High Intensity Muon Beams in Osaka - MuSIC

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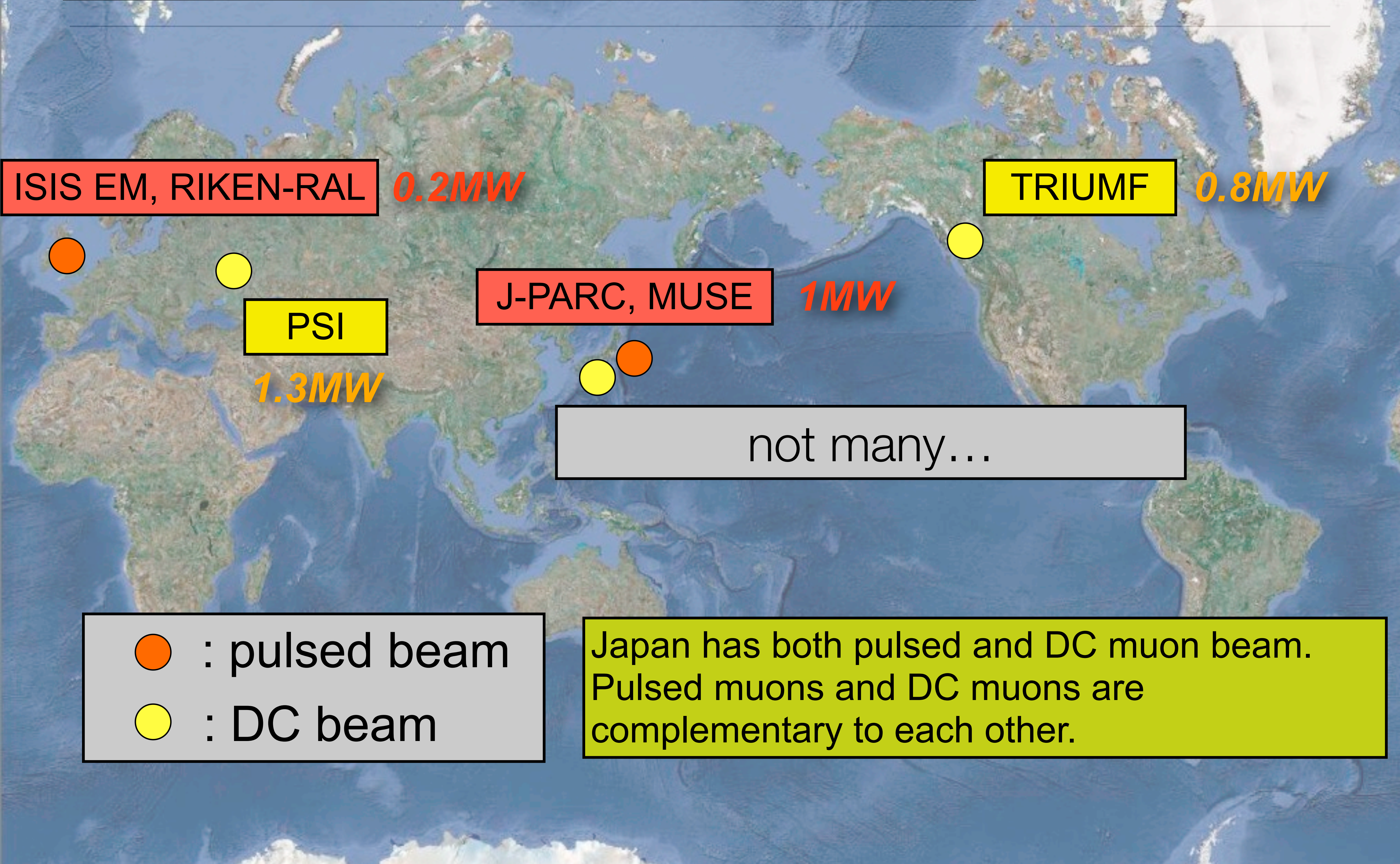
Outline

- Highly Intense Muon Beam Source
  - Pion Capture
  - Muon Transport
  - COMET
- MuSIC facility at Osaka University
- MuSIC stage-I for μSR
- PRISM demonstration at MuSIC
  - Phase Rotation at FFAG
- Summary

Muon Beam Sources

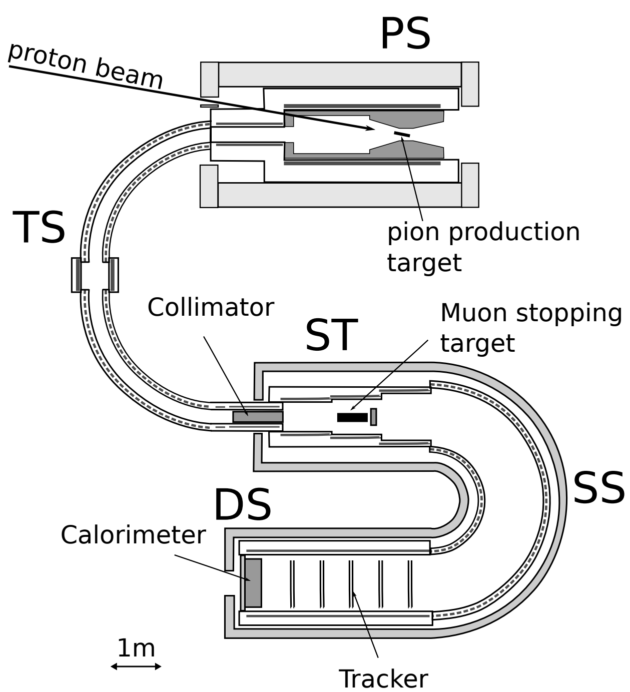
Muon facility in the world



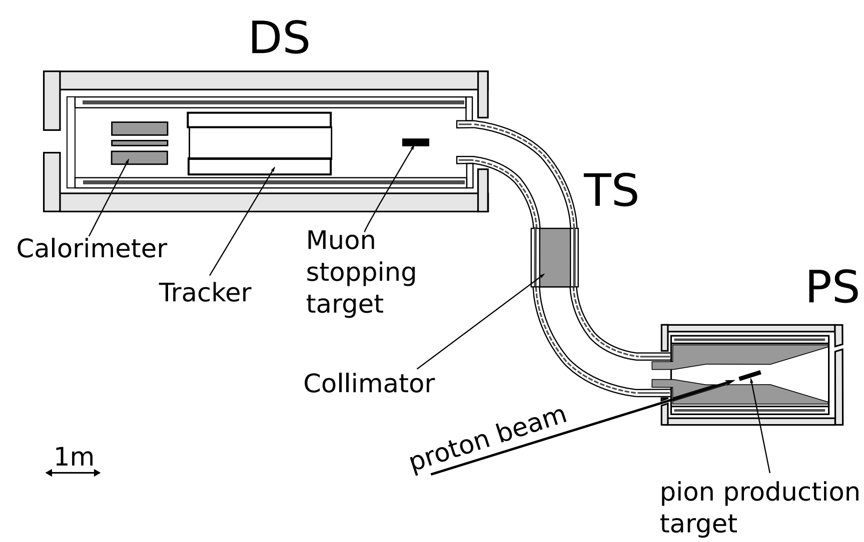
Japan has both pulsed and DC muon beam. Pulsed muons and DC muons are complementary to each other.

Needs for Highly Intense Muon Beam Sources

COMET 5T, 56kW

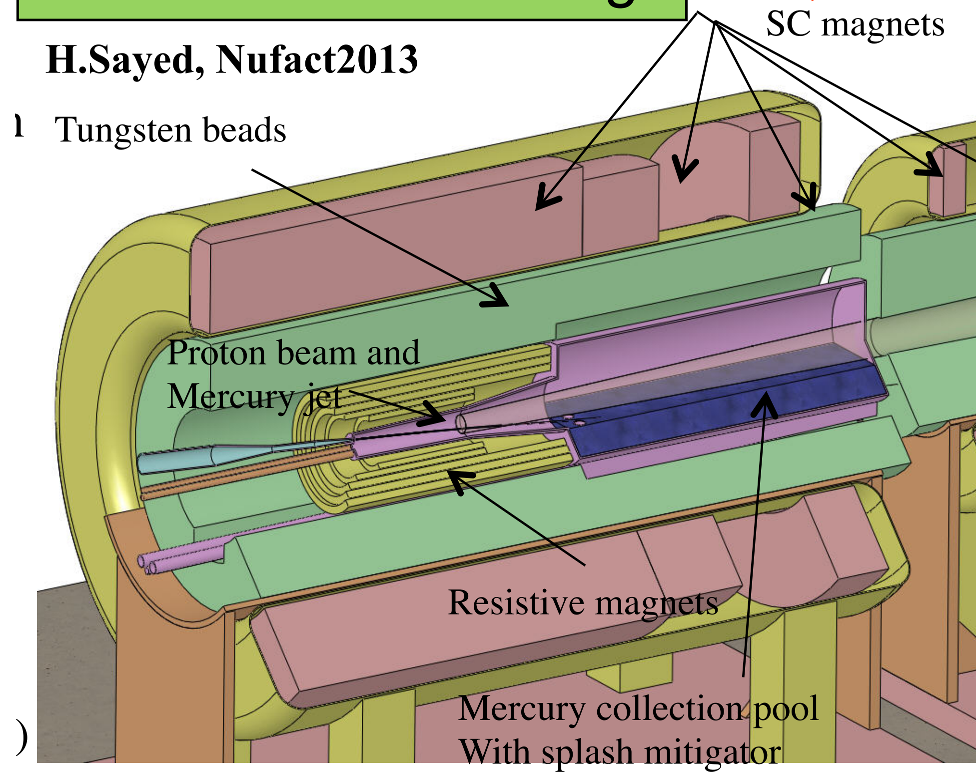


Mu2e 4.6T, 8kW



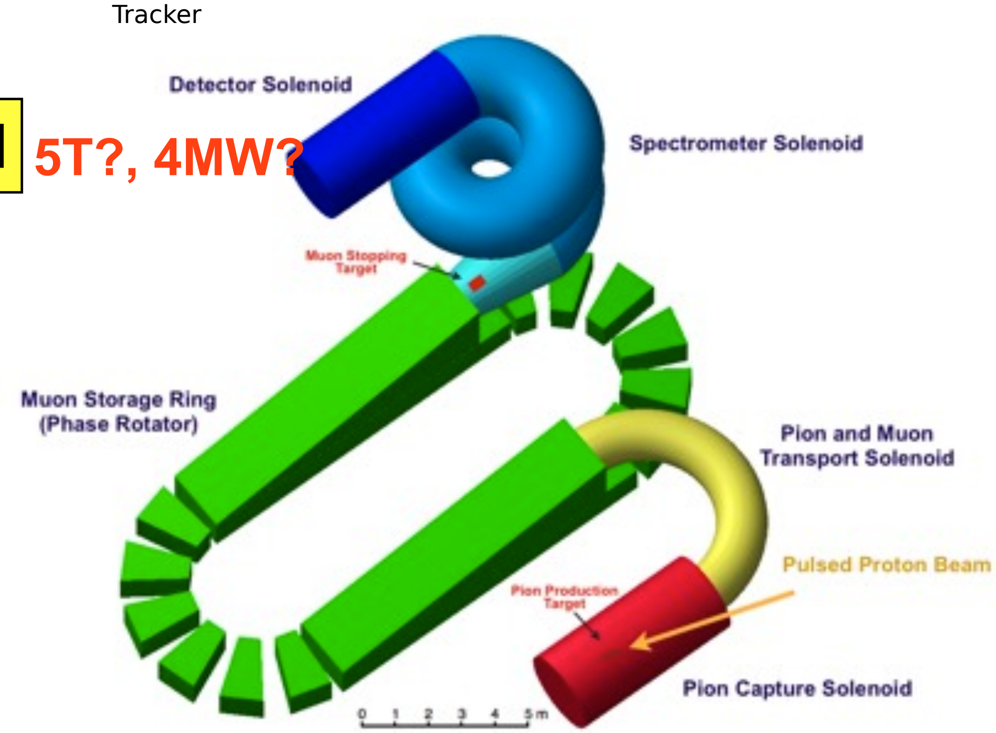
NuFact baseline design 20T, 4MW

H.Sayed, Nufact2013



5-T copper magnet insert; 10-T Nb3Sn coil + 5-T NbTi outsert.
Desirable to eliminate the copper magnet (or replace by a 20-T HTS insert).

PRISM 5T?, 4MW?

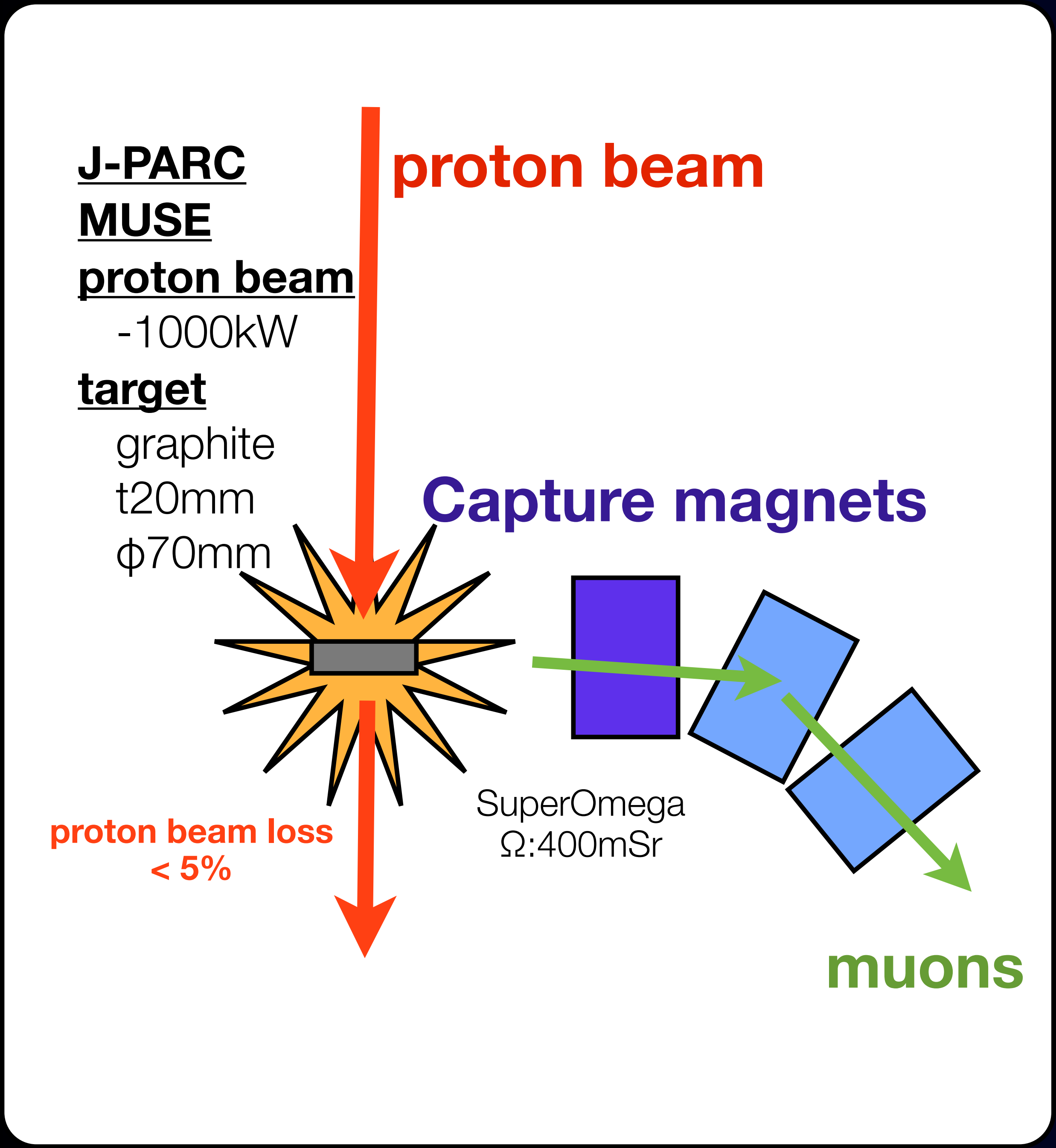


Pion Capture

Conventional Muon Beamline

Conventional Muon Beamline

Conventional muon beamline



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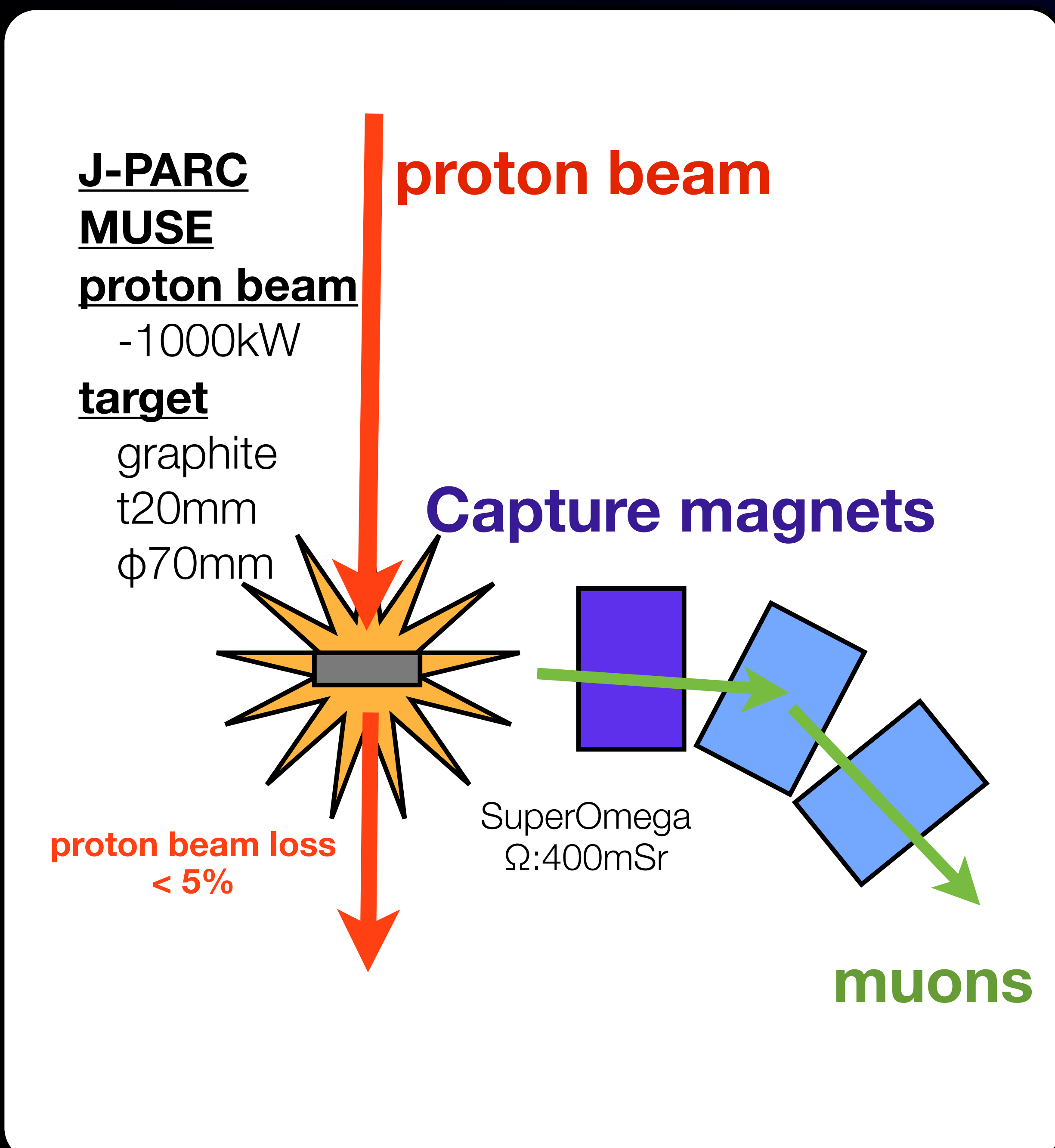
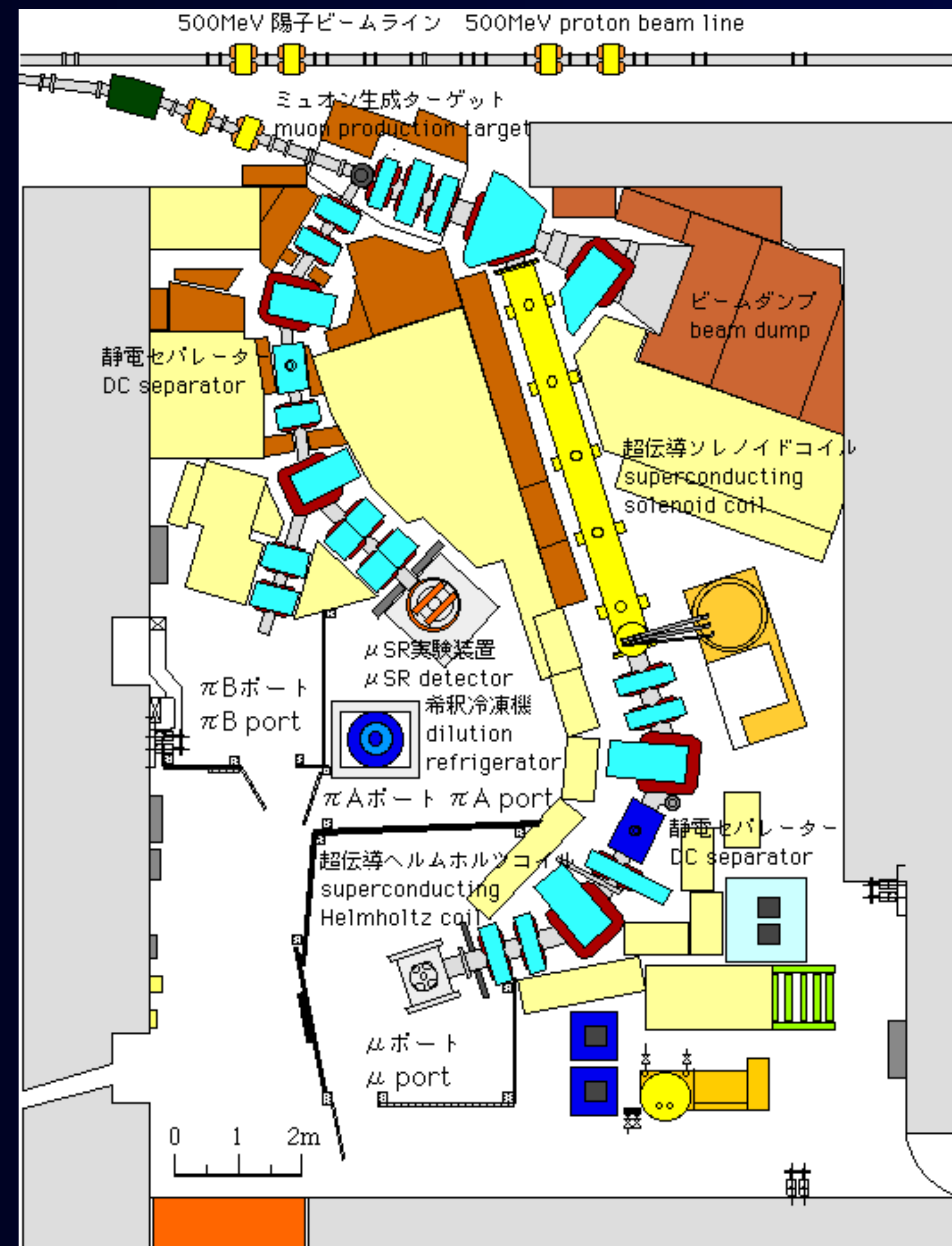
Conventional muon beamline



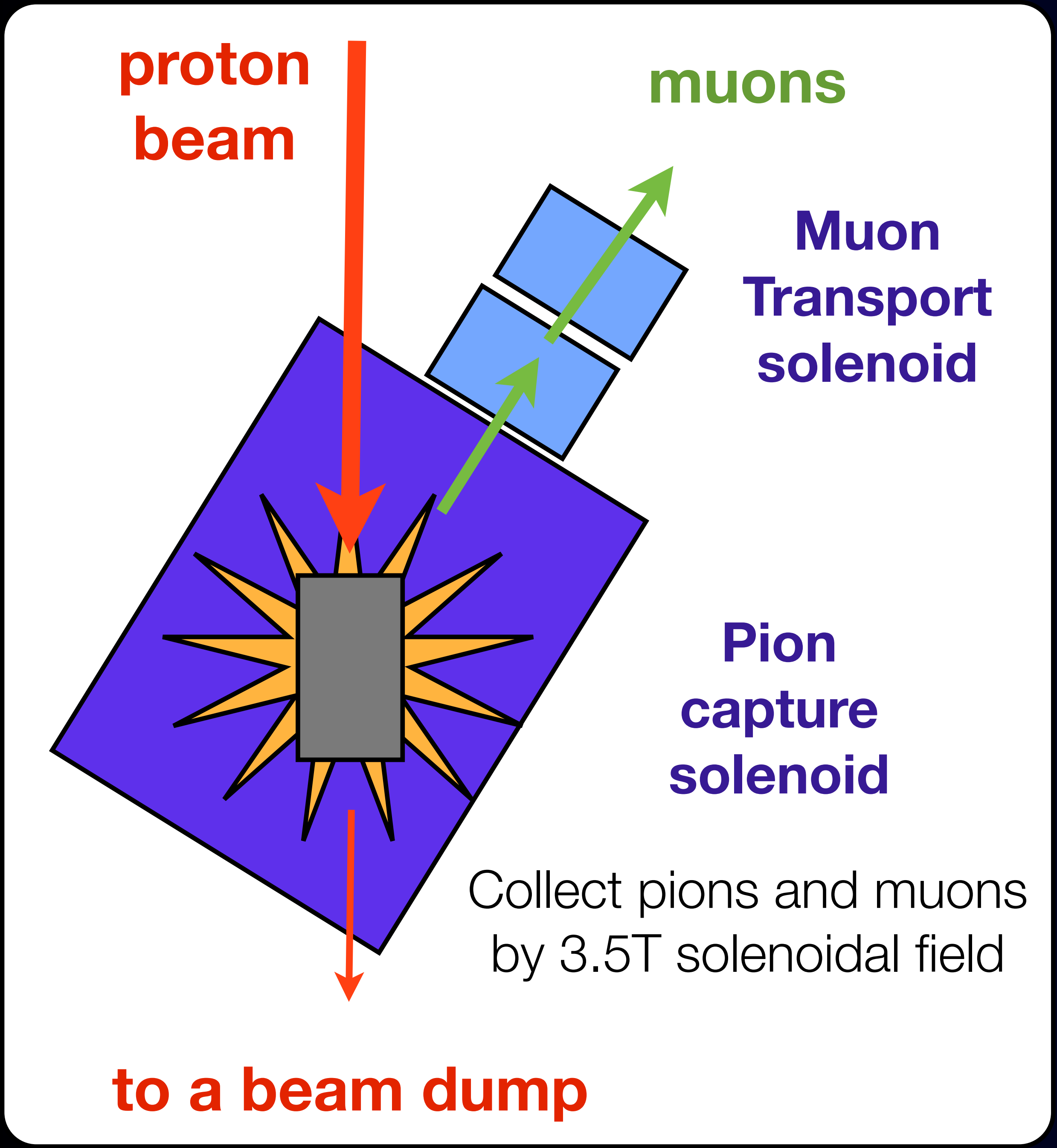
KEK 0.5GeV proton Muon facility



Novel Muon Beamline

Novel Muon Beamline

Novel muon beamline



Novel Muon Beamline

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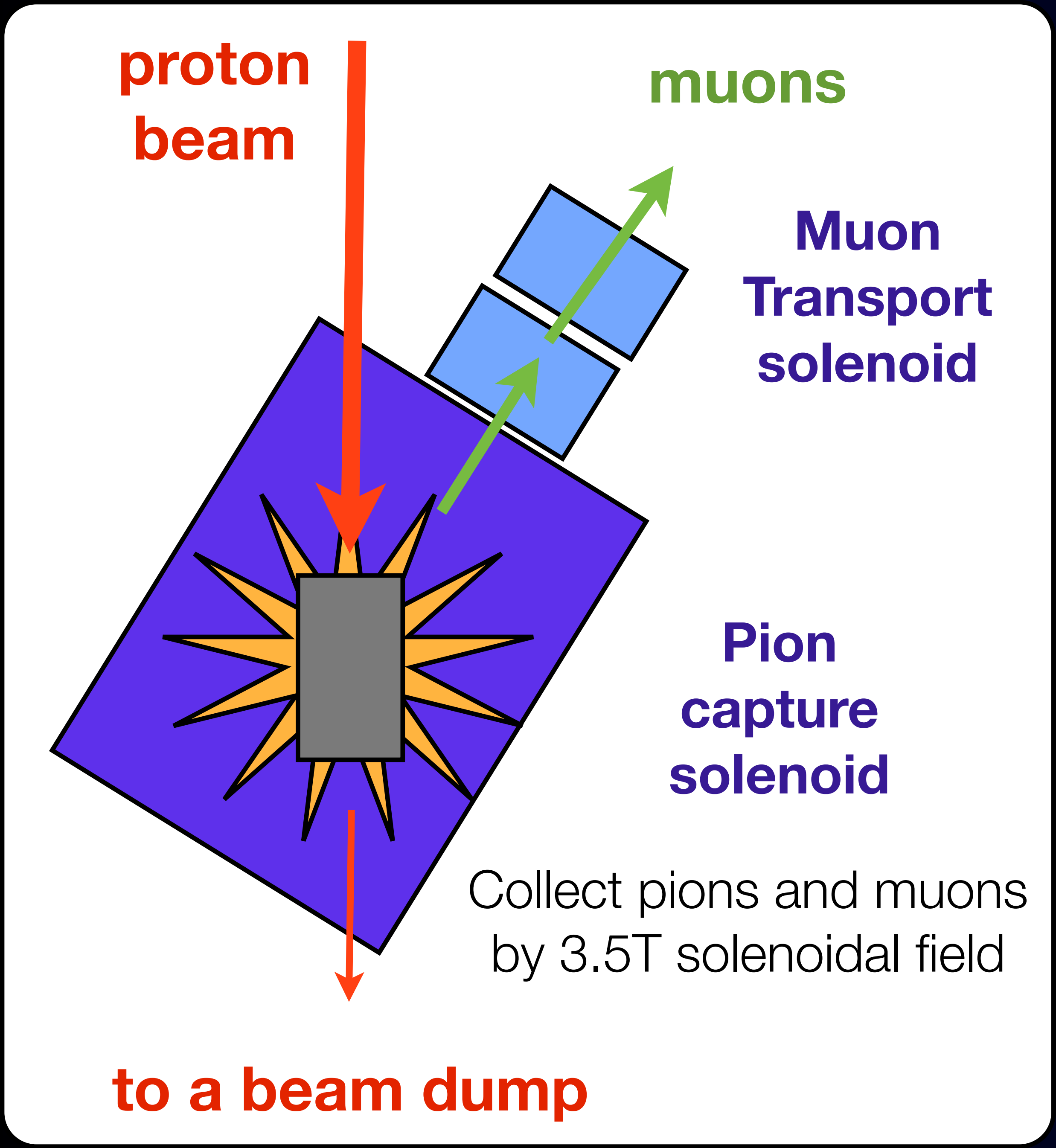
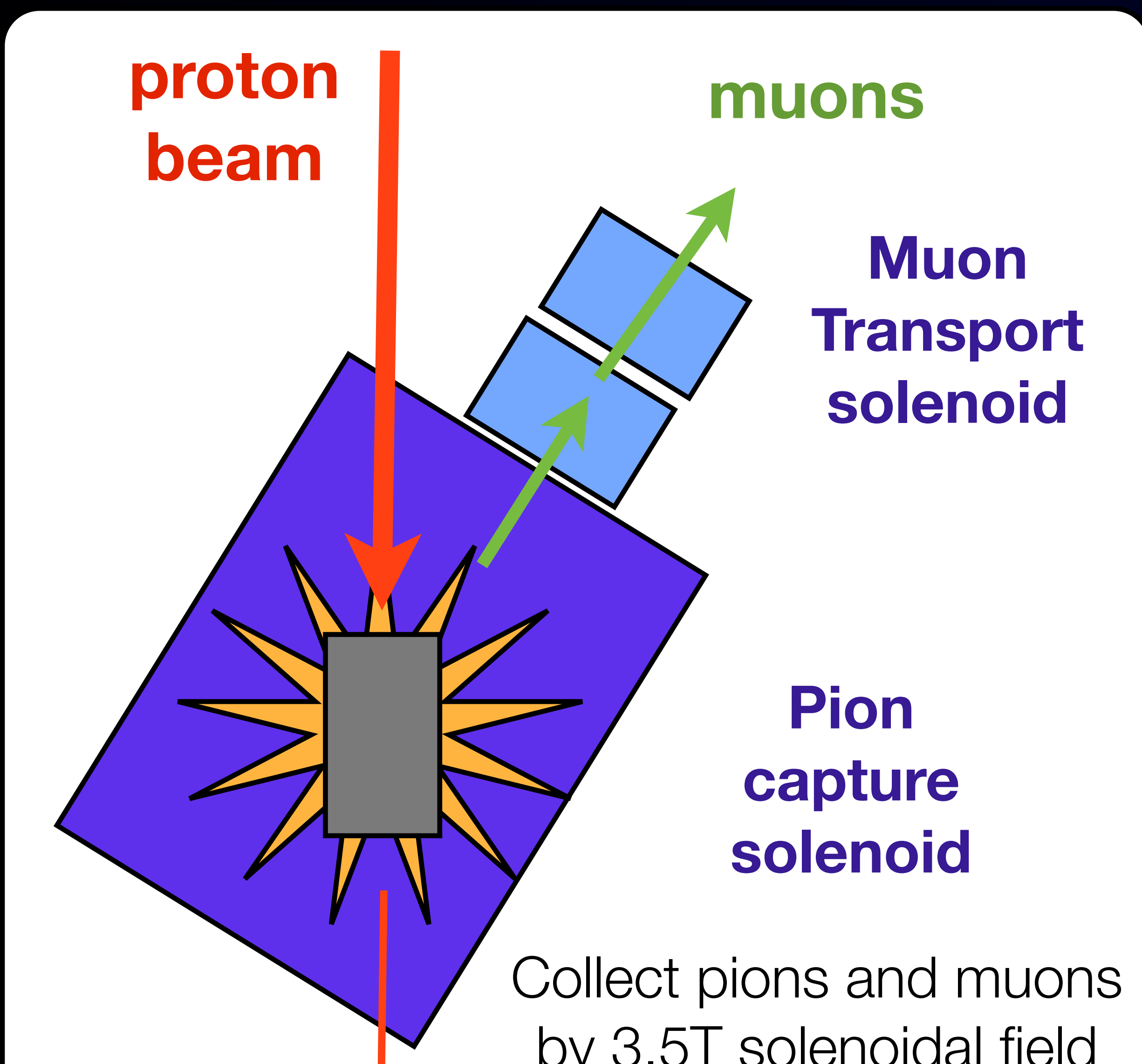


- A long pion production target of 1.5 interaction length is used.
- Pions coming out from the side of the long target are captured and transported to a muon beamline.
- Pions and muons (from pion decays) are transported through solenoid magnets.

Novel Muon Beamline

Novel muon beamline



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Beam intensity improvement of about 1000 expected

Muon Transport

Charged Particle Trajectory in Curved Solenoids

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

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

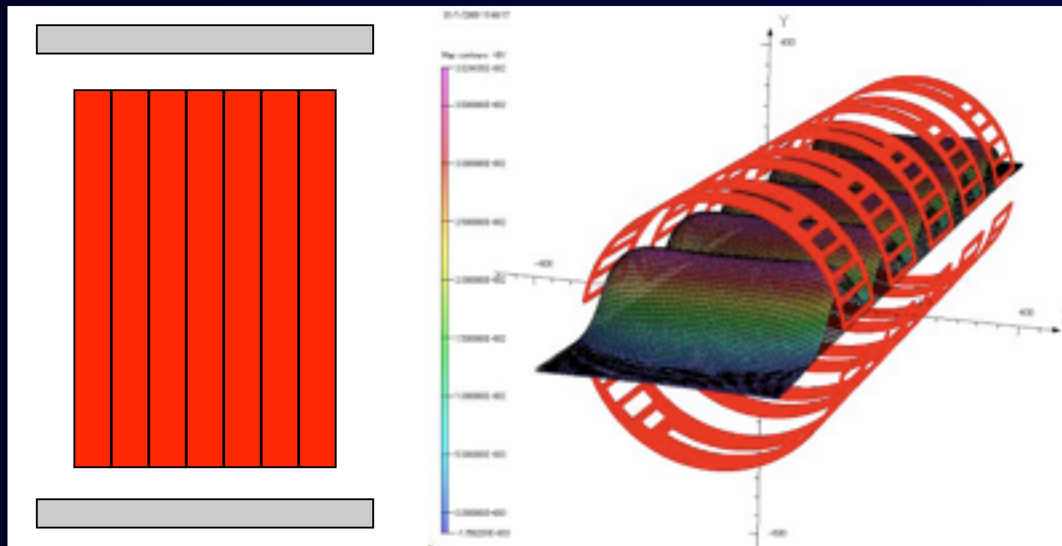
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This can be used for charge and momentum selection.

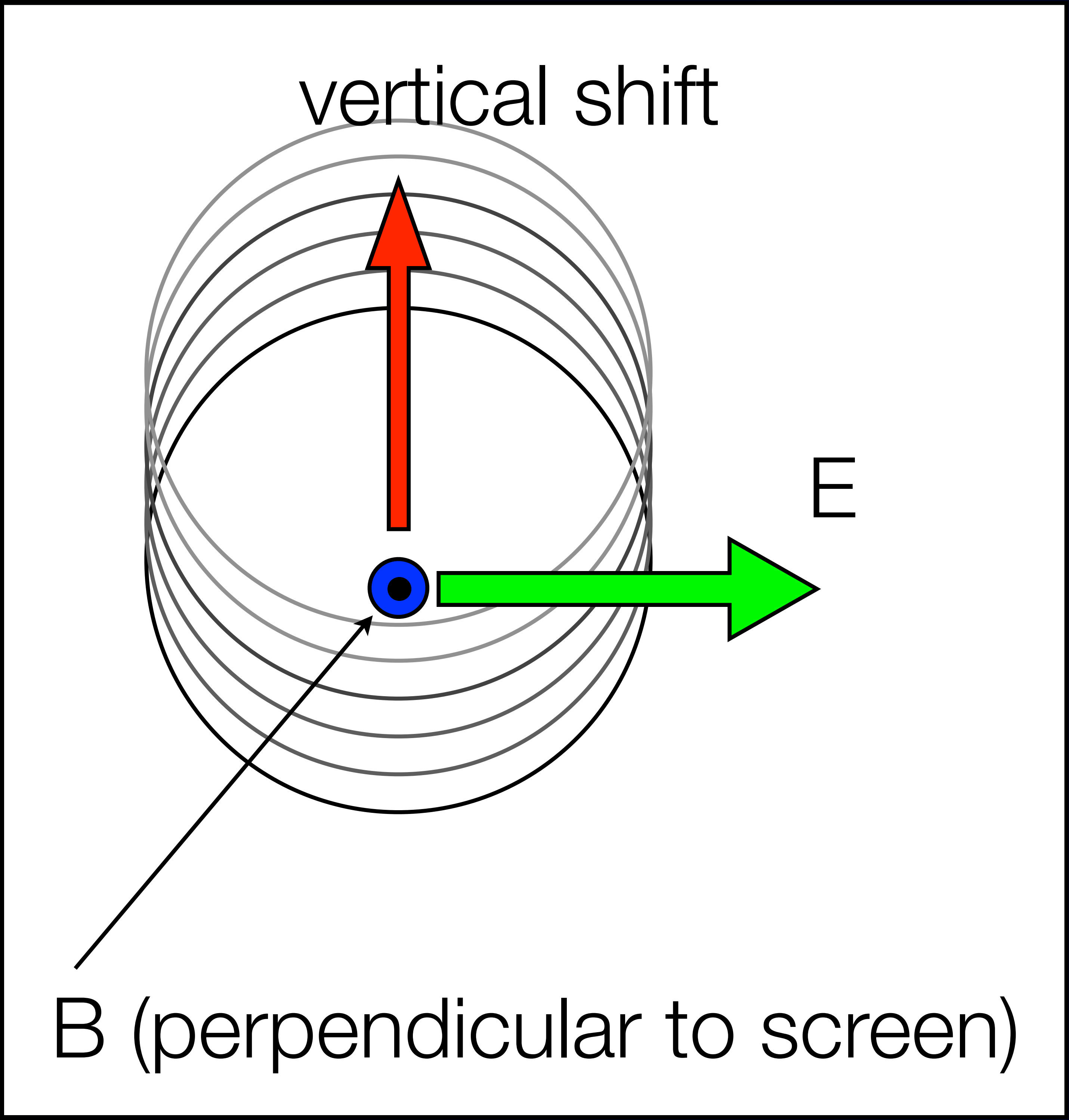
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

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

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

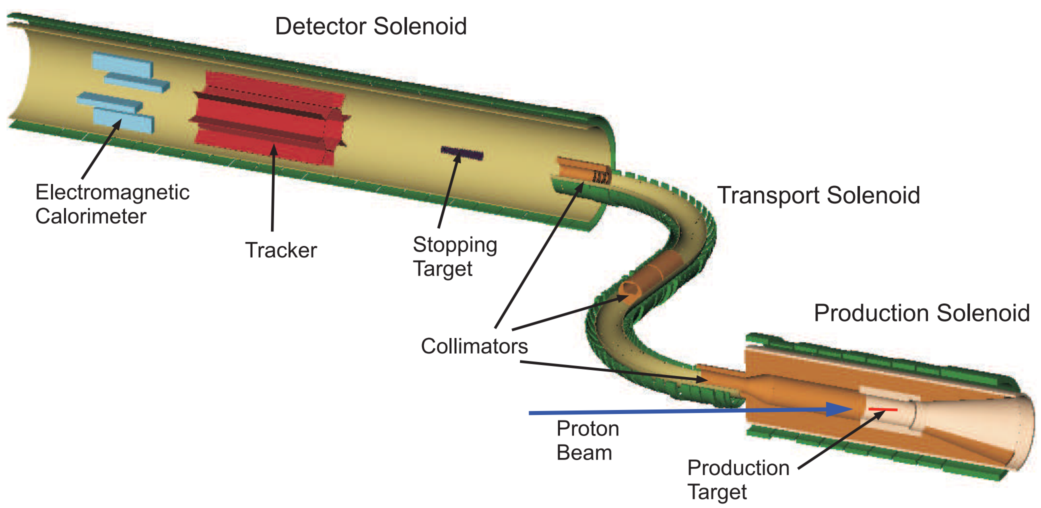


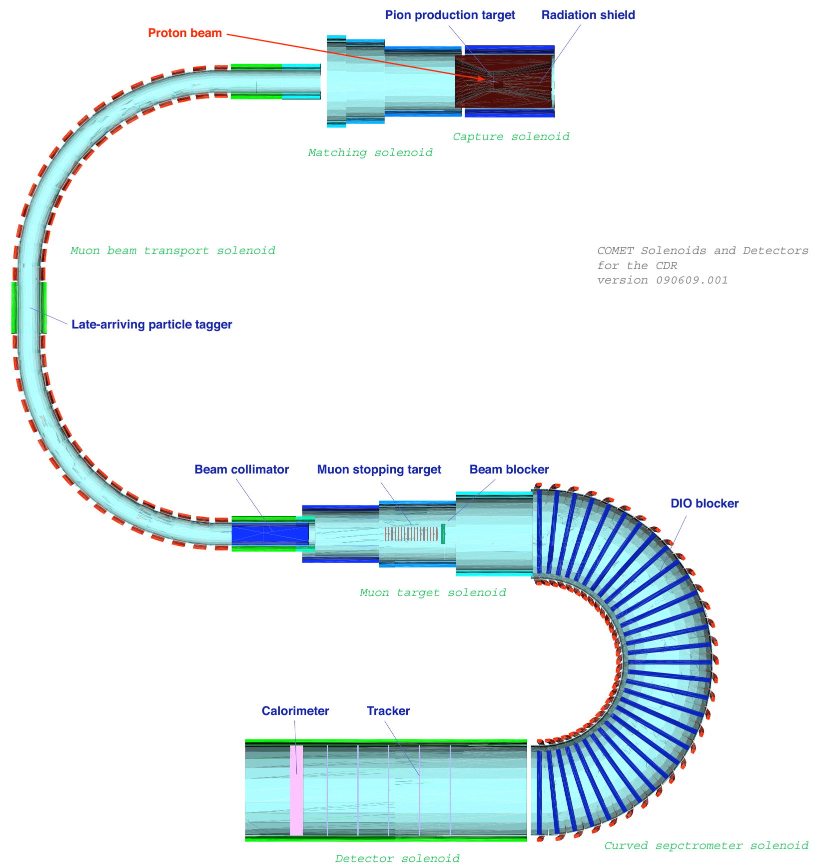
EM Physics for Particle Trajectories in Toroidal Magnetic Field

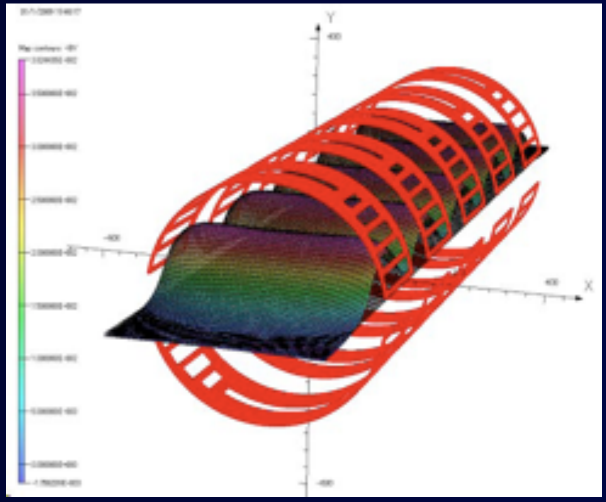


- For helical trajectory in a curved mag. field, a centrifugal force gives E in the radial direction.
- To compensate a vertical shift, an electric field in the opposite direction shall be applied, or a vertical mag. field that produces the desired electric field by v x B, can be applied.

Mu2e vs. COMET





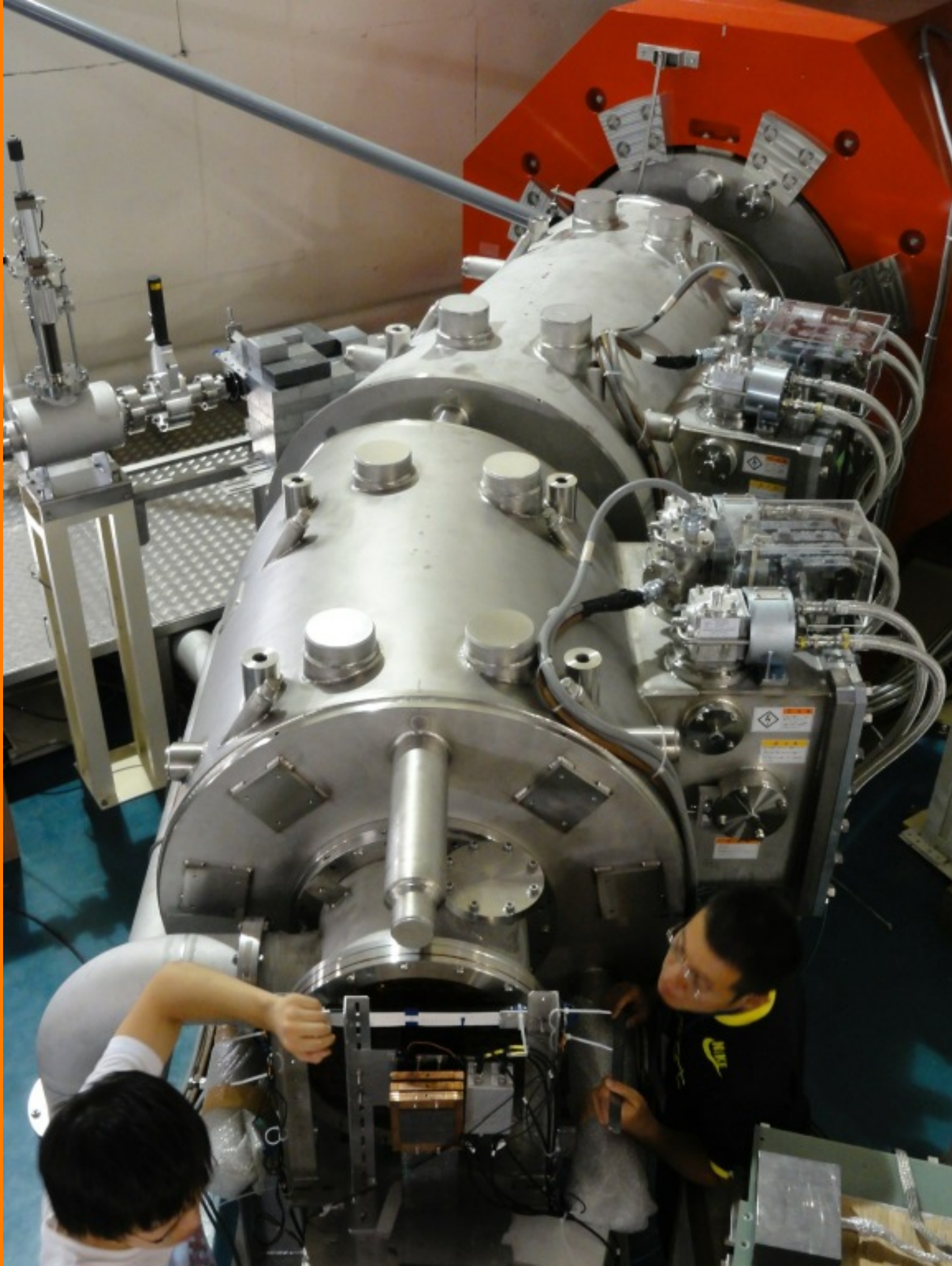


	Mu2e	COMET
muon beam line	2x 90° bends (opposite direction)	2x 90° bend (same direction)
electron spectrometer	straight solenoid	curved solenoid

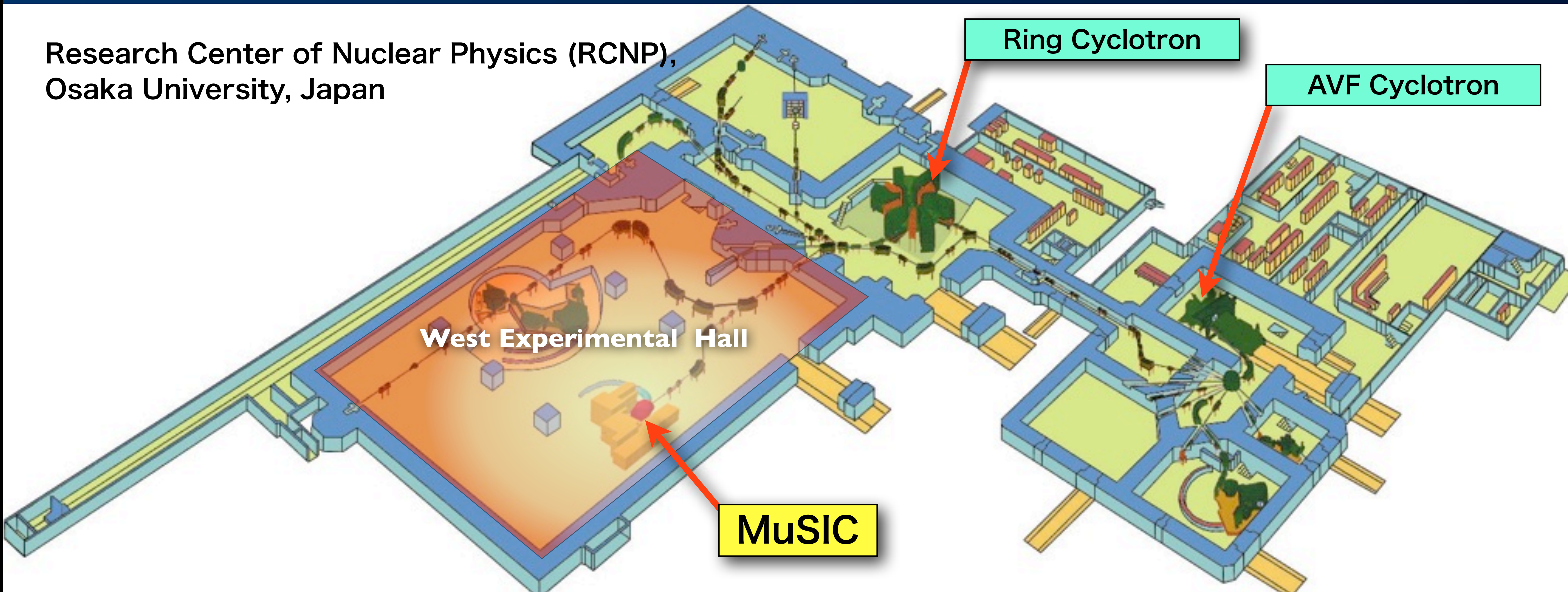
Dipole Coils

COMET curved solenoids have dipole coils on top of the solenoids, to keep muons with momentum of interest in the bending plane.

MuSIC



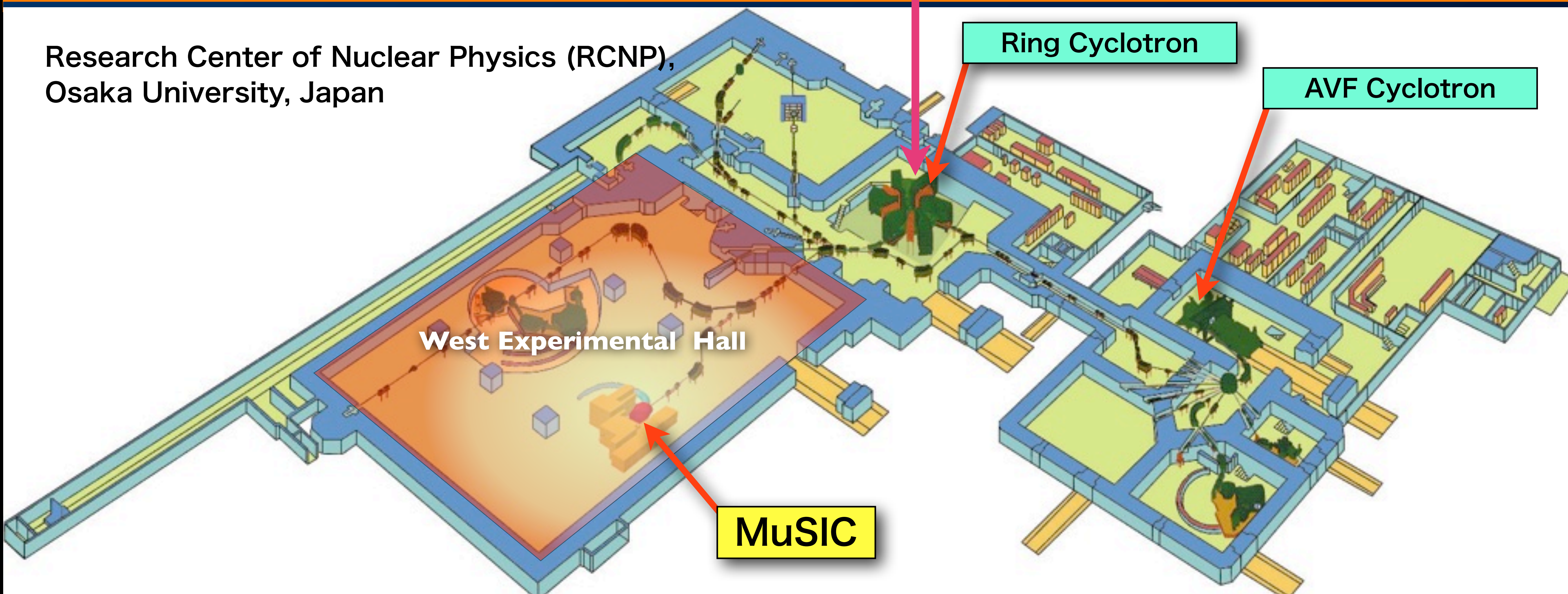
RCNP, Osaka University



- RCNP has two cyclotrons. A proton beam with 392MeV, 1 μA is provided from the Ring Cyclotron (up to 5 μA in near future).
- The MuSIC is in the largest experimental hall, the west experimental hall.

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

RCNP, Osaka University



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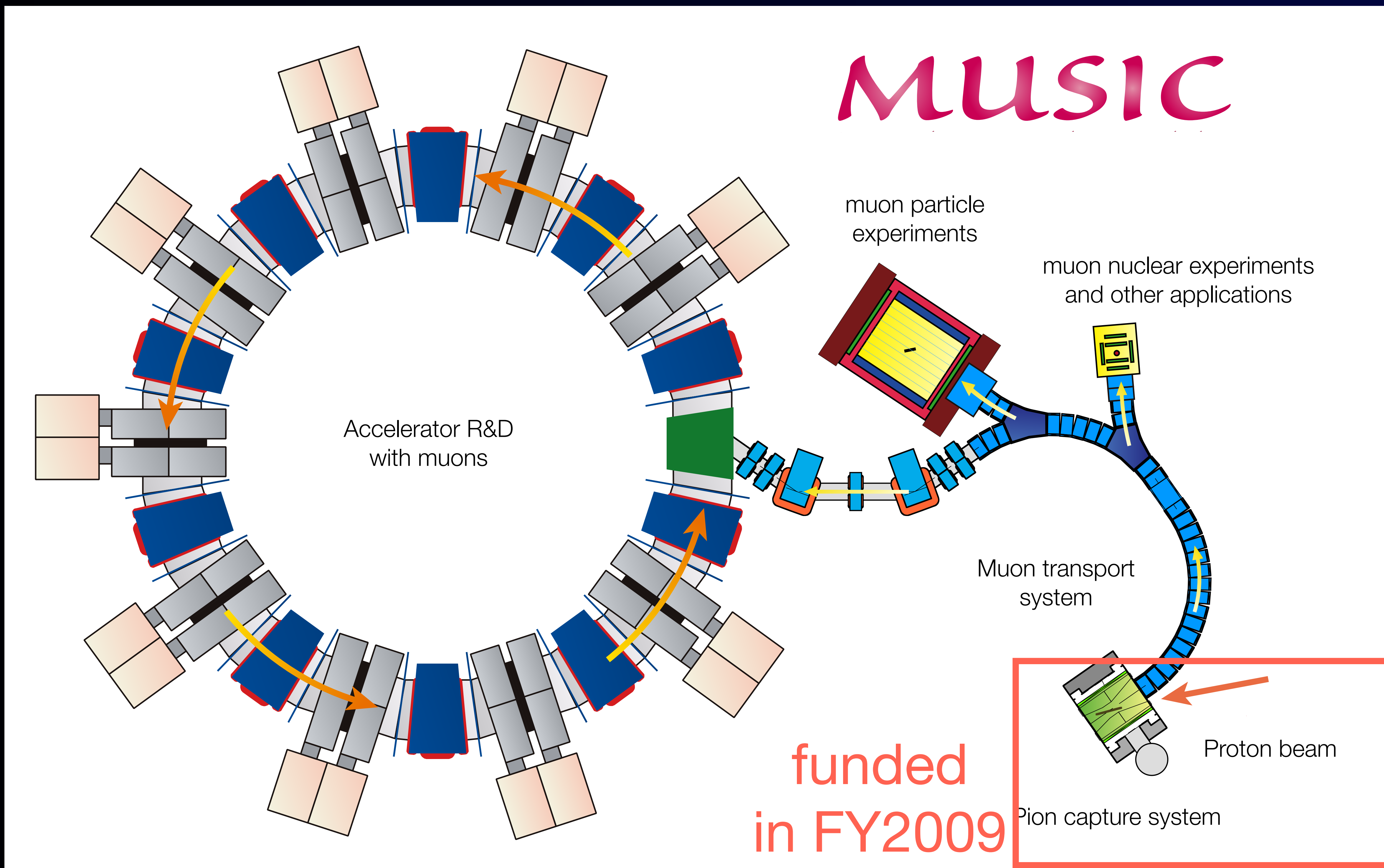
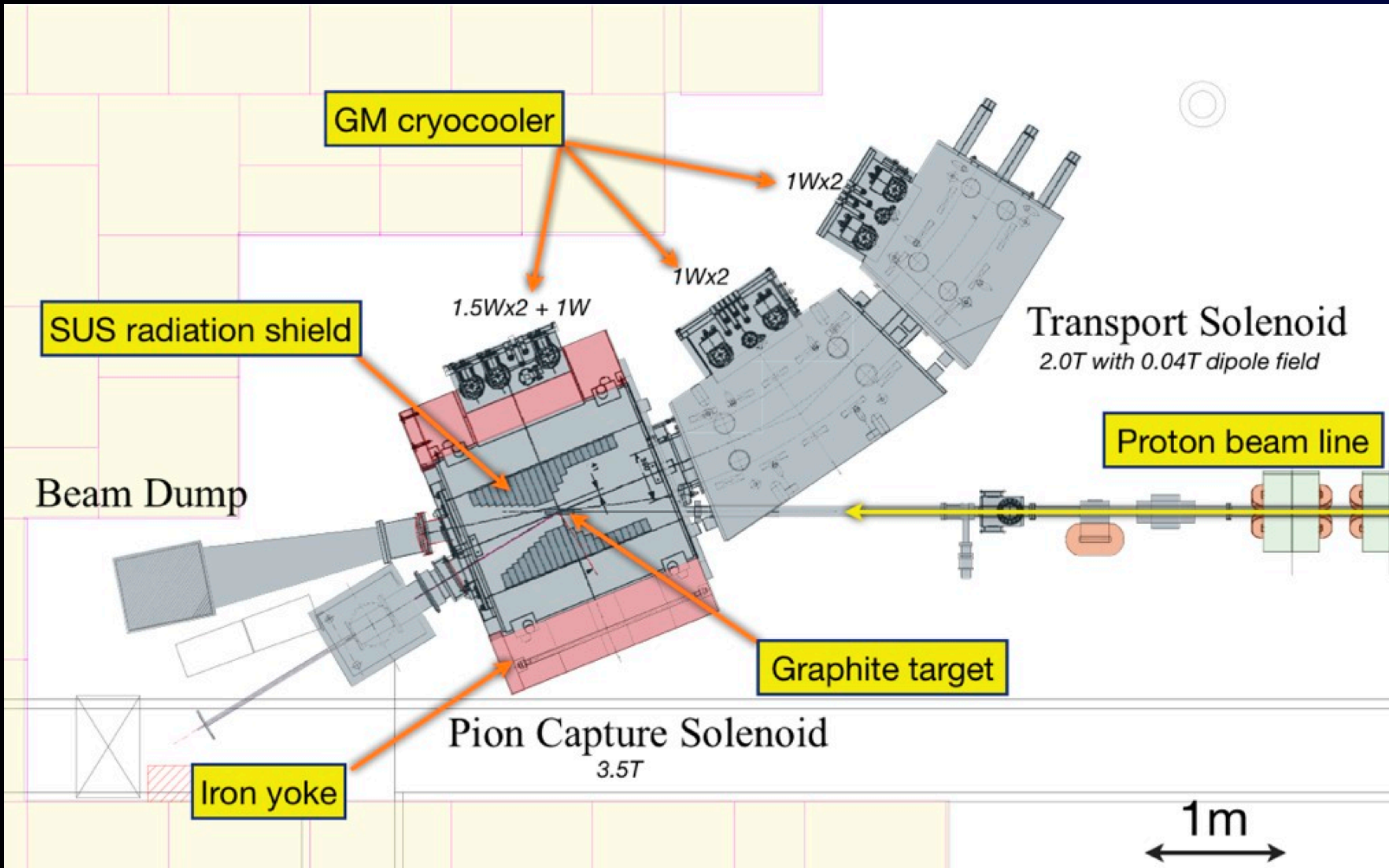
MuSIC (=Muon Science oriented Intense Channel)



What is MuSIC at RCNP ?

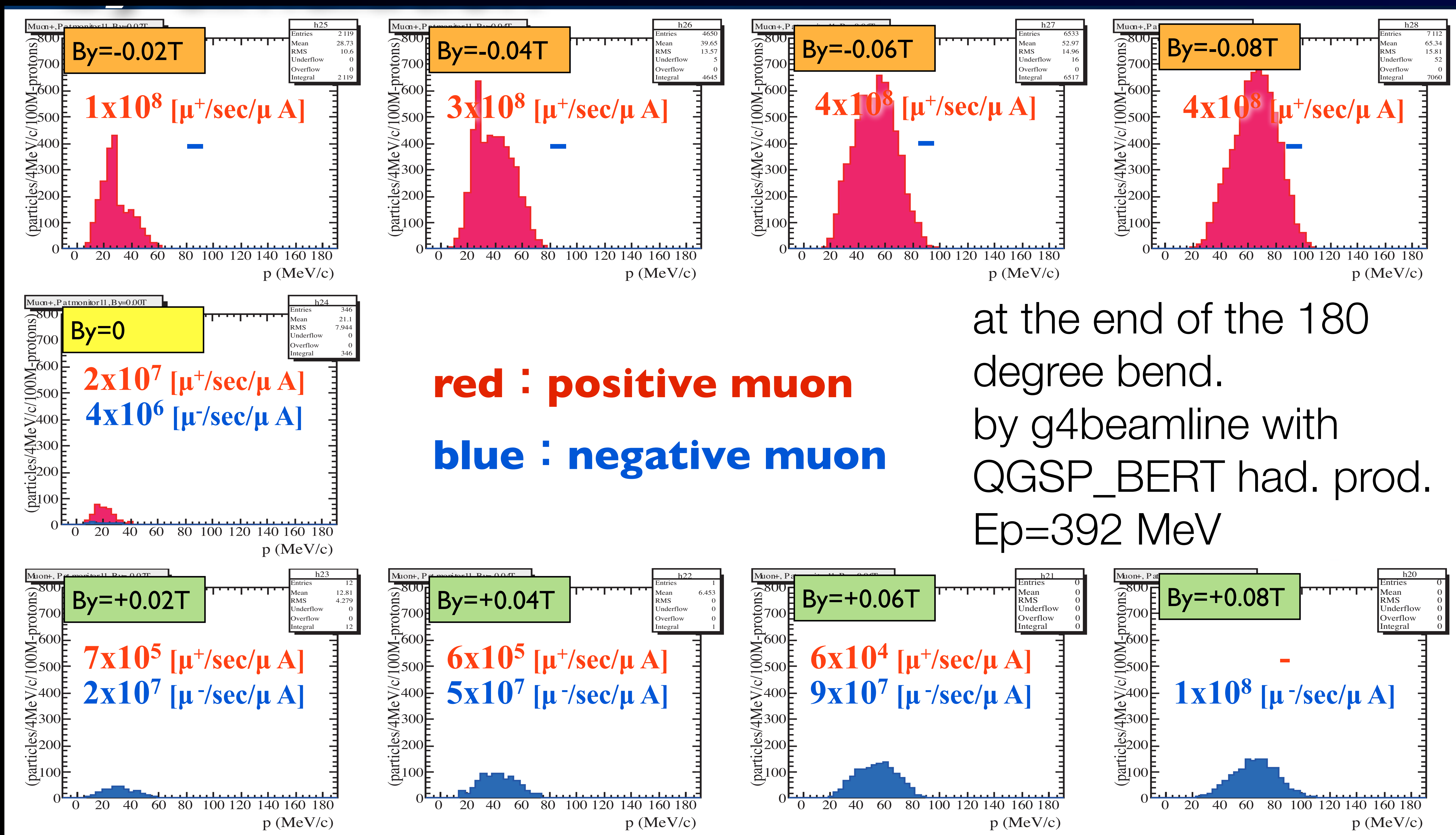
- **MuSIC**
  - The world's most efficient DC muon beam source using the first pion capture solenoid system.
  - Design muon intensity :
    - $10^{8\text{-}9}\,\mu$/s @392MeV,1$\,\mu$A (400W) proton beam from the RCNP ring cyclotron
- **Technical points of the MuSIC**
  - The first pion capture solenoid system
    - muon collection efficiency > 10^3 than conventional muon beam lines.
    - Radiation issues (coil cooling for the heat load)
  - A muon transport solenoid with dipole field
- **Task of the MuSIC**
  - Develop superconducting magnet technologies
  - Demonstrate and test the performance of the pion capture system.
  - Start muon programs at RCNP

Pion Capture System for MuSIC



MuSIC Layout

MuSIC Muon Beam Simulations



at the end of the 180 degree bend.
by g4beamline with QGSP_BERT had. prod.
Ep=392 MeV

History of the MuSIC Project

Osaka University

- 2009JPY
  - Construction of a proton beam line, pion capture system, and transport solenoid (up to 36 deg)
- 2010JPY
  - Commissioning of super-conducting magnets of pion capture and transport
  - 2010, Jul. : 1st beamtest (I_{proton}=3nA)
    - proton beam hits the production target,
    - Every system worked successfully,
    - observed secondary particles ay the end of the transport solenoid
  - 2011, Feb. : 2nd beam test (I_{proton}=~4nA)
    - muon beam was counted form their life spectrum,
- 2011JYP
  - 2011, Jun. : 3rd beam test (I_{proton}=~4nA)
    - muon life measurements with a higher statistics
    - muonic-Xray measurements
      - the design muon collection efficiency was confirmed by the measurement
  - 2011, Oct. : 4th beam test (I_{proton}=~4nA)
    - muonic-Xray measurements with a higher statistics
    - measurement of neutron flux and energy around the MuSIC
  - 2012, Mar. : East side radiation shielding blocks were located.
- 2012JYP
  - 2012, Jun 18-22 : 5th beam test
    - measurements for muon energy and spatial distribution
    - the system was operated with a high current proton beam **(I_{proton}=~1microA)**

Construction

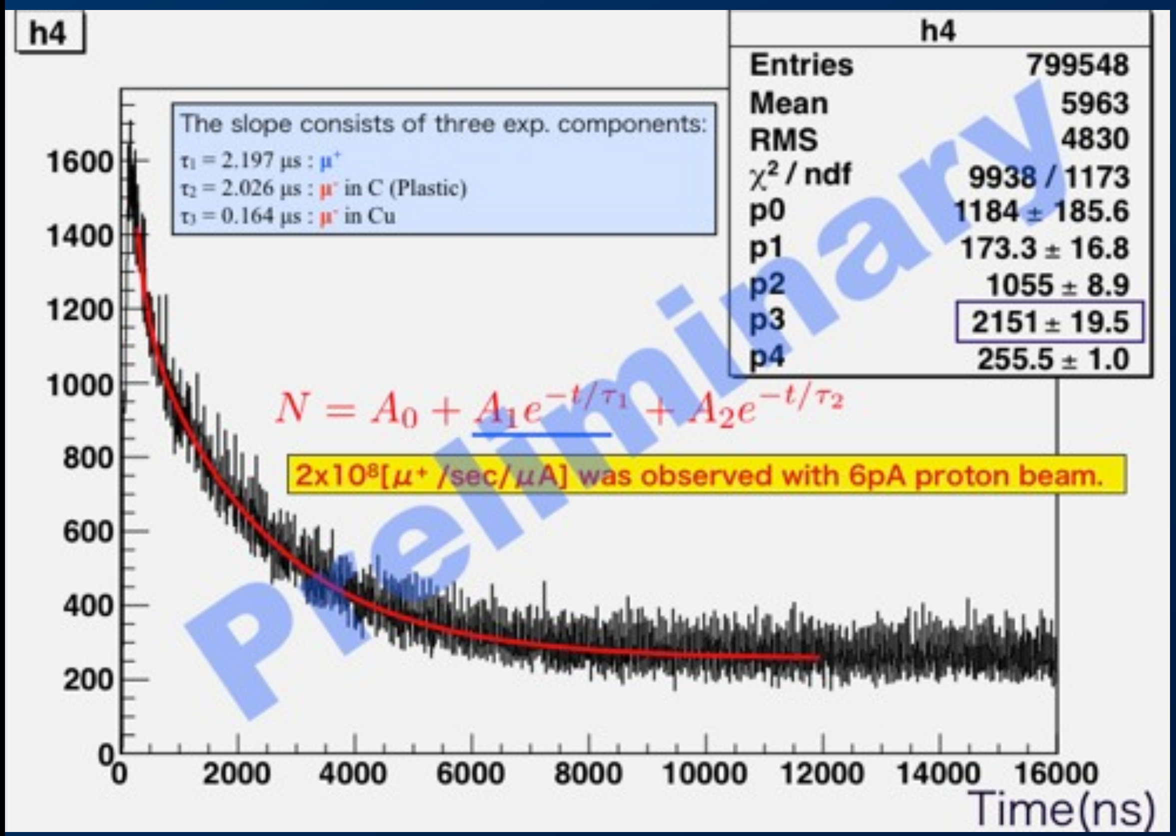
Commissioning

Muon collection efficiency

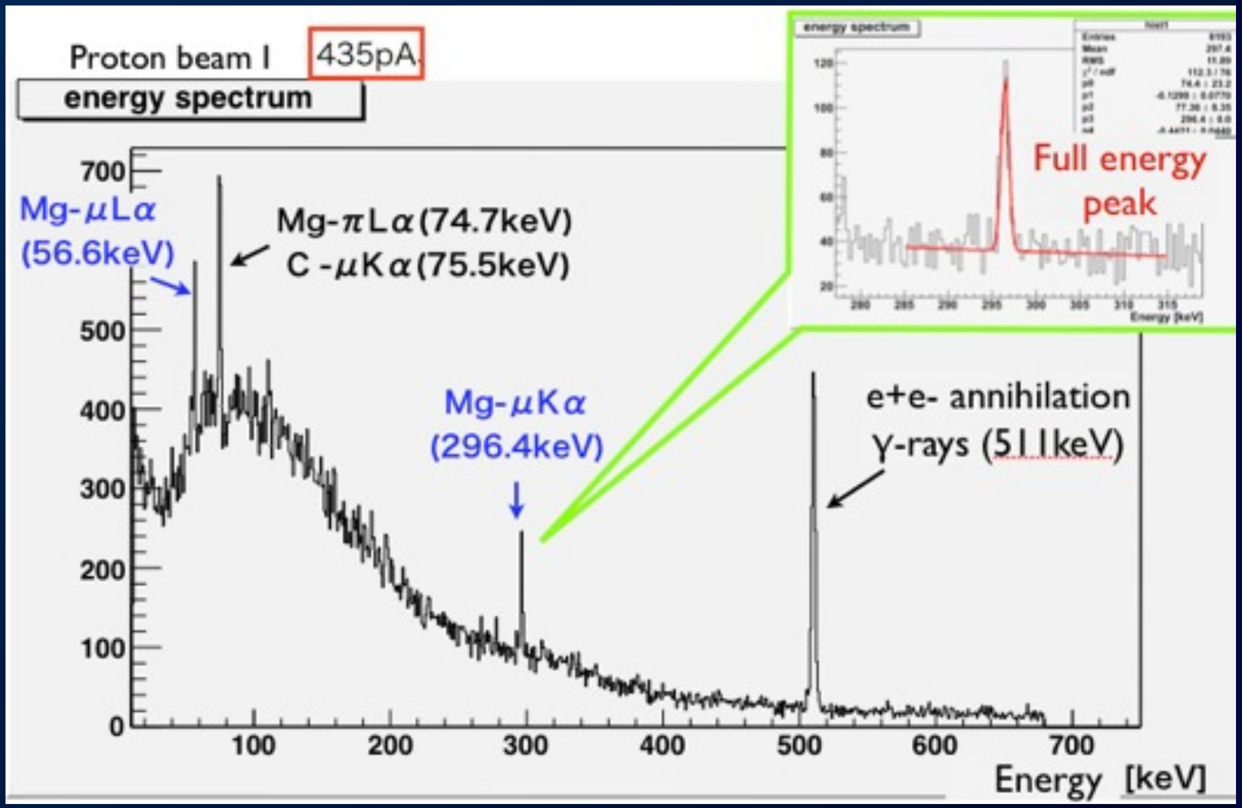
High current operation

Muon Yield Measurements

Muon life（Stopping target: Cu）



Muonic X-rays（Stopping target: Mg）



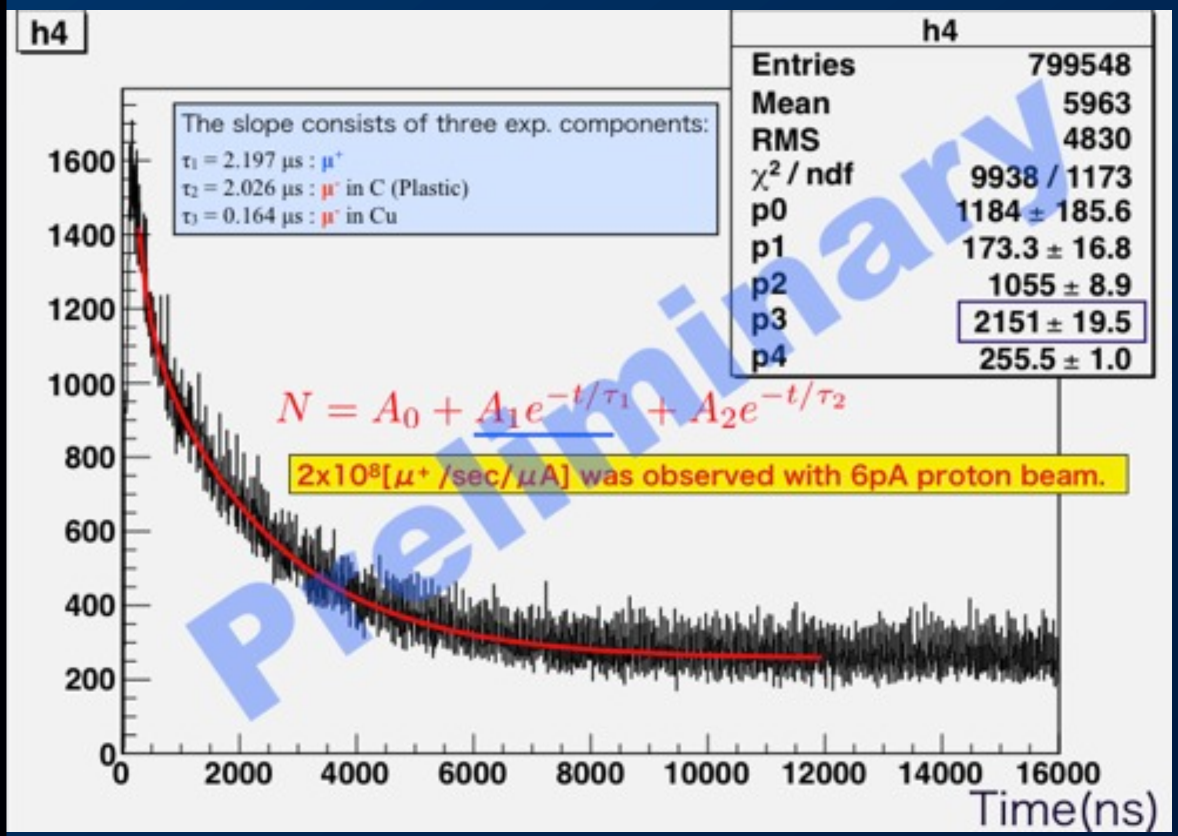
Measured muon yield at the exit of the 36° transport solenoid

	simulation	measurement
positive muon [μ^+/sec/μA]	2 x 10^8	3 x 10^8
negative muon [μ^-/sec/μA]	1.4 x 10^8	(1.7 ± 0.3) x 10^8

The μ production efficiency shows good agreement with the design value.

Muon Yield Measurements

Muon life (Stopping target: Cu)



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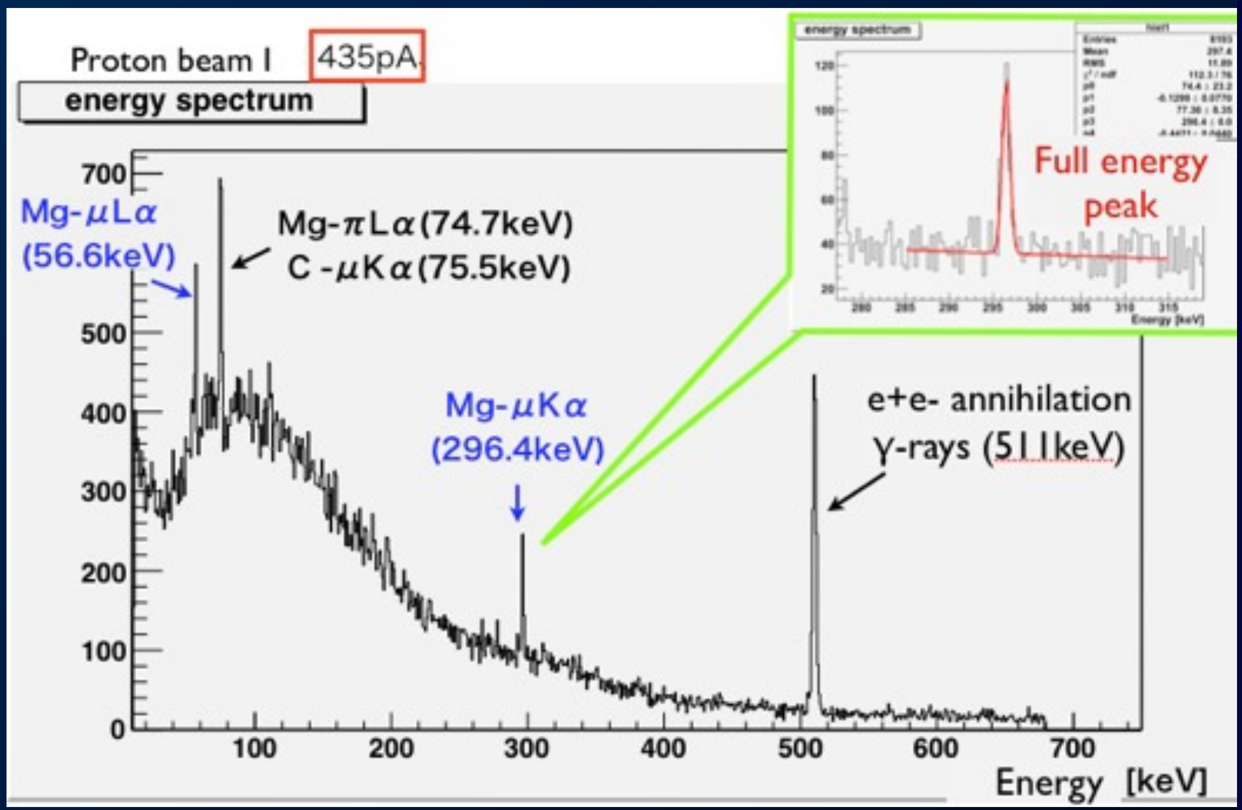


MuSIC muon yields

μ^+ ~3x10⁸/s for 400W

μ^- ~1x10⁸/s for 400W

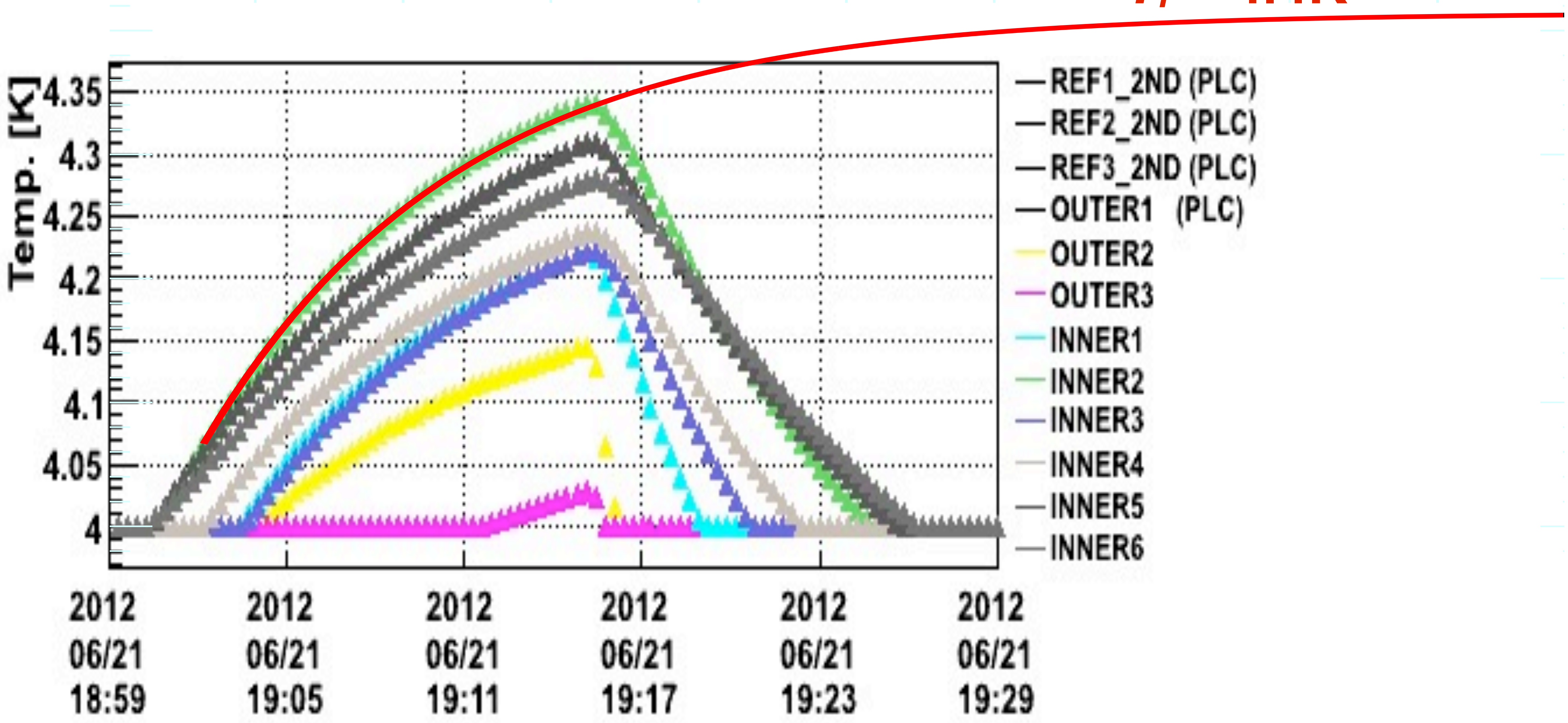
cf. 10⁸/s for 1MW @PSI

Req. of x10³ achieved...

Temperature Rise of MuSIC Superconducting Magnet

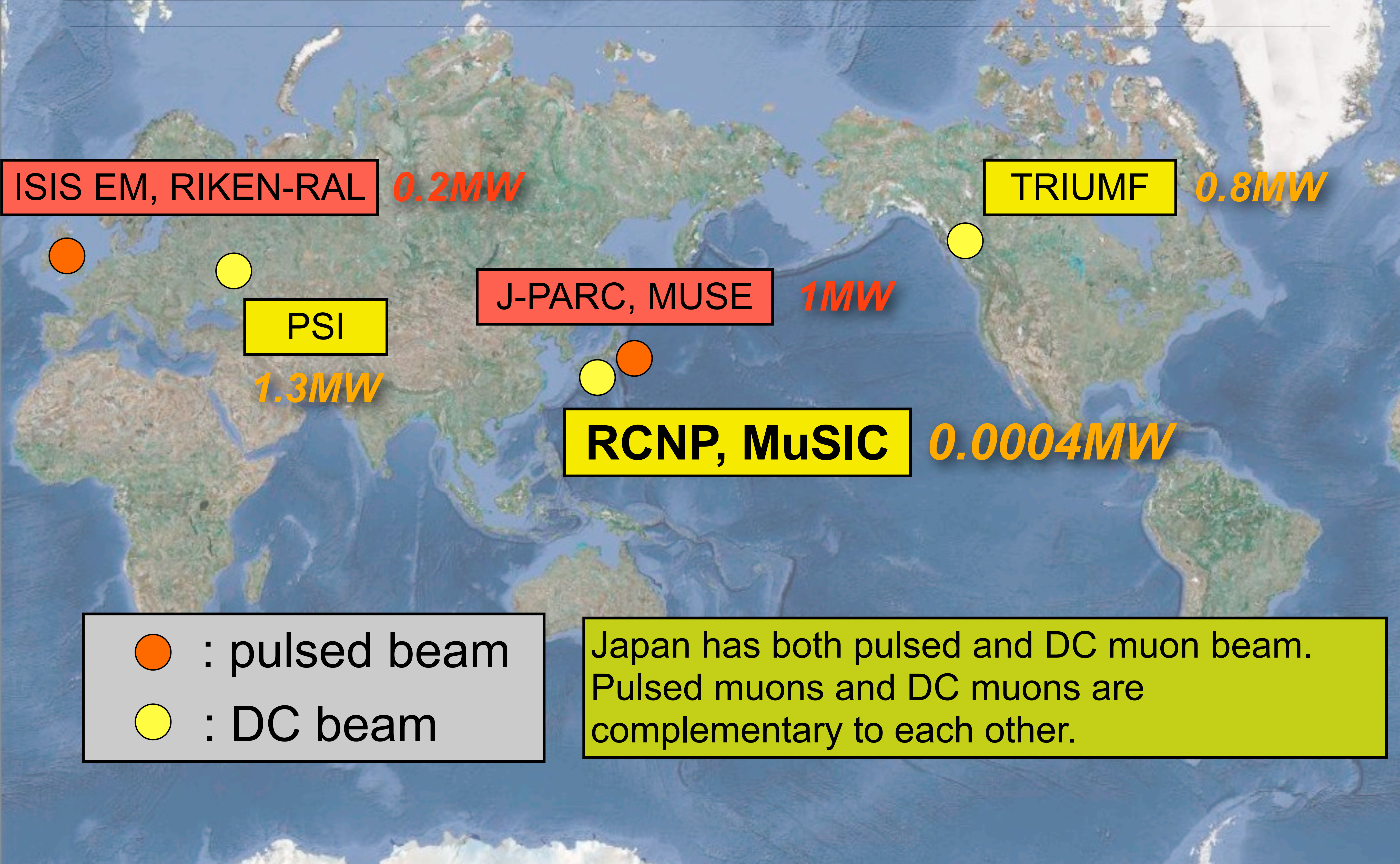
$$T = T_0 + (T_f - T_0)(1 - e^{-t/\tau})$$

T_f ~ 4.4K



The coil temperature up to ~6.5K is acceptable.
MuSIC can work with 400W proton beam.

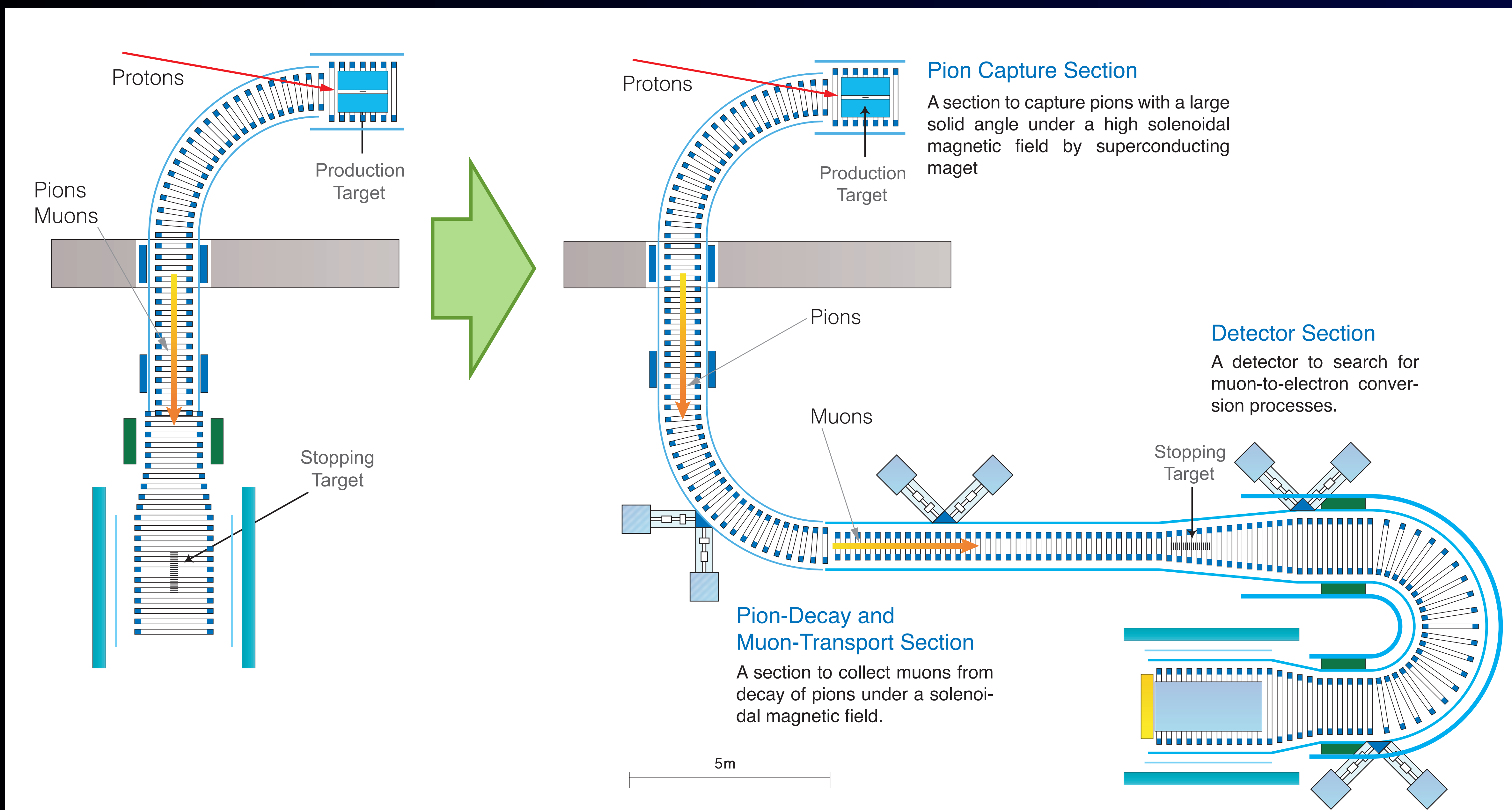
Muon facility in the world



Japan has both pulsed and DC muon beam.
Pulsed muons and DC muons are complementary to each other.

COMET Staged Approach

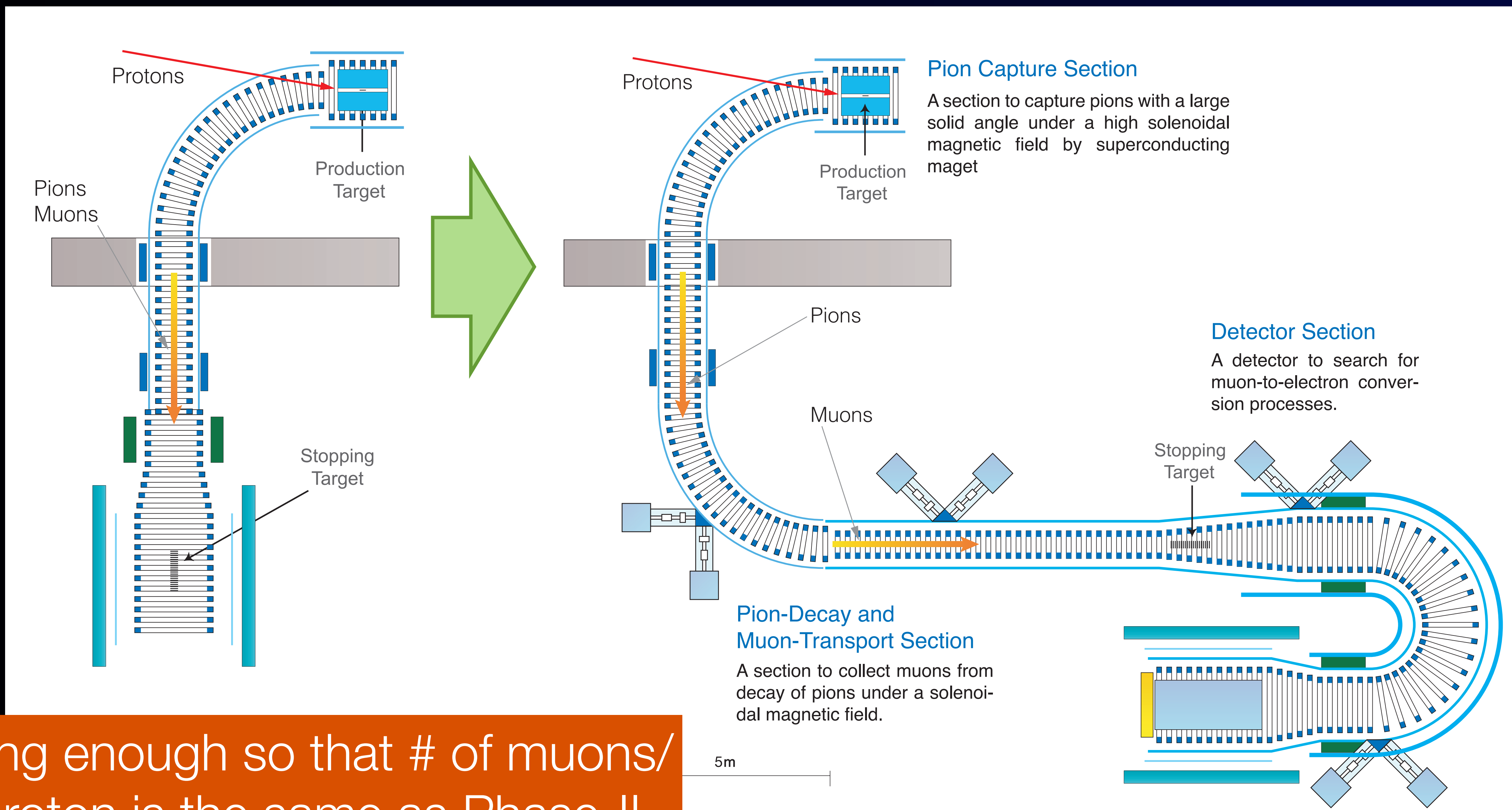
COMET Phase-I COMET Phase-II



COMET Staged Approach

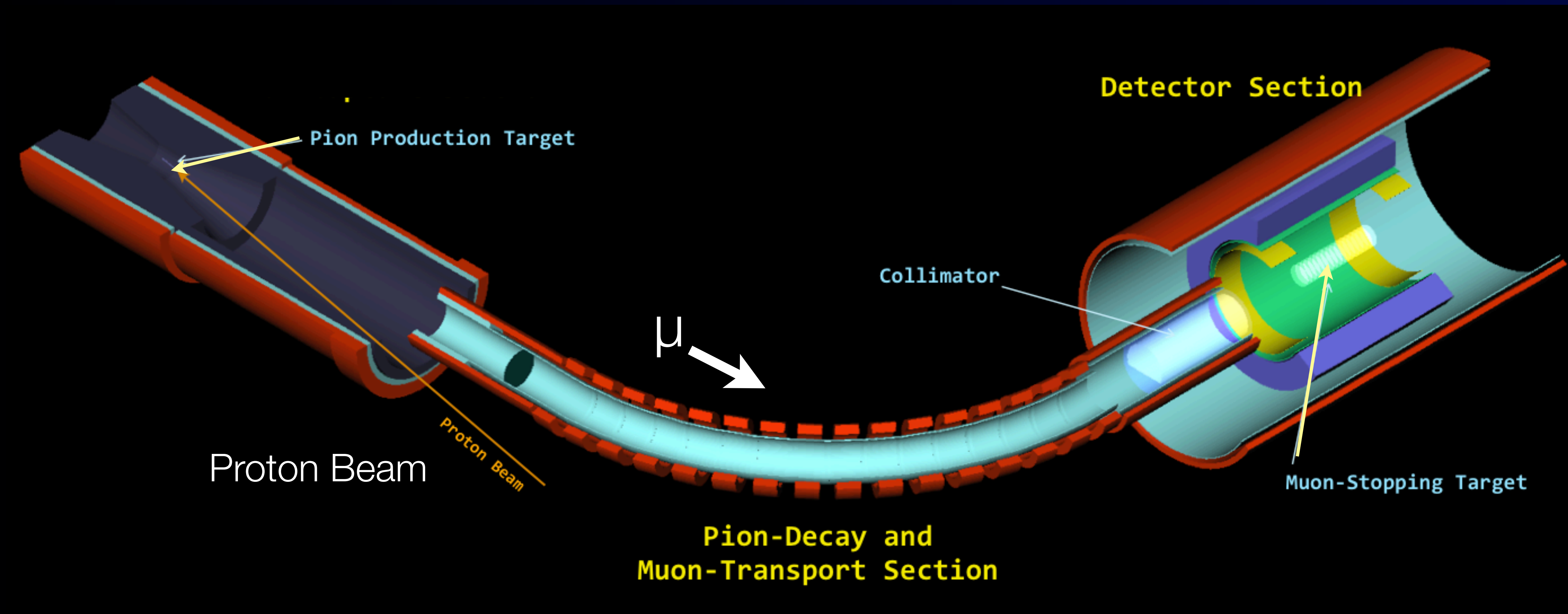
COMET Phase-I

COMET Phase-II



long enough so that # of muons/proton is the same as Phase-II.

COMET Phase-I at J-PARC



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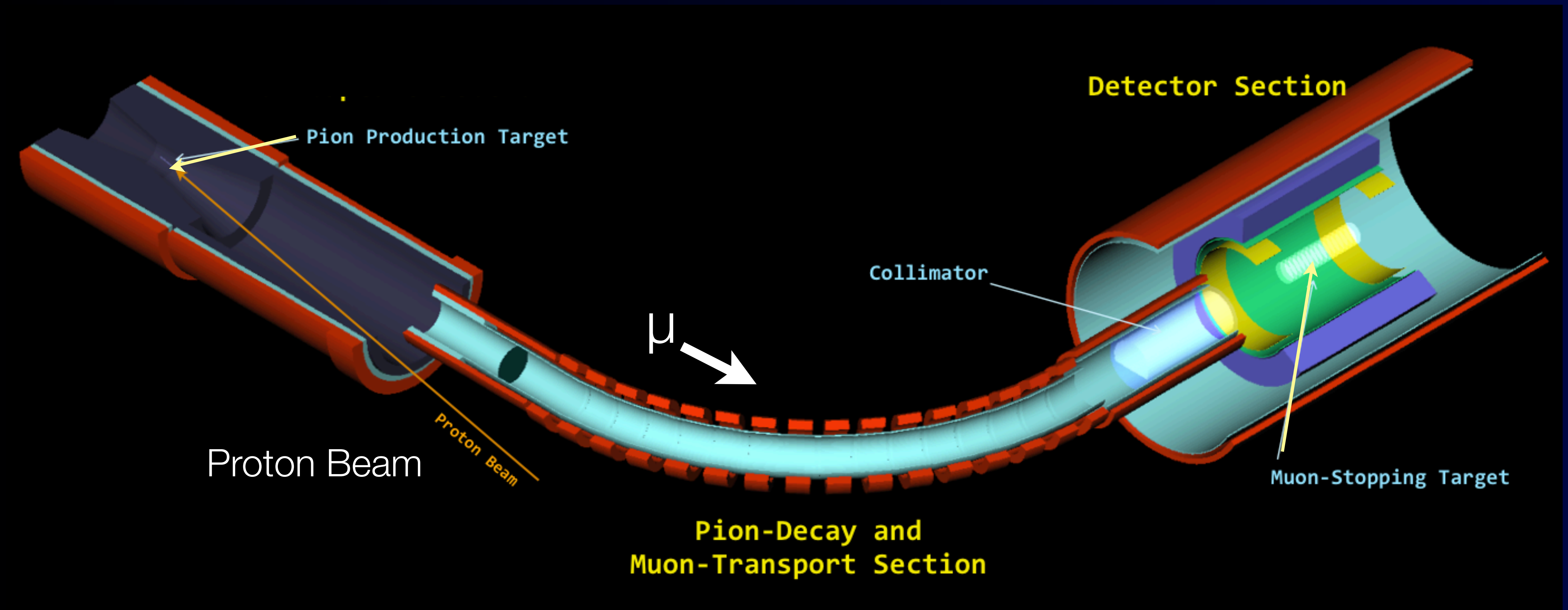
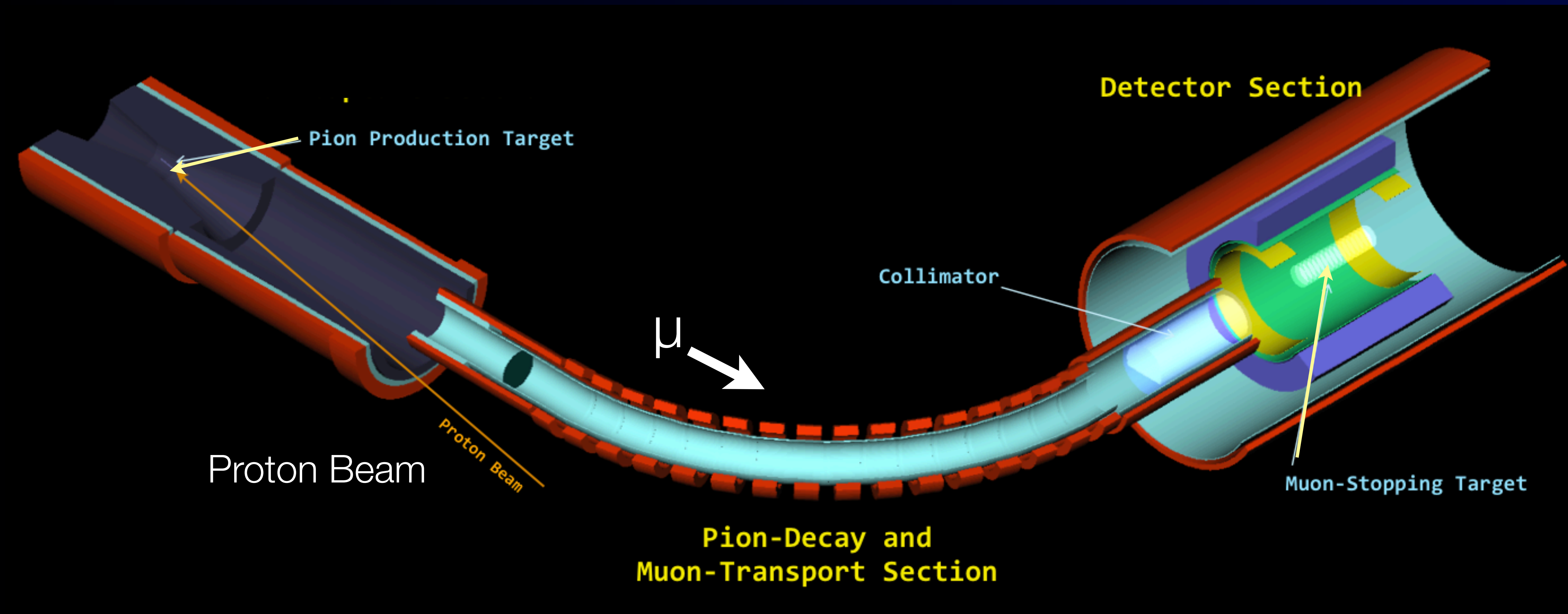


COMET muon beam-line：

$6x10^9$ muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I at J-PARC



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COMET Phase-I detector：

About 10^{16} muons are stopped in the target. Electron from μ-e conversion will be measured

Stage-I MuSIC
Beam Line
(a la Akira Sato)

Muon Science with a DC Muon Beam

- **+ Particle Physics :**
  - search for $\mu \rightarrow eee$ (muon LFV) $10^{8\text{-}9} \mu^+/sec$
    - DC continuous beam is critical
- **+ Materials Science :**
  - μSR (a μSR apparatus is needed) $10^{5\text{-}6} \mu^+/sec$, po
- **- Nuclear Physics :**
  - nuclear muon capture (NMC) $10^{4\text{-}5} \mu^-/sec$
    - nuclear matrix element study for $0\nu\ \beta\beta$ decay
  - pion capture and scattering
- **- Chemistry :**
  - chemistry on pion/muon atoms $10^{4\text{-}5} \mu^-/sec$
- **Accelerator / Instruments R&D**
  - (for PRISM/neutrino factory/muon collider) :
    - Superconducting solenoid magnets
    - FFAG, RF
    - cooling methods
    - muon acceleration, deceleration, and phase rotation

DC muon is necessary to reduce accidental BGs

cf. COMET(μ-e) needs a pulsed muon beam.

with a good time resolution

<u>measure muonic Xrays</u>

high trigger rate is possible

cf. with pulsed muons, the trigger rate is limited by pulse rate.

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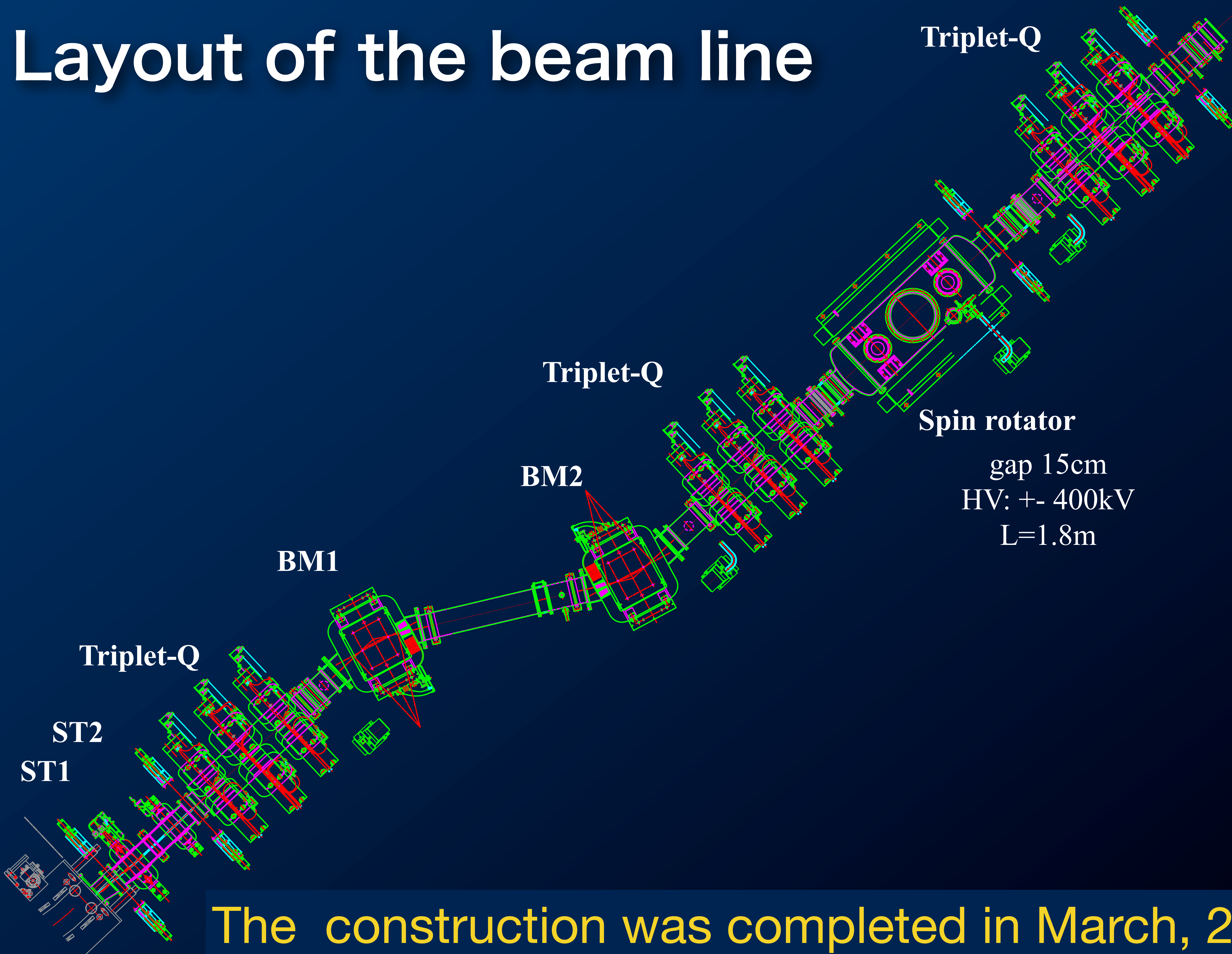
Goals for Beam Performance

Osaka University

- Positive muon：DC-μSR
  - beam size： ϕ10mm
  - angle：< 50mrad
  - intensity：2~4 x 10^4/sec

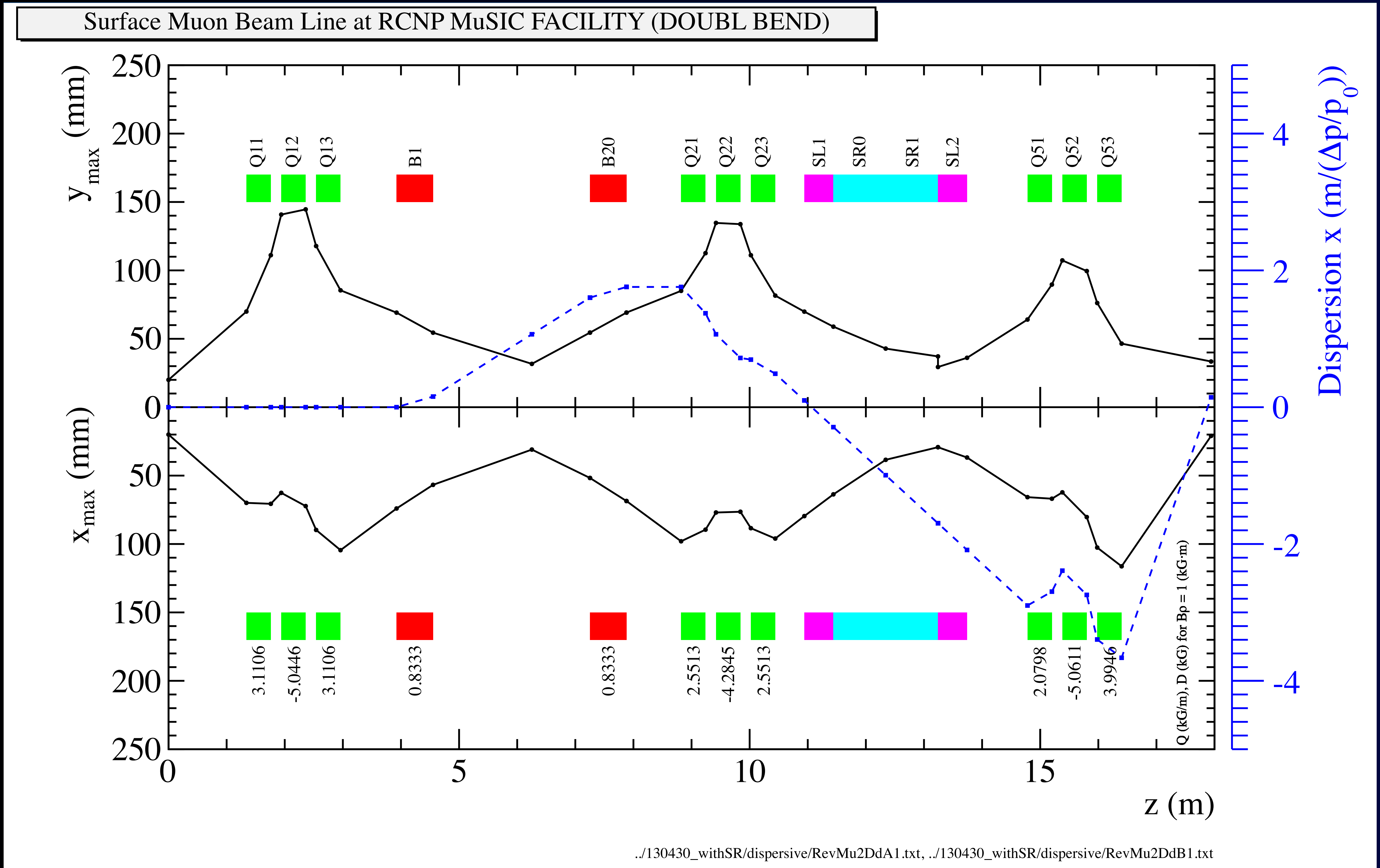
- Negative muon：nuclear phys. chemi. μ-X
  - beam size： ϕ10mm~Φ50mm
  - angle：< 200mrad
  - intensity：2×10^4 ~2×10^5/sec

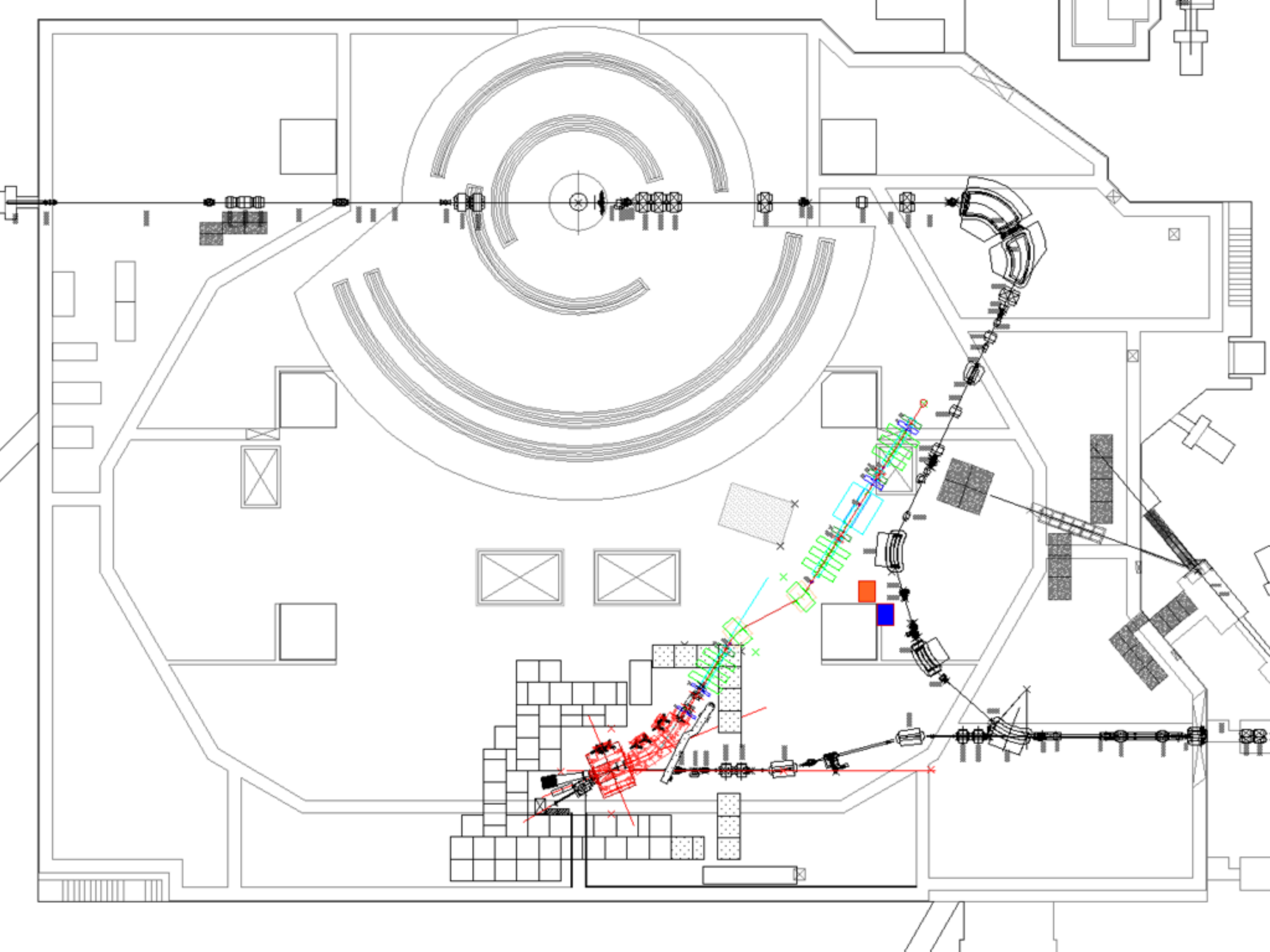
Layout of the beam line



The construction was completed in March, 2014.

Beam Optics


Surface Muon Beam Line at RCNP MuSIC FACILITY (DOUBL BEND)
y_{max} (mm)
x_{max} (mm)
Dispersion x (m/(Δp/p_0))
z (m)
Q11
Q12
Q13
B1
B20
Q21
Q22
Q23
SL1
SR0
SR1
SL2
Q51
Q52
Q53
3.1106
-5.0446
3.1106
0.8333
0.8333
2.5513
-4.2845
2.5513
2.0798
-5.0611
3.9946
Q (kG/m), D (kG) for Bρ = 1 (kG·m)
../130430_withSR/dispersive/RevMu2DdA1.txt, ../130430_withSR/dispersive/RevMu2DdB1.txt



MuSIC Stage-I

Current Status

- RCNP has been shut off for its building renovation.
- MuSIC had a beam time (of one day) which was not sufficient for commissioning.
- MuSIC is expecting another beam time in Fall, 2014.

Summary for MuSIC Phase-I

MuSIC has successfully demonstrated the performance of a pion capture system.

Now we are working very hard to construct a DC muon line for the low intensity application as a stahe-1 of the MuSIC.

(+) **Materials Science :**

- μSR (a μSR apparatus is needed) $10^{5\text{-}6}\mu^{+}$/sec, polarized

(-) **Nuclear Physics :**

- nuclear muon capture (NMC) $10^{4\text{-}5}\mu^{-}$/sec
  - nuclear matrix element study for $0\nu\ \beta\beta$ decay
- pion capture and scattering

(-) **Chemistry :**

- chemistry on pion/muon atoms $10^{4\text{-}5}\mu^{-}$/sec

Stage-1

Summary

- New innovative muon sources with solenoid system has been developed.
- MuSIC facility at Osaka Unviersity has demonstrated that the pion capture system increases muon production intensity of a factor of about 1000.
- MuSIC Stage-1 for application to μSR has been constructed and will be commissioned.

Summary

- New innovative muon sources with solenoid system has been developed.
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IKU (go ahead)