Super beams

Ken Sakashita (KEK), Neutrino2010, June/15/2010

Contents:

1. Motivation of super beam long baseline ν experiment

   "super beam" = conventional ν beam (ν from decay of π,K) with ~MW class proton accelerator

2. Current&Future experiments w/ super-beams
3. Summary

Physics Motivation@Super beam LBL exp.

✦ discover $\nu_\mu \rightarrow \nu_e$ appearance → a finite θ_{13}

Current long-baseline(LBL) ν osc. exp. with ~0.7MW beam power (T2K & NOvA)

$U_{e3} = s_{13}e^{-i\delta}$

NEUTRINOS

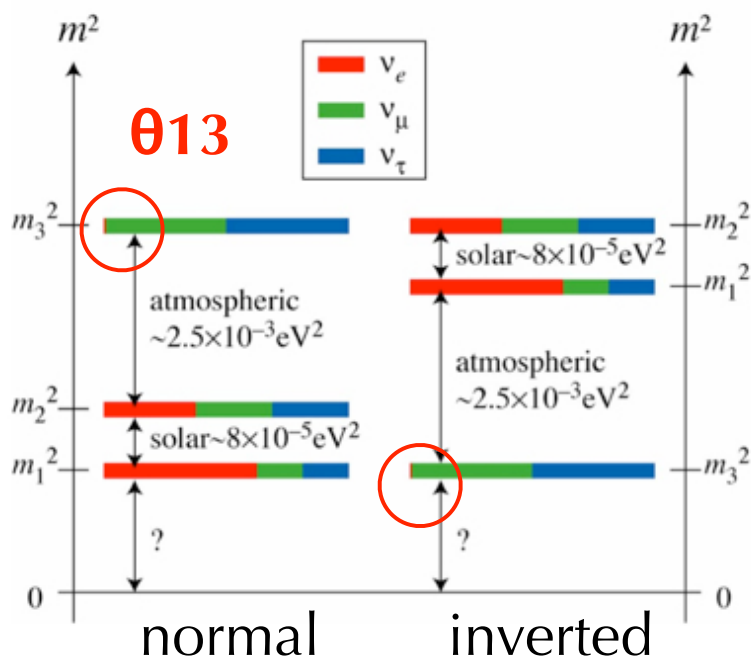
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \boxed{?} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

✦ CPV in lepton sector

✦ Mass hierarchy

$\nu_\mu \rightarrow \nu_e$ *in future LBL exp. with multi MW super beam and giant detector*

✦ precise measurement → (e.g.) Is θ_{23} maximal ?

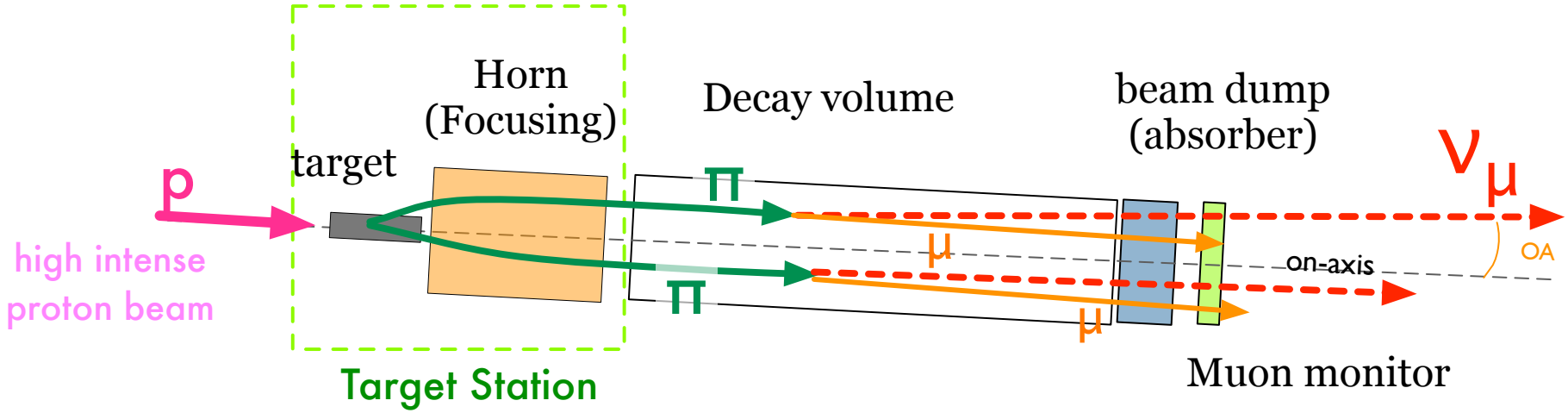


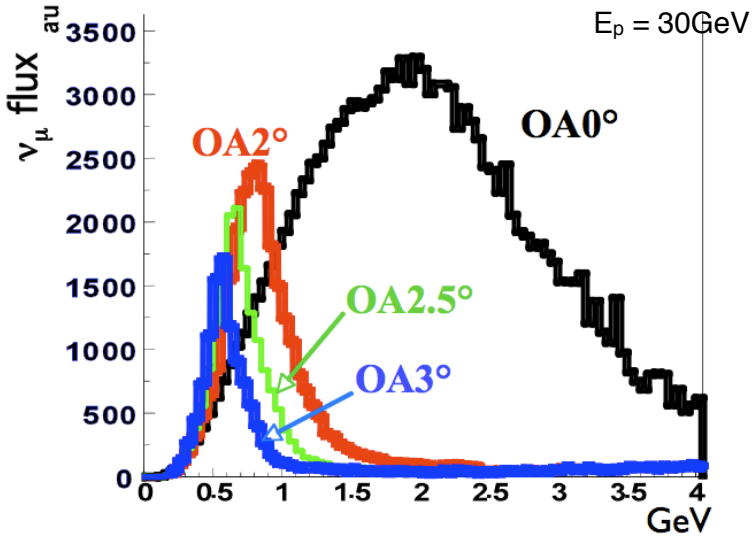
✦ Dirac or Majorana

✦ Absolute Mass scale

non-accelerator ν exp.

Feature of ν super beam





- Conventional ν beam w/ ~MW proton beam
  - high intense & pure ν_μ from π/K decays
  - small ν_e contamination (~1%) from μ and K decays
  - ν energy : wide with on-axis (WBB) or narrow with off-axis method (NBB)
  - ν / $\bar{\nu}$ can be switched by flipping horn polarity

e.g. T2K beam
* OA2.5° NBB (E_{peak}=600MeV)
* 0.4% beam-ν_e @ peak E_ν

Powerful ν_μ sources for CPV search

CPV in $\nu_\mu \rightarrow \nu_e$ oscillation

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \quad \theta_{13}$$

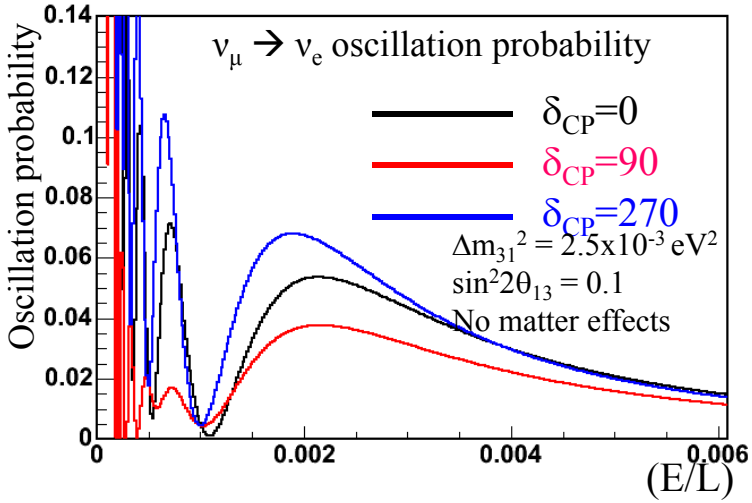
$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \quad \text{CPC}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \quad \text{CPV}$$

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \quad \text{solar}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\left(1 - 2S_{13}^2\right) \quad \text{matter effect}$$

$$\boldsymbol{\delta \rightarrow -\delta,\ a \rightarrow -a \text{ for } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$



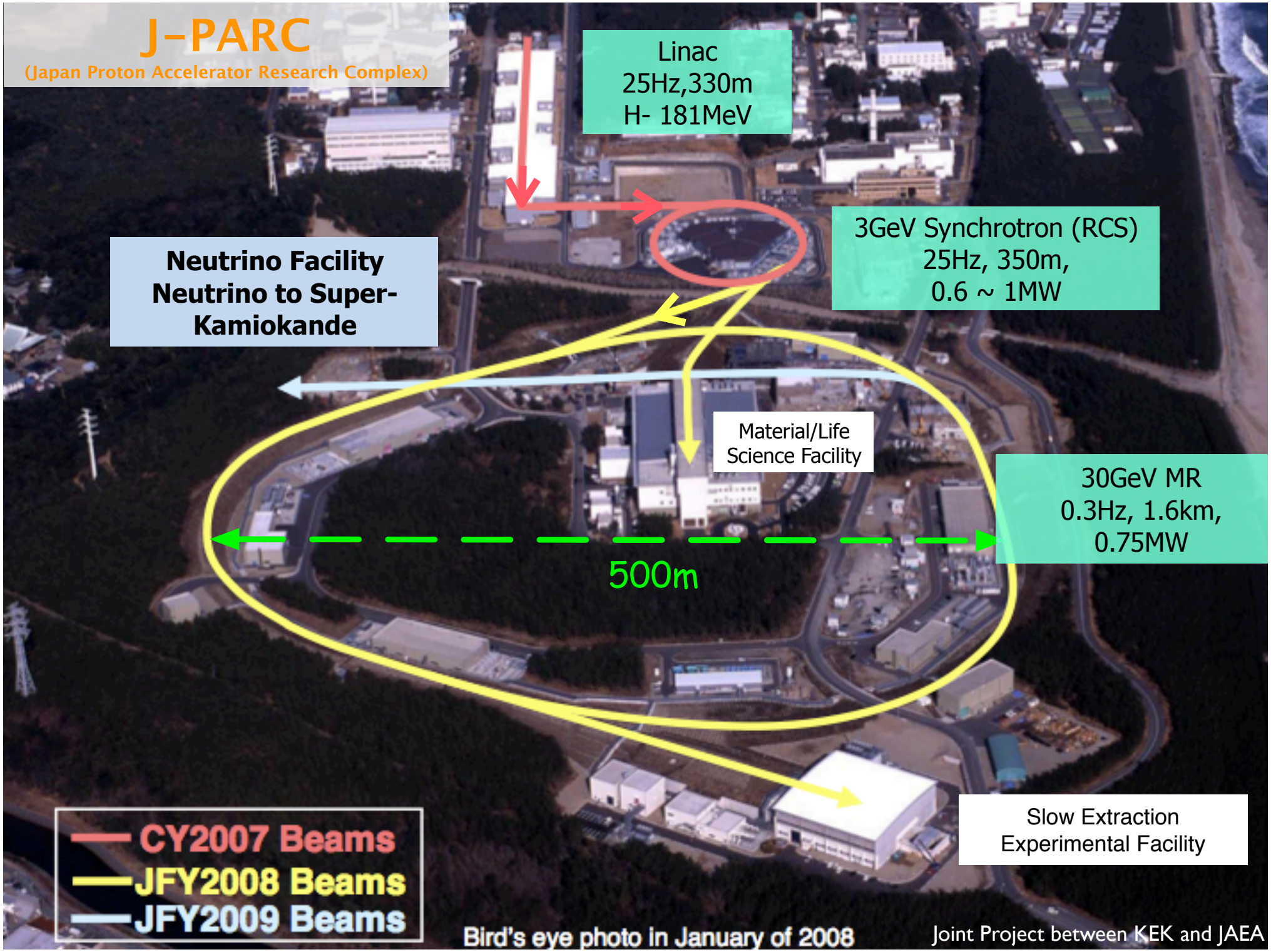
- How to explore CPV in experiment
  - ν_e energy spectrum (1st, 2nd osc. maximum and minimum)
    - WBB, long baseline, good energy resolution, only ν run is necessary
  - difference between ν and $\bar{\nu}$ beam (e.g. $\nu_\mu \rightarrow \nu_e$ ⟺ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
    - also NBB
    - ν and $\bar{\nu}$ run → similar statistics necessary

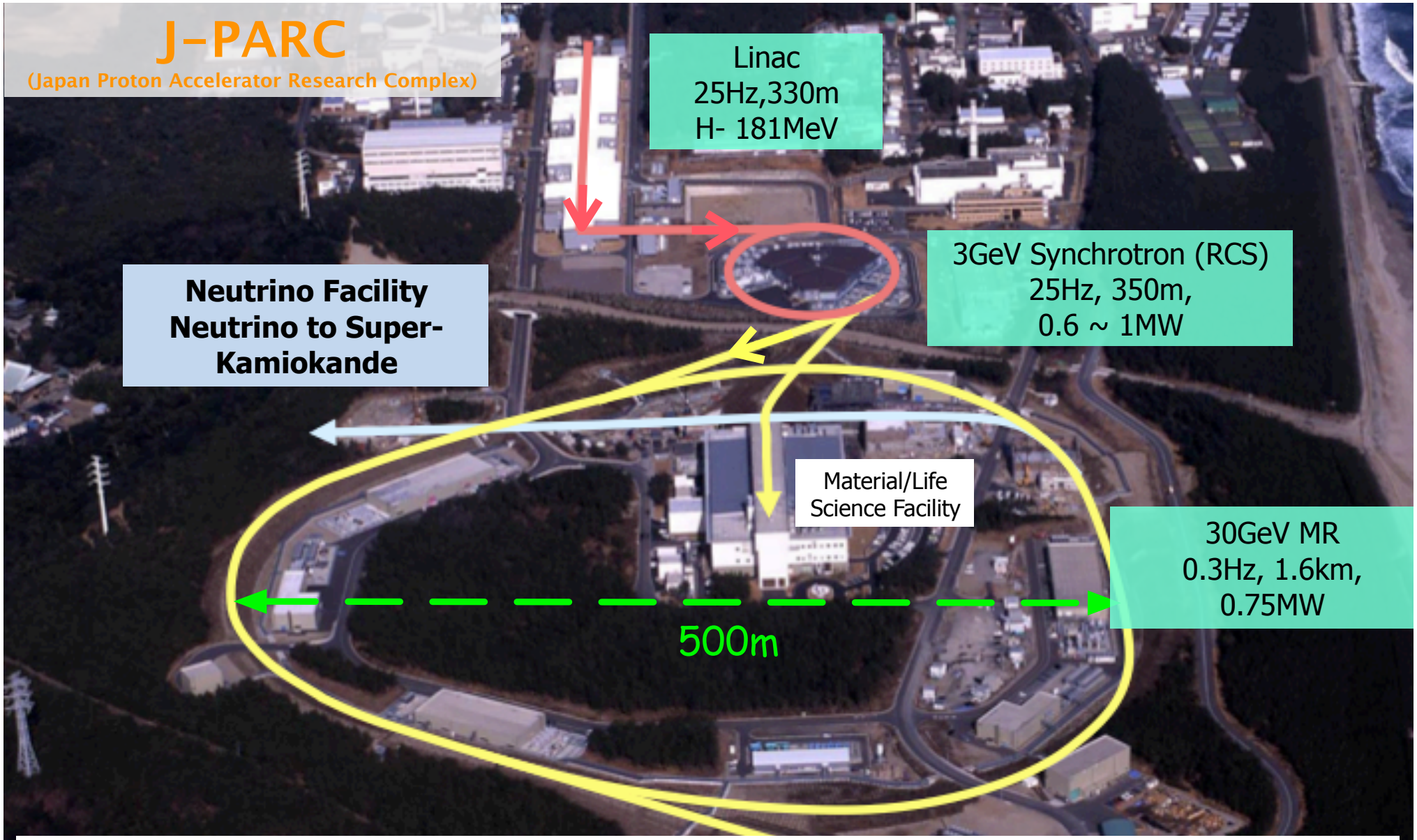
current & future ν beams and LBL experiments

Need both high power ν beam and giant ν detector for future CPV experiments

	current	*plan*	*under discussion*
J-PARC/KEK	~0.05MW	0.75 MW	1.7MW
	T2K (θ_{13})		JPARC-to-somewhere (CPV, hierarchy, θ_{13})
	22.5kton W.C. (SK)		540kton W.C. or 100kton LArTPC
FNAL	~0.3MW	0.7 MW	~2MW (Project-X)
	NuMI/MINOS (ν_μ disapp.)	NOvA (θ_{13}, hierarchy)	FNAL-to-DUSEL (CPV, hierarchy, θ_{13})
		14kton Liquid Scint.	~300kton W.C. and/or ~50kton LArTPC
CERN	~0.3MW	0.4MW	2MW(HP-PS2) ~ 4MW(HP-SPL)
	CNGS/OPERA (ν_τ app.)		130~2300km site (CPV, hierarchy, θ_{13})
			~500kton W.C. or ~100kton LArTPC or ~50kton LiquidScint.

JPARC current & future


J-PARC
(Japan Proton Accelerator Research Complex)
Linac
25Hz,330m
H- 181MeV
3GeV Synchrotron (RCS)
25Hz, 350m,
0.6 ~ 1MW
Neutrino Facility
Neutrino to Super-Kamiokande
Material/Life Science Facility
30GeV MR
0.3Hz, 1.6km,
0.75MW
500m
Slow Extraction Experimental Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008
Joint Project between KEK and JAEA

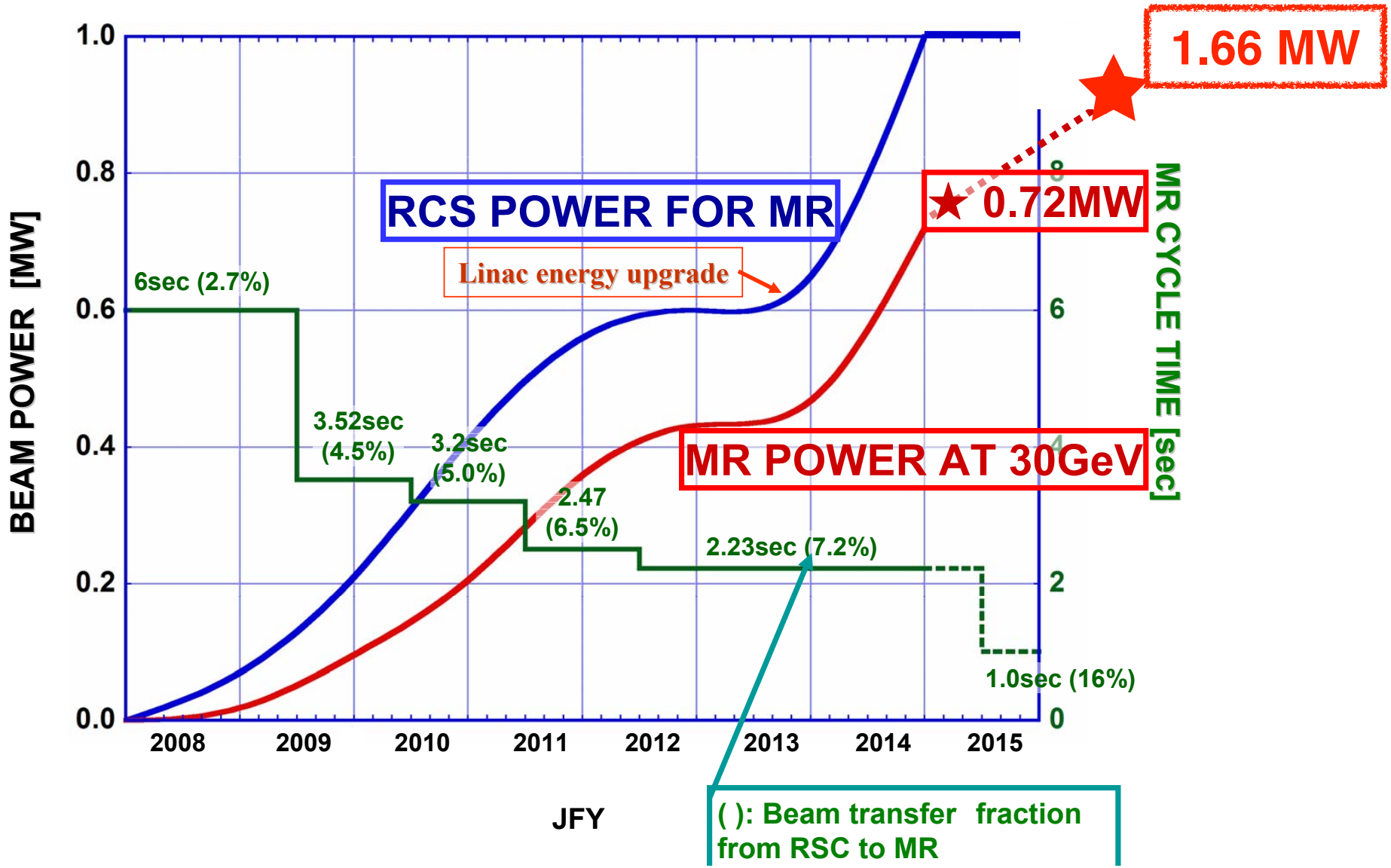


MR & Neutrino beam facility operation :

- ~0.05 MW continuous operation
  → next step is beyond 0.1MW toward 0.75MW after this summer shut down
- beam loss control is in progress toward high power operation

MR Power Improvement Scenario

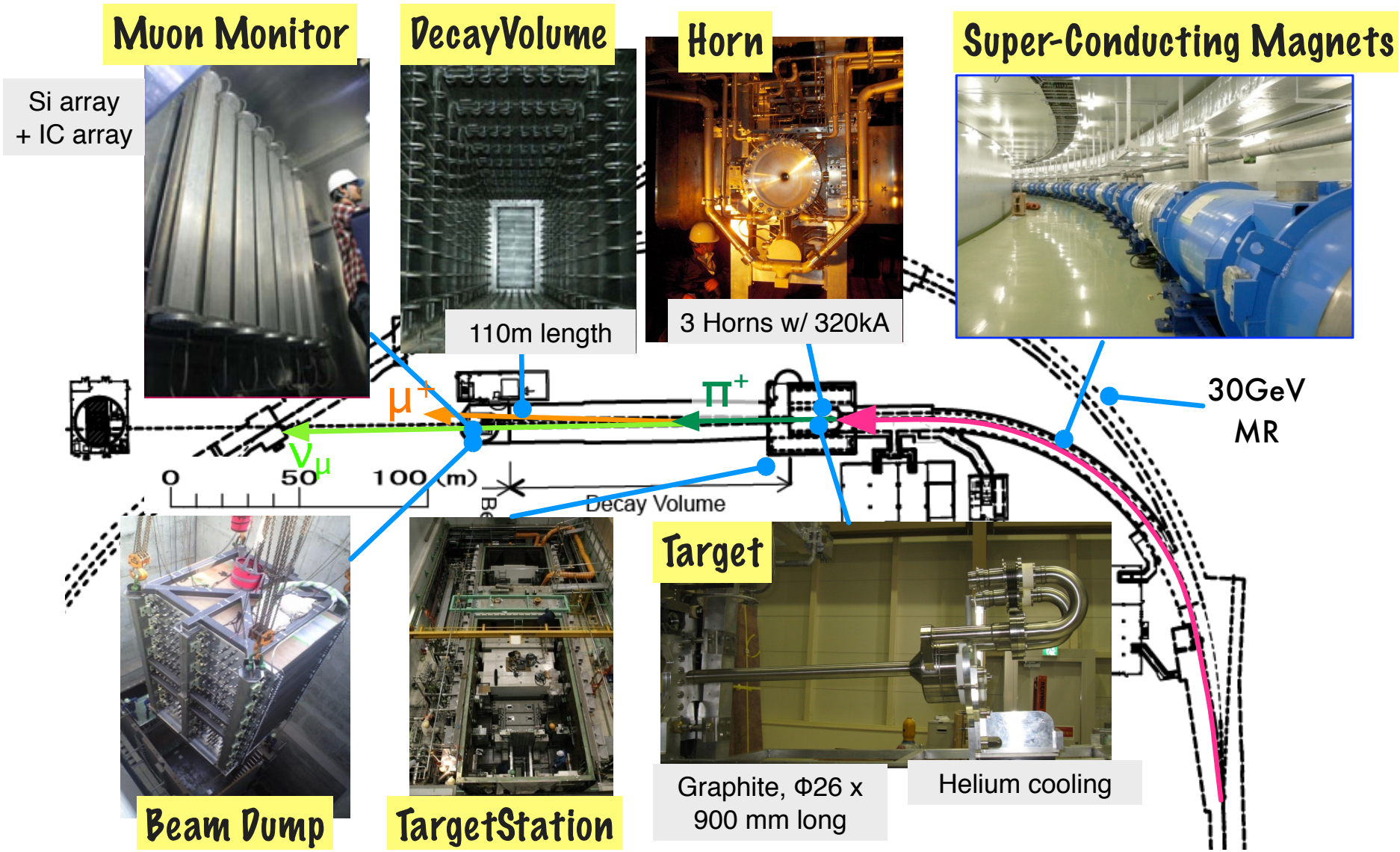
Increase rep. rate and/or increase # of protons toward high power (~1.66MW)



J-PARC Neutrino beam facility

2MW is tolerable for J-PARC ν beam-line without any major upgrade

step by step toward high power beam (radiation, cooling, beam-loss control etc..)



Future CPV exp. with J-PARC super beam (1)

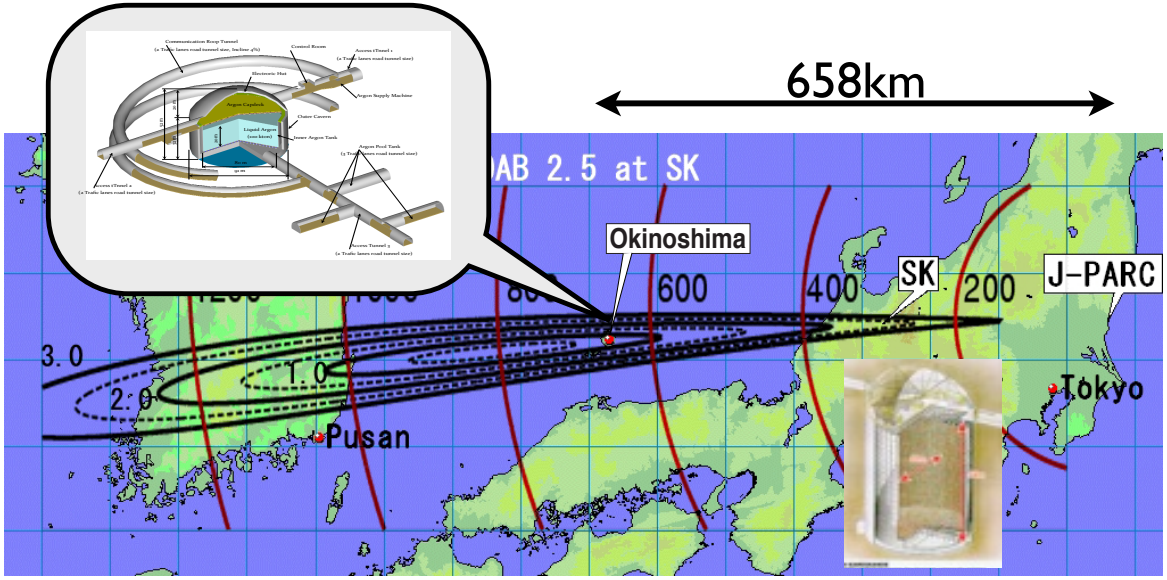
energy spectrum measurement

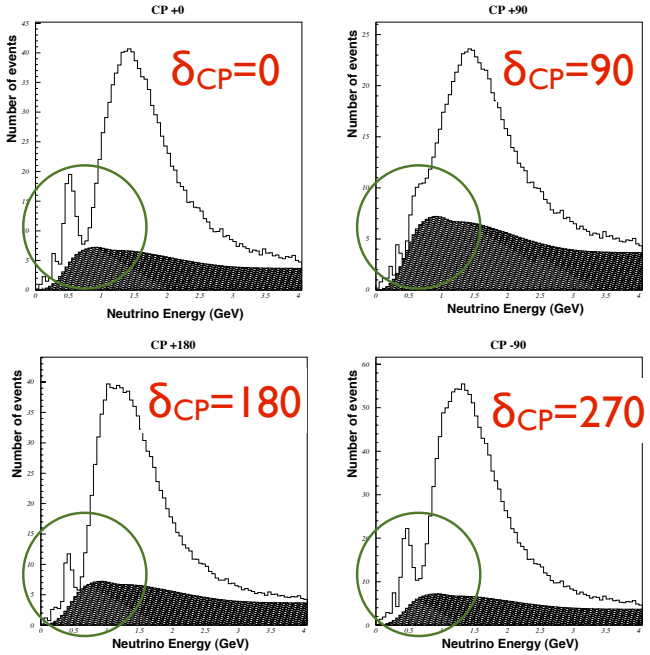
WBB with OA=0.76°

L=658km → ~500MeV@2nd max.

100kton LArTPC@Okinoshima

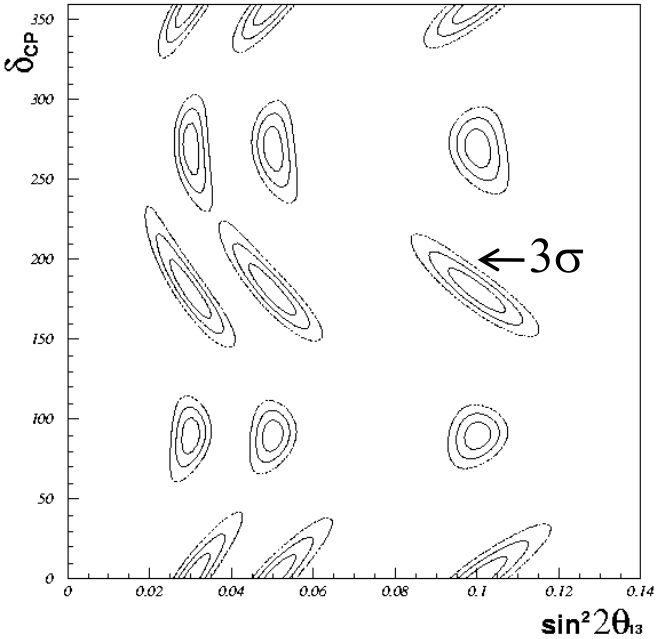
* good energy resolution
* good e/π^0 discrimination





$\sin^2 2\theta_{13}$=0.03 & varying CP phase

CP Measurement Potential



only ν run :
5year x 1.66MW

CPV 3σ discovery
almost all δ
for $\sin^2 2\theta_{13} > 0.02$

detector R&D is
in progress

see T.Hasegawa's talk

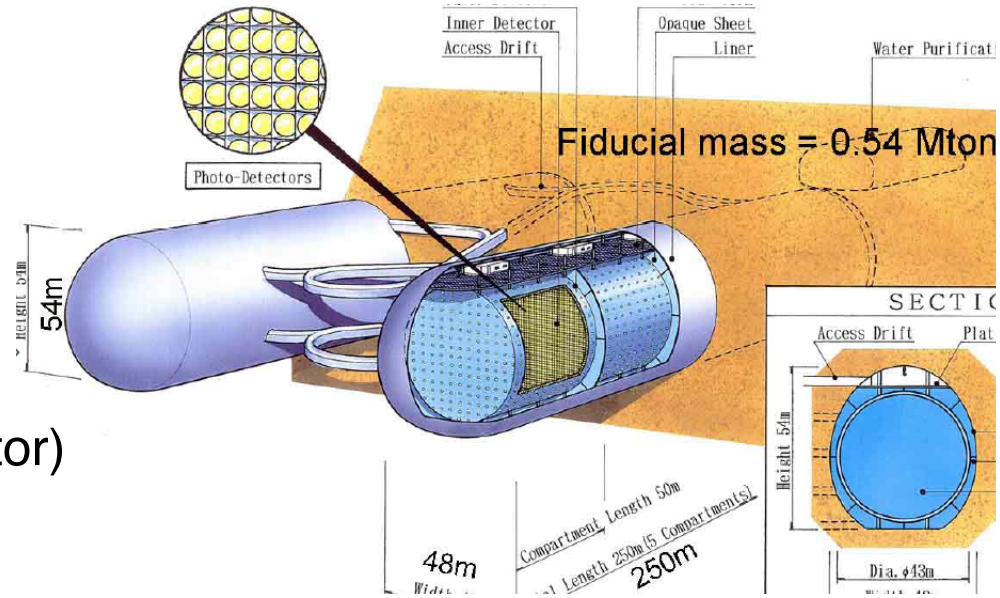
Future CPV exp. with J-PARC super beam (2)

difference between ν and $\bar{\nu}$

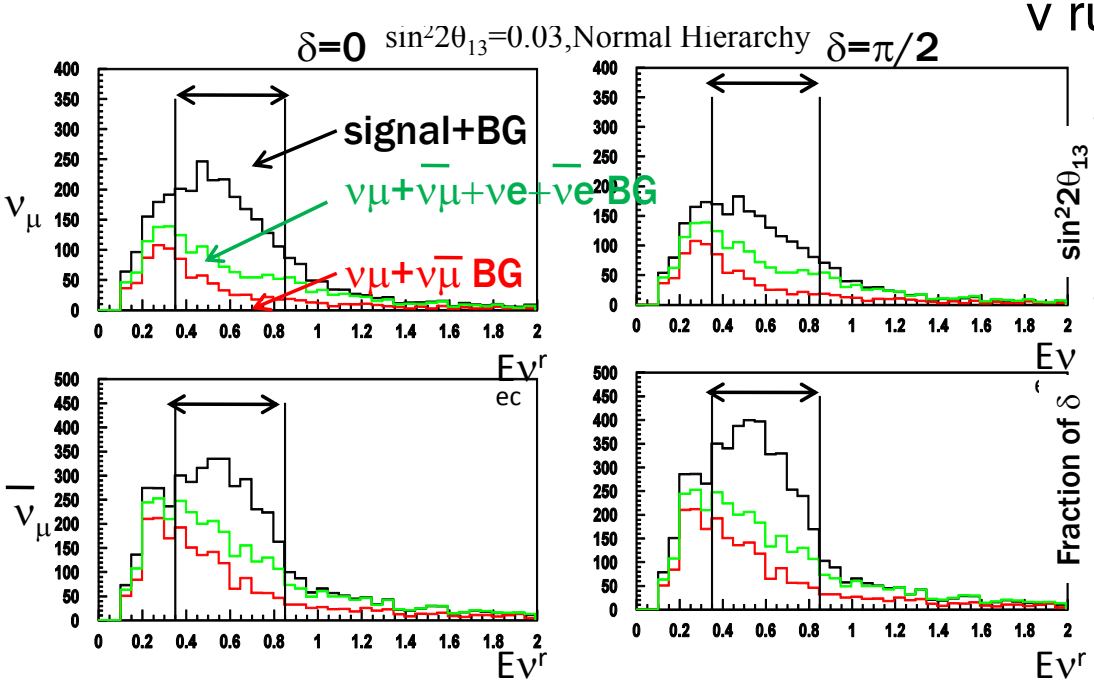
NBB with OA=2.5° → small high E tail
(low π^0 bkg.)

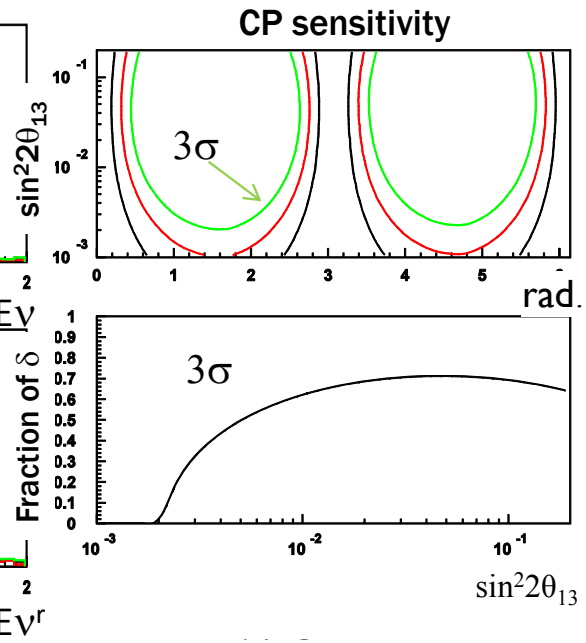
L=295km → 600-700MeV@1st max
(config. is same as T2K except for detector)

540 kton Water cherenkov detector
* good PID e/μ @ sub-GeV



ν run x 2.2year + $\bar{\nu}$ run x 7.8 year





det. optimization is in progress

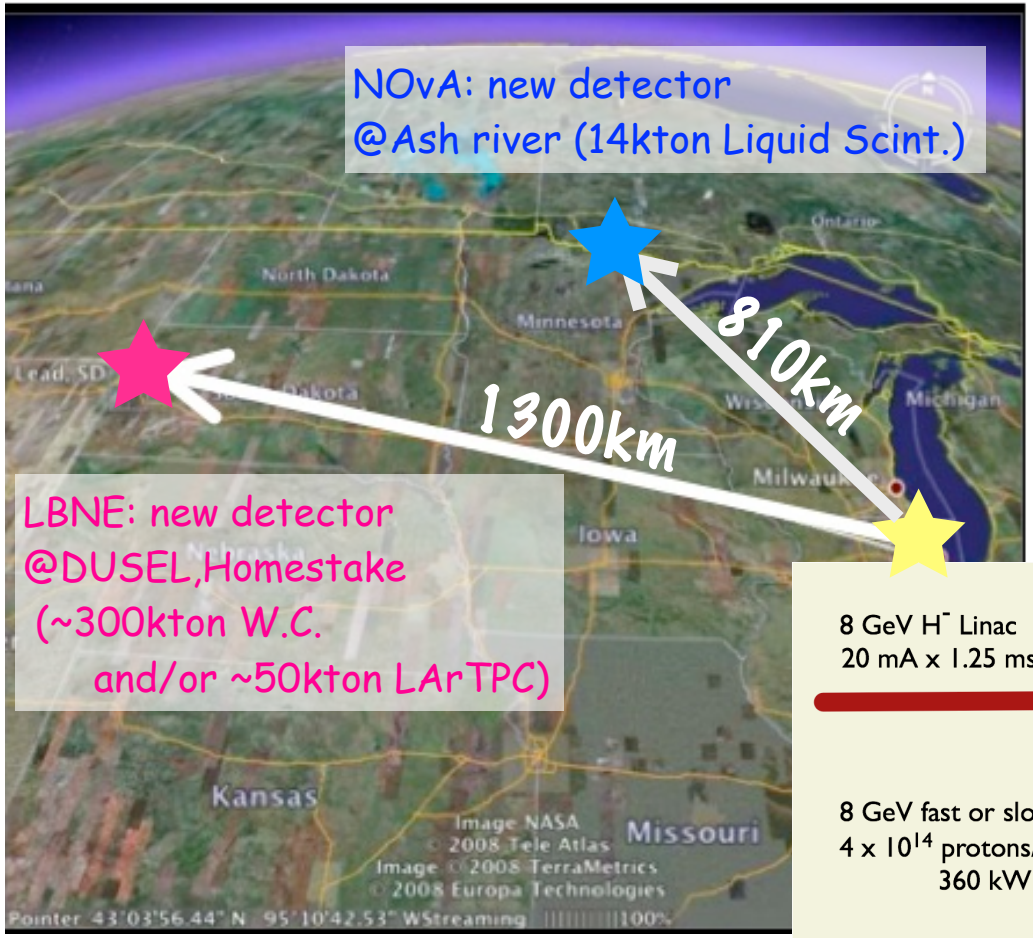
see M.Shiozawa's talk

K.Kaneyuki @NP08

Future CPV exp. with super beam @U.S.

LBNE : FNAL to DUSEL

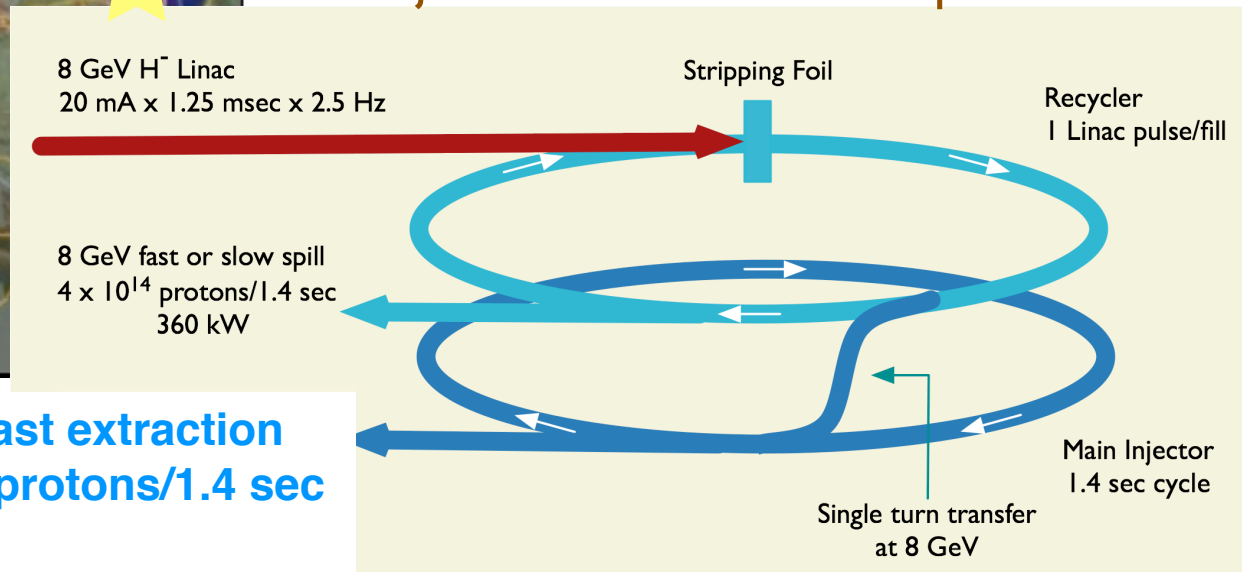
* L=1300km →CPV + mass hierarchy



* new ν beam-line to DUSEL
* accelerator :
  MI upgrade 300kW → 700kW
  (also NOvA)

new accelerator(2MW) *Project-X*

Project-X accelerator complex



see K.Heller's and R.Svoboda's talk

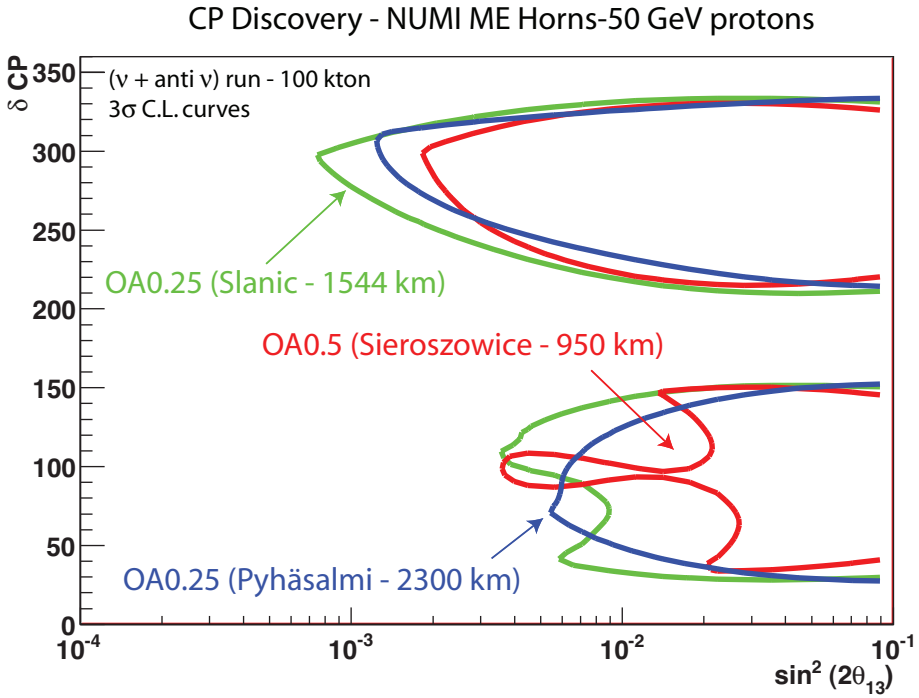
120GeV Fast extraction
1.6 x 10^{14} protons/1.4 sec
2.1MW

Future CPV exp. with super beam @Europe

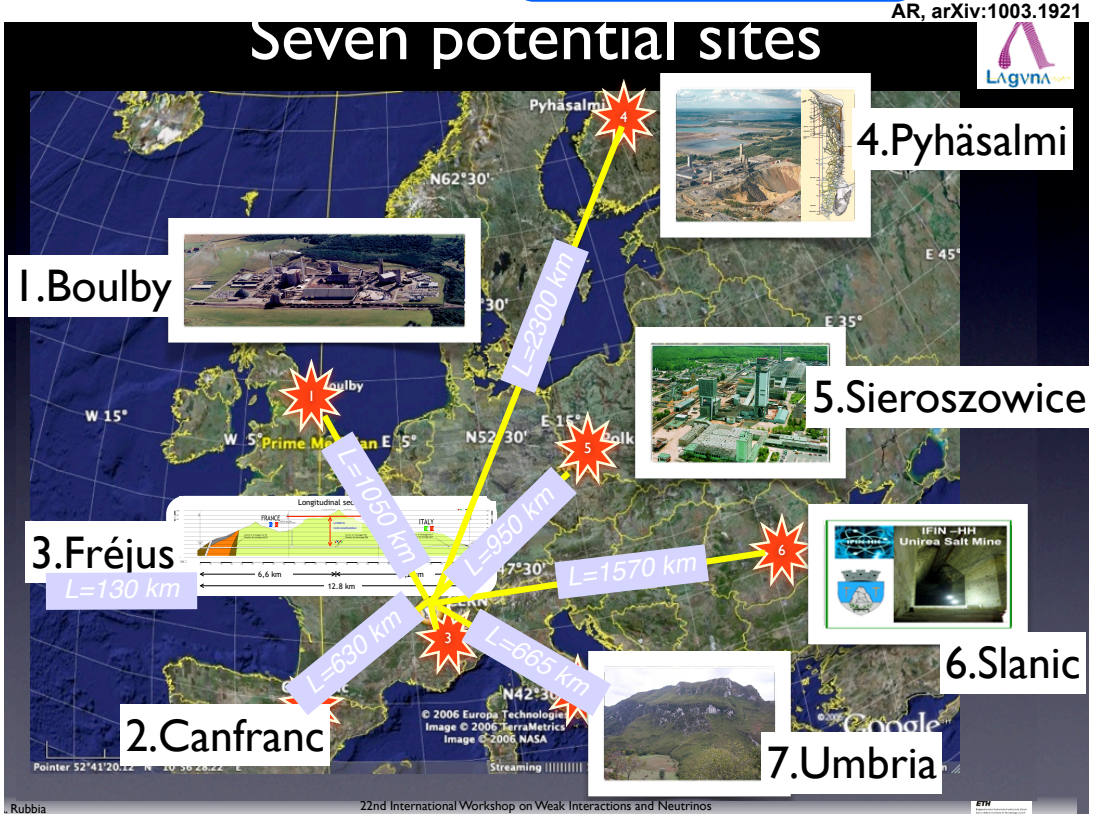
- new superbeam & detector
  - under study for optimal config.
- very long baseline with superbeam
  → CPV + mass hierarchy

	PS+SPS	SpS RF upgrade	SPL+PS2+ SPS new RF	SPL + PS2	New HP-PS	Booster + RCS 4 MW
Machine param.		[33]		[35]	this paper	[37]
Proton energy E_p		400 GeV		50 GeV		30 GeV
$ppp(\times 10^{13})$	4.8	7	10	12.5	25	10
T_c (s)	6	7.2	4.8	2.4	1.2	$(8.33\text{Hz})^{-1}$
Beam power (MW)	0.5	0.6	1.3	0.4	1.6	4
Global efficiency	0.8	0.8	0.8	1.0	1.0	1.0
Beam sharing	0.85	0.85	0.85	0.85	0.85	1.0
Running (d/y)	200	200	200	200	200	200
N_{pot}/yr $(\times \mathbf{10^{19}})$	**9.4**	**11.4**	**24.5**	**77**	**300**	**1437**
$E_{tot} \equiv E_p \times N_{pot}$ $(\times 10^{22}$ GeV·pot/yr)	4	4.5	10	4	15	43
E_{tot} increase compared to CNGS	$\times 2$	$\times 2$	$\times 4$	$\times 2$	$\times 5$	$\times 16$

AR, arXiv:1003.1921



100kton LArTPC x 1.6MW (HP-PS2)
ν run x 5year + $\bar{\nu}$ run x 5year



Summary of future ν super beam experiments

already existing or upgrade existing acc/beam-line construct new one

	motivation	Beam Power [MW]	ν beam facility	detector	baseline [km]	ν energy (peak E_ν)	experimental method
JPARC-Okinoshima	**CPV, θ_{13} (hierarchy)**	1.66	existing	100kton LArTPC	658	WBB (1.2GeV)	1st, 2nd max
JPARC-Kamioka	**CPV, θ_{13}**	1.66	existing	540kton W.C.	295	NBB (0.7GeV)	ratio of ν and $\bar{\nu}$
FNAL-DUSEL	**CPV, θ_{13}, hierarchy**	0.7 2.1	need new one	~300kton WC. and/or ~50kton LArTPC	1300	WBB (3GeV)	1st, 2nd max
CERN-Frejus	**CPV, θ_{13}**	4 (HP-SPL)	need new one	~440kton W.C.	130	on-axis low energy (0.2GeV)	ratio of ν and $\bar{\nu}$
CERN-Pyhasalmi	**CPV, θ_{13}, hierarchy**	1.6 (HP-PS2)	need new one	100kton LArTPC	2300	WBB (3GeV)	1st, 2nd max

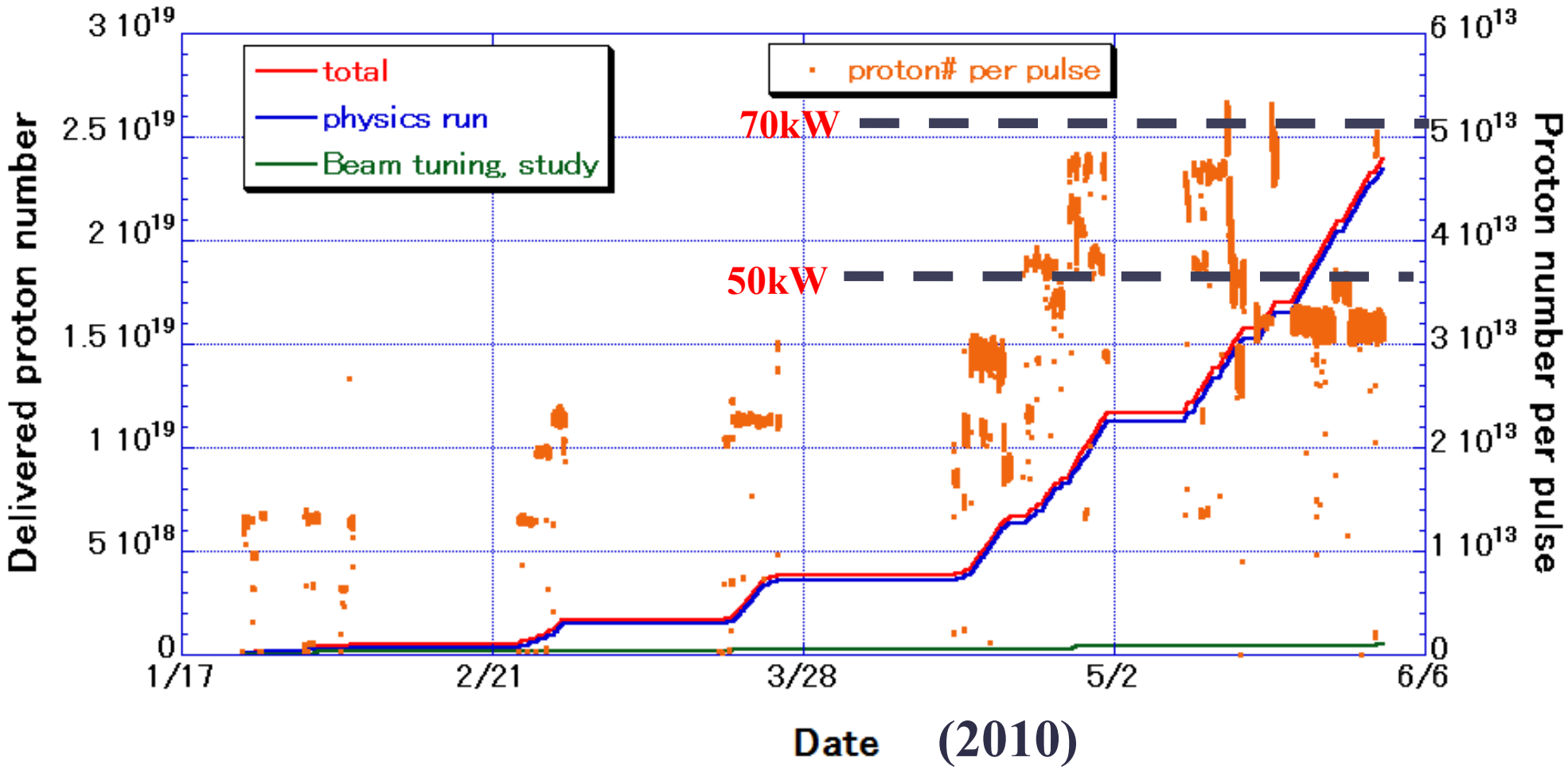
Summary

- Future super beam LBL experiments aim for discovery of CPV in lepton sector and mass hierarchy
  - upgrading or newly constructing ν super beam (~2MW) and new main ν detector
    - J-PARC accelerator is planed to be upgraded to 1.66MW
    - ~2MW is tolerable for J-PARC ν beam-line without any major upgrade
  - competitive CPV discovery potential down to $\sin^2 2\theta_{13} \sim 10^{-2}$
  - a lot of R&D processes are in progress
    - for increasing accelerator beam power and main ν detector

Future super beam ν oscillation experiments are promising to explore and discover CPV in lepton sector because we know how to build and cost of super beams

backup

T2K beam intensity



- ~50kW continuous operation
- Trial up to 100kW done

MR Power Improvement Scenario toward MW-class power frontier machine

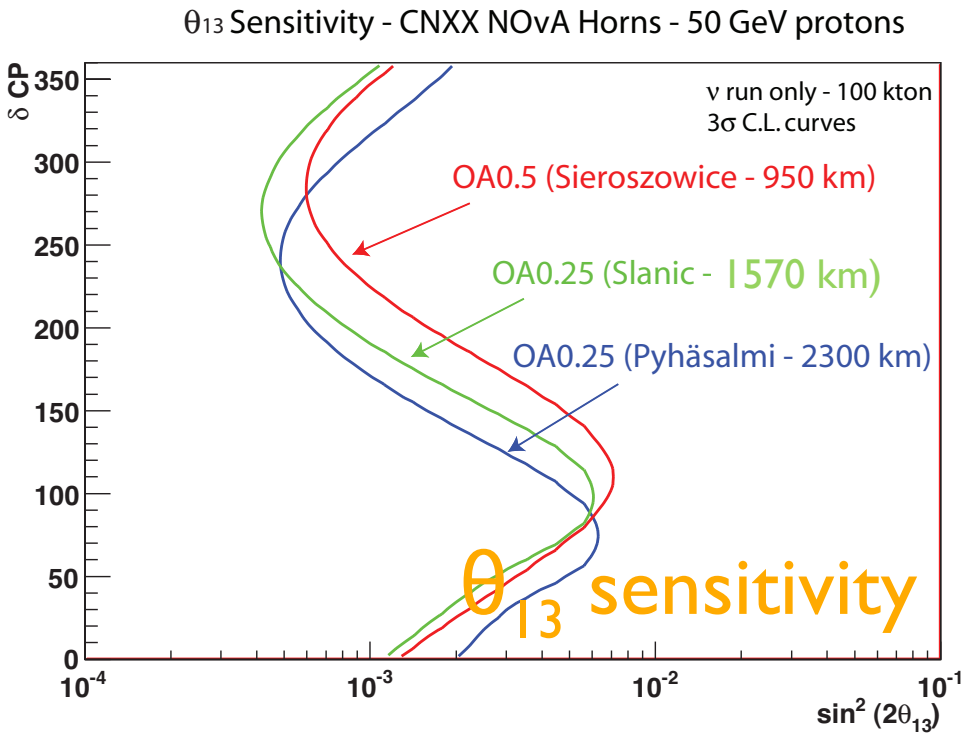
Increase rep. rate (up to 2Hz) and/or increase # of protons

	Day1 (up to Jul.2010)	Next Step	KEK Roadmap
Power(MW)	0.1	0.45	1.66
Energy(GeV)	30	30	30
Rep Cycle(sec)	3.5	3-2	1.92～0.5
No. of Bunch	6	8	8
Particle/Bunch	1.2×10^{13}	$<4.1\times10^{13}$	$4.1\sim8.3\times10^{13}$
Particle/Ring	7.2×10^{13}	$<3.3\times10^{14}$	$3.3\sim6.7\times10^{14}$
LINAC(MeV)	181	181	400
RCS	h=2	h=2 or 1	h=2 or 1

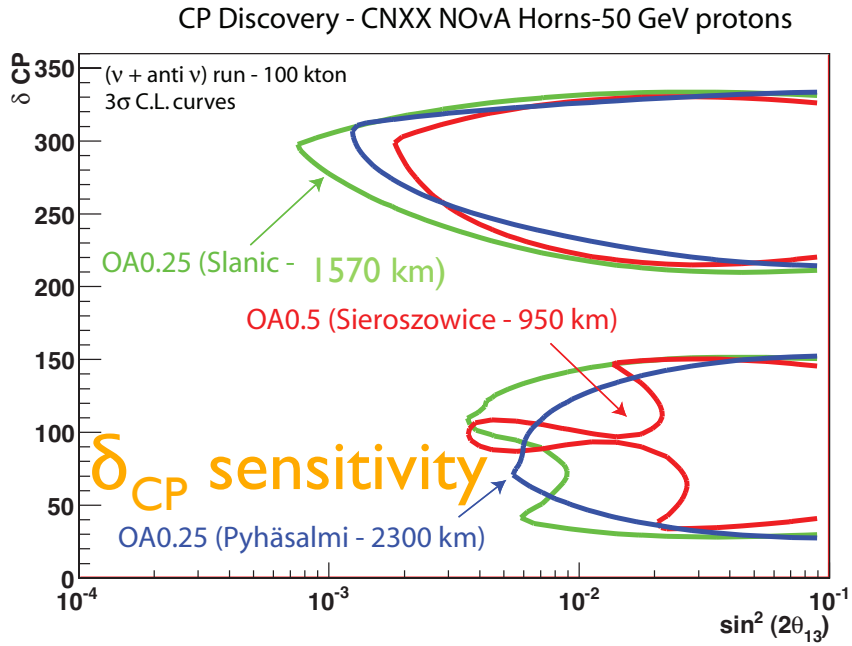
Rapid cycle

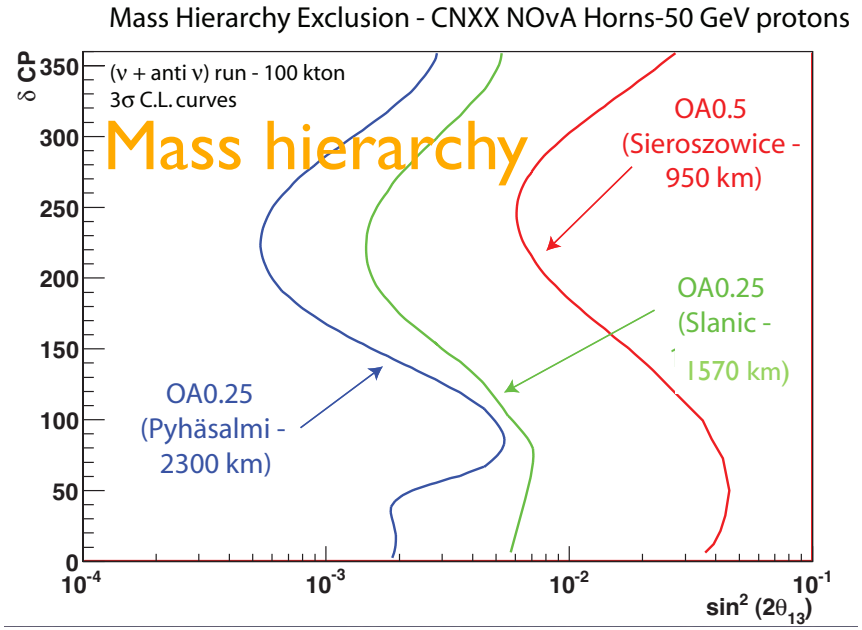
add more RF and improve magnet power-supply

100kton LArTPC x 1.6MW (HP-PS2)
ν run x 5year



100kton LArTPC x 1.6MW (HP-PS2)
ν run x 5year + $\bar{\nu}$ run x 5year





Mass hierarchy sensitivity (J-PARC to Okinoshima)

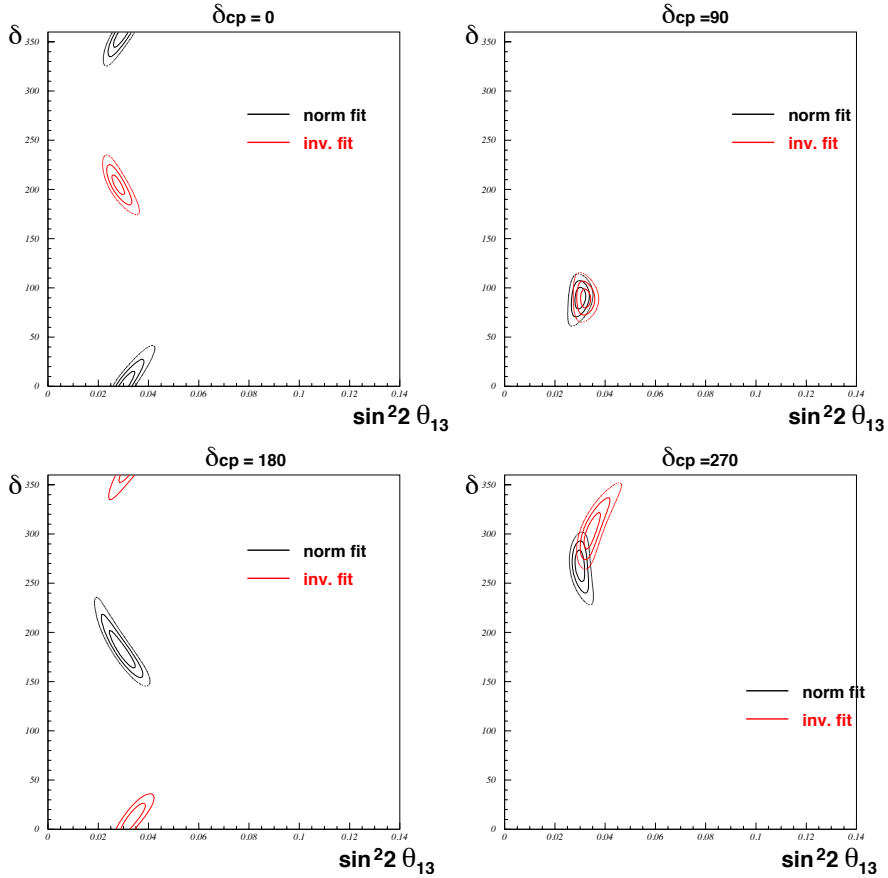


Fig. 7: Mass hierarchy investigation with neutrino run only. If fits with both hierarchy hypotheses provide neither 0 nor 180°, one can declare discovery of CP violation in the leptonic sector. If any of the fits results in a δ_{CP} of 0 or 180°, then an anti-neutrino run could be envisaged.

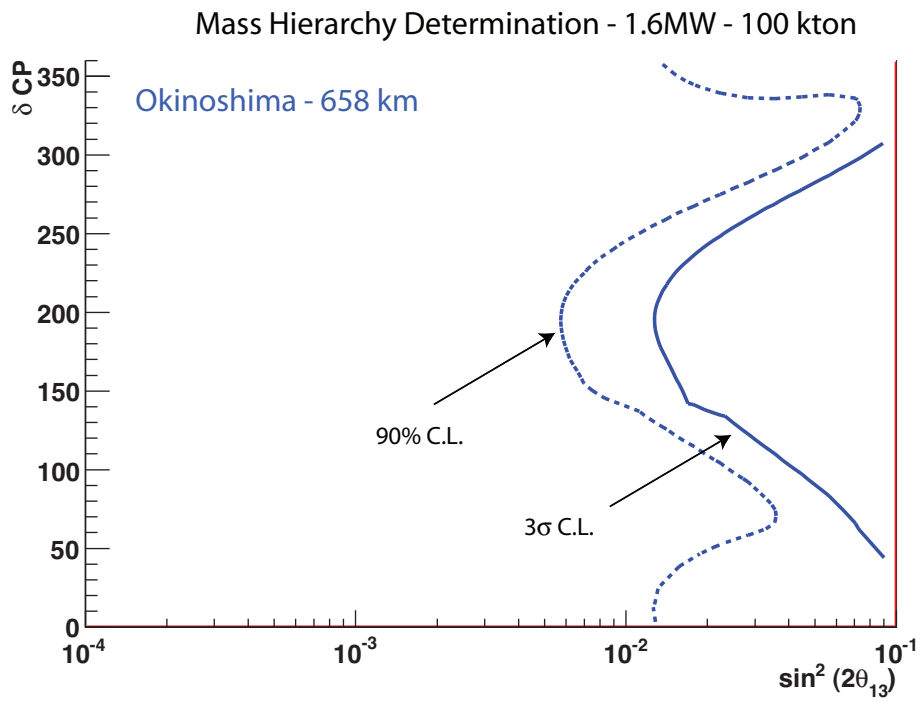


Fig. 10: Mass hierarchy discrimination at 90%C.L. and 3σ for 5+5 years neutrino-antineutrino runs.

New ν beam-line for LBNE @FNAL

Start with a 700 kW beam, and then take profit of the significantly increased beam power (2.3 MW) available with Project X