What is a Neutrino Factory ?

Neutrino Beam Sources

- Pion-decay based neutrino beam

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\pi^- \to \mu^- \overline{\nu}_\mu$$

Prompt decays

  - As beam backgrounds

$$K \to \mu\nu, K \to \pi l \nu$$

$$\mu \to e\nu\overline{\nu}$$

  - Beam normalization uncertainty ~ 10%

- Muon-decay based neutrino beam
  - After decays of pions and kaons

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

$$\mu^- \to e^- \overline{\nu}_e \nu_\mu$$

  - Less beam background
  - Beam normalization better known

More Neutrinos !

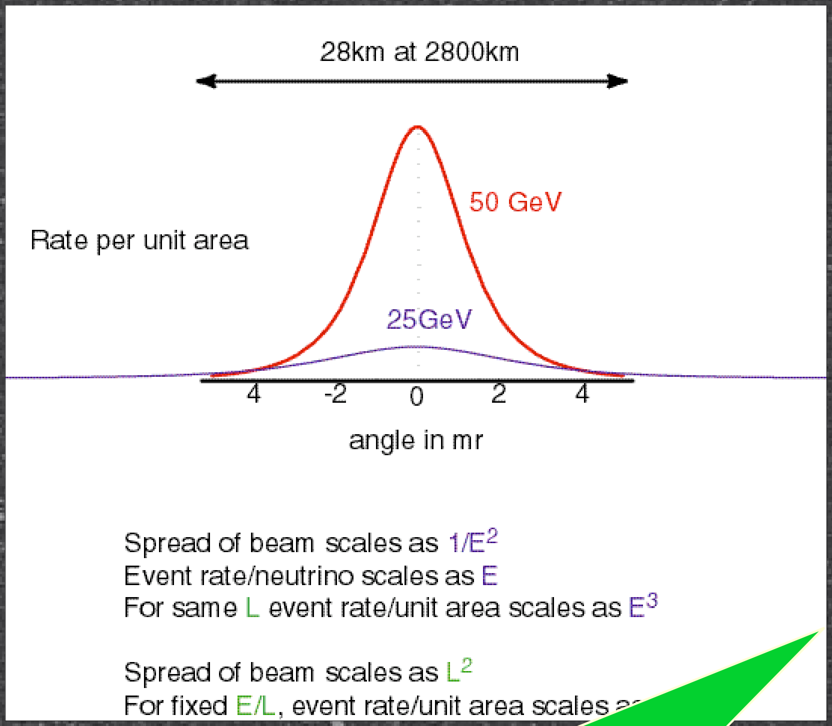
- Given the proton beam power, numbers of pions and muons are similar.
- Acceleration of parent particles gives more neutrinos by boosting.
- Pion production cross section is high around 200-300 MeV/c.
- Only muons live long enough to accelerate.

$$N \propto \gamma^2$$

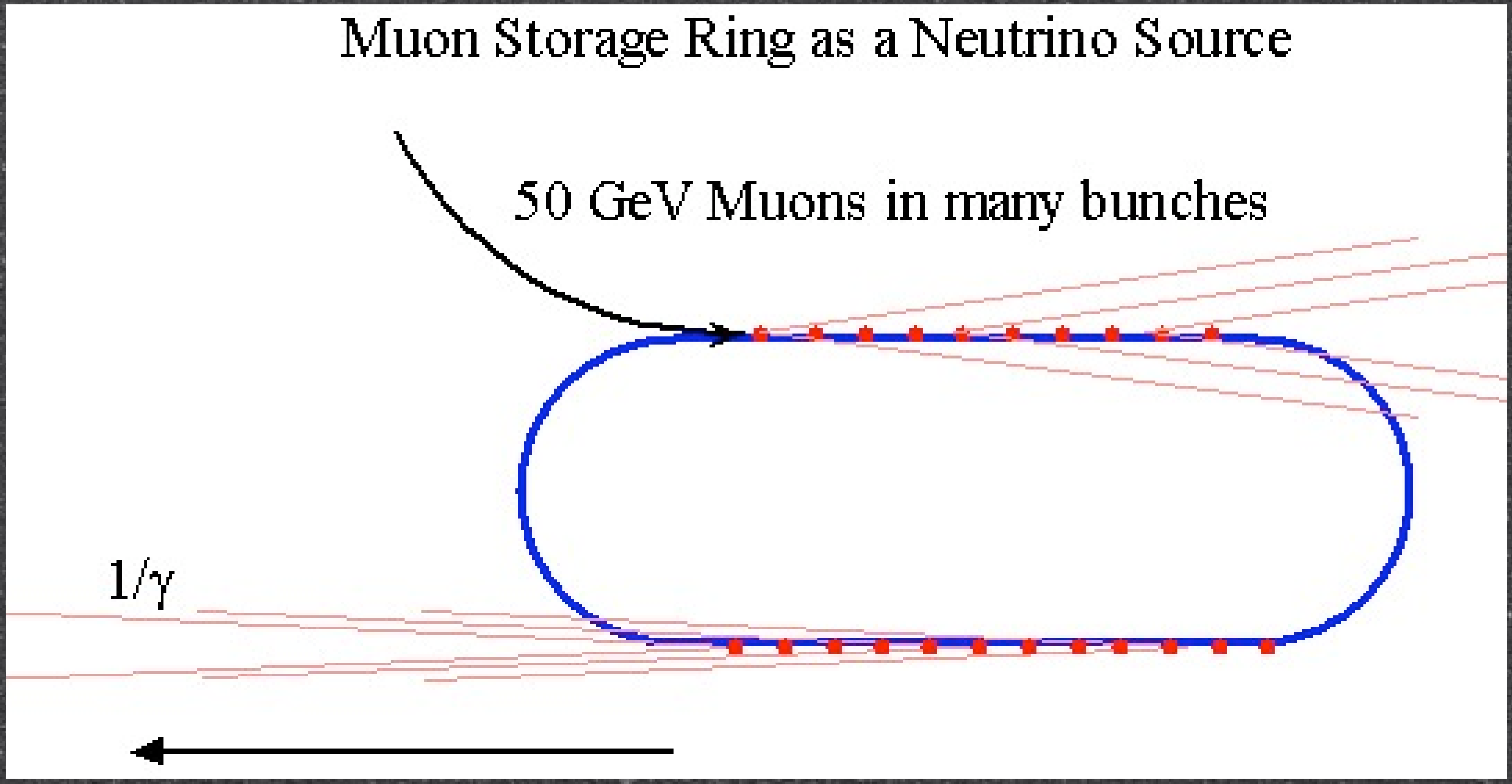
Muon acceleration!!!

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, γ=500 and beam spread is 2 mrad



$$\theta \propto \frac{1}{\gamma}$$

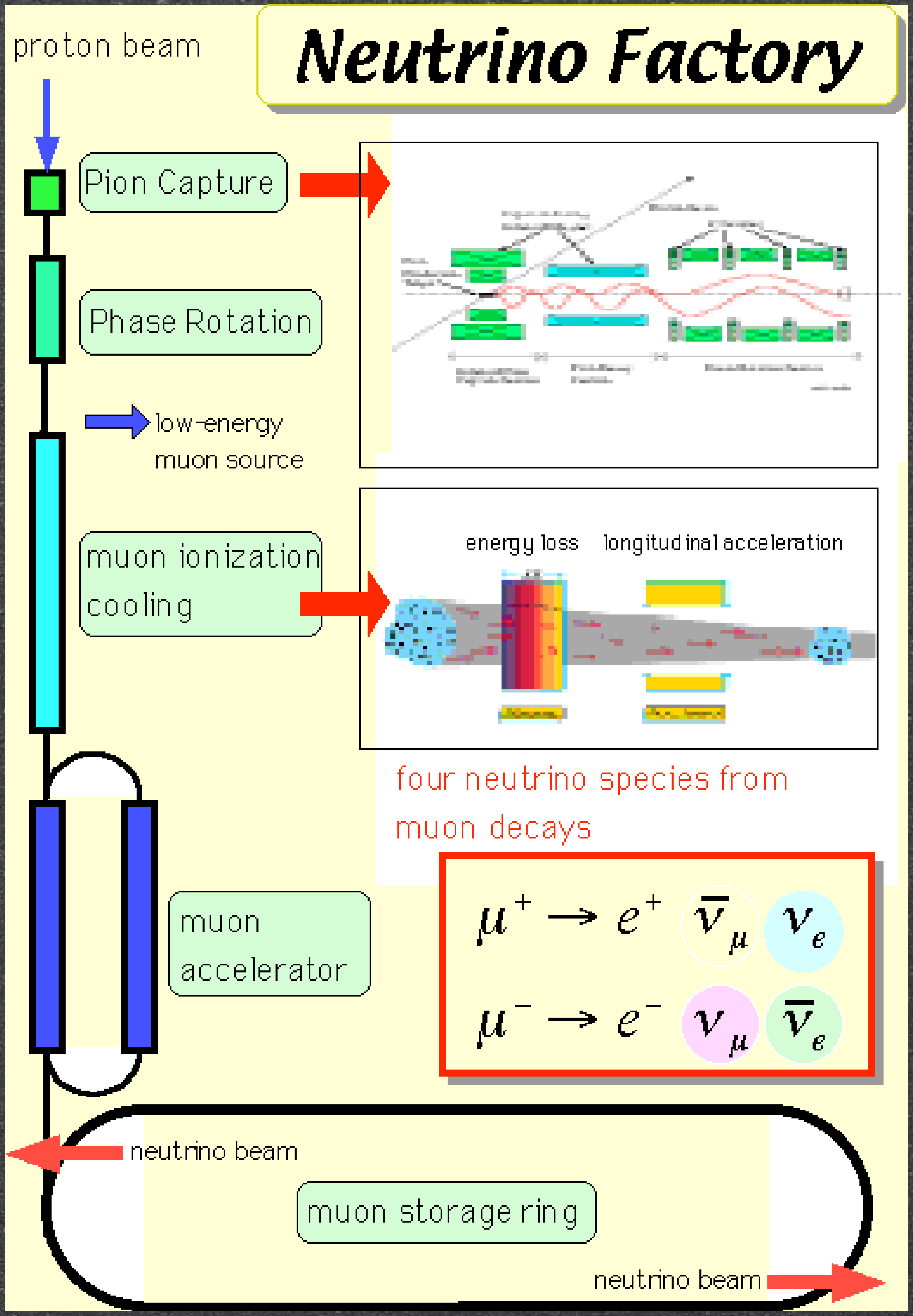
$$N \propto \gamma^2$$

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 than10^{-4} level
    - a few % level at the conventional sources.
- Precise knowledge on neutrino intensity and emittance

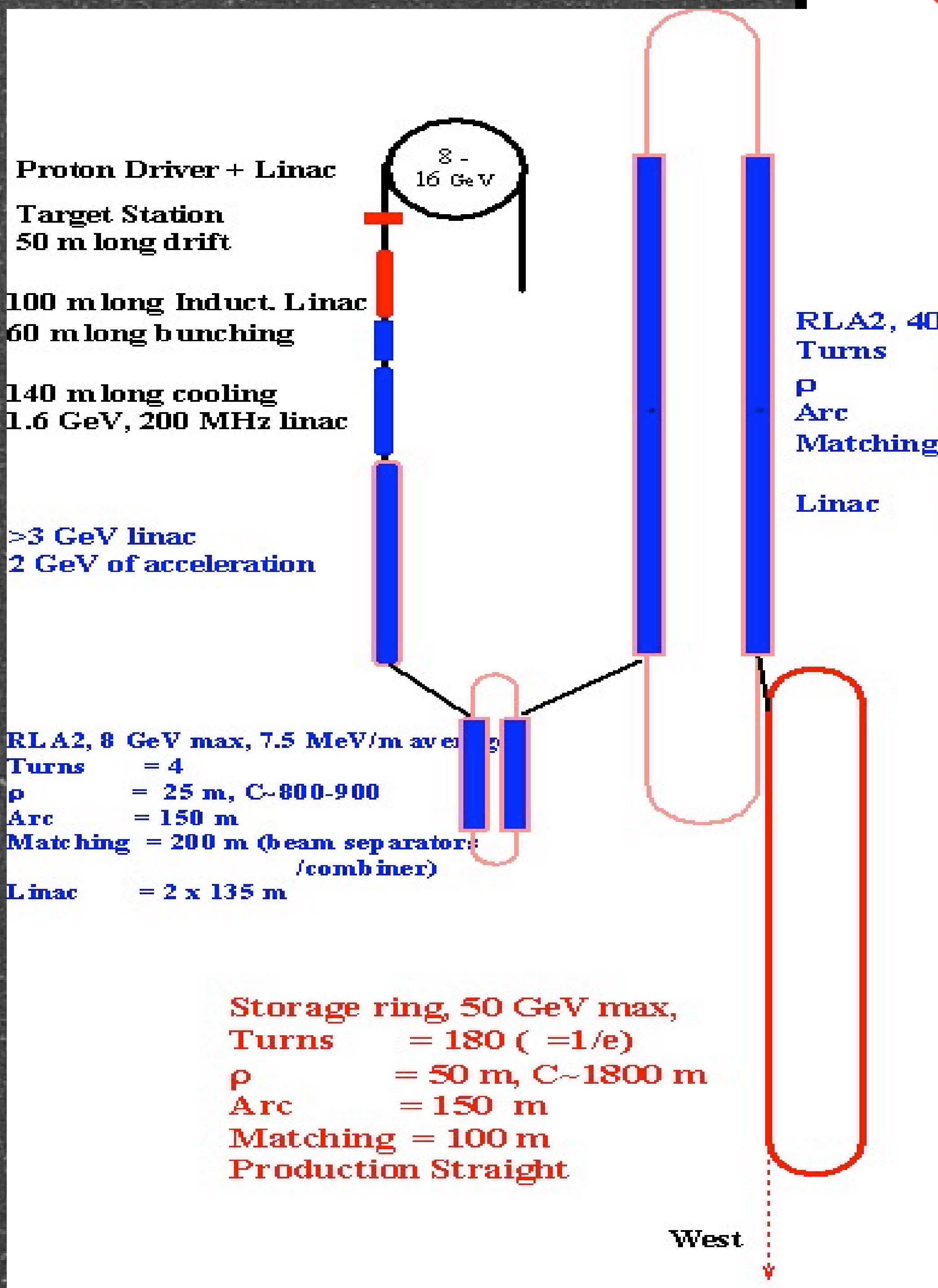
NuFACT Scheme

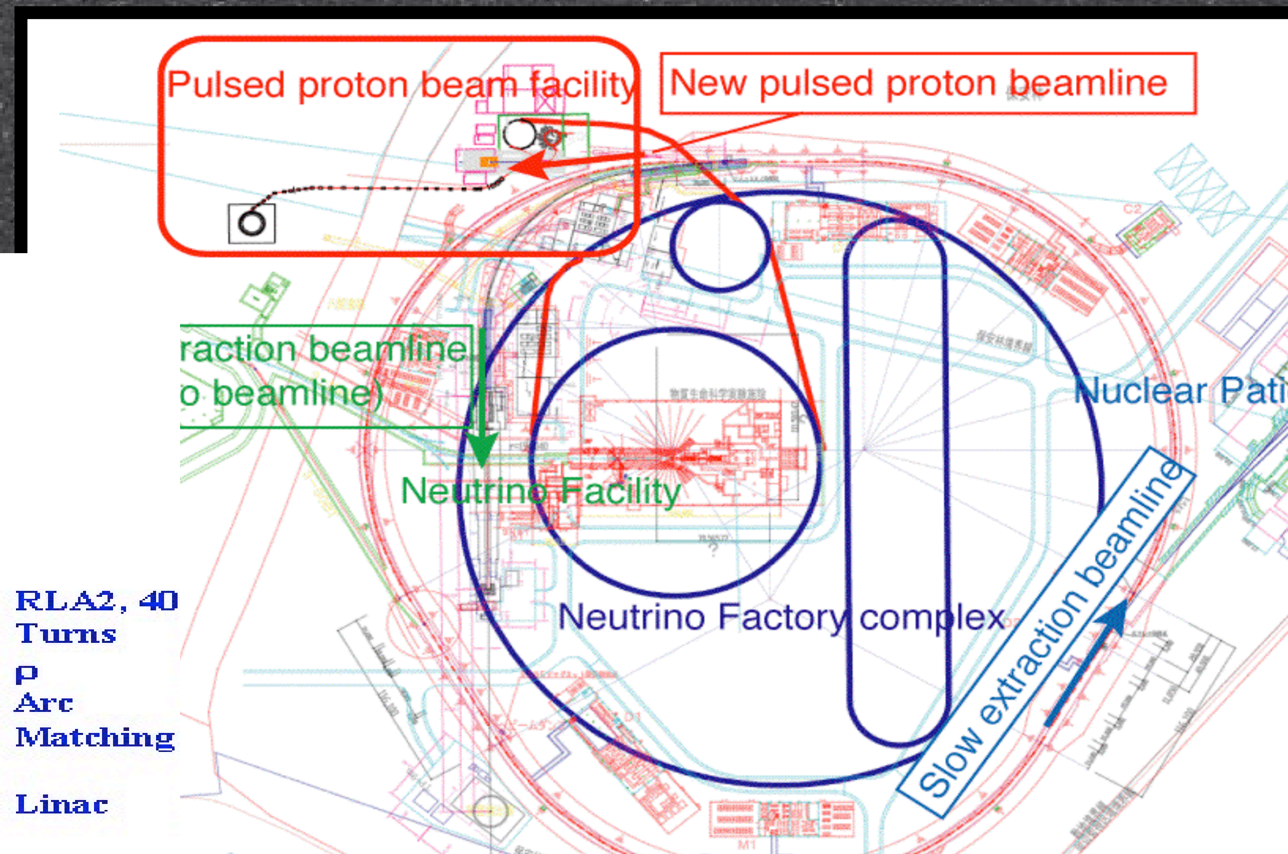
- Proton on target
- Pion Collection
- Phase Rotation
- Ionization Cooling
- Acceleration
  - FFAG acceleration
- Storage Ring



NF Studies in the World

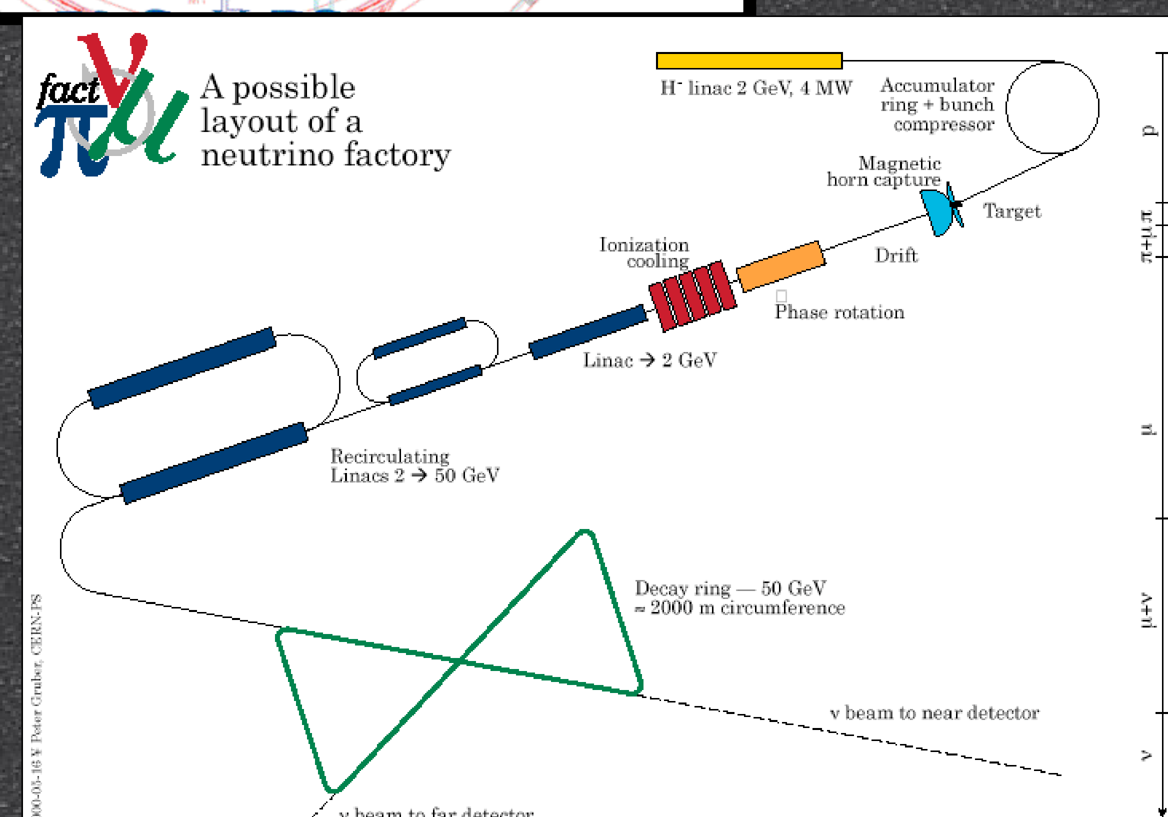
US





Japan

Europe



Neutrino Oscillation Physics at a Neutrino Factory

Neutrino Oscillation

flavor states : ν_α $\alpha = e, \mu, \tau, \ldots$

mass states : ν_i $i = 1, 2, 3, \ldots$

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

Maki-Nakagawa-Sakata matrix

For 3 Neutrino Mixing

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

atm unknown solar Majorana phases

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

- 3 mixing angles θ_a , θ_s , θ_x
- 3 complex phases δ , ϕ_2 , ϕ_3 (CP)

Oscillation probabilities do not depend on ϕ_2 , ϕ_3

Present Knowledge

Atmospheric neutrinos

$$\Delta m_{32}^2 = \Delta m_{atm}^2 \approx 3\times10^{-3} eV^2$$

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

Reactor Neutrinos

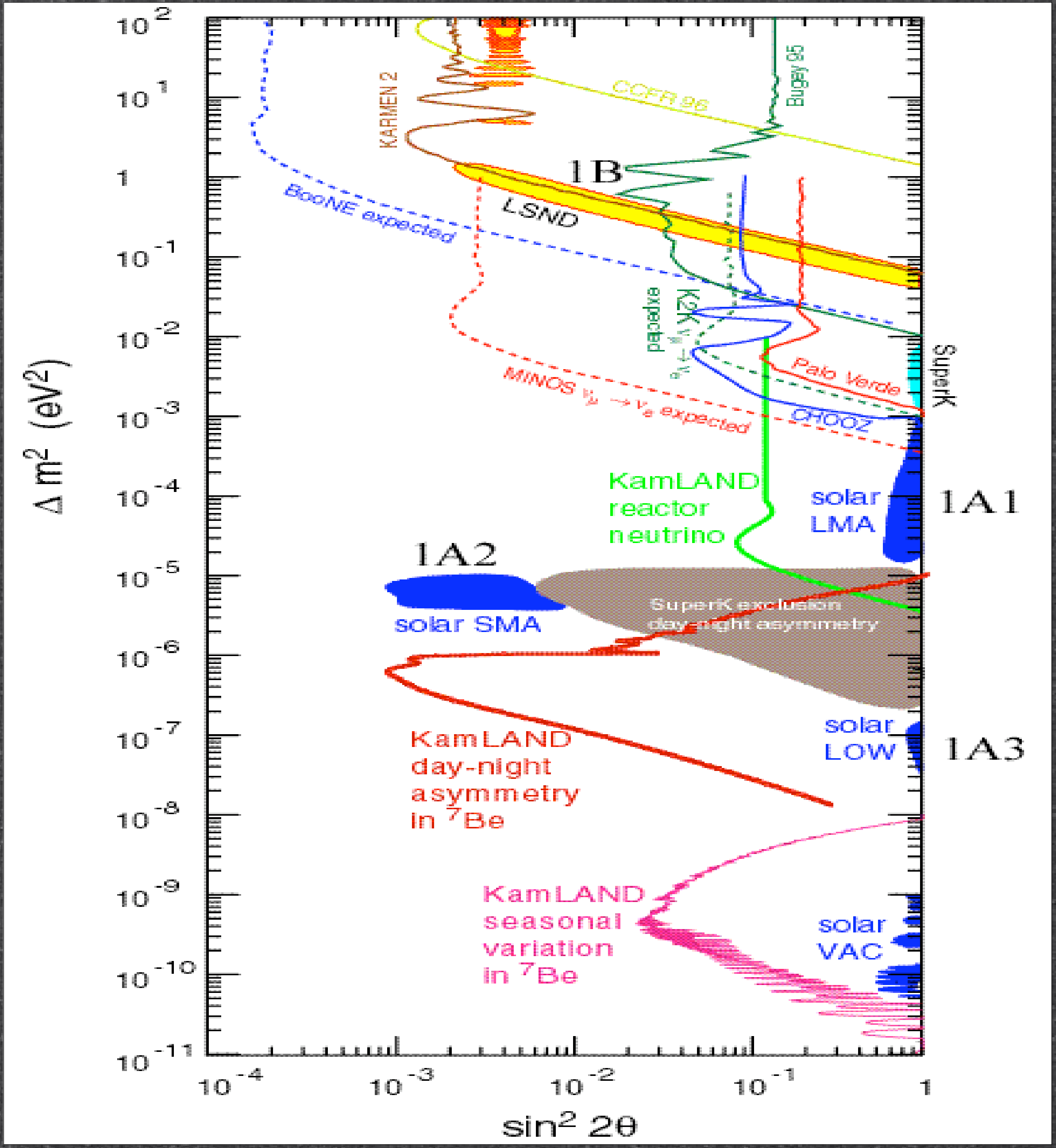
$$sin^2 2\theta_{13} < 0.1$$

Solar Neutrinos

$$\Delta m_{21}^2 = \Delta m_{solar}^2 = 7\times10^{-5}$$

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

No Information on δ_{CP}



Oscillation Signature at NF

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

$\nu_\mu \rightarrow \mu^-$

oscillation ↓ $\bar{\nu}_\mu \rightarrow \mu^+$

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

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

oscillation ↓ $\nu_\mu \rightarrow \mu^-$

Look for wrong signed Muons.

charge identification is needed.

NuFACT Event Rates

Charged current (CC) event rate

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

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

Oscillation event rate

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

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

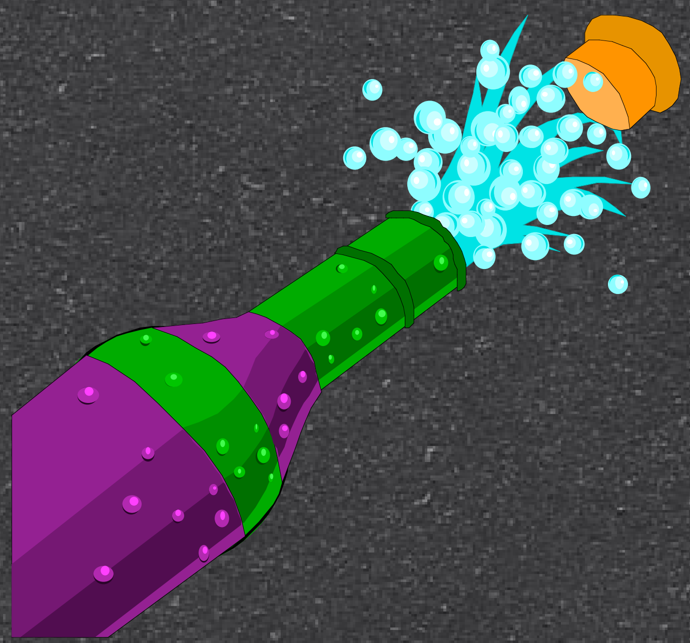
$$\propto \frac{E_\mu^3}{L^2} \cdot \frac{L^2}{E_\mu^2} = E_\mu$$

a number of CC event rate/year

10 kton detector

10^{21} muons/year

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



Oscillation Programs

- Observation of $\nu_e \to \nu_\mu$ oscillation
  - Sign of δm^2 (pattern of neutrino masses)
  - Matter effect
- First observation of $\nu_e \to \nu_\tau$ oscillation
- Unitarity of MNS matrix
- Measurement of oscillation

$$\nu_\mu \to \nu_\tau$$
$$\nu_\mu \to \nu_e$$

- Search for CP violation

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

  - Matter effect
- Search for T violation

$$P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)$$

  - No matter effect
  - Detection harder
- Search for CPT violation

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

θ_{13} Reach

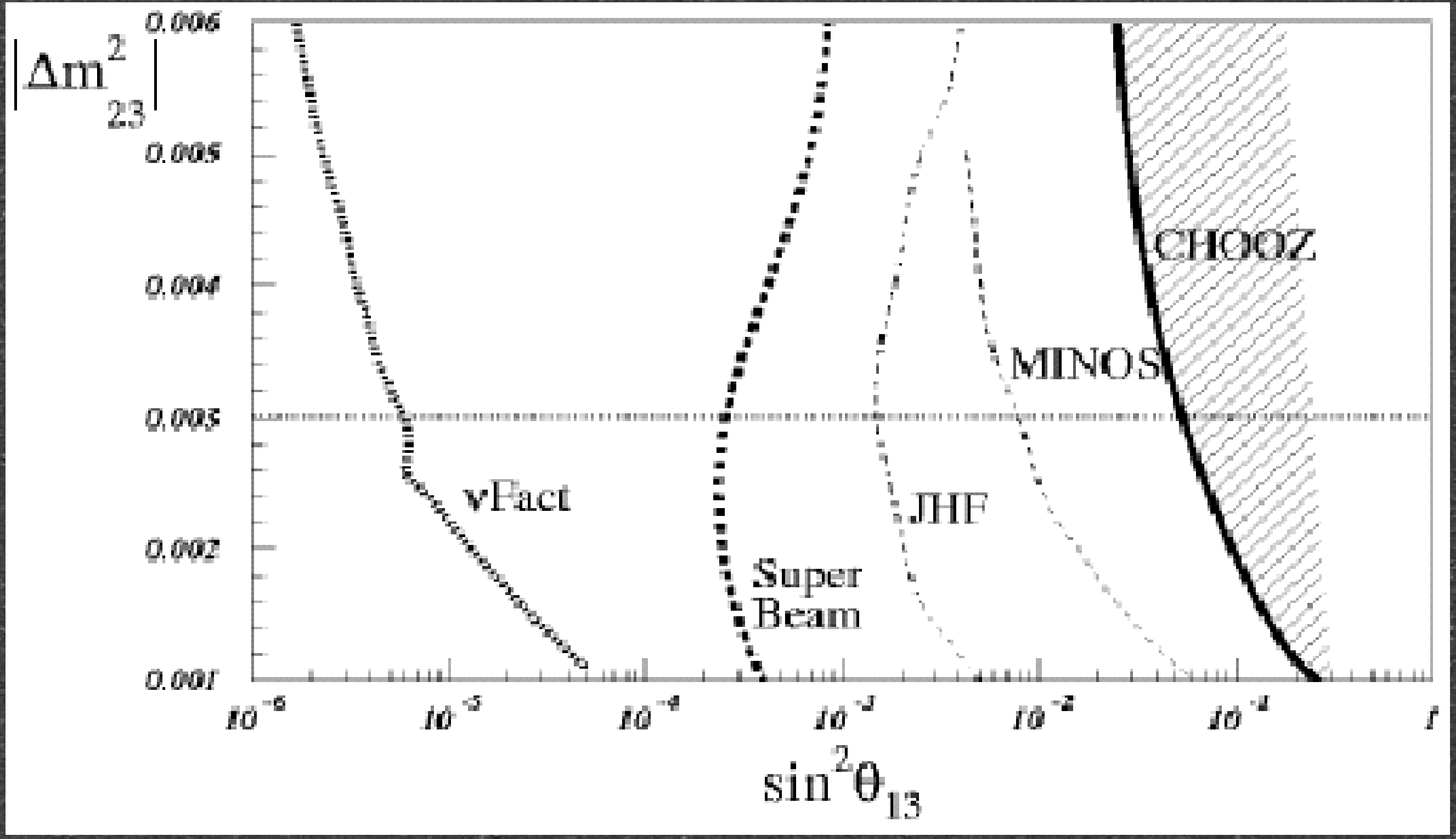
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.267\Delta m^2_{32}L/E_\nu)$$
$$P(\nu_e \rightarrow \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.267\Delta m^2_{32}L/E_\nu)$$
$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.267\Delta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

L=baseline (km)
E_ν=energy (GeV)

A high energy ν_e beam offers unique possibilities!

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

Gives best sensitivity to θ_{13} of any technique:



CP Violation

CP-odd osc. probability

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

possible only if Δm_{12}^2 and s_{12} are large and s_{13} is large

LMA　　　　need to know

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

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

CP-odd asymmetry

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

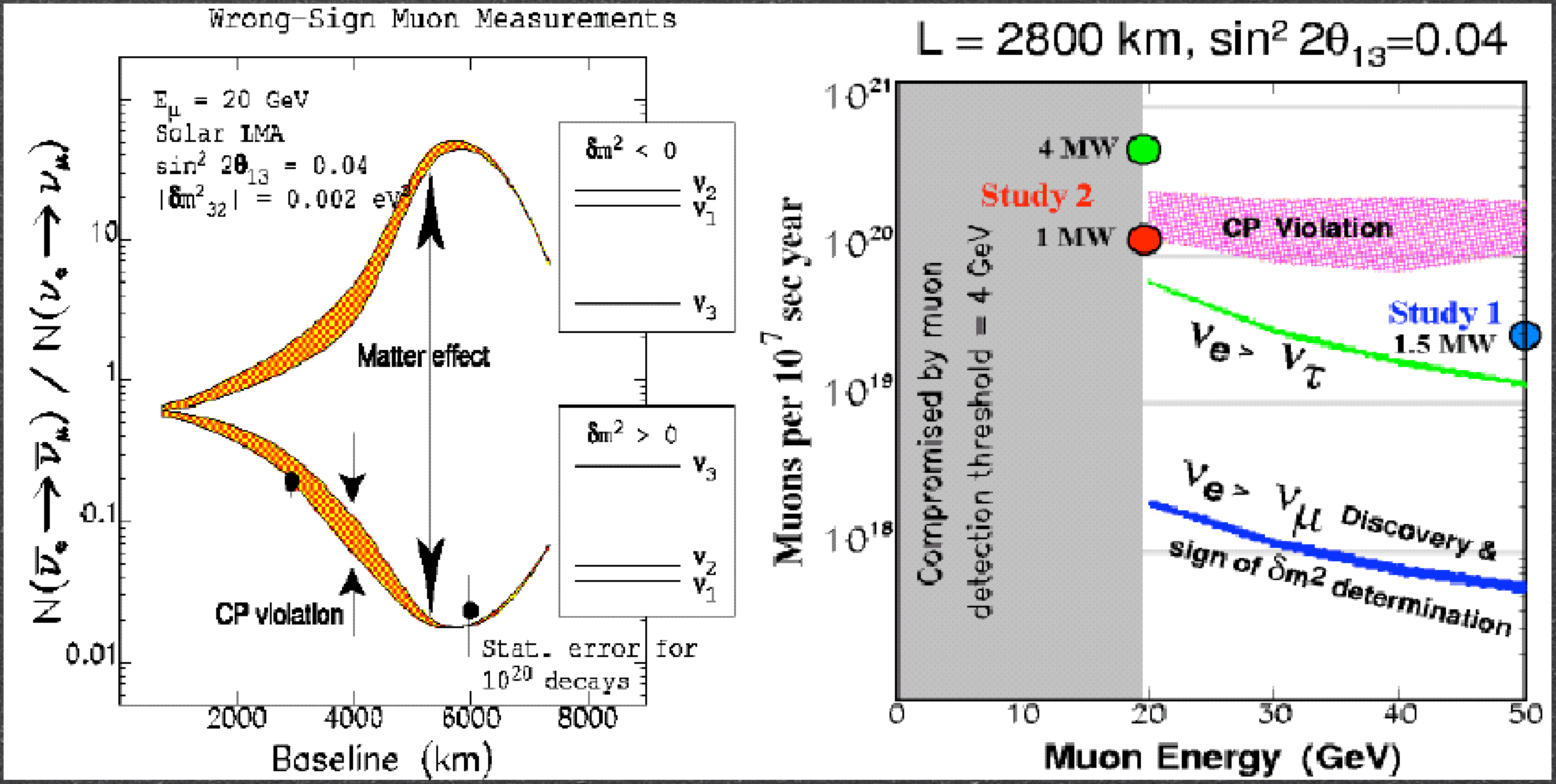
Figure of Merit

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

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

CP Reach

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



Discovery Reach Summary

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

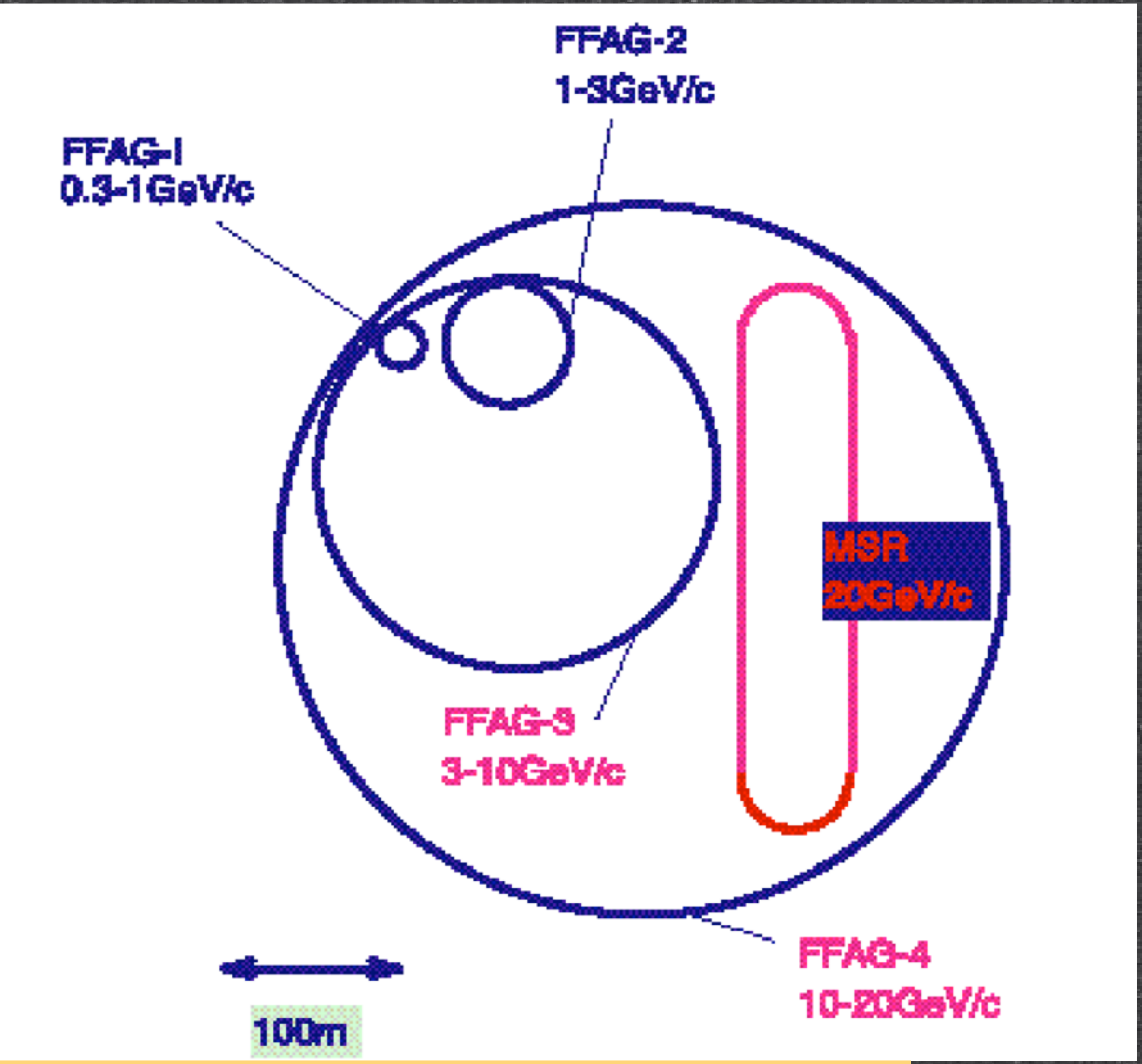
J-PARC Case
(Neutrino Factory)

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 !!!

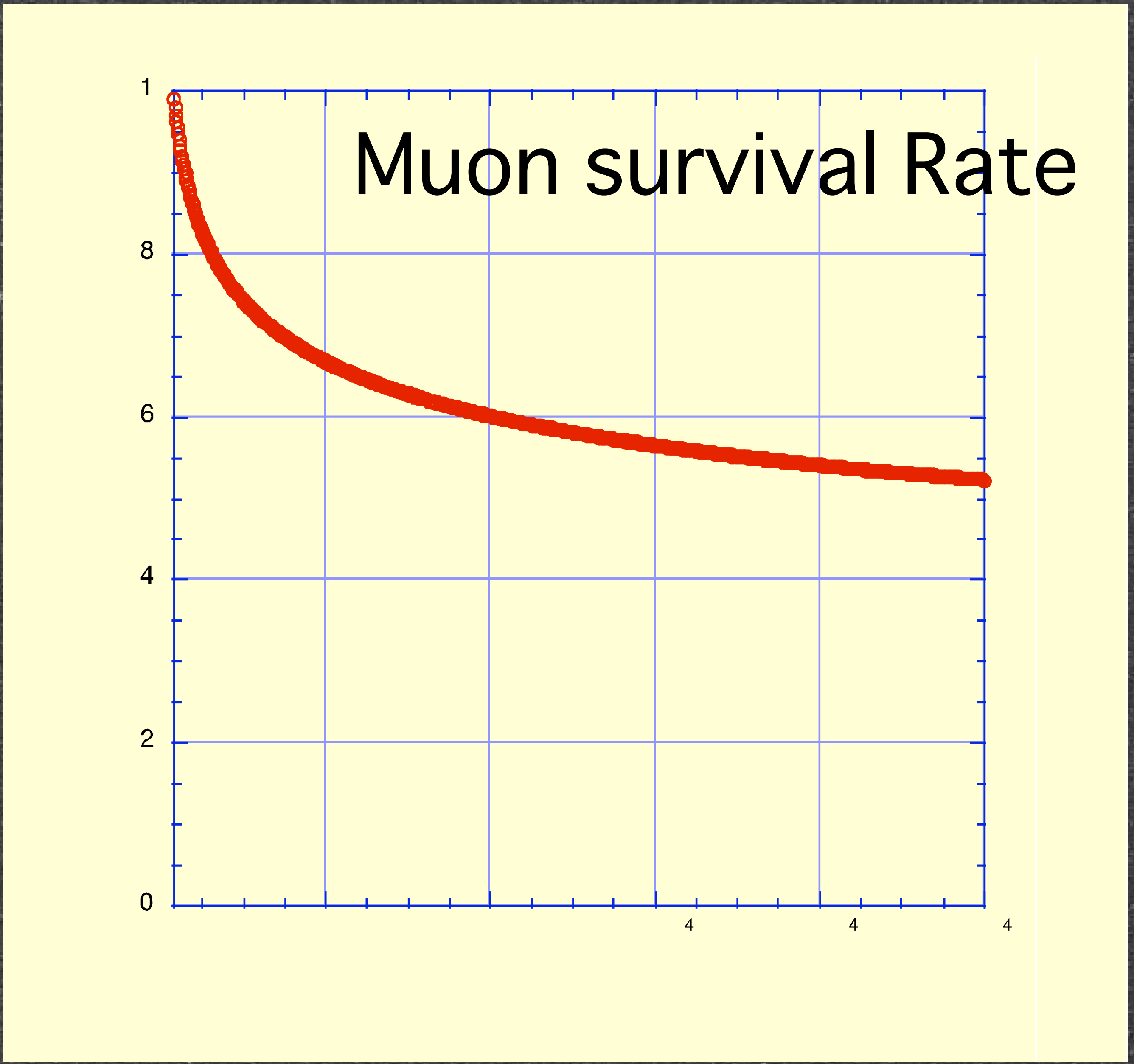
A series of 3-4 FFAG rings



Muon Acceleration based on a series of FFAGs

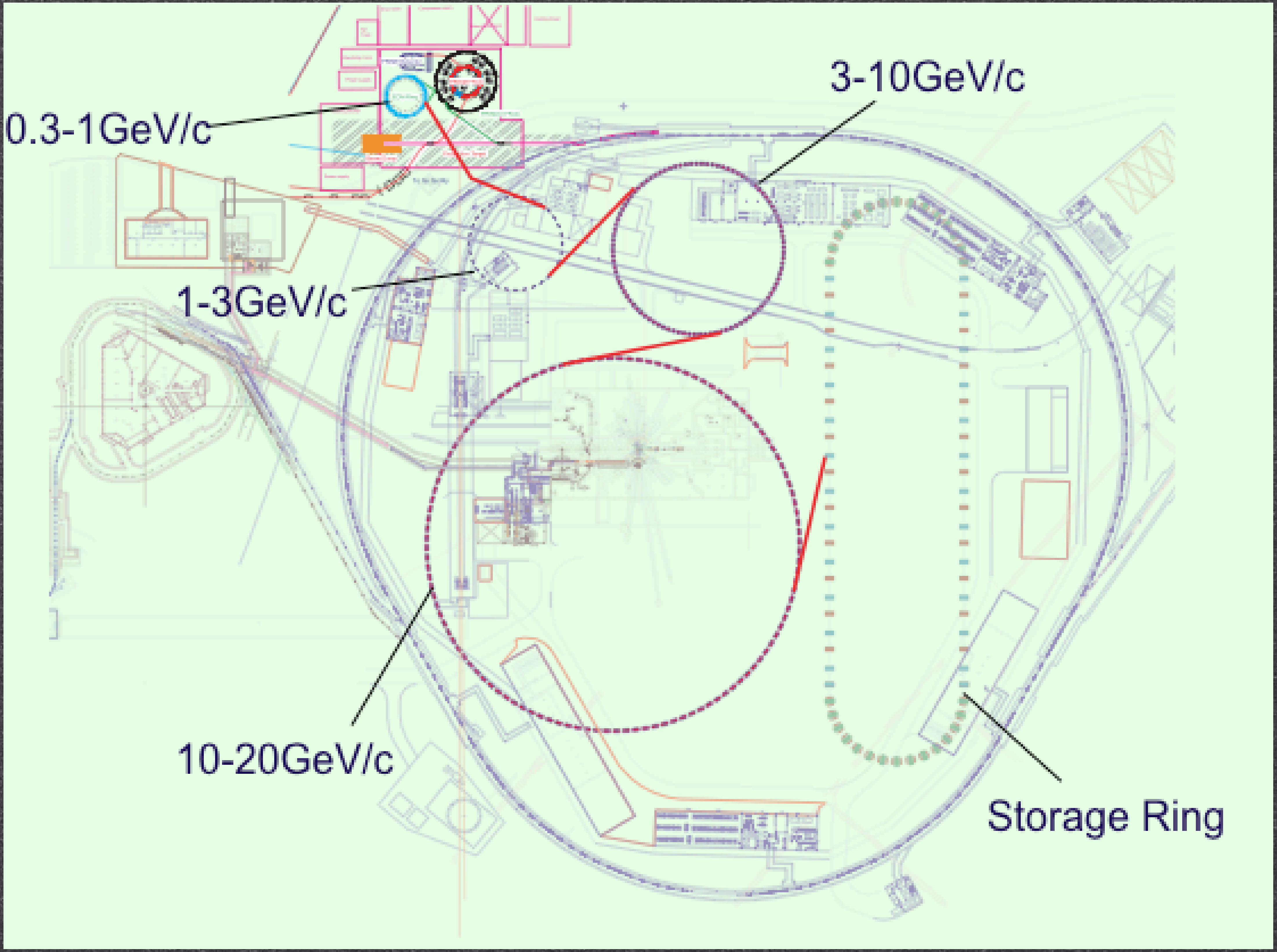
Muon Yield Estimation

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



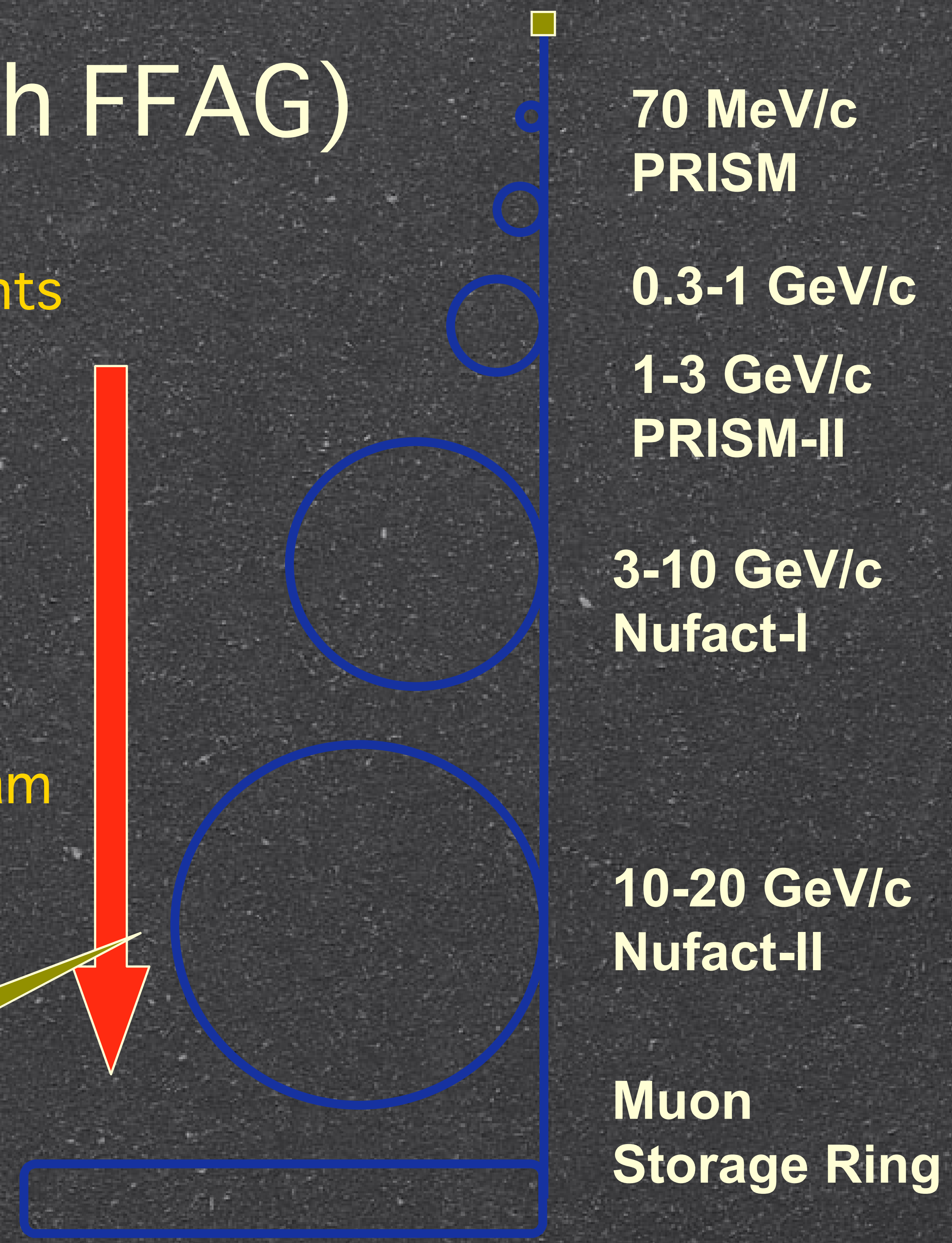
$$\text{Yield} = 2 \times 10^{21} \times 0.3 \times 0.52 \times 0.3$$
$$= 1 \times 10^{20} \text{ muons/decay/year}$$

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



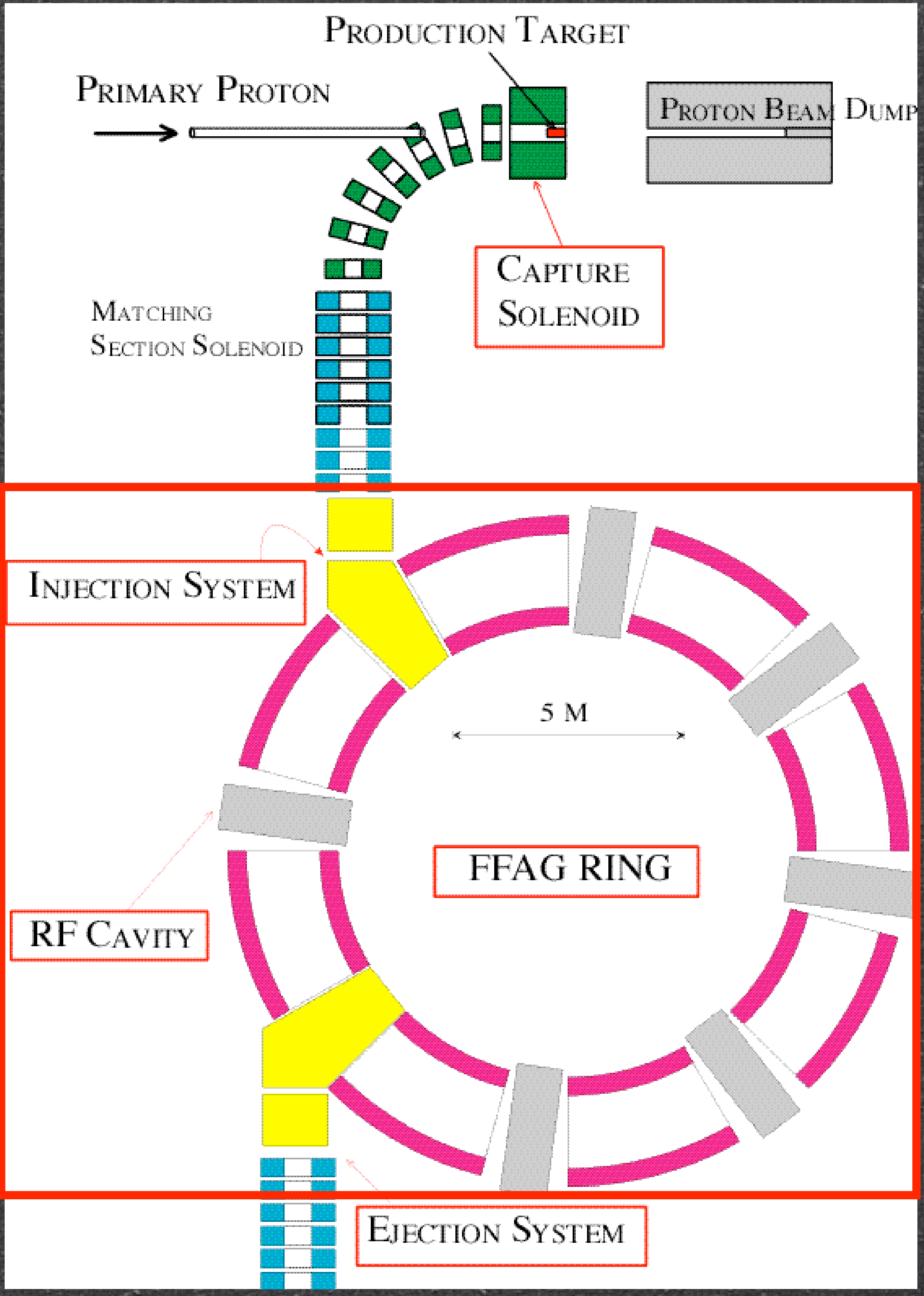
Physics outcome at each stage

PRISM R&D STATUS

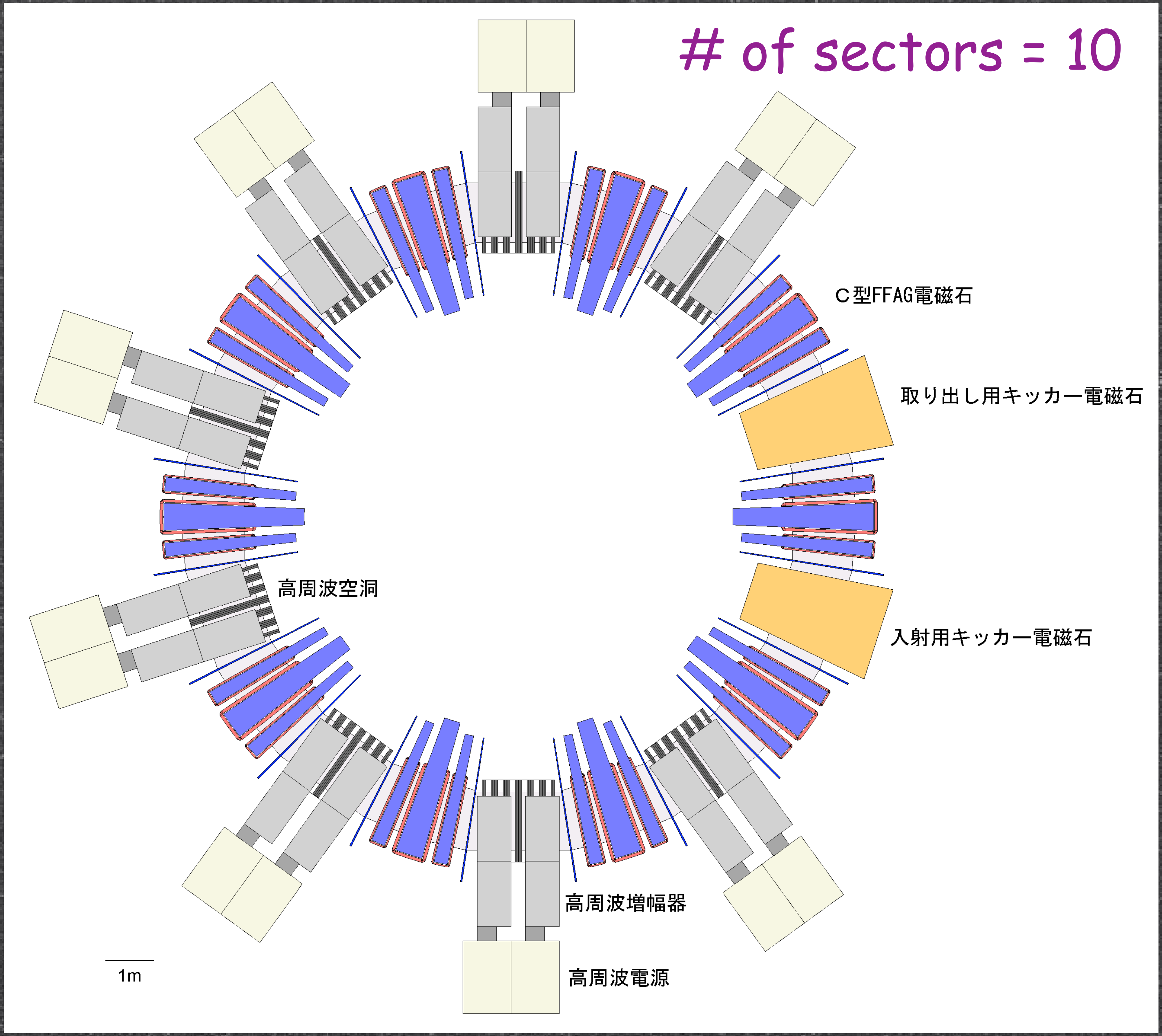
PRISM Ring Construction

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)

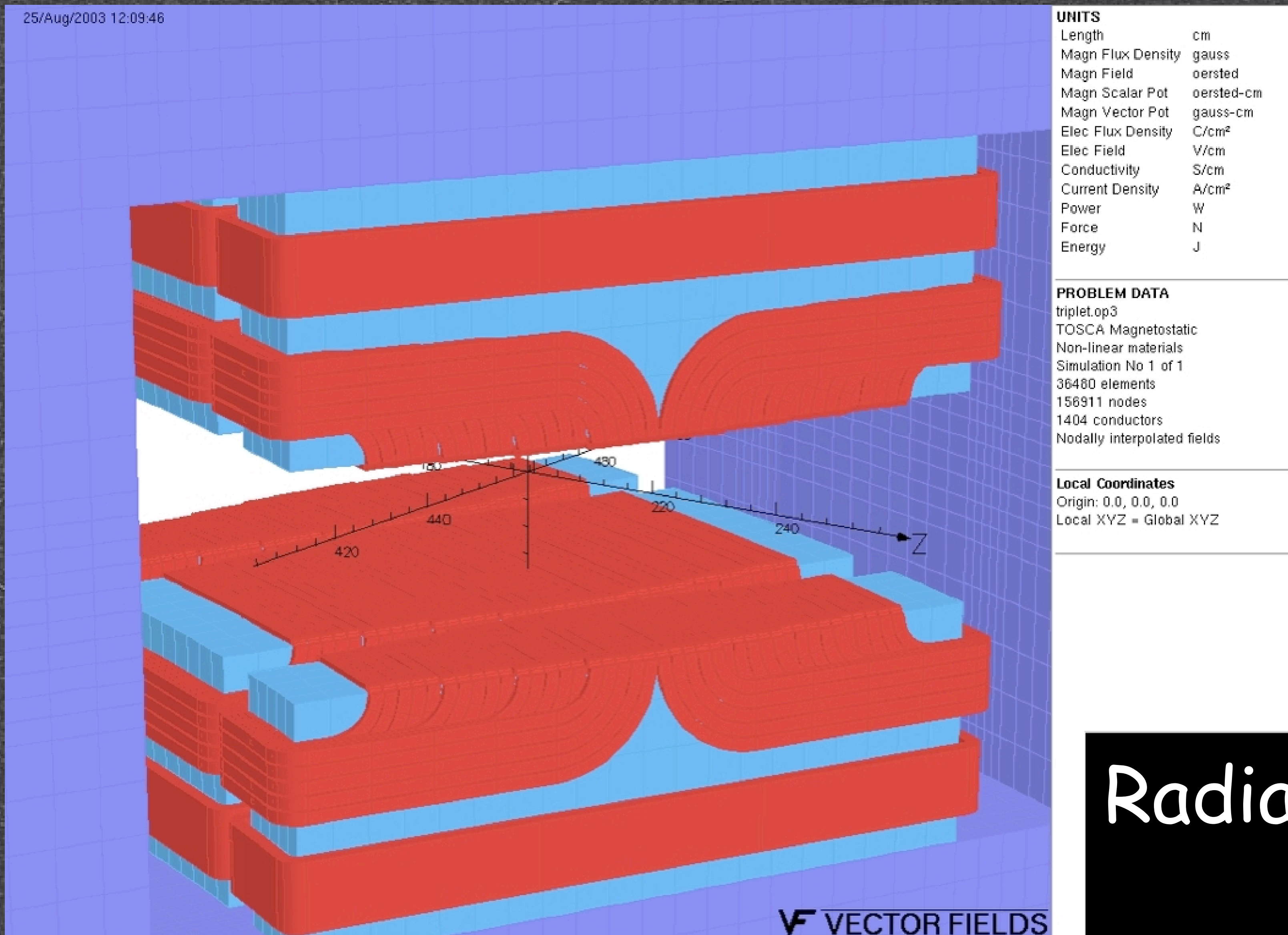
JFY2006:

FFAG magnets (4)

JFY2007:

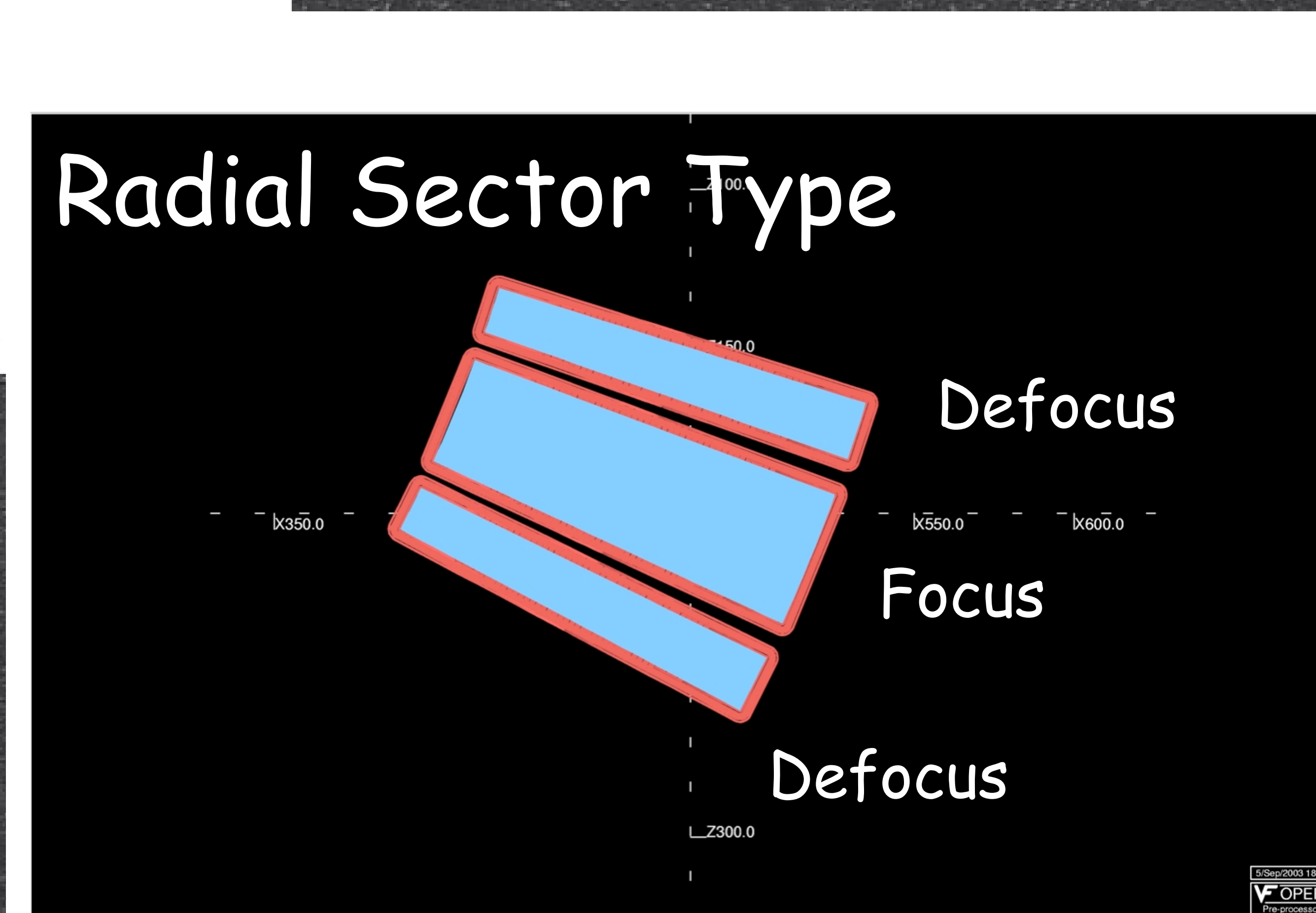
chambers, etc.

FFAG Magnet Design



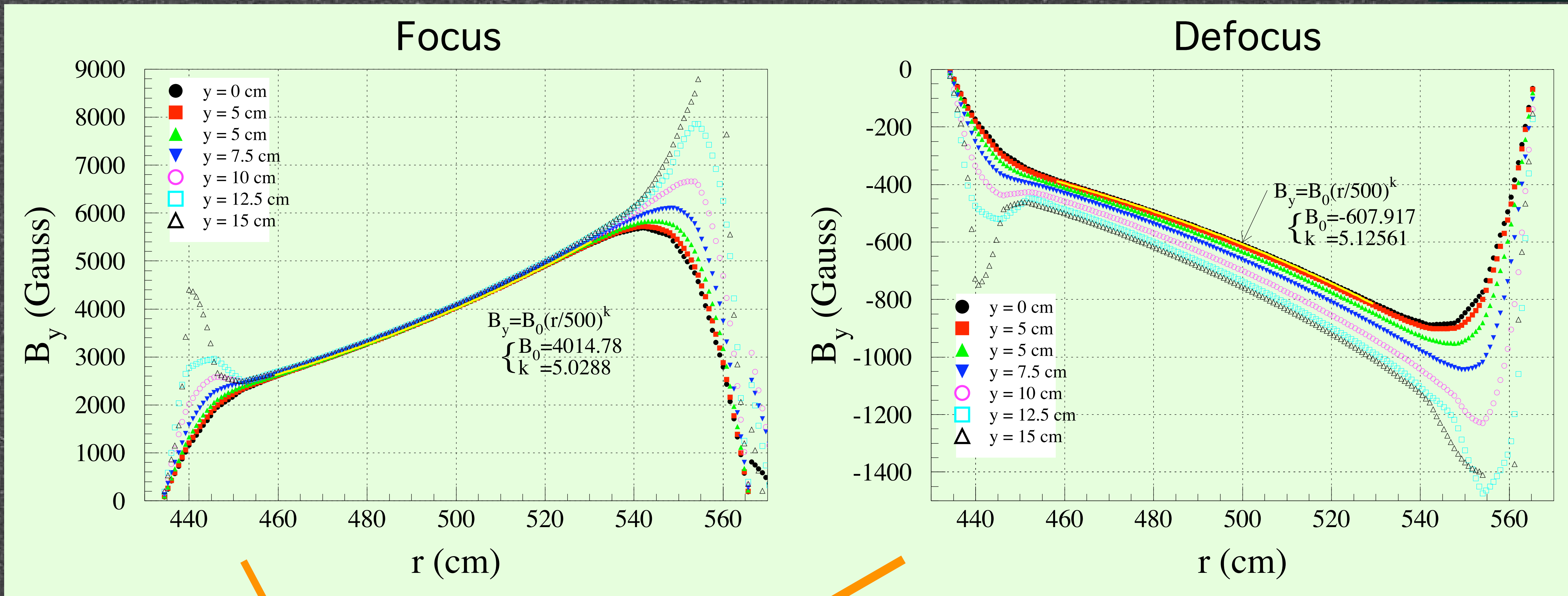
FFAG field

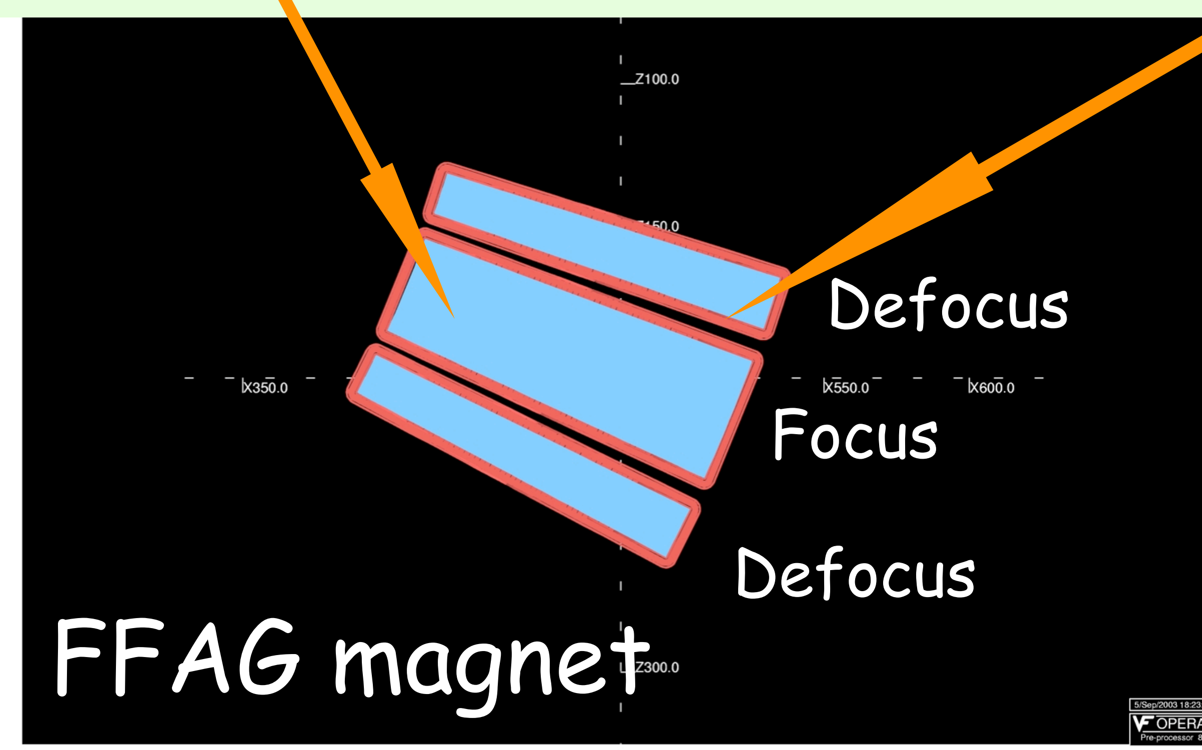
$$B(r) = B_0\left(\frac{r}{r_0}\right)^k$$



Y. Arimoto

FFAG Field Calculation





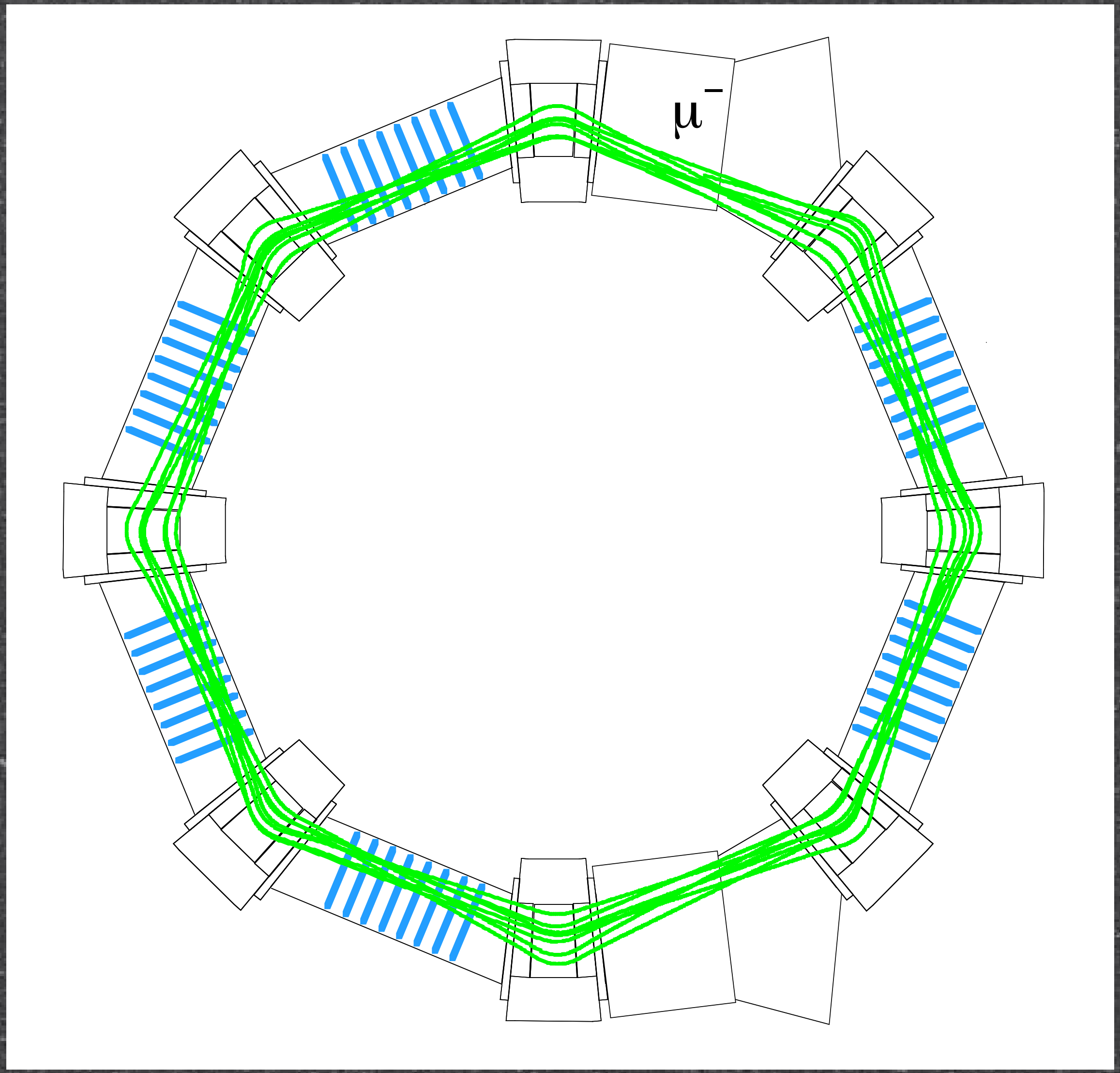
3-dim. Field Calculation

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

Y. Arimoto

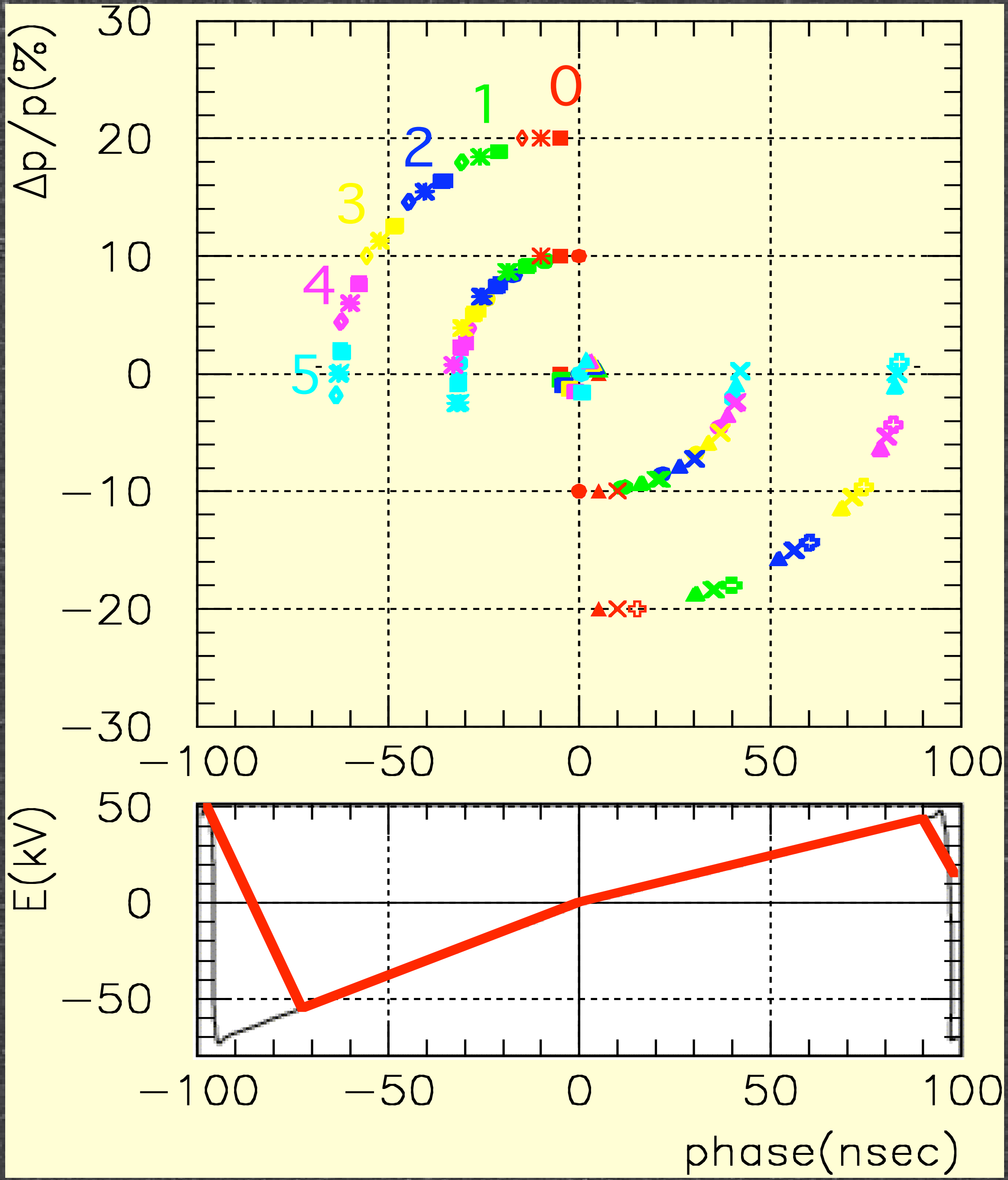
Tracking Simulation

GEANT3 simulation with TOSCA magnetic field



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

$\pm 5nsec$ muon width at given momentum



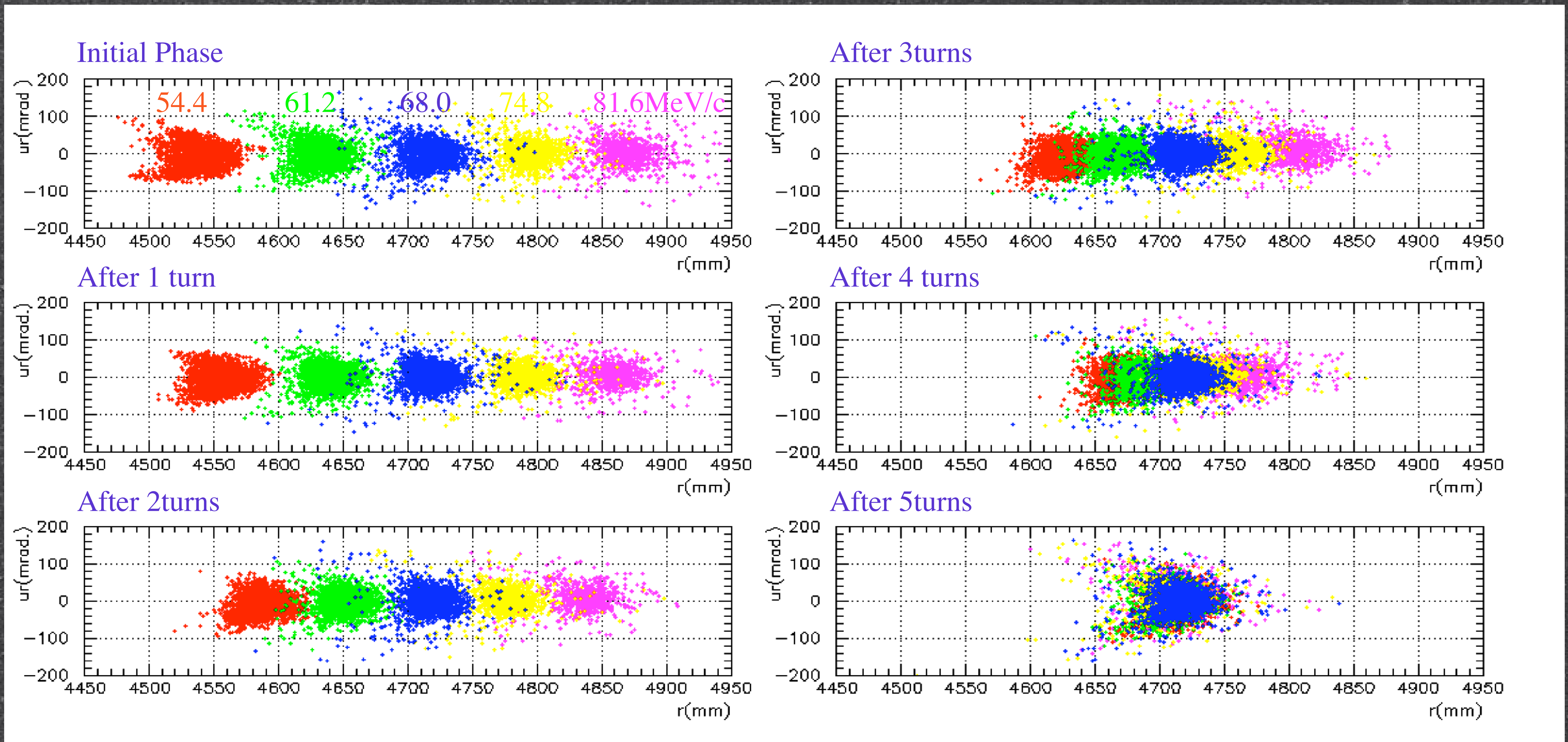
RF 5MHz, 250 kV/m

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

A. Sato

Phase Rotation Simulation

Horizontal

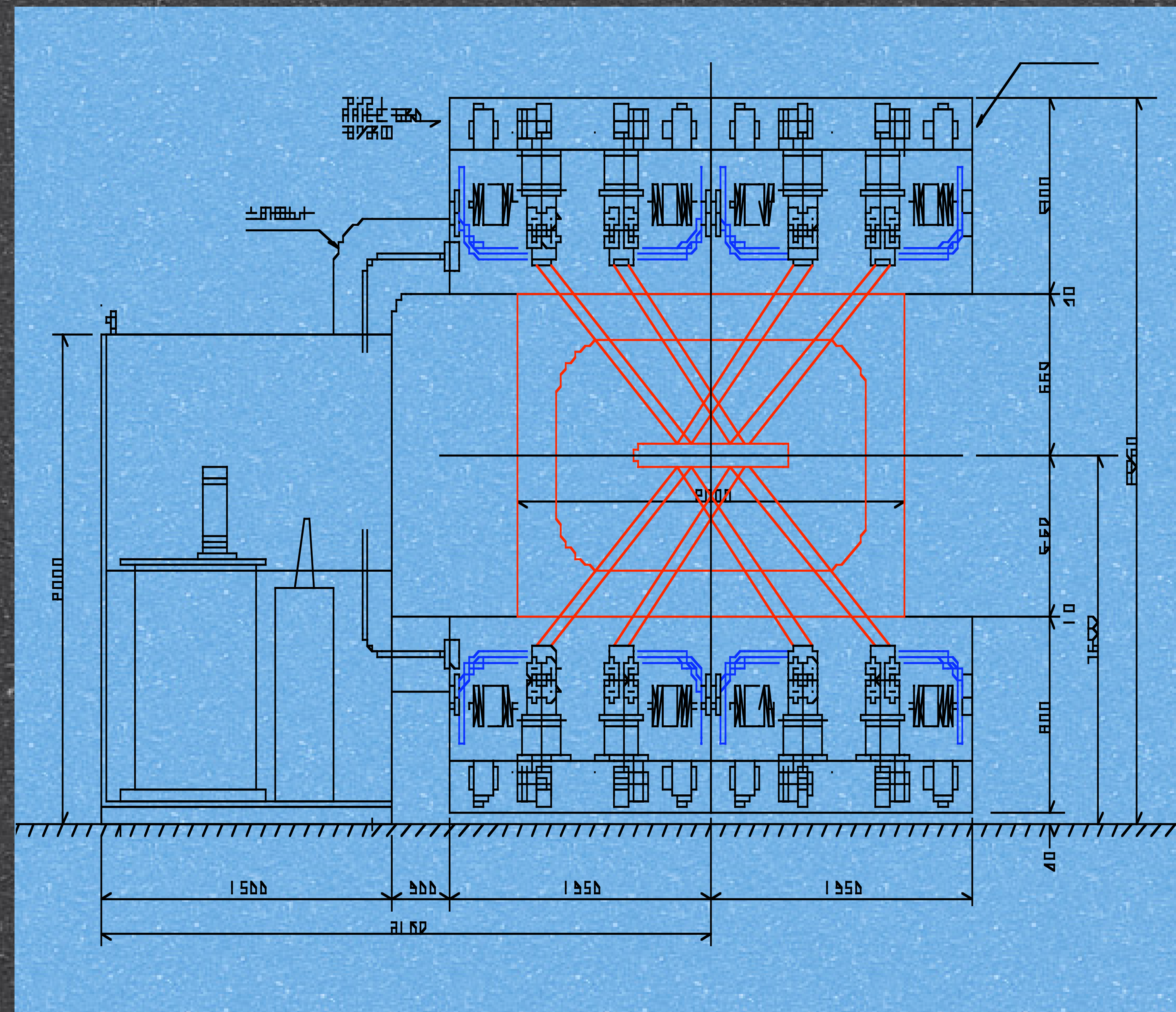


A. Sato

PRISM RF System

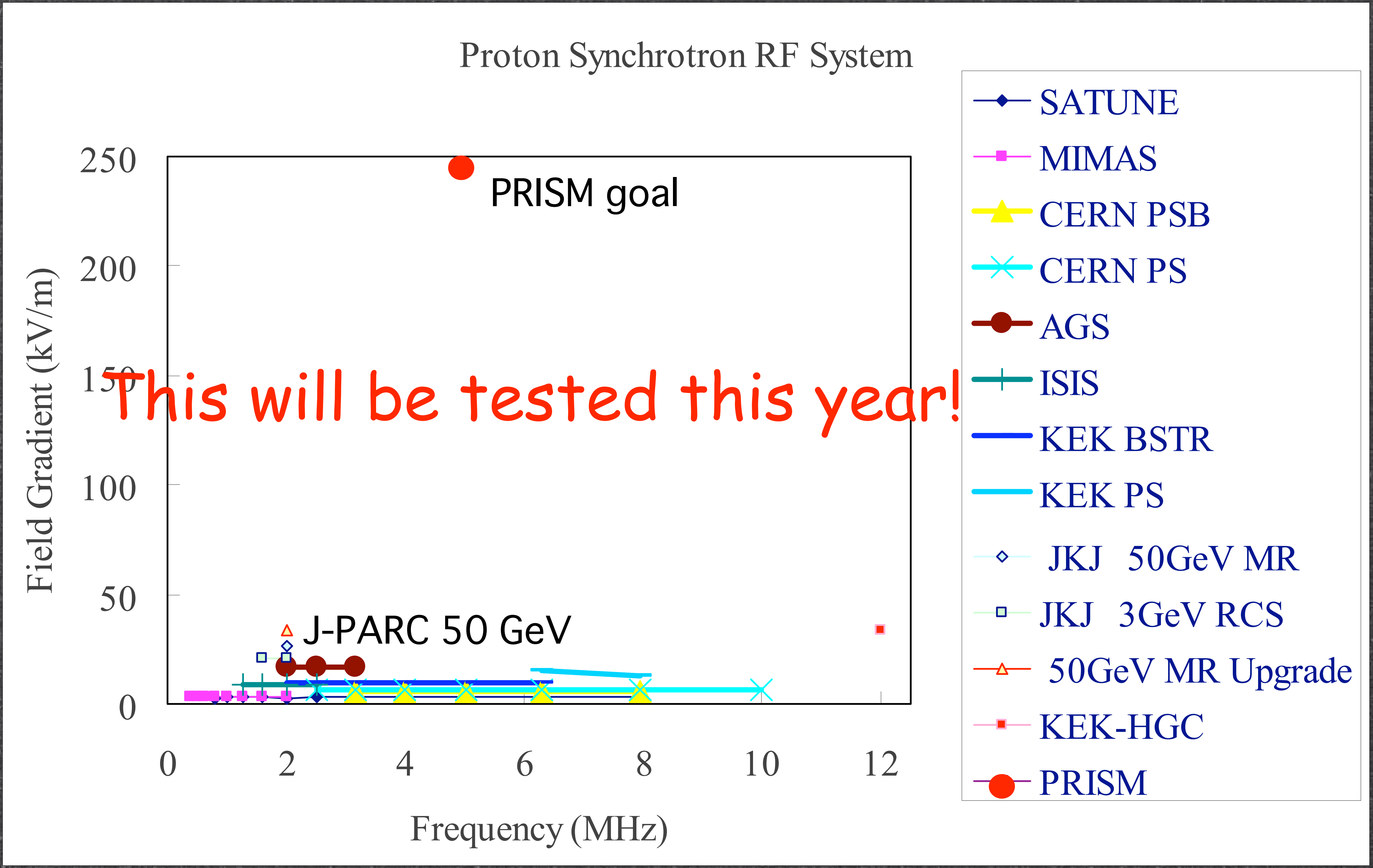
C. Ohmori, M. Aoki

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



RF cavity and amplifiers are constructed in 2003/2004

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.

NuFact04

July 26-August 1, 2004
Osaka University, Japan