A High-Intensity, High-Luminosity Muon Source PRISM and A Search for Muon-electron Conversion

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Osaka University

November 9th, 2005

"Flavour in the Era of the LHC", CERN

Outline

- Muon to Electron Conversion
  - What ?
  - Experimental
- PRISM Project (muon source)
  - PRISM and PRIME
  - PRISM FFAG-ring R&D and Roadmap
- at J-PARC
- Summary

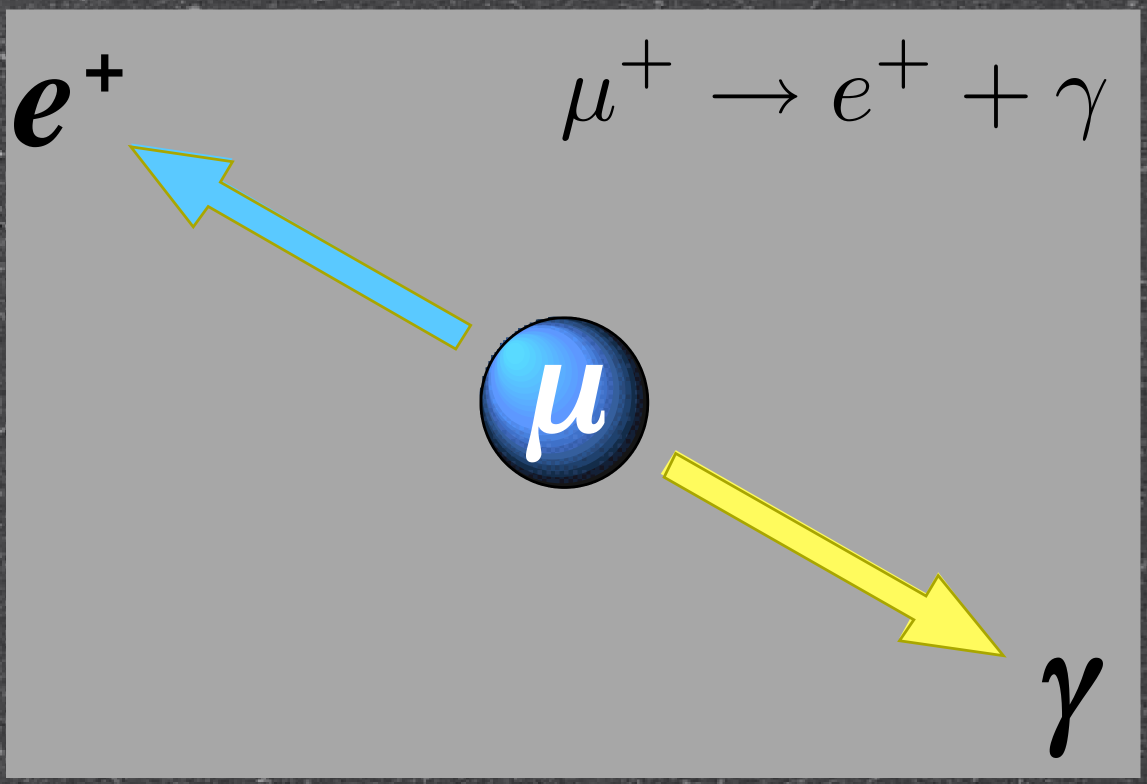
Upper Limits for LFV

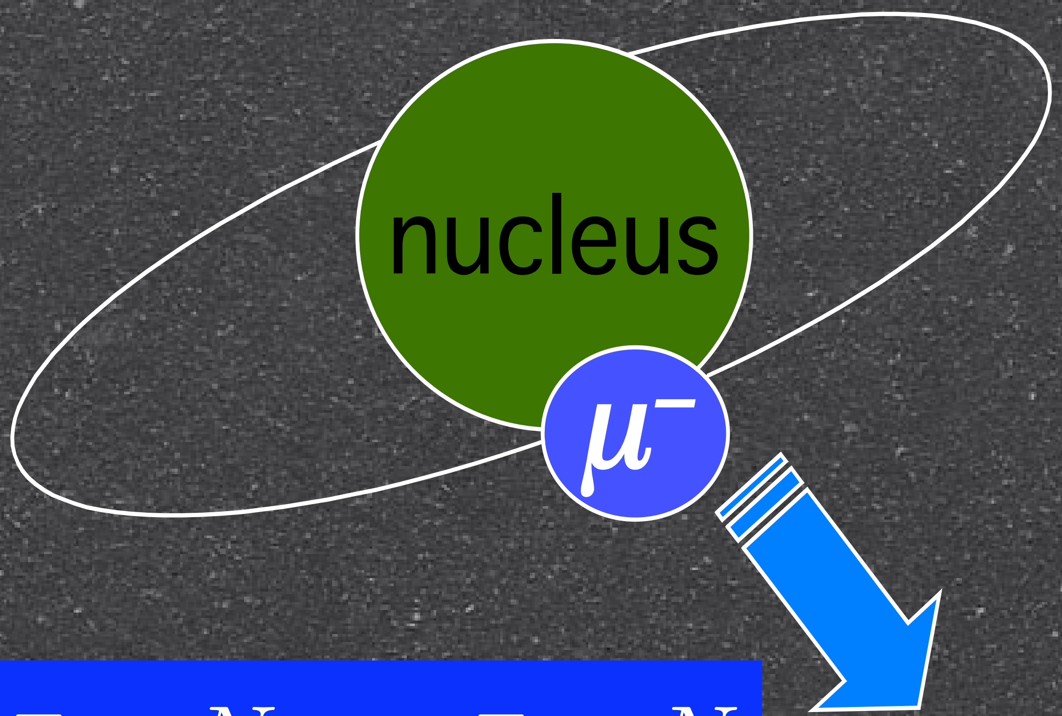
Process	Current	Future
$\mu^+ \to e^+ \gamma$	1.2×10^{-11}	$<10^{-13}$(MEG)
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	
$\mu^- A \to e^- A$ (Ti)	6.1×10^{-13}	$<10^{-18}$(PRISM)
$\mu^- A \to e^- A$ (Al)		$<10^{-16}$(MECO)
$\tau \to \mu \gamma$	3.2×10^{-7}	
$\tau \to lll$	$1.4 - 3.1 \times 10^{-7}$	
$G_{Mu\overline{Mu}}/G_F$	3×10^{-3}	$\Delta L_f = 2$

Why the Muon ?

- LFV Sensitivity in the muon is the best over the other systems because of enormous beam intensity (10^8/sec) , and will be the best for future prospect of muon beam intensity (~10^{12}/sec - 10^{14}/sec), thanks to R&D studies of neutrino factory front-end.
- The muon provides a clean test ground, on the contrast to hadrons where QCD corrections needed introduces sensitivity limits,

$\mu \rightarrow e\gamma$ & μ-e conversion





$$\mu^- + N \rightarrow e^- + N$$

Signature

$E_e = E_\gamma = m_\mu/2$

back-to-back, same time

Background

(1) radiative decay

(2) accidentals

Signature: $E_e = m_\mu - B_\mu$

monoenergetic electron

Background:

(1) bound muon decay

(2) radiative pion/muon catpure

(3) cosmic rays, etc.

Photon-mediated SUSY LFV

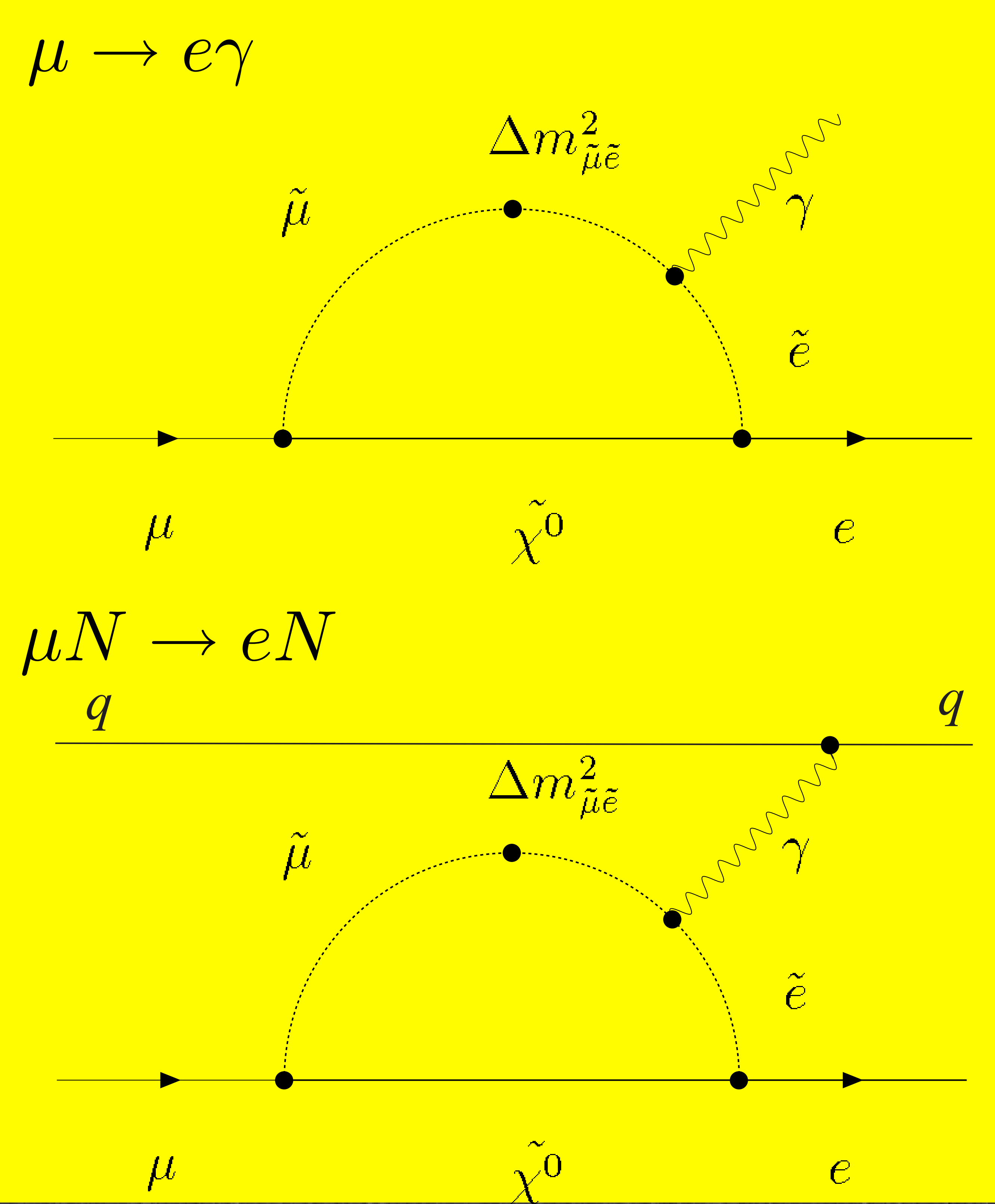
$\mu - e$ conversion vs.
$\mu \to e\gamma$

If photon-mediated,

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$

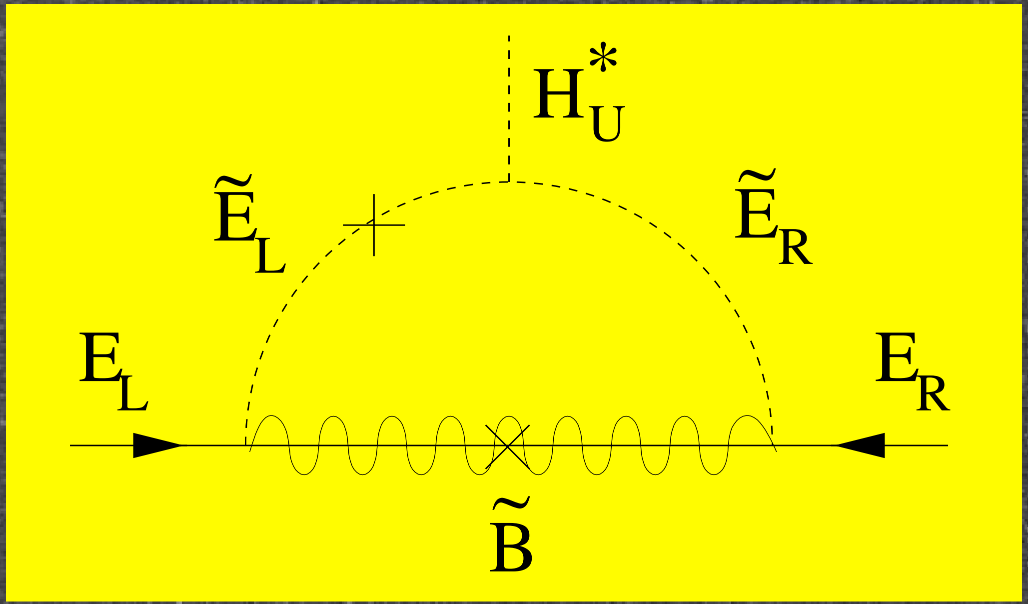
But, experimentally,

$\mu \to e\gamma$	$< 1.2 \times 10^{-11}$
$\mu N \to eN$	$< 6 \times 10^{-13}$



Higgs-mediated SUSY LFV

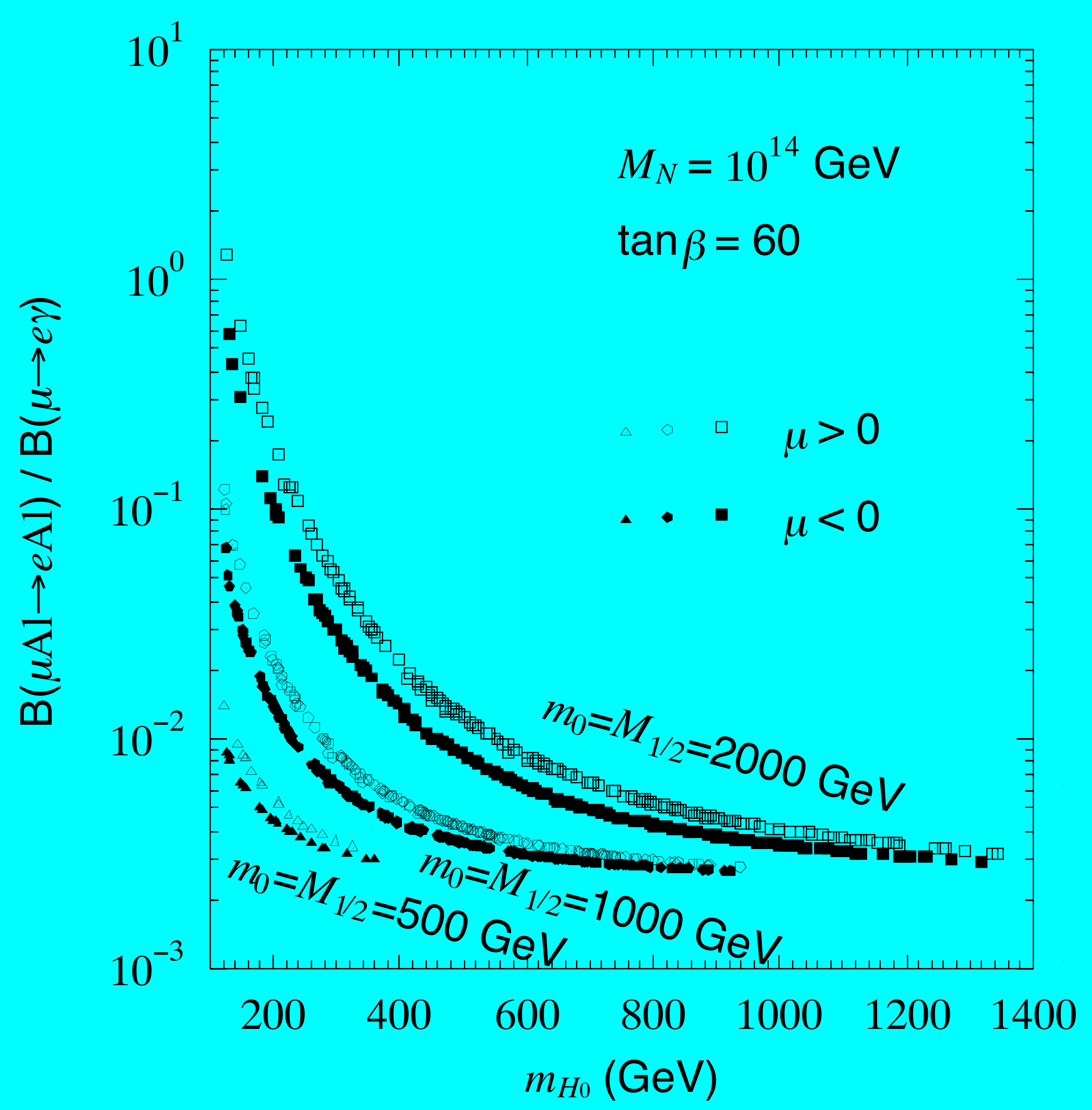
Higgs-exchange for LFV in SUSY Seesaw model



As the H_0 mass is light, the contribution of the Higgs-mediated diagram becomes larger.

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim O(1)$$

at $H_0 \sim 200$ GeV



Kitano, Koike, Komine, Okada

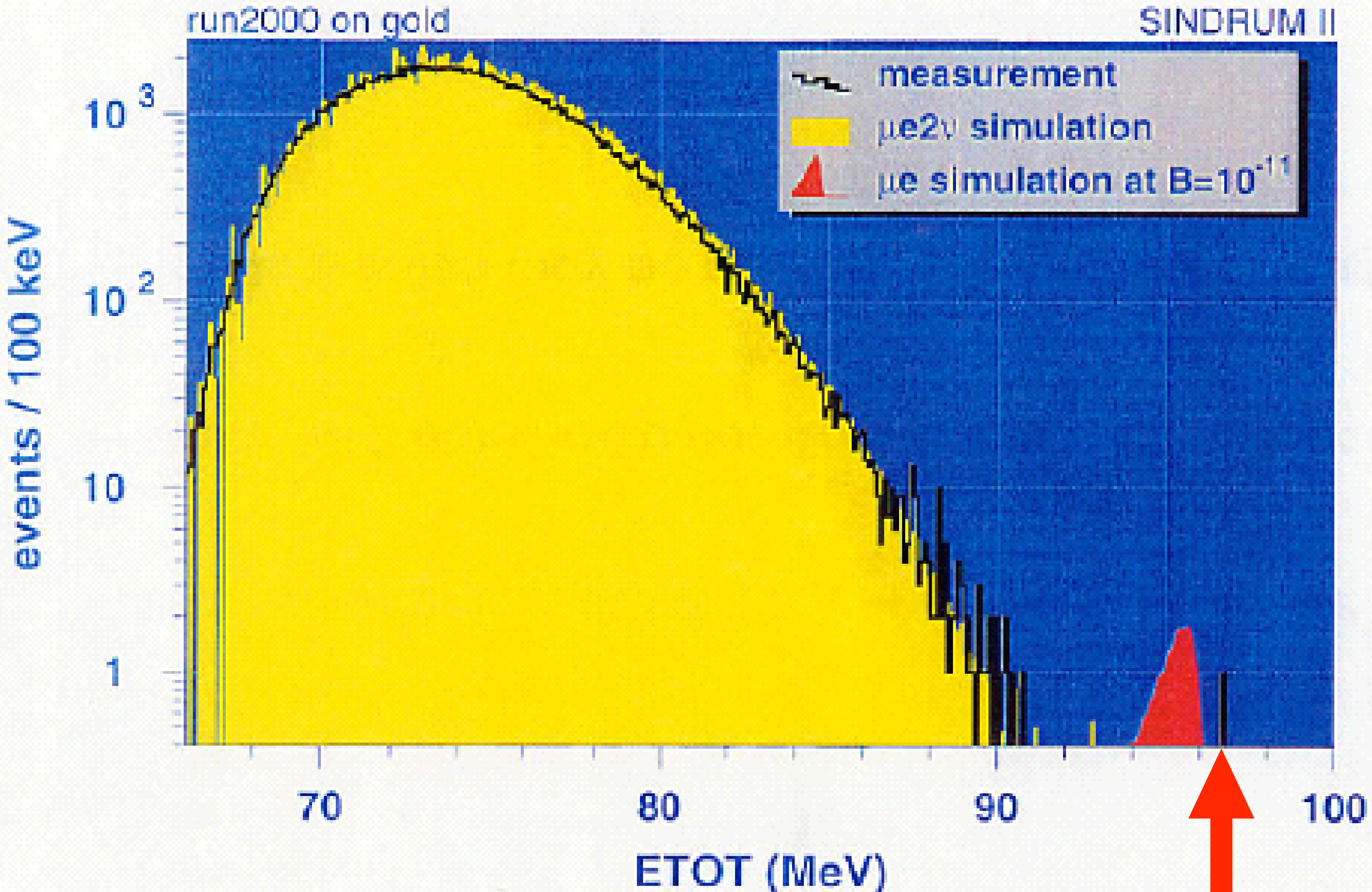
Which Muon LFV Process Next ?

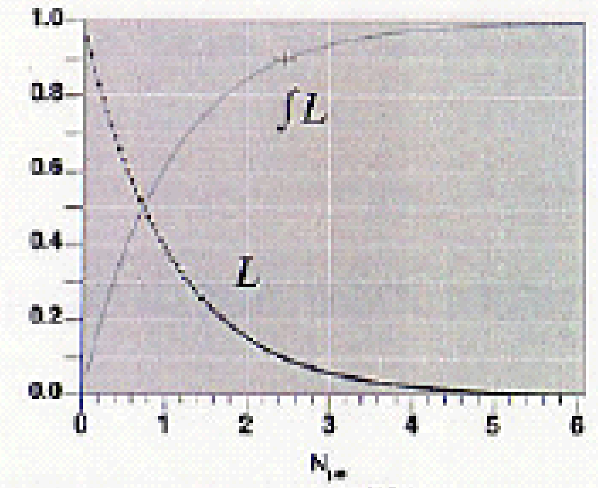
	issue	beam requirement
$\mu \longrightarrow e\gamma$	detector-limited	a continuos beam
$\mu \longrightarrow eee$	detector-limited	a continuos beam
$\mu N \longrightarrow eN$	beam-limited	a pulsed beam

SINDRUM-II μ-e conversion

Final result

μe Conversion on Gold





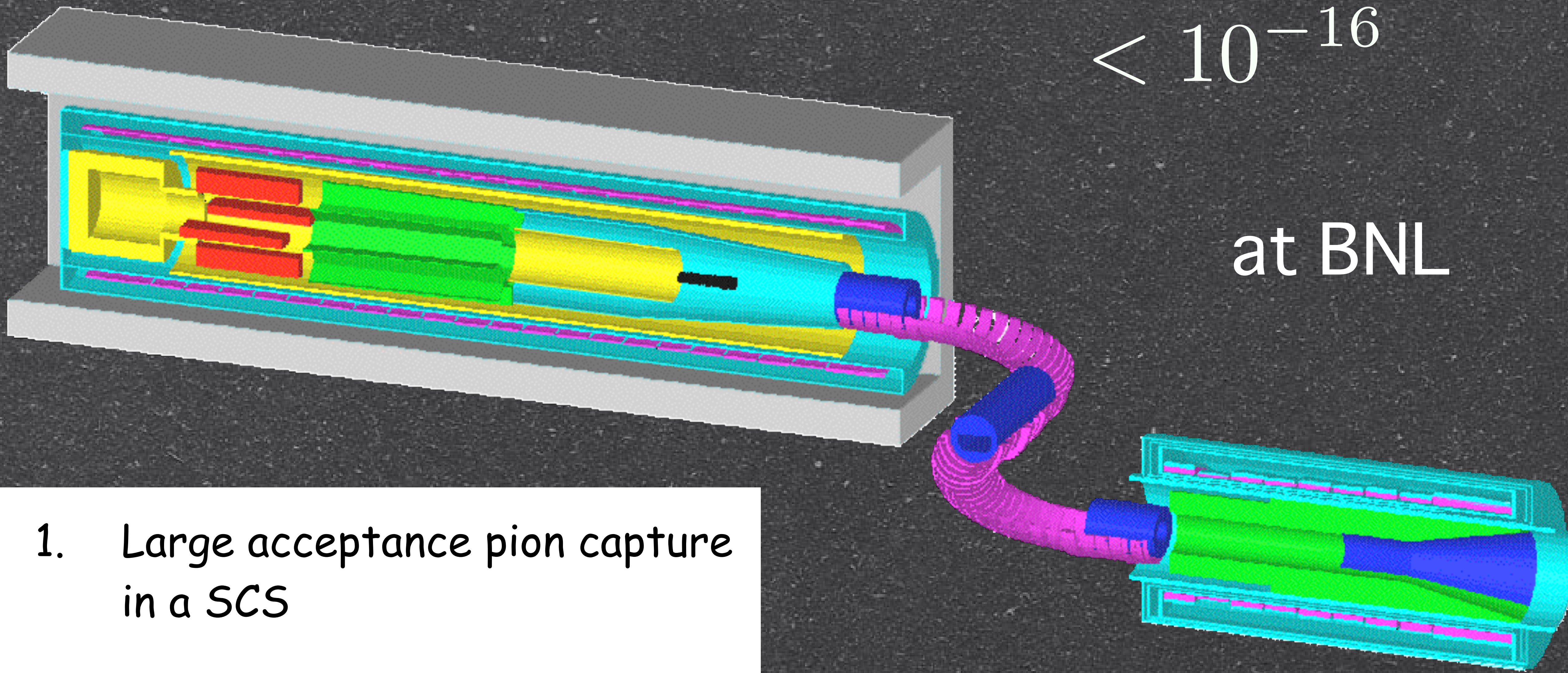
$\mathcal{L}(N_{\mu e})$ and $\int_0^{N_{\mu e}^{max}} \mathcal{L}(n)dn.$

μ^- stops	$4.4 \pm 0.3 \times 10^{13}$
$f_{cap} \times \Omega \times \epsilon_{tot}$	7.0%
single event sensitivity	$3.3 \pm 0.2 \times 10^{-13}$
90% C.L. limit	2.45 events

In the likelihood analysis of the energy distribution a flat background from cosmic rays and radiative pion capture was allowed.

Result: $B_{\mu e}^{gold} < 8 \times 10^{-13}$ 90% C.L.

MECO μ-e conversion



$< 10^{-16}$

at BNL

cancelled in 2005.

1. Large acceptance pion capture in a SCS
2. Muon transport (60 – 120 MsV/c) in a curved solenoid
3. Long detector solenoid with muon stpping target and tracking system

Beam Requirements for μ-e conversion

Beam is critical element for μ-e conversion

MECO

- Higher muon intensity
  - more than 10^{12} μ^-/sec
- pulsed beam
  - rejection of background from proton beam

- Less beam contamination
  - no pion contamination
    - ⇛ long flight path
  - beam extinction between pulses
    - ⇛ kicker magnet

- Narrow energy spread
  - allow a thinner muon-stopping target
    - ⇛ better e^- resolution and acceptance

- Point Source
  - allow a beam blocker behind the target
    - ⇛ isolate the target and detector
    - ⇛ tracking close to a beam axis

PRISM

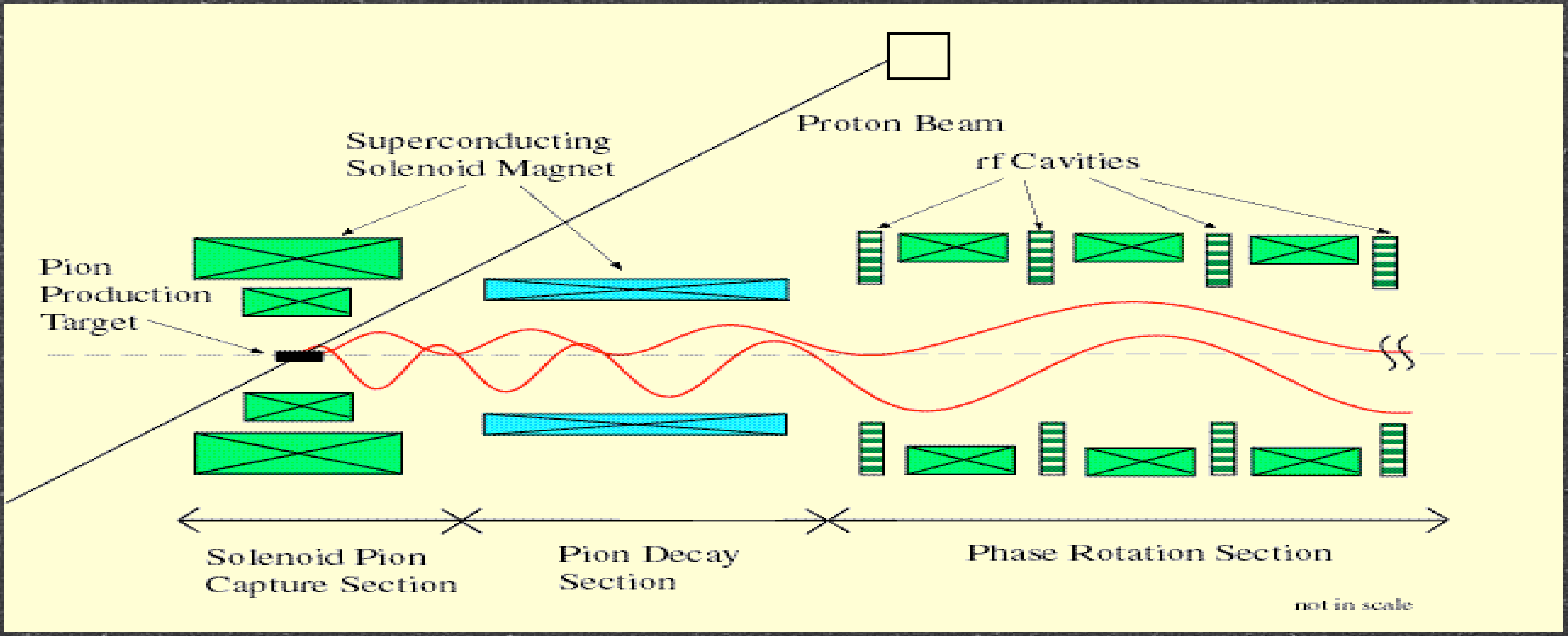
PRISM

PRISM

PRISM=Phase Rotated Intense Slow Muon source

PRISM is a high intensity muon source
with narrow energy spread and high purity.

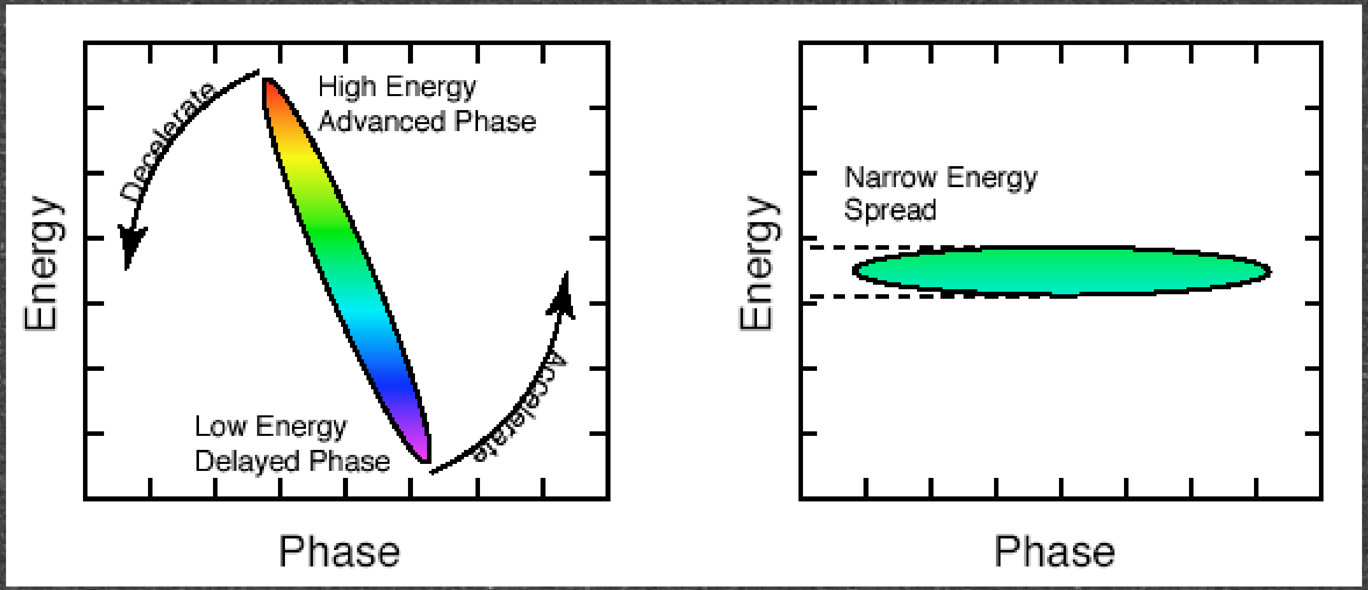
- high intensity: (Solenoid Pion Capture)
- narrow momentum width: (Phase rotation)
- small emittance (in future): (Cooling)



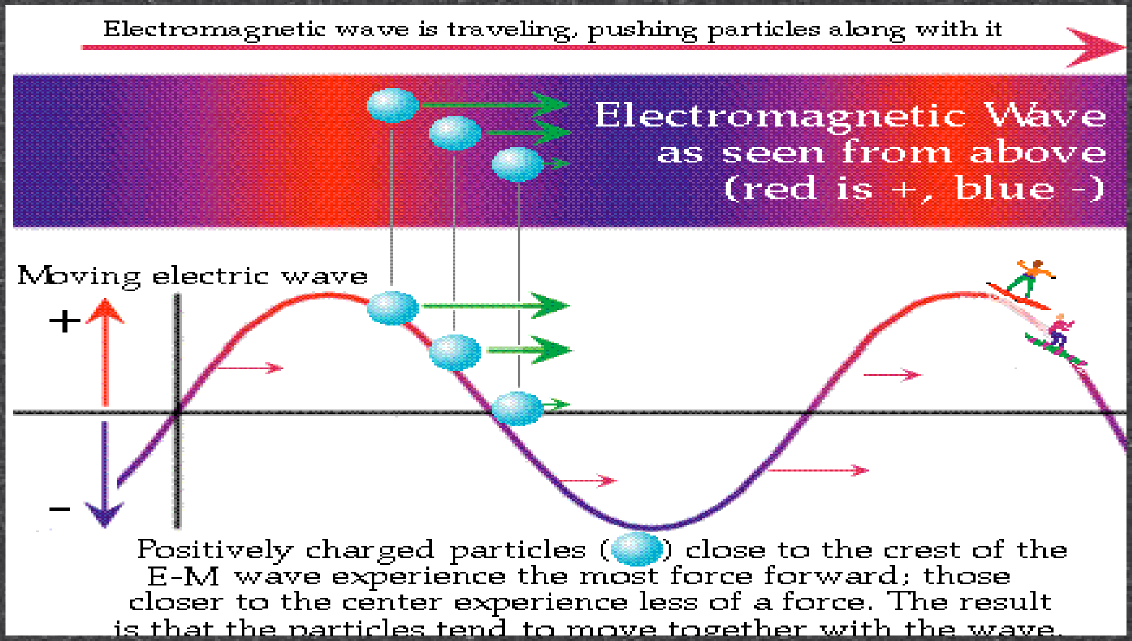
What is Phase Rotation ?

Phase rotation = decelerate particles with high energy

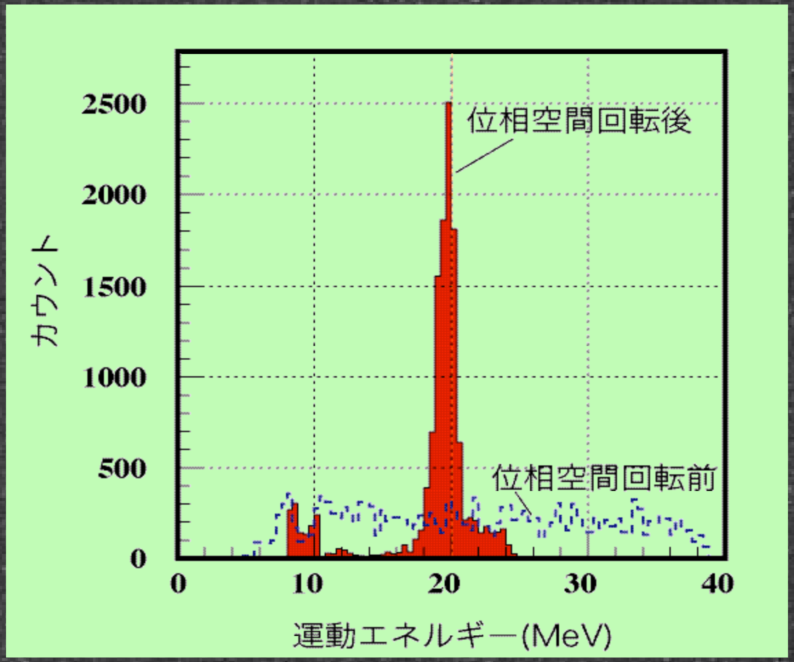
and accelerate particle with low energy by high-field RF so as to make the energy spread narrower.



If proton bunch is narrow, high-energy particles come earlier and low-energy particles come late.



Need Compressed Proton Bunches



FFAG for Phase Rotation

- a ring instead of linear systems
  - reduction of # of rf cavities
  - reduction of rf power consumption
  - compact

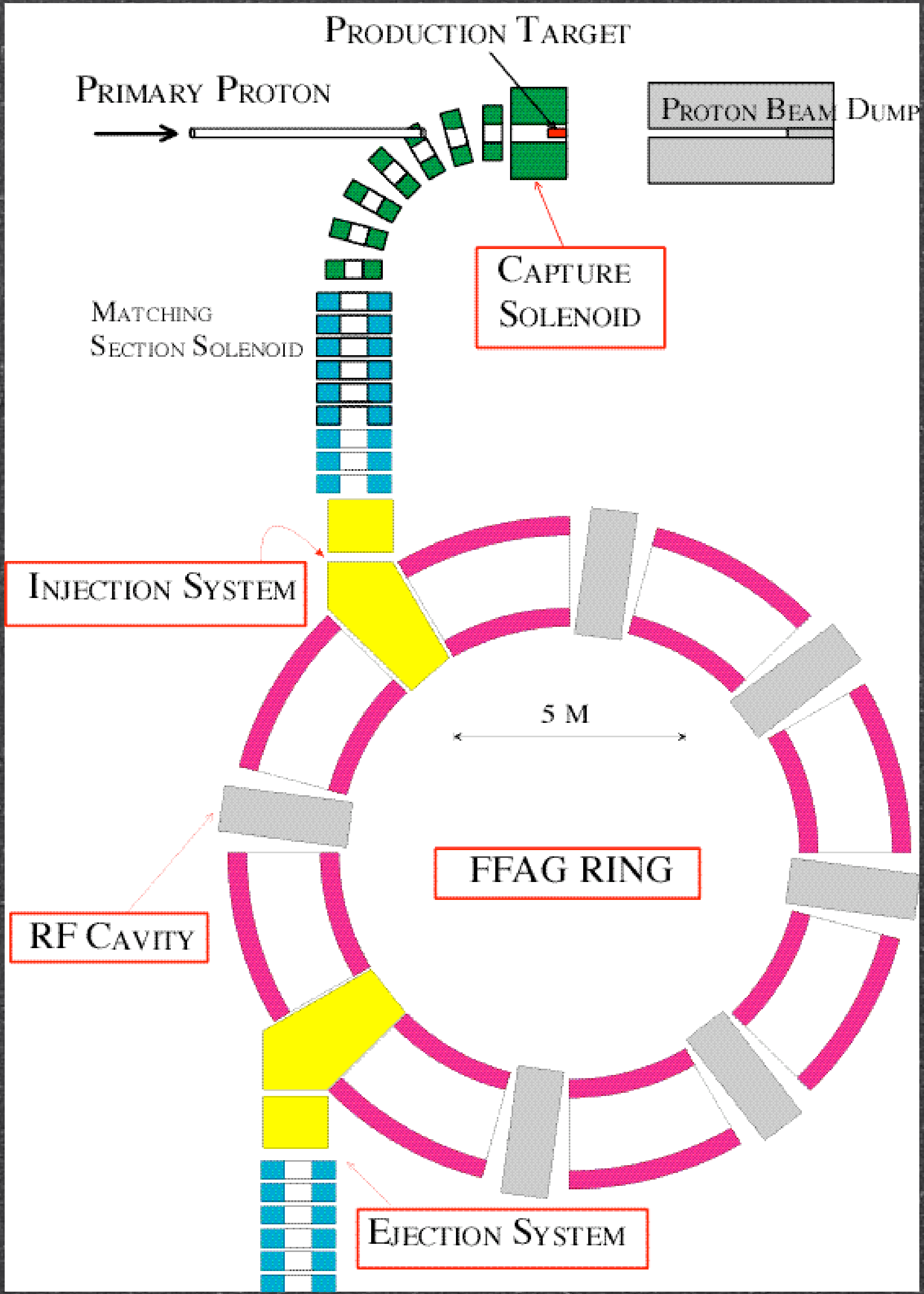
FFAG = Fixed Field Alternating Gradient Synchrotron

- synchrotron oscillation for phase rotation
  - not cyclotron (isochronous)
- large momentum acceptance
  - larger than synchrotron
  - ± several 10 % is aimed
- large transverse acceptance
  - strong focusing
  - large horizontal emittance
  - reasonable vertical emittance at low energy

PRISM

PRISM=Phase Rotated Intense Slow Muon source

- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width:
  - 3 % (<--- 30 %)
  - by phase rotation (5-6 turns)
- pion contamination : 10^{-18} for 150m
- Repetition : 100 Hz



PRISM Yield Estimation

estimated for about 0.75 MW beam power
depend on technology choice、and not fully optimized yet.

Target material	Capture field	Transport field	Muon yield per 10^{14} protons	Muon yield per 4×10^{14} protons
Graphite	16 T	4 T	4.8×10^{10}	19×10^{10}
	16 T	2 T	3.6×10^{10}	14×10^{10}
	12 T	4 T	3.6×10^{10}	14×10^{10}
	12 T	2 T	3.0×10^{10}	12×10^{10}
	8 T	4 T	3.0×10^{10}	12×10^{10}
	8 T	2 T	2.4×10^{10}	9.6×10^{10}
	6 T	4 T	1.8×10^{10}	7.2×10^{10}
	6 T	2 T	1.8×10^{10}	7.2×10^{10}
Tungsten	16 T	4 T	13×10^{10}	50×10^{10}
	16 T	2 T	11×10^{10}	46×10^{10}
	12 T	4 T	9.6×10^{10}	38×10^{10}
	12 T	2 T	9.0×10^{10}	36×10^{10}
	8 T	4 T	6.0×10^{10}	24×10^{10}
	8 T	2 T	7.2×10^{10}	29×10^{10}
	6 T	4 T	4.2×10^{10}	17×10^{10}
	6 T	2 T	4.8×10^{10}	19×10^{10}

Target length
3 interaction length
FFAG acceptance
H:20000πmm mrad
V:3000π mm mrad
$\varepsilon_{dispersion} = 100\%$
$\varepsilon_{FFAG} = 100\%$

now H:40000 πmm mrad, V:6500 πmm mrad

PRIME

PRIME

PRIME = PRIsm Mu E experiment

using PRISM **Aim at 10^{-18}**

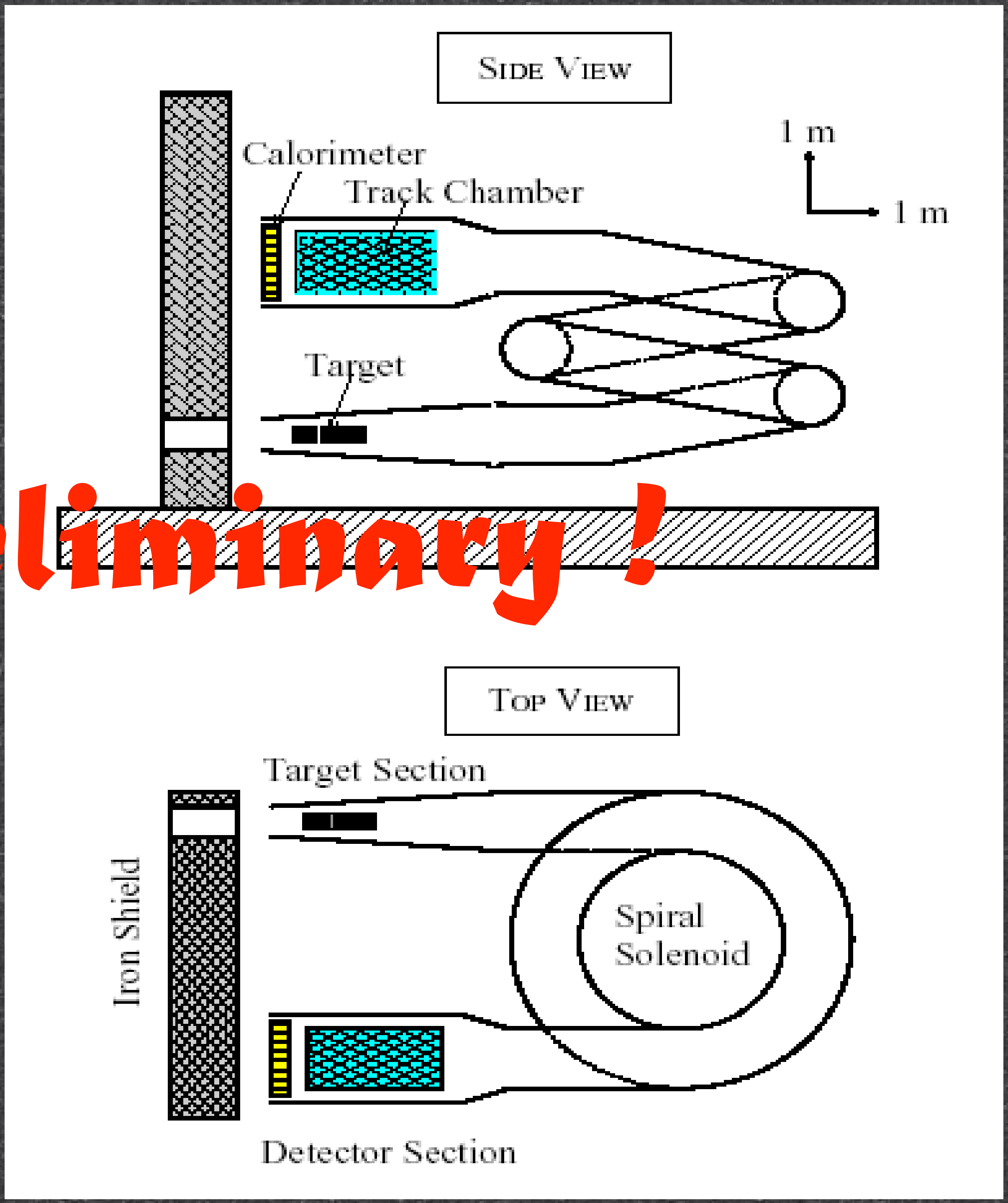
Detector Option:

Spiral solenoid spectrometer

eliminate low energy particles by a toroidal magnetic field

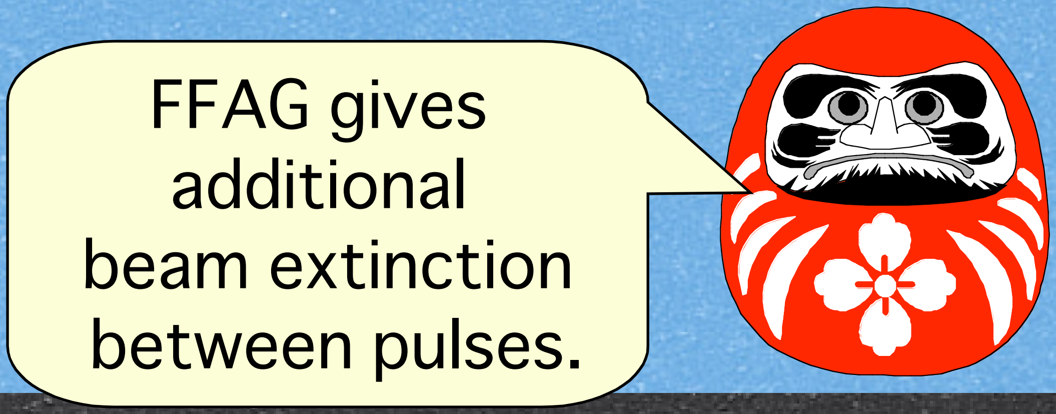
$$D = \frac{1}{0.3B}\frac{s}{R}\frac{(p_s^2 + \frac{1}{2}p_t^2)}{p_s}$$

Preliminary !

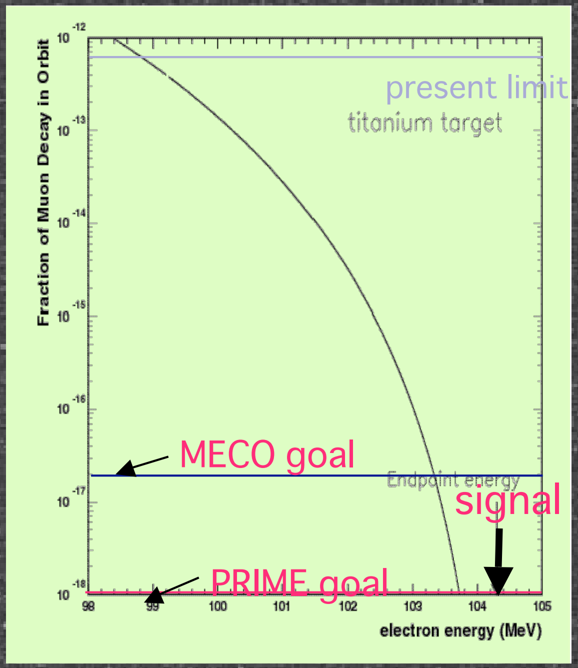


BG Rejection Summary

- muon decay in orbit
  - $(E_0\text{-}E)^5$
  - better e^+ momentum resolution
    - a thin muon stopping target is helpful. (=several 100 g)
- radiative muon capture
  - endpoint for Ti = 89.7MeV
    - signal = 104.3 MeV
  - better e^+ momentum resolution
    - a thin muon stopping target
- radiavtive π capture
  - long flight length (150m)
    - 30 m FFAG circumference x 5 turns
  - π surviving rate: 10^{-18} at 68 MeV/c
- cosmic ray backgrounds
  - 1kHz (duty factor: 1/1000)
- long transit time backgrounds
  - FFAG timing (kicker)
- anti-proton
  - absorber before FFAG
- beam electrons, electrons from muon decay in flight
  - FFAG's momentum accpetance:
  - different β (out of time)
  - not bunched at FFAG ?



PRIME Background Rates



Muon Decay in Orbit ($\propto (E_{\mu e} - E_e)^5$)
Detector Resolution $\Delta E_e = 235$ keV

Preliminary !

at the sensitivity of 10^{-18}

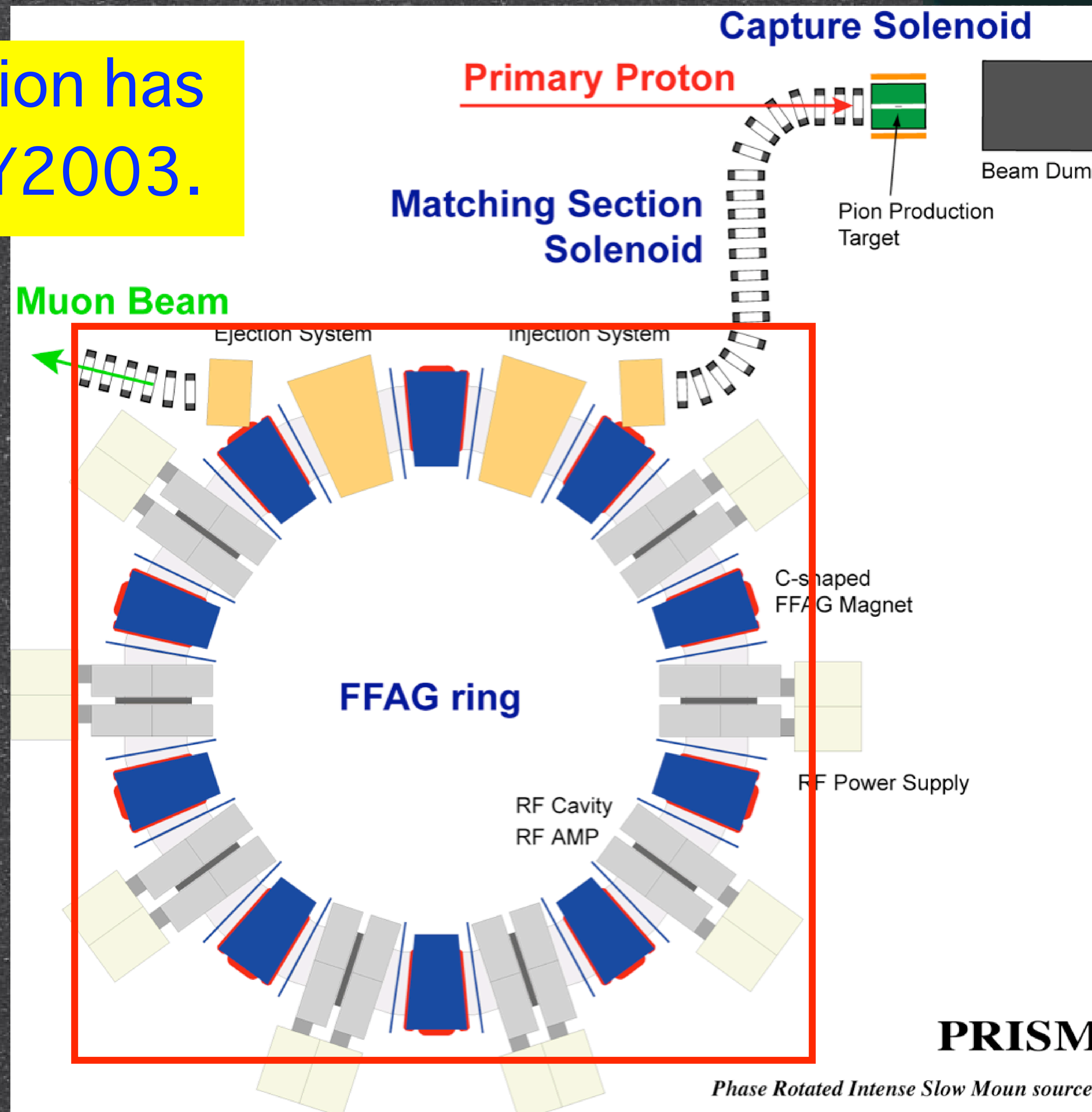
Background	Rate	comment
Muon decay in orbit	0.05	energy reso 350keV(FWHM)
Radiative muon capture	0.01	end point energy for Ti=89.7MeV
Radiative pion capture	0.03	long flight length in FFAG, 2 kicker
Pion decay in flight	0.008	long flight length in FFAG, 2 kicker
Beam electron	negligible	kinematically not allowed
Muon decay in flight	negligible	kinematically not allowed
Antiproton	negligible	absorber at FFAG entrance
Cosmic-ray	< 10^-7 events	low duty factor
Total	0.10	

PRISM-Ring R&D

PRISM Ring Construction

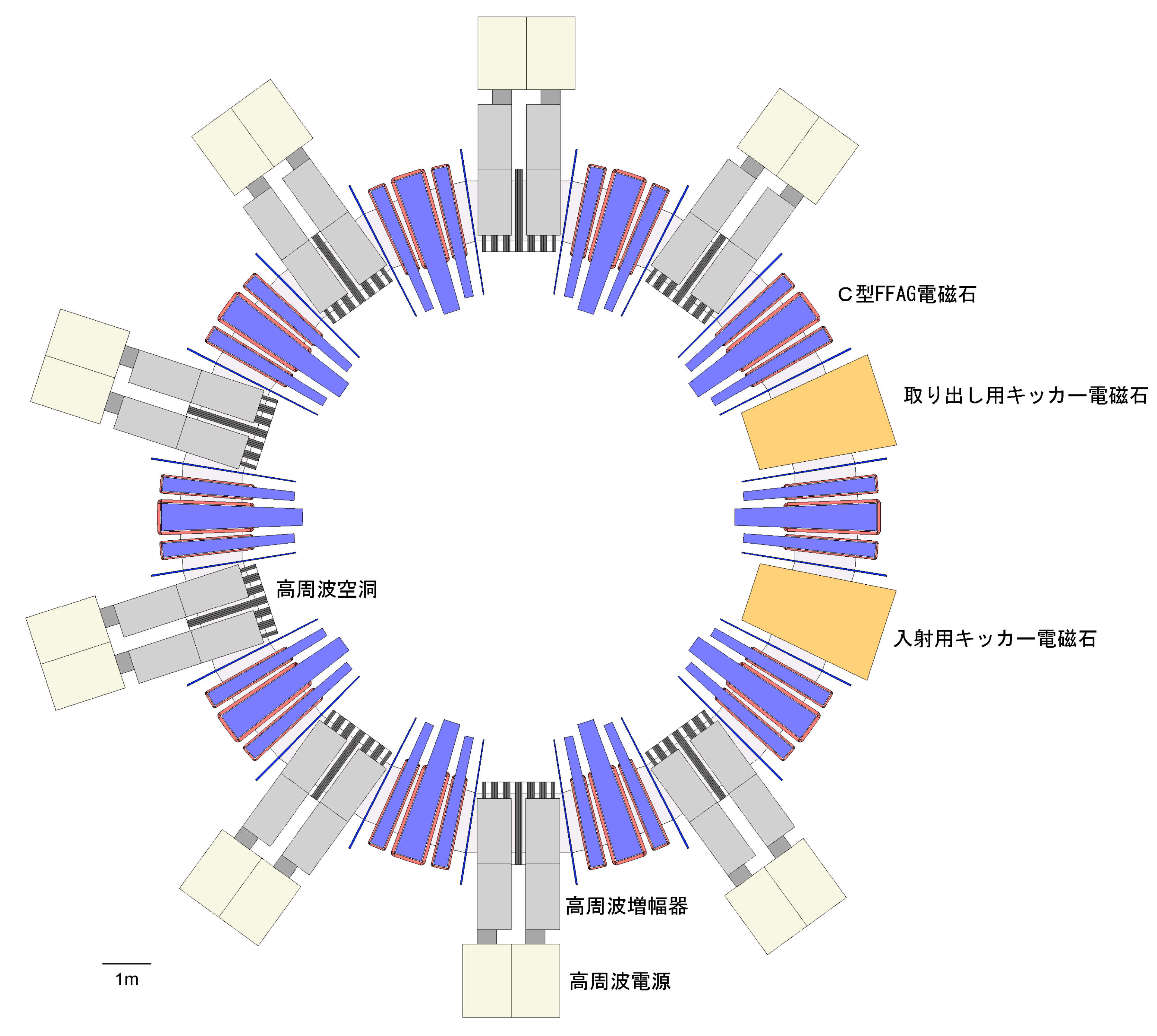
PRISM ring construction has been approved in JFY2003.

- FFAG ring
- 5 year plan
  - construction at Osaka university
- Goals
  - proton/muon phase rotation
  - muon acceleration
  - muon cooling?

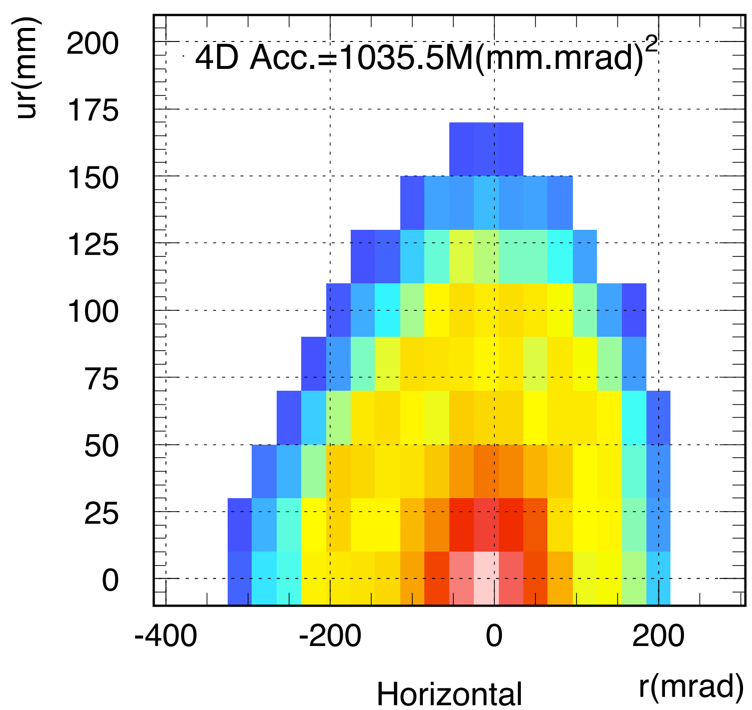


PRISM Lattice

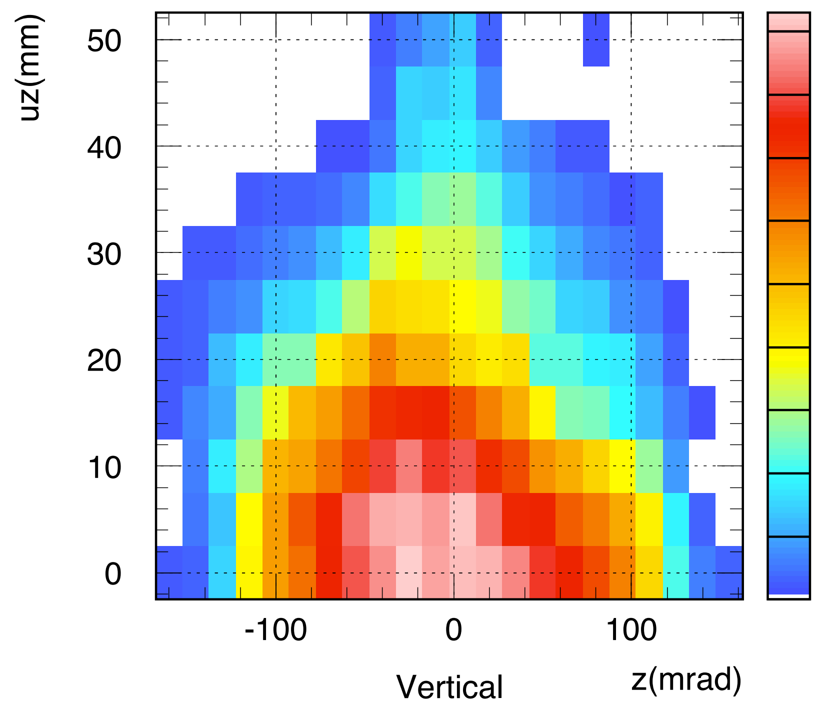
- SCALING FFAG
- N=10
- k=5(4.6-5.2)
- F/D(BL)=8
- r0=6.5m for 68MeV/c
- half gap = 15cm
- mag. size 110cm @ F center
- Triplet
  - θ_F=4.40deg
  - θ_D=1.86deg
- tune
  - h : 2.86
  - v : 1.44
- acceptance
  - h : 40000 π mm mrad
  - v : 6500 π mm mrad



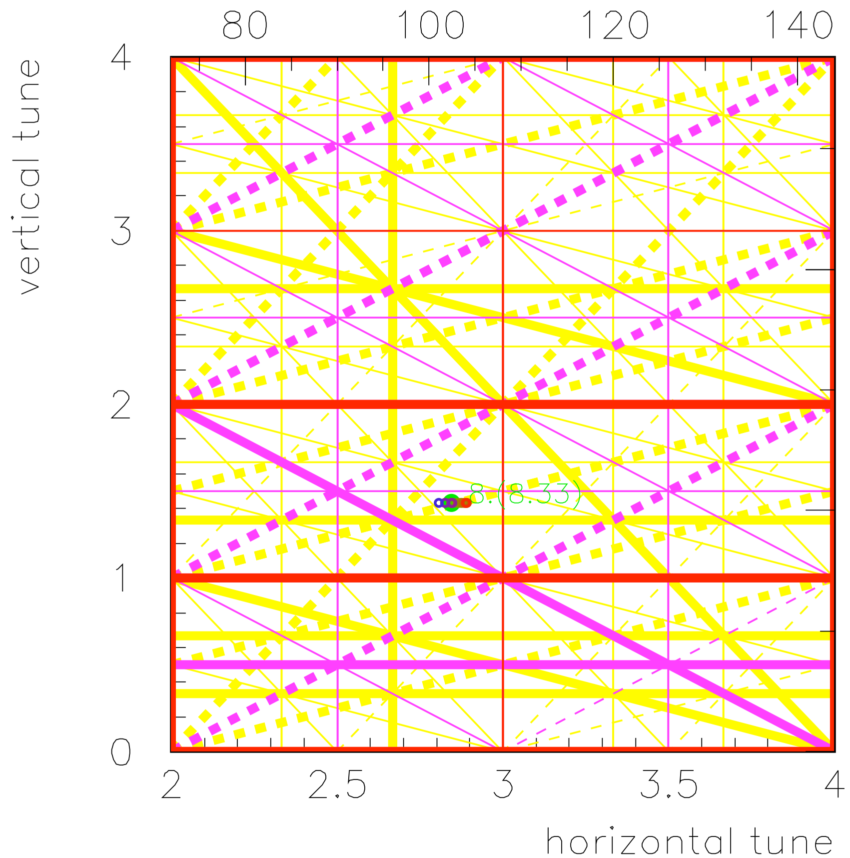
PRISM-FFAG Acceptance

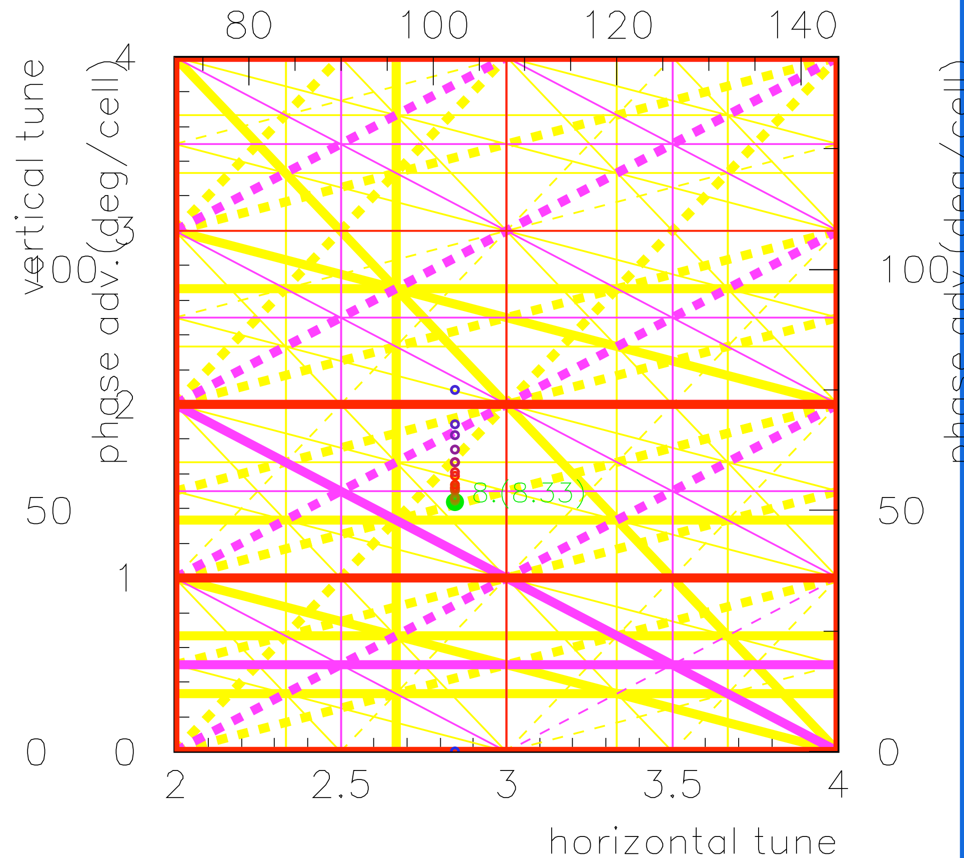


Horizontal Acceptance
40000π mm mrad



Vertical Acceptance
6500π mm mrad



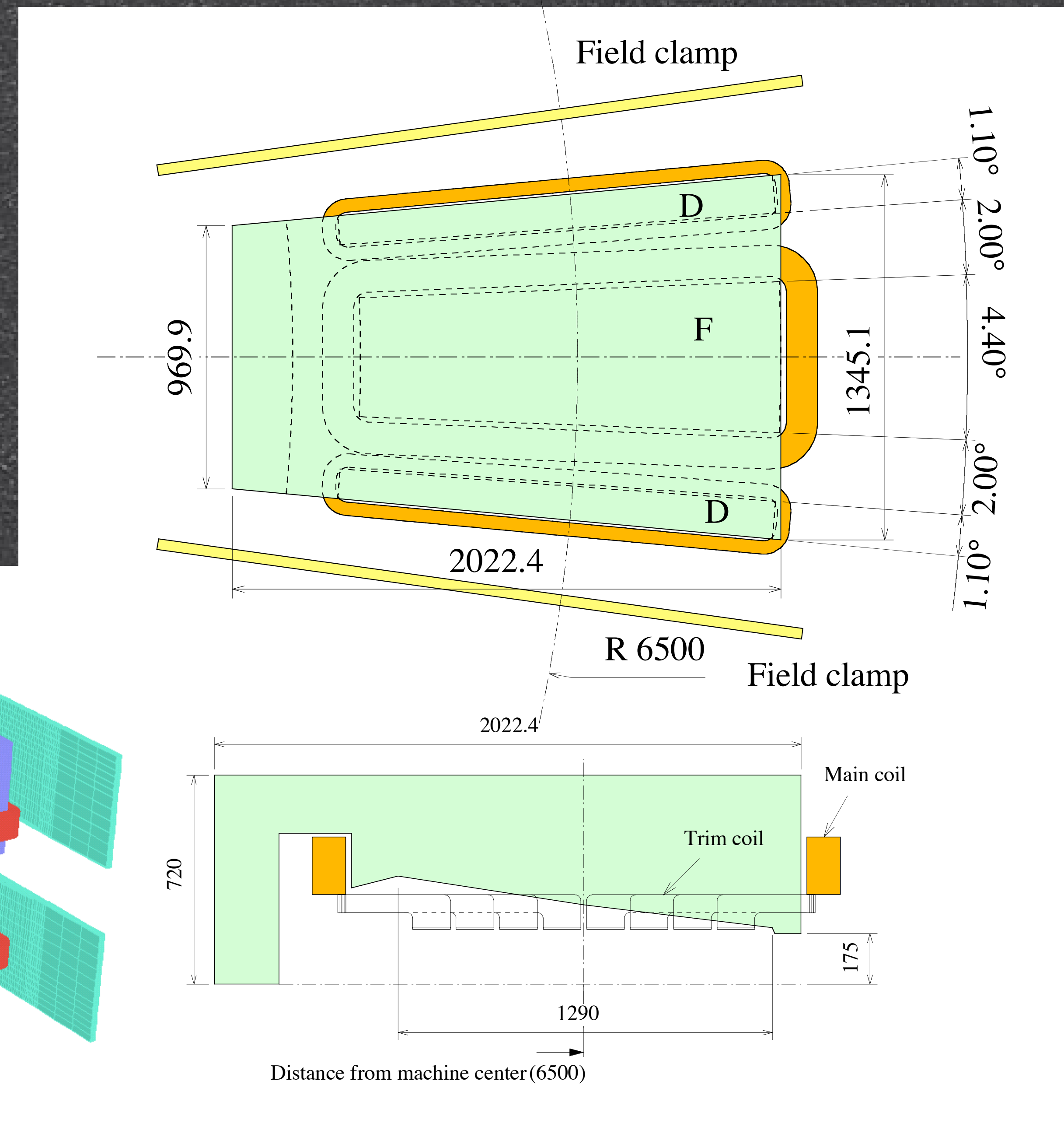


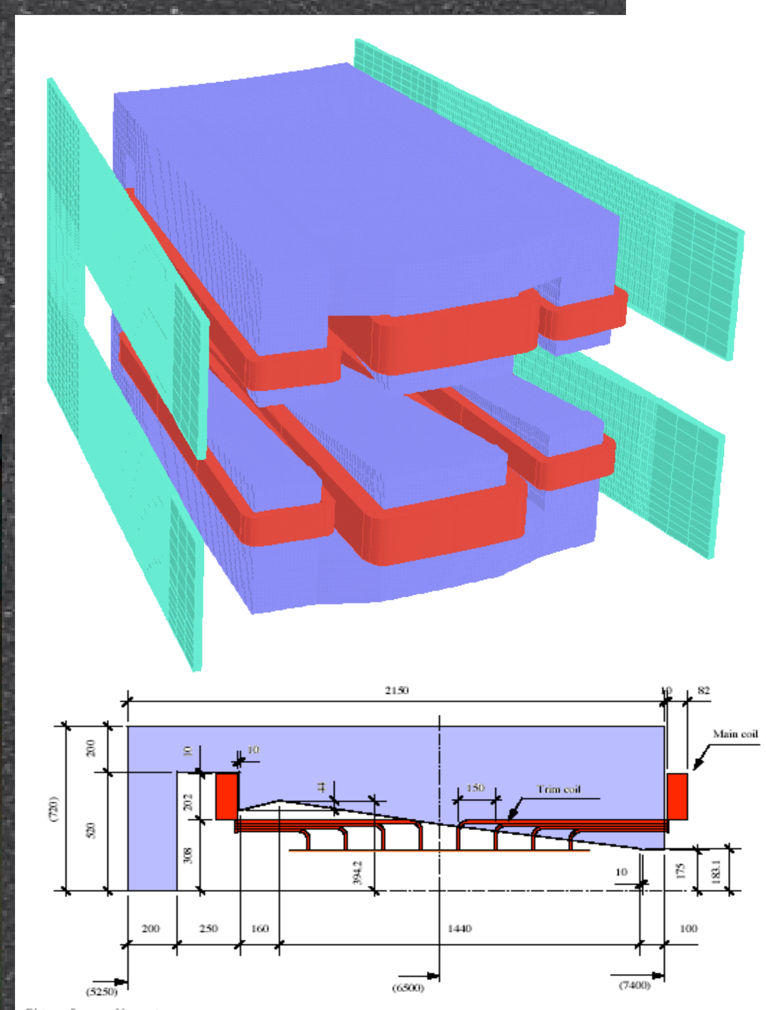
N=10
F/D=8
k=5
r0=6.5m
H:2.86
V:144

a la Akira Sato (Osaka)

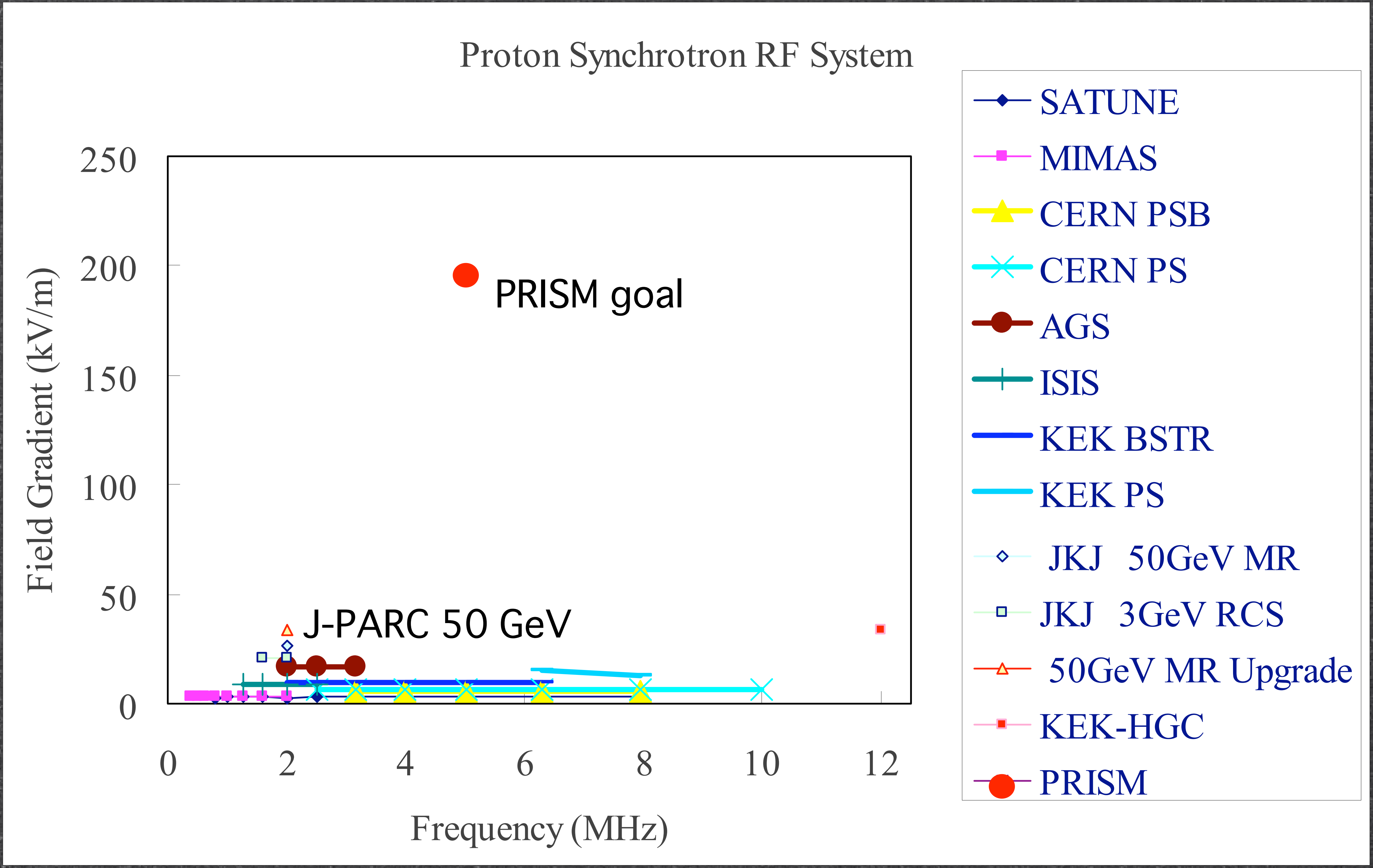
PRISM FFAG Magnet

- Radial Sector type
  - DFD Triplet
- Large Aperture
- Field gradient
- Trim coil
- C-shape



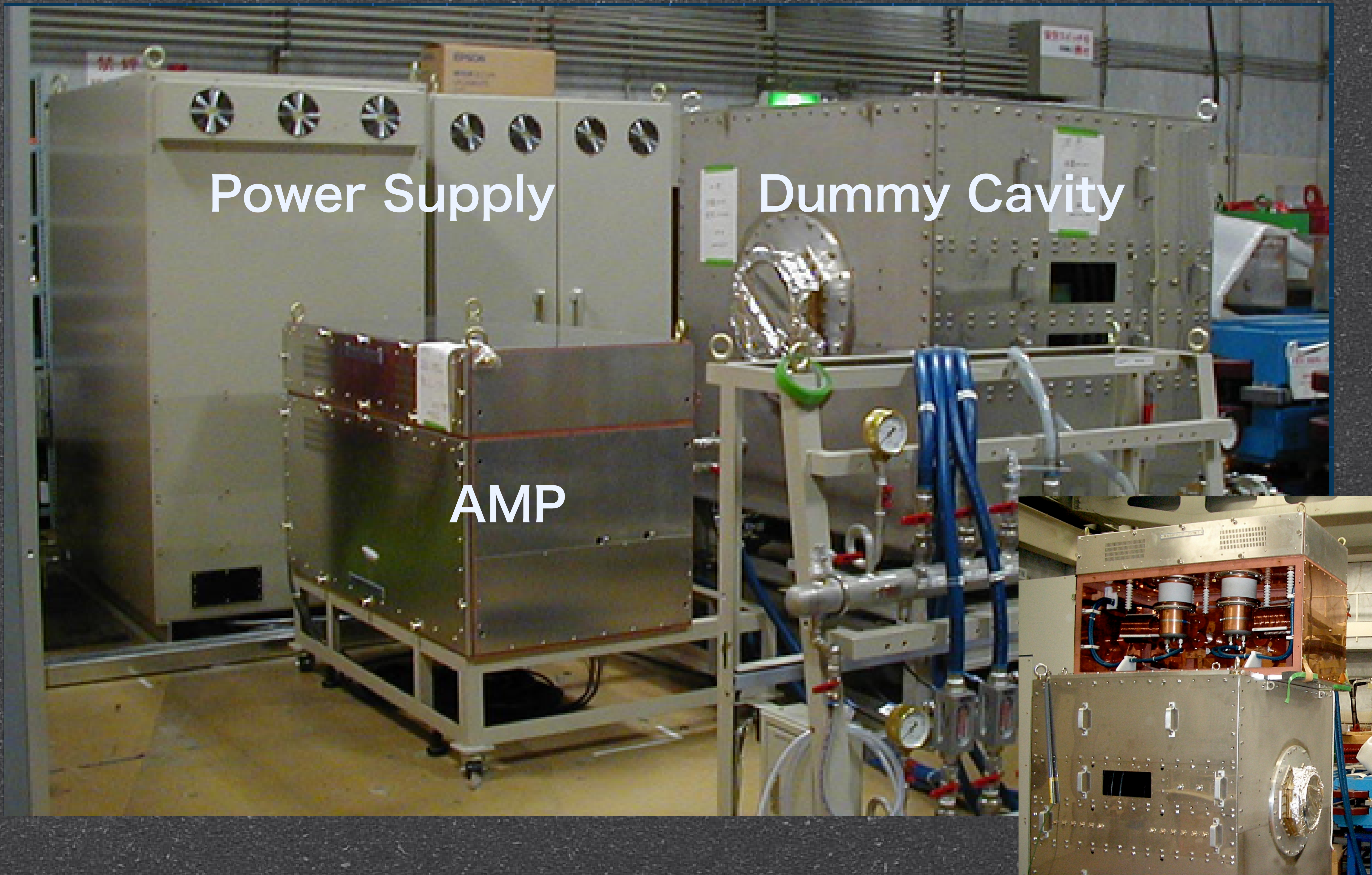


PRISM RF Field Gradient



PRISM goal > 200 kV/m

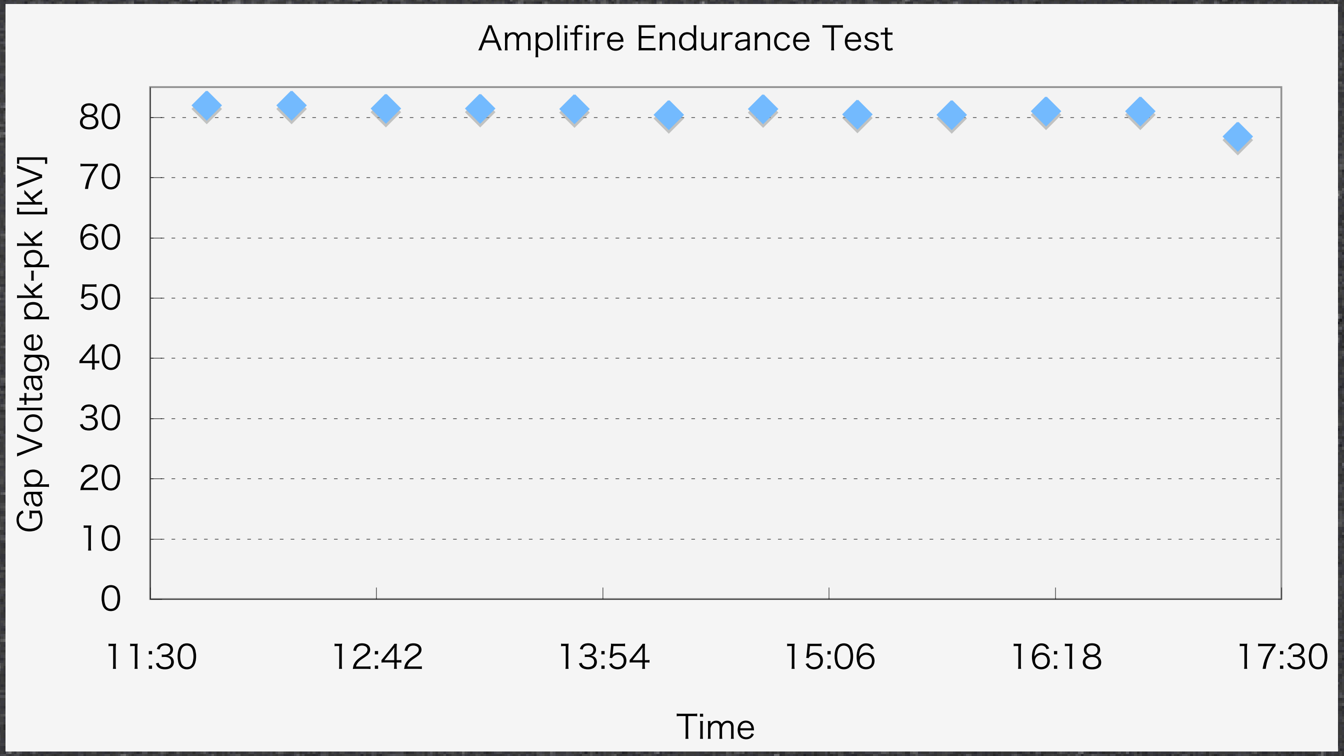
RF Amp. at RCNP, Osaka



Amp. & Test Cavity

PRISM RF Amplifier Test

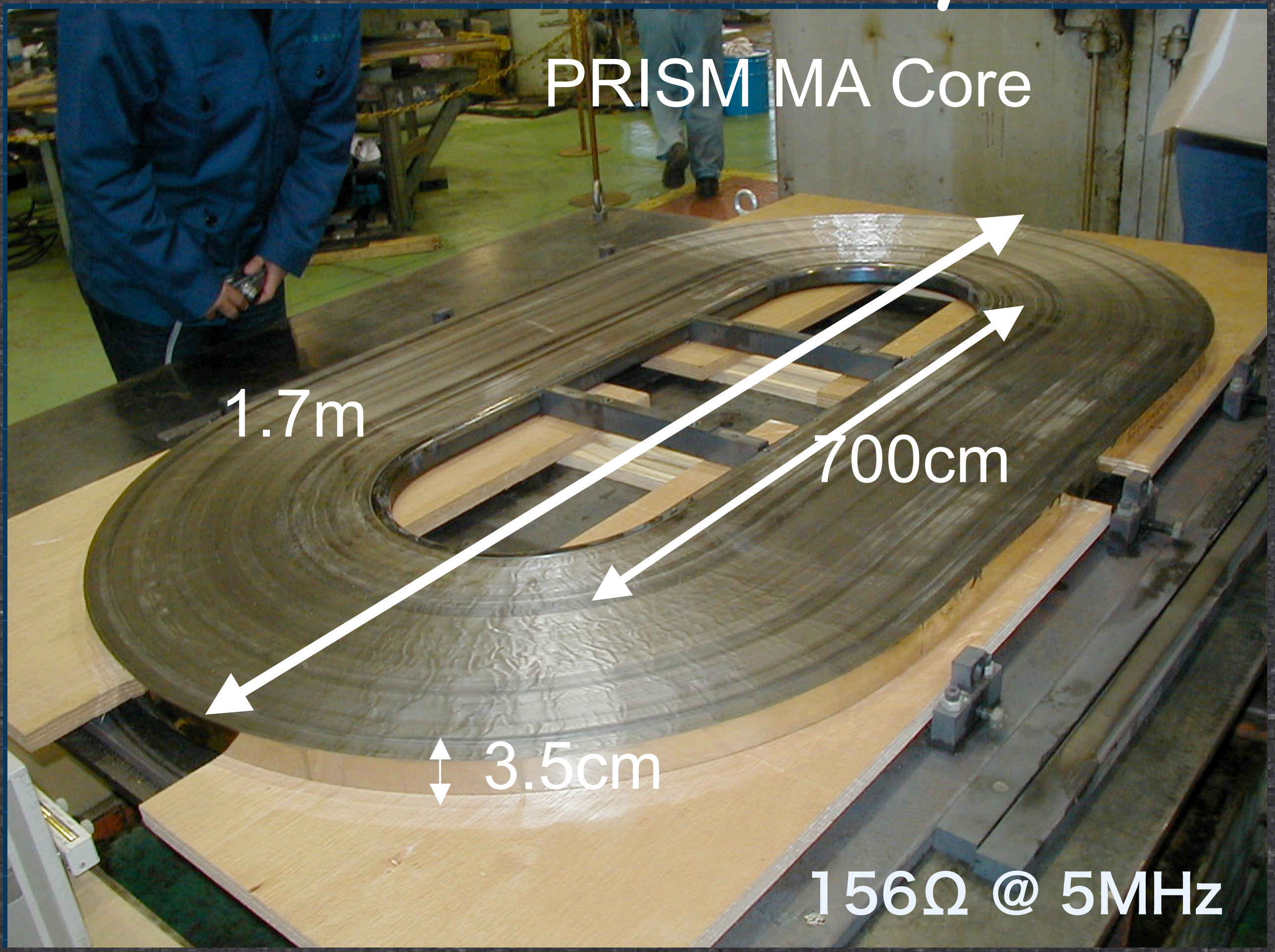
- Test Station of PRISM RF Sytem
  - RF Amplifier and Power supply
  - Test RF Cavity (1 gap、700kΩ)
- Gap voltage of 86 kV p-p at 5 MHz achieved
  - correspond to about 150kV/m
- Long-term test
  - 100 Hz repetition
  - Burst length 30μsec
  - more than 6 hours



PRISM RF Cavity

1 gap, Length 33cm,
6 MA cores, 2cm gap

rf cavity core



PRISM Roadmap

PRISM Staging

Phase I

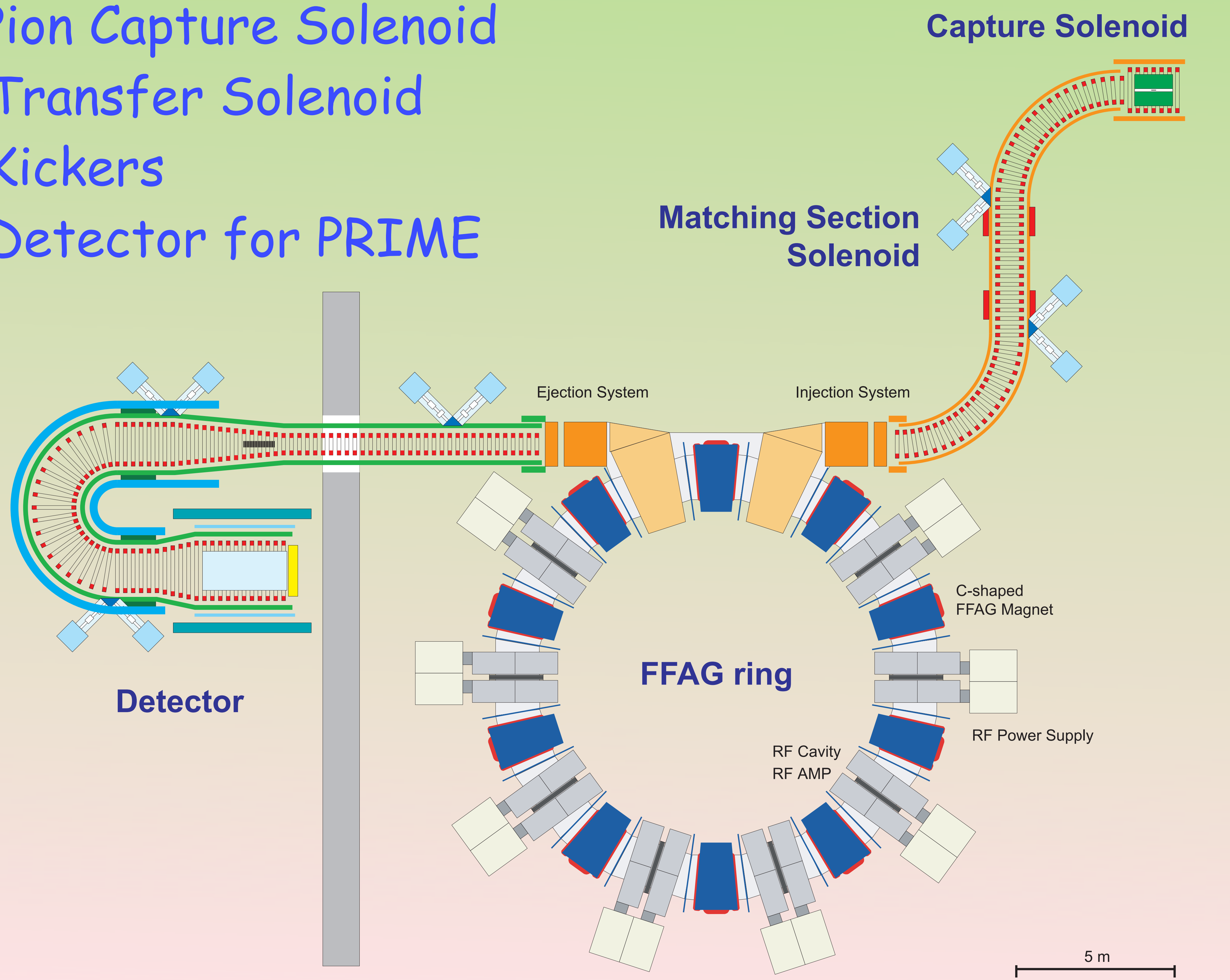
- Construct the Whole PRISM instumentations.
- Test the performance of PRISM.
- 2006-2009

Phase II

- Bring PRISM to any high-intensity hadron facility .
- carry out the experiment (PRIME).
- after 2010

PRISM + PRIME

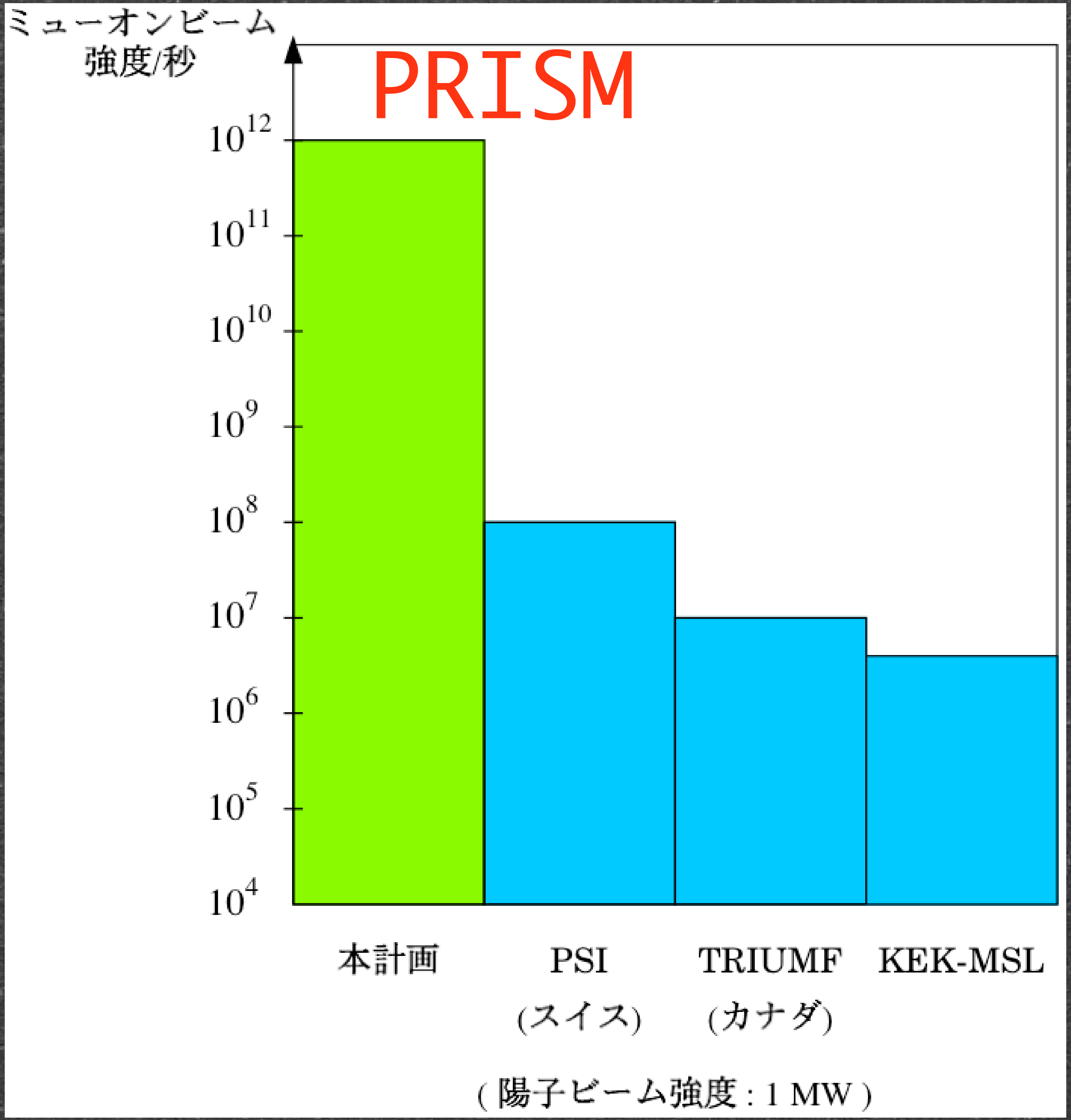
(1) Pion Capture Solenoid
(2) Transfer Solenoid
(3) Kickers
(4) Detector for PRIME



Muon Intensities

Proton-Normalized Muon Intensity

- verify the performance of high-intensity and high-luminosity muon source (front end of mini-neutrino factory).
- (right) muon beam intensity scaled to 1MW proton beam



at J-PARC

LOI to J-PARC

year 2003

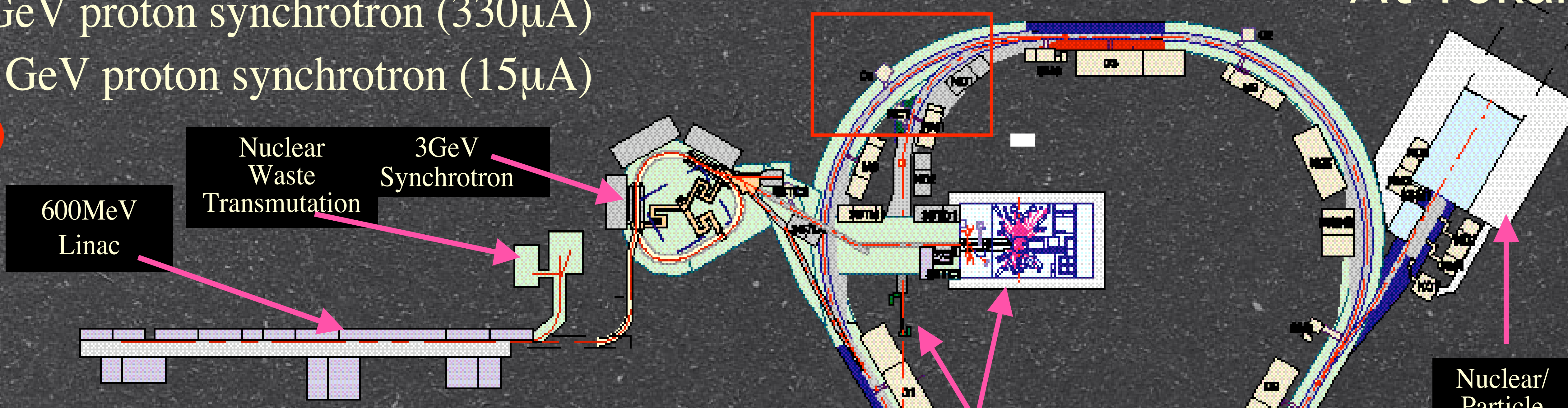
	title	contact persons
1	The PRISM Project - A Muon Source of the World-Highest Brightness by Phase Rotation -	Y. Mori, K. Yoshimura, N. Sasao, Y. Kuno
2	An Experimental Search for the μ-e Conversion Process Towards an Ultimate Sensitivity of the Order of 10^{-18}	Y. Mori, K. Yoshimura, N. Sasao, Y. Kuno
3	Request for A Pulsed Proton Beam Facility at J-PARC	R.S. Hayano, Y. Kuno
4	A Study of Neutrino Factory in Japan	Y. Mori, Y. Kuno
5	Search for a Permanent Muon Electric Dipole Moment at 10^{-24} ecm Level	Y. Semertzidis, J. Miller, Y. Kuno
6	An Improved Muon (g-2) Experiment at J-PARC	L. Roberts
7	A Study of a Target System for a 4-MW, 50-GeV Proton Beam	K. McDonald, H. Kirk, Y. Kuno, Y. Yoshimura

Only related to muon physics

J-PARC at Tokai

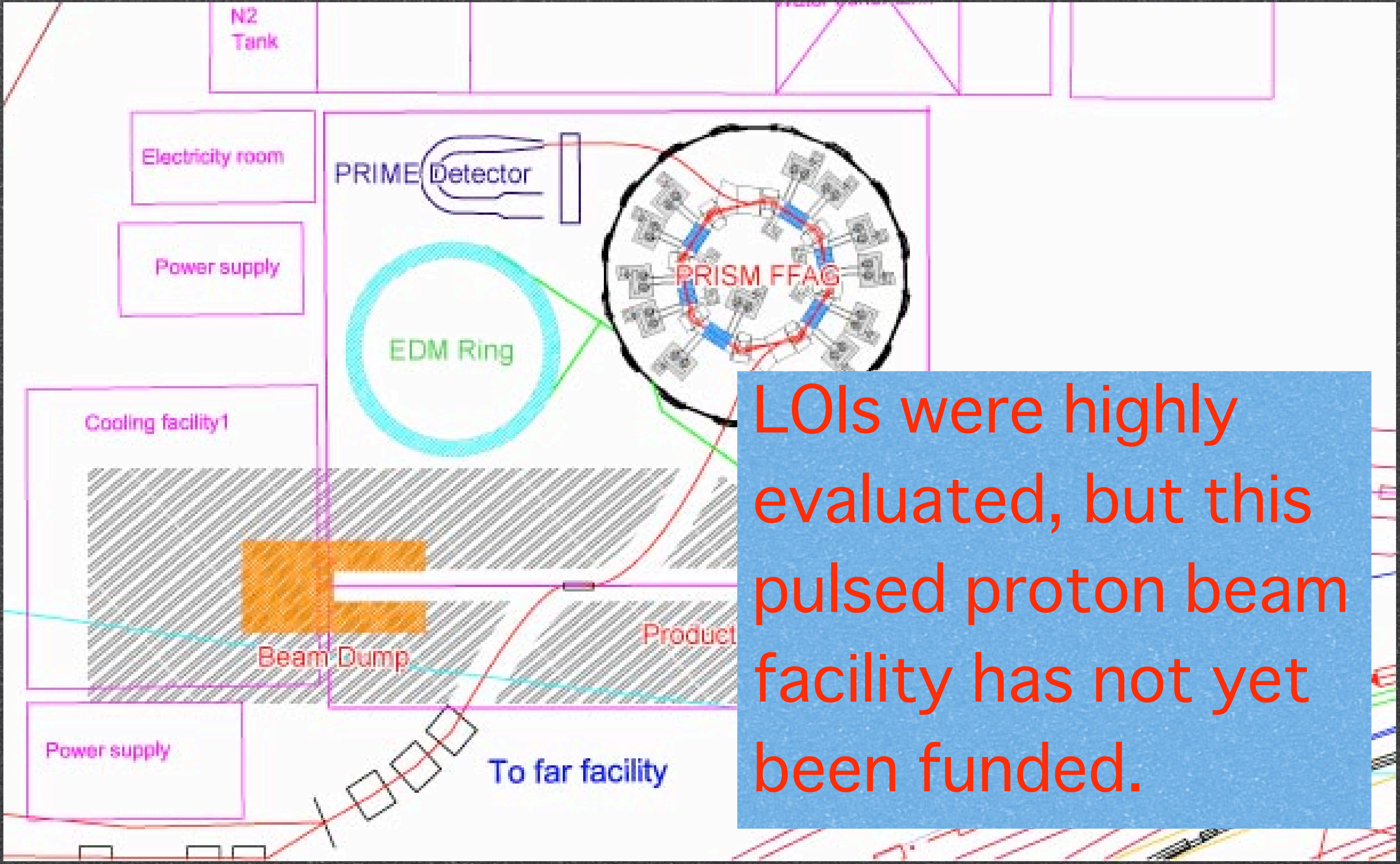
J-PARC = Japan Proton Accelerator Research Complex

400 (200) MeV proton linac
3 GeV proton synchrotron (330μA)
50 GeV proton synchrotron (15μA) (40)



Muon Factory@J-PARC

Pulsed Proton Beam Facility is newly requested to J-PARC.



LOIs were highly evaluated, but this pulsed proton beam facility has not yet been funded.

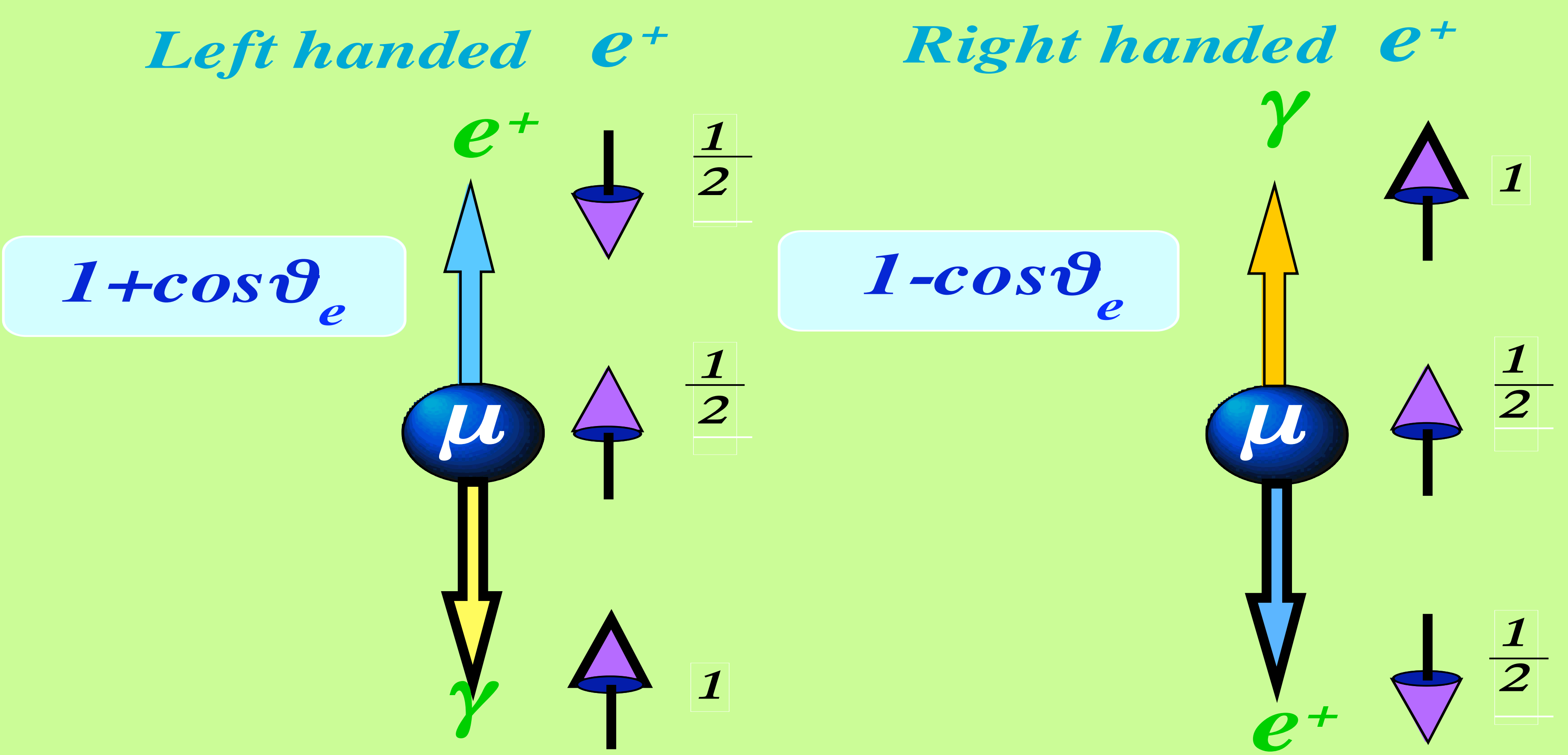
Summary

- Search for charged lepton mixing, in particular in the muon, would provide great opportunity to find new physics beyond the Standard Model.
- The high-intensity, high-luminosity muon source, PRISM, is planned in Japan to search for a muon to electron conversion at 10^{-18}. The PRISM-FFAG ring is now under construction at Osaka university.
- Funding bids of the PRISM/Phase-I is now being prepared.
- Look forward to discovery !

End of My Slides

after observation

Polarized $\mu \to e\gamma$



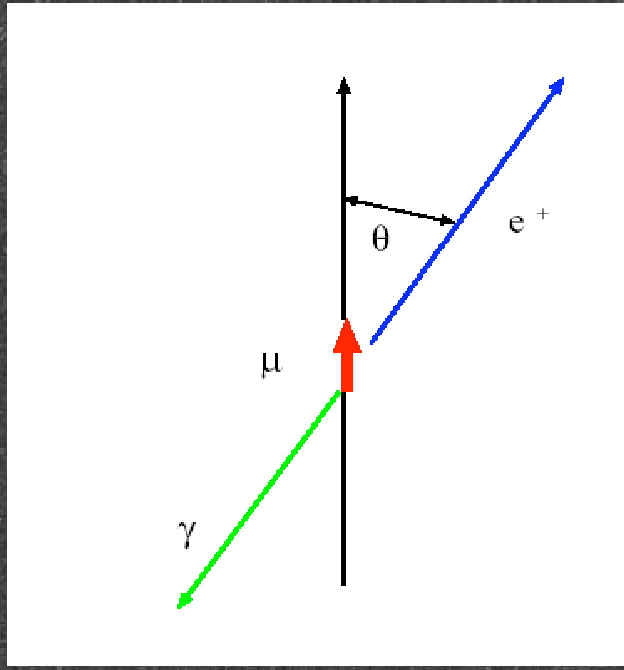
useful to distinguish different theoretical models

SU(5) SUSY-GUT	*non-unified SUSY with heavy neutrino* *Left-right symmetric model*

SO(10) SUSY-GUT

Y.Kuno and Y. Okada, Physical Review Letters 77 (1996) 434

Y.Kuno, A. Maki and Y. Okada, Physical Reviews D55 (1997) R2517-2520

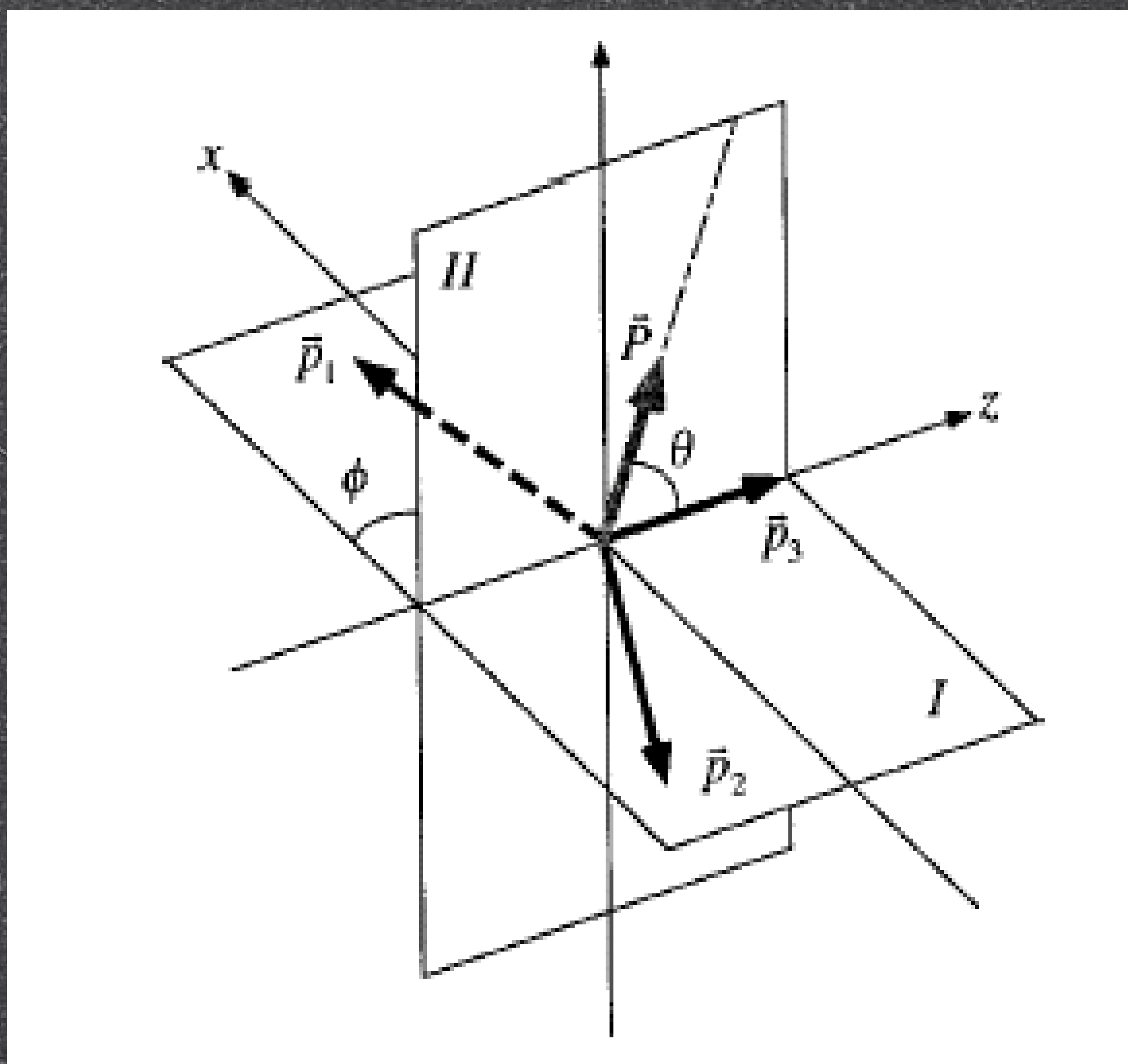


P-odd asymmetry reflects whether right or left-handed slepton have flavor mixing,

after observation

T-odd (CPV) in LFV

$$\mu^+ \to e^+ e^+ e^-$$



Two P-odd and one T-odd asymmetry

$$\vec{P}_\mu \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-})$$

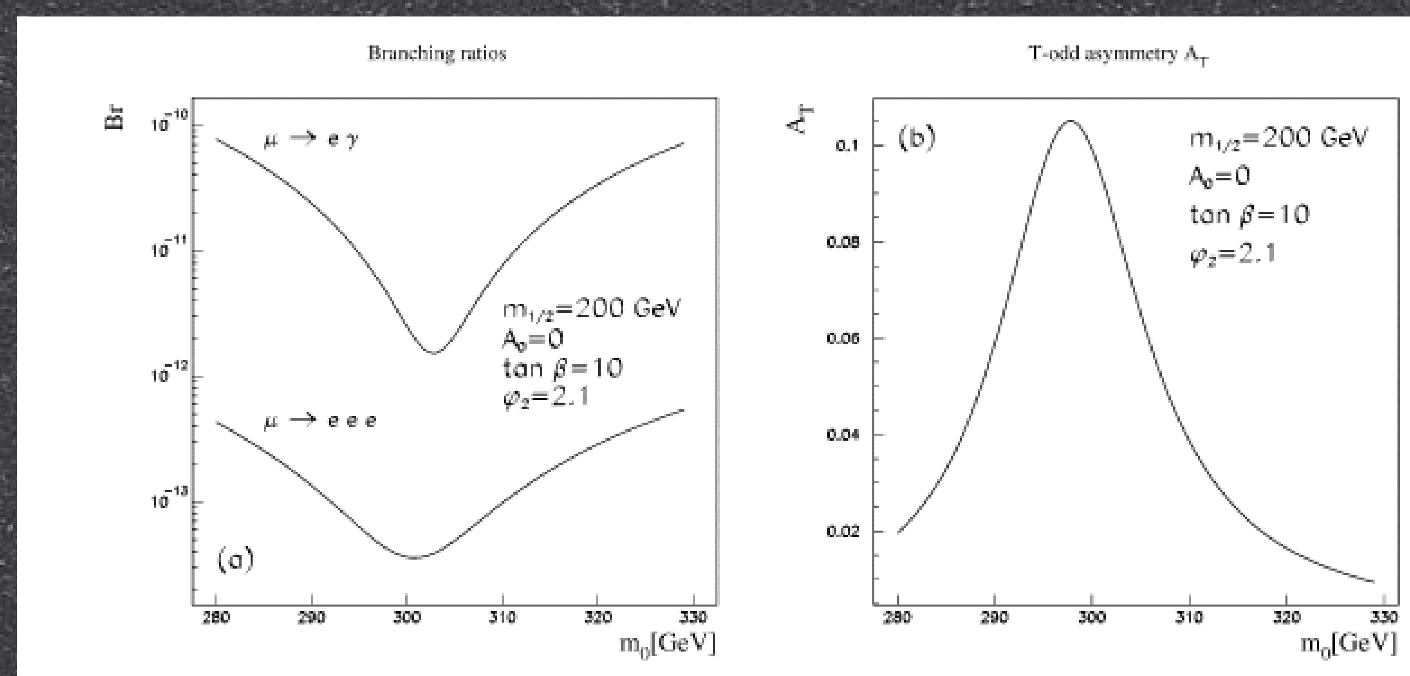
P and T-odd asymmetries in SUSY GUT models

	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	+100%	-100% − +100%
A_{P_1}	-30% − +40 %	$\simeq -A_{\mu\to e\gamma}/10$
A_{P_2}	-20% − +20 %	$\simeq -A_{\mu\to e\gamma}/6$
$\lvert A_T \rvert$	$\lesssim$15%	$\lesssim$ 0.01%

Y.Okada, K.Okumura and Y.Shimizu, 2000

Y.Okada,K.Okumura,and Y.Shimizu, 2000

T-odd asymmetry in the SUSY seesaw model



Leptogenesis

J.Ellis,J.Hisano,S.Lola, and M.Raidal, 2001