μ-e conversion search at J-PARC COMET

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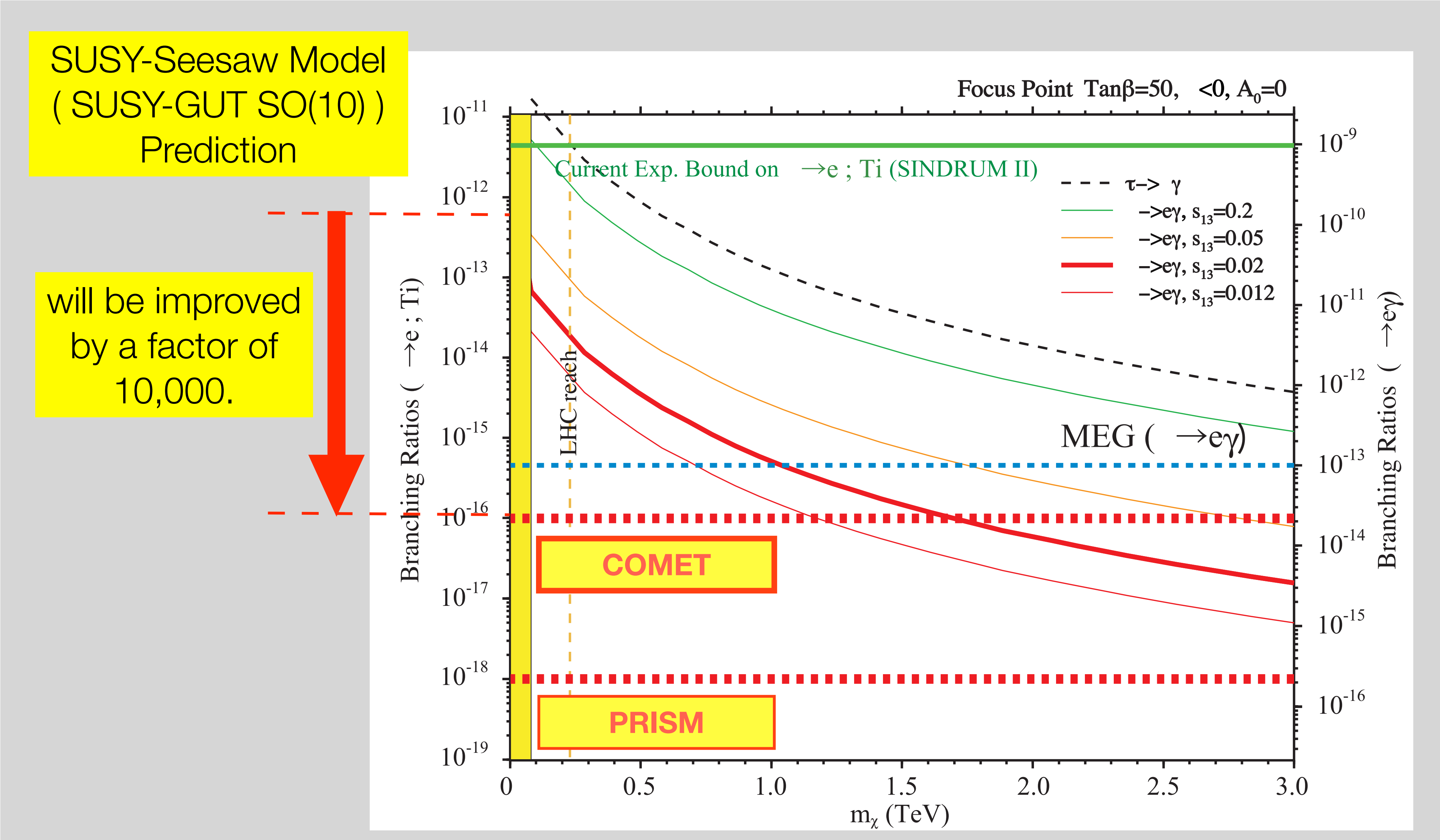
on behalf of the COMET collaboration

Outline

- Physics motivation
- Status
- Design in the CDR
  - Possible layout
  - Proton beam
  - Muon beam
  - Spectrometer
  - Detector
  - Sensitivity and backgrounds
- Timeline
- Summary



Original fig. from A. Masiero et al., J. High Energy Phys. JHEP03, (2004) 046. Fig. 10

COMET Sensitivity Goal: $B(\mu^- + Al \to e^- + Al) < 10^{-16}$

Milestone and Status of the COMET

- **Dec. 2006: Letter of intent to J-PARC**
- **Nov. 2007: Proposal to J-PARC**
- **Dec. 2008: The 1st international collaboration meeting**
- Redesign, reevaluation, and R&Ds
- **Jun. 2009: Conceptual design report**
  - This presentation is based on the CDR.
- **18th July 2009: Presentation at the 8th PAC meeting**
  - To get the stage-1 scientific approval. The PAC made a special session for COMET (a half day!) to evaluate the CDR.
  - The result will be officially announced by the PAC in a month. The CDR, the presentation files, and outputs from the PAC will be available via the PAC web page soon.
  - URL: http://j-parc.jp/NuclPart/PACmeeting_0907_e.html
- **A technical design report would be submitted in one year.**

The COMET Collaboration

48 people from 13 institutes (20th July 2009)

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COMET Design in the CDR

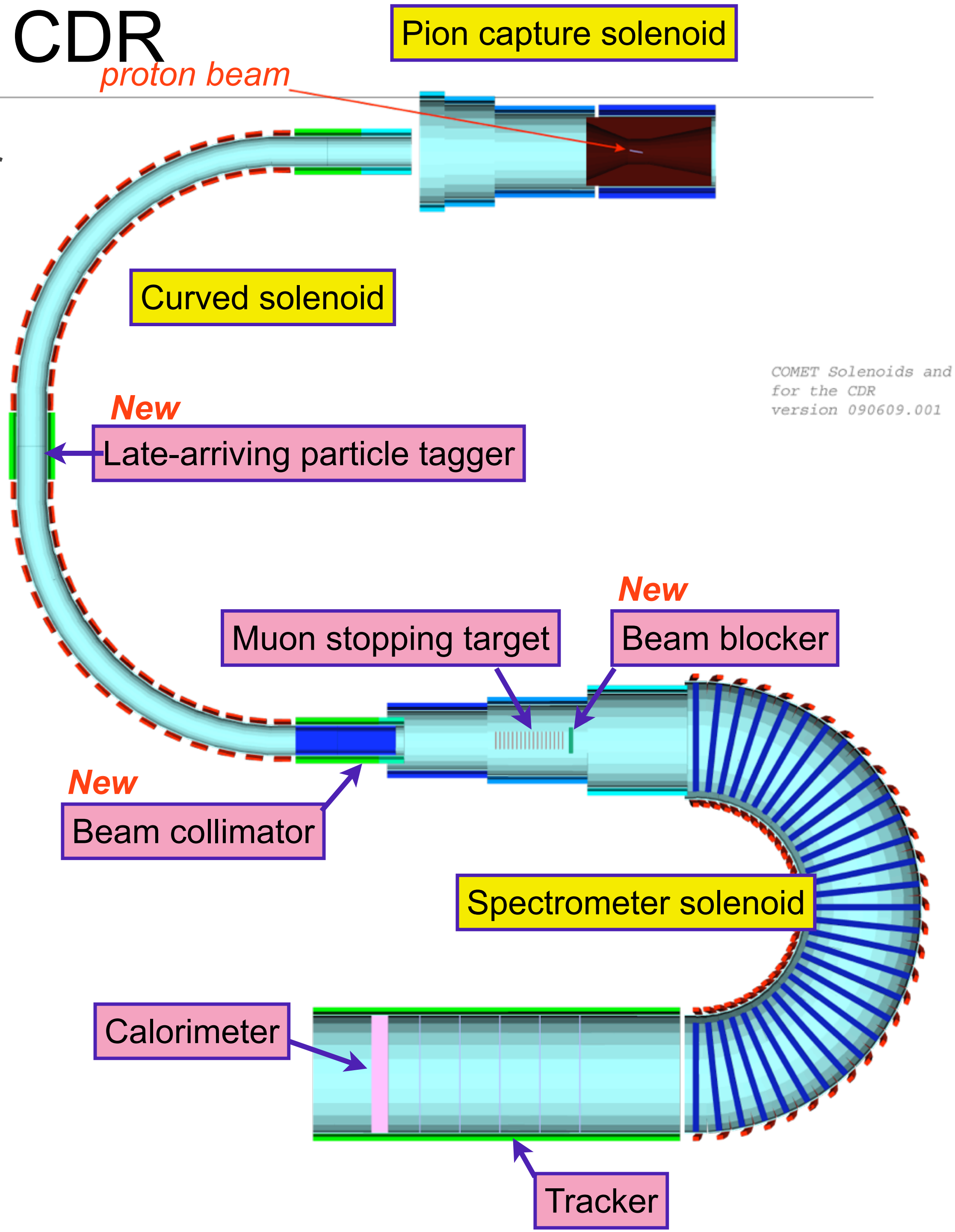
Conceptual Design Report
for
Experimental Search for Lepton Flavor Violating $\mu^- - e^-$
Conversion at Sensitivity of 10^{-16}
with a Slow-Extracted Bunched Proton Beam
(COMET)

J-PARC P21

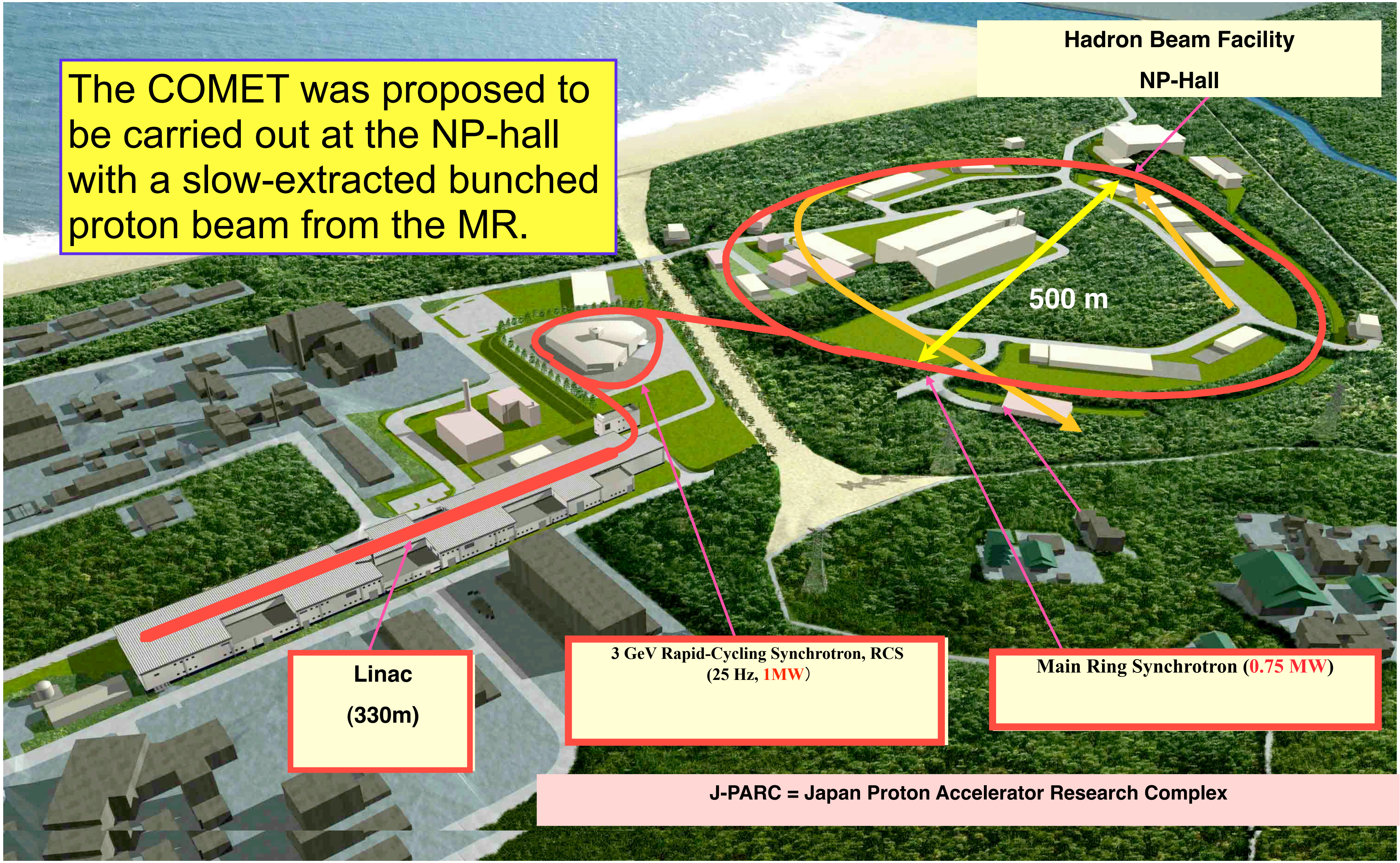
June 23, 2009

COMET Layout in the CDR

- We reexamine a lot of things after the proposal. Some of new components were introduced in the layout.
- ***New components:***
  - a late-arriving particle tagger
  - a muon beam collimator
  - a muon beam blocker
- ***Redesigned:***
  - proton beam
  - pion capture solenoid
  - spectrometer solenoid
  - layout at the NP hall
- ***Reevaluated:***
  - sensitivity
  - backgrounds
  - detector rates

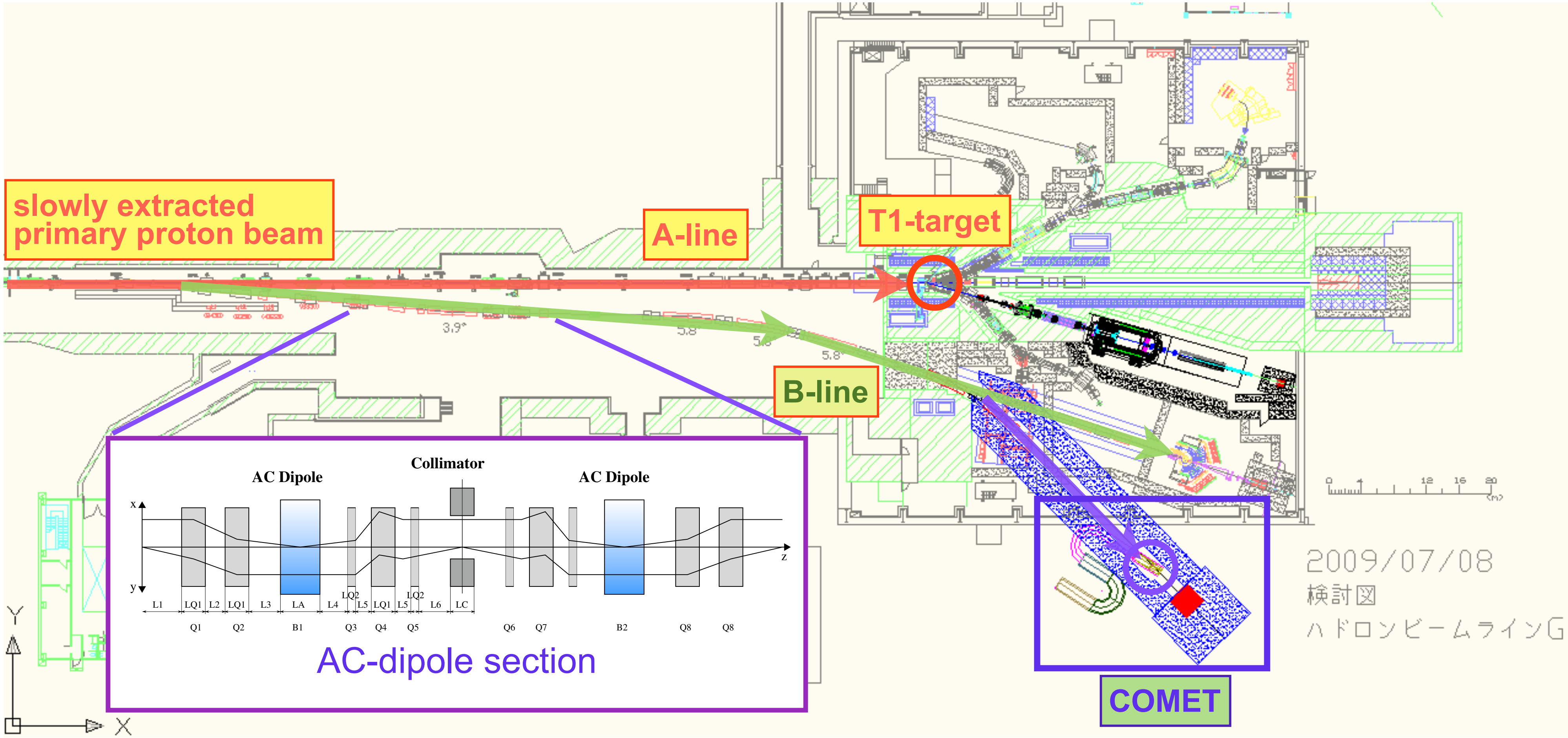


Possible Layout at the NP-hall, J-PARC

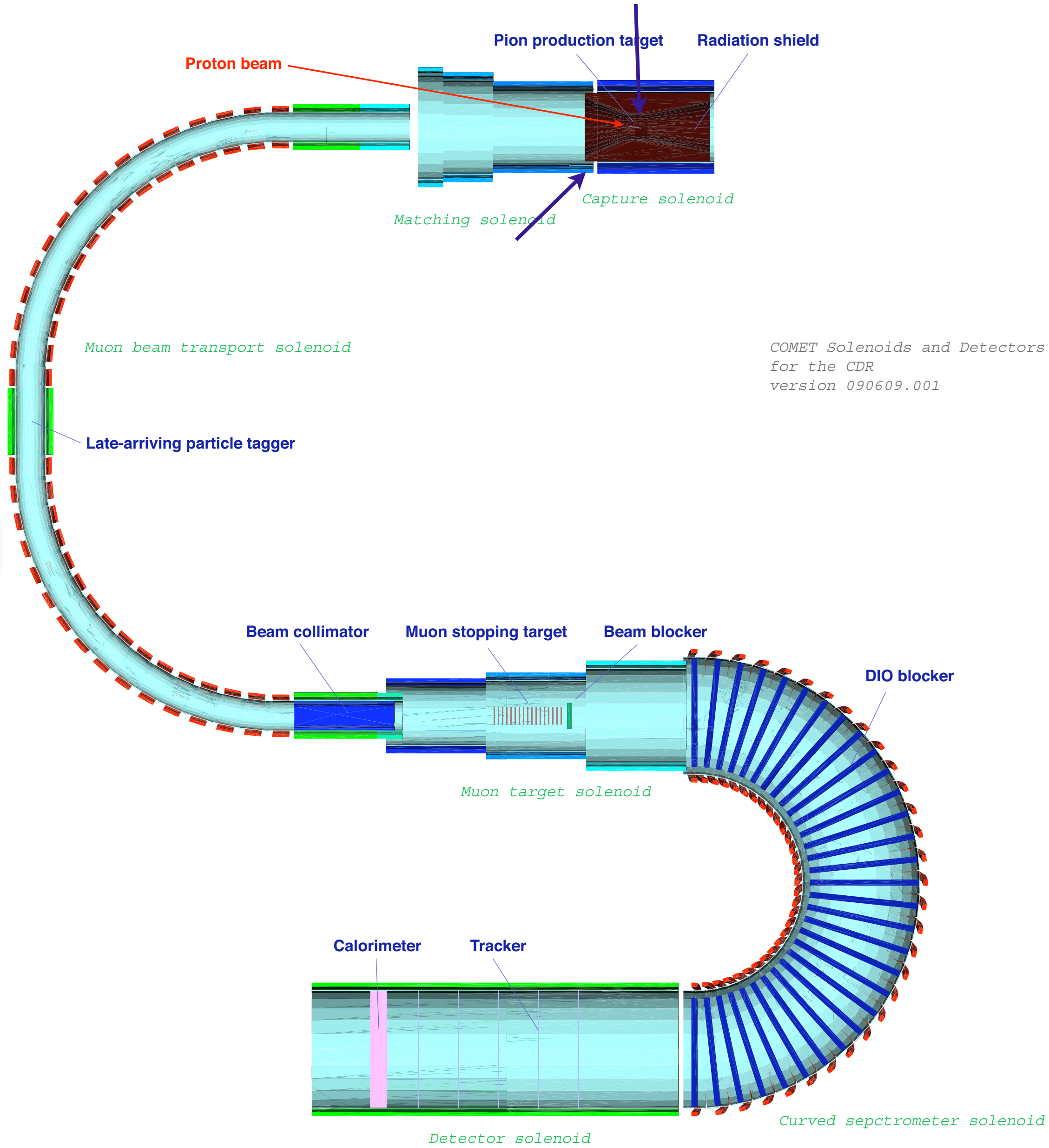


Possible Layout at the NP-hall, J-PARC

- Discussed in the muon task force
  - Target and beam dump outside the hall
  - Share the upstream proton transport line with the high p beam line
  - External extinction device in the switch yard

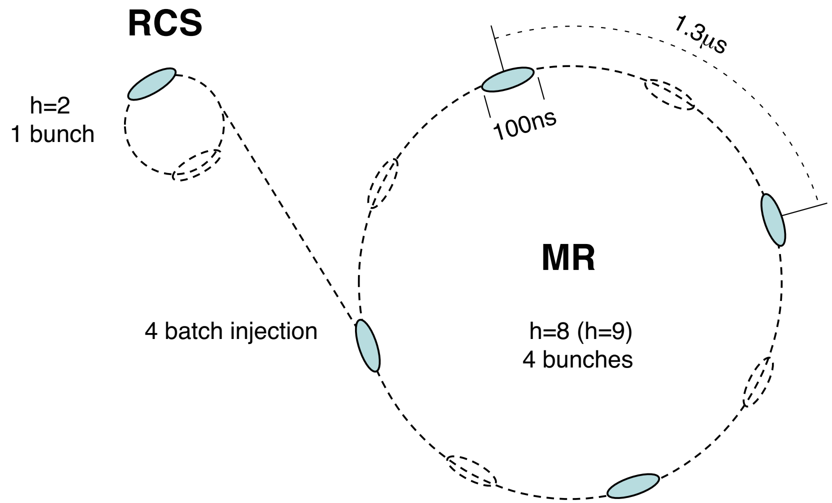


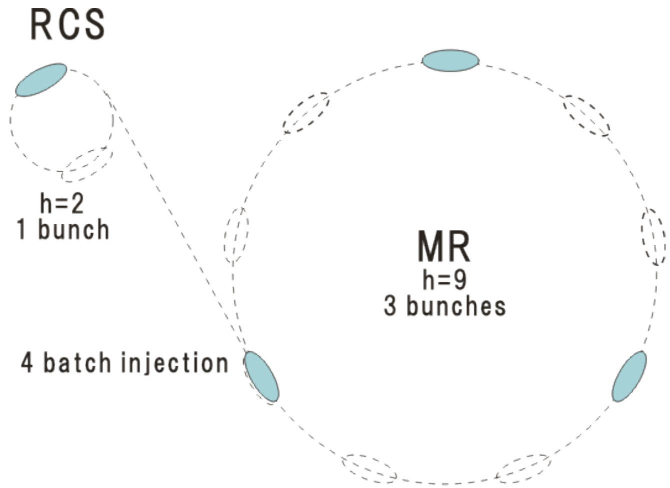
Proton Beam

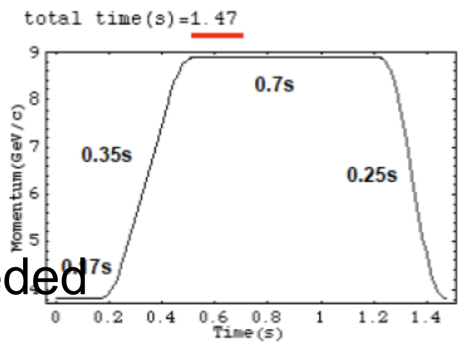

Proton beam
Pion production target
Radiation shield
Capture solenoid
Matching solenoid
Muon beam transport solenoid
COMET Solenoids and Detectors
for the CDR
version 090609.001
Late-arriving particle tagger
Beam collimator
Muon stopping target
Beam blocker
DIO blocker
Muon target solenoid
Calorimeter
Tracker
Detector solenoid
Curved sepctrometer solenoid

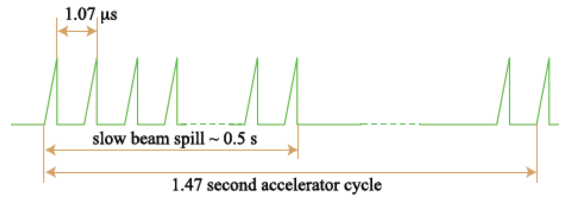
Proton Beam

- **Proton beam**
  - slowly extracted pulsed proton beam
  - 8GeV, 7μA = 56kW
  - pulse width: 100ns
  - pulse separation; 1.3μsec
  - extinction: < 10^{-9} with extinction devices
- ***Scheme A***
  - RCS: h=2 with one empty bucket
  - MR:h=9 with 5 empty buckets
  - Bunched slow extraction
  - Slow extraction with RF cavity ON
- ***Scheme B***
  - RCS: h=2 with one empty bucket
  - MR:h=9 with 6 empty buckets
    - Wider bunch-bunch separation
      - ->Longer meas. time per bunch
      - ~1.3μsec ->~1.8μsec
      - Less effect of the prompt BG
    - Beam power is ¾ of the nominal scheme
- Need further investigation is needed



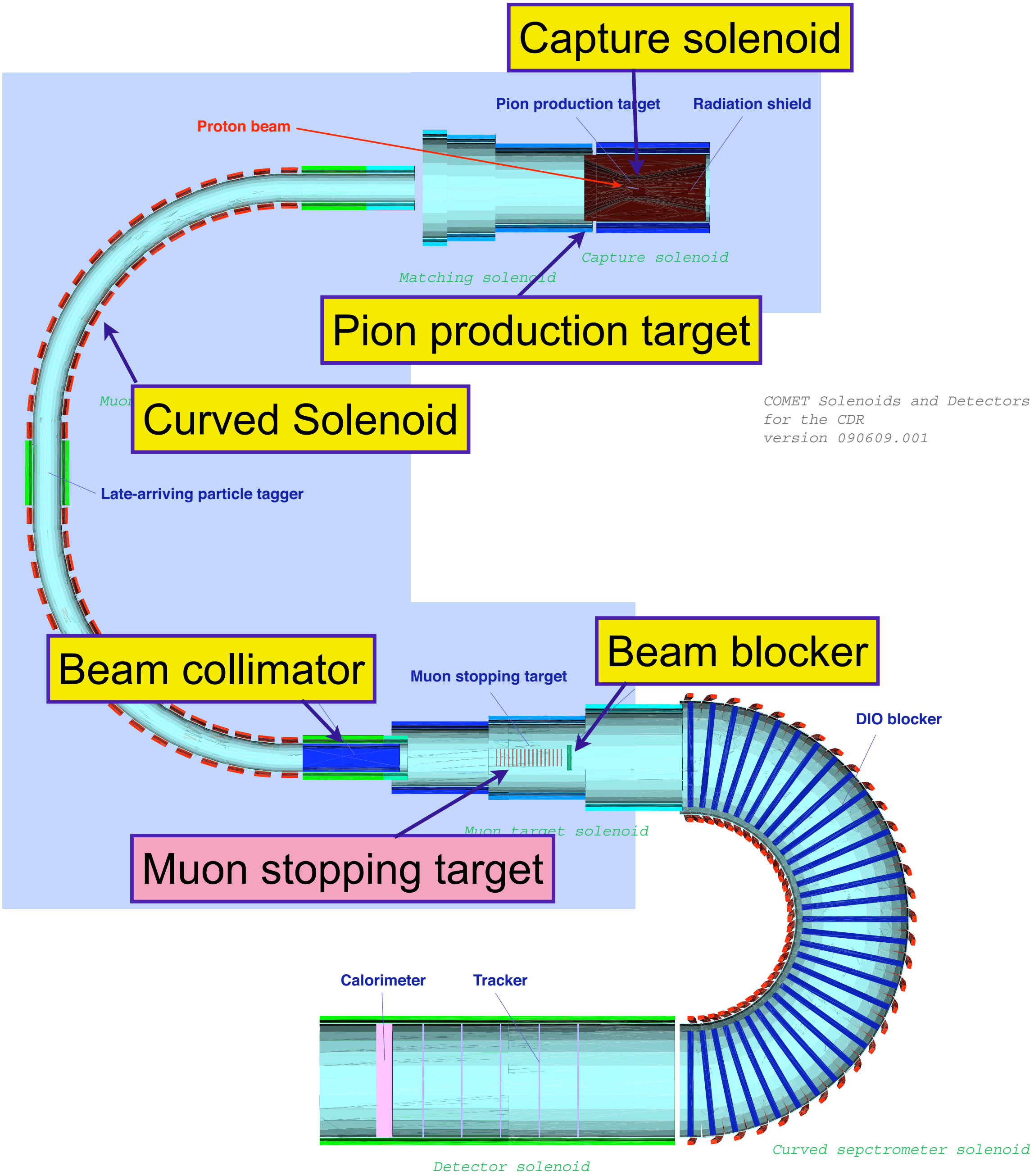






Muon Beam

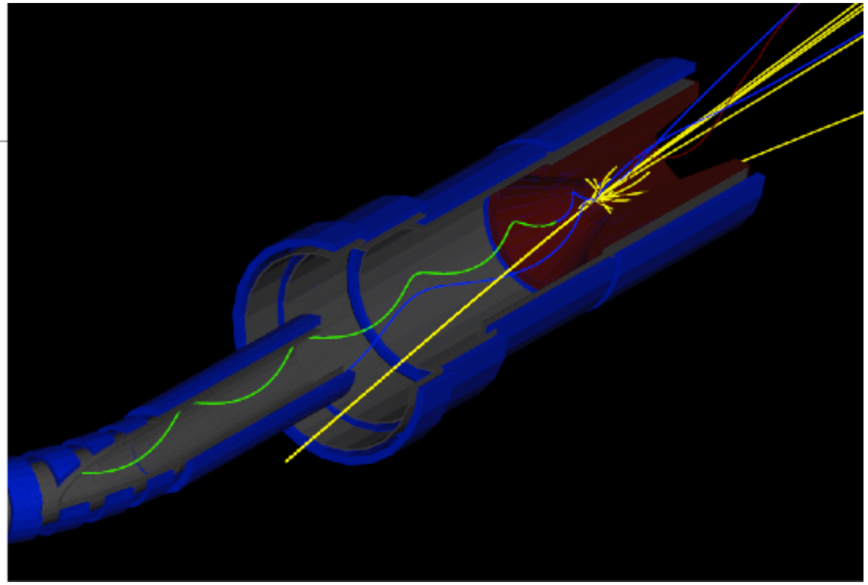
Capture solenoid
Production target
Transport solenoid

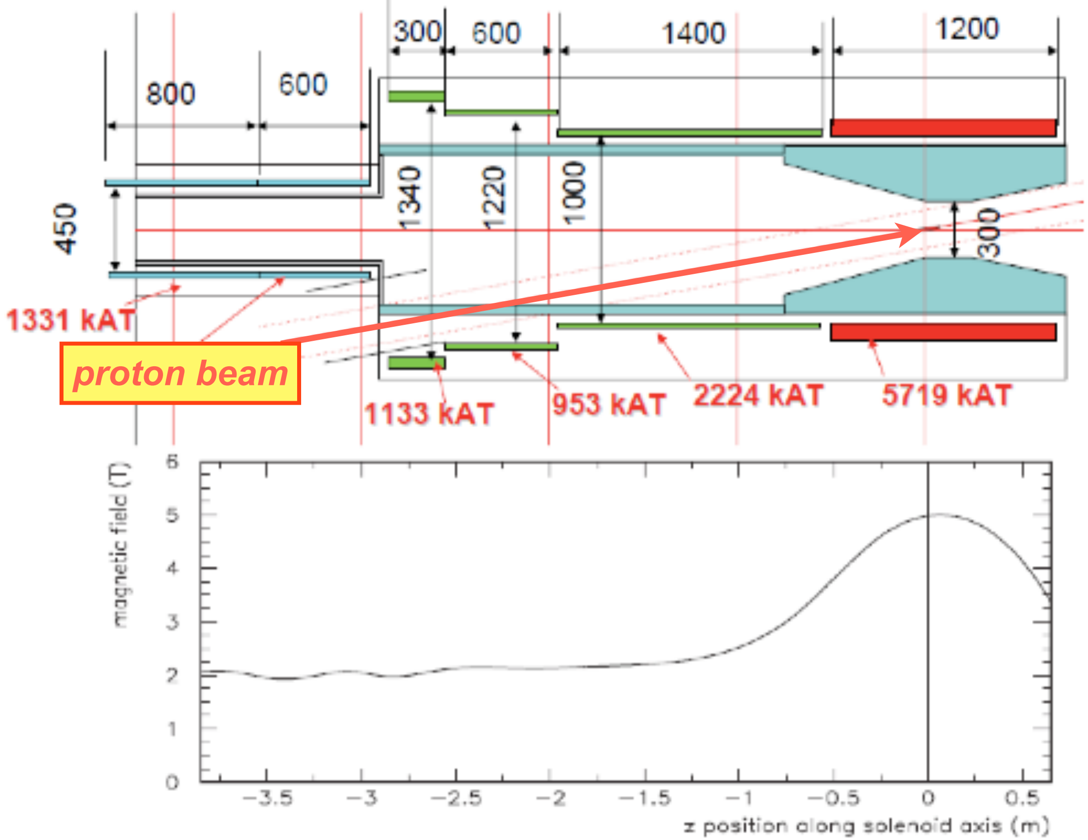


Target and Capture Solenoid

- Capture the backward pions from target in solenoid magnet with 5T magnetic field
- Consists of subsequent superconducting solenoid coils to avoid radiation damage
- Pion production target
  - tungsten (or heavy material)
  - r = 6mm, L = 160mm
  - water cooling
- Capture solenoid
  - High field: 5T
  - Large bore: 1m
  - 30cm-thick tungsten shield
  - Short to avoid radiation
- Matching coils
  - Large bore: 1.0m - 1.3m
  - clearance for proton beam

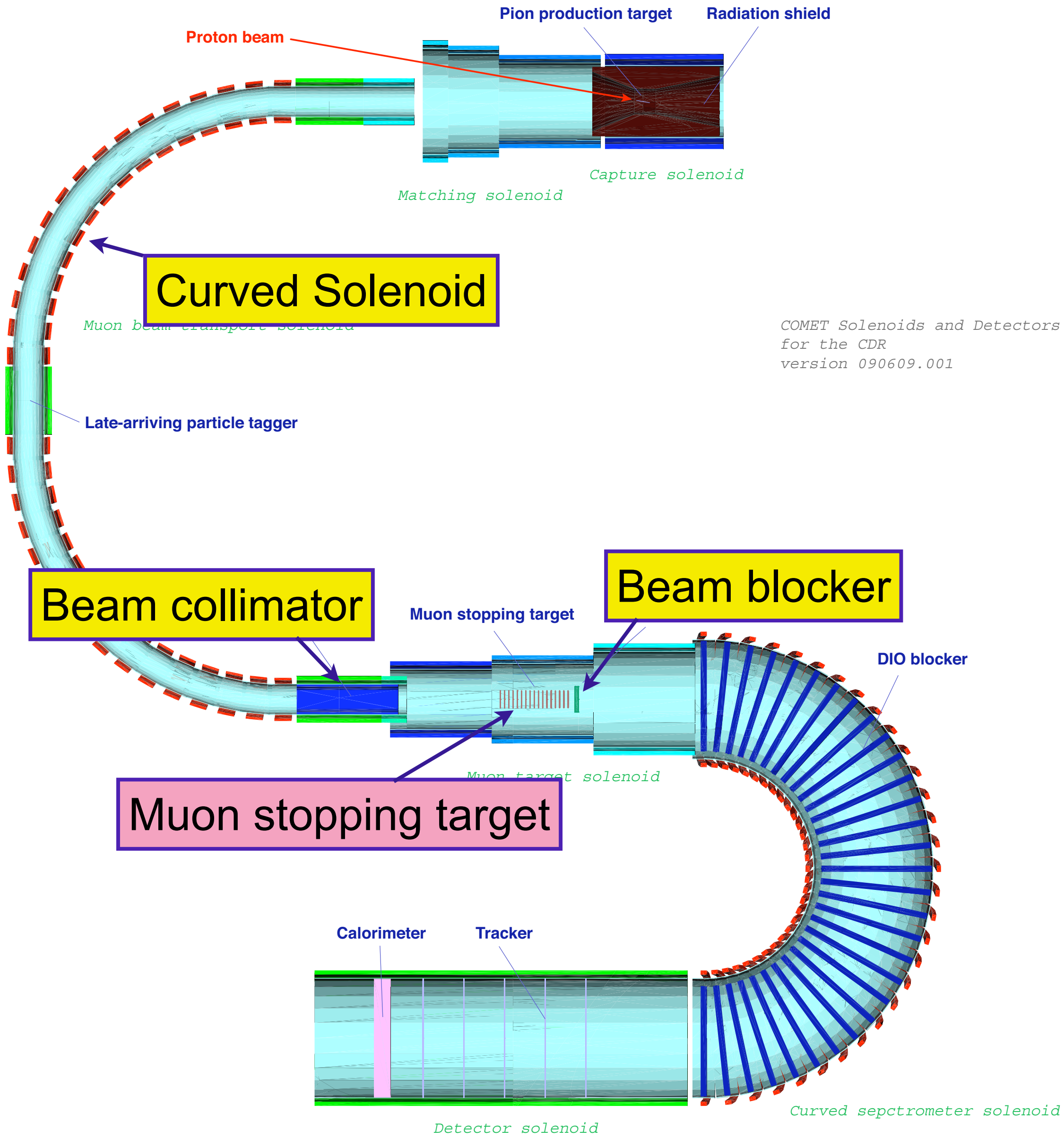
Solenoid designs will be presented by Ogitsu-san.





Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- **Requirements :**
  - long enough for pions to decay to muons (> 20 meters ≈ $2\mathrm{x}10^{-3}$).
  - negative charge selection
  - high transport efficiency (P_μ~40 MeV/*c*)
  - low momentum selection (P_μ<75 MeV/*c*)
- **curved solenoid** transport system with a **beam collimator, and** a **beam blocker** is adopted.



Charged Particle Trajectory in Curved Solenoids

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

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

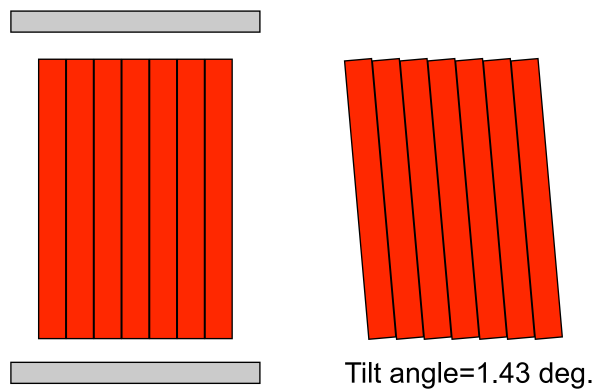
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

- This effect can be used for charge and momentum selection at the muon transport and the spectrometer solenoids.

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

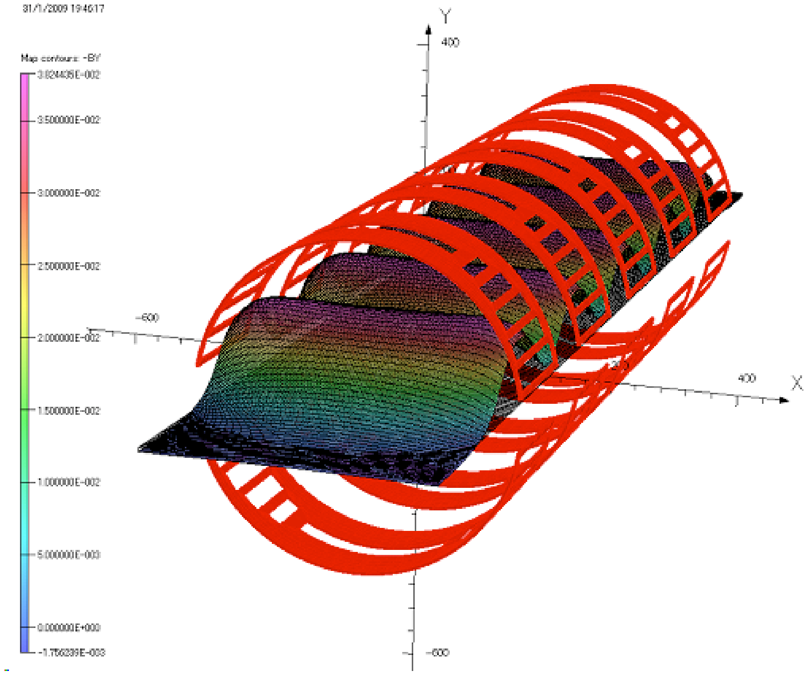
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

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

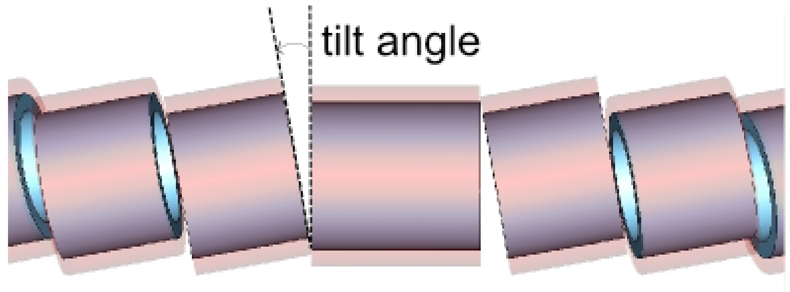


Dipole fields for drift compensation

- We propose two options to realize this dipole field:



Additional dipole coils

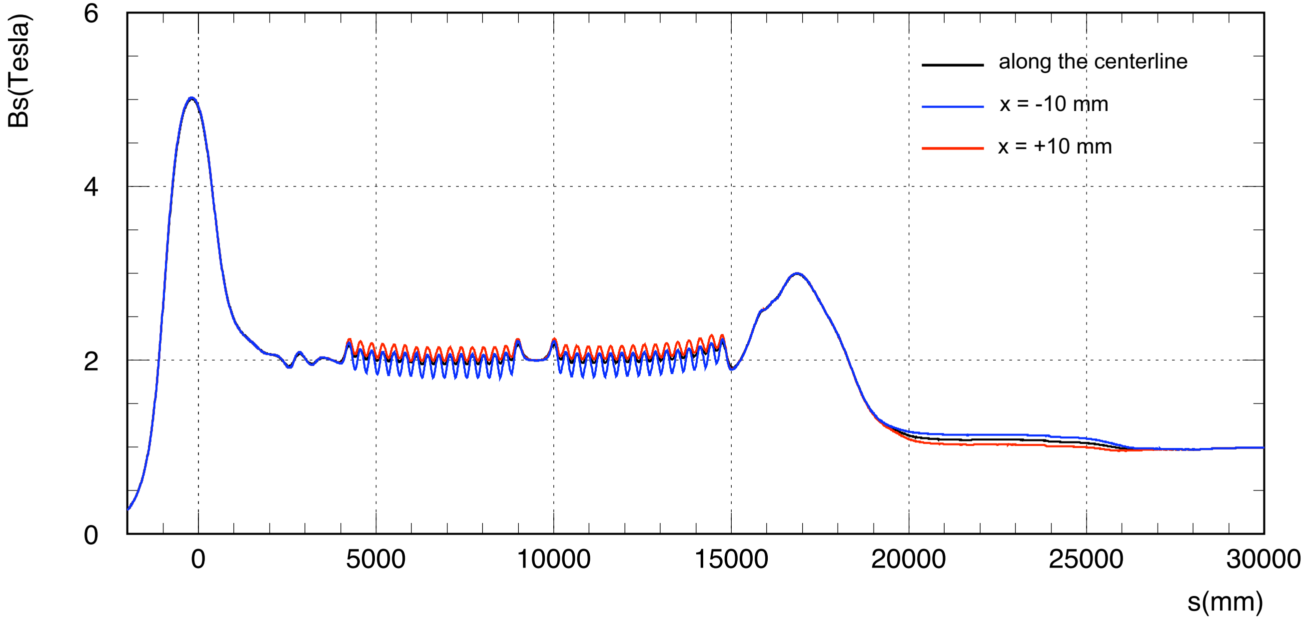


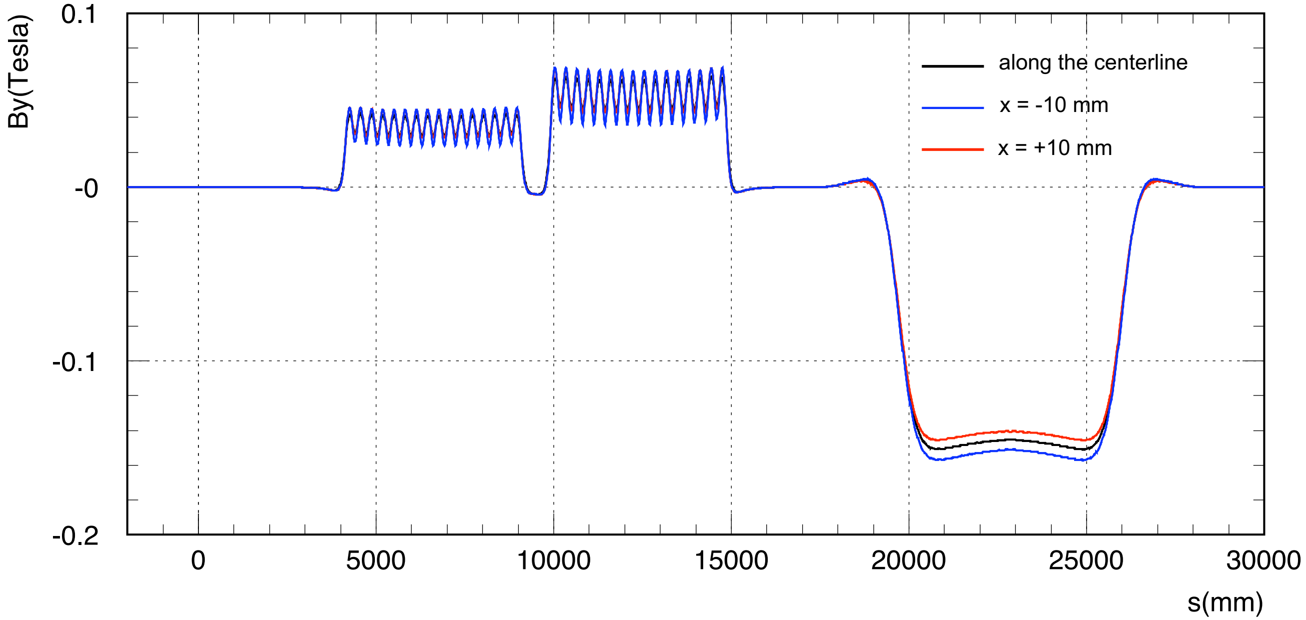
Tilting coils

- Superconducting wires wound on each element of the transport solenoid coils.
- Field magnitude can be tuned by a setting of the coil current.

- Some of coil elements are tilted to produce the vertical dipole field.
- Field magnitude can be tuned by a setting of the tilted coil current.
- Cost effective.

Magnetic field configuration of the solenoids





Specification of the COMET solenoids

production target

18 m

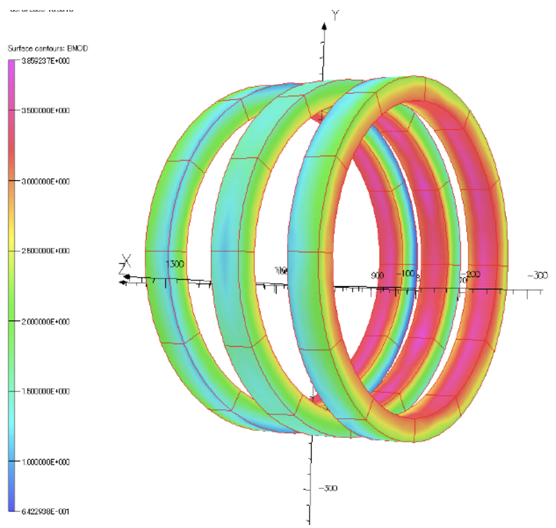
stopping target

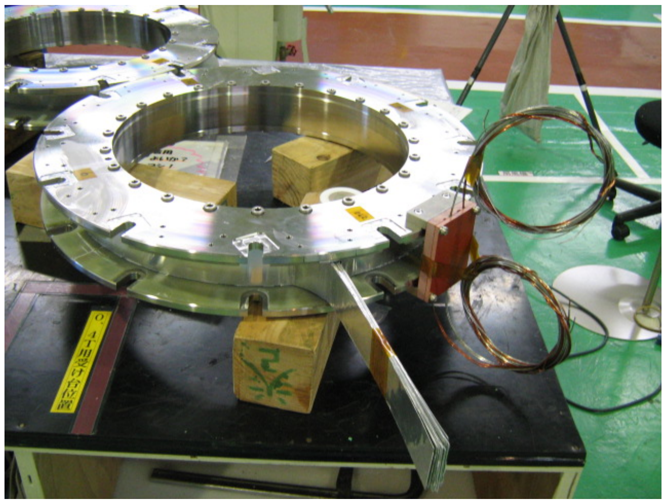
Name	L_{total} (mm)	B_z (T)	B_y (T)	$L_{segment}$ (mm)	IR_{coil} (mm)	t_{coil} (mm)	J (A/mm^2)	IR_{duct} (mm)	$N_{segment}$	θ_{bend} (deg.)	R_{bend} (mm)
CS01	1200	5-4	0	1200	500	90.0	53.0	420	1	-	-
MS01	1400	4-2	0	1400	500	30.0	53.0	450	1	-	-
MS02	600	2	0	600	610	30.0	53.0	560	1	-	-
MS03	300	2	0	300	670	60.0	62.9	620	1	-	-
MS04	600	2	0	600	225	30.0	37.8	175	1	-	-
TS01	800	2	0	800	225	30.0	55.5	175	1	-	-
TS02B	4912	2	0.030	200	225	30.0	84.0	175	16	90	3000
TS03	800	2	0	800	225	50.0	32.0	175	1	-	-
TS04B	4912	2	0.050	200	225	30.0	84.0	175	16	90	3000
TS05	1200	2	0	1000	225	50.0	24	175	1	-	-
DS01	300	2.5	0	300	225	50.0	8.5	175	1	-	-
DS02	1200	3	0	1200	400	50.0	52.2	350	1	-	-
DS03	1200	2	0	1200	470	50.0	34.3	420	1	-	-
DS04	1200	1	0	1200	610	50.0	16.9	560	1	-	-
DS05B	6356	1	0.145	73	750	50.0	49.4	700	31	180	2000
DS06	4400	1	0	4400	750	50.0	16.1	700	1	-	-

Total length of the solenoid channel from the production target to the stopping target is 18m. We can achieve an enough pion suppression with a beam collimator.

R&D on the Transport Solenoid

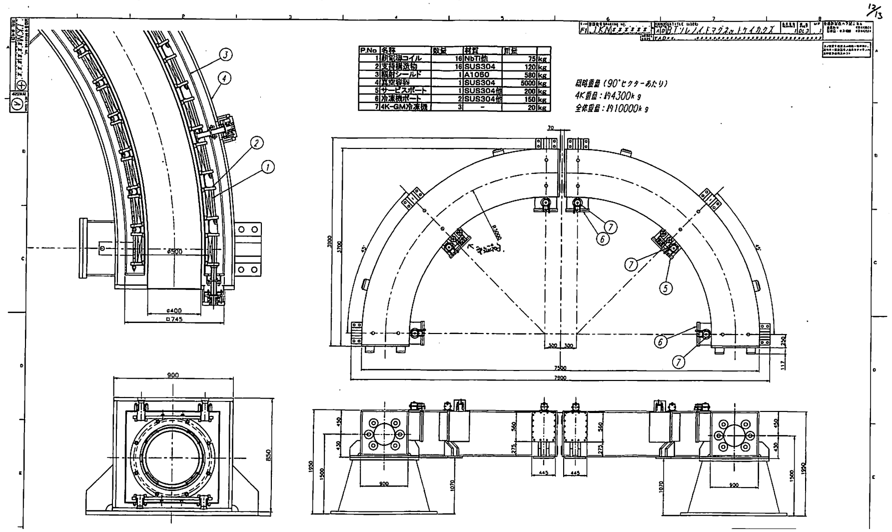
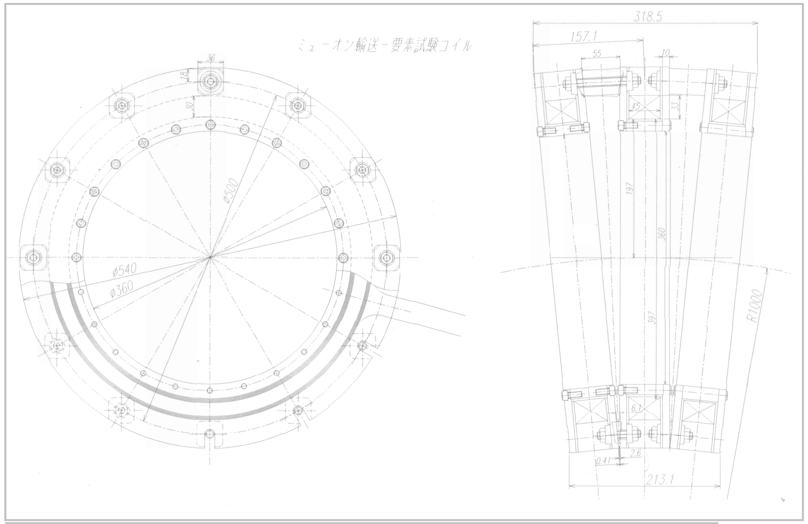
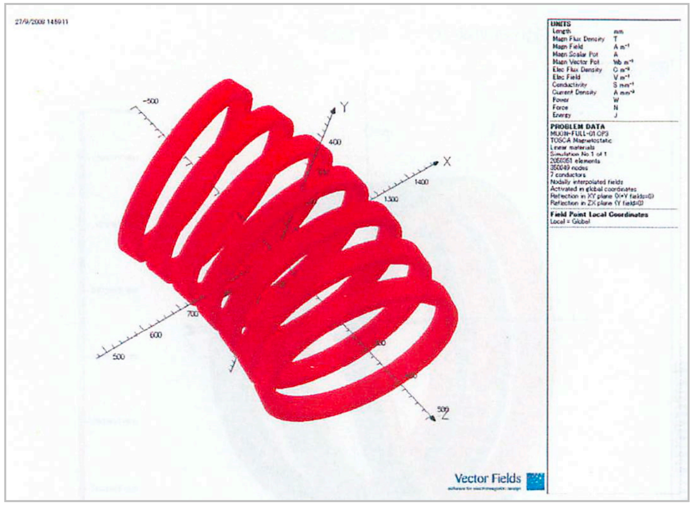
- Transport Solenoid would be easier than the capture solenoid:
  - field magnitude ~ 2 T
  - smaller radiation load
- NbTi copper stabilized conductor, which is widely used in MRI magnets and commercially available, will be used.
- The solenoid will be constructed by arranging coil “pancakes” electrically and thermally connected in series along the curve.
- We are studying basic parameters by a prototype comprising of 3 pancakes.
  - cooling performance
  - electromagnetic forces between pancakes
  - quench back system
- A new high-Tc superconductor, MgB_2, will be used for one of the coils for the first time.
  - MgB_2 will be used for the electron-spectrometer and detector solenoids

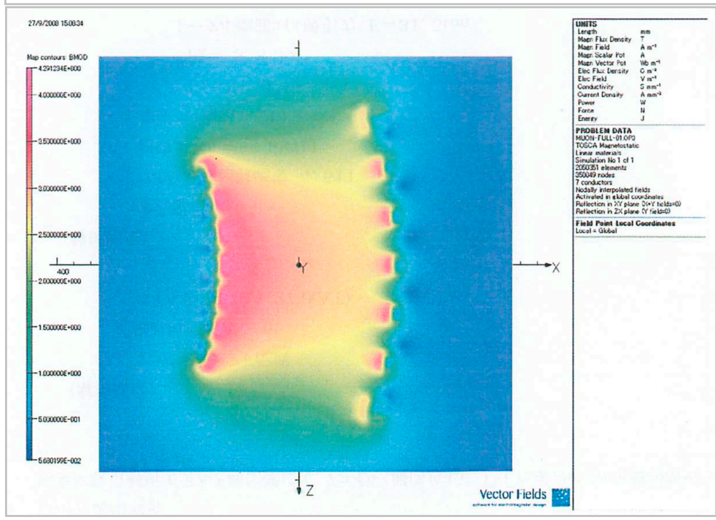




R&D on the Transport Solenoid

- Engineering design of the curved solenoid will be started from next year.



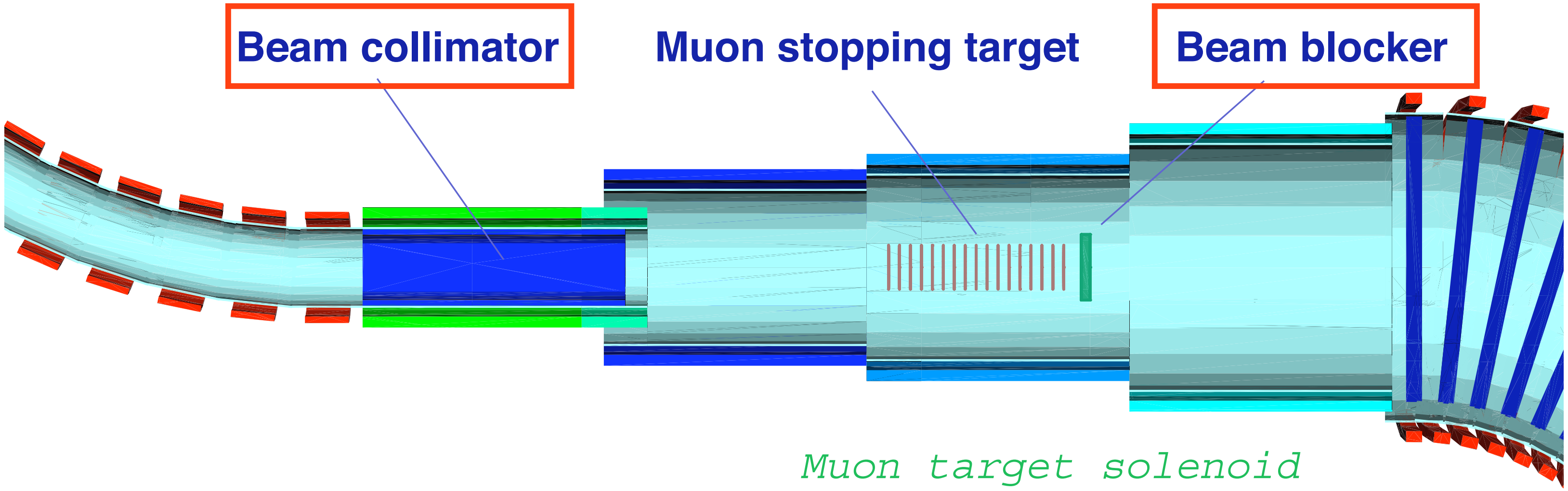
- Construction of the curved solenoid, which consists 8 pancakes with the additional dipole coils, will be constructed by the end of March 2010 for MUSIC project. We can share the design knowledge.

Muon Beam Collimator and Blocker

- The muon beam collimator is placed in front of the muon-stopping target
- **Beam collimator**
  - It suppress the energetic muons (>75MeV/*c*).
  - *and eliminates muons which would not stop in the target and other charged particles that would become the backgrounds.*
- **Beam blocker**
  - It blocks the beam particles which didn't stop in the target, so that they do not enter the torus section, to reduce the detector hit rate.

Beam Collimator	
Inner Radius	150 mm
Lower Jaw	-100 mm from the beam center
Length	1.2 m
Material	Tungsten

Beam Blocker	
Radius	150 mm
Length	40 mm
Material	Tungsten
Position	100 mm downstream of the last target disk

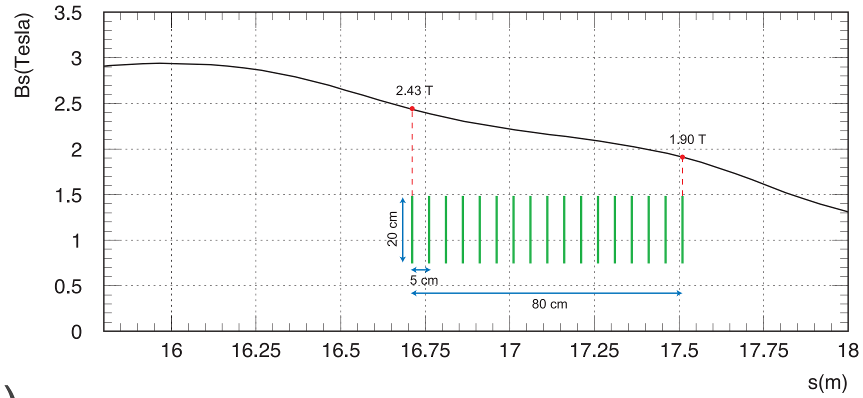


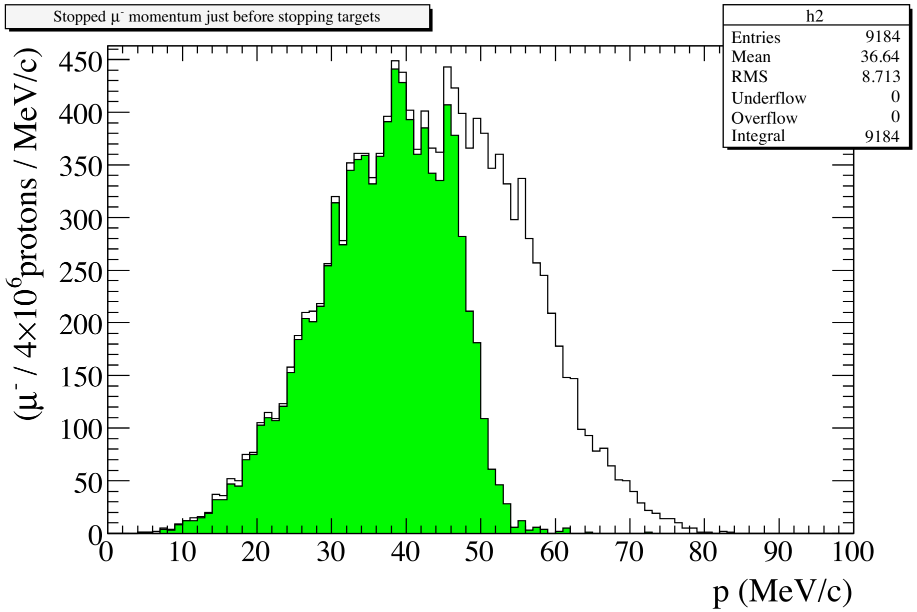
Muon Stopping Target

- Target material
  - First choice : aluminum

	aluminum	titanium	lead
Atomic number	13	22	82
Lifetime of muonic atoms (μsec)	0.88	0.33	0.082
Relative $\mu^{-}-e^{-}$ conversion branching ratio	1	1.7	1.15

- Configuration (preliminary)
  - material : aluminum disk
  - disk radius : 100 mm
  - disk thickness : 200 μm
  - a number of disks : 17
  - disk spacing : 50 mm
  - a graded magnetic field (for mirroring).

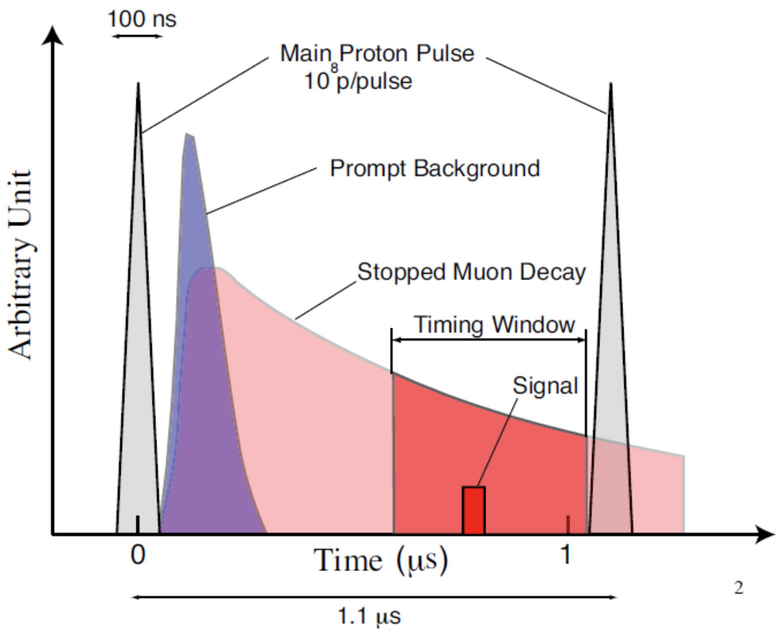


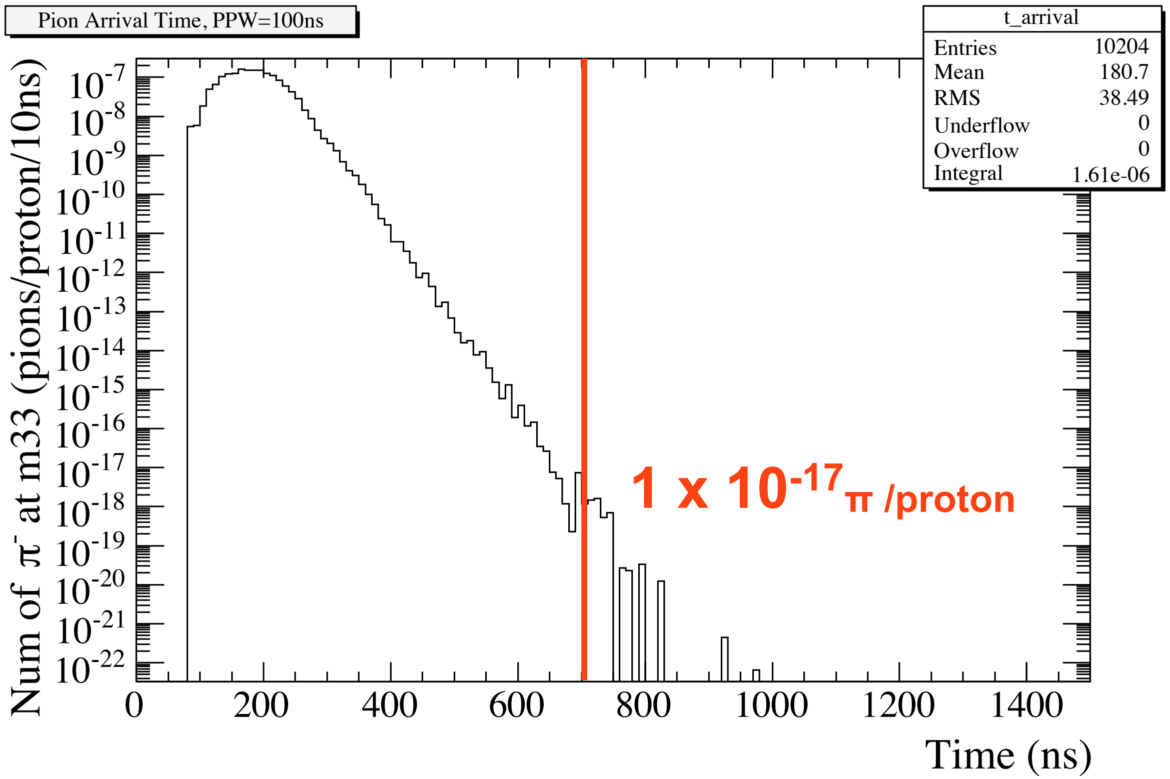


- Muon stopping efficiency
  - **66%**
- Number of stopped muons
  - **0.0023 μ/proton**

Performance of Muon Transport : π contamination

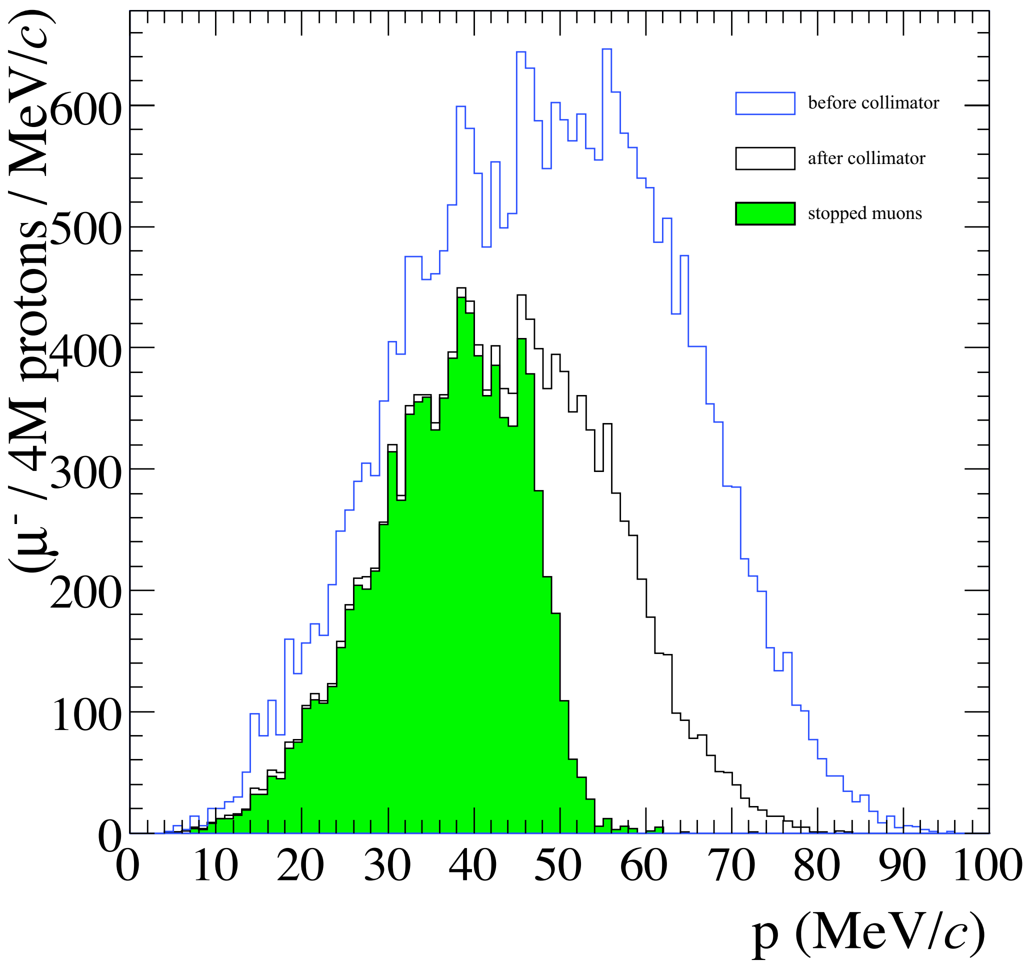
- We need to wait to open the detection window for a several ns after a proton pulse hits the production target until the prompt background decayed out.
- The detection window was taken starting from 700ns after the proton pulse hit the production target, considering an arrival time distribution of pions.
- It gives a ratio of late arriving pions of 1×10^{-17} π/proton, which gives the expected background from the radiative capture of delayed pions 0.002.





Performance of Muon Transport : Muon Yield

- The beam collimator can suppress the energetic muons keeping a high transport efficiency for the low-energy muons.

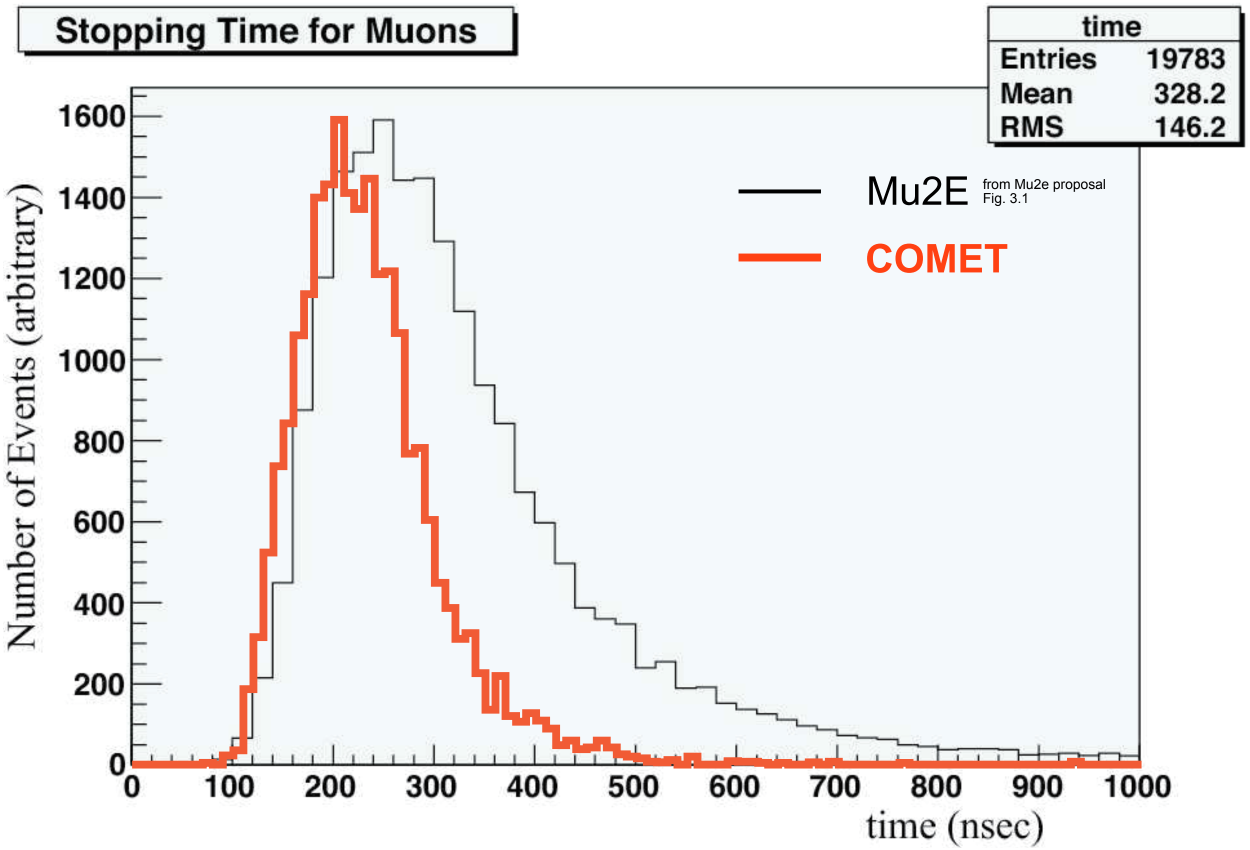


Rate of μ transported to the target: 0.0035 μ/proton

μ with P_μ>75MeV/*c*: 10^{-5} μ/proton

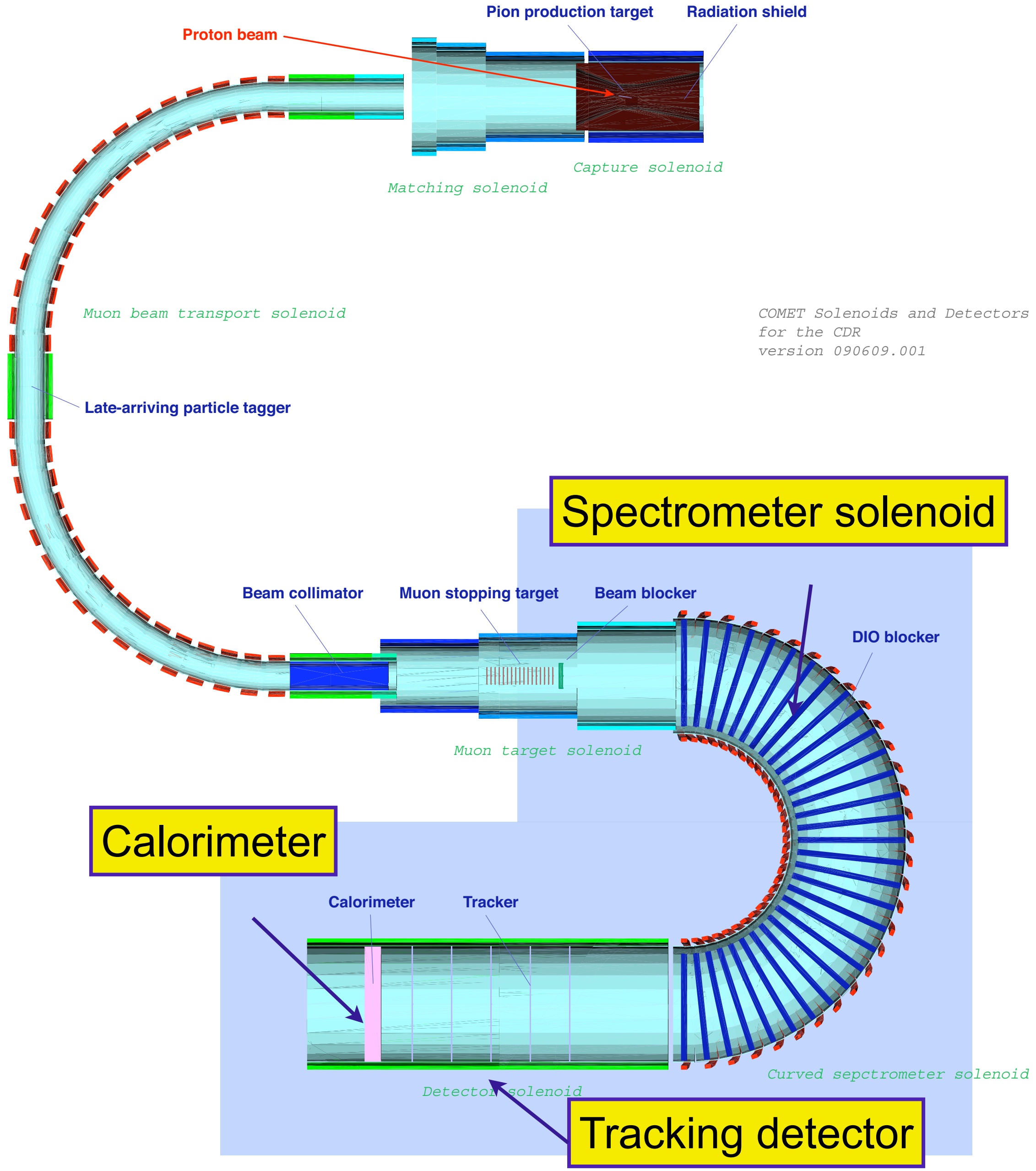
Comparison b/w COMET and Mu2E

	COMET	Mu2E
Number of stopped muons [μ/proton]	0.0023	0.0025
Number of transported muons to the target [μ/proton]	0.0035	0.0043
Muon stopped efficiency	0.66	0.58

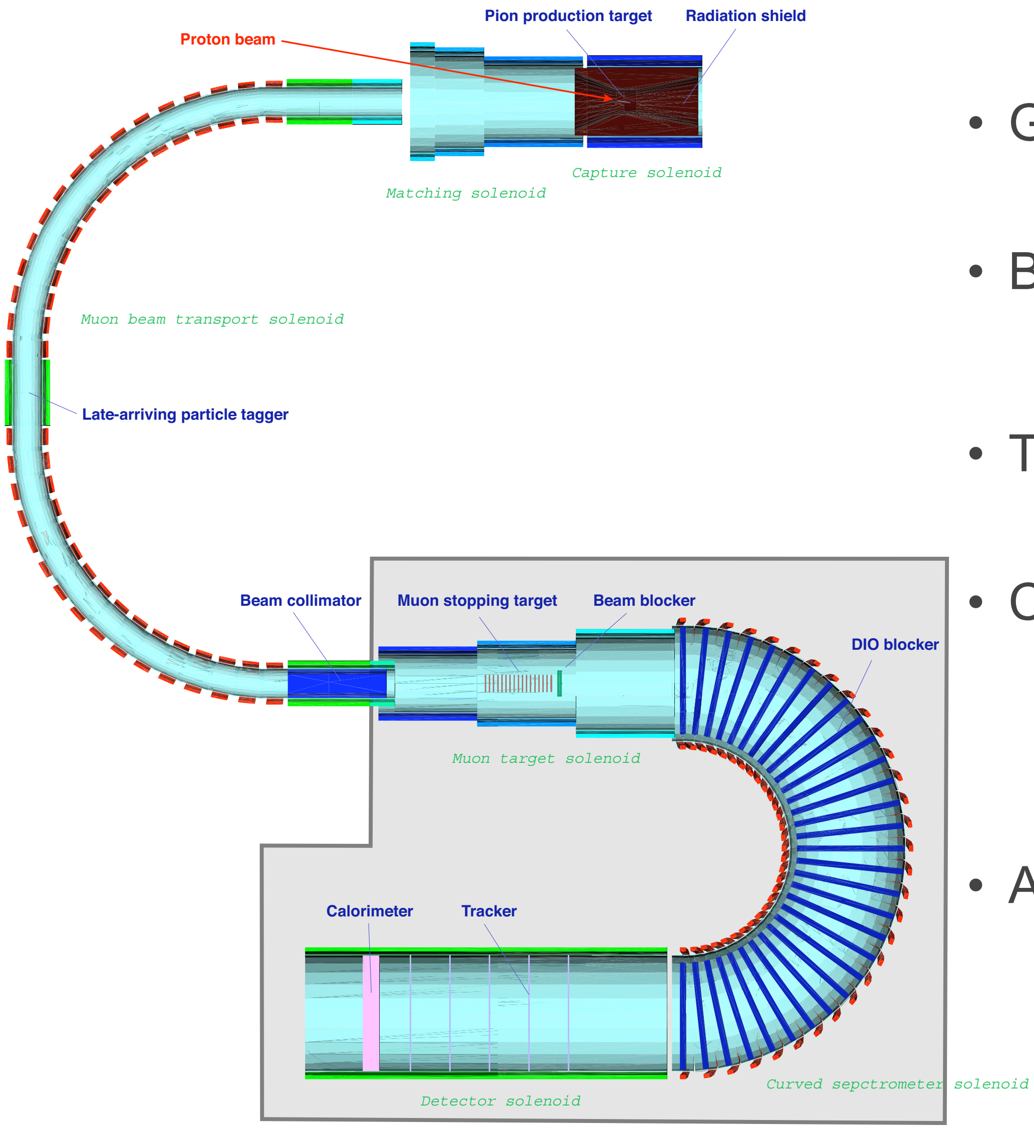


Detector

Spectrometer solenoid
Tracking detector
Trigger calorimeter



Detector Overview

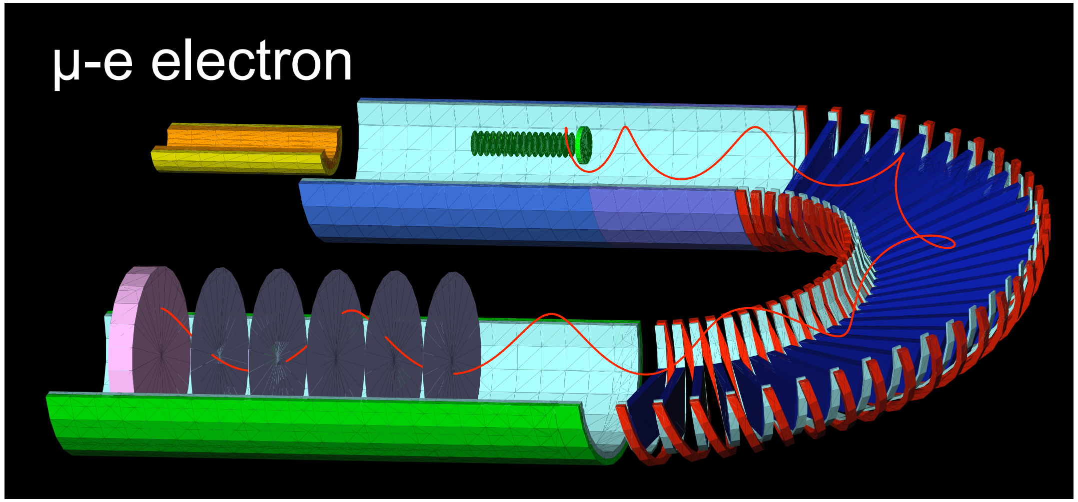


- Curved Solenoid & DIO Blocker
  - To suppress low momentum electrons.
- Graded Field at Muon Target Solenoid
  - To maximize transmission efficiency of the curved solenoid.
- Beam Blocker
  - To prevent beam particles entering to a detector solenoid.

- Tracker
  - Low mass to be transparent to γ's.
  - f < 1 MHz
- Calorimeter
  - Trigger
  - Cosmic Muon suppression
  - f < 1 MHz for Ee > 10 MeV
  - <E> pile-up ~ 1 MeV

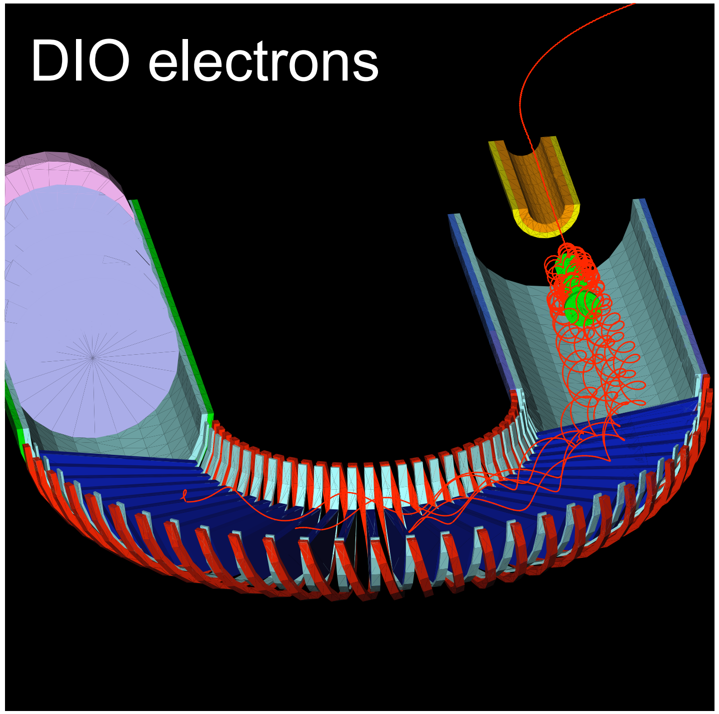
- Active Time Window: 0 ~ 1.3 μs
  - No beam flash to blind detectors.
  - be able to record prompt background events -> better background estimation in the off-line analysis.

Electron Transport Solenoid



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

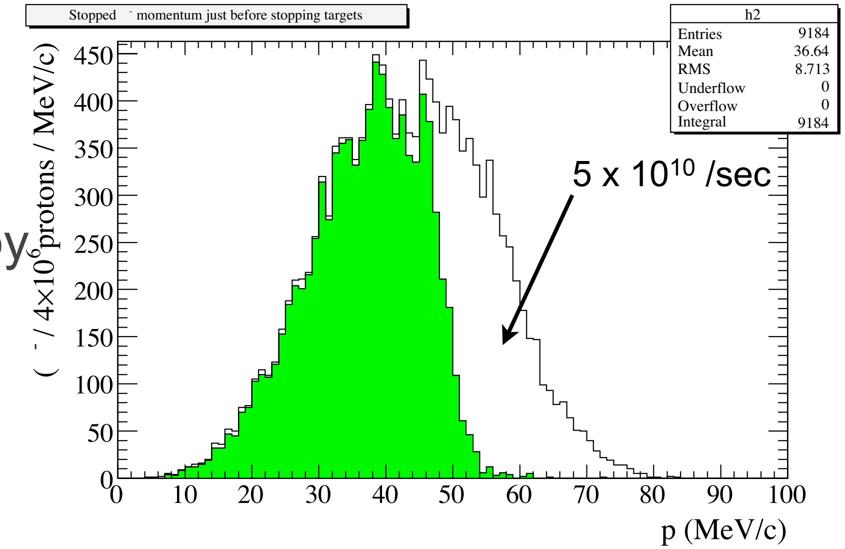
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan*(P_T/P_L)



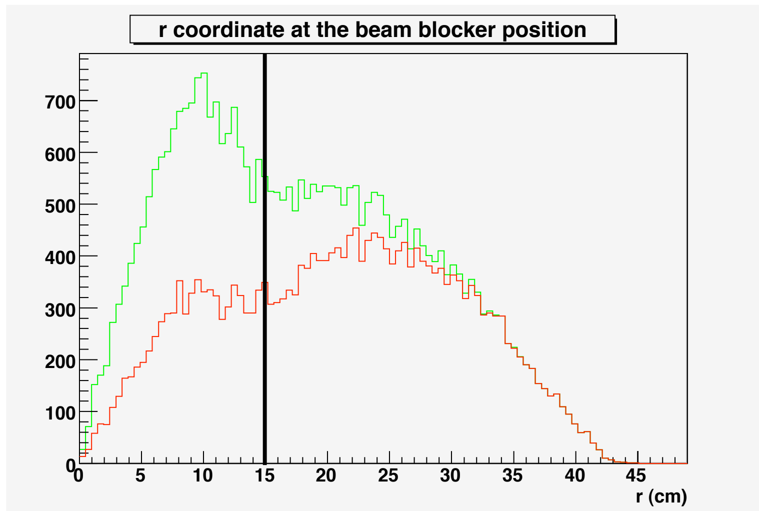
Graded B Field around the muon target	3 T -> 1 T
Main B Field	1 T
Compensation B Field	0.17T
Small Radius (inner)	70 cm
Large Radius	2 m
DIO Blocker Hight	20 cm below the median plane, slightly slanted
DIO Blocker Coverage	Whole the curved section
DIO Blocker Material	Aluminum
Beam Blocker Radius	15 cm
Gross Acceptance Loss by Beam Blocker	53%
Net Acceptance Loss by Beam Blocker	25%

Muon Beam Flash & Beam Blocker

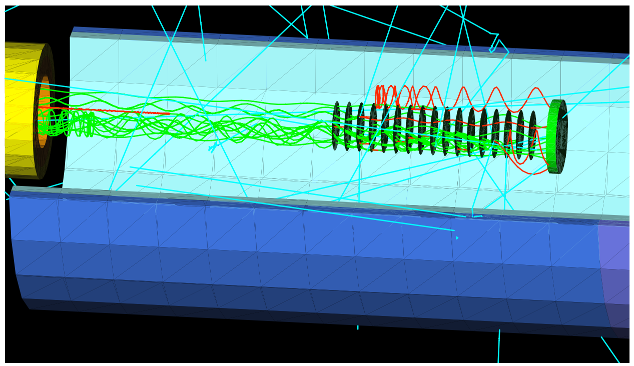
- Muon stopping efficiency = 66%
- Muon rate = 1.5 x 10^{11} /sec
- Did-not-stop muon rate = 5 x 10^{10} /sec
  - Would produce 9-GHz of tracker hits by beam muons.
  - Would produce GHz of DIO electrons from muons stopped in DIO blocker.



- Beam Blocker
  - 30 cmΦ tungsten blocker
  - prompt tracker rate < 150 kHz
  - delayed tacker rate < 700 kHz
  - net acceptance loss is only 25%.



green: all electrons, red: p_T>50 MeV/c

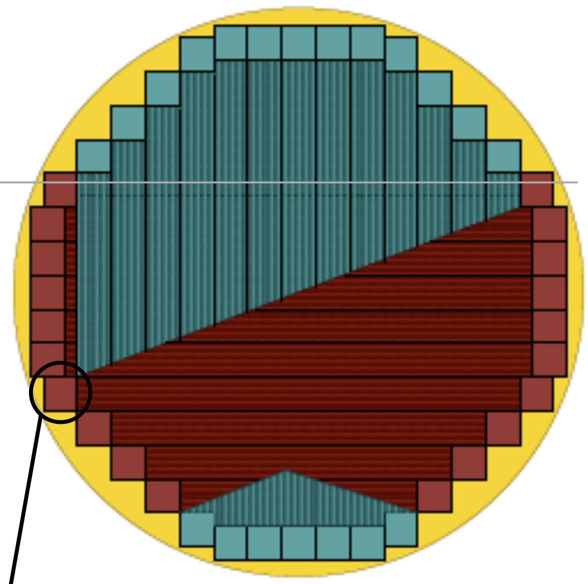


Detector Rate

	Tracker (kHz/plane)	Calorimeter (kHz/plane)	Energy (MeV)
Prompt			
Beam Flash Muons	< 150	< 150	15-35
Delayed			
DIO Electrons from target	10	10	50-60
DIO Electrons from DIO blocker	< 300	< 300	< 50
Back-scattering Electrons	200	200	< 40
Muon Decay in Calorimeter	---	< 150	< 55
Protons from target	---	---	---
Neutrons from target	---	10	~1
Photons from DIO-electron	150	9000	<E> = 1
Total	<800	$<10^4$	

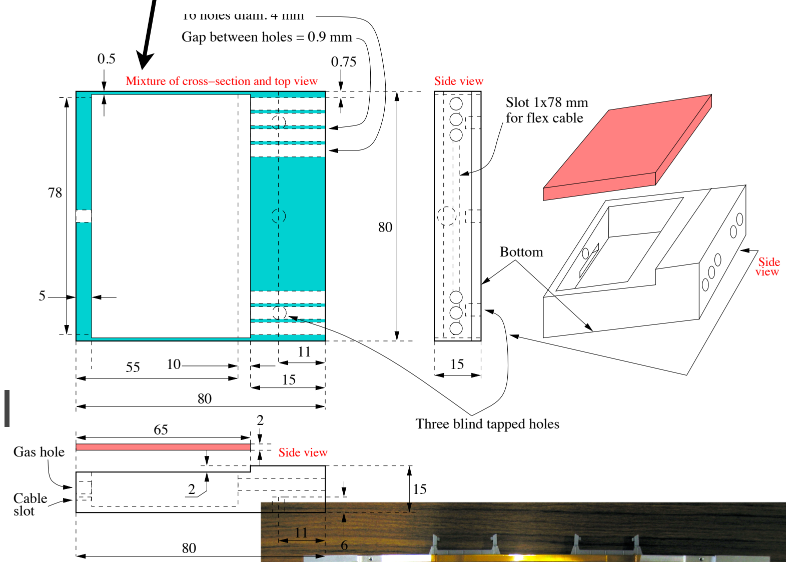
- Two orders of magnitude less rate than that of MECO-type.
- **No proton backgrounds**
  - better track reconstruction
- **Detector is alive even during prompt timing**
  - be capable to study the nature of the prompt backgrounds from real data.
    -> reliable background estimation.

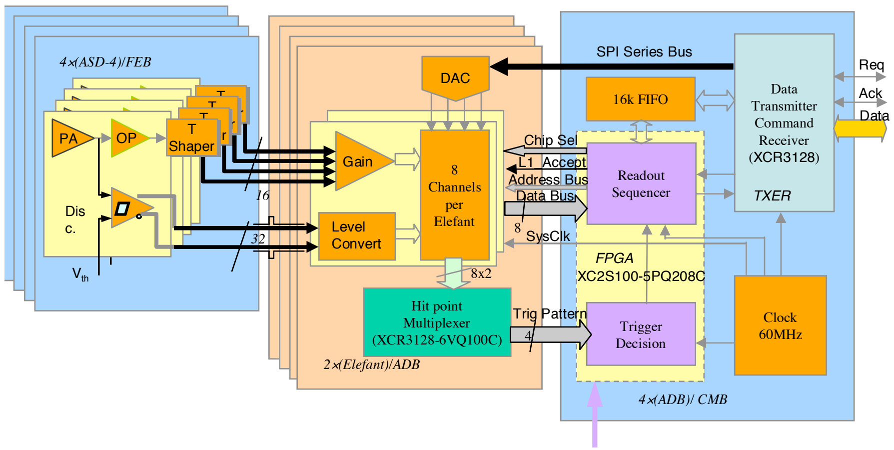
Tracking Detector

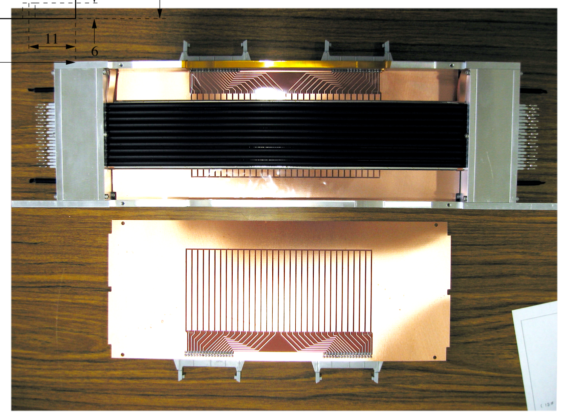


- Main detector to measure Ee
- Thickness should be about 0.01 radiation-length to suppress γ backgrounds.
- Spatial resolution < 0.5 mm
- Hit multiplicity ~ 1 per plane per event

- Straw tube tracker
  - 5mmΦ, 208 tubes per sub-layer
  - four layers per station
    - anode readout (X, X', Y, Y')
  - five stations, 48 cm apart
- Amps and Digitizers are in vacuum
- Optical-link to the outside of the vacuum vessel



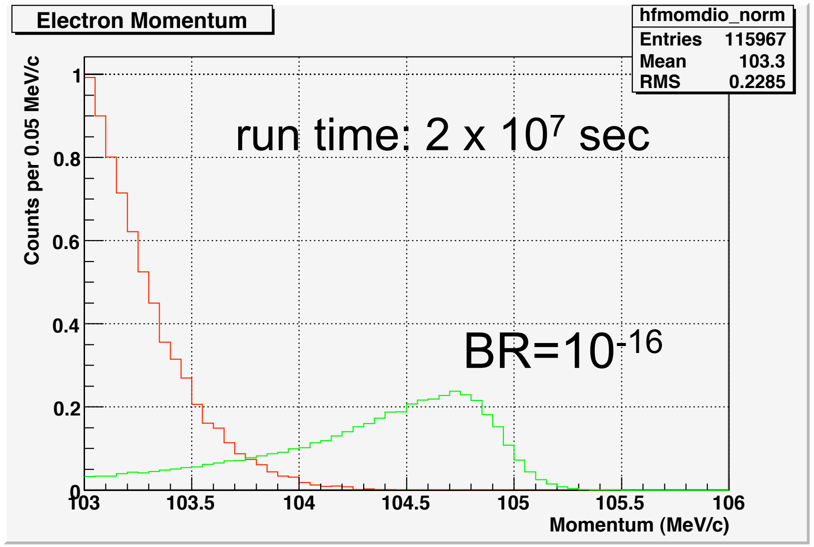


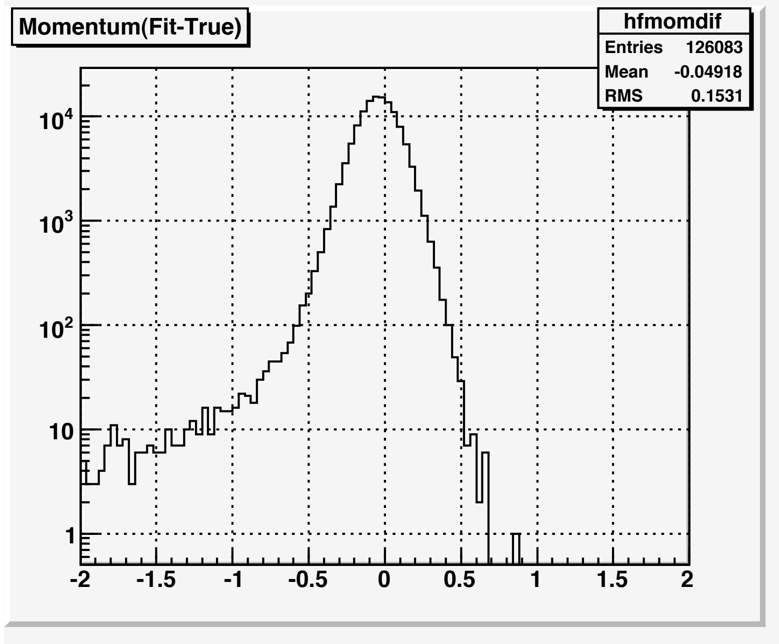


Track Fitting Simulation

- 5 x-y Tracking Stations
  - 1-T uniform B
  - 480 mm spacing
  - Polyimide:160μm[t] per plane
- Multiple Scattering by Break Point Method
- Require single hit for each plane

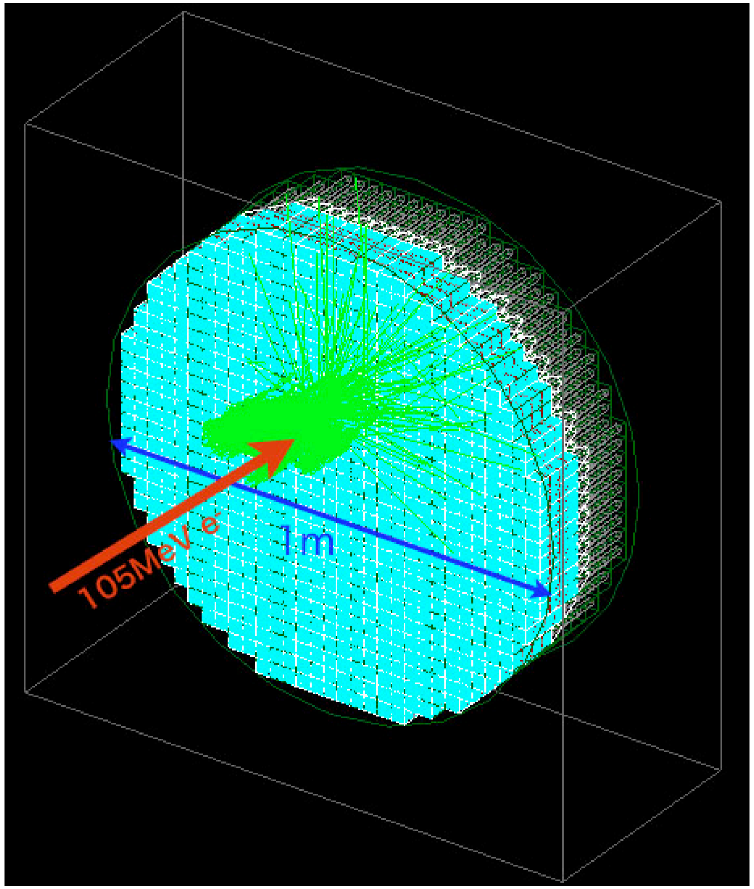
- σ[tracking] = 150 keV/c
- rms[total] = 770 keV/c
- modest spatial resolution of tracker < 500 μm
- Resolution function distribution is narrow enough: 1 MeV/c < 10^{-5}
- The effect of multiple tracks
  - Since the tracker rate is small, the multiple tracks can be just trashed with very small efficiency loss.





Trigger Calorimeter

- Trigger Source
  - Timing for Tracker
- Energy measurement
  - Better trigger condition
  - Redundancy to Ee measurement
  - E/p cut to cosmic muons
- Position measurement
  - Improve track recognition.



- f = 92 kHz per crystal

Energy resolutions obtained from this study for PDE=0.25 and 0.75.

		PDE = 0.25	PDE = 0.75
Crystal	Length (mm)	σ_{E_e} (MeV)	σ_{E_e} (MeV)
GSO(Ce)	120	4.8	4.4
LYSO	120	2.6	2.5
PWO	100	22.2	13.4

- Choice of Photon Detector
  - APD
  - MPPC
- R&Ds with LYSO and MPPS is underway.

Signal Sensitivity

Table 11.3: Summary of the expected sensitivity for 2.0×10^7 sec running.

Total number of protons: N_p	**8.5×10^{20}**	
Proton kinetic energy	8	[GeV]
Harmonics of MR	8	
Bunch time spacing	657	[nsec]
Number of RF bunches filled with protons per spill	4	
Time between adjacent filled bunches	1314	[nsec]
Number of protons in each RF bunch	1.6×10^{13}	
Cycle time of MR (=spill period)	1.47	[sec]
Flat top for the slow extraction	0.7	[sec]
Number slow-extracted pulse in a spill	5.3×10^5	[pulses/spill]
Number of Protons in each slow-extracted pulse	1.2×10^8	
Average beam current	7.0	[μA]
Average beam power	56	[kW]
Average proton intensity	4.4×10^{13}	[protons/sec]
Total running time	2.0×10^7	[sec]
Running time per year	1.0×10^7	[sec/year]
Number of stopped muons per proton: $N_{\mu/p}^{stop}$	**0.0023**	[muons/proton]
Rate of muons per proton transported to the target	0.0035	[muons/proton]
Muon stopped acceptance	0.66	
Number of stopped muons: $N_{\mu/year}^{stop}$	1.0×10^{18}	[muons/year]
Total number of stopped muons: N_{μ}^{stop}	2.0×10^{18}	
Fraction of captured muon: f_{cap}	**0.61**	
Net acceptance: $A_{\mu\text{-}e}$	**0.031**	
Geometrical acceptance, fitting and selection criteria	0.09	
Solid angle with mirroring acceptance	*(0.73)*	
Muon beam stop acceptance	*(0.57)*	
Curved solenoid acceptance	*(0.47)*	
Track reconstruction efficiency	*(0.88)*	
Track quality cut efficiency	*(0.89)*	
Transverse momentum cut efficiency	*(0.83)*	
E/p cut efficiency	*(0.99)*	
Helix pitch cut efficiency	*(0.99)*	
Momentum selection efficiency	*(0.72)*	
Timing window selection efficiency	0.39	
Trigger acceptance and DAQ live efficiency	0.90	
Single event sensitivity = $(N_p \cdot N_{\mu/p}^{stop} \cdot f_{cap} \cdot A_{\mu\text{-}e})^{-1}$	**2.6×10^{-17}**	
90% confidence level upper limit	**6.0×10^{-17}**	
Events per 1×10^{-16} BR	**3.8**	

- The experimental sensitivity has been re-examined.
- There is an ambiguity in production cross-section.

a total proton exposure of 8.5×10^{20}.

a total number of stopped muons per proton 0.0023

single event sensitivity 2.6×10^{-17}

90% C.L. upper limit of 6.0×10^{-17}

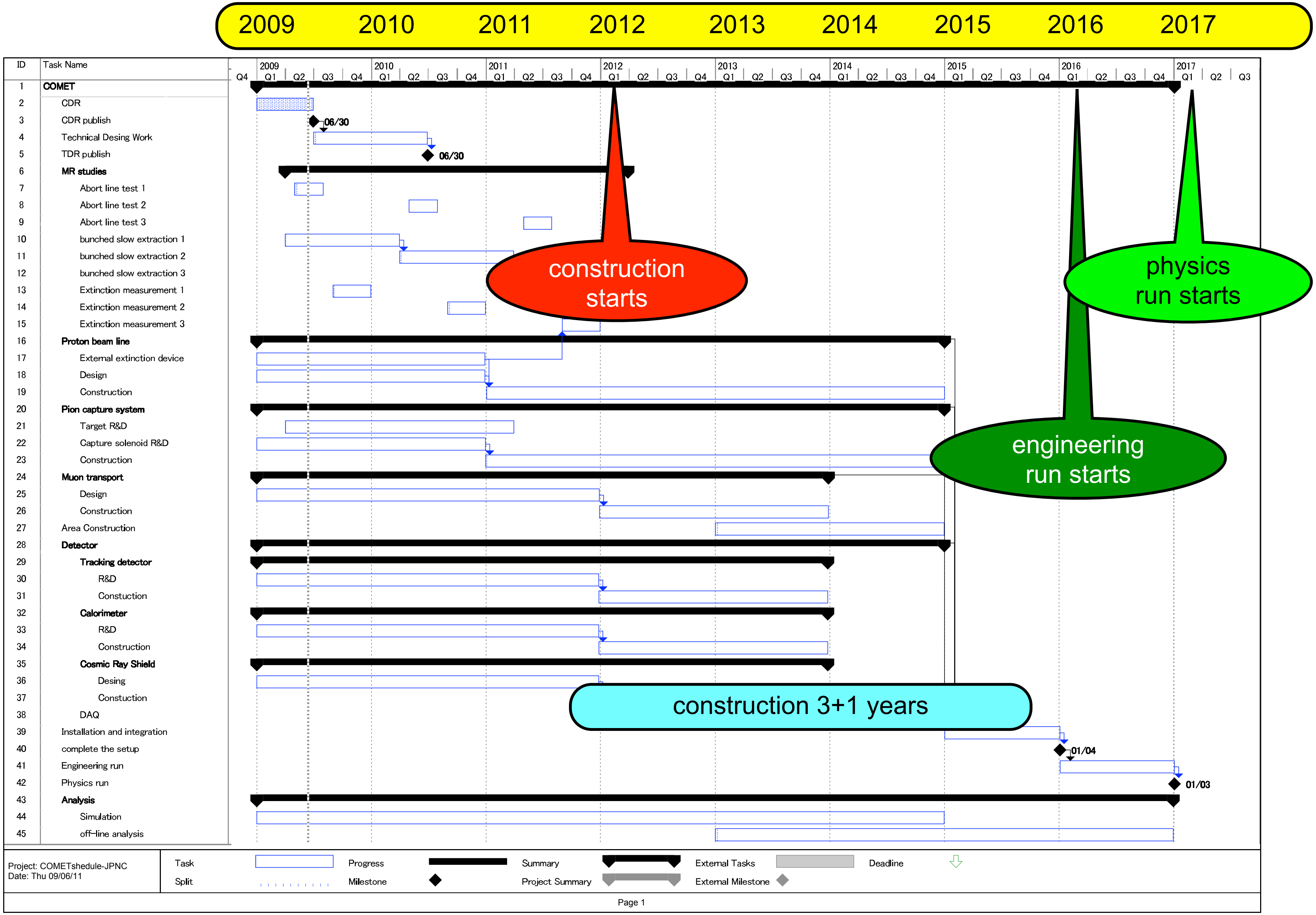
Backgrounds

- The backgrounds has been also re-examined with the new configuration.
- Generation of $>10^{18\text{-}20}$ events in MC is practically impossible. Therefore, during the design stage, backgrounds were estimated by taking a product of multiple (hopefully independent) parameters.
- In the off-line analysis, study with real data is necessary.

Beam Related Prompt Backgrounds	
Radiative Pion Capture	0.05
Beam Electrons	< 0.1
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Beam Related Delayed Backgrounds	
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Physics Backgrounds	
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ- Capt. w/ n Emission	< 0.001
μ- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Backgrounds	
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

Expected background events are about 0.34.

Wishful Timeline



Critical Paths for Feasibility R&D studies

Proton beam extinction

Proton beam extinction with external extinction devices should be measured.

It is requested that AC dipole magnets may be constructed in 2011 and proton beam extinction with them should be tested in the proton "B" line in year 2012.

SC magnet design

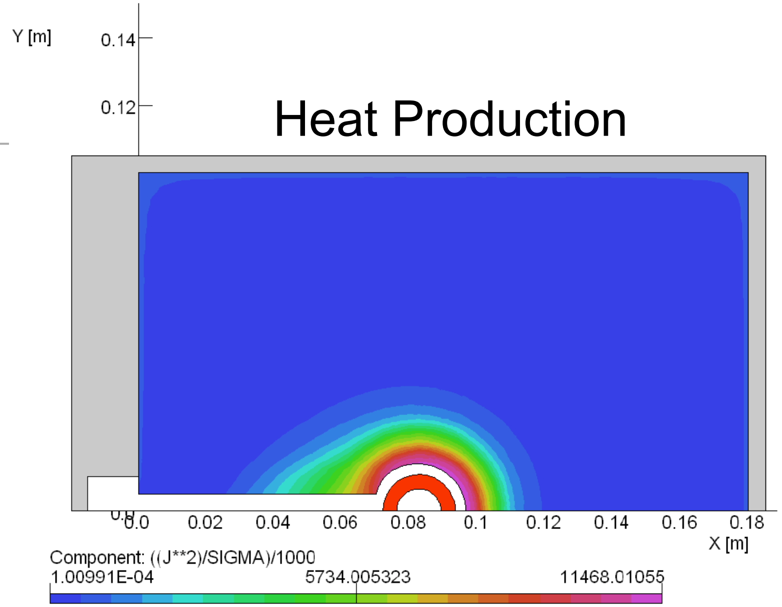
The designs of the SC solenoid magnets should be finalized soon with help from industries in 2009 and 2010. The issue is those in radiation-environment, in particular for the pion capture solenoid.

Production of aluminum-stabilized superconductors should be made one year before the construction of the pion capture solenoids in 2011.

AC dipole Design and R&D

parameter	this AC dipole	typical AC dipole
ε	5π mm.mrad	
β_y	50 m	
Effective Length (L)	2 m	
Full width	5 cm	
Gap	1 cm	
Peak B field	600 Gauss	BL ~ 300 Gauss.m
Peak stored energy	1.43 J	
Frequency	300-400 kHz	20 - 70 kHz
Duty	50-100%	< 1%

- Ferrite hysteresis Loss
  - MnZn (low loss, low resistivity)
- Thermal cooling scheme
- Conductor insulation scheme
  - Single brick test in this summer.
- high Q-value resonant power supply
- Completion of the conceptual design by the end of this year.
- Design study of AC dipole magnets has also been started at KEK.



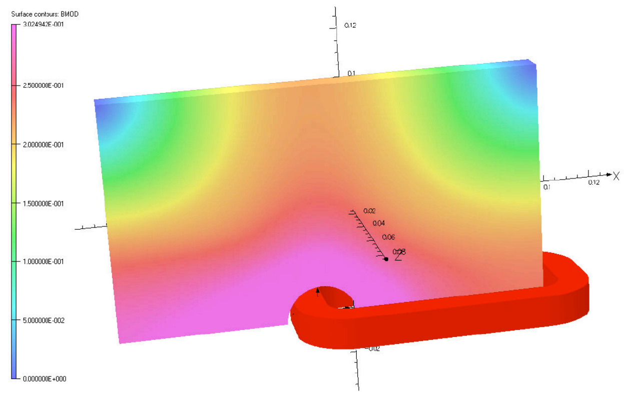
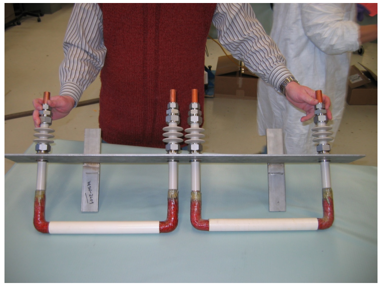
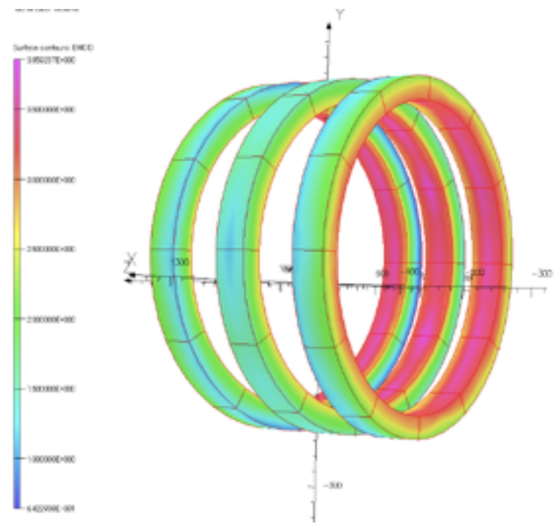


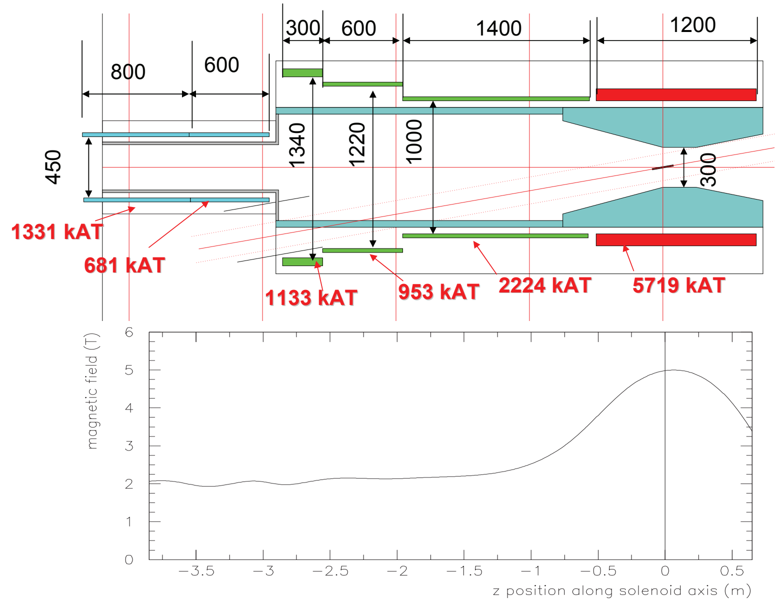
Fig. 1. The flux density in the ferrite plate at peak current 13 A.



SC magnet R&D Plan

- 3 solenoid prototype coils
  - fabricated in year 2008
  - one of the three : MnB2
- Discussion with companies has started on the design of SC solenoids.
- Prototyping of SC solenoids at the MUSIC project at RCNP, Osaka University.
- Discussion on aluminum-stabilized superconductors has started with KEK and under the US-Japan program.





(Wishful) Time Line for R&D for Critical Path

	2009	2010	2011	2012
proton extinction measurement	measurement of proton beam extinction at abort line	design of external extinction devices / measurements at secondary beam	construction of external extinction devices (procurement)	measurement of proton beam extinction with external devices
SC solenoid R&D	optimization of pion capture solenoid / design of SC solenoids with companies	design of SC solenoids with companies / prototyping of SC solenoid (MUSIC)	production of aluminum-stabilized SC (procurement)	construction of SC solenoids

Summary

- The COMET is a new experiment of searching for coherent neutrino-less conversion of muons to electron (μ-e conversion) at a sensitivity of 10^{-16}. This sensitivity is a factor of 10,000 better than the current experimental limit.
- The experiment is planned to carry out in the J-PARC NP Hall by using a bunched proton beam slowly-extracted from the J-PARC main ring.
- A conceptual design report has been submitted to the J-PARC PAC and presentations were given at the PAC meeting last week to get the stage-1 scientific approval. Outcomes will be officially announced by the PAC in a month.
- In the CDR, we introduce a lot of components to improve the COMET performance. The sensitivity and backgrounds have been also reevaluated.
- Many R&Ds and simulation studies are underway: solenoid, extinction measurement and monitor, calorimeter, silicon, and full G4 simulation ...
- The COMET collaboration is rapidly growing and many working groups are being formed. You are welcomed to join the collaboration!