

*What is a Neutrino  
Factory?*

# Neutrino Beam Sources

- Pion-decay based neutrino beam

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ \nu_\mu \\ \pi^- &\rightarrow \mu^- \bar{\nu}_\mu\end{aligned}$$

Prompt  
decays

- As beam backgrounds

$$\begin{aligned}K &\rightarrow \mu\nu, K \rightarrow \pi l\nu \\ \mu &\rightarrow e\nu\bar{\nu}\end{aligned}$$

- Beam normalization uncertainty  $\sim 10\%$

- Muon-decay based neutrino beam

- After decays of pions and kaons

$$\begin{aligned}\mu^+ &\rightarrow e^+ \nu_e \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- \bar{\nu}_e \nu_\mu\end{aligned}$$

- Less beam background
  - Beam normalization better known

# More Neutrinos !

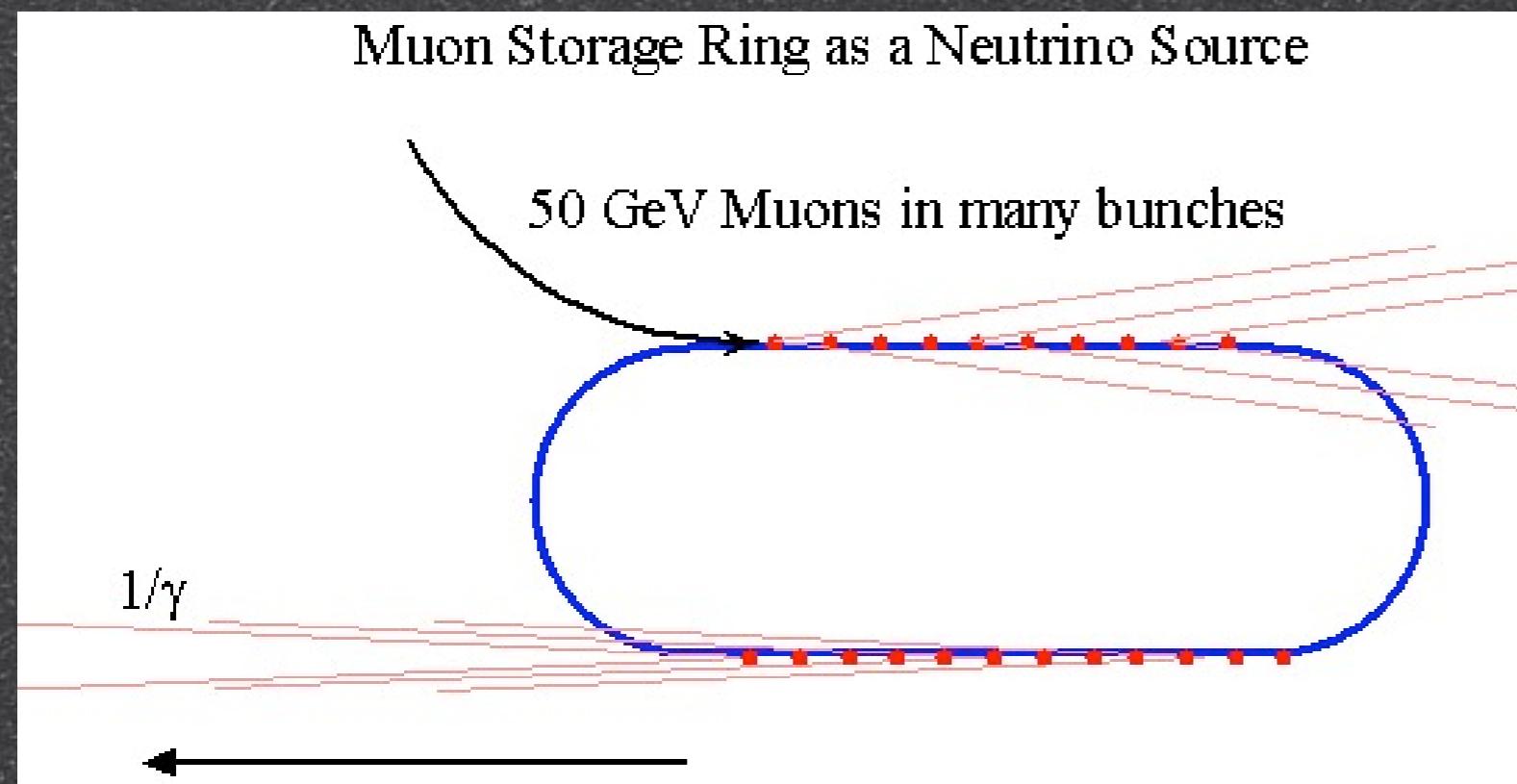
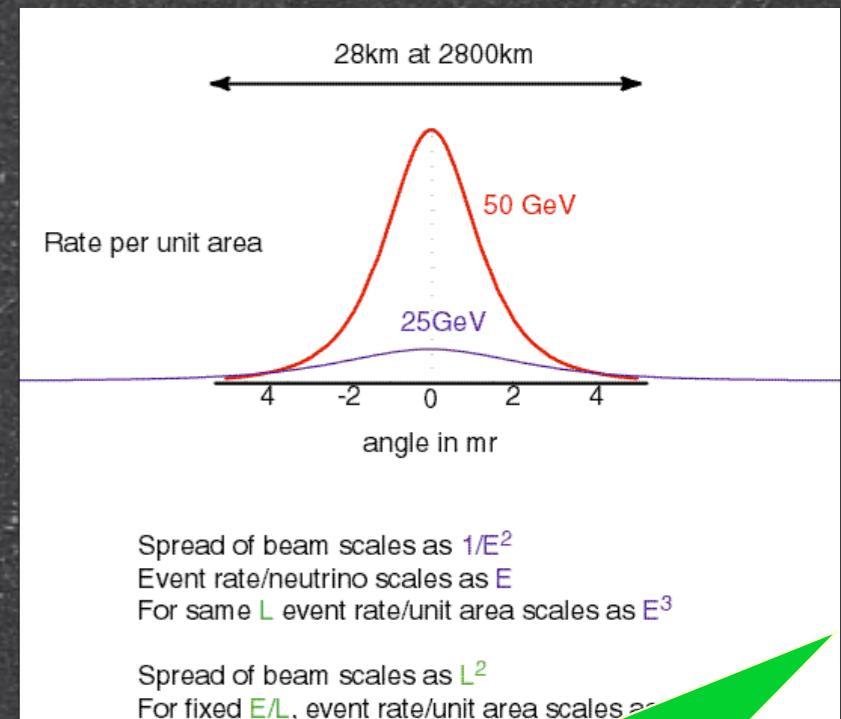
- Given the proton beam power, numbers of pions and muons are similar.
- Acceleration of parent particles gives more neutrinos by boosting.
- Pion production cross section is high around 200-300 MeV/c.
- Only muons live long enough to accelerate.

$$N \propto \gamma^2$$

Muon acceleration!!!

# Muon Storage Ring

- Muons at high energy do not decay quickly...
  - At 10 GeV, average muon lifetime is 0.2 msec.
- Storage ring with long straight section would be needed.
  - Two straight sections give at least two experiments (with different baselines).



At 50 GeV,  $\gamma=500$  and beam spread is 2 mrad

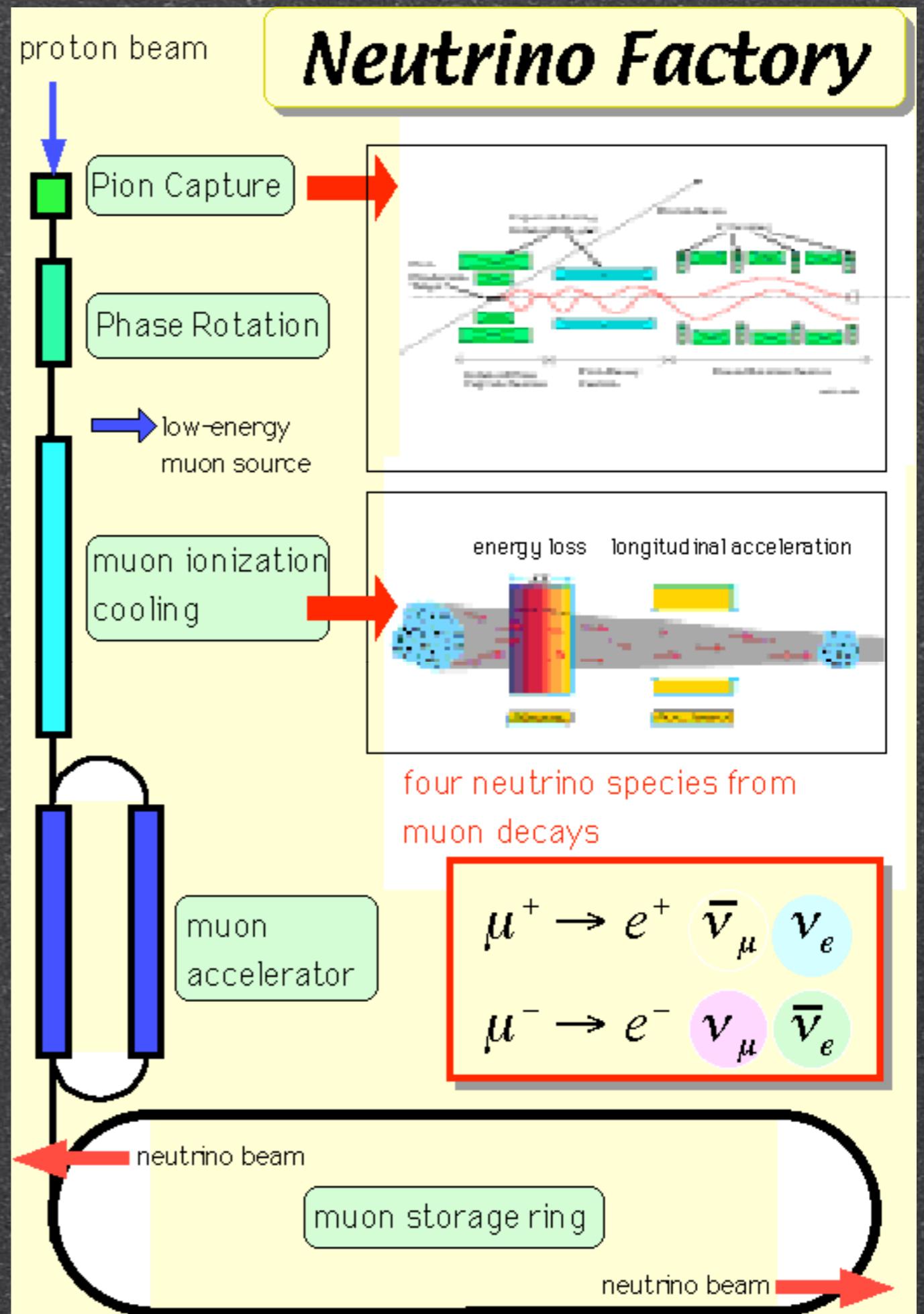
$$\theta \propto \frac{1}{\gamma}$$
$$N \propto \gamma^2$$

# Advantages of NuFACT

- High neutrino intensity at high energy (several 10 GeV)
  - $10^{19} - 10^{21}$  neutrinos/year.
  - about 100 times intensity at a few 10 GeV energy range.
- Both muon and electron neutrinos available
  - Energetic electron neutrino
    - Only NuFACT and Beta beams
- Extremely low backgrounds
  - Less than  $10^{-4}$  level
    - a few % level at the conventional sources.
- Precise knowledge on neutrino intensity and emittance

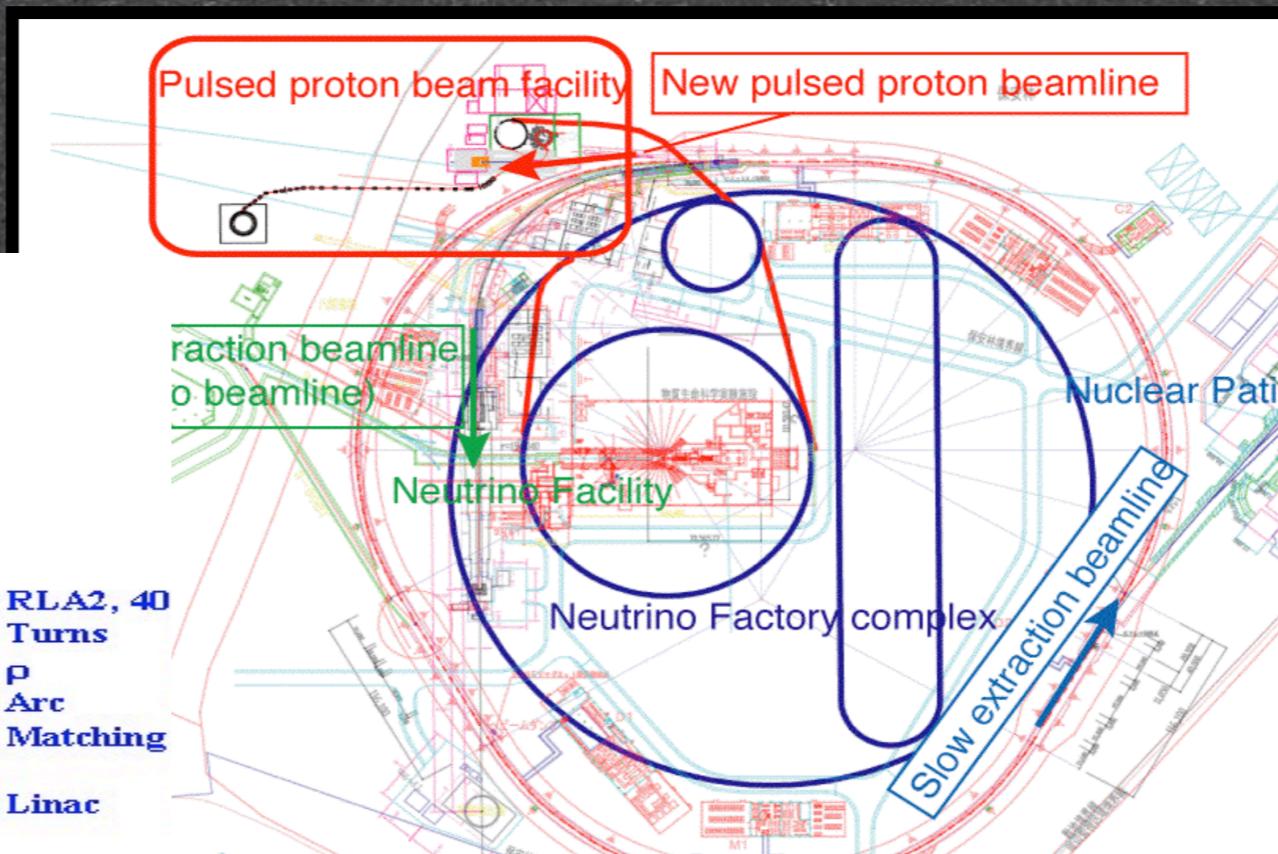
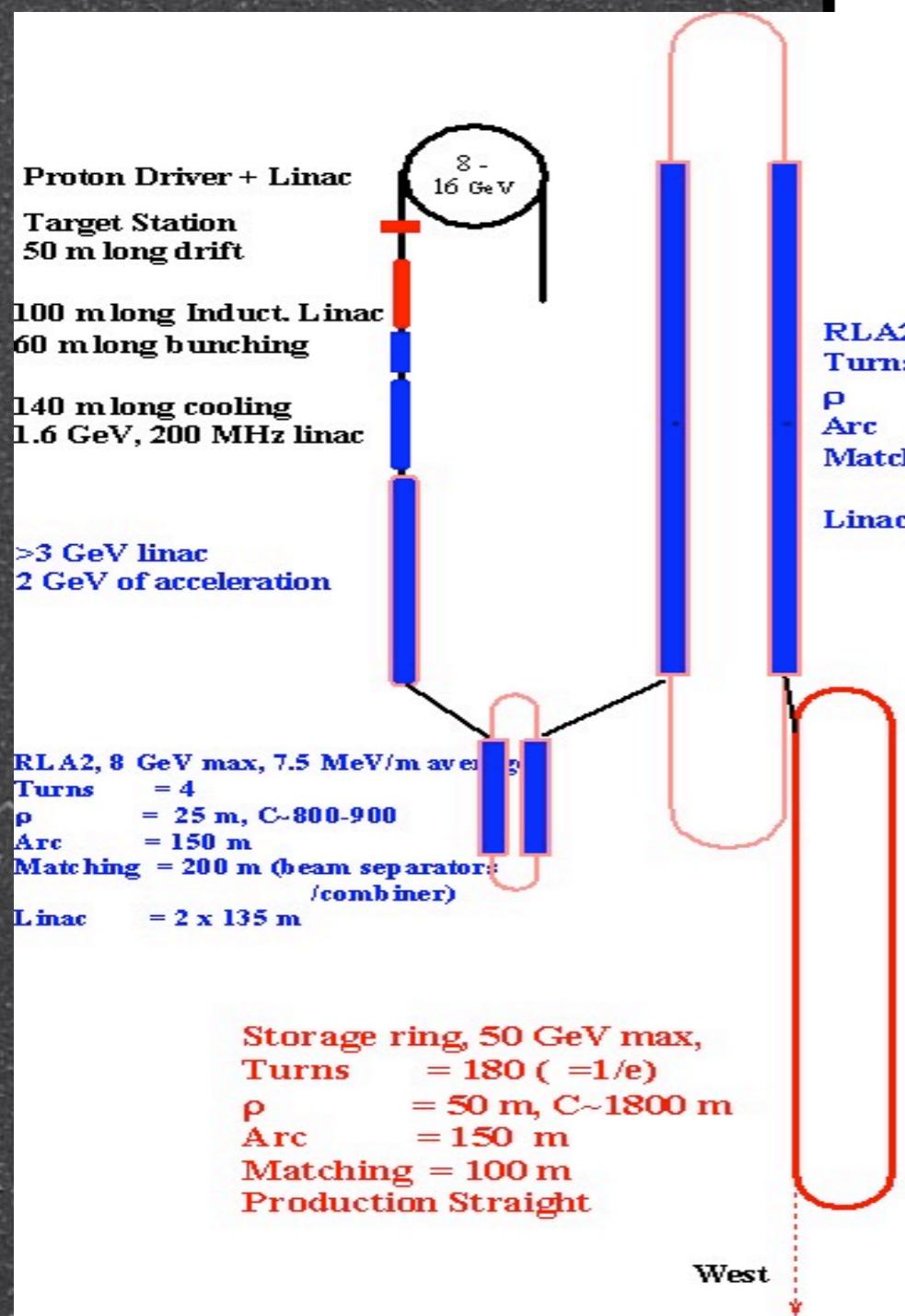
# NuFACT Scheme

- Proton on target
- Pion Collection
- Phase Rotation
- Ionization Cooling
- Acceleration
- FFAG acceleration
- Storage Ring



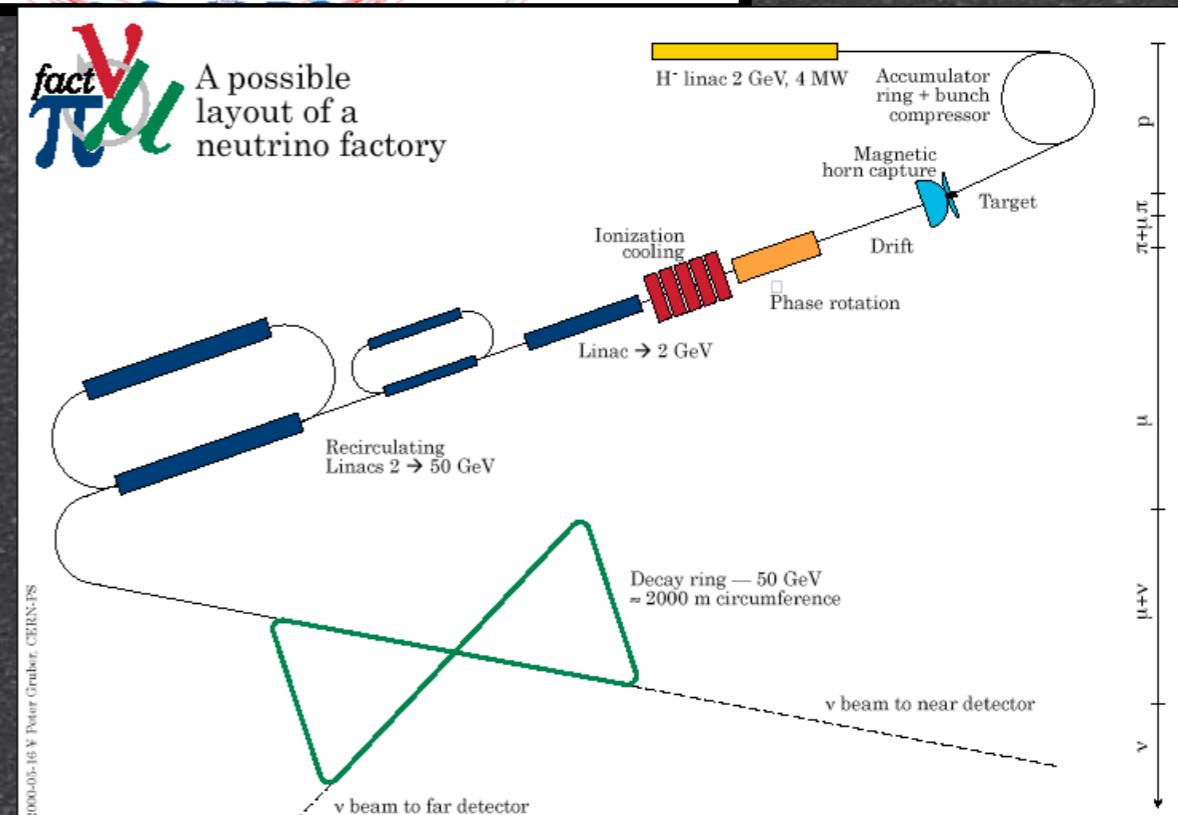
# NF Studies in the World

US



Europe

Japan



# *Neutrino Oscillation Physics at a Neutrino Factory*

# Neutrino Oscillation

flavor states :  $\nu_\alpha$        $\alpha = e, \mu, \tau, \dots$   
 mass states :  $\nu_i$        $i = 1, 2, 3, \dots$

Vacuum oscillations:  $P(\nu_\alpha \rightarrow \nu_\beta) \cong \left| \sum_{j=1}^n V_{\beta j} e^{-i \frac{m_j^2}{2E} L} V_{\alpha j}^* \right|^2$

Maki-Nakagawa-  
Sakata matrix

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix} \begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix} \begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i(\frac{1}{2}\phi_2)} & 0 \\ 0 & 0 & e^{i(\frac{1}{2}\phi_3 + \delta)} \end{bmatrix}$$

atm                          unknown                          solar                          Majorana phases

$c \equiv \cos \theta$      $s \equiv \sin \theta$

For 3 Neutrino Mixing

- 3 mixing angles  $\theta_a, \theta_s, \theta_x$
- 3 complex phases  $\delta, \phi_2, \phi_3$  (CP)

Oscillation probabilities do not depend on  $\phi_2, \phi_3$

# Present Knowledge

Atmospheric neutrinos

$$\Delta m_{32}^2 = \Delta m_{atm}^2 \approx 3 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} \approx (0.9 - 1.0)$$

Reactor Neutrinos

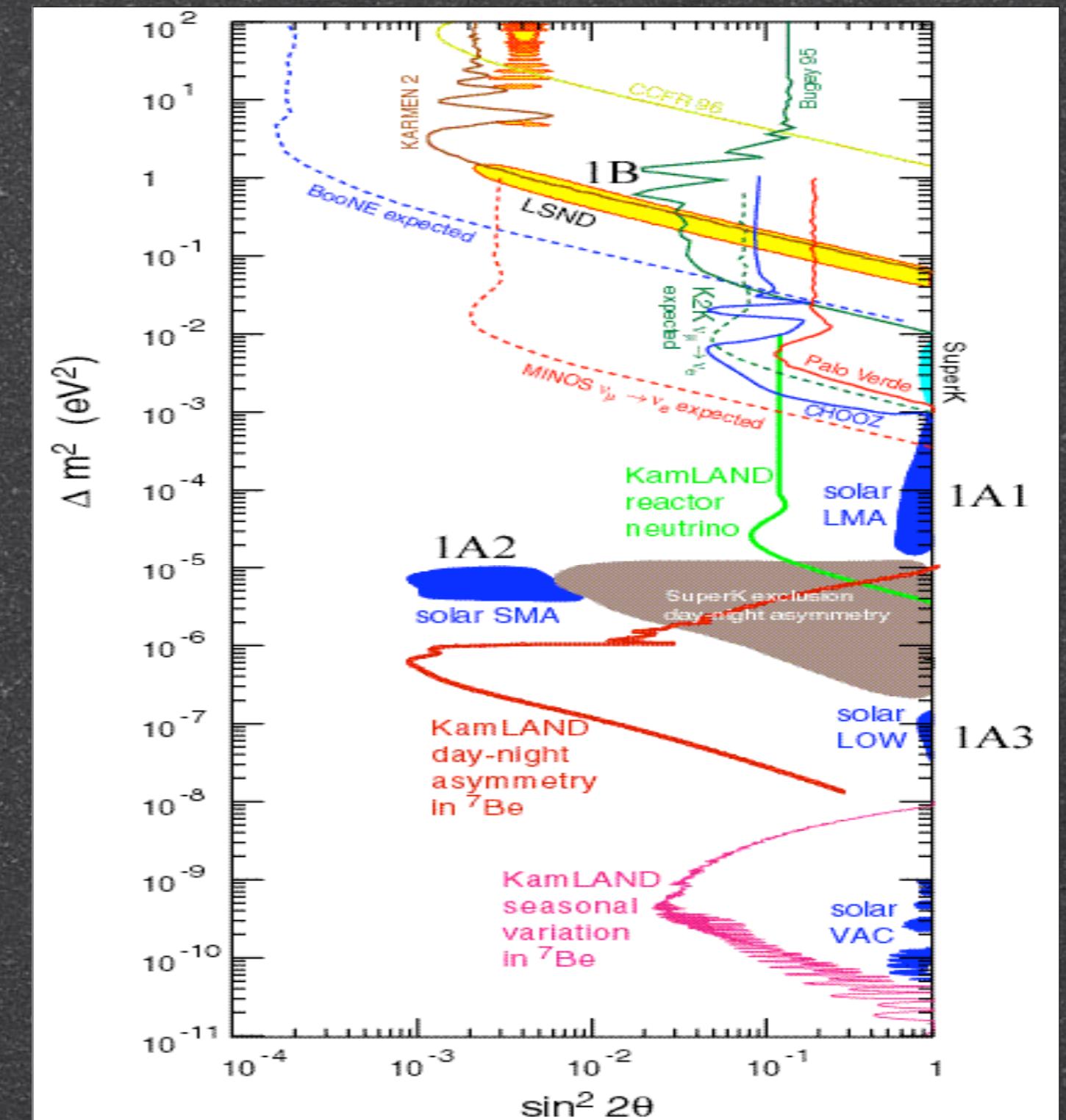
$$\sin^2 2\theta_{13} < 0.1$$

Solar Neutrinos

$$\Delta m_{21}^2 = \Delta m_{solar}^2 = 7 \times 10^{-5}$$

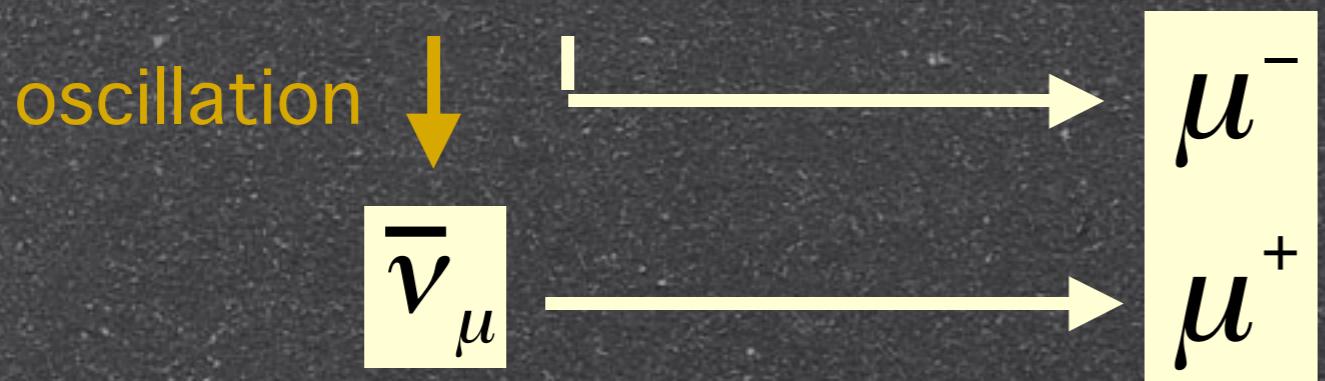
$$\sin^2 2\theta_{12} \sim 0.8$$

No Information on  $\delta_{CP}$



# Oscillation Signature at NF

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



Look for  
wrong signed  
Muons.

charge identification is needed.

# NuFACT Event Rates

Charged current  
(CC) event rate

$$N_{CC}(\nu_e \rightarrow e) \propto \theta_\nu^2 \cdot \sigma$$

$$\propto \frac{E_\mu^2}{L^2} \cdot E_\mu = \frac{E_\mu^3}{L^2}$$

Oscillation event rate

$$N_{osc}(\nu_e \rightarrow \mu)$$

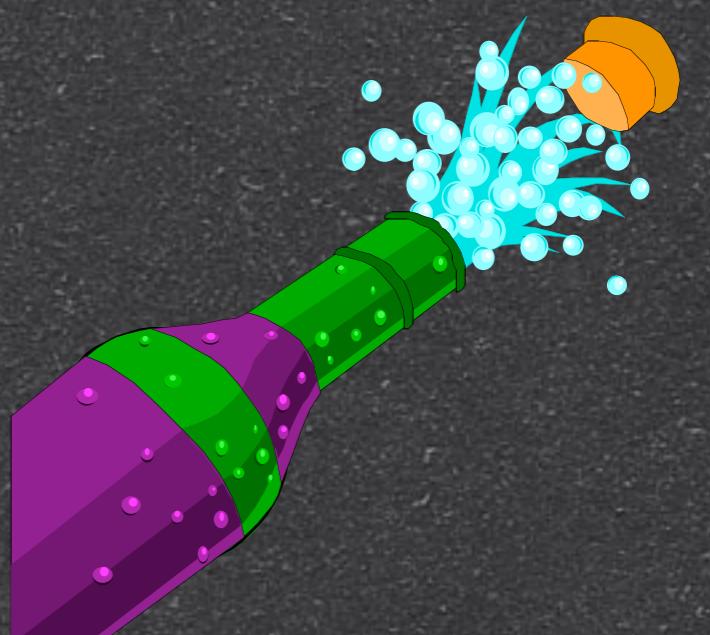
$$\propto \theta_\nu^2 \cdot \sigma \cdot P(\nu_e \rightarrow \nu_\mu)$$

$$\propto \frac{E_\mu^3}{L^2} \cdot \frac{L^2}{E_\mu^2} = E_\mu$$

a number of CC event rate/year

10 kton detector

$10^{21}$  muons/year



	$L=1000\text{ km}$	$L=1500\text{ km}$
$E_\mu = 20\text{ GeV}$	$3.2 \times 10^5$	$1.4 \times 10^5$
$E_\mu = 30\text{ GeV}$	$1.1 \times 10^6$	$4.8 \times 10^5$

# Oscillation Programs

- Observation of  $\nu_e \rightarrow \nu_\mu$ 
  - Sign of  $\delta m^2$  (pattern of neutrino masses)
  - Matter effect
- First observation of  $\nu_e \rightarrow \nu_\tau$  oscillation
- Unitarity of MNS matrix
- Measurement of  $\nu_\mu \rightarrow \nu_\tau$  oscillation
- Search for CP violation  $P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$ 
  - Matter effect
- Search for T violation  $P(\nu_e \rightarrow \nu_\mu) - P(\nu_\mu \rightarrow \nu_e)$ 
  - No matter effect
  - Detection harder
- Search for CPT violation  $P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

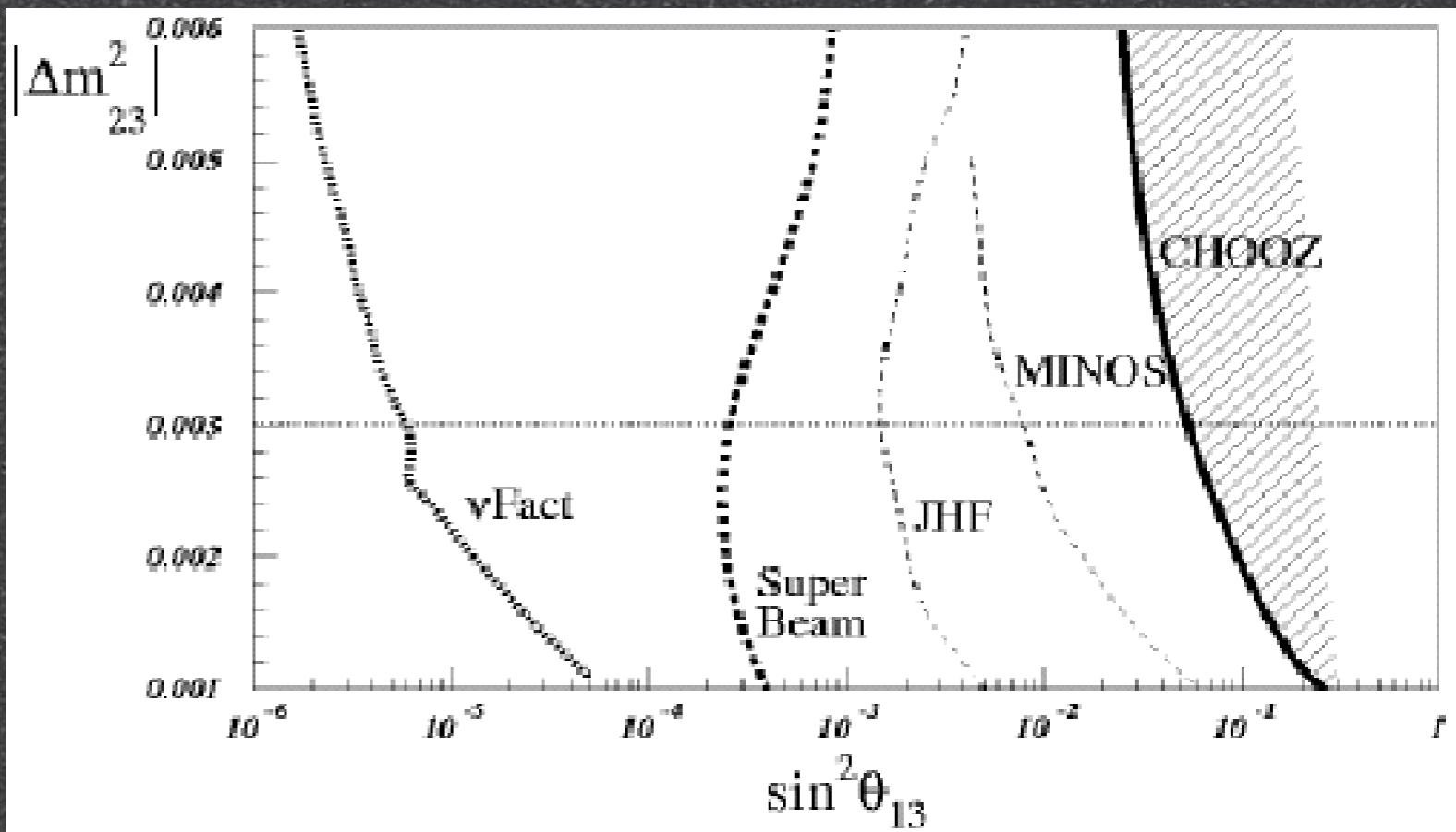
# $\theta_{13}$ Reach

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{32}^2 L/E_\nu)$$
$$P(\nu_e \rightarrow \nu_\tau) = \cos^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{32}^2 L/E_\nu)$$
$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2(1.267 \Delta m_{32}^2 L/E_\nu)$$

A neutrino factory gives the best precision for measuring all of the neutrino mixing parameters!

Gives best sensitivity to  $\theta_{13}$  of any technique:

L=baseline (km)  
E<sub>ν</sub>=energy (GeV)  
A high energy ν<sub>e</sub> beam offers unique possibilities!



# CP Violation

CP-odd osc. probability

$$P(\nu_e - \nu_\mu) - P(\bar{\nu}_e - \bar{\nu}_\mu) = 16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin \delta \times \\ \sin\left(\frac{\Delta m_{12}^2}{3E} L\right) \sin\left(\frac{\Delta m_{13}^2}{3E} L\right) \sin\left(\frac{\Delta m_{23}^2}{3E} L\right)$$

possible only if  $\Delta m_{12}^2$  and  $s_{12}$  are large and  $s_{13}$  is large

LMA

need to know

$$P_{CP-odd}(\nu_e \rightarrow \nu_\mu) \approx -4J \frac{\delta m_{21}^2 L}{2E_\nu} \sin^2\left(\frac{\delta m_{31}^2 L}{4E_\nu}\right)$$

Jarlskog parameter :  $J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin(\delta)$

Figure of Merit

CP-odd asymmetry

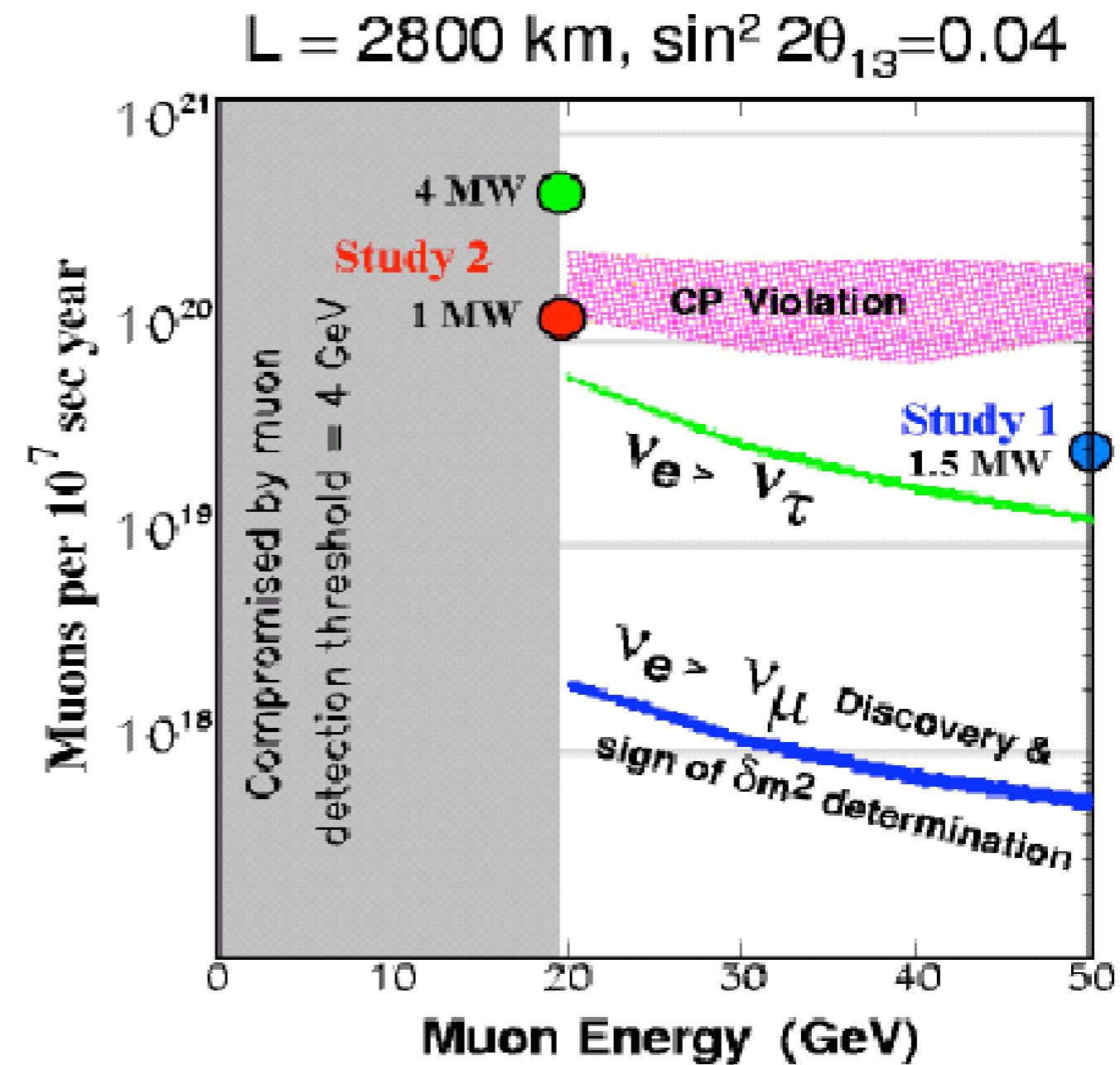
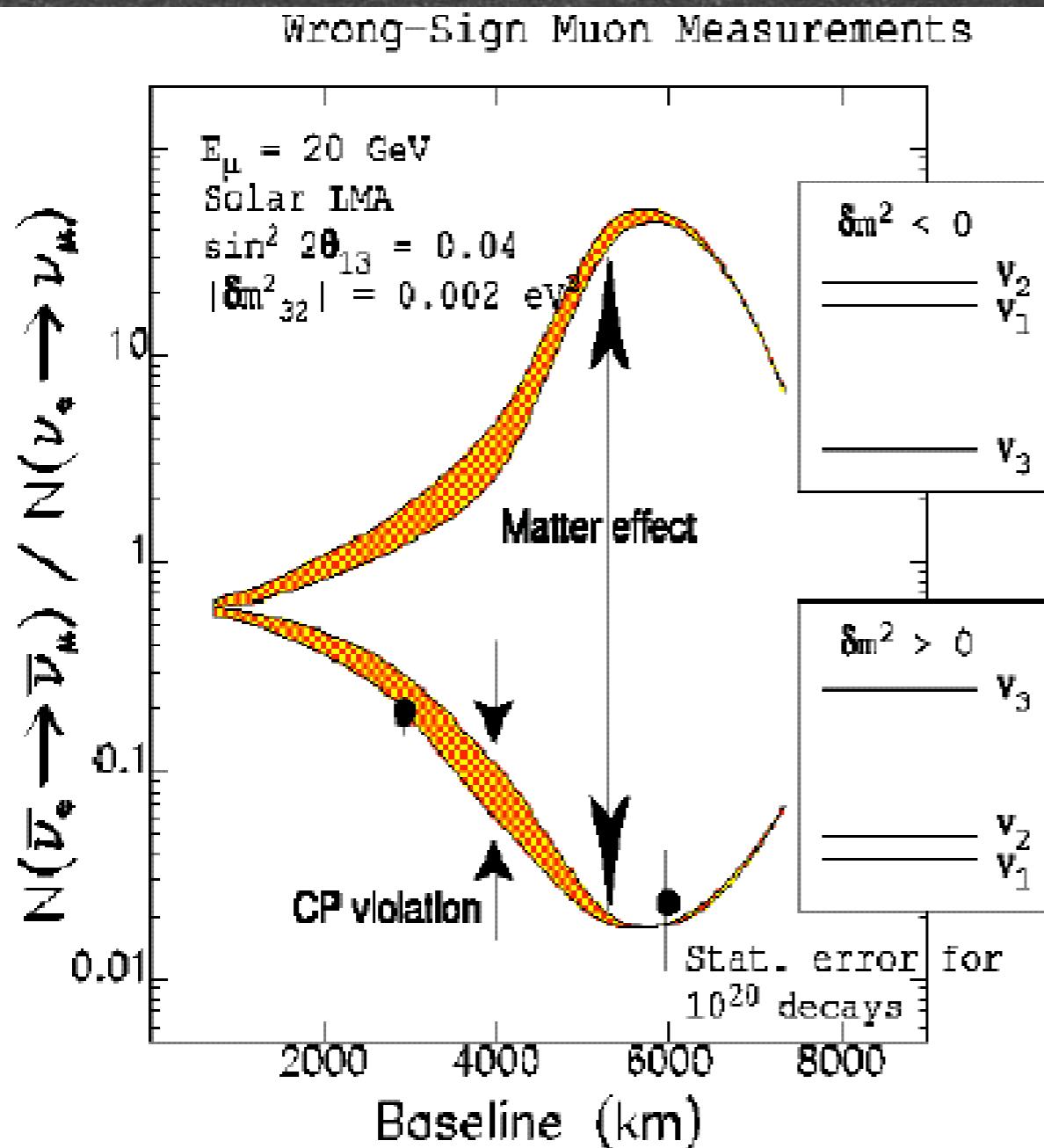
$$A_{CP} = \frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} \propto \frac{L}{E_\nu}$$

$$N_{osc} \propto \left(\frac{E_\nu}{L}\right)^2 \sin^2\left(\frac{\delta m_{31}^2 L}{4E_\nu}\right) \sigma(E_\nu) \propto E_\nu$$

$$FOM \equiv A_{CP-odd}^2 \times N_{osc} \propto \left(\frac{L}{E_\nu}\right)^2 E_\nu$$

# CP Reach

Comparing  $\nu_e \rightarrow \nu_\mu, \bar{\nu}_e \rightarrow \bar{\nu}_\mu$  gives both  $\text{sgn}(\Delta m^2_{32})$  and CP phase:



# Discovery Reach Summary

	$\text{sign}(\delta m_a^2)$	CP-violation
Superbeam	$3 \times 10^{-3}$	$3 \times 10^{-2}$
NuFact (entry level)	$3 \times 10^{-4}$	$2 \times 10^{-3}$
NuFact (high performance)	$1 \times 10^{-4}$	$5 \times 10^{-4}$

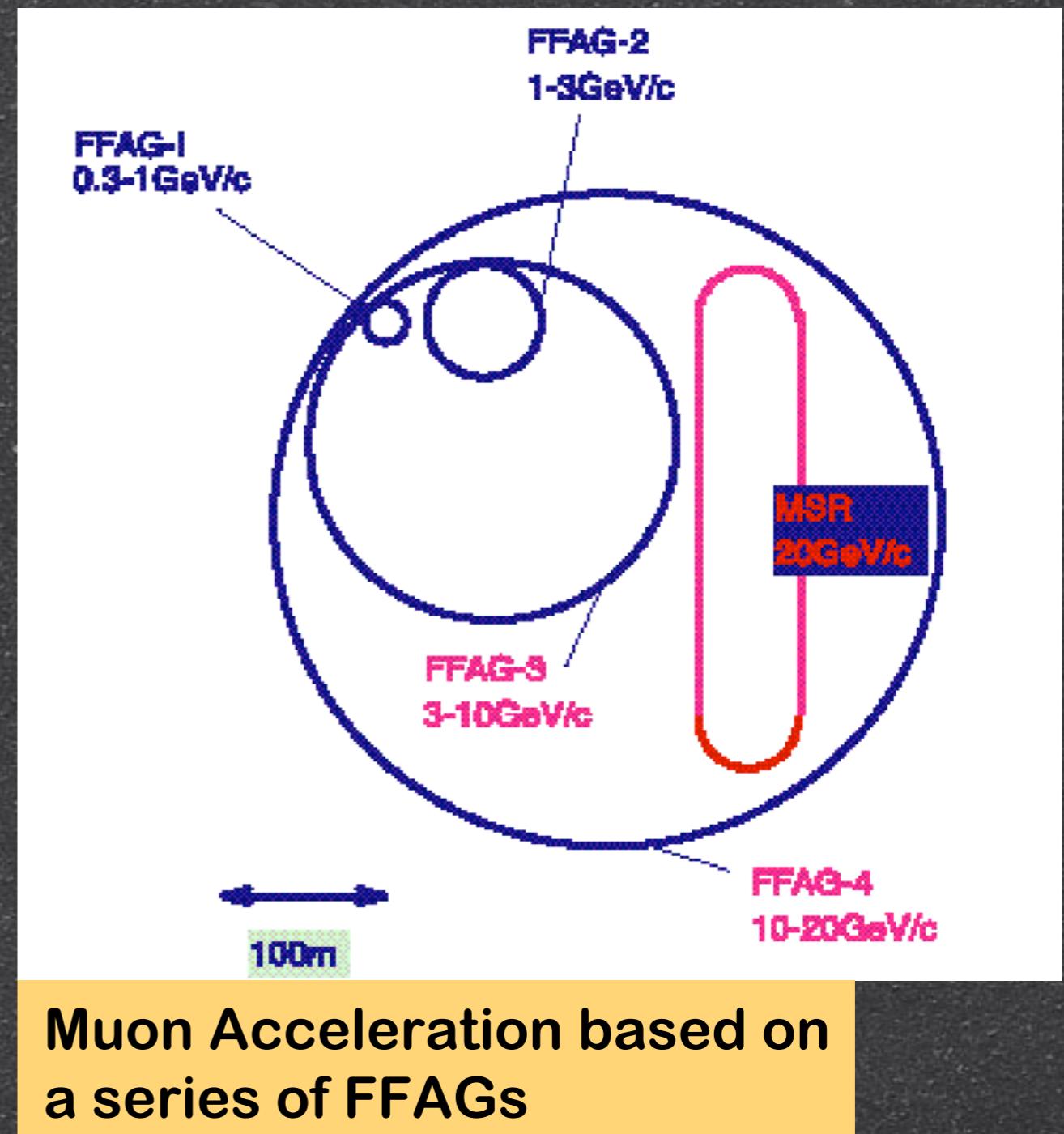
# *J-PARC Case (Neutrino Factory)*

Sorry, not mentioning  
the others !

# FFAG-based Acceleration

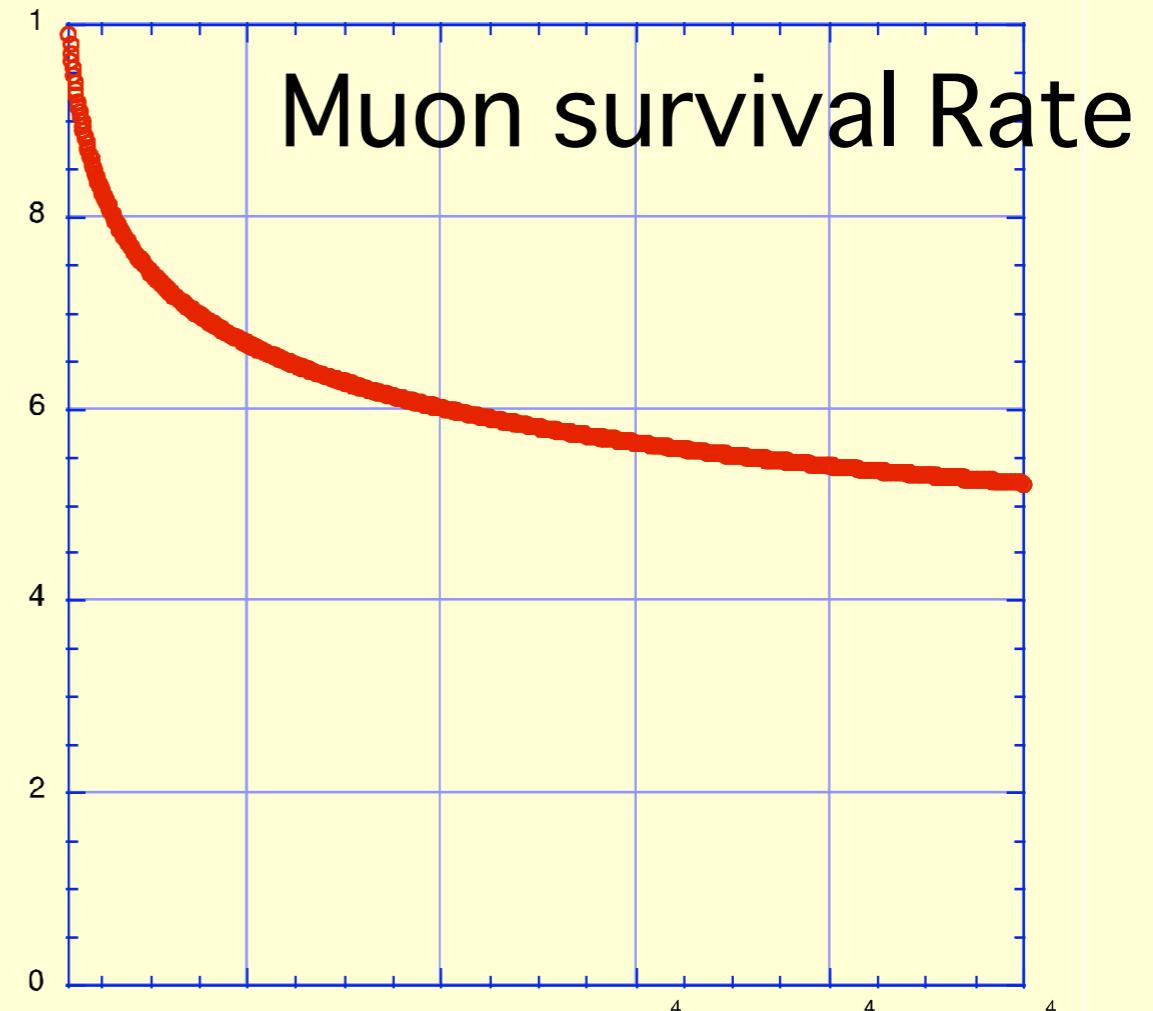
- FFAG
  - Large acceptance
  - Fast acceleration
  - **Muon cooling is not mandatory** (better if available).
- Advantages
  - less RF cavities and power.
  - simple and compact
- Either Scaling or Non-scaling !!!

A series of 3-4 FFAG rings



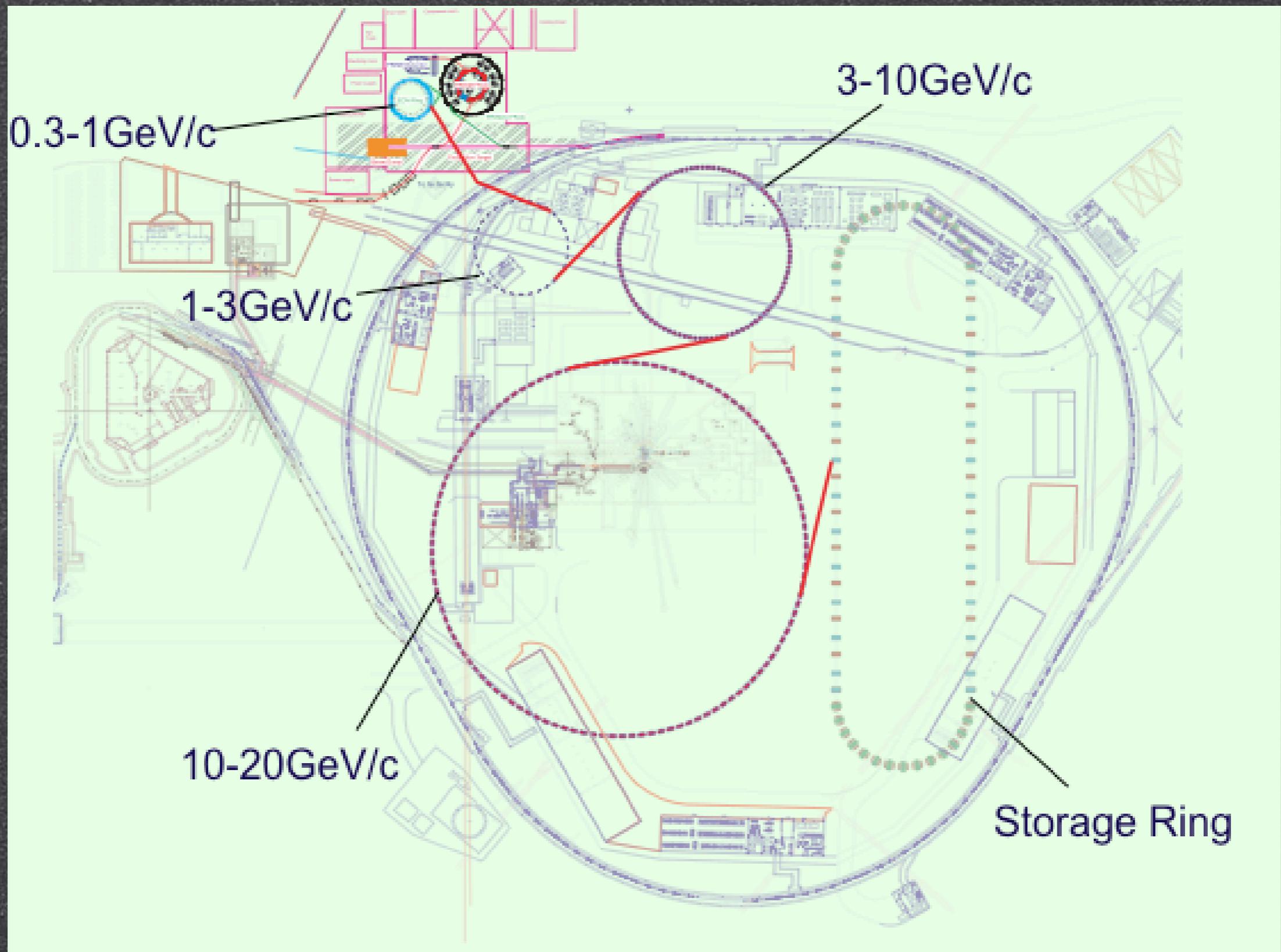
# Muon Yield Estimation

- Muon Capture: 0.3 muons/proton
- Proton intensity:  $2 \times 10^{21}$ /year
- Muon survival rate: 0.5 for  $E=1\text{MV/m}$  to 20 GeV
- Fraction of one straight section: 0.3



$$\begin{aligned}\text{Yield} &= 2 \times 10^{21} \times 0.3 \times 0.52 \times 0.3 \\ &= 1 \times 10^{20} \text{ muons/decay/year}\end{aligned}$$

# NuFACT at J-PARC

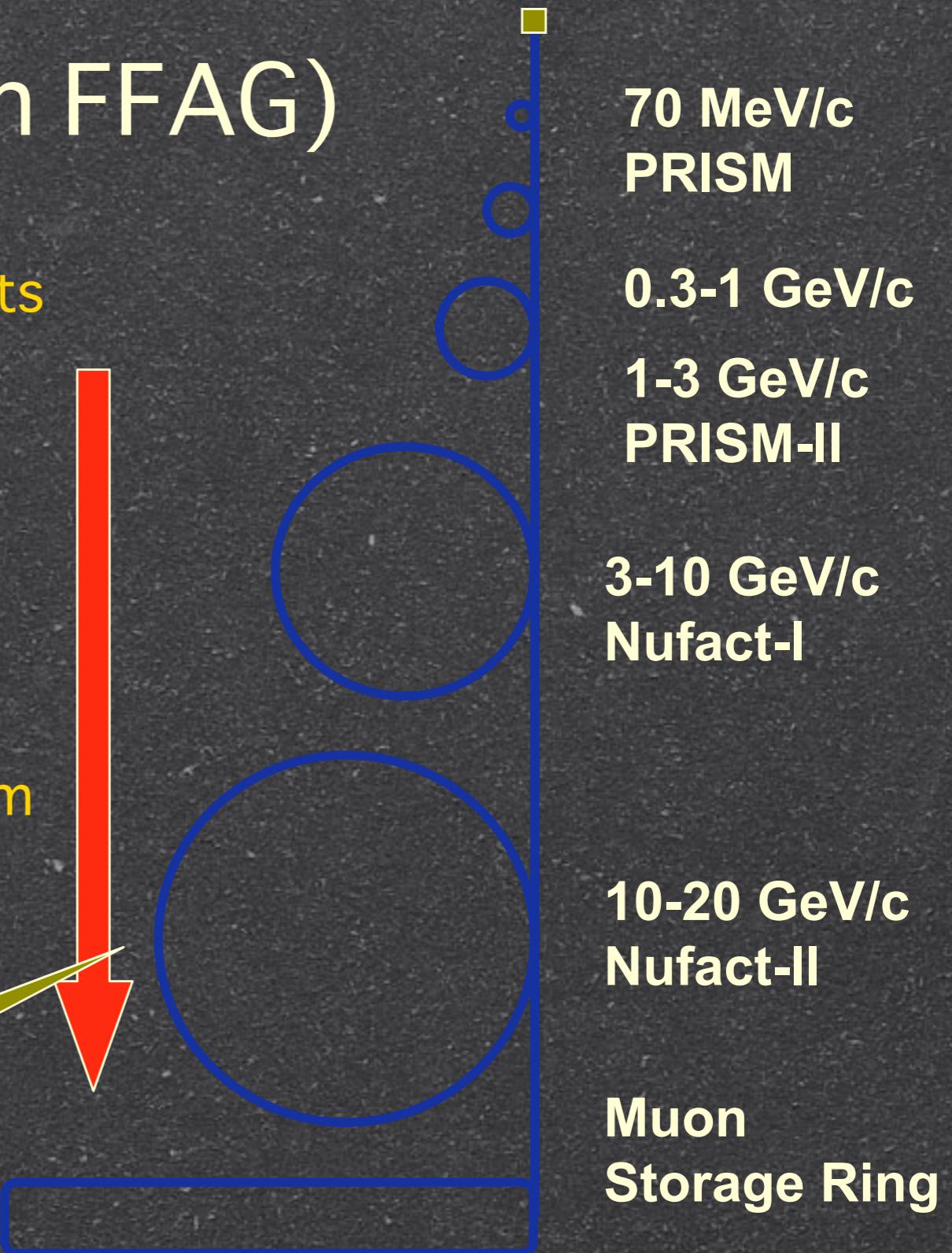


# From MF to NF

## ■ Staging scenario (with FFAG)

- Muon Factory (PRISM)
  - For stopped muon experiments
- Muon Factory-II (PRISM-II)
  - Muon moments ( $g-2$ , EDM)
- Neutrino Factory-I
  - Based on 1 MW proton beam
- Neutrino Factory-II
  - Based on 4.4 MW proton beam
- Muon Collider

Physics outcome  
at each stage



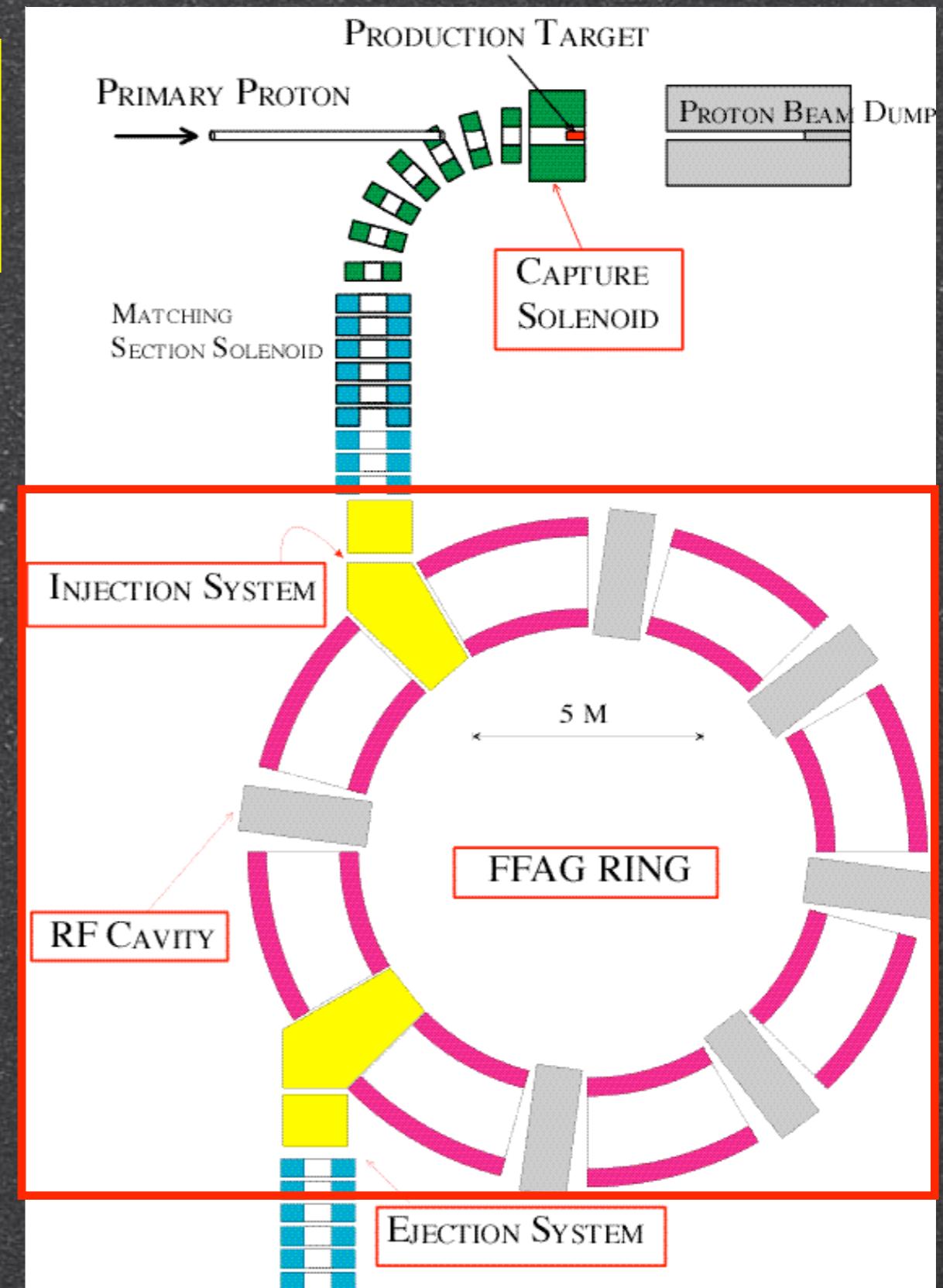
# *PRISM R&D STATUS*

# PRISM Ring Construction

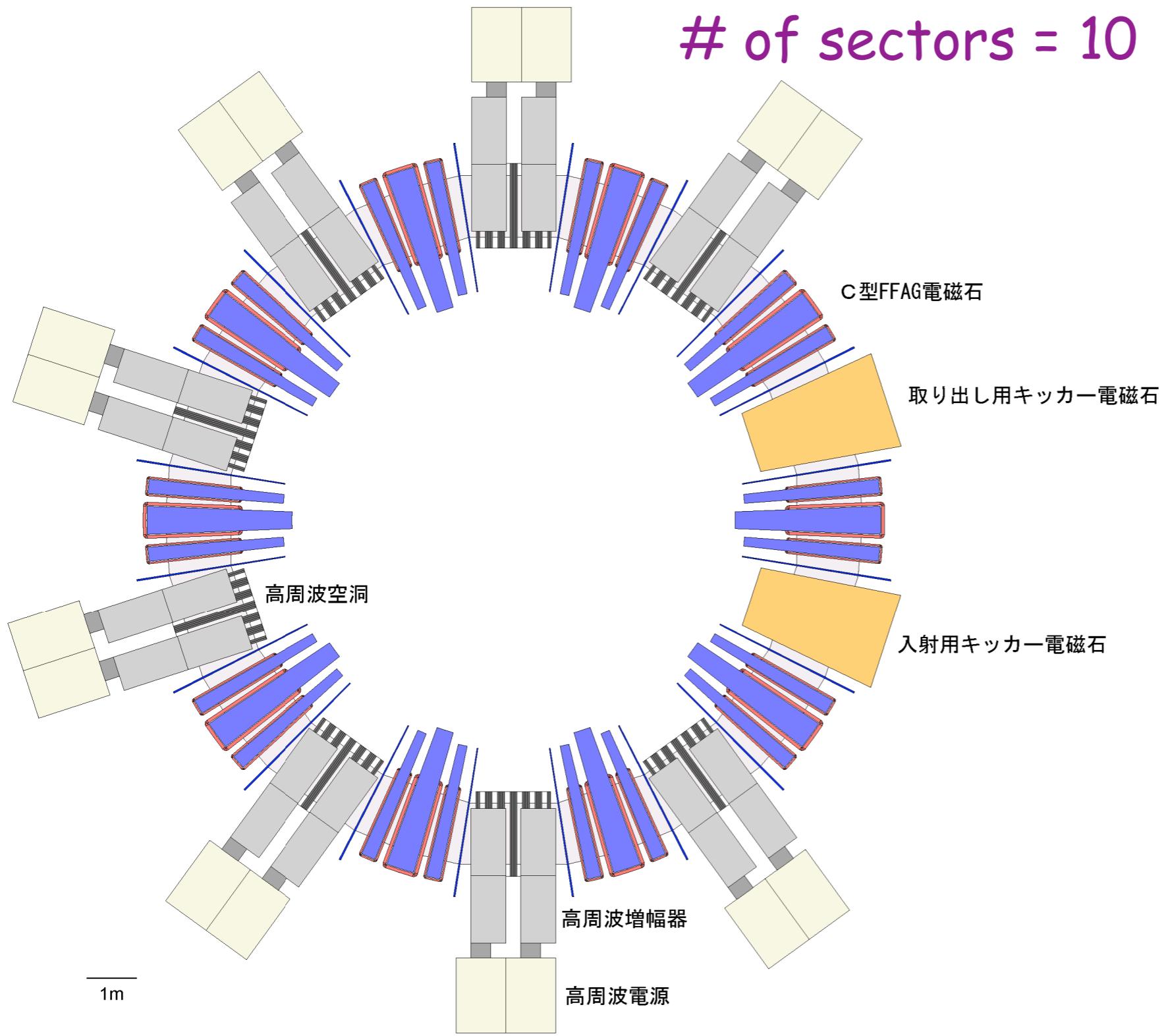
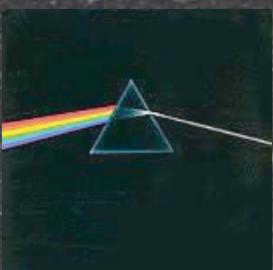


PRISM ring construction has been approved in JFY2003.

- FFAG ring
- 5 year plan
- construction at Osaka university
- Plan before J-PARC
  - proton/muon phase rotation
  - muon acceleration
  - muon beam cooling



# PRISM-FFAG Layout



JFY2003:  
rf amp. and cores

JFY2004:  
rf cavity (1)  
FFAG magnet (2)

JFY2005:  
FFAG magnets (4)

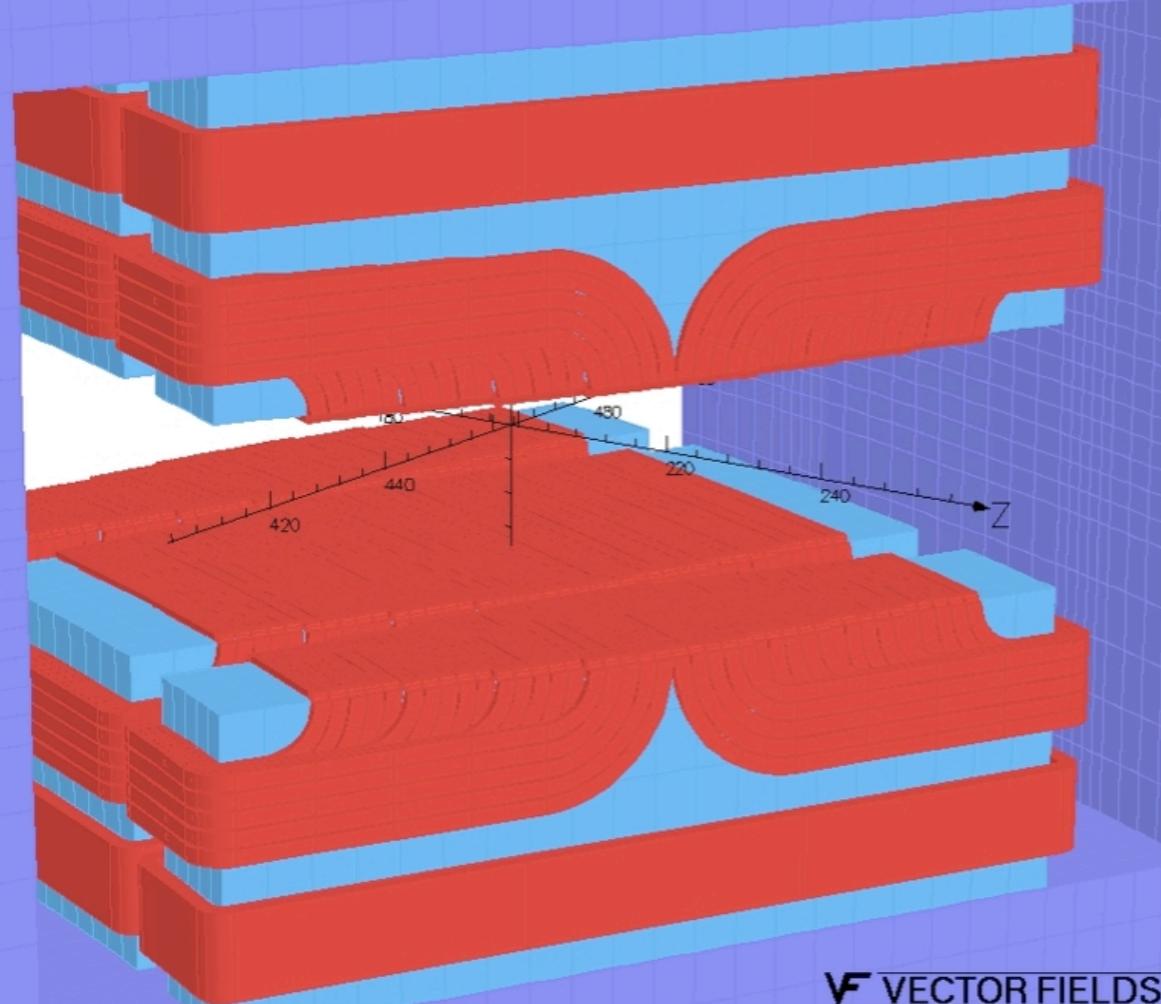
JFY2006:  
FFAG magnets (4)

JFY2007:  
chambers, etc.



# FFAG Magnet Design

25/Aug/2003 12:09:46



Y. Arimoto

UNITS	
Length	cm
Magn Flux Density	gauss
Magn Field	oersted
Magn Scalar Pot	oersted-cm
Magn Vector Pot	gauss-cm
Elec Flux Density	C/cm <sup>2</sup>
Elec Field	V/cm
Conductivity	S/cm
Current Density	A/cm <sup>2</sup>
Power	W
Force	N
Energy	J

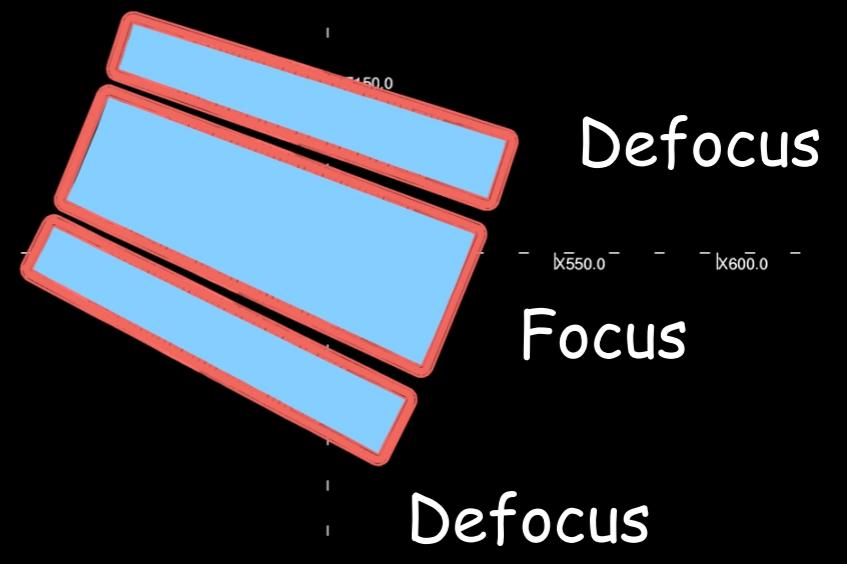
**PROBLEM DATA**  
triplet op3  
TOSCA Magnetostatic  
Non-linear materials  
Simulation No 1 of 1  
36480 elements  
156911 nodes  
1404 conductors  
Nodally interpolated fields

**Local Coordinates**  
Origin: 0.0, 0.0, 0.0  
Local XYZ = Global XYZ

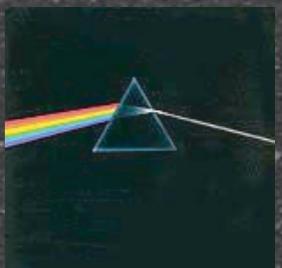
FFAG field

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

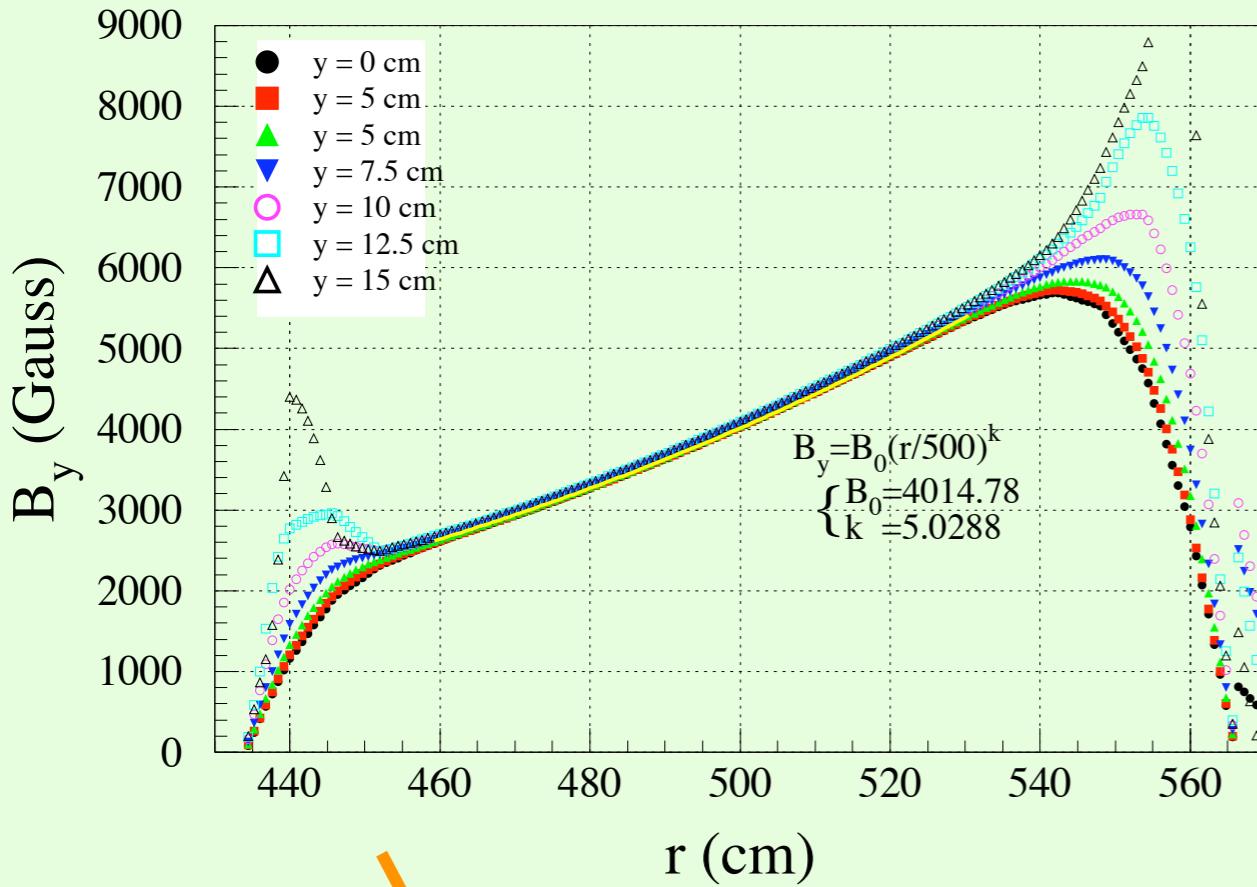
Radial Sector Type



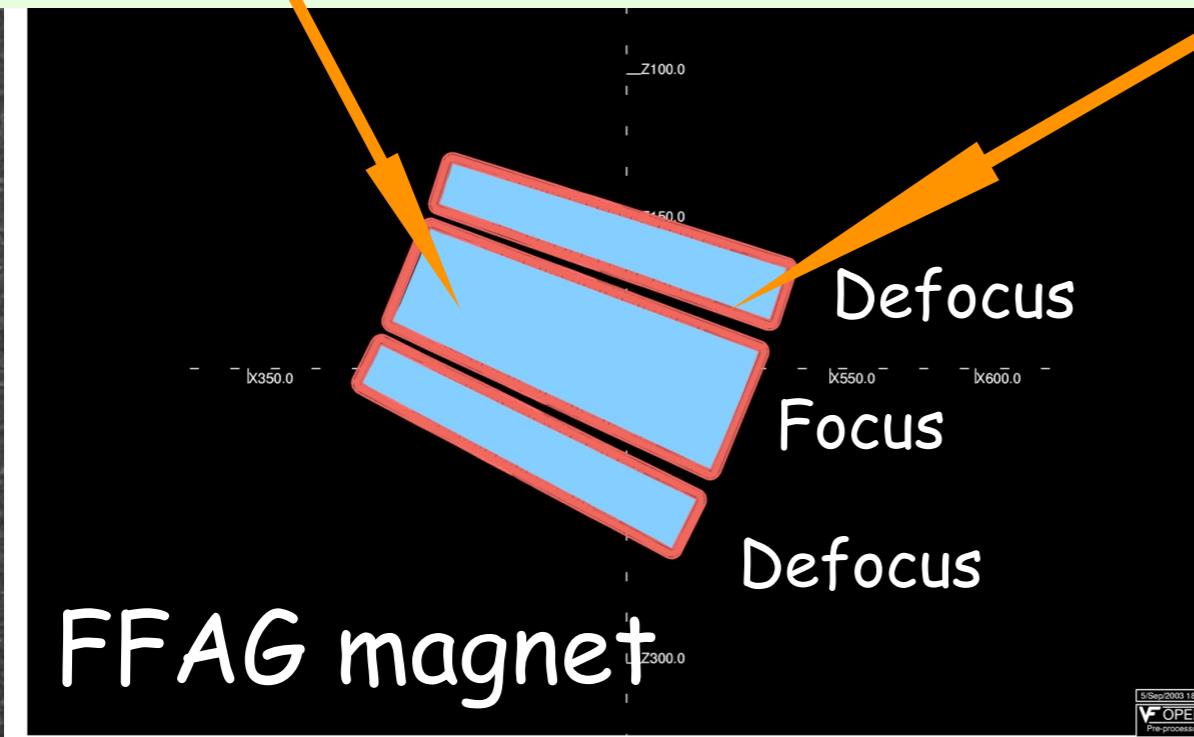
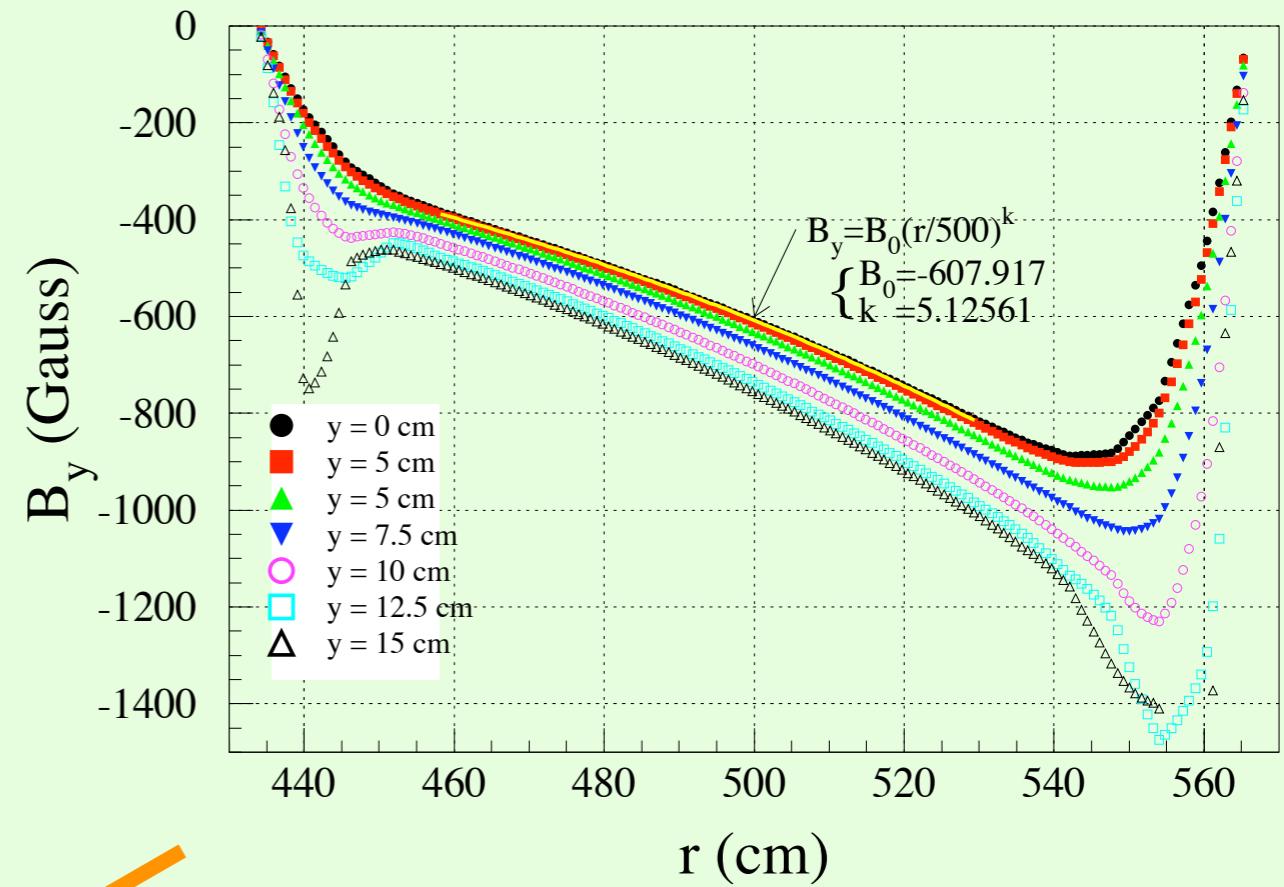
# FFAG Field Calculation



Focus



Defocus



3-dim. Field Calculation

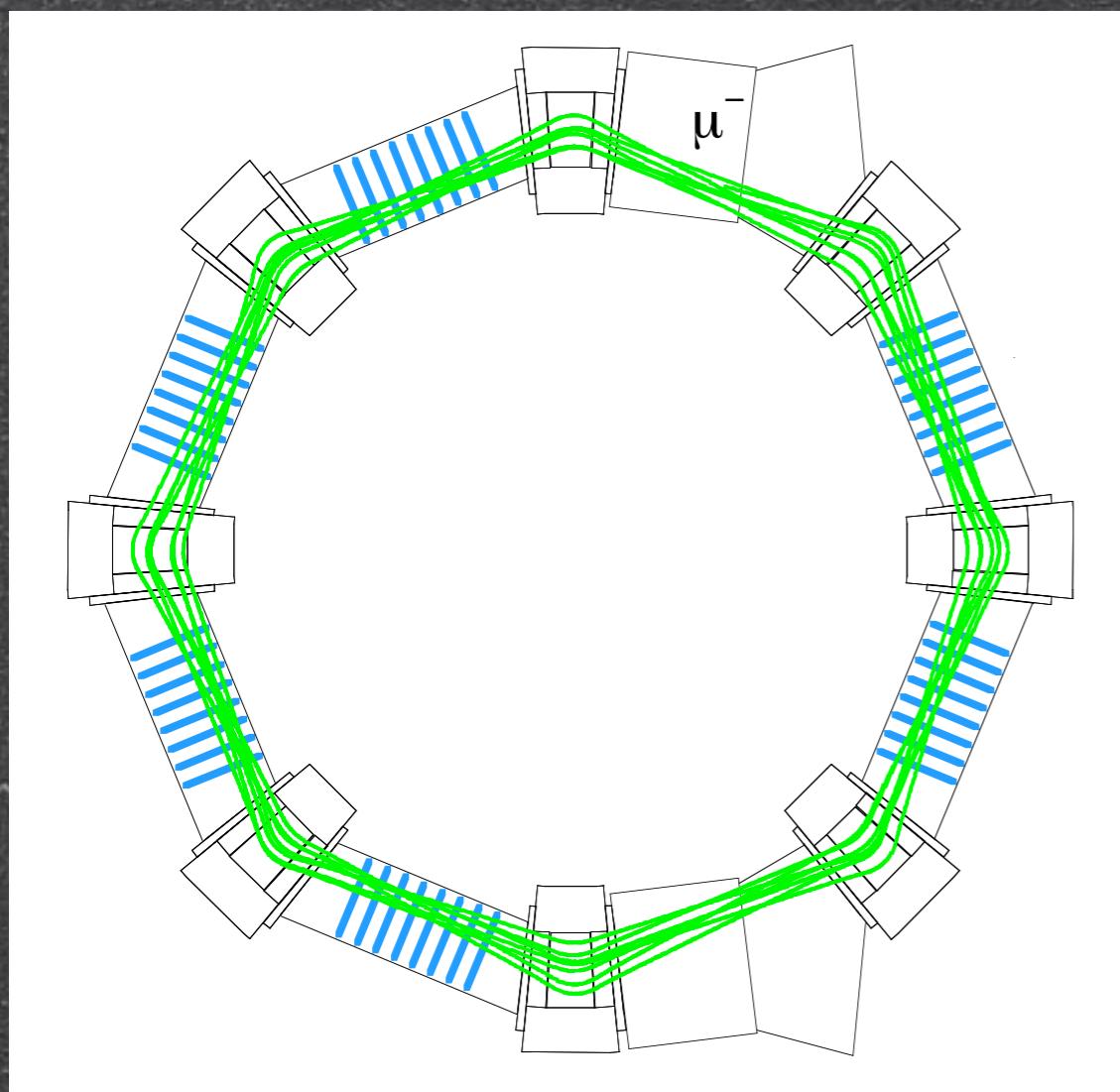
$$B(r) = B_0 \left( \frac{r}{r_0} \right)^k$$

Y. Arimoto

# Tracking Simulation

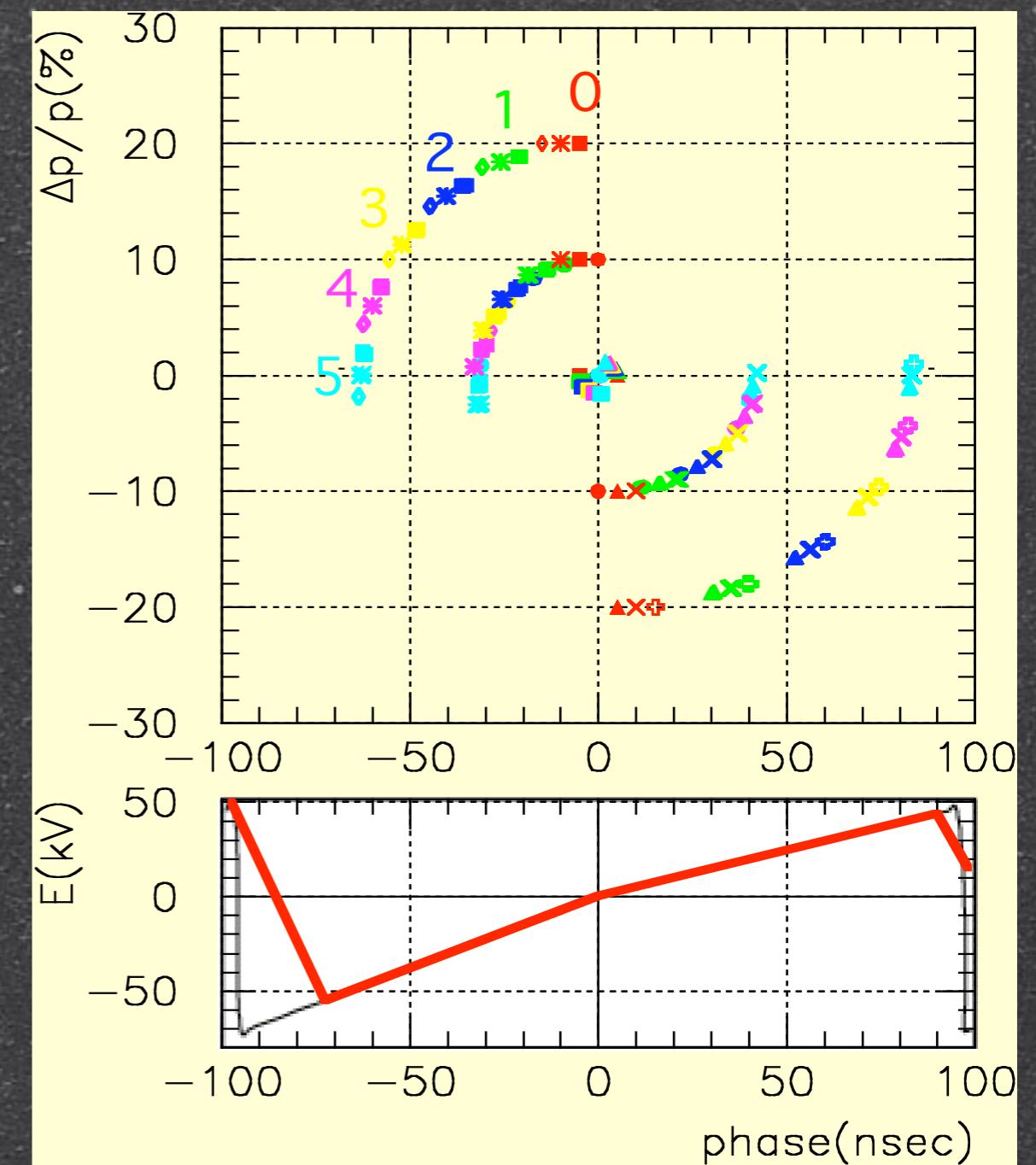


GEANT3 simulation with  
TOSCA magnetic field



not a sinusoidal, but a saw-tooth shape is needed.

$\pm 5\text{nsec}$  muon width at given momentum



RF 5MHz, 250 kV/m

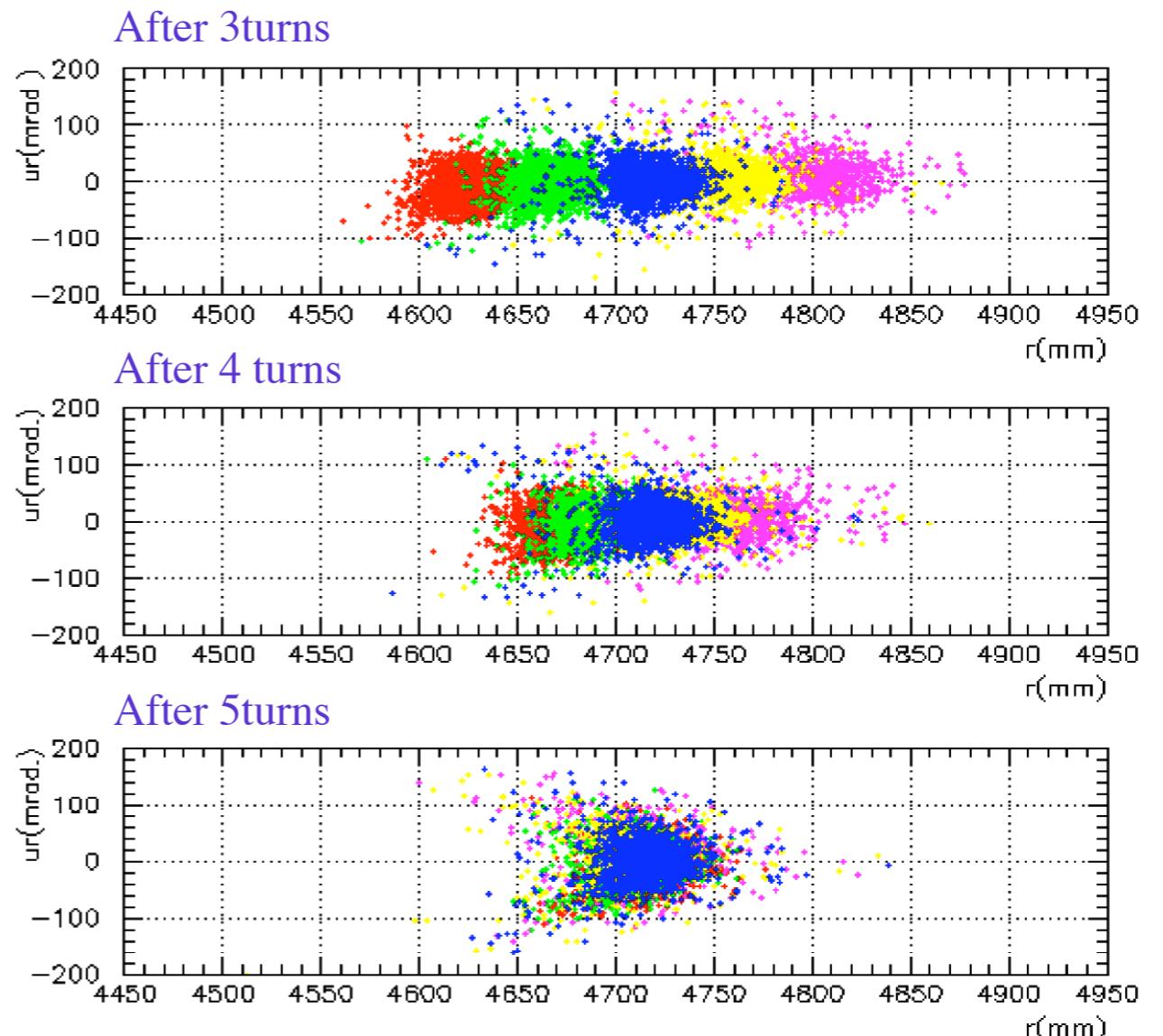
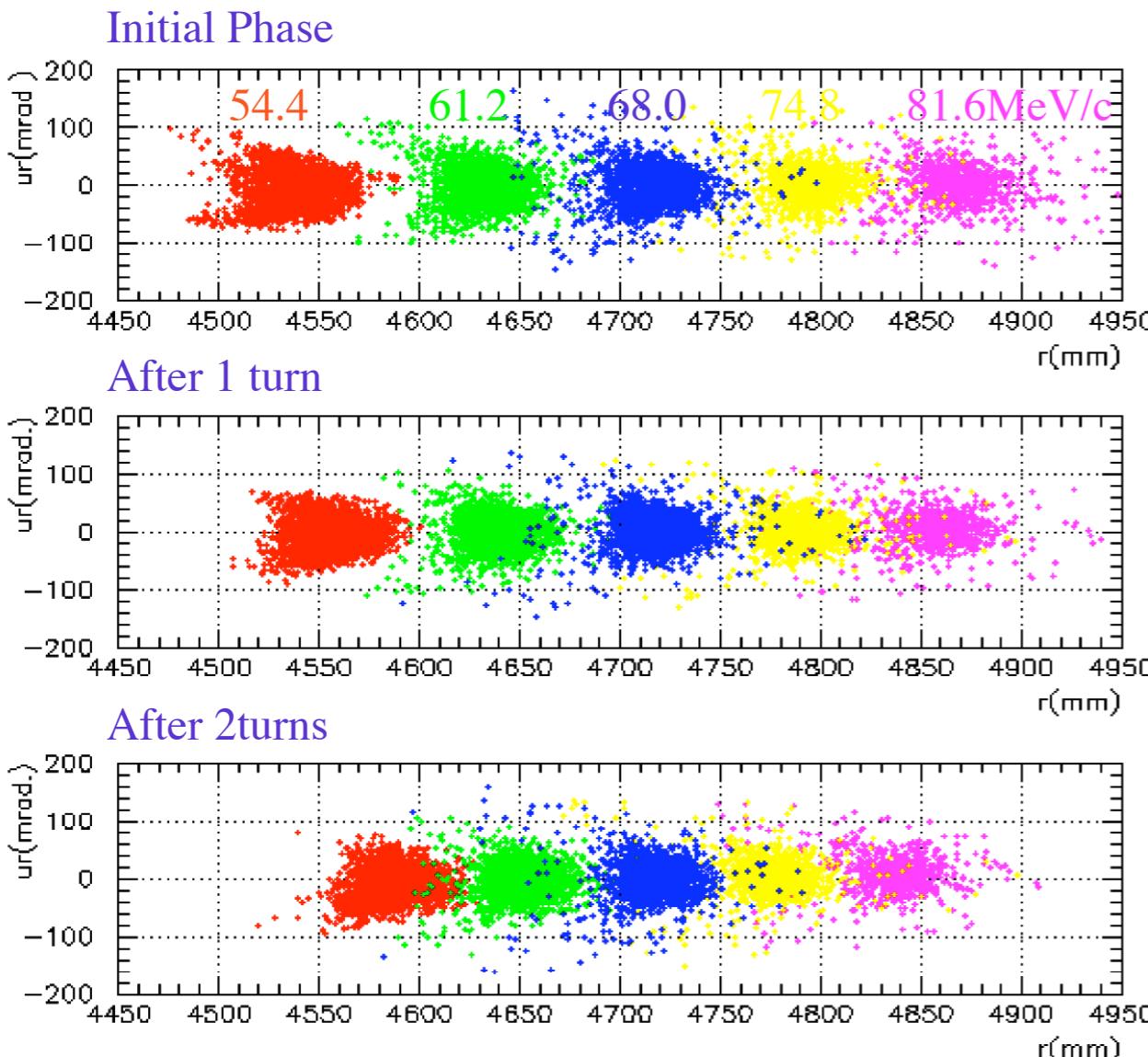
$\Delta p/p = \pm 3\%$

A. Sato

# Phase Rotation Simulation



## Horizontal

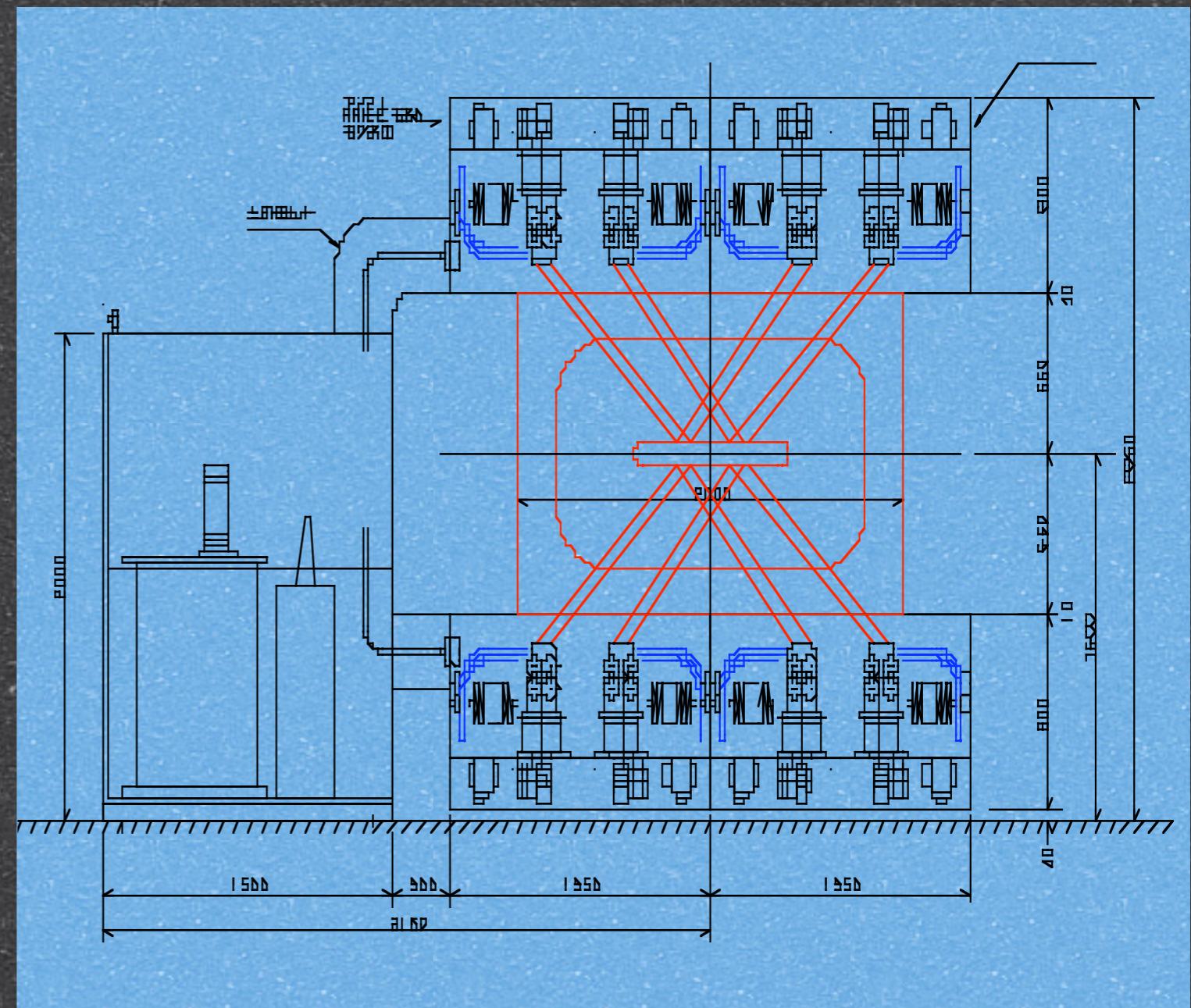


# PRISM RF System

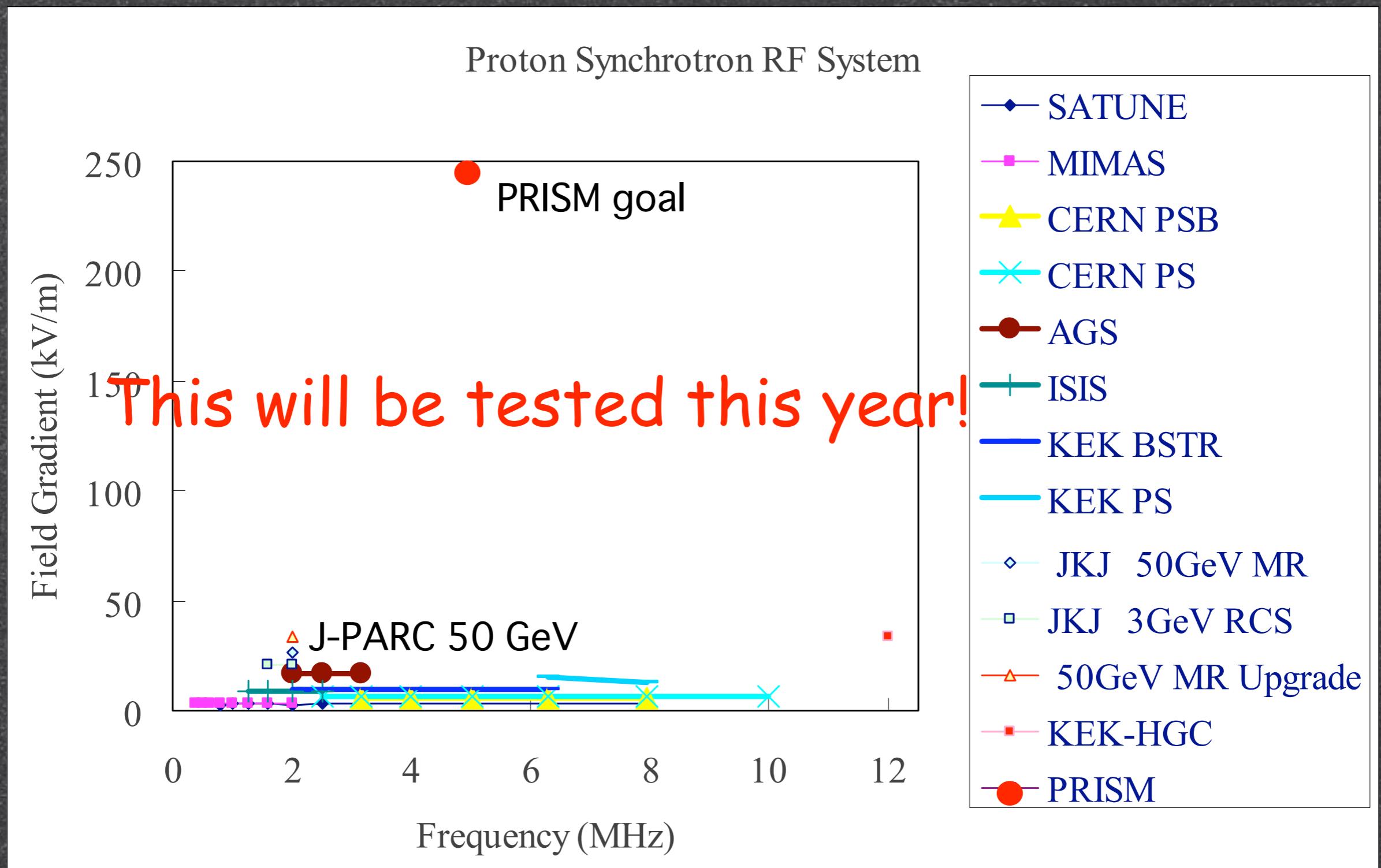


C. Ohmori, M. Aoki

Field gradient	250kV/m
# of gaps	4
Impedance	1 kohm/gap
core	MA 4 cores/gap
Duty	0. 1 % air cooling
Power Tube	EIMAC 4CW150K DC35-40kV 900 kW(peak)
Amplifier	AB-class, push-pull for each gap



# PRISM RF Field Gradient



PRISM goal > 250 kV/m

# Summary

- Physics potential for a Muon Factory
  - Muon LFV and muon EDM.
- Physics potential for a Neutrino Factory
  - MNS matrix and CP violation
- The use of FFAG for muon acceleration would be critical.
- J-PARC case is shown.
- The PRISM-FFAG ring construction has started.
- We should work hard and together so as not to miss the opportunity of the great discovery.

6th International Workshop on Neutrino Factories & Superbeams

# NuFact 04

July 26 - August 1, 2004  
Osaka University, Osaka, Japan

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# NuFact04

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