Overview of Pion Capture Solenoids for MuSIC/COMET/PRISM

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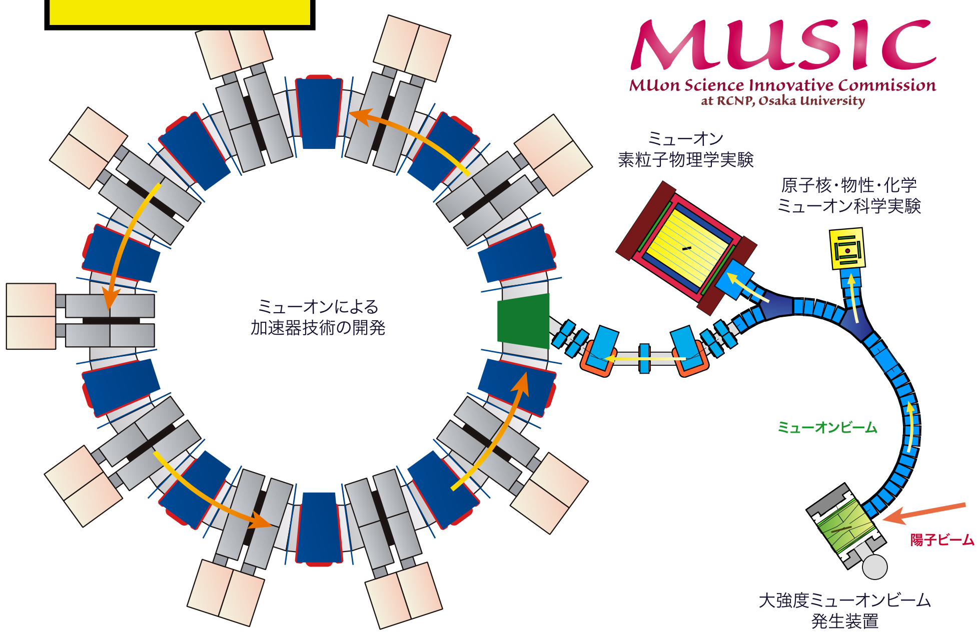
Pion Capture Solenoid mini-Workshop @ BNL
2010/11/29-30

Wishful Staging Scenario from MuSIC to NF

2009-2016

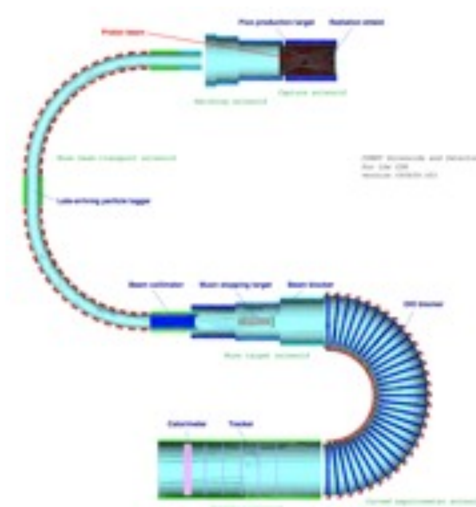
MuSIC



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

2017-

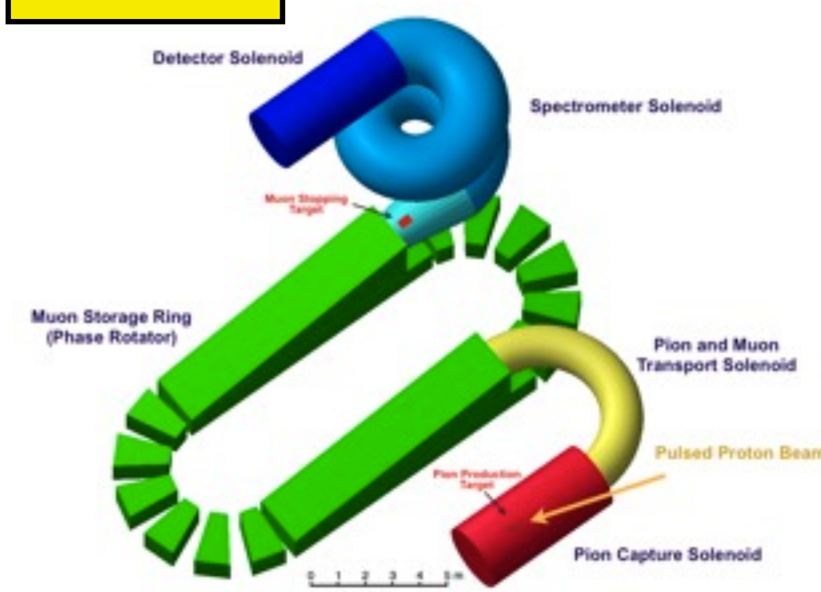
COMET/Mu2e



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 →

2019?? **Neutrino factory**
Muon collider

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

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

Staging Programs for the μ-e conversion

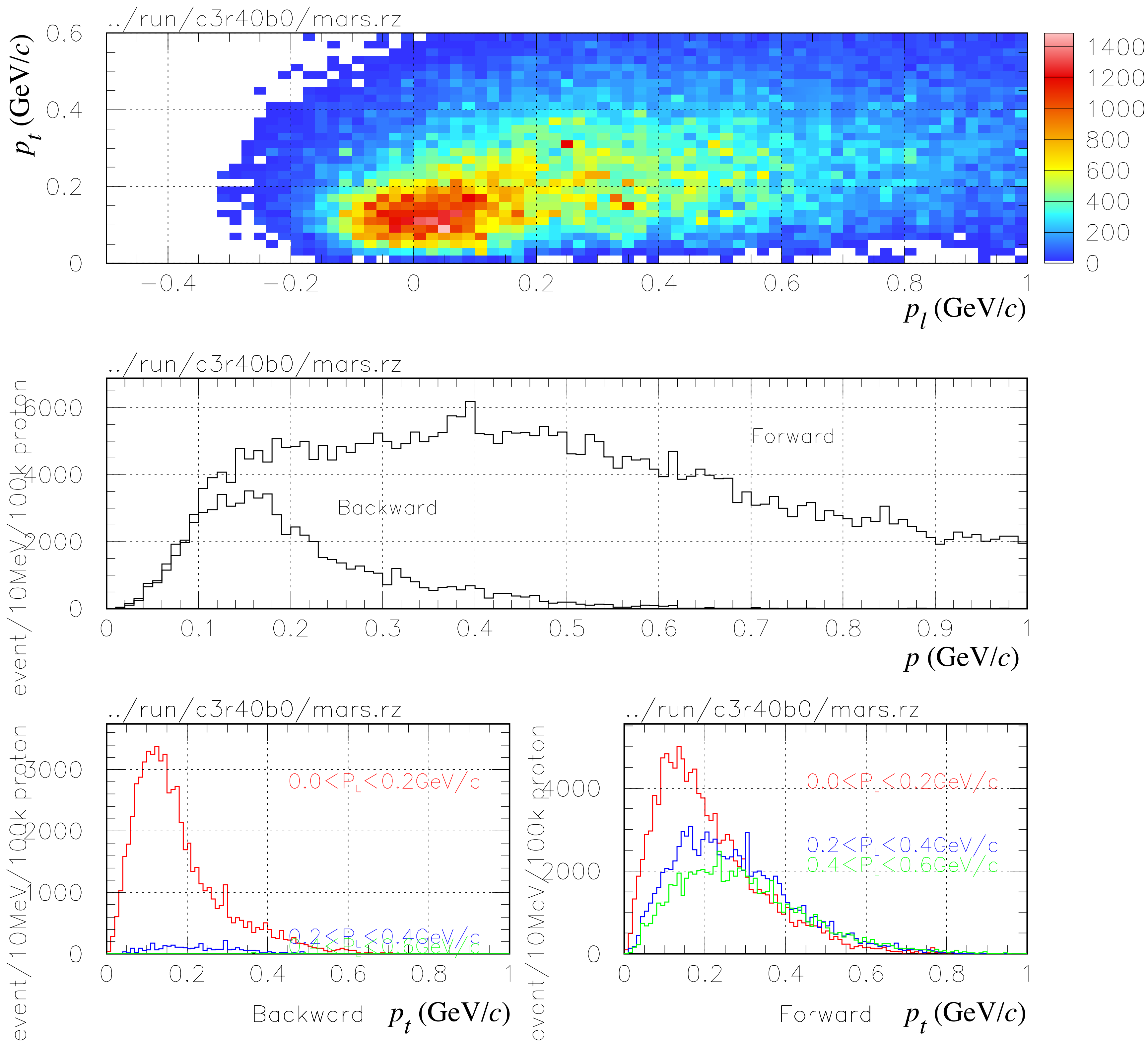
	MuSIC	COMET	PRISM/PRIME
Physics	μ→eee nuclear physics material science	BR(μ-e)<10^{-16}	BR(μ-e)<10^{-18}
μ intensity	10^8μ/s	10^{11}μ/s	10^{12}μ/s
DC/Pulse	DC	Pulse width <100ns	Pulse width <10ns
Phase Potation?	No	No	Yes
Proton Beam	400W (400MeV, 1μA)	56kW (8GeV, 7μA)	2MW (2-5GeV?)
B_{max} of π Capture Solenoid	3.5 Tesla	5 Tesla	5 Tesla

Comparison on the pion capture systems

	MuSIC	COMET	PRISM	NuFact(1)
Muon Intensity	10^{8}/sec	10^{11}/sec	10^{12}/sec	$10^{12\text{-}13}$/sec
Muon Momentum	20-70 MeV/c **(Backward)**	20-70 MeV/c **(Backward)**	20-70 MeV/c **(Backward)**	170-500 MeV/c **(Forward)**
Time structure	**Continuous**	Pulsed	Pulsed	Pulsed
Proton Beam Power	**400W (0.4GeV)**	56kW (8GeV)	**2-3MW (~8GeV)**	**4MW (8GeV)**
Production Target	**Graphite**	Tungsten	Tungsten?	Mercury jet
Capture Solenoid Max. Field Strength	3.5 T	5.0 T	**12-16 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

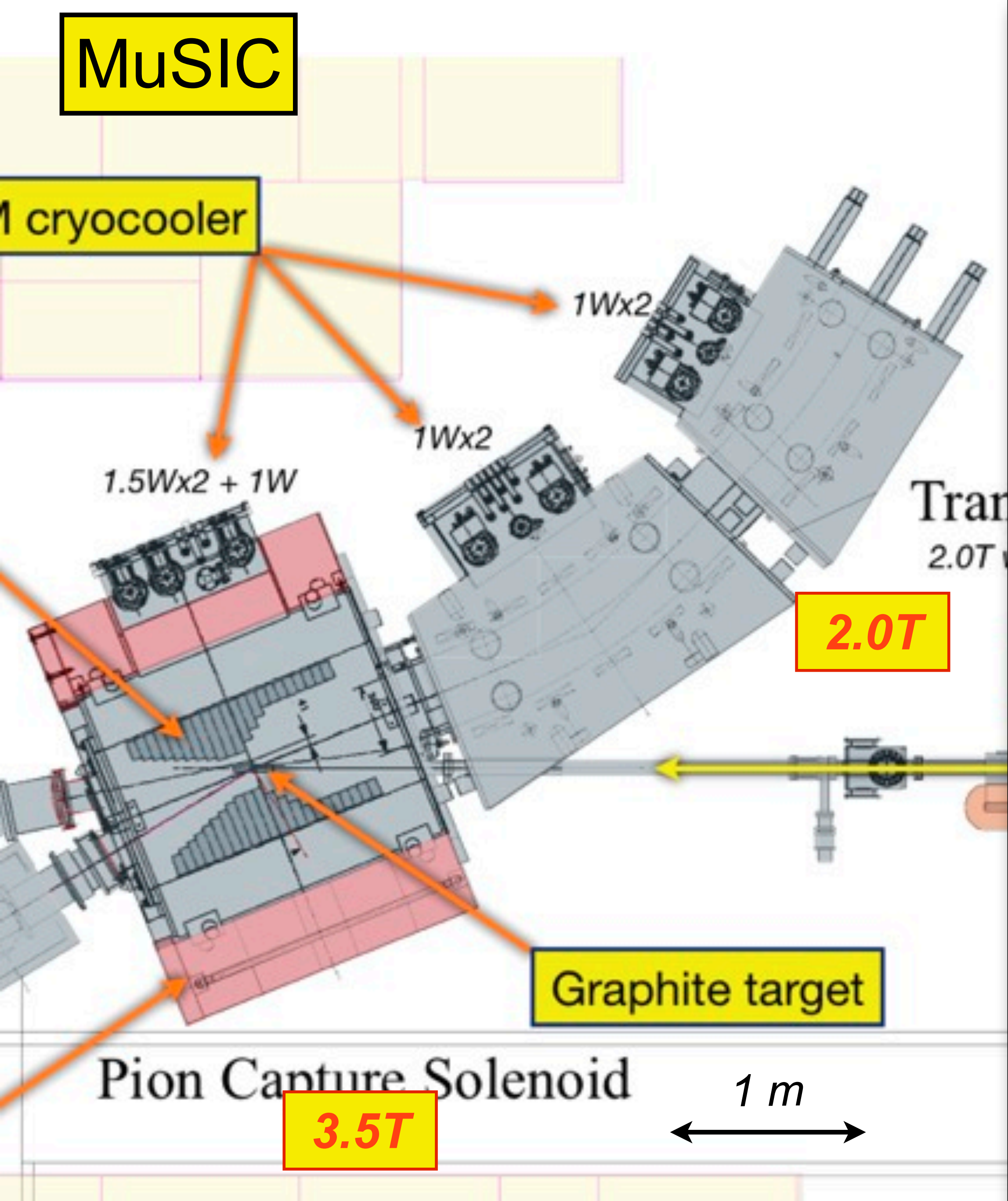
Backward and Forward Pion/Muon



A lot of radiation to forward direction

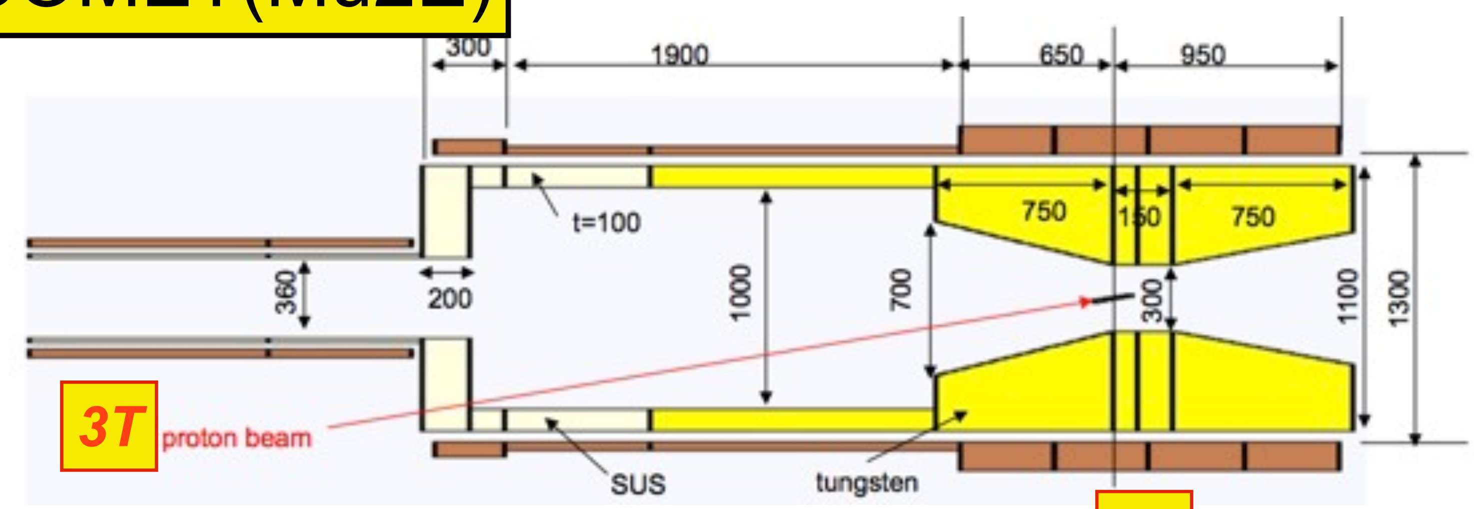
Pion Capture System in MuSIC,COMET, and NuFact

MuSIC

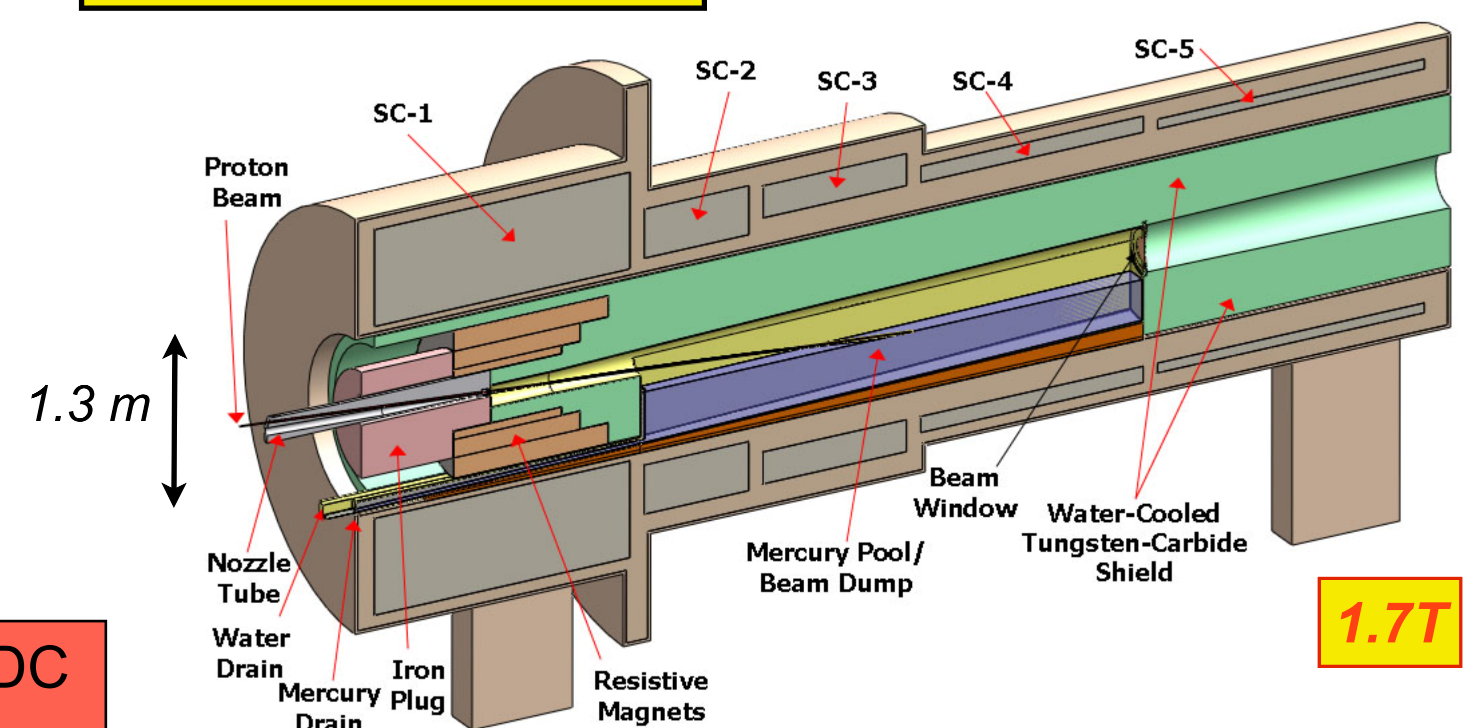


MuSIC aims to provide the world intense DC muon beam with the 400W proton beam.

COMET(Mu2E)



Neutrino Factory



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

MUSIC (=MUon Science Innovative Commission)

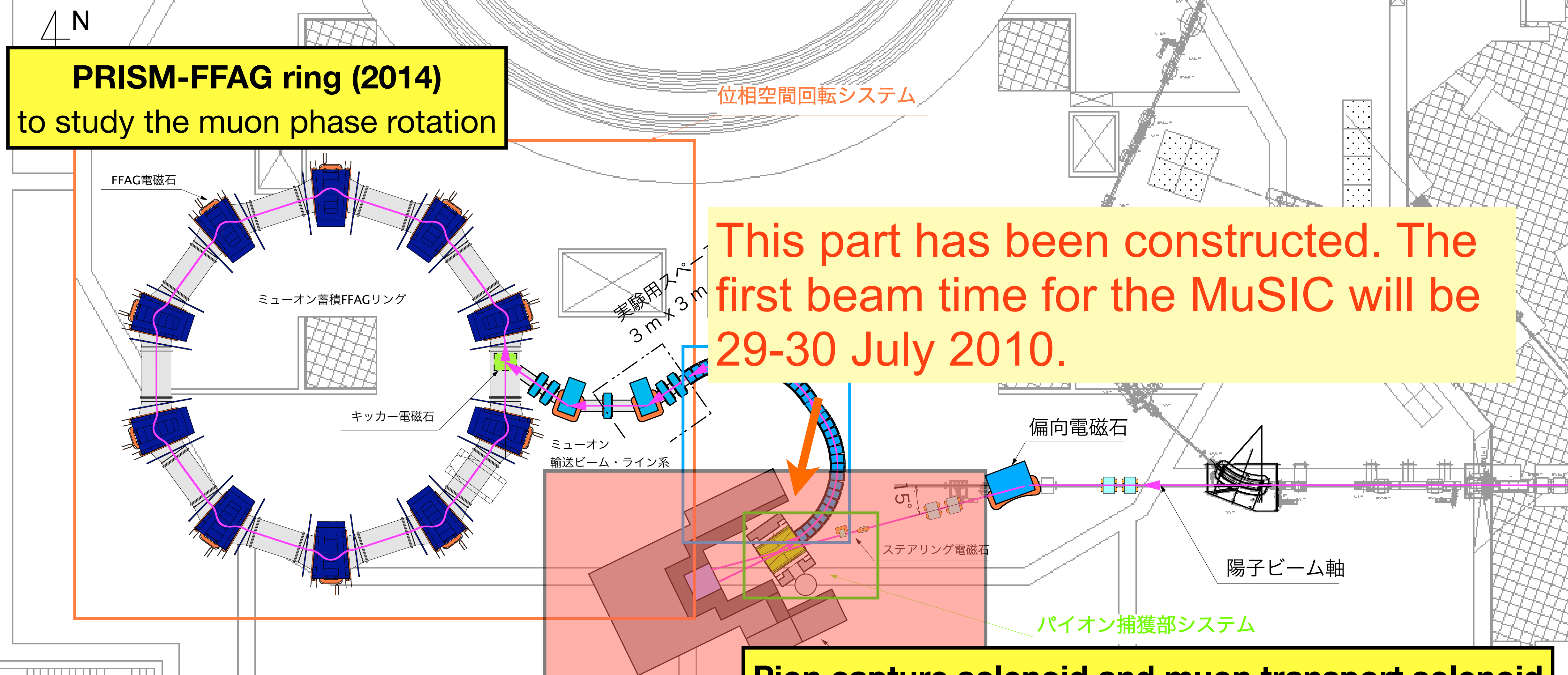
muon yield estimation

0.4 kW (400MeV, 1μA protons)

10^9 muons/sec (for MUSIC)

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

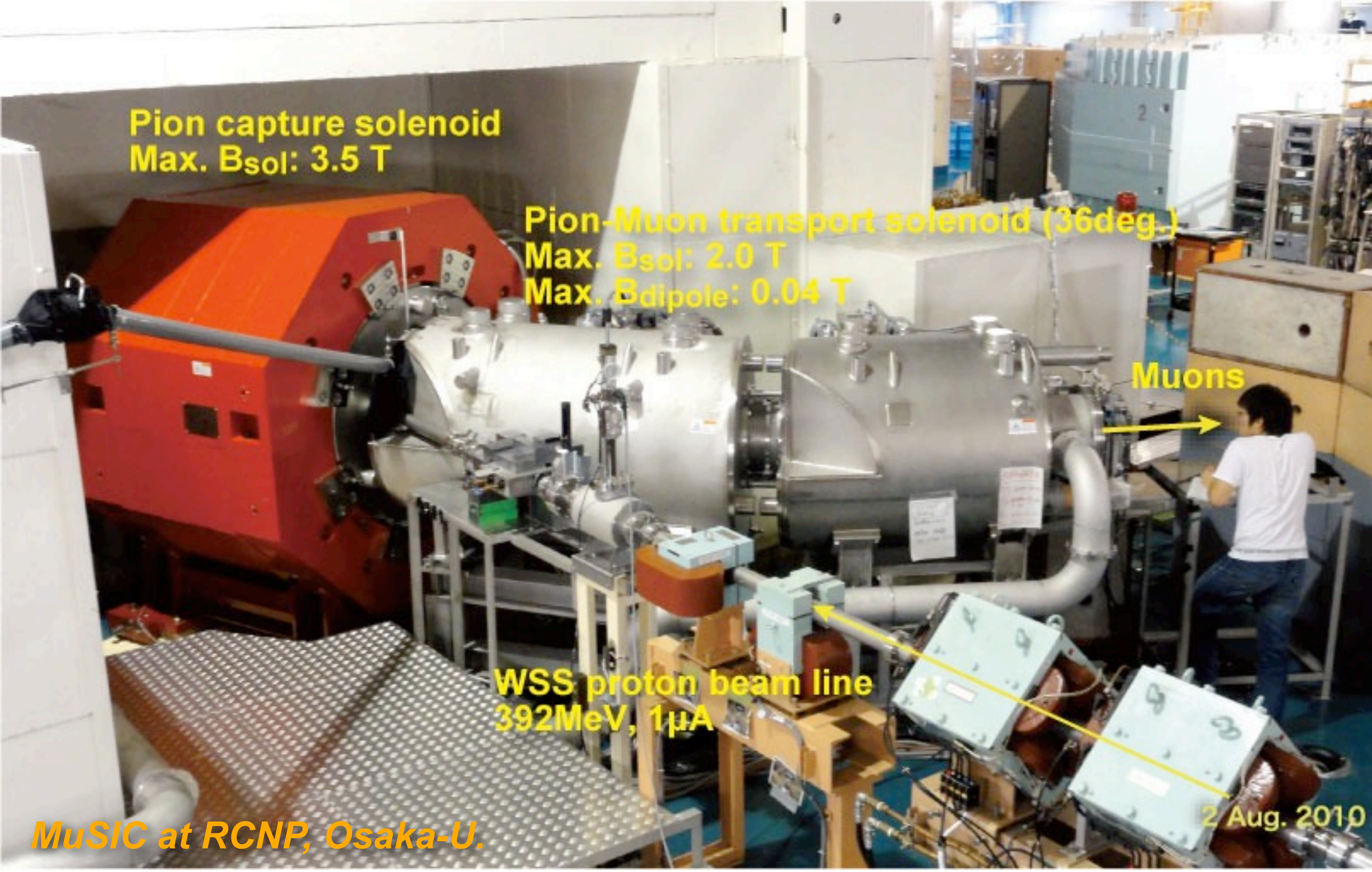
PRISM-FFAG ring (2014)
to study the muon phase rotation



This part has been constructed. The first beam time for the MuSIC will be 29-30 July 2010.

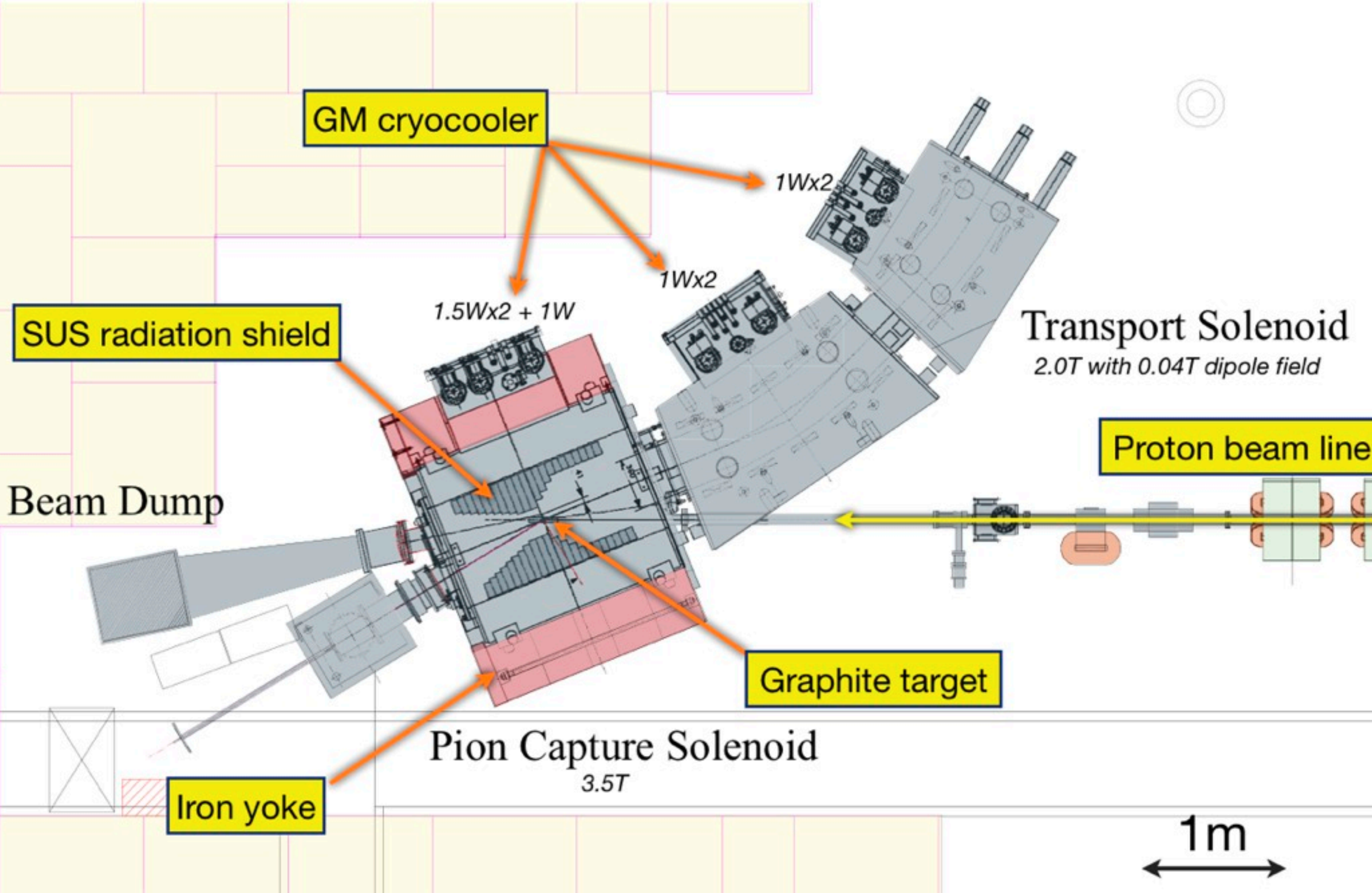
Pion capture solenoid and muon transport solenoid
the first pion capture system,
as a prototype of COMET/Mu2E/PRISM
Neutrino factory

MuSIC final layout plan in 2014



The 1st beam test has been performed at 29-30 July, 2010.
The 2nd beam test will be in 13-15 Feb. 2011.

MuSIC in 2010

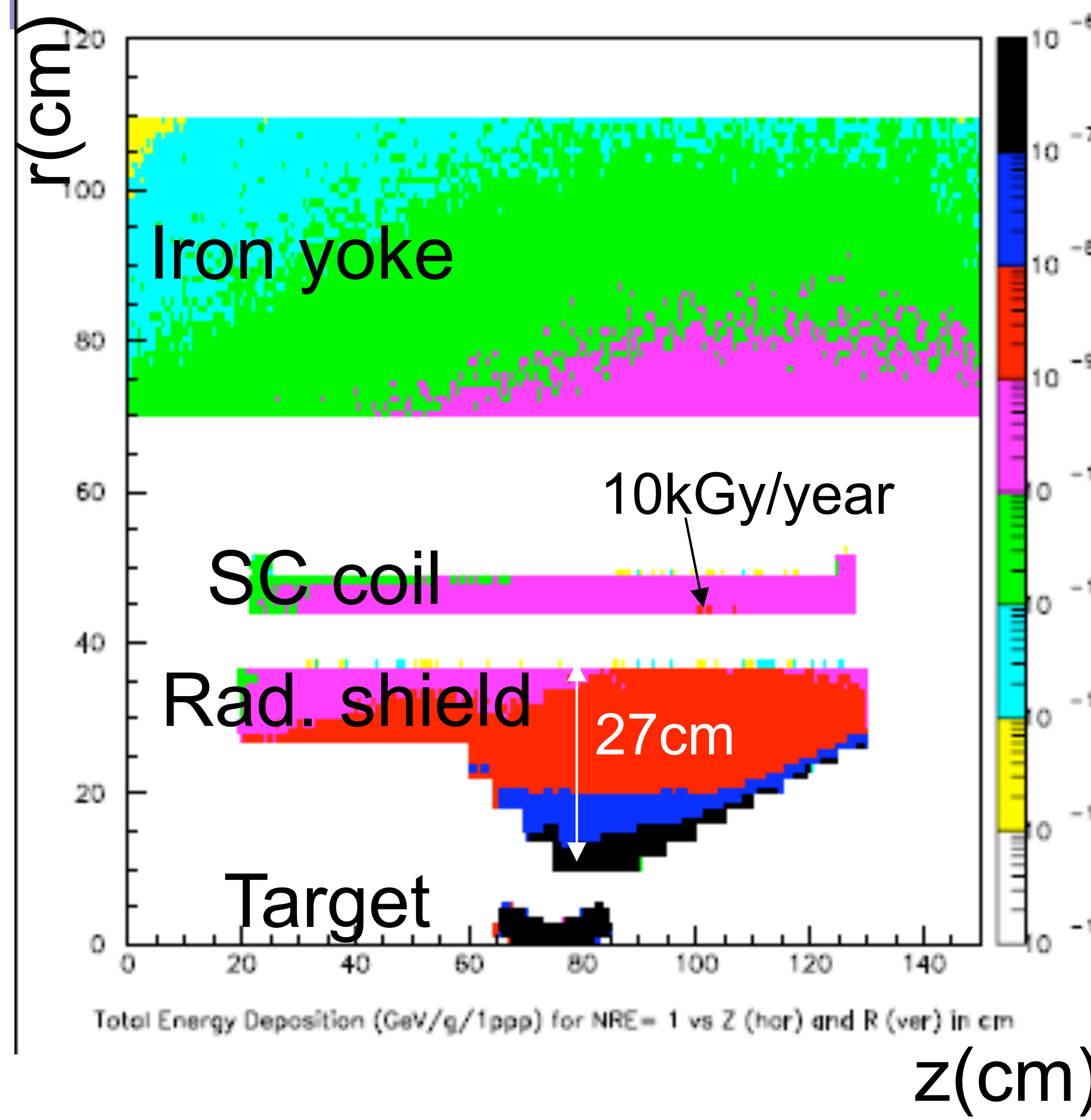


Requirements to the superconducting solenoids

- 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

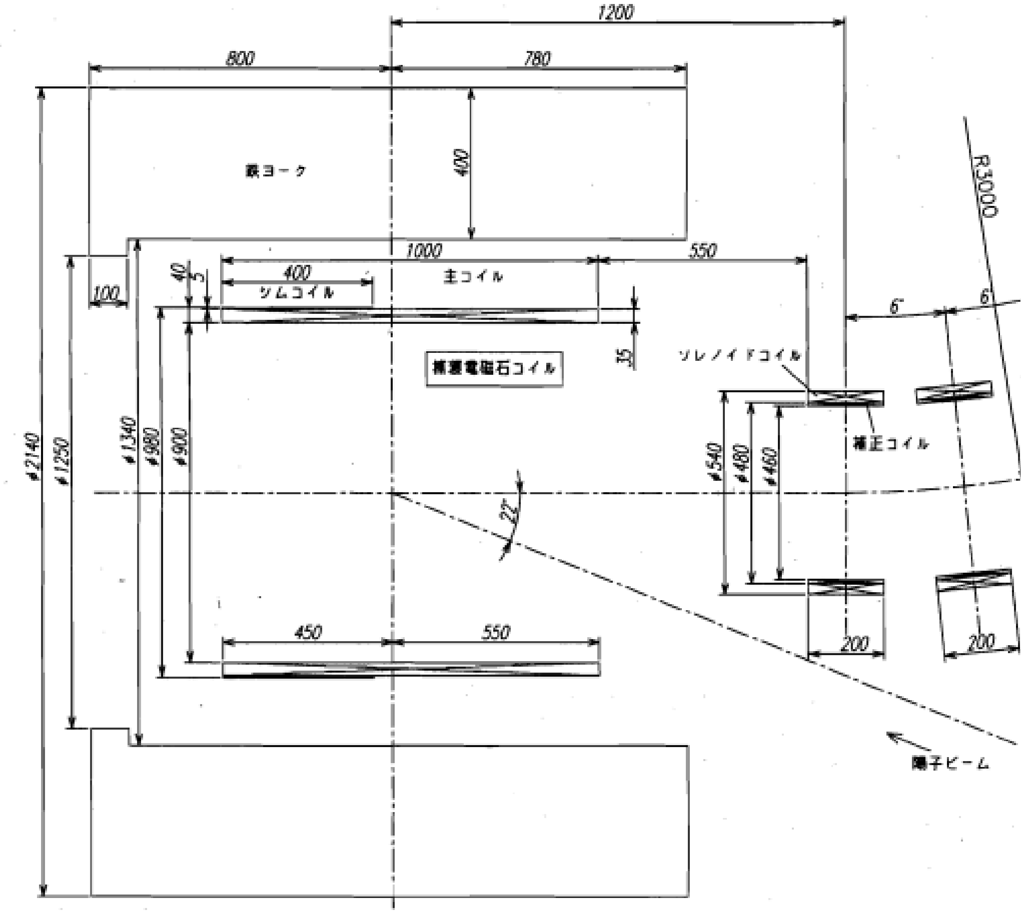
Pion capture solenoid: radiation issue

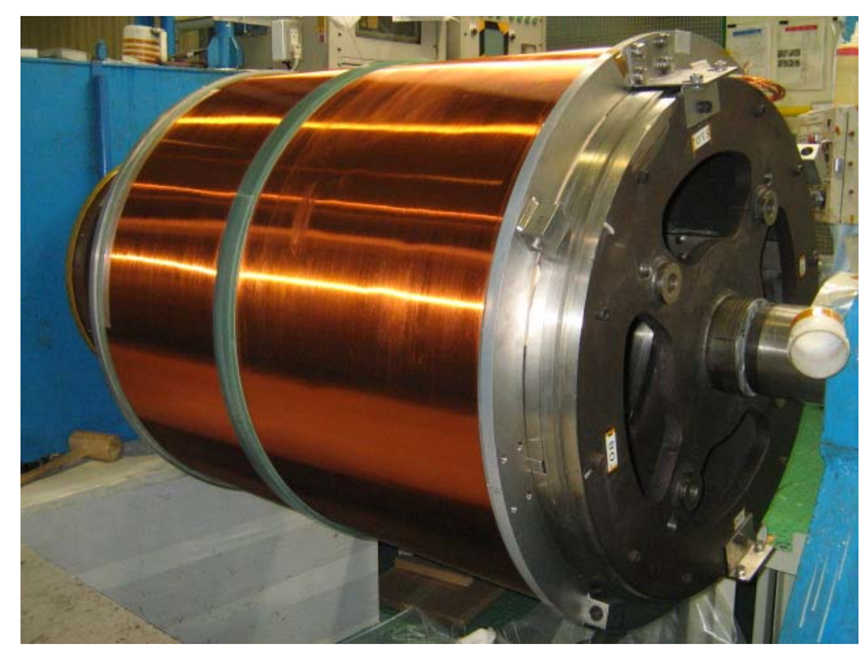
- Radiation shields (27cm thick stainless steels) are installed b/w the target and the coils.
- MC simulation by MARS (M.Yoshida)
  - Heat deposit: 0.6W
    - 0.4W in the coils(~1ton)
    - 0.2W in the coil supports
  - Dose on the coils < 10kGy/year
  - Heat load
    - 100W on the target
    - 50W on the rad. shields
  - Neutron flux: 5×10^{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



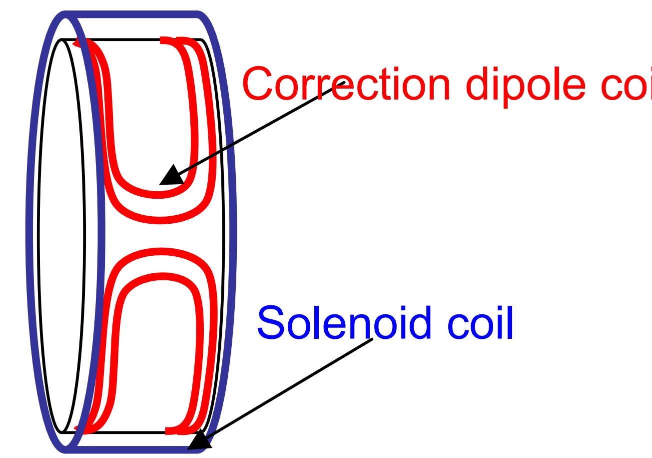


Transport solenoids

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

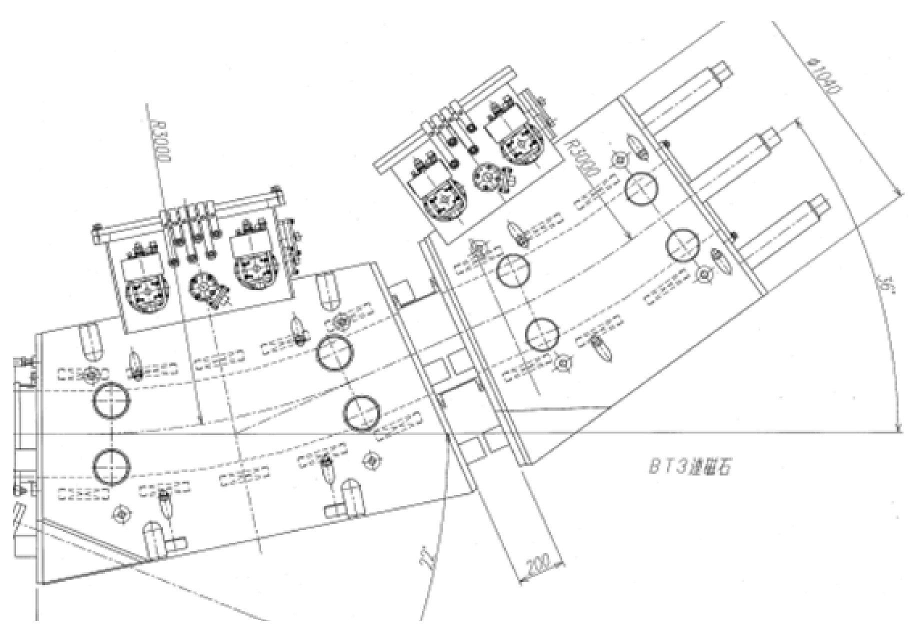
Solenoid coils

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

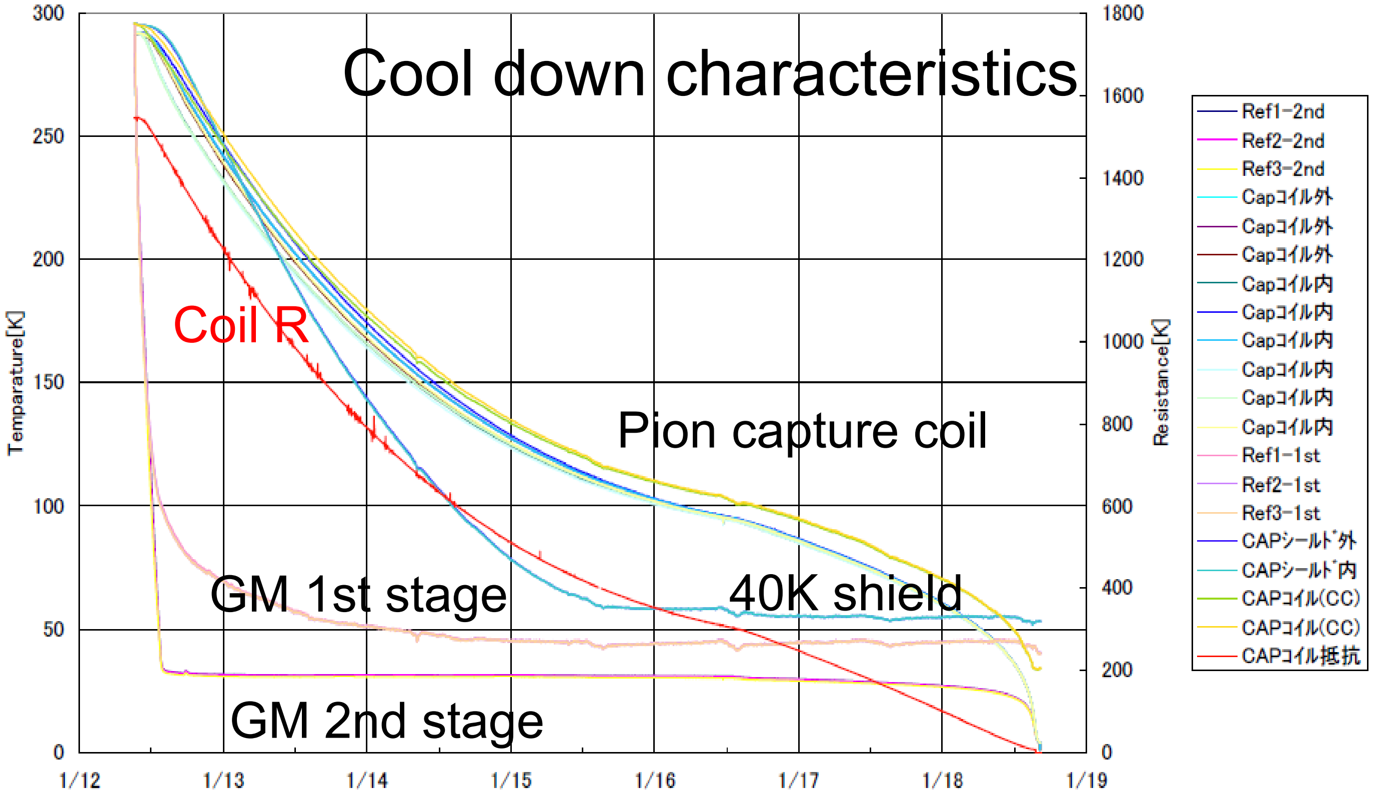


Refrigeration

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

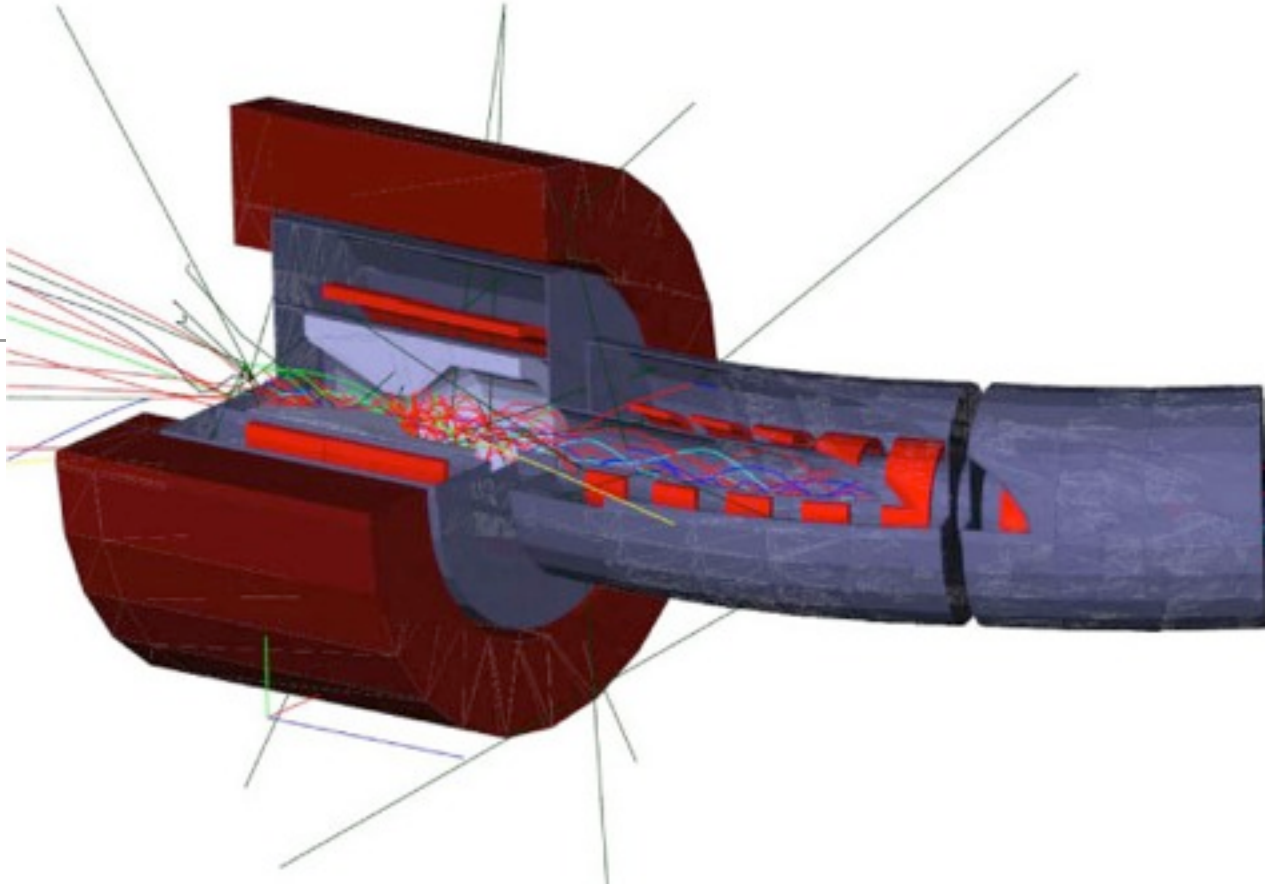
- Pion capture solenoid
  - 4K: 1W+nucl. heating 0.6W
  - 300K→40K: 50W
    - GM 1st stage
  - 3 x GM cryocoler
    - 1.5Wx2+1Wx1 @4K
    - 45Wx2+44W @40K
- Transport solenoid
  - 4K: 0.8W
  - 300K→40K : 50W
    - GM 1st stage
  - 2 x Cryocoolers on each cryostat (BT5,BT3)
    - 1Wx2 @4K
    - 44Wx2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

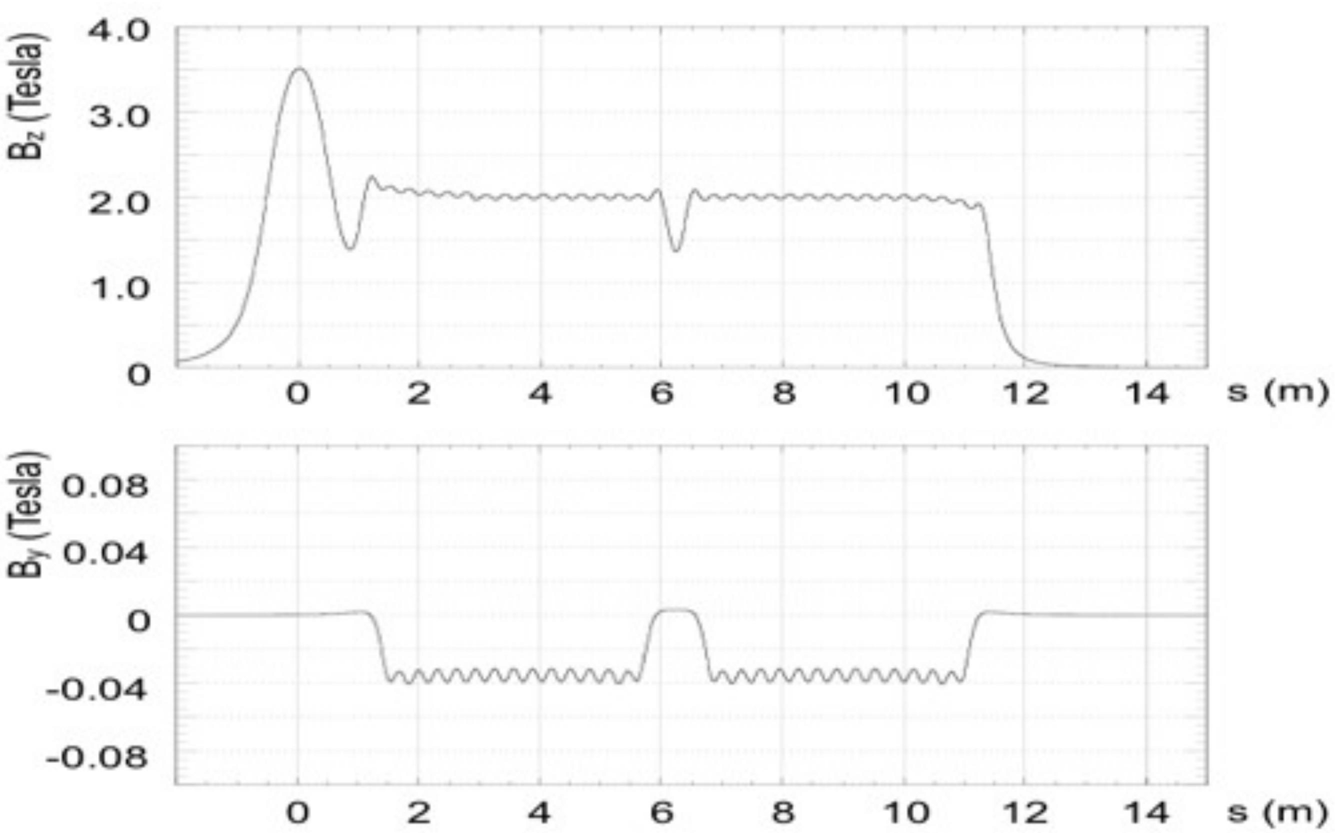
- Achievable temperature
  - Pion capture solenoid : 3.7K
  - Transport solenoids : 4.2K-4.5K(BT3), 4.5K-5.8K(BT5)

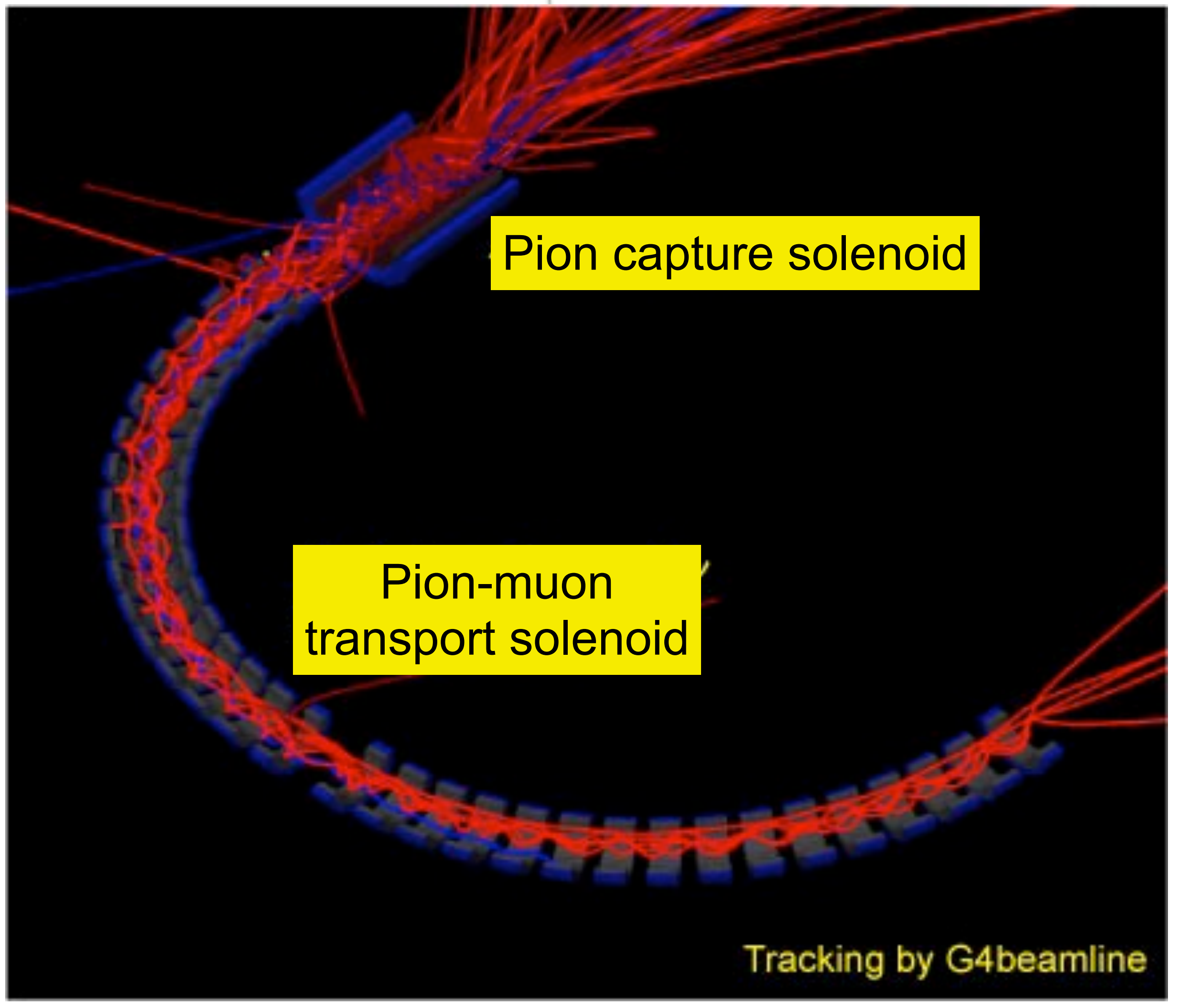


Expected Muon Yield

- 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

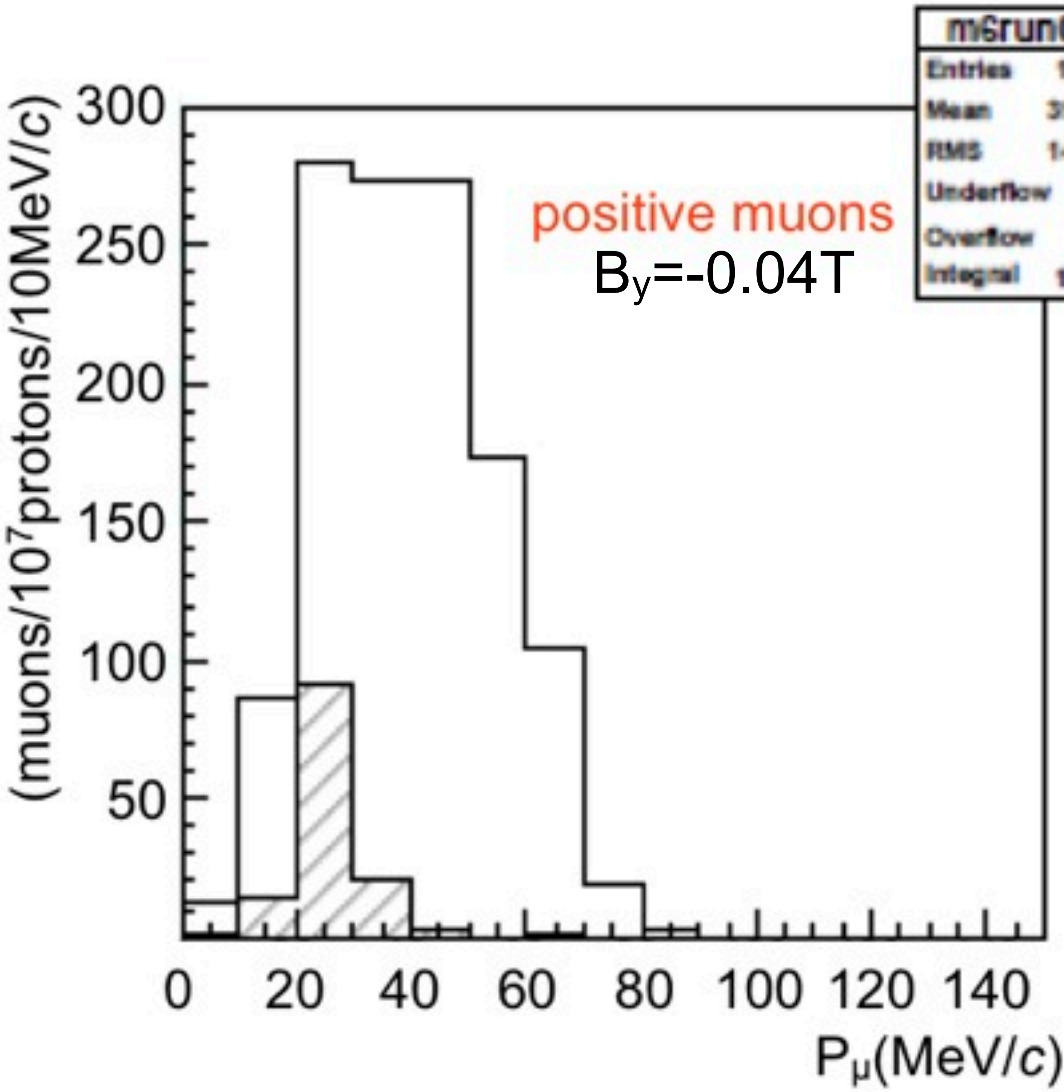


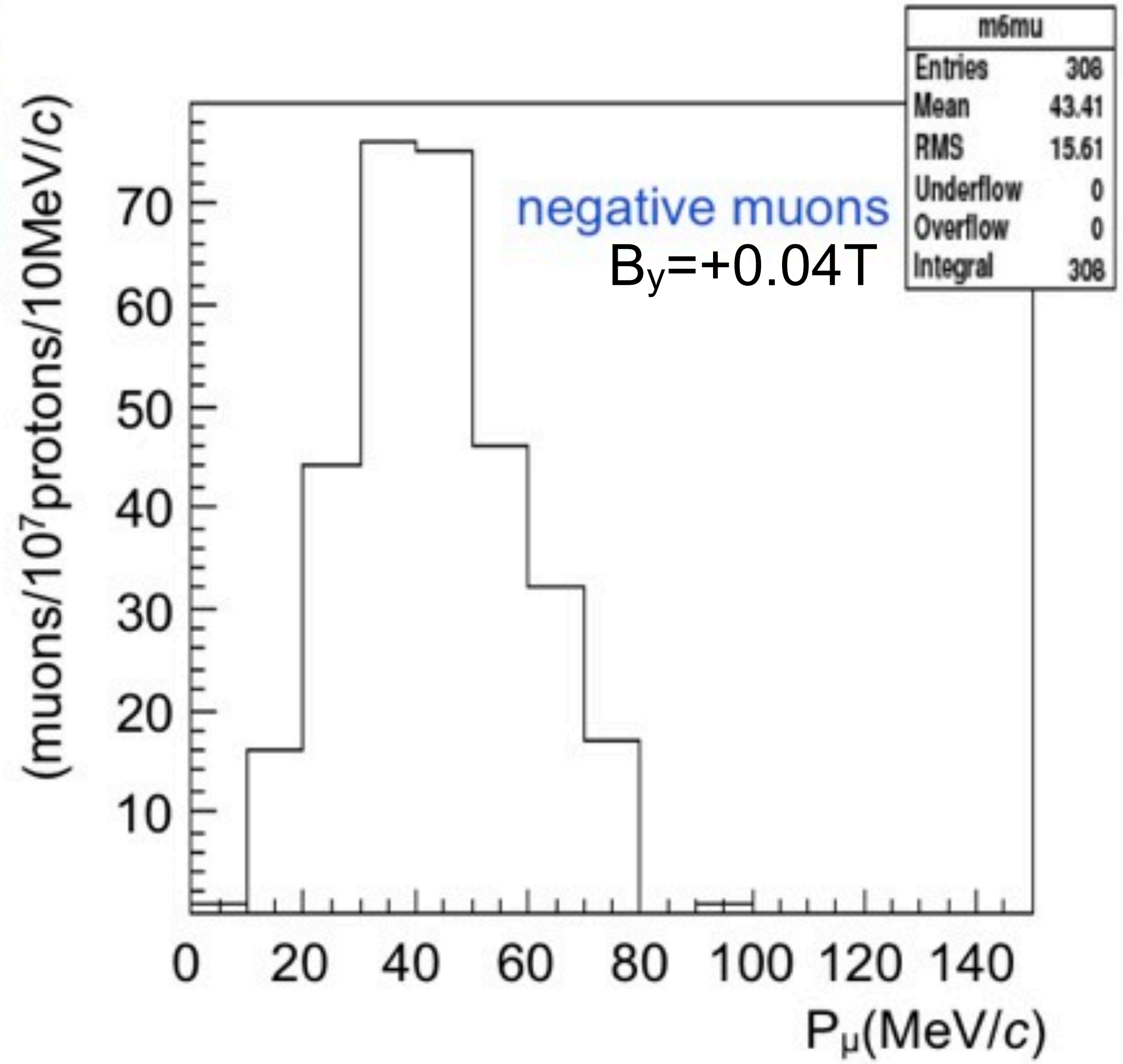




Simulation results for $B_y=\pm 0.04T$

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

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

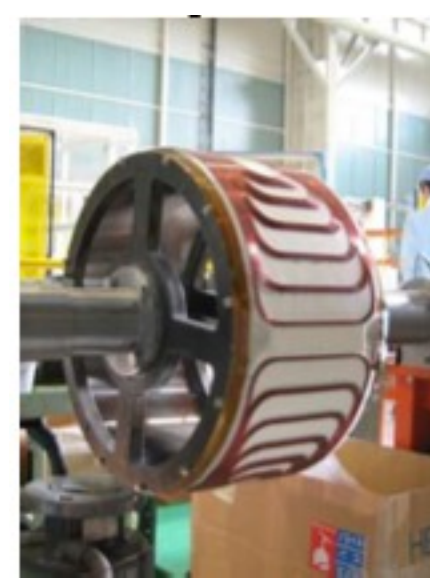
D : drift distance
B : Solenoid field
θ_{bend} : Bending angle of the solenoid channel
p : Momentum of the particle
q : Charge of the particle
θ : atan(P_T/P_L)

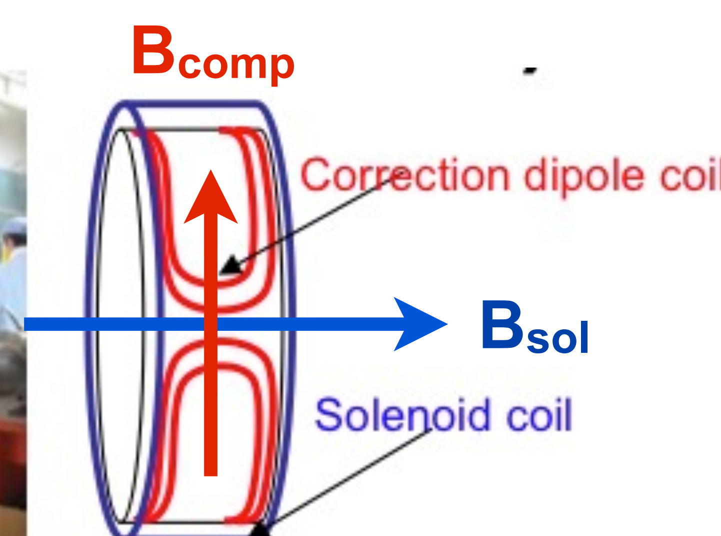
- This effect can be used for charge and momentum selection.

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

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

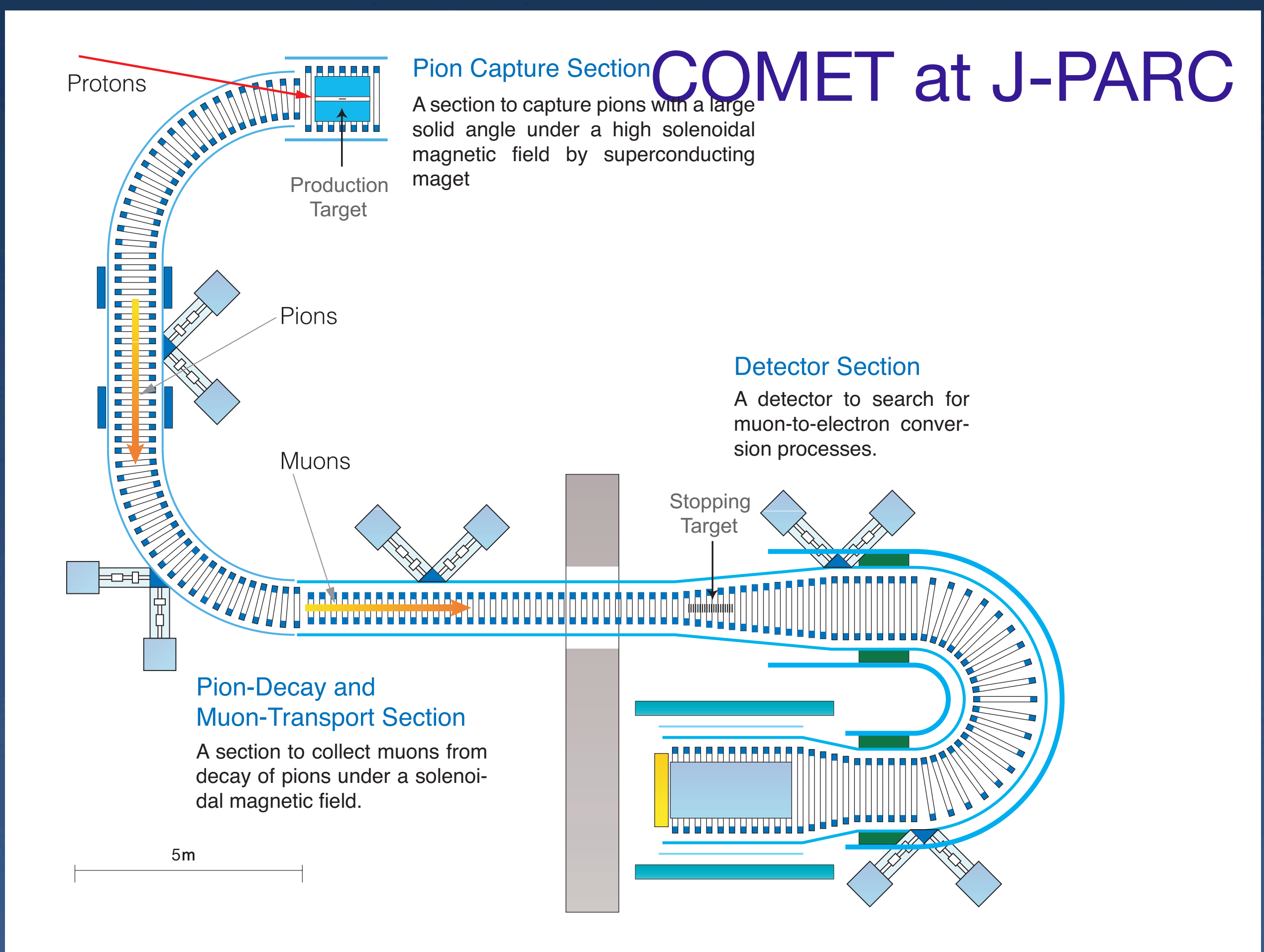
p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ : atan(P_T/P_L)



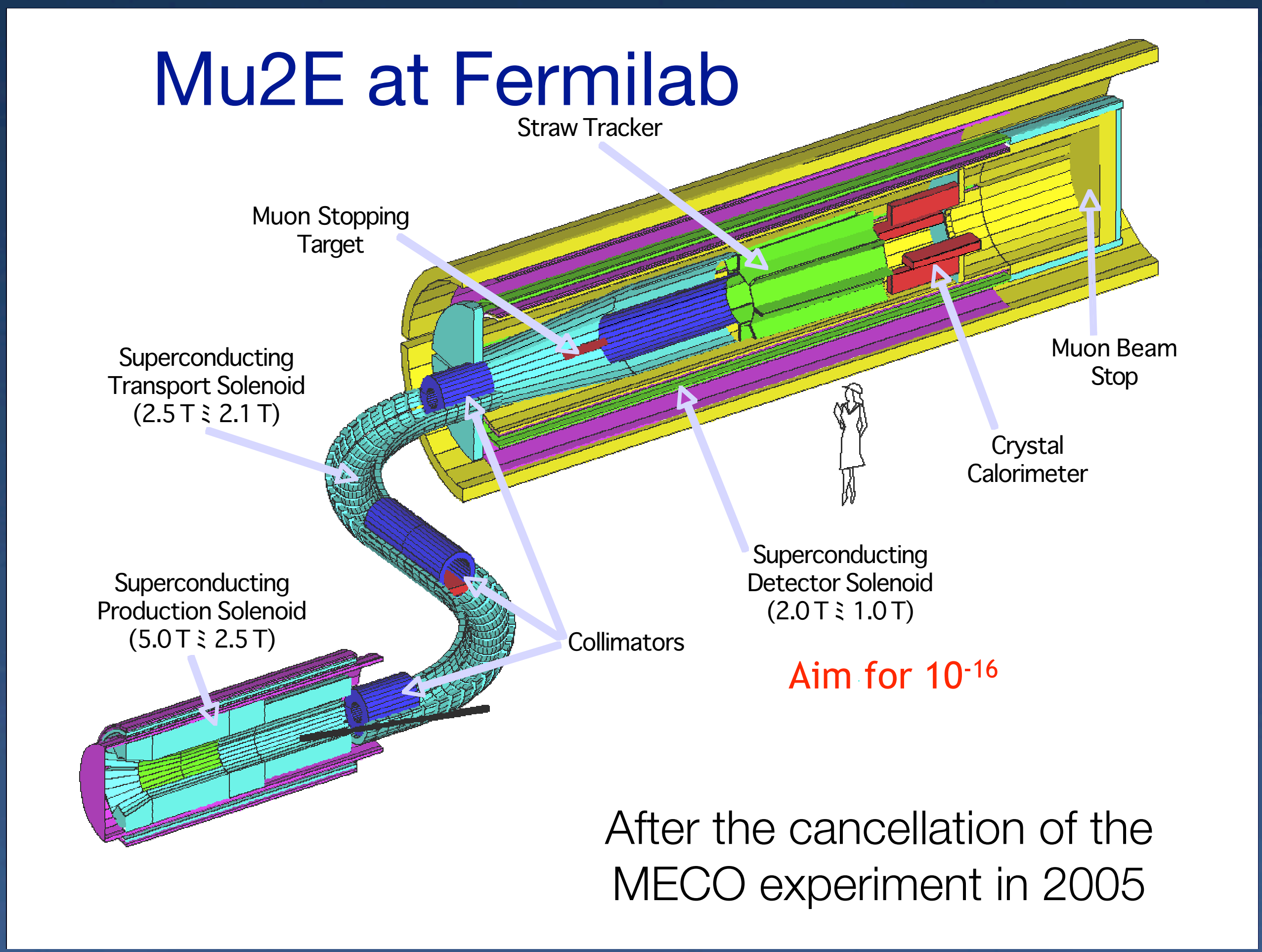


COMET and Mu2E: S.E.S.~10^{-16}

- To achieve a single event sensitivity (S.E.S.) of 10^{-16}, we need:
  - High intense muon beam: ~10^{11} μ/sec
  - Pulsed muon beam: for the BG rejection
- Two experiments have been proposed to be carried out around 2016.



Stage-1 approval July 2009 at J-PARC



CD0 approval Nov. 2009 by DOE

PRISM Task Force

- The PRISM-FFAG Task Force was proposed and discussed during the last PRISM-FFAG workshop at ICL (1-2 July'09).
- The aim of the Task Force is to address the technological challenges in realizing an FFAG based μ-e conversion experiment, but also to strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.
- The following key areas of activity were identified and proposed to be covered within the Task Force:
  - - physics of muon to electron conversion,
  - - proton source,
  - - pion capture,
  - - muon beam transport,
  - - injection and extraction for PRISM-FFAG ring,
  - - FFAG ring design including the search for a new improved version,
  - - FFAG hardware R&D for RF system and injection/extraction kicker and septum magnets.
- Studies will continue to obtain a feasible design, aiming on CDR in 2011.

Synergy between PRISM and Neutrino Factory

Members of PRISM Task Force

- **J. Pasternak (contact person)**, Imperial College London / RAL STFC
- L. J. Jenner, A. Kurup, Imperial College London / Fermilab
- Y. Uchida, Imperial College London
- B. Muratori, S. L. Smith, Cockcroft Institute / STFC-DL-ASTeC
- K. M. Hock, Cockcroft Institute / University of Liverpool
- R. J. Barlow, Cockcroft Institute / University of Manchester
- C. Ohmori, KEK/JAEA
- H. Witte, T. Yokoi, JAI, Oxford University
- J-B. Lagrange, Y. Mori, Kyoto University, KURRI
- Y. Kuno, A. Sato, Osaka University
- D. Kelliher, S. Machida, C. Prior, STFC-RAL-ASTeC
- M. Lancaster, University College London

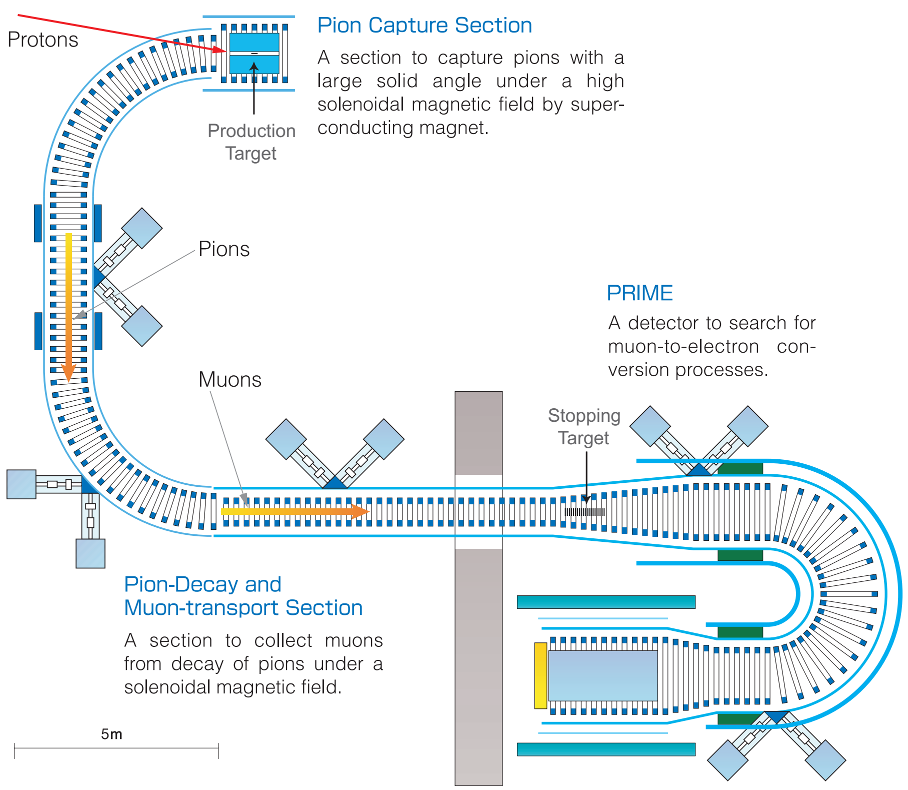
Many young physicists. We are trying to apply our skills, which got thorough the NF related studies, to the muon physics experiment!

Welcome to join us!

as on IPAC'10 paper

Staging Plan of μ-e conv. in Japan

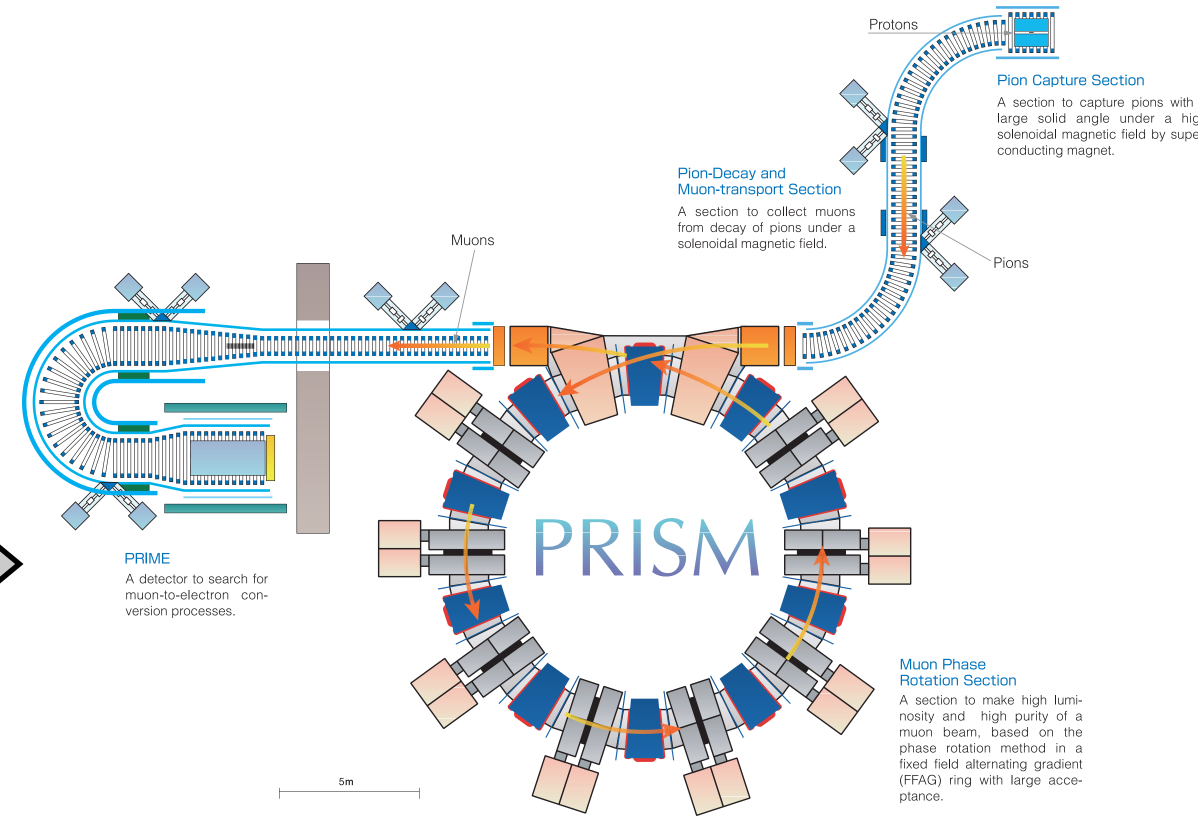
1st Stage : COMET



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

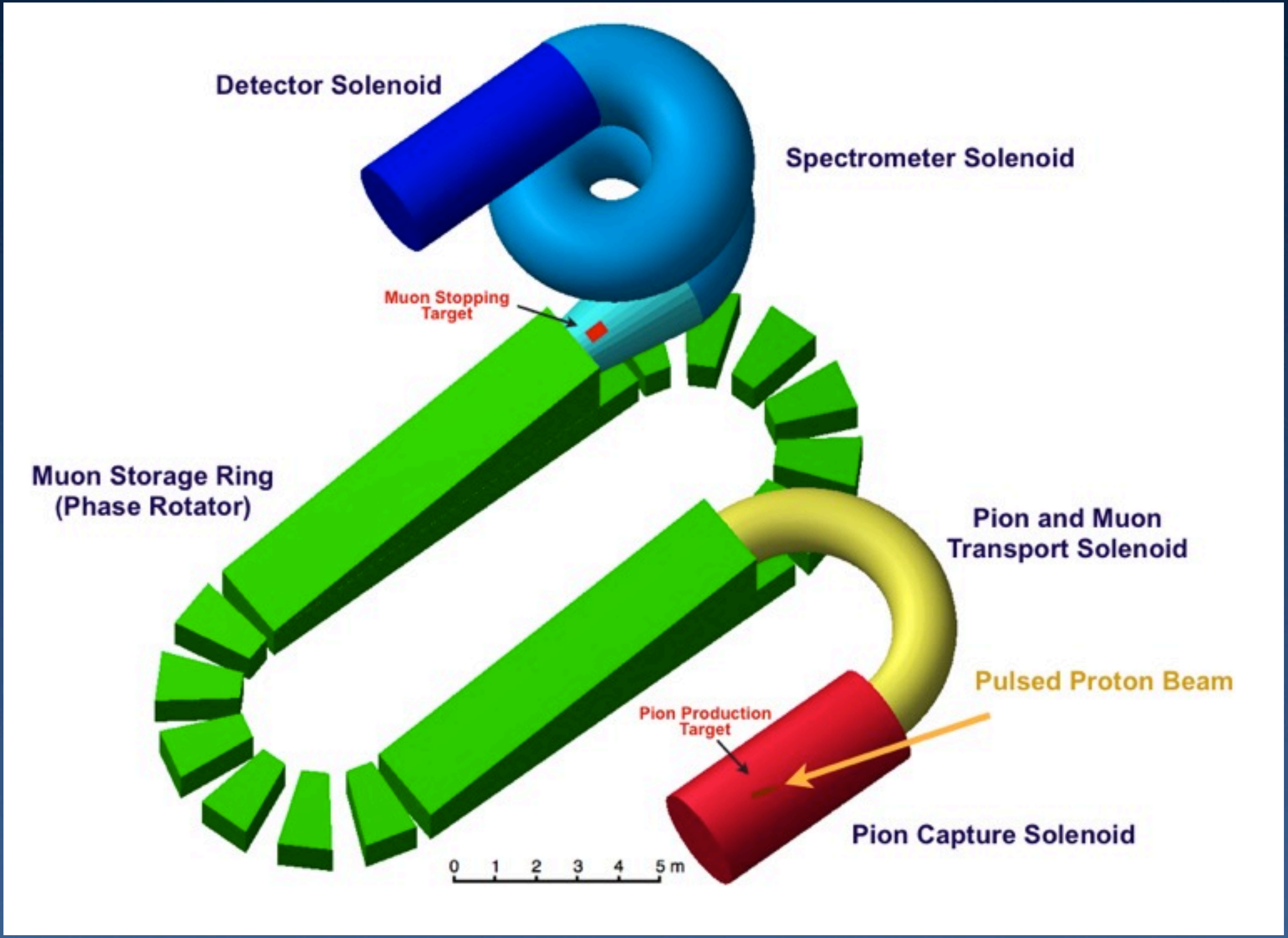
2nd Stage : PRISM/PRIME



$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

Schematic Layout of New PRISM



Pion Capture Solenoid R&D in Japan

- The first SC pion capture system has been build in Osaka for MuSIC.
- Design study for the COMET/PRISM capture solenoid.
  - Measurement of radiation heating using a mockup.
    - Nuclear Instruments and Methods in Physics Research A 545 (2005) 88–96
  - Neutron Irradiation Experiments for Pure Stabilizers at Low Temperature
  - MgB_2?

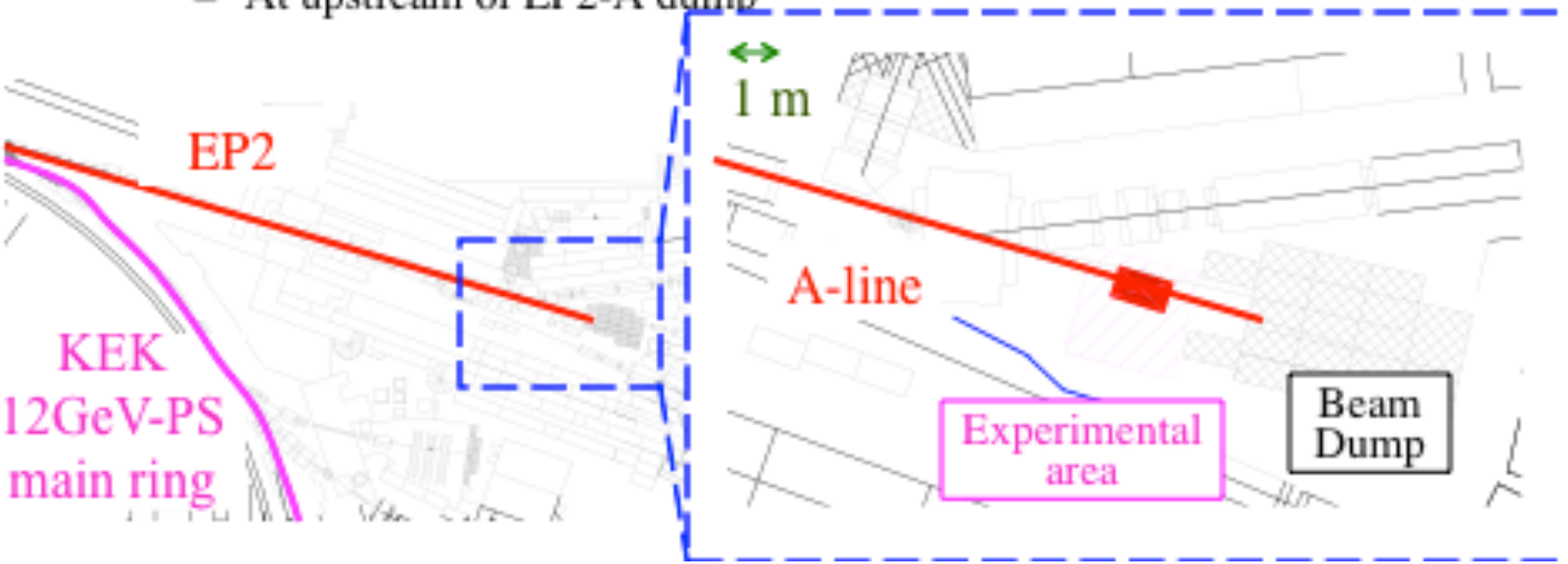
Experimental Conditions (KEK 12GeV-PS)

Beam parameters

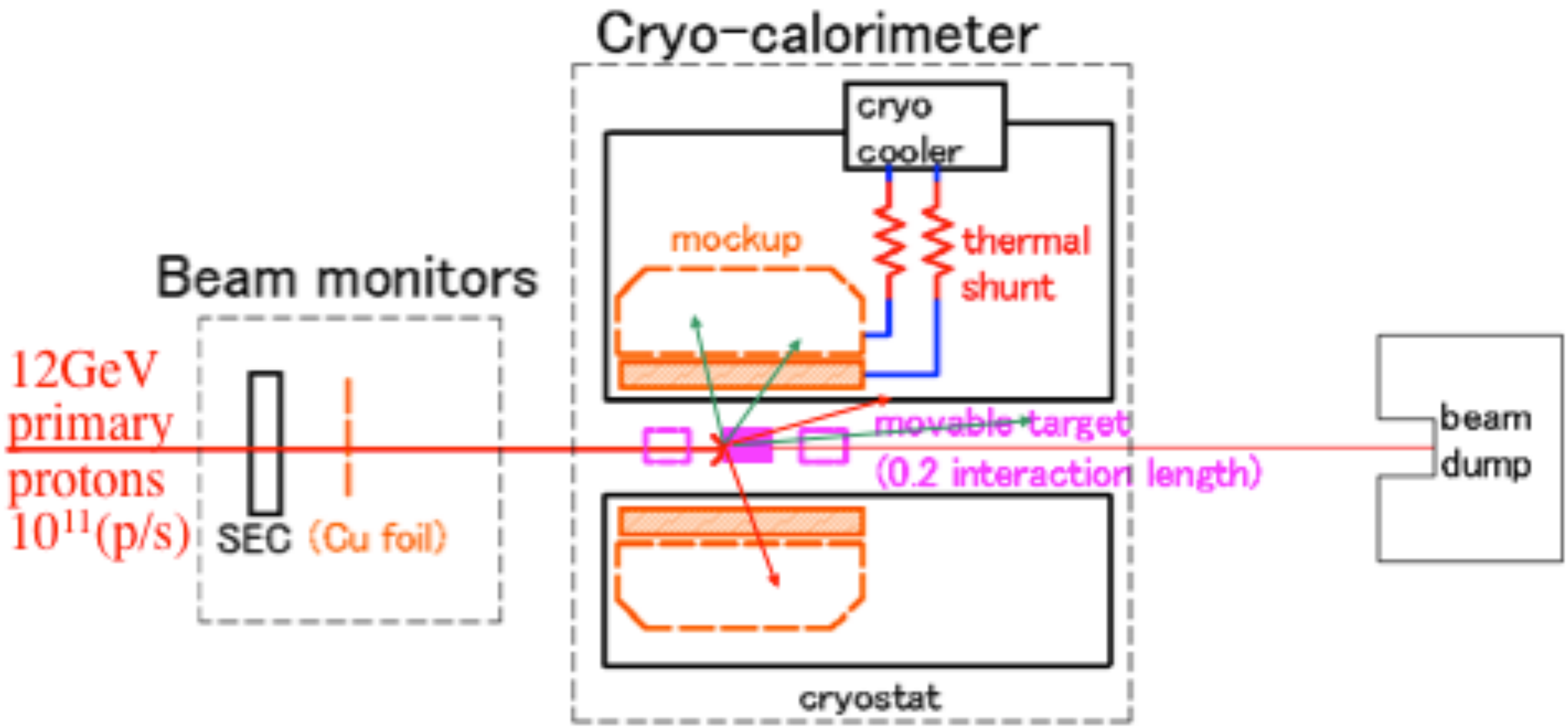
- 12 GeV proton
- Intensity ~10^{11} (protons/sec)
- Slow extraction

Experimental area

- At upstream of EP2-A dump



Experimental setup



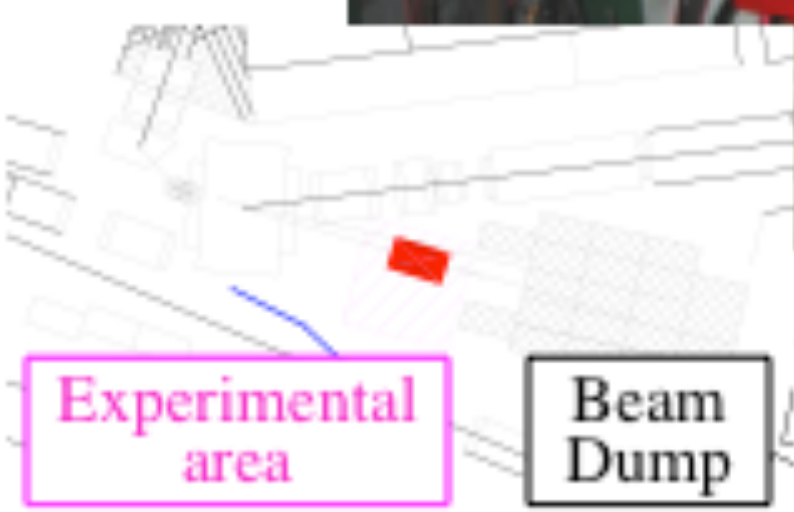
- Sensitive measurement of radiation heat load to the mockup with the cryo-calorimeter

Experimental Installation

12GeVPS
primary
protons

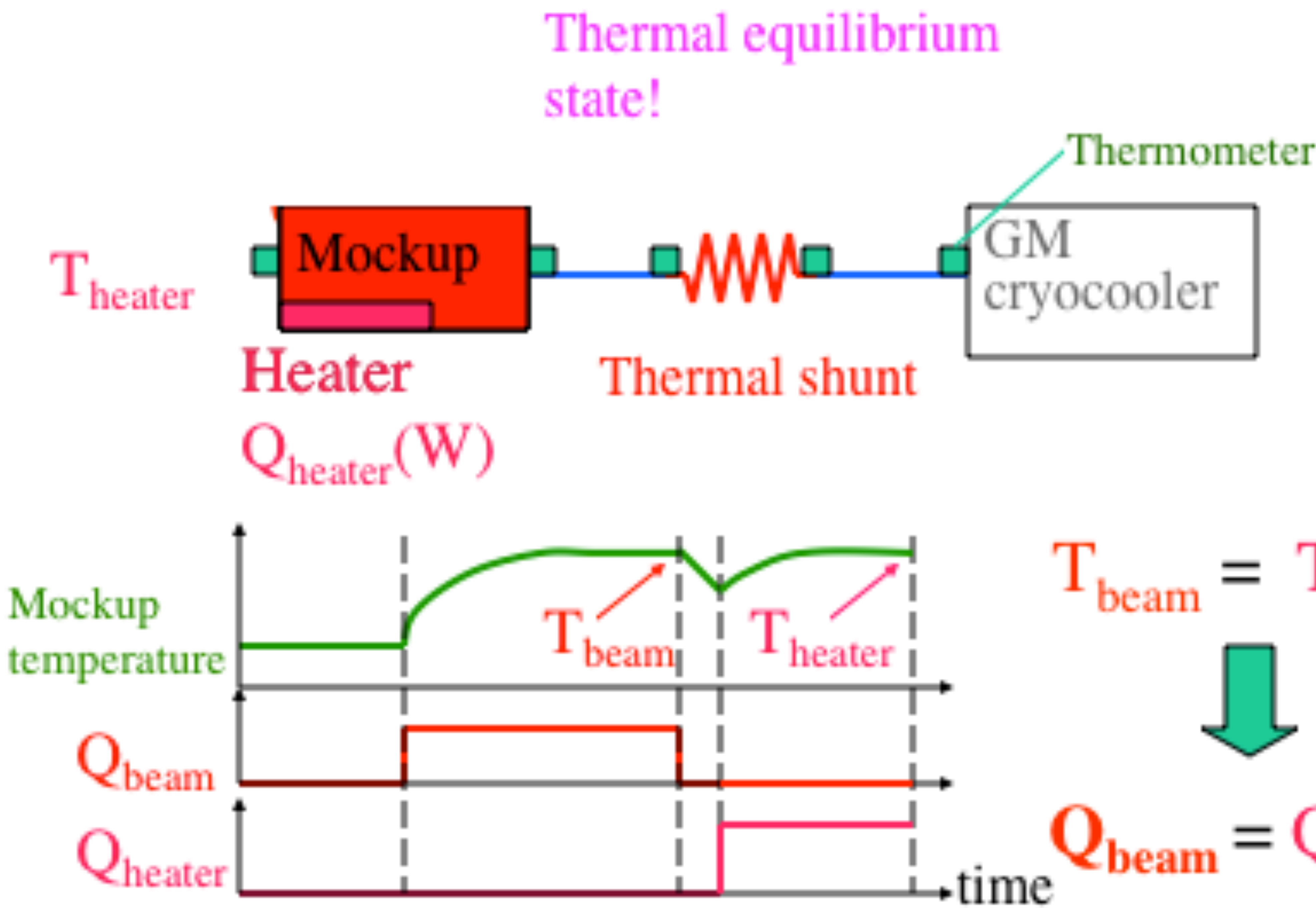
12GeV
~10^{11}(p/s)

Beam dump



Mockup

How to Measure Radiation Heat Load



$$T_{beam} = T_{heater}$$

$$\Downarrow$$

$$\mathbf{Q_{beam}} = Q_{heater}$$

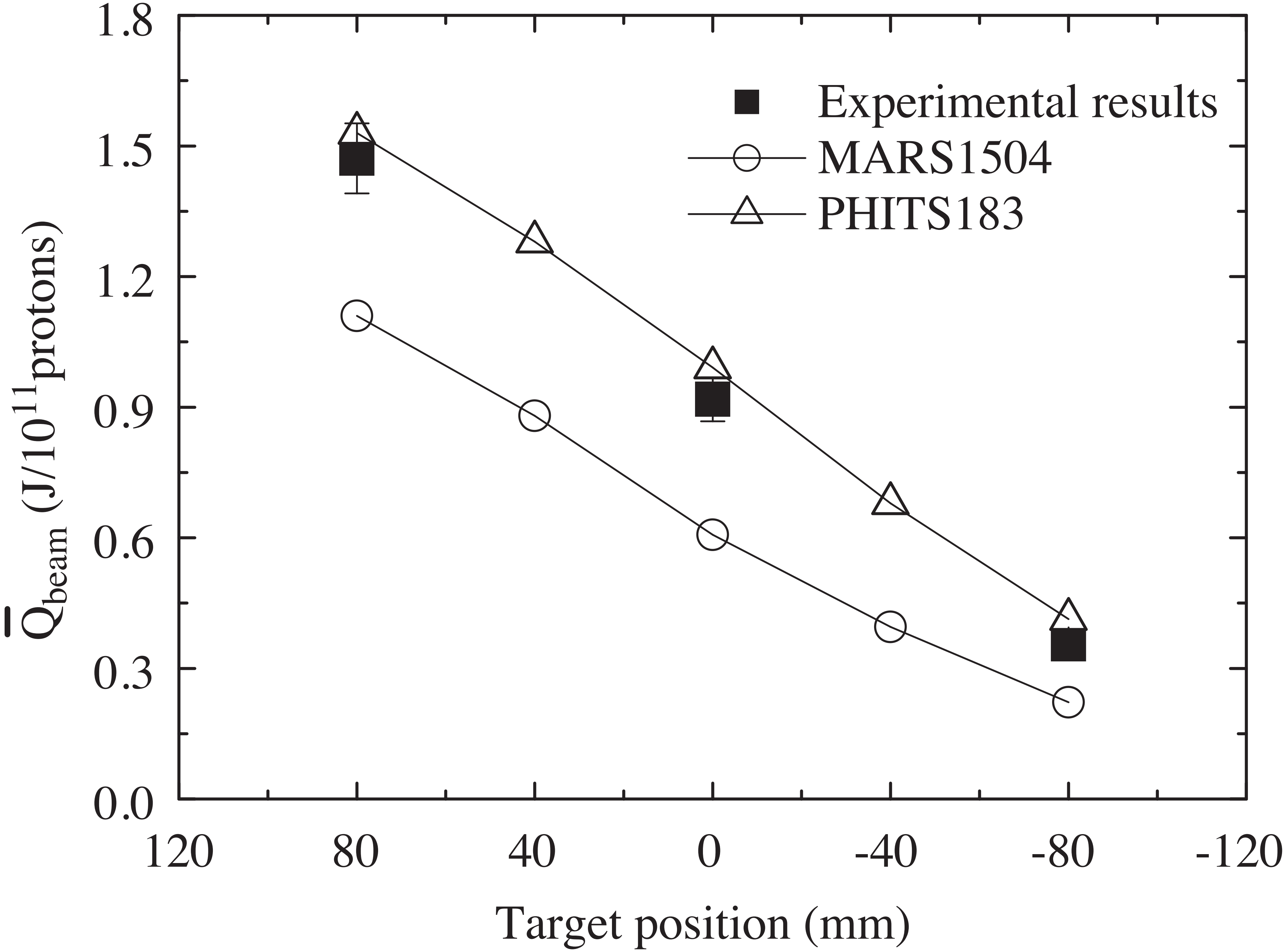


Fig. 12. Comparison of the simulation results with the normalized heat flux.

Relationship among the programs

towards the ultimate μ-e conversion study