FFAG : Fixed-Field Alternating Gradient Synchrotron

Proton Driver for Muon Source

Yoshiharu Mori (KEK)

Proton Driver for Pulsed Muon Source : Specifications

Beam energy	~1GeV
Beam power	~1MW (ave. cur. ~ 1mA)
Beam rep. rate	~10kHz
Bunch width	<100ns

Compact, Low cost......

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

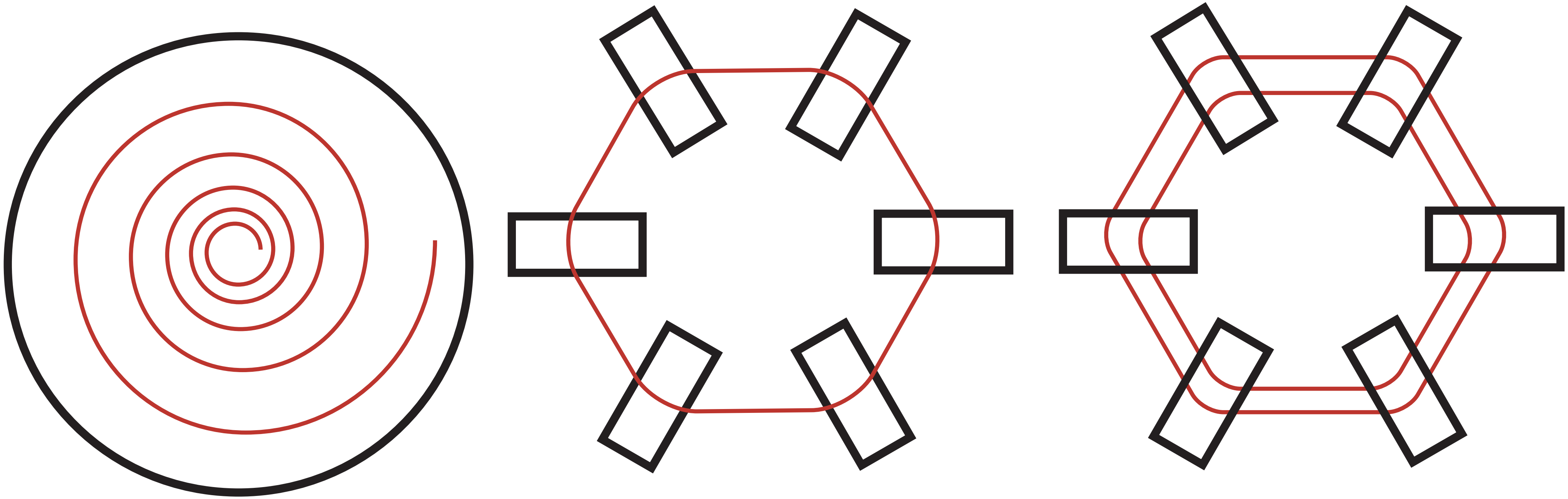
Circular Accelerator

Synchrotron:

* Strong Focusing in 3D directions(trans. & long.).
  Betatron and Synchrotron Oscillations.
  ---> Stable beam acceleration

but, B is time-varying to keep a closed orbit constant.
---> Duty Factor : small ~1%(rep. rate:~10Hz)
Small beam power compared with other cw or semi-cw machines.

Fixed B -----> Fixed Field Alternating Gradient(FFAG)



Cyclotron

*isochronous

Synchrotron

*const. closed orbit

(varying mag. field)

FFAG

*varying closed orbit

(const. mag. field)

FFAG加速器の特徴

シンクロトロンは加速途中で
磁場が変化する。

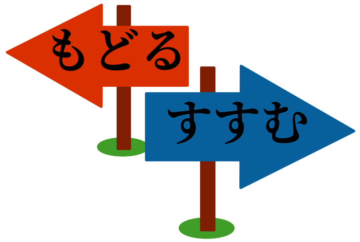
加速の繰り返しが遅い。

FFAG加速器は加速の途中でも
磁場は変化しない。

加速の繰り返しが速い。

NEXT :

FFAG加速器の未来



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 machine so far!

(1)Relatively large at high energy (>30GeV) : Big Magnet

(2)Complicated magetic field configuration : 3D design

(3)RF cavity : Large beam aperture : Variable Frequency & High Gradient.

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

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

b)Constant n

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

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

b) Spiral Sector

/small excursion

/less tunable

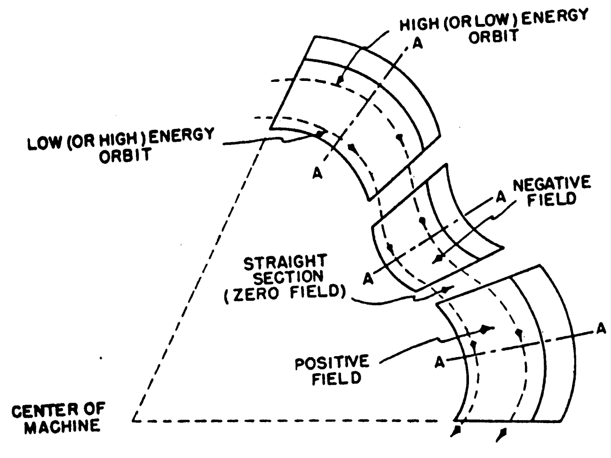


FIG. 2. Plan view of radial-sector magnets.

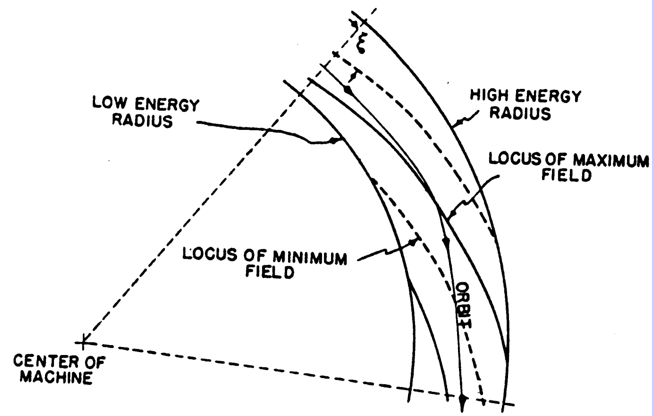


FIG. 3. Spiral-sector configuration.

FFAG Accelerator

Comparison with ordinary synchrotron

	FFAG	ord. Synchrotron
1. Magnetic Field	Static (Fixed)	Time varying
2. Closed Orbit	Moving	Fixed
3. Focusing	Strong	Strong
4. Duty Factor	Large ~10-50%	Small ~1 %
(Repetition Cycle)	(~>1kHz)	(~10Hz)
5. Space charge/Instability	Not critical	Severe
	(small particle numbers per bunch)	

Problems to be solved:

* complicated magnetic field ---> 3D codes(TOSCA etc.)

* RF system : high field & rapid tuning

--> " High Gradienet & Broad Band RF Cavity"

FFAG : revival again 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

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**.

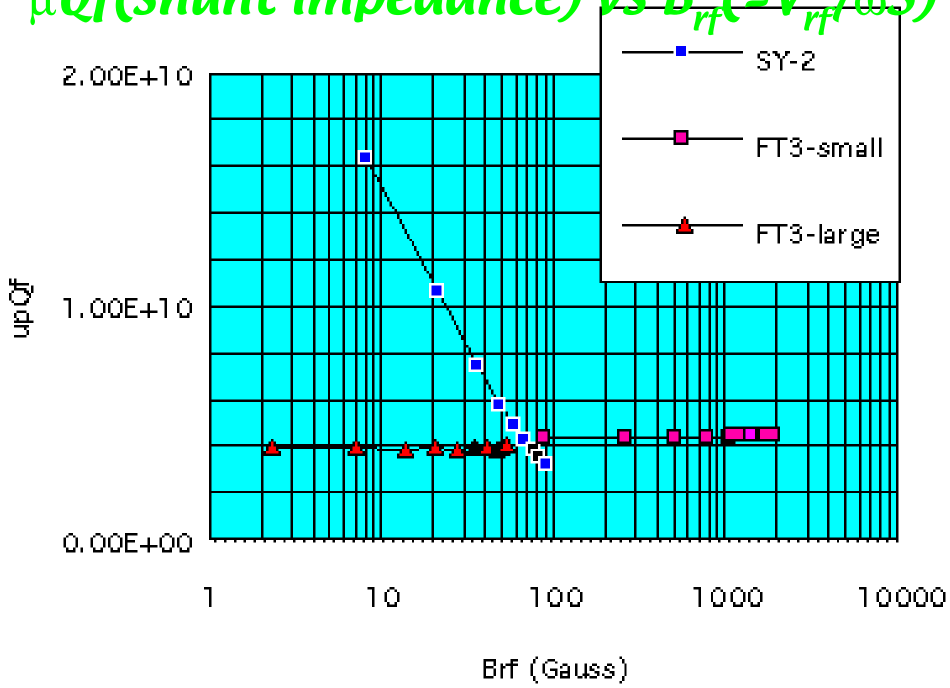
(2) A high Curie temperature, typically **570°C** for FINEMET.

(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).

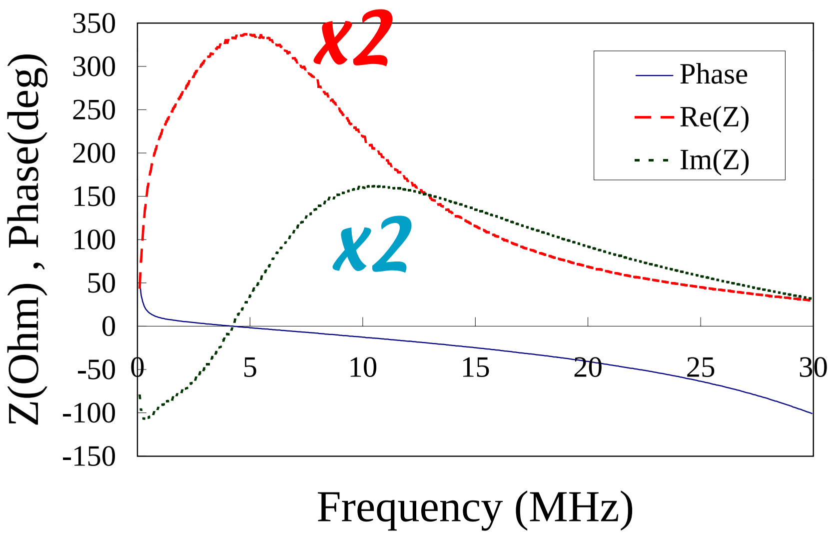
Prototype of MA-loaded Cavity

Single Gap MA-loaded Cavity

E~50kV/m

RF Voltage	20kV
No. of Cores	6
Shunt Impedance	500-750 W
Q	1
Total Length	40 cm

Measured Cavity Impedance & Phase



Multi-beam Acceleration

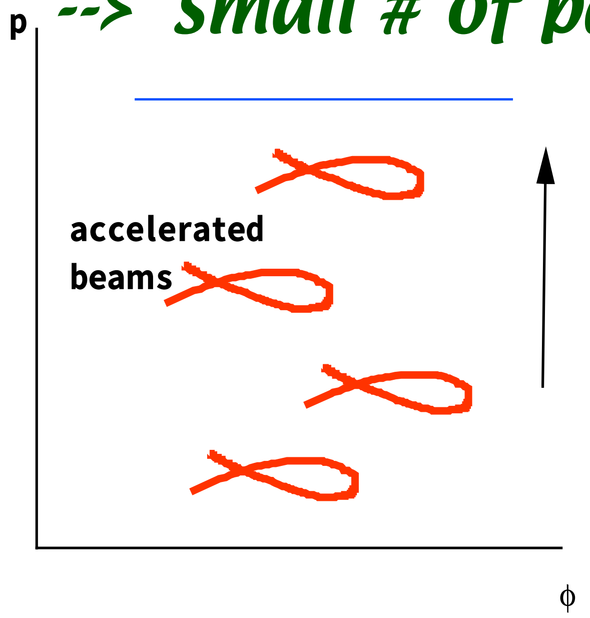
multi-bunch in different orbit :

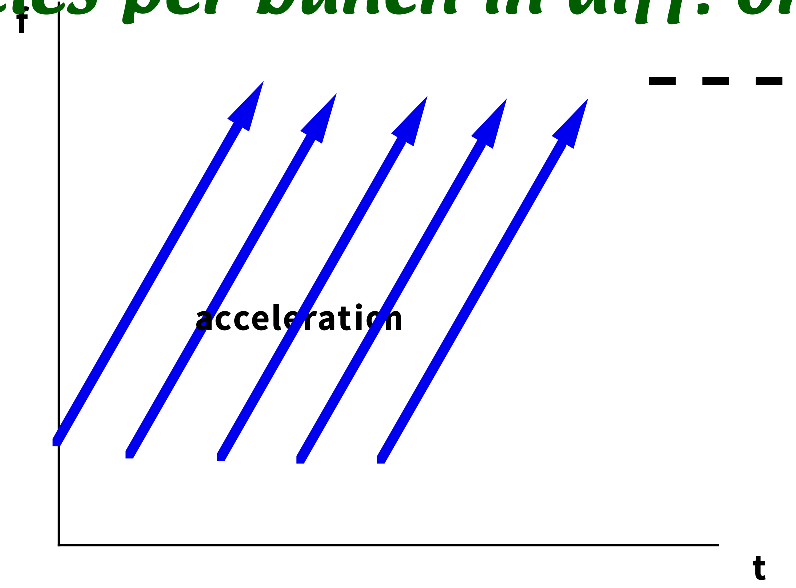
*cw machine (Cyclotron) as an injector

*increase acceleration cycle w/o large rf voltage

*small space charge effect

--> small # of particles per bunch in diff. orbit

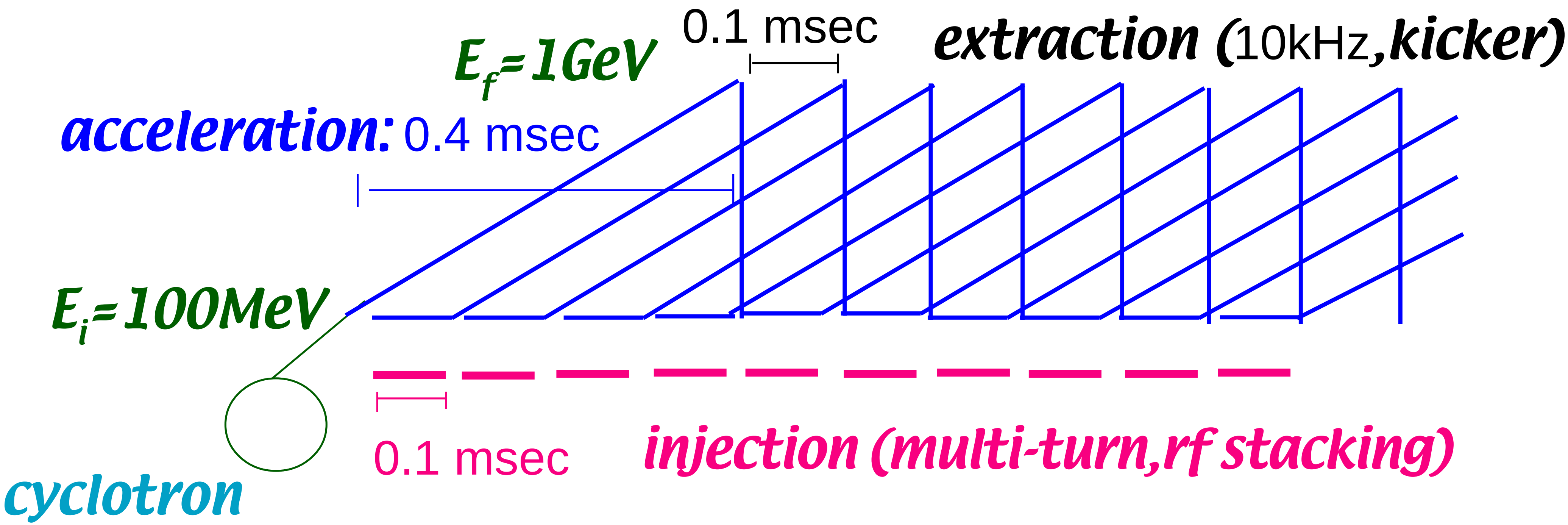




FFAG : multi-beam operation

cf. **1GeV - 10mA (10MW) FFAG**

Injector	Cyclotron (H+/H-)	Accelerator	FFAG
energy	100MeV	energy	1GeV
current	I=10mA	intensity	$6x10^{12}$ppp(|ΔQ|<-0.1)
		rep. rate	10kHz eq.(2.5kHz)



Development of proton FFAG accelerator

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

aims:

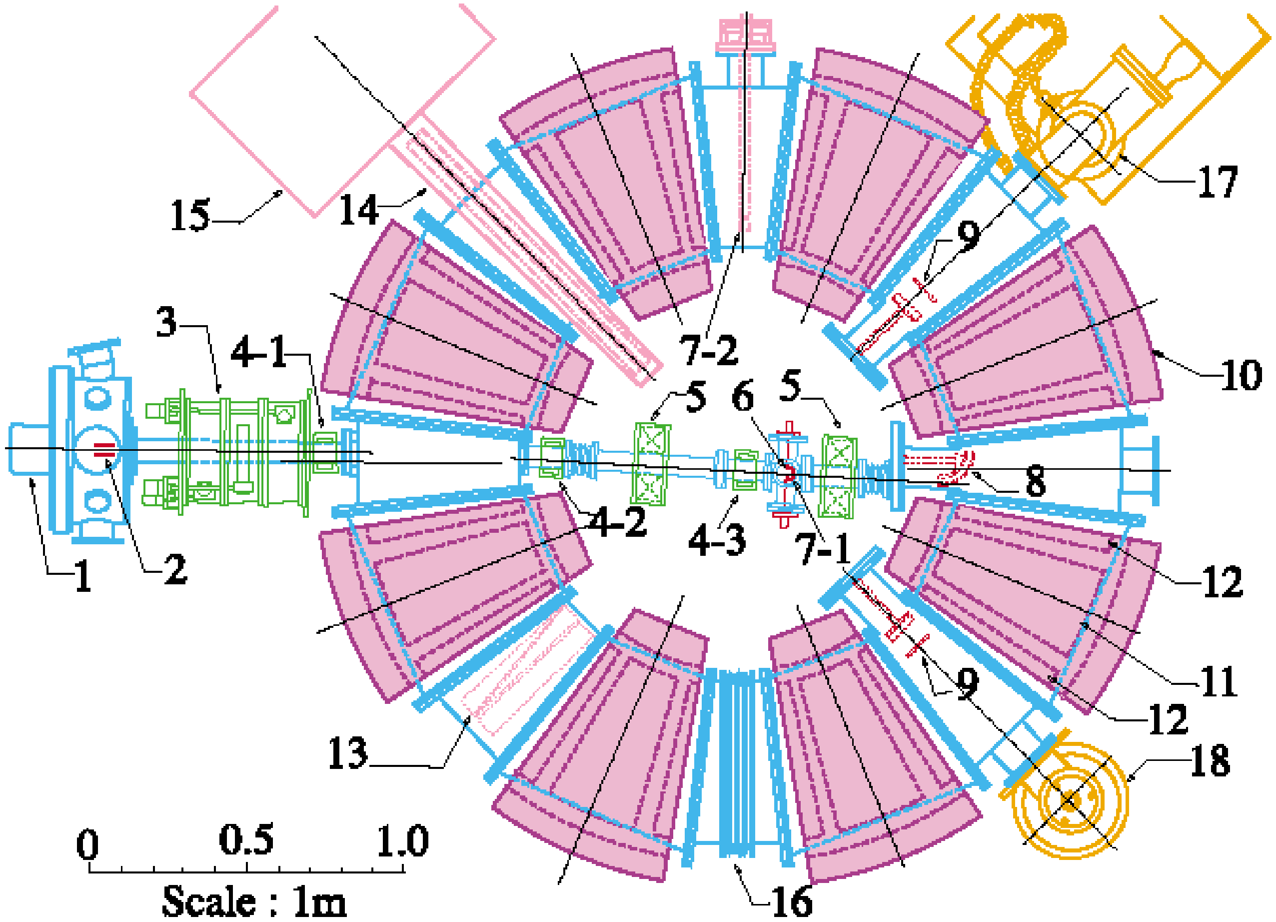
(1) fast acceleration : t<1msec --> 1kHz rep. rate

(2) first proton FFAG accelerator

(parameters)

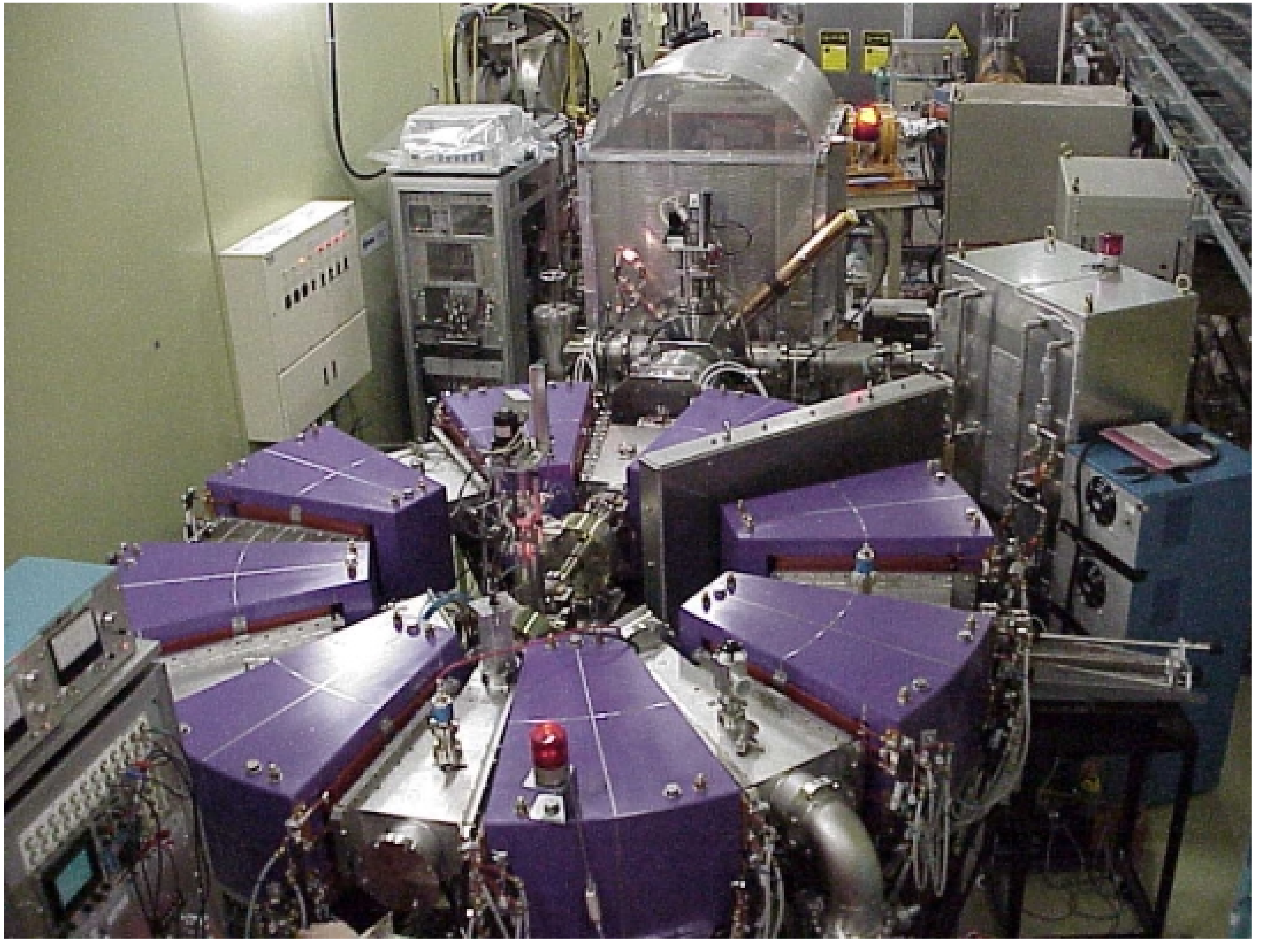
Type of magnet		Radial sector type (Triplet)
No. of sectors		8
Field index(k-value)		2.5
Energy		50keV(injection) ~ 500keV
Reptition rate		1kHz
Magnetic field	Focus-mag. :	0.14~0.32Tesla
	Defodus-mag. :	0.04~0.13Tesla
Radial of closed orbit		0.81~1.14m
Betatron tune	Horizontal :	2.17~2.22
	Vertical :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

PoP proton FFAG accelerator



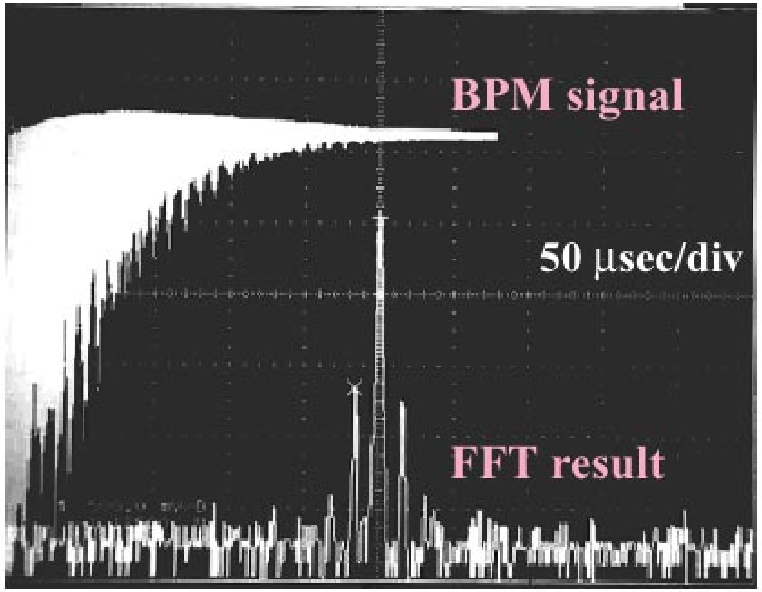
1: ion source
2: chopper electrode
3: triplet-quadrupole magnet
4: steering magnet
5: solenoid magnet
6: beam slit
7: Faraday cup
8: septum electrode
9: bump electrode
10: sector magnet
11: F-magnet pole
12: D-magnet pole
13: beam position monitior
14: RF cavity
15: RF amplifier
16: vacuum bellows
17: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

PoP proton FFAG model



Beam Acceleration

[injection]



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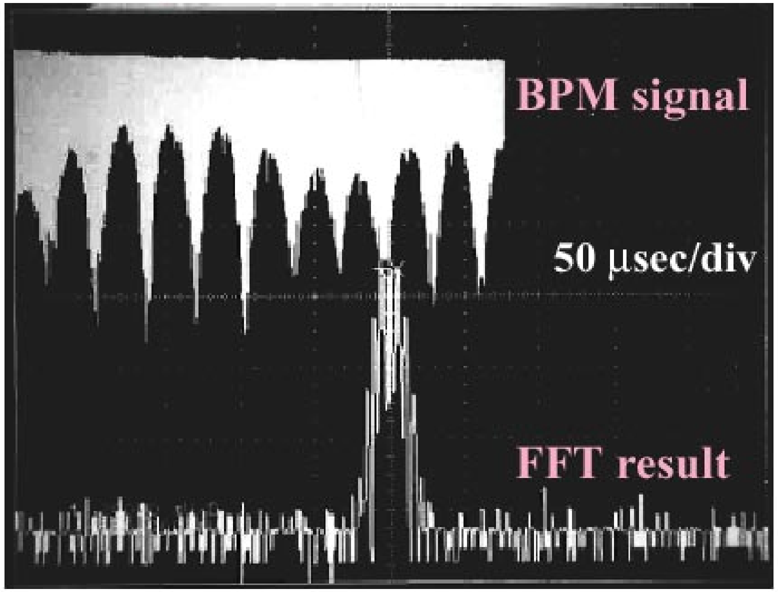


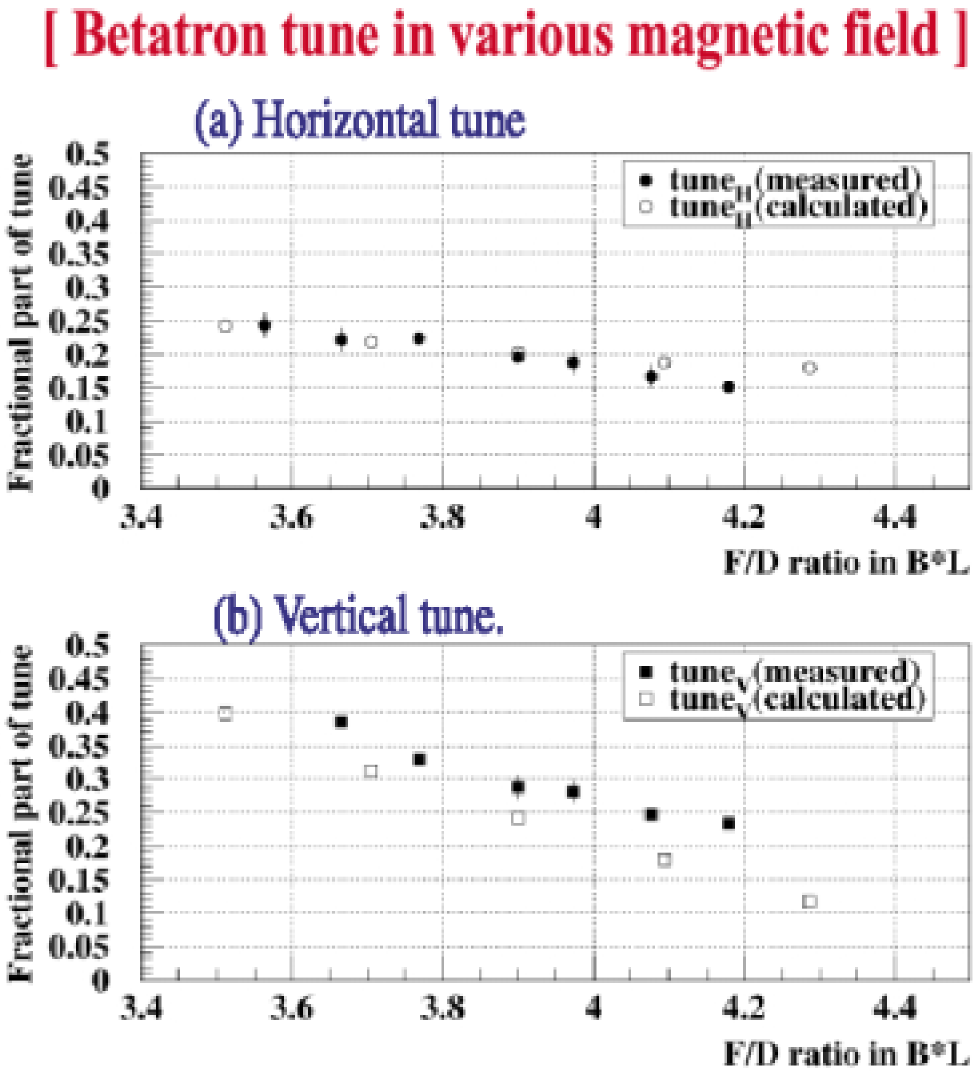
revolution frequency :

610kHz → 1.251MHz

synchrotron frequency :

24.06kHz → 16.78MHz

Measured Betatron Tunes



150-MeV proton FFAG accelerator

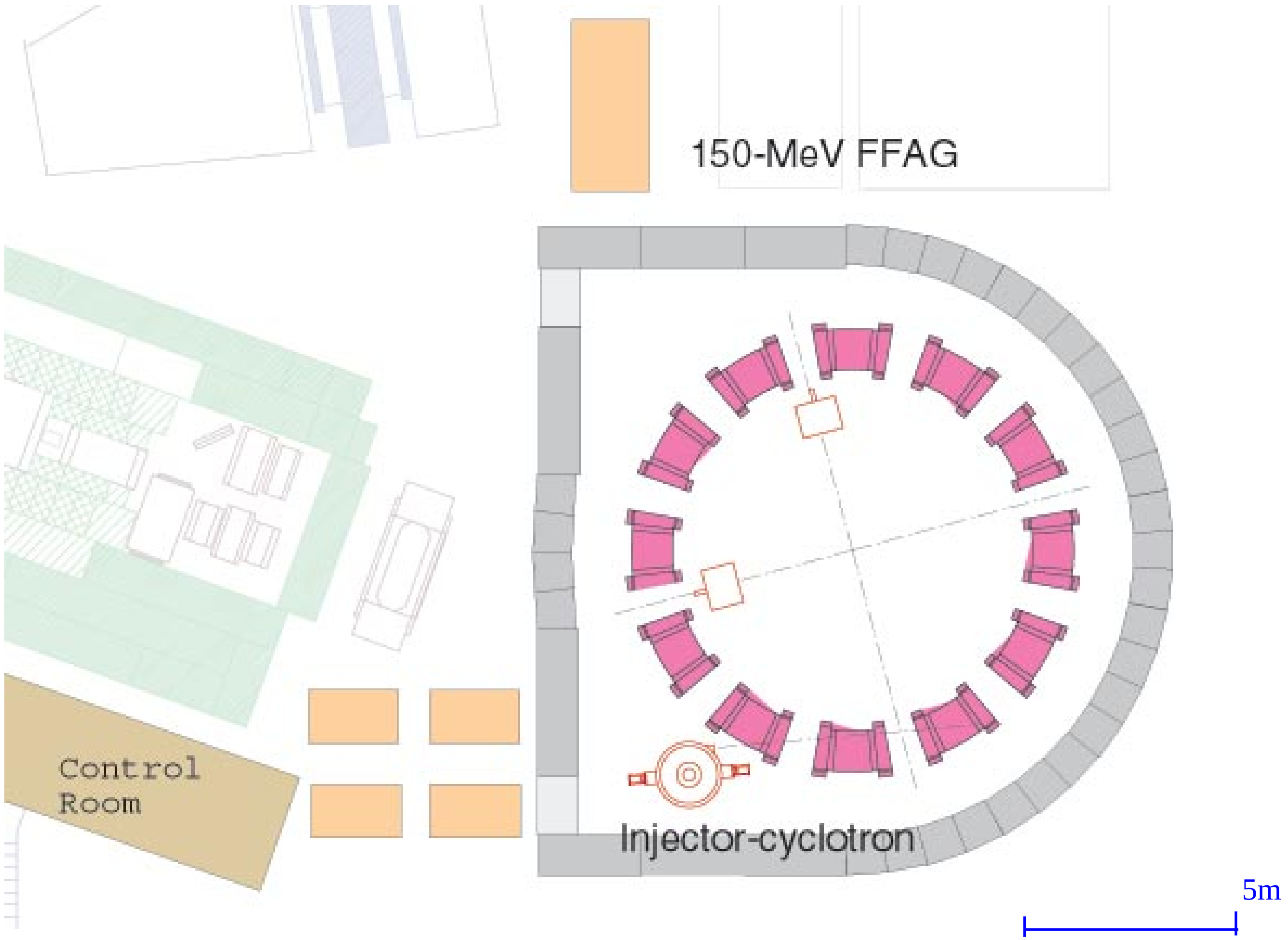
Prototype for various applications:

Madical application : Cancer therapy
Muon phase rotation : PRISM project

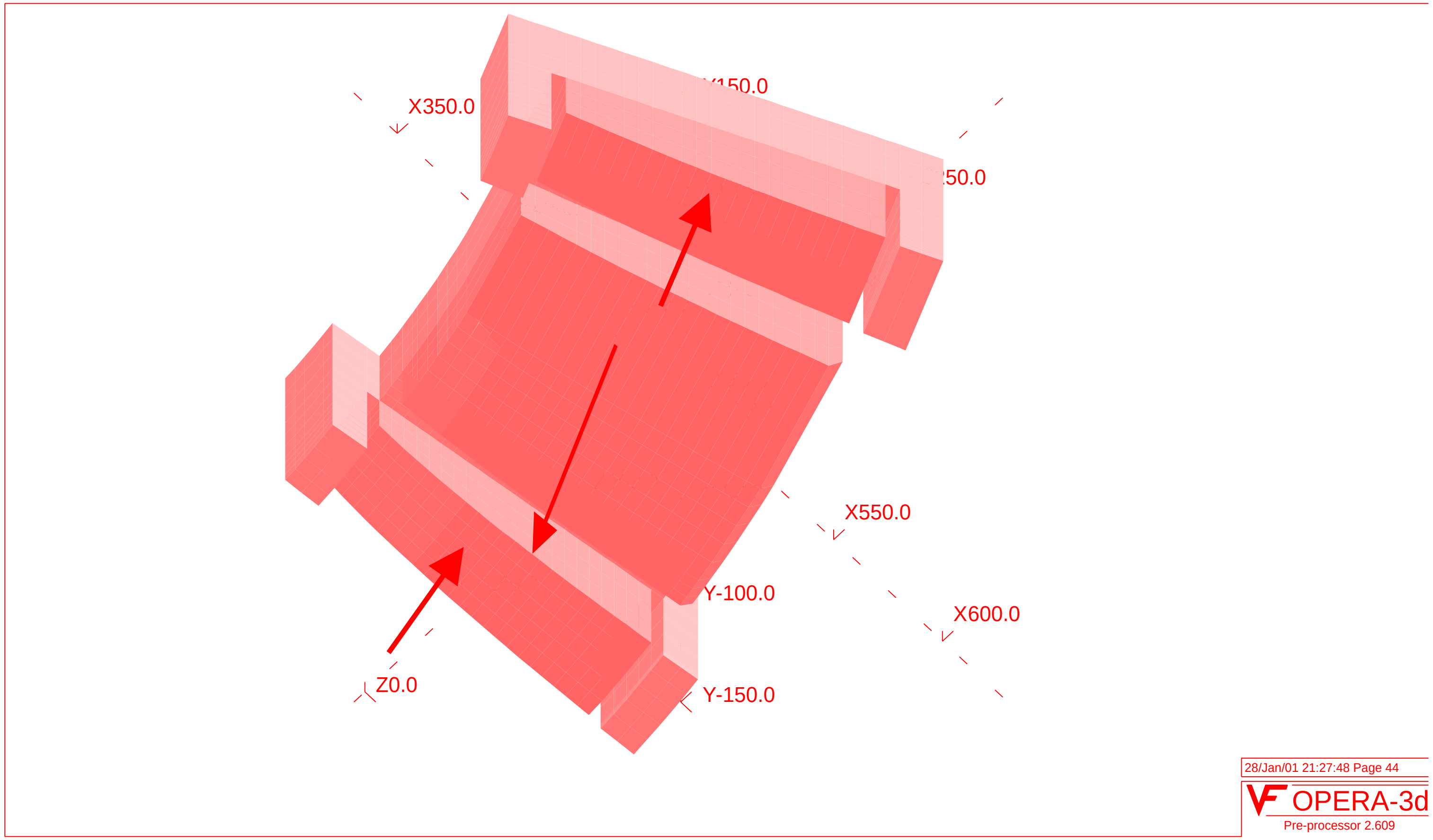
150MeV FFAG main parameters

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 :	3.8
Vertical :	2.2
rf frequency	1.5 -4.6MHz

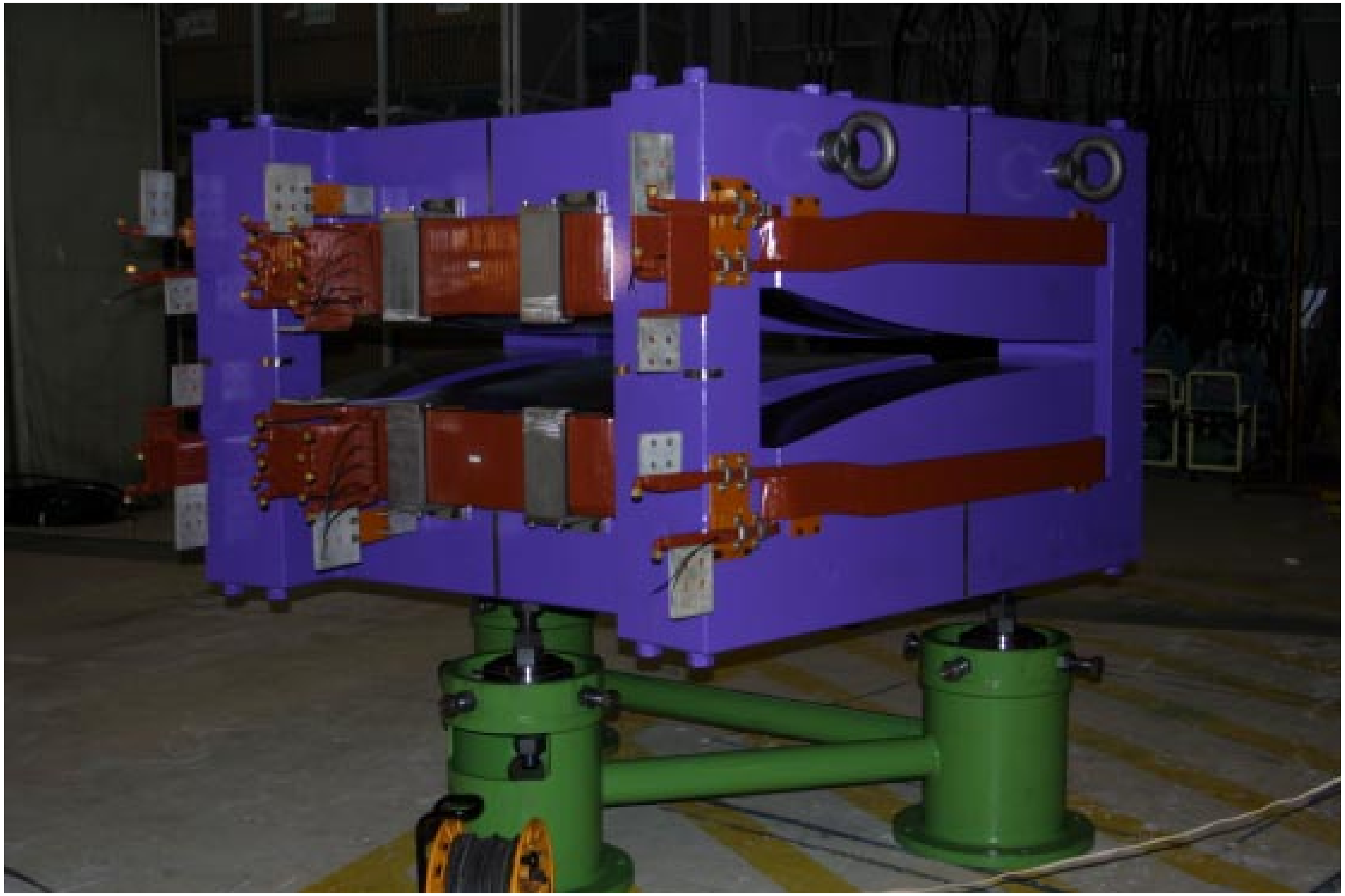
150-MeV proton FFAG accelerator



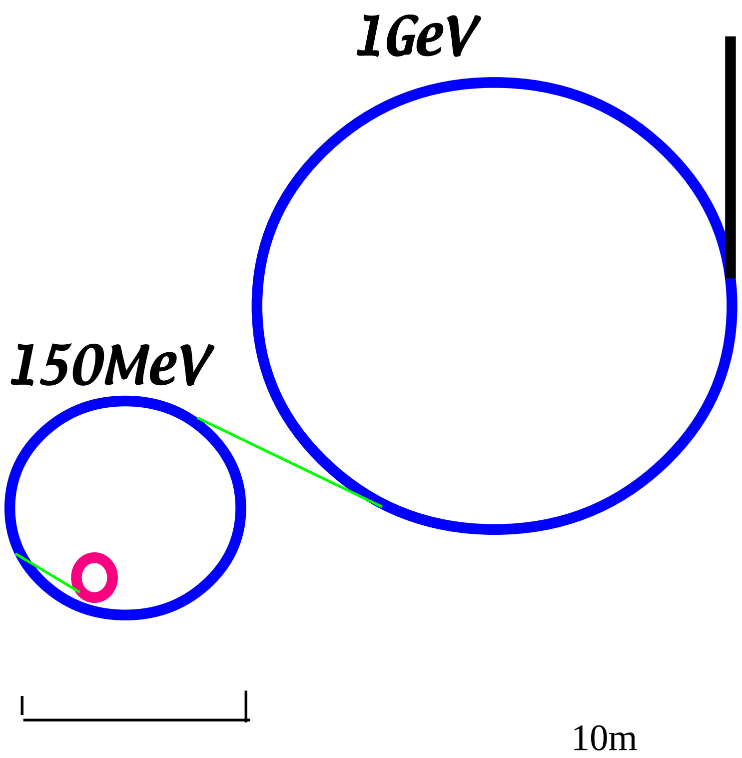
Yoke-free magnet of triplet sector FFAG



Magnet of 150-MeV proton FFAG



1GeV-1MW-10kHz FFAG Proton Driver



Energy	150MeV-1GeV
Intensity	6x1011ppp
Rep. Rate	10kHz (1kHz x10)
Ave. Current	1mA (Beam Power 1MW)
Radius	~16m
k	25
# of cell	48
rf freq.	5.43MHz - 8.08MHz
rf voltage	~850kV
bunch width	~40ns