A New DC Muon Beam Source: MuSIC - Status and Prospects -

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International Workshop on Neutrino Factories, Super Beams and Beta Beams: NuFact2012
July 23-28, 2012, Williamsburg, VA USA

20+5 min

Contents

- Overview of the MuSIC
    - Concept
    - Status and schedule
    - Expected muon yield by simulation
    - Design
- Results from beam tests
    - Muon collection efficiency
    - high current operation
- Summary

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Overview

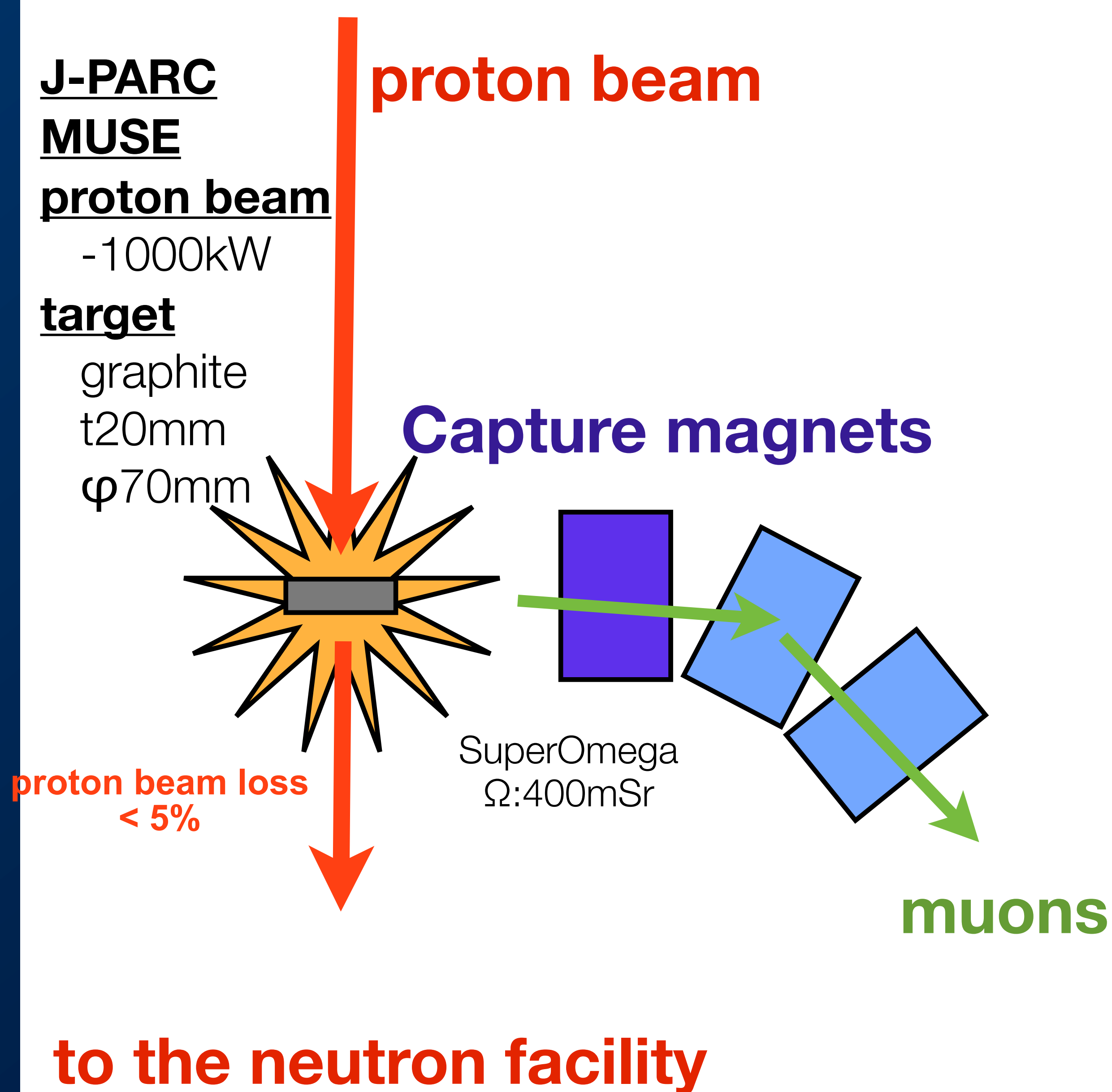
What is the MuSIC?

- **MuSIC**
  - The world's most efficient DC muon beam source using the first pion capture solenoid system.
    - 400W proton beam from RCNP ring cyclotron
  - Design muon intensity：
    - $10^{8\text{-}9}$ μ/s @392MeV,1μA proton beam
  - One on the main projects of RCNP program in a new program of Research Center for Subatomic Science.
- **Technical points of the MuSIC**
  - The first pion capture solenoid system
    - muon collection efficiency > 10^3 than conventional muon beam lines
  - A muon transport solenoid with dipole field

Muon collection at the MuSIC

Conventional muon beam line

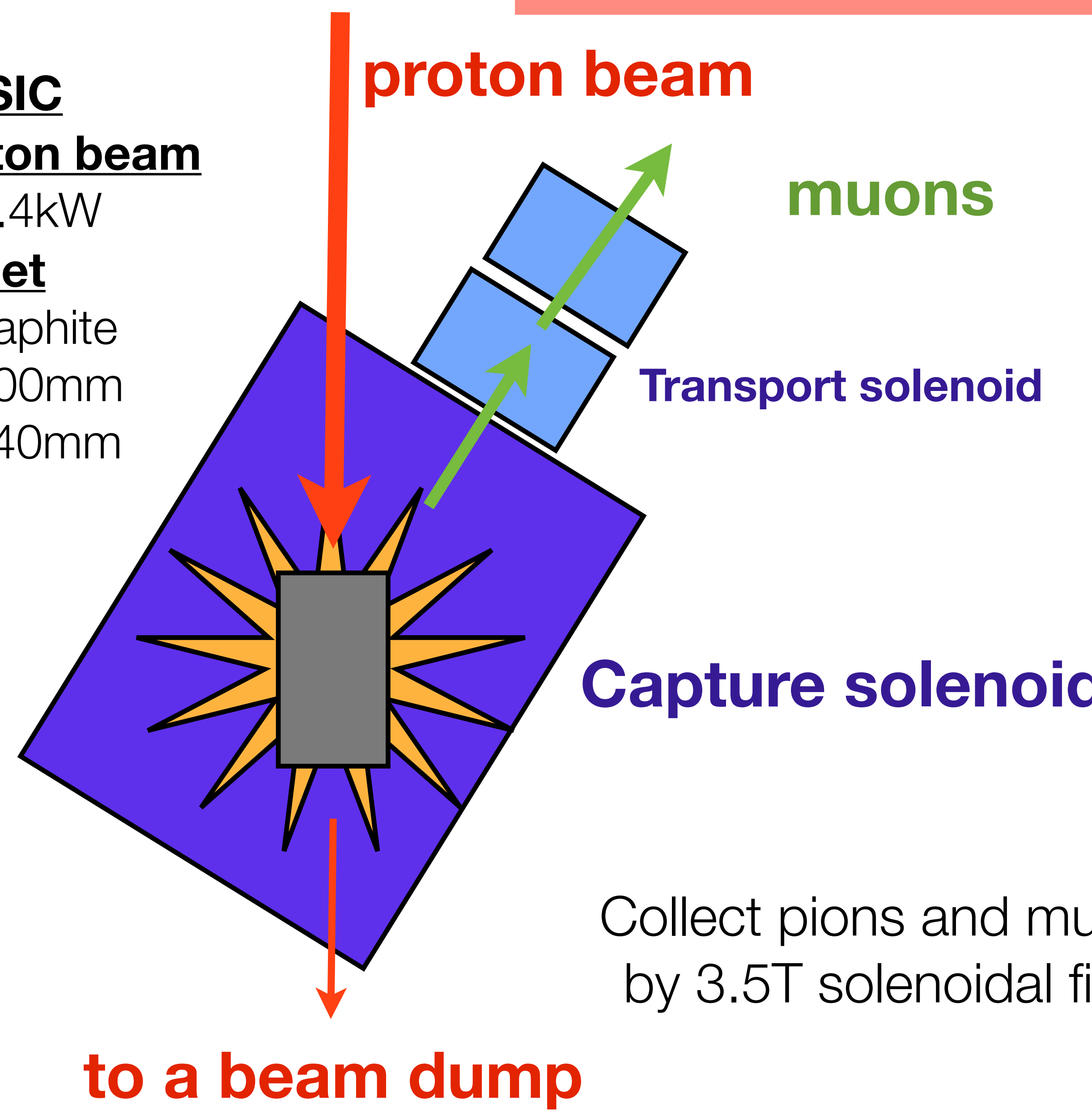
J-PARC
MUSE
proton beam
-1000kW
target
graphite
t20mm
φ70mm



MuSIC

MuSIC,COMET/Mu2e,PRISM,
Neutrino factory,
Muon collider

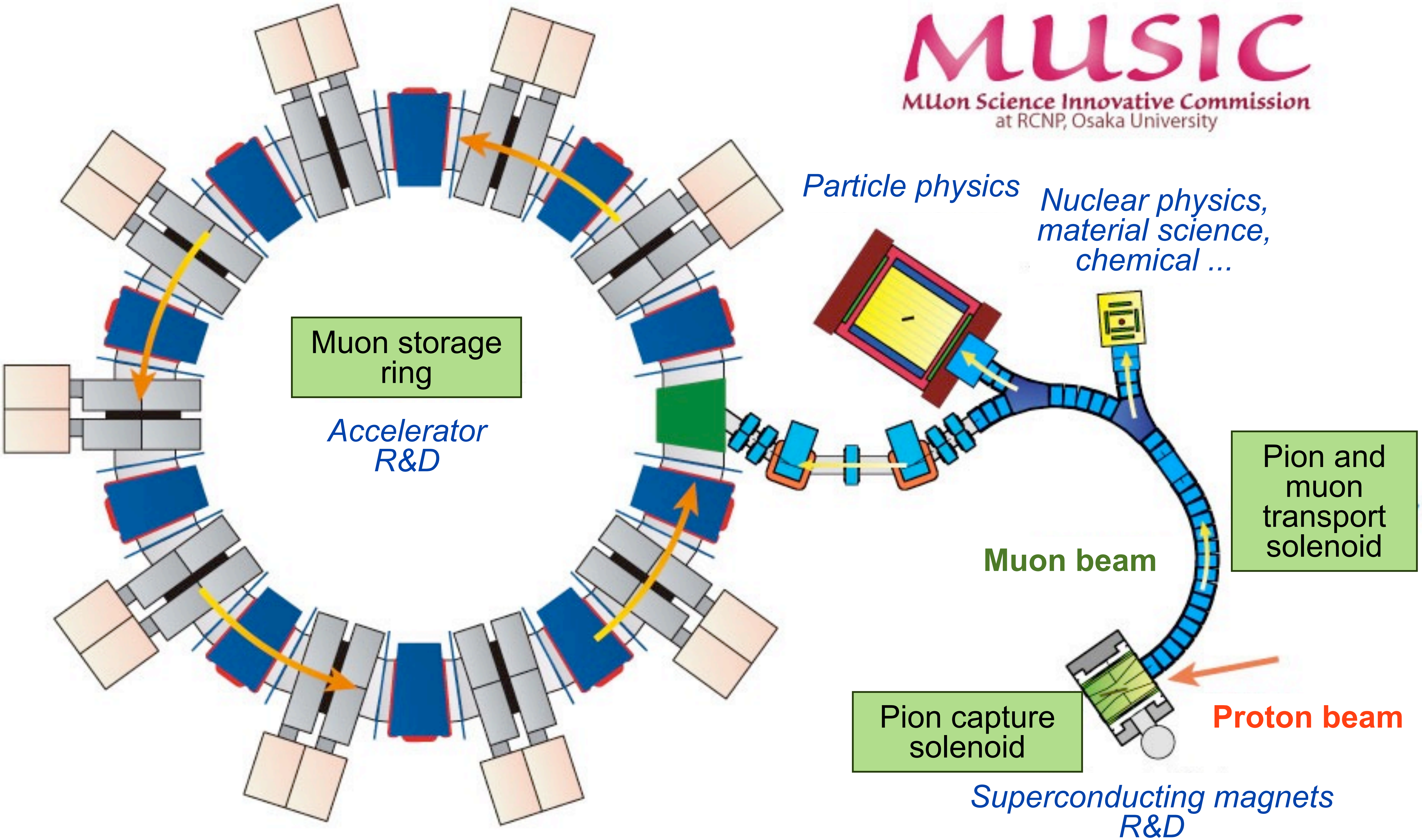
MuSIC
proton beam
-0.4kW
target
graphite
t200mm
φ40mm



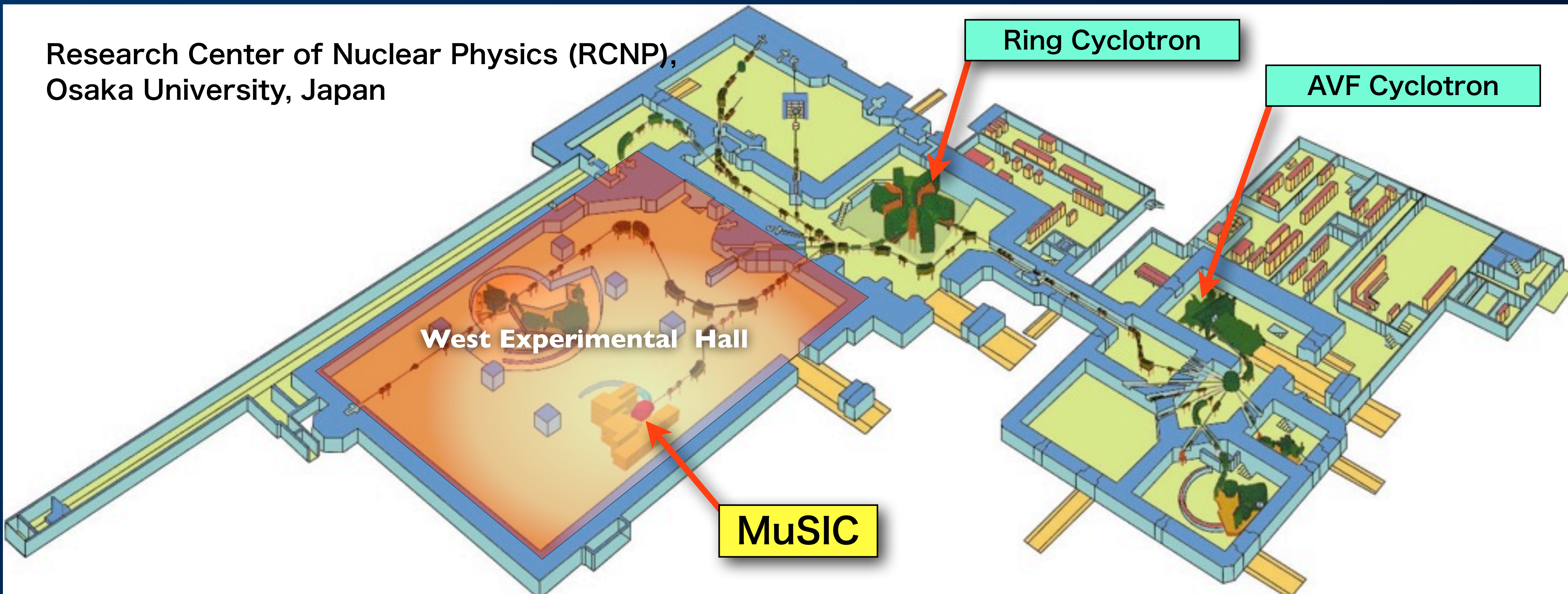
Collect pions and muons
by 3.5T solenoidal field

Large solid angle & thick target

The Final Layout of MuSIC



MUSIC@RCNP, Osaka Univ.



- 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.

History of MuSIC Projects

Construction

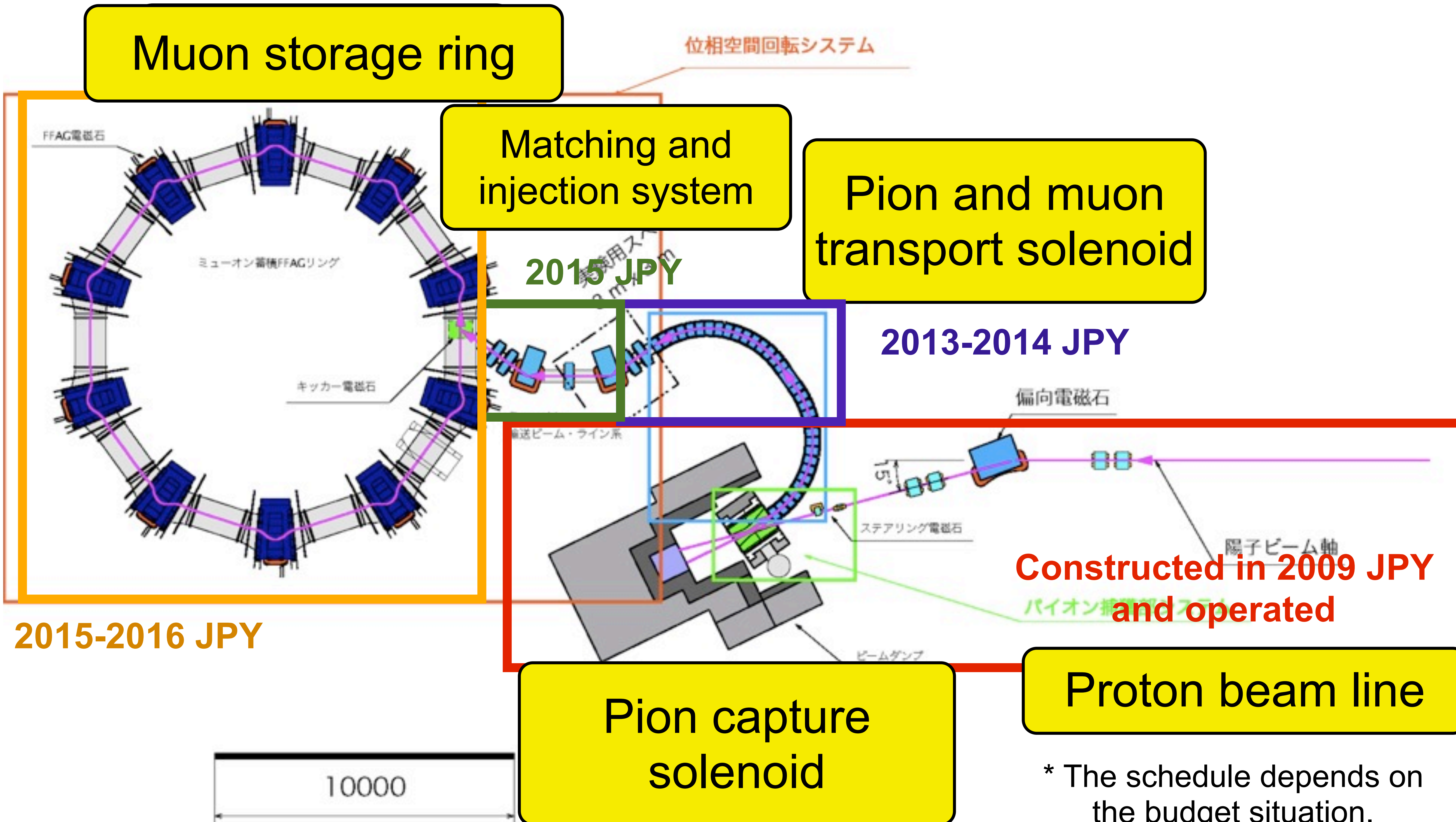
- 2009JPY
  - Construction of a proton beam line, pion capture system, and transport solenoid (up to 36 deg)
- 2010JPY
  - Commissioning of super-conducting magnets of pion capture and transport
  - 2010, Jul. : 1st beamtest (I$_{proton}$=3nA)
    - proton beam hits the production target,
    - Every 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)**

Commissioning

Muon collection efficiency

High current operation

Schedule



* The schedule depends on the budget situation.

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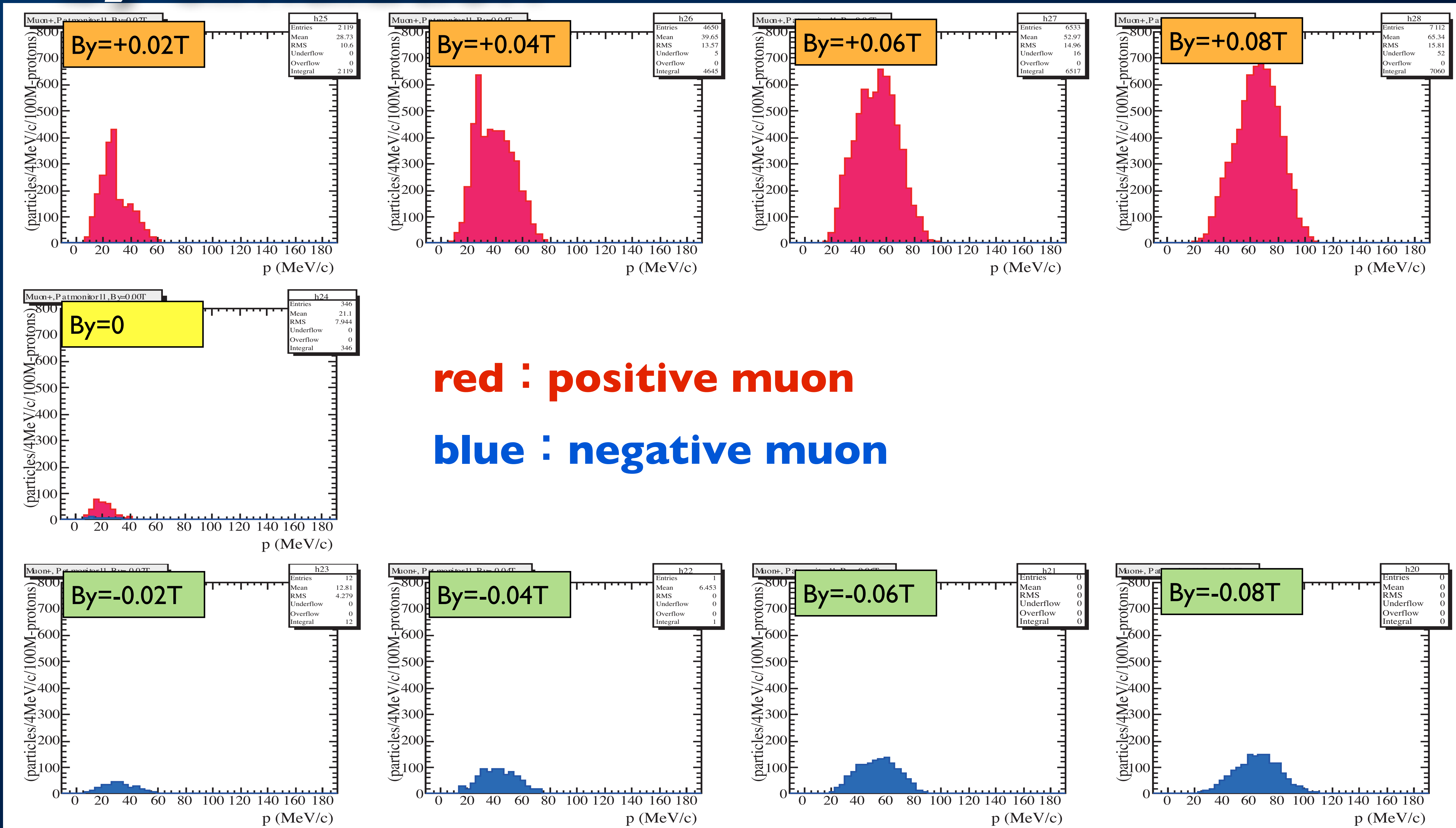
Muon beam from MuSIC by simulation

by g4beamline, QGSP_BERT, E_p=392MeV



- Changing magnitude and direction of the dipole field, we can select charge and momentum of the beam.

Muon beam from MuSIC by simulation

by g4beamline, QGSP_BERT, E_p=392MeV

B_y (T)	$N(\mu^+)$ for I_p=1μA	$N(\mu^-)$ for I_p=1μA	$N(\mu^+)/N(\mu^-)$
-0.08	0	1E+08	0
-0.06	0	9E+07	0
-0.04	6E+04	5E+07	1E-03
-0.02	7E+05	2E+07	3E-02
0	2E+07	4E+06	5E+00
0.02	1E+08	0	-
0.04	3E+08	0	-
0.06	4E+08	0	-
0.08	4E+08	0	-

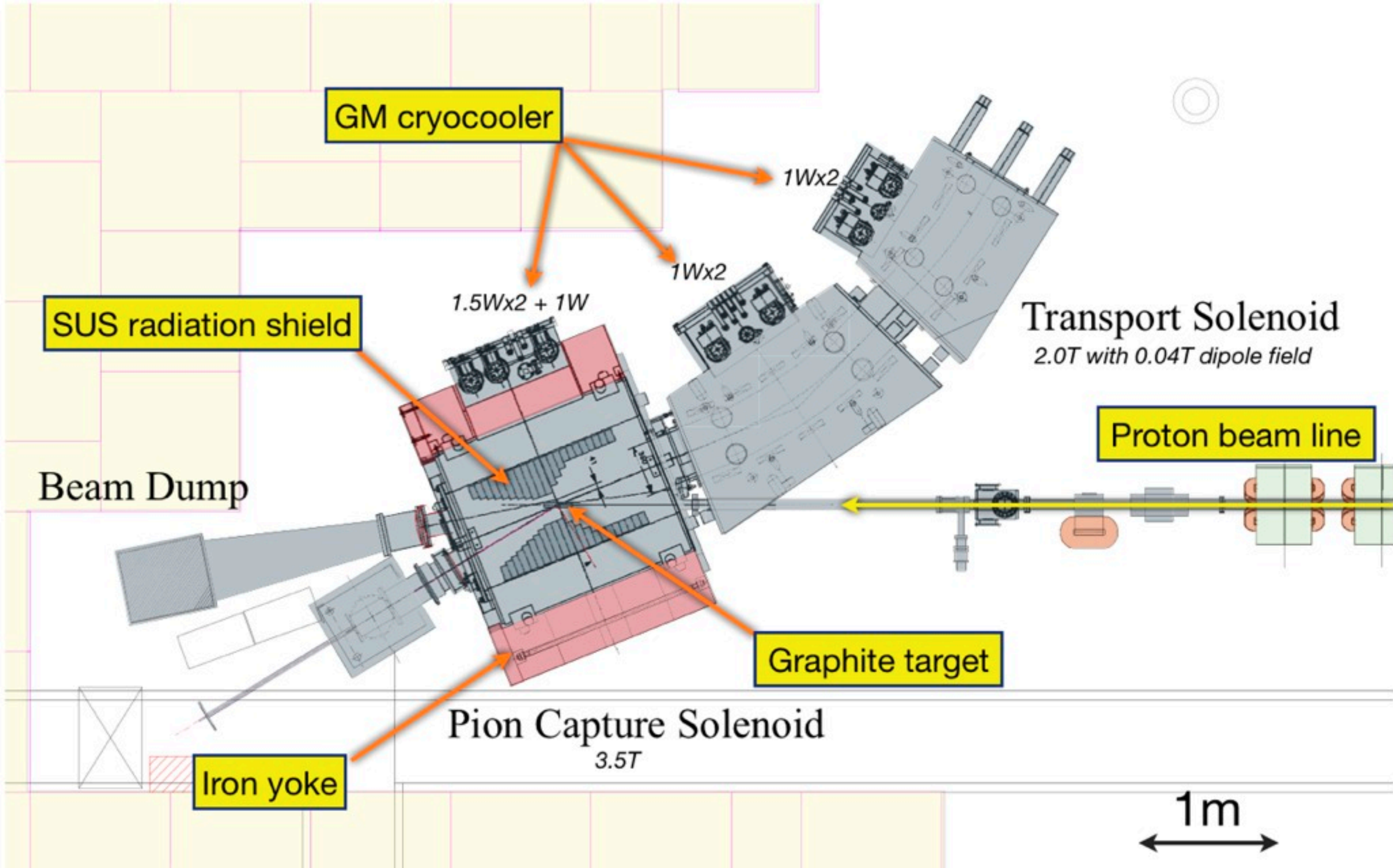
The proton beam current will be upgraded to 5μA in near future.

Examples of Muon Science at MuSIC

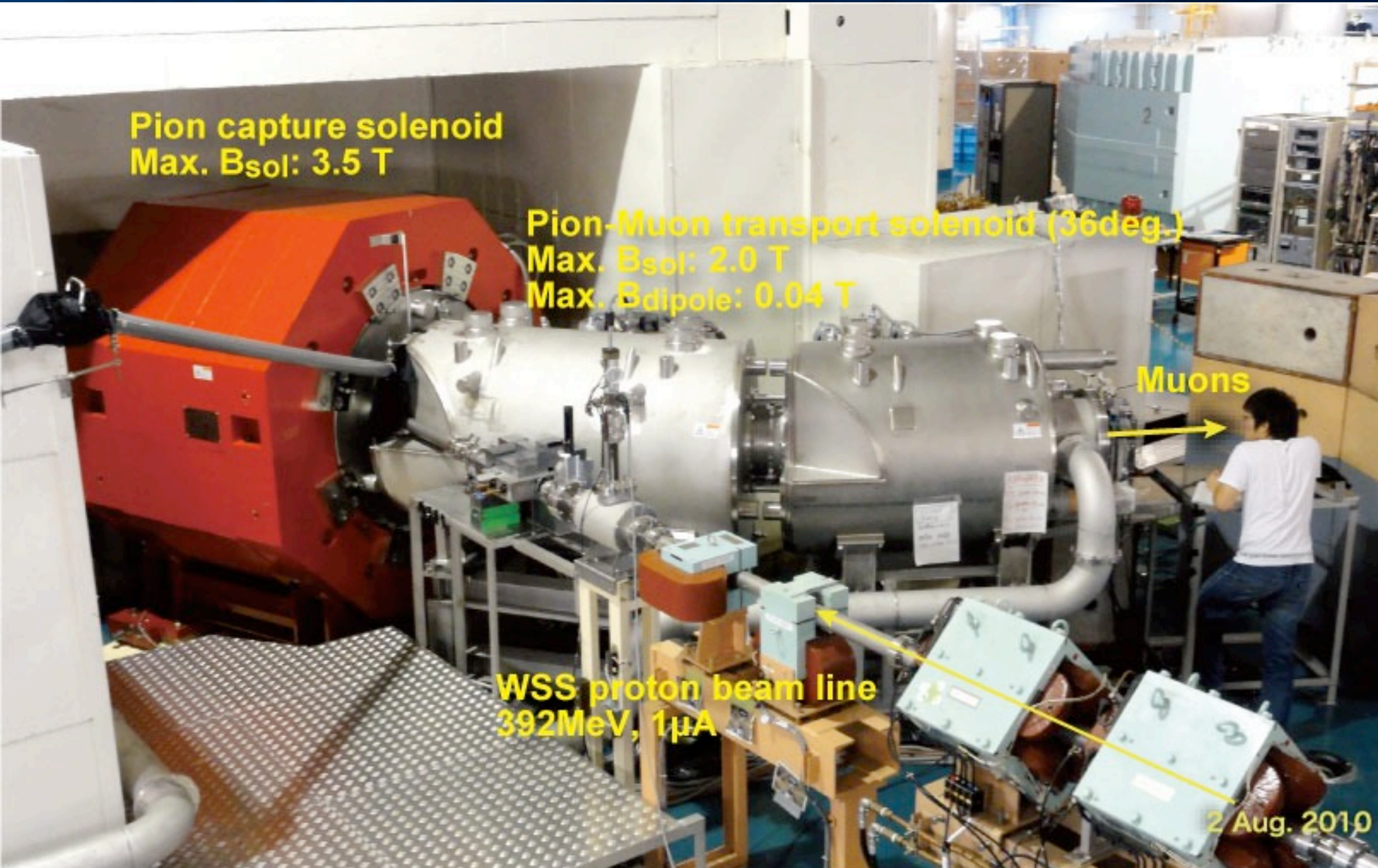
- **Particle Physics :**
  - search for $\mu \to eee$ (muon LFV) — $10^{8\text{-}9}\mu^+$/sec
    - DC continuous beam is critical
- **Nuclear Physics :**
  - nuclear muon capture (NMC) — $10^{5\text{-}6}\mu^-$/sec
  - pion capture and scattering
- **Chemistry :**
  - chemistry on pion/muon atoms — $10^{5\text{-}6}\mu^-$/sec
- **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

Details

MuSIC: Present Layout



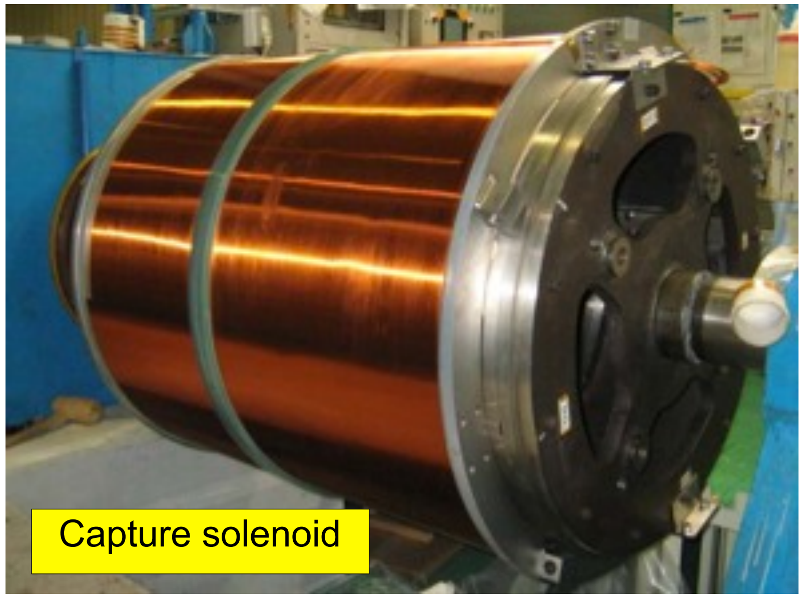
MuSIC@RCNP-West Hall (~2012 Feb)

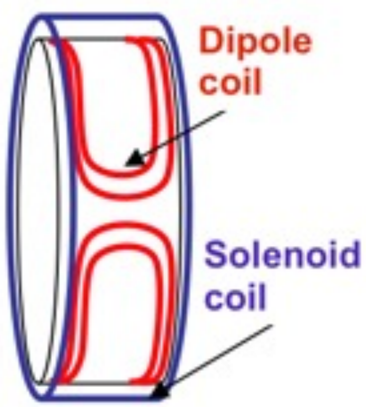


Superconducting Magnets

Superconducting Coils

Conductor	Cu-stabilized NbTi
Cable diameter	Φ1.2 mm
Cu/NiTi ratio	4
RRR (R_{293K}/R^{10K} at 0T)	230-300





Operation current	145 A
Max field on axis	3.5 T
Bore	Φ900 mm
Length	1000 mm
Inductance	400 H
Stored energy	5 MJ
Quench back heater (Cu wire)	1.2 mm dia. ~1Ω@4 K

Solenoid coil of the capture solenoid

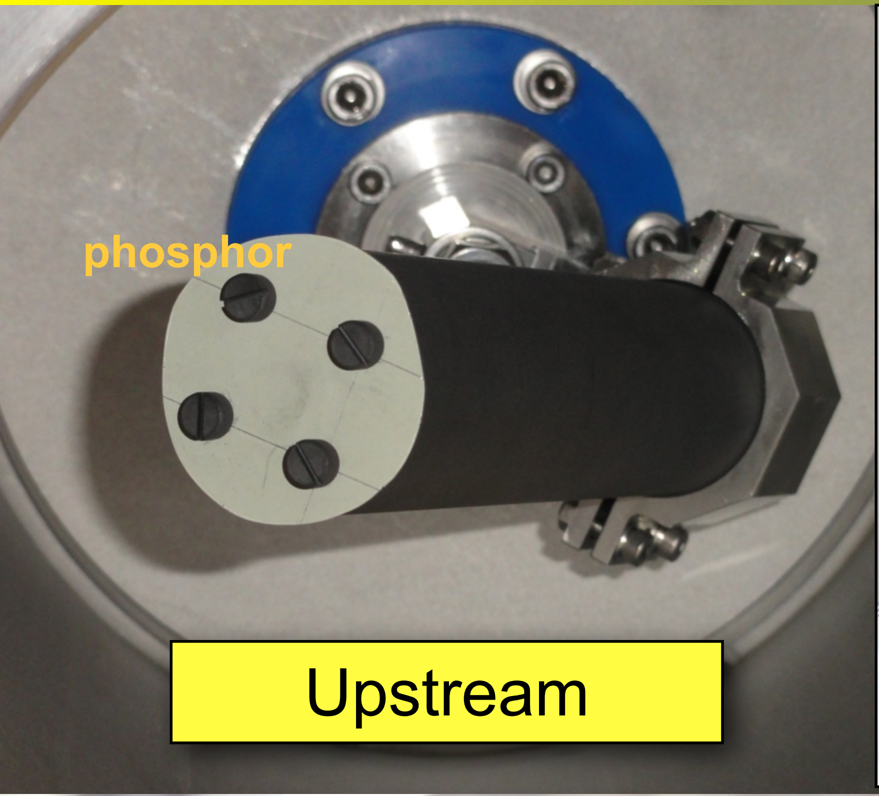
Operation current	145 A
Max field on axis	2.0 T
Bore	Φ480 mm
Length	200 mm x 8 coils
Inductance	124 H
Stored energy	1.4 MJ
Quench back heater (Cu wire)	1.3 mm dia. ~0.05Ω/coil@4K

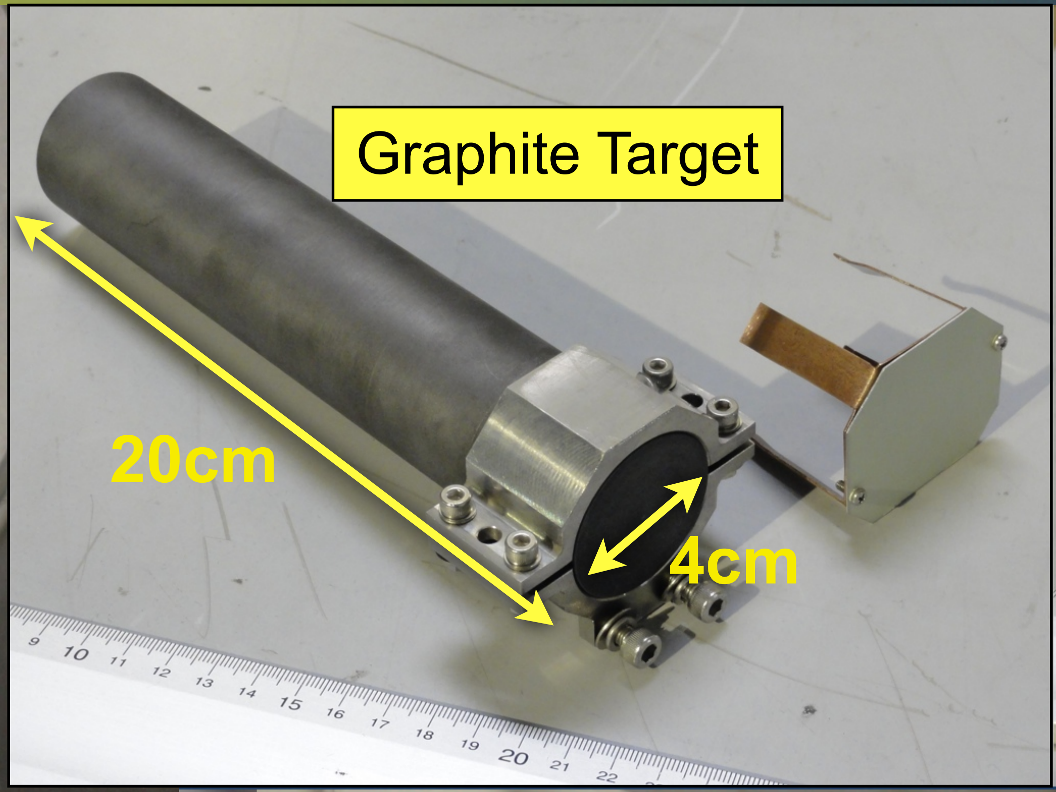
Solenoid coil of the transport solenoid

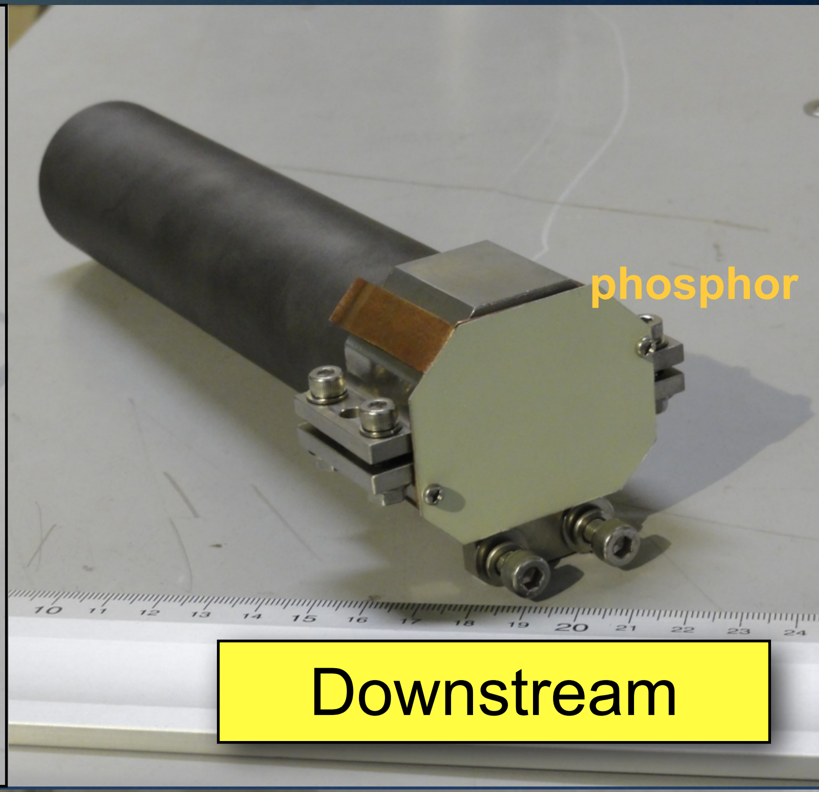
Operation current	115 A
Max field on axis	0.04 T
Bore	Φ460 mm
Length	200 mm/coil
Inductance	0.04 H/coil
Stored energy	280 J/coil

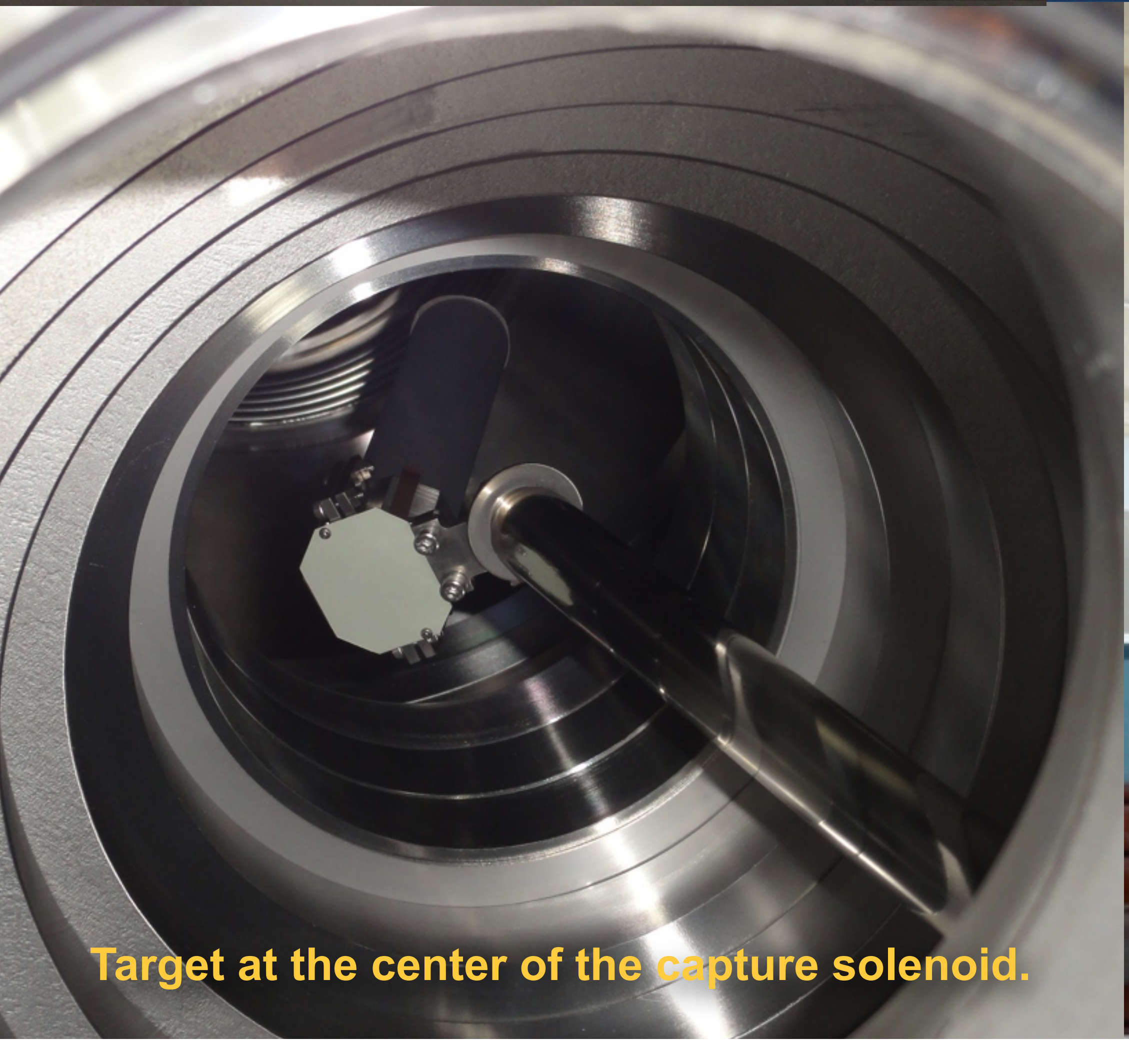
Dipole coil of the transport solenoid

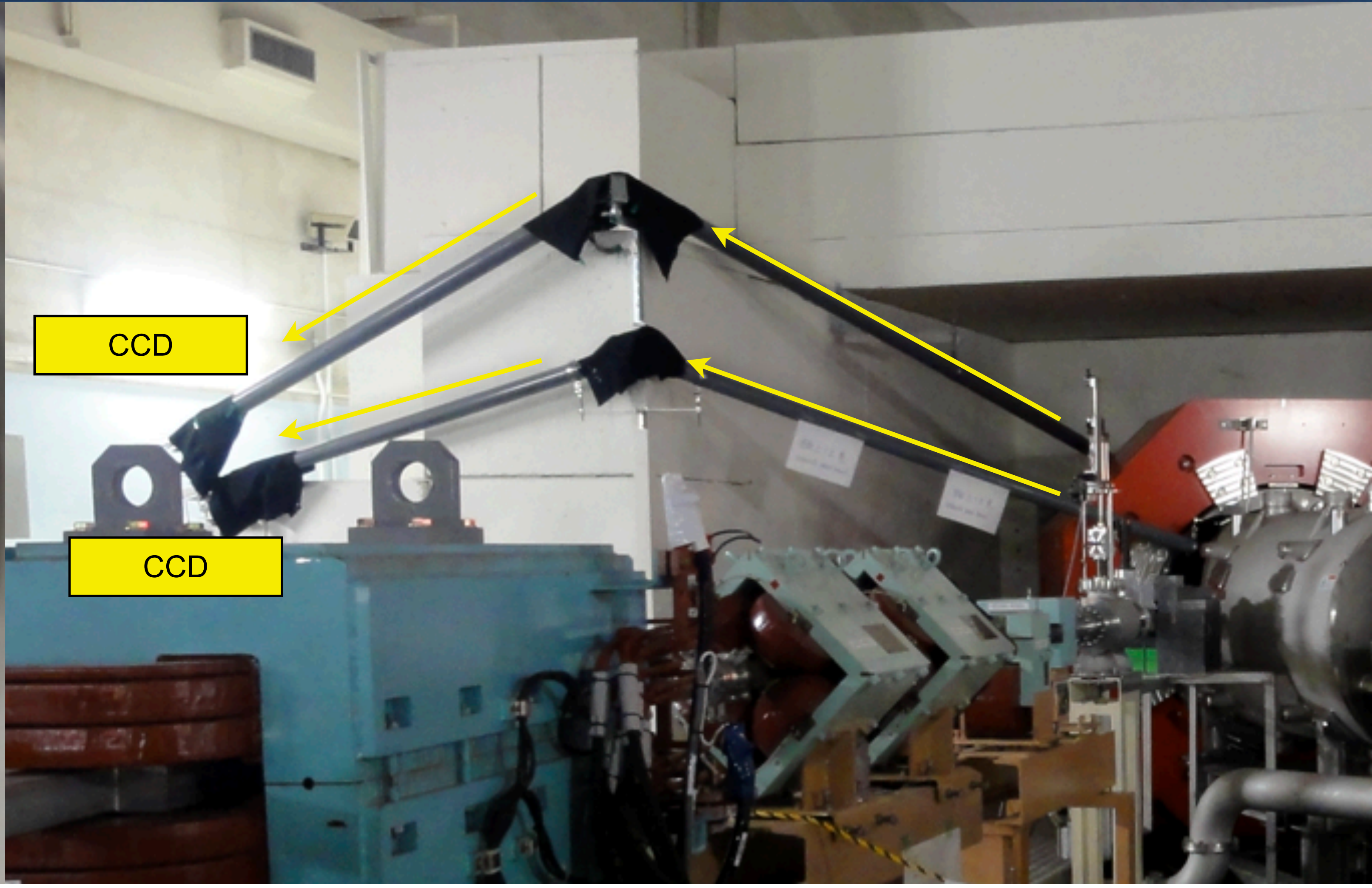
Proton Beam Monitoring on the Target











Proton Beam on the target

Beam Tests

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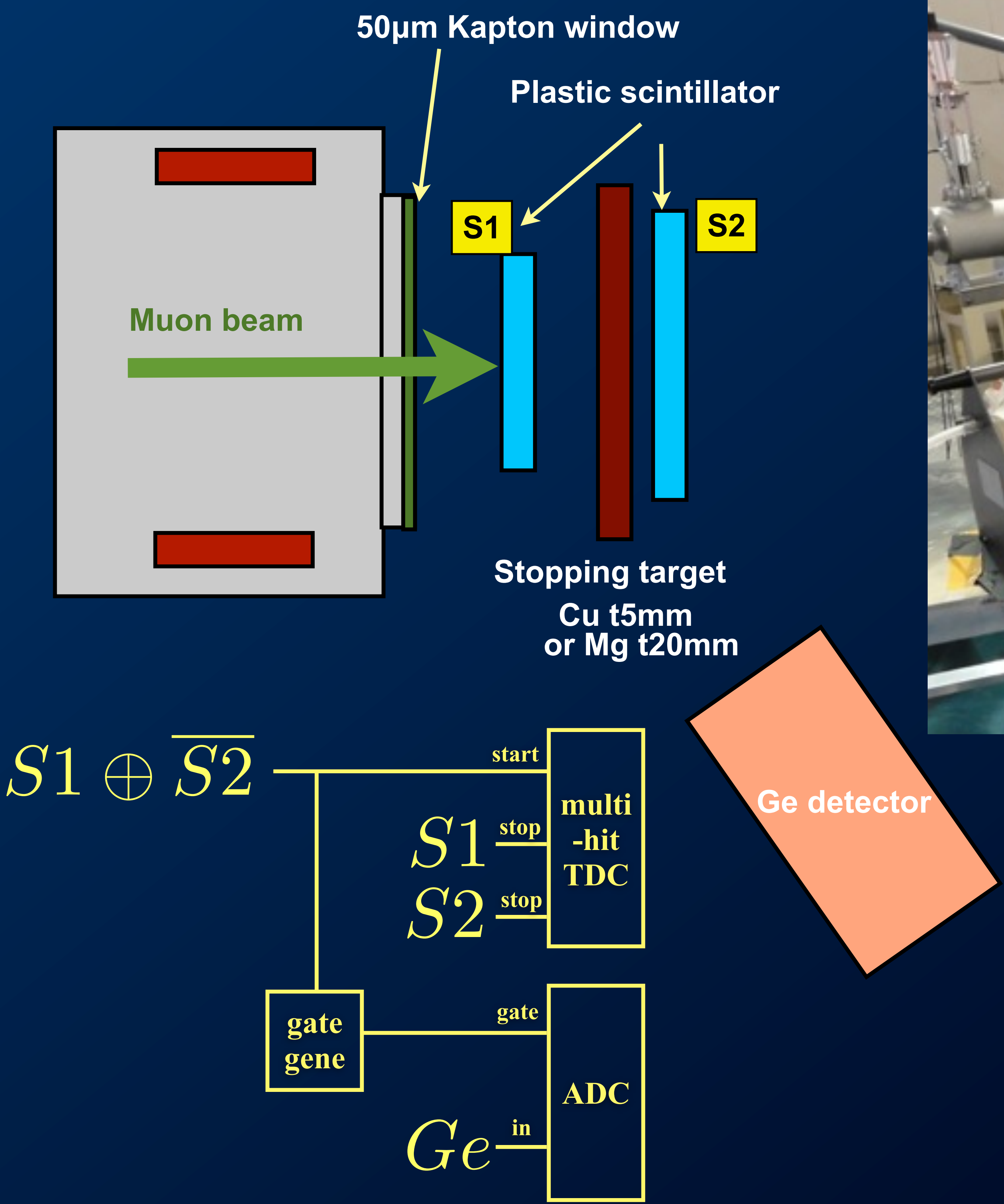
Construction

Commissioning

Muon collection efficiency

High current operation

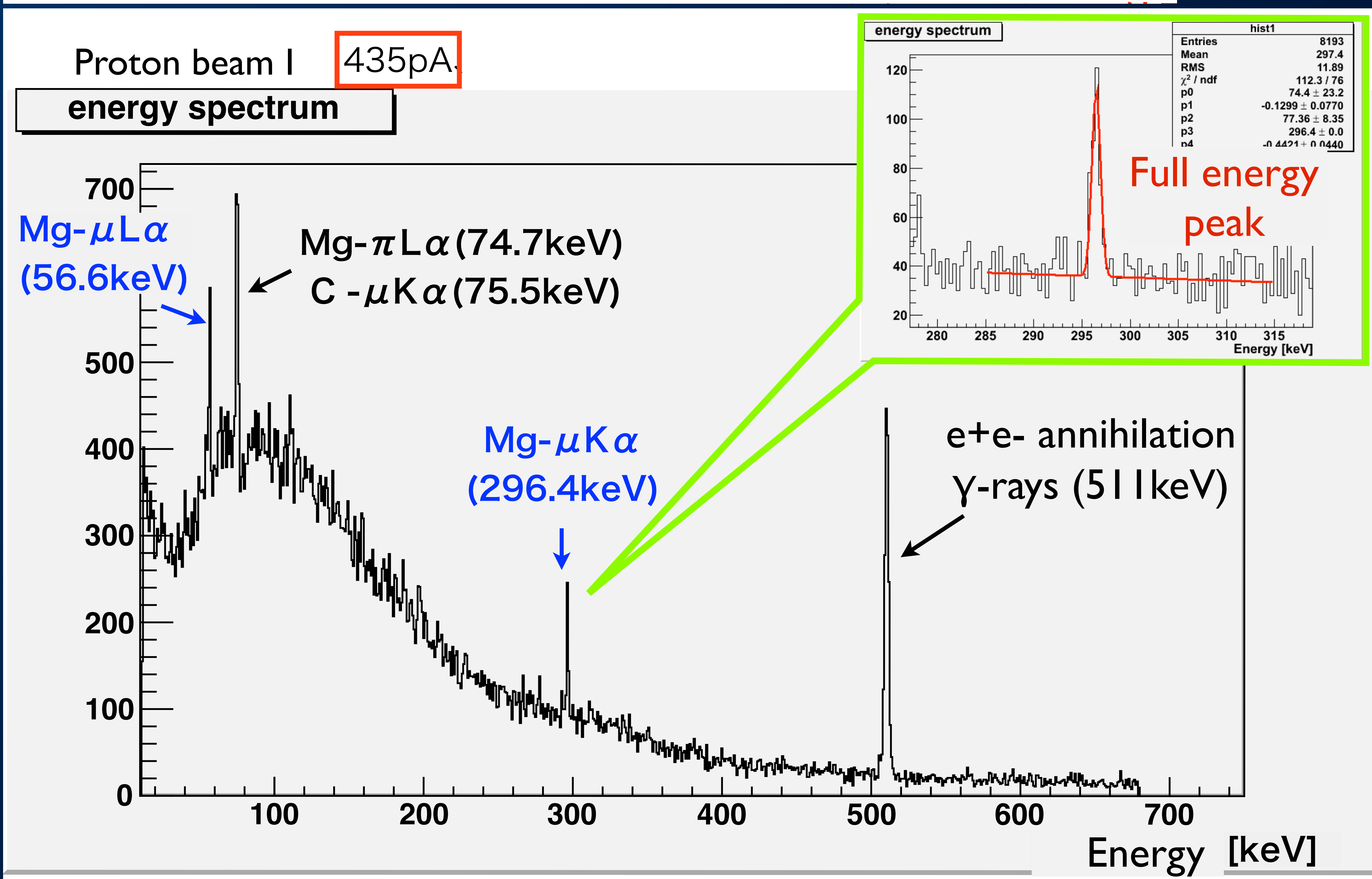
Setup: muon life and muonic-X-ray



Results from muonic X-ray

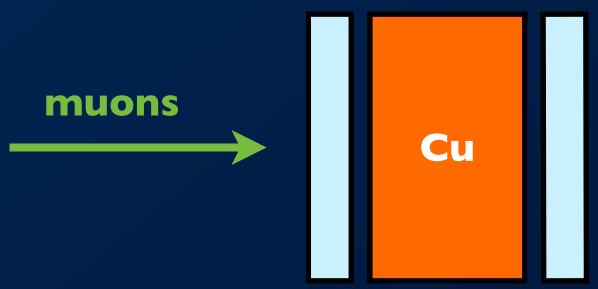
Number of negative muons at the 36 deg exit for 1μA proton beam

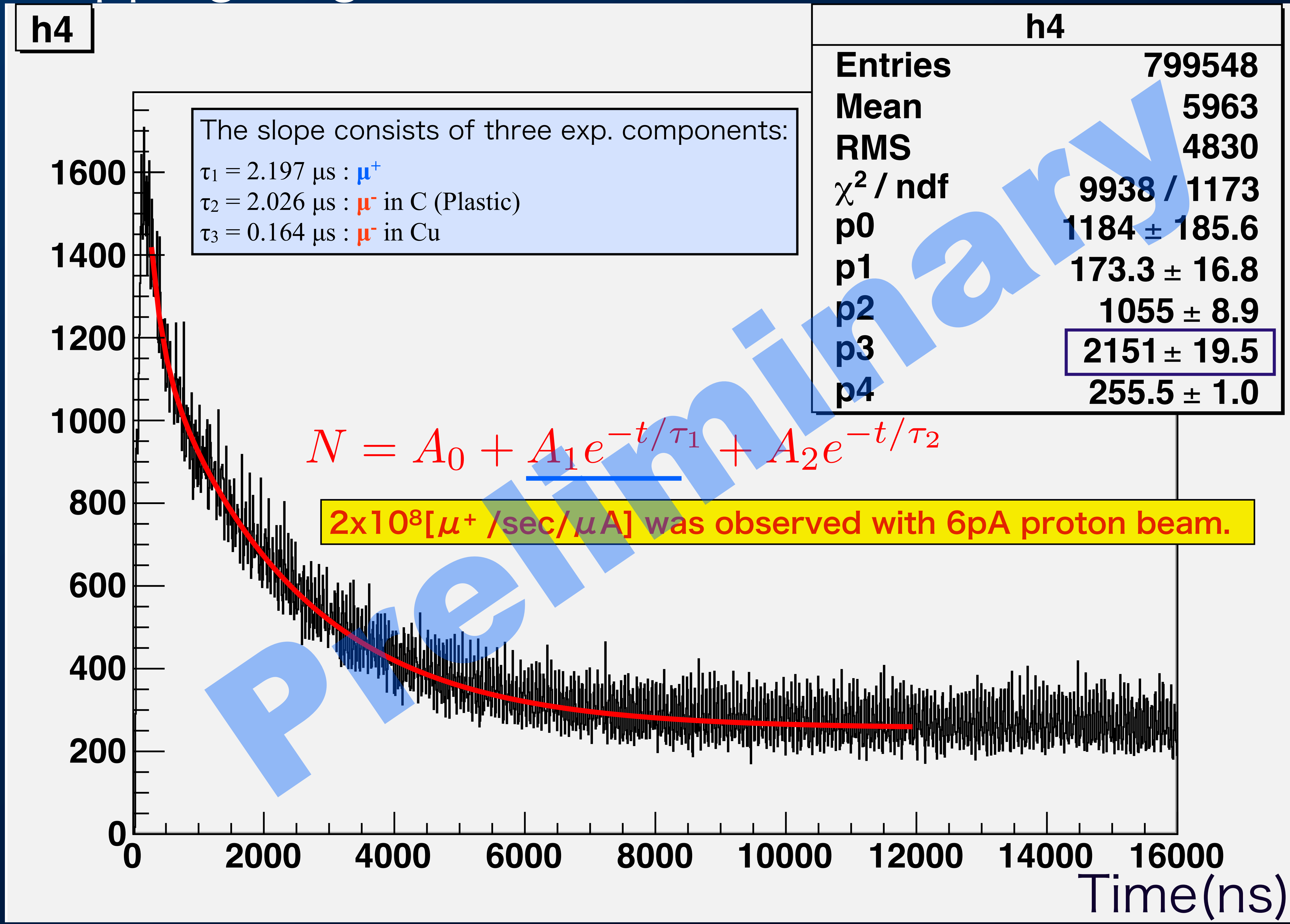
	beam test	simulation
Num. of muons [1/sec]	$(1.7\pm0.3)\times10^8$	1.4×10^8



Muon Life

- Stopping target : Cu





Operation with 400W proton beam

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Commissioning

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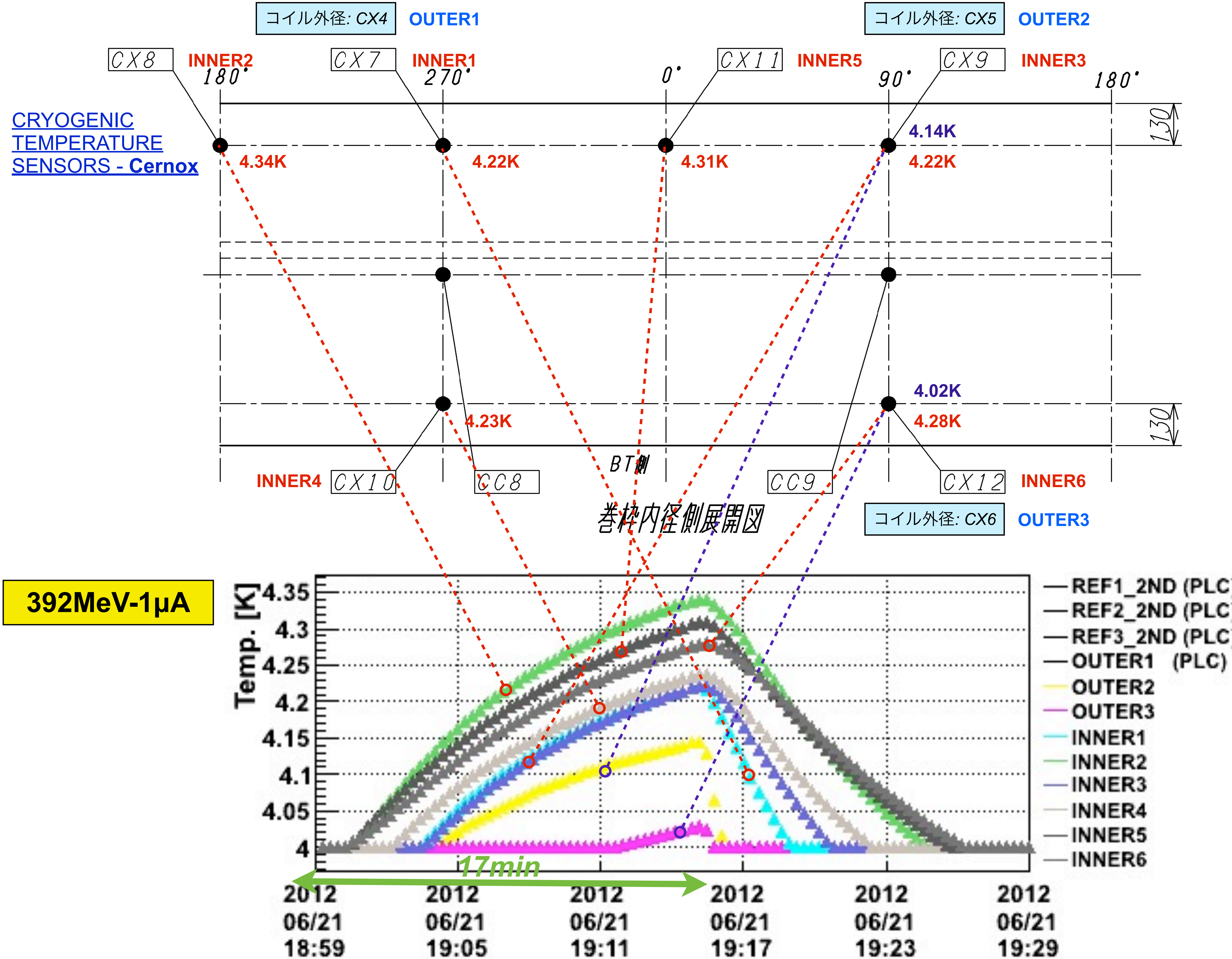
Muon collection efficiency

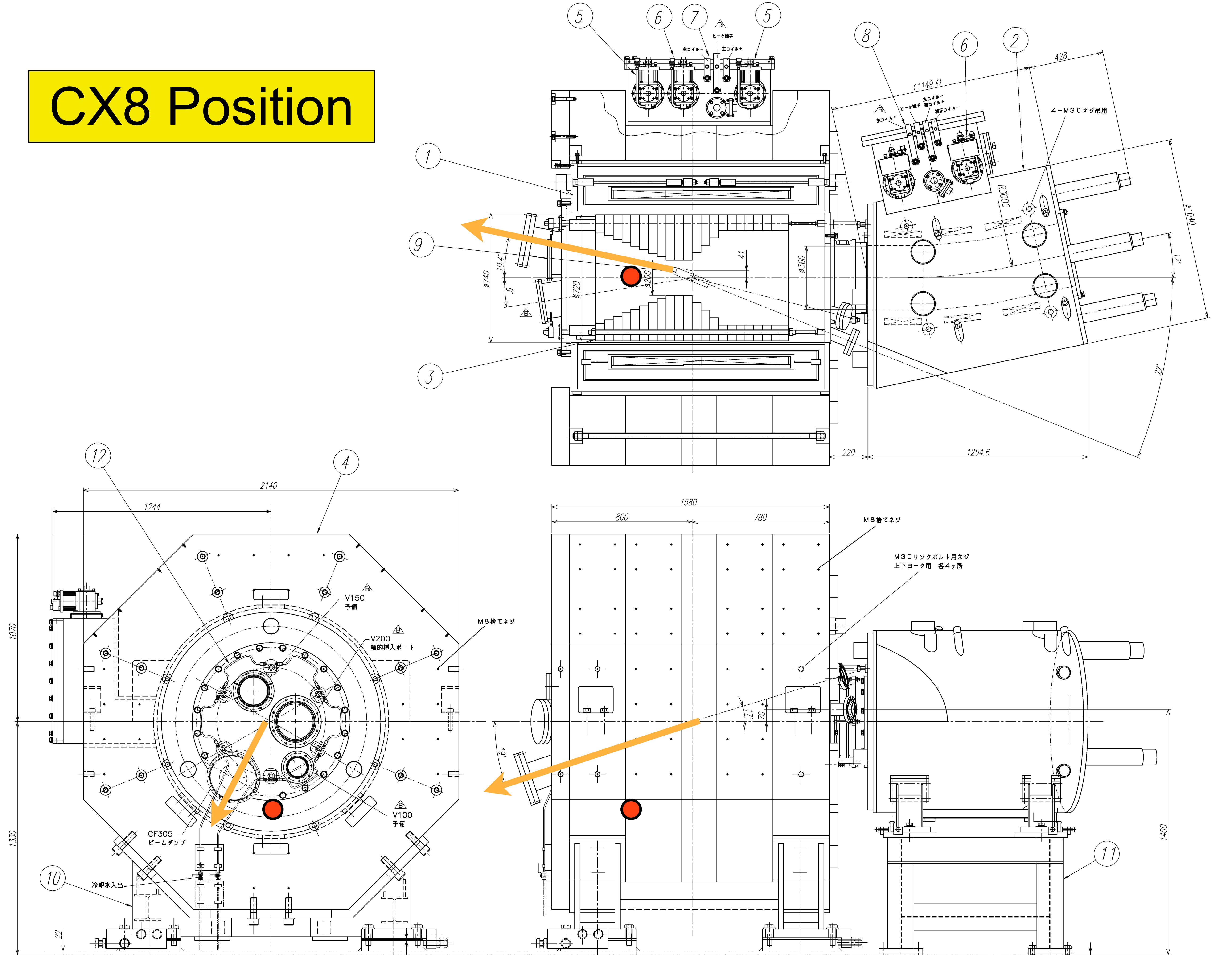
- 2012JYP
  - 2012, Jun 18-22 : 5th beam test
    - measurements for muon energy and spatial distribution
    - the system was operated with a high current proton beam **(I_{proton}=~1microA)**

High current operation



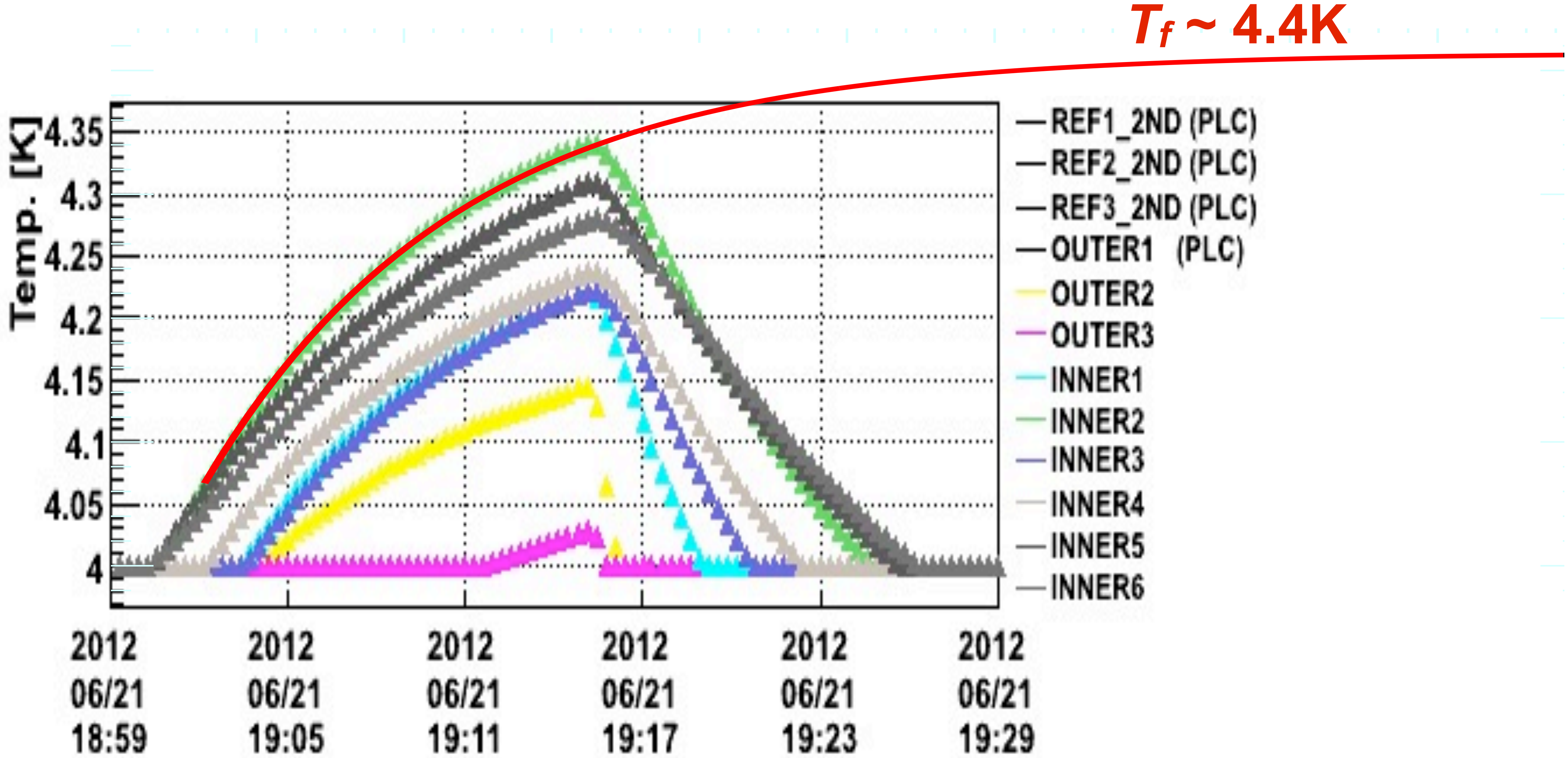
コイル外径: CX4
OUTER1
コイル外径: CX5
OUTER2
CX8
INNER2
CX7
INNER1
CX11
INNER5
CX9
INNER3
180°
270°
0°
90°
180°
CRYOGENIC TEMPERATURE SENSORS - Cernox
4.34K
4.22K
4.31K
4.14K
4.22K
4.02K
4.23K
4.28K
130
BT側
INNER4
CX10
CC8
CC9
CX12
INNER6
巻枠内径側展開図
コイル外径: CX6
OUTER3
392MeV-1μA
Temp. [K]
4.35
4.3
4.25
4.2
4.15
4.1
4.05
4
17min
2012 06/21 18:59
2012 06/21 19:05
2012 06/21 19:11
2012 06/21 19:17
2012 06/21 19:23
2012 06/21 19:29
REF1_2ND (PLC)
REF2_2ND (PLC)
REF3_2ND (PLC)
OUTER1 (PLC)
OUTER2
OUTER3
INNER1
INNER2
INNER3
INNER4
INNER5
INNER6

CX8 Position



Terminal Temperature

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



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

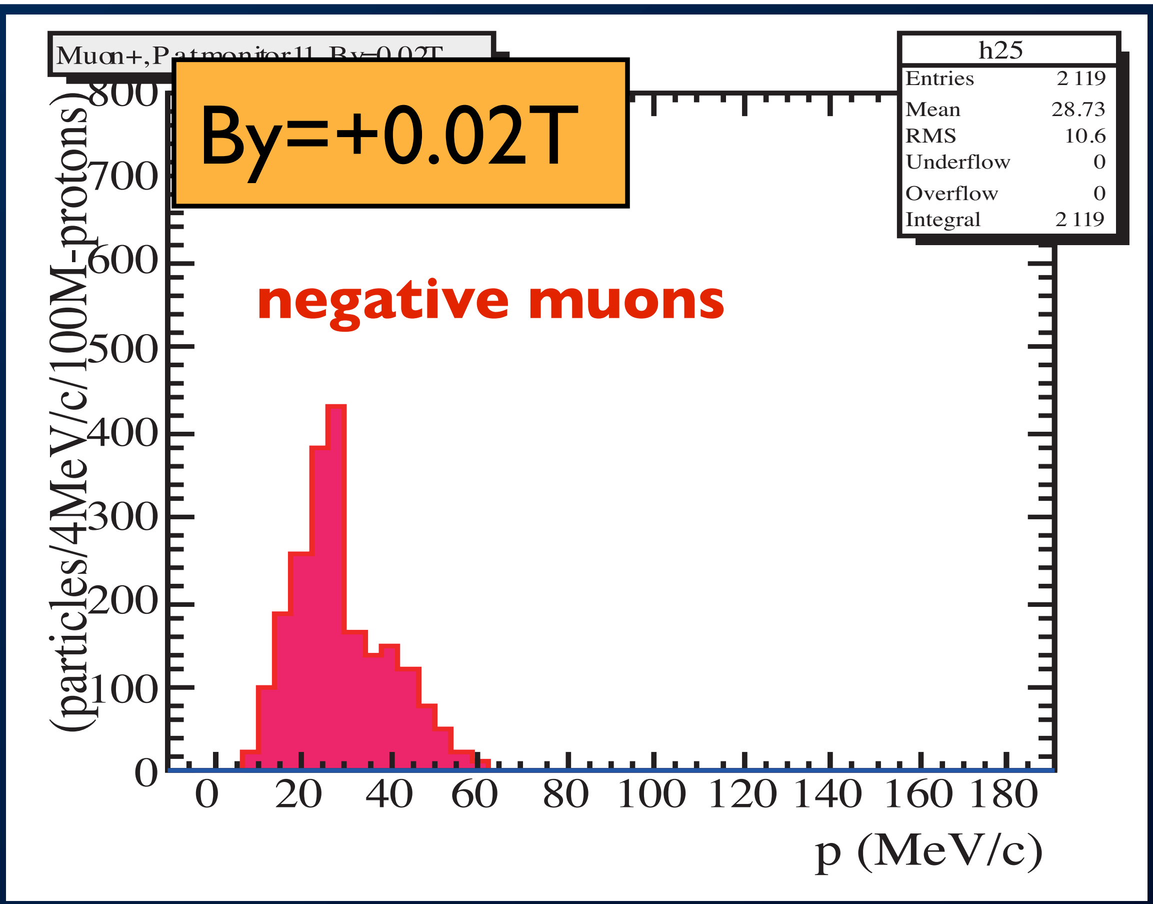
Summary

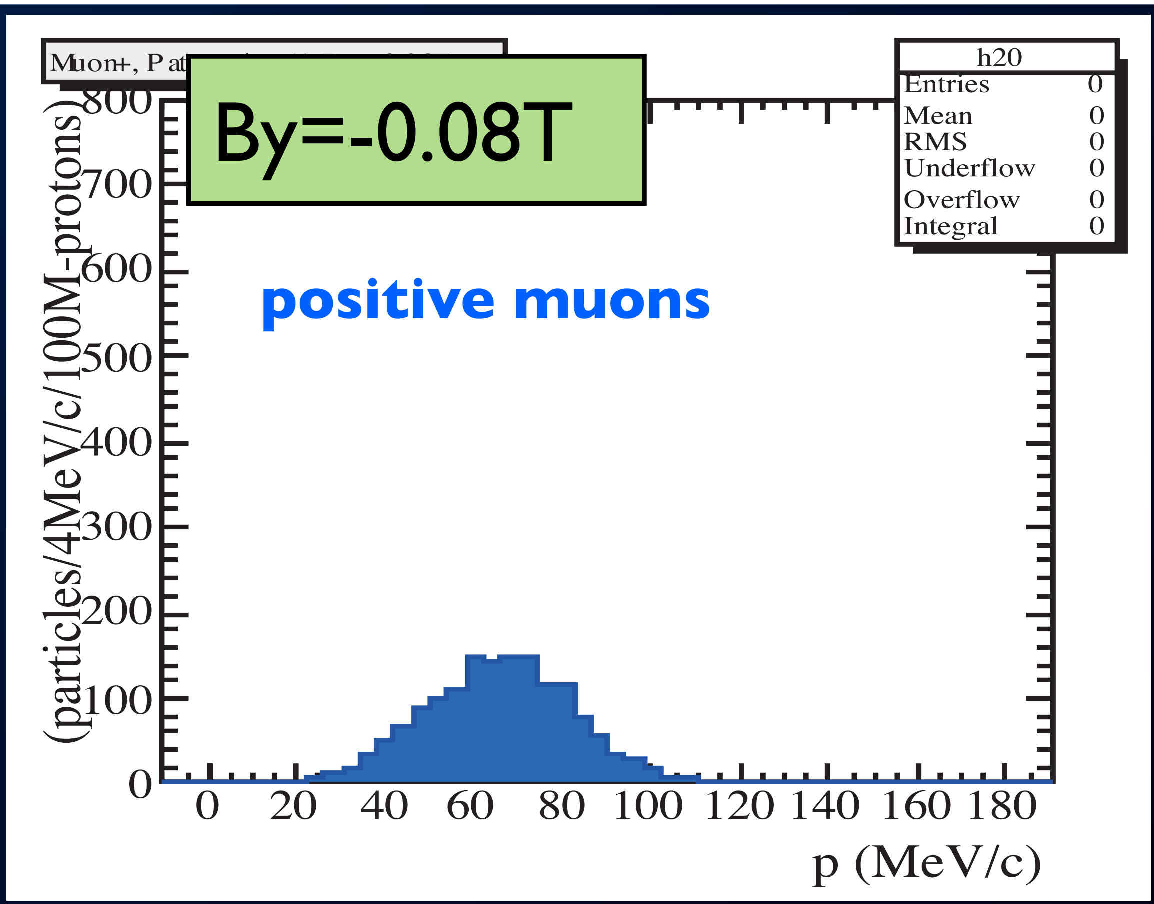
- A new intense DC muon beam line is under construction at RCNP, Osaka University. This is the first muon facility which adopts a superconducting pion capture system. It would provide >10^8muons/sec with a 400W proton beam.
- The pion capture solenoid and a 36 deg. of transport solenoid have been build.
- Five beam tests with a low current proton beam have been performed. The results from muon life and muonic X-ray measurements conclude more than 10^8 muons/sec with 392MeV, 1μA proton is achievable at the MuSIC.
- Finally, the system successfully have been operated with 392meV-1μA proton beam in June, 2012.
- The MuSIC also can be considered as one of the very important R&D programs for not only the COMET project, and also PRISM/PRIME and Neutrino factories and Muon collider.

A Future Plan of RCNP: 1MW proton cyclotron

2023~???

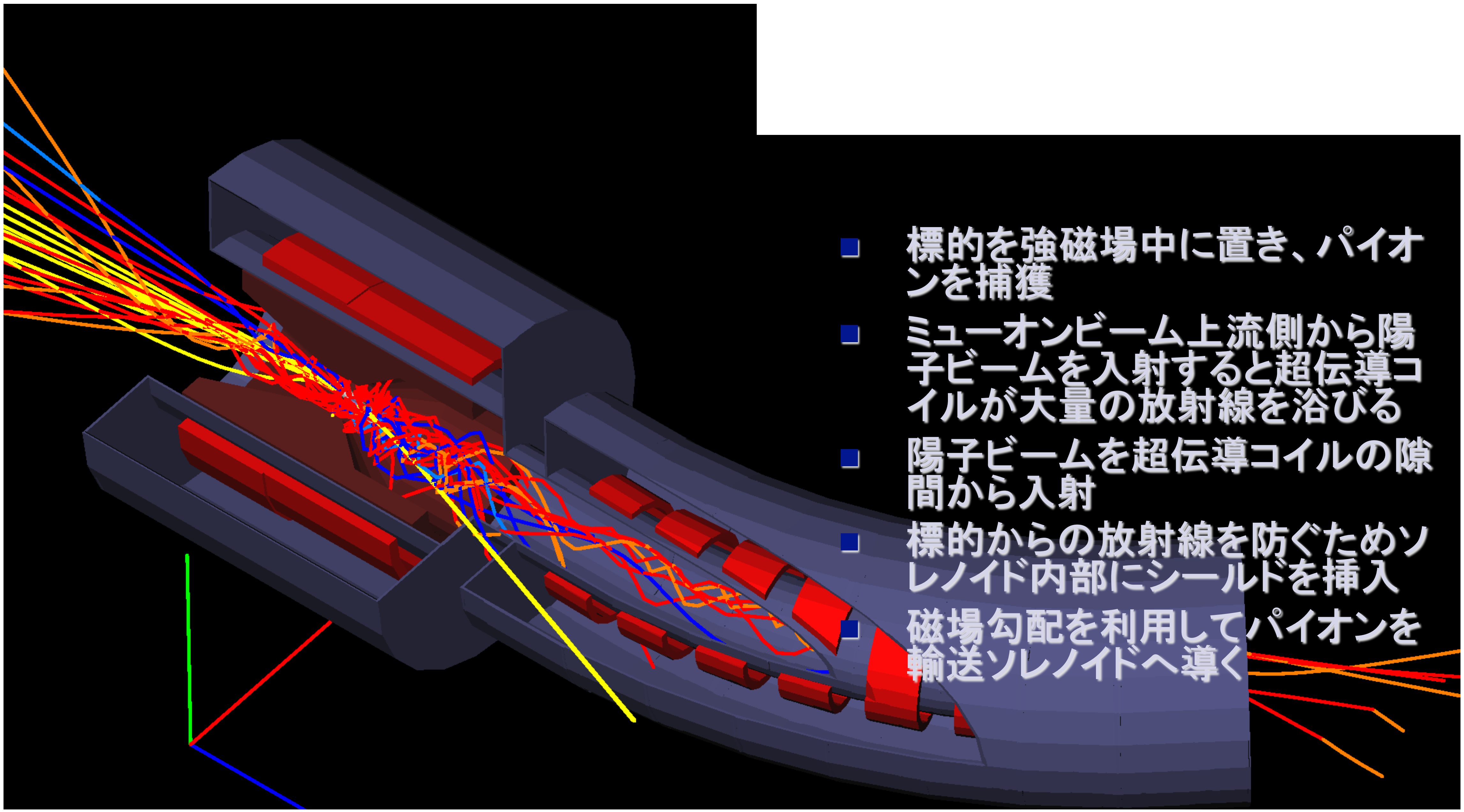
		The present MuSIC	A future plan
Proton cyclotron	proton beam energy	400 MeV	400 MeV
	proton beam current	1 μA	**2.5 mA**
	proton beam power	400 W	x 2.5 x 10^3 **1 MW**
MuSIC system	production target	Graphite, L=20cm	x 2 Tungsten, 16cm
	Solenoid field	3.5 Tesla	x 1.4 5.0 Tesla
Muon beam	μ^+ yield	1×10^8 /sec	**7×10^{11} /sec**
	μ^- yield	1×10^8 /sec	**7×10^{11} /sec**





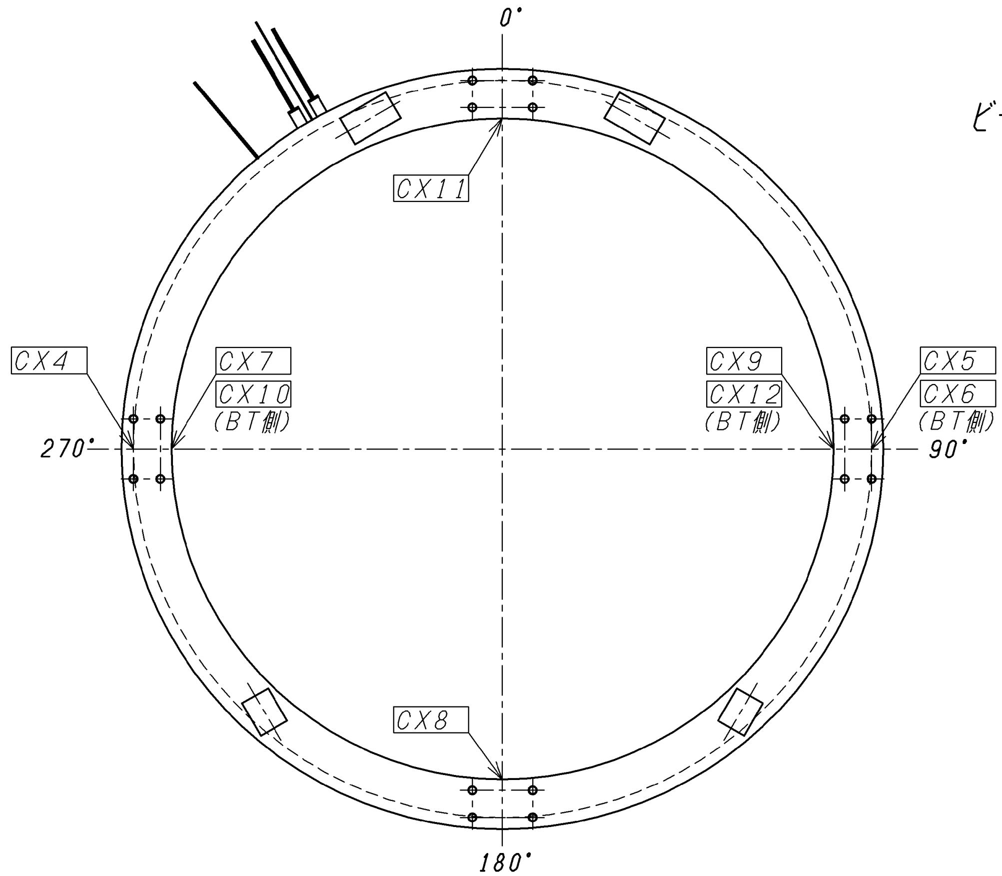
Backup Slides

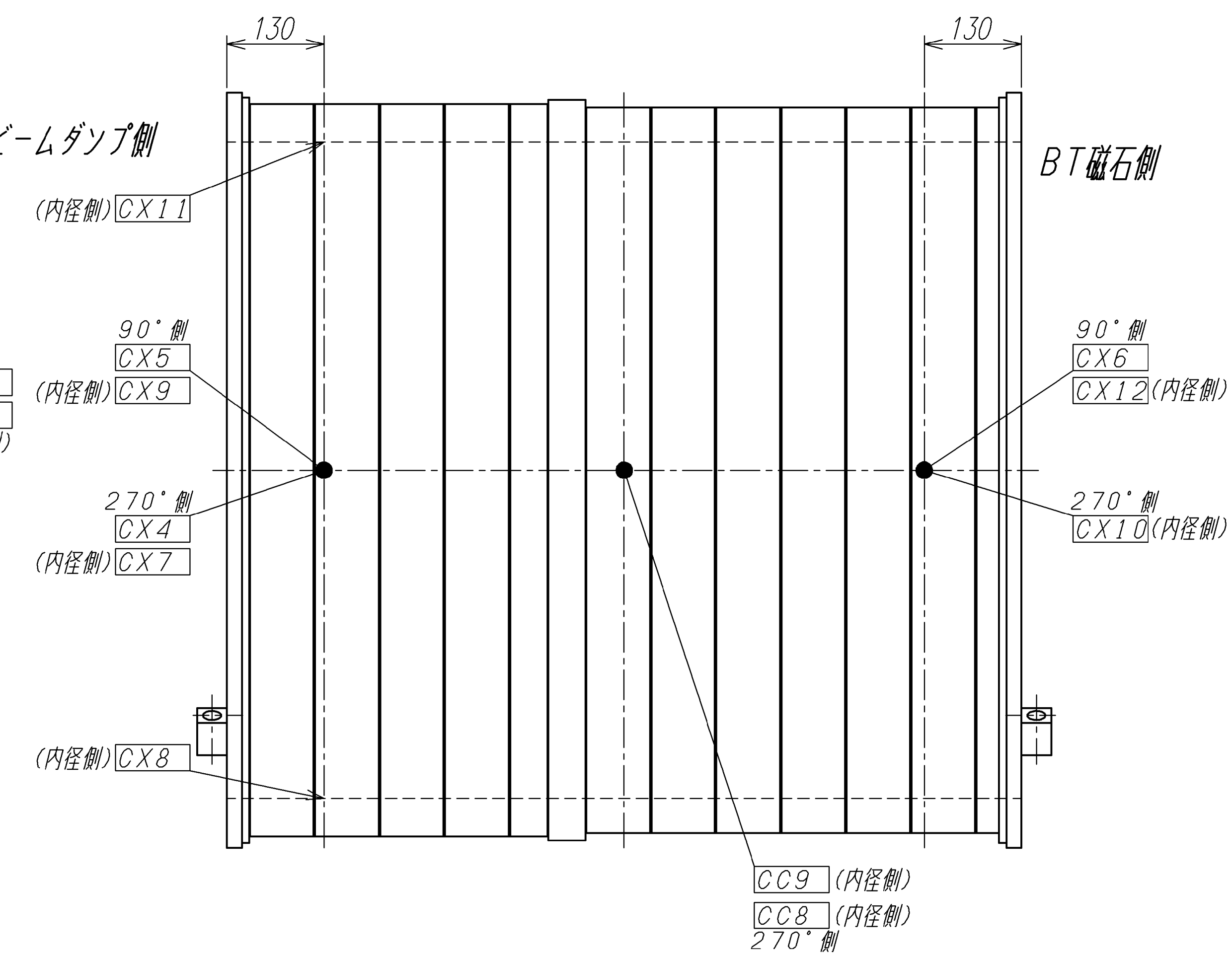
パイオン捕獲システム



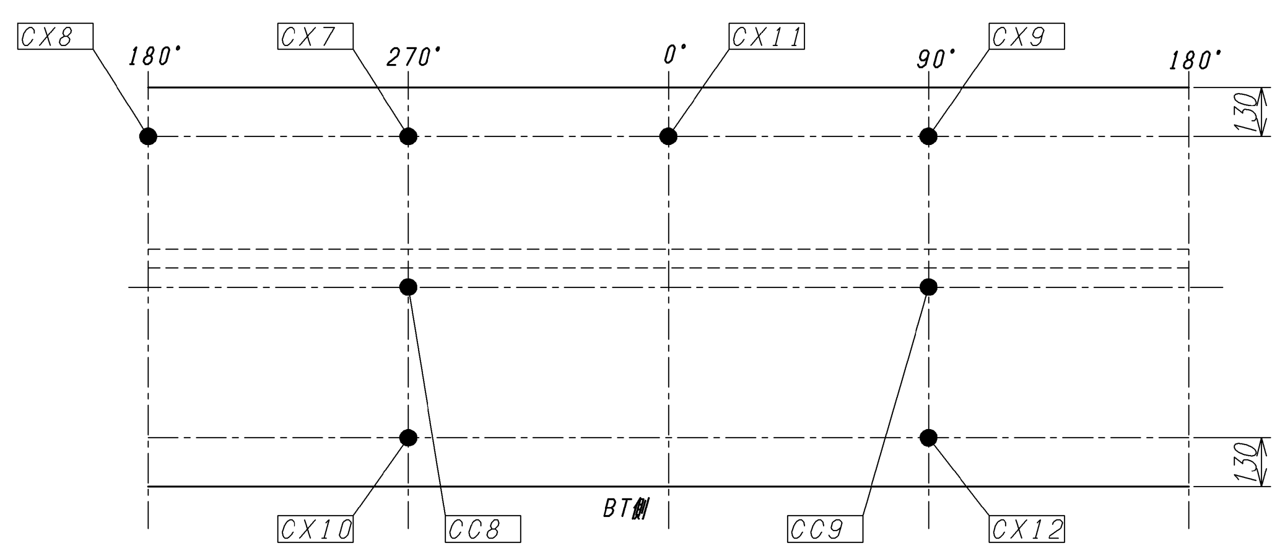
すべての超伝導コイルは液体ヘリウムを使わず、GM冷凍機で冷やす

→ 低コスト・運転が楽　　→ 放射線による核発熱を1W以下に抑える必要あり。

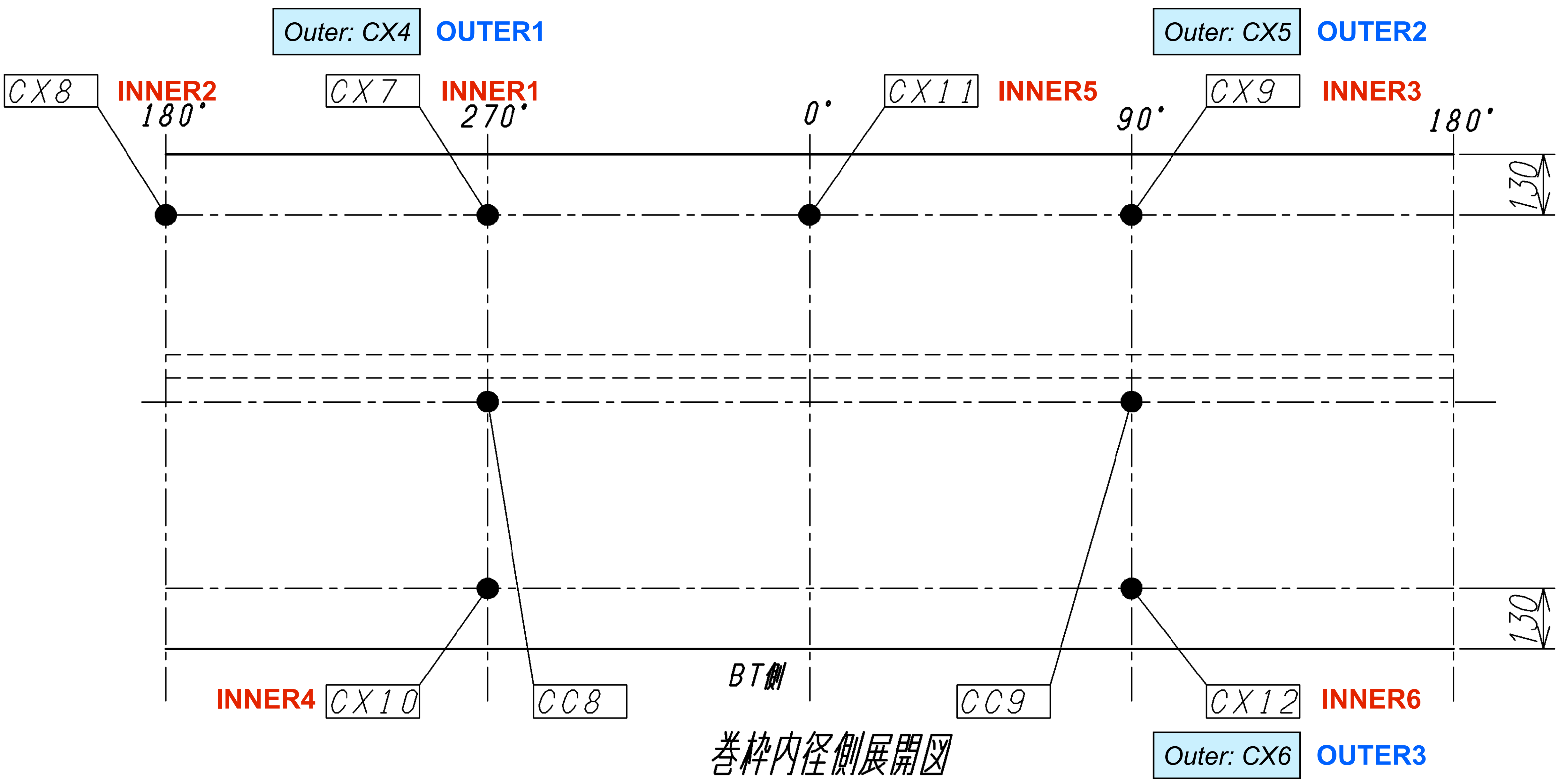




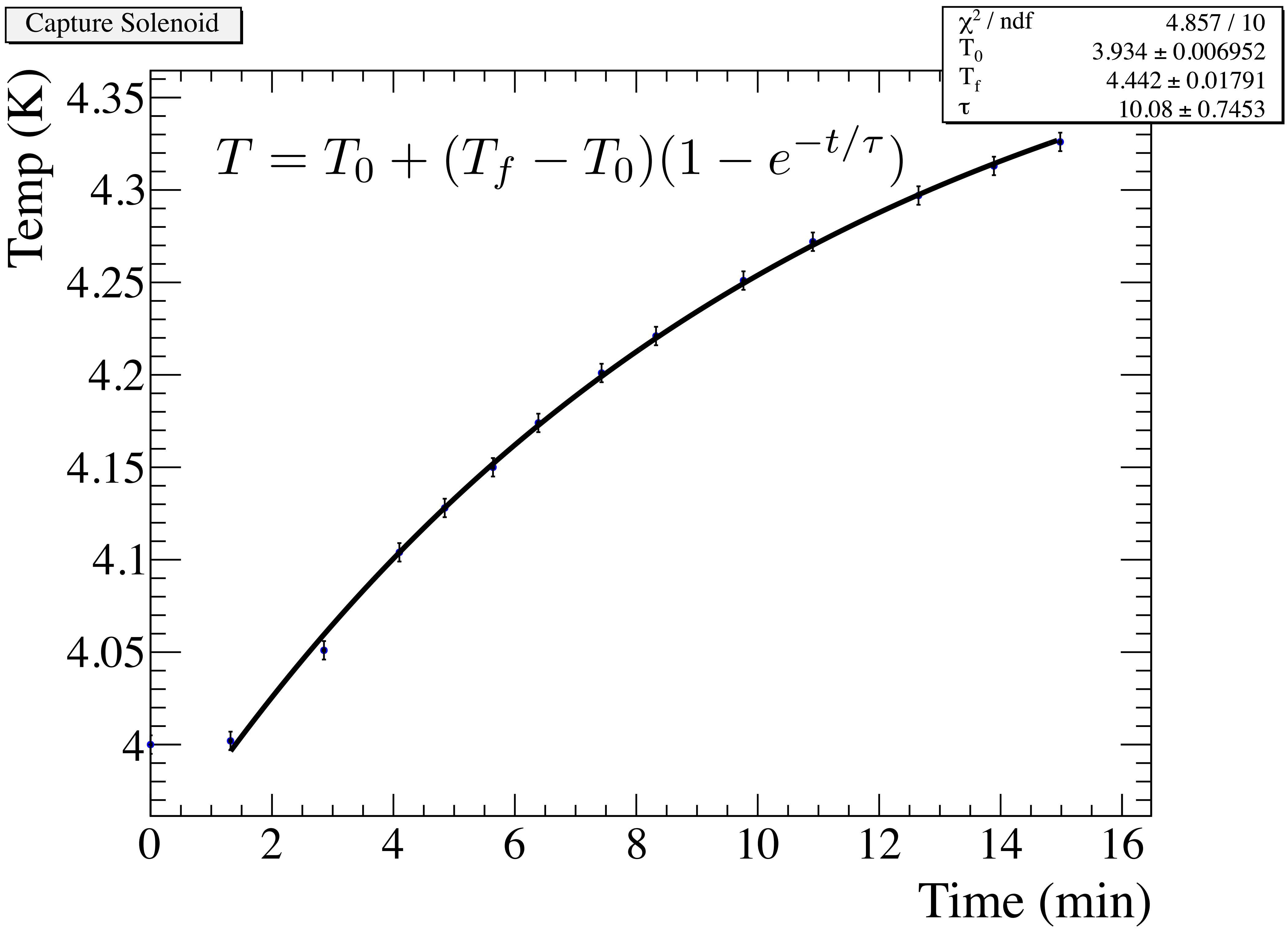
巻枠計測線取付位置



巻枠内径側展開図

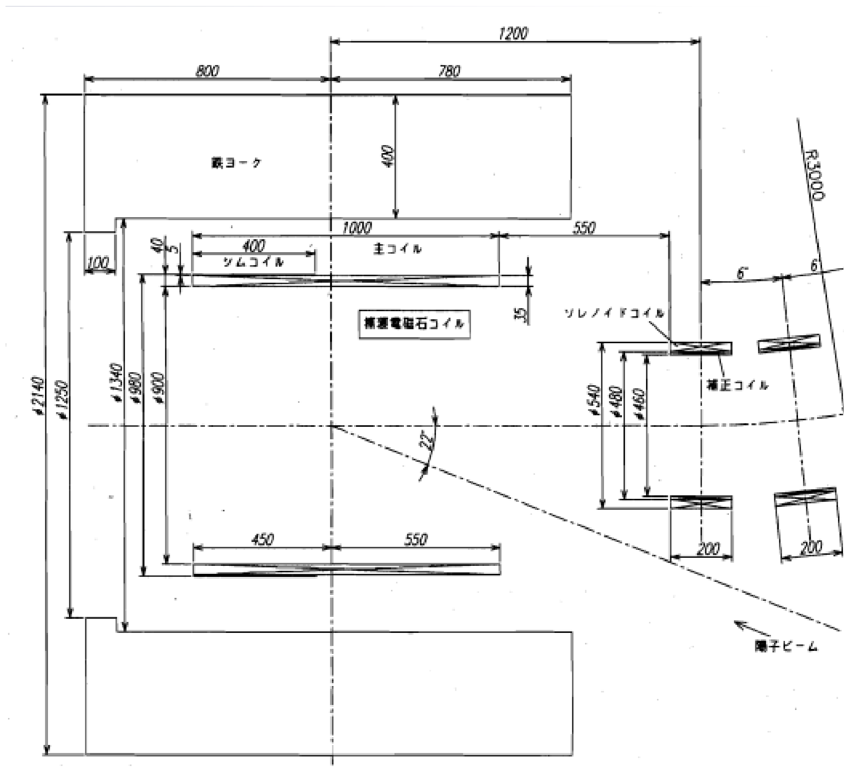


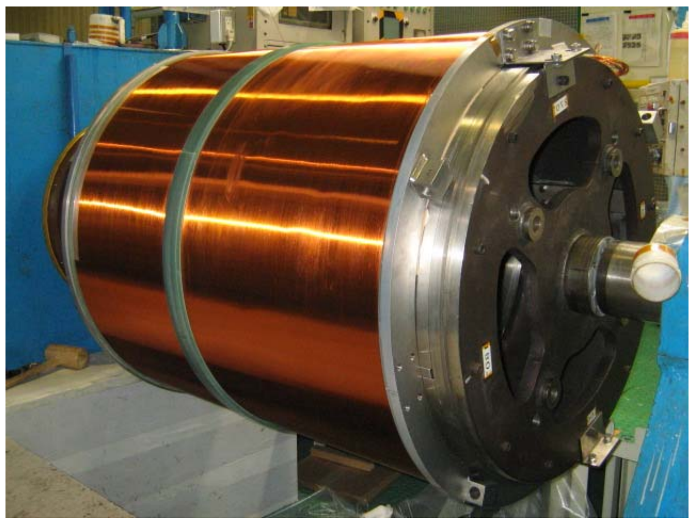
Outer: CX4
OUTER1
Outer: CX5
OUTER2
CX8
INNER2
CX7
INNER1
CX11
INNER5
CX9
INNER3
180°
270°
0°
90°
180°
130
130
BT側
INNER4
CX10
CC8
CC9
CX12
INNER6
Outer: CX6
OUTER3
巻枠内径側展開図


Capture Solenoid
χ^2 / ndf 4.857 / 10
T_0 3.934 ± 0.006952
T_f 4.442 ± 0.01791
τ 10.08 ± 0.7453
$T = T_0 + (T_f - T_0)(1 - e^{-t/\tau})$
Temp (K)
4.35
4.3
4.25
4.2
4.15
4.1
4.05
4
0
2
4
6
8
10
12
14
16
Time (min)

パイオン捕獲システム：仕様

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



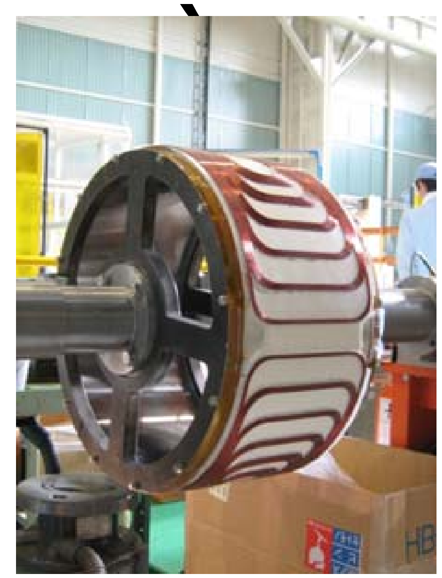


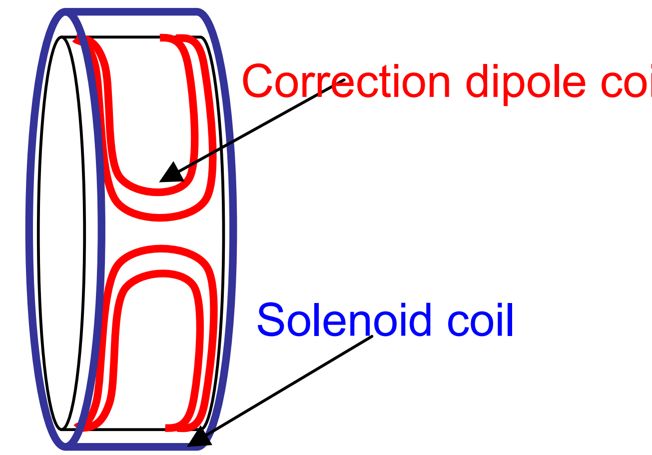
ミューオン輸送ソレノイド

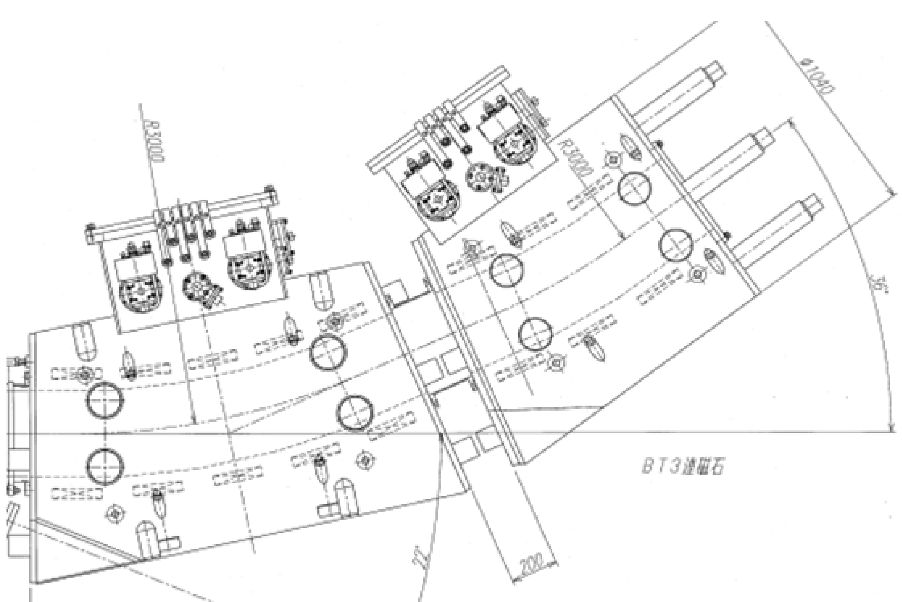
世界初の実用：
cosθ巻き超伝導双曲電磁石

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







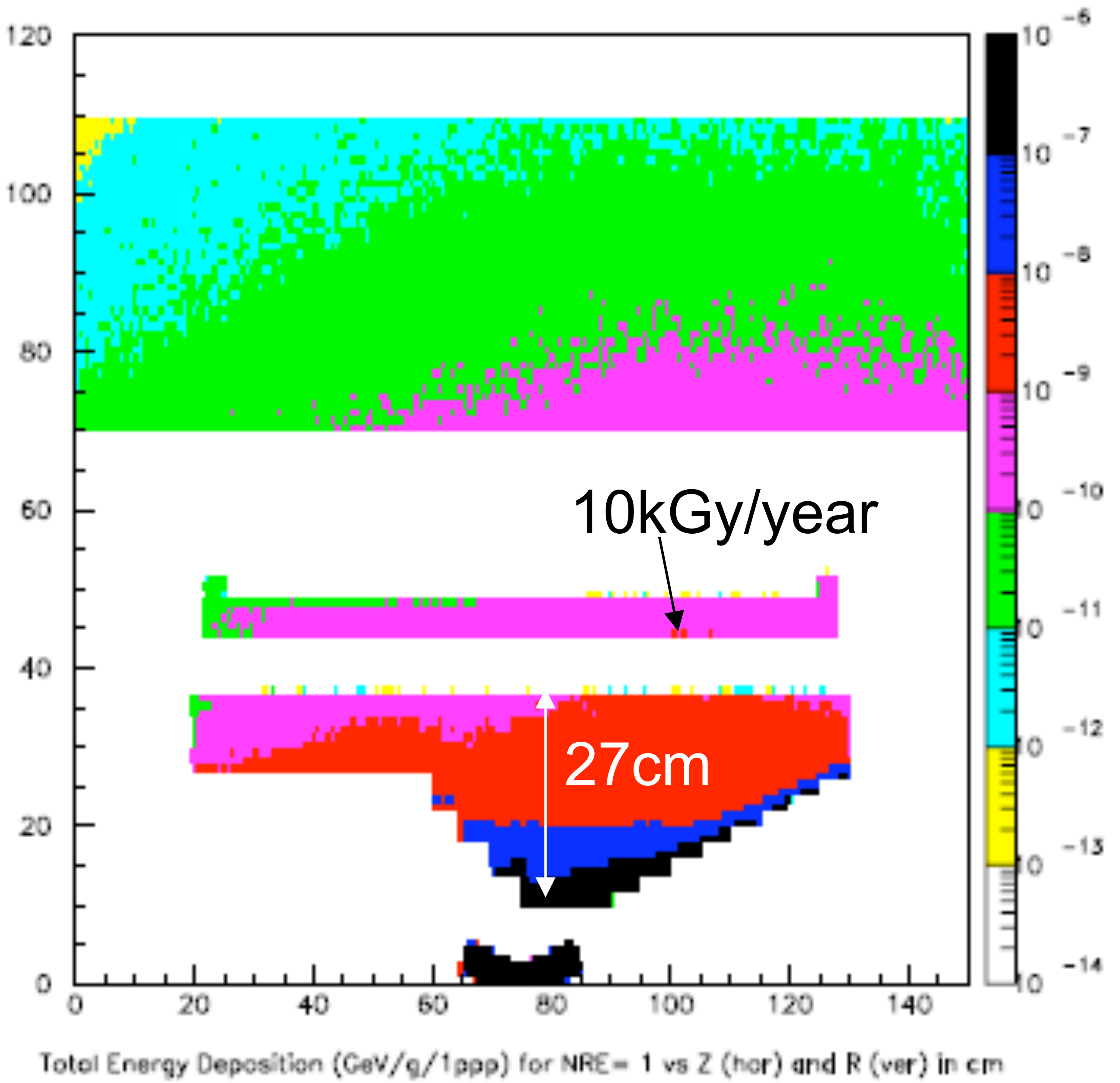
Correction dipole coils

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

パイオン捕獲システム：放射線環境

- 27cm厚 ステンレスシールド
- コールドマス核発熱　0.6W
  - 0.4W in coil (~1ton)
  - 0.2W in coil support
- 超伝導コイルの被爆量 ~10kGy/year
- ターゲット: 100W
- シールド: 50W

- 中性子フラックス
  - 5×10^{18} neutrons/m^2/year
  - 超伝導線のアルミ導体の劣化は起こらない。
    - 10^{20}-10^{22} n/m^2
  - ダイオードはソレノイドから離し、制御盤内に設置。

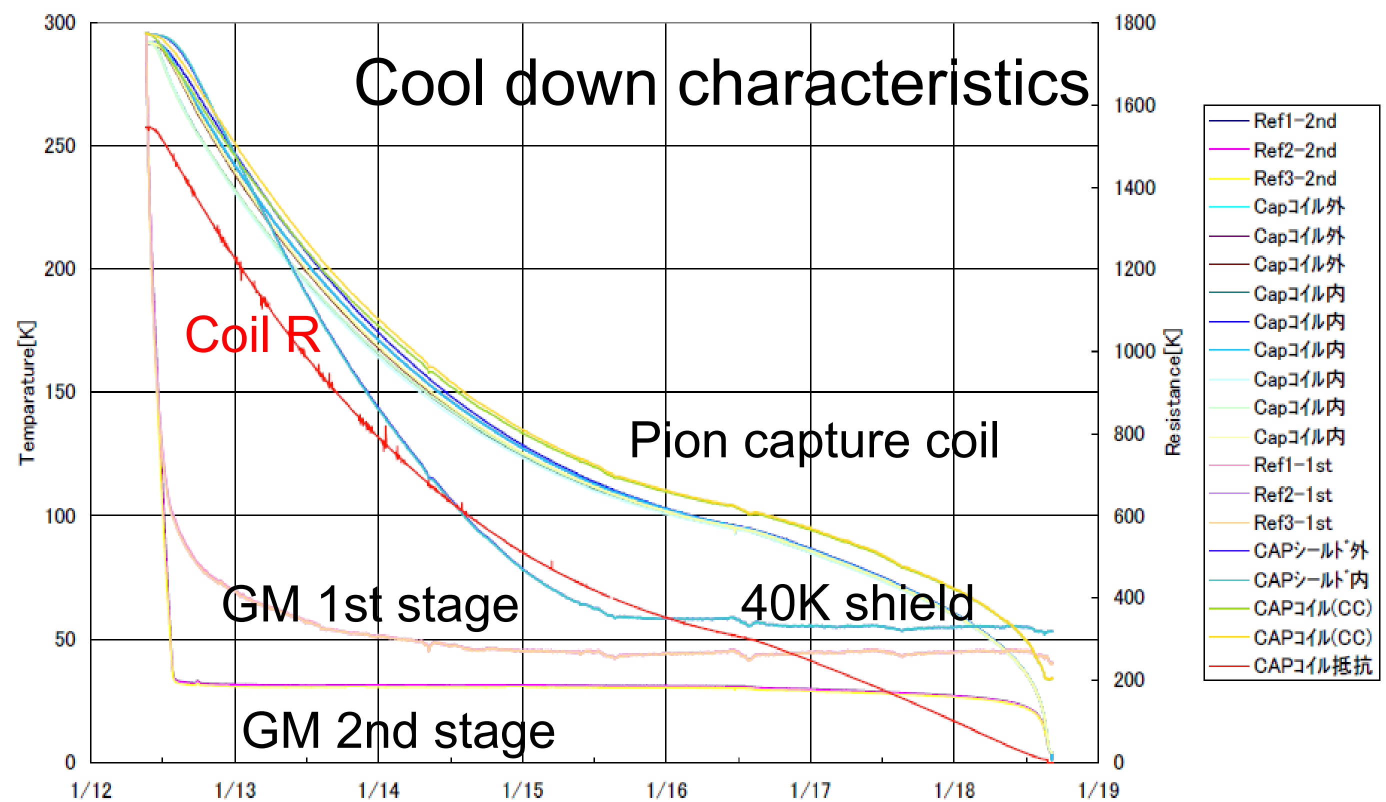


Refrigeration

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

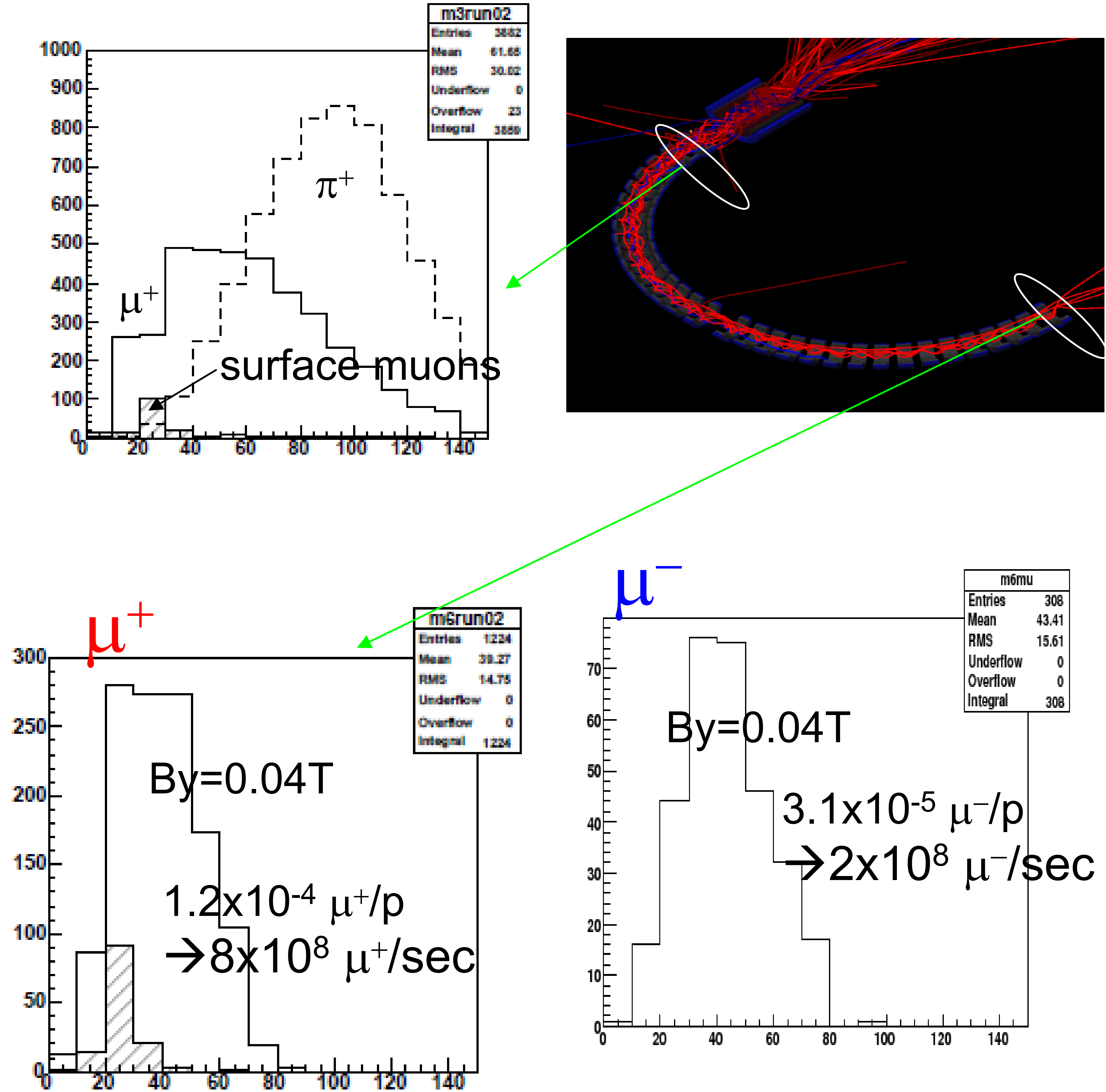
- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 300K→40K: 50W
    - GM 1st stage
  - 3 x GM cryocoler
    - 1.5Wx2+1Wx1 @4K
    - 45Wx2+44W @40K
- Transport solenoid
  - 4K: 0.8W
  - 300K→40K : 50W
    - GM 1st stage
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K
    - 44Wx2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

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



Expected muon yields

- Assuming 400MeVx1μA proton beam
- Quite high intensity μ^+/ μ^- can be achieved
- 8×10^8 μ^+/sec
- 2×10^8 μ^-/sec



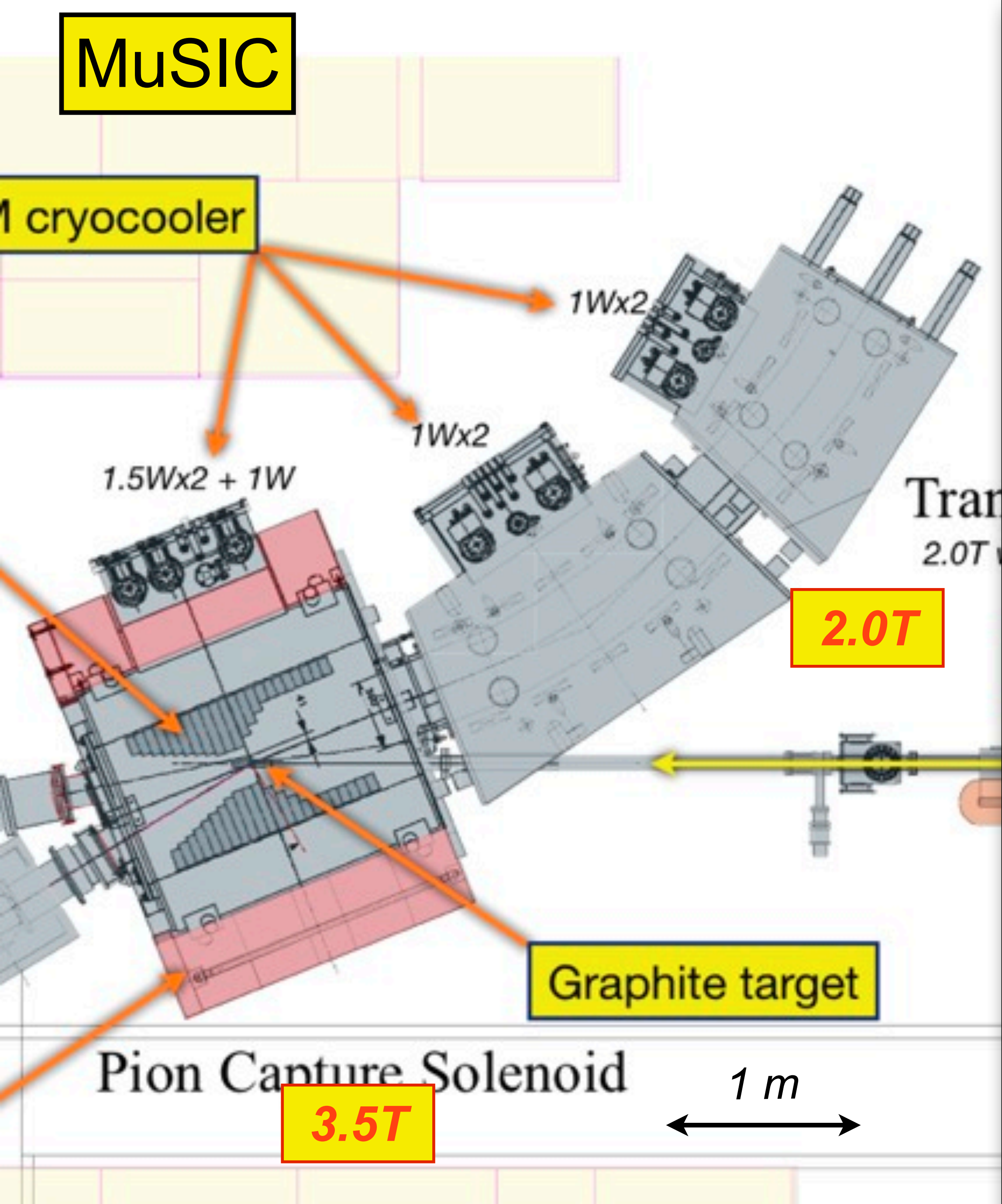
Comparison on the pion capture systems

	MuSIC	COMET	NuFact[1]
Muon Intensity	10^8/sec	10^{11}/sec	$10^{12\text{-}13}$/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

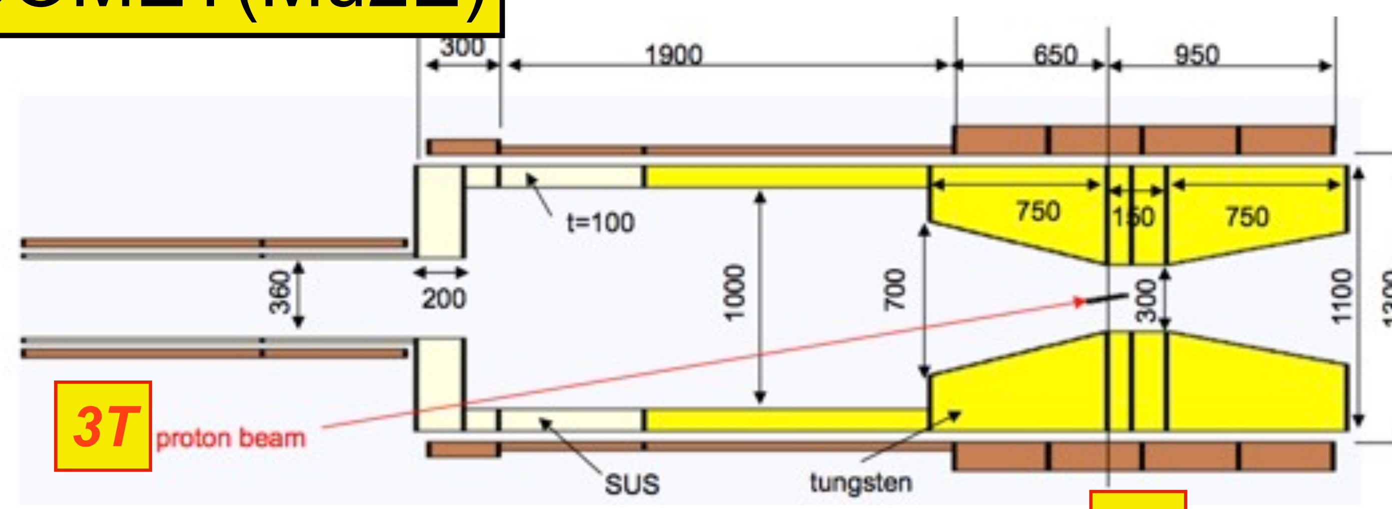
Pion Capture System in MuSIC,COMET, and NuFact

MuSIC

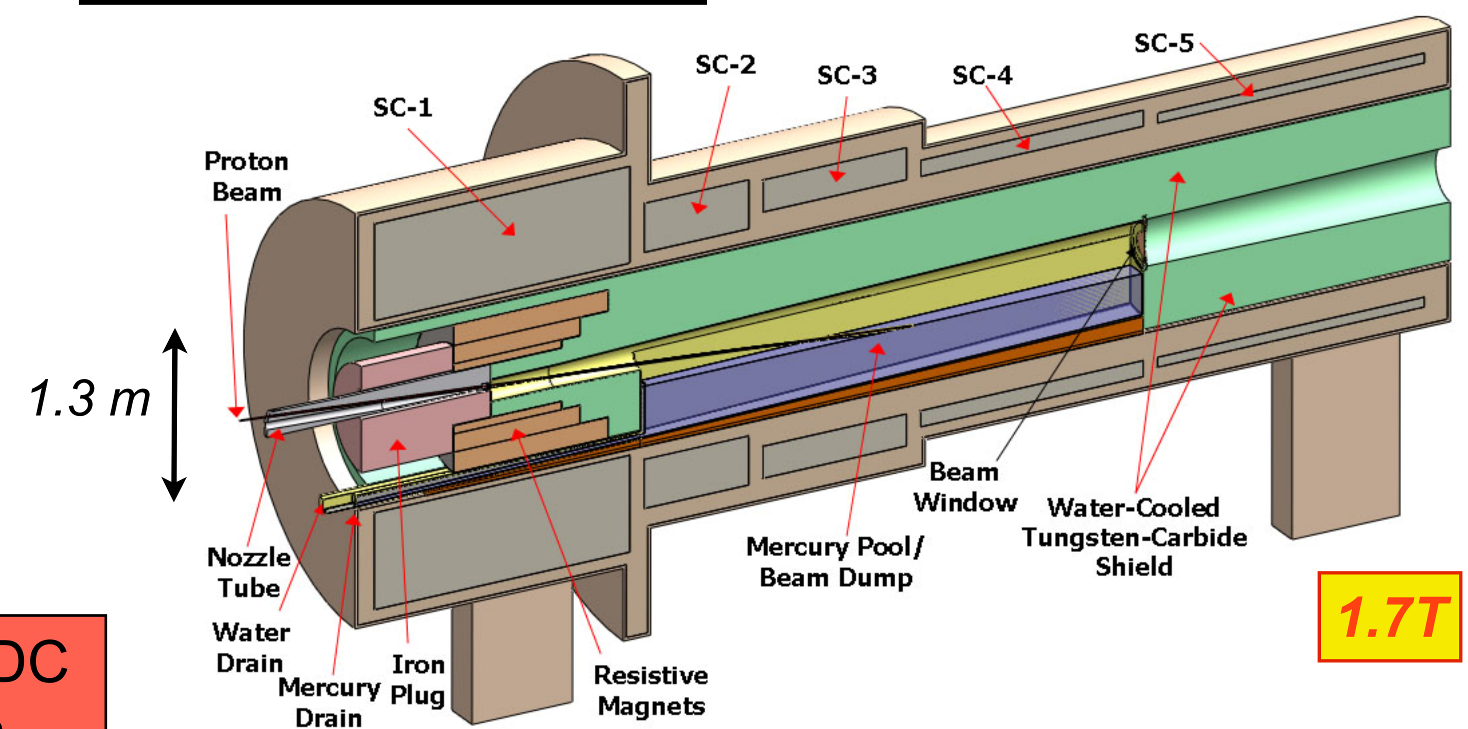


MuSIC aims to provide the world intense DC muon beam with the 400W proton beam.

COMET(Mu2E)



Neutrino Factory



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