The T2K program

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Neutrino facility construction group

Talk at plenary session of NUFACT05, June 21, 2005

Contents

- Introduction of T2K experiment
- J-PARC
- Neutrino beam facility
- Neutrino detectors & physics
  - ⇒ at session 5 of WG1 on June 23

T2K experiment

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Super-K: 50 kton Water Cherenkov

Phase2: Hyper-K

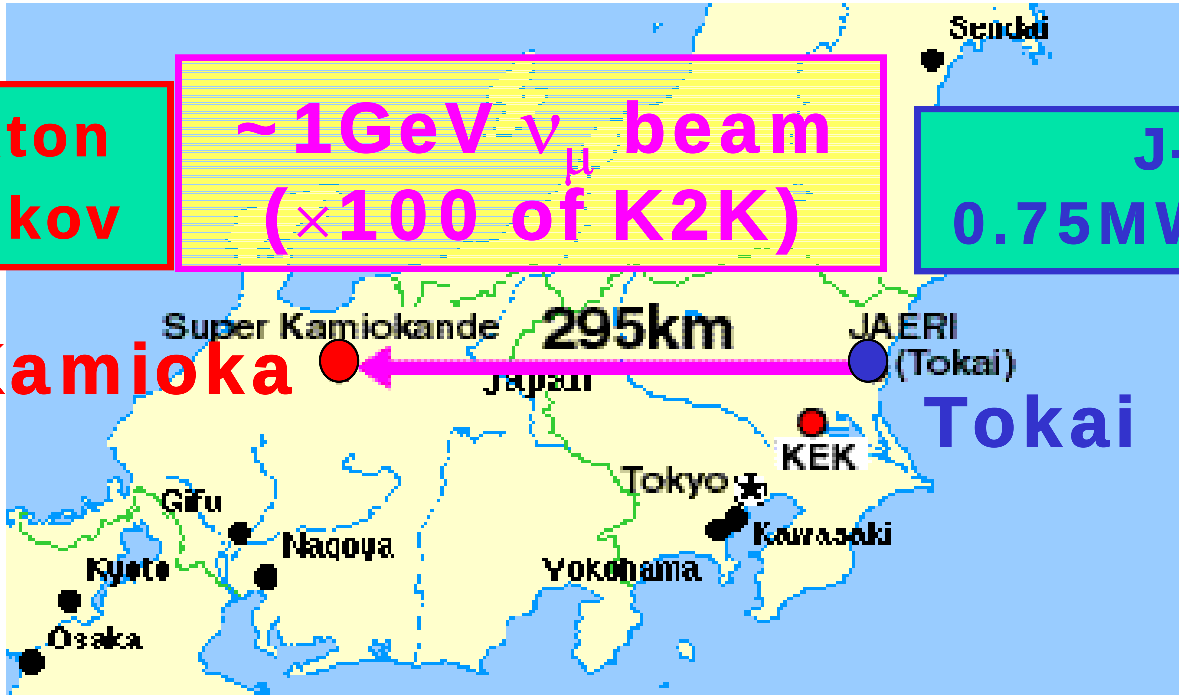
~1GeV ν_μ beam ($\times$100 of K2K)

J-PARC 0.75MW 50GeV PS

Phase2: 4 MW

Kamioka

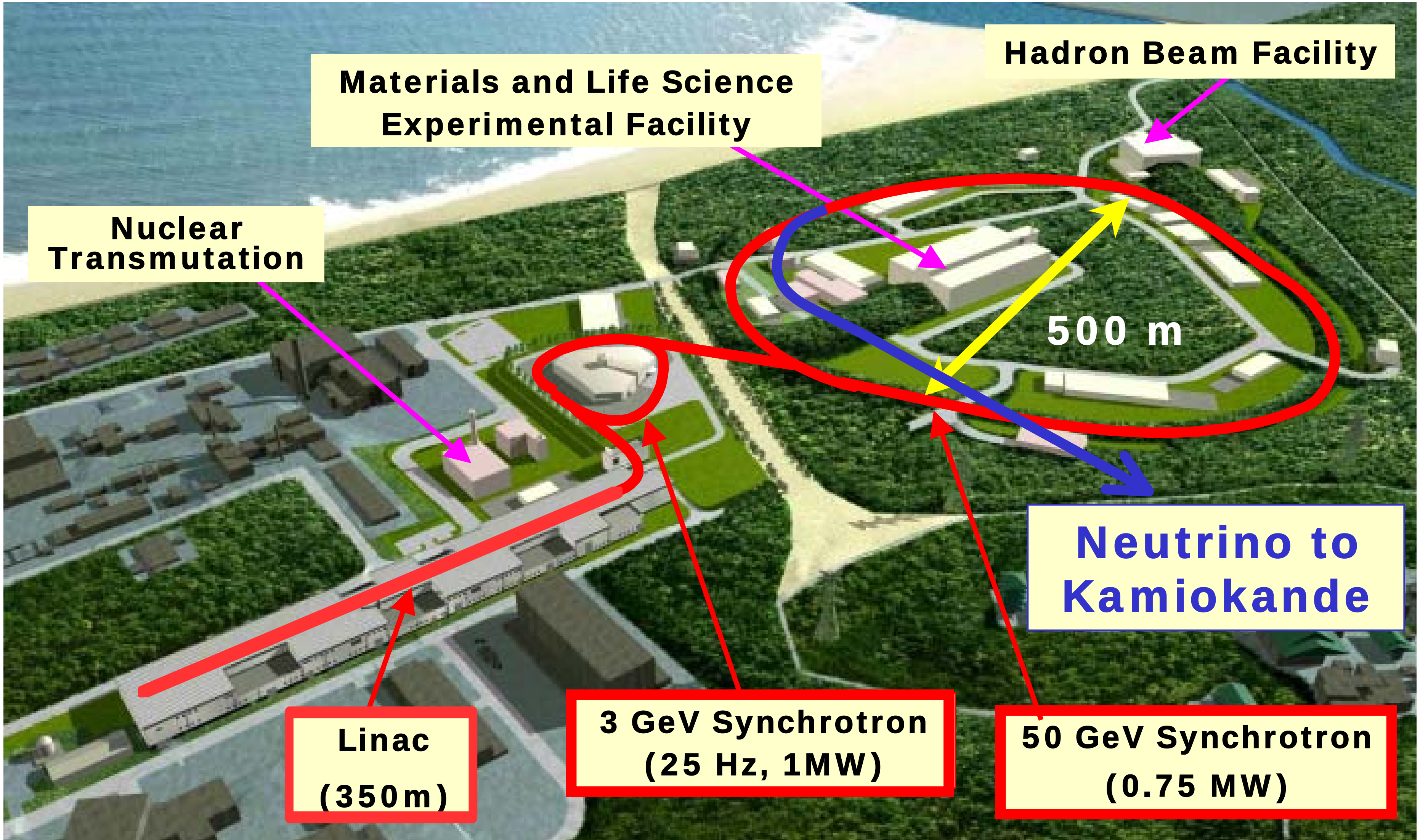
Tokai



Physics motivations

- **Discovery of $\nu_\mu \to \nu_e$ appearance**
- **Precise meas. of disappearance $\nu_\mu \to \nu_x$**
- **Discovery of CP violation (Phase2)**

J-PARC Facility



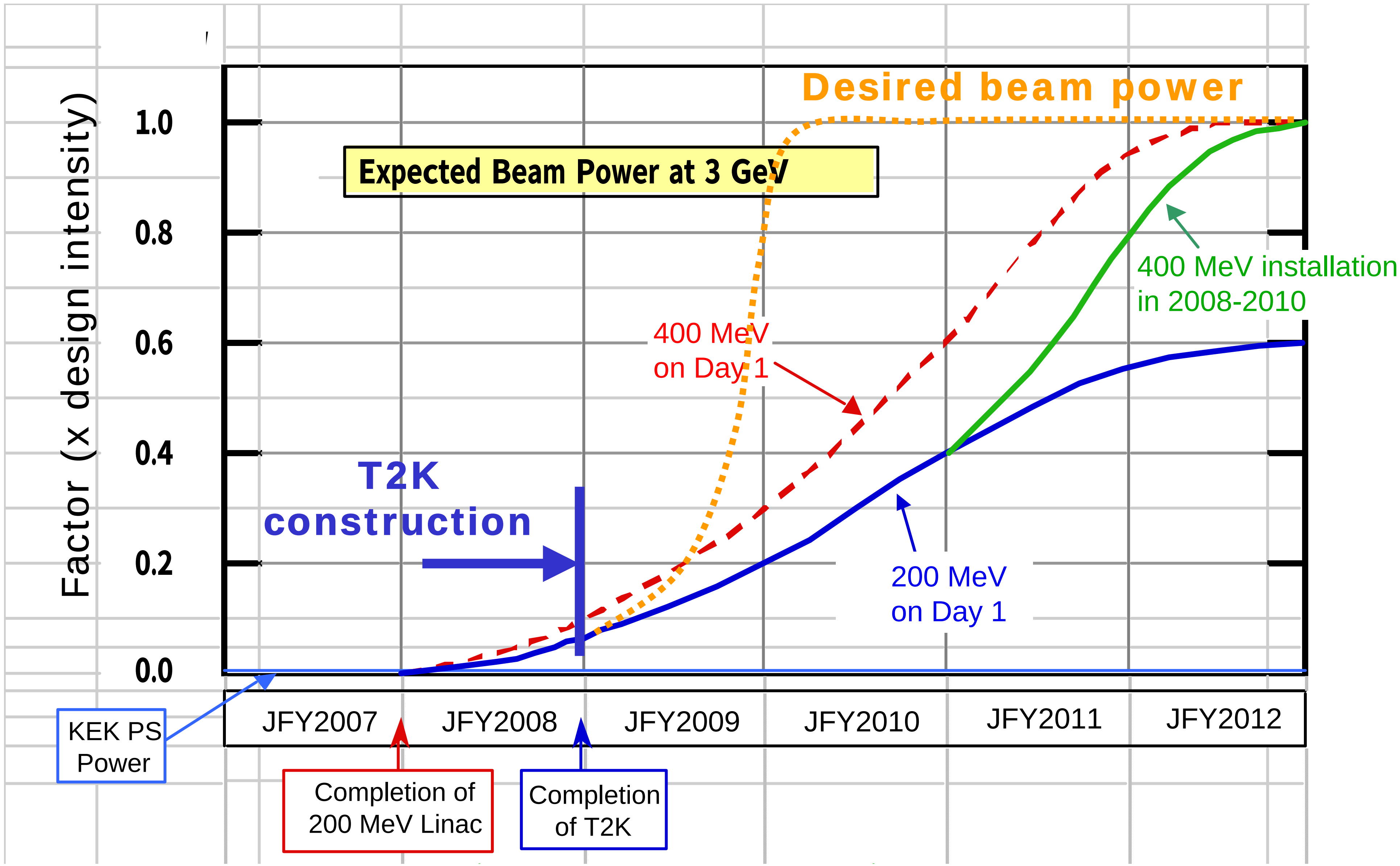
J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAERI

J-PARC status

- Buildings for LINAC and 3GeVPS finished.
- North-east part of tunnel for 50GeVPS finished.
- South-west part of tunnel will finish in FY2006.
- First beam on 50GeV PS in FY2008

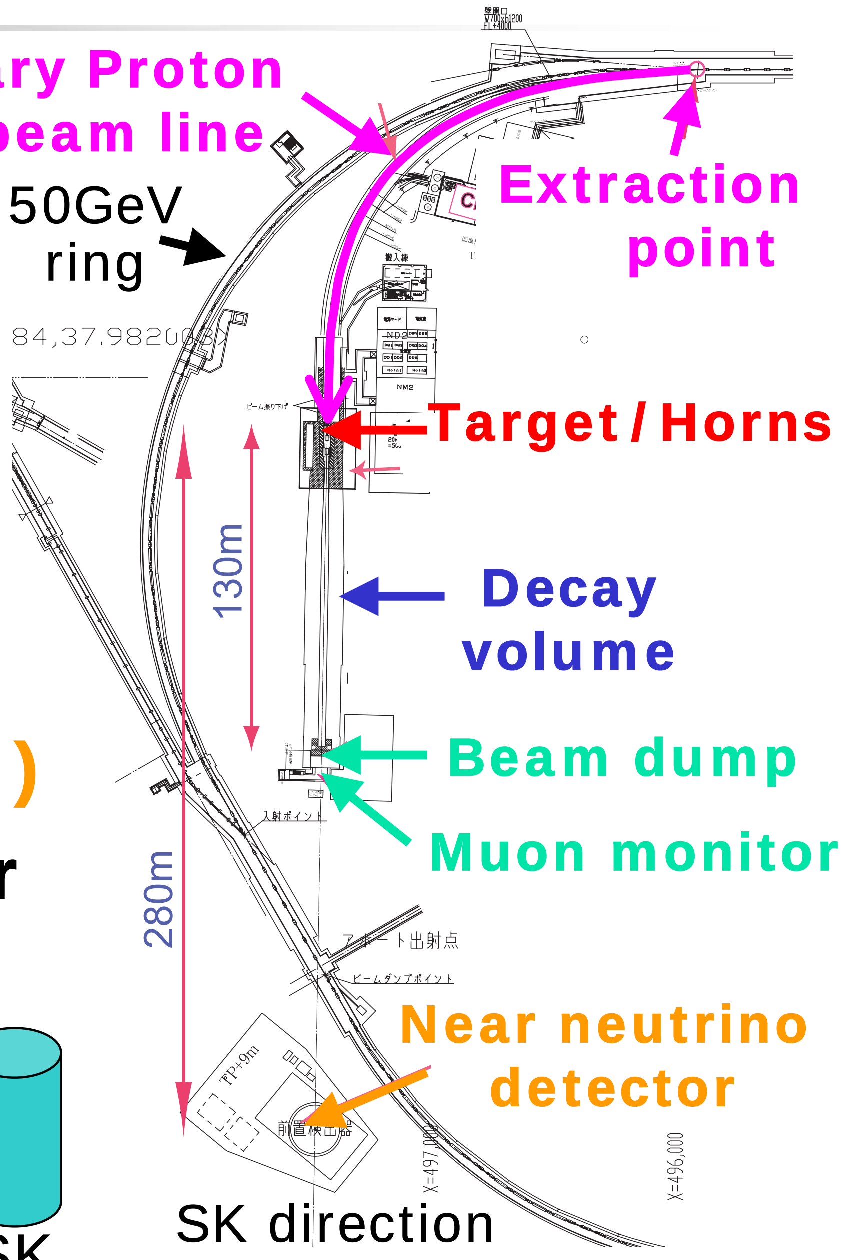
Expected Beam Power

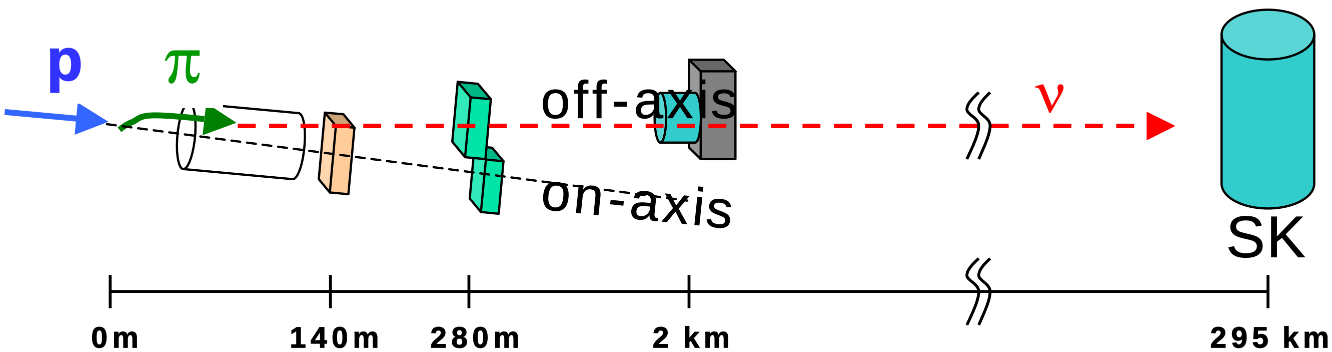


Neutrino facility

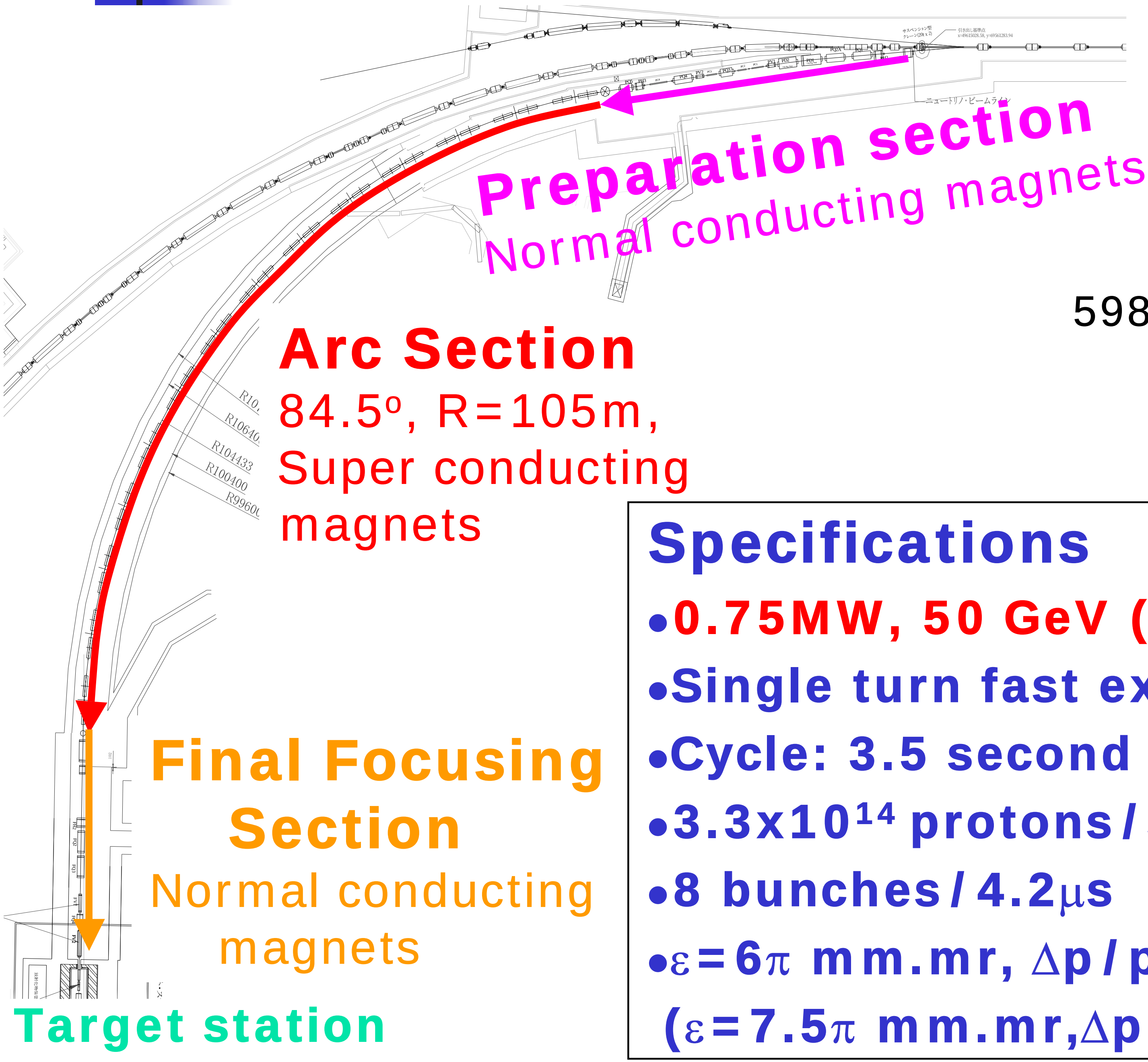
Components

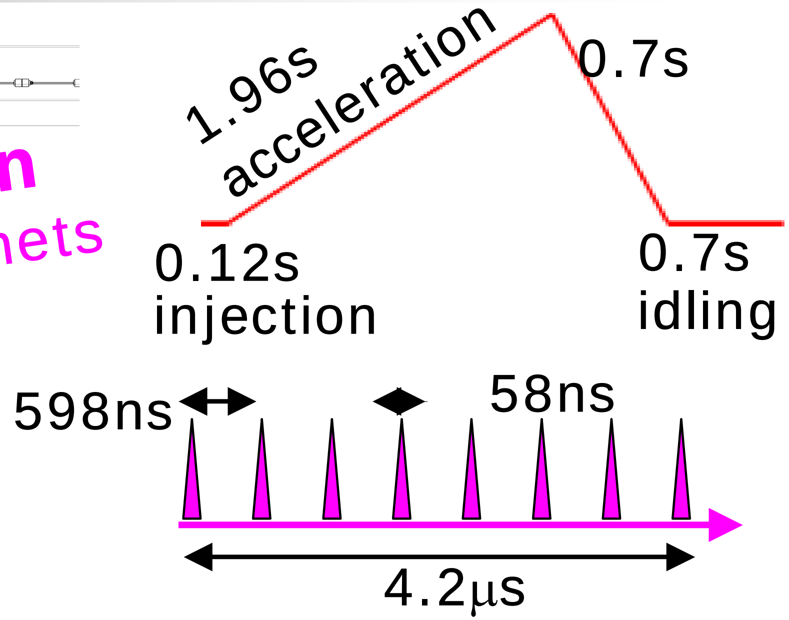
- Primary proton beam line
- Target / Horns
- Decay volume (130m)
- Beam dump
- Muon monitor
- Near neutrino detector (280m)
- Second near neutrino detector (~2km): future option





Proton beam line



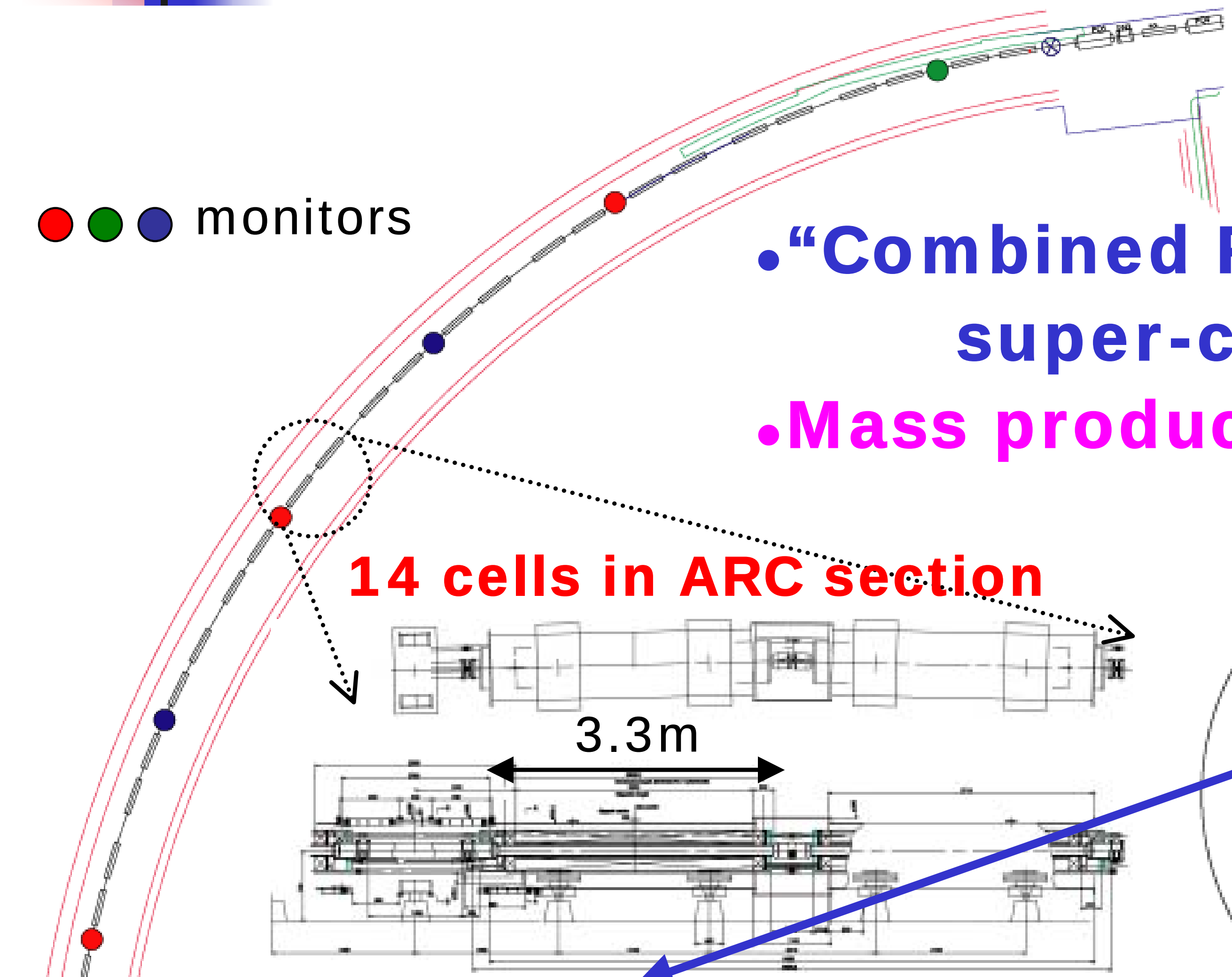


Specifications

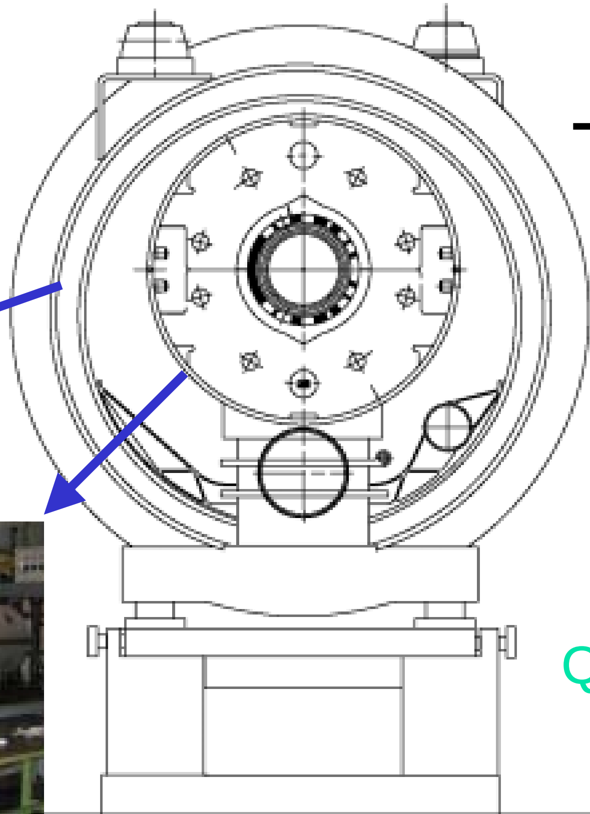
- **0.75MW, 50 GeV (40GeV@t=0)**
- **Single turn fast extraction**
- **Cycle: 3.5 second**
- **3.3×10^{14} protons/spill**
- **8 bunches/4.2μs**
- **$\varepsilon = 6\pi$ mm.mr, $\Delta p/p = 0.31\%$**
  ($\varepsilon = 7.5\pi$ mm.mr, $\Delta p/p = 0.36\%$@40GeV)

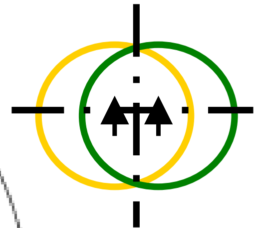
Arc section

●●● monitors

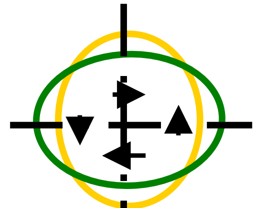


- “Combined Function” super-conducting magnets
- Mass production starts soon.



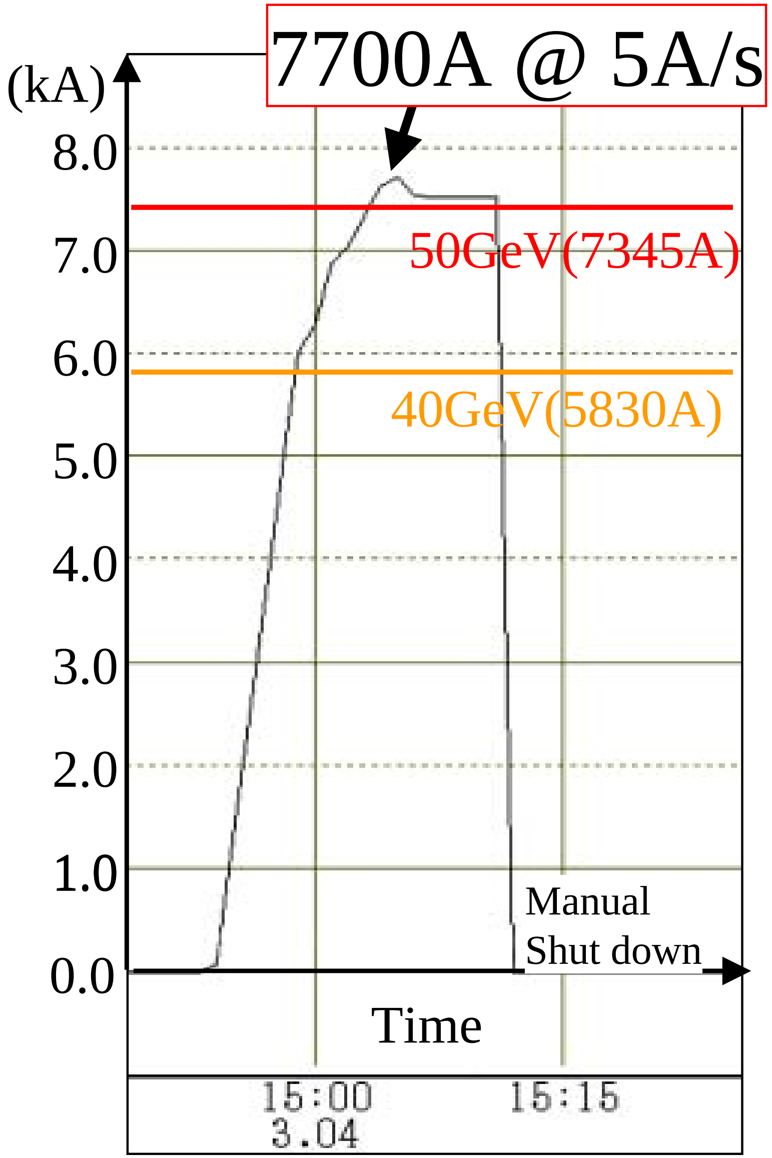


Dipole
2.6T

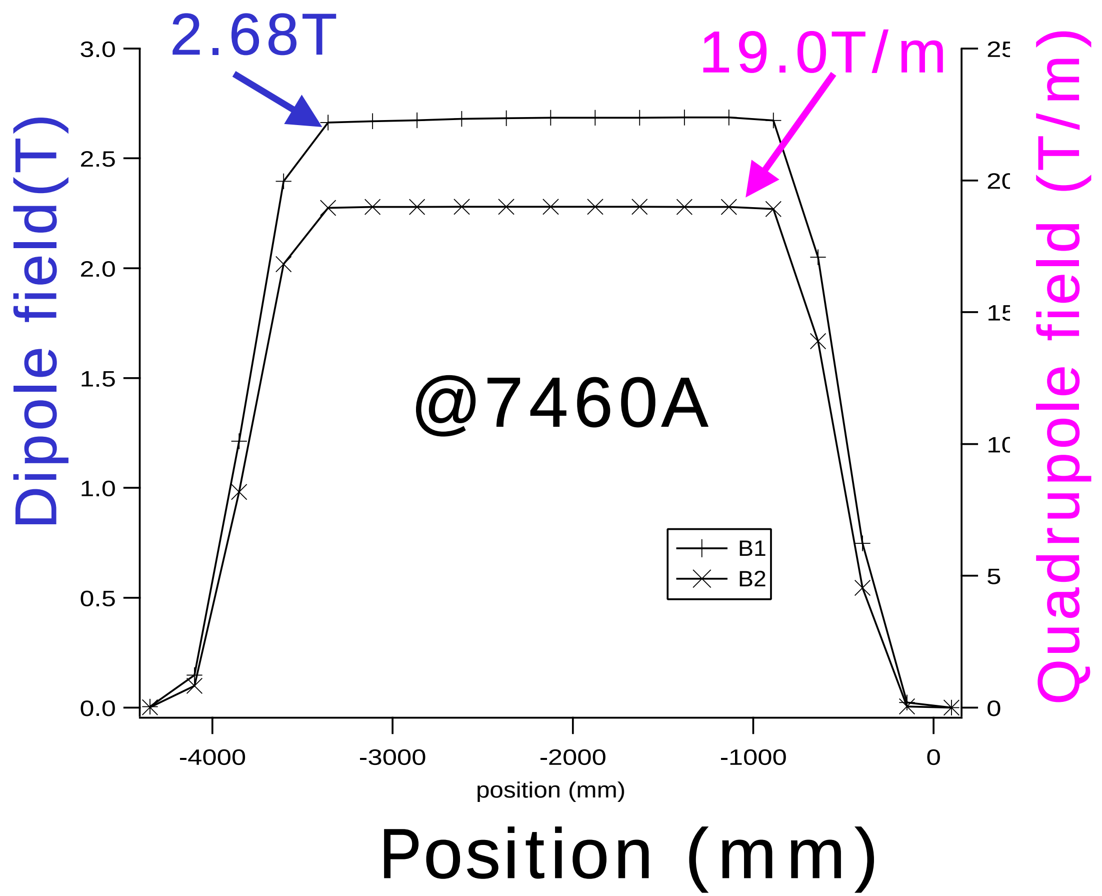


Quadruple
18.6T/m

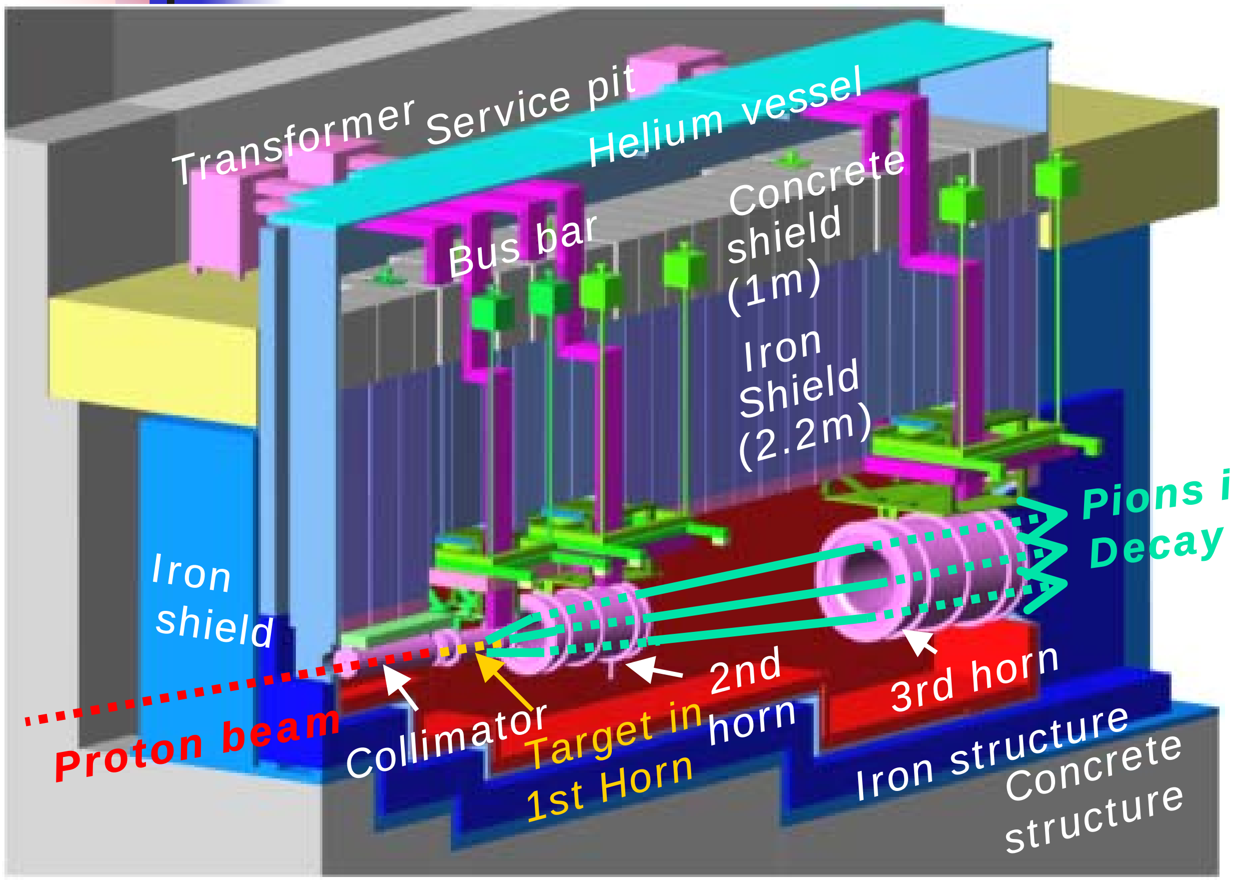
Superconducting magnet



Prototype magnet worked
- **as designed**
- **without quench**



Target and horns



•Prototype inner conductor for 3rd horn

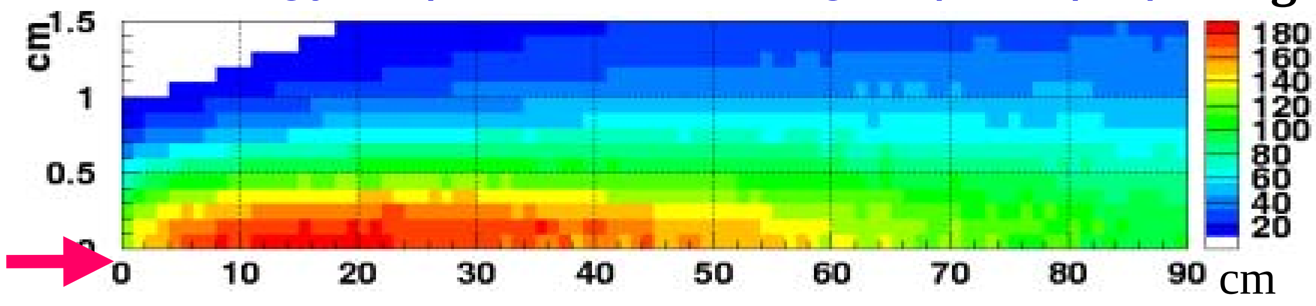
•Prototype inner & outer conductor for 1st horn

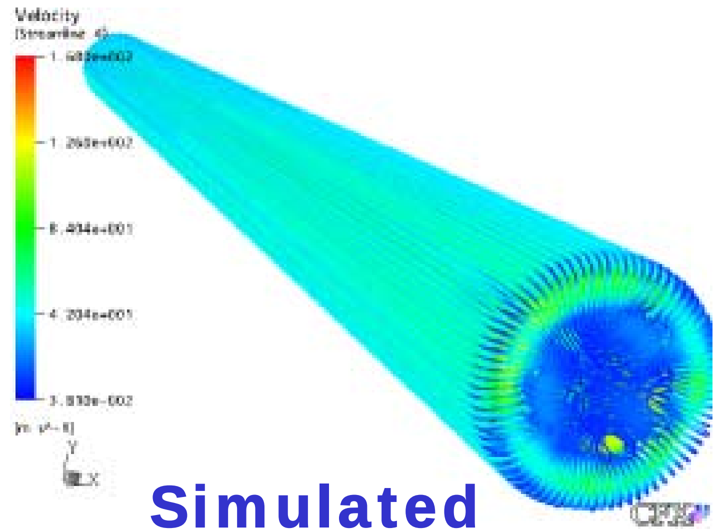
- Graphite target in 1st horn
- 3 horns made with Aluminum
- Water cooling test for horn finished
- 320kA pulse current test in this year

Target

- Carbon graphite target: 30mm(D)x900mm(L)
- 2 interaction length (70% int.)
- Energy deposit: 58kJ/spill

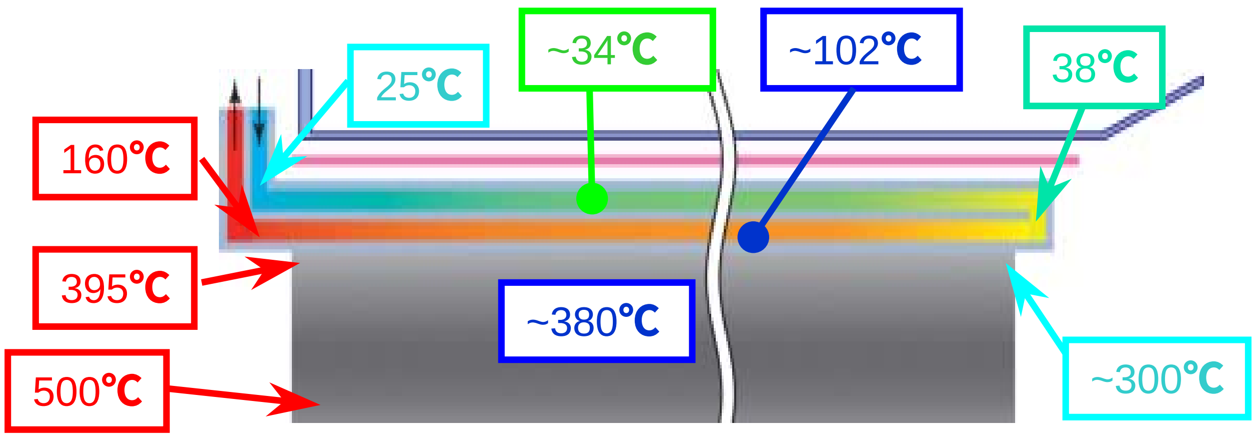
Energy deposit in the target (/ 1 spill)





Simulated streamline of He gas

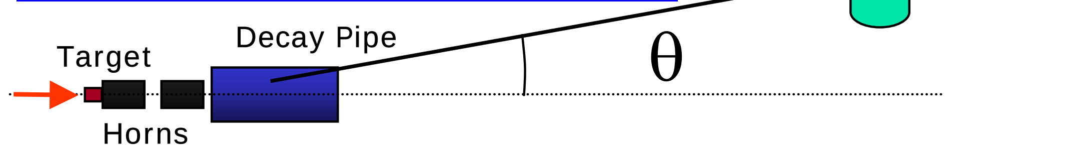
- Cooled by He gas at outer surface (640W/m^{2}K achieved)

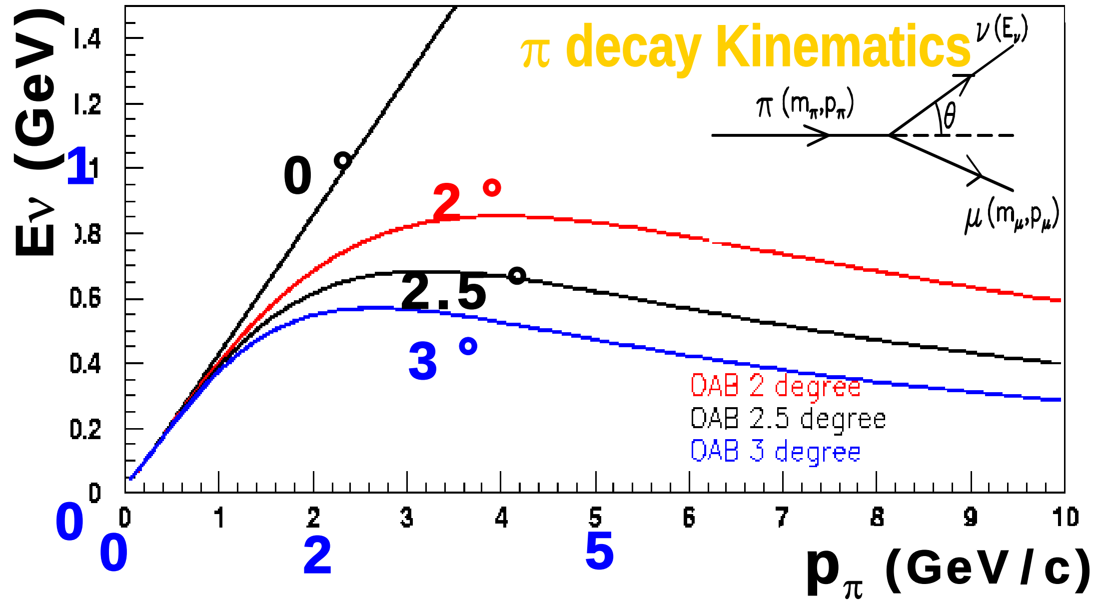


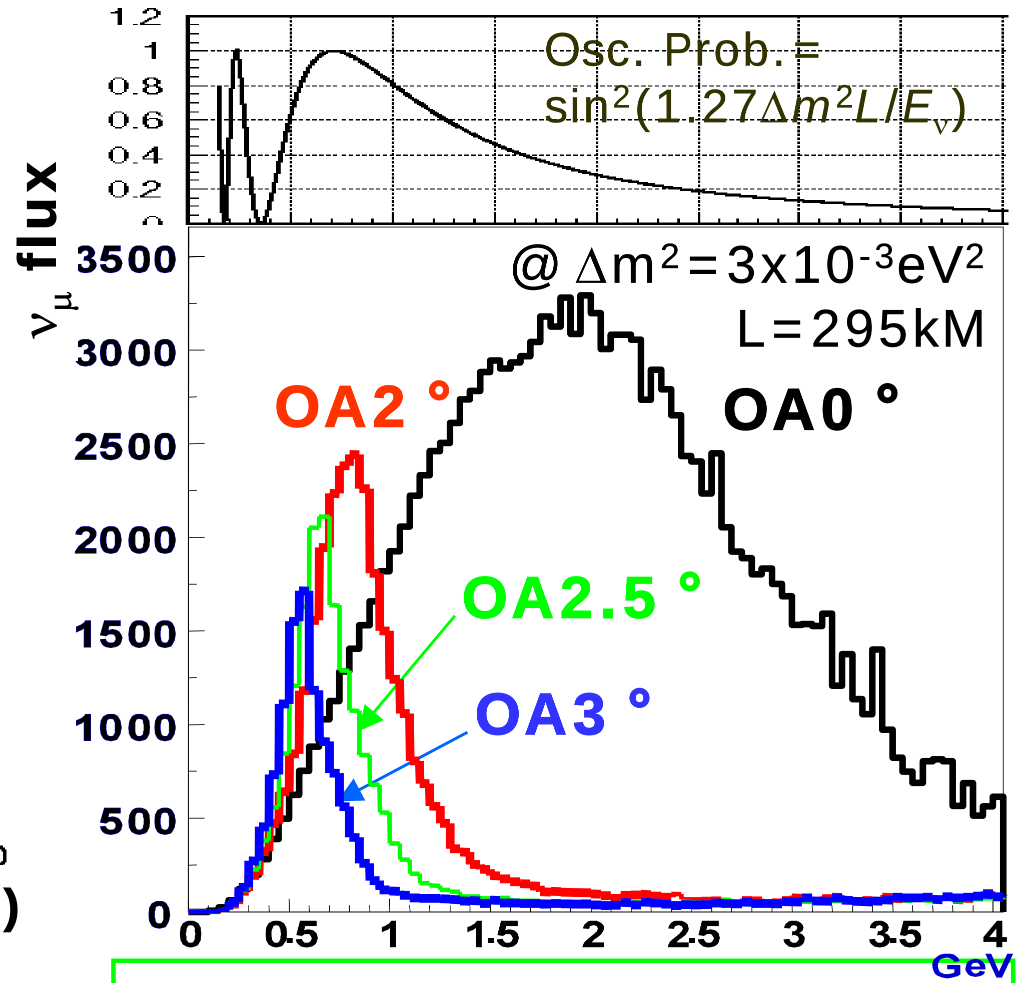
Prototype of target and cooling tube

Off-axis beam

First Application
(ref.: BNL-E889 Proposal)



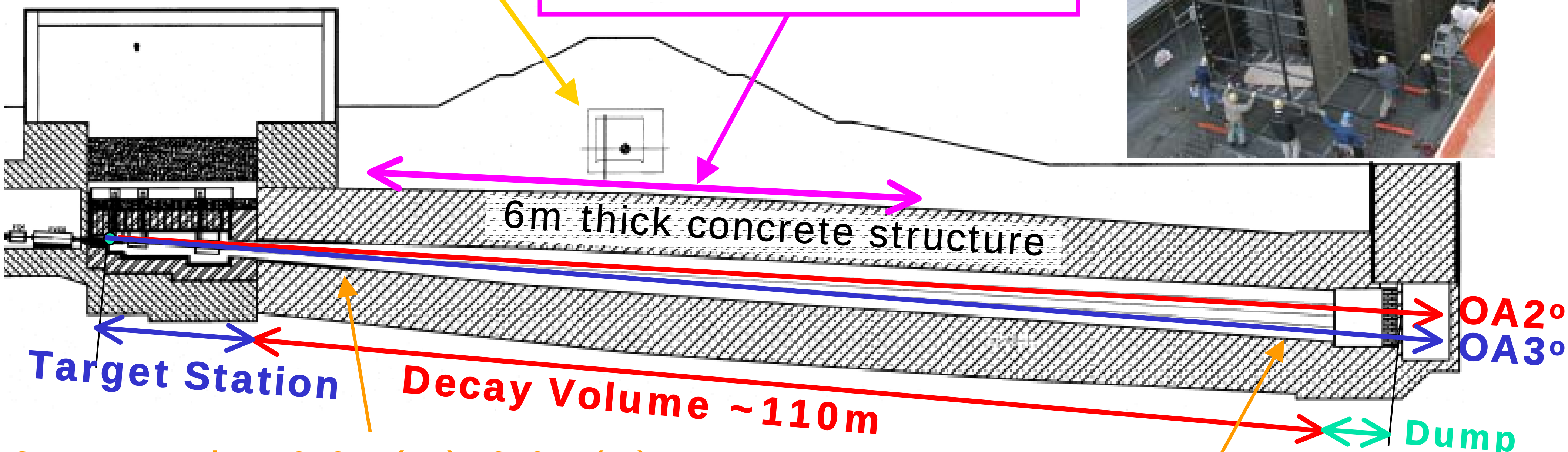




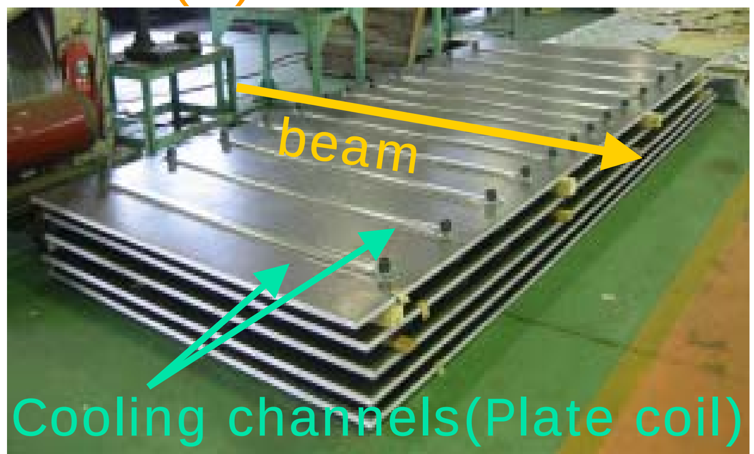
- Detector is intentionally misaligned from WBB axis
- Quasi Monochromatic Beam
- x2~3 intense than NBB
- Tuned at oscillation maximum

Statistics at SK
(OAB 2.5 deg, 1 yr, 22.5 kt)
~ 2200 ν_μ tot
~ 1600 ν_μ CC
ν_e ~0.4% at ν_μ peak

Decay Volume



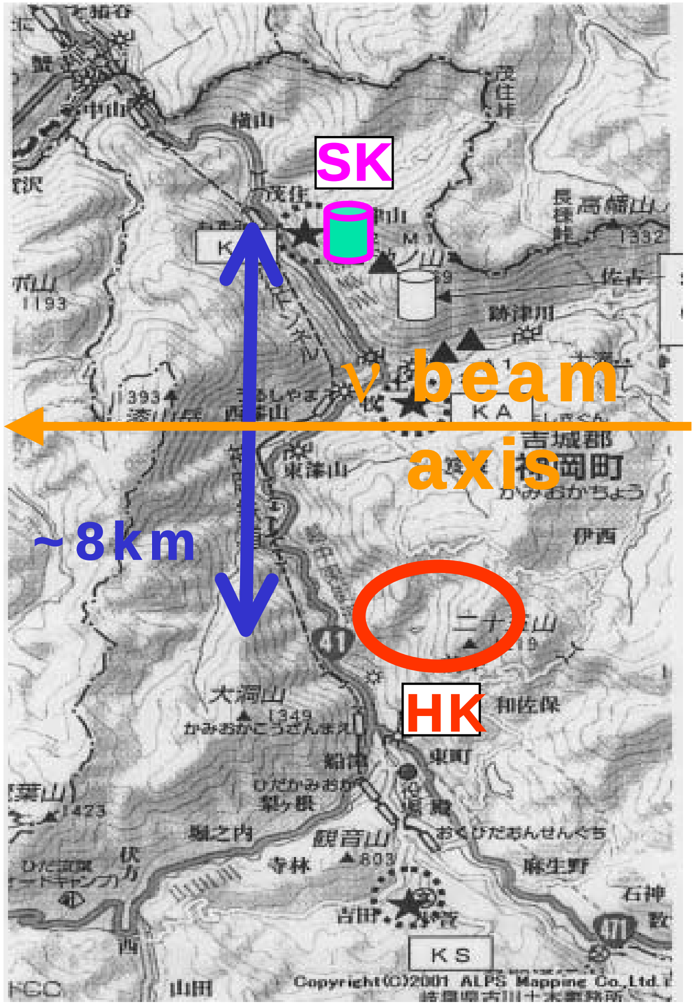
- **Cover Off Axis angle : 2°~3°**
- **Square box shape pipe made with water cooled iron plates (T<60°C at 4MW)**
- **Filled by 1atm Helium gas**



Off-axis beam at SK / HK

Decay pipe

- common Off-axis angle for SK / HK
- covers 2º ~ 3º



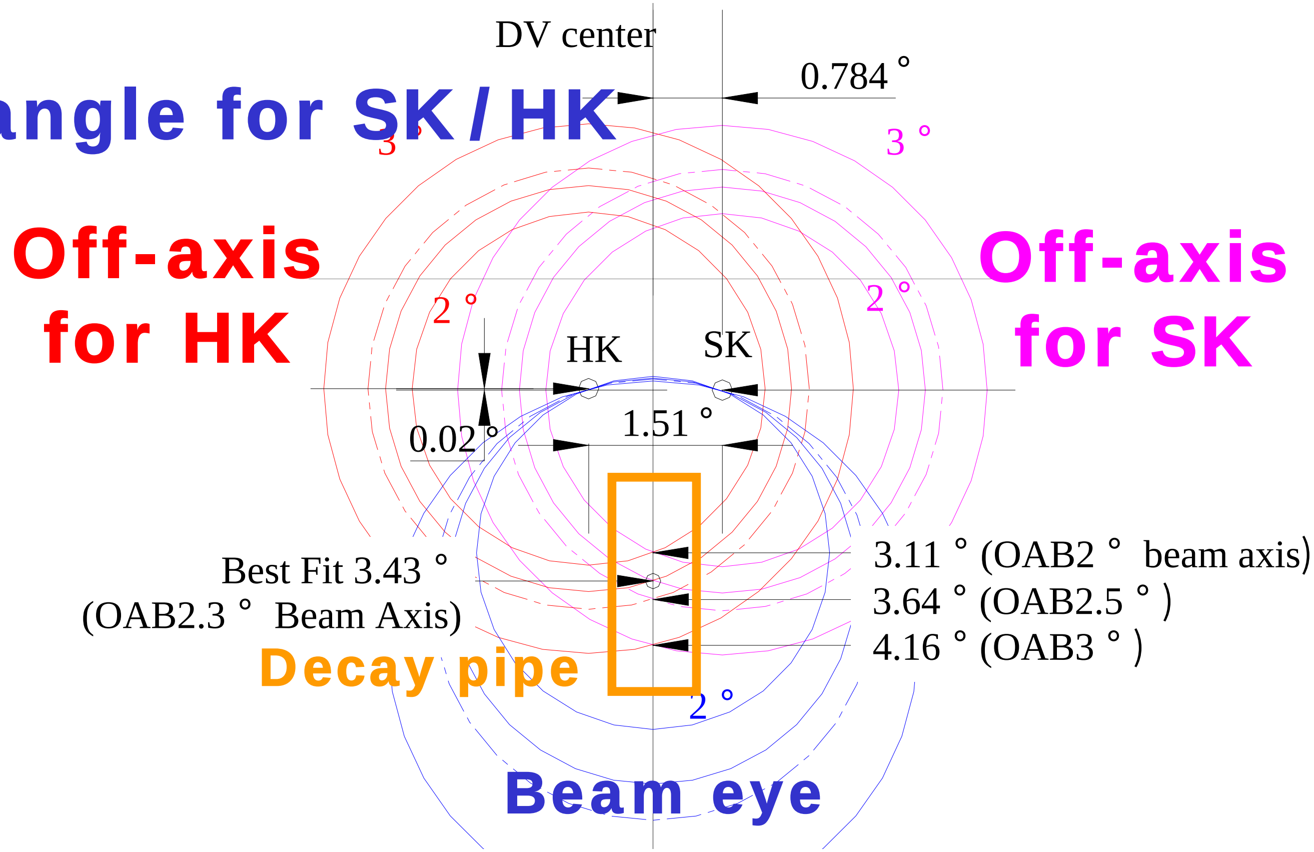


表 3.1: E_ν at the oscillation maximum for the baseline length of 295km and corresponding off-axis angle.

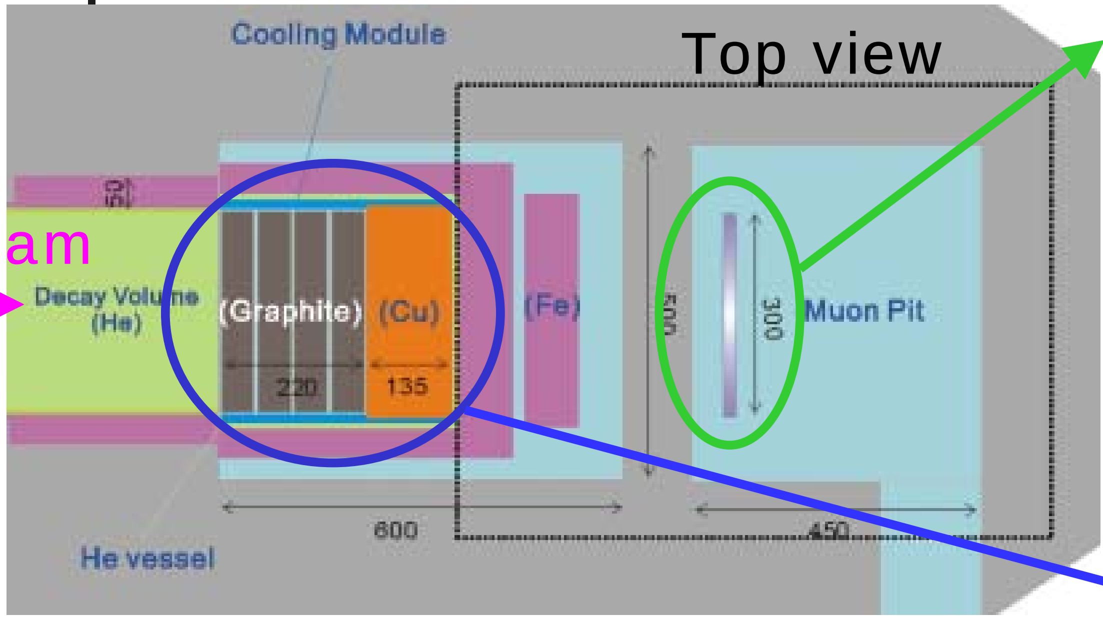
Δm^2	2.04	2.18	2.75	3.17	3.28
$[10^{-3}eV^2]$	(90% A.R.)	(80% A.R.)	(best fit)	(80% A.R)	(90 % A.R)
$E_\nu[GeV]$	0.487	0.520	0.656	0.756	0.782
OA angle[deg.]	3.1	3.0	2.4	2.1	2.0

Cover this region

Civil construction of DV

Beam dump & Muon monitor

beam

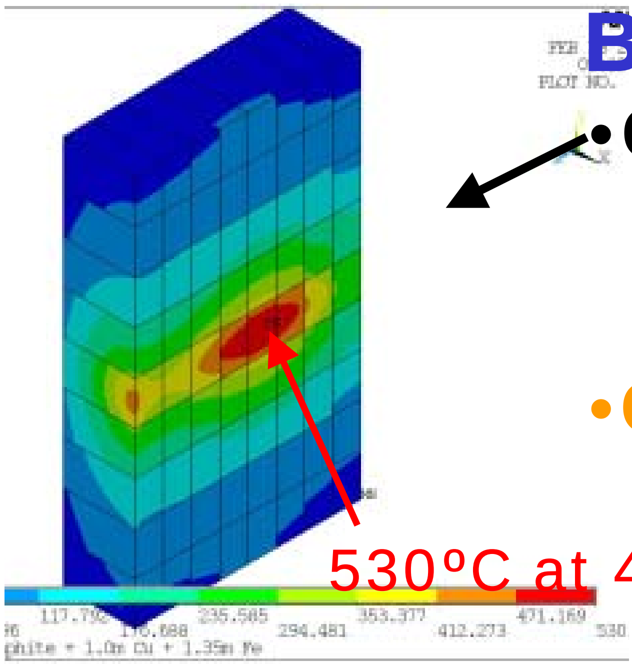


Muon monitors

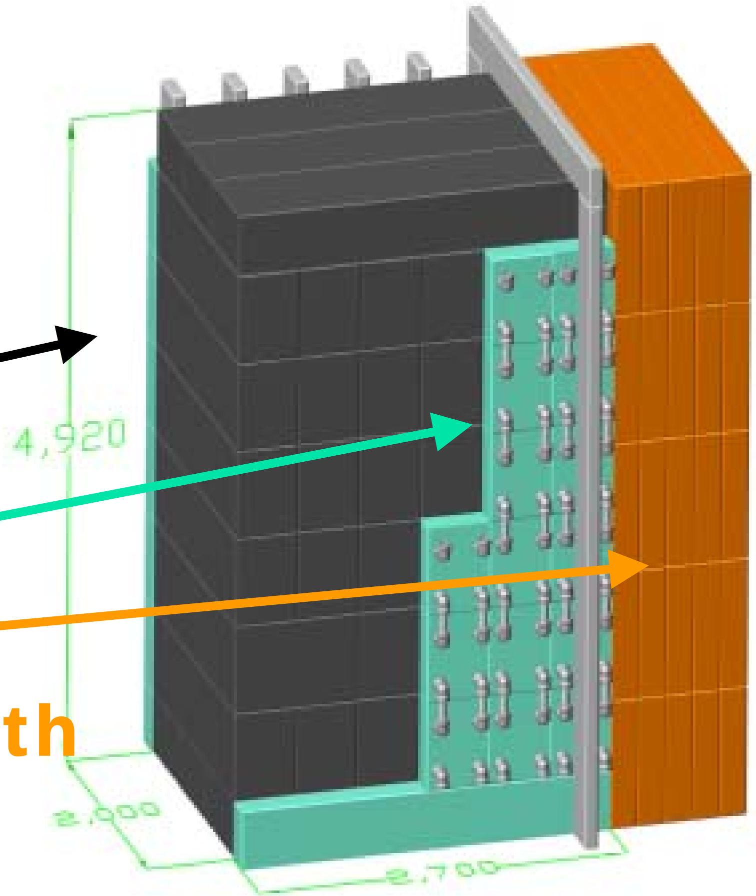
- spill-by-spill monitor of beam direction / intensity
- Ionization chambers
- Silicon or Diamond Detectors

Beam dump

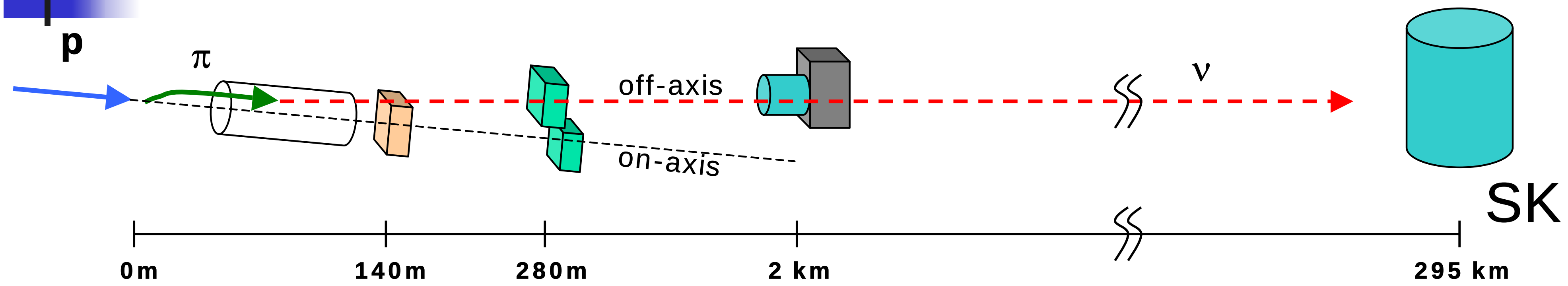
- Graphite blocks with cooling modules
- Copper blocks with cooling path



530ºC at 4MW



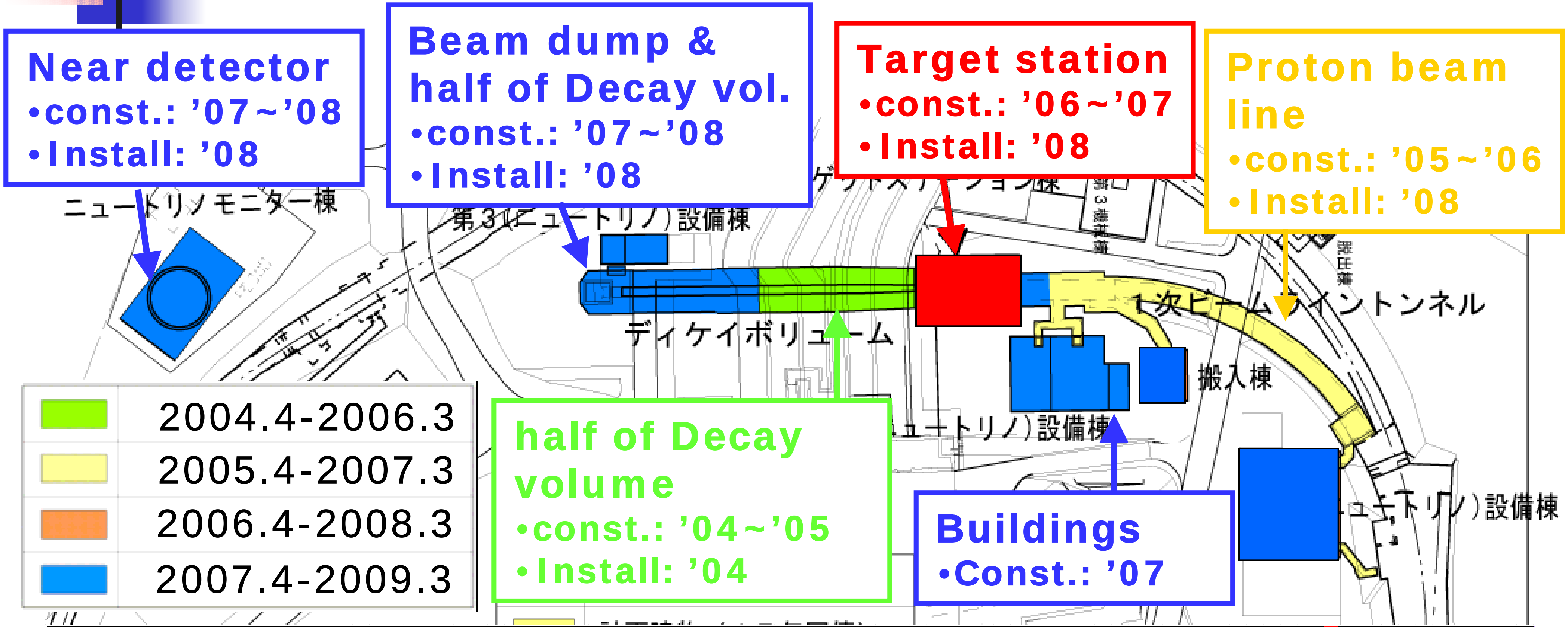
Neutrino detectors

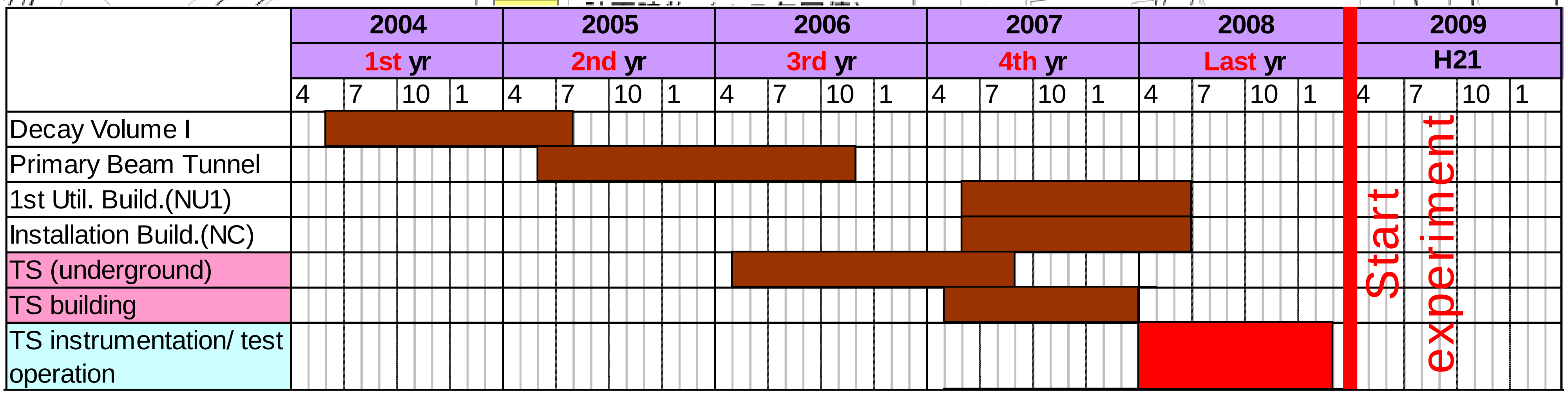


- **Near detector @280m**
  - **Neutrino intensity / spectrum / direction**
  - **Two detector systems for on and off axis.**
- **Second Near Detector @2km**
  - **future option to reduce systematic errors**
  - **ν_μ energy spectrum and ν_e background study with almost same condition as for SK**
- **Far Detector @295km: Super Kamiokand**

⇒ at session 5 of WG1 on June 23

Schedule of ν beam line





Summary

- T2K collaboration started in 2003.
  - Discovery of $\nu_{\mu}\rightarrow\nu_{e}$ appearance
  - 100 times larger intensity than K2K
  - Off axis(2~3°) configuration with SK
- Neutrino beam facility
  - Construction started in 2004
- Start T2K-I experiment in 2009
- Future upgrade for T2K-pahse-II
  with 4MW beam and Hyper-Kamiokande

supplement

Possible upgrade to 4MW

- Preliminary study done
- Rep. rate x 2.5
  - Double RF cavities (space OK)
  - Eliminate idling time in acc. cycle
- # of circulating protons x 2

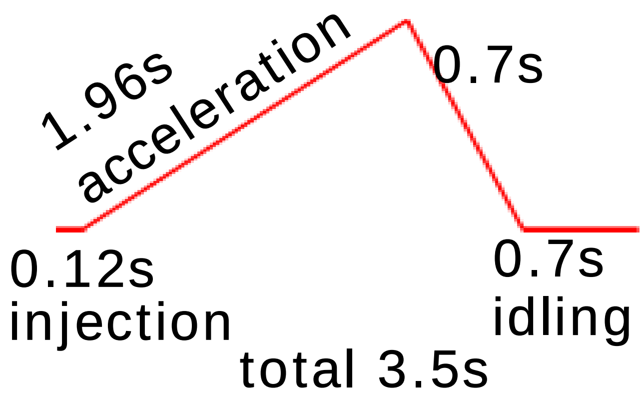
  "barrier bucket method"

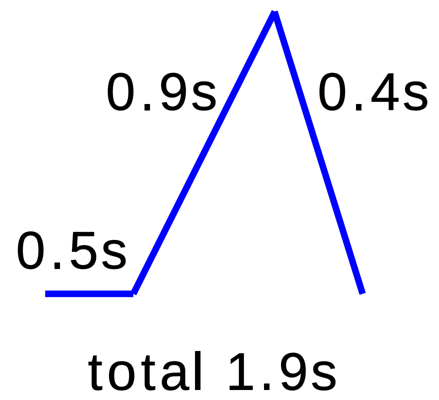
  to avoid space charge limit
- Issues

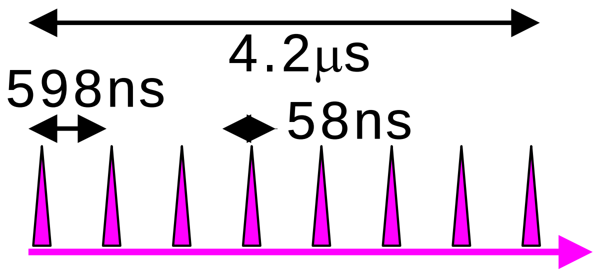
  Achieve first goal (0.75MW)

  Beam loss

  Target,

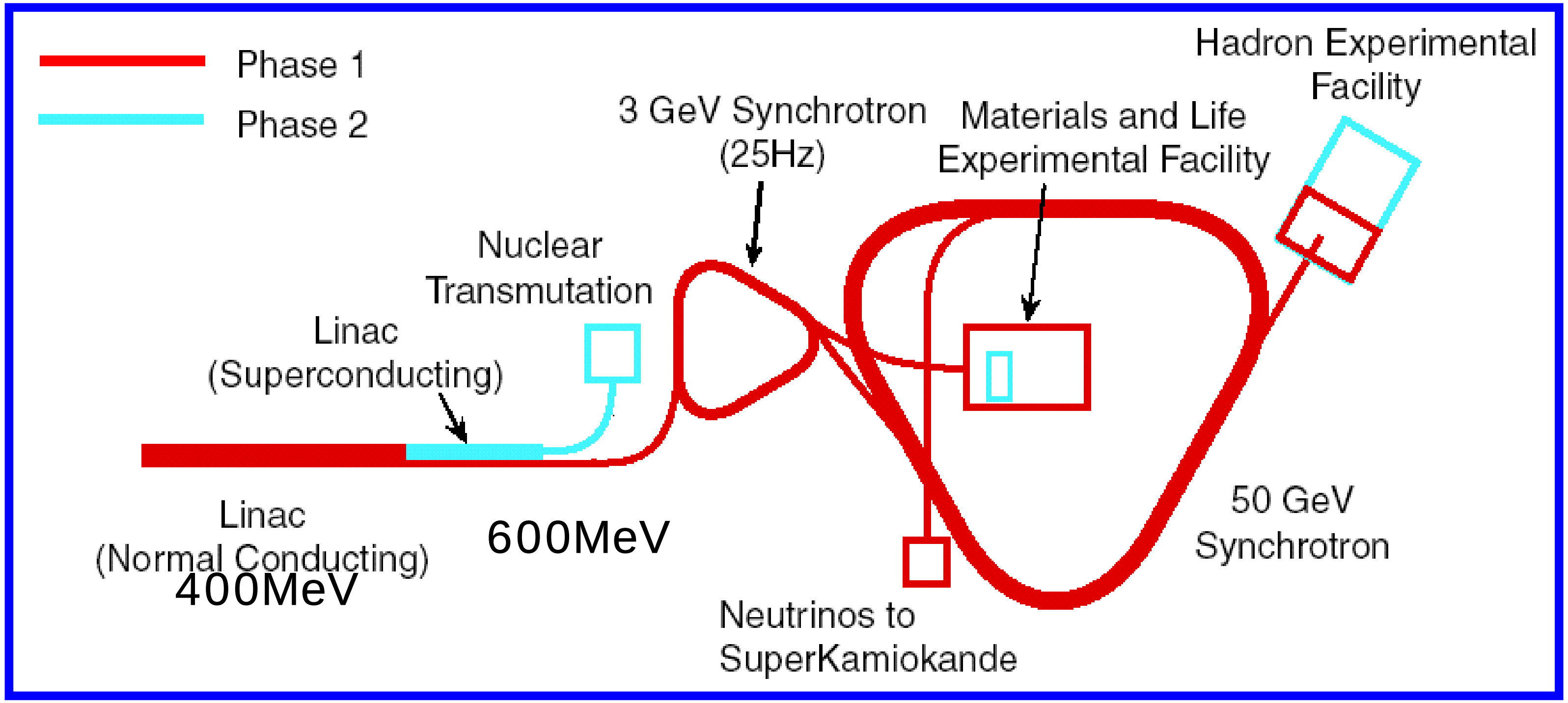






Phase-I

- day-1 — Linac 180MeV, 30mA, 25Hz
  - RCS 3GeV, 0.6MW
  - MR 40GeV, 400kW
- Next Stage — Linac 400MeV, 50mA, 25Hz
  - RCS 3GeV, 1.0MW
  - MR 40GeV, 670kW

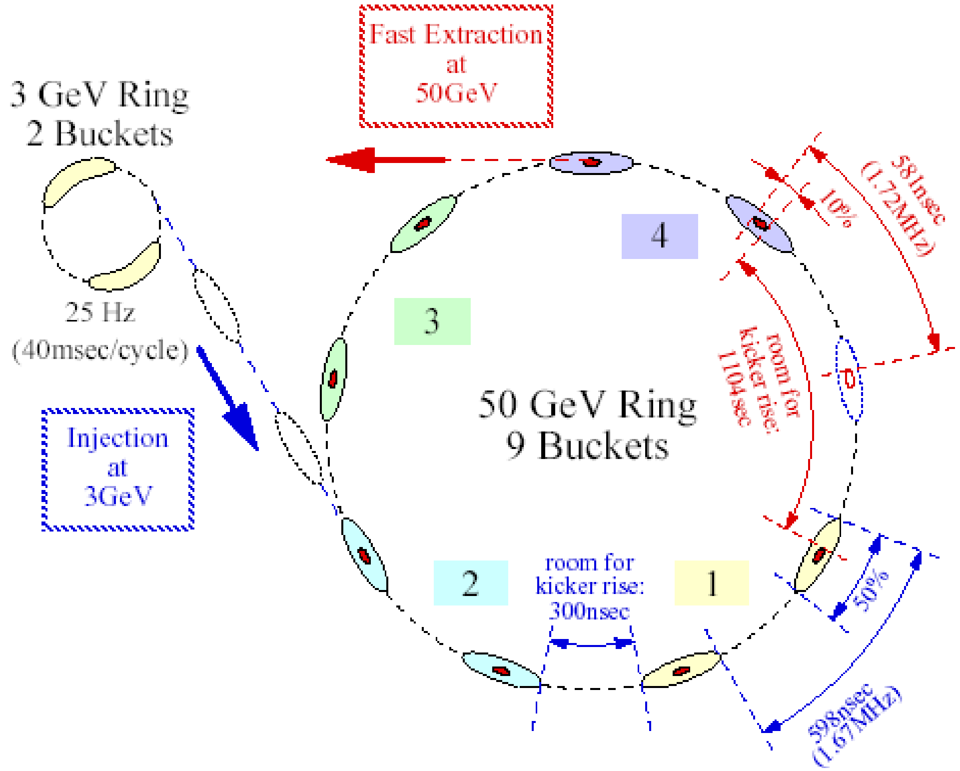


Phase-II

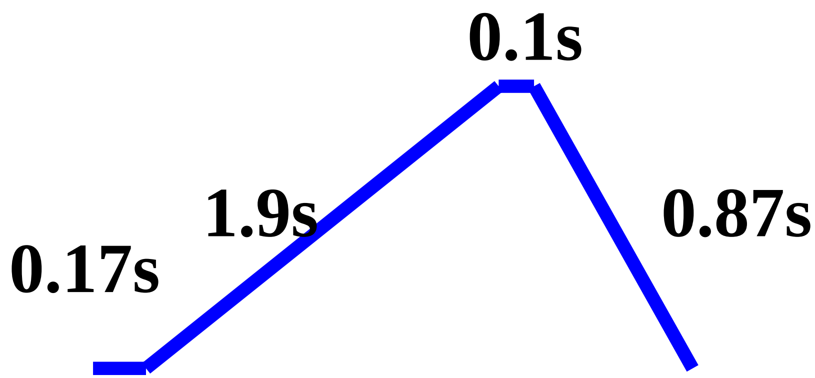
- Nuclear Transmutation Facility(ADS)
  - →Linac 600MeV,50Hz
- Extension of Hadron and Neutron Facility
- MR 50GeV, 750kW

MR Patterns and Beam Power (Phase-I)

MR h=9, 8bunches



40GeV fast extraction

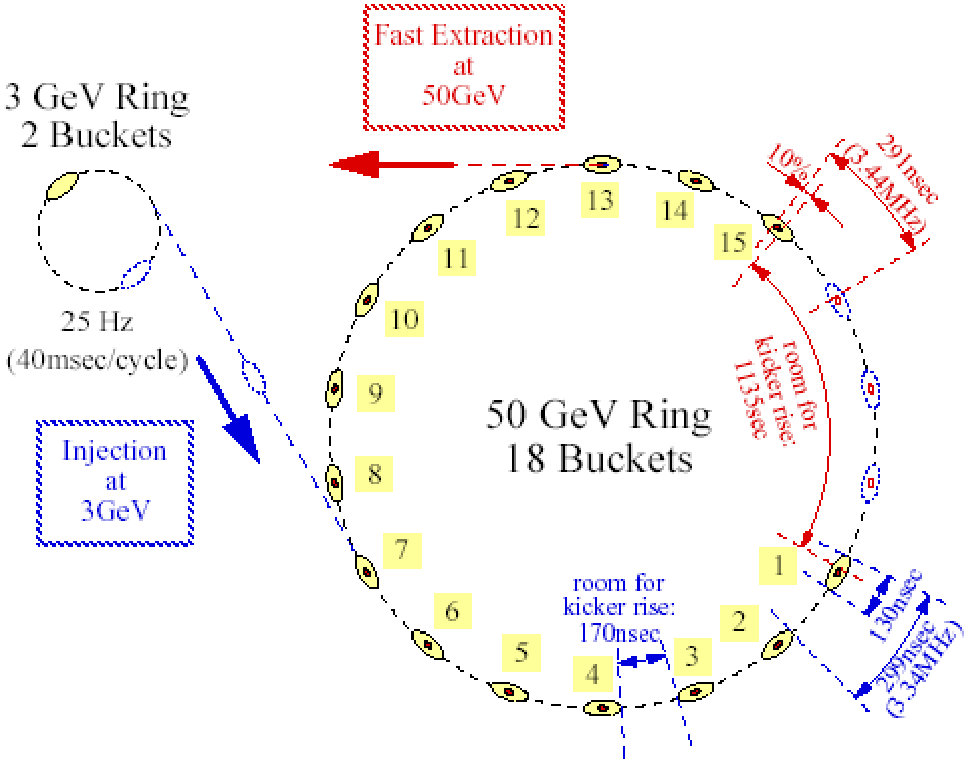


total 3.2s

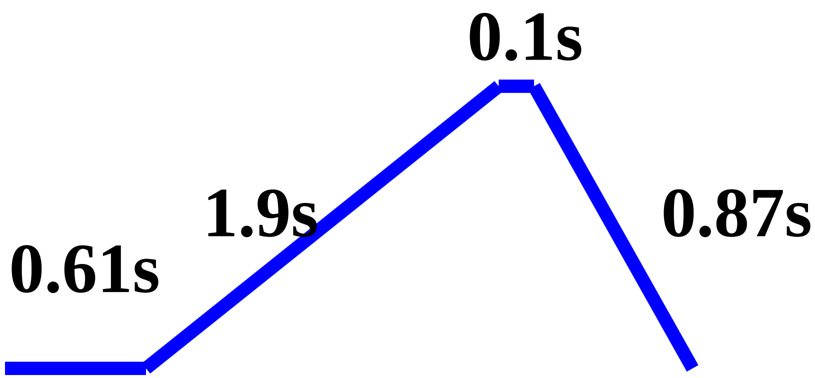
beam current: 16.7μA
beam power: 666kW
(400MeV Linac)

MR Patterns and Beam Power

MR h=18, 15bunches



40GeV fast extraction



total 3.48s

beam current: 17.2μA
beam power: 689kW
(180MeV Linac)

Higher beam Power (MR)

- Increase Rep. Rate
- Increase Injected Particles by Stacking

- beam loss issue

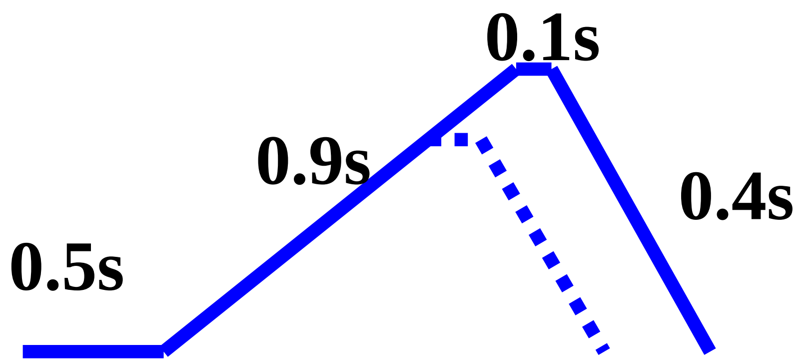
Rep. Rate
- energy storage system
- magnet power supply
- rf system
- water cooling system

My Personal Page!!

MR Energy

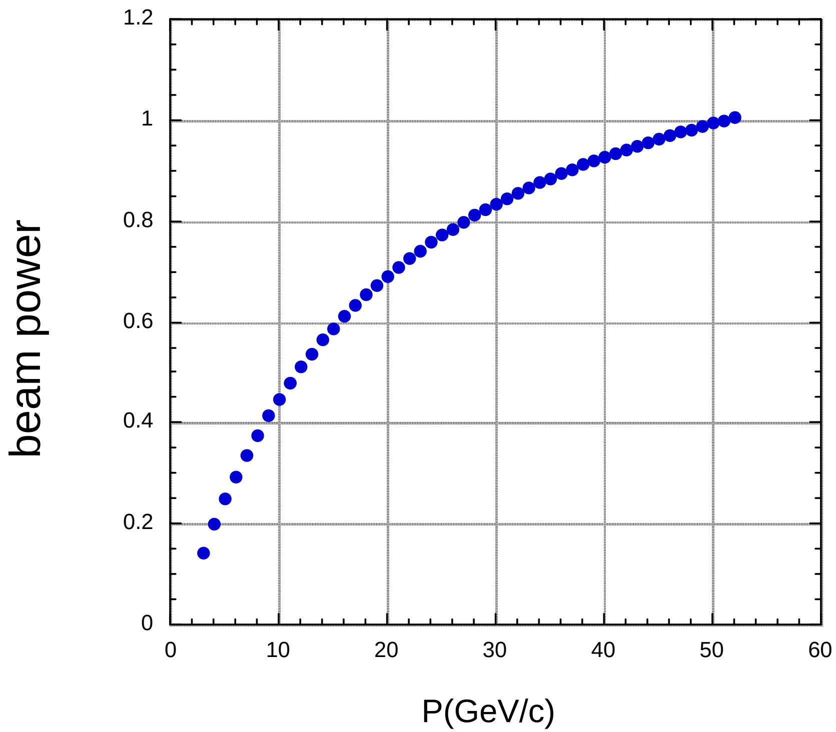
50GeV Assumed pattern

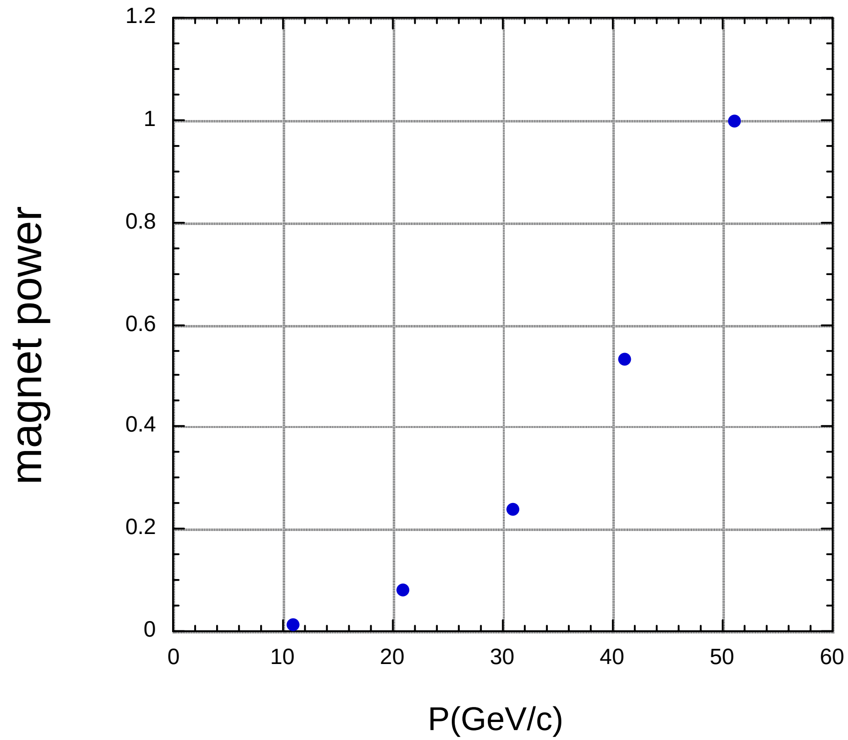
requirement
- beam power ---40GeV?
- high energy -->50GeV



total 1.9s

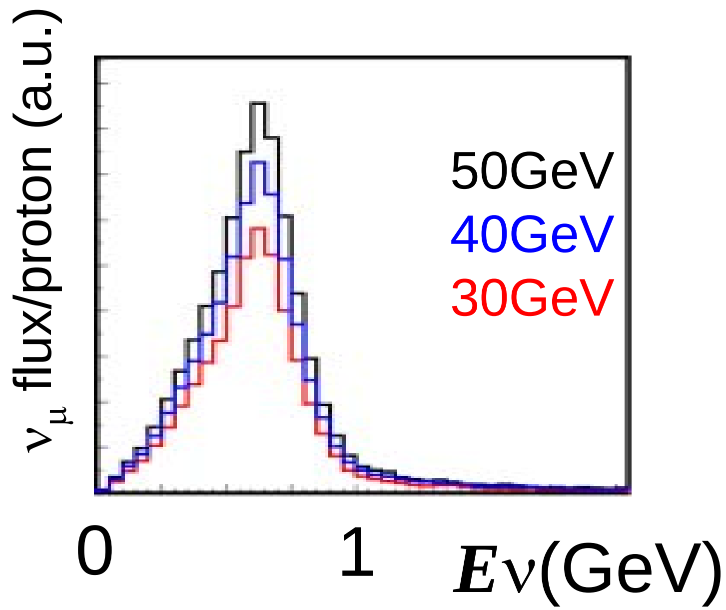
beam power=energy×current



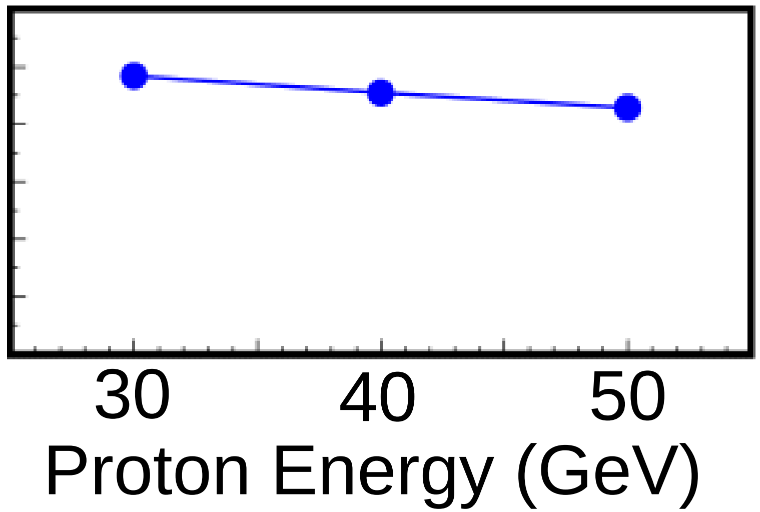


High Intensity

Neutrino Flux ∝ ~ Proton beam power (E_p x N_p)



Peak Flux normalized by Beam Power

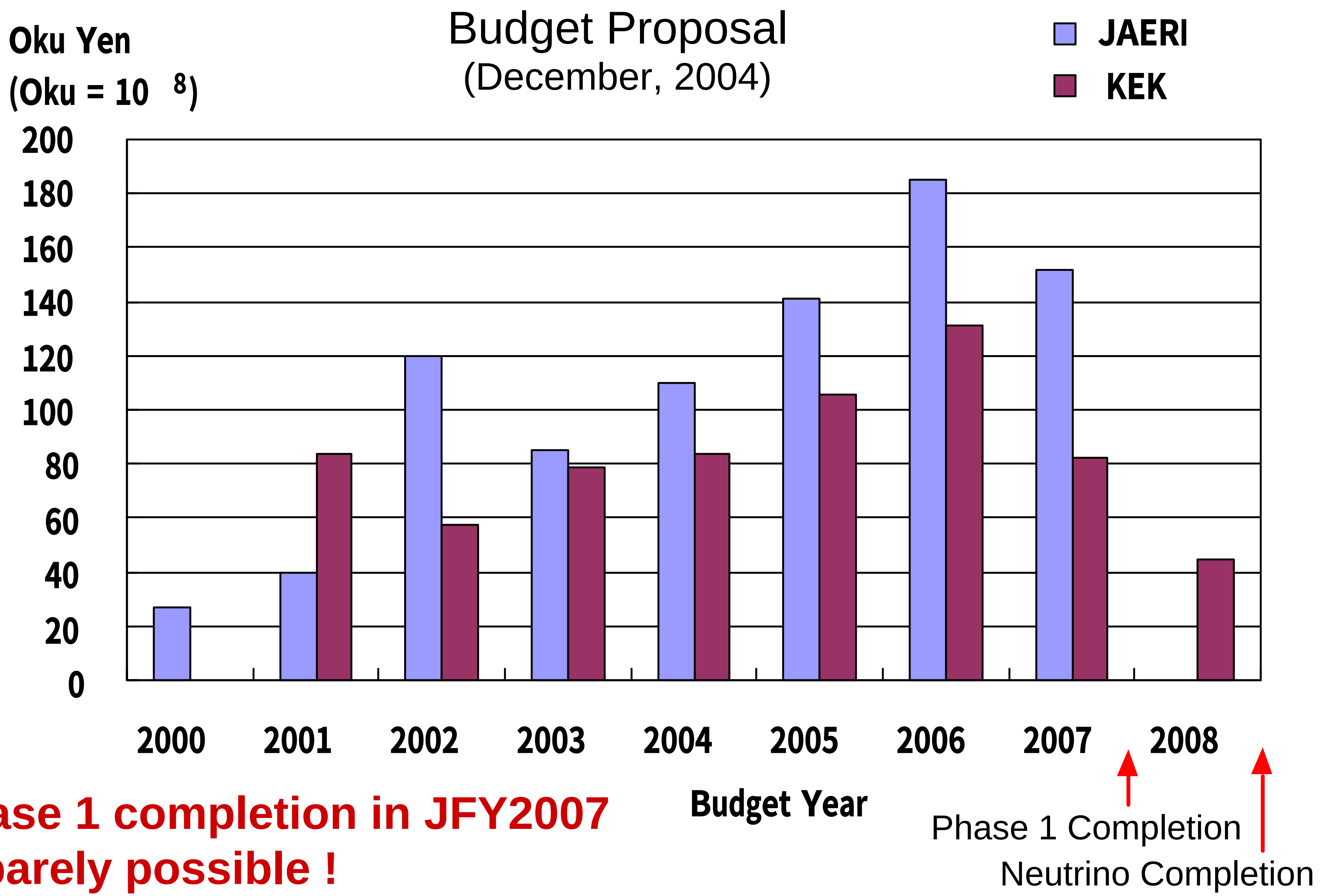


- **750kW** @ J-PARC 50GeV (design)

High Beam Power→

- Controlling **BEAM LOSS is CRITICAL**
  - Radio-activation of beam line components (maintenance)
  - Radiation shielding
- Cooling problem
  - Most of 750kW heat deposited in target area, decay volume, beam dump
  - (cf ~13kW escaped with neutrino)

Budget Decision for 2005



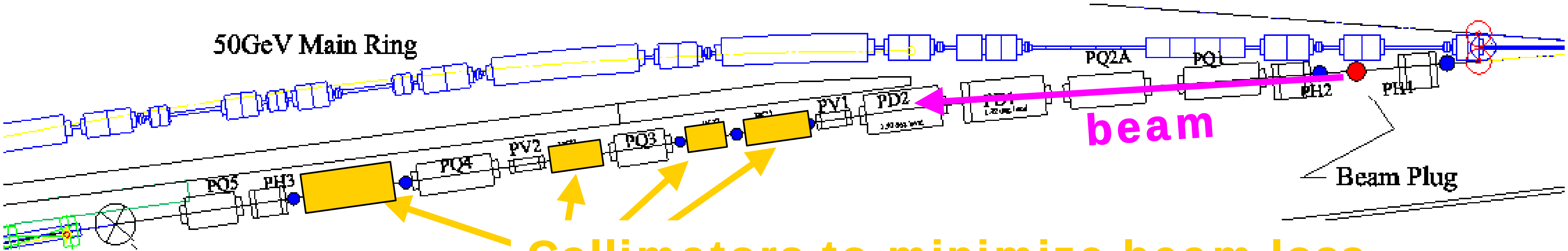
1) Phase 1 completion in JFY2007 is barely possible !
2) Need a big increase in JFY2006.

Requirements on ν beam

- Intense beam
  - Very far detector, extremely small cross section, search small osci. probability
  - ➔ High proton beam power: J-PARC 0.75MW 50 GeV PS
  - ➔ High efficiency pion collection with magnetic Horns
- Fast time structure
  - Background in detector: Cosmic rays, atmospheric ν
  - Discriminate by timing information
  - ➔ Single-Turn Fast Extraction
- Narrow energy spectrum
  - As many ν's as possible at oscillation maximum
  - As less ν's as possible at small osc. prob. (reduce BG)
  - ➔ Off-axis beam

Preparation Section

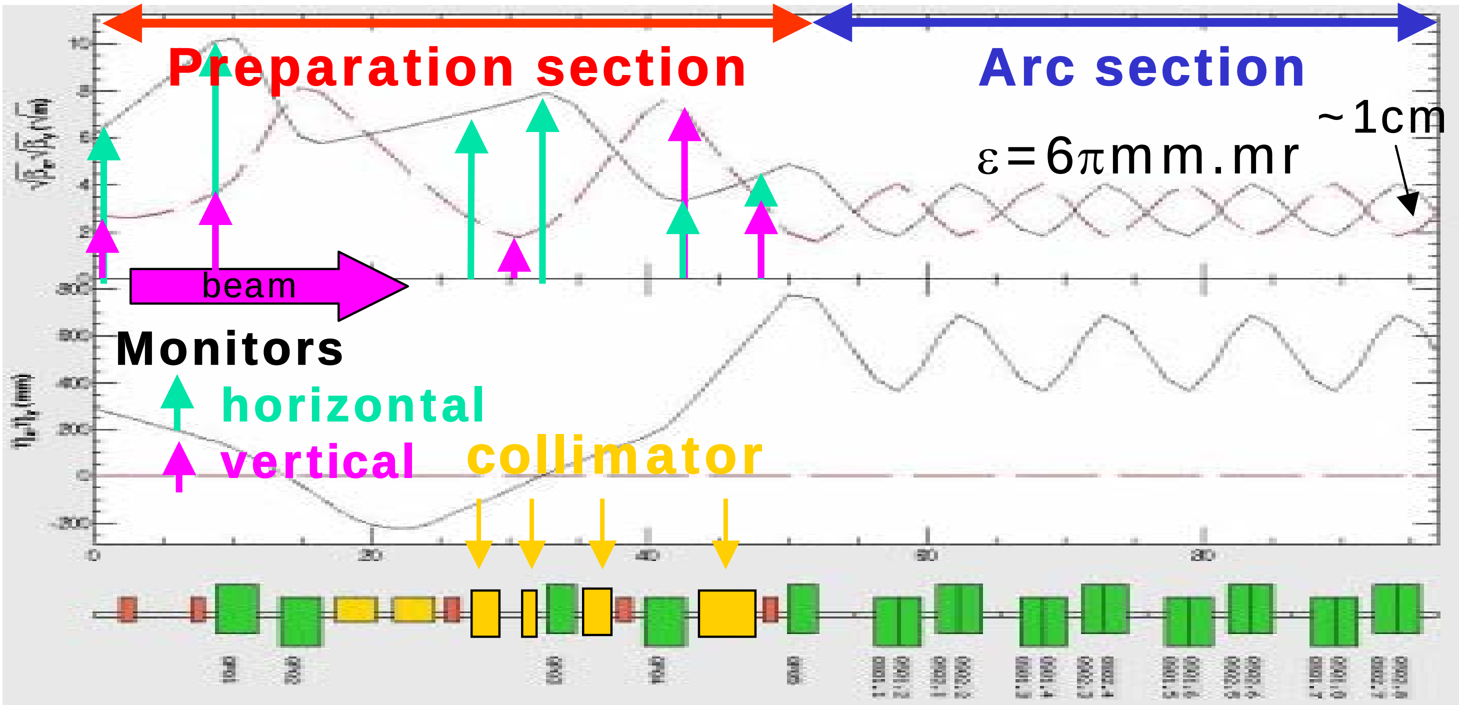
- Matching beam from PS to ARC section



Collimators to minimize beam loss
& heat load at super-conducting magnets

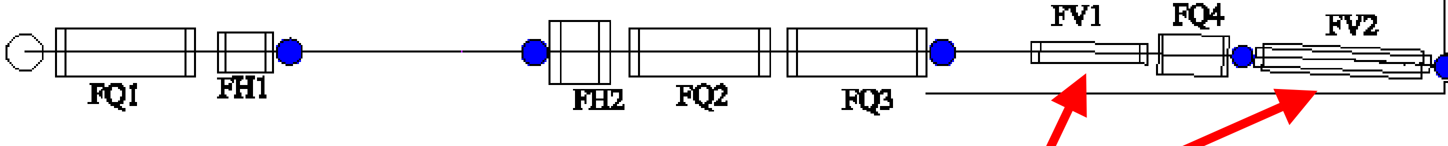
Top view

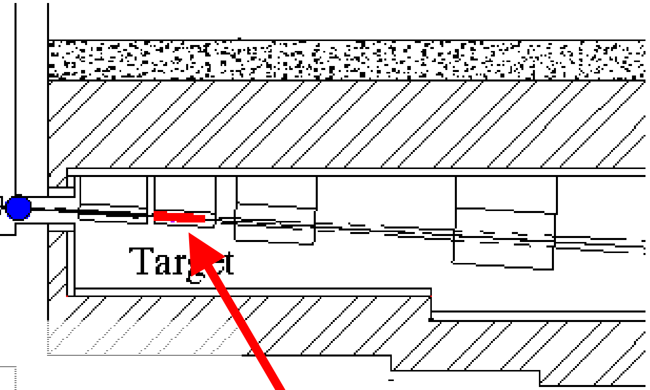
- Dipole(H):2
- Quadrupole:5
- Steering:5
- 5 with MIC



Final Focusing section

- **Bending / focusing beam to target**

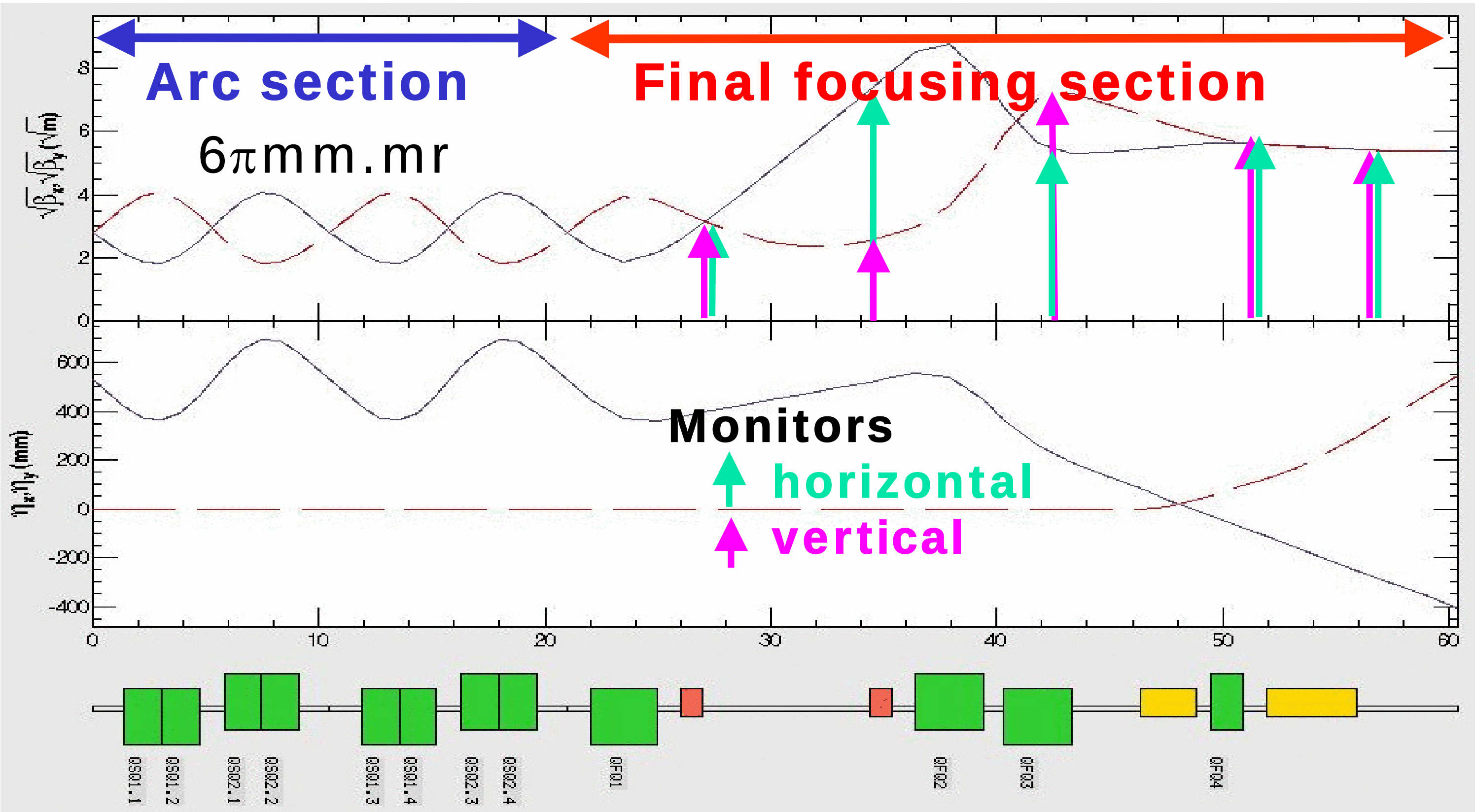




Side view

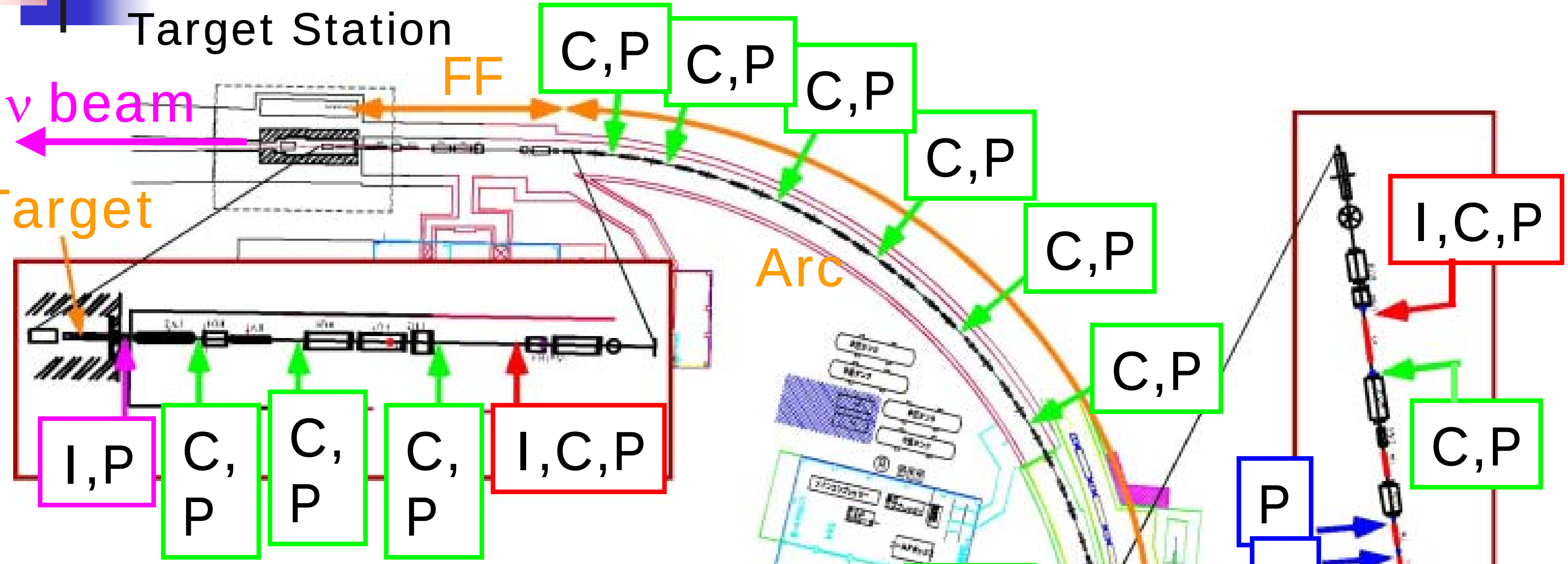
Vertical dipole magnets to change off-axis angle (2°~3°)

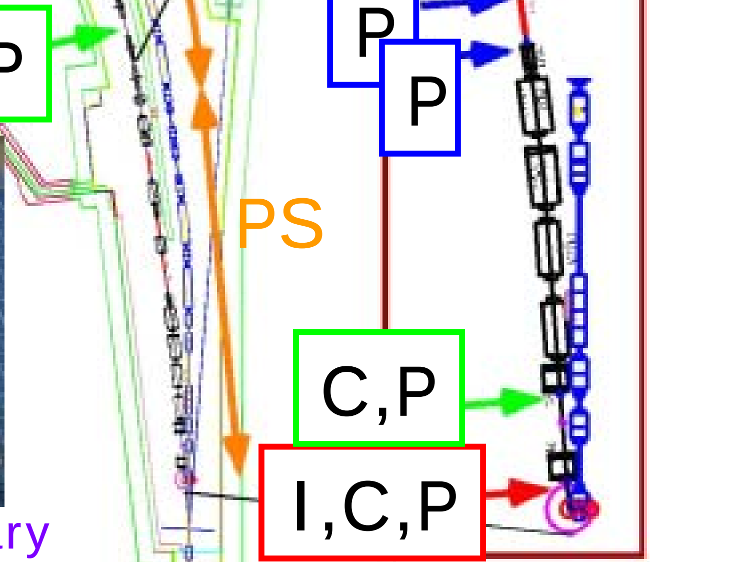
σ_r~6mm at target



- **Dipole(V):2**
- **Quadrupole:4**
- **Steering:2**

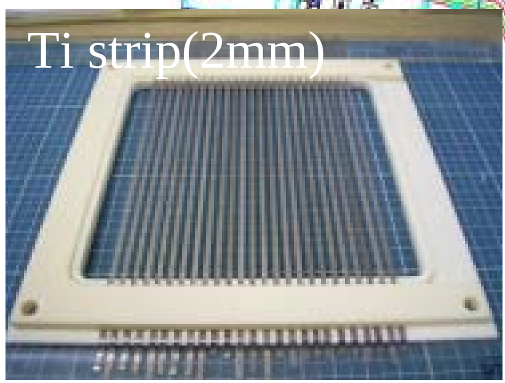
Beam monitors





Beam Monitor

- **I: Intensity (CT)**
- **C: Center Position (ESM / LPM)**
- **P: Profile (SSEM / RGBPM)**
- **Loss monitor**



Segmented Secondary Emission Monitor (SSEM)

Long baseline oscillation

Maki-Nakagawa-Sakata (MNS) matrix $|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$ $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{-i\delta}} \end{pmatrix} \cdot \boxed{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **Precise meas. of disappearance $\nu_\mu \to \nu_x$**

$$P_{\mu \to x} \approx 1 - \cos^4\theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2(1.27\Delta m_{23}^2 L / E_\nu)$$

- **Discovery of $\nu_\mu \to \nu_e$ appearance**

$$P_{\mu \to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m_{13}^2 L / E_\nu)$$

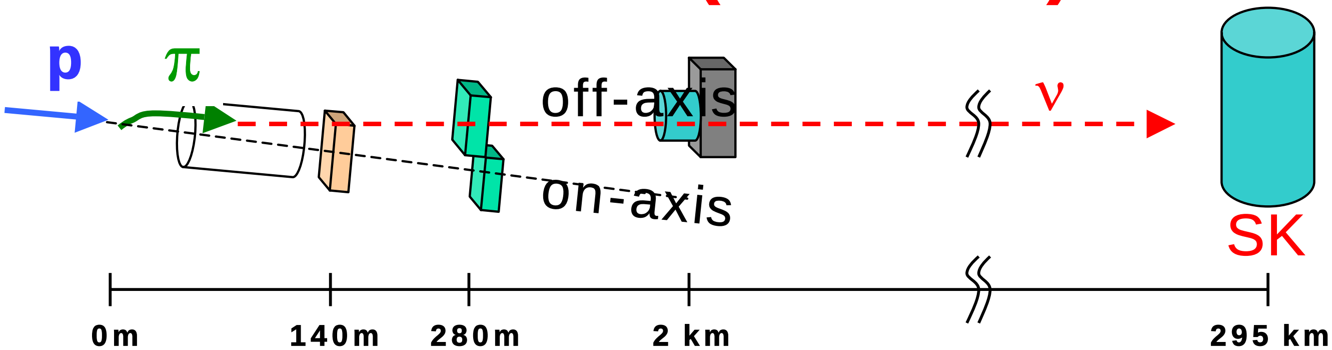
- **Discovery of CP violation (Phase2)**

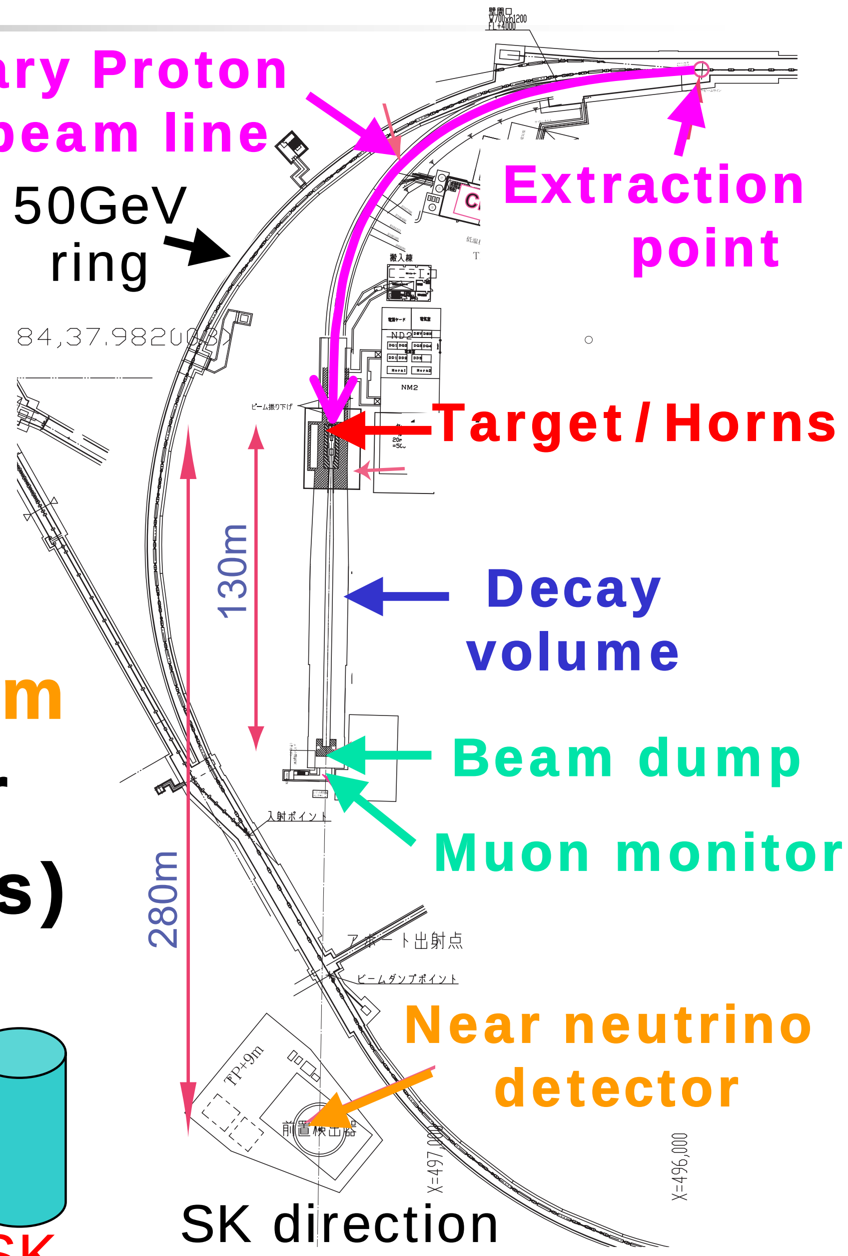
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

J-PARC Neutrino facility

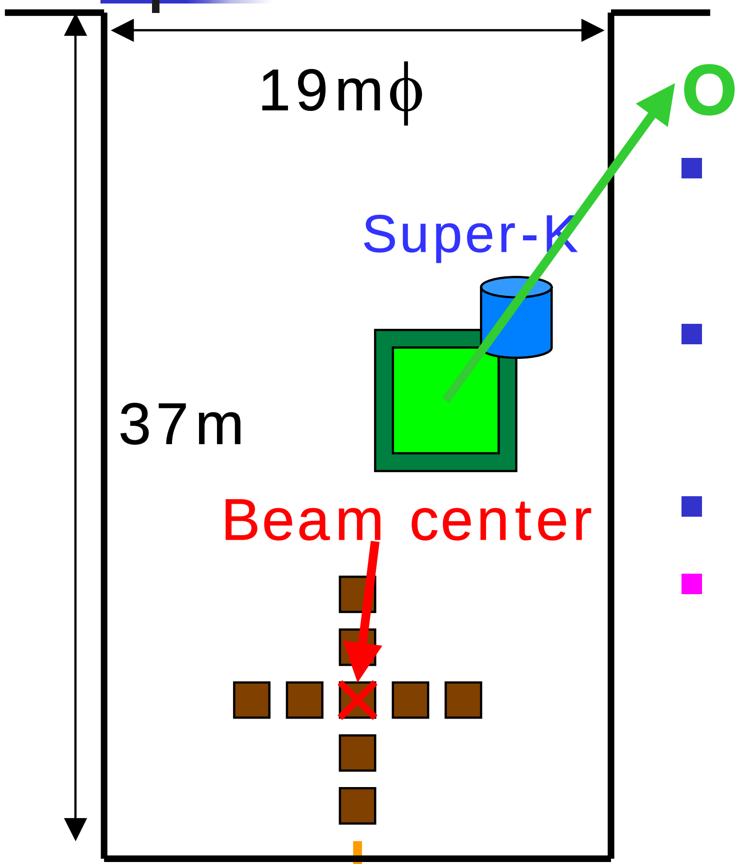
Components

- Primary proton beam line
  - 50GeV, 0.75MW, Fast extracted
- Target / Horns
- Decay volume (130m)
- Beam dump & Muon monitor
- Near neutrino detectors @280m
- Second near neutrino detector @2km: future option (Off-axis)
- Far detector SK (Off-axis)



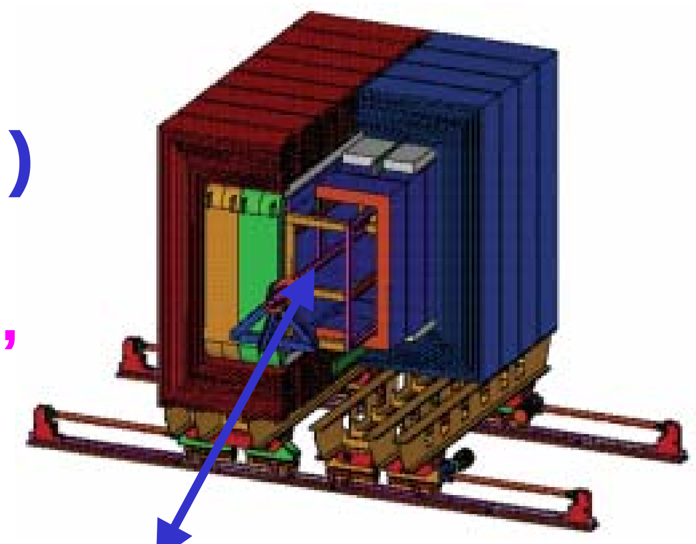


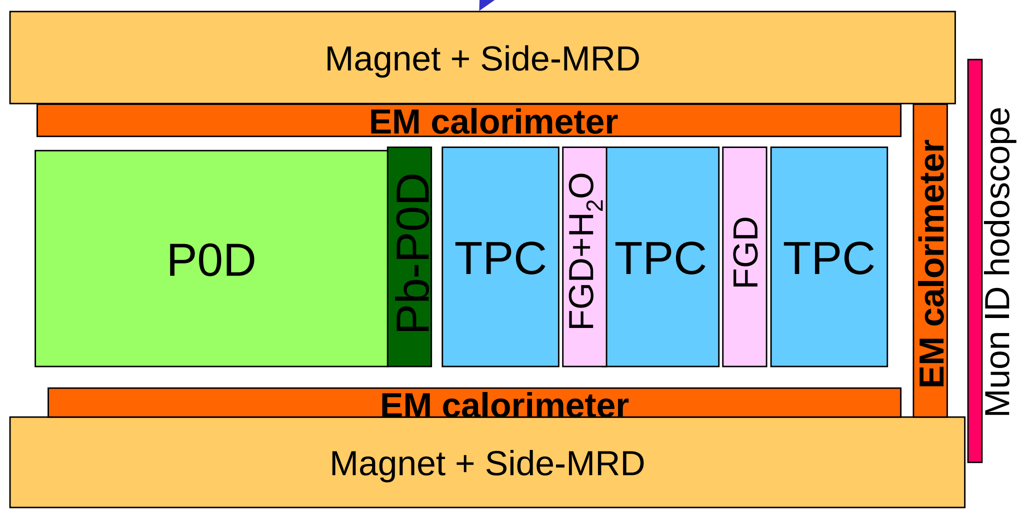
Near Detector @ 280m

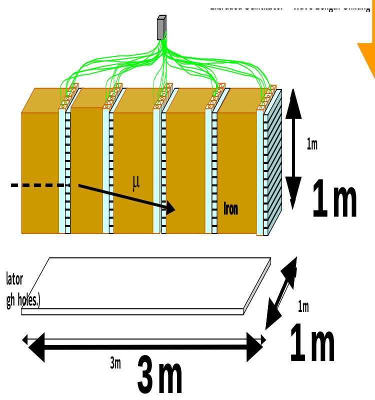


Off-axis (~2°)

- ν_μ and ν_e fluxes and spectra
- ν interaction study (CC-QE,non-QE,π^0,)
- Kaon contributions
- UA1 mag, FGD, TPC, Ecal,..







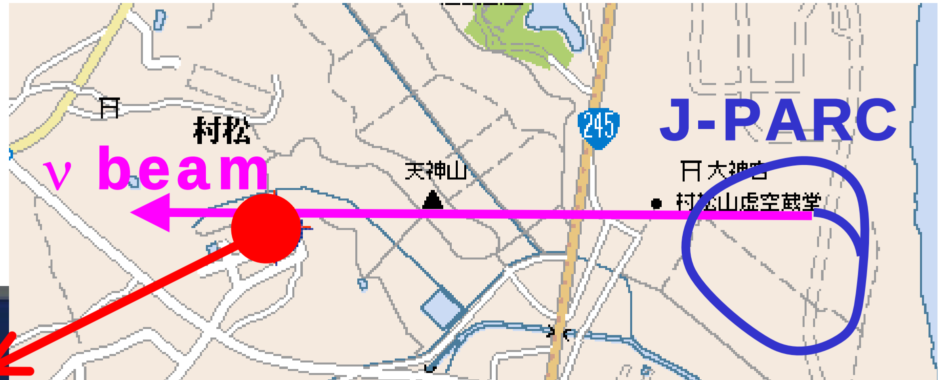
On-axis (0°)

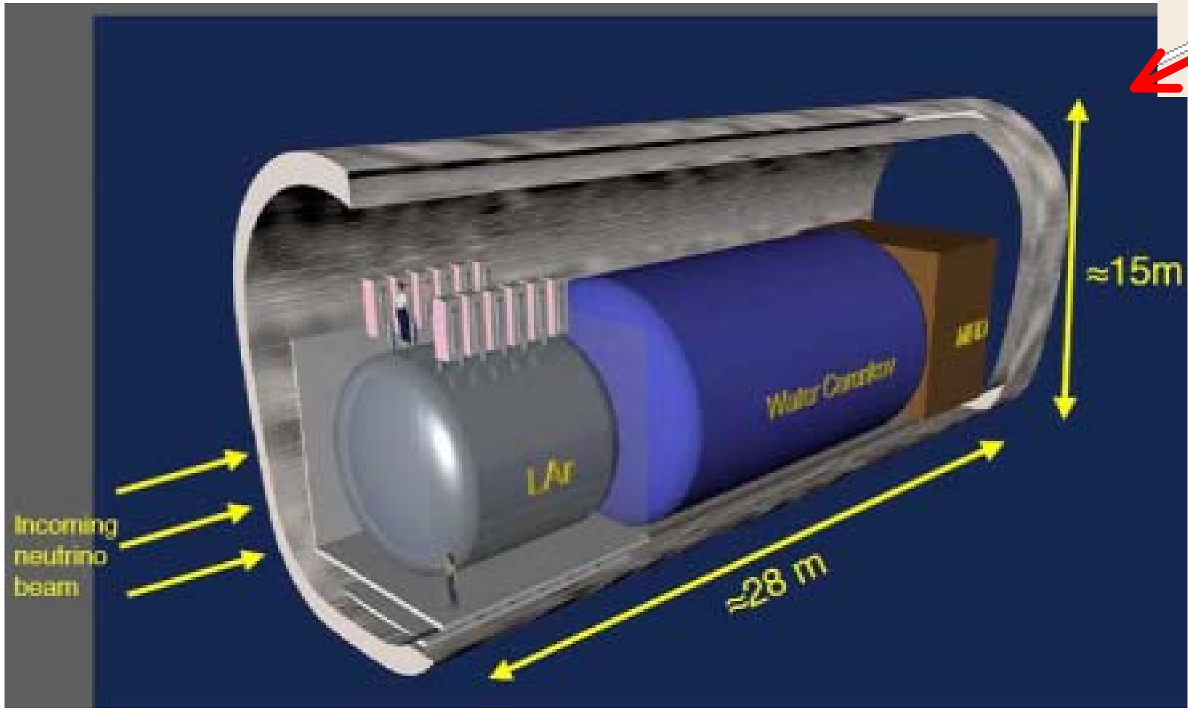
- Beam direction
- Grid layout

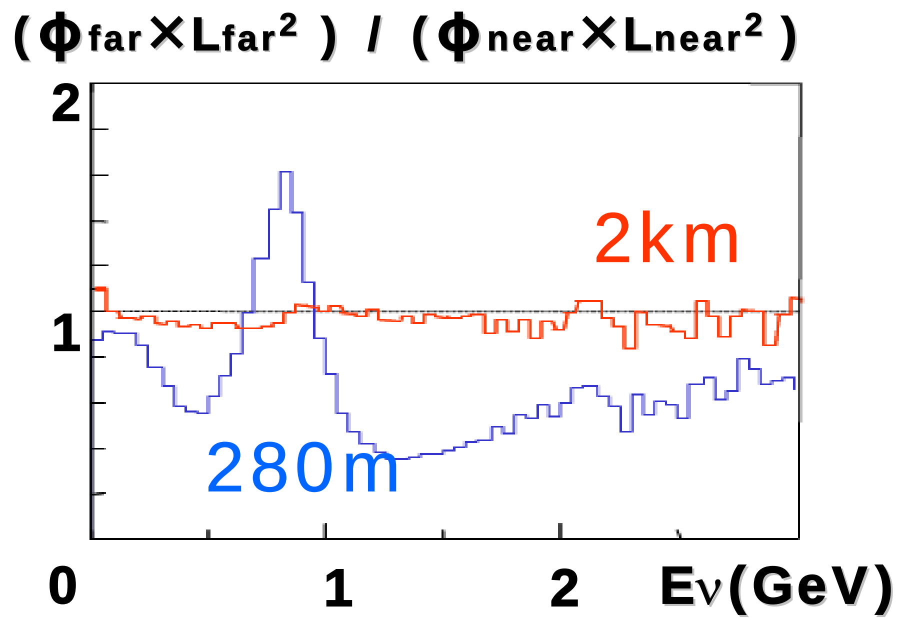
Near Detector @2km

Future option to reduce systematic errors

- ν_μ energy spectrum
  for ν_μ disappearance
- ν_e background study
  for ν_e appearance

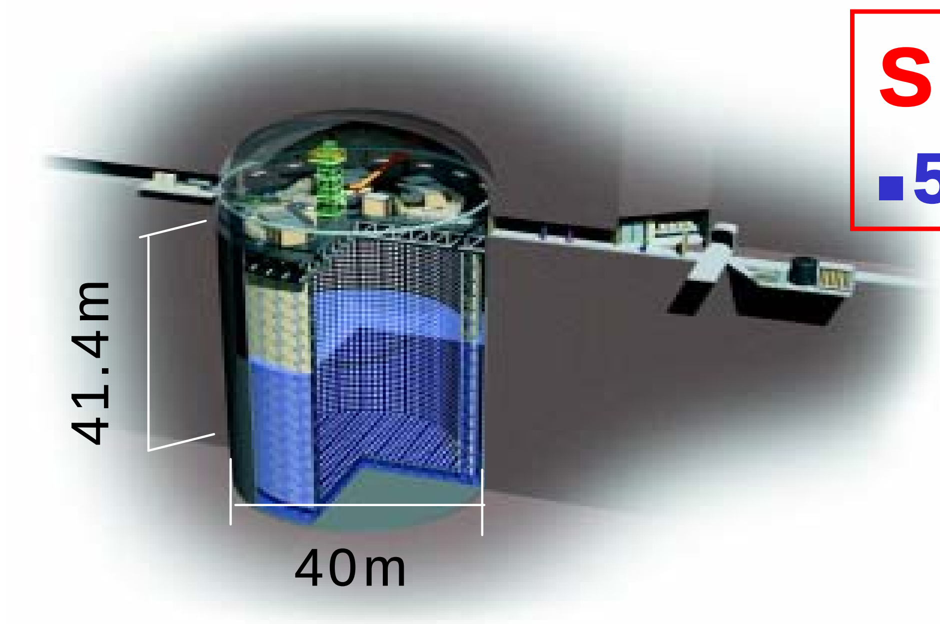






⇒ Next speaker

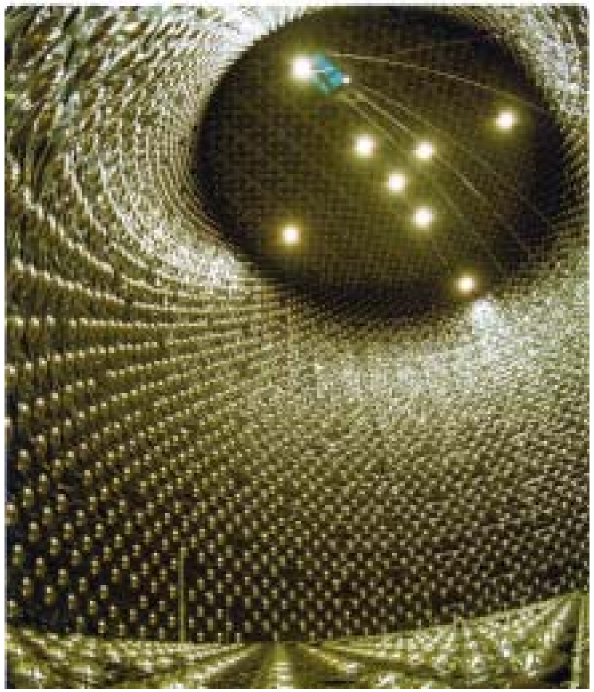
Far Detector: SK



Super-Kamiokande

- 50kt water Cherenkov

- Partial reconstruction in 2002
  - 47% of PMT's(~5200)
- Full reconstruction
  - PMT's attachment: Nov.2005 ~ Mar.2006
  - Water filling: Apr. ~ May 2006
  - Data taking: from June 2006



ν_μ disappearance

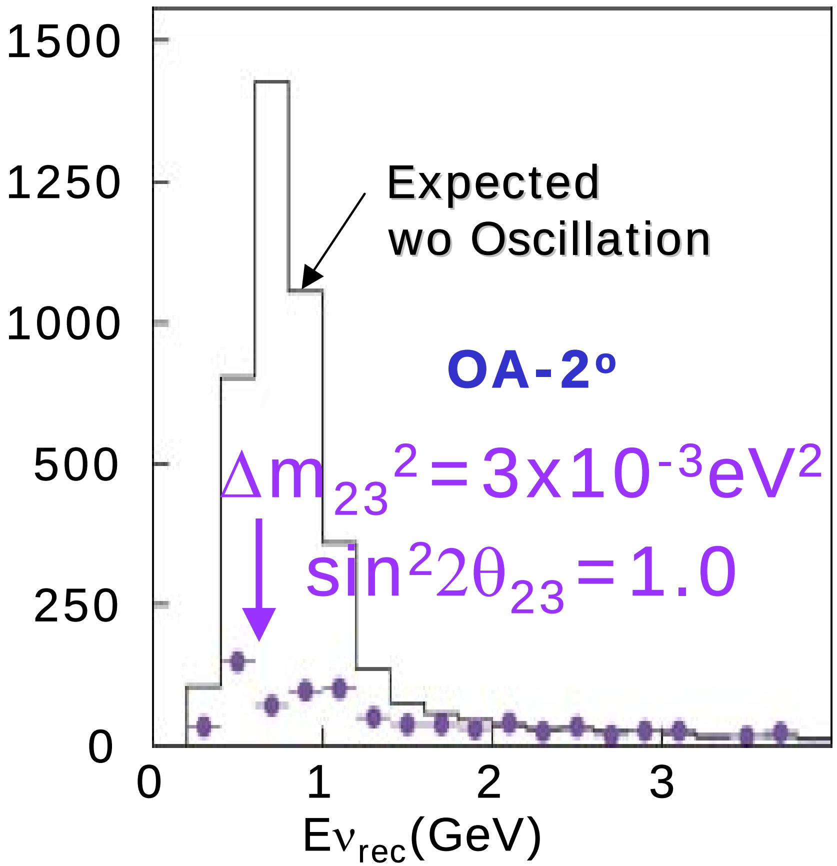
Precise measurement of θ_{23} & Δm_{23}

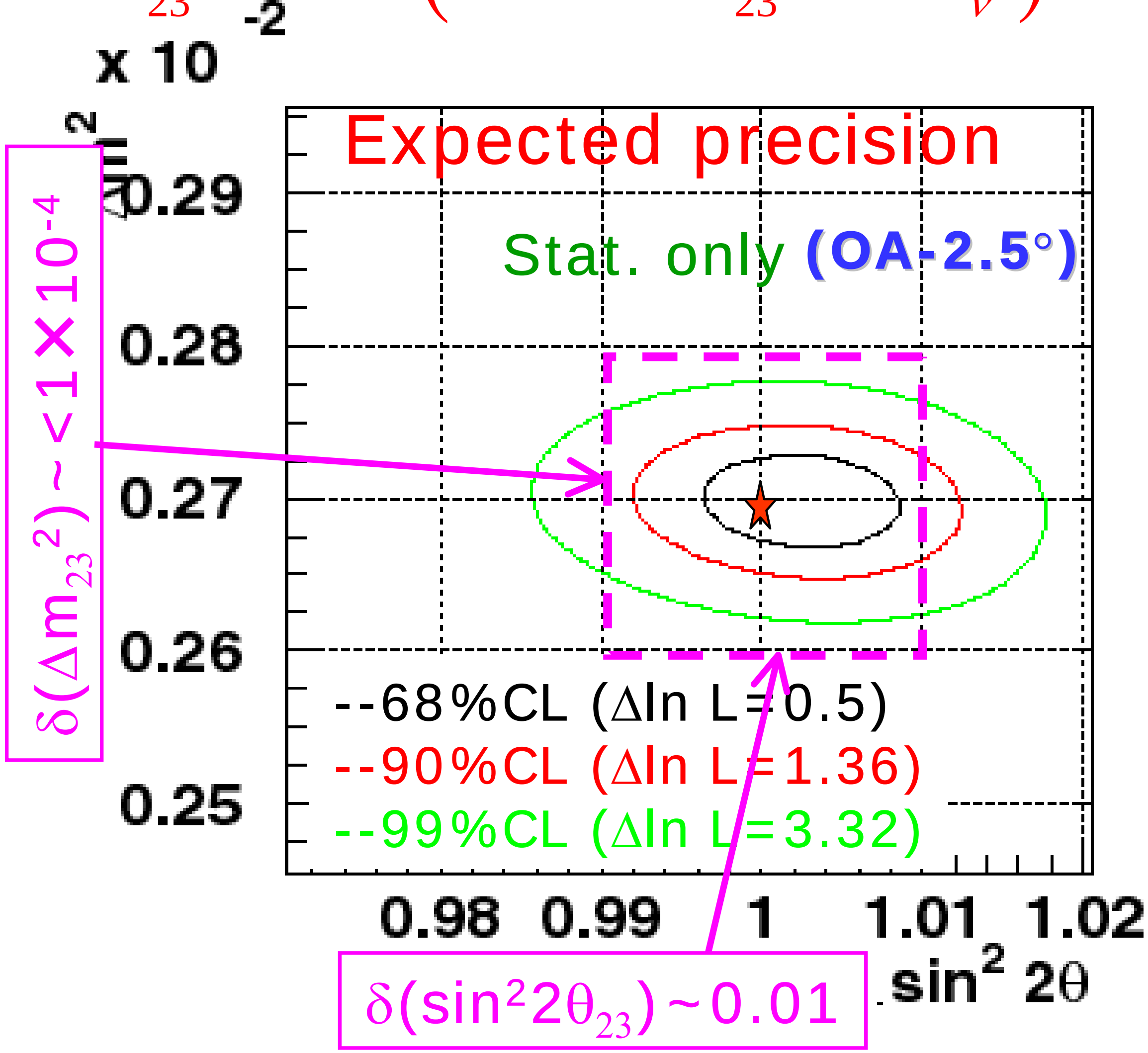
$\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$

m3
m2
m1

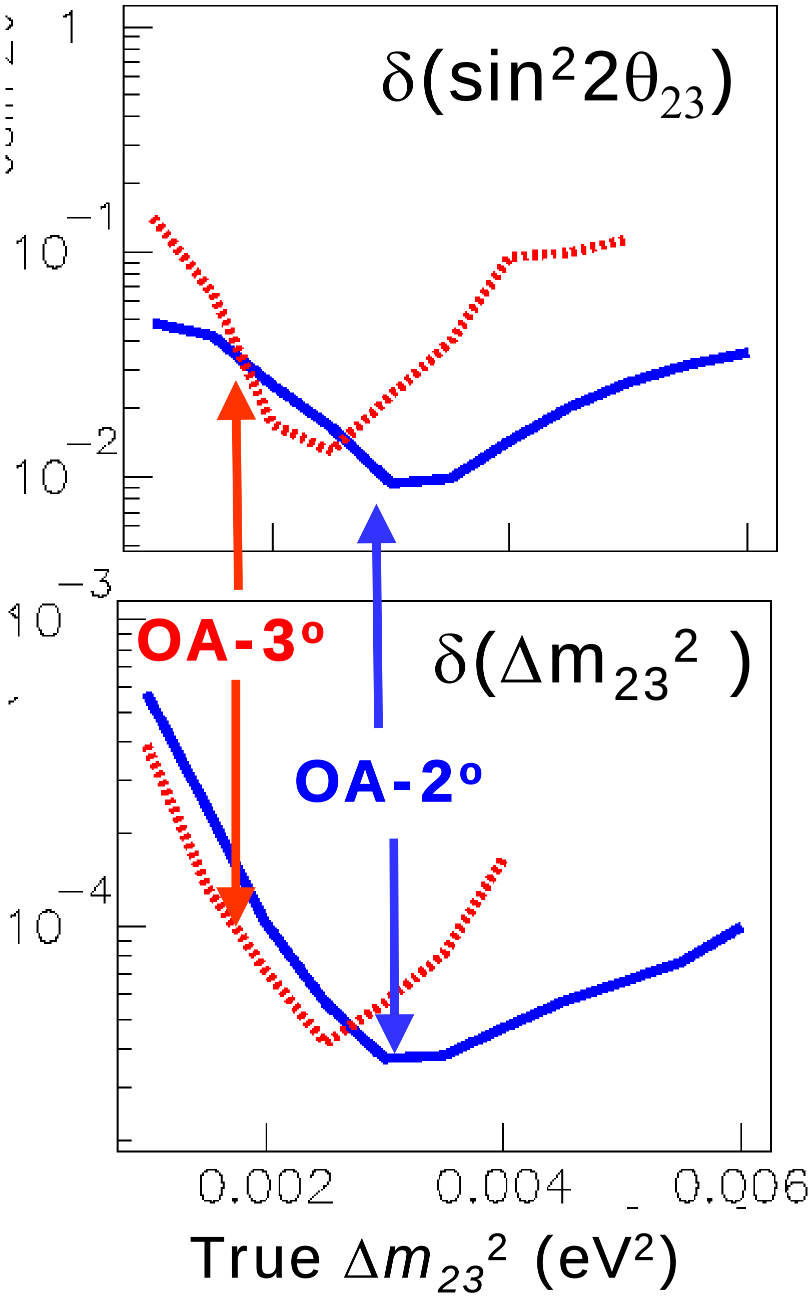
$$P_{\mu \to x} \approx 1 - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2 \left(1.27 \Delta m^2_{23} L / E_\nu\right)$$

5years(5×10²¹ POT)

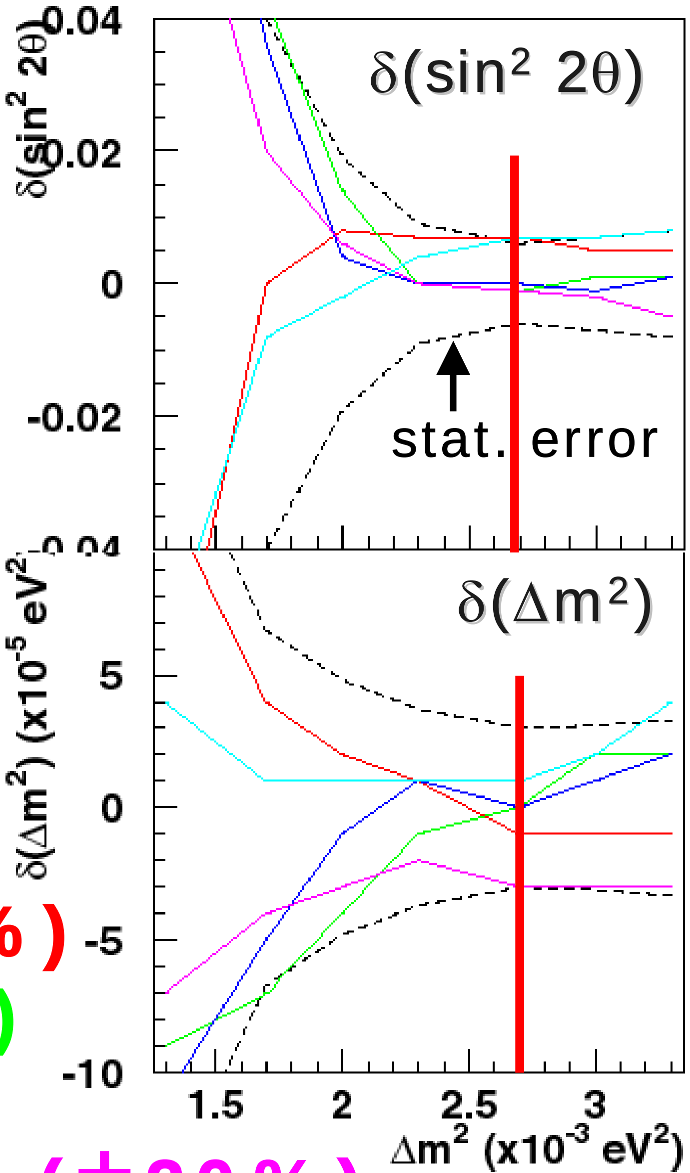




Sensitivity on disappearance



Effect of systematic error



- Norm. (+5%)
- NQE (+5%)
- E_{SK} (+1%)
- beam shape (±20%)
- beam width (5%)

Discovery of ν_e appearance

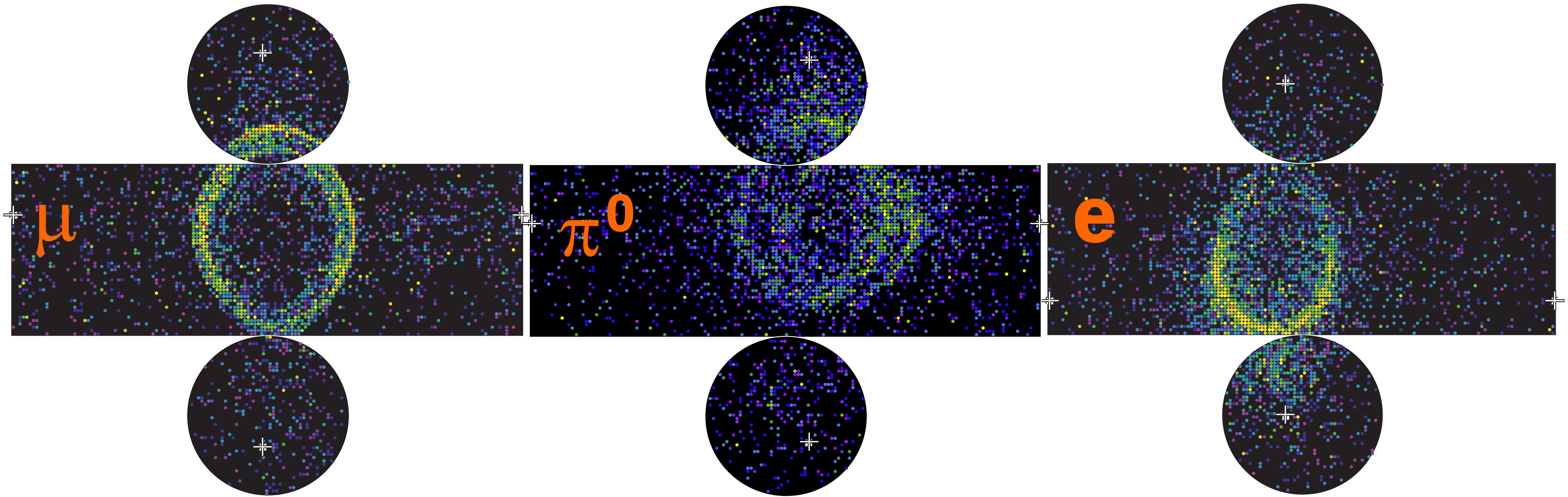
ν_e appearance: θ_{13} & Δm_{13}

$$P_{\mu \to e} \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \left(1.27\, \Delta m_{13}^2 L / E_\nu \right)$$

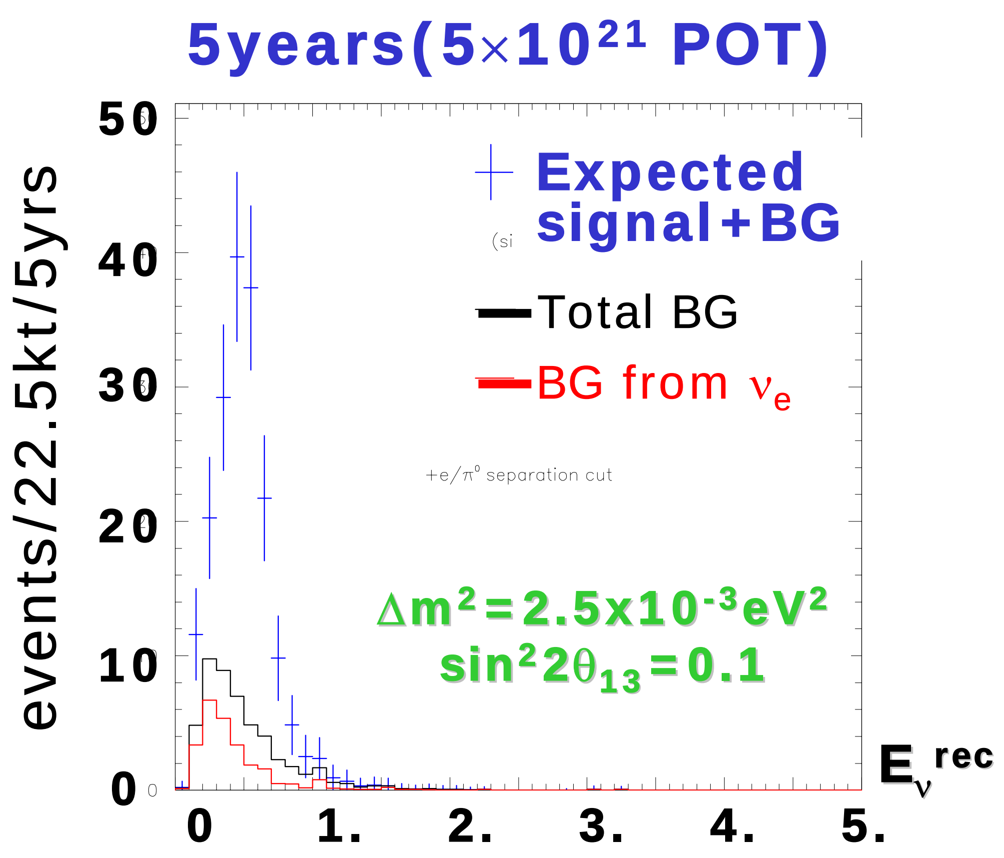
Background for ν_e appearance

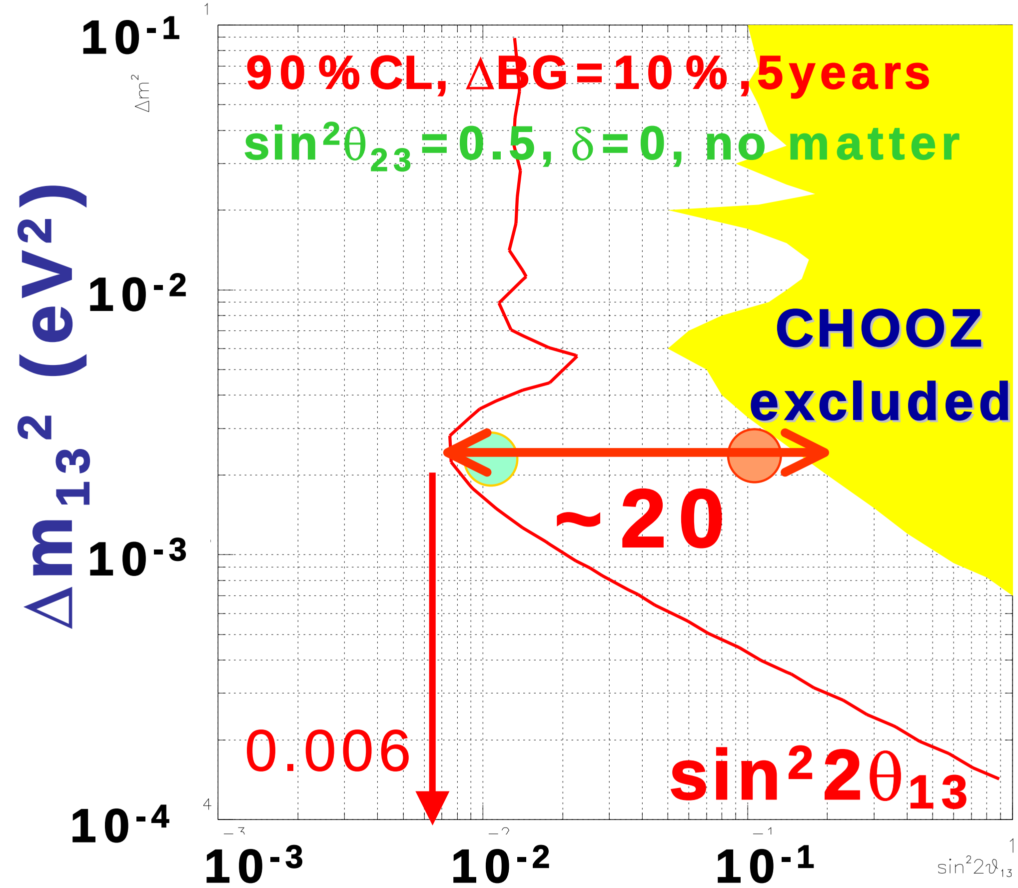
- Intrinsic ν_e component in initial beam
- Merged π^0 ring from ν_μ interactions

Requirement:10% uncertainty for BG estimation



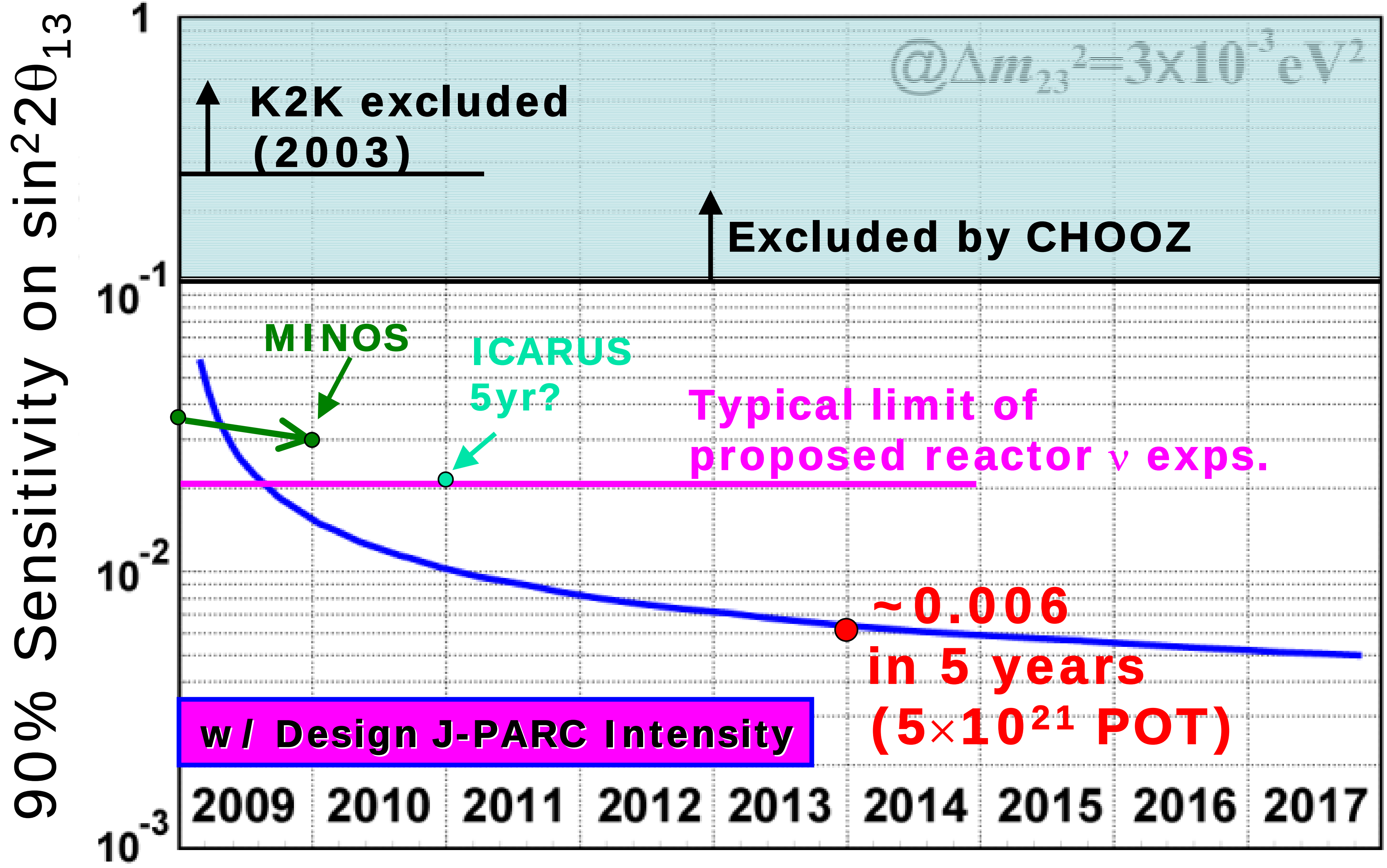
Sensitivity on appearance



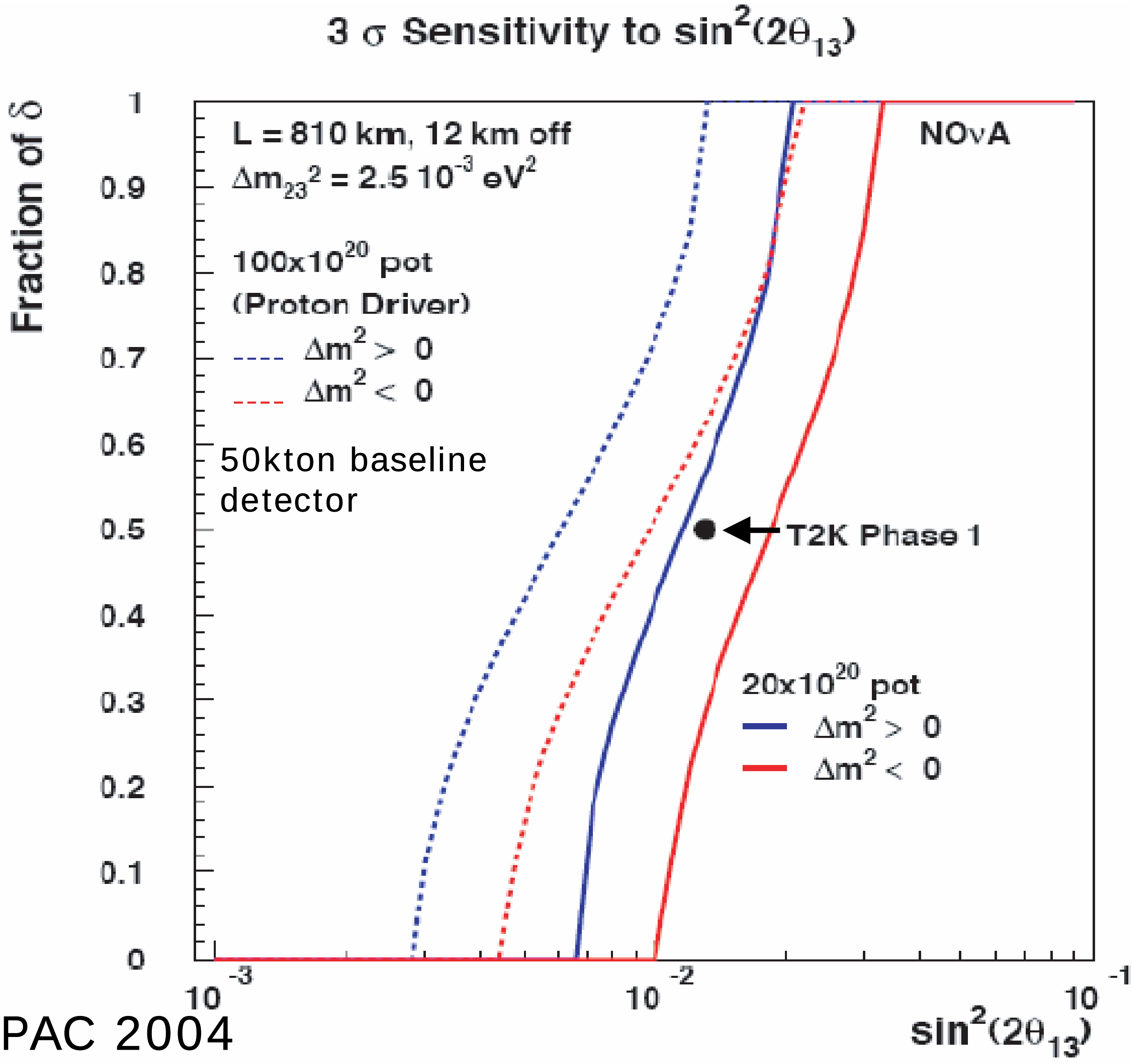


$\sin^2 2\theta_{13}$	Background in Super-K			Signal	Signal + BG
	ν_μ	ν_e	total		
0.1	10	13	23	103	126
0.01				10	33

Development of sensitivity



Comparison with NOvA



Feldman, Aspen PAC 2004

T2K phase-II

x~100 sensitivity for CP violation

- **J-PARC: 0.75MW ⇒ 4MW (x5)**
- **SK:22.5kton ⇒ HK:0.54Mton (x24)**

CP violation in lepton sector

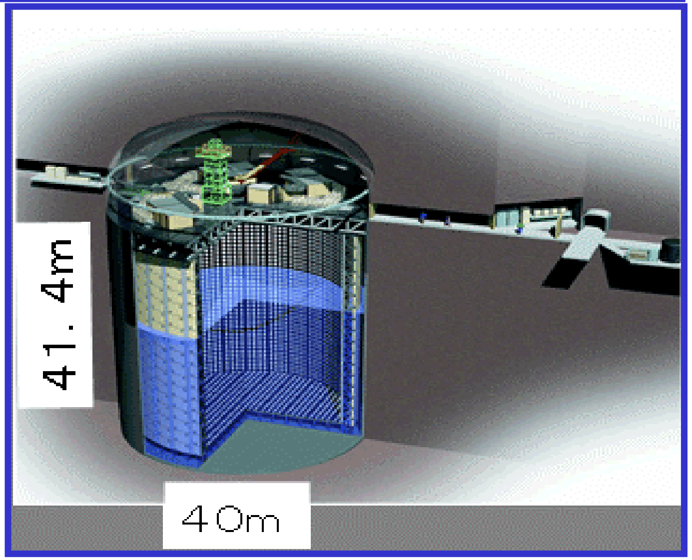
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}{}^2 L}{4E_\nu} \bullet \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \bullet \boxed{\sin \delta}$$

Maki-Nakagawa-Sakata (MNS) matrix $|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$ $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{-i\delta}} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

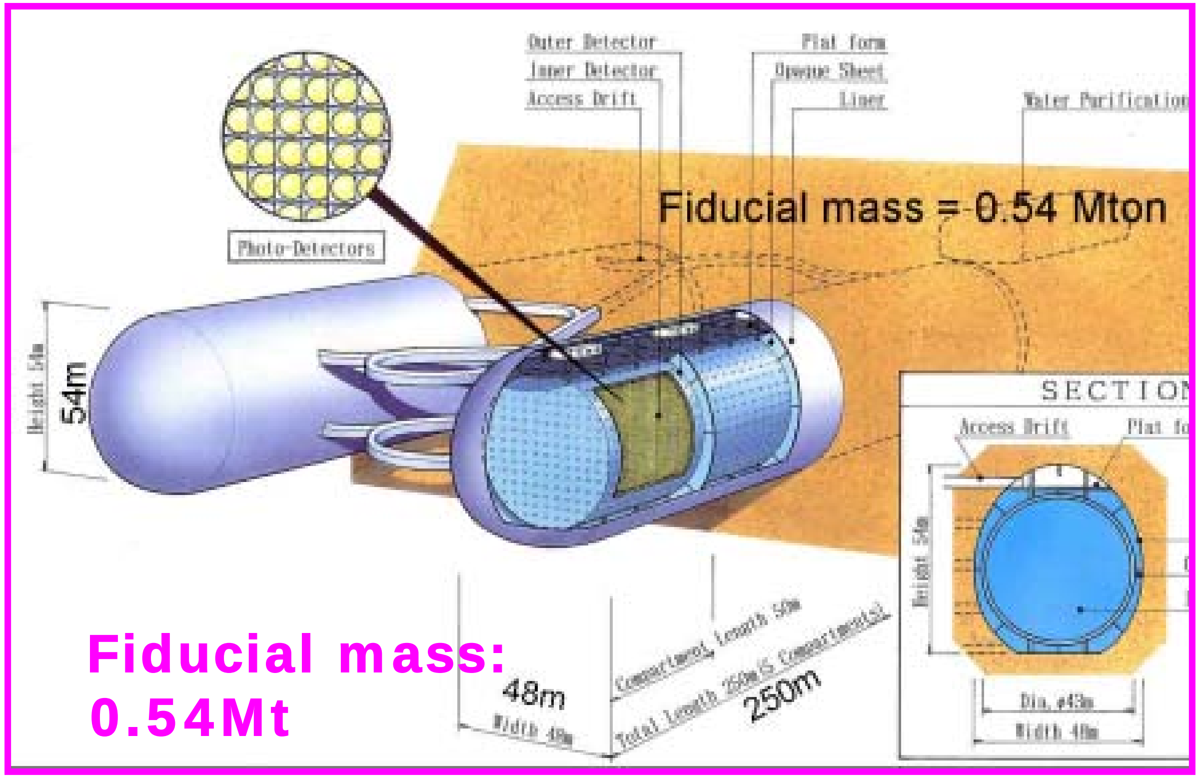
Hyper-Kamiokande

Super-Kamiokande
(50kt, 11000 PMT's)



Fiducial mass: 22.5kt

Hyper-Kamiokande
(~1Mt,~200000 photo-sensors)



Fiducial mass: 0.54Mt

- **Not official, Not approved**

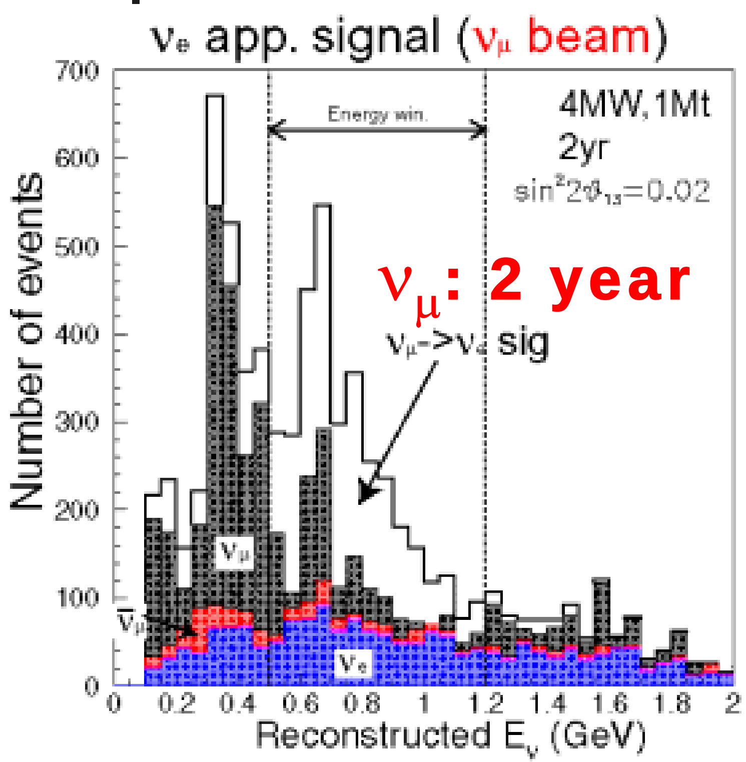
2008	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23

T2K-I

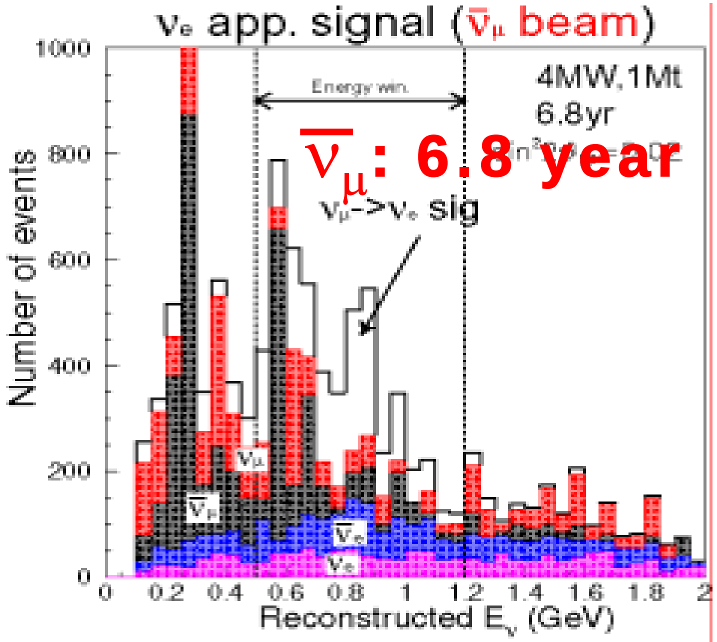
HK construction
(7~10 years)

T2K-II

Expected signal and BG



Very Preliminary



$\sin^2 2\theta_{13} = 0.02$

4MW, 540kt

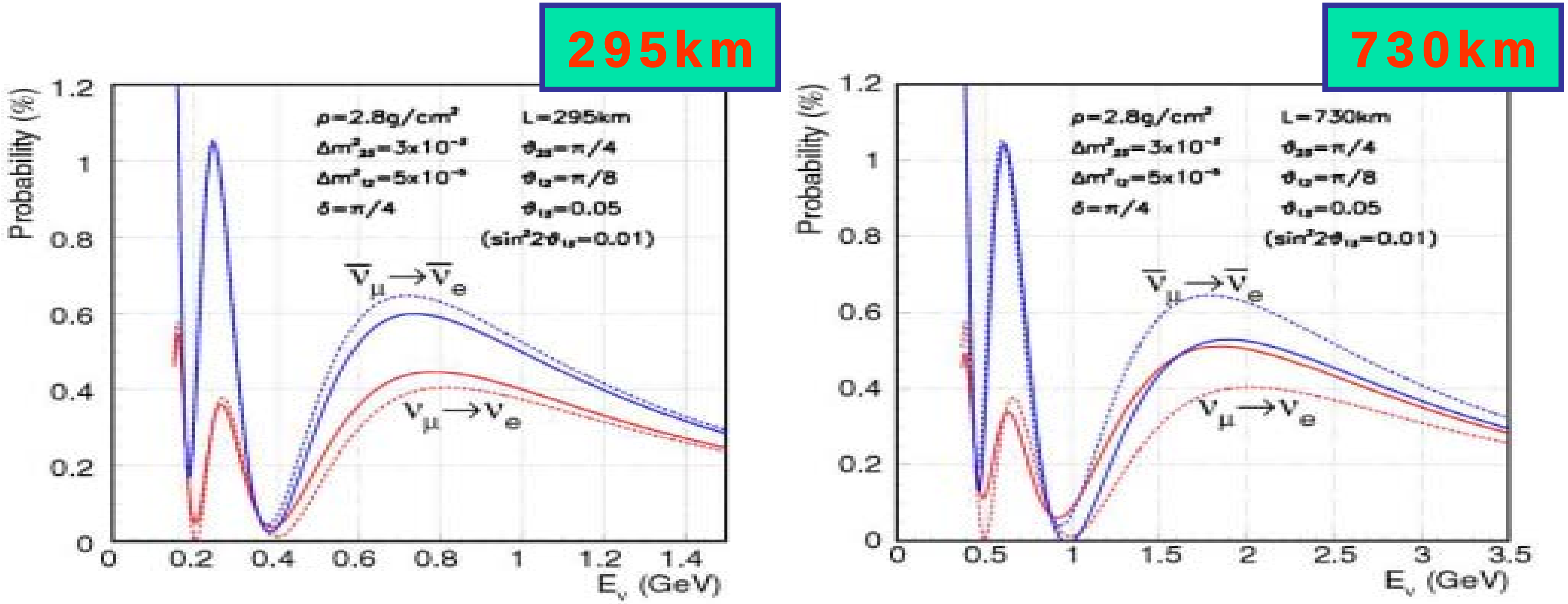
$\Delta m_{21}^2 = 6.9\times10^{-5}\,\mathrm{eV}^2$
$\Delta m_{32}^2 = 2.8\times10^{-3}\,\mathrm{eV}^2$
$\theta_{12} = 0.594$
$\theta_{23} = \pi/4$

$\sin^2 2\theta_{13} = 0.01$

	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\nu_\mu \to \nu_e$	536	229	913	370	66	450	26
$\bar{\nu}_\mu \to \bar{\nu}_e$	536	790	1782	399	657	297	430

CPV vs matter effect

$\nu_\mu \rightarrow \nu_e$ osc. probability w/ CPV/matter



@$\sin^2 2\theta_{13}$=0.01

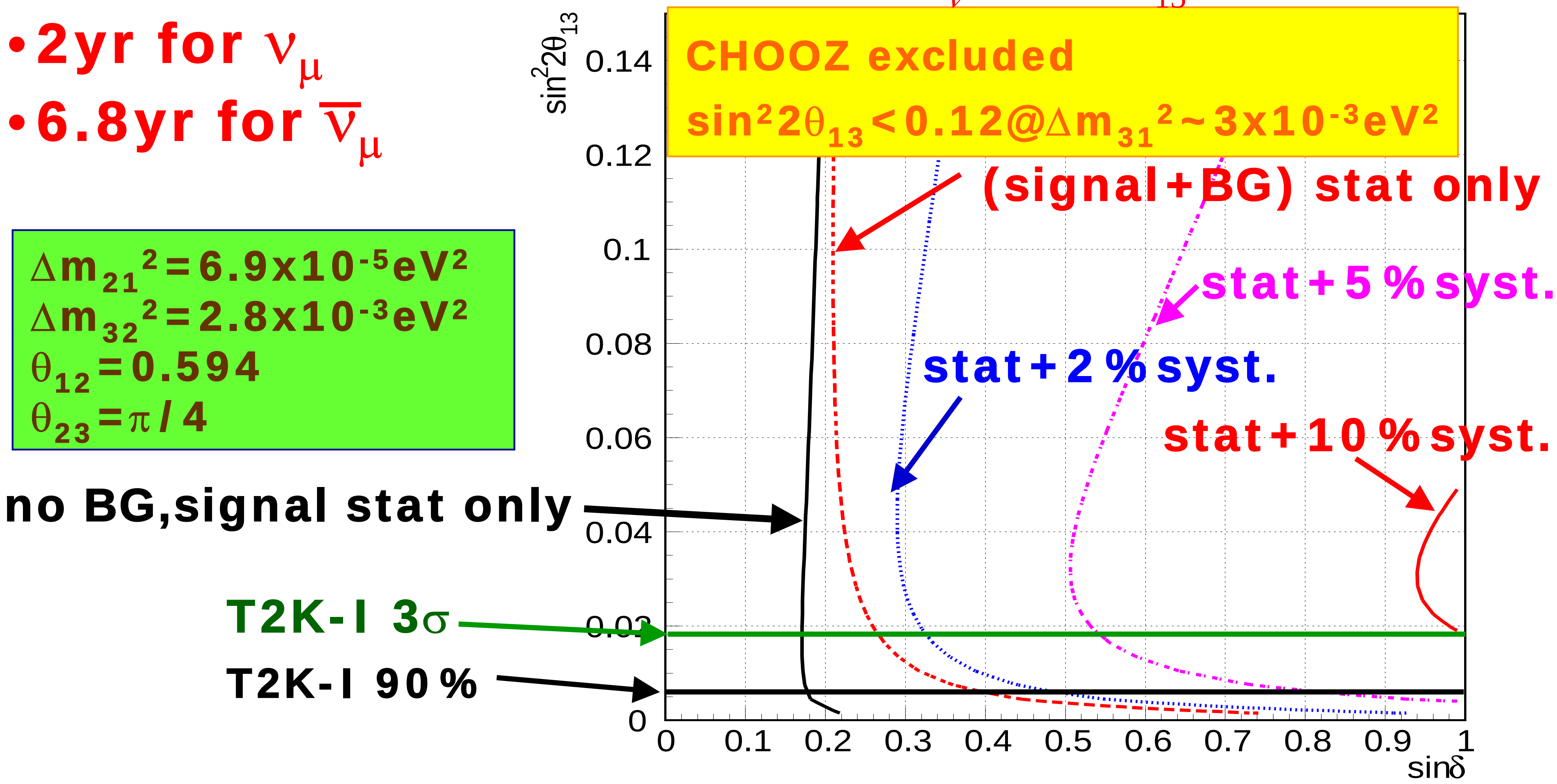
J-PARC/T2K: smaller distance/lower energy
small matter effect
⇒Pure CPV & Less sensitivity on sign of Δm^2

3σ Sensitivity for CPV

- 4MW, 540kt
- 2yr for ν_μ
- 6.8yr for $\overline{\nu}_\mu$

$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

$\Delta m_{21}{}^2 = 6.9\times10^{-5}$eV^2
$\Delta m_{32}{}^2 = 2.8\times10^{-3}$eV^2
$\theta_{12} = 0.594$
$\theta_{23} = \pi/4$



3σ CP sensitivity : |δ|>20°
for $\sin^2 2\theta_{13} > 0.01$ with 2% syst.