A new intense DC muon beam with a solenoid pion capture system - MuSIC -

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Tata Institute of Fundamental Research, Mumbai, India

We have build a superconducting pion capture system at RCNP(Research Center of Nuclear Physics), Osaka University, for a new intense DC muon beam line, which is now under construction. **The target muon intensity is 10^8/sec with 400W proton beam!**

Contents

* Pion capture systems for intense muon beams
* Features of MuSIC
* Status and construction schedule
* Design of solenoids
* Expected muon beam
* Conclusions

The first superconducting pion capture system in the world.

This project is referred as ***MuSIC***.

2010.8.2

We need intense muon beams!

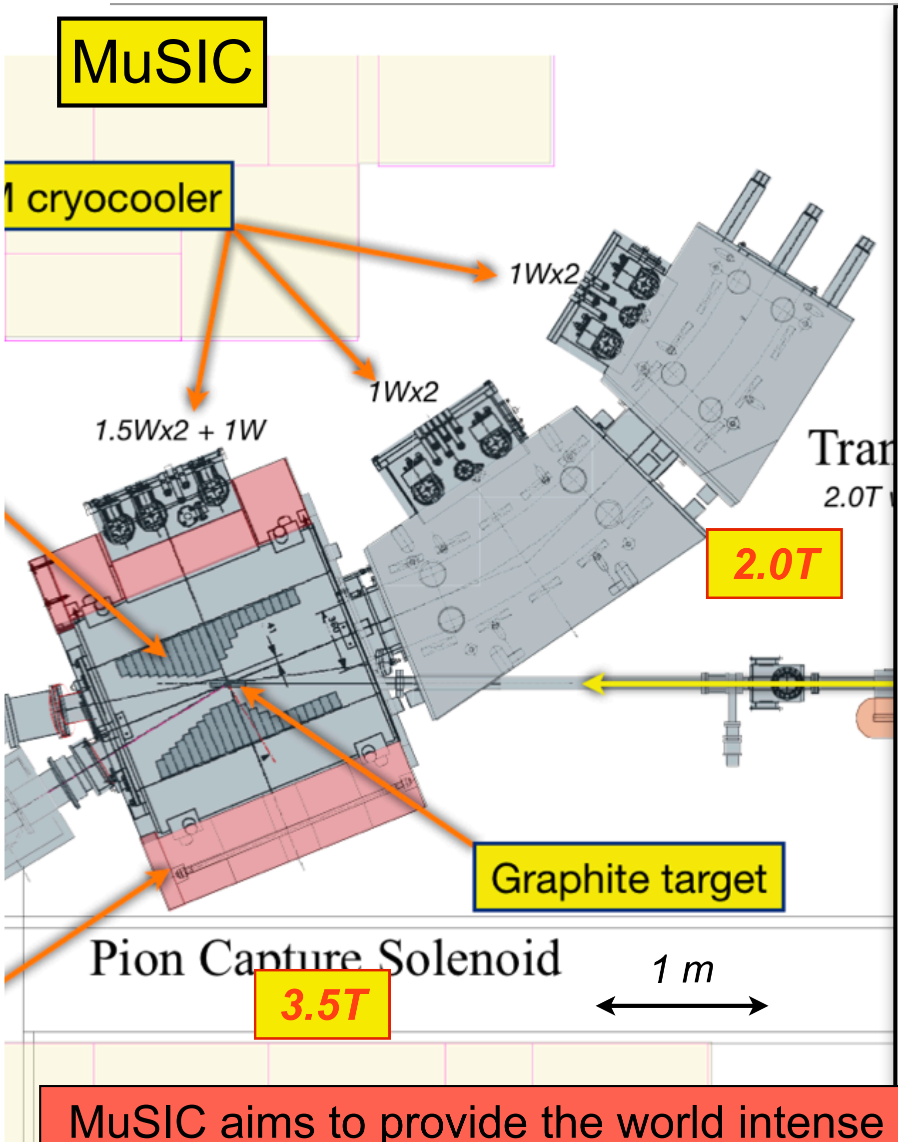
- Future muon related programs under discussion:
  - Searches for the muon to electron conversion in a muonic atom
    - COMET at J-PARC / Mu2e at FNAL: SES ~ 10^{-16}
    - PRISM: SES~ 10^{-18}
  - Neutrino factory: neutrino physics
  - Muon collider: high energy frontier
  - ...
- These programs need 10^{11}-10^{14} muons/sec.
- But the highest muon intensity available now is 10^{8}muons/sec at PSI
  - Design intensity of J-PARC MUSE is 4×10^{8}muons/sec
- We need 3-6 order of magnitude higher intense muon beam.
- **Pion capture systems with superconducting magnets** are considered to realize such intense muon beams.

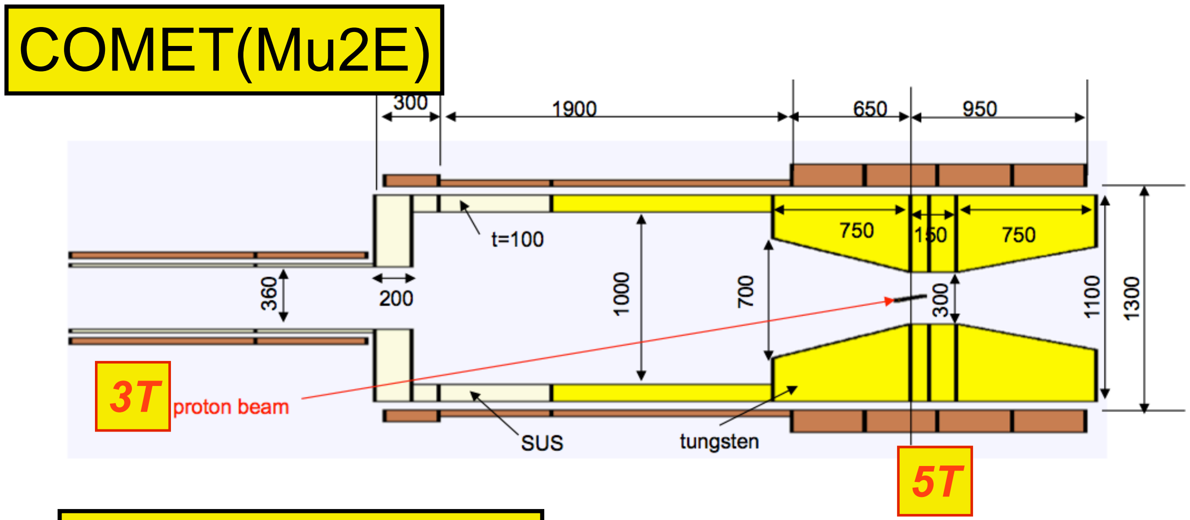
Comparison on the pion capture systems

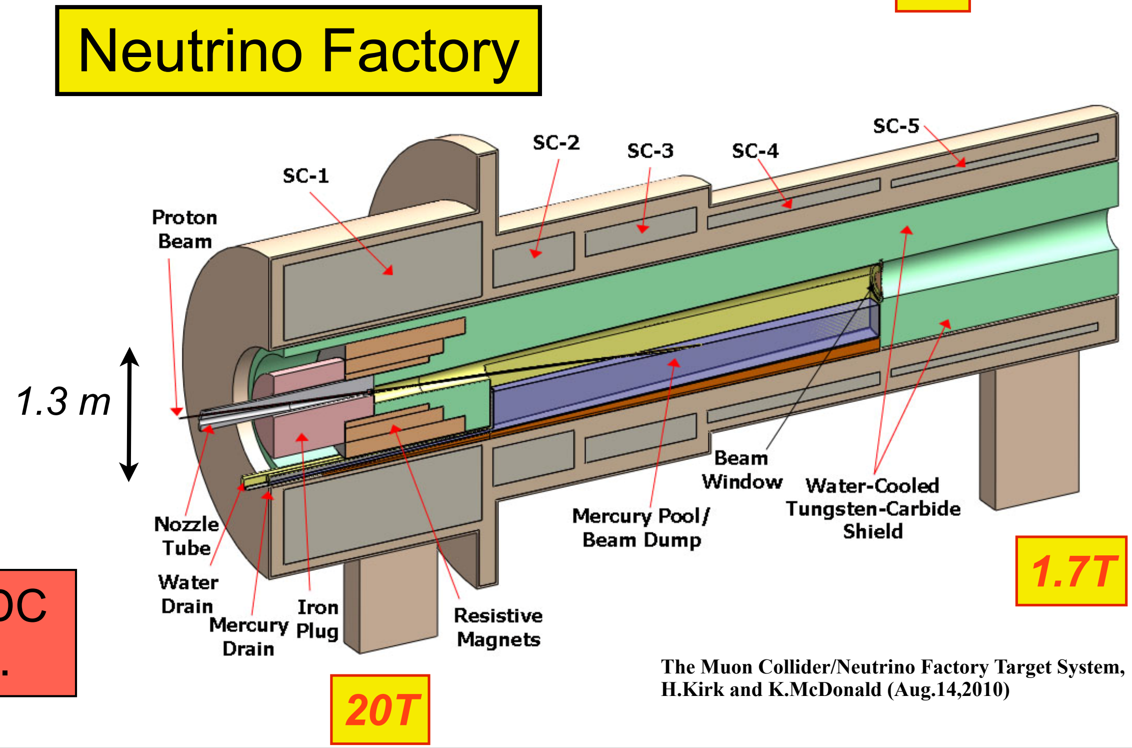
	MuSIC	COMET	NuFact[1]
Muon Intensity	10^{8}/sec	10^{11}/sec	10^{12-13}/sec
Muon Momentum	20-70 MeV/c (Backward)	20-70 MeV/c (Backward)	170-500 MeV/c (Forward)
Time structure	Continuous	Pulsed	Pulsed
Proton Beam Power	400W (0.4GeV)	56kW (8GeV)	4MW (8GeV)
Production Target	Graphite	Tungsten	Mercury jet
Capture Solenoid Max. Field Strength	3.5 T	5.0 T	20 T
Inner radius of Main SC Coil	0.45 m	0.65 m	0.64 m
Outer radius of Main SC Coil	1.0 m	1.6 m	1.78 m

(1) Based on The Muon Collider/Neutrino Factory Target System, H.Kirk and K.McDonald (Aug.14,2010) and Study-II report

Pion Capture System in MuSIC,COMET, and NuFact







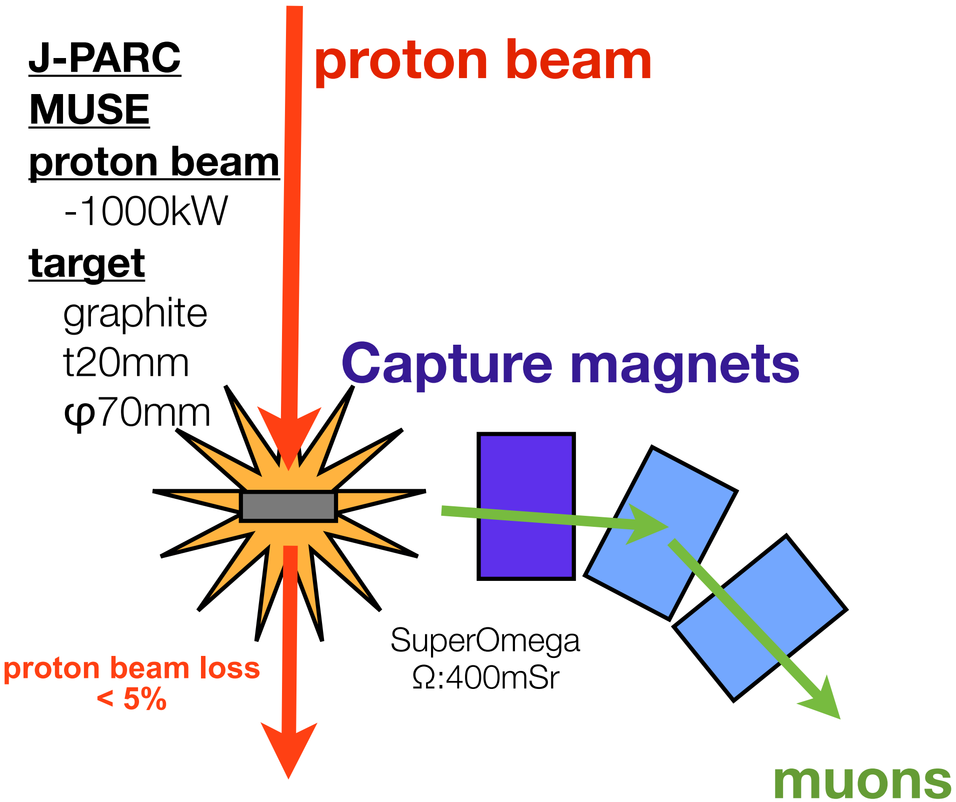
The Muon Collider/Neutrino Factory Target System, H.Kirk and K.McDonald (Aug.14,2010)

MuSIC aims to provide the world intense DC muon beam with the 400W proton beam.

Production and Collection of Pions and Muons

Conventional muon beam line

J-PARC
MUSE
proton beam
-1000kW
target
graphite
t20mm
φ70mm

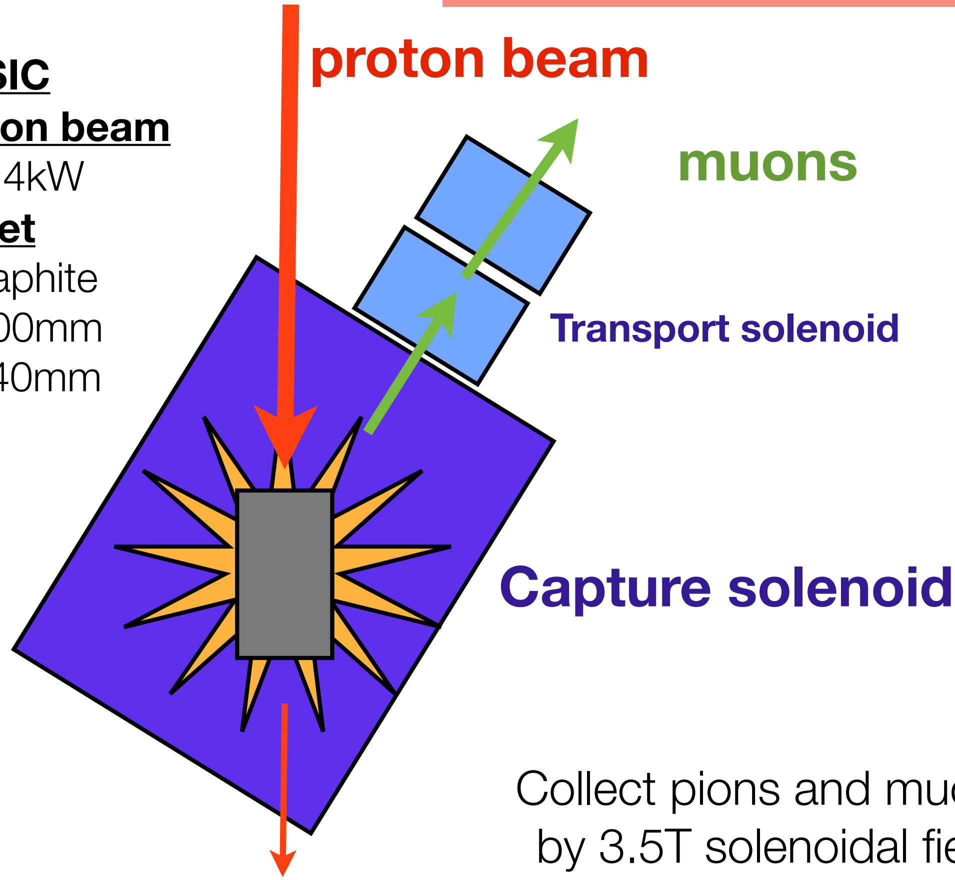


to the neutron facility

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

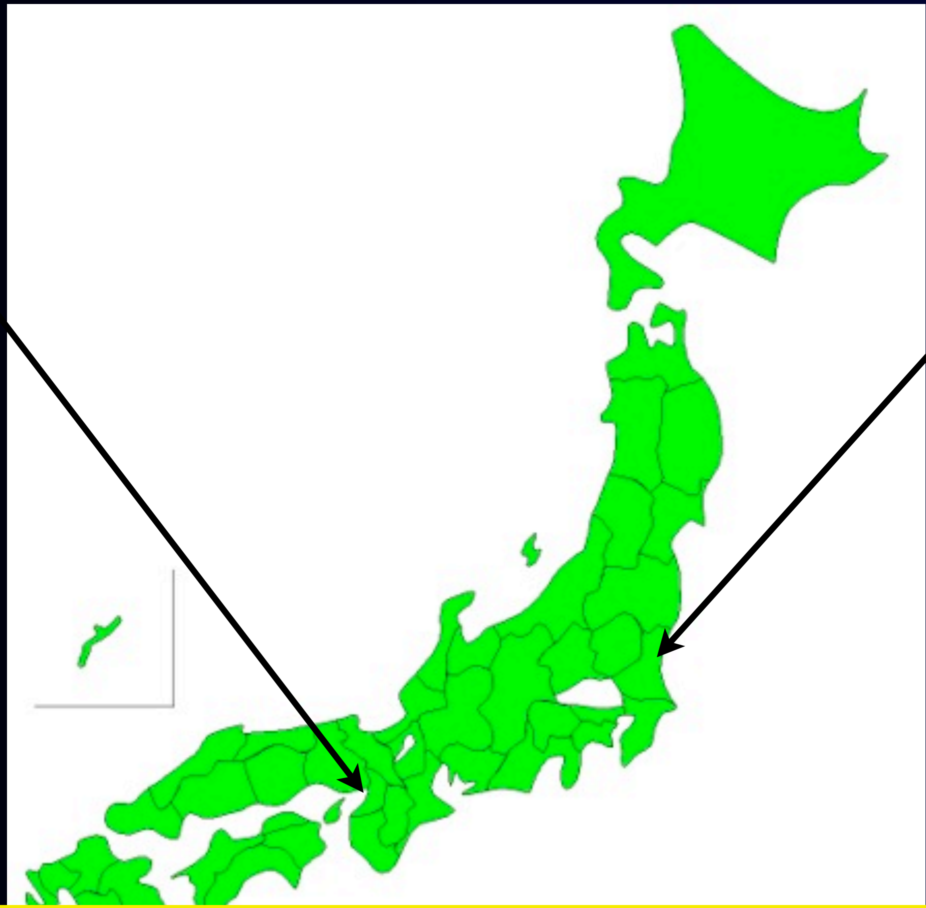
Large solid angle & thick target

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

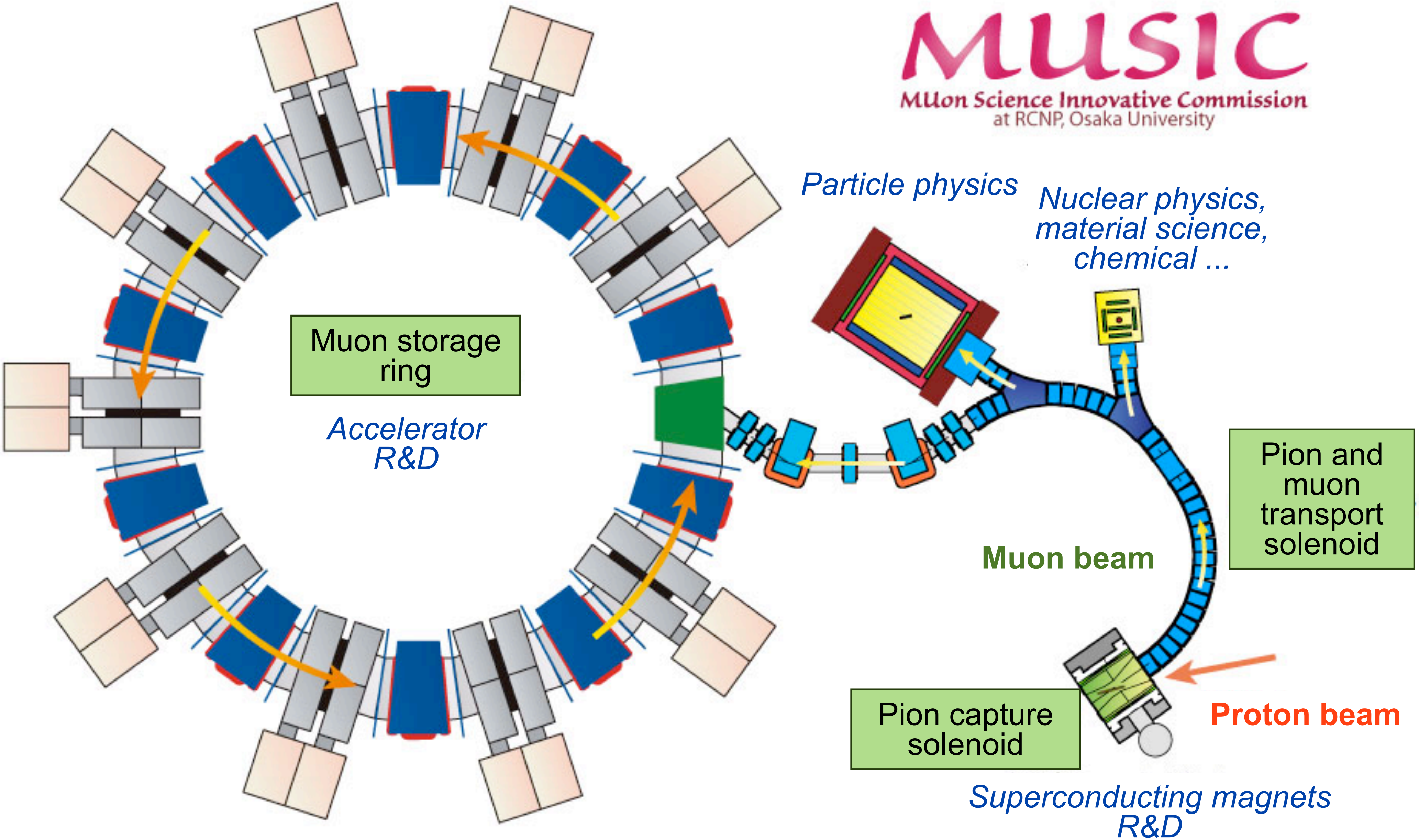
Japan will be the only country which has both DC and pulsed muon beam facilities.

MUSE vs. MUSIC

	MUSE	MUSIC
location	J-PARC	RCNP
beam power	1000 kW	0.4 kW
intensity	10^8/sec	10^7-10^8/sec
time structure	pulsed (25 Hz)	continuous
beam polarization	high	medium(to be studied)
multiple use	many channels	only one channel

Muon Physics Examples at MuSIC

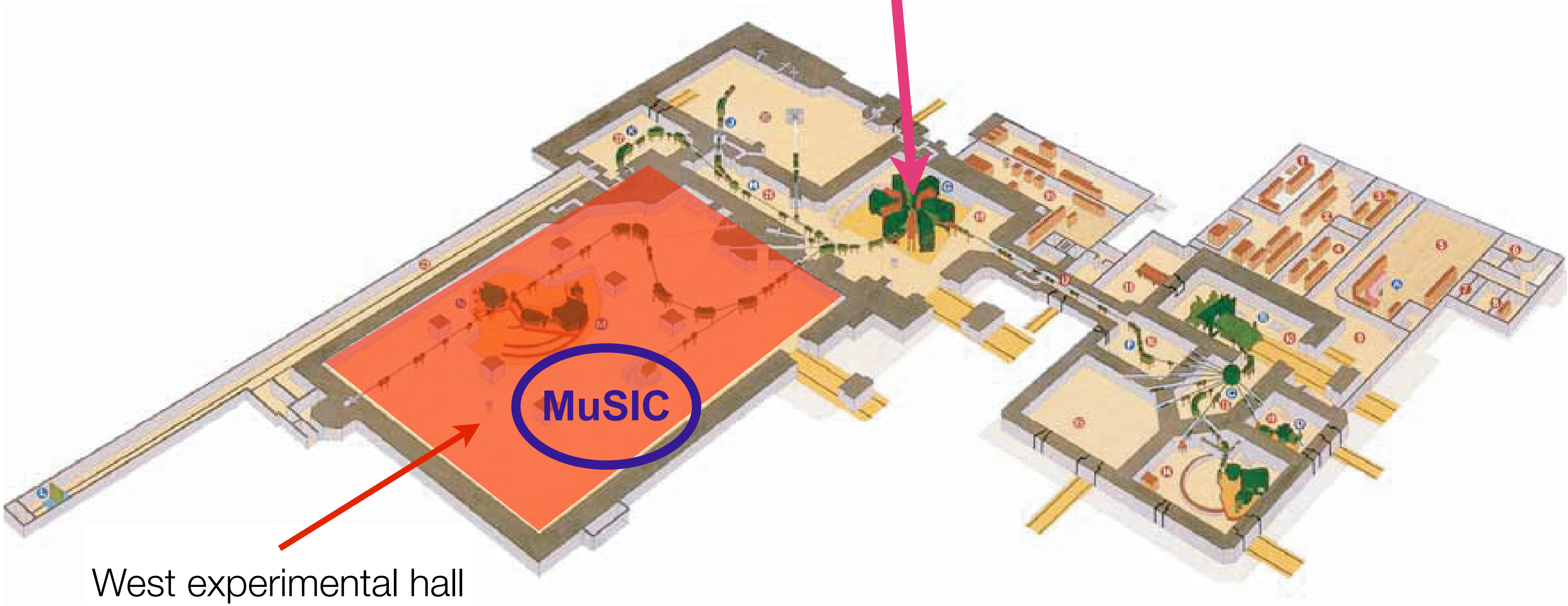
- **Particle Physics** :
  - search for μ→eee (muon LFV) **$10^{8\text{-}9}\mu^+$/sec**
    - DC continuous beam is critical
- **Nuclear Physics** :
  - nuclear muon capture (NMC) **$10^{5\text{-}6}\mu^-$/sec**
  - pion capture and scattering
- **Chemistry** :
  - chemistry on pion/muon atoms **$10^{5\text{-}6}\mu^-$/sec**
- **Materials Science** :
  - μSR (a μSR apparatus is needed) **$10^{5\text{-}6}\mu^+$/sec, polarized**
- **Accelerator / Instruments R&D** (for PRISM/neutrino factory/muon collider) :
  - Superconducting solenoid magnets
  - FFAG, RF
  - cooling methods
  - muon acceleration, deceleration, and phase rotation



MUSIC
MUon Science Innovative Commission
at RCNP, Osaka University
Particle physics
Nuclear physics,
material science,
chemical ...
Muon storage
ring
Accelerator
R&D
Pion and
muon
transport
solenoid
Muon beam
Pion capture
solenoid
Proton beam
Superconducting magnets
R&D

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.



The beam current would be upgraded to 5 microA in future.

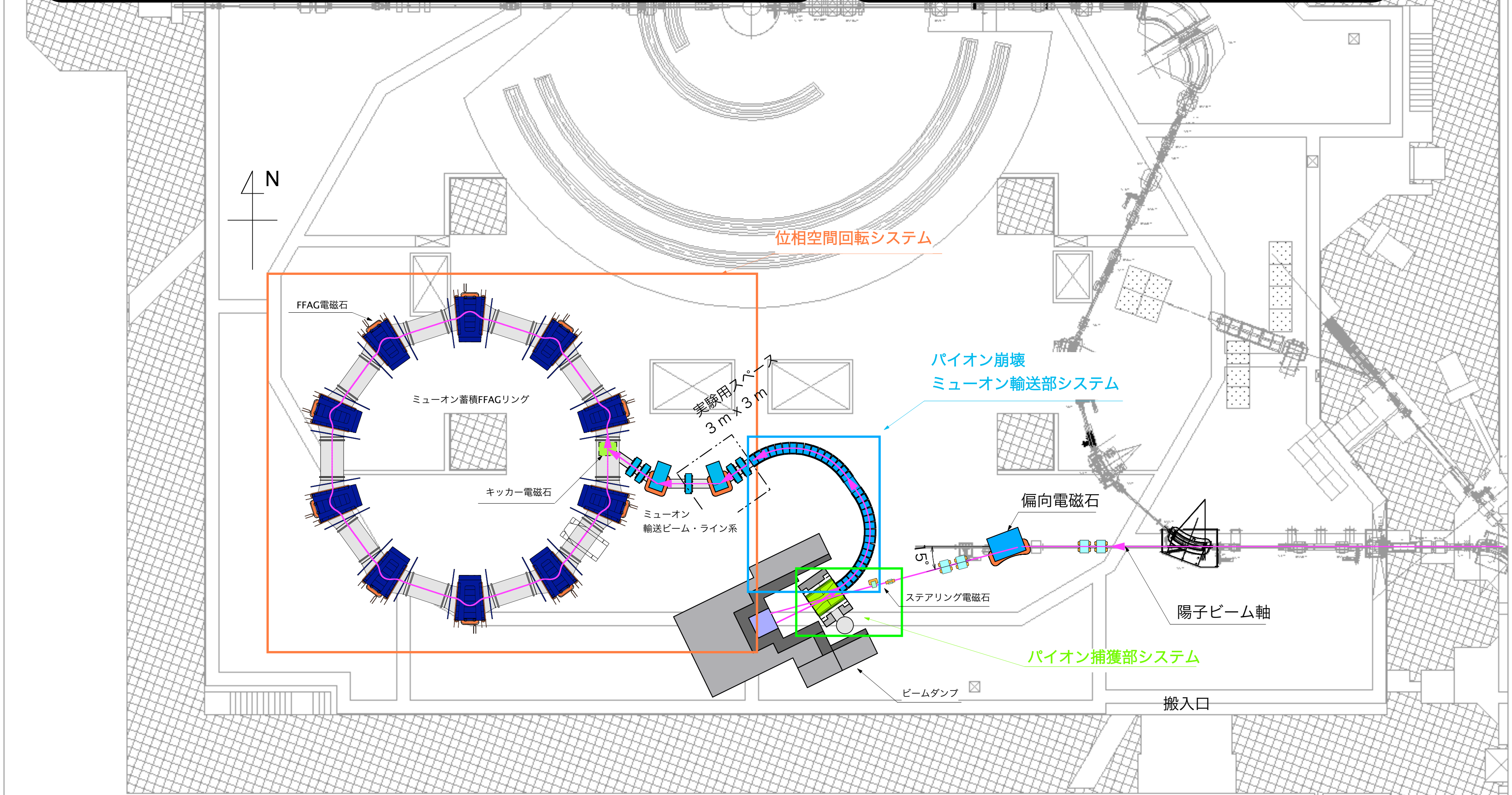
MuSIC (=MUon Science Innovative Commission)

muon yield estimation

proton beam 0.4 kW (400MeV, 1μA)

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

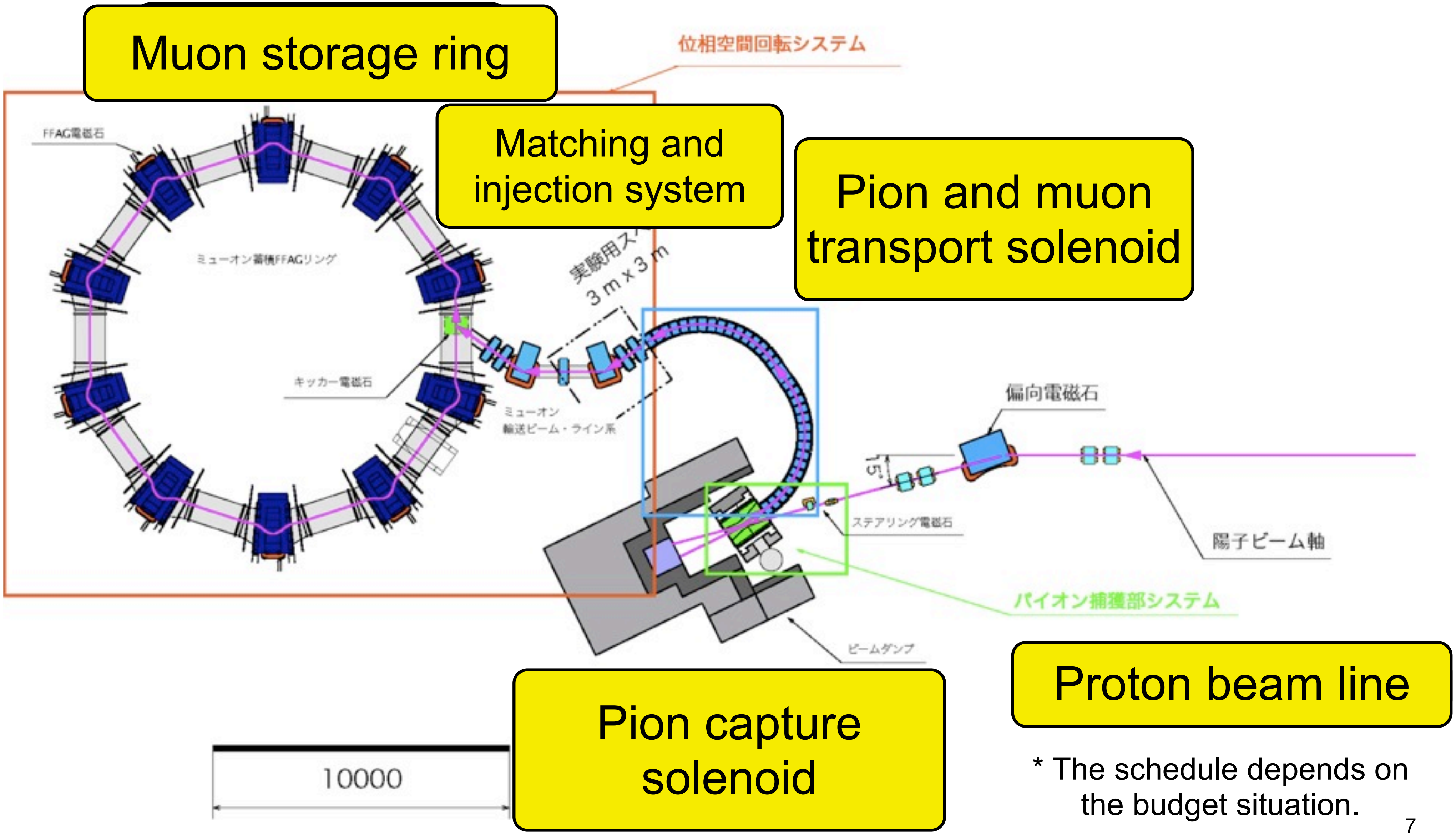
Nuclear and particle physics,
material science
chemistry, and accelerator R&Ds
will be possible.



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.

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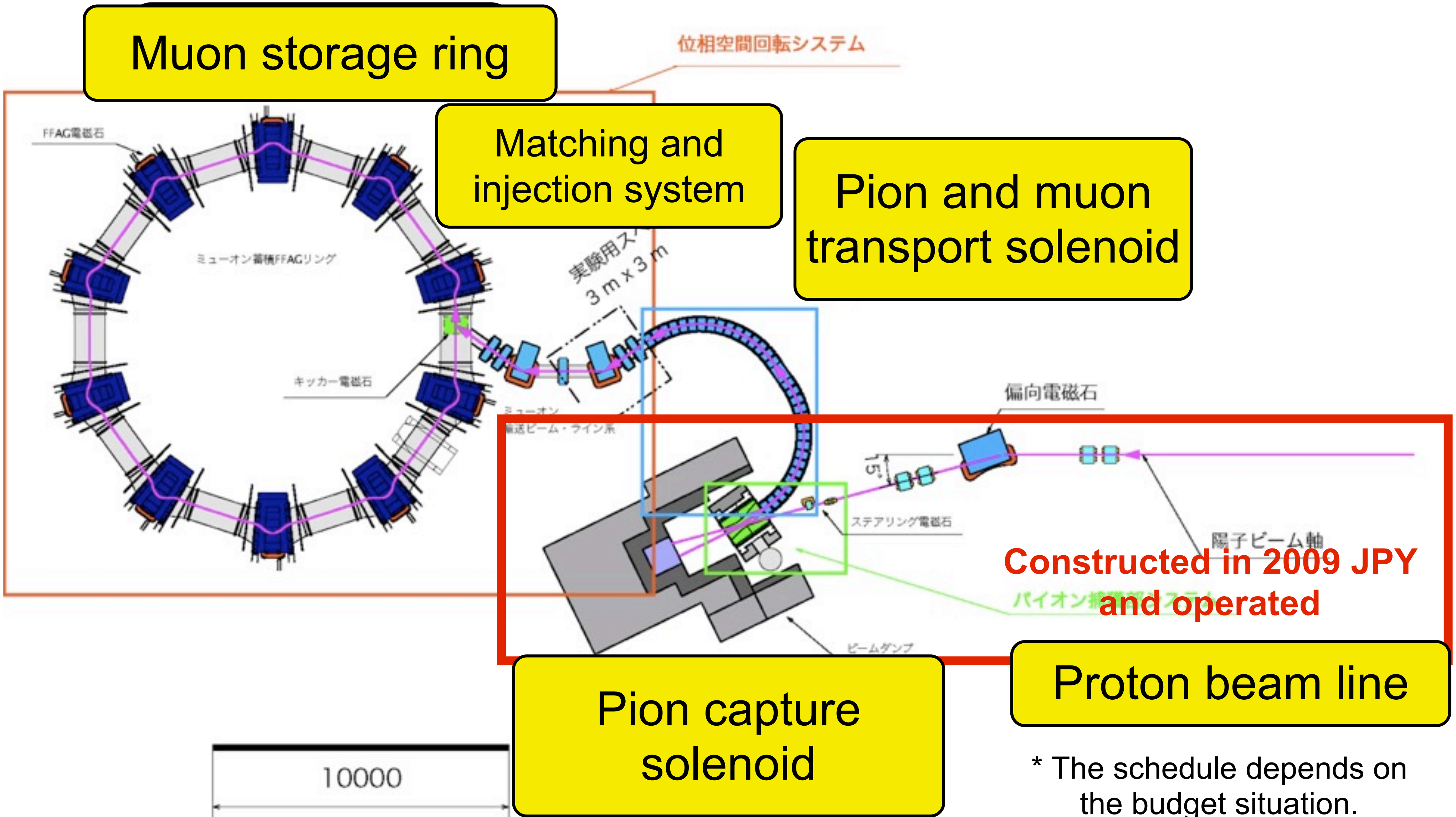

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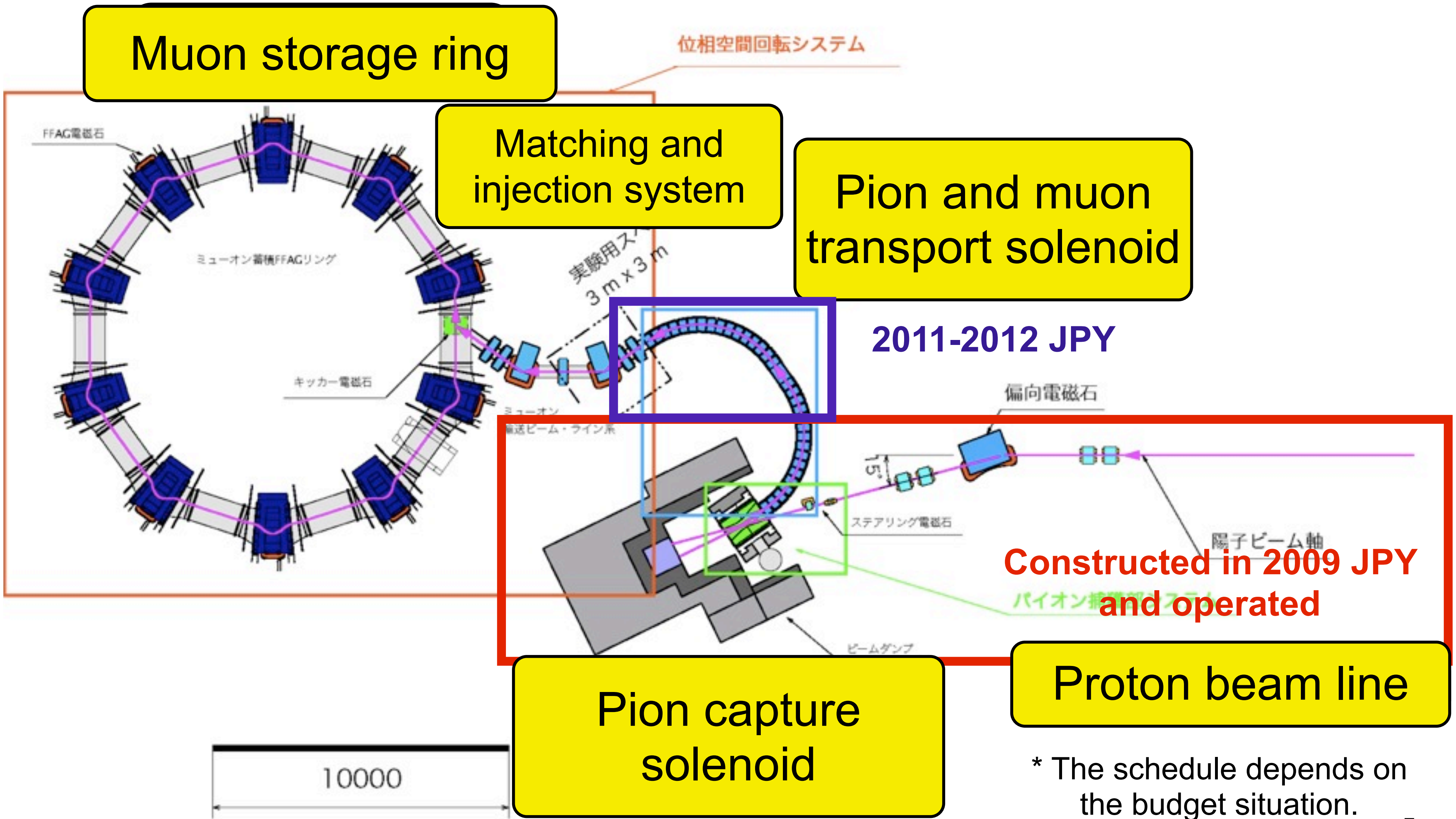

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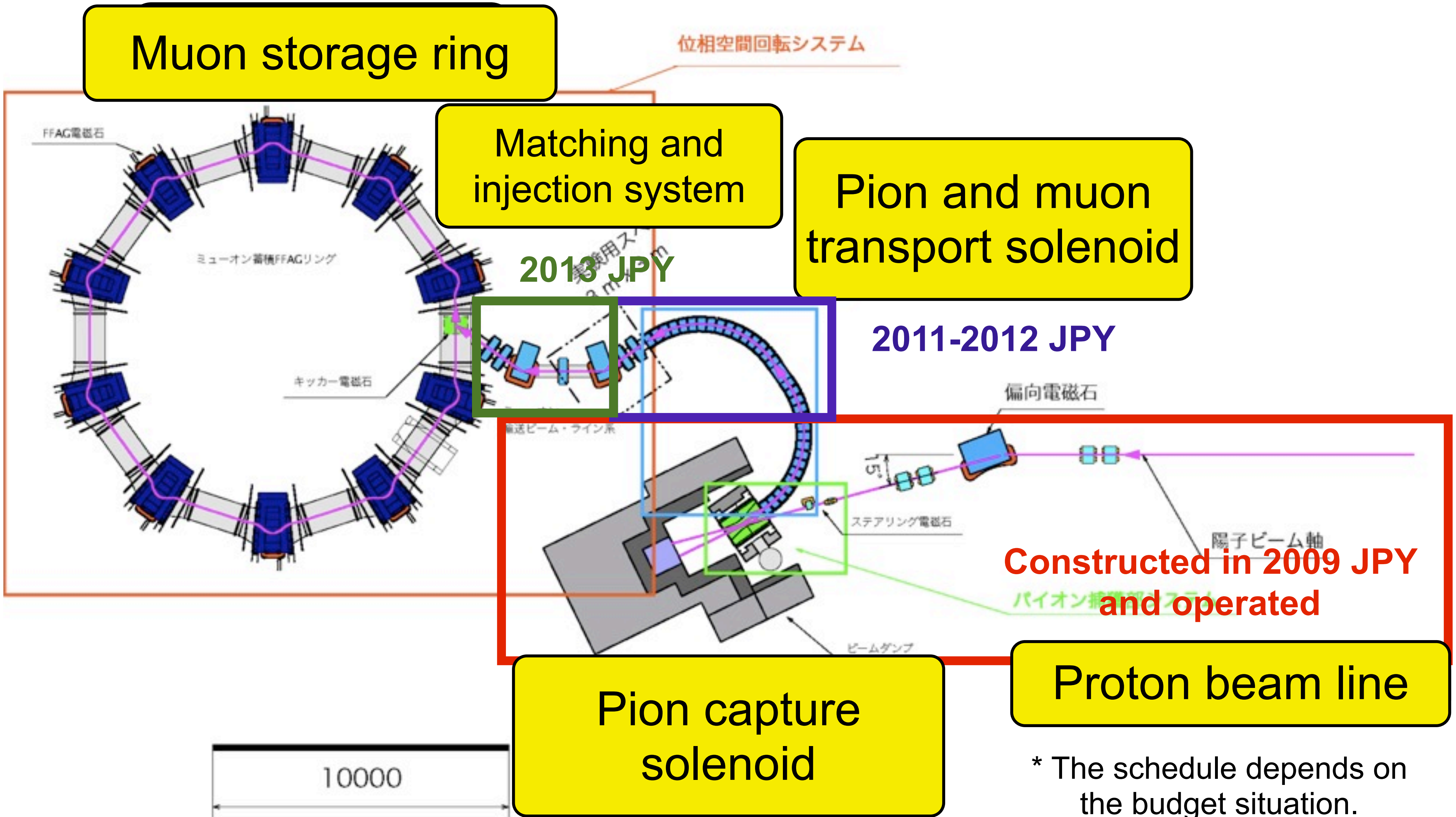

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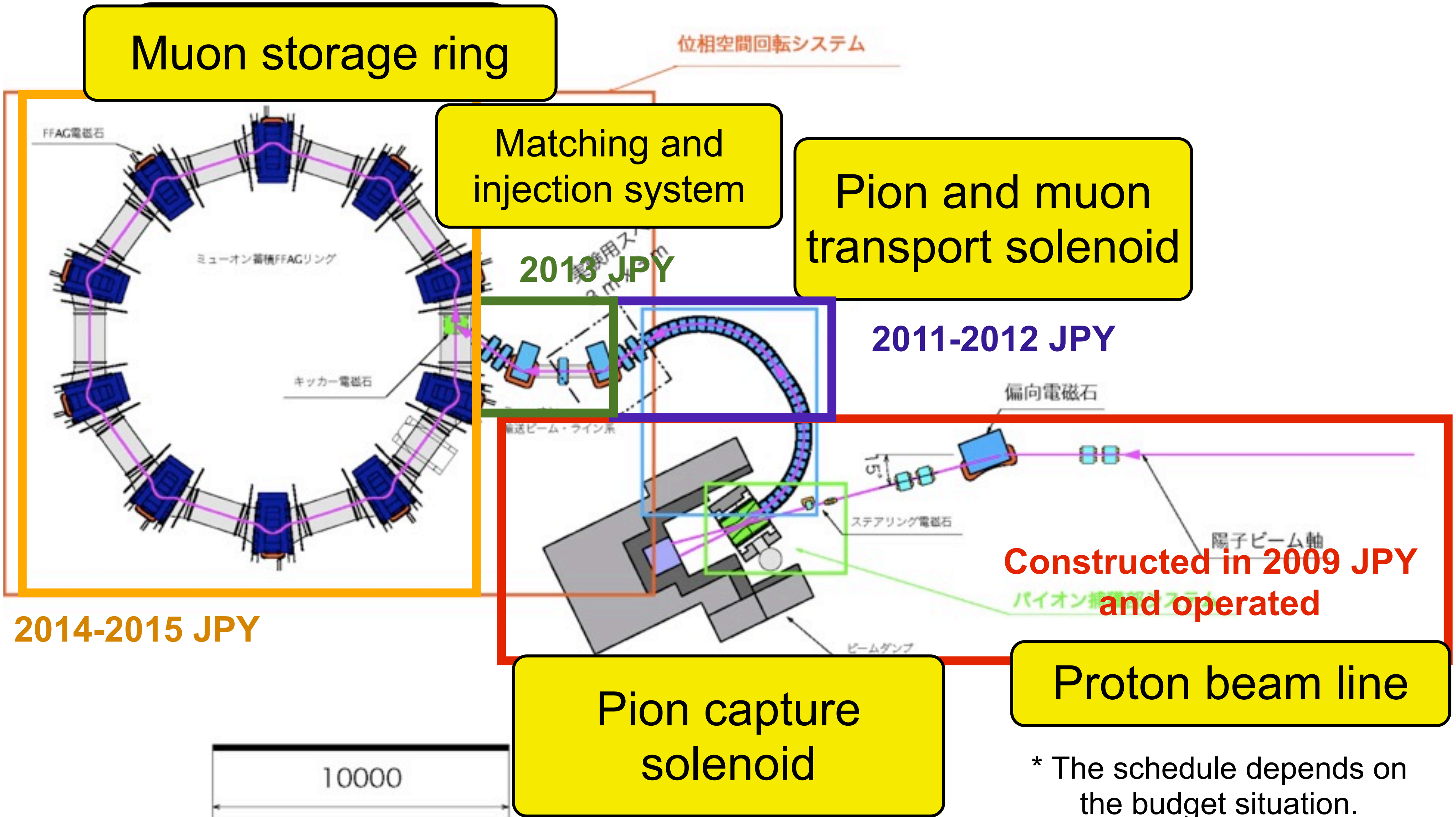

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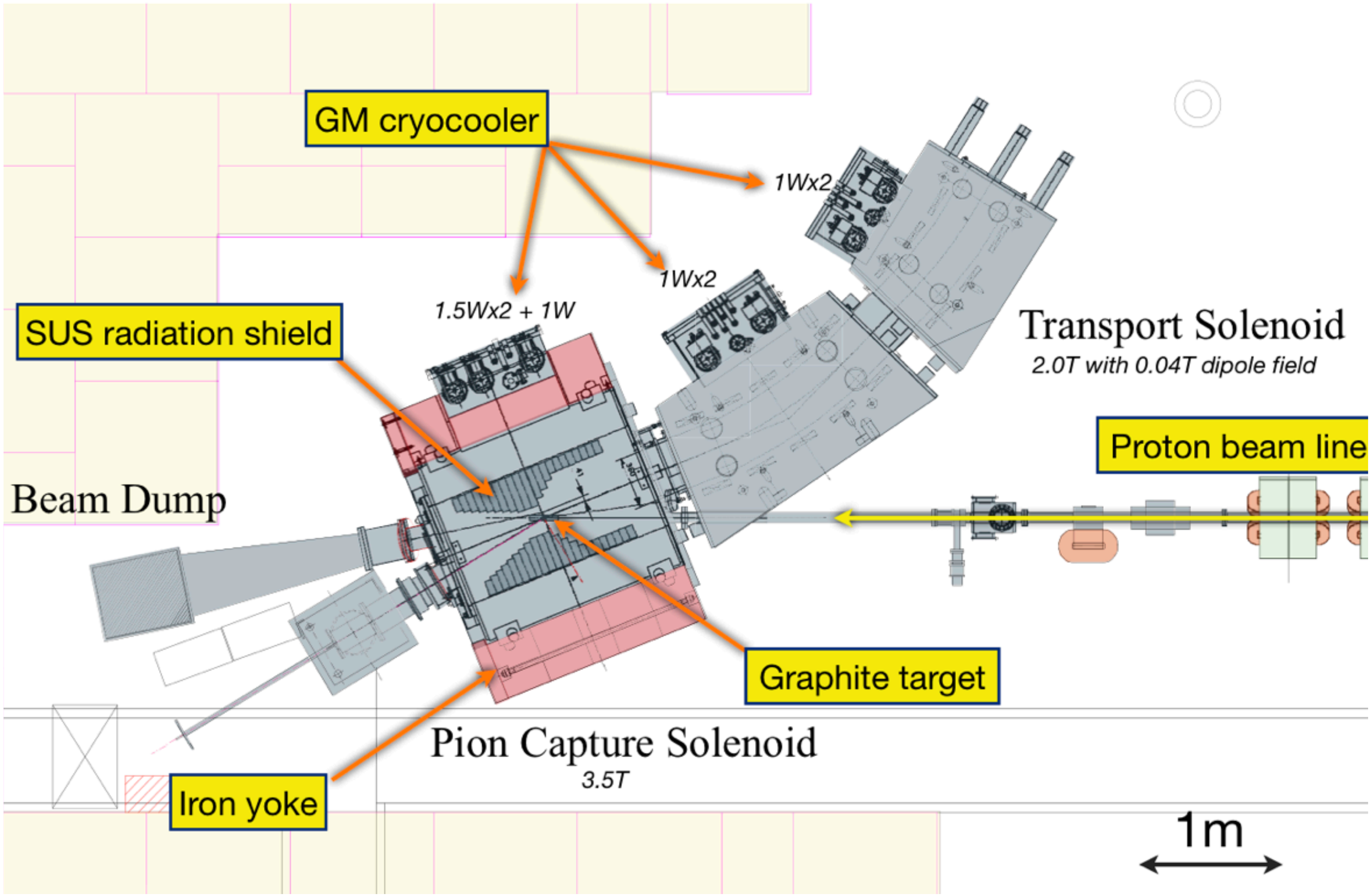
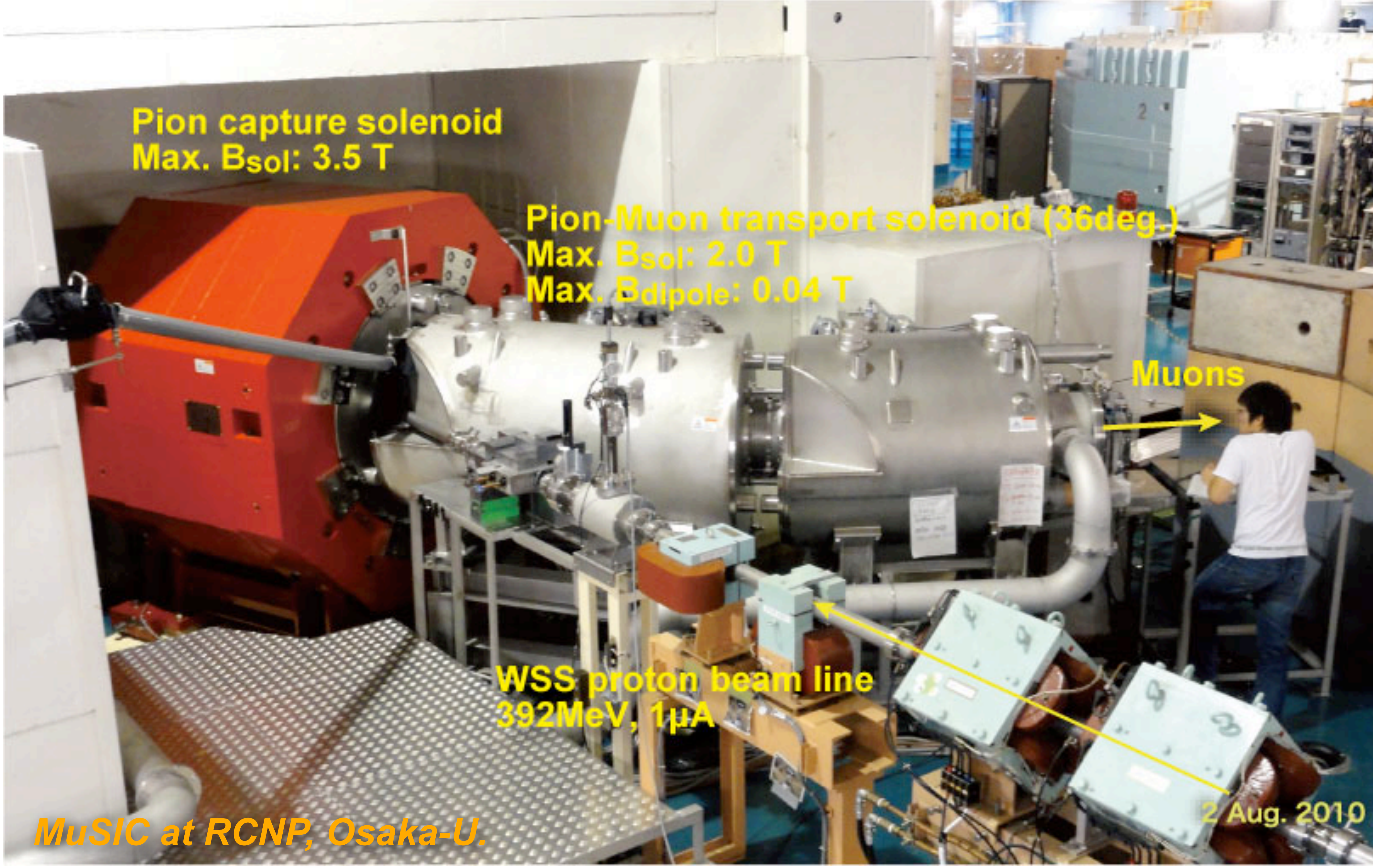
MuSIC in 2010





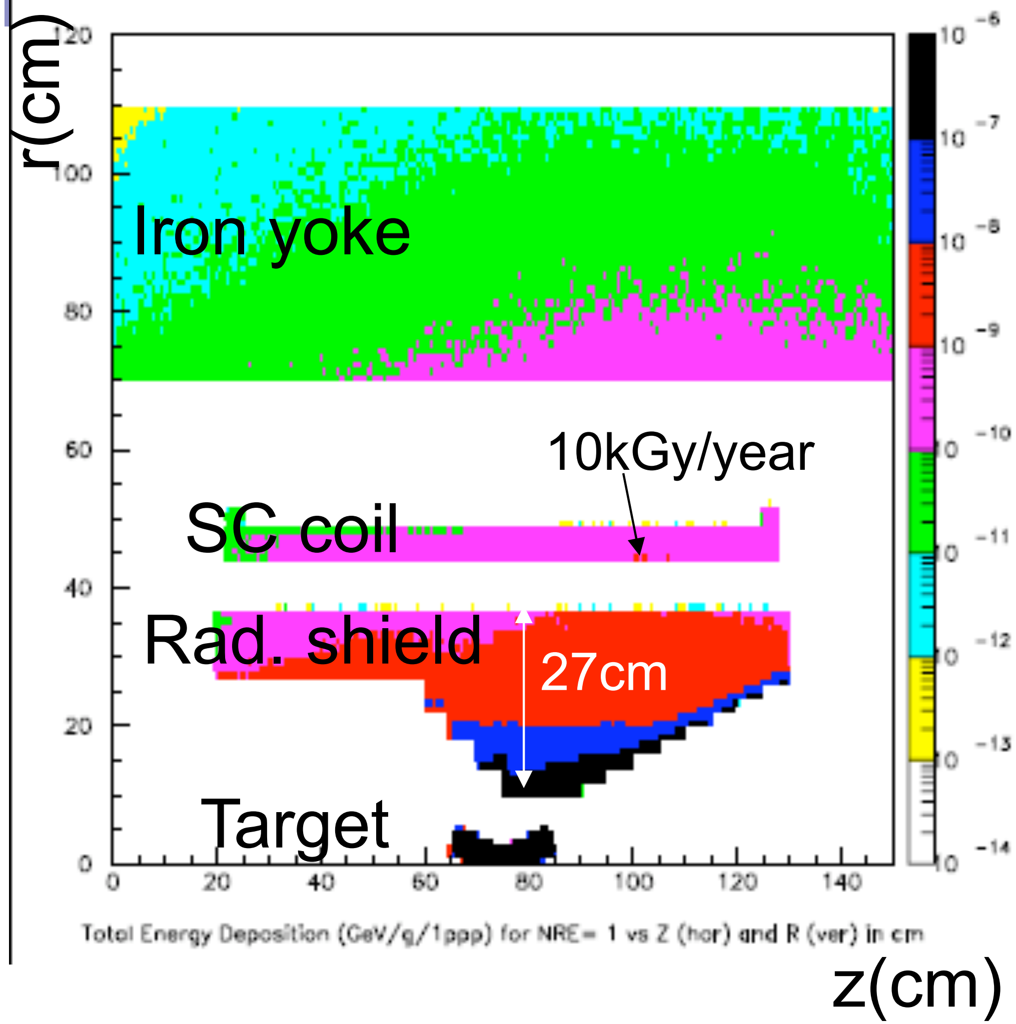
The 1st beam test has been performed at 29-30 July, 2010.
The 2nd beam test will be in January 2011.

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

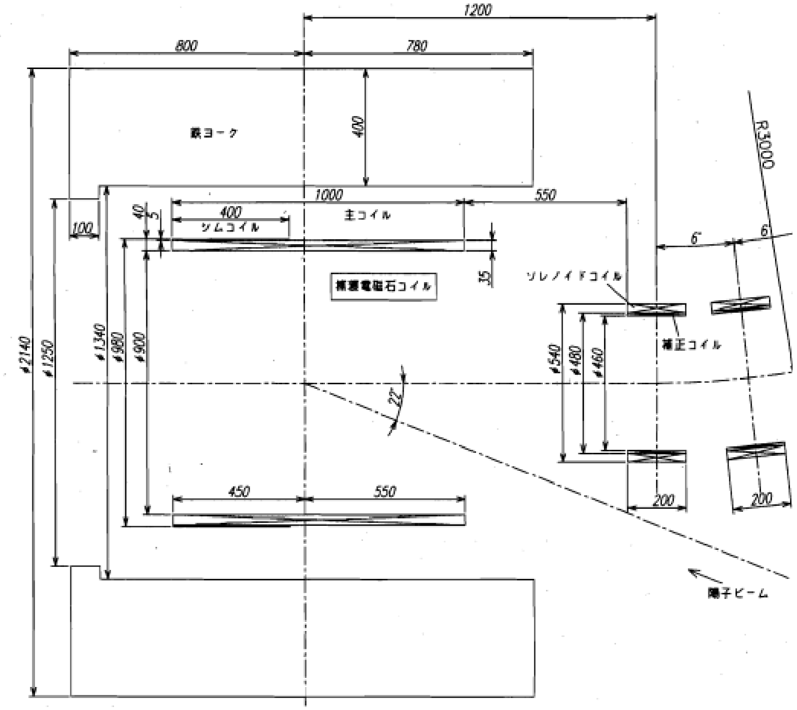
Pion capture solenoid: radiation issue

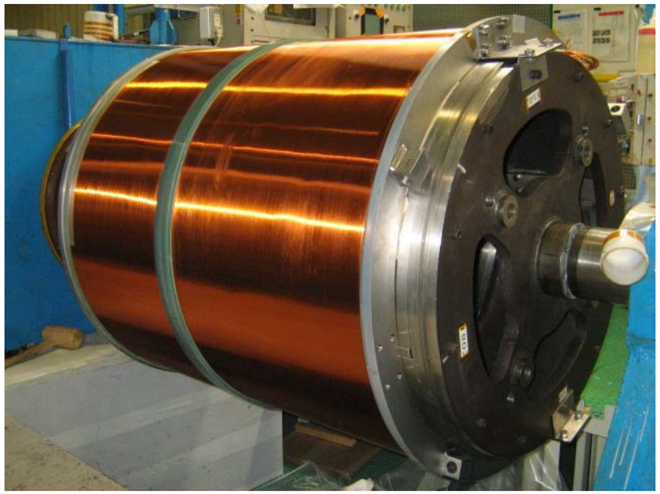
- Radiation shields (27cm thick stainless steels) are installed b/w the target and the coils.
- MC simulation by MARS (M.Yoshida)
  - Heat deposit: 0.6W
    - 0.4W in the coils(~1ton)
    - 0.2W in the coil supports
  - Dose on the coils < 10kGy/year
  - Heat load
    - 100W on the target
    - 50W on 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



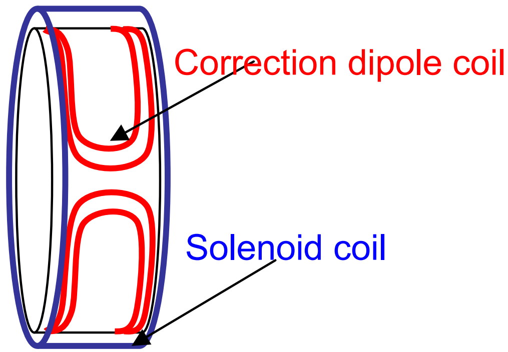


Transport solenoids

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

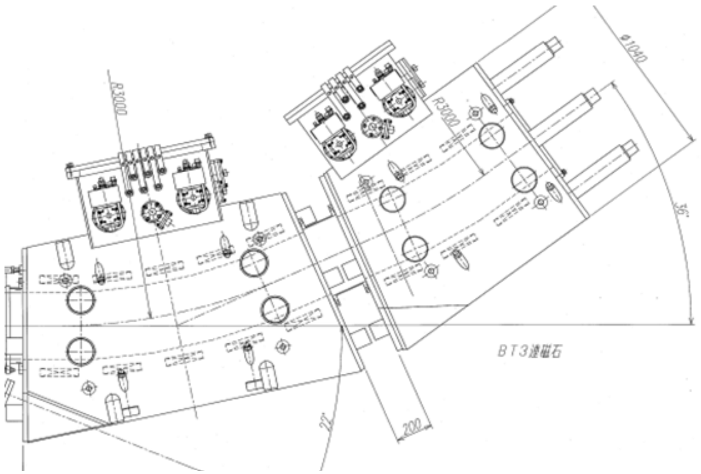
Solenoid coils

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

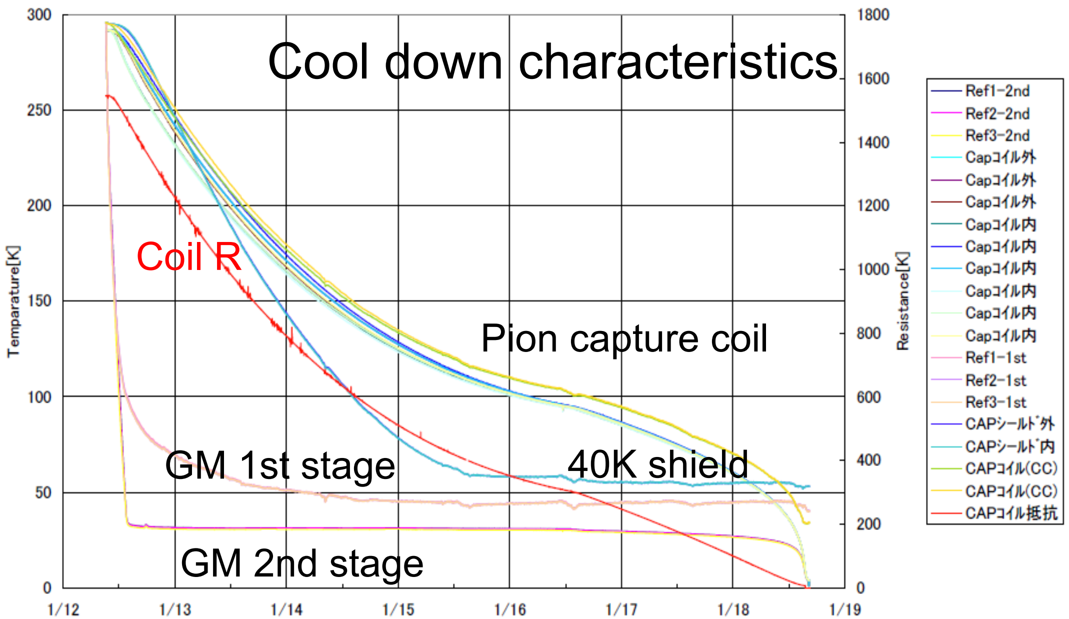
Coil layout	Saddle shape dipole
	6 layers
	528 turns (1 set)
Current	115A (Bipolar)
Field	0.04T
Aperture	ϕ460mm
Length	200mm
Inductance	0.04H/Coil
Stored Energy	280J/Coil



Refrigeration

- Conduction cooling by GM cryocoolers
- Can be cooled down within 1 week with pre-cooling by LN2

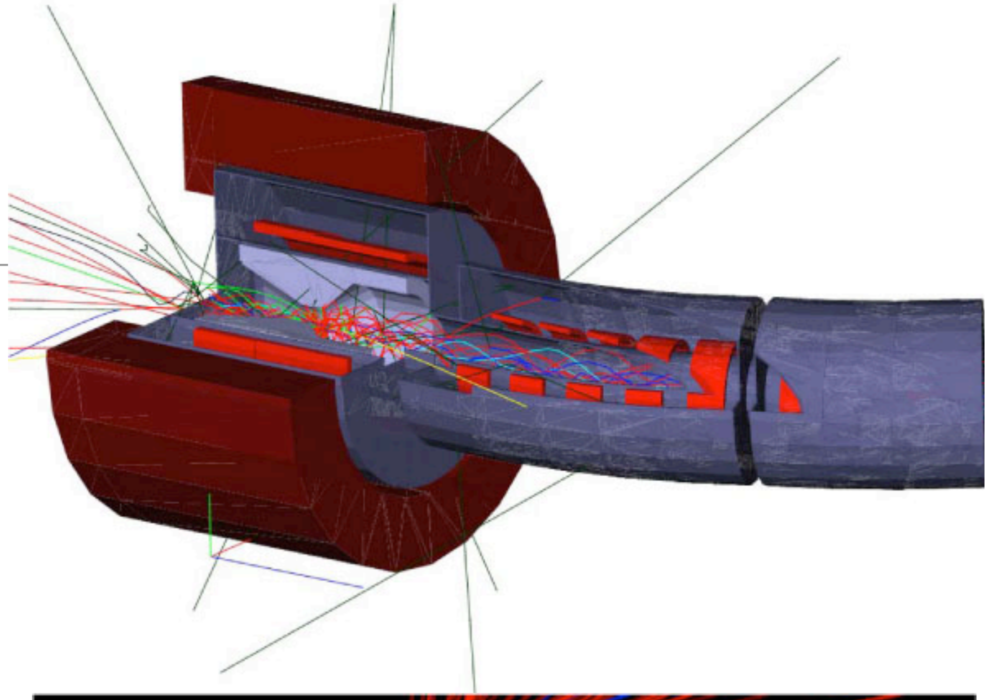
- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 300K→40K: 50W
    - GM 1st stage
  - 3 x GM cryocoler
    - 1.5Wx2+1Wx1 @4K
    - 45Wx2+44W @40K
- Transport solenoid
  - 4K: 0.8W
  - 300K→40K : 50W
    - GM 1st stage
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K
    - 44Wx2 @40K

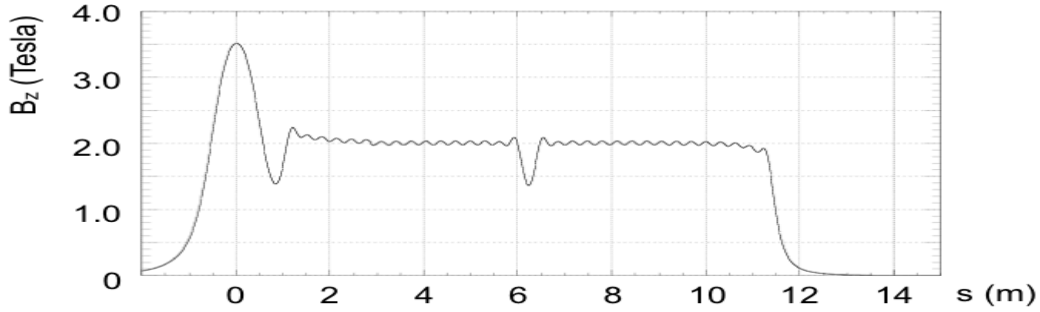


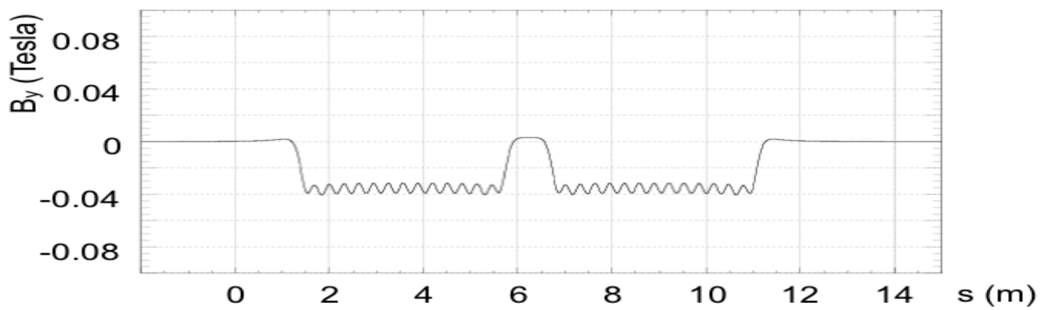
- Achievable temperature
  - Pion capture solenoid : 3.7K
  - Transport solenoids : 4.2K-4.5K(BT3), 4.5K-5.8K(BT5)

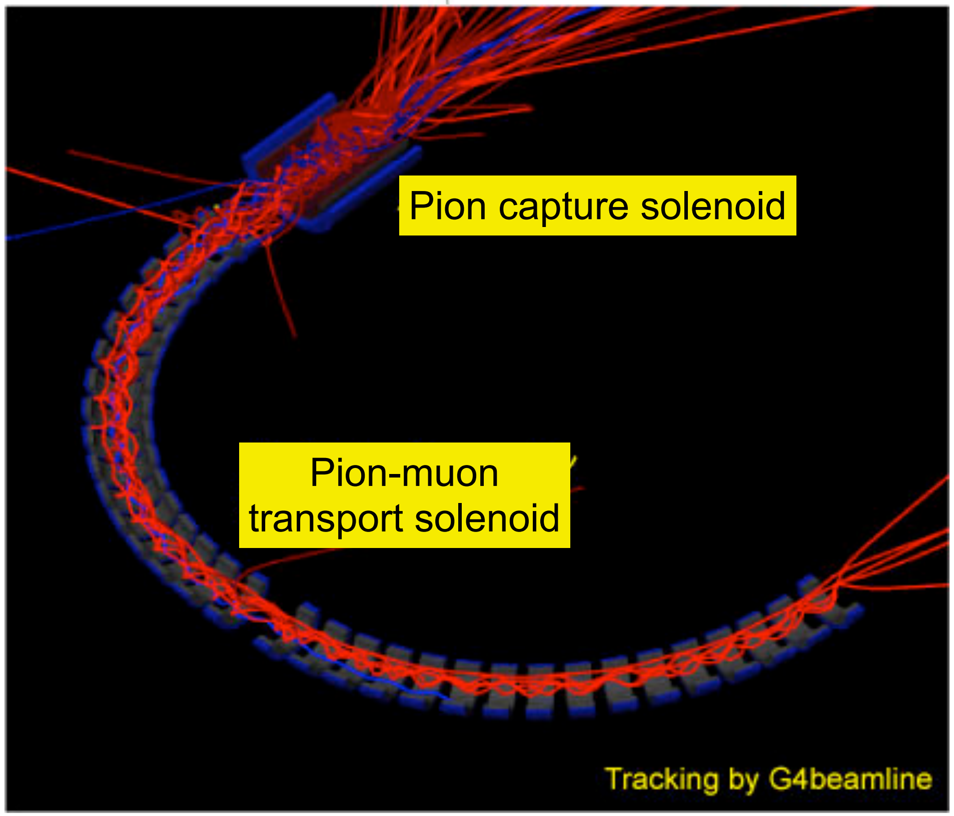
Expected Muon Yield

- 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



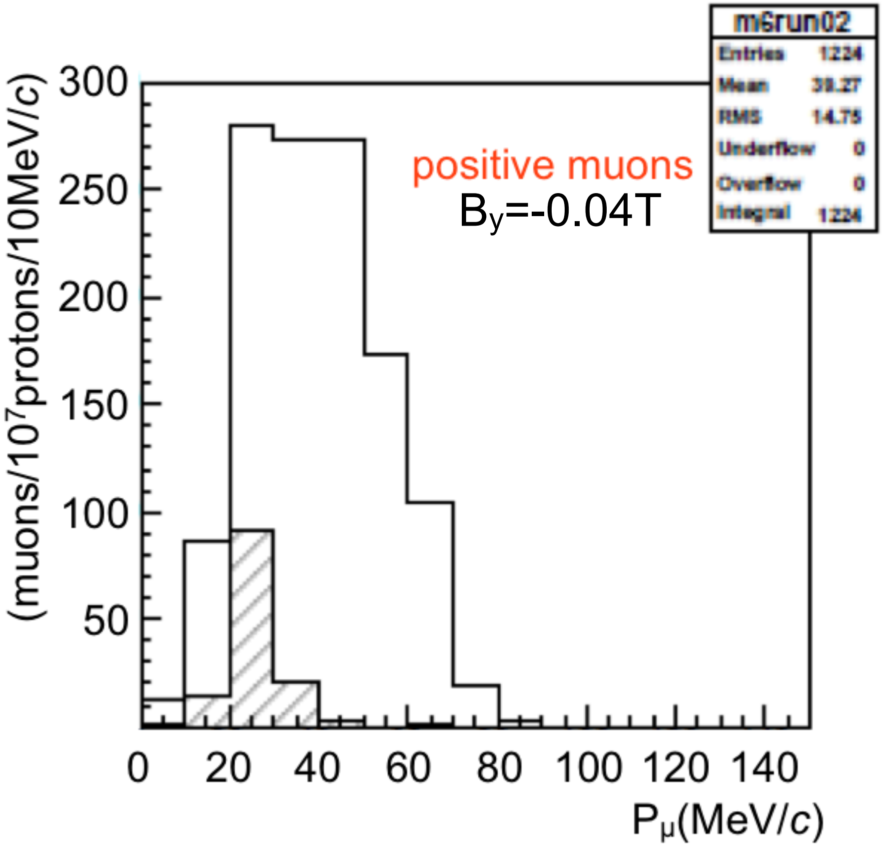


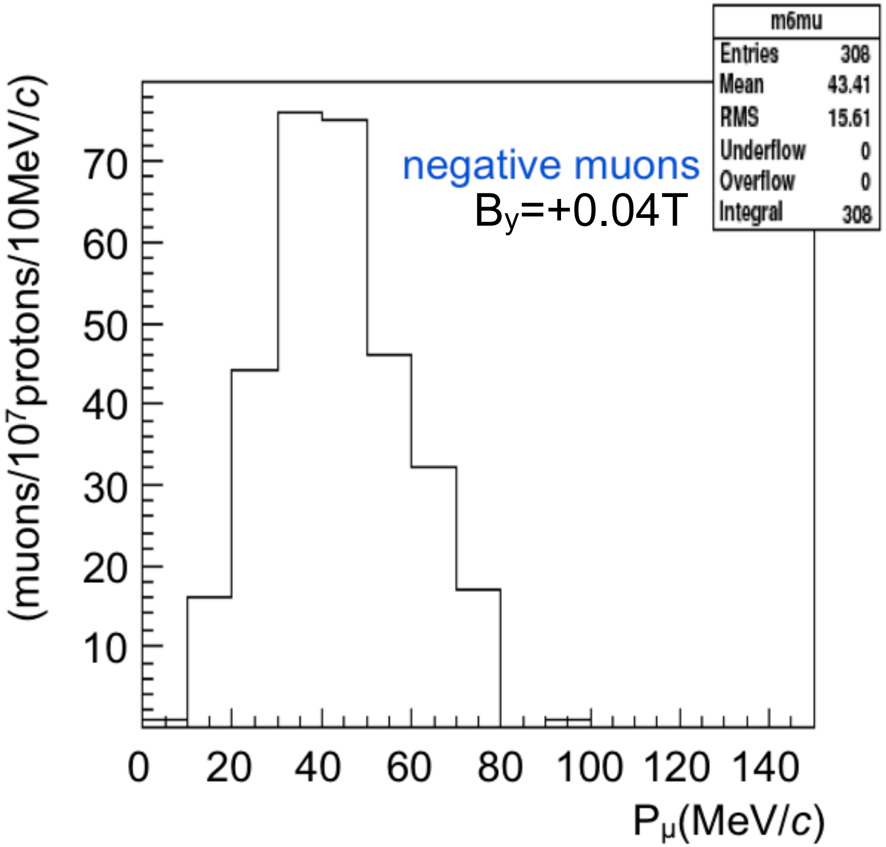




Simulation results for $B_y = \pm 0.04T$

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

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

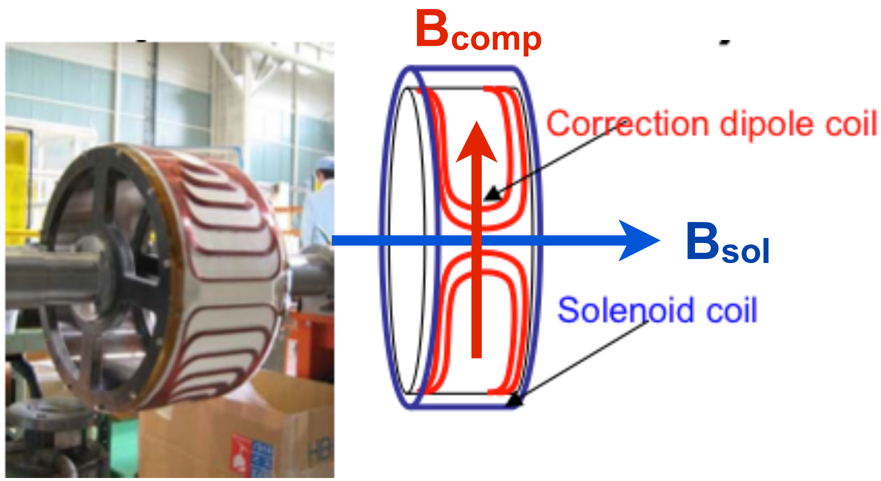
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan*(P_T/P_L)

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

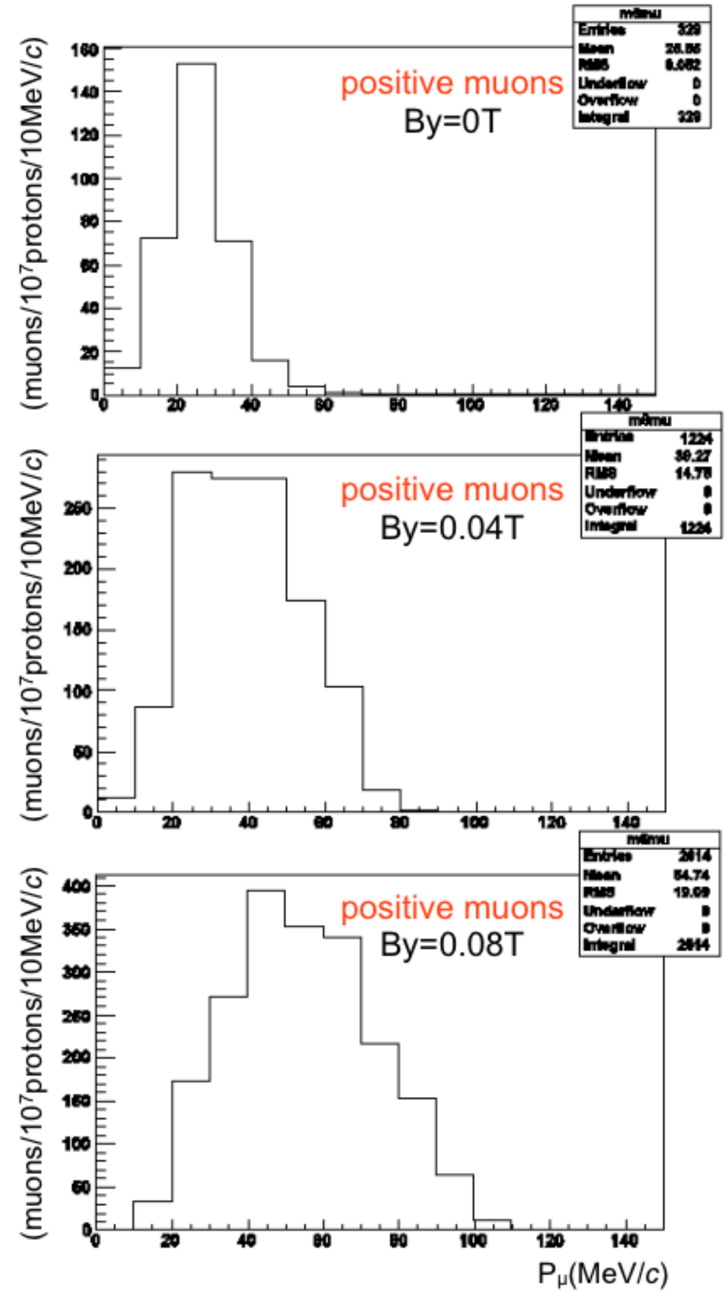
- This drift can be compensated by an auxiliary dipole field parallel to the drift direction given by

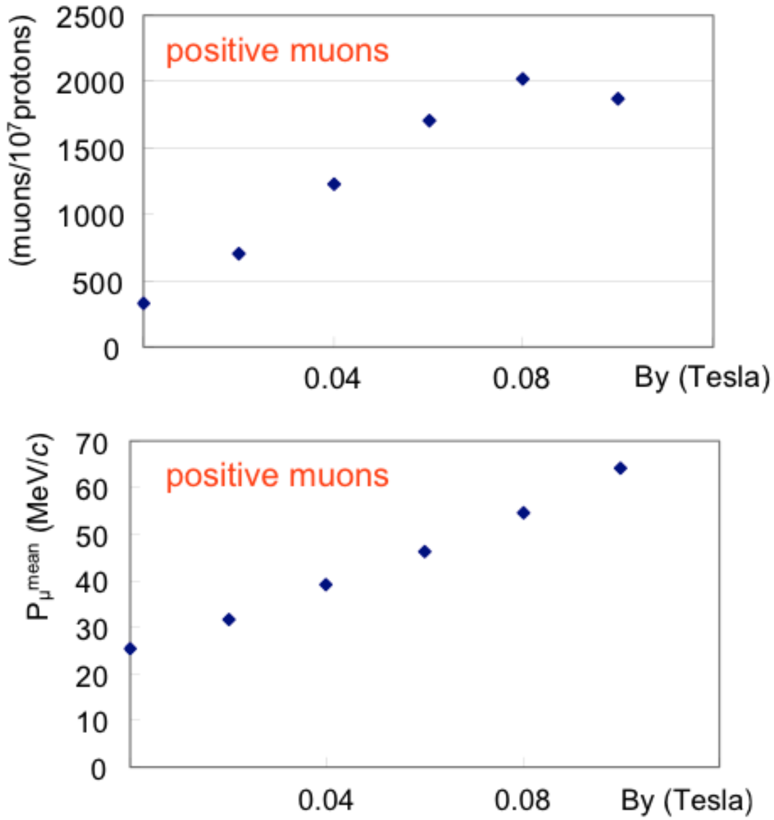
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

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

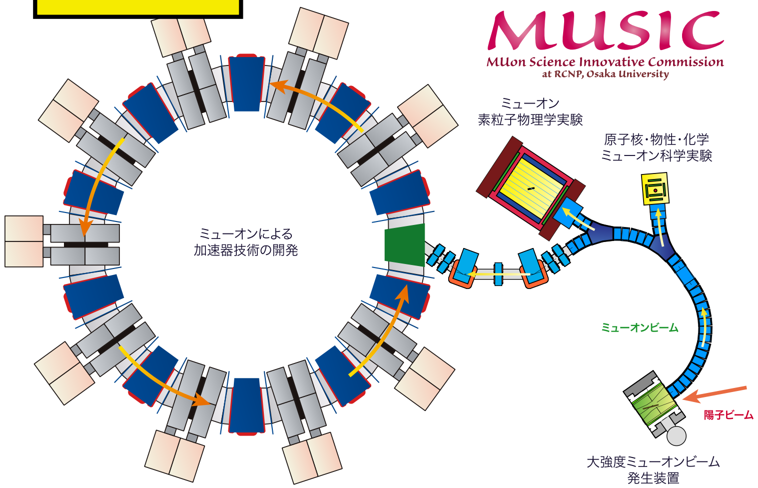




Wishful Staging Scenario

2009-2016

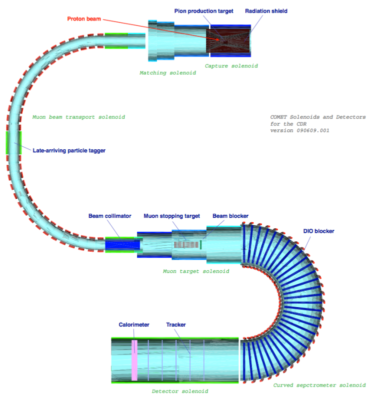
MuSIC



Proton beam:0.4kW
DC muon:10^8/s

2017-

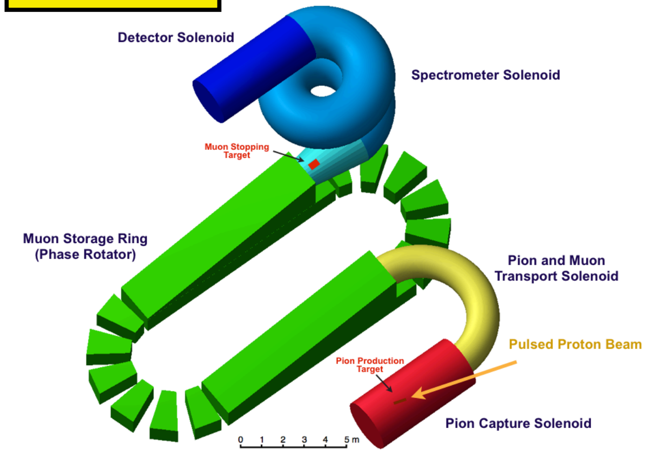
COMET/Mu2e



Proton beam:56kW
pulsed muon:10^{11}/s

2020?

PRISM



Proton beam:1000-4000kW
pulsed muon:$10^{12\text{-}13}$/s

μ-eee search
Solenoid R&D → **μ-e conv. search** → **The ultimate μ-e conv. study**
Accelerator R&D → **The ultimate μ-e conv. study**

2019?? **Neutrino factory**
Muon collider

pulsed muon:$10^{13\text{-}14}$/s

MuSIC is a very important step
for the future muon programs.

Conclusions

- A new intense DC muon beam line is under construction at RCNP, Osaka University. The construction would be finished in 5 years (depends on the budget situation). This is the first muon facility which adopts a superconducting pion capture system. It would provide 10^8muons/sec.
- The pion capture solenoid and a 36 deg. of transport solenoid have been build and successfully operated with a 4nA proton beam.
- We still need to design and optimize the transport solenoid and muon storage ring. Studies for the muon beam optimization for various experiments have been just started.
- Your comments on design of the beamline and beam quality are very welcomed. If you are interest in MuSIC, please join us.