Neutrino Factory in Japan: based on FFAG

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Introduction

What is "Neutrino Factory"?

High-intensity & high-energy neutrino source based on muon storage ring

neutrino energy: few GeV - several 10 GeV

muon decay in storage ring : $\mu^+ \rightarrow \overline{\nu}_\mu, \nu_e \quad \mu^- \rightarrow \nu_\mu, \overline{\nu}_e$

Physics

Oscillation : MNS matrix(U_{MNS})

1) θ_{13}

2)sign of Δm^2_{32}

3) CP violation in neutrino sector

Neutrino yield ---> $10^{20} \sim 10^{21}$ νs/year/straight sec.

Why Neutrino Factory in Japan?

1 Neutrino Physics in Japan

Super-KAIMIOKANDE(atomospheric neutrino)

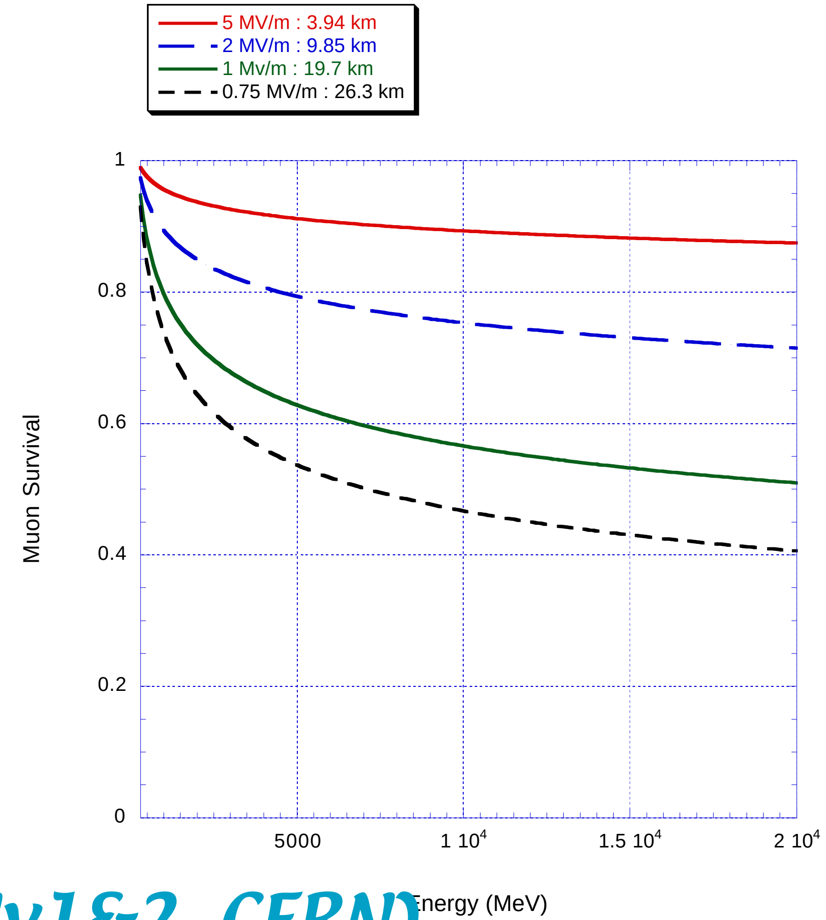
Long Base-line (KEK 12-GeV PS to KAMIOKA) K2K

2 High Intensity Proton Accelerator Project

Proton Driver beam power > 1 MW

50-GeV PS Joint Project KEK/JAERI

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 ($e_{H,V}$ & 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?

How large acceptqance is needed?

Muon & pion yield with fixed trans. acceptance

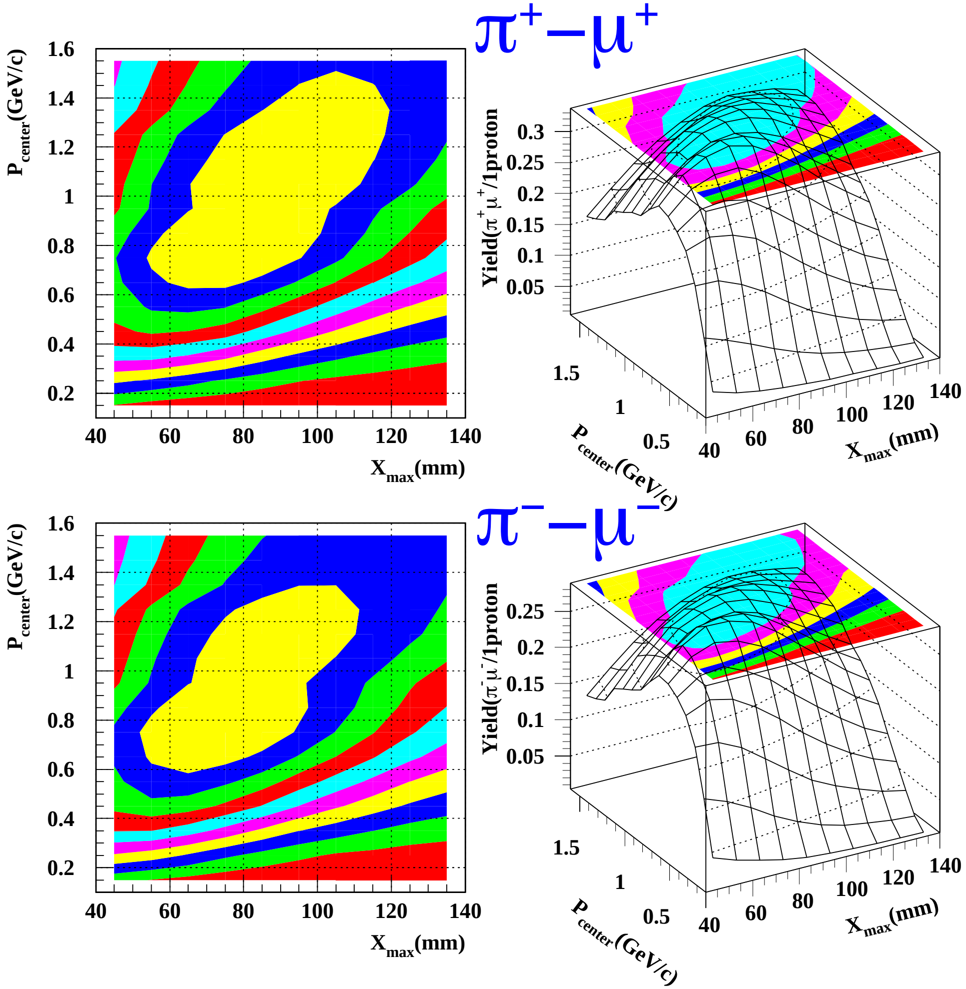
assumed acceptance:

$\varepsilon_n(100\%)=0.03\pi m.rad$

dp/p = +- 50%

proton driver :

JHF 50GeV MR (0.75MW)



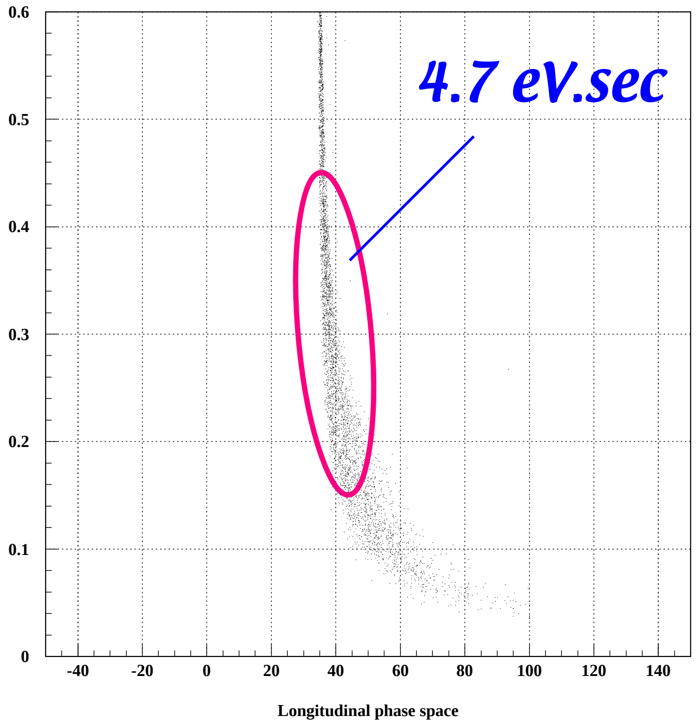
peak yield

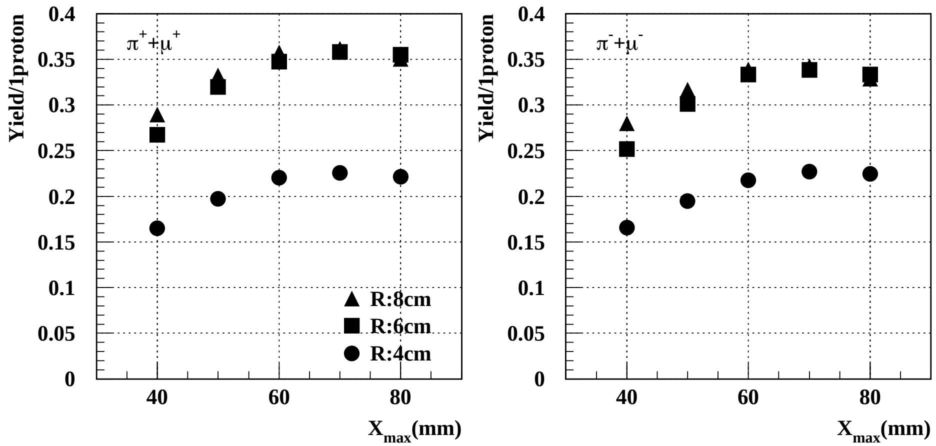
0.3 muons/proton

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

Accelerator Scenario - FFAG Option

FFAG(Fixed-Field Alternating Gradient) Accelerator

(1) Large momentum acceptance

$\Delta p/p$ ~ +- 50% or more

(2) Large aperture

A_n ~ 0.03 πm.rad @ 300MeV/c

(3) Scaling type

$p/p_0 \sim (r/r_0)^{k+1}$: tunes=const., $\xi=0$,

$\alpha=1/(k+1)$=const. :no higher orders MCF

Low freq. rf : phase slip --> negligible

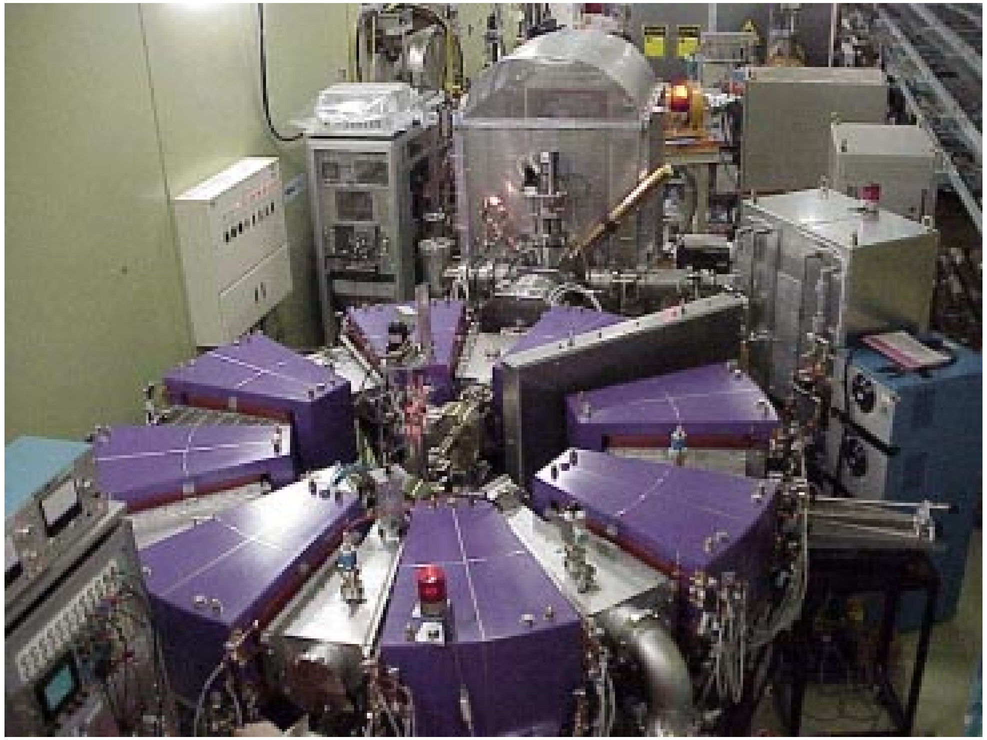
(*Non-scaling type)

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

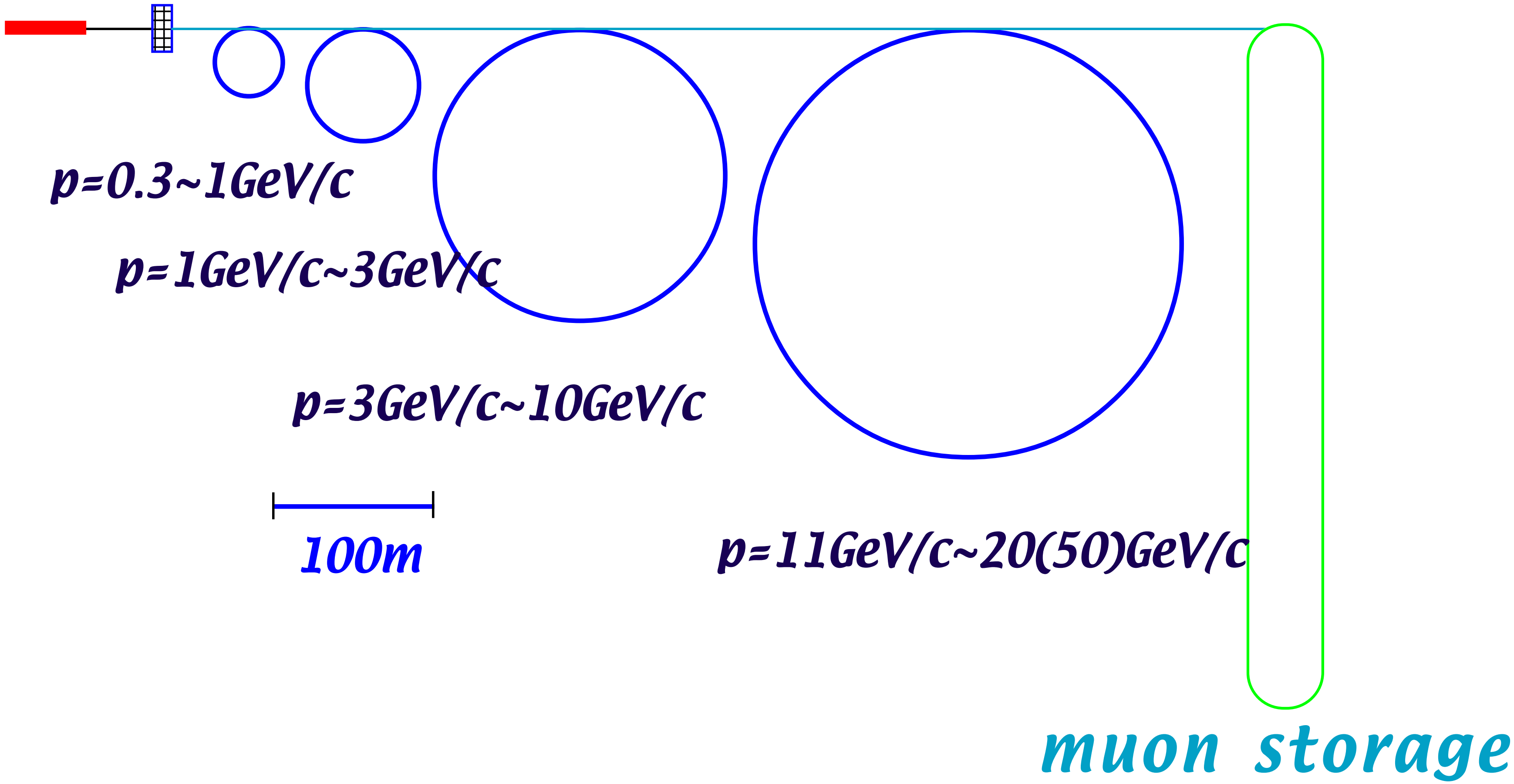


PoP FFAG synchrotron

Accelerator Scenario - FFAG Option

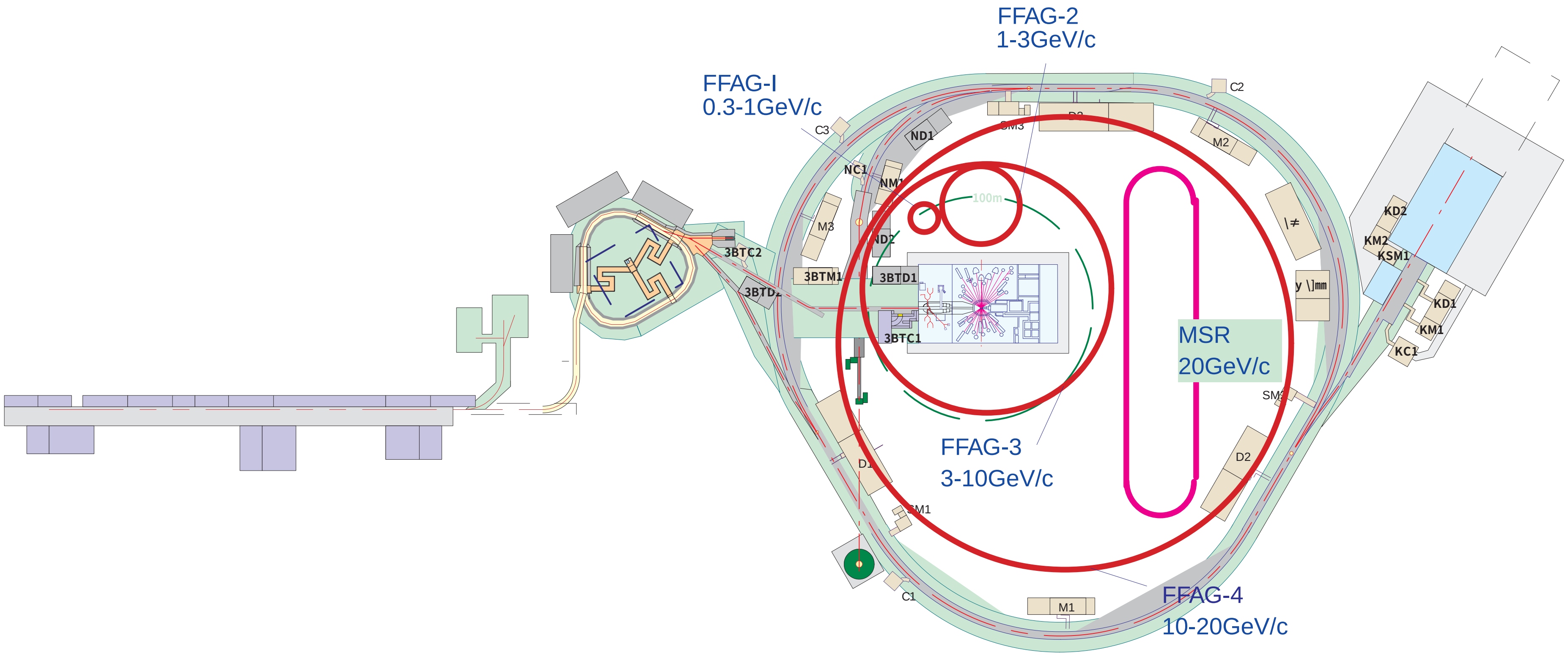
(1)Low Freq.(~MHz) & High Gradient RF E> 1MV/m

(2)Acceptance : Trans.:0.01-0.02πm.rad, Long.ΔP/P~+-50% @p=0.3GeV/c



Neutrino Factory in Japan - FFAG Scenario

FFAG based neutrino factory

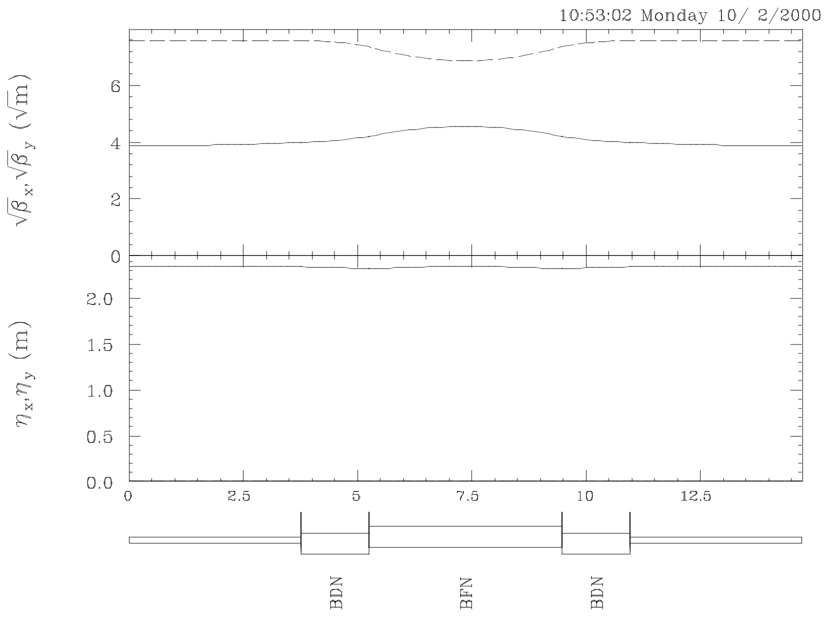


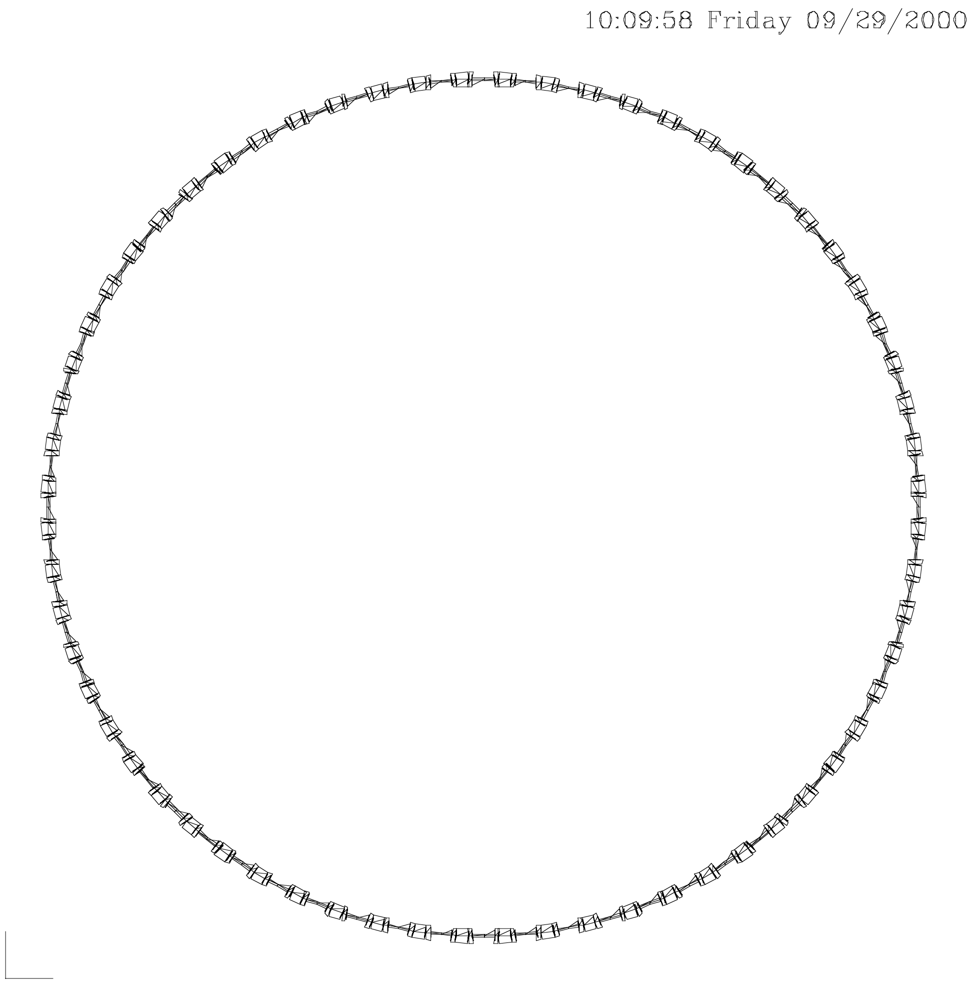
FFAG Parameters

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





Aperture of FFAG: Is it large with large k?

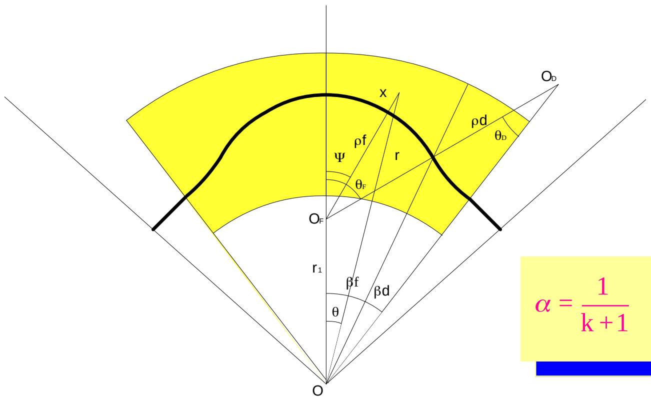
larger ring --> large k --> large non-linear field?

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

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

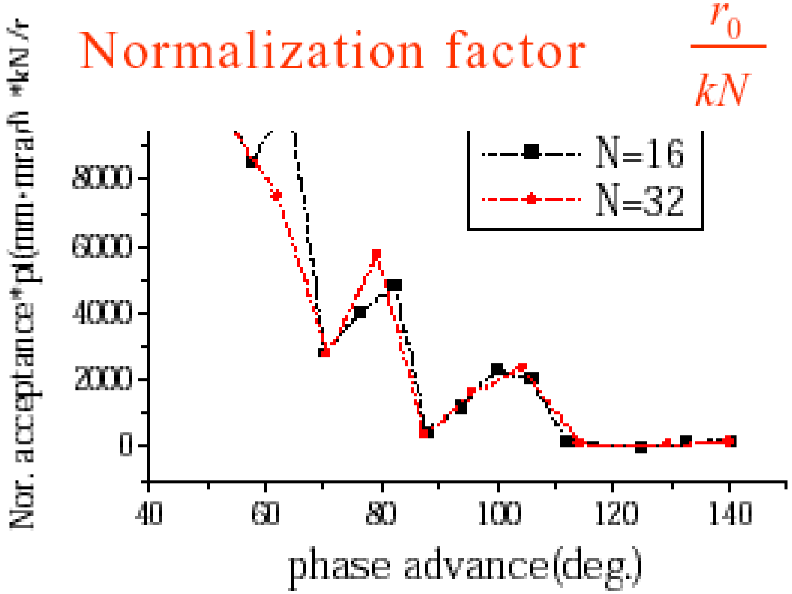
$$W = \frac{x^2}{\beta}$$

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



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

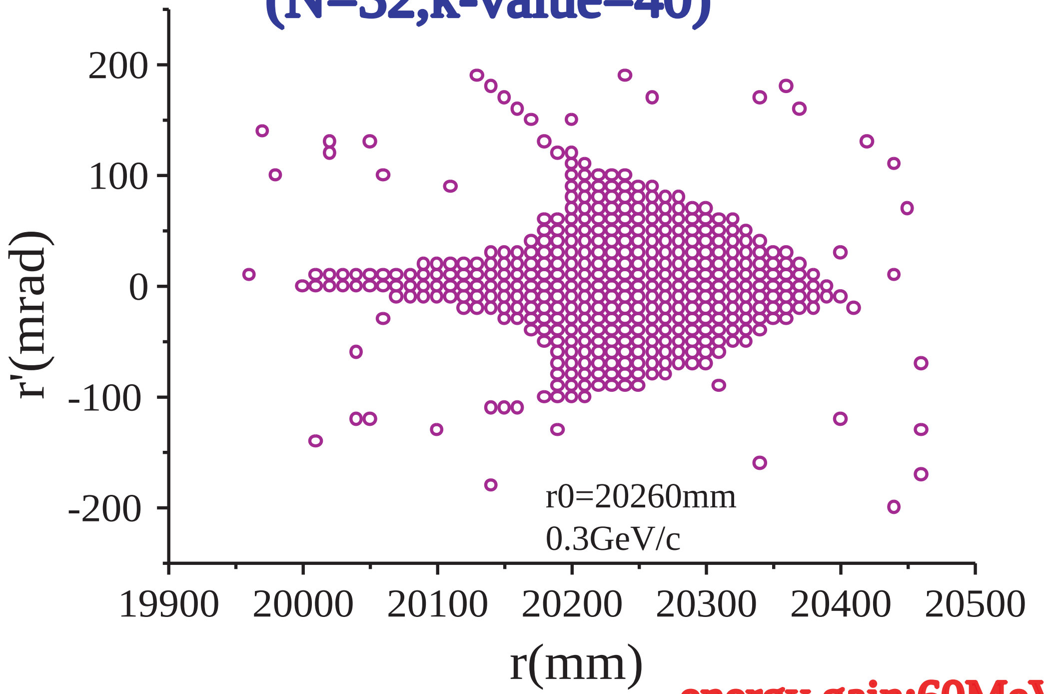
Normalization factor $\frac{r_0}{kN}$



Dynamic aperture depends mostly on phase advance/cell!

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

normal conducting version
Horizontal Acceptance
(N=32,k-value=40)



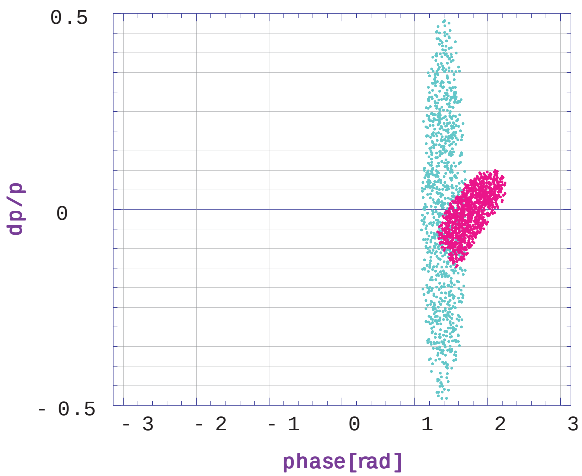
energy gain:60MeV/turn

phase advance / cell ~ 90 degrees

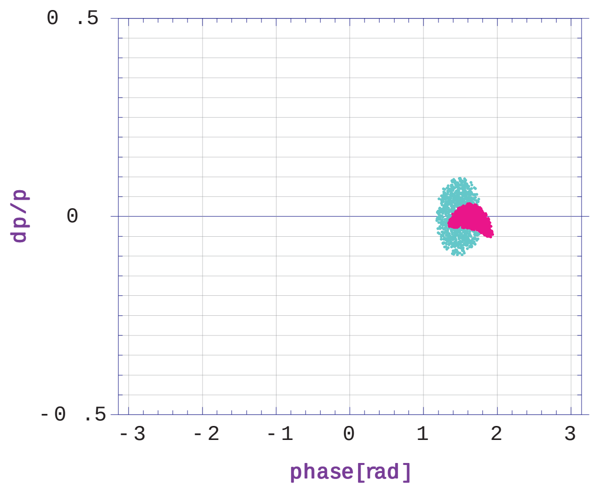
A_H ~ >10000π mm.mrad

Longitudinal motions in the FFAG rings

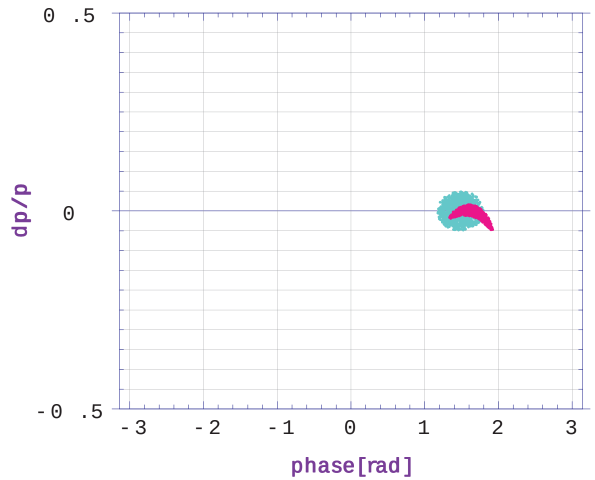
0.3 ~ 1 GeV/c



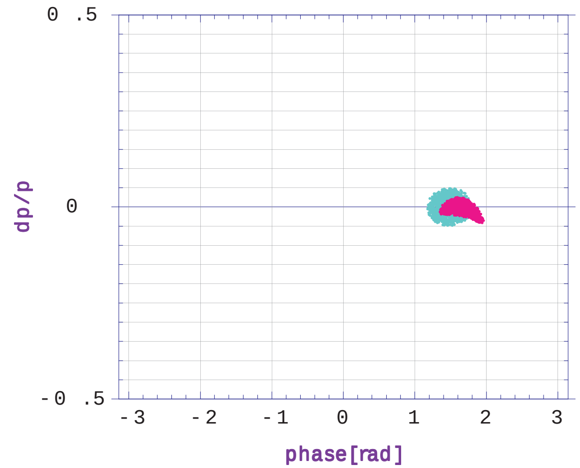
1 ~3 GeV/c



3 ~ 10 GeV/c



10 ~20 GeV/c



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)

Hardware R&D

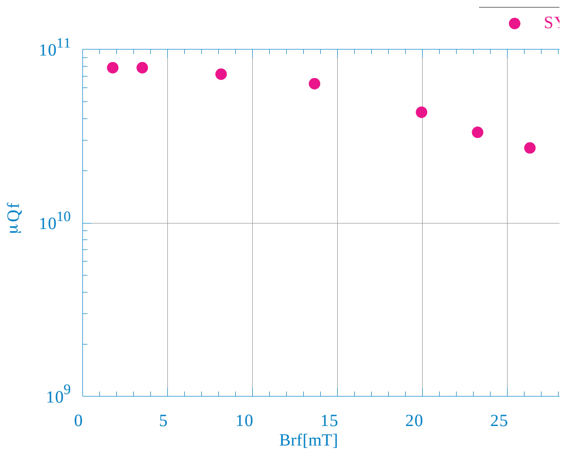
1) Low freq. & high gradient RF system :1MV/m, 5-10MHz

a)SY20 ferrite cavity

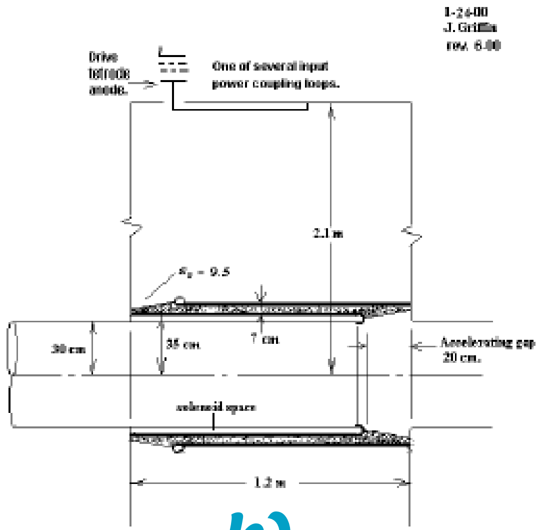
b)Ceramic gap cavity

c)Air gap cavity

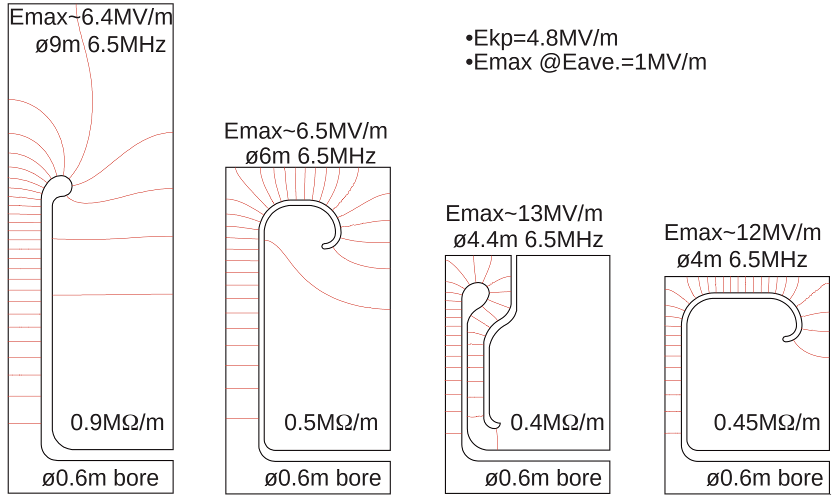
US-Japan collaboration (a, b)



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.

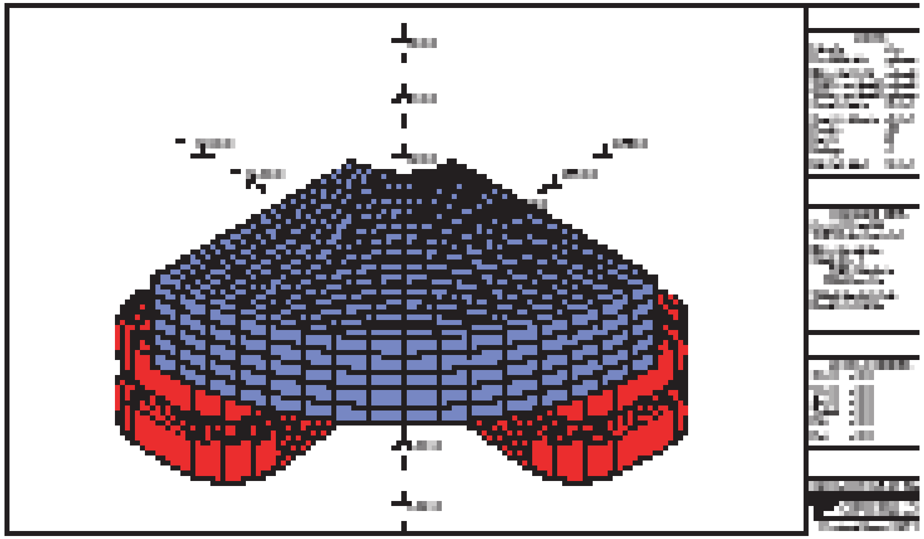
in total:

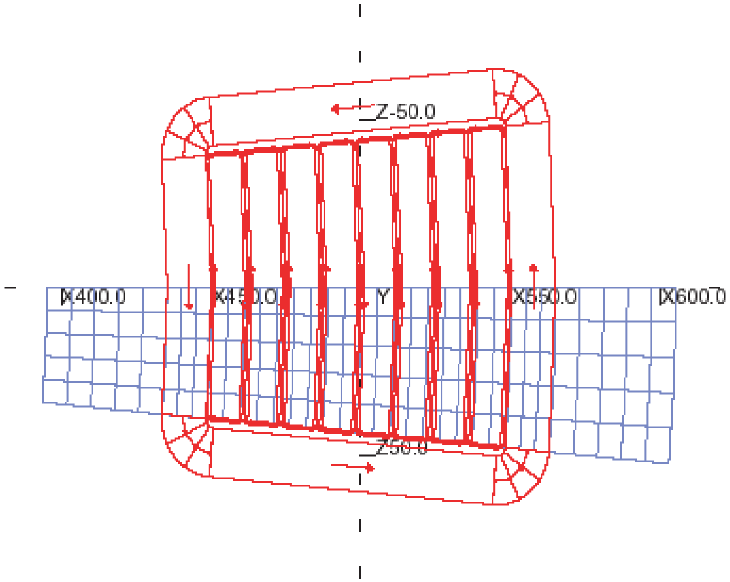
750 x 100kw anode diss. tetrode

1MW anode power supply

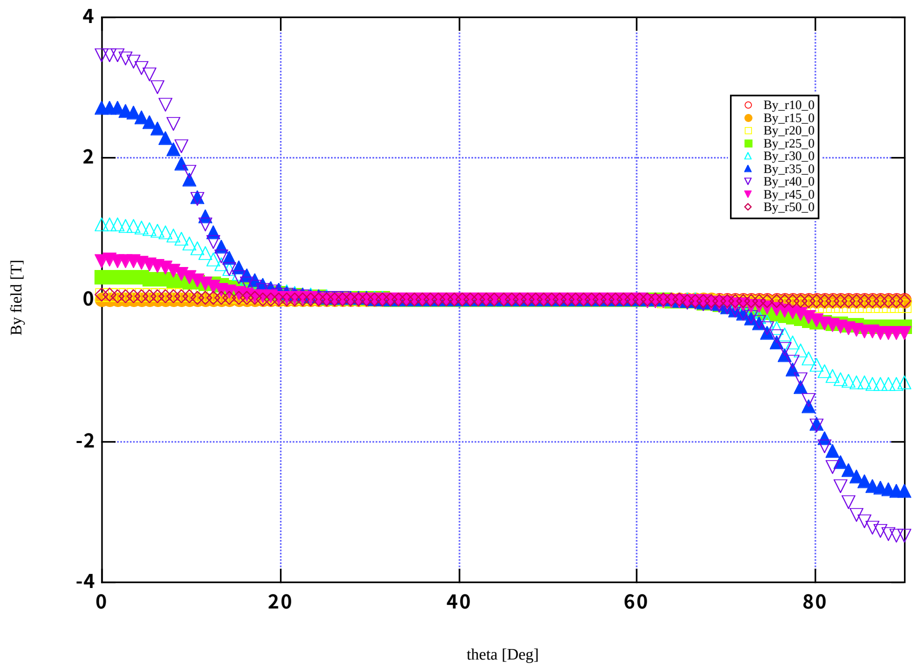
Hardware R&D

Superconducting Magnet for FFAG

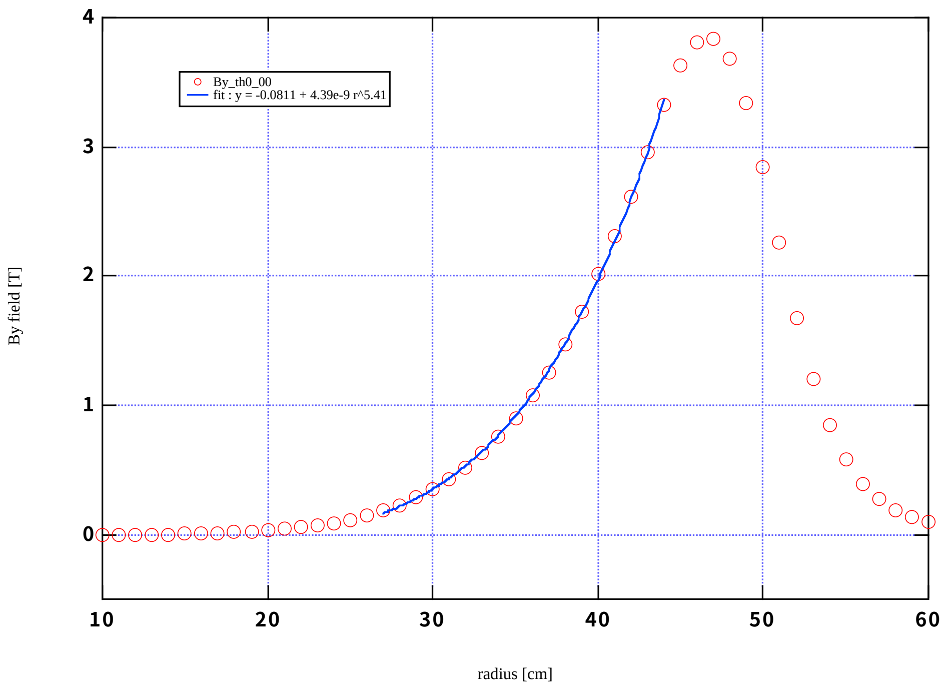




Magnetic field configuration of SC magnet



θ direction



radial direction

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.