | 4 kVp |
| イオン源 | : | H+, 100keV, 10mA |



# FFAG neutron source with ERIT