R&D Activities for Neutrino Beam in Asia

Yoshitaka Kuno
Department of Physics
Osaka University

October 23rd, 2010
NuFACT10 Workshop
Tata Institute of Fundamental Research, Mumbai, India

Outline

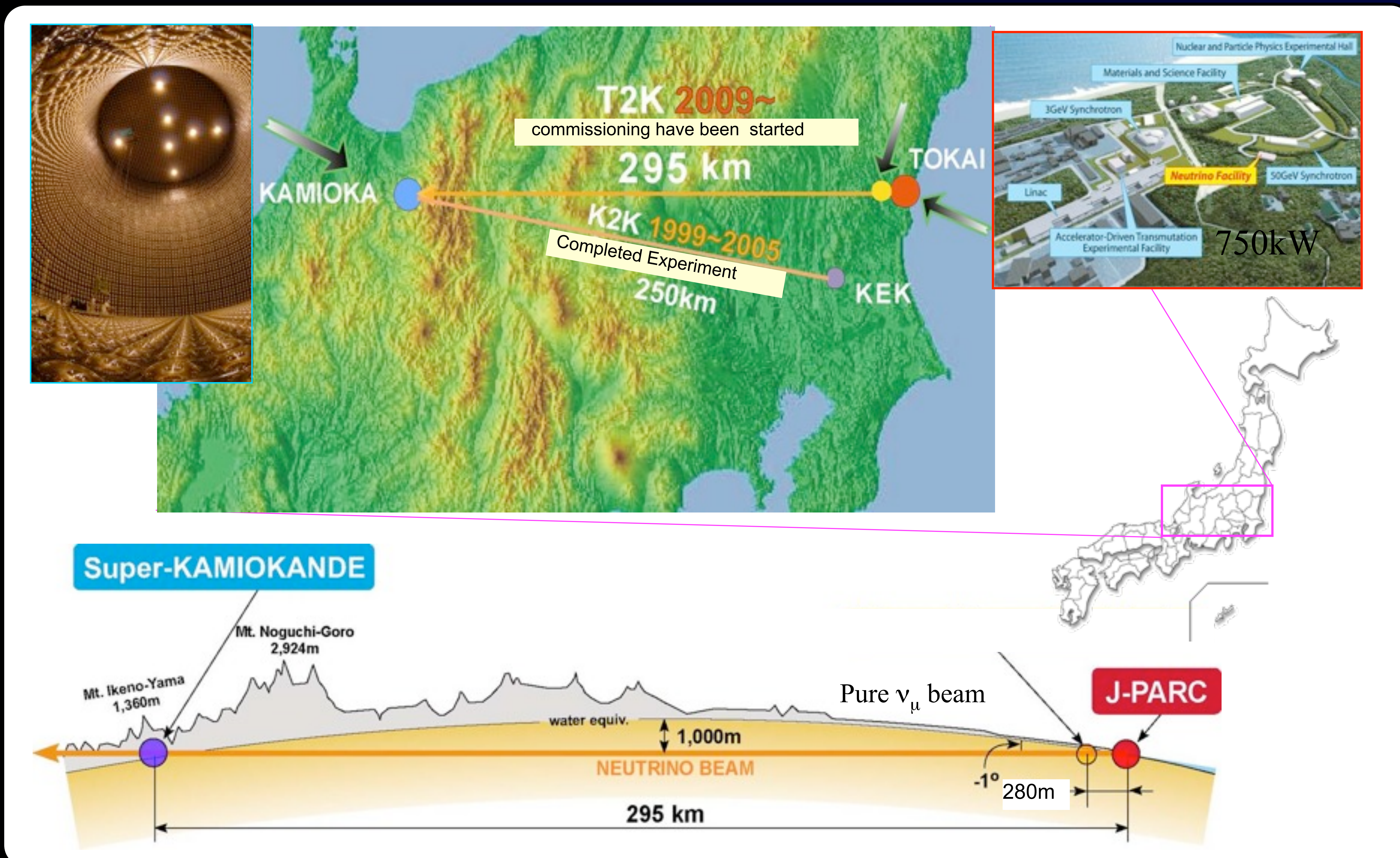
- Conventional Super Neutrino Beam
- Neutrino Beam based on Muon decays
  - Study on Muon Acceleration
  - Demonstration of a Highly Intense Muon Source
- Summary

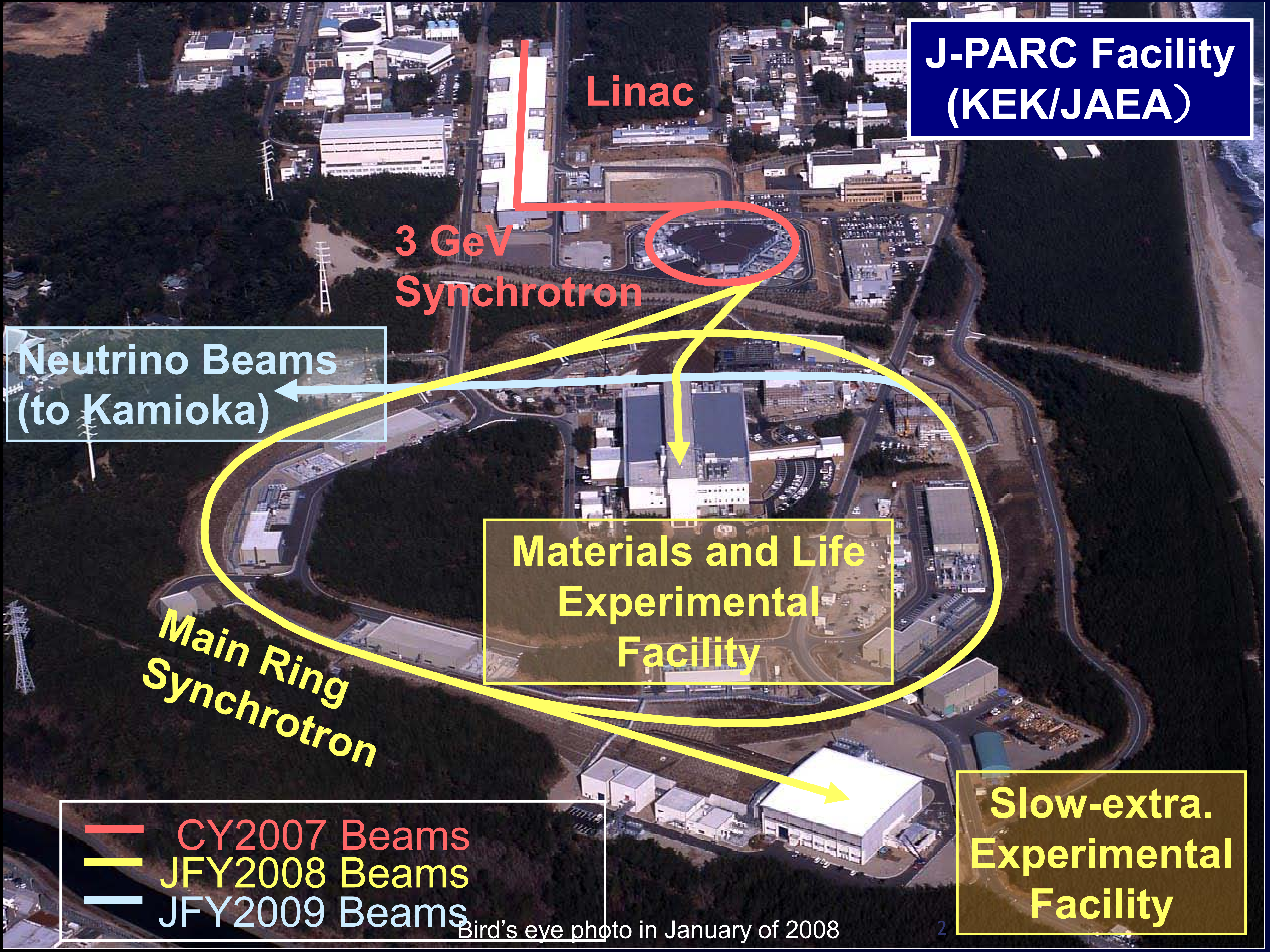
Conventional
Super Neutrino Beam

T2K Future Plan

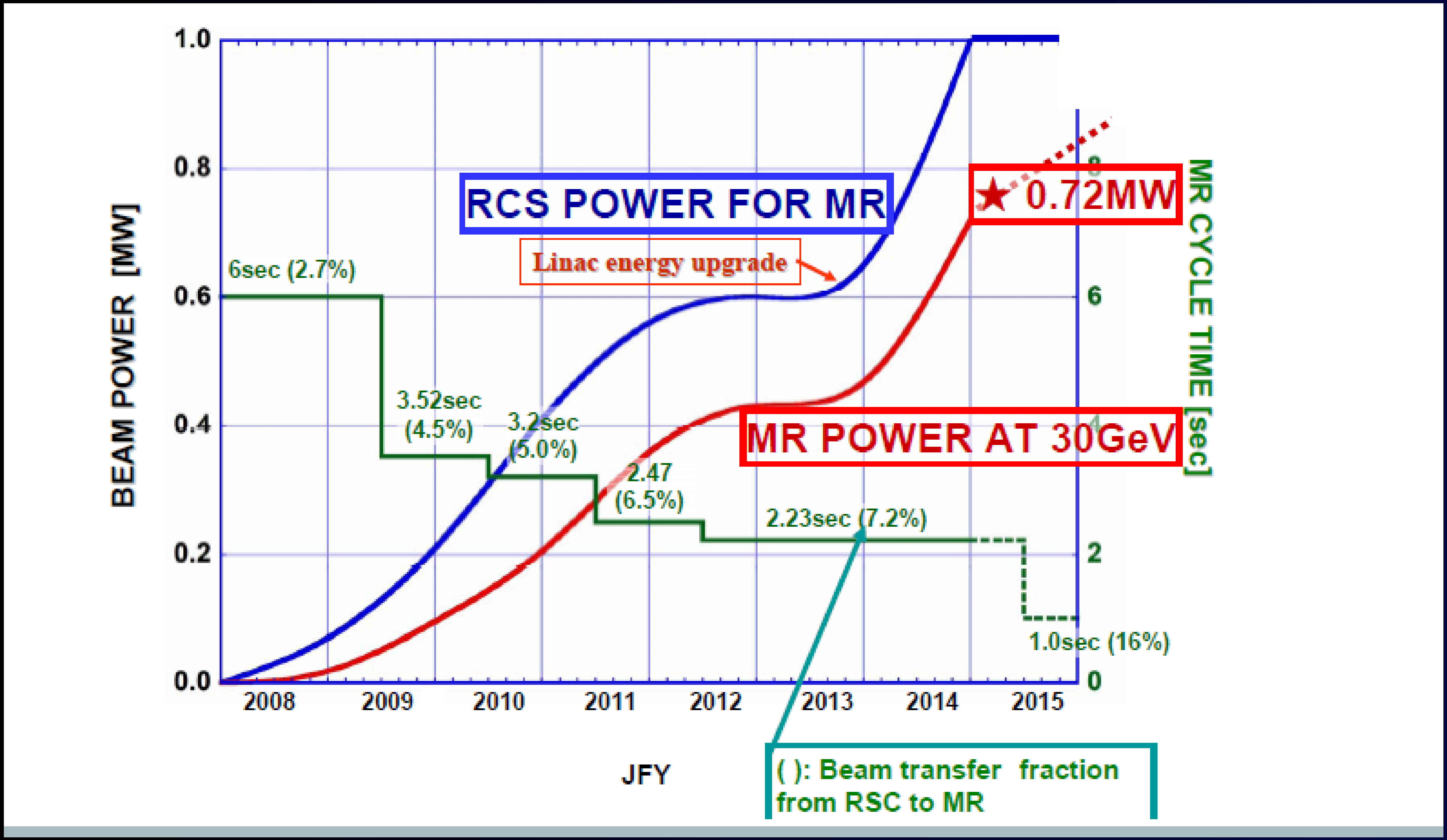
from Prof. Takashi Kobayashi

Neutrino Beam in Japan - T2K




J-PARC Facility
(KEK/JAEA）
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
Main Ring
Synchrotron
Slow-extra.
Experimental
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Short-term Scenario of Beam Power Improvement at J-PARC Main Ring



studies and R&D on power supply, RF configuration, etc. are being made.

Long-term Scenario for MW Beam Power Improvement at J-PARC

	Day1 Achieved ! (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	2.2	1.92～0.5
No. of Bunch	6	8	8
Particle/Bunch	1.2×10^{13}	2.5×10^{13}	$4.1\sim8.3\times10^{13}$
Particle/Ring	7.2×10^{13}	2.0×10^{14}	$3.3\sim6.7\times10^{14}$
LINAC(MeV)	181	181	400
RCS	h=2	h=2	h=2 or 1

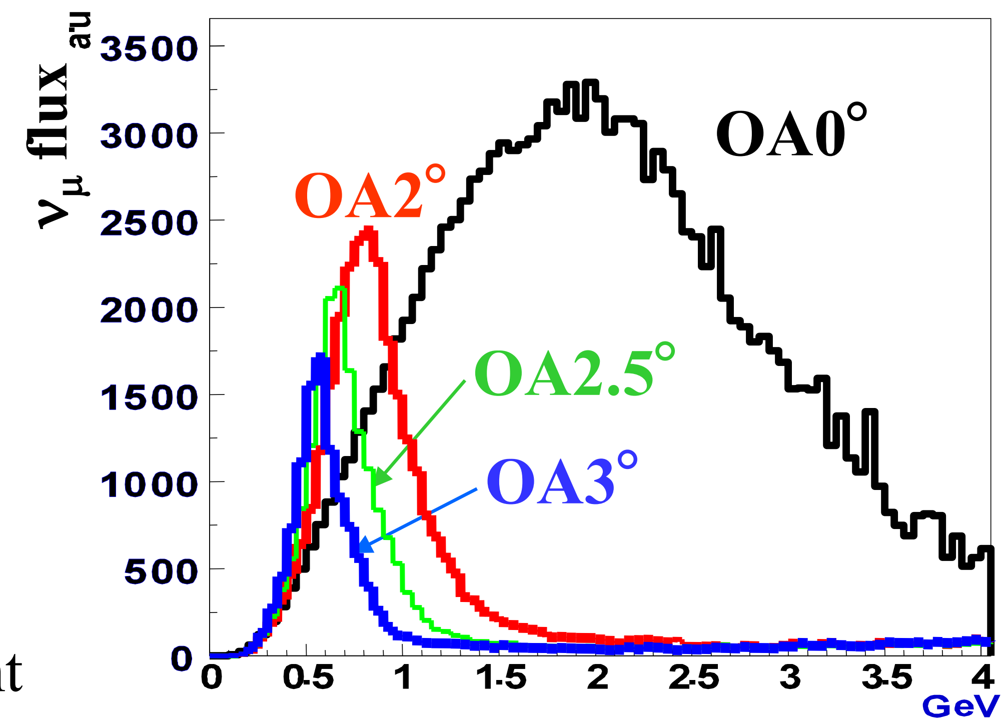
by combination of high rep. cycle and high beam density

T2K Beamline for a MW beam

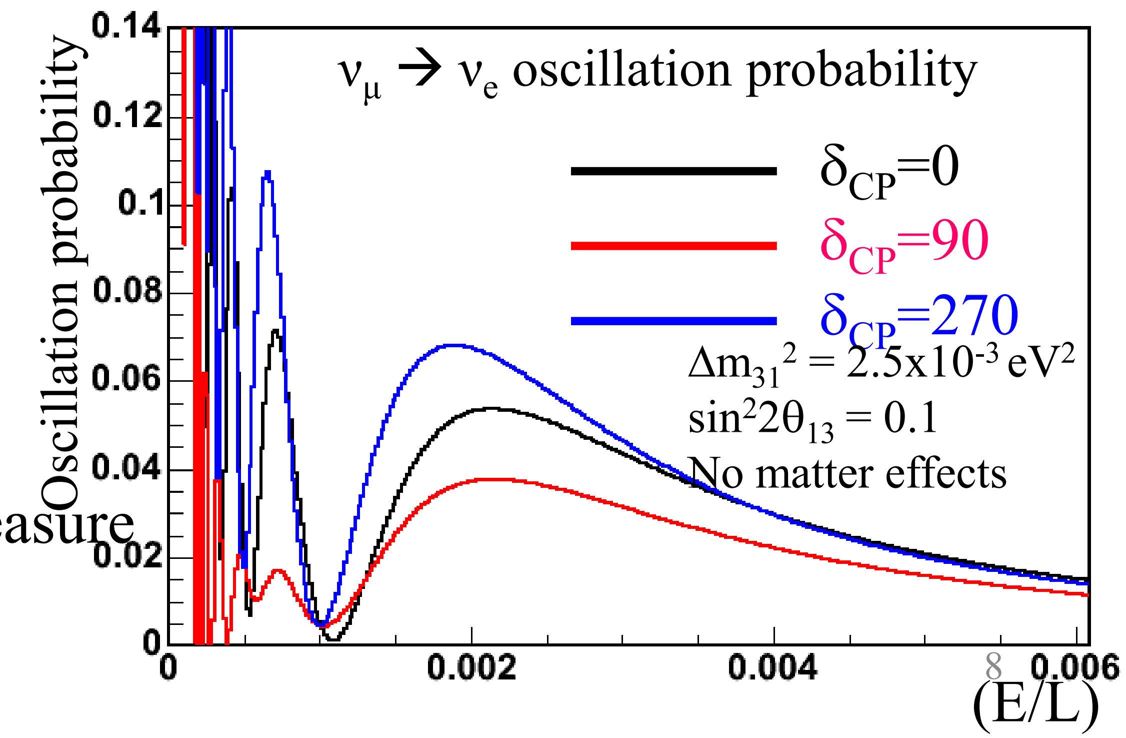
According to Prof. Takashi Kobayashi (KEK), major upgrade of the T2K beamline may not be needed for a beam power up to about 2 MW.

Neutrino Beam - Angle and Baseline

- Off-axis angle
  - On-Axis: Wide Energy Coverage,
    ◯Energy Spectrum Measurement
    ×Control of π^0 Background
  - Off-Axis: Narrow Energy Coverage,
    ◯Control of π^0 Background
    ×Energy Spectrum Measurement
    → Counting Experiment



- Baseline
  - Long:
    ◯ 2nd Osc. Max. at Measurable Energy
    × Less Statistics
    ? Large Matter Effect
  - Short:
    ◯ High Statistics
    × 2nd Osc.Max.Too Low Energy to Measure
    ? Less Matter Effect

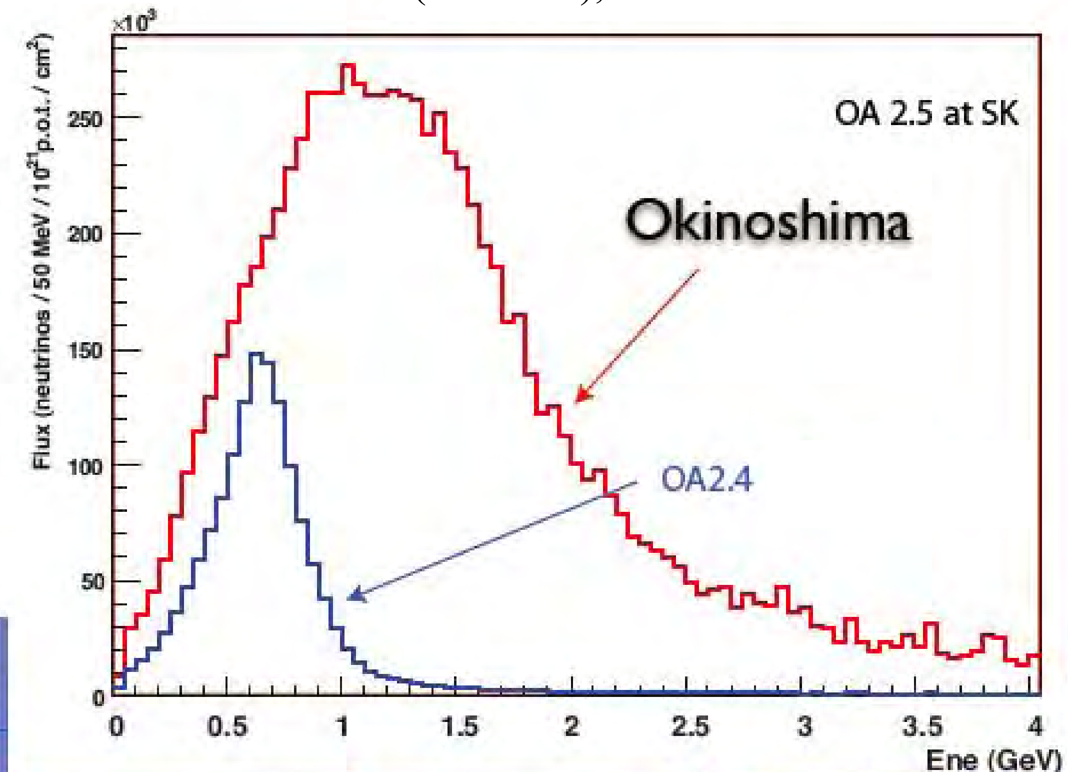


Three Future Scenario of Long Baseline Neutrino Oscillation Program at J-PARC

Scenario 1

J-PARC to Okinoshima

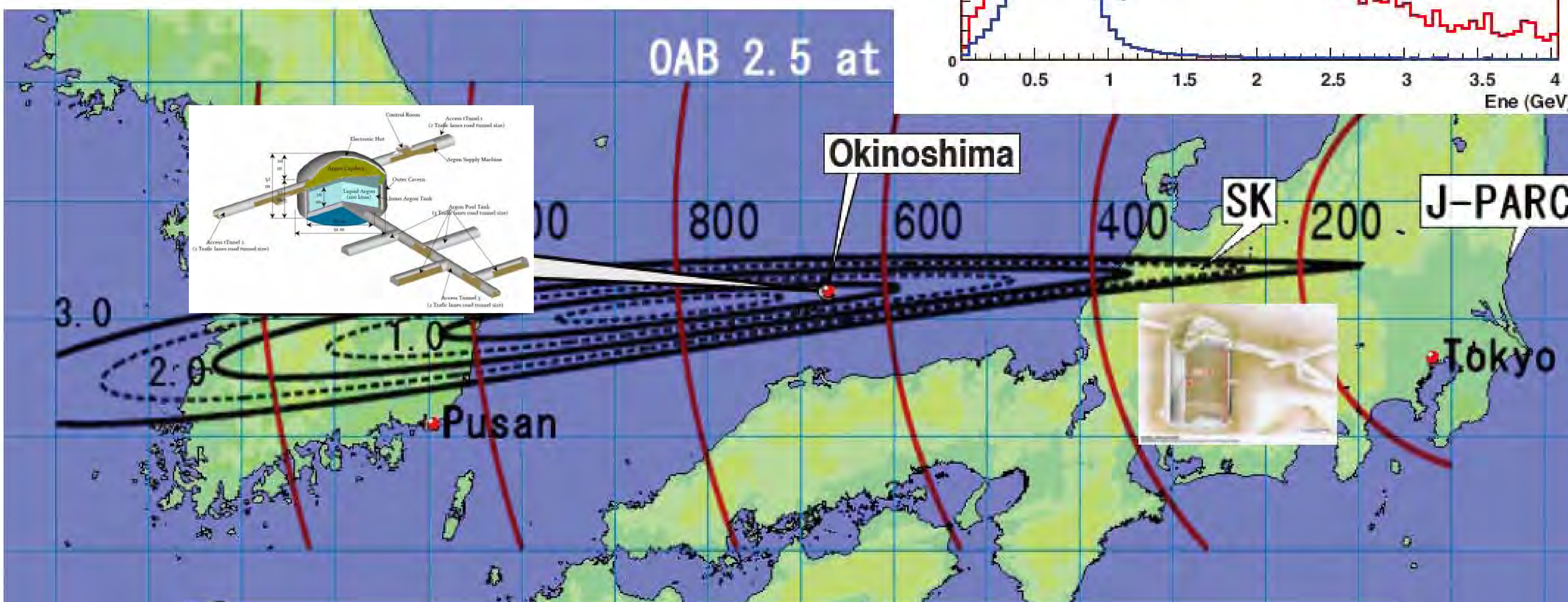
P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111



Distance = 658 km

Off-axis angle = 0.76°
(2.5° @ SK)

100 kton liquid Argon



→ Extract δ_{CP} from fit of 1st & 2nd maximum

Scenario 1

J-PARC to Okinoshima: Sensitivities

CP Violation

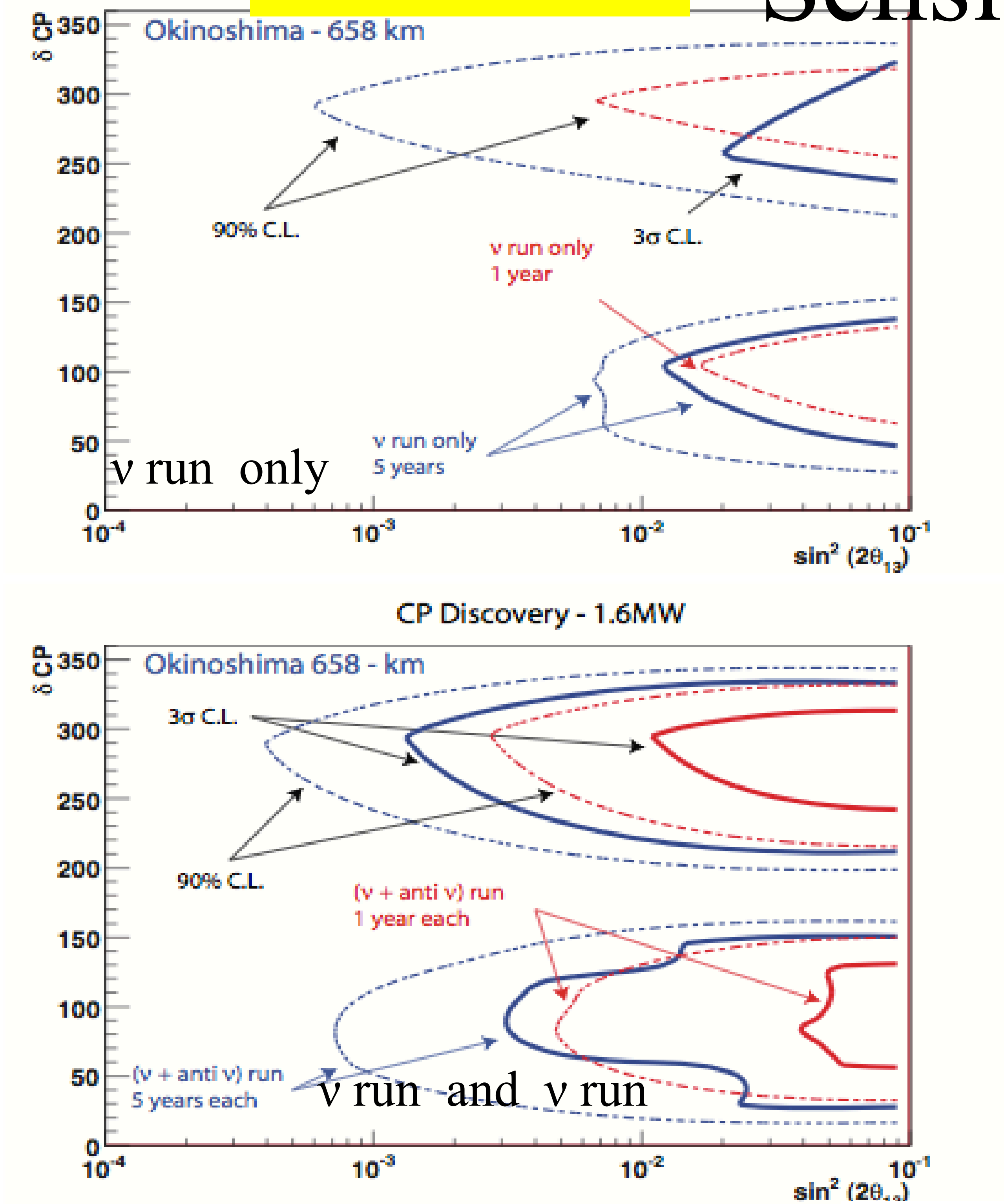


Fig. 9: Discovery potential for CP-violation at 90%C.L. and 3σ for (top) 1 resp. 5 years 1+1 resp. 5+5 years neutrino-antineutrino runs.

Hierarchy

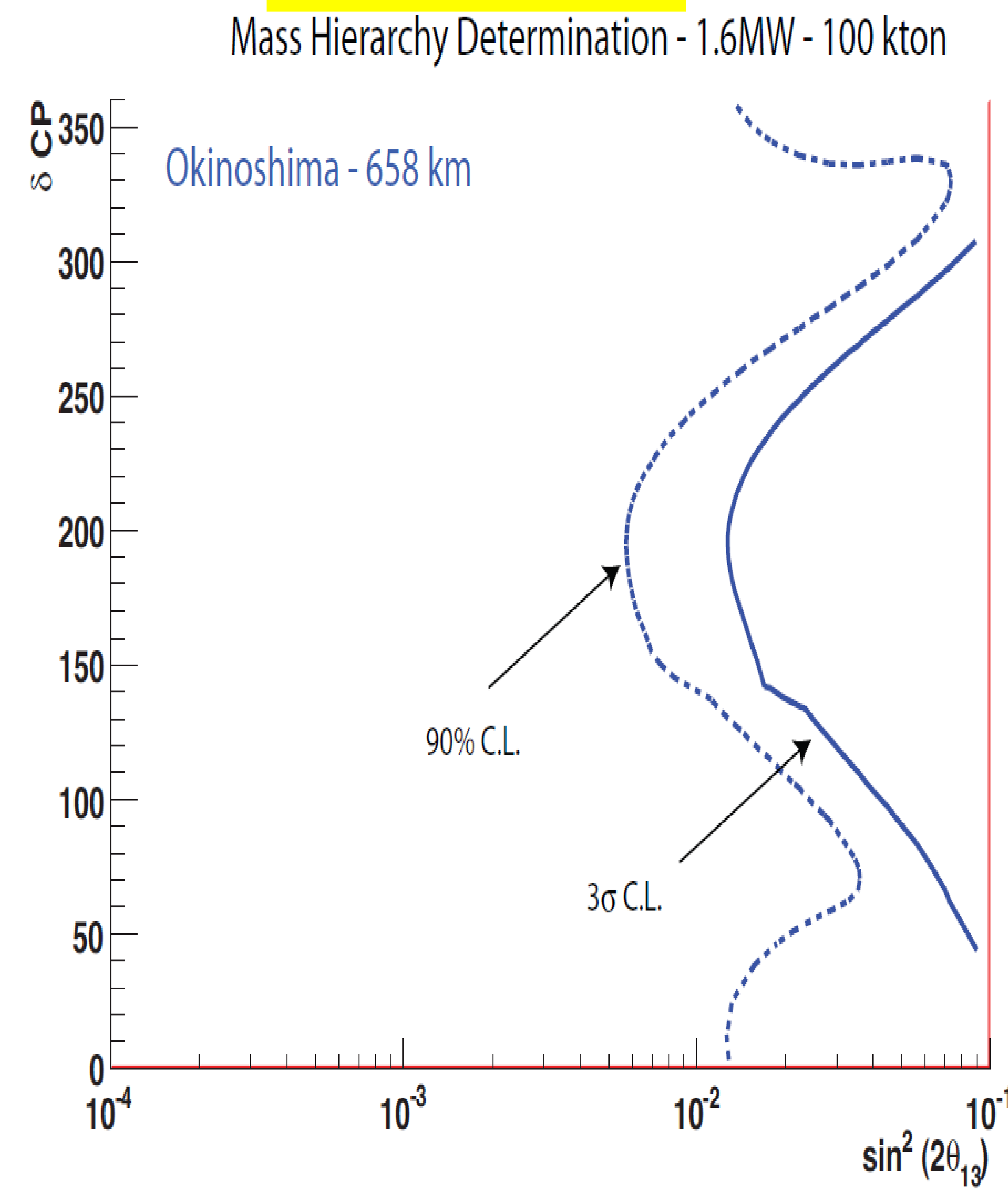
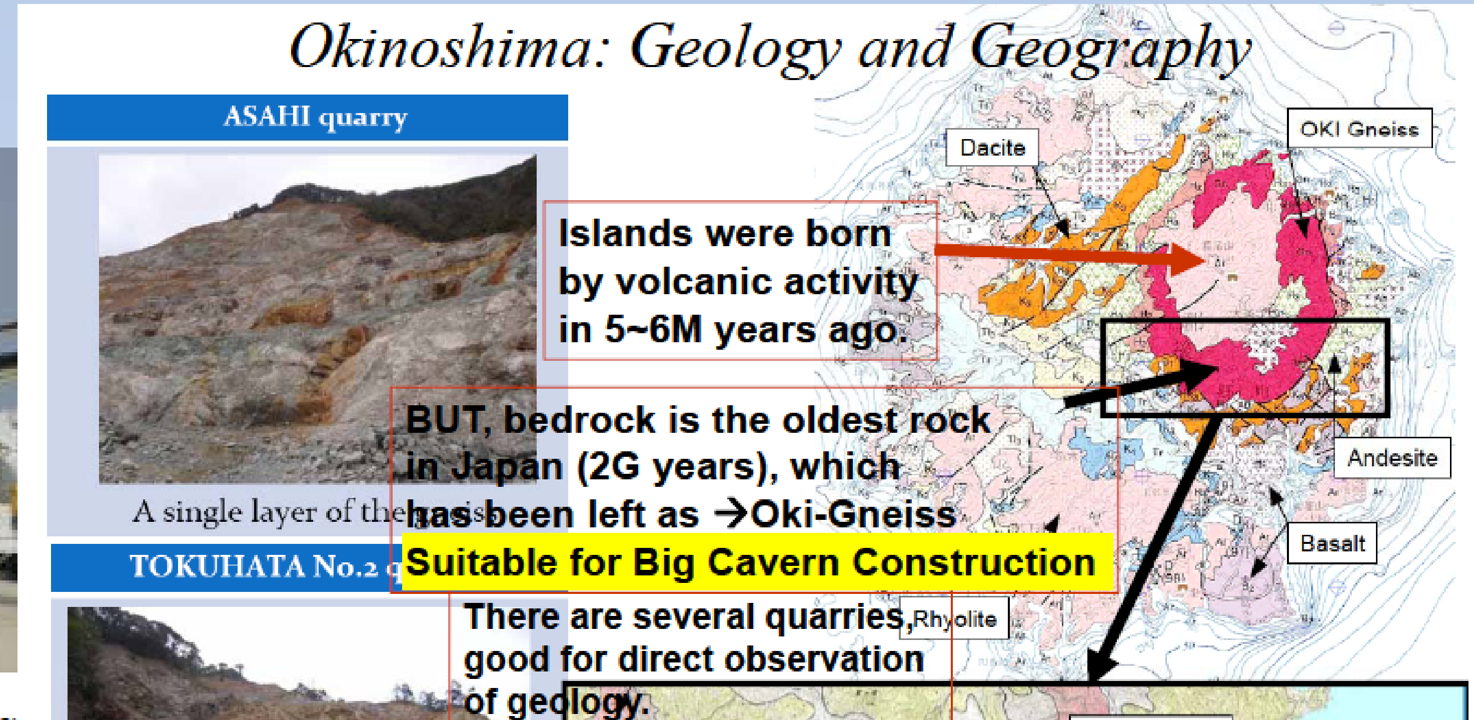


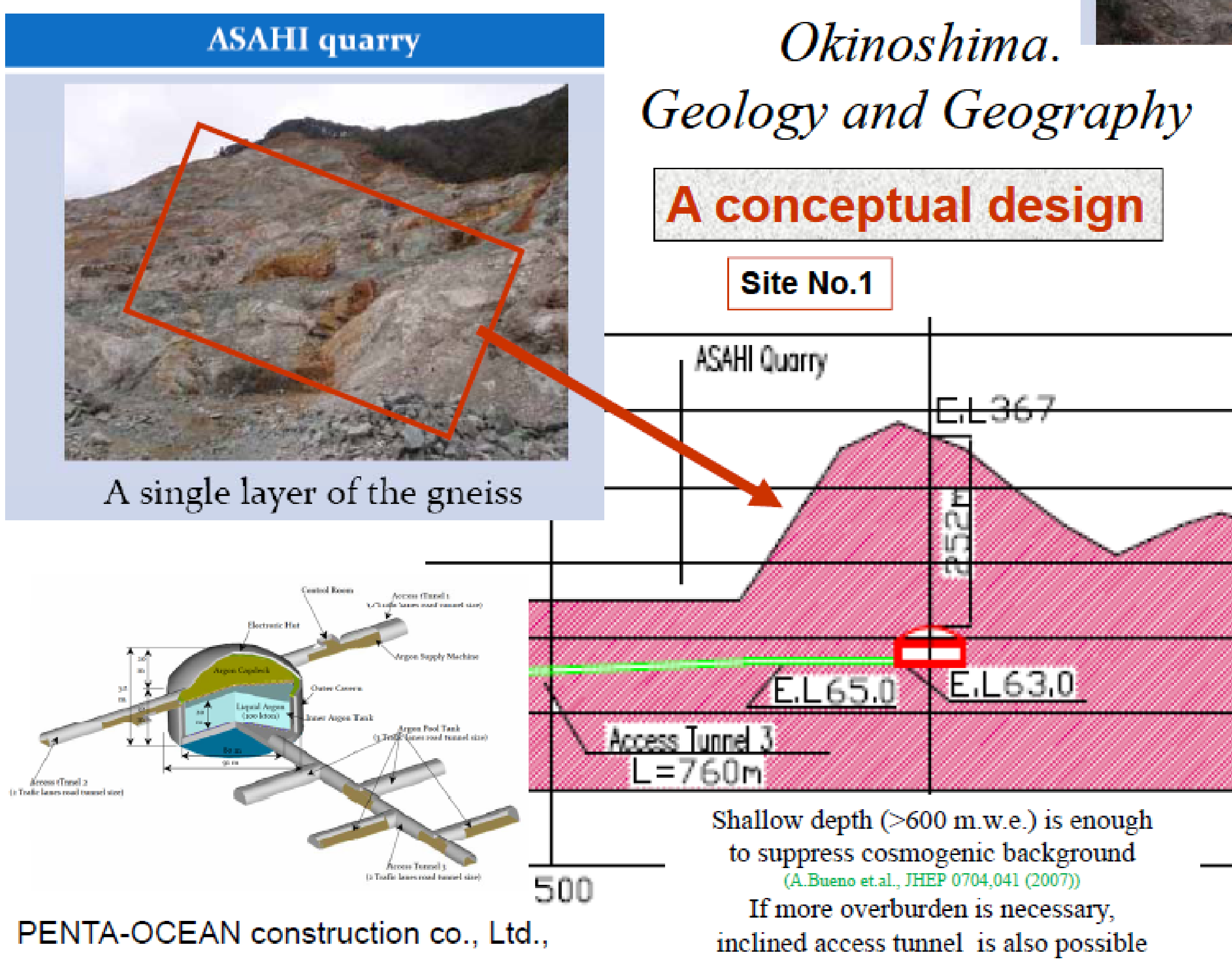
Fig. 10: Mass hierarchy discrimination at 90%C.L. and 3σ for 5+5 years neutrino-antineutrino runs.

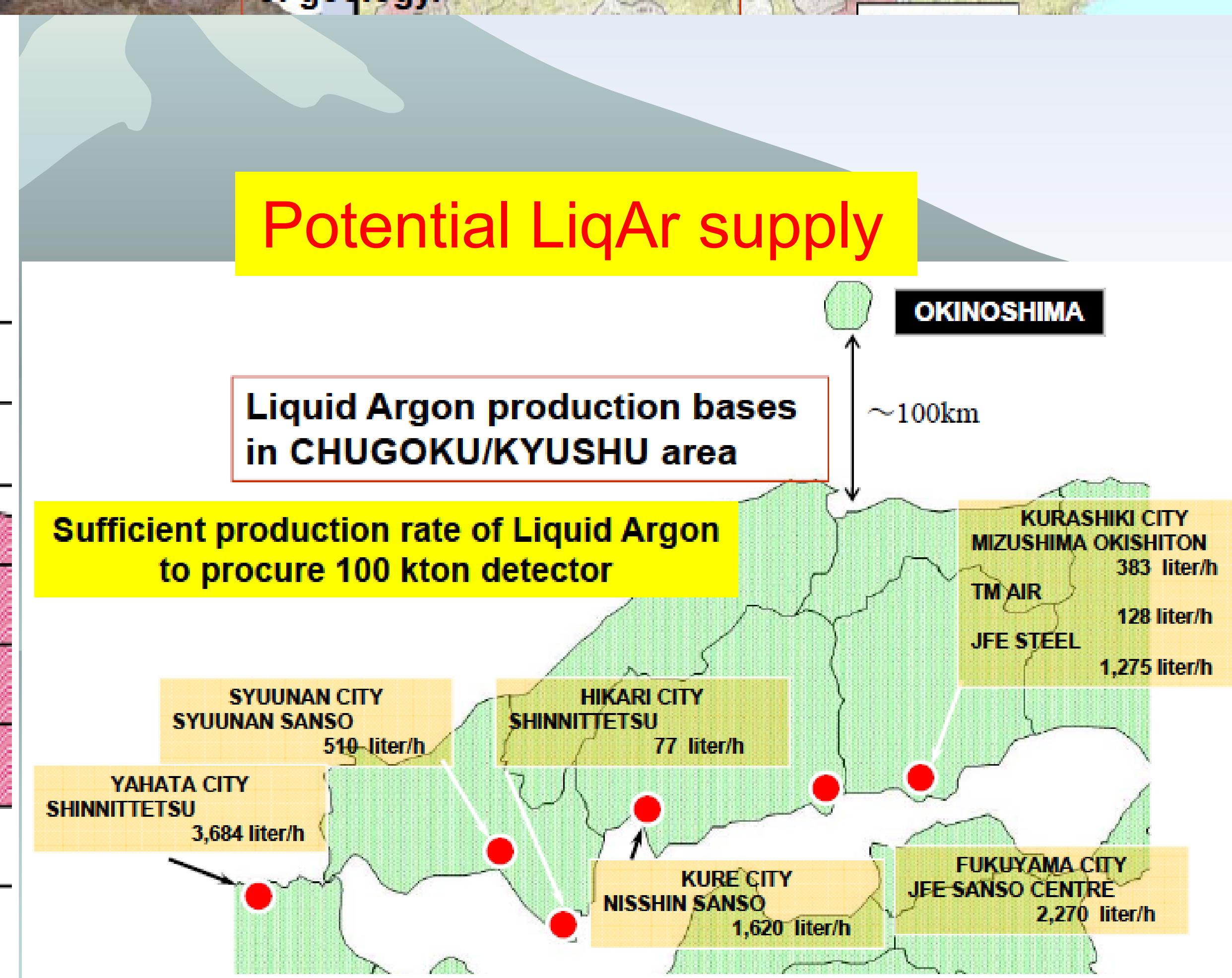
J-PARC-Okinoshima feasibility studies

(Some examples)

Site visit





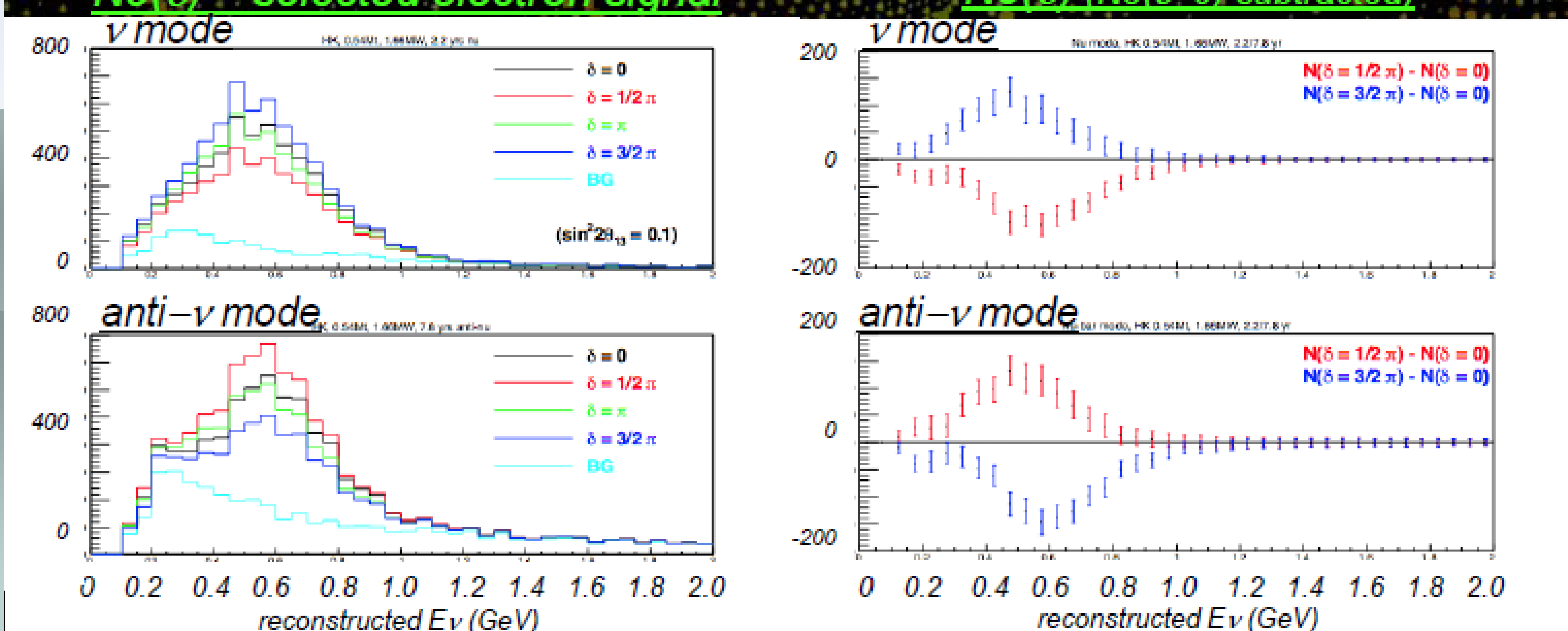


Scenario 2: J-PARC-HyperK @ Kamioka

Shiozawa, Nu2010

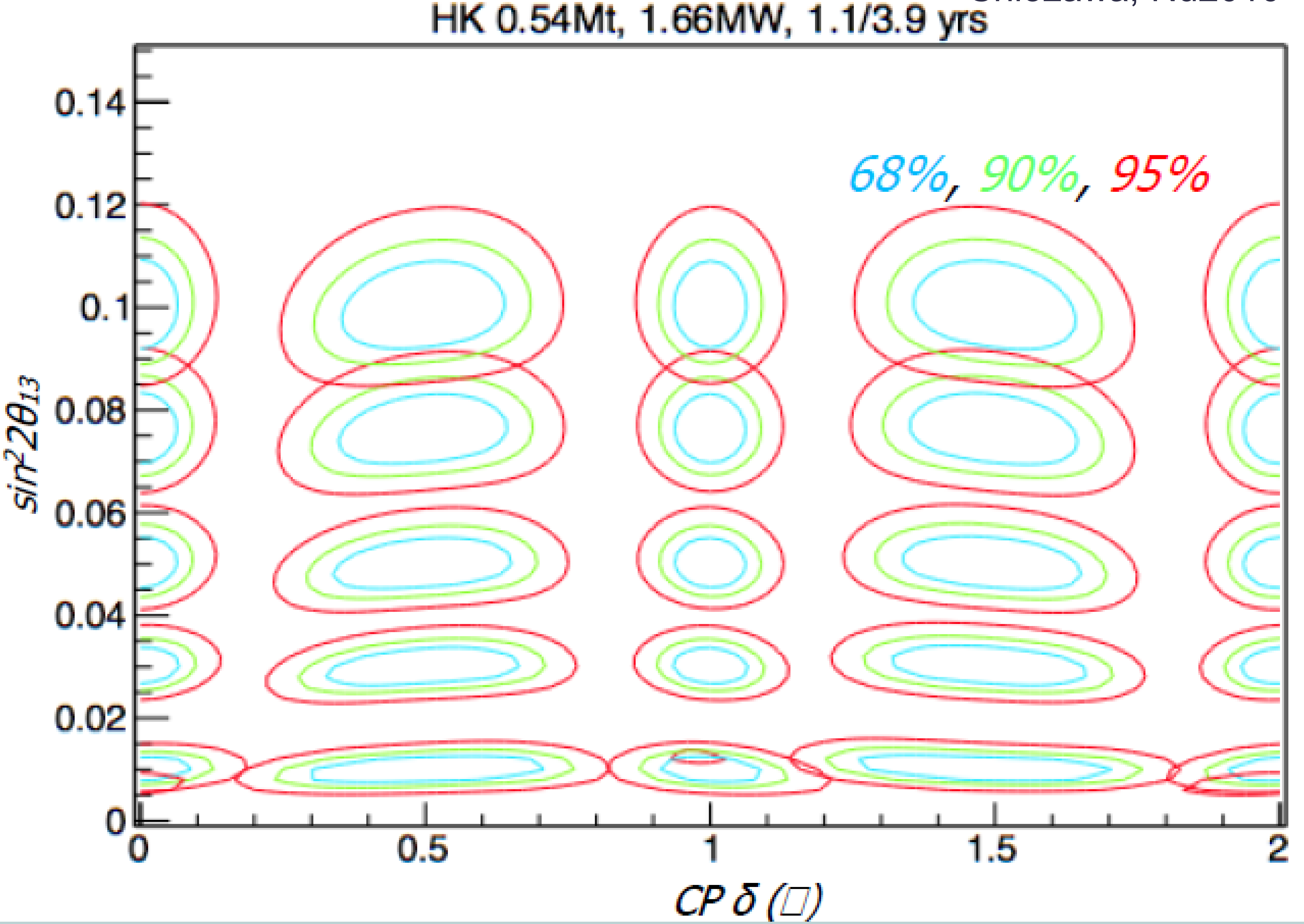
item	parameters
ν beam	Quasi-monochromatic beam (off-axis 2.5 degree, Eν=~0.6GeV) Upgraded to 1.66MW
Far ν detector	0.54Megaton
Data taking period	5 yrs (1.1 yrs ν mode + 3.9 yrs anti-ν mode) – 10yrs *1 yrs = 10^7 sec
Electron selection	Single-Ring, Pe>100MeV/c, no decay-e, $M\pi0<100MeV/c^2$, $\cos\theta_\mu < 0.9$
systematic errors (reference)	5% for νe signal, NC BG, beam νe (anti-νe), ν mode/anti-ν mode normalization
ν parameters	$\sin^2\theta_{23}$=0.5, Δm^2_{23}=2.4x10^{-3}eV^2(normal hierarchy), $\sin^2\theta_{12}$=0.32, Δm^2_{12}=7.6x10^{-5} eV^2

Ne(δ) = selected electron signal *Ne(δ) (Ne(δ=0) subtracted)*



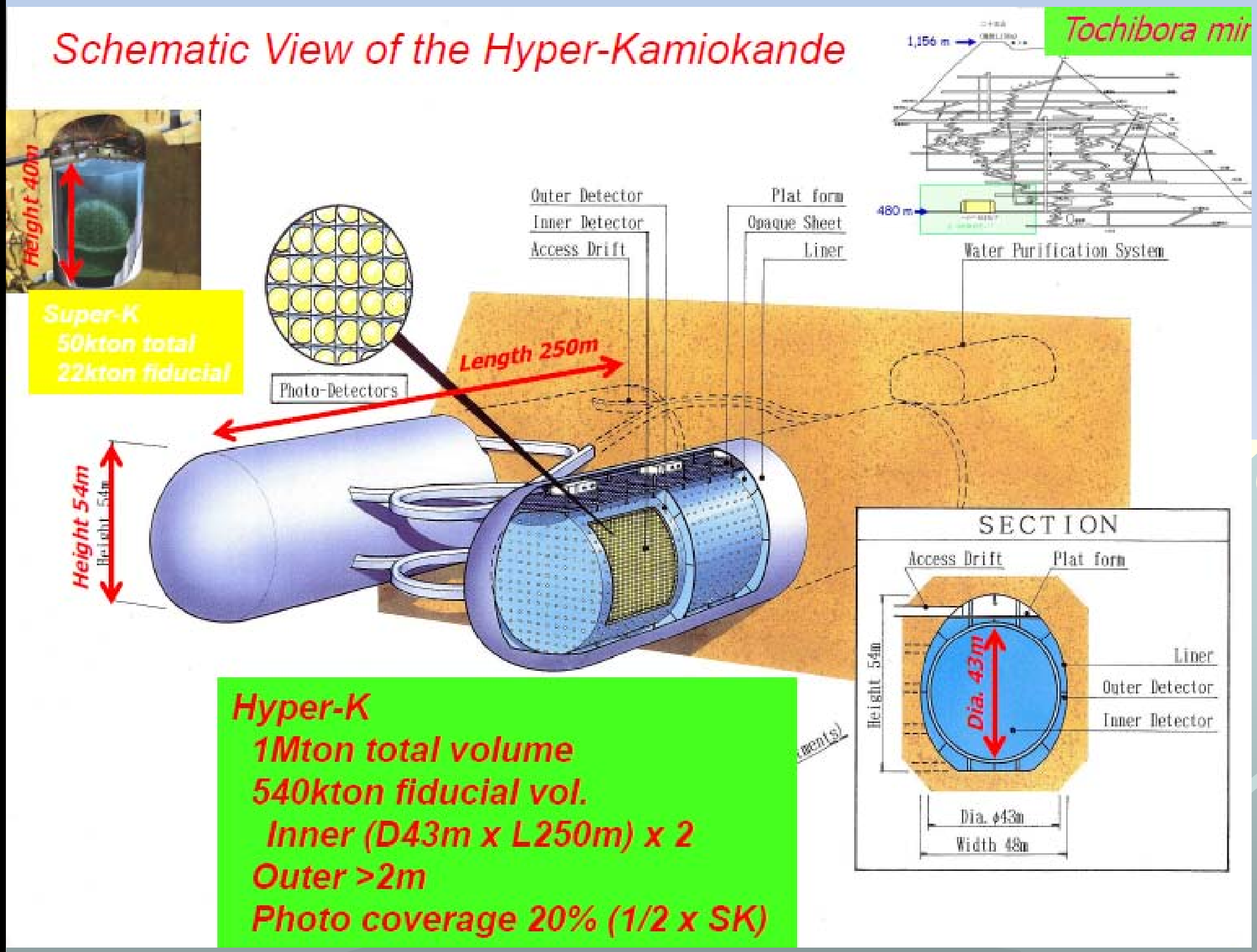
Scenario 2: J-PARC-HyperK @ Kamioka

Shiozawa, Nu2010



Hyper-K feasibility studies

Shiozawa, Nu2010



Site studies so far

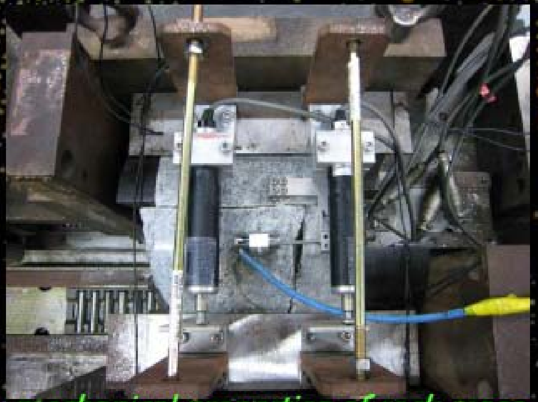
✓ site selection (Tochibora mine, +480-550m s.l.)

✓ geological sketching – very sound intact mass in excellent condition
✓ core boring – geological map, joint orientation survey
✓ rock sampling – mechanical property of rock mass and joint
✓ initial state of stress in the rock mass

✓ conceptual design of cavern and layout (two 250m tunnels with 100m spacing)
✓ FEM analysis of the cavern

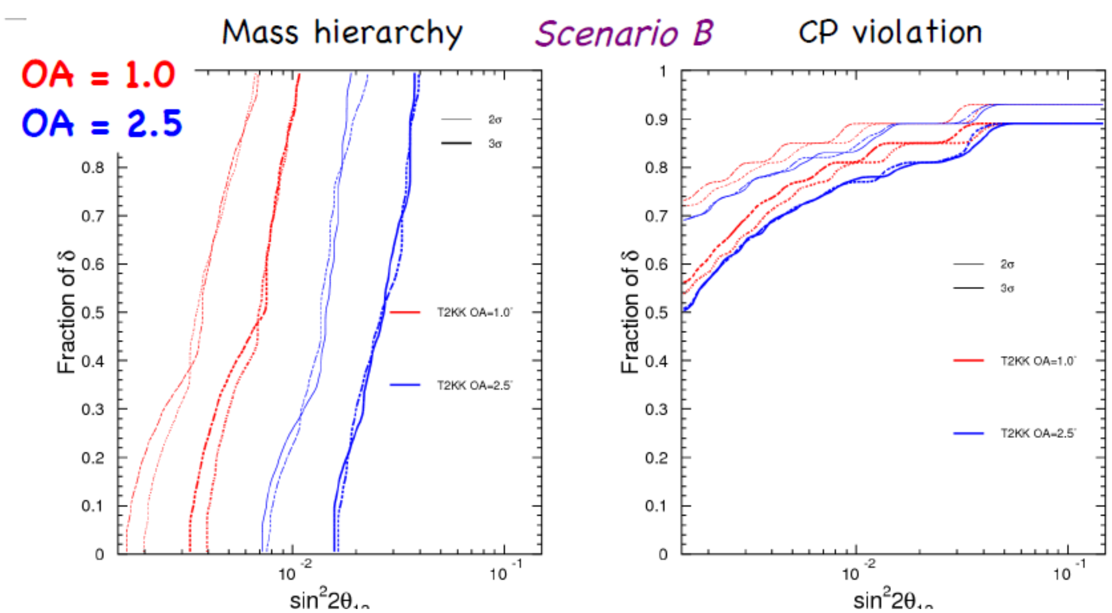
✓ clean natural water supply

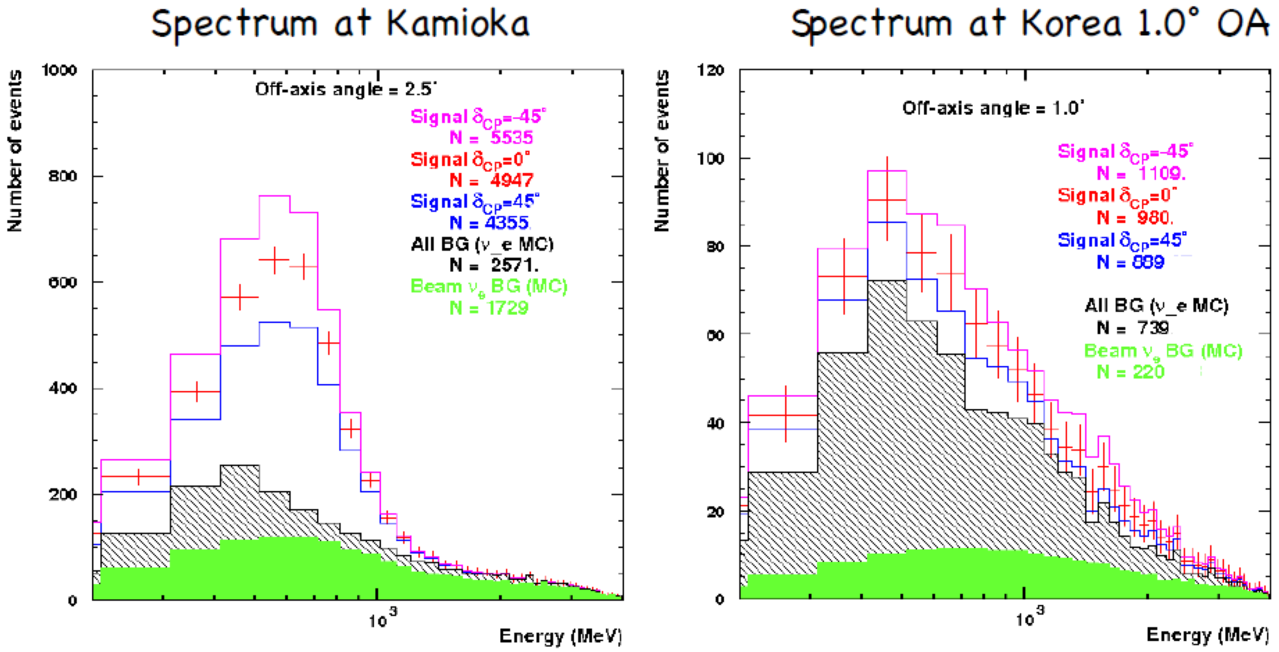

Initial state of stress in the rock mass (important for cavern design)


mechanical properties of rock mass as well as joint measurements

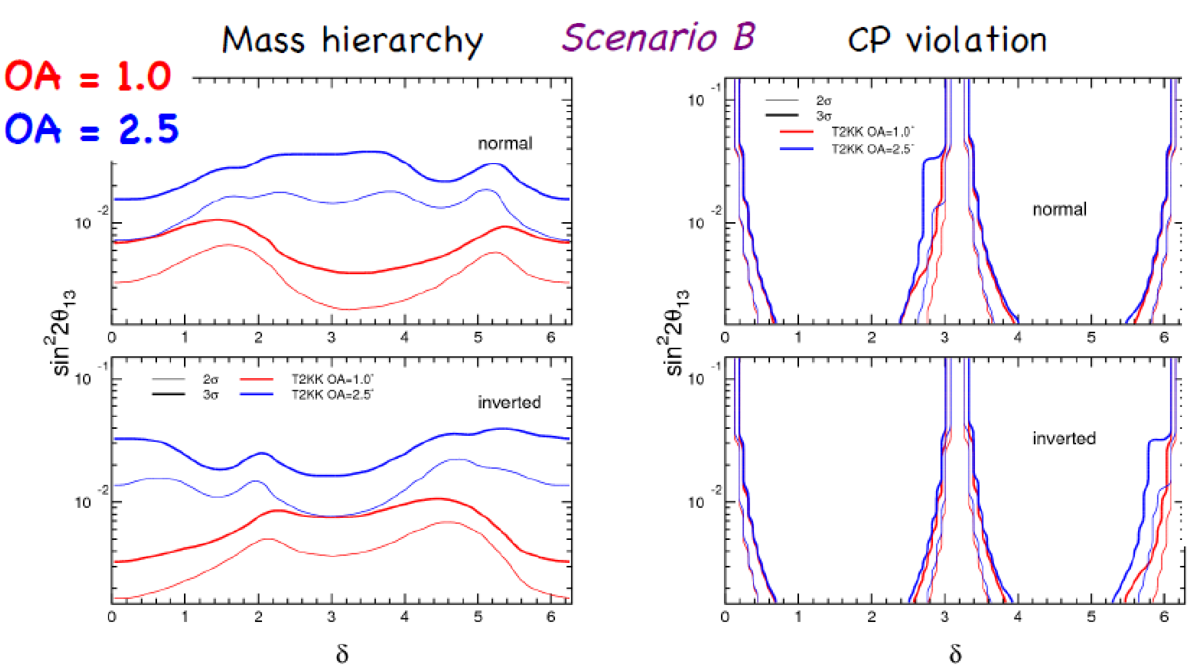
Scenario 3

- •Cover 2nd Maximum @ Korea
- •Cover 1st Maximum @ Kamioka
- •5Years ν+5Years $\bar{\nu}$ Run 1.66MW
- •270kt Water Cherenkov Detector each @ Korea, Kamioka





Sin²(2θ13)=0.04, neutrino, normal hierarchy, Scenario B



F.Dufour@NP08

(study is initiated by M.Ishitsuka et. al. hep-ph/0504026)

Neutrino Beam
based on Muon Decays

FFAG Muon Acceleration

from Prof. Y. Mori's talk
pl. visit J.B. Lagrange on Sunday

ADVANTAGES OF SCALING FFAG FOR MUON ACCELERATION

- Free from resonance crossing. Large transverse accepance can be realized.
- Free from longitudinal emittance degradation caused by path-length(time-of-flight) difference for large emittance beam.
- Numbers of RF cavities can be less compared with RLA. Construction cost can be reduced.

DESIGN STUDY OF ADVANCED SCALING FFAG FOR MUON ACCELERATION

- Required specifications
  - Energy range 3.6 -12.6 GeV
  - Acceptance
    - horizontal >30π mm.rad
    - longitudinal >150mm
  - RF frequency for acceleration 200MHz
  - To accelerate simultaneously μ^+ and μ^-

DESIGN OF SCALING FFAG

ACCELERATION INSIDE OF RF STATIONARY BUCKET

Principle: use the synchrotron motion to accelerate beam going from the low energy to the high energy part of a stationary rf bucket.

Case of scaling FFAGs: since the momentum compaction is constant with energy, the longitudinal dynamics can be analytically described without

assuming $\frac{\Delta p}{p}$ small(*).

(*) see E. Yamakawa and Y. Mori's paper to appear in proceedings of FFAG'09 conference.

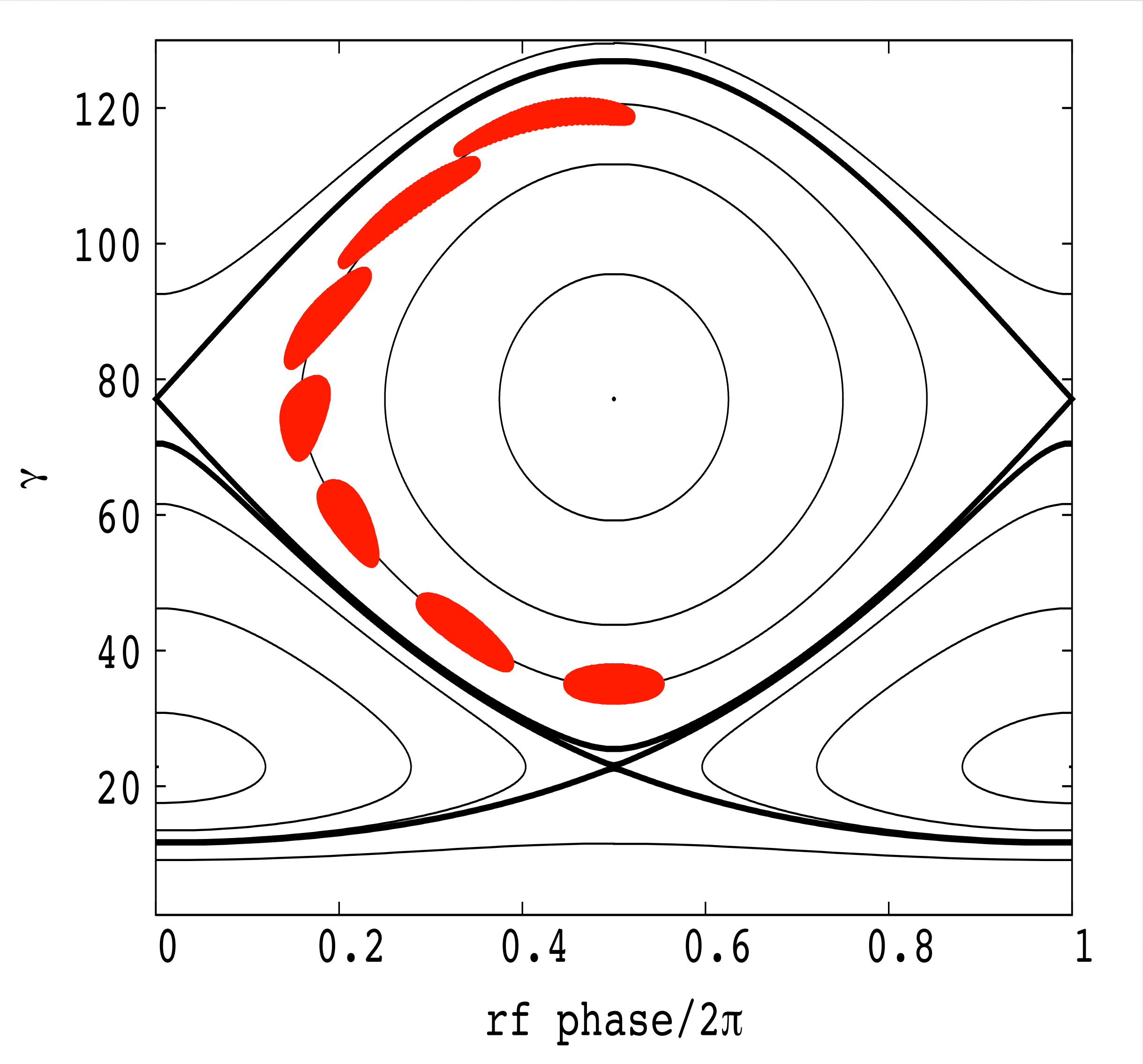


Figure 1 - Longitudinal phase space showing the acceleration of a muon beam (red) inside the stationary rf bucket of a scaling FFAG ring. Hamiltonian contour are shown in black.

CHOICE OF WORKING POINT

Emittance scan in the case of a ring made of 225 identical FDF triplet FFAG cells. Legends in the top left corner of each diagram give values of acceptances normalized in the case of 3.6 GeV muons. Normal structure resonances lines, plotted up to the octupole, are superimposed.

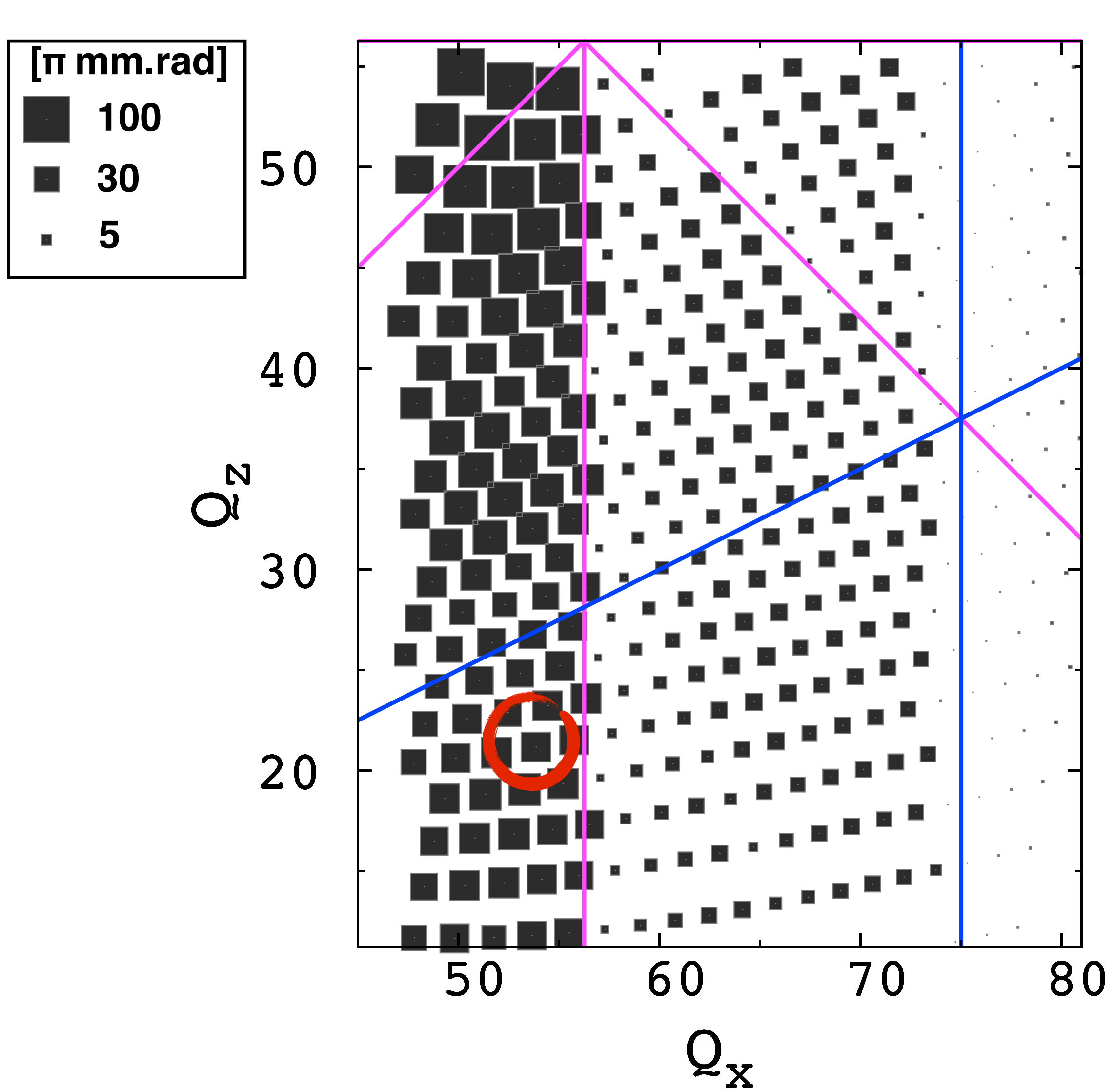


Figure 2a - Horizontal acceptance scan.

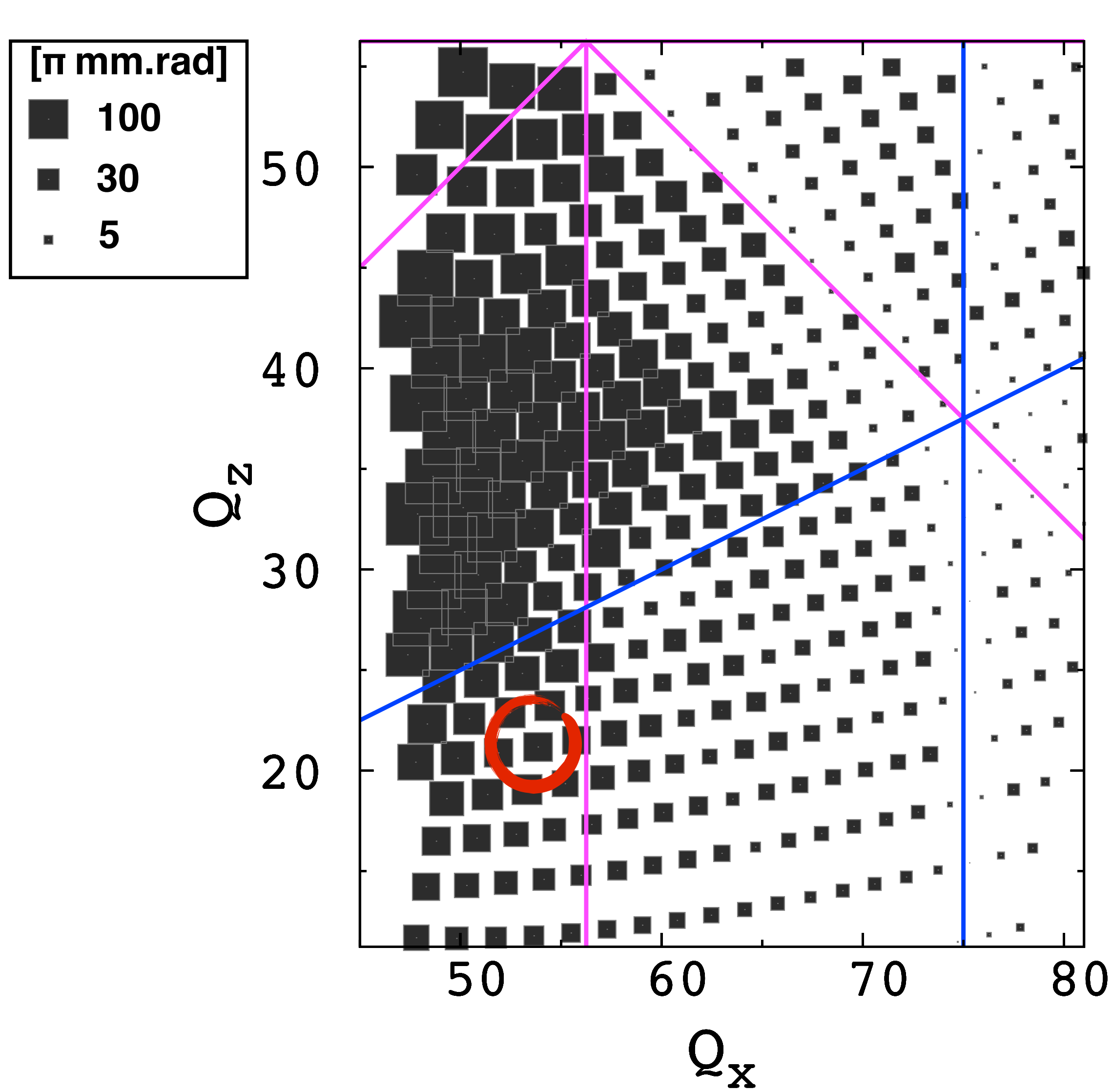


Figure 2b - Vertical acceptance scan.

PARAMETERS OF A 3.6 -12.6 GEV MUON RING

Lattice type	FDF triplet
Injection/extraction energy	3.6/12.6 GeV
RF frequency	200 MHz
Number of turns	6
RF peak voltage (per turn)	1.8 GV
Synchronous energy	8.04 GeV
Mean radius	~160.9 m
B_{max}(@ 12.6 GeV)	3.9 T
Field index k	1390
Total orbit excursion	14.3 cm
Harmonic number h	675
Number of cells	225
Long drift length	~1.5 m
Horiz. phase adv. per cell	85.86 deg.
Vert. phase adv. per cell	33.81 deg.

Table 1 - Example of 3.6 to 12.6 GeV muon scaling FFAG ring parameters.

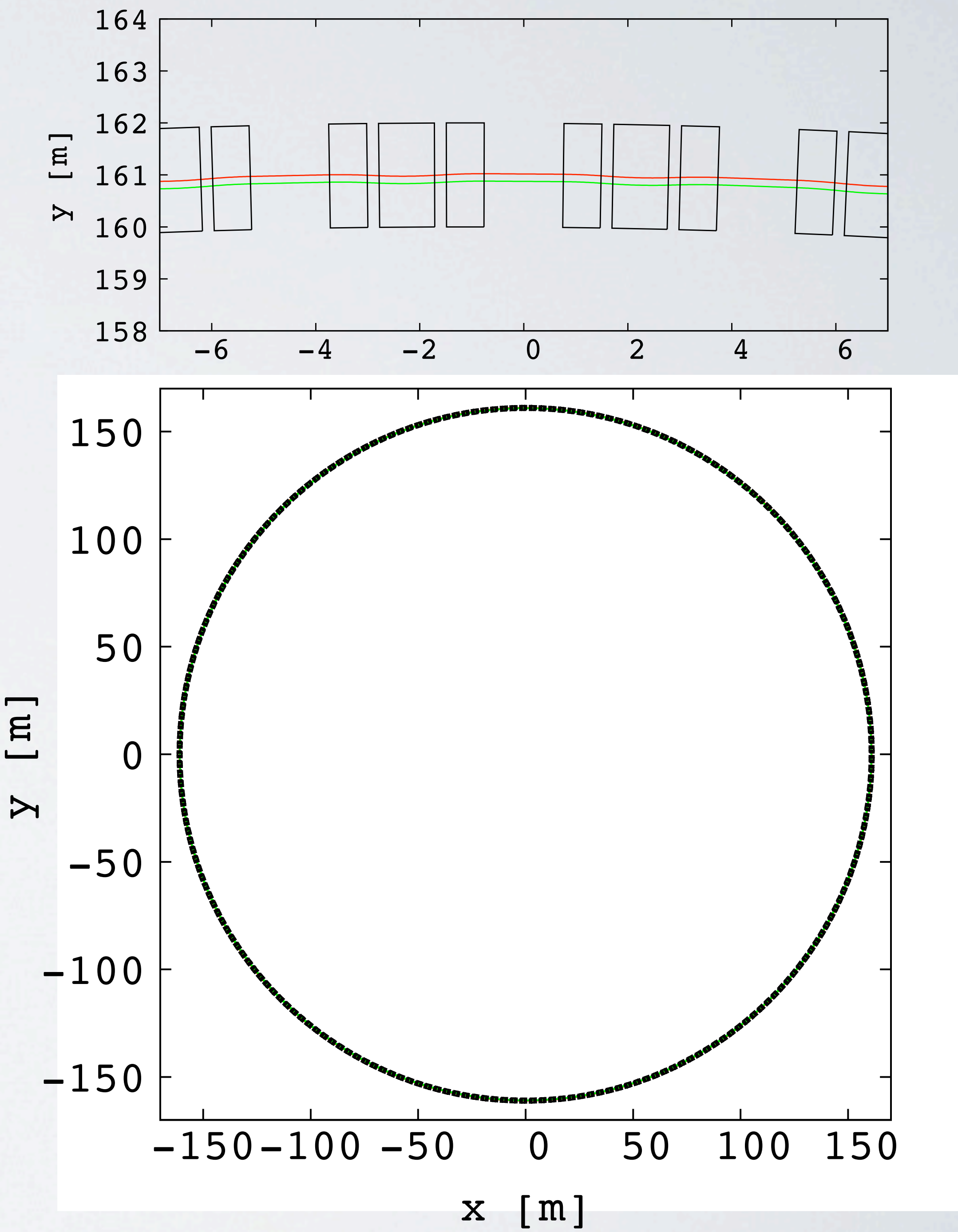
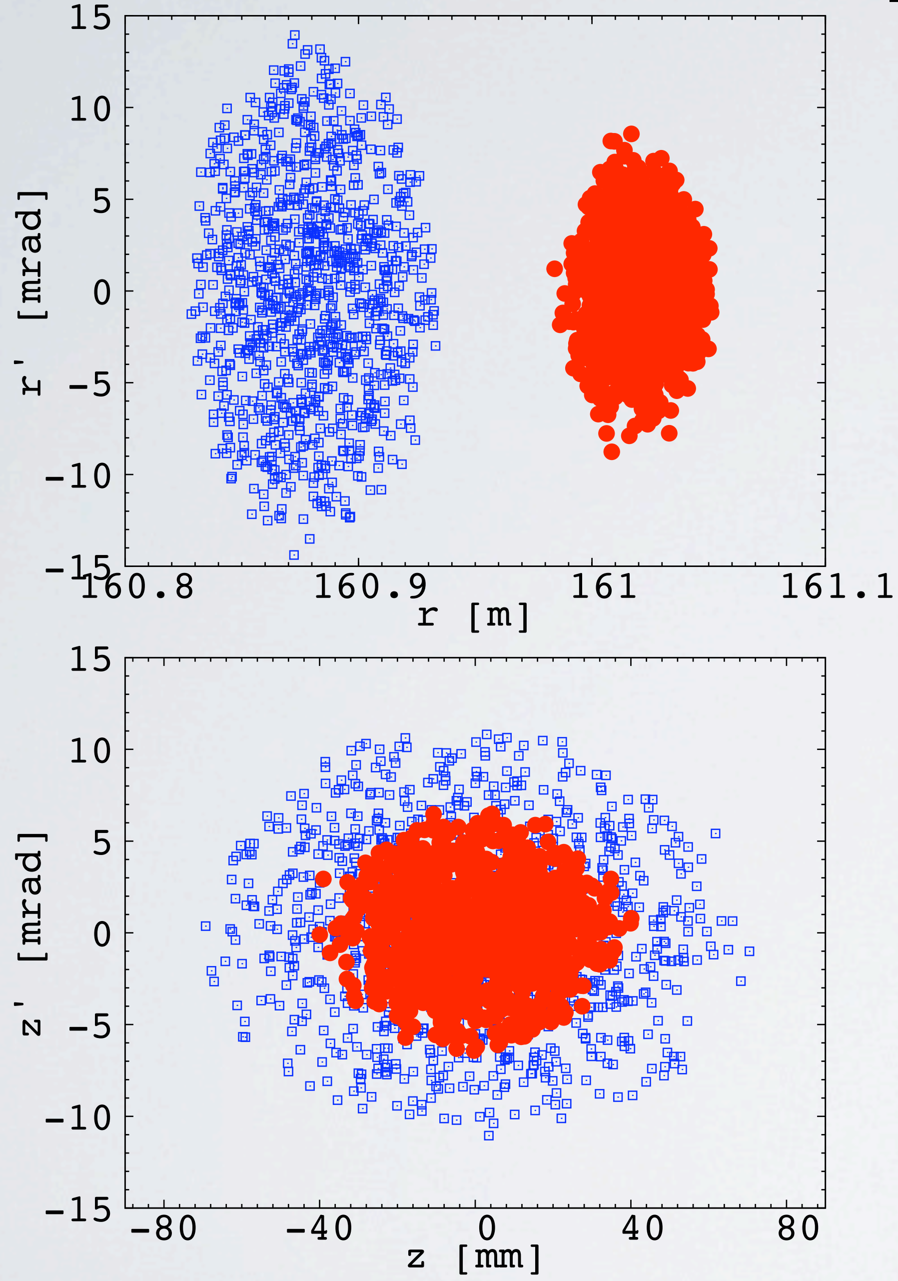


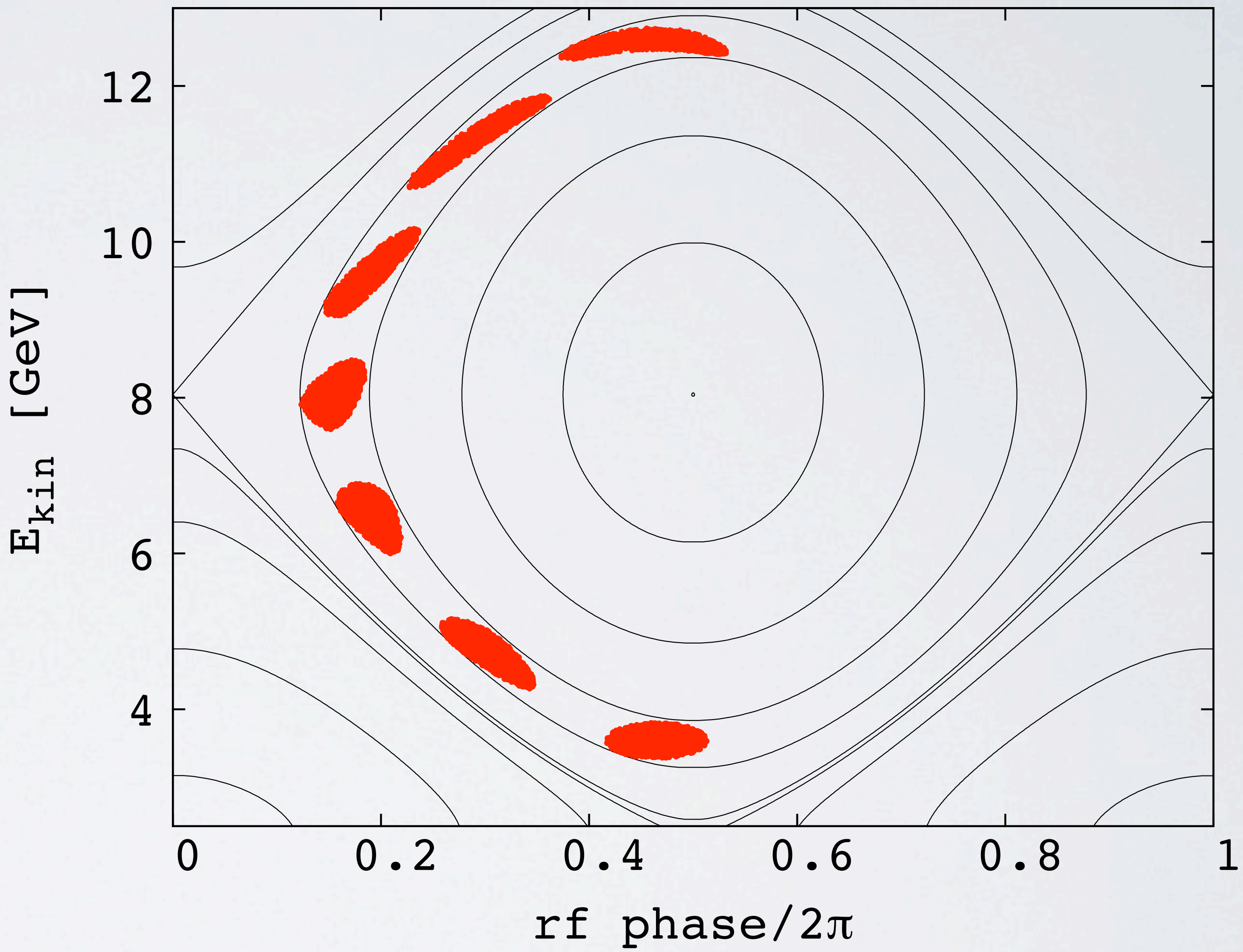
Figure 3 - Ring layout.

FULL ACCELERATION CYCLE
6D TRACKING

- Tracking results -



Figures 8 - Initial (blue) and final (red) particles distribution in the horizontal (top), and vertical (bottom) phase space.



Figures 9 - longitudinal phase space plot showing a 6-turn acceleration cycle. Hamiltonian contours are superimposed.

R&D on a Highly Intense Muon Source
- MuSIC@Osaka -

a la Akira Sato's talk (22nd)

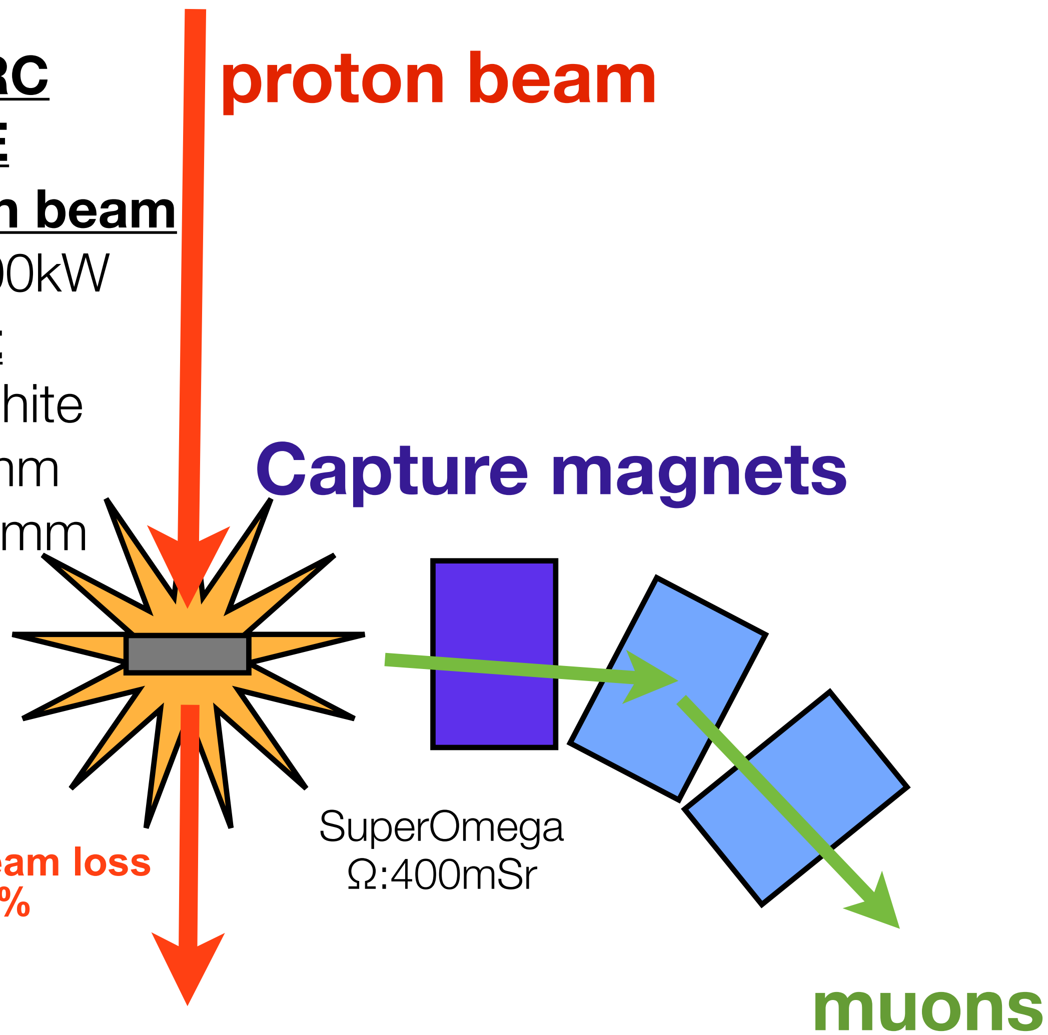
Production and Collection of Pions and Muons

Conventional muon beam line

J-PARC MUSE

proton beam
-1000kW

target
graphite
t20mm
φ70mm



proton beam loss
< 5%

to the neutron facility

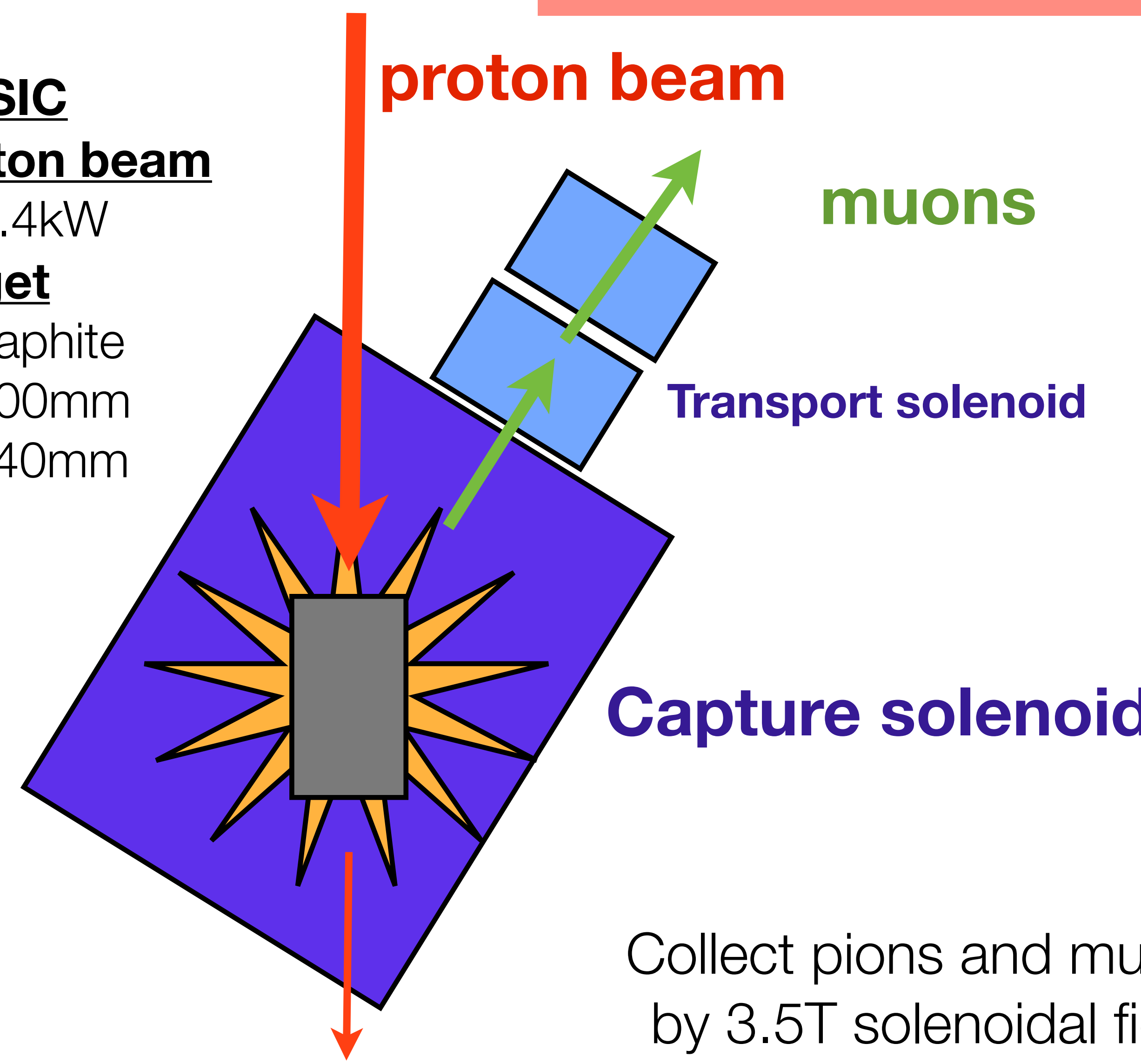
Much efficient

MuSIC,COMET,PRISM,
Neutrino factory,
Muon collider

MuSIC

proton beam
-0.4kW

target
graphite
t200mm
φ40mm

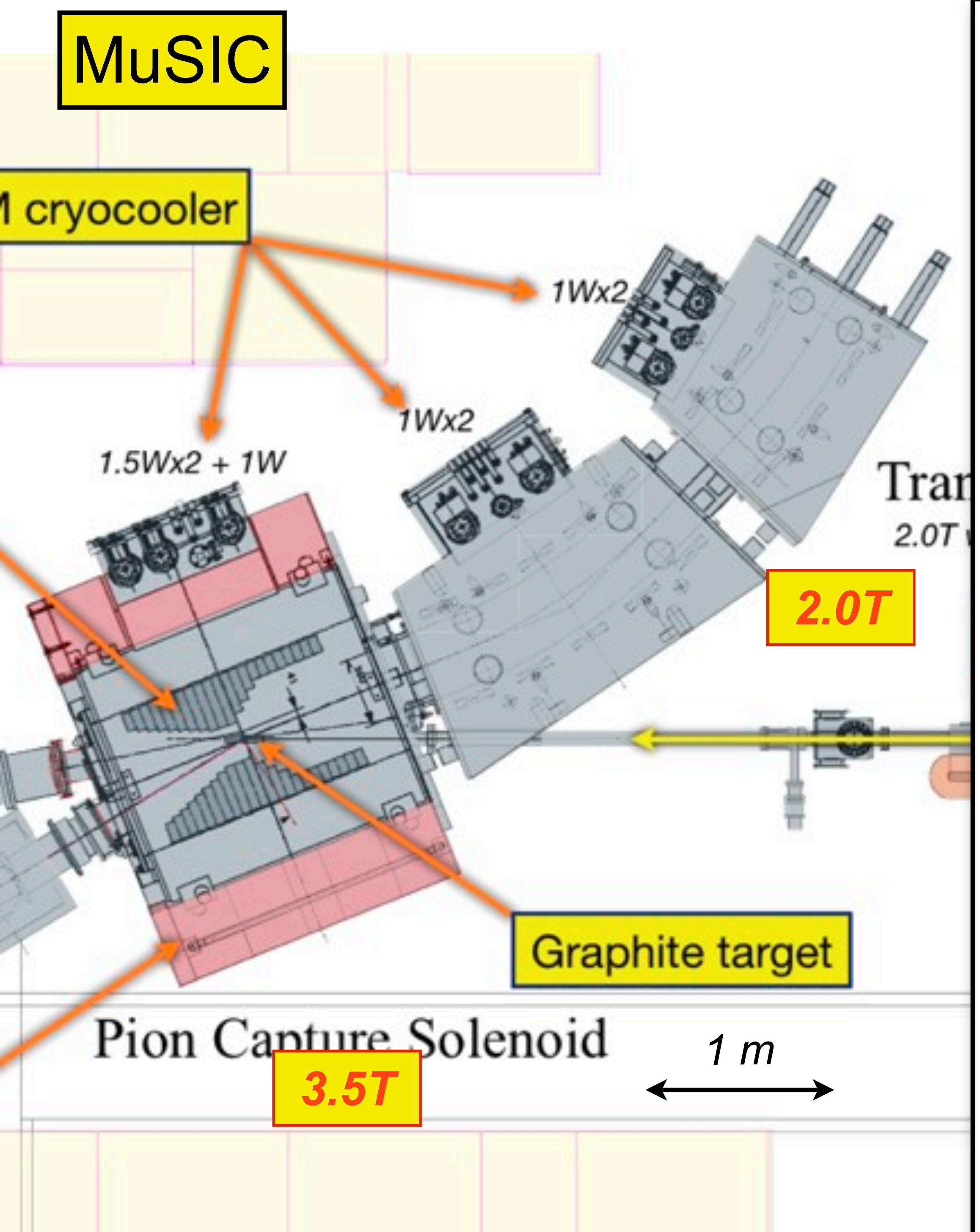


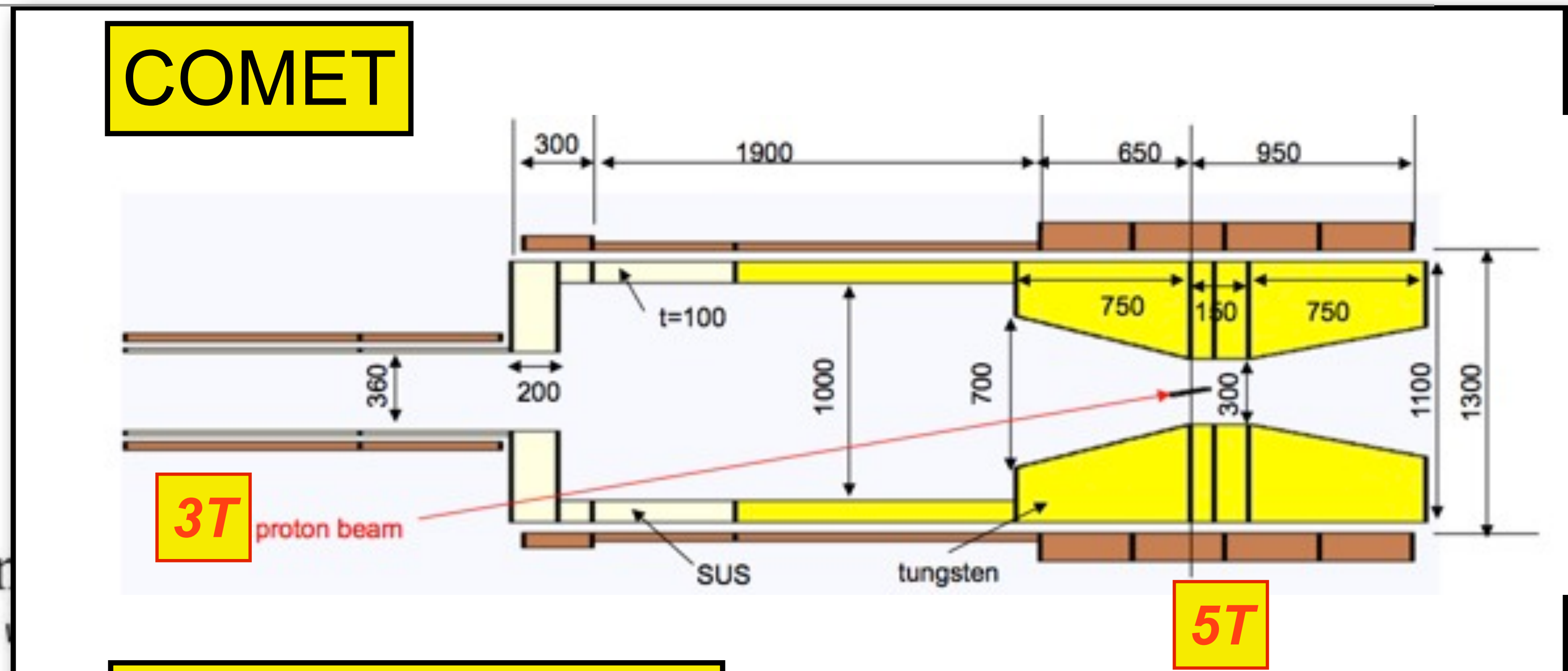
Collect pions and muons
by 3.5T solenoidal field

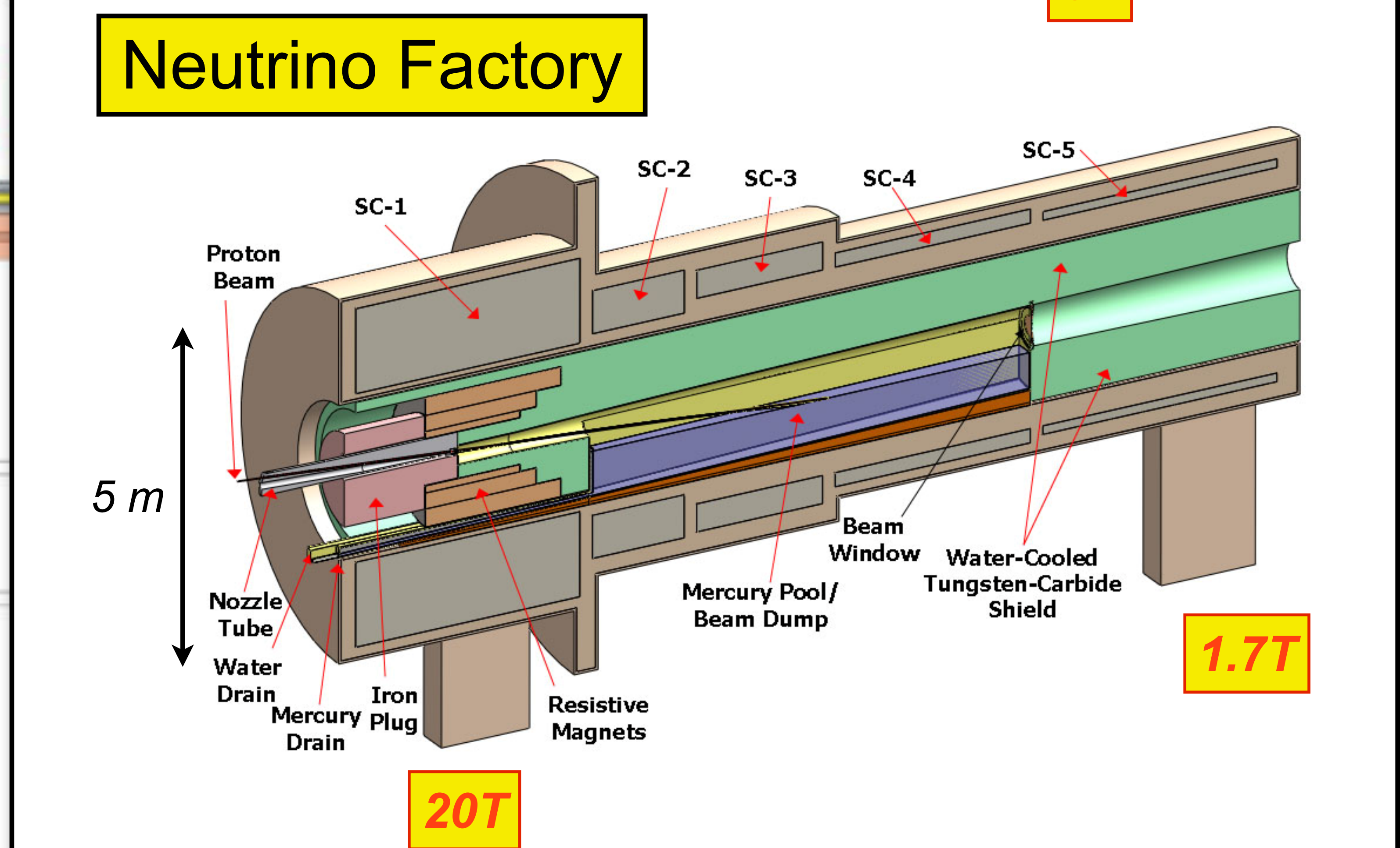
to a beam dump

Large solid angle & thick target

Pion Capture System in MuSIC,COMET, and NuFact







MuSIC at RCNP, Osaka University

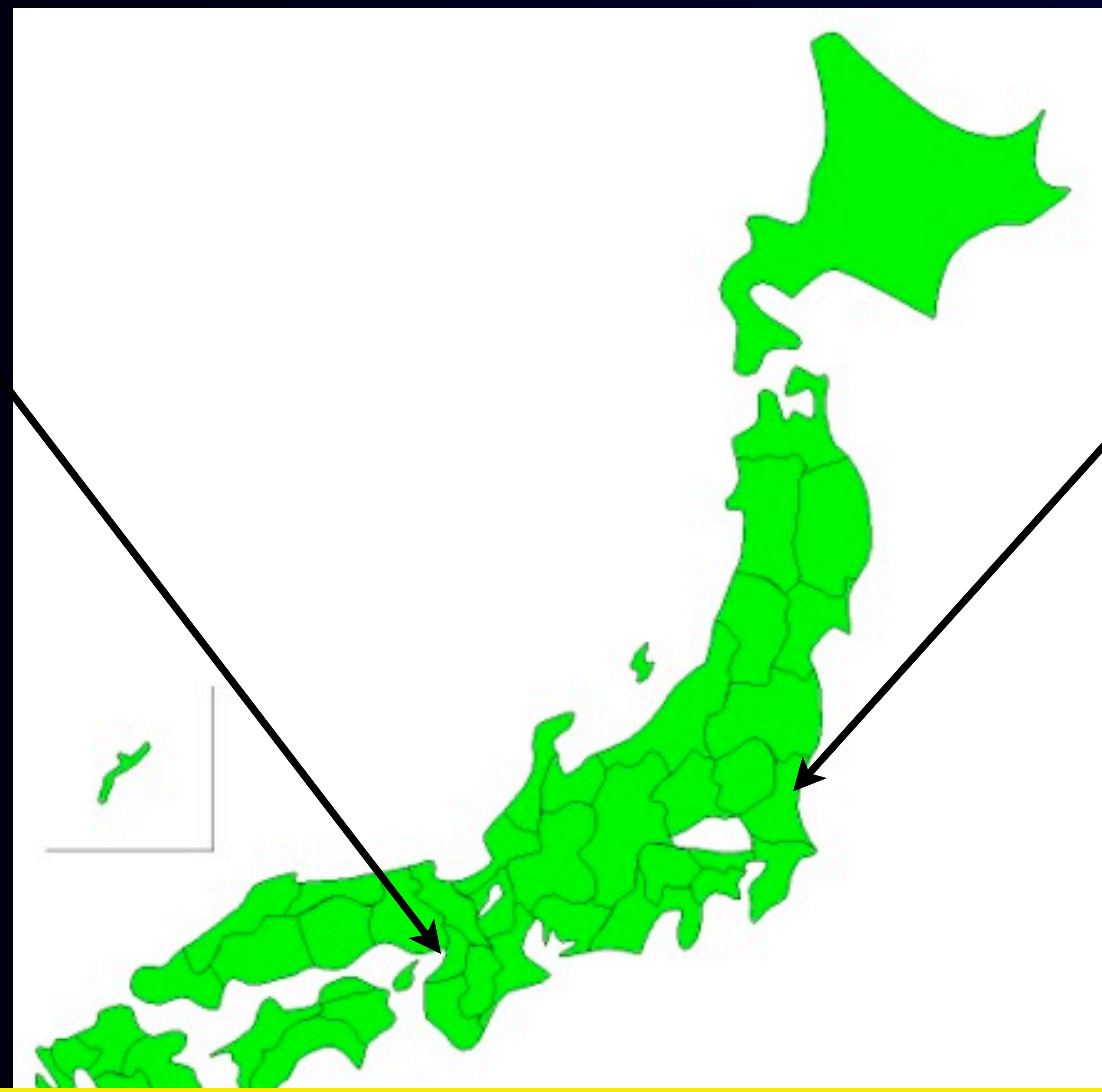
Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.

Muon Science in Japan

DC muon

Muon Facility
MuSIC
(Osaka)

400W
CW
10^8 /sec
single channel



Pulsed muon

Muon Facility
MUSE
(J-PARC)

1000kW
pulsed (25 Hz)
10^8 /sec
many channels

Japan will be the only country which has both DC and pulsed muon beam facilities.

MUSIC Specification

	MUSIC
location	RCNP
beam power	0.4 kW
intensity	10^8-10^9/sec
time structure	continuous
beam momentum	20 - 140 MeV/c
beam polarization	medium (at full intensity)

Muon Physics Programs at MUSIC

- Particle Physics :
  - search for $\mu \rightarrow eee$ (muon LFV)
    - DC continuous beam is critical
    - TPC to track 3 electrons/positrons
- Nuclear Physics :
  - nuclear muon capture (NMC)
  - pion capture and scattering
- Materials Science :
  - μSR (a μSR apparatus is needed)
- Chemistry
  - chemistry on pion/muon atoms
- Accelerator / Instruments R&D (for neutrino factory/muon collider)
  - Superconducting solenoid magnets
  - FFAG, RF
  - cooling methods

Demonstration of COMET muon beam

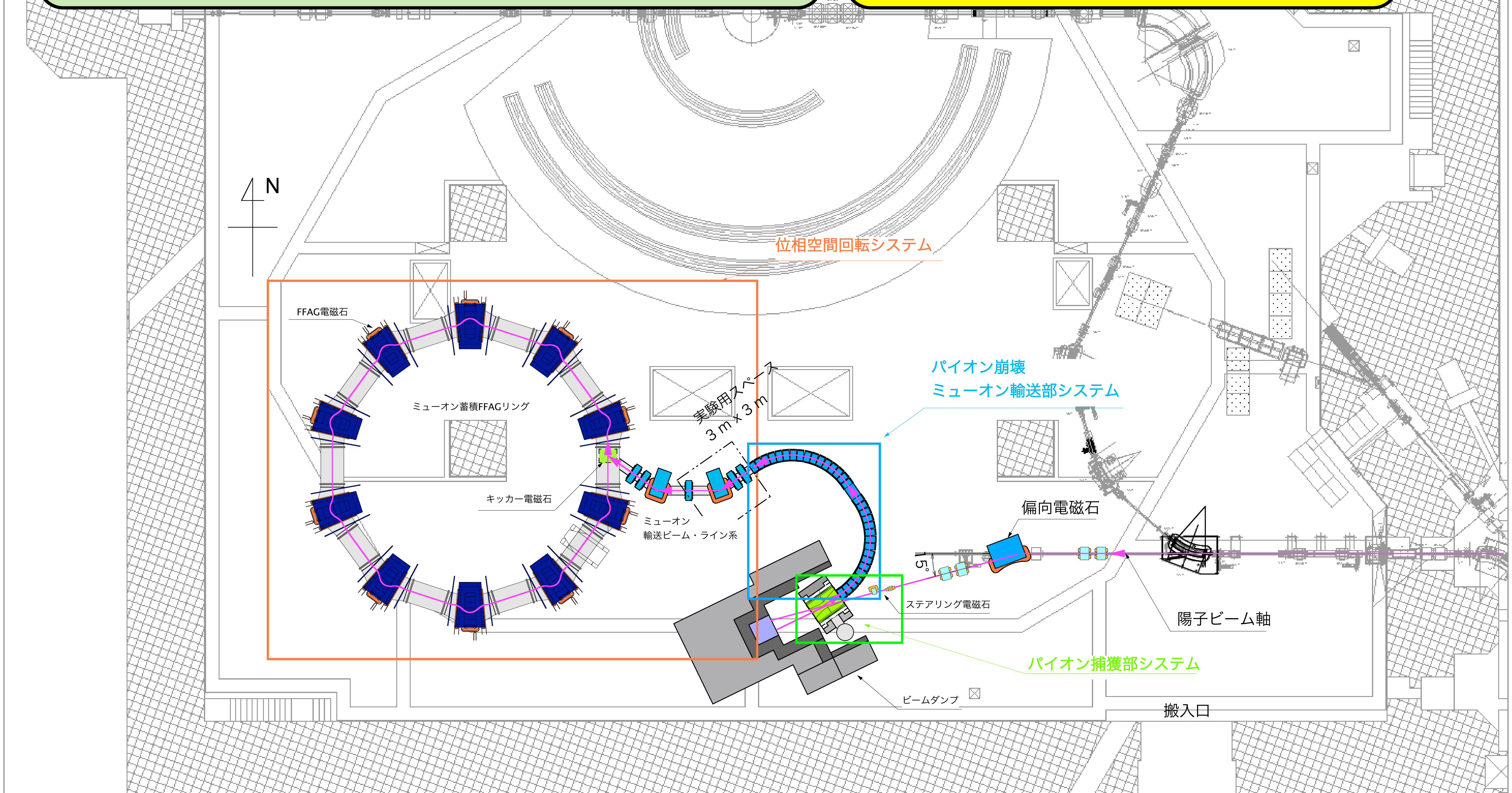
MuSIC (=MUon Science Innovative Commission)

muon yield estimation

proton beam 0.4 kW (400MeV, 1μA)

$10^{8\sim9}$ muons/sec

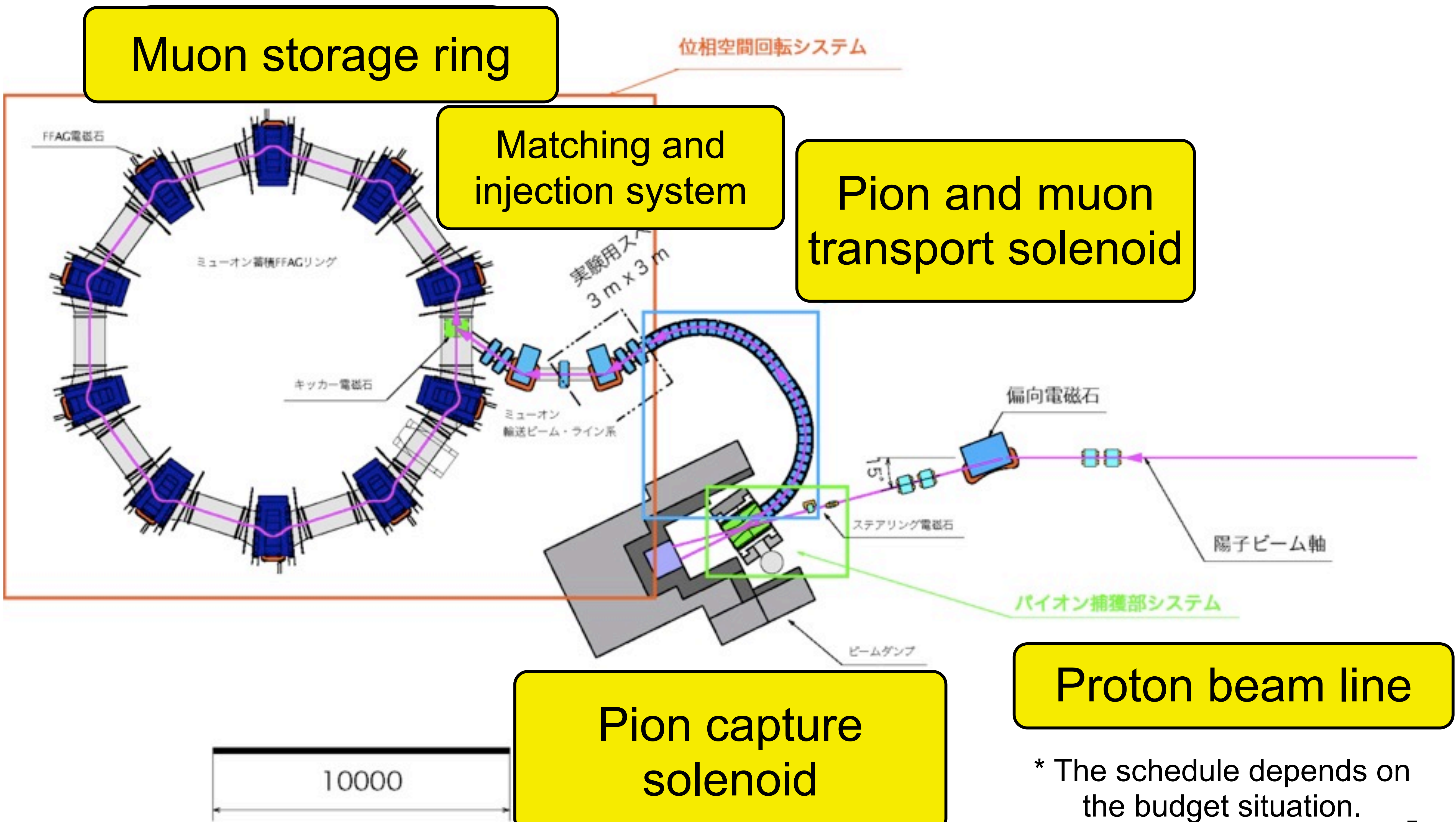
Nuclear and particle physics, material science chemistry, and accelerator R&Ds will be possible.



A final layout plan of the MuSIC in the W-hall, RCNP, Osaka Univ.

Construction Status and Schedule

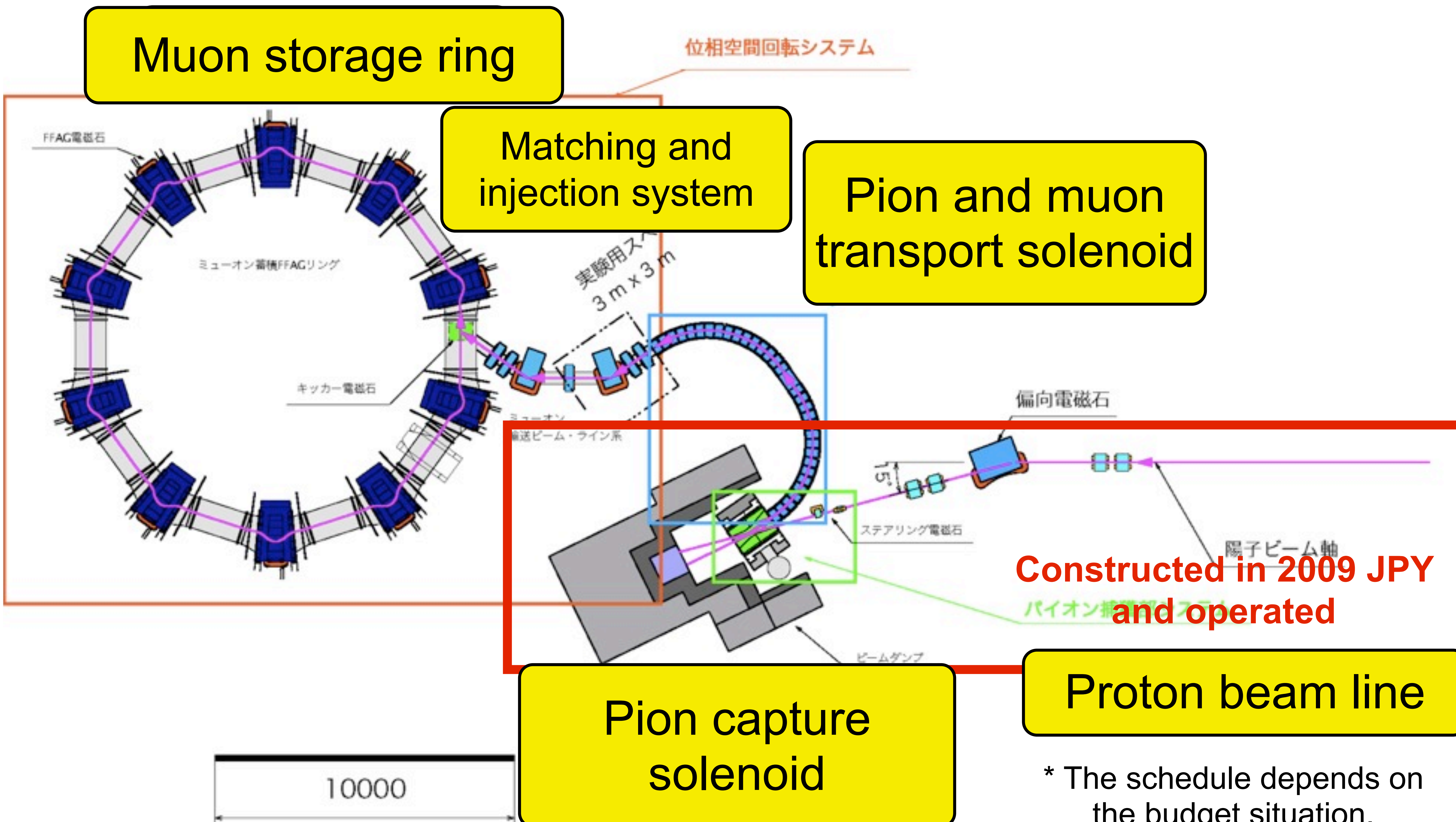
The construction has started at 2009, and will be finished in 5 years.



* The schedule depends on the budget situation.

Construction Status and Schedule

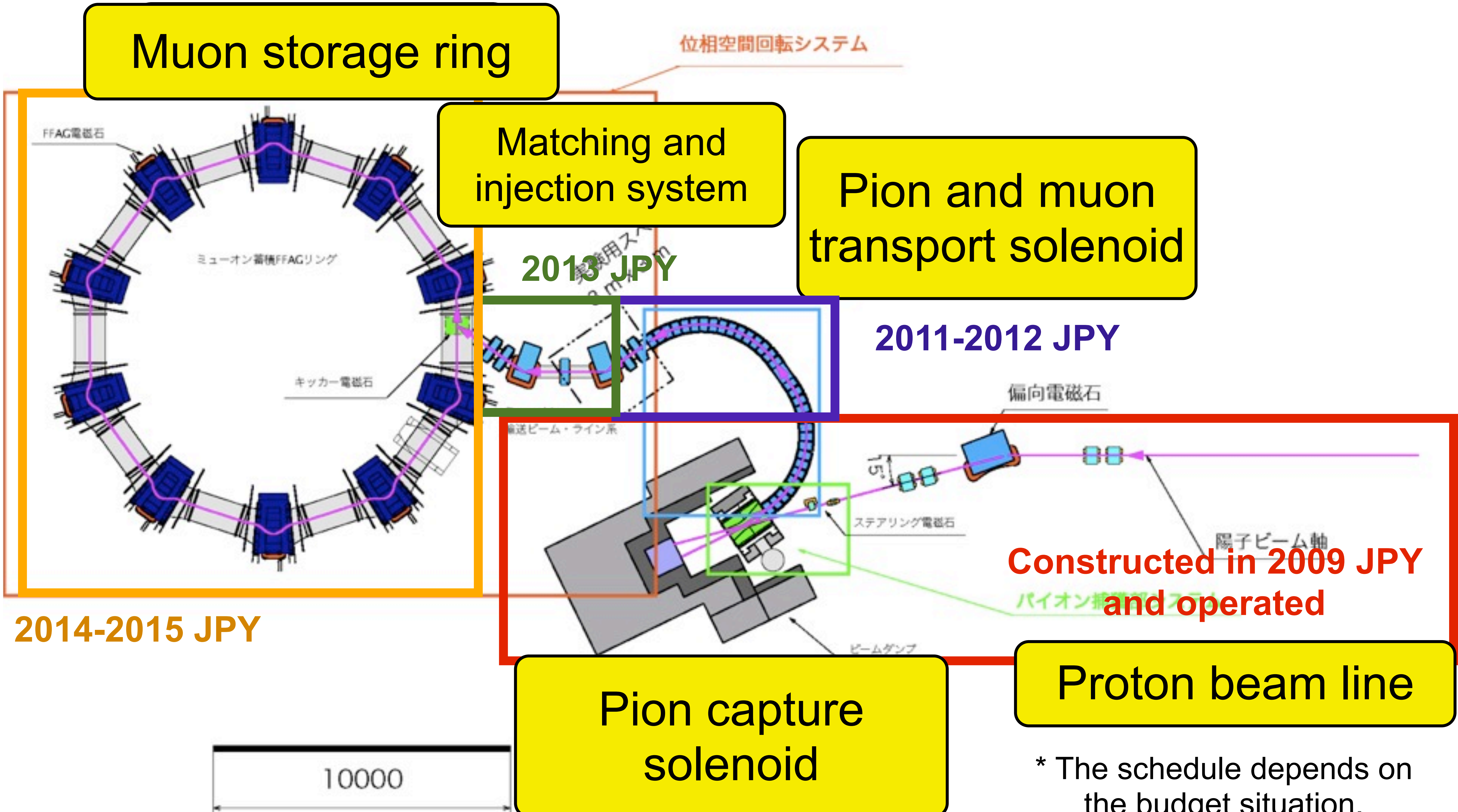
The construction has started at 2009, and will be finished in 5 years.



* The schedule depends on the budget situation.

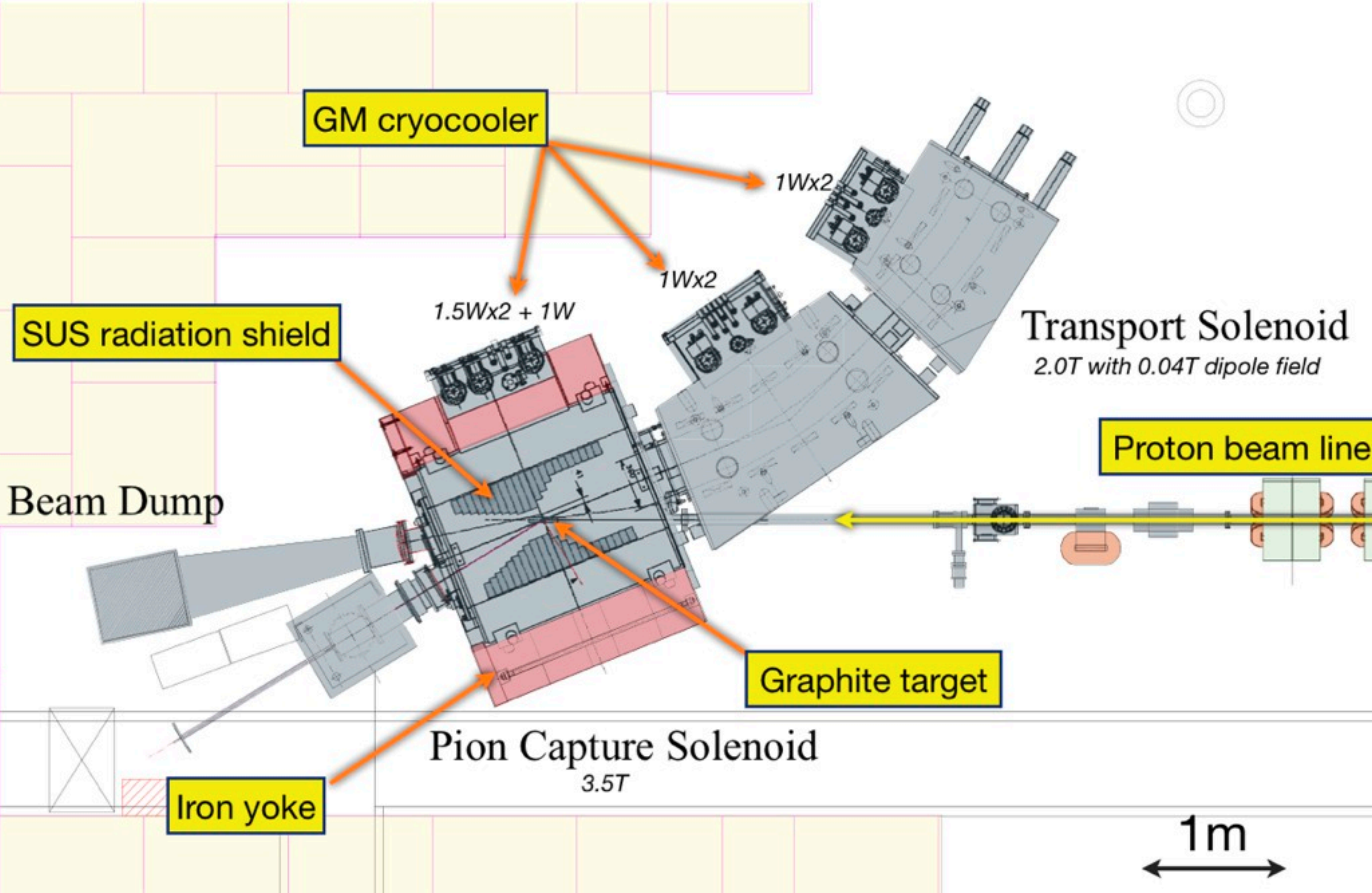
Construction Status and Schedule

The construction has started at 2009, and will be finished in 5 years.



* The schedule depends on the budget situation.

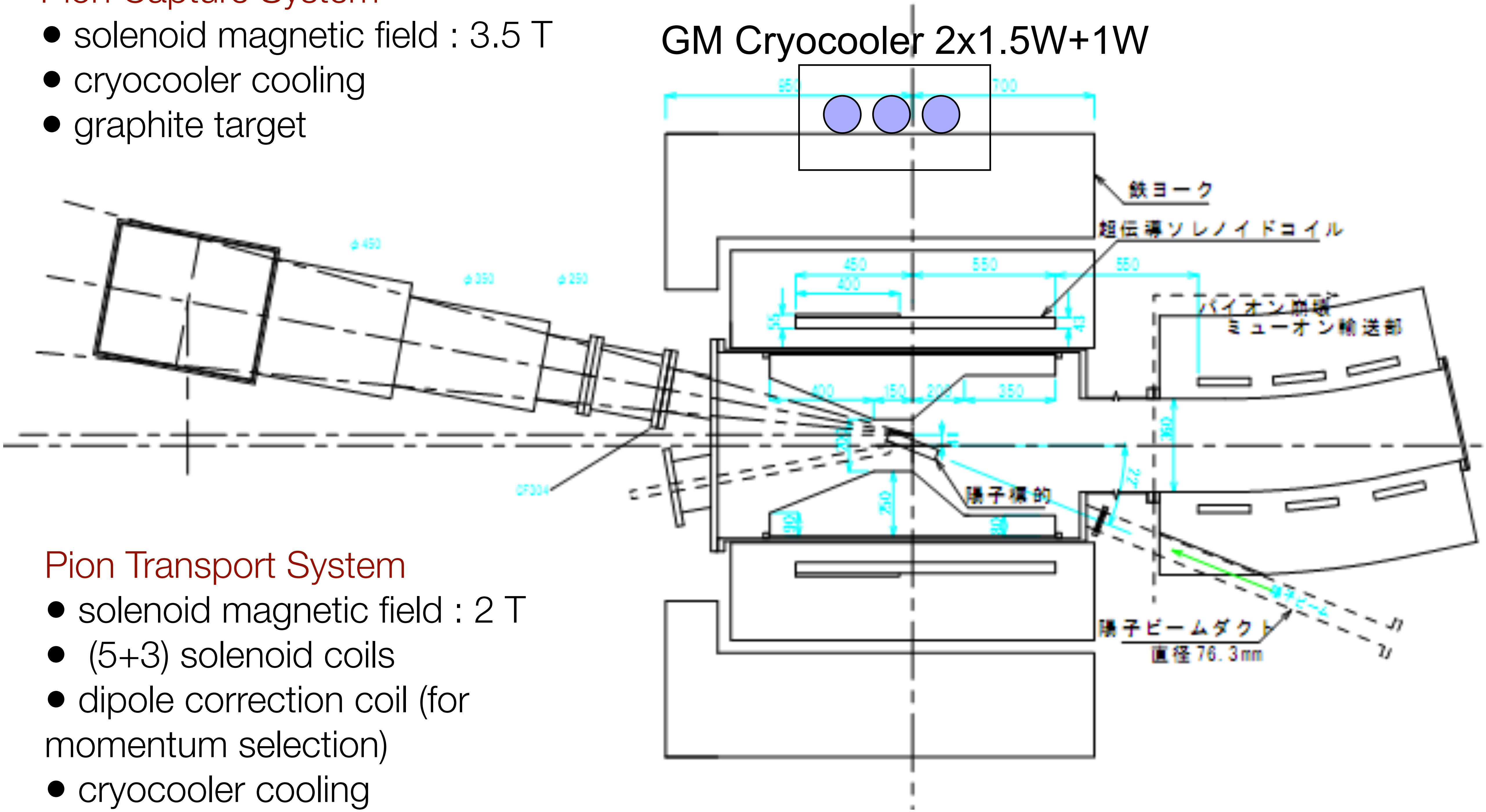
MuSIC in 2010



Pion Capture System and Pion/Muon Transport System

Pion Capture System

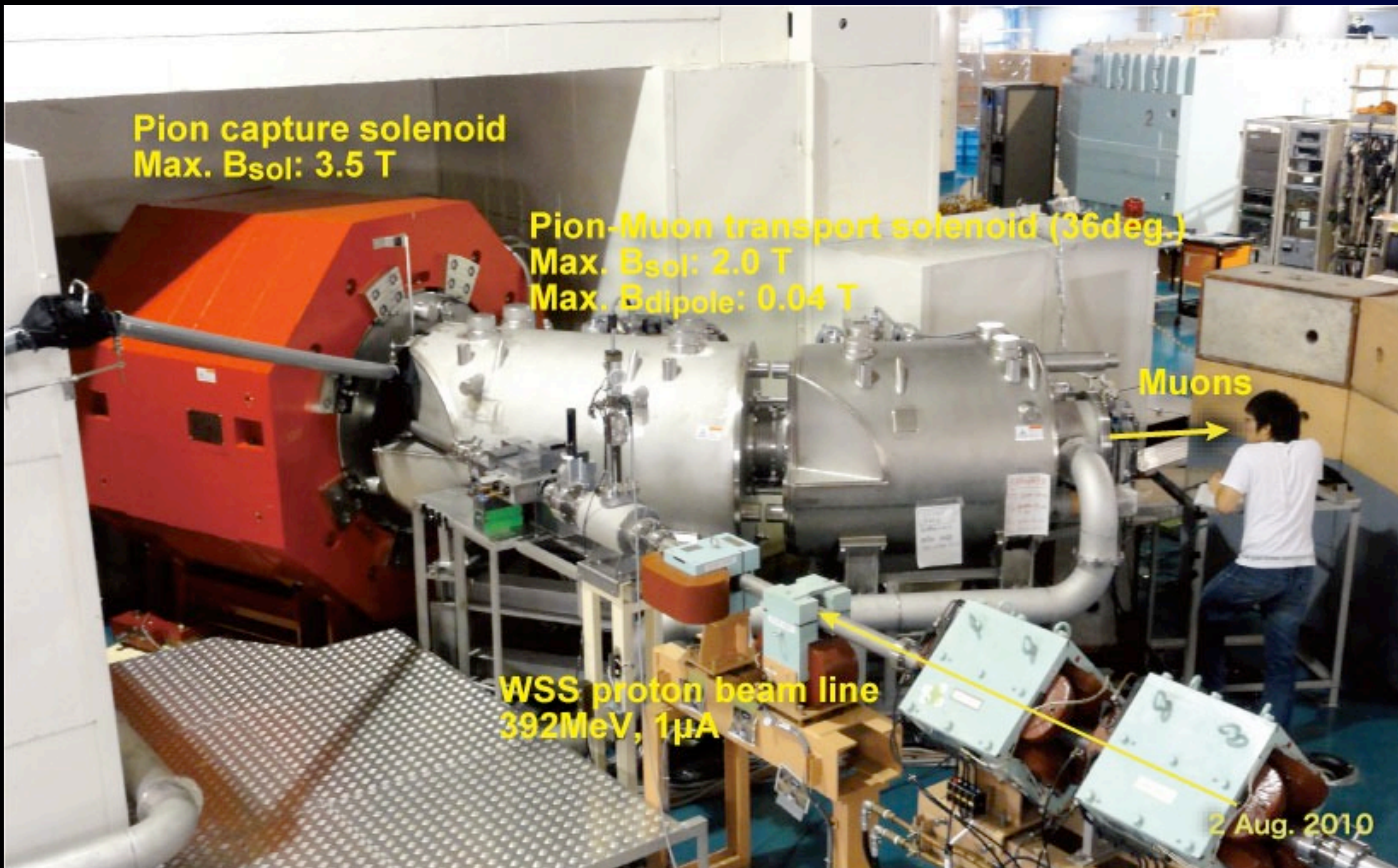
- solenoid magnetic field : 3.5 T
- cryocooler cooling
- graphite target



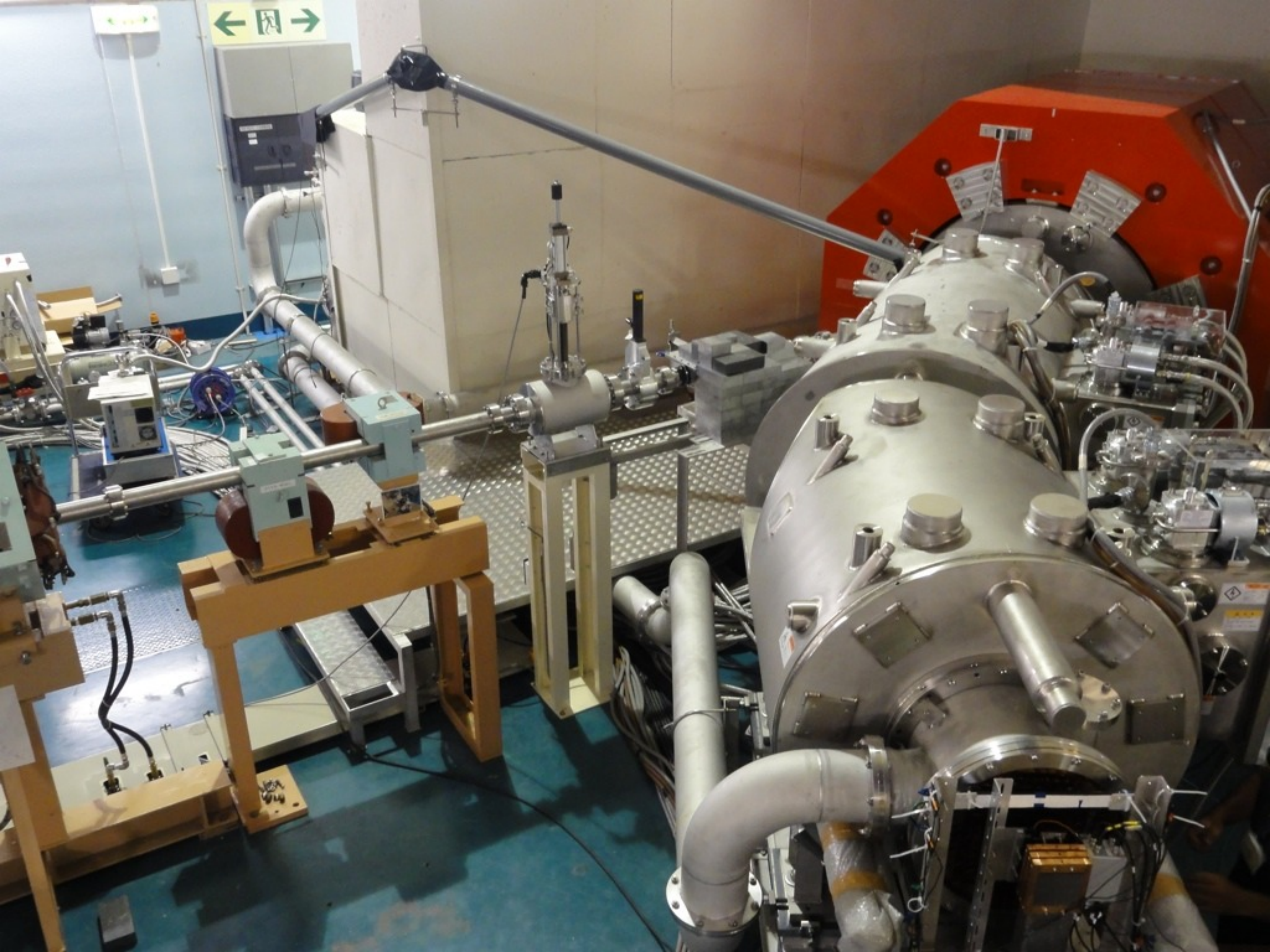
Pion Transport System

- solenoid magnetic field : 2 T
- (5+3) solenoid coils
- dipole correction coil (for momentum selection)
- cryocooler cooling

MuSIC



Pion capture solenoid
Max. B_{sol}: 3.5 T
Pion-Muon transport solenoid (36deg.)
Max. B_{sol}: 2.0 T
Max. B_{dipole}: 0.04 T
Muons
WSS proton beam line
392MeV, 1μA
2 Aug. 2010

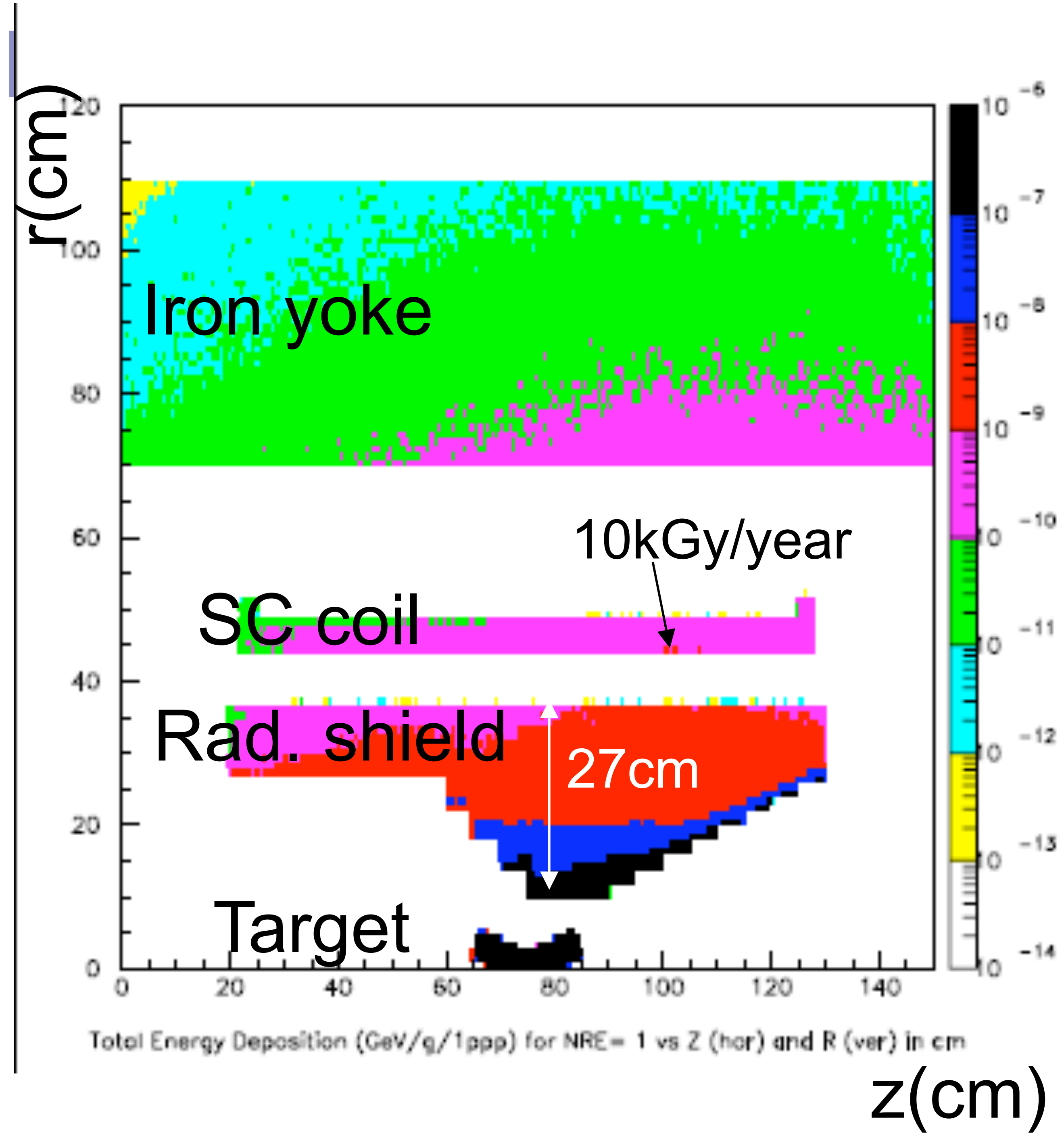


Requirements to the superconducting solenoids

- Strong magnetic field on the pion production target
  - Trap pions in 3.5 T
    - Superconducting coils surrounding the target
- Long solenoid transport channel with a big aperture
  - Pions decay out and muons transported in 2T solenoid
  - ~10m long
  - 360mm dia. bore
  - Correction dipole field for momentum and charge selection
- LHe free refrigeration
  - Conduction cooling by GM cryocoolers
    - Heat deposit on the coils < 1W
    - Dose < 1MGy
      - for insulator, glue ...
    - Neutron flux $< 10^{20} n/m^2$
      - avoid degradation of the stabilizer of SC wires

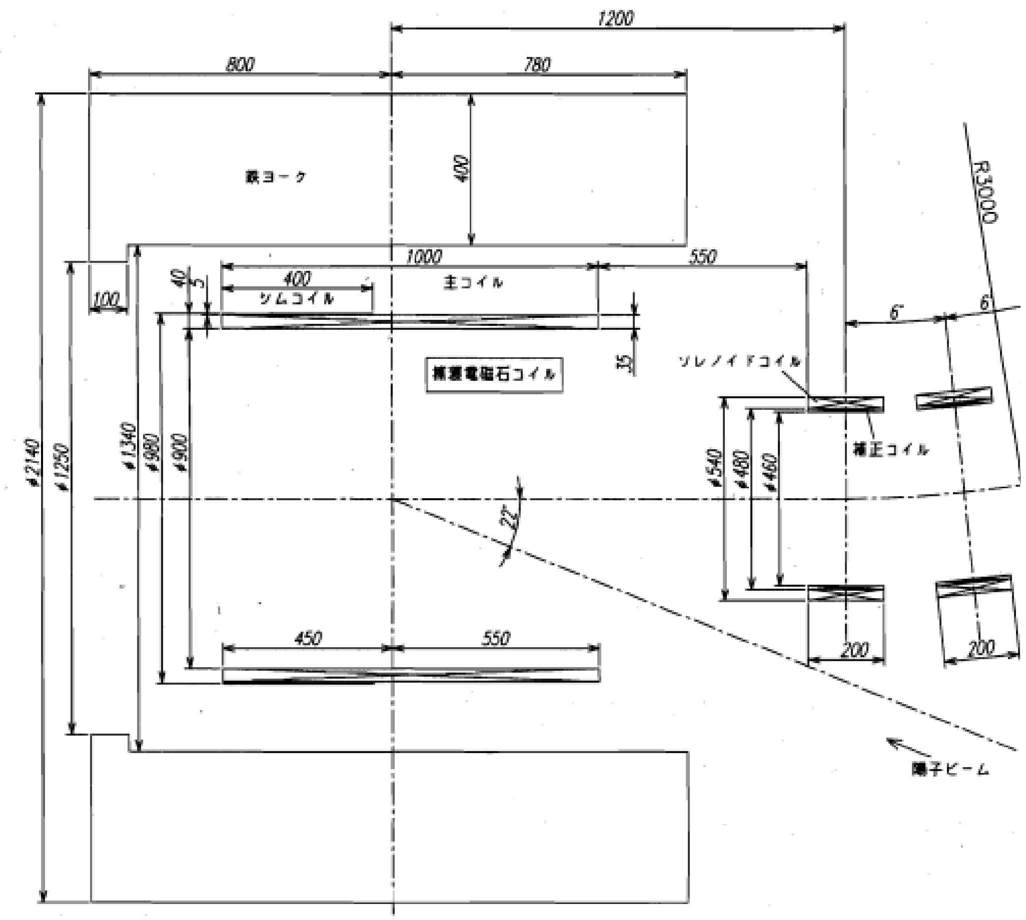
Pion capture solenoid: radiation issue

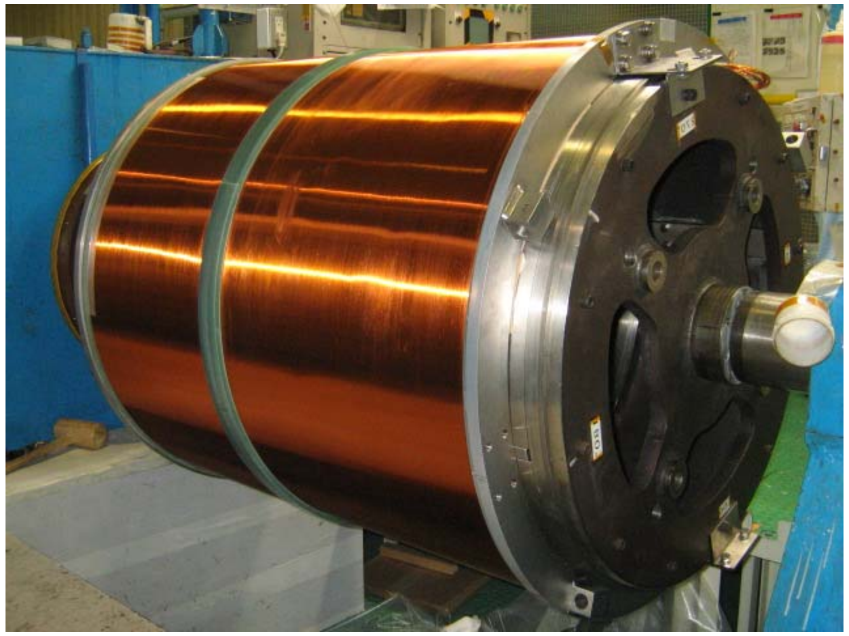
- Radiation shields (27cm thick stainless steels) are installed b/w the target and the coils.
- MC simulation by MARS (M.Yoshida)
  - Heat deposit: 0.6W
    - 0.4W in the coils(~1ton)
    - 0.2W in the coil supports
  - Dose on the coils < 10kGy/year
  - Heat load
    - 100W on the target
    - 50W on the rad. shields
  - Neutron flux: $5 \times 10^{18} n/m^2/year$
    - no degradation is expected



Pion capture solenoid: parameters

Conductor	Cu-stabilized NbTi
Cable diameter	ϕ1.2mm
Cu/NbTi ratio	4
RRR (R293K/R10K at 0T)	230-300
Operation current	145A
Max field on axis	3.5T
Bore	ϕ900mm
Length	1000mm
Inductance	400H
Stored energy	5MJ
Quench back heater Cu wire	1.2mm dia. ~1Ω@4K



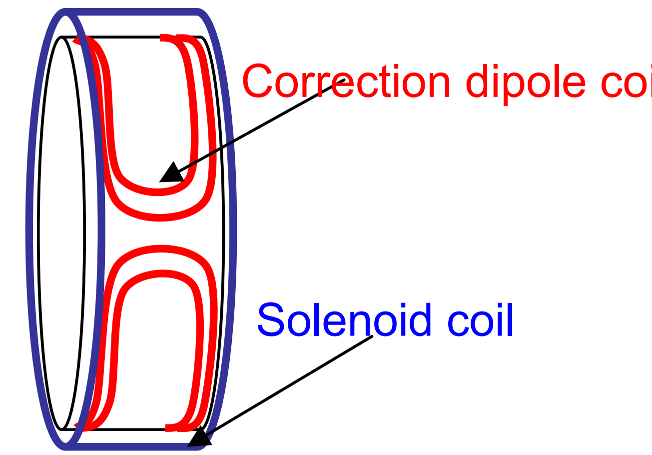


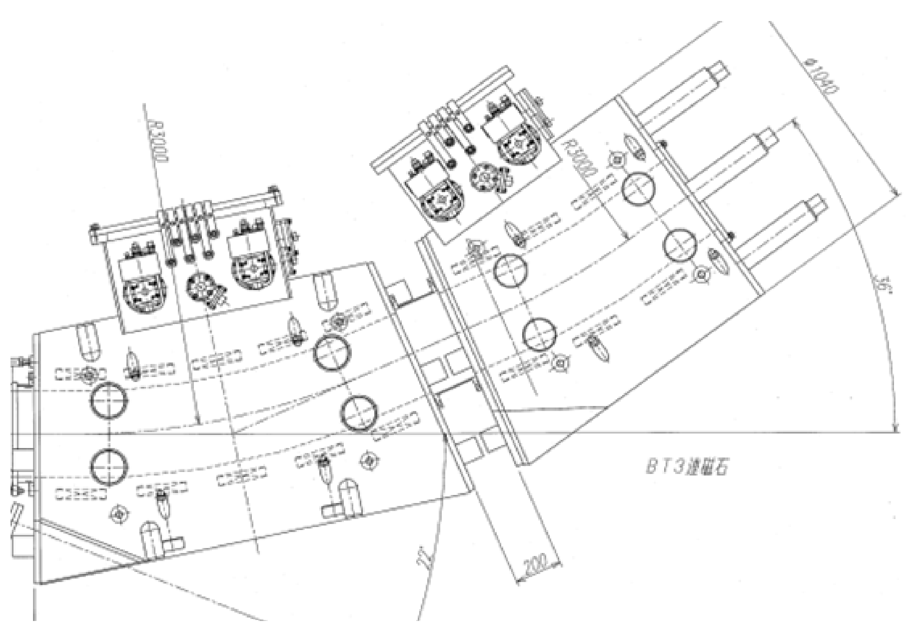
Transport solenoids

The world first working beam line which adopts cosθ winding dipole coils

Solenoid coils

Operation current	145A
Field on axis	2T
Bore	ϕ480mm
Length	200mm x8Coils
Inductance	124H
Stored energy	1.4MJ
Quench back heater Cu wire	1.3mm dia. ~0.05Ω/Coil@4K



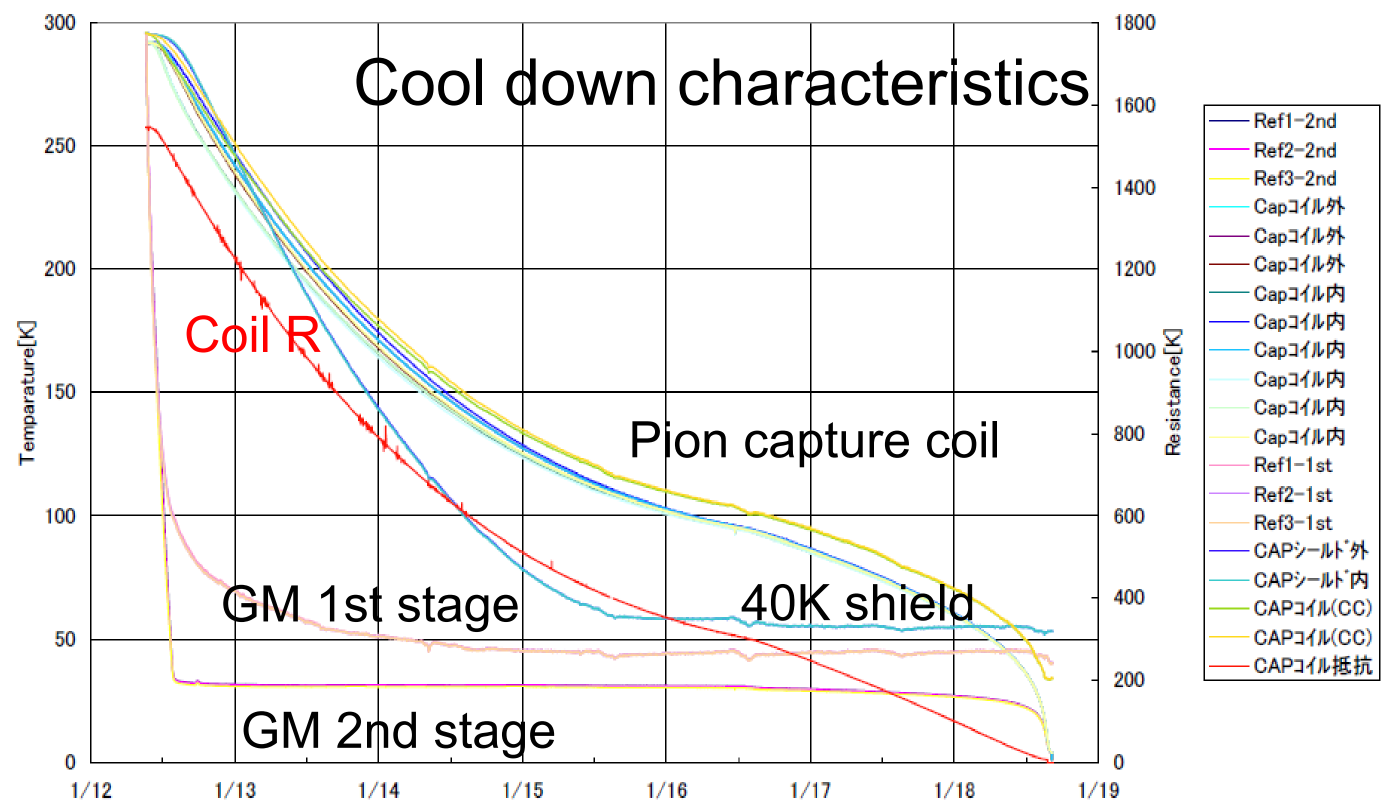


Correction dipole coils

Coil layout	Saddle shape dipole
	6 layers
	528 turns (1 set)
Current	115A (Bipolar)
Field	0.04T
Aperture	ϕ460mm
Length	200mm
Inductance	0.04H/Coil
Stored Energy	280J/Coil

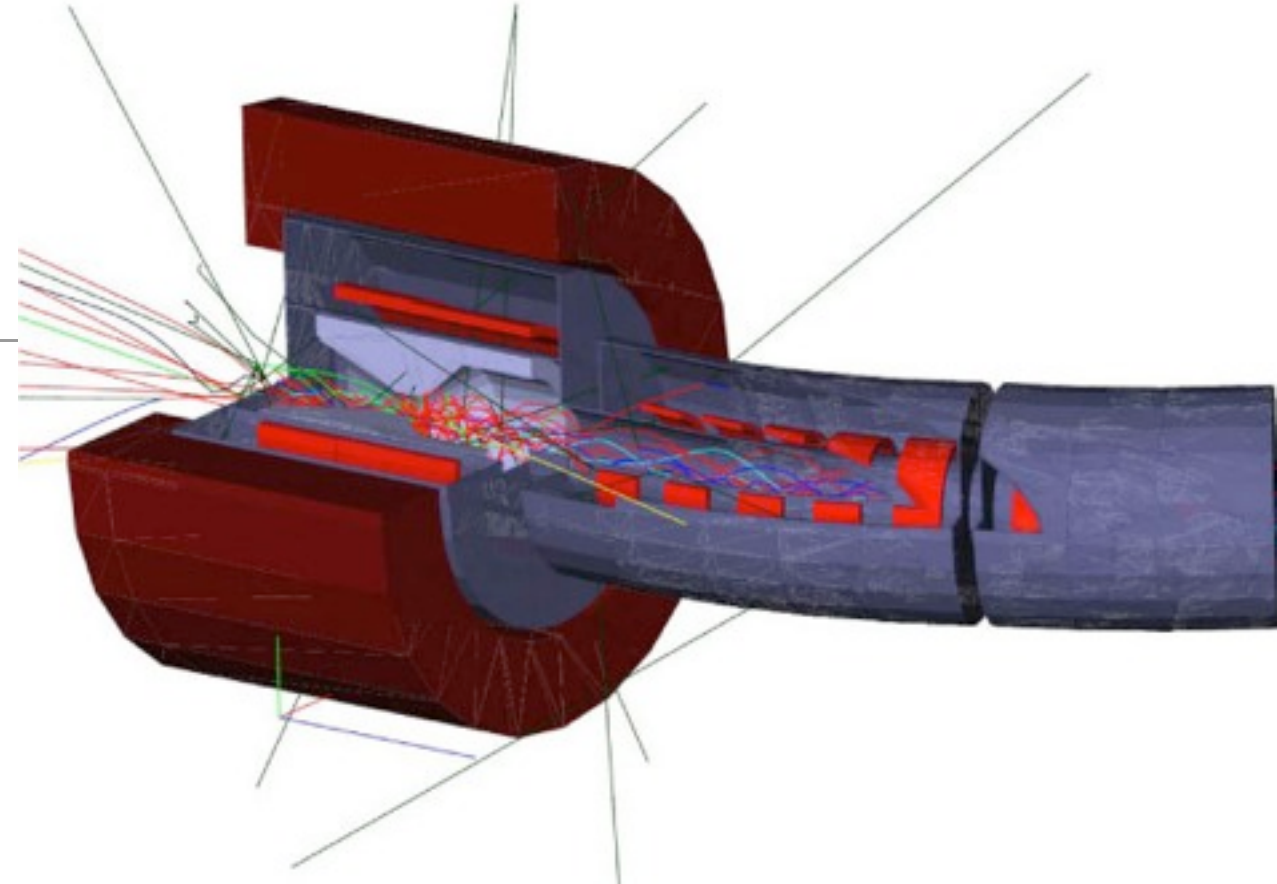
Refrigeration

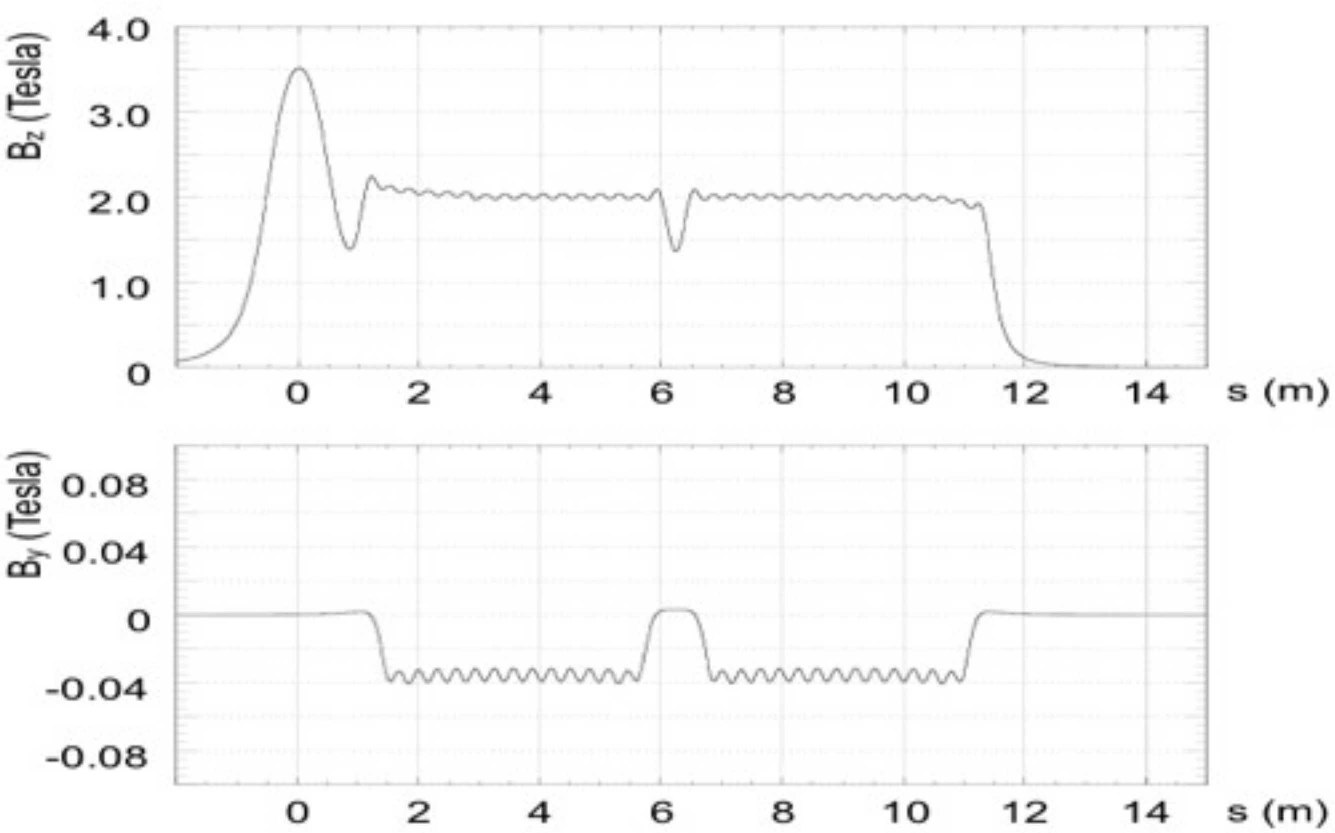
- Conduction cooling by GM cryocoolers
- Can be cooled down within 1 week with pre-cooling by LN2
- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 300K→40K: 50W
    - GM 1st stage
  - 3 x GM cryocoler
    - 1.5Wx2+1Wx1 @4K
    - 45Wx2+44W @40K
- Transport solenoid
  - 4K: 0.8W
  - 300K→40K : 50W
    - GM 1st stage
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K
    - 44Wx2 @40K
- Achievable temperature
  - Pion capture solenoid : 3.7K
  - Transport solenoids : 4.2K-4.5K(BT3), 4.5K-5.8K(BT5)

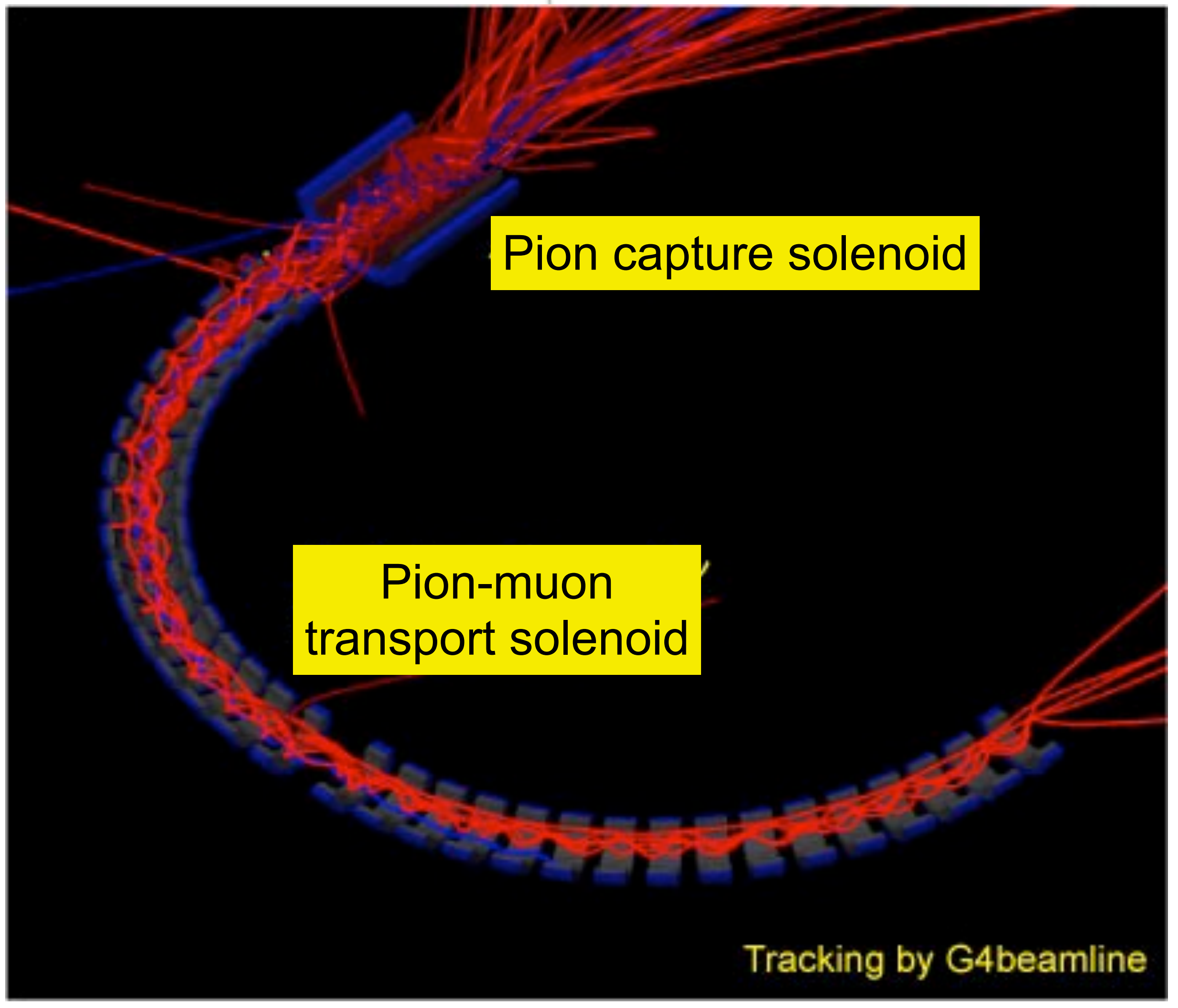


Expected Muon Yield

- MC simulations were performed from the production target to the end of the transport solenoid (180ded.)
  - by Dr. M.Yoshida
- **Simulation codes:**
  - Hadron production at the graphite target
    - MARS
  - Tracking in the magnetic field
    - g4beamline

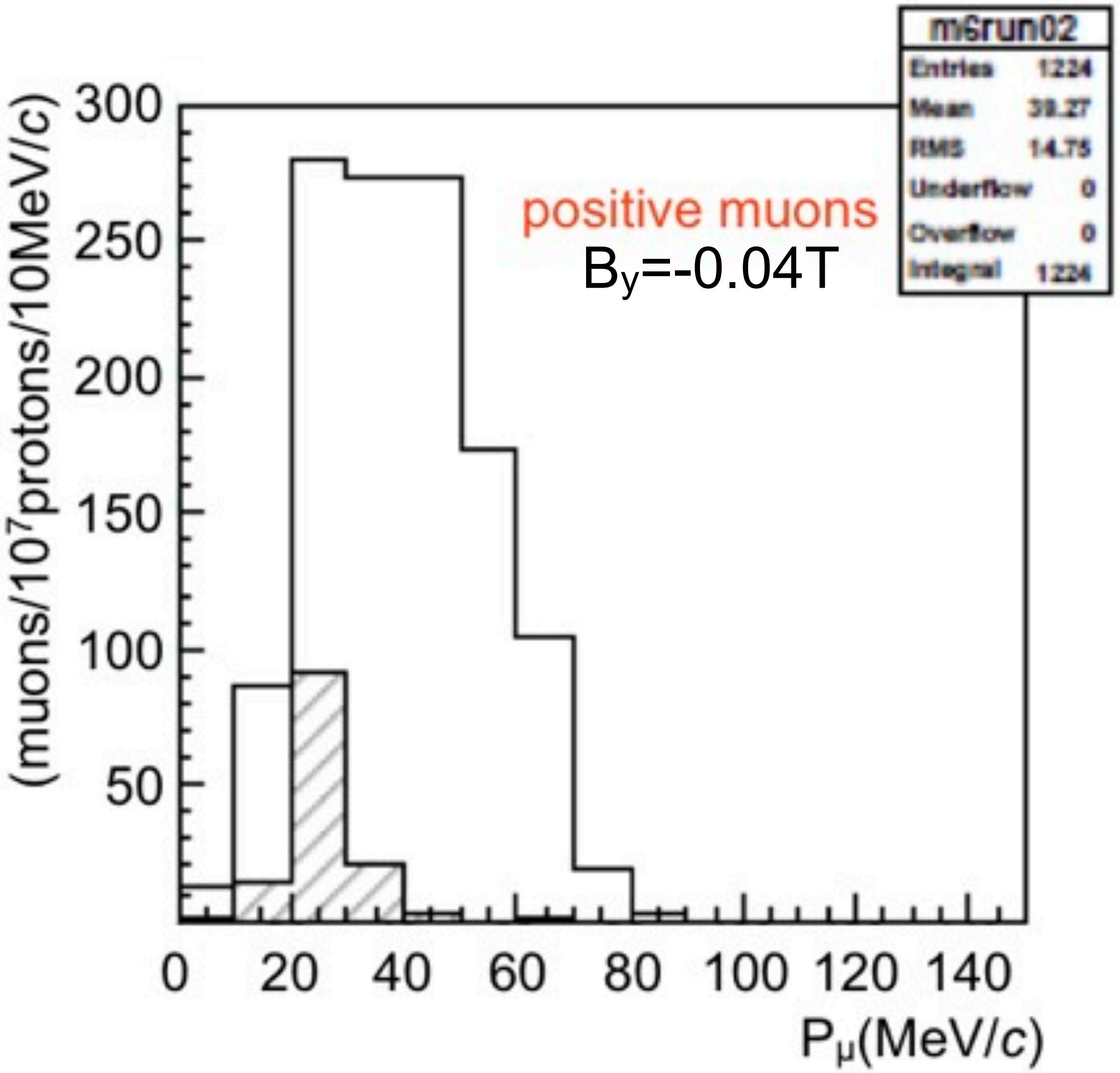


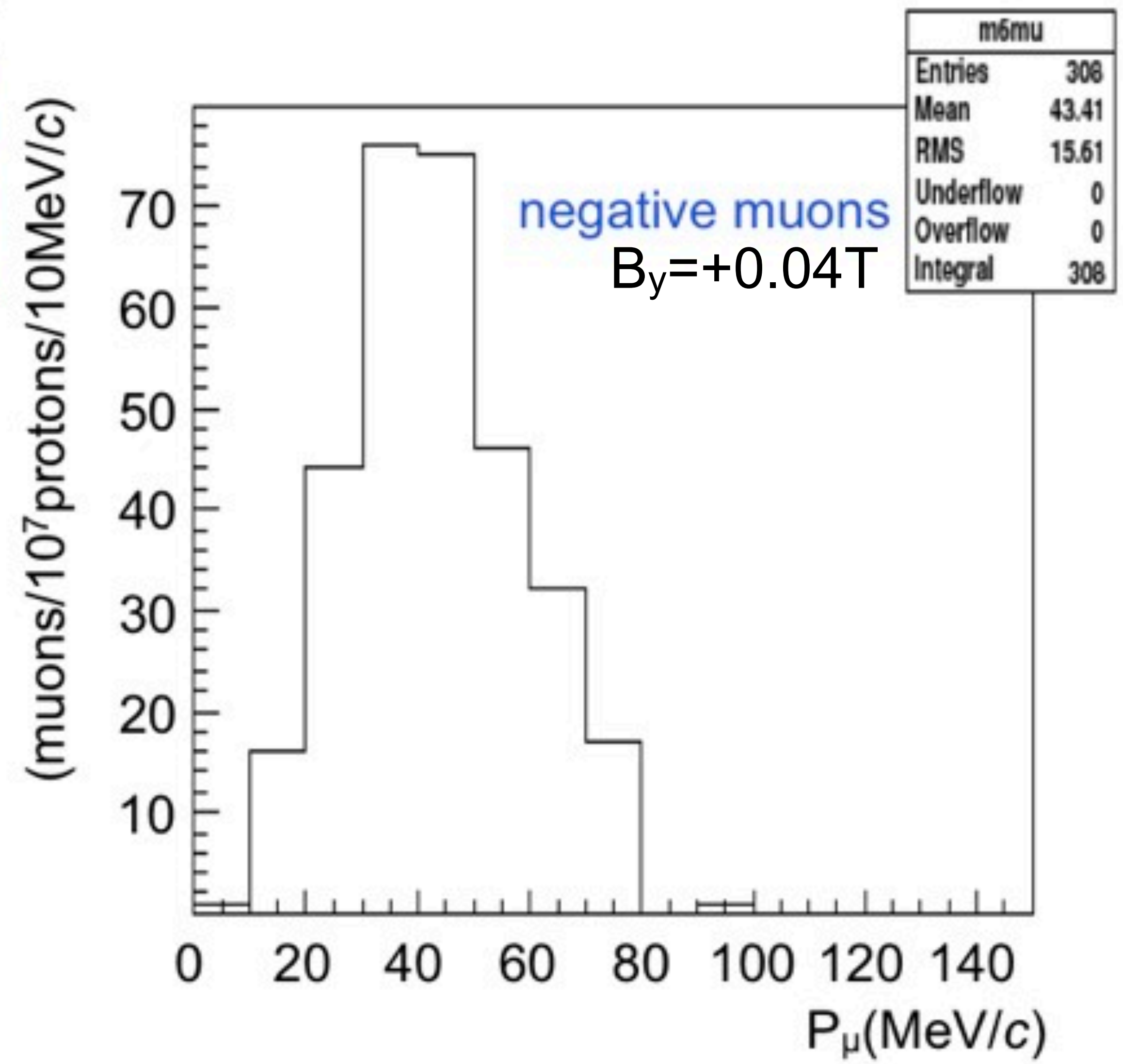




Simulation results for B_y=±0.04T

This is just an example. We need to optimize the beam characteristic for various experiments using collimators, DC separators, and so on.





$8\times10^8\ \mu^+$/sec
for 400MeV, 1 μA proton beam

$2\times10^8\ \mu^-$/sec
for 400MeV, 1 μA proton beam

- At the end of the transport solenoid (180 deg.)
- Charge of the muons can be selected by changing the direction of the dipole field.

Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

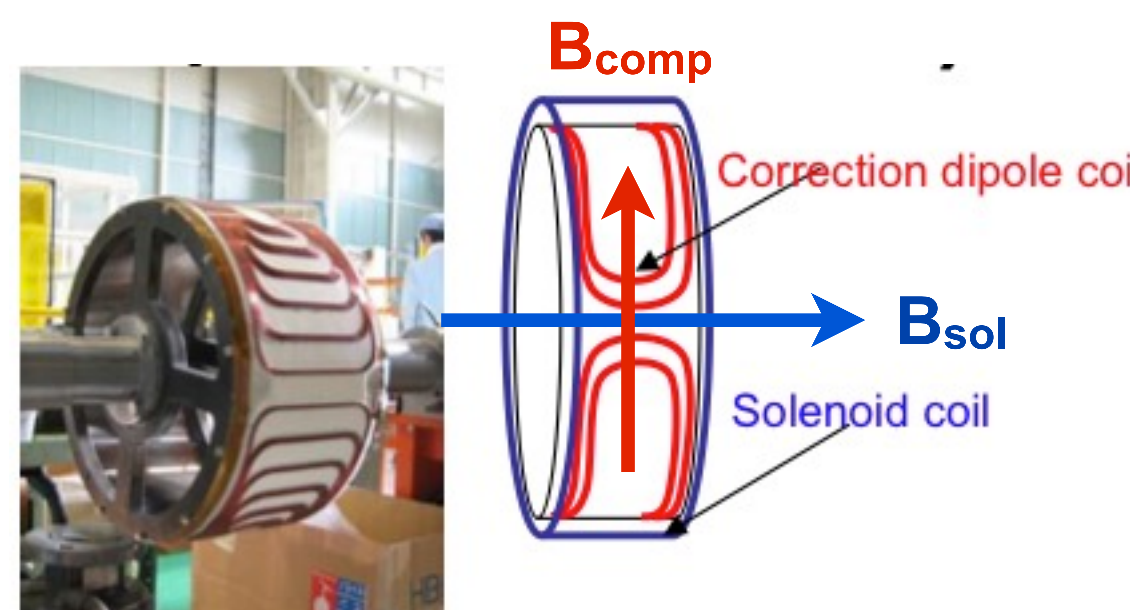
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This effect can be used for charge and momentum selection.

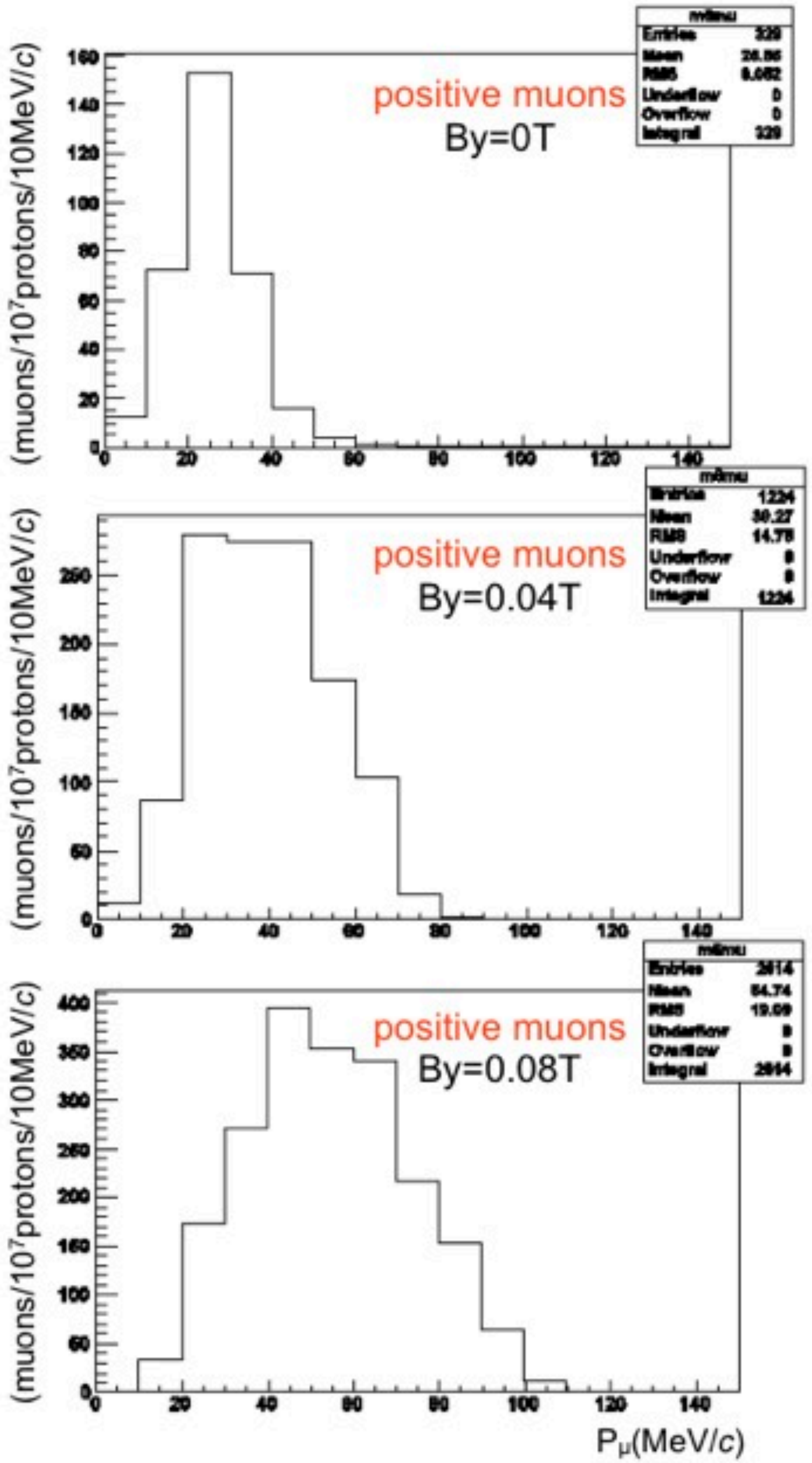
- This drift can be compensated by an auxiliary dipole field parallel to the drift direction given by

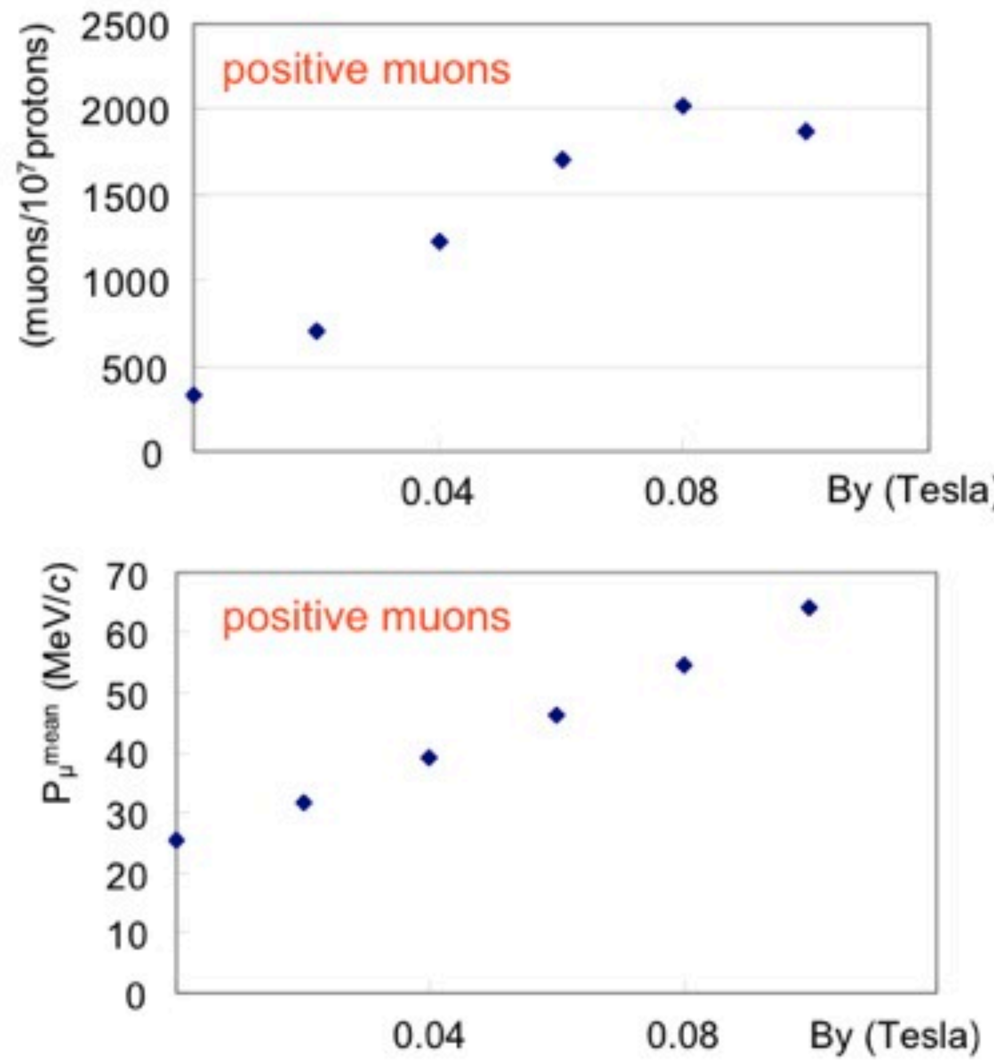
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ *: atan(*P_T/P_L*)*



Momentum vs Dipole field B_y

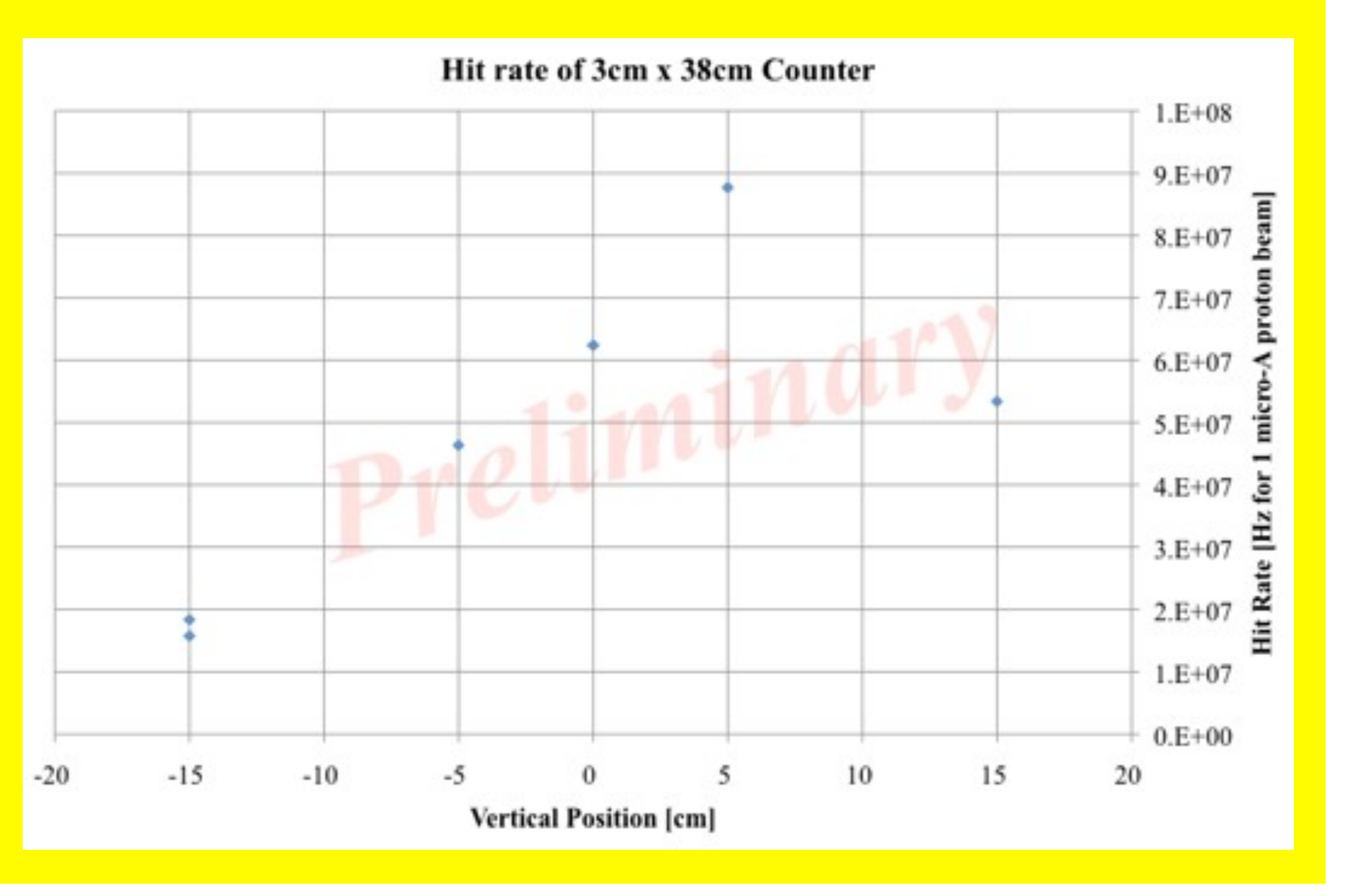




MuSIC First Beam from 29th and 30th, July, 2010

- A 36 hour beam time with 1 nA
- Measurements on
  - beam intensity and
  - beam spatial distribution
- Analysis is still being made.
- Preliminary results (right)
  - vertical beam distribution
  - integrated rate: 6×10^8 Hz/μA
  - some corrections further needed to get final numbers.
- Future works
  - particle ID
    - mixture of pions, muons and electrons
  - momentum distribution
  - dipole field correction

counting rates as a function of vertical position

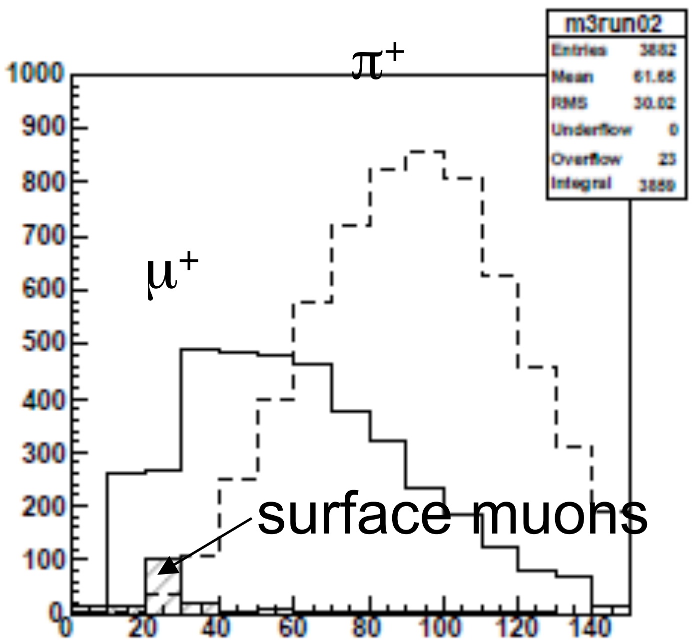


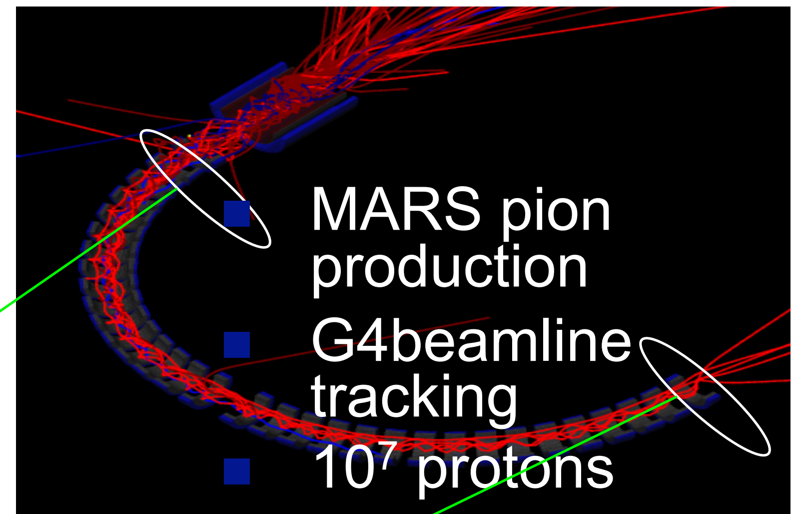
Summary

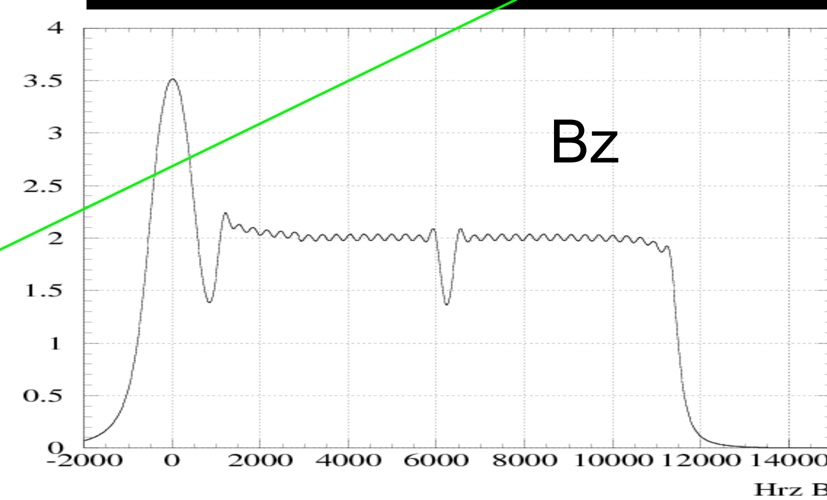
- Future plans of the T2K upgrade are discussed. There are three scenarios.
- For neutrino beam based on muon decays, muon accelleration by scaling FFAGs is studied.
- R&D of a highly intense muon source at Osaka University (the MuSIC project) is going on. A muon intensity of 10^8 /sec is expected.
-

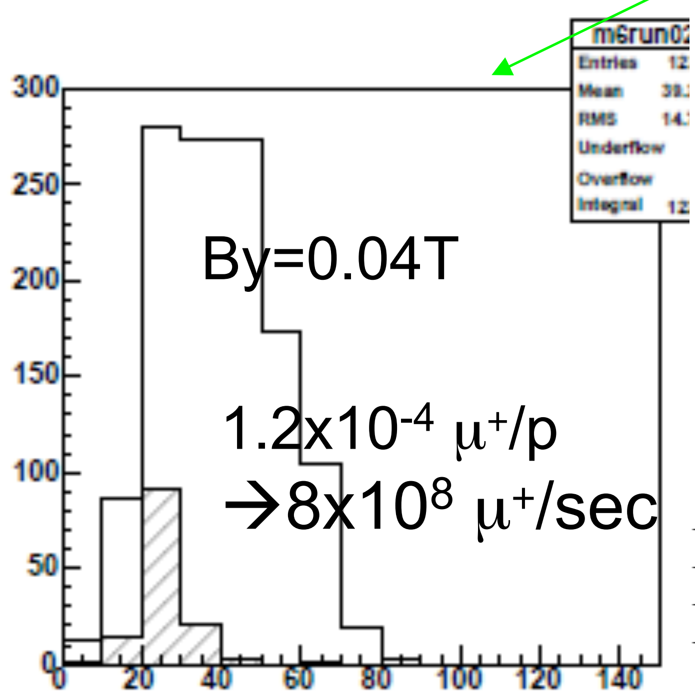
Backup

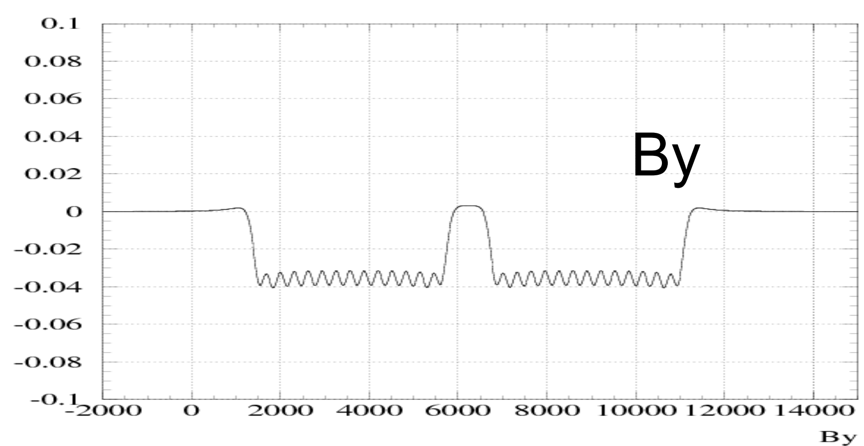
G4Beamline Simulation on Muon Yields











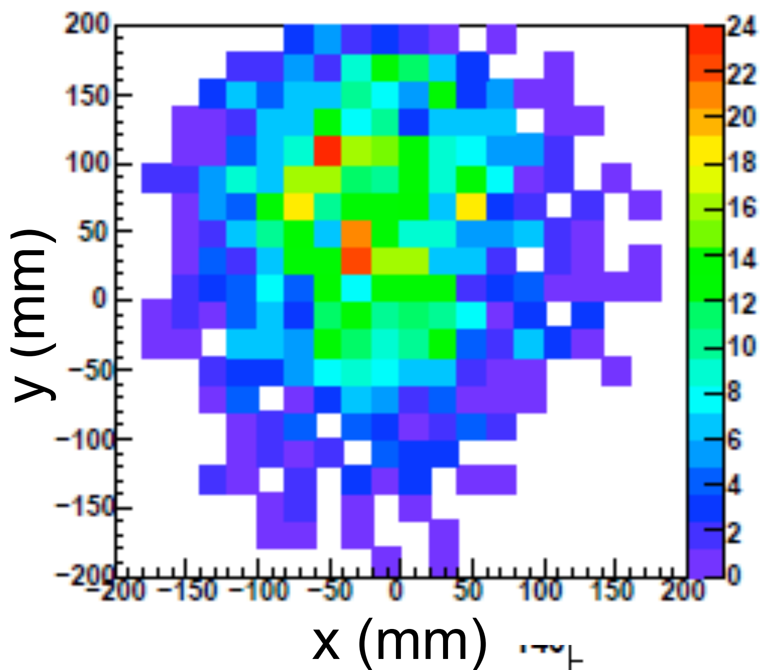
muon yield estimation
50 kW : 10^{11} muons/sec
(for COMET)
0.4 kW : 10^9 muons/sec
(for MUSIC)

8x10^8 μ^+/sec

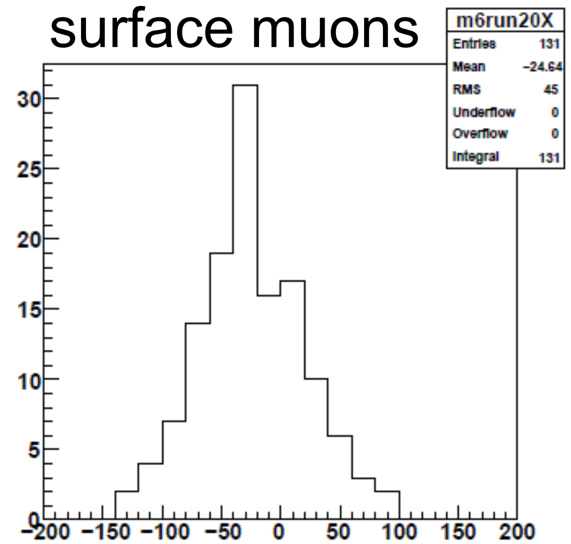
2x10^8 μ^-/sec

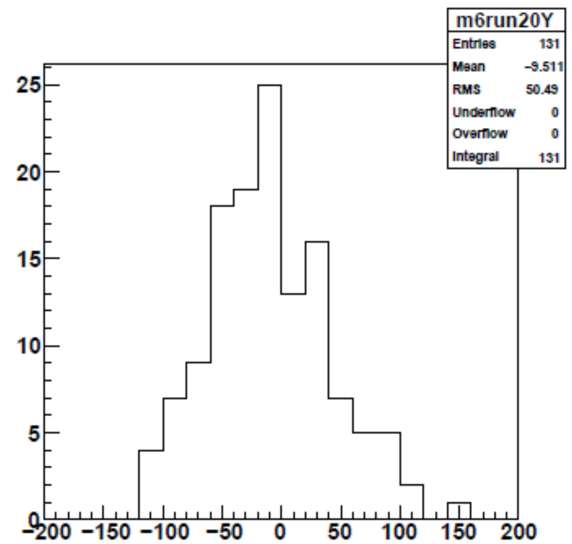
Muon Beam Profile at MUSIC

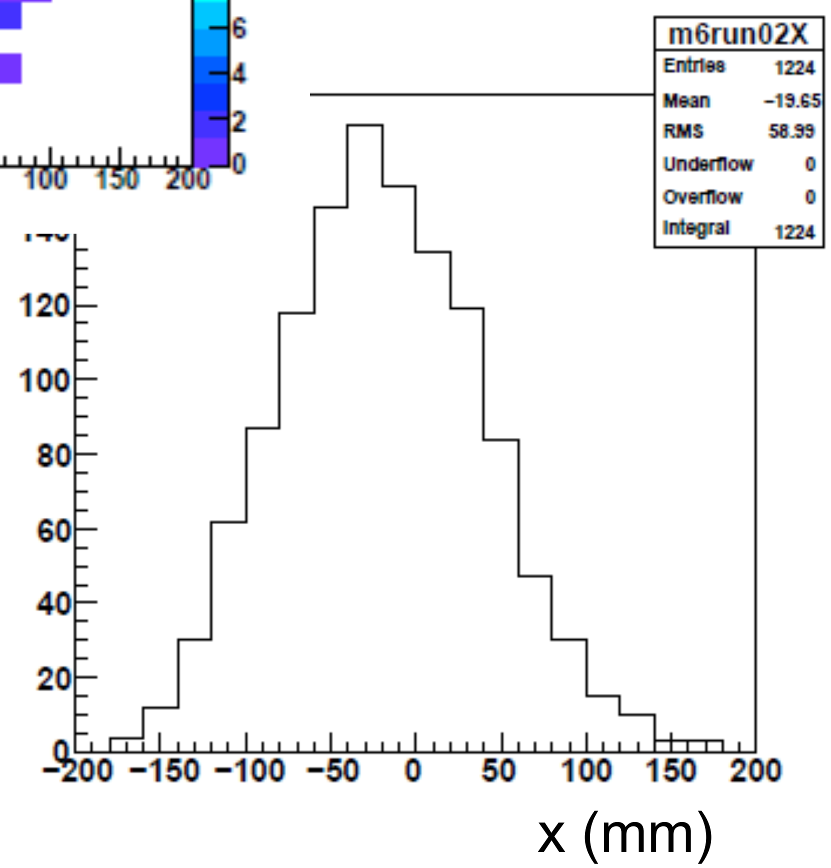
Muon profile

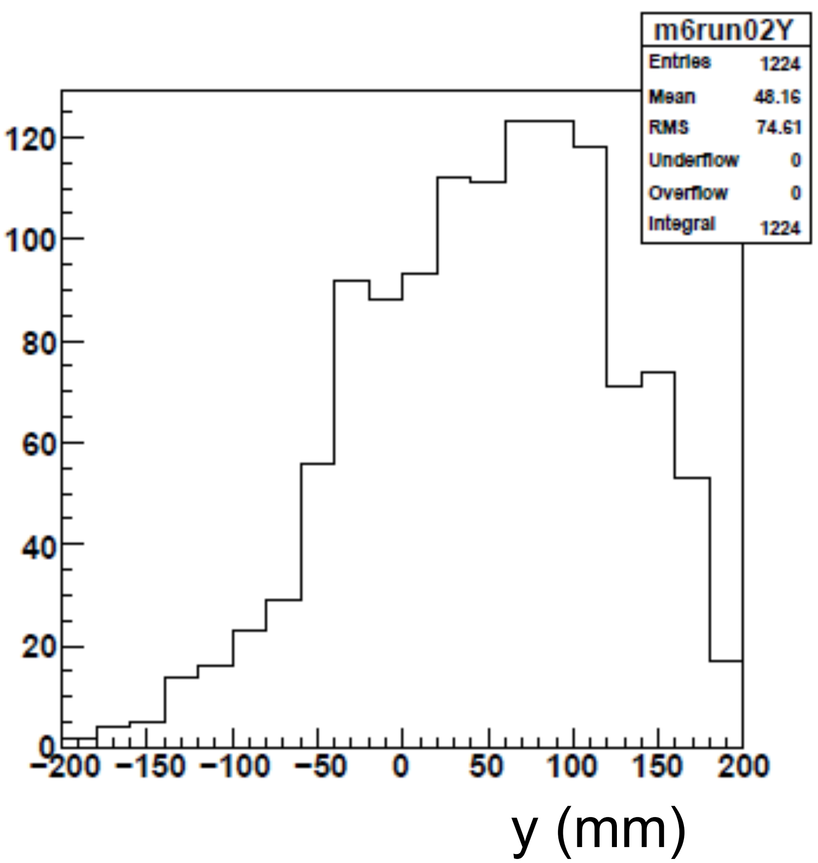


surface muons





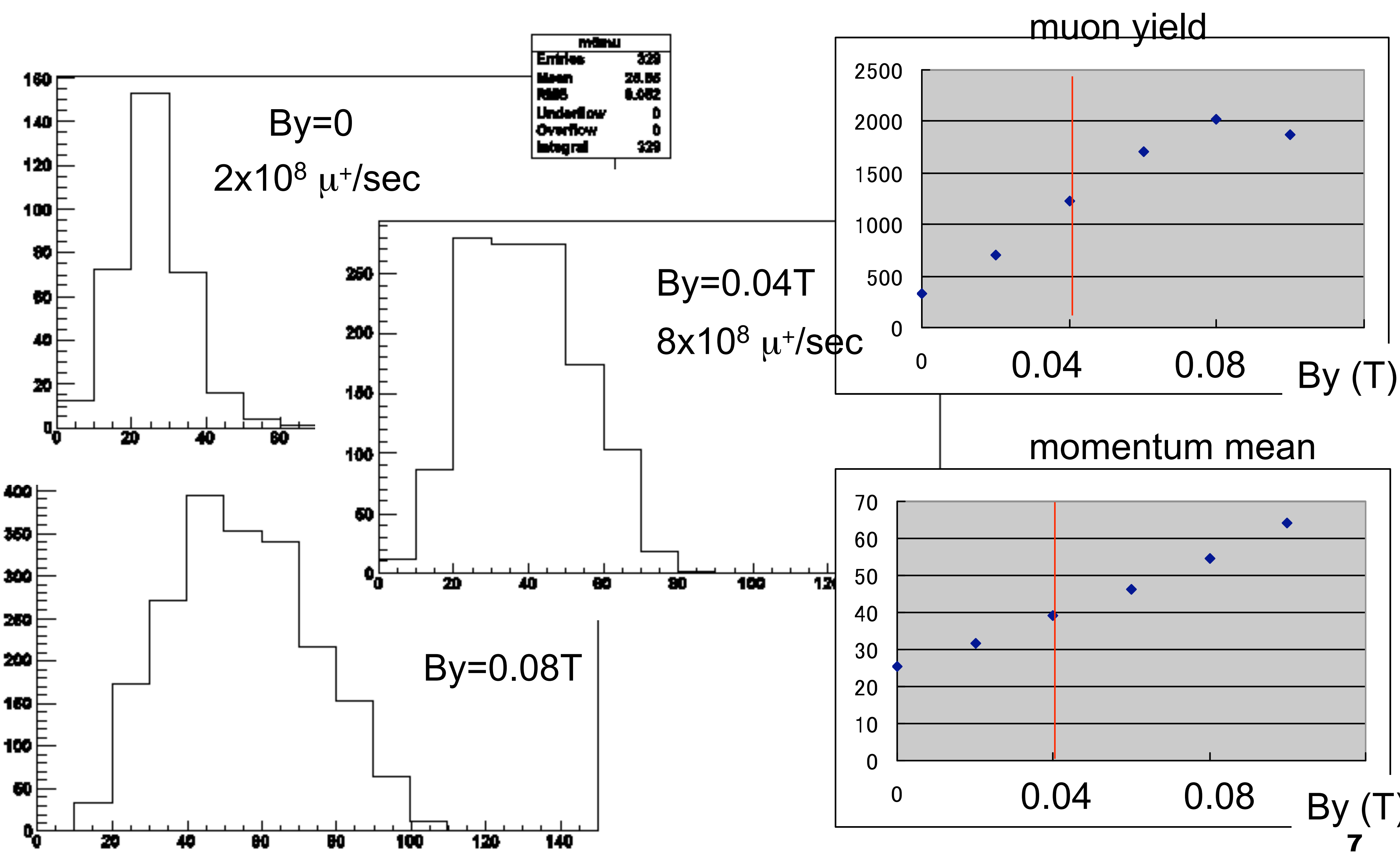




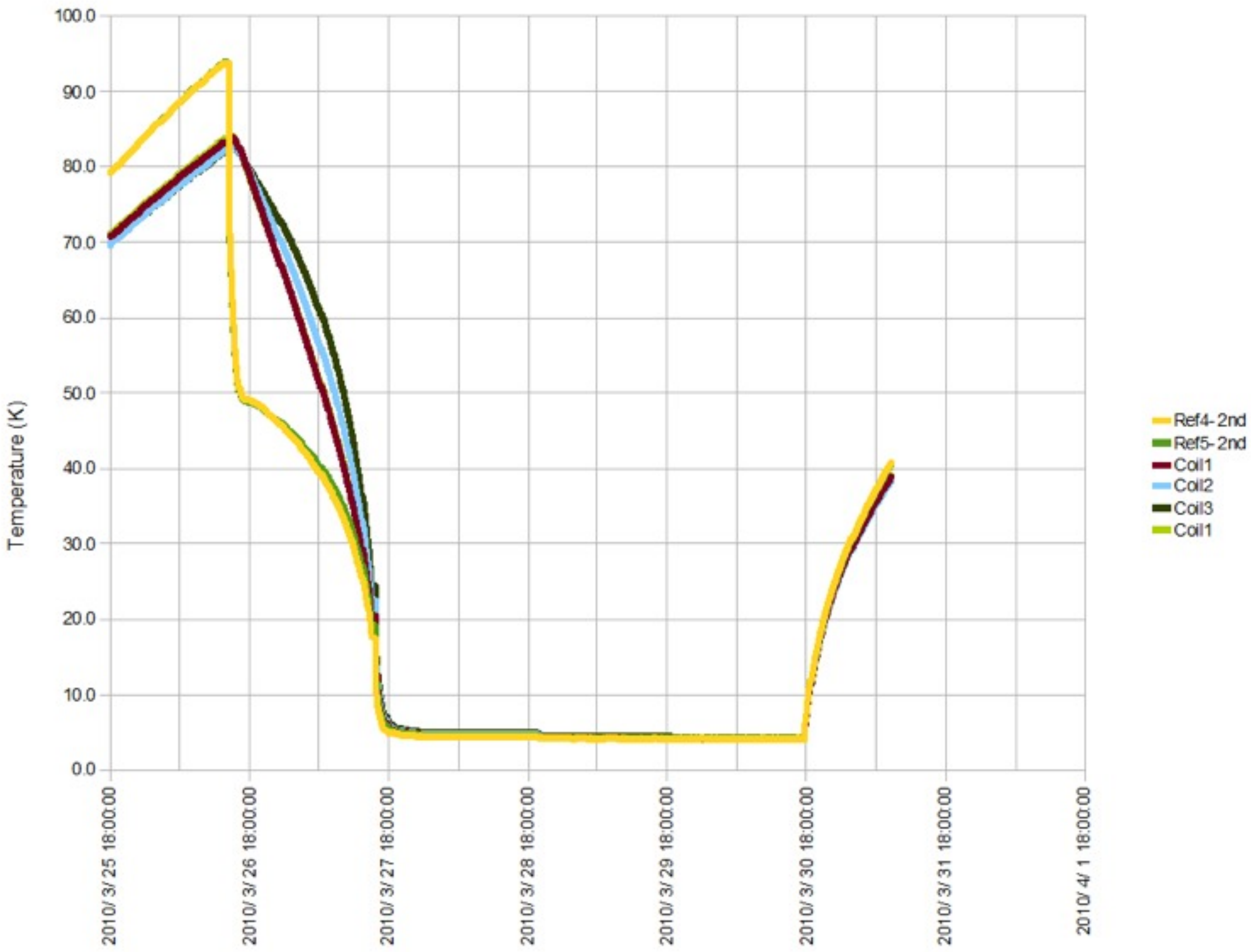
Muon Momentum Selection by Dipole Fields

By: dipole field

Momentum selection

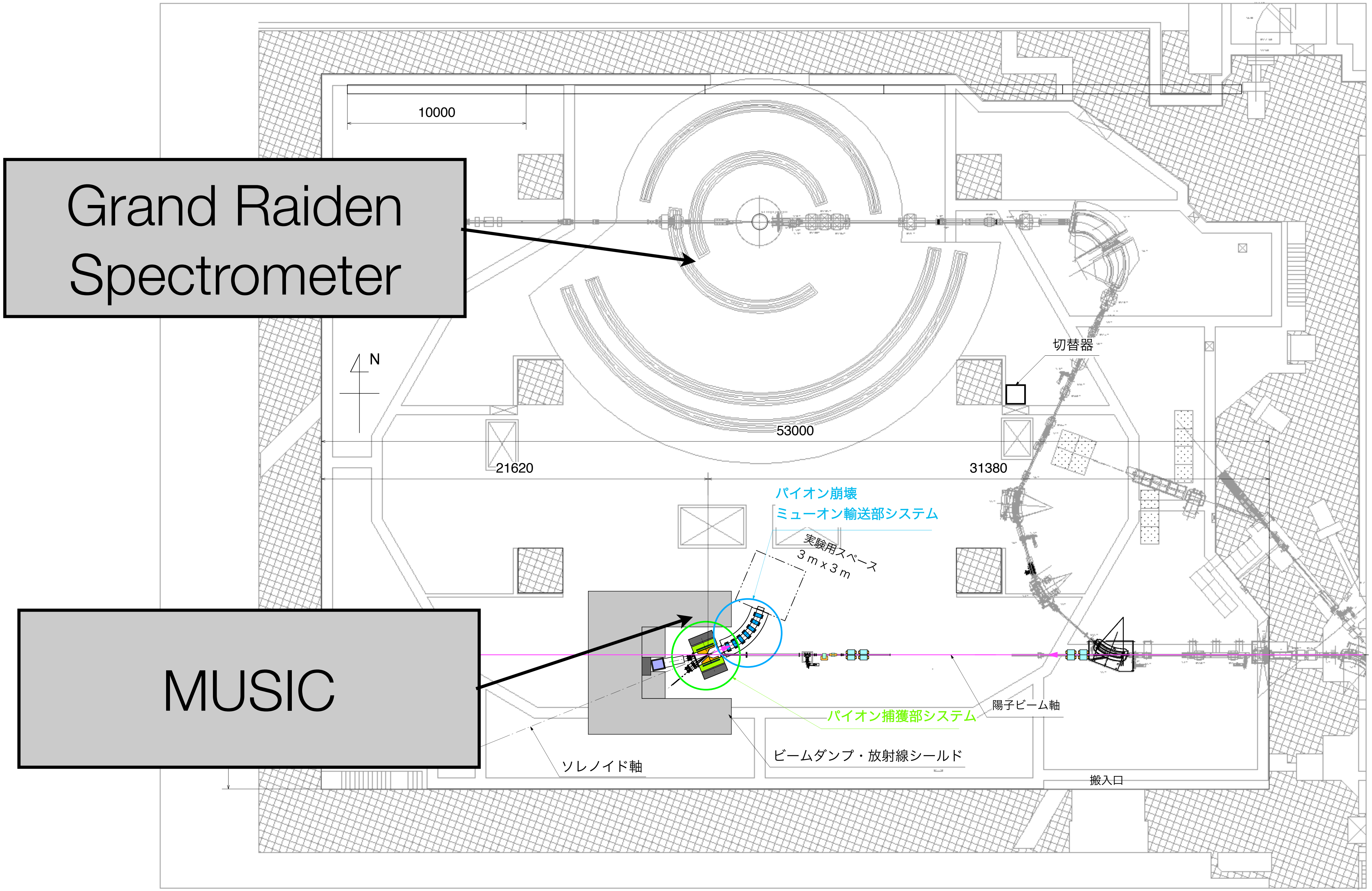


Cooling of the superconducting solenoids (1)



Cooling of Superconducting Solenoids (2)


The West Experimental Hall and the MUSIC



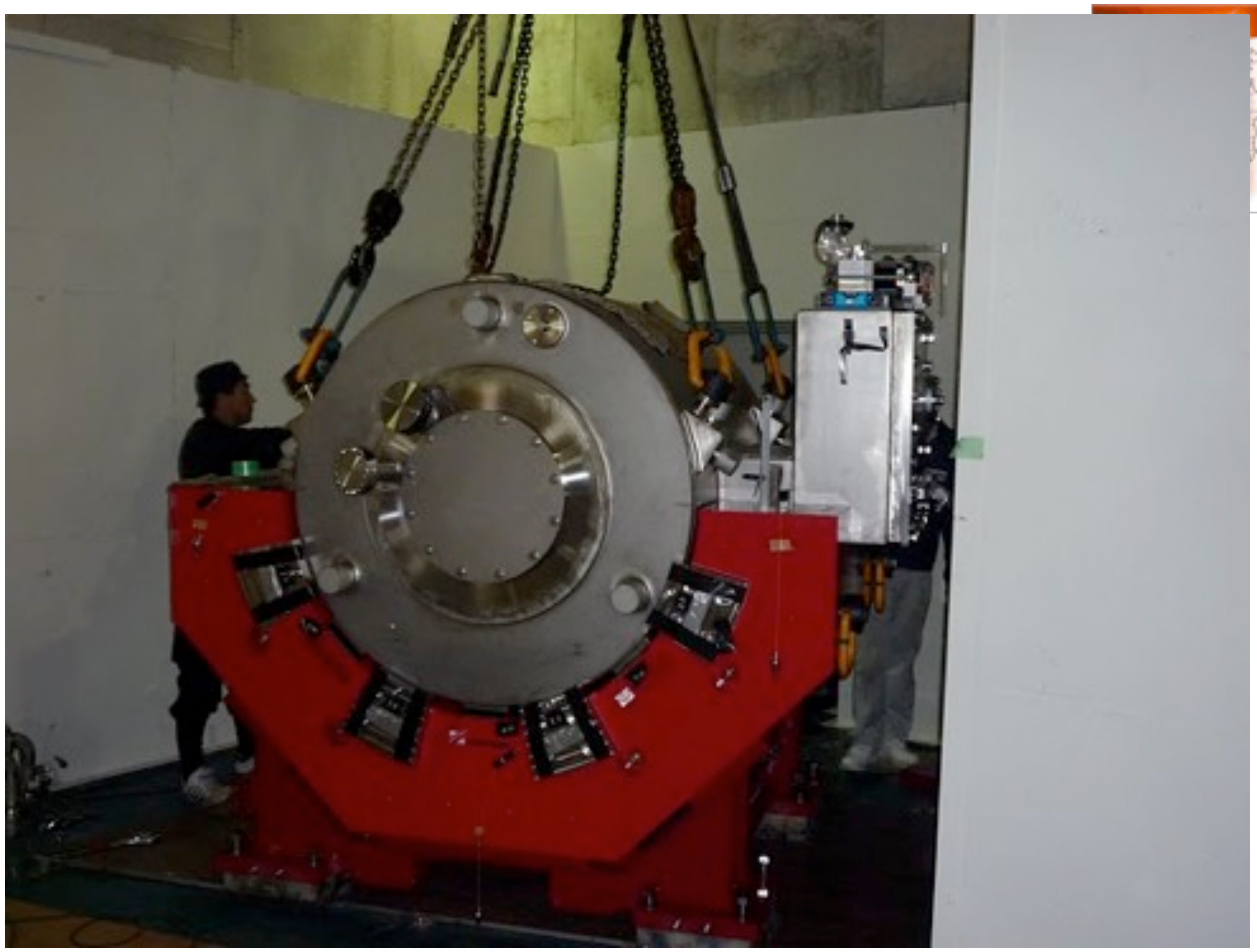
Restriction

- When a proton beam is on for nuclear experiments with the Grand Raiden spectrometer, we cannot enter the West experimental hall.
- Most of the beam times in May, June and July are reserved for such experiments using the Grand Raiden spectrometer.
- And therefore our access to the MUSIC is limited (for maintenance days or when the beam is on for the west experimental hall.)

Things to do for the MUSIC commissioning

- Construction of scintillation counters for
  - beam intensity measurement
    - plastic scintillators
  - beam profile measurement
    - hodoscope or fiber-grooved counters with MPPC
  - beam particle identification (muon/pion/proton/electron)
    - X-ray measurements
    - range ?
- DAQ
  - not decided
- Monte Carlo simulation (GEANT4) on beam optics
  - collimator design in the beamline
  - eliminate beam backgrounds (electrons, protons, neutrons)


に入るな


F-50