Development of FFAG at KEK

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Needs for large beam power & rapid acceleration

1. Large Beam Power

Proton Driver:

- secondary particle production (K,μ,π,n,RI.....)
- spallation neutron source
- ADS for nuclear energy breeding

2. Rapid Acceleration

Acceleration of short-lived particles:

- muon ---- Neutrino Factory, Muon Collider
- unstable nuclei

ENERGY : 1 ~ 10 GeV, CURRENT : ~ mA

WHAT is FFAG?

FFAG=***Fixed Field Alternating Gradient***

Fixed Field => Static Magnetic Field like **Cyclotron**

・・・ no time-varying magnetic field

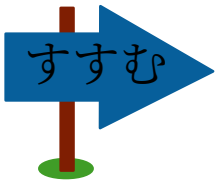
Alternating Gradient => 3-D Strong Focusing in Beam Motion like **Synchrotron**

・・・alternating layout of "F" and "D" magnets

FFAG Accelerator was proposed by Tihiro Ohkawa in 1953

High Repetition -> High Intensity Beam

BEAM EXTRACION -> by "Kicker Magnet" in FFAG



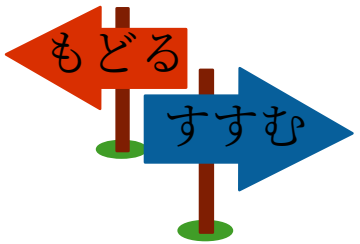
Features of FFAG

time-varying field in acceleration

Slow Acceleration
Low Repetition

static field in acceleration

Rapid Acceleration
High Repetition



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KEK laboratory demonstrates fixed-frequency synchrotron

This 2.5 m diameter experiment at the Japanese KEK laboratory has demonstrated fixed-frequency proton acceleration.

The Japanese KEK laboratory has for the first time demonstrated an alternative method of accelerating protons to high energy – the fixed-field, alternating gradient (FFAG) synchrotron.

In a normal variable frequency synchrotron, the radiofrequency of the applied electric fields (which accelerate the circulating beam) is increased to remain in step with the beam as it becomes increasingly distorted by relativity.

In such a synchrotron the beams circulate inside a magnetic tube, obviating the need for a large magnet to enclose the whole machine (as had been the case for the cyclotron). In

This is the FFAG idea, which was first proposed and demonstrated for electrons by the Midwestern Universities Research Association team in Chicago.

Under the leadership of Yoshiharu Mori, design at KEK started in January 1999 and the first beam was accelerated on 16 June 2000. The fact that these machines use fixed fields allows them to operate at high repetition rates and produce high-intensity beams. The price to pay is large apertures, a larger circumference and consequently massive magnets, which has favoured so far the now classical alternating gradient pulsed synchro-

pop (proof-of-principle)

FFAG at KEK

World First Proton FFAG Accelerator !

Cardinal Conditions of FFAG

Magnetic field configuration

* Zero-chromaticity

---> Betatron functions are scaling for enerygy.:ν_x,ν_y constant

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

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

a)Geometrical similarity

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

b)Constant n

$$\left.\frac{\partial n}{\partial p}\right|_{\theta=const.} = 0$$

FFAG Magnetic Field Configuration

Scaling type of FFAG

a)Geometrical similarity b)Constant n

$$(a)\ \ r\left(\frac{\partial\theta}{\partial r}\right)_{\vartheta} = \varsigma = const.\,, \qquad (\mathrm{b})\ \ n_{\Gamma} = -\frac{r}{B}\left(\frac{\partial B}{\partial r}\right)_{\theta}$$

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

Magnetic Field Configuration : Scaling Type

a) Radial Sector

/tunable

/short straight section

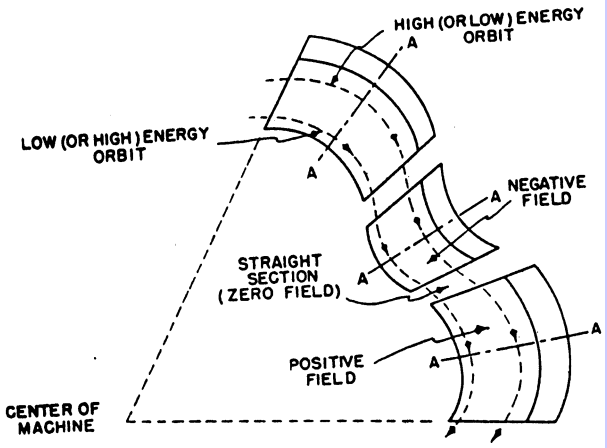


FIG. 2. Plan view of radial-sector magnets.

b) Spiral Sector

/small excursion

/less tunable

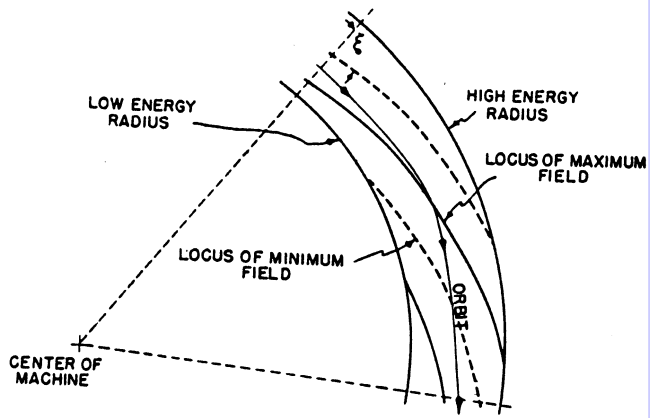


FIG. 3. Spiral-sector configuration.

Magnetic Field Configuration : Scaling Type

Orbit Excursion :

$$\Delta R \cong \left[\left(\frac{B}{B_0} \right)^{1/k} - 1 \right] R_0$$

K : Large (>>1) --> Orbit excursion ~ small : <1m

Large non-linear field for large K --> "Dynamic Aperture"

$$B \propto r^k = r_0 \left[1 + k\Delta r + \frac{k(k-1)}{2!} \Delta r^2 + \frac{k(k-1)(k-2)}{3!} \Delta r^3 + \cdots\cdots \right]$$

FFAG accelerator

FFAG principle : Ohkawa (1953), Symon, Kolomensky ~'50s

Magnetic field strength : constant ---> Moving orbit

@MURA project

(1)proof-of-principle machine :electron model->worked successfuly!

(2)30GeV proton machine:proposal

(3) proton-proton collider(two beam accelerator):proposal

No practical proton machine so far!

(1)Complicated magetic field configuration : 3D design

(2)RF cavity : Variable Frequency & High Gradient=>High Rep.

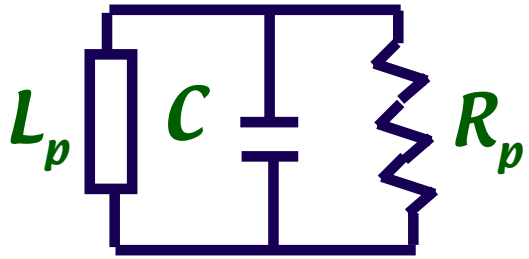
High Gradient & Broad-band RF cavity

Contradiction between HG & BB?

High gradient(HG): high shunt impedance

Broad band(BB) : low Q (<1)

$$Q = \frac{R_p}{\omega L_p} \rightarrow R_p = \mu\mu_0 QfG$$



air-gap cavity : μ=1, then Q_{air} should be high.

If large μ material at rf frequency is used, Q can be low. cf. Q_{air} =10000 eq. μ=10000, Q=1

HG & BB Cavity--> possible with high μ material

But, ferrite cannot be used!

Magnetic Alloy

A high-permeability soft magnetic alloy, such as FINEMET and METGLAS has become available for applying the RF cavity, recently.

Characteristics of MA:

(1) The μQf-value remains constant at a high RF magnetic field (Brf) of more than 2 kG.

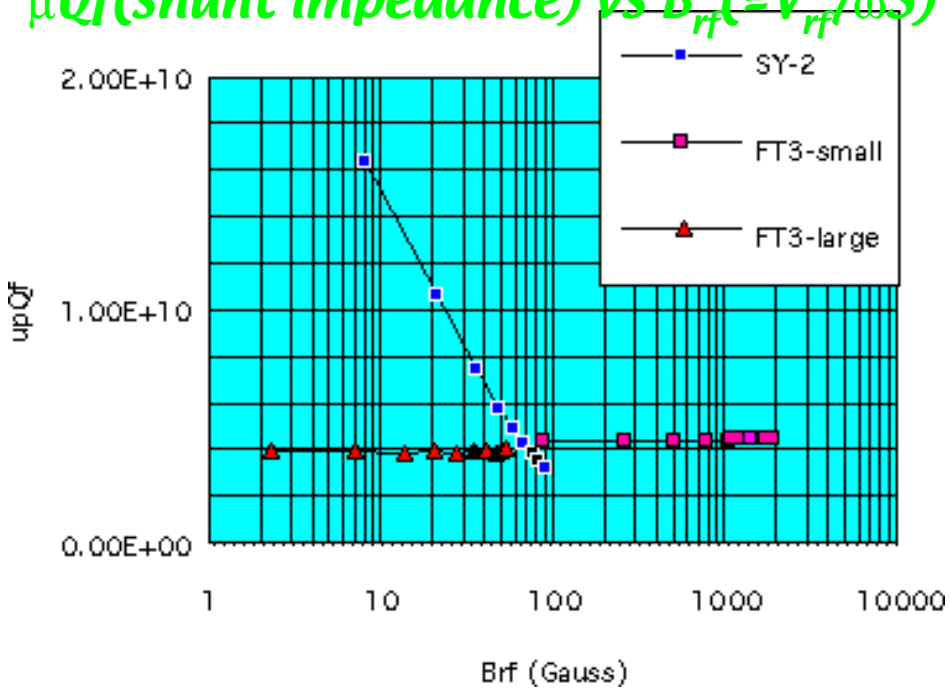
(2) A high Curie temperature, typically 570°C for FINEMET.

(3) The intrinsic Q-value is small. No frequency tuning loop is necessary in the cavity control system because of its low Q-value (Q~1). This substantially widens the stable operating region of the cavity loading phase angle under heavy beam loading. The longitudinal coupled-bunch instability may be reduced

(4)The Q-value can be increased up to more than 10(Q>10) by a radial gap with cut-core configuration.

(5) Fabrication of a large core is possible because the core is formed by winding the very thin tapes.

μQf(shunt impedance) vs B_{rf}(=$V_{rf}/\omega S$)



Typical characteristics of Ni-Zn ferrite and Magnetic Alloy(FINEMET).

Power Test of High Gradient Test Cavity

TEST CAVITY

*Single core (O.D=580mm,I.D=250mm, t=25mm)

*Direct water cooling

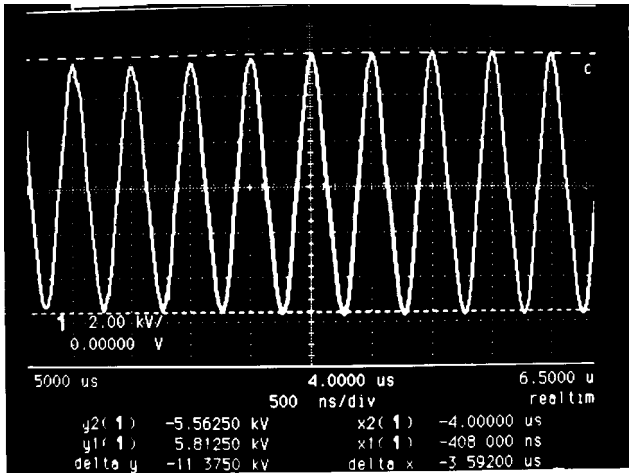
*RF power :30kW max.(B-class)

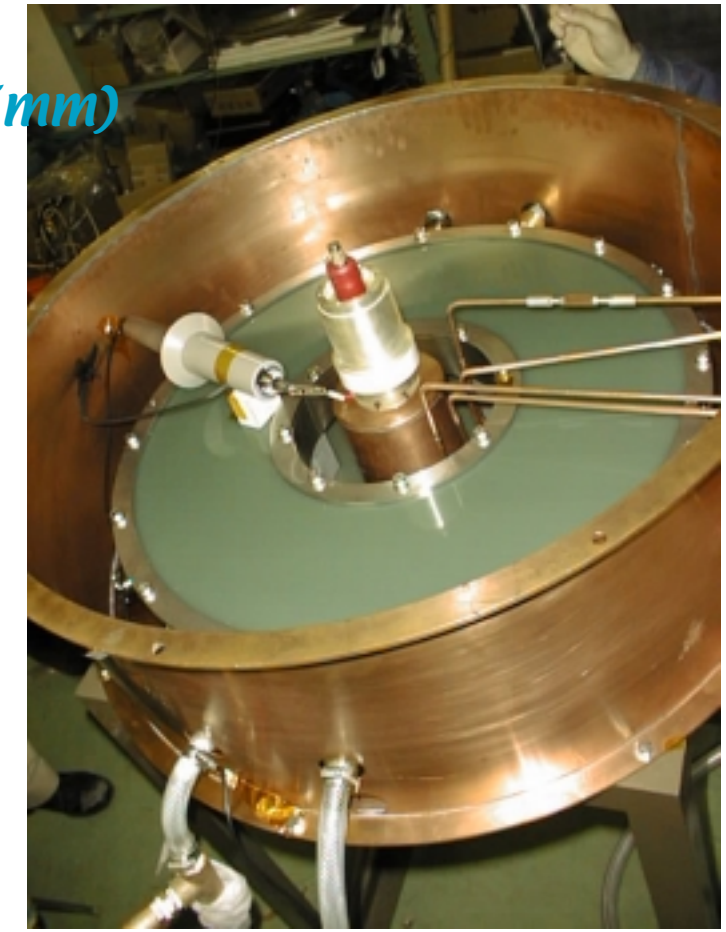
Achieved:

EFG = 100kV/m (cw)

EFG = 220kV/m (burst)

(limited by RF amplifier)





The gap voltage of the test cavity. The maximum RF voltage of 5.5kV(=220kV/m)was obtained.

FFAG : revival 2000

New type RF Cavity @KEK

"High Gradient & Broad band" (f ~ MHz)

"Magnetic Alloy (MA) loaded Cavity"

MA tape : "FINEMET"(nano-crystal alloy)

*High gradient : 50 ~100 kV/m (ferrite ~10kV/m)

*Broad band : no need for frequency tuning(Q~1)

Large Repetition Rate : ~1kHz
Large beam aperture : MA tape

Development of proton FFAG accelerator

PoP (proof-of-principle) model using MA cavity

aims:

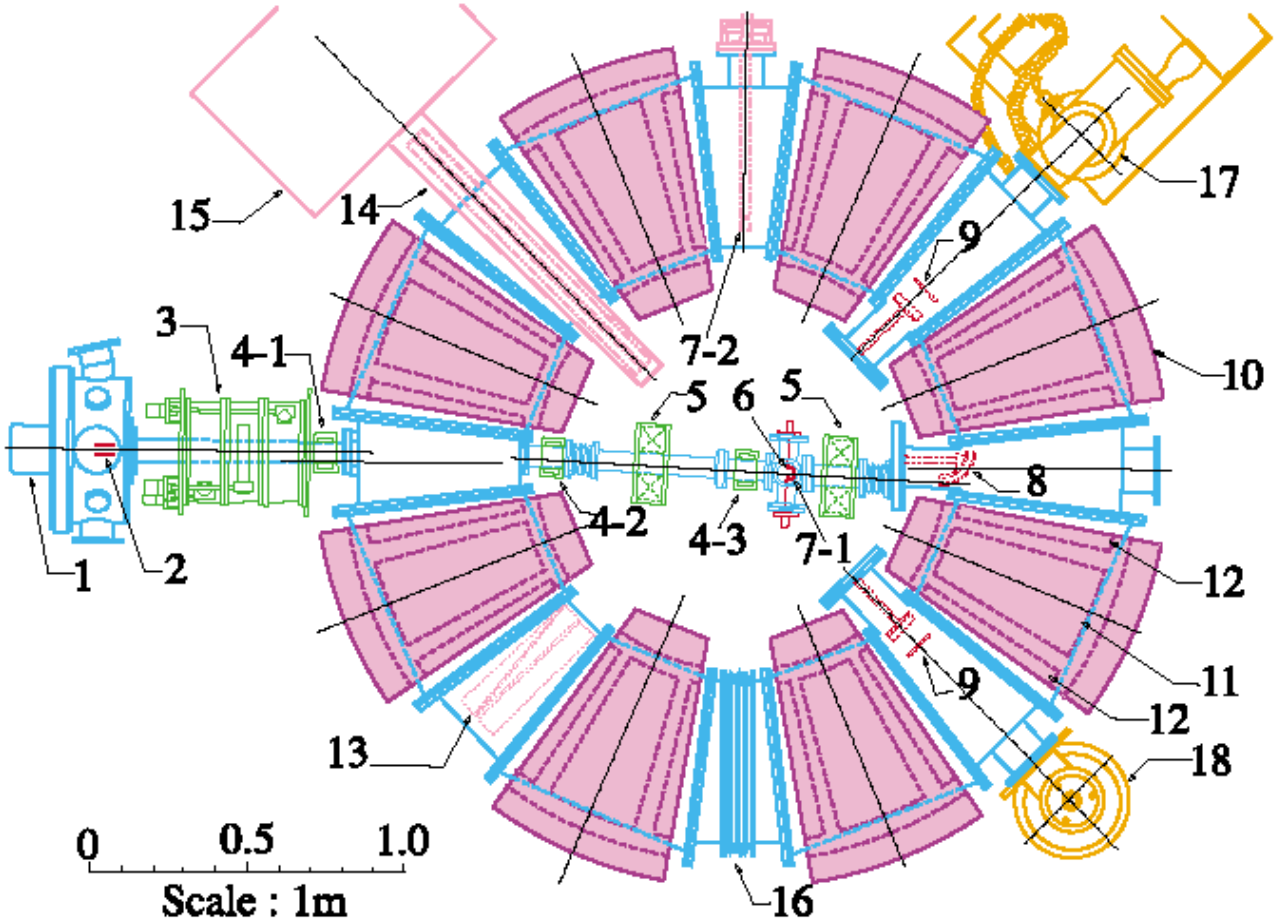
(1) fast acceleration : t<1msec --> 1kHz rep. rate

(2) first proton FFAG accelerator

(parameters)

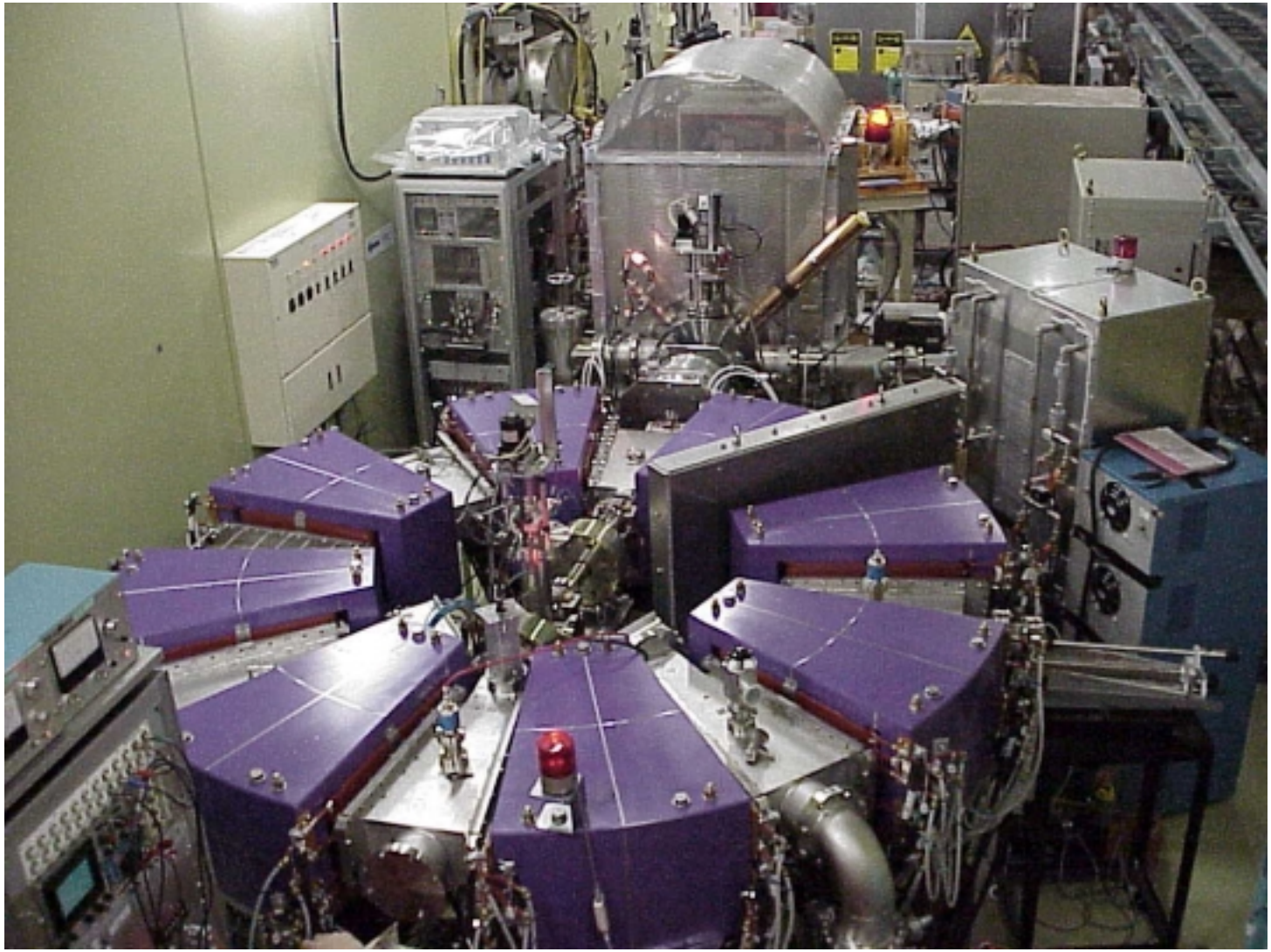
Type of magnet		Radial sector type (Triplet)
No. of sectors		8
Field index(k-value)		2.5
Energy		50keV(injection) ~ 500keV
Reptition rate		1kHz
Magnetic field	Focus-mag. :	0.14~0.32Tesla
	Defodus-mag. :	0.04~0.13Tesla
Radial of closed orbit		0.81~1.14m
Betatron tune	Horizontal :	2.17~2.22
	Vertical :	1.24~1.26
rf frequency		0.61~1.38MHz
rf voltage		1.3~3.0kVp

PoP proton FFAG accelerator



1: ion source
2: chopper electrode
3: triplet-quadrupole magnet
4: steering magnet
5: solenoid magnet
6: beam slit
7: Faraday cup
8: septum electrode
9: bump electrode
10: sector magnet
11: F-magnet pole
12: D-magnet pole
13: beam position monitior
14: RF cavity
15: RF amplifier
16: vacuum bellows
17: turbo molecular pump
18: cryopump

PoP proton FFAG model



Radial Sector -Triplet Type

$$\frac{\pi}{N} = \theta_F - \theta_D, N : \text{sector number}$$

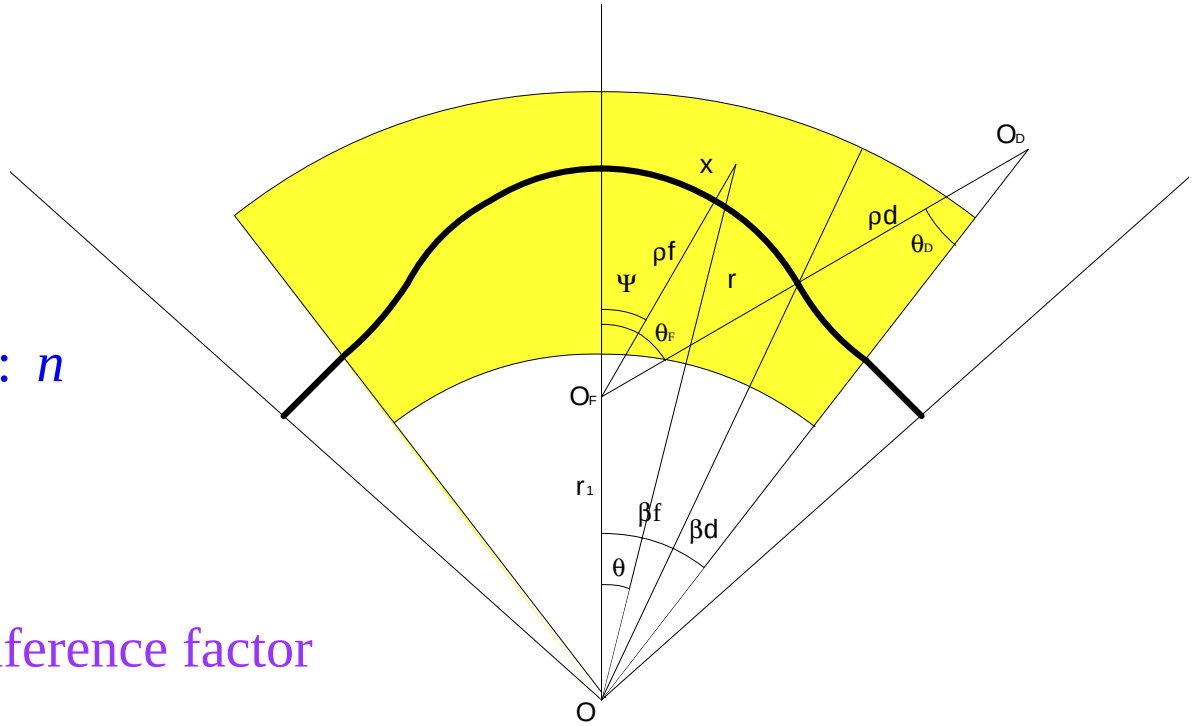
geometrical field index : k

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

field index (seen by particle): n

$$n = k\frac{1+\xi\cos\psi}{1+2\xi\cos\psi+\xi^2}$$

$$\xi = \zeta - 1, \quad \zeta = \frac{r_0}{\rho_{F,D}} \ : \text{ circumference factor}$$



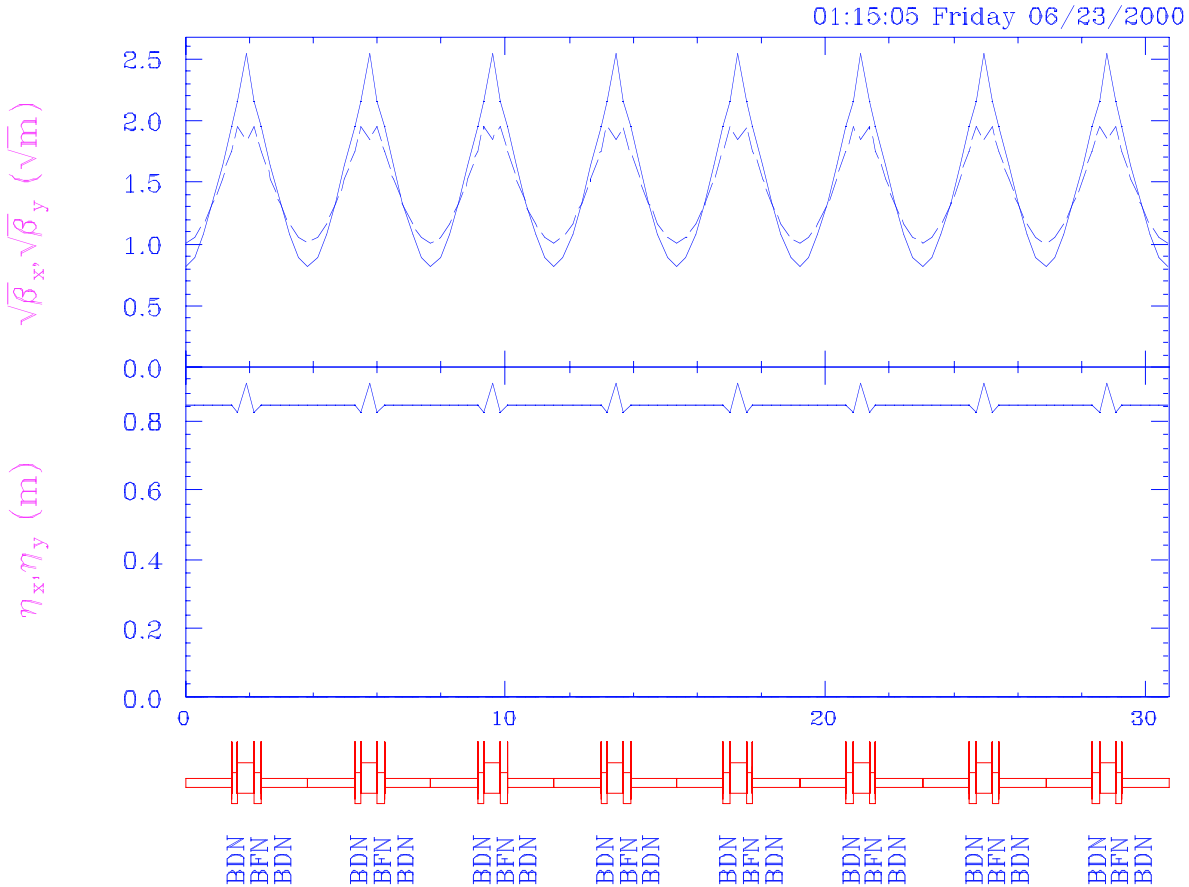
$$\alpha = \frac{1}{k+1} \ : \text{ momentum compaction factor}$$

Beam Optics Parameters

Linearized beam parameters : SAD

betatron tunes

ν_x	3.13
ν_y	2.78

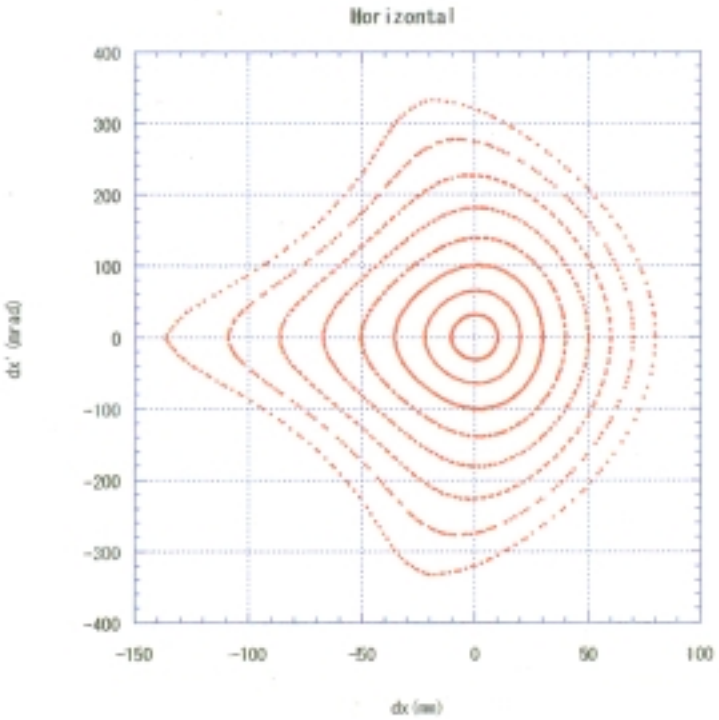


Acceptance

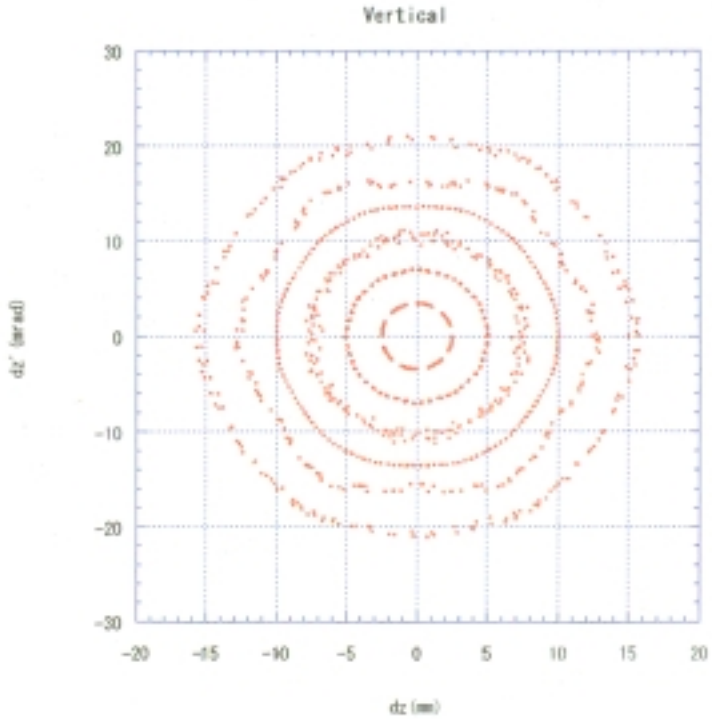
@500keV
200Turns

A_h > 10000 mm.mrad
A_v > 300 mm.mrad

Horizontal(Wv=0pimmmrad)



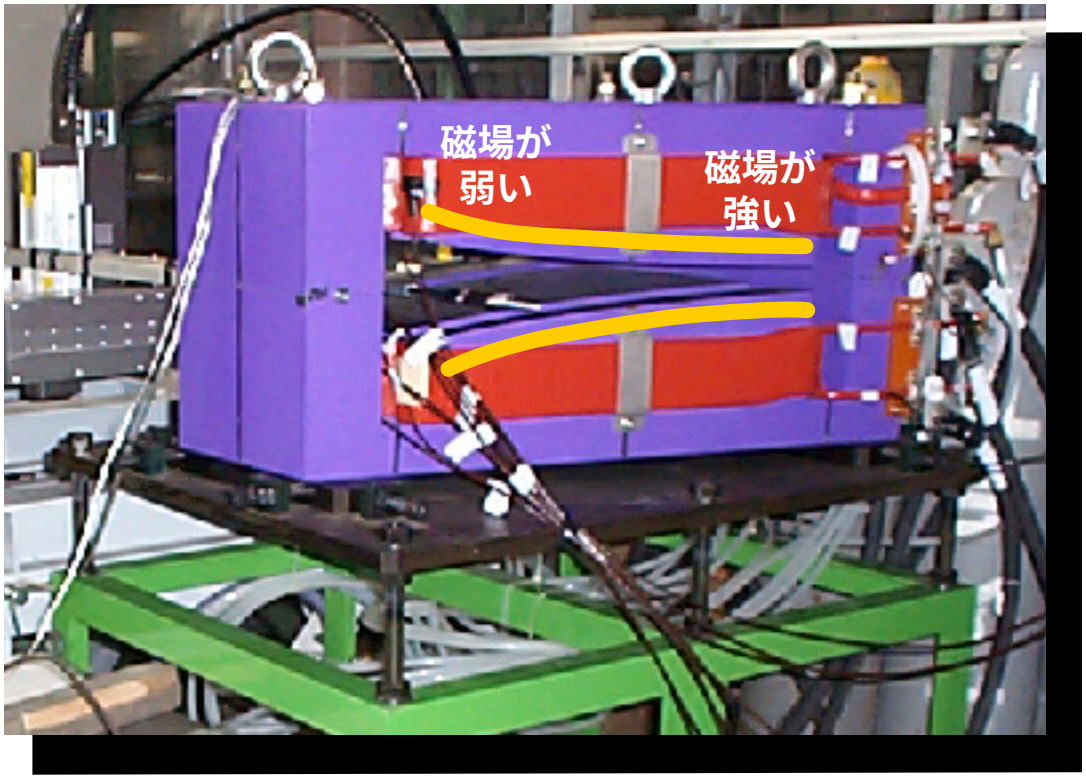
Vertical(Wh=0pimmmrad)

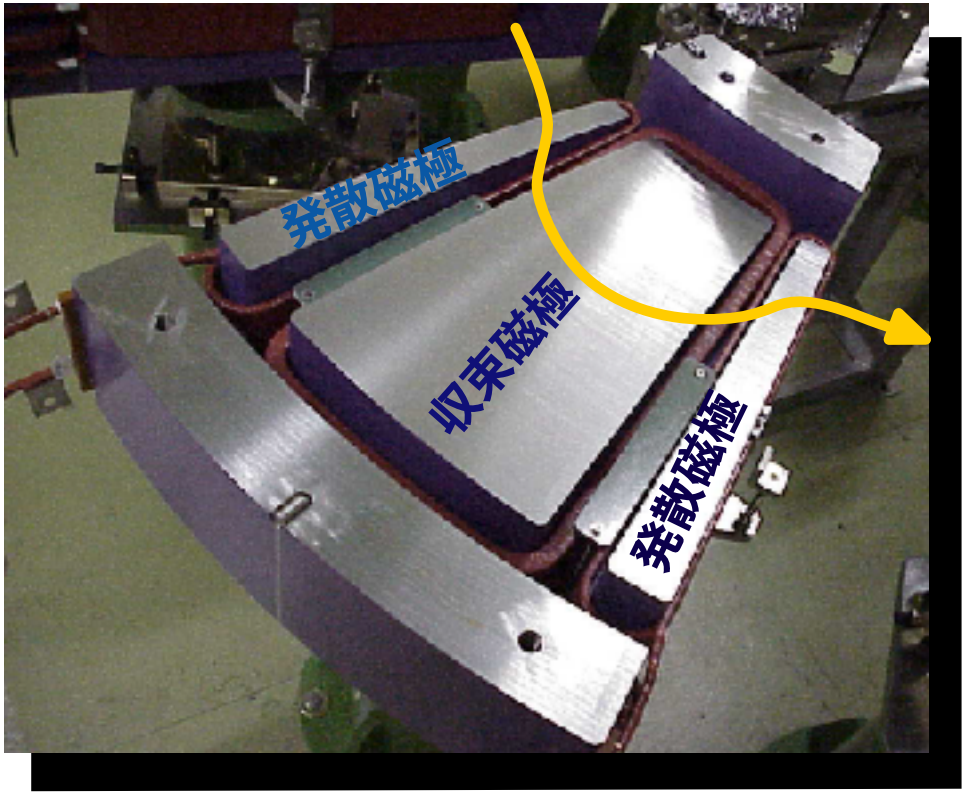


FFAG Magnet

・磁極の形状で磁場勾配を作っている。
・発散・収束・発散の３つの電磁石をひとまとまりにしている。

=>　強い収束力を得る！





rf Accel. Cavity

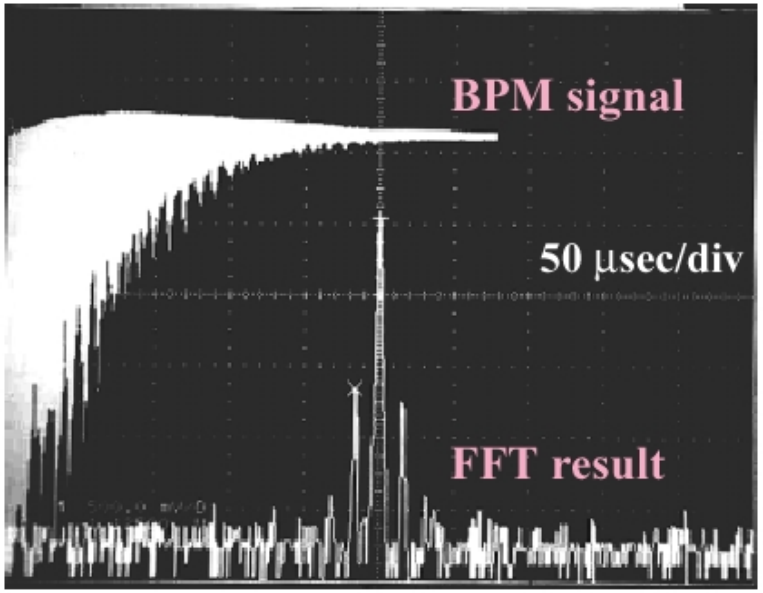
加速空洞とはビームを加速する装置です。

金属磁性体を用いた広帯域の加速空洞
により従来の10倍の電場強度が得られます。

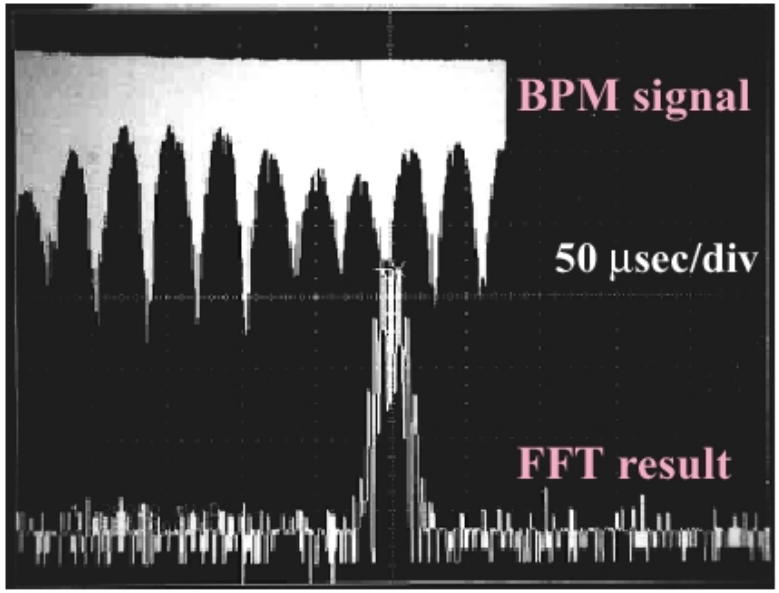
・広い加速周波数の変化に対応
・コンパクトな加速空洞を実現

Beam Acceleration

[injection]



[flat top]



revolution frequency :

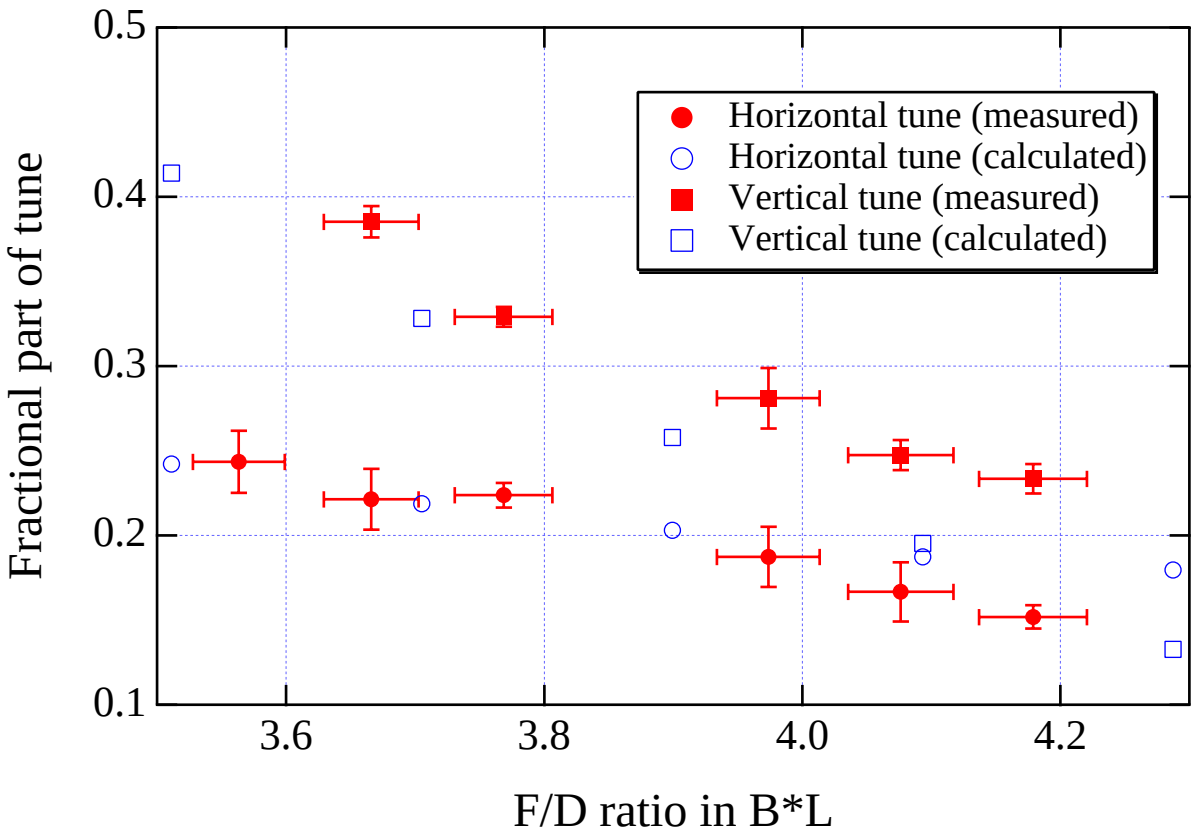
610kHz → 1.251MHz

synchrotron frequency :

24.06kHz → 16.78MHz

Betatron Tune (2)

betatron tune vs F/D ratio



Betatron tune shift as a function of F/D ratio:

- vertical

- horizontal

The vertical tune can be adjustable by changing F/D ratio !

RF Knockout Resonance & Betatron tune

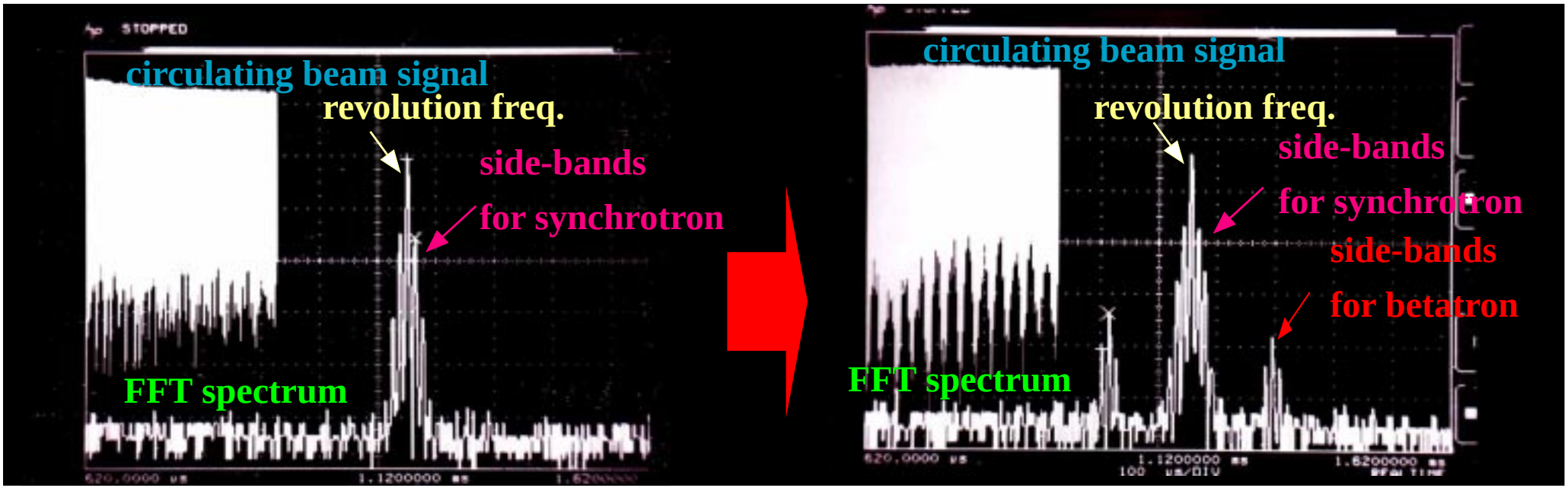
RF knockout resonance :

$$p\nu_h + q\nu_V = \pm m \pm \frac{f_{RF}}{f_{rev}}$$

(p,q,m = integer)

250keV flat top

250keV flat top after RF knockout



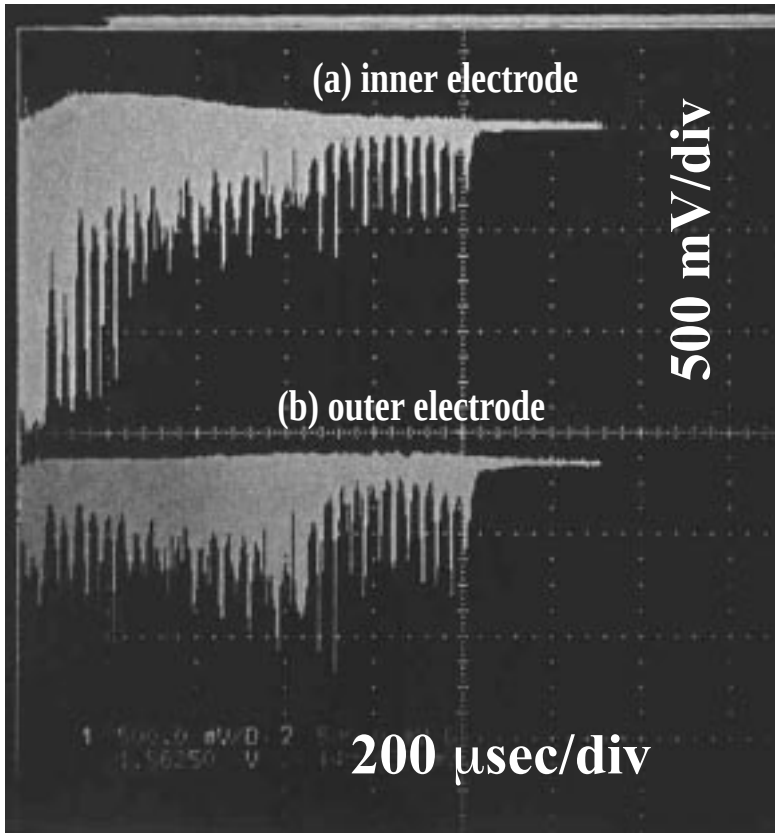
fractional part of betatron tune

ν_h=0.195 (0.199@E_inj)

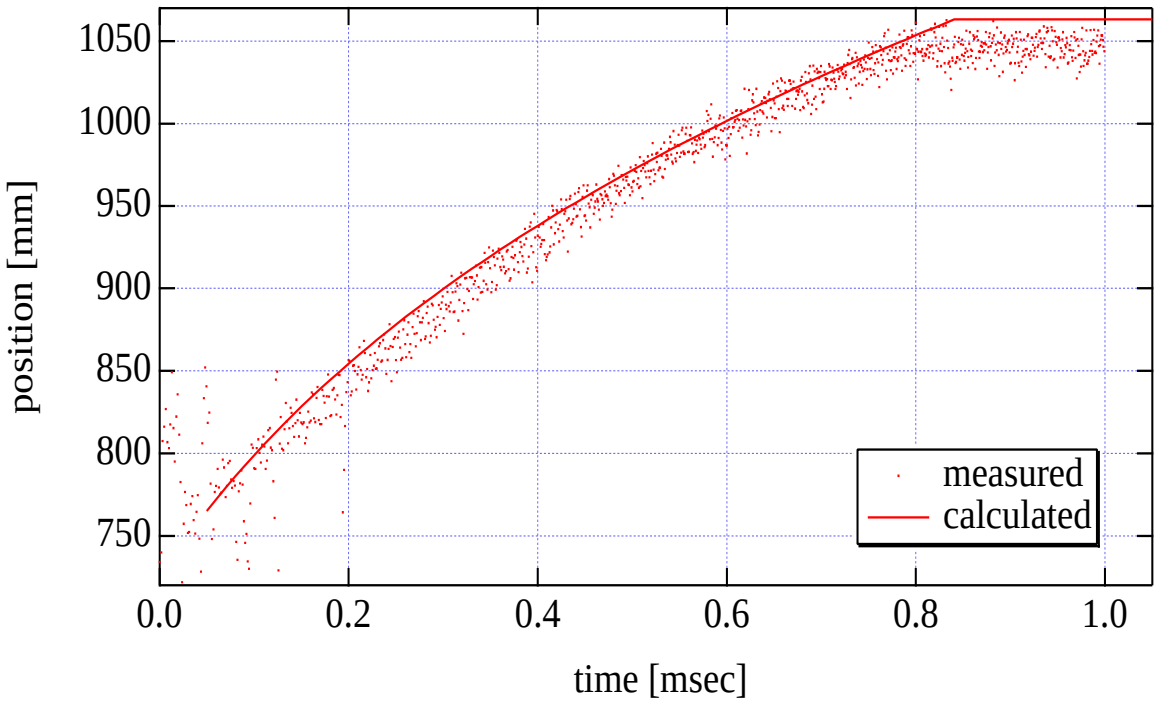
Zero-chromaticity is satisfied!

Beam Acceleration

BPM signals during the acceleration



beam orbit shift

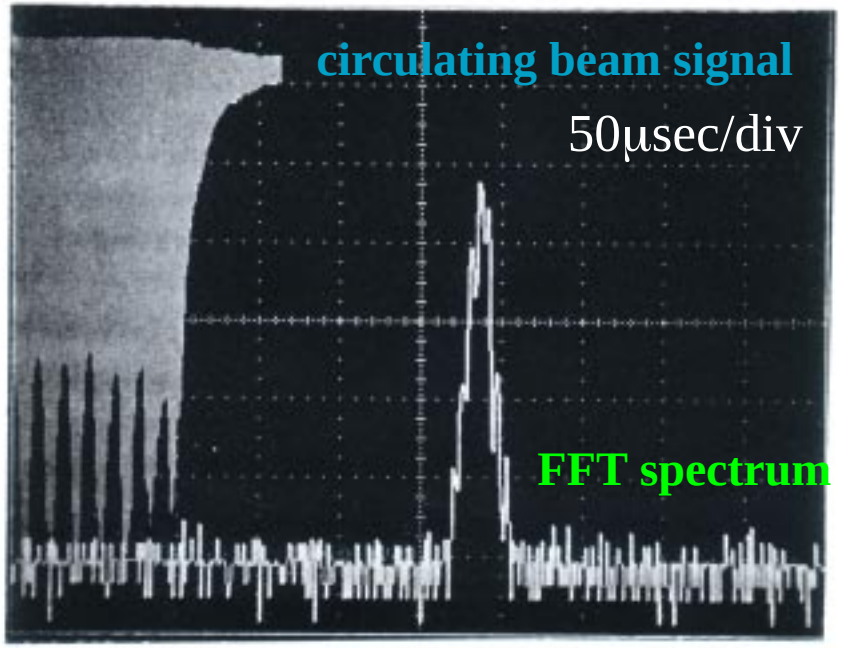


The beam is accelerated from 50keV to 500keV within 1msec.

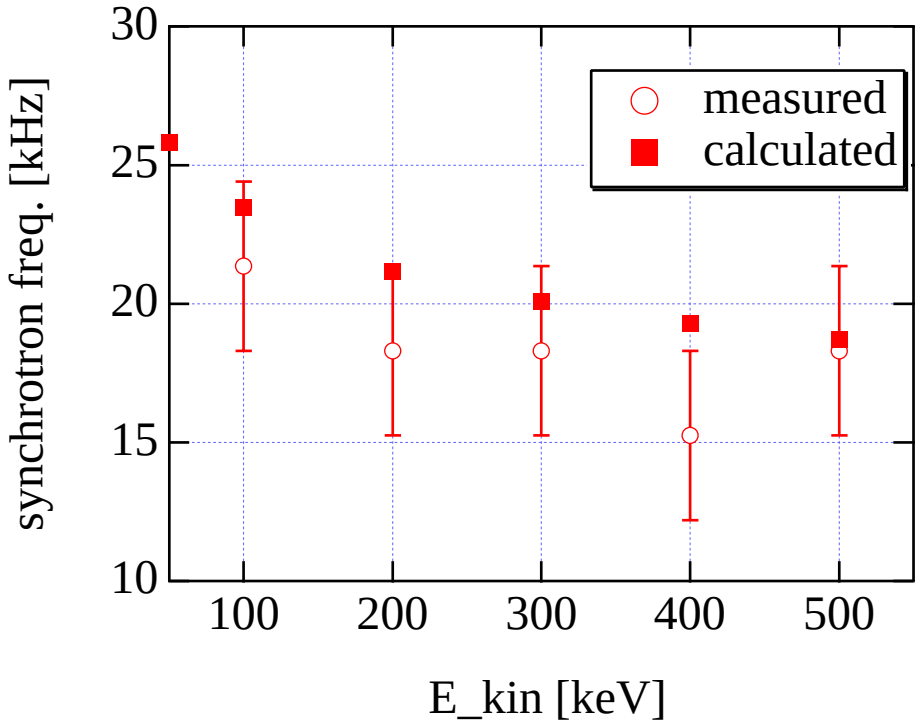
=> The beam orbit shifts from 765mm to 1050mm.

Synchrotron Frequency

at 500keV (flat top)



synchrotron freq. vs E_{kin}@flat top



revolution frequency: 1.379MHz

synchrotron frequency: 18.3kHz

The observed synchrotron frequency agreed with those expected by the beam simulation.

Resonance Crossing

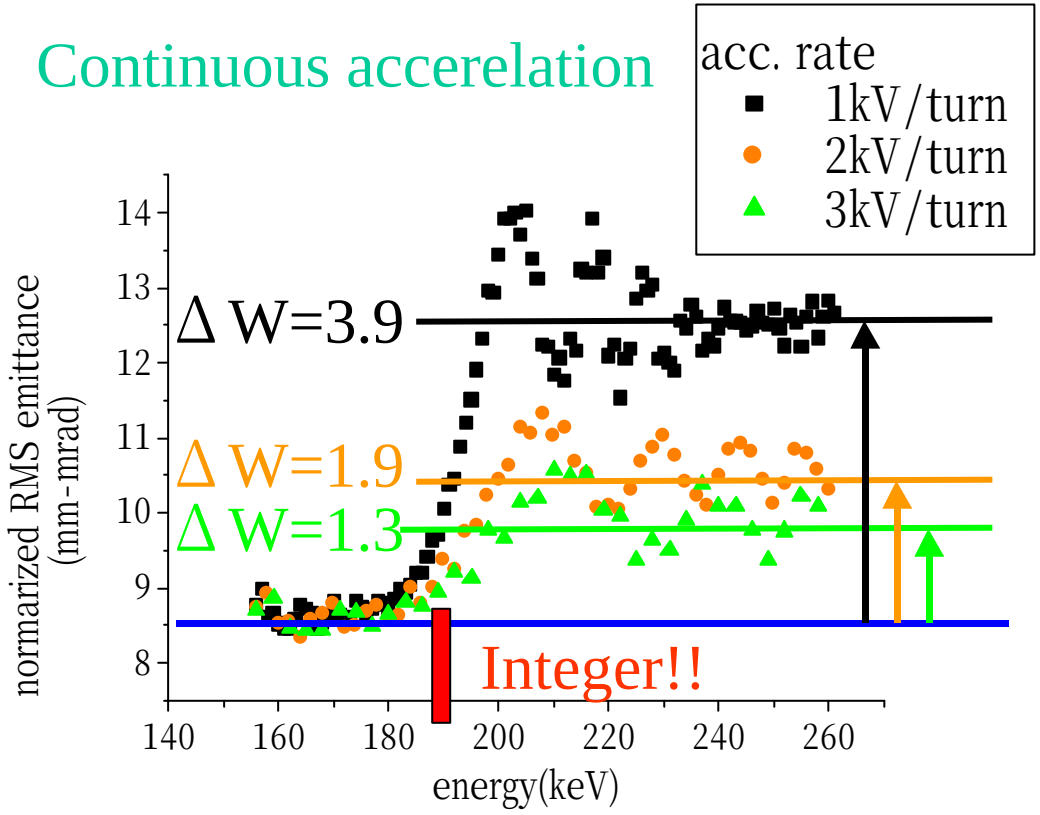
With Rapid Acceleration

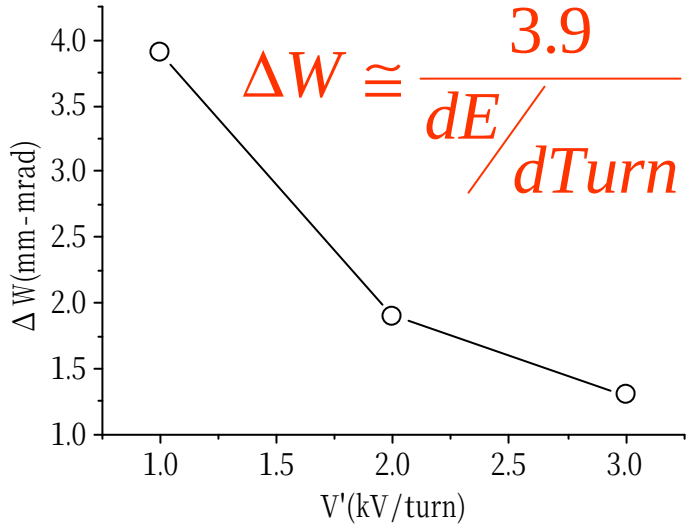
For non-scaling FFAG
or For semi-scaling FFAG
where to keep perfect scaling is difficult.

Vertical Emittance Growth Caused by Alignment Error

One of the magnet is displaced 0.1mm vertically.

Continuous accerelation





$$\Delta W \cong \frac{3.9}{dE/dTurn}$$

The emittance growth is in inverse proportion to the acceleration rate.

Quadrupole Error in Misalignment of FFAG Magnet

Br of main body(B_θ=0): $$B_r = \frac{kB_0}{r_0}\left(\frac{r}{r_0}\right)^{k-1} z - \frac{k^2(k-2)B_0}{3!\,r_0^{\,3}}\left(\frac{r}{r_0}\right)^{k-3} z^3 \cdots$$

Feed Down Caused by Misalignment $z \rightarrow z - z_0$

$$-\frac{k^2(k-2)B_0}{3!\,r_0^{\,3}}\left(\frac{r}{r_0}\right)^{k-3}(z-z_0)^3 = -\frac{k^2(k-2)B_0}{3!\,r_0^{\,3}}\left(\frac{r}{r_0}\right)^{k-3}(z^3 - 3z_0 z^2 + 3z_0^{\,2} z - z^3)$$

Term of Quadrupole Like: $$Q_{error} z = -\frac{k^2(k-2)B_0 z_0^{\,2}}{2r_0^{\,3}} z$$

In this case $$-\frac{k^2(k-2)B_0 z_0^{\,2}}{2r_0^{\,3}} \cong 4\times 10^{-13}\ (T/m) \Leftarrow z_0 = 0.1mm$$

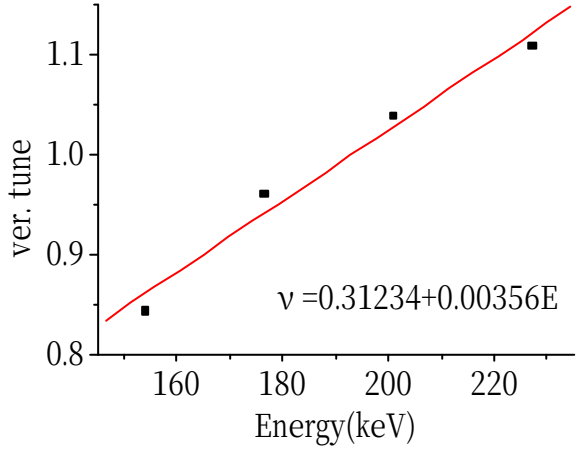
$$dn = \frac{1}{2p}\int_0^C b\Delta K ds = \frac{1}{2p}\int_0^C b\,\frac{Q_{error}}{B_0 r} ds \cong 3\times 10^{-14}$$

Stop band is negligible.

Criterion for Rate of Tune Change

Magnetic field determines $\frac{dn}{dE}$ $\frac{dE}{dTurn}$: *acceleration rate*

Rate of tune change $\frac{dn}{dE}\frac{dE}{dTurn} \equiv \frac{dn}{dTurn}$



$$\frac{dn}{dE} = 0.00365\ (keV^{-1})$$

$$\frac{dn}{dTurn} = 0.00365\ (keV^{-1}) * 3(keV/turn)$$

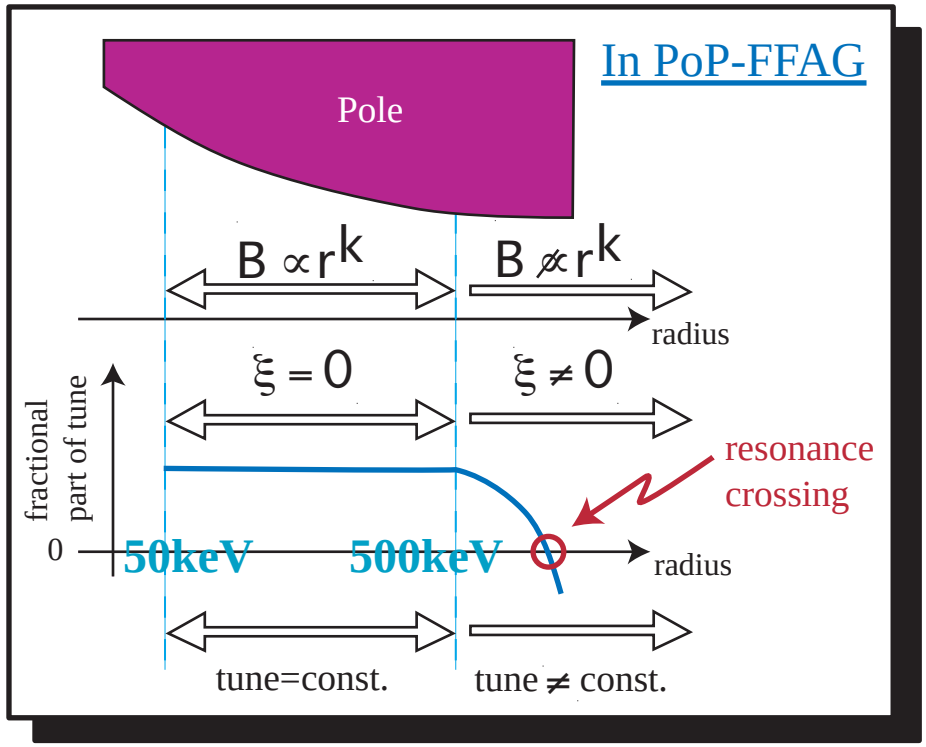
$$\approx 0.01(turn^{-1})$$

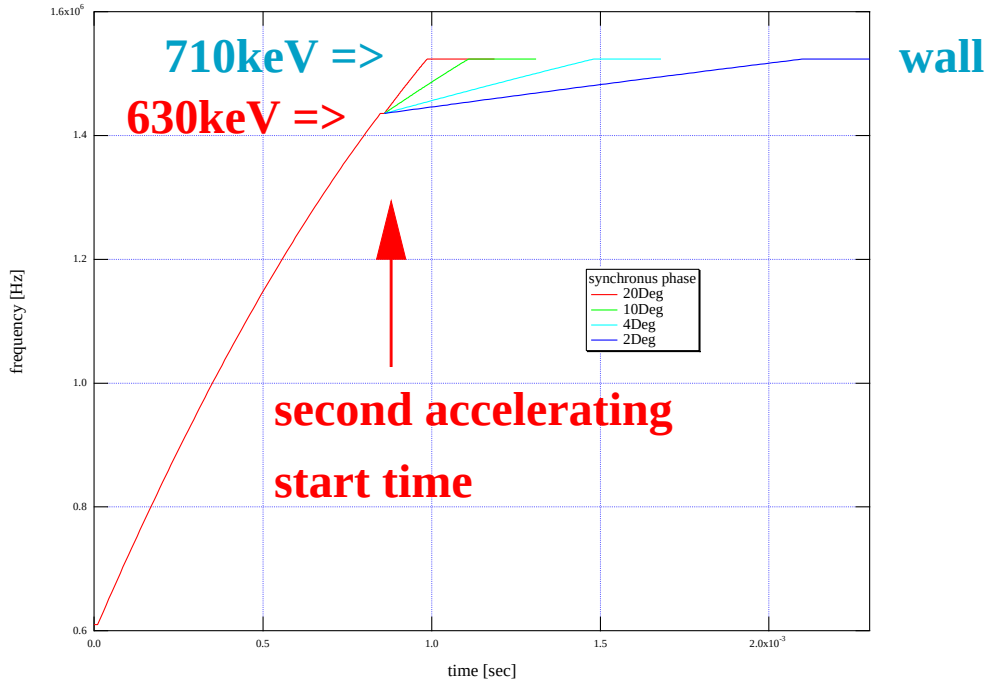
If the COD is the same order as that of this example,
The vertical integer resonance crossing will be achieved
with the rate of tune change an order of 0.01(turn^{-1})

Resonance crossing & Fast Acceleration (1)

In FFAG synchrotron.....

the fast acceleration => the beam can be accelerated even if the betatron tune crosses the resonance line during the acceleration !





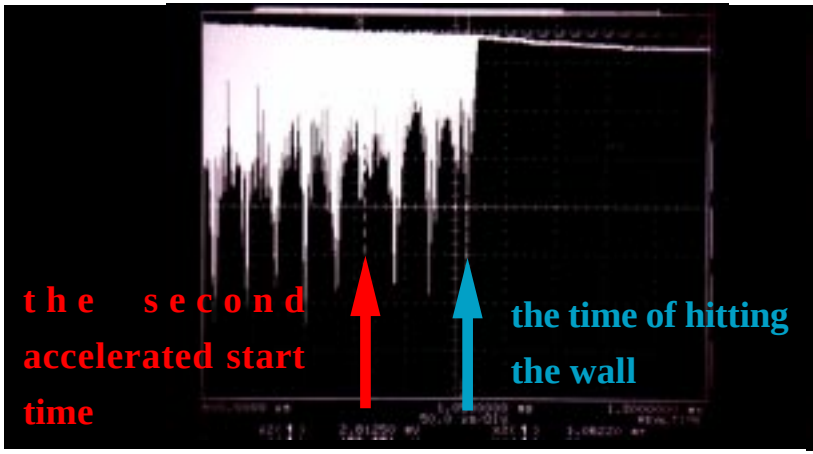
accelerating speed can be changed !

Resonance crossing & Fast Acceleration (2)

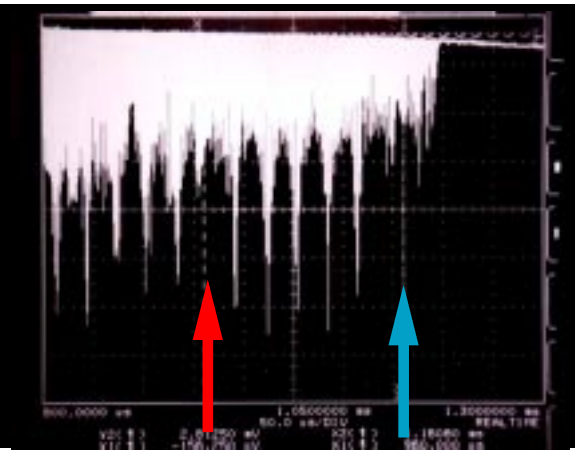
the beam was accelerated from 630keV to 710keV

in various accelerating speed !

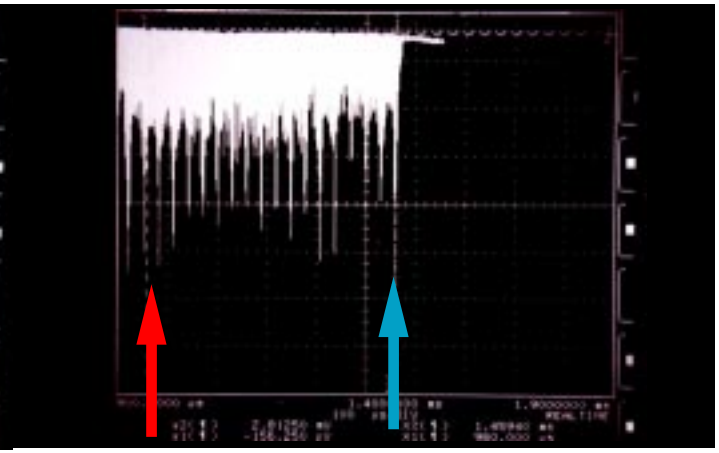
ϕ_s=20 Deg



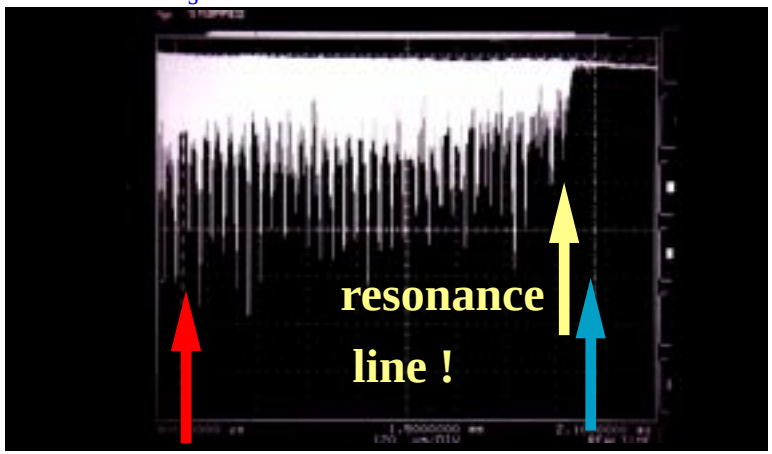
ϕ_s=10 Deg



ϕ_s=4 Deg



ϕ_s=2 Deg

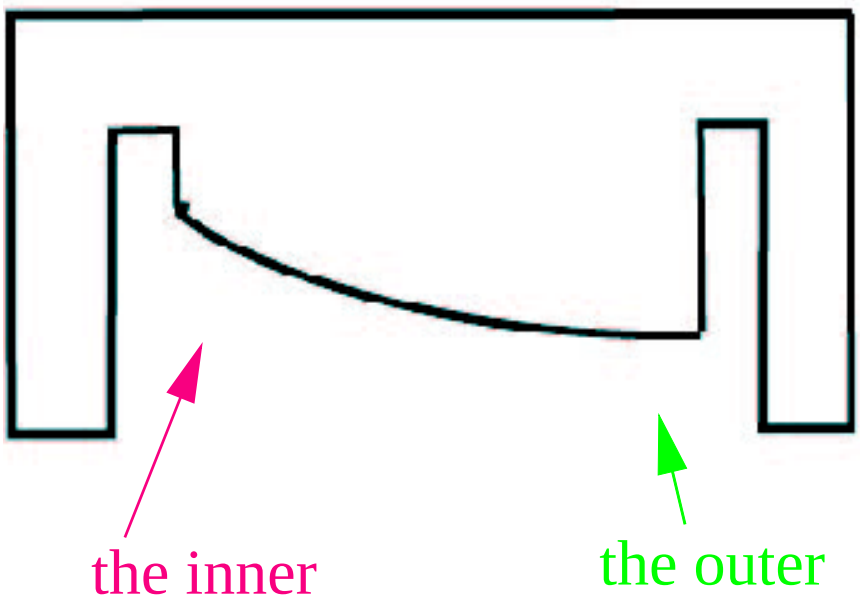


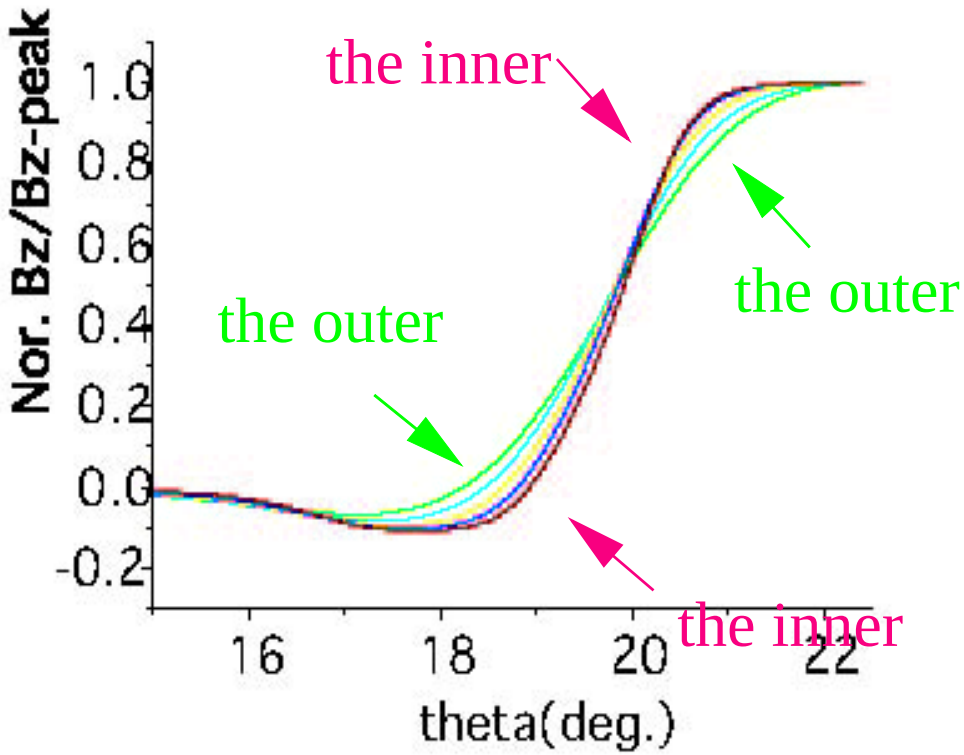
accelerating speed:

slow => doesn't cross the resonance line

fast => can cross the resonance line

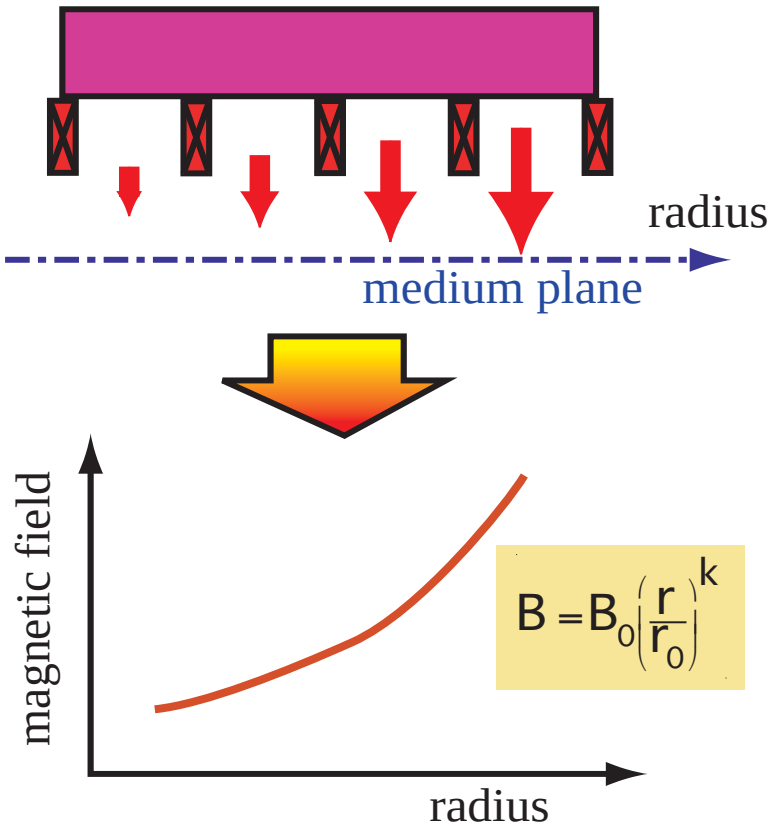
Normalized Field Strength at Median Plane





Distributed coils arrangement

Magnetic field with large k-value can be made by distributed coil arrangement!

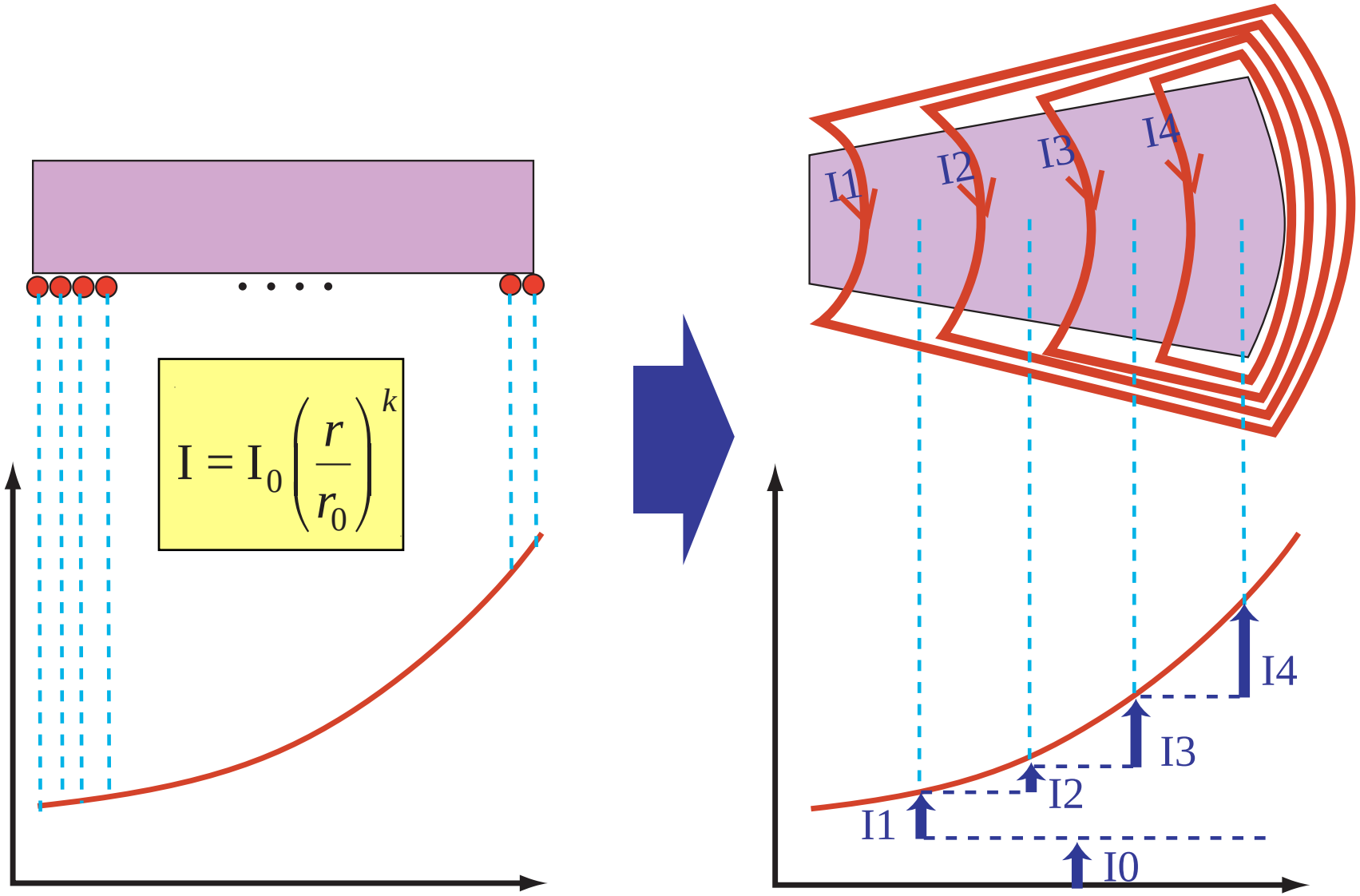


adv. : - possible to change k-value !
- possible to make a long pole !
- possiple to make a high field !

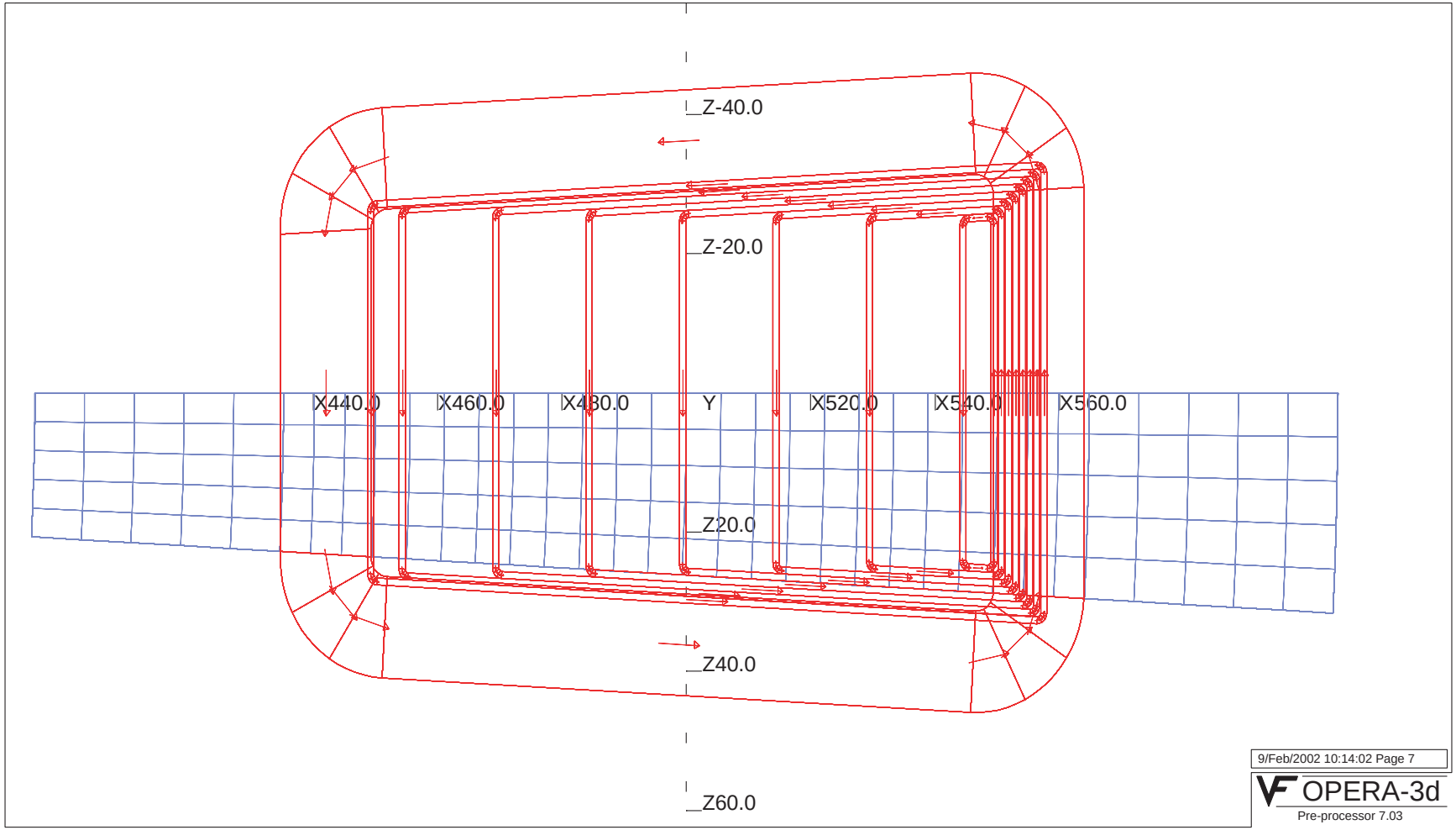
disadv. : - complicate operation !
(each coil needs to have a different set of current)
- field quality may be not so good !
(Field fluctuates according to the coil distribution.)

We should be careful in designing the magnet with this method!!

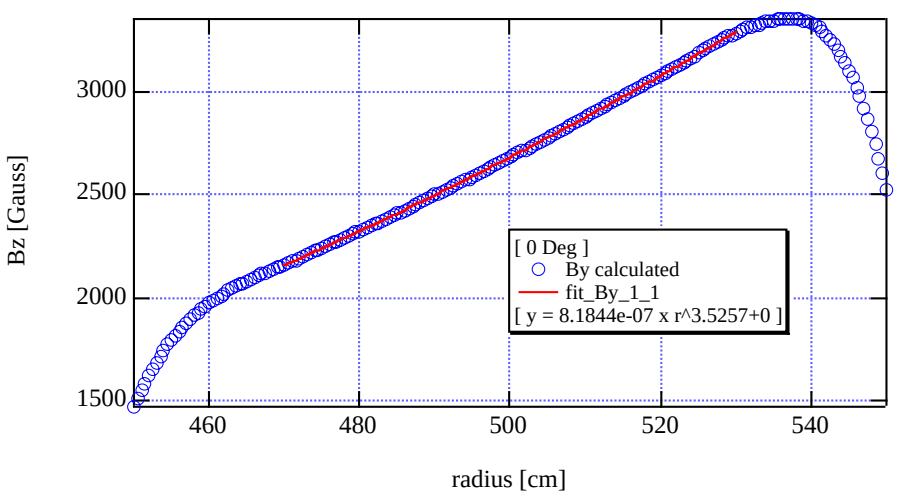
distributed coils type 1

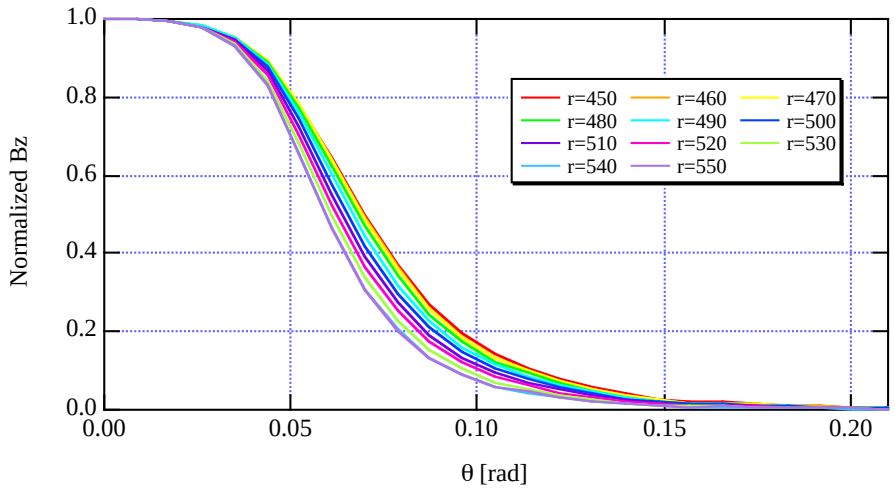


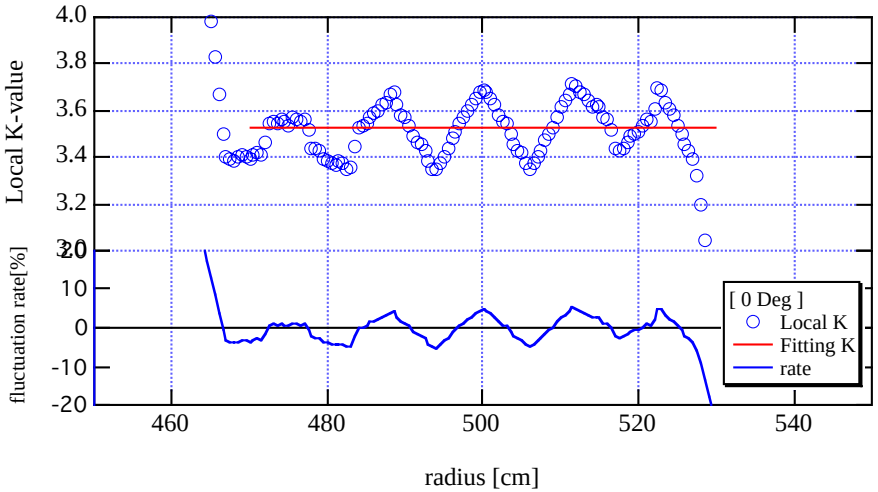
distributed coils type 1

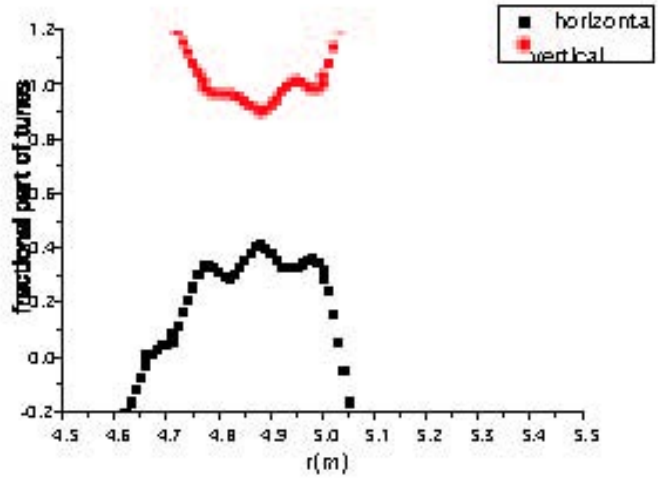


distributed coils type 1

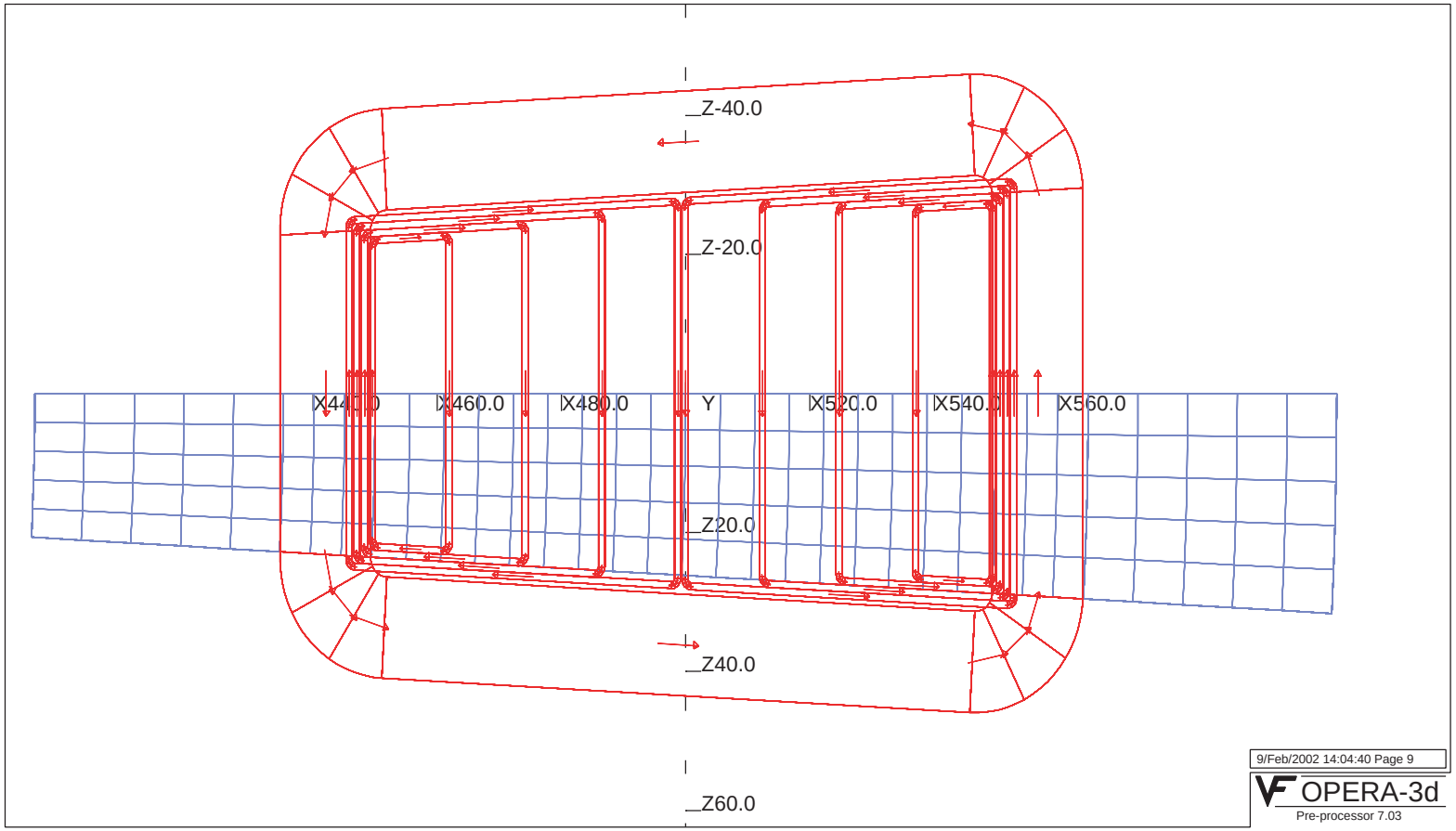




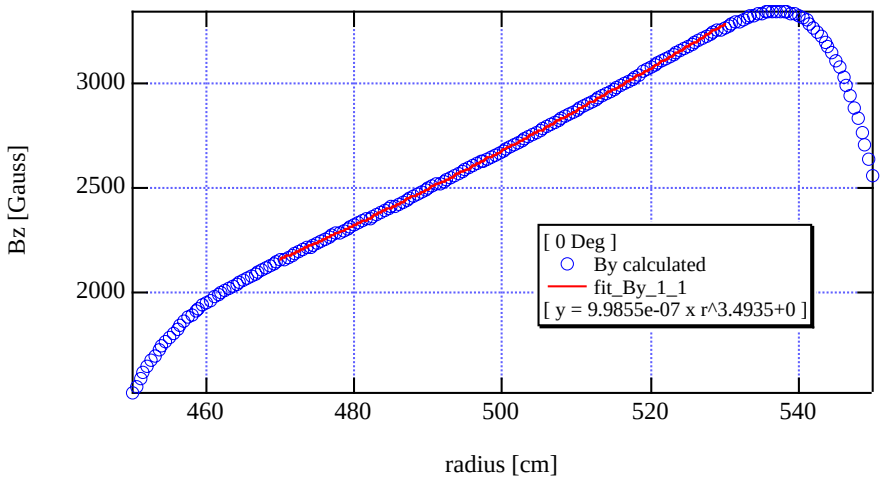


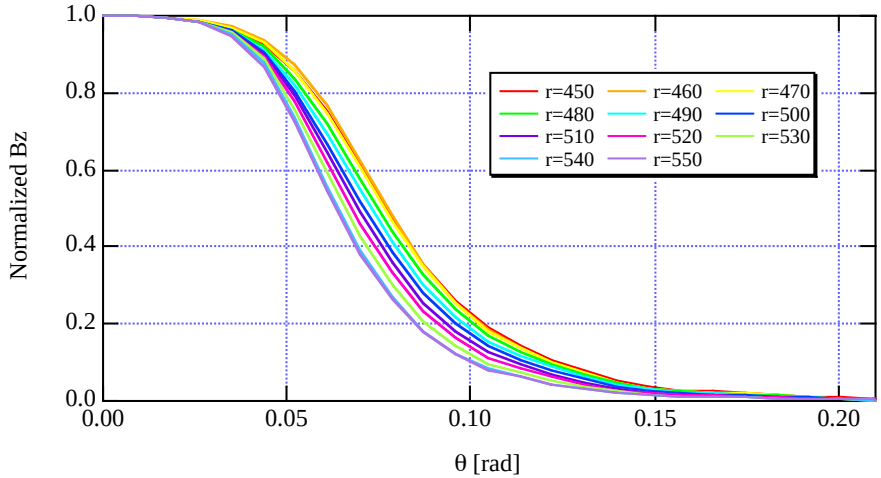


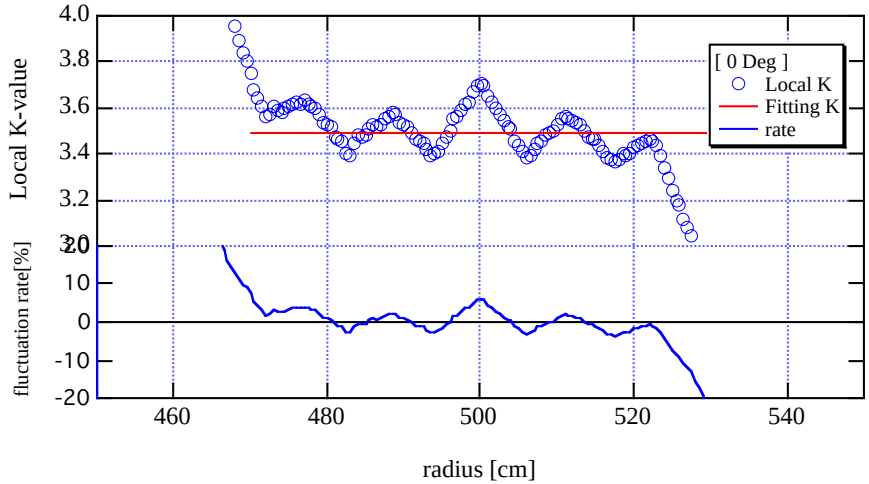
distributed coils type 3

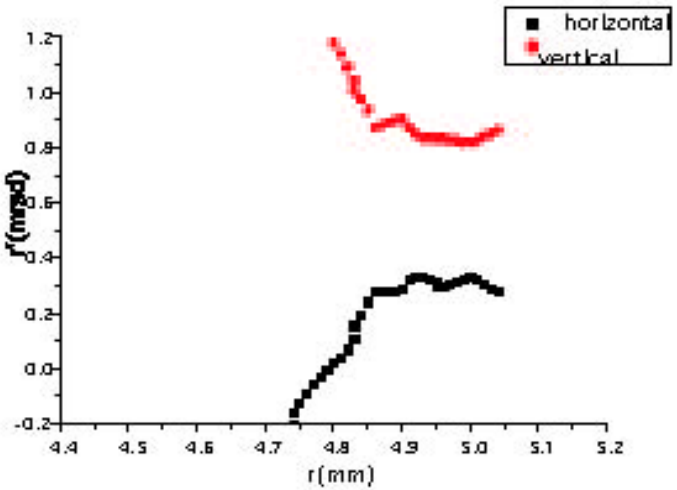


distributed coils type 3









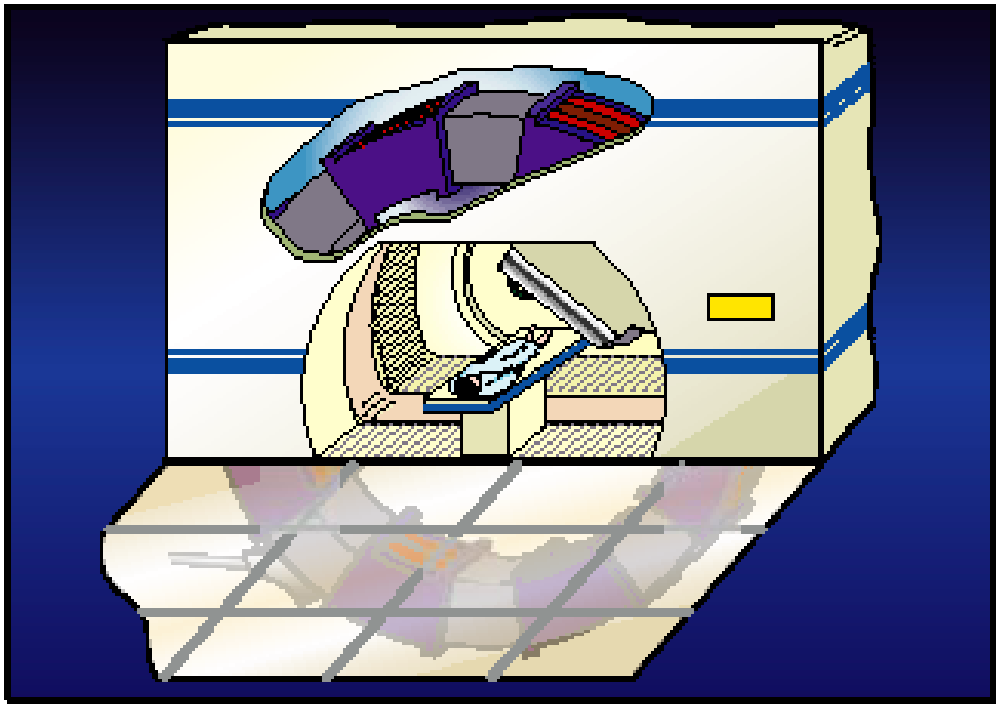
FFAG proton model R&D

R&D of 150-MeV FFAG

Purpose of 150MeV-FFAG

Medical Application => **Proton Cancer Therapy**

Proto type of 150MeV-FFAG R&D for Future Cancer Therapy

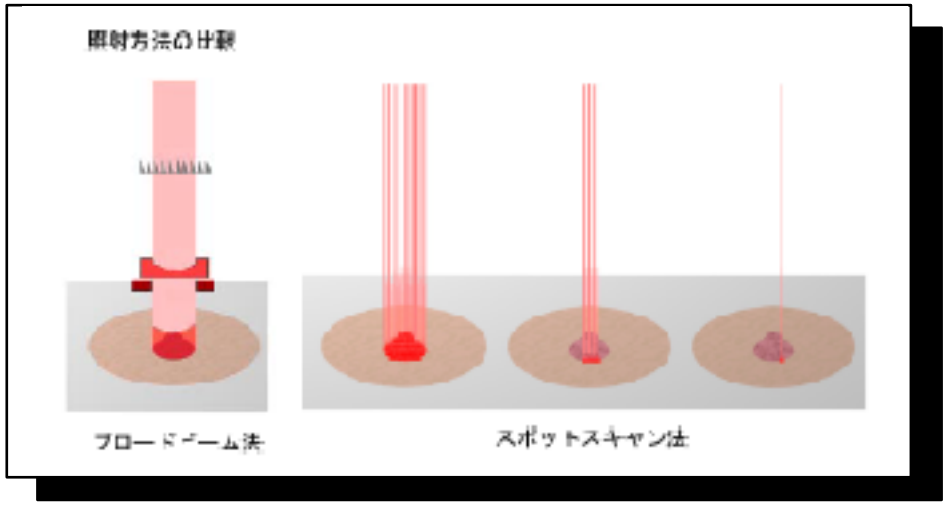


◀ FFAG加速器を用いた癌治療の将来像

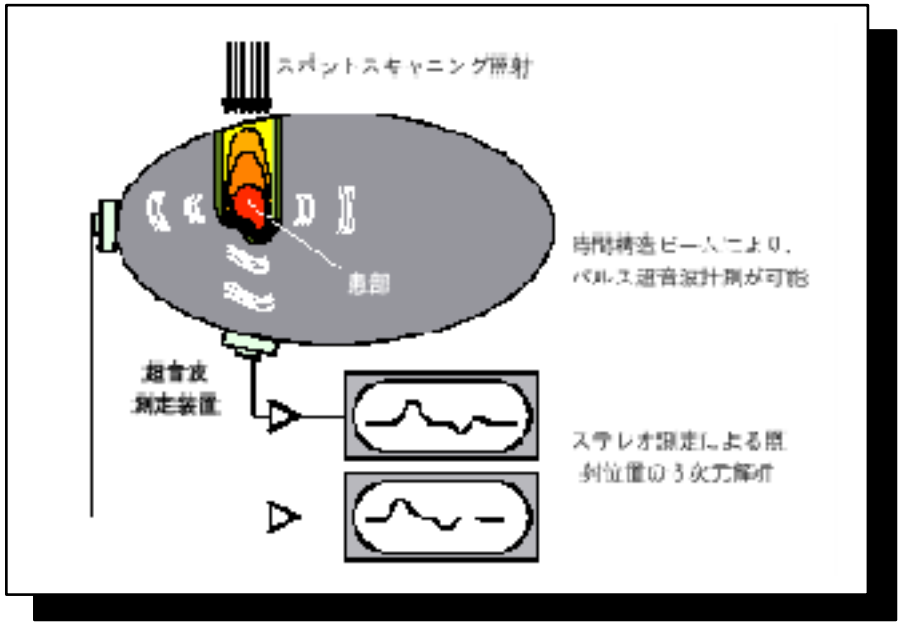
Appl. to Cancer Therapy

High Repetition Acceleration : FFAG opens New Schemes in Beam Therapy
(1)3D Fast Spot-Scanning (2)" in-situ" Dosemetry by Super Sonic Phonon

3D Fast Spot Scanning



"in-situ" dosemetry by Super Sonic Phonon



150-MeV proton FFAG accelerator R&D

Prototype for various applications:

construction 2000-2004

Injector : H^- Cyclotron (12-MeV:~50μA)

High repetition extraction: kicker(IGBT power supply)

Applications: Cancer therapy,Muon phase rotation

150MeV FFAG main parameters

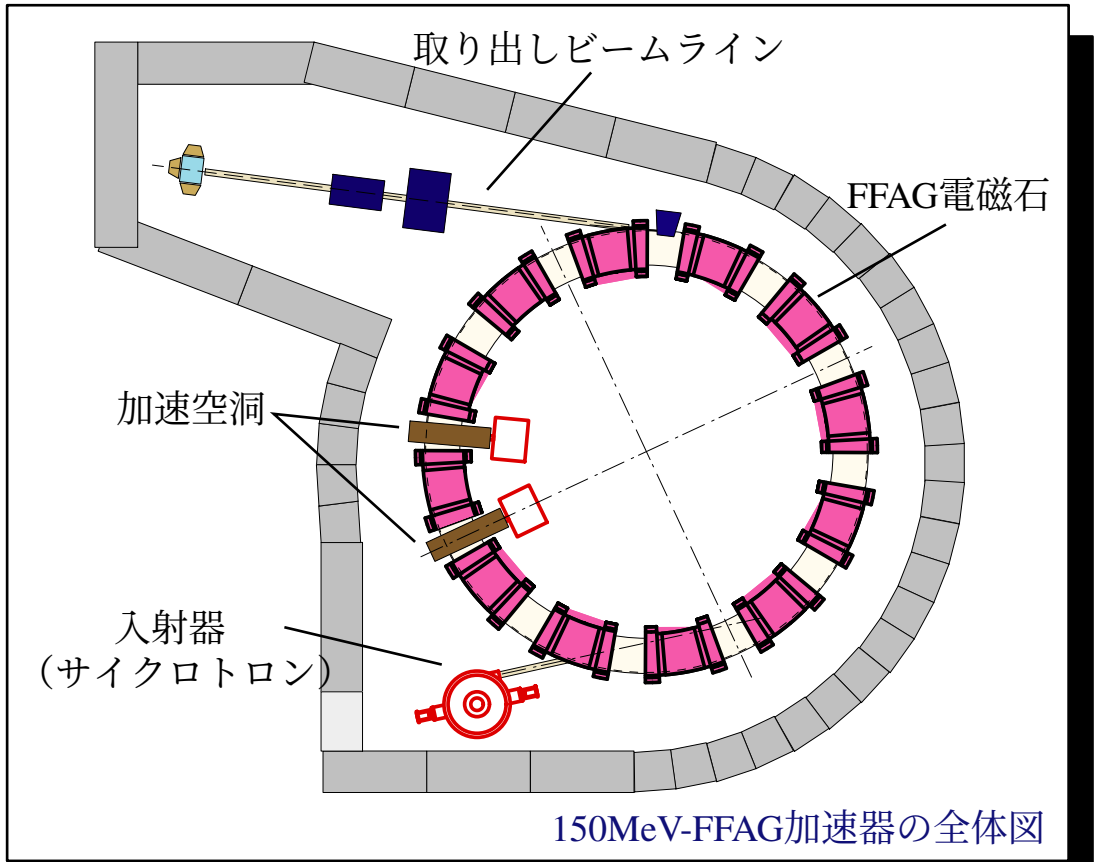
No. of sectors	12	Closed orbit radius	4.4m -5.3m
Field index(k -value)	7.5	Betatron tune	
Energy	12MeV - 150MeV	Horizontal :	3.8
Repetition rate	250Hz (1kHz)	Vertical :	2.2
Max. Magnetic field		rf frequency	1.5 -4.6MHz
Focus-mag.:	1.63 Tesla	rf voltage	25kV
Defocus-mag.:	0.13 Tesla	Injector	12-MeV Cyclotron

150MeV-FFAG

150MeV-FFAG 加速器は12MeVで入射した陽子を
150MeVまで加速して取り出します。

主な設計パラメータ

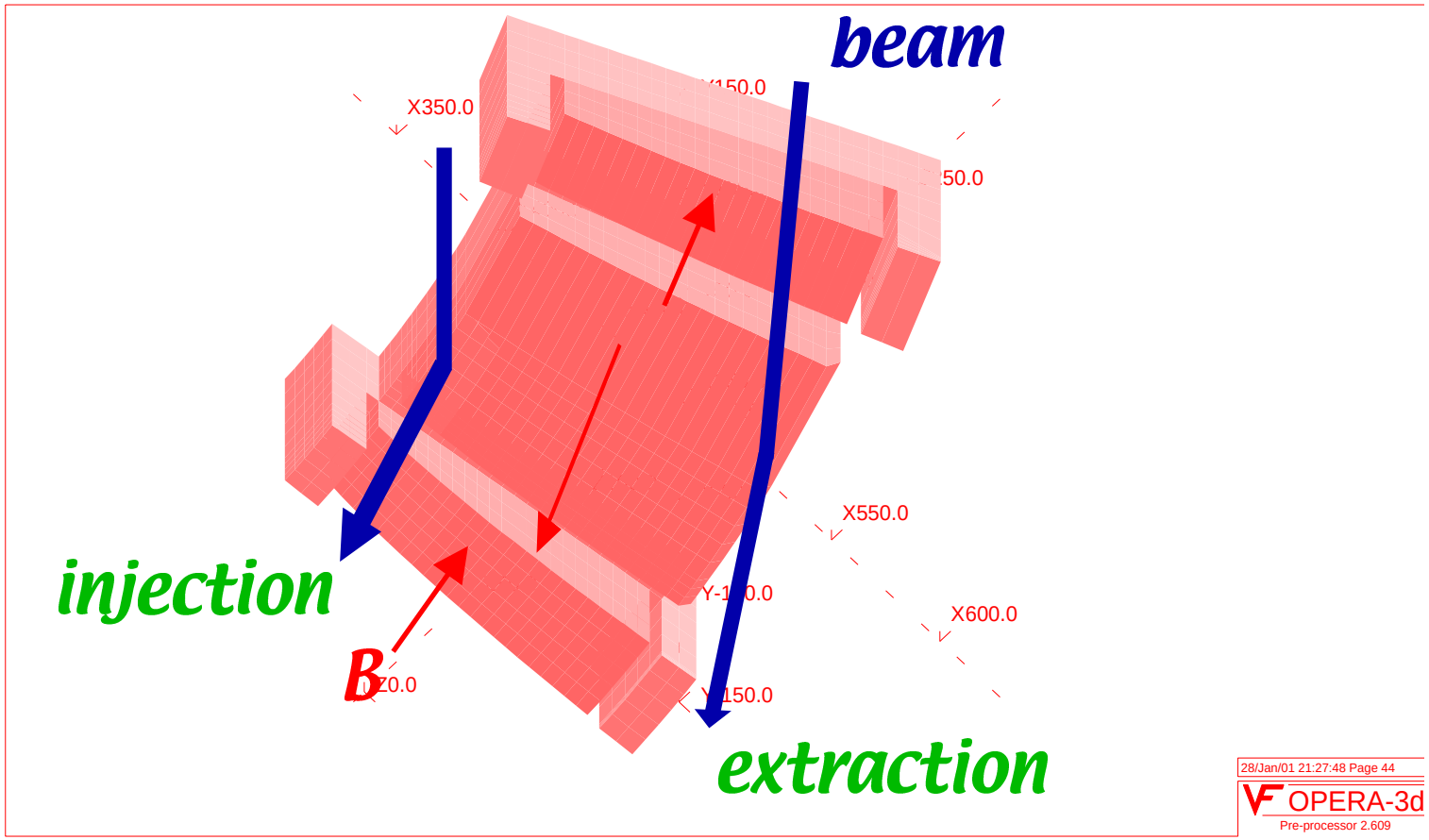
エネルギー	12MeV => 150MeV
入射器	サイクロトロン
電磁石	１２台
加速空洞	２台
繰り返し	1kHz



150MeV-FFAG加速器の全体図

Yoke-free magnet of triplet sector FFAG

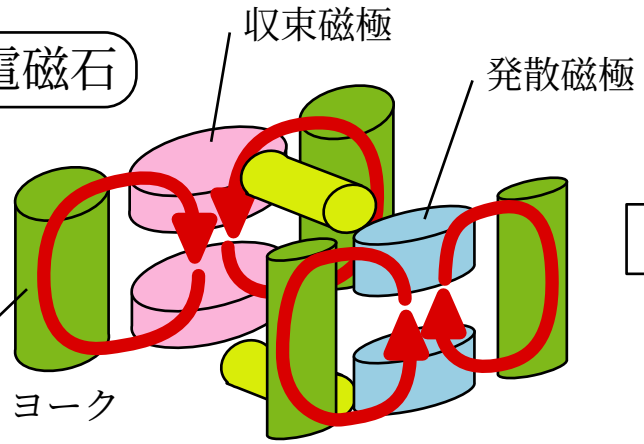
injection & extraction : large flexibility

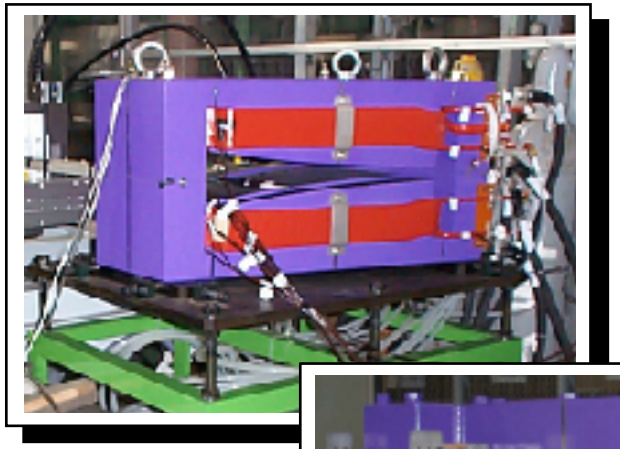


(3) 新しい電磁石

150MeV-FFAG加速器では新しい電磁石が開発しました。
これにより加速したビームを取り出すことが容易になります。

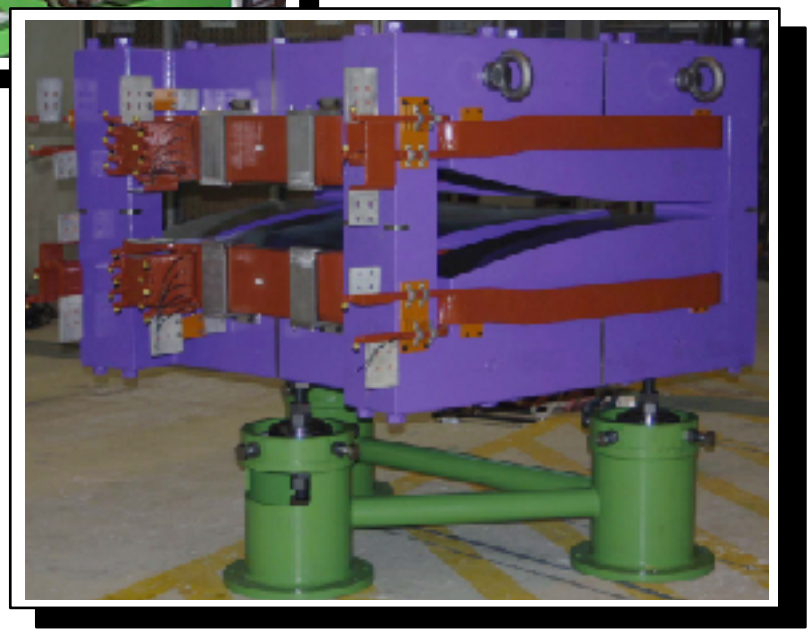
従来の電磁石





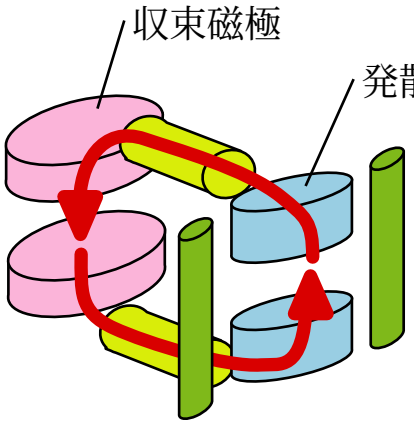
PoP-FFAG用電磁石

150MeV-FFAG用電磁石

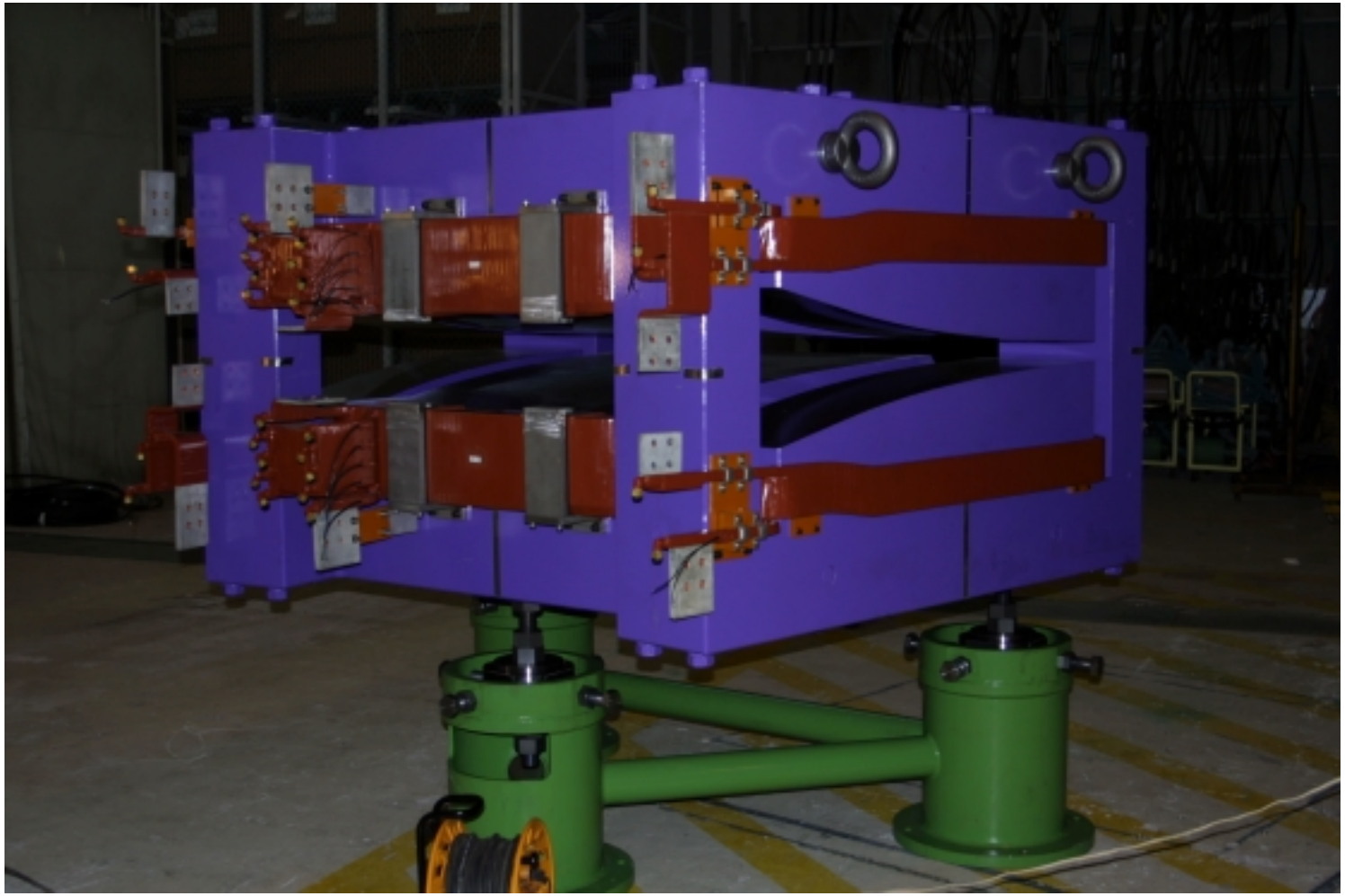


新しい電磁石
『ヨーク・フリー電磁石』

リターン・ヨークを取り外した！



Magnet of 150-MeV proton FFAG



Summary

FFAG is wonderful !

*PoP proton FFAG : works successfully!
*150-MeV proton FFAG : under construction
*FFAG based Neutrino Factory : design and R & D

FFAG is good for short-lived secondary particles(μ,RI)
because ---> (1) Fast Acceleration ~μsec
(2) Large Acceptance >10,000πmm,mrad
$\Delta p/p$>+-50%

FFAG Web site http://hadron.kek.jp/FFAG