Neutrino Factory in Japan: based on FFAG

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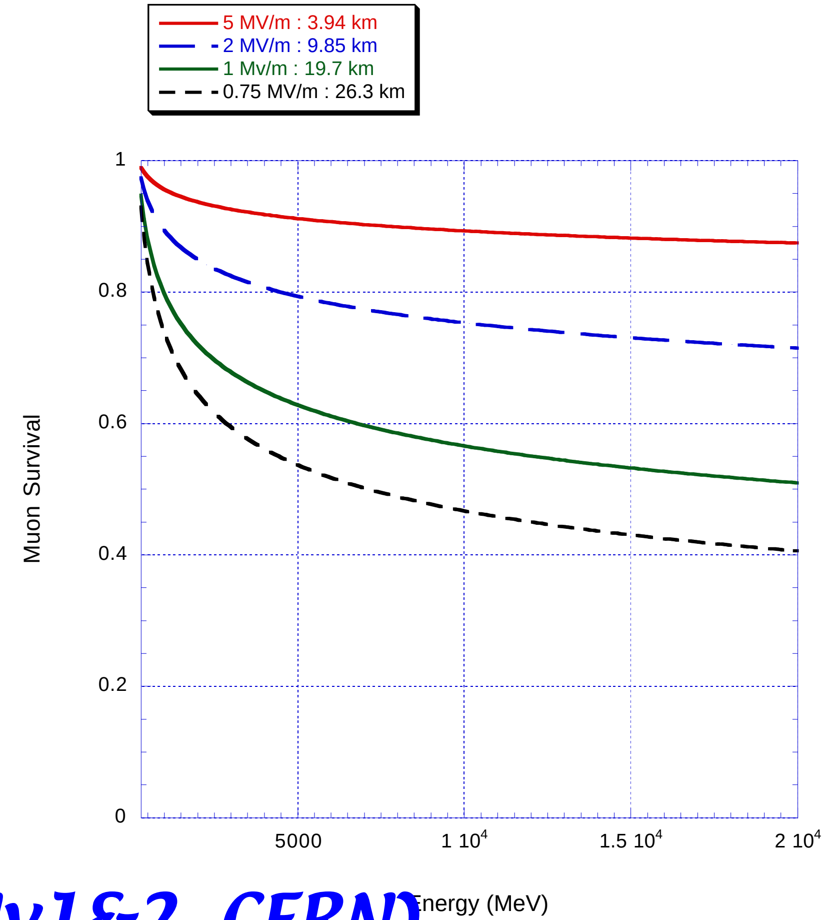
1. Introduction
2. Scenario of muon acceleration
3. Neutrino Factory based on FFAG
4. Summary

Muon Suvival for various accelerating filed

0.3 GeV/c- 20 GeV/c

E=5MV/m -> 3.9 km

E=0.75MV/m -> 26.3 km



Conventional Scheme

“ PJK “ Scenario (USA:study1&2, CERN)

---> based on “Cooling +Linear accelerators”

Neutrino Factory Scenario

Linear accelerator based scenario (PJK Scenario)

* high accel. field gradient :E > 5 MV/m (L ~ 4 km)

High frequency rf (f > 100 MHz)

pro : muon survival >85%

con : small acceptance ($\varepsilon_{H,V}$ & dp/p)

need "phase rotation & muon cooling"

high cost

Neutrino Factory Scenario

Ring accelerator scenario (FFAG Scenario)

* low accel. field gradient: E ~ 0.5-1 MV/m

# of turns ~ >30 turns (R ~0.15 km):

pro: **low frequency rf (f~ 5-10 MHz)**

large acceptance ($\varepsilon_{H,V}$ & dp/p)

no-need "phase rotation &muon cooling"

low cost (*depend on scheme)

con: **muon survival ~50% , however,**

large acceptance may compensate it.

large acceptace & quick acceleration?

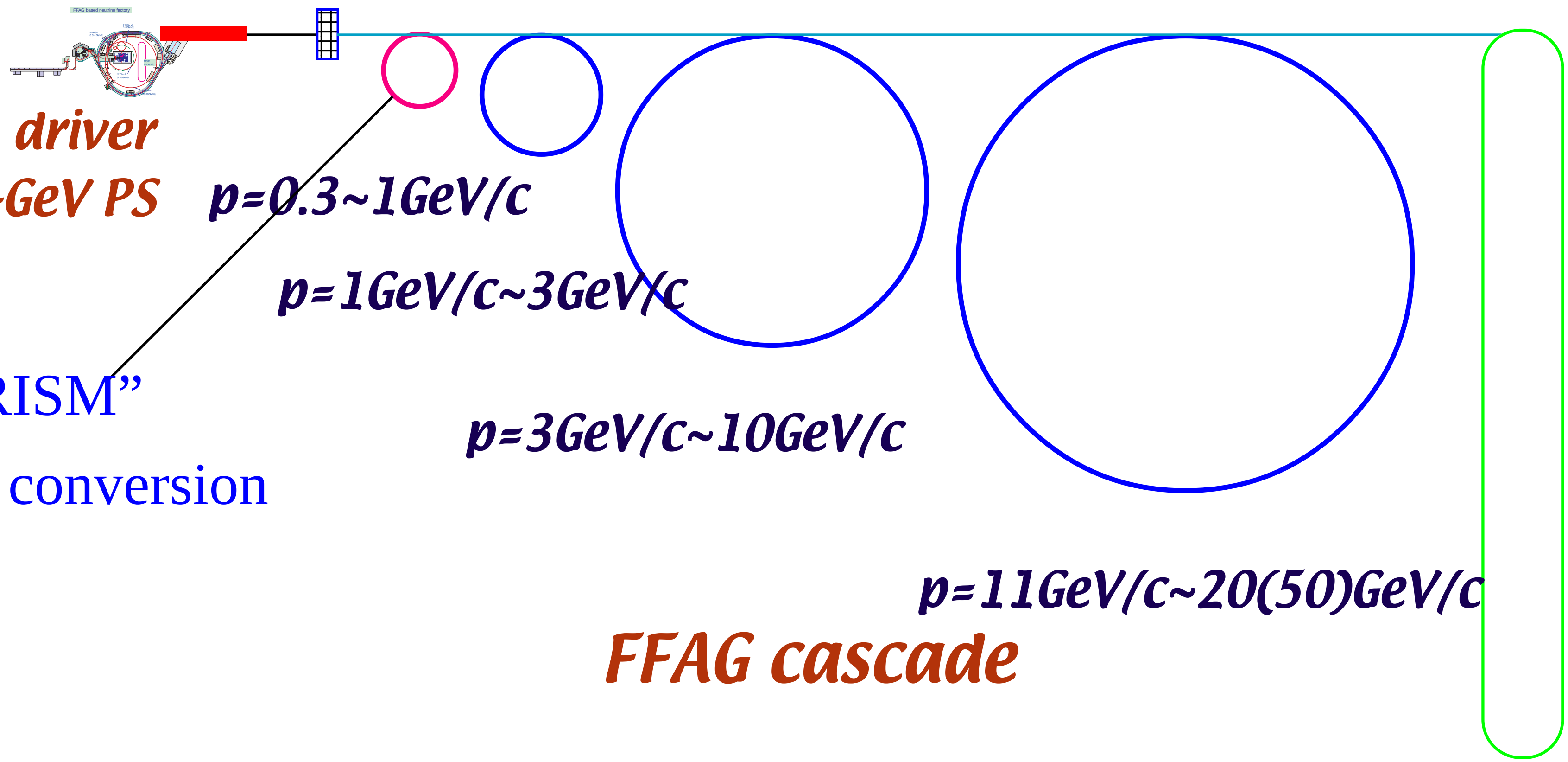
Conceptual Design of Neutrino Factory in Japan

Scenario

* FFAG accelerator complex for muon acceleration
  - i) large acceptance : $\varepsilon^{N}_{h,v}$ ~0.03mrad, dp/p~0.5
  - ii) no-cooling & no-phase rotation

* Proton driver : JHF 50-GeV PS
  - i) beam power : ~MW
  - ii) construction(phase-I) completed in 2007

Accelerator Scenario - FFAG Option



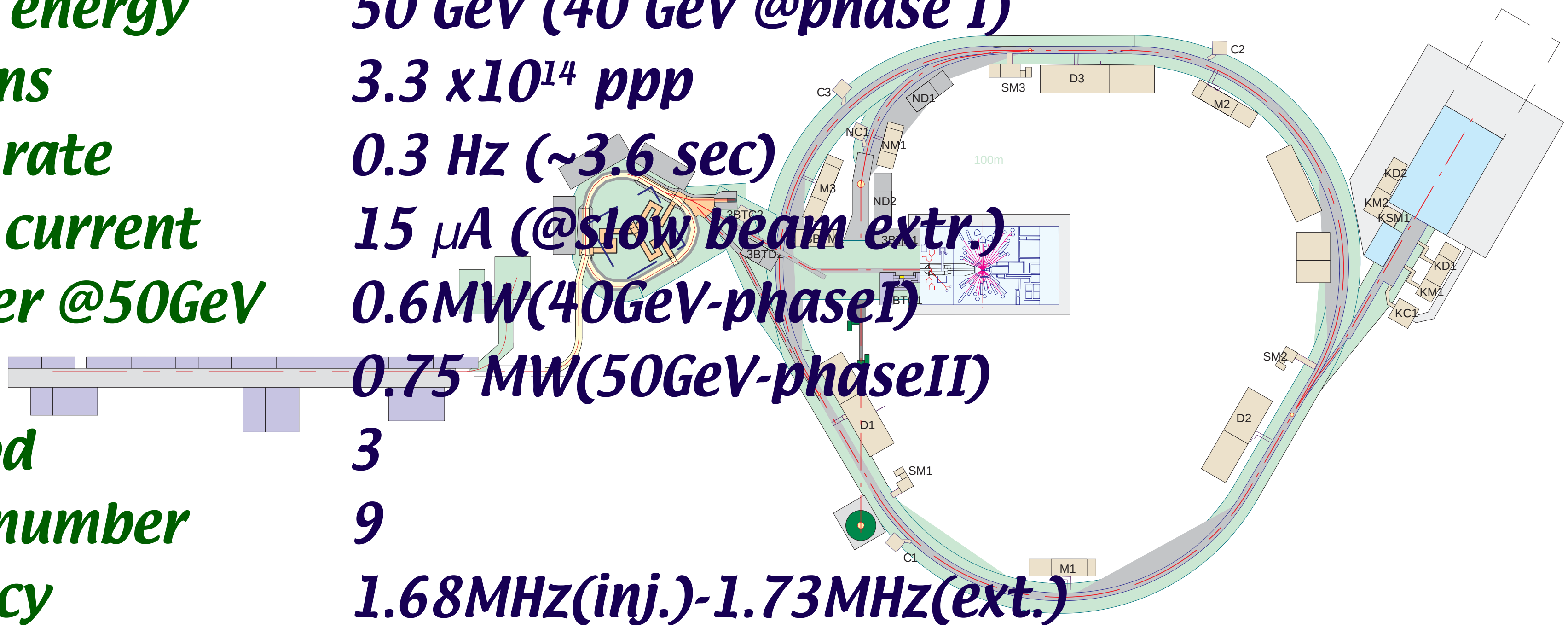
Proton Driver

Proton Driver

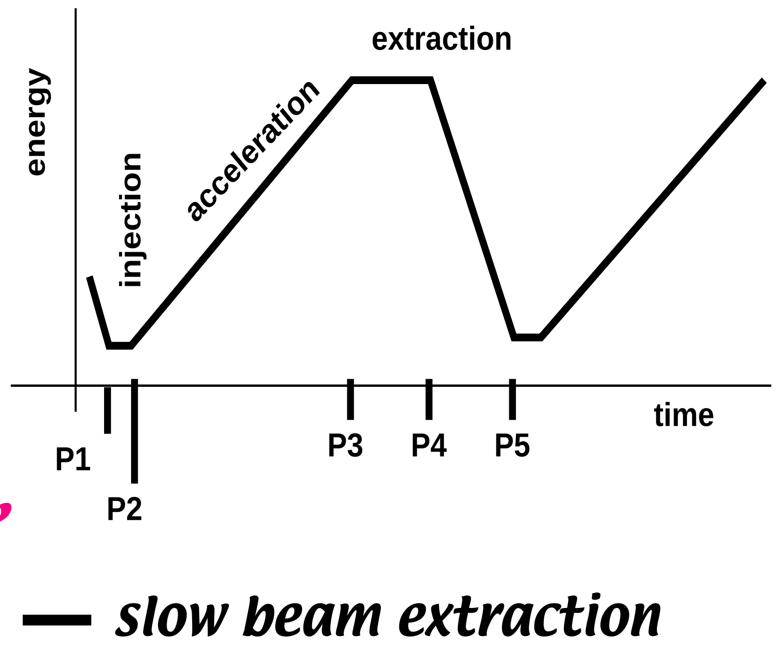
Proton driver is JHF 50-GeV PS.

JHF High Intensity Proton Synchrotron

injection energy	3 GeV
extraction energy	50 GeV (40 GeV @phase I)
# of protons	3.3 x10^{14} ppp
repetition rate	0.3 Hz (~3.6 sec)
ave. beam current	15 μA (@slow beam extr.)
beam power @50GeV	0.6MW(40GeV-phaseI)
	0.75 MW(50GeV-phaseII)
superperiod	3
harmonic number	9
rf frequency	1.68MHz(inj.)-1.73MHz(ext.)



Possible Upgrading Path in Future



1) Increase main ring cycle

MR cycle 3.64 sec. --> 1.5 sec.

Beam Power ~ 2 MW

* rf voltage : x2

* maget power supply : FWG

" no needs to change main parts"

2) Increase beam intensity

Beam stacking 4 batches ---> 8 batches @ injection

Beam Power ~ 4MW

* barrier bucket beam stacking : modest space charge

" Beam losses have to be reduced"

Target & Capture

How large acceptqance is needed?

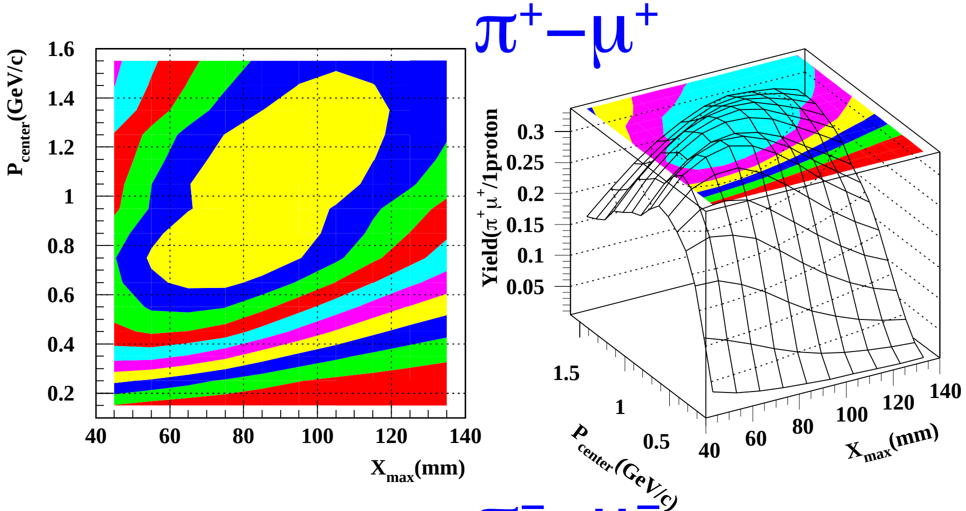
Muon & pion yield with fixed trans. acceptance

assumed acceptance:

- $\varepsilon_n(100\%)=0.03\pi m.rad$
- dp/p = +- 50%

proton driver :

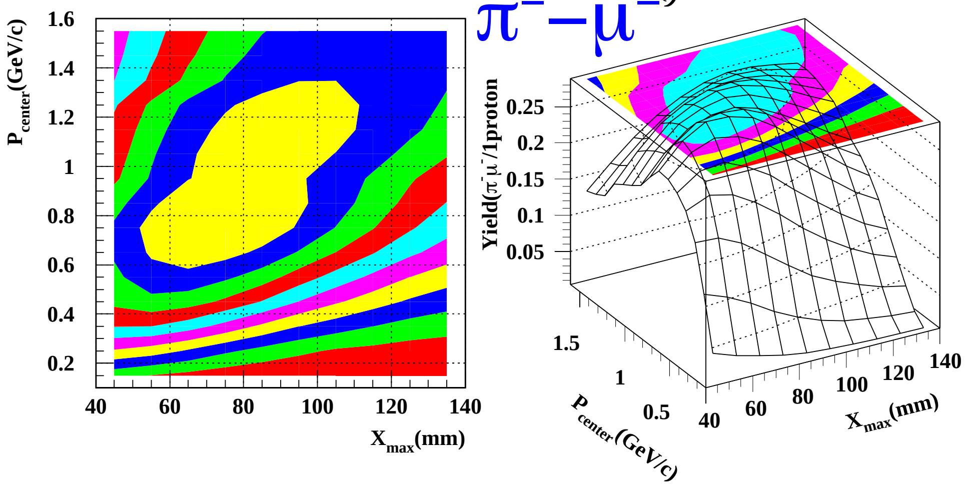
- JHF 50GeV MR (0.75MW)



peak yield

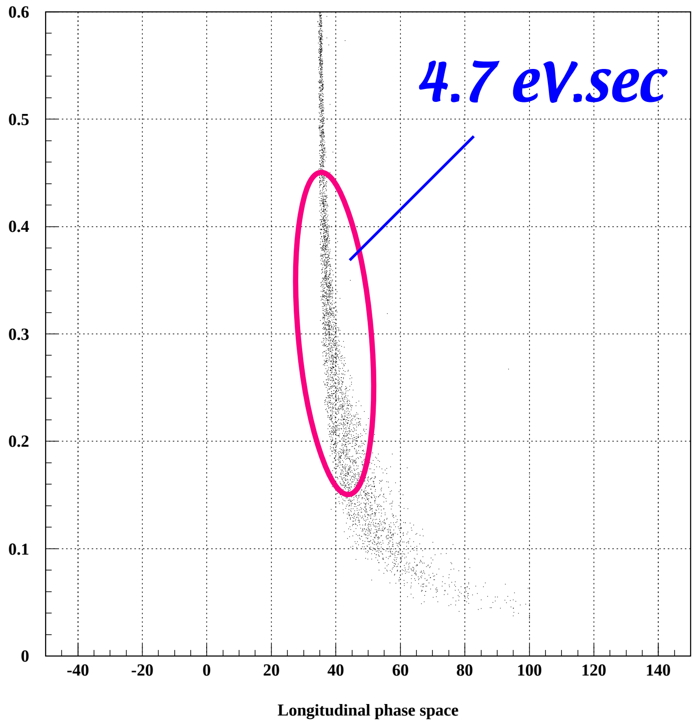
0.3 muons/proton

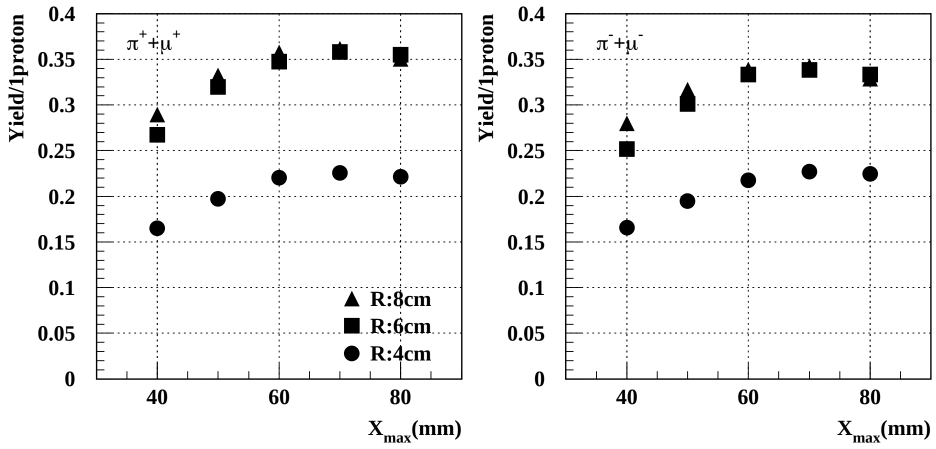
p_μ = 0.4~1.5GeV/c



Accelerator Scenario - FFAG Option

Direct Acceleration by Low Frequency RF
No Phase Rotation, No Cooling





$\Delta p/p$=+-50%@300MeV/c

A_n=0.03πm.rad

~ 0.3muons / proton
JHF 50-GeV Proton Driver

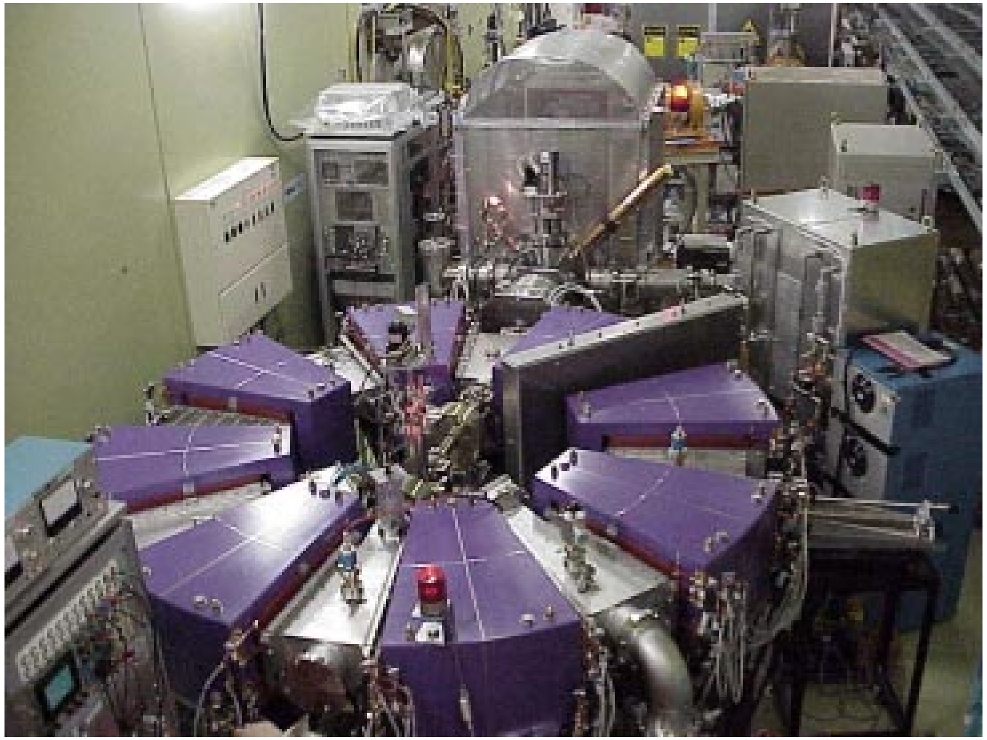
FFAG accelerators

FFAG Accelerator

idea --> 50's (Ohkawa, Symon,Kolomenski)
proton acceleration --> PoP FFAG (KEK),2000

1) fixed magnetic field
2) AG focusing
3) synchrotron osc.

* large acceptance
(trans. & long.)
* quick acceleration



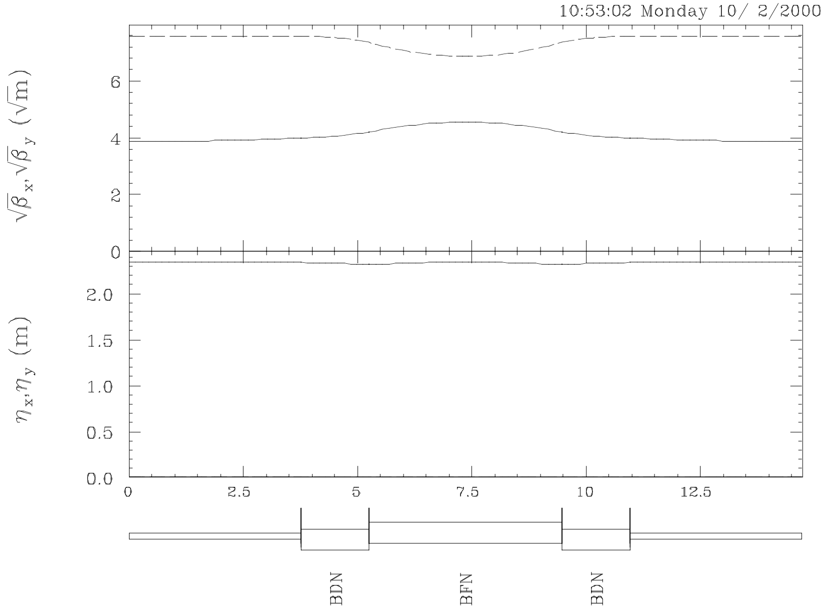
PoP FFAG synchrotron

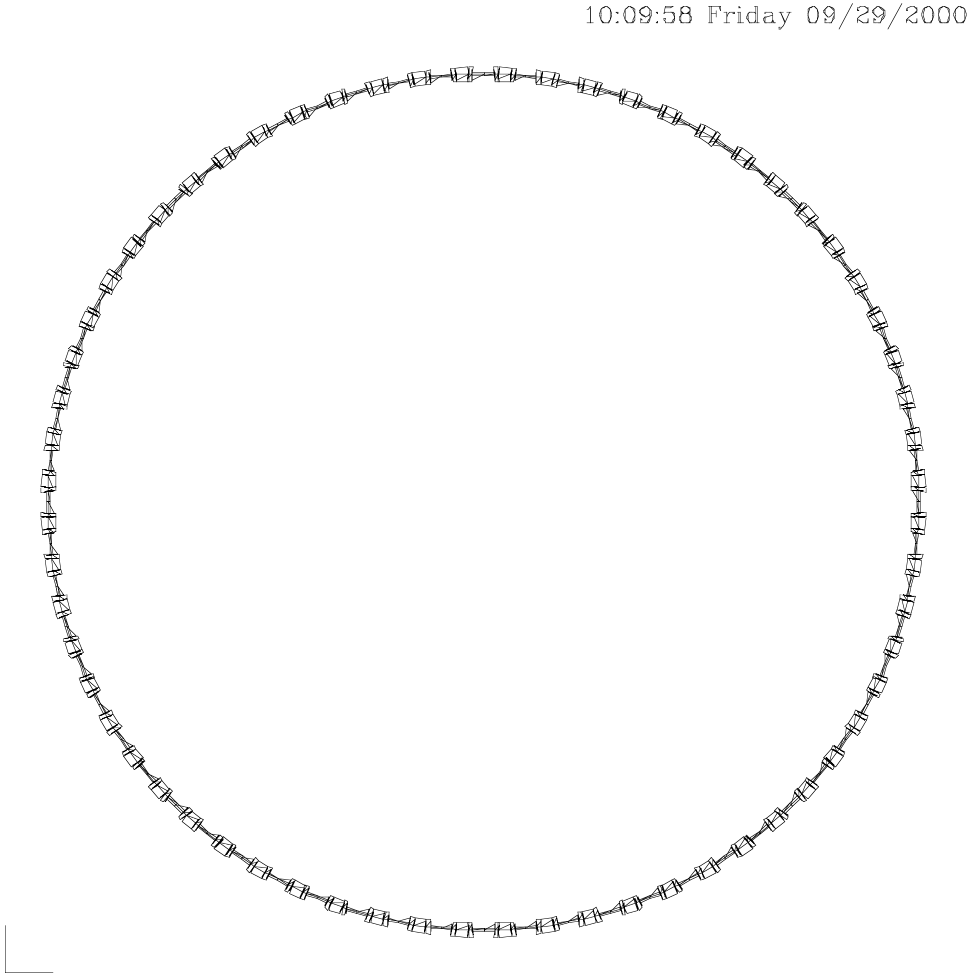
FFAG Parameters

momentum(GeV/c)	0.3~1	1~3	3~10	10~20
number of sector	16	32	64	120
k number	15	63	220	280
average radius(m)	10	30	90	200
max. B field(T)	2.8	3.6	5.4	6.0
tune	5.826	13.704	27.911	22.333
	4.590	4.048	4.089	6.333
drift length(m)	2.120	3.299	5.046	5.668
BF length(m)	1.065	1.575	2.169	2.685
BD length(m)	0.367	0.544	0.813	1.062
orbit excursion(m)	0.77	0.52	0.813	0.49
transition γ	4	8	14.9	16.8

FFAG 10 - 20 GeV

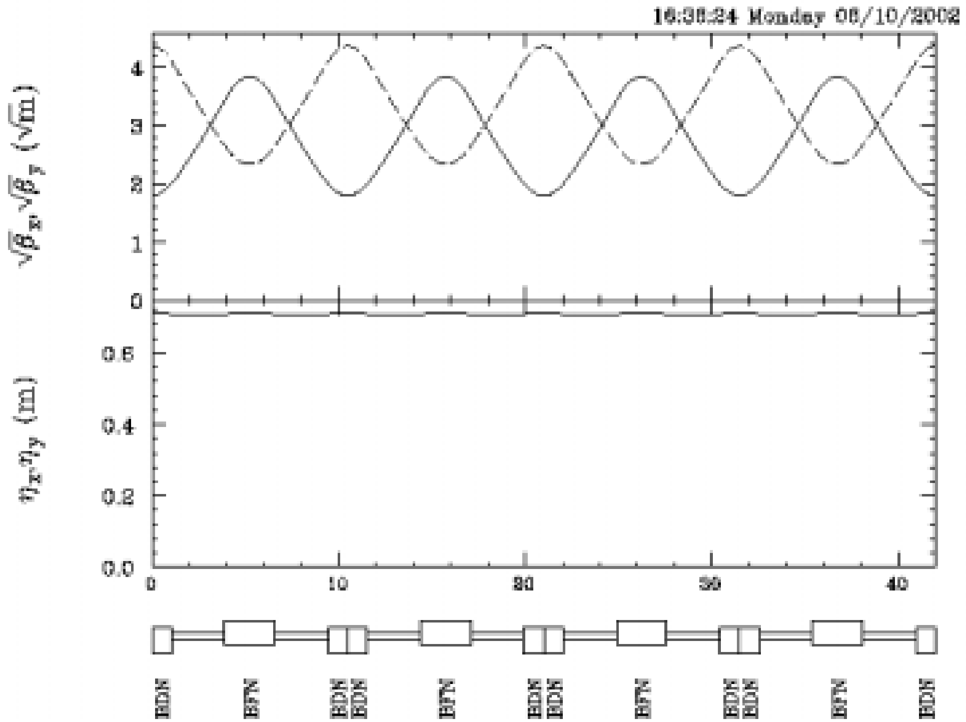
r	200m
# of sector	120
B field	6.0T





10-20GeV FFAG , singlet FODO new version

k=280, N=200



Aperture of FFAG: Is it large with large k?

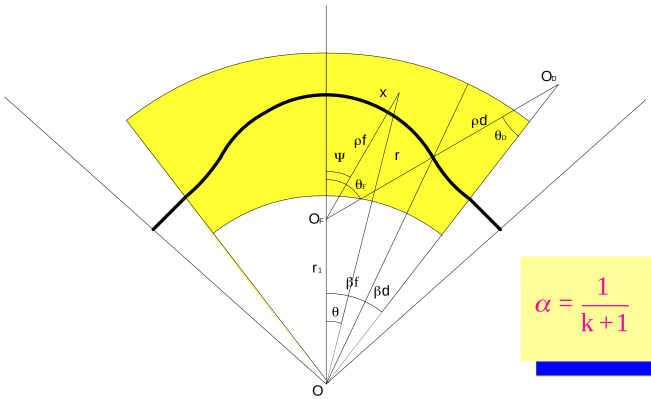
larger ring --> large k --> large non-linear field?

$$B = B_0\left(\frac{r}{r_0}\right)^k = B_0\left(1+\frac{k}{r_0}x+\frac{k(k-1)}{2!r_0^{\,2}}x^2+\cdots\right)$$

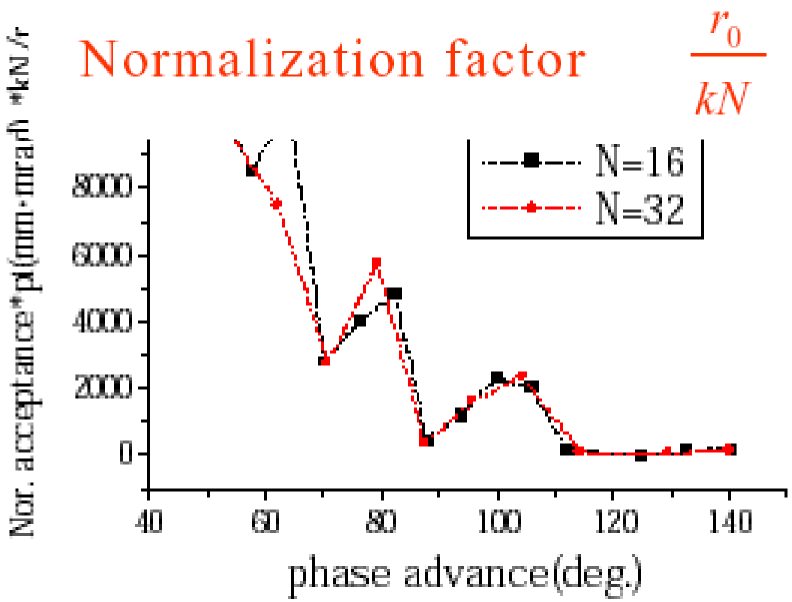
$$\cong B_0\left(1+(\frac{k}{r_0}x)+\frac{1}{2!}(\frac{k}{r_0}x)^2+\cdots\right)$$

$$W = \frac{x^2}{\beta}$$

$$\cong x^2\left(\frac{k}{r_0 N}\right) = \frac{r_0}{kN}(\frac{k}{r_0}x)^2 \quad \because$$

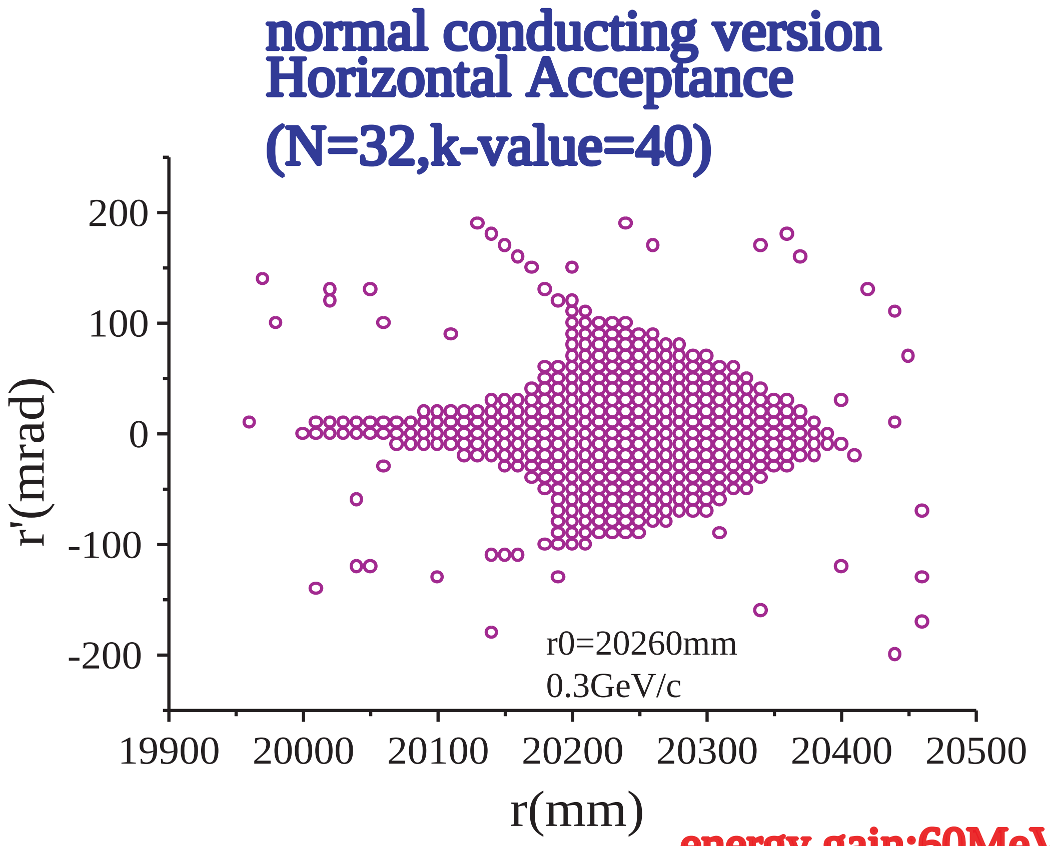


$\alpha = \frac{1}{k+1}$: momentum compaction factor



Dynamic aperture depends mostly on phase advance/cell!

Dynamic Aperture of FFAG ring (0.3-1GeV/c)



energy gain:60MeV/turn

phase advance / cell ~ 90 degrees

A_H ~ >10000π mm.mrad

Momentum Compaction & Longitudinal Motion Scaling FFAG

Magnetic field configuration: $B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k F(\theta - h \ln \frac{r}{r_0})$

Momentum compaction factor: α

$$\frac{\Delta C}{C} = \alpha \frac{\Delta p}{p}$$

Orbit length relations:

$$C(p_2) = C(p_1)\left(\frac{p_2}{p_1}\right)^{\frac{1}{1+k}}$$

$$\therefore \alpha = \frac{1}{1+k}.$$

* Higher orders such as $\alpha_1, \alpha_2, \cdots = 0$ in scaling FFAG. No higher orders in momentum compaction!

Scaling FFAG

Momentum compaction factor : $\alpha = \frac{1}{1+k}$ & No higher orders.

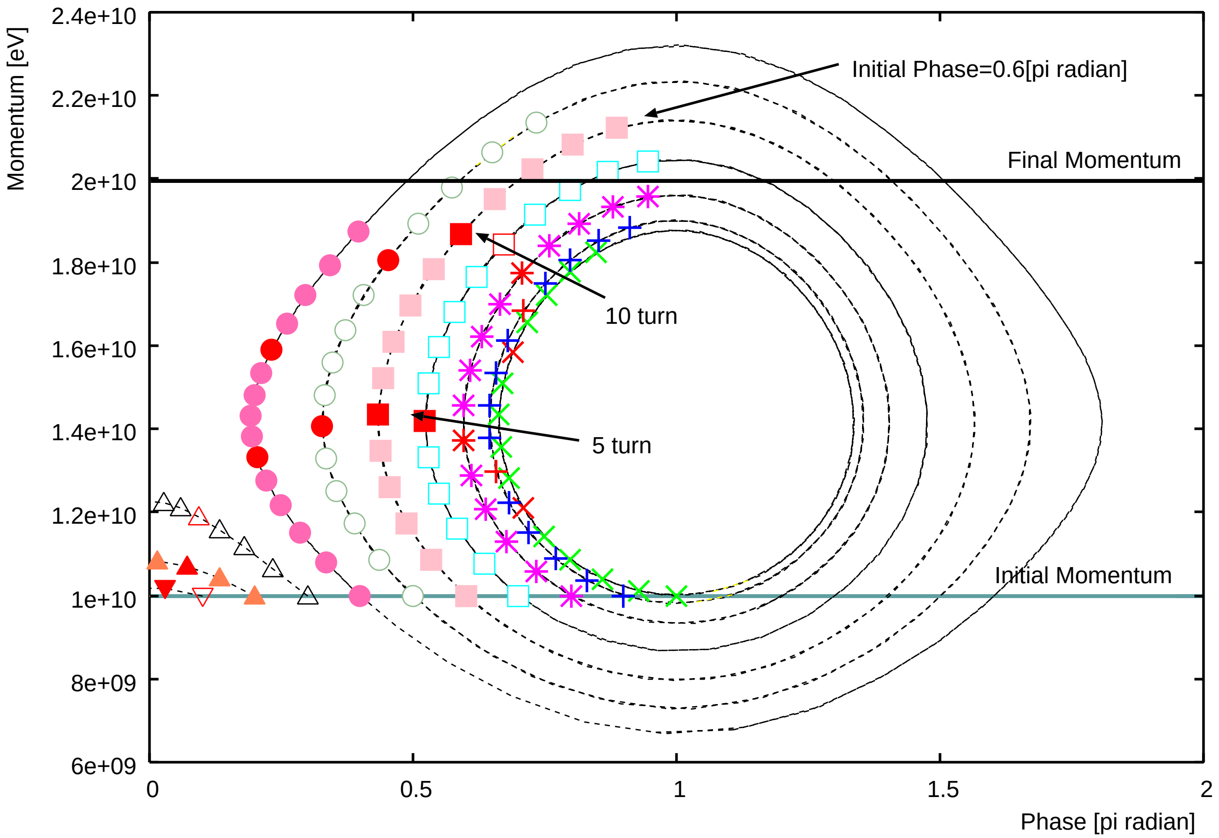
----> No bucket distortion even at large momentum spread.

cf.

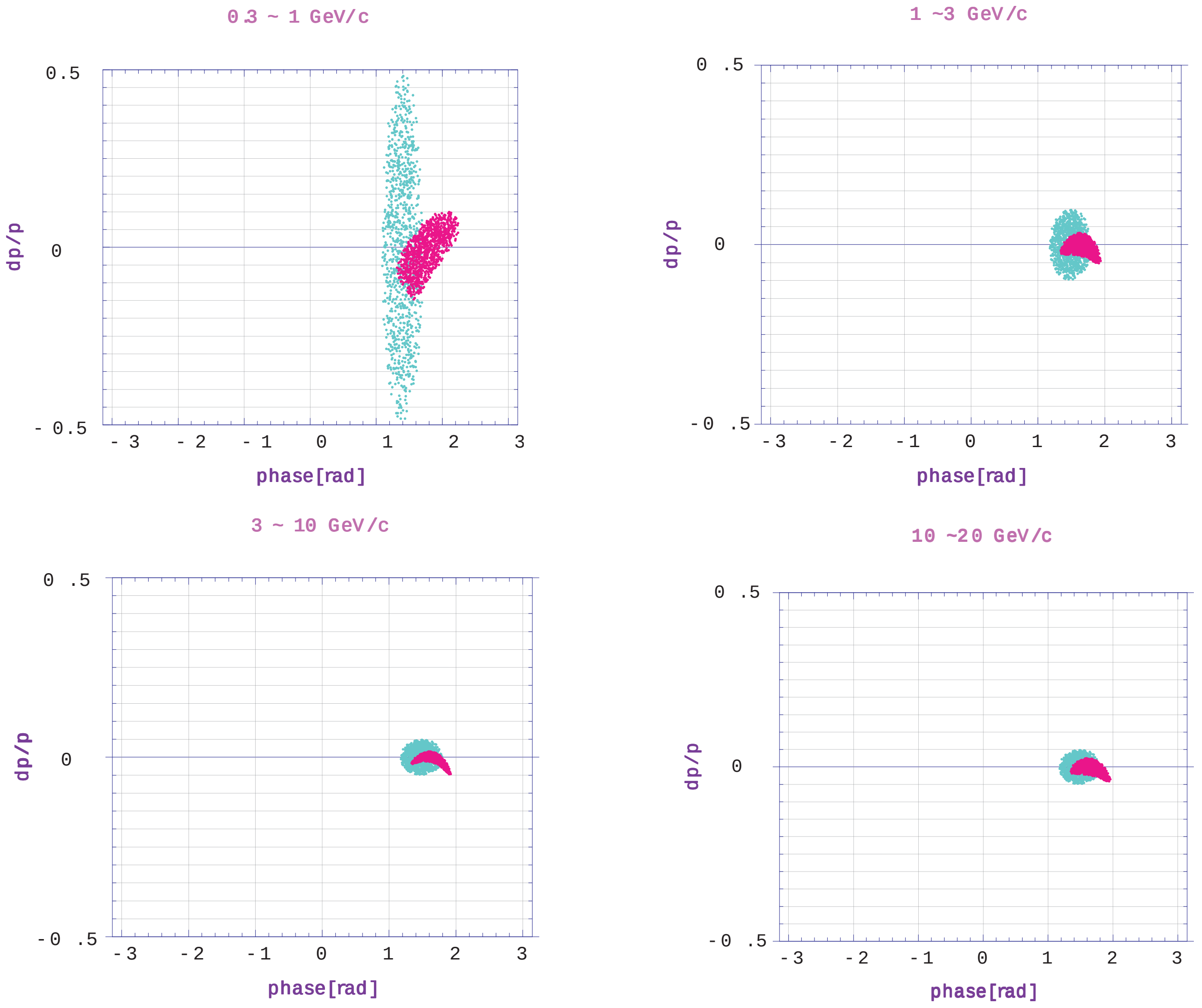
FFAG Muon Accelerator

10-20GeV

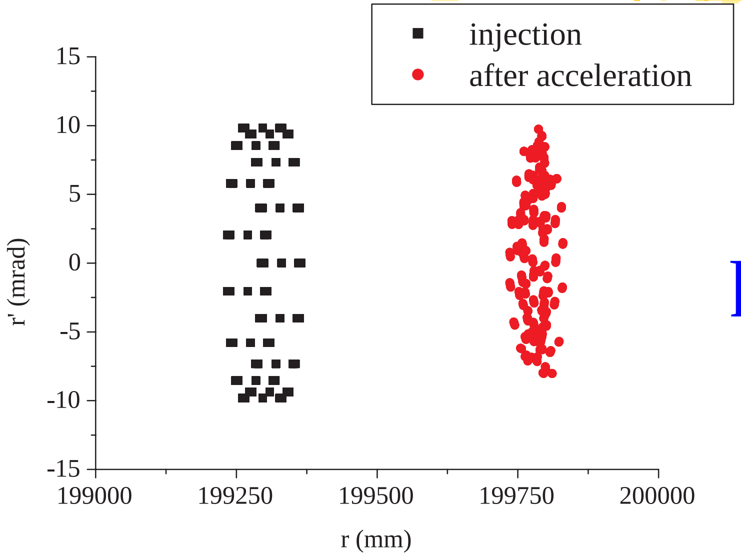
eV'=0.7MeV/m



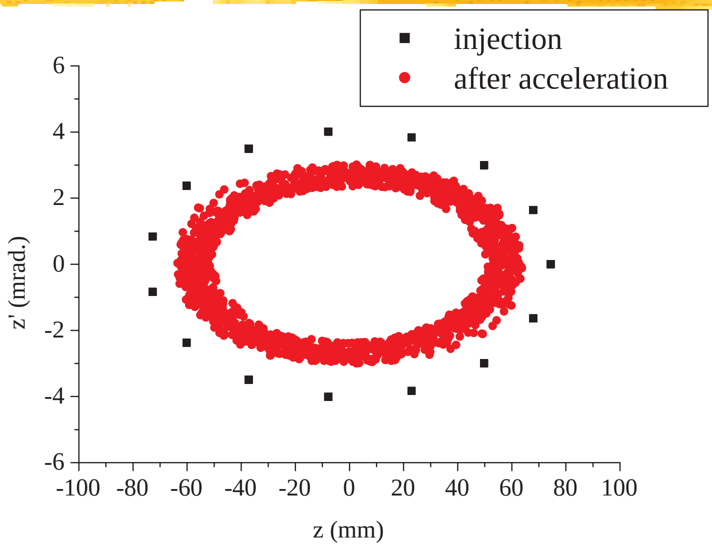
Longitudinal motions in the FFAG rings



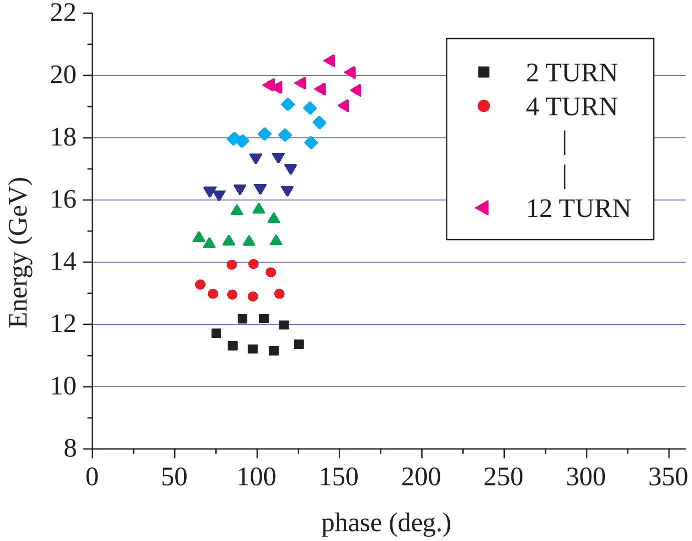
Beam tracking -3D 10-20 GeV ring



hor.



ver.



ε^{T}_{N}=0.03πm.rad, ε^{L}_{N}=5eV.sec

magnet: multi-pole model

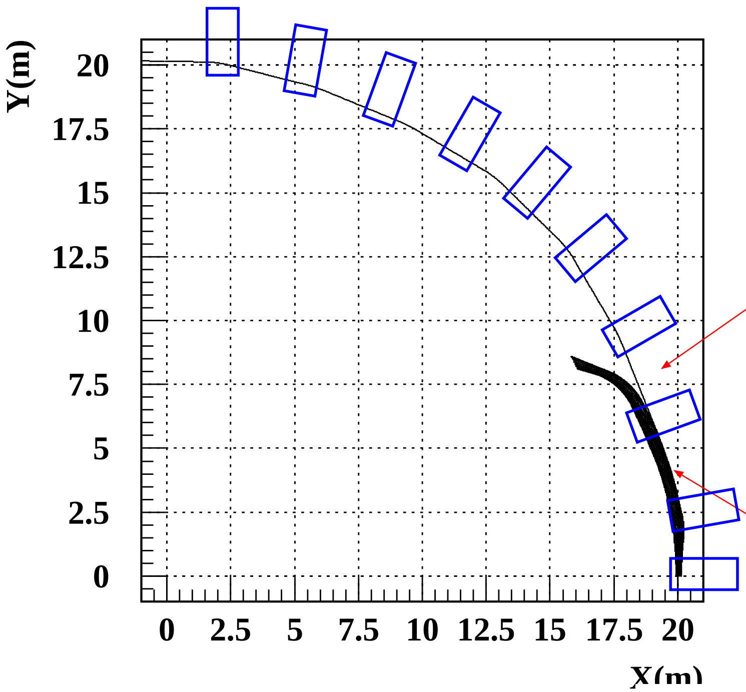
rf freq.=7MHz, eV'=0.7MeV/m

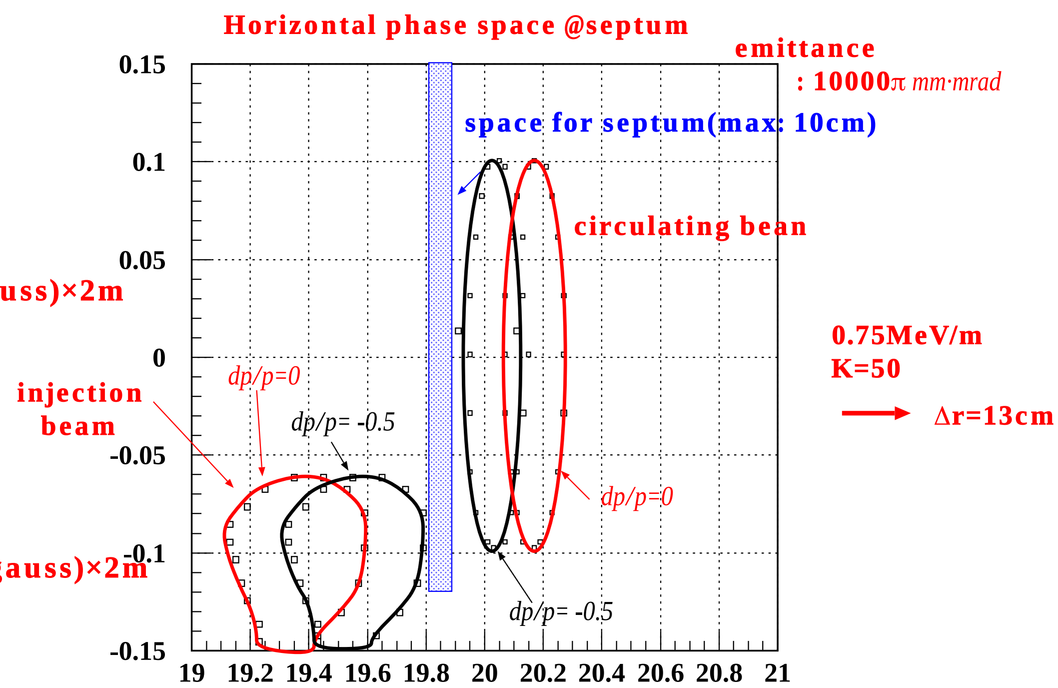
long.

Beam Injection

cf. 1GeV ring : ε_n=0.03πm.rad, dp/p=+-50%

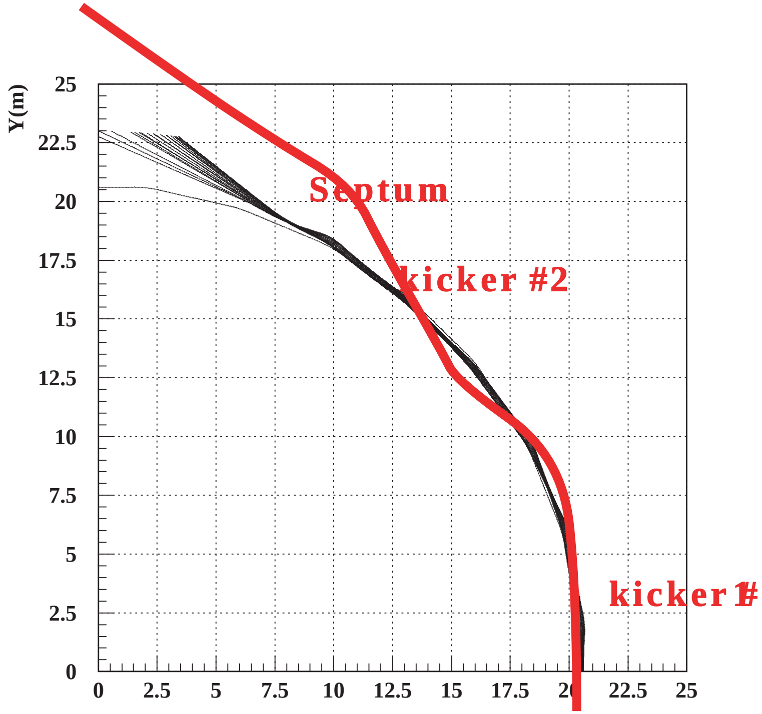
kicker magnet : 1.5kG, septum magnet : 1.5T

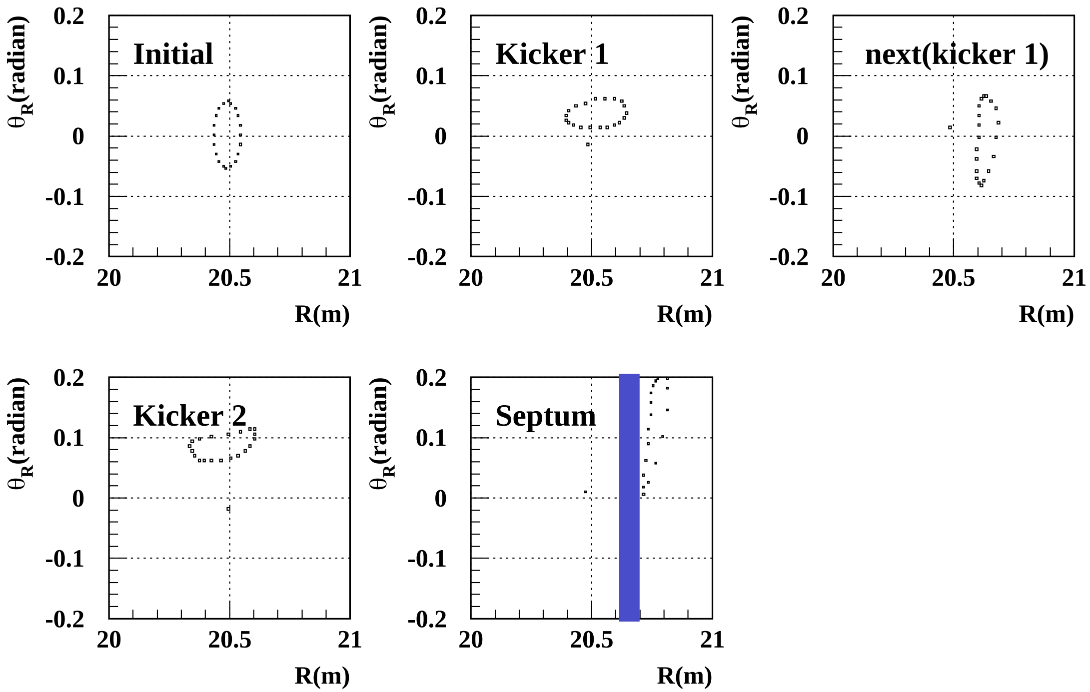




Beam Extraction-1

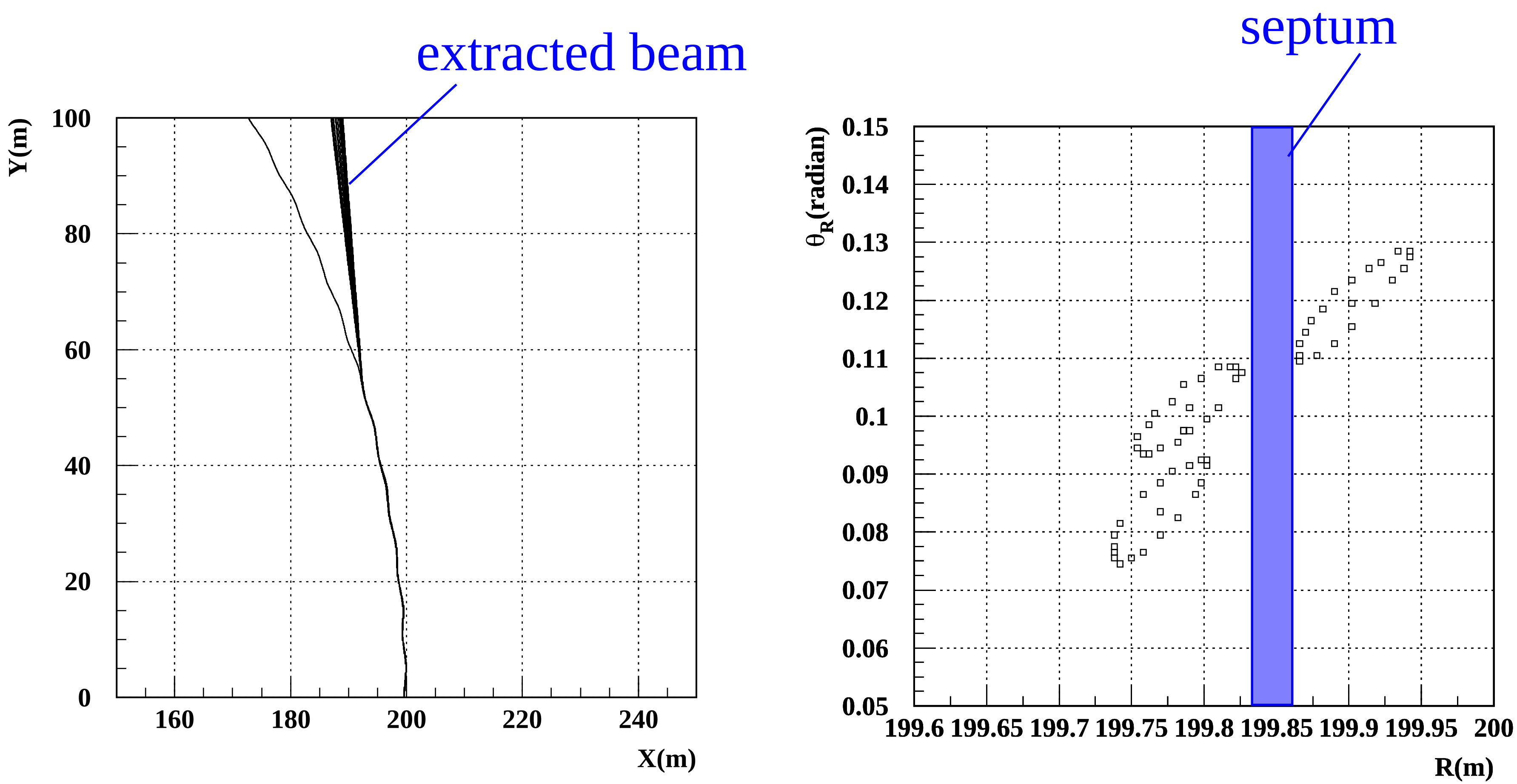
cf. 1 GeV ring





Beam Extraction-2

cf. 10-20GeV ring



Cooling in FFAG

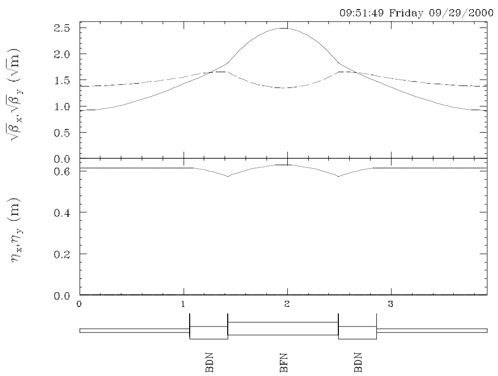
Cooling in FFAG

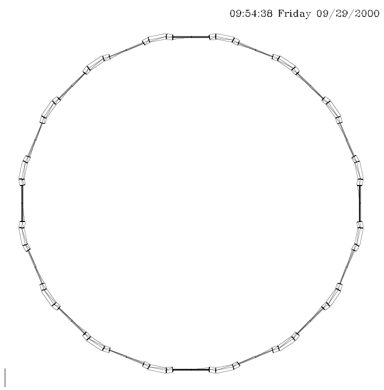
FFAG based Neutrino Factory does not need Muon Cooling. But, some cooling may help the cost reduction.

"Ring Cooling" in the FFAG first(0.3-1GeV/c) ring

H. Schonauer(CERN)

* 10atm H_2 gas or Liq . hydrogen target in the ring
* only for transverse cooling





cf. E=0.3~1GeV/c

eV' =1MeV/m

β~1.5m

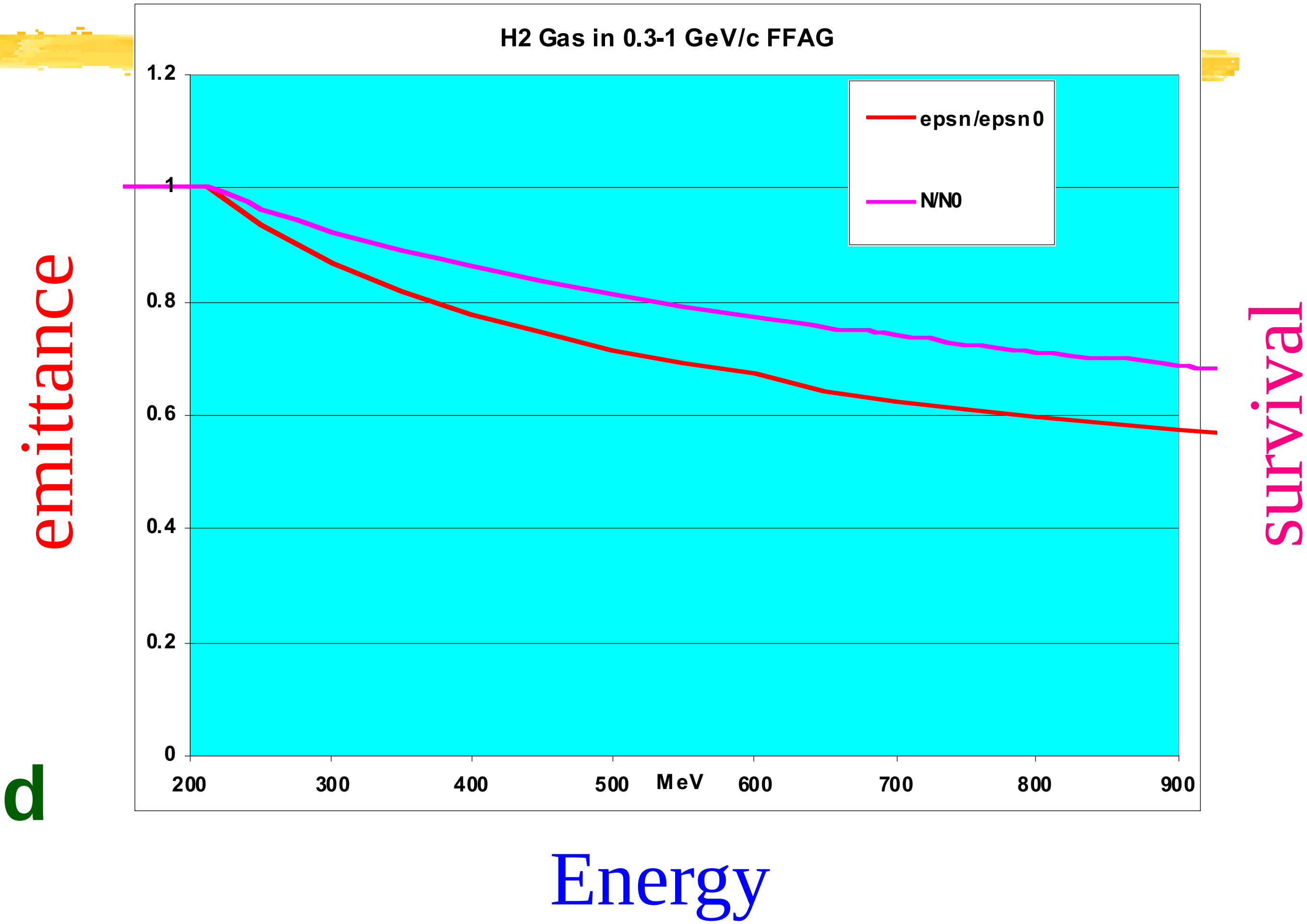
Muon Cooling in FFAG ring(0.3-1GeV/c)

cf. E=0.3~1GeV/c

eV' =1MeV/m

f_{rf}=5MHz

β~1.5m



Emittnace cooled

~ 50%

Large enough for maget cost reduction!

Hardware R&D

150-MeV proton FFAG accelerator

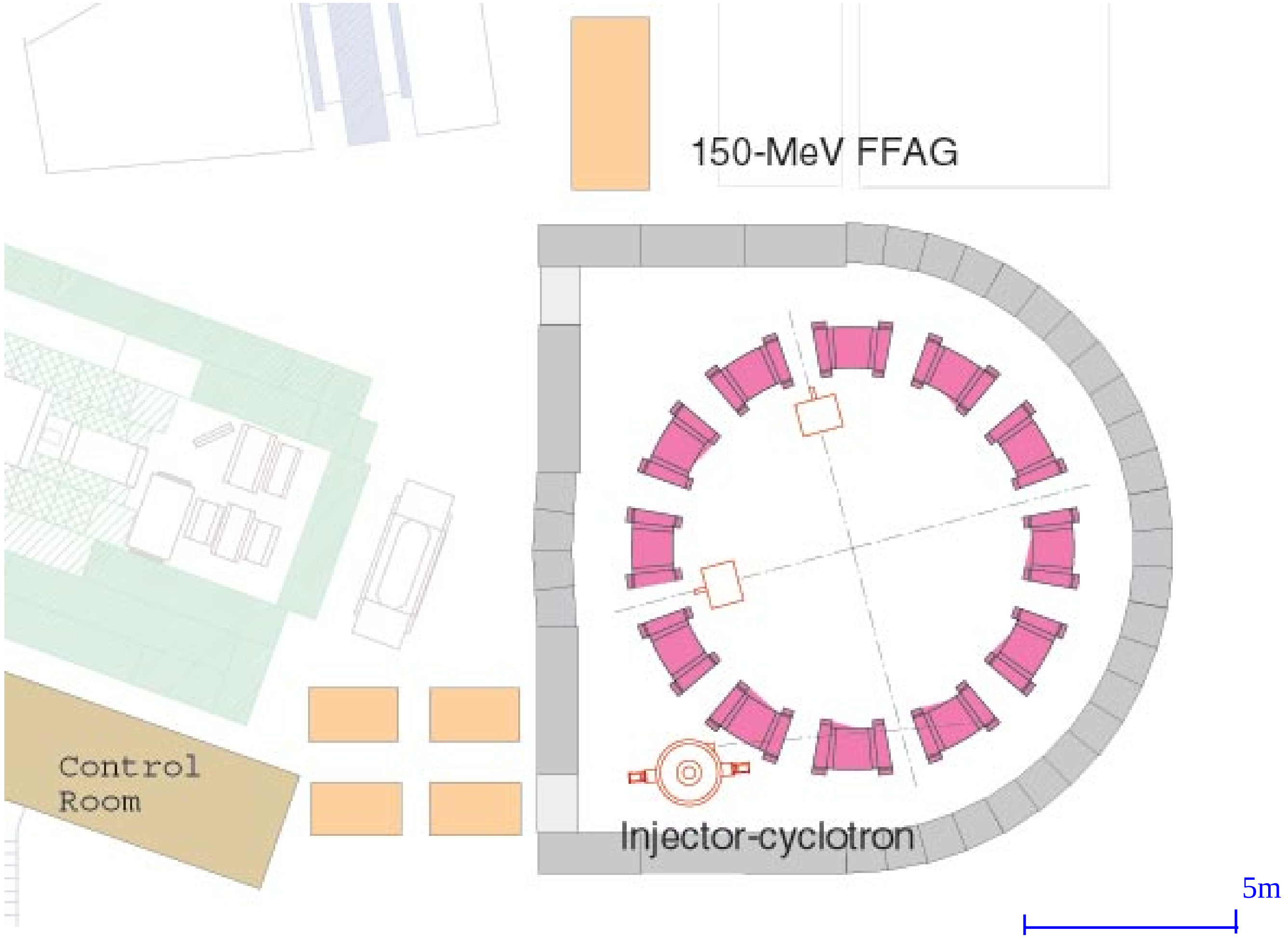
Prototype for various applications:

Madical application : Cancer therapy
Muon phase rotation : PRISM project

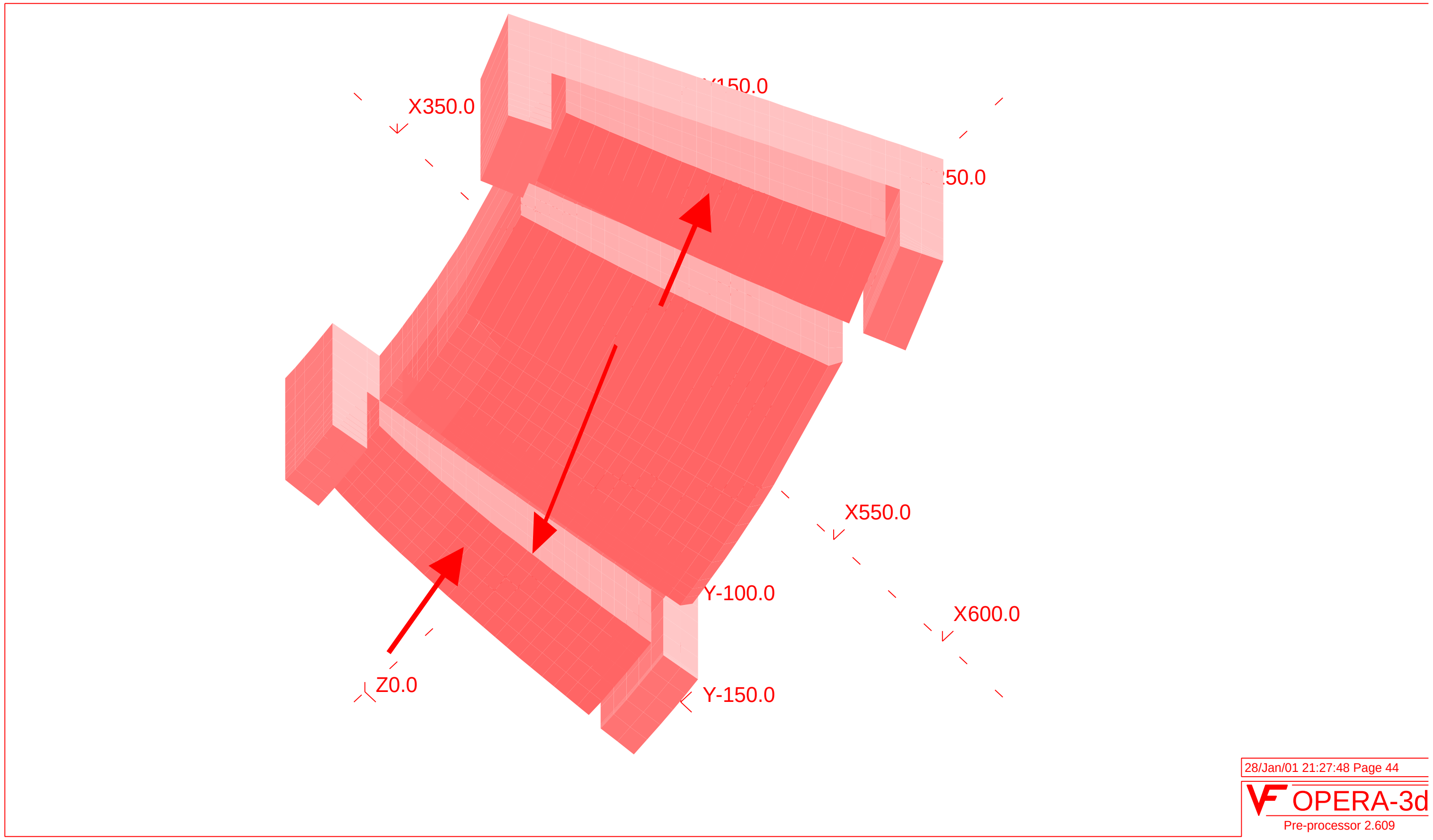
150MeV FFAG main parameters

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

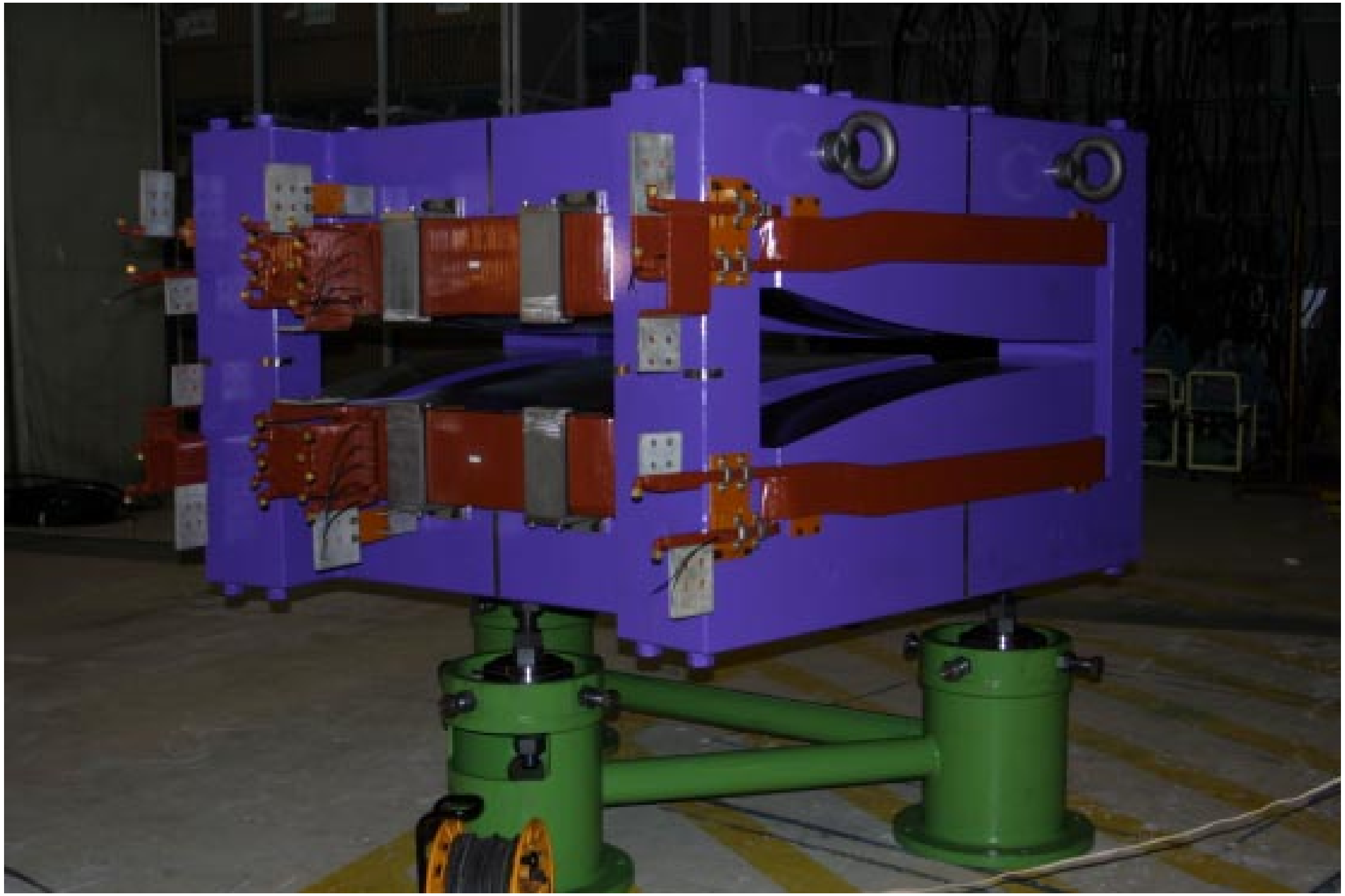
150-MeV proton FFAG accelerator



Yoke-free magnet of triplet sector FFAG



Magnet of 150-MeV proton FFAG

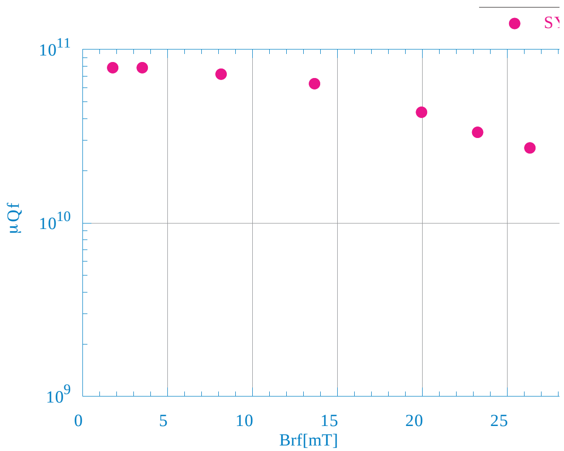


Hardware R&D

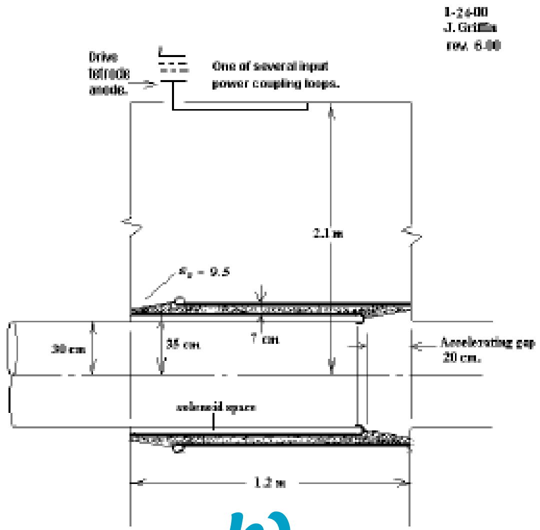
1) Low freq. & high gradient RF system :1MV/m, 5-10MHz

- a)SY20 ferrite cavity
- b)Ceramic gap cavity
- c)Air gap cavity

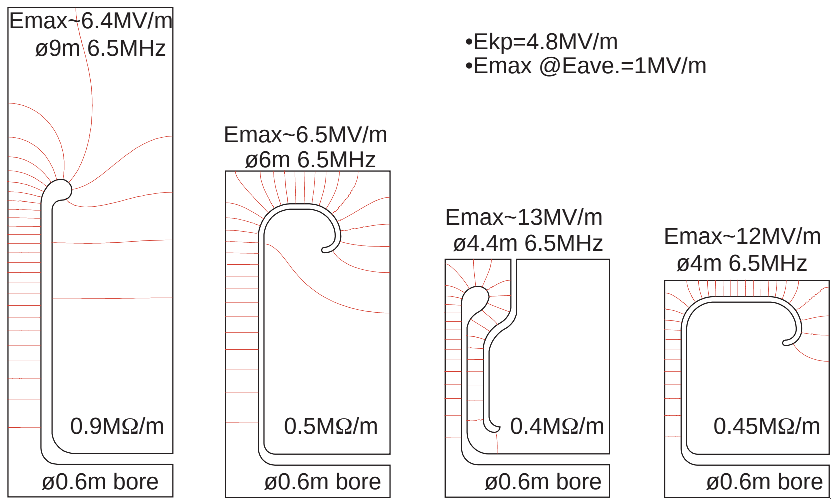
US-Japan collaboration



a)



b)



c)

rf power : total peak power ~750MW (air gap cavity)

ave. rf power ~1MW

Hardware R&D

rf amplifier & power supply:

100kW anode dissipation tetrode

--> ~1MW in burst mode operation

anode power supply depends on ave. rf power.

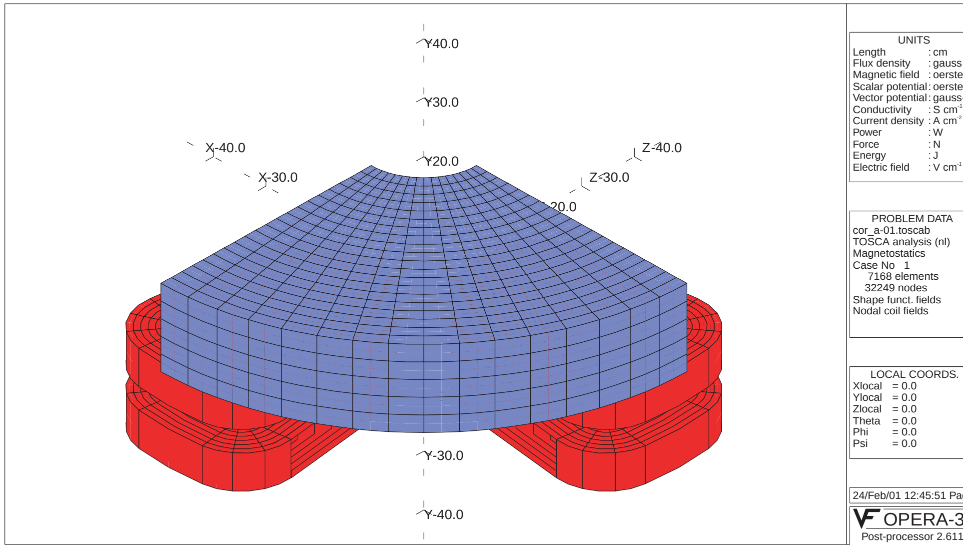
in total:

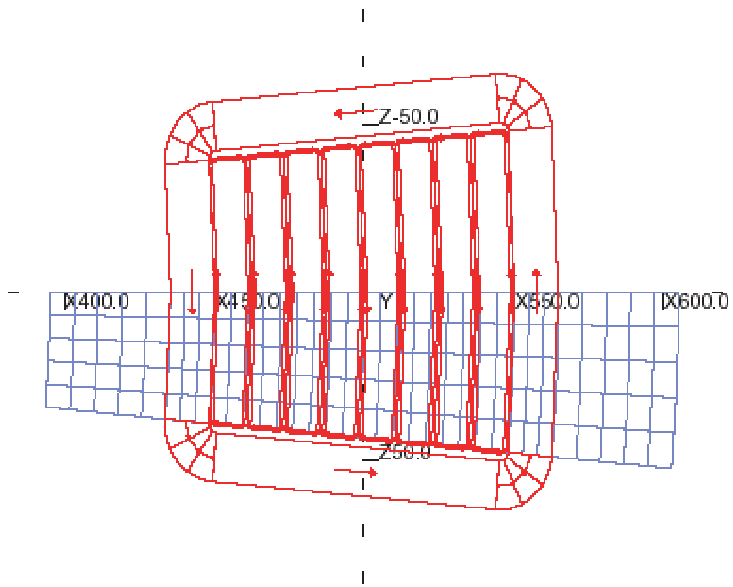
750 x 100kw anode diss. tetrode

1MW anode power supply

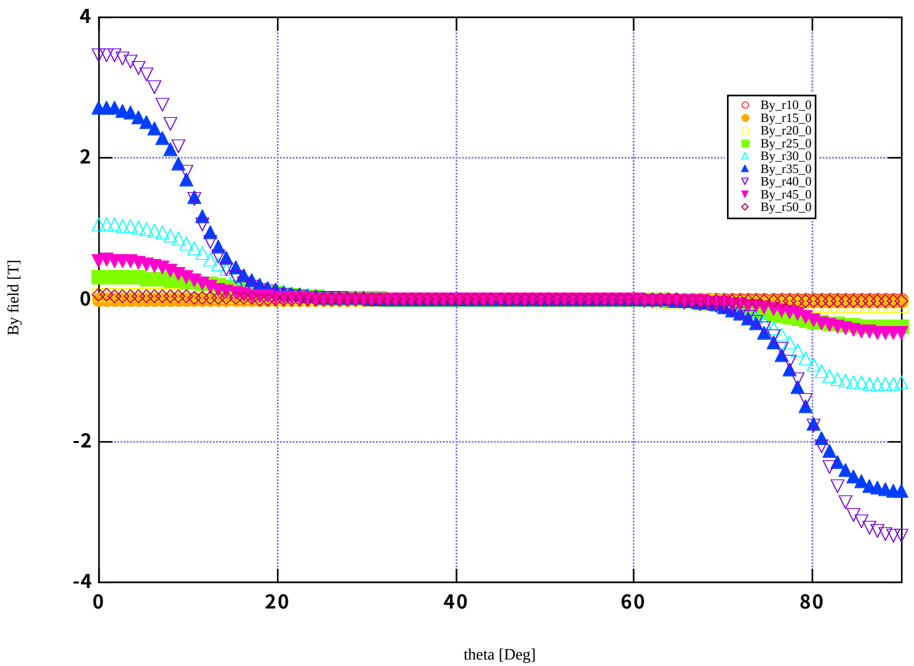
Hardware R&D

Superconducting Magnet for FFAG

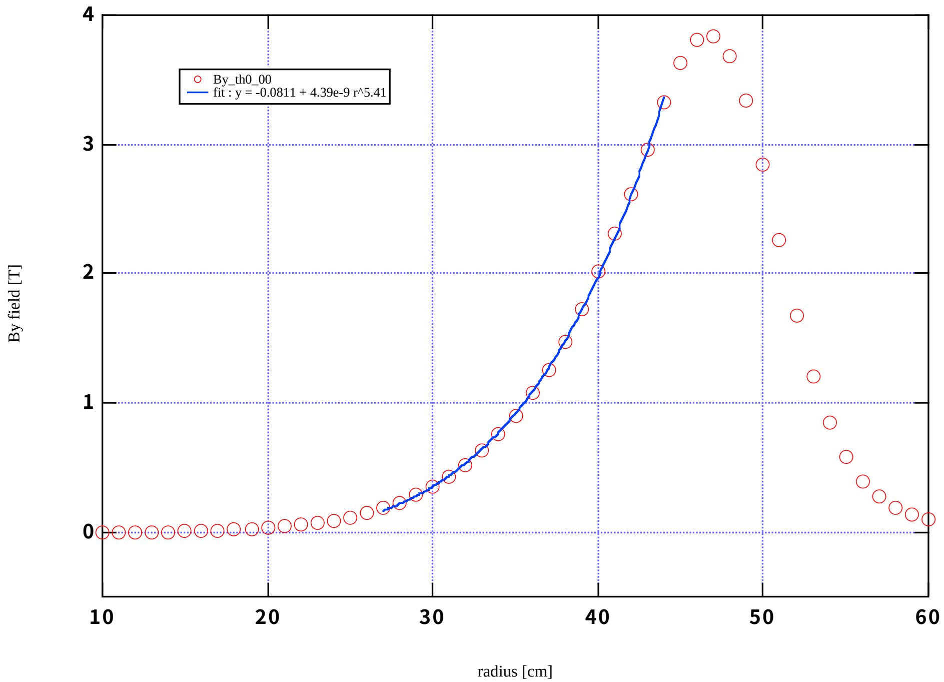




Magnetic field configuration of SC magnet



θ *direction*



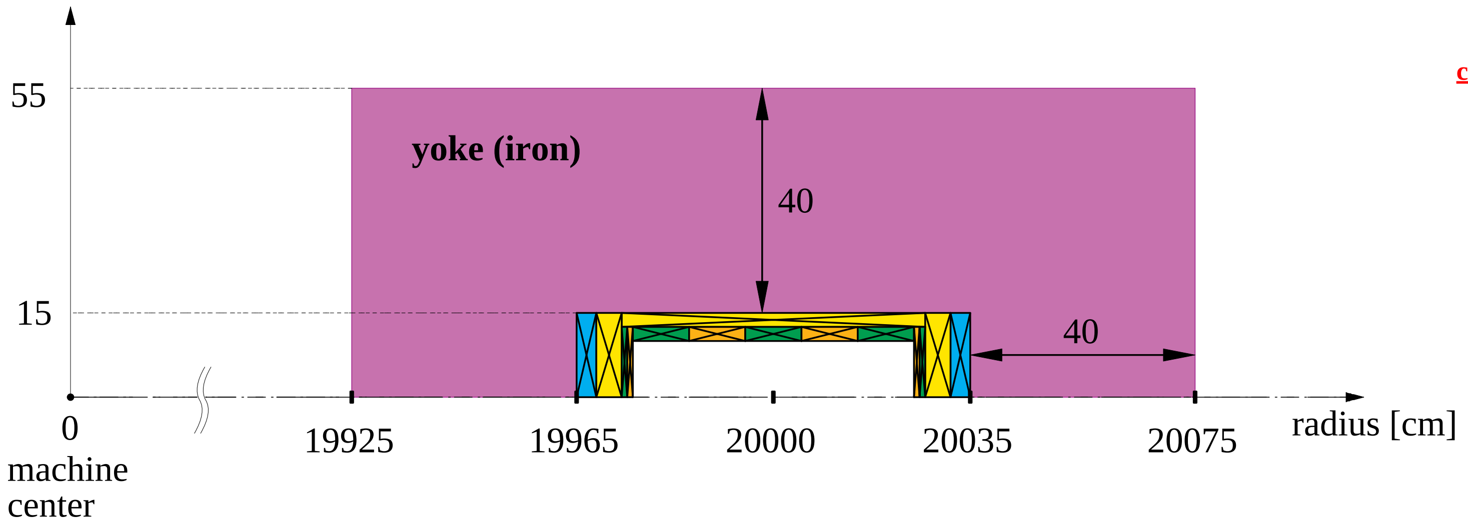
radial direction

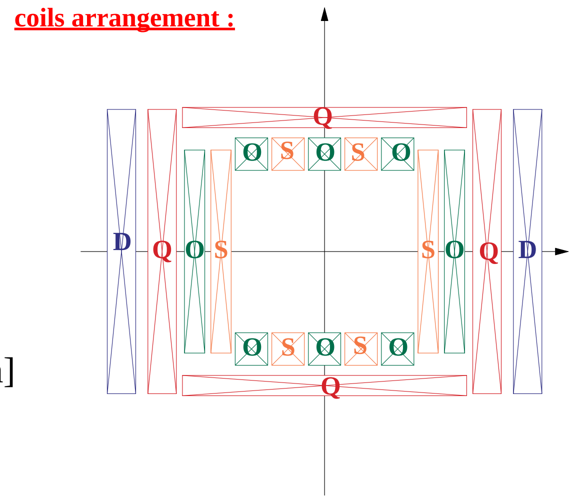
FFAG-Magnet design   B=6T for 10-20GeV ring

Magnetic field for FFAG:

$$B = B_0\left(\frac{r}{r_0}\right)^k \Rightarrow B = B_0 + \frac{kB_0}{r_0}x + \frac{k(k-1)B_0}{2!\,r_0^{\,2}}x^2 + \frac{k(k-1)(k-2)B_0}{3!\,r_0^{\,3}}x^3 + \ldots$$

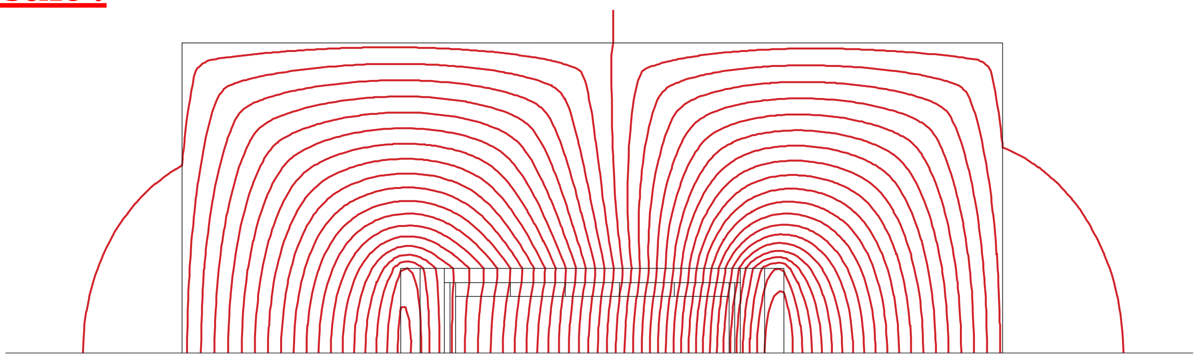
Dipole   Quadrupole   Sextupole   Octupole

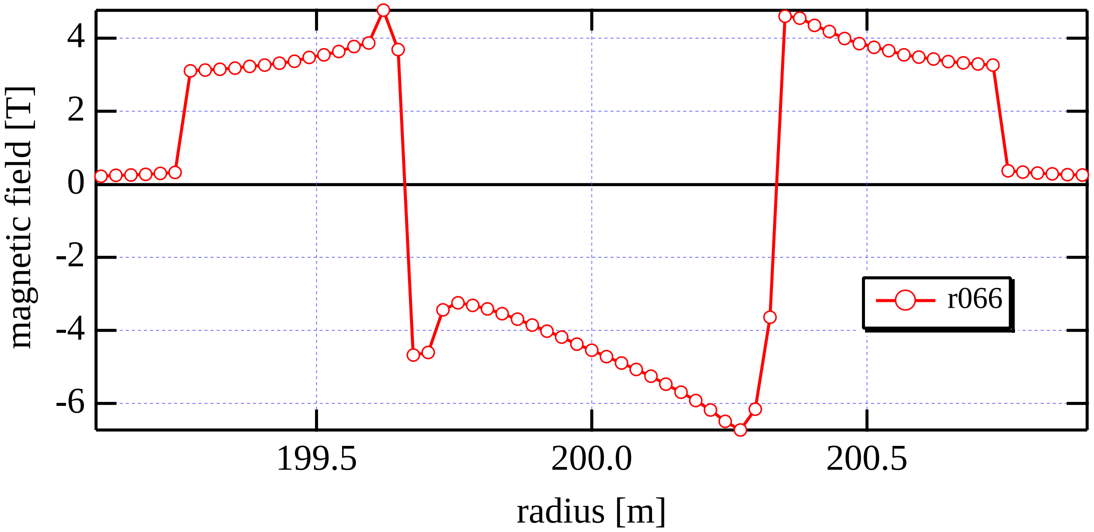




2D Magnetic Field Calculation (1)

result :





Design target :

r0	200 [mm]
B0	4.5 [T]
k	280

Filed components :

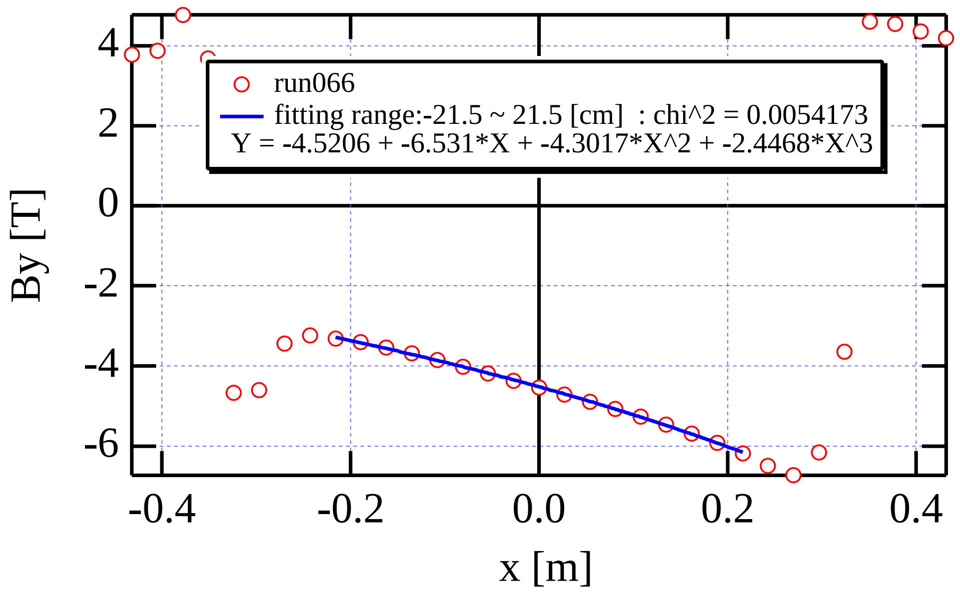
$B_{Di.}$	4.5 [T]
$B_{Quad.}$	6.3 [T/m]
$B_{Sext.}$	4.39 [T/m^2]
$B_{Oct.}$	2.04 [T/m^3]

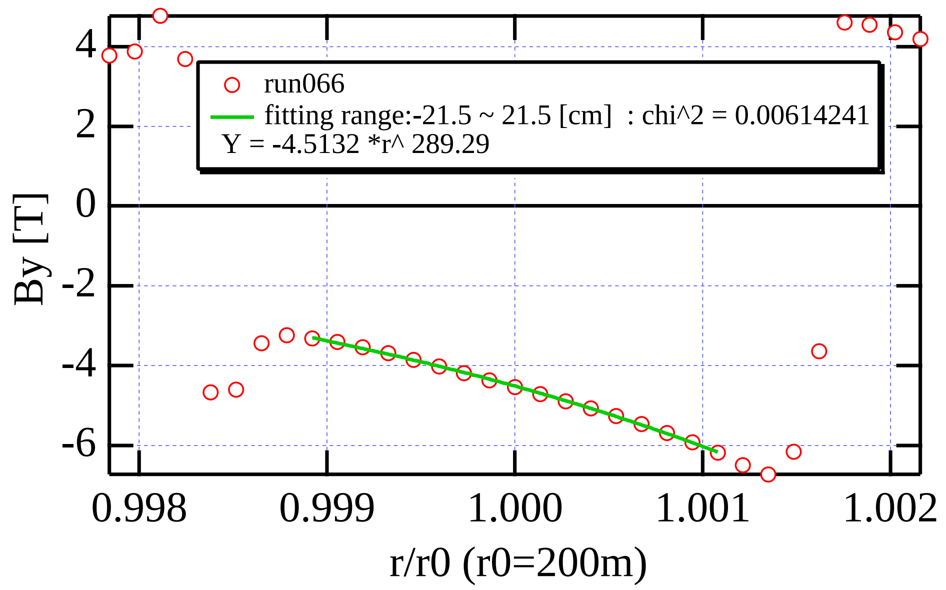
Calculated coil currents

$I_{Di.}$	1517192.242 [ATurn]	(144.494 [A/mm^2])
$I_{Quad.}$	508461.834 [ATurn]	(37.664 [A/mm^2])
$I_{Sext.}$	-16557.738 [ATurn]	(-6.623 [A/mm^2])
$I_{Oct.}$	4978.177[ATurn]	(1.991 [A/mm^2])

2D Magnetic Field Calculation (2)

Analysis :





polynomial fitting

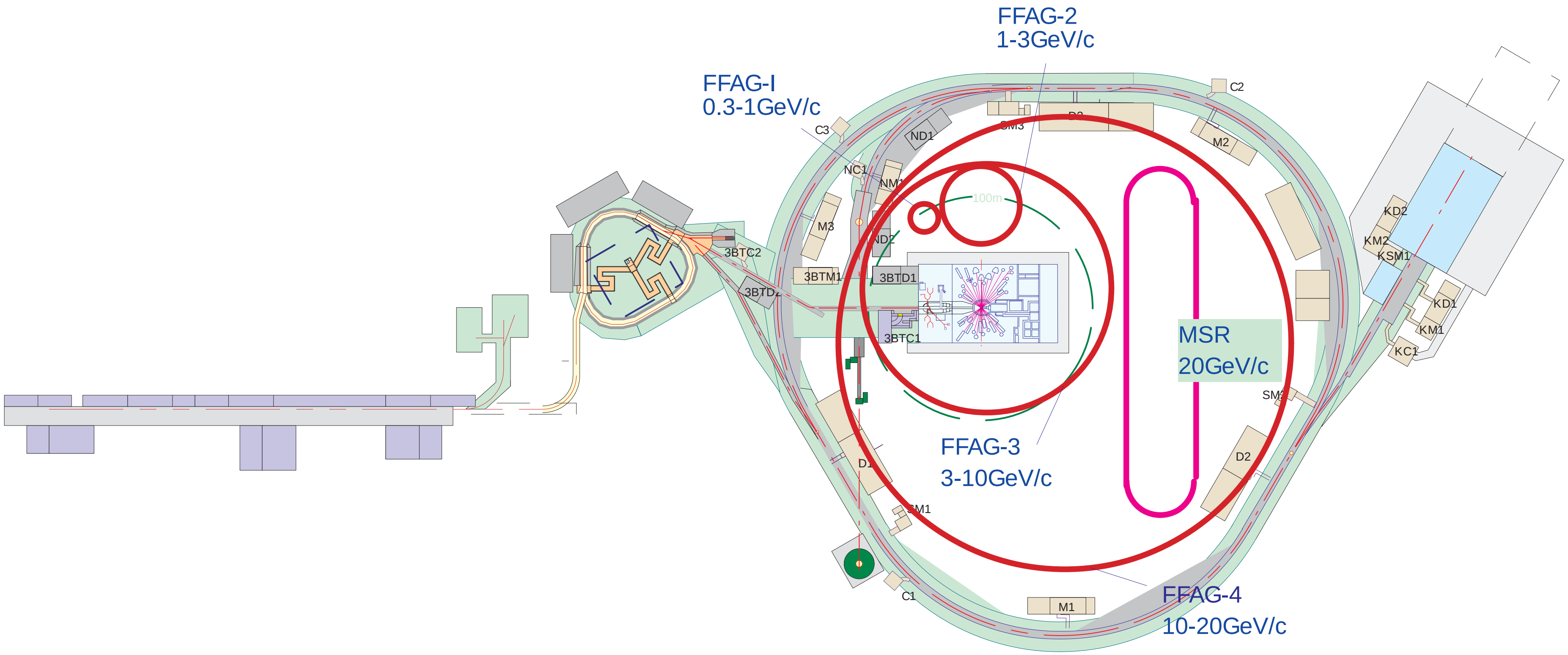
$B_{Di.}$	-4.52 [T]
$B_{Quad.}$	-6.53 [T/m]
$B_{Sext.}$	-4.30 [T/m^2]
~~$B_{Oct.}$~~	~~-2.45 [T/m^3]~~

r^k fitting

B0	-4.51 [T]
k	289.3

Neutrino Factory in Japan - FFAG Scenario

FFAG based neutrino factory



Parameters

FFAG

no phase rotation,no cooling

proton driver	50GeV(1-4MW)
Accelerator	
FFAG-0(PRISM)	0.3-1GeV
FFAG-1	1-3 GeV
FFAG-2	3-10 GeV
FFAG-3	10-20 GeV
storage ring	C~800m

Intensity

phase 1	$3x10^{20}$ muon/y(1MW)
phase 2	$1.2x10^{21}$ muon/y(4MW)

Linac

USA:study1

proton driver	50GeV(1-4MW)
phase rotation	80MeV/c
cooling	100m
acceleration	
linac	2GeV
FFAG	2-11GeV
RCL	11-20(50)GeV
storage ring	C~1000m

Intensity

phase 1	10^{20} muon/y (1MW)
phase 2	$4x10^{20}$ muon/y (4MW)

(*USA Study2 ~5 times)

Summary

FFAG based neutrino factory : feasible

R&D

1)optimization
- FFAG lattice (inj. ext.)
- hybrid rf (low & high freq.)

2)beam simulation (trans. & long.)

3)hardware: rf cavity, sc-magnet etc.