Facilities in Japan

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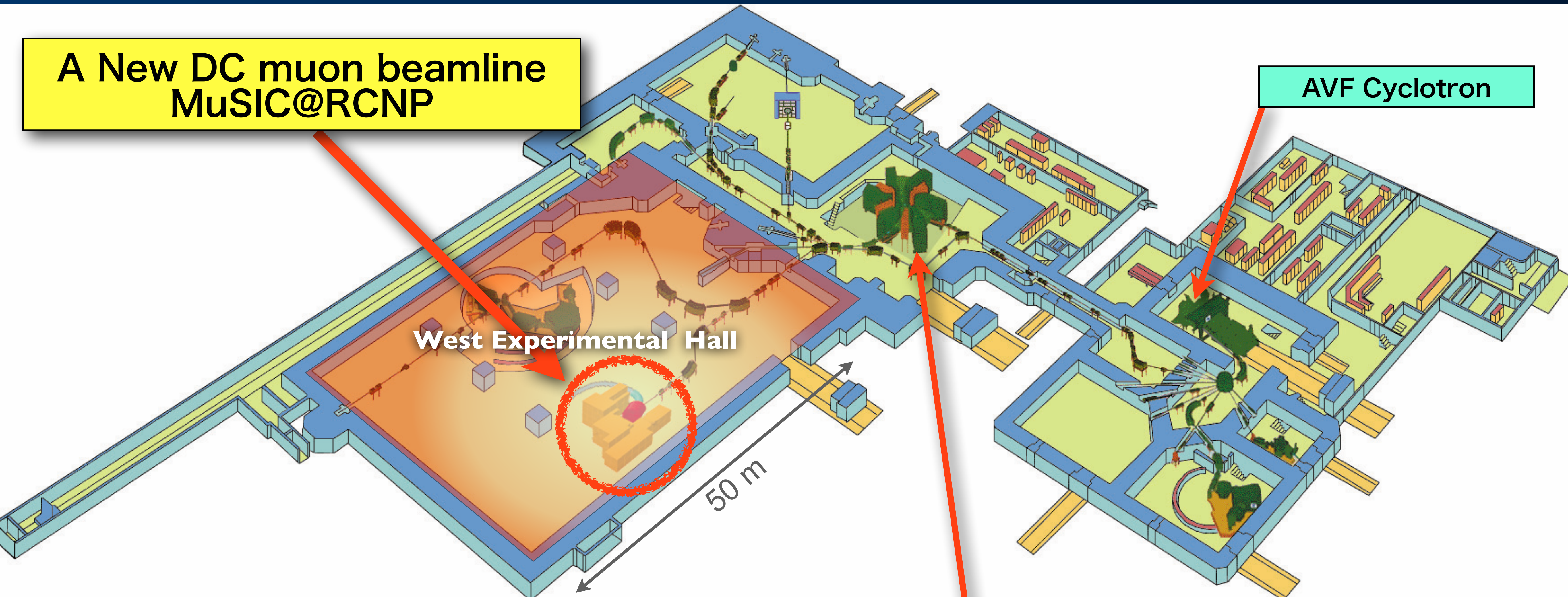
Workshop on Muon Collider Testing Opportunities,
24 March 2021, Zoom

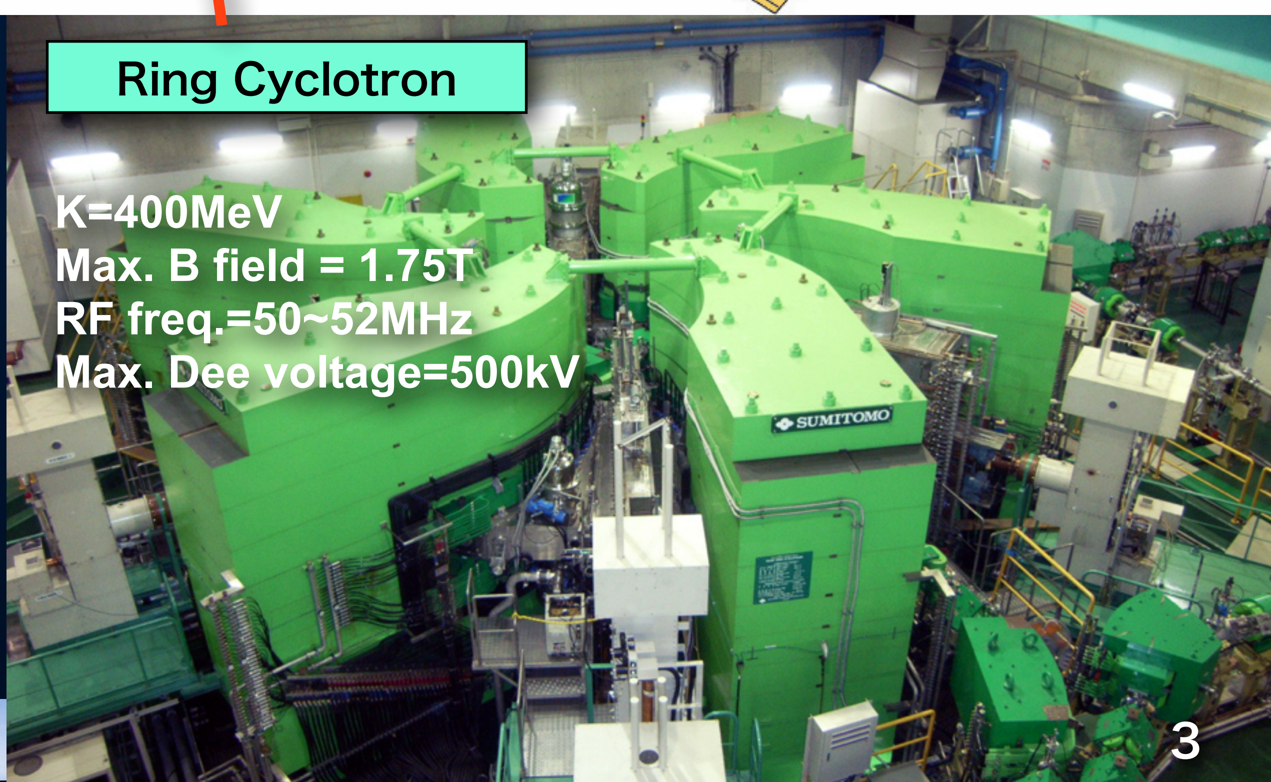
Outline

- Muon activities in Japan
- Proton/Muon facilities
  - RCNP, Osaka (DC muons)
  - J-PARC, COMET (pulsed muons, ~1MHz)
  - J-PARC, MLF, MUSE (pulsed muons, 25Hz)
- FFAs
- Summary

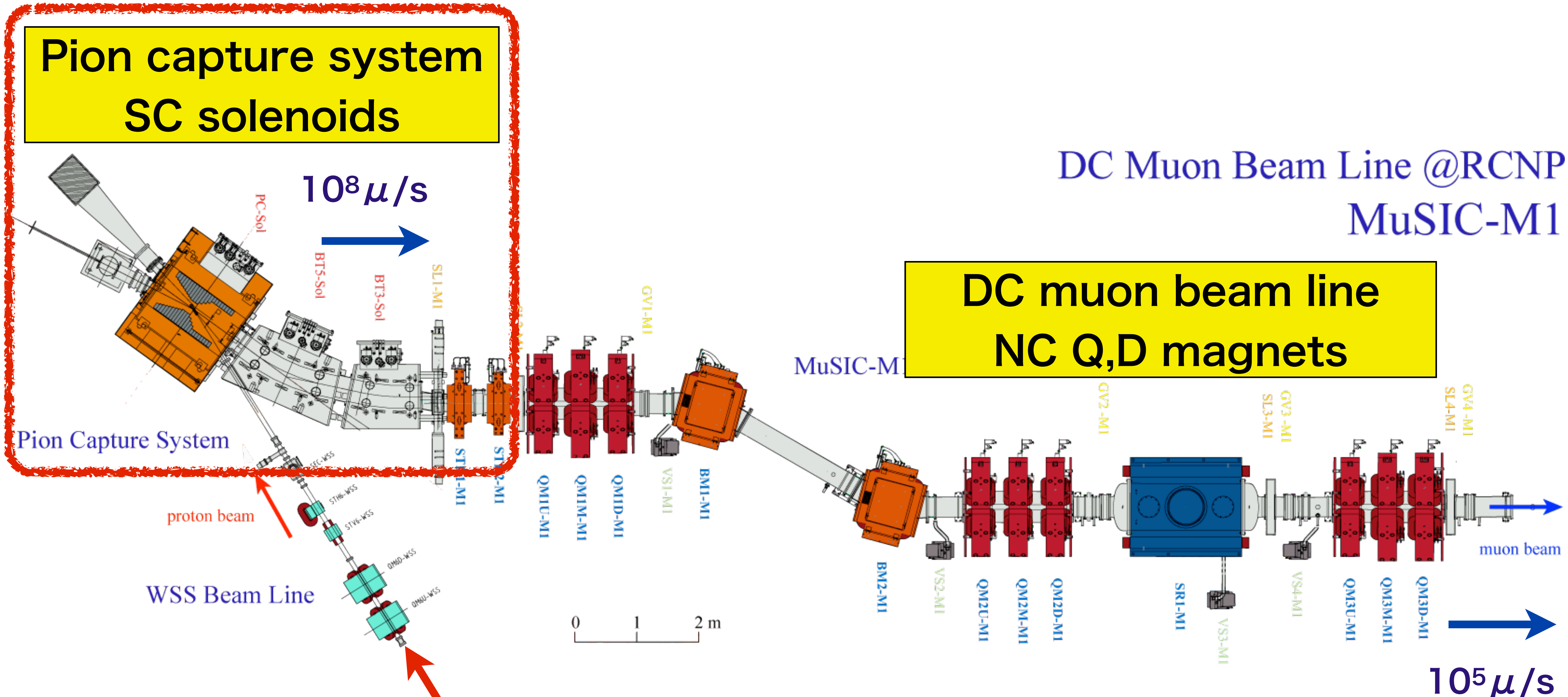
Research Center of Nuclear Physics (RCNP), Osaka University, Japan



- RCNP has two cyclotrons.
  - A proton beam with 392MeV, 1.1μA is provided from the Ring Cyclotron (up to 5μA in near future).
- A new DC muon beam facility, MuSIC, was built in the largest experimental hall, the west experimental hall.

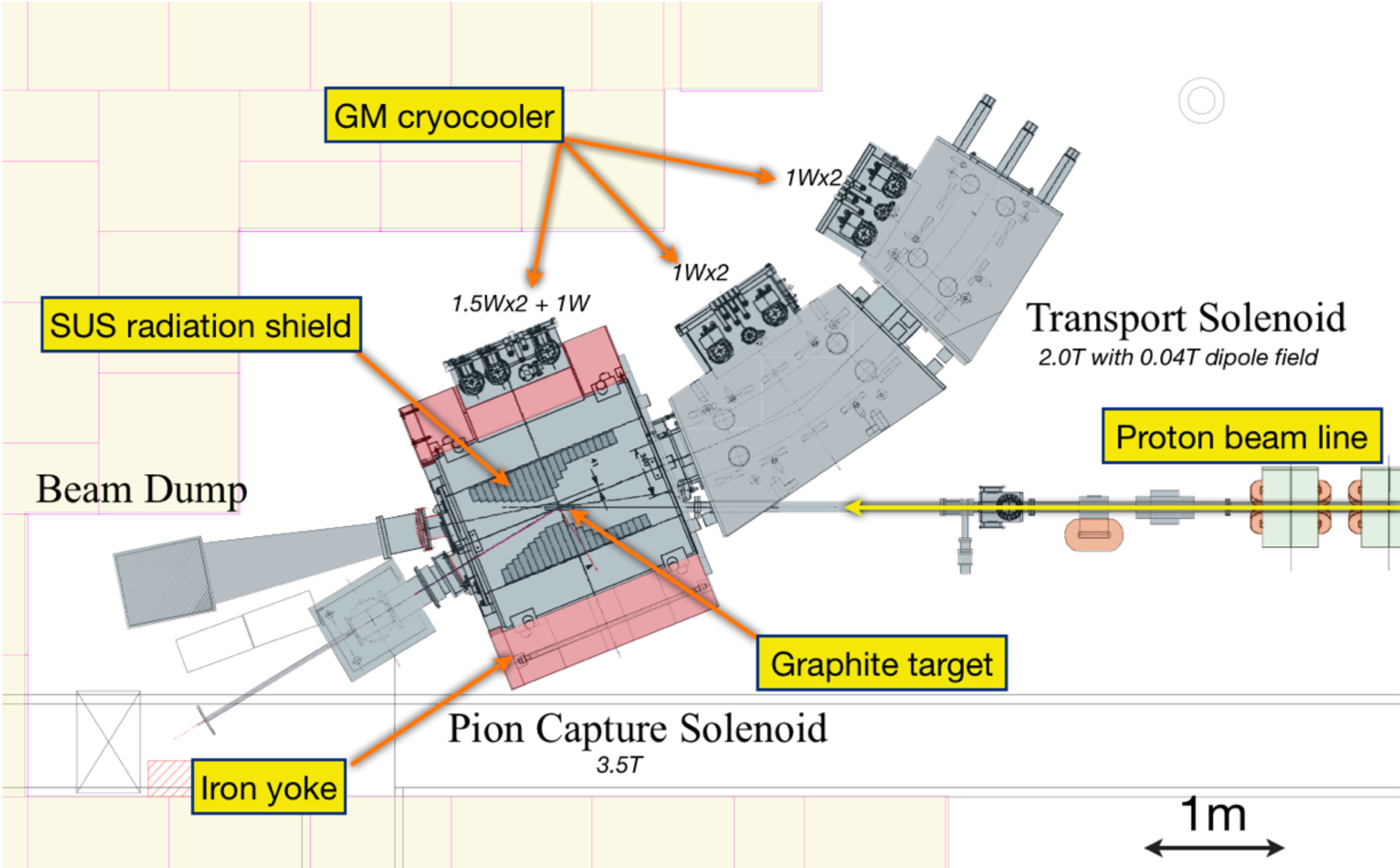


A New DC muon beam line: RCNP-MuSIC

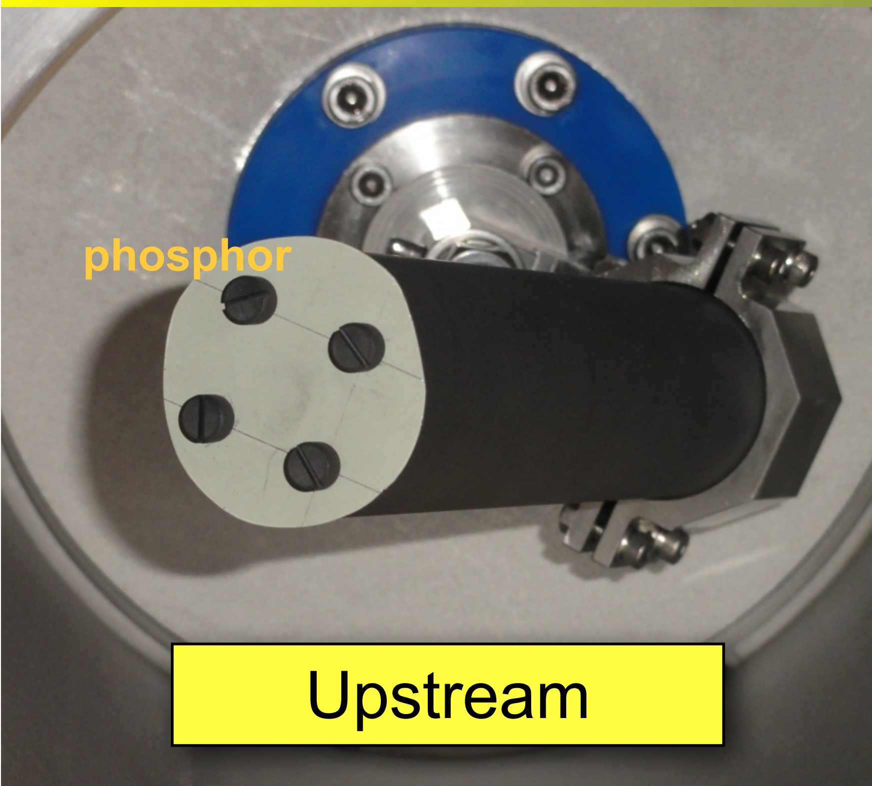


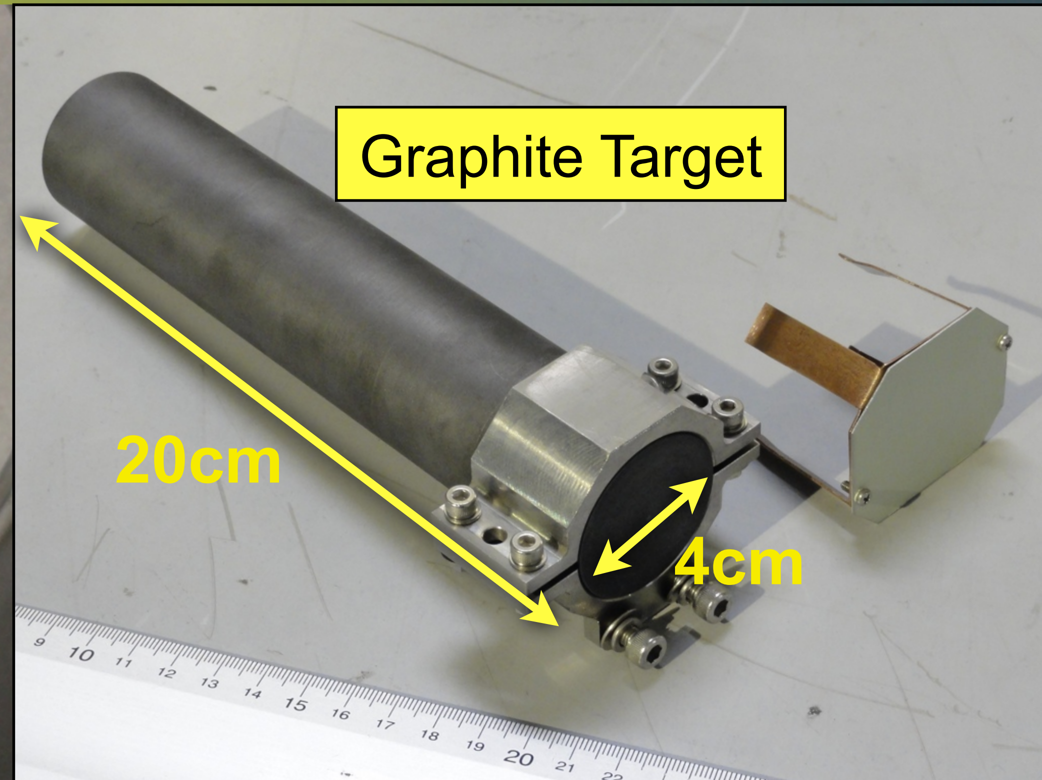
Proton beam 392MeV, 1.1 μA
from the ring cyclotron

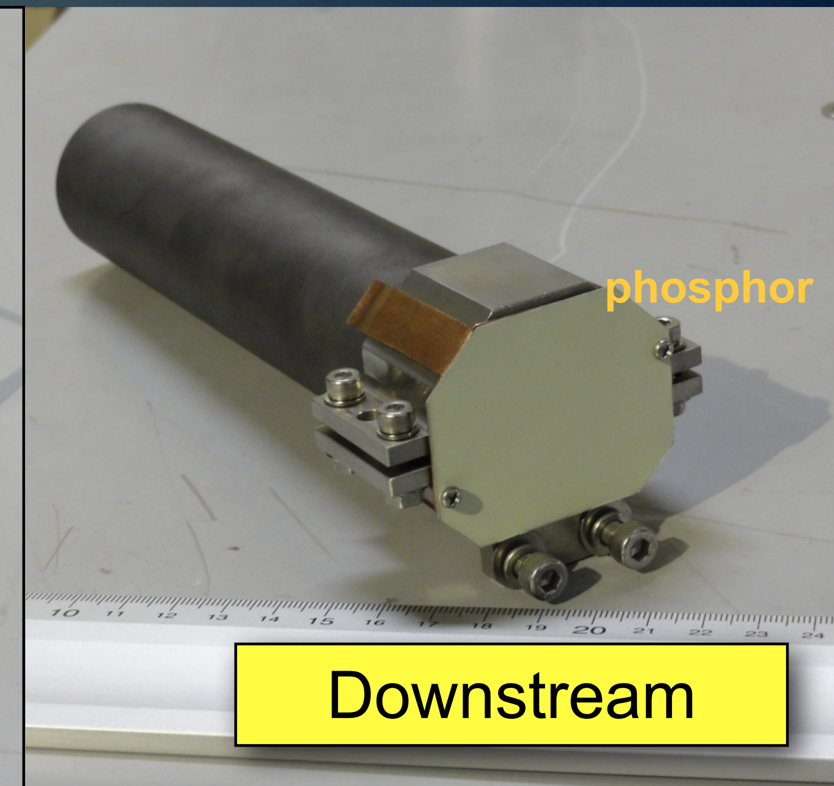
MuSIC: Pion Capture System

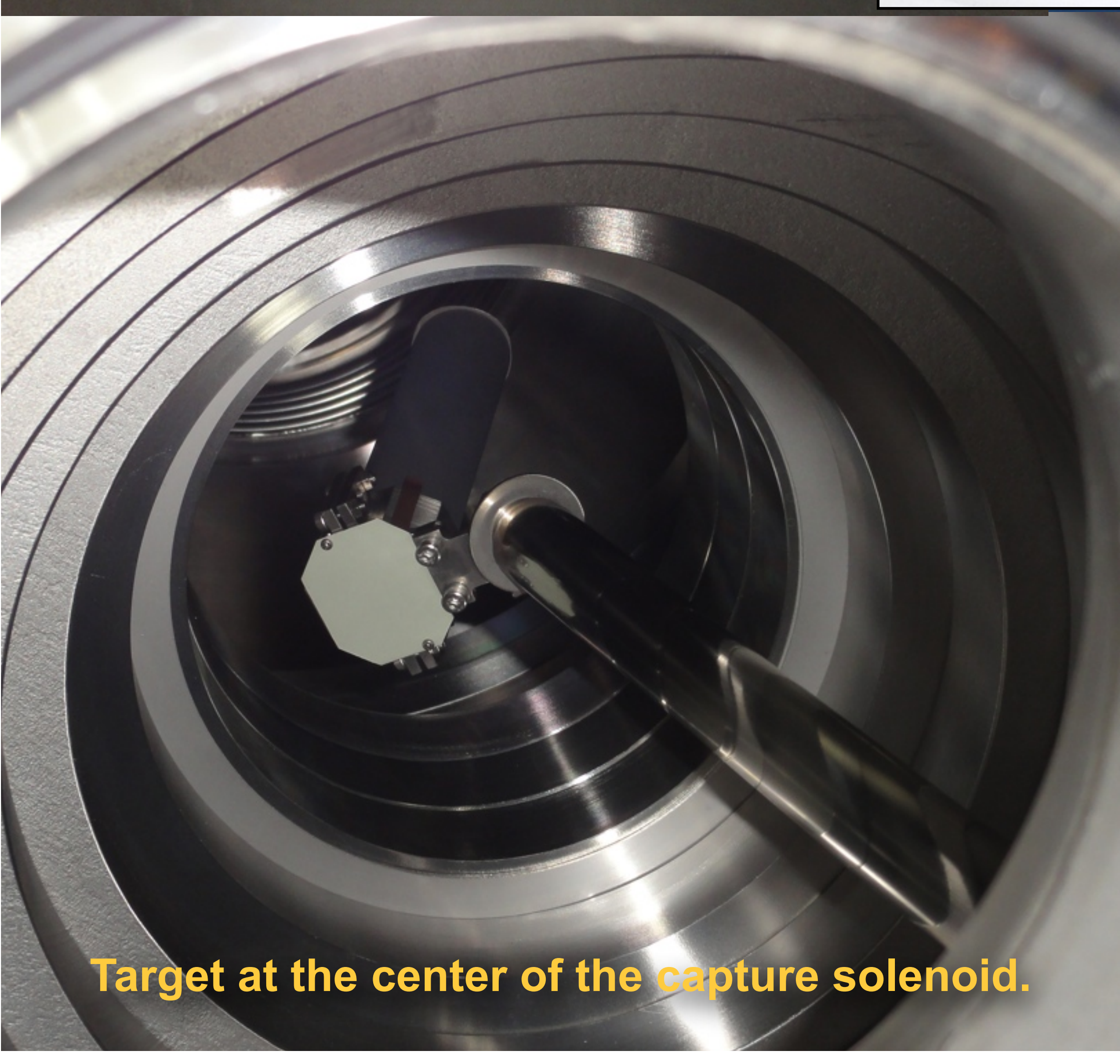


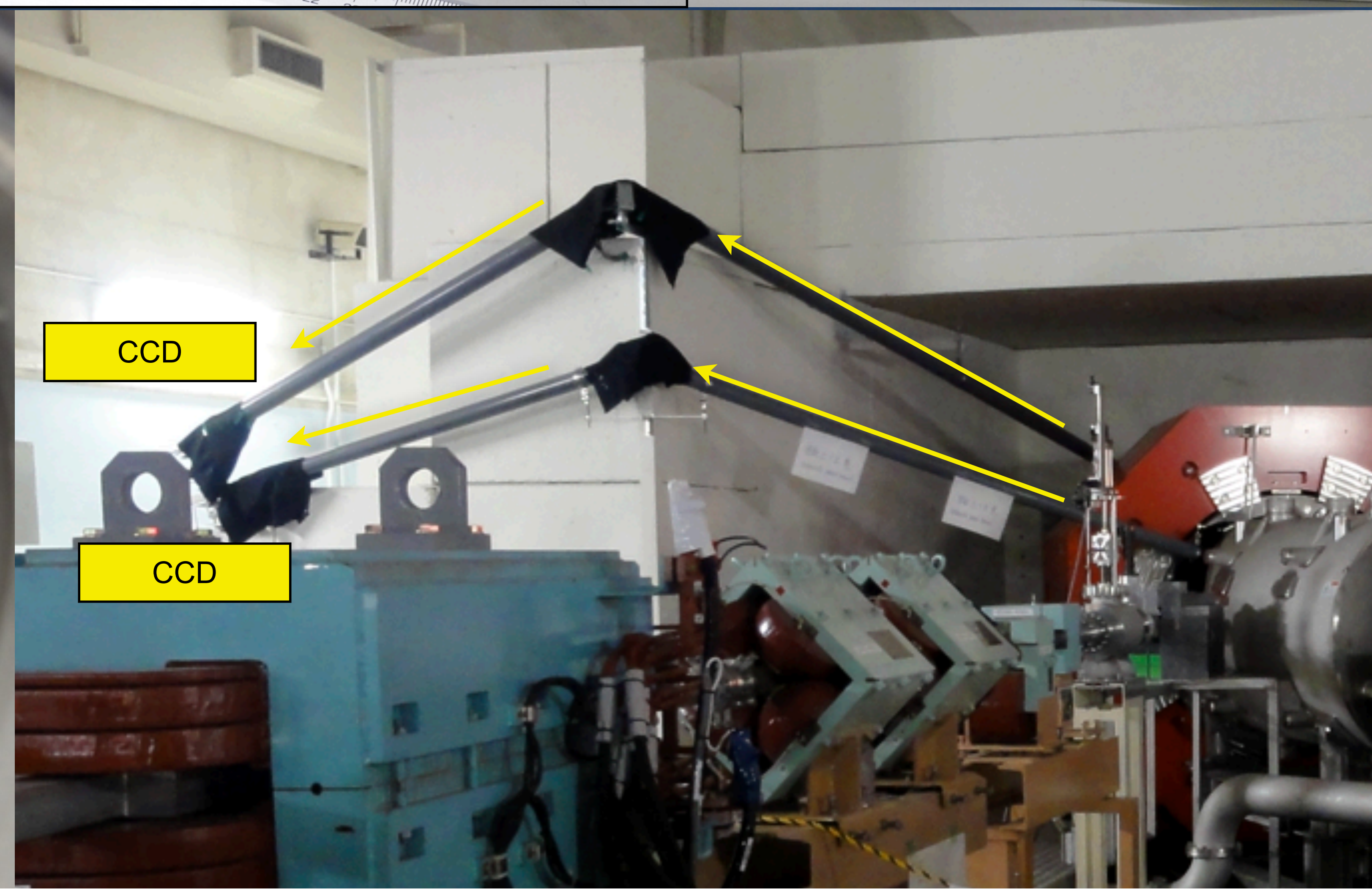
Proton Beam Monitoring on the Target



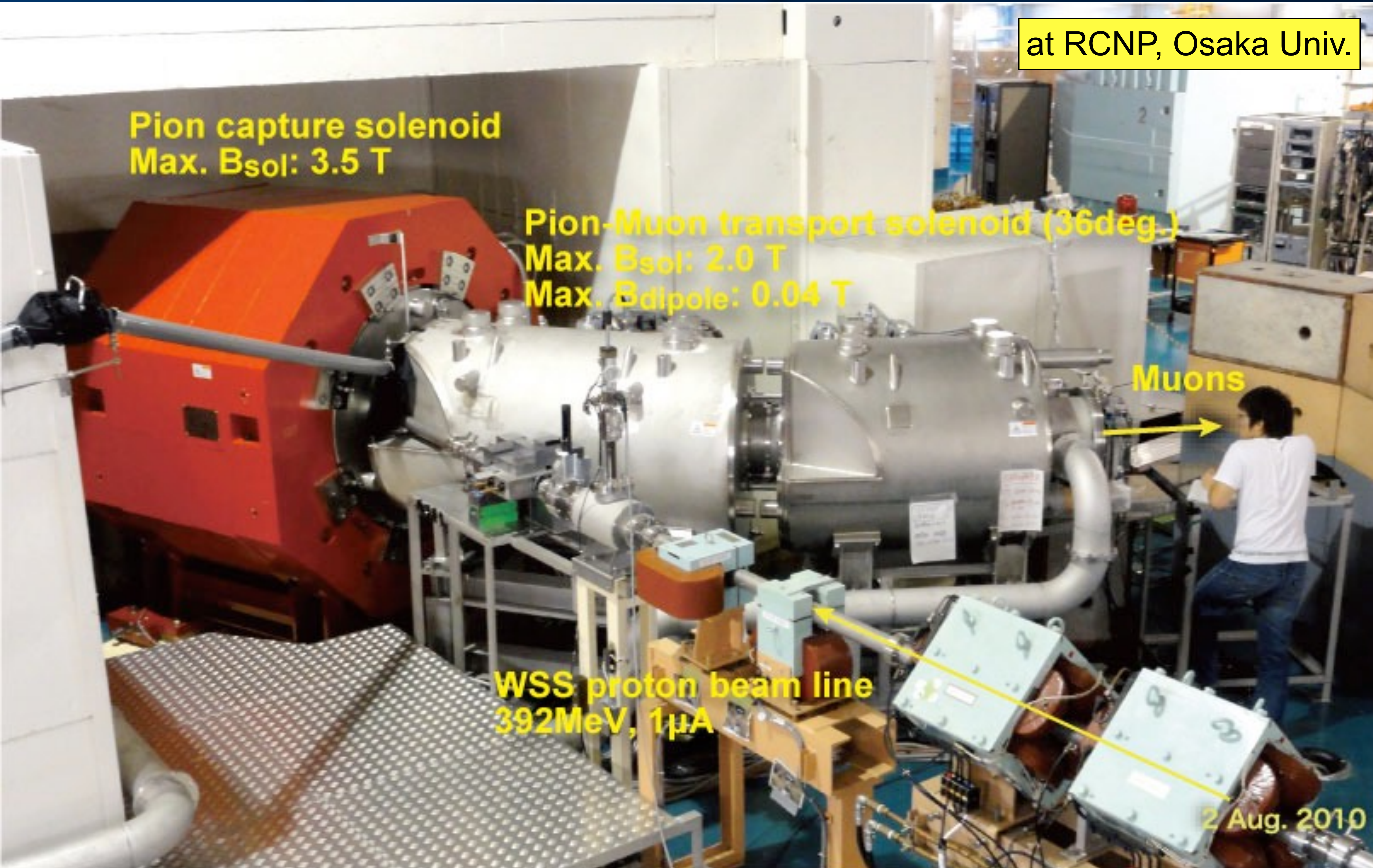








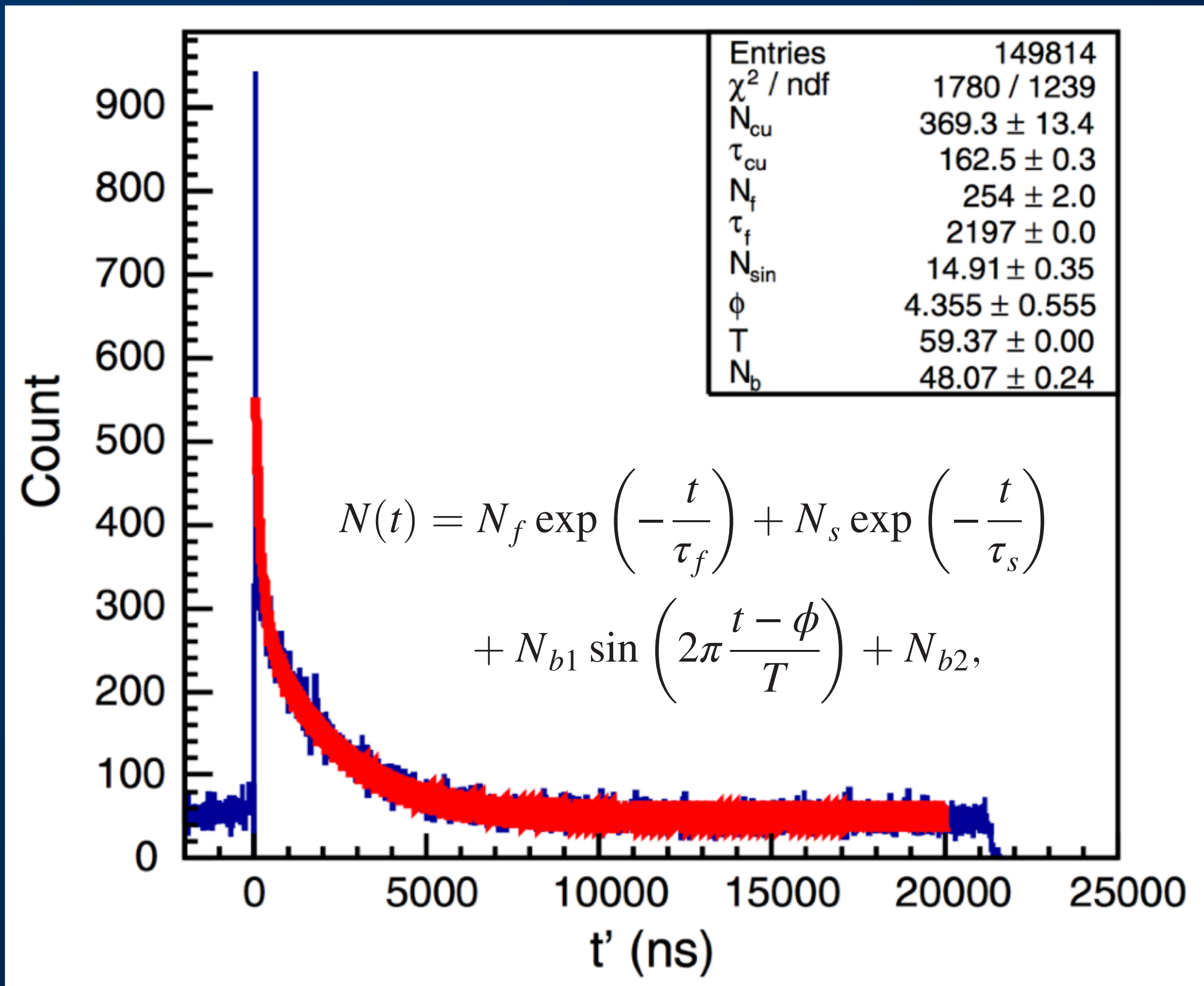
The 1st pion capture system : MuSIC



S. Cook, et. al., Phys. Rev. Acc. and Beam **20**, 030101 (2017)

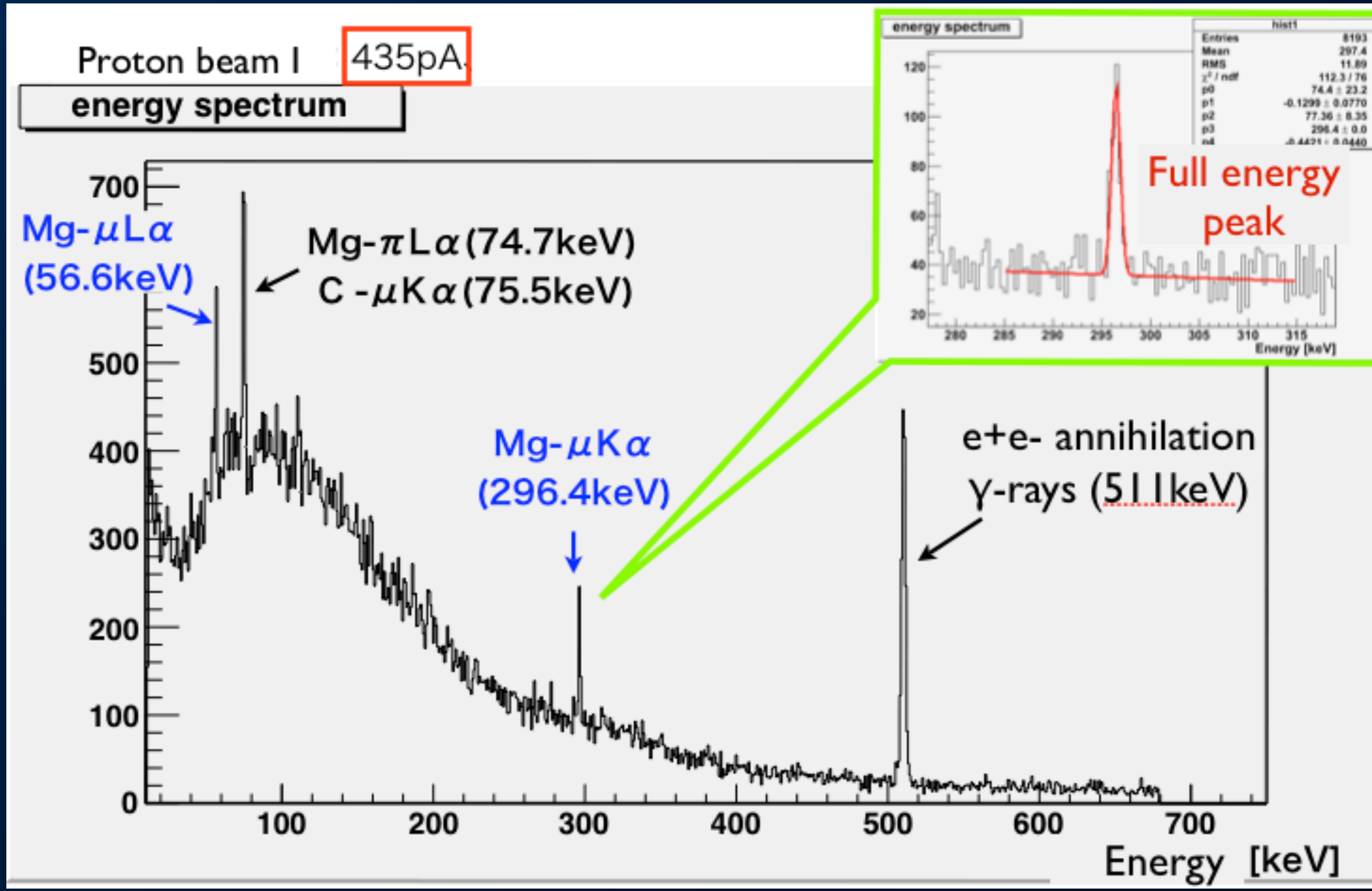
Muon yield @ the solenoid exit

Muon life (Stopping target: Cu)



$$N(t) = N_f \exp\left(-\frac{t}{\tau_f}\right) + N_s \exp\left(-\frac{t}{\tau_s}\right) + N_{b1} \sin\left(2\pi \frac{t-\phi}{T}\right) + N_{b2},$$

Muonic X-rays (Stopping target: Mg)



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

	measurement
positive muon [μ^+/sec for 400W]	(4.2 ± 1.1) x 10^8
negative muon [μ^-/sec for 400W]	(3.6 ± 0.4) x 10^7

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

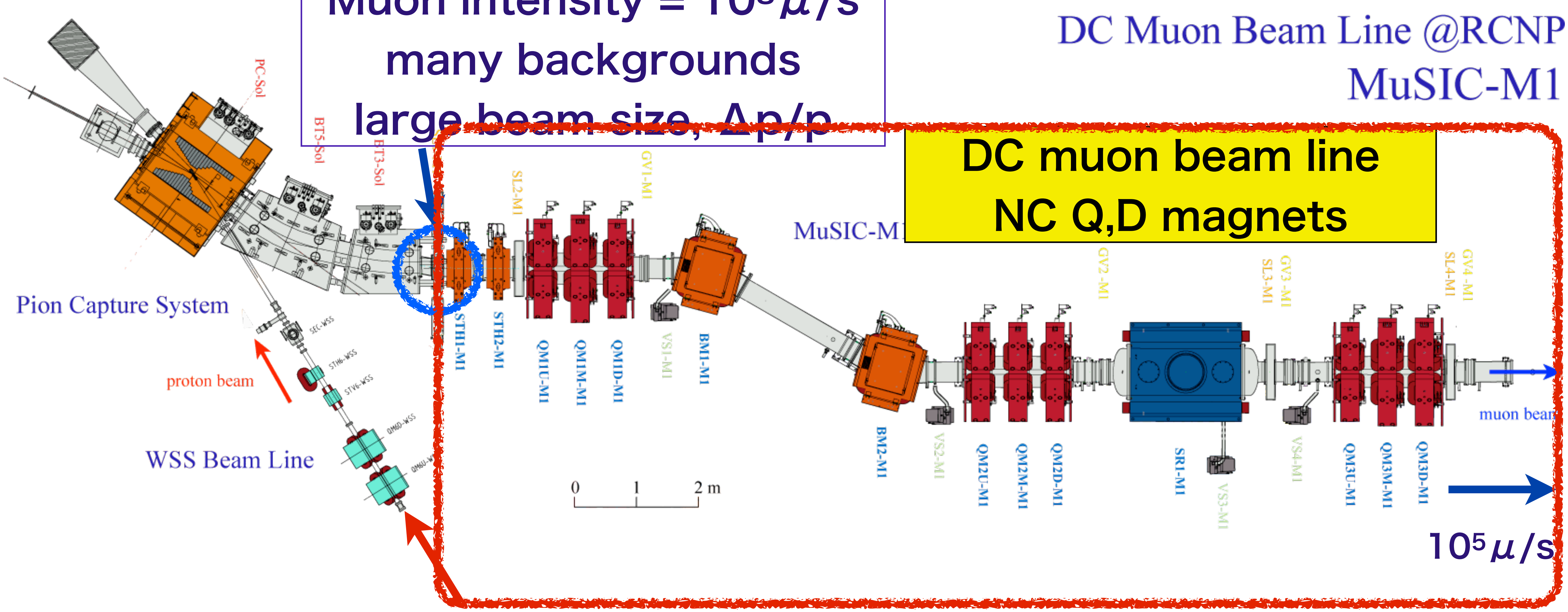
MuSIC Pion Capture followed by ...

- MuSIC successfully demonstrated a muon intensity = $10^8 \mu$/s is available with a 431W proton beam. It correspond to ~ $10^6 \mu^+$/s/W and ~ $10^5 \mu^-$/s/W, over a factor of 1000 higher than other muon facilities.
- For COMET (elementary particle physics)
  - Combination with a 56kW proton beam at J-PARC can make $>10^{11} \mu^-$/s for μ-e conversion experiments. The COMET collaboration is building another pion capture system for COMET at J-PARC hadron hall.

A New DC muon beam line: RCNP-MuSIC

Pion capture system
SC solenoids

Muon intensity = $10^8 \mu/s$
many backgrounds
large beam size, $\Delta p/p$



DC muon beam line
NC Q,D magnets

$10^5 \mu/s$

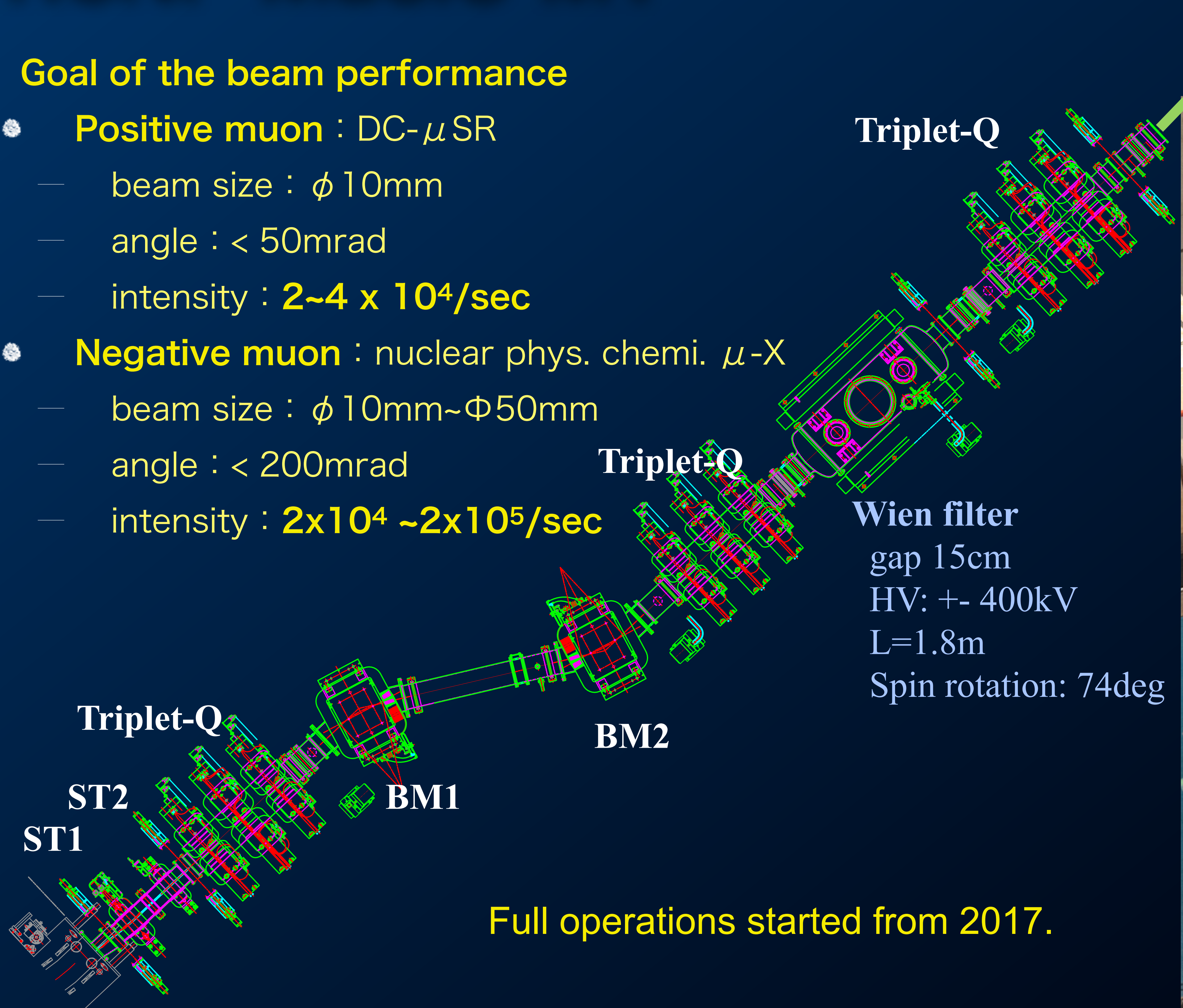
Proton beam 392MeV, $1 \mu A$
from the ring cyclotron

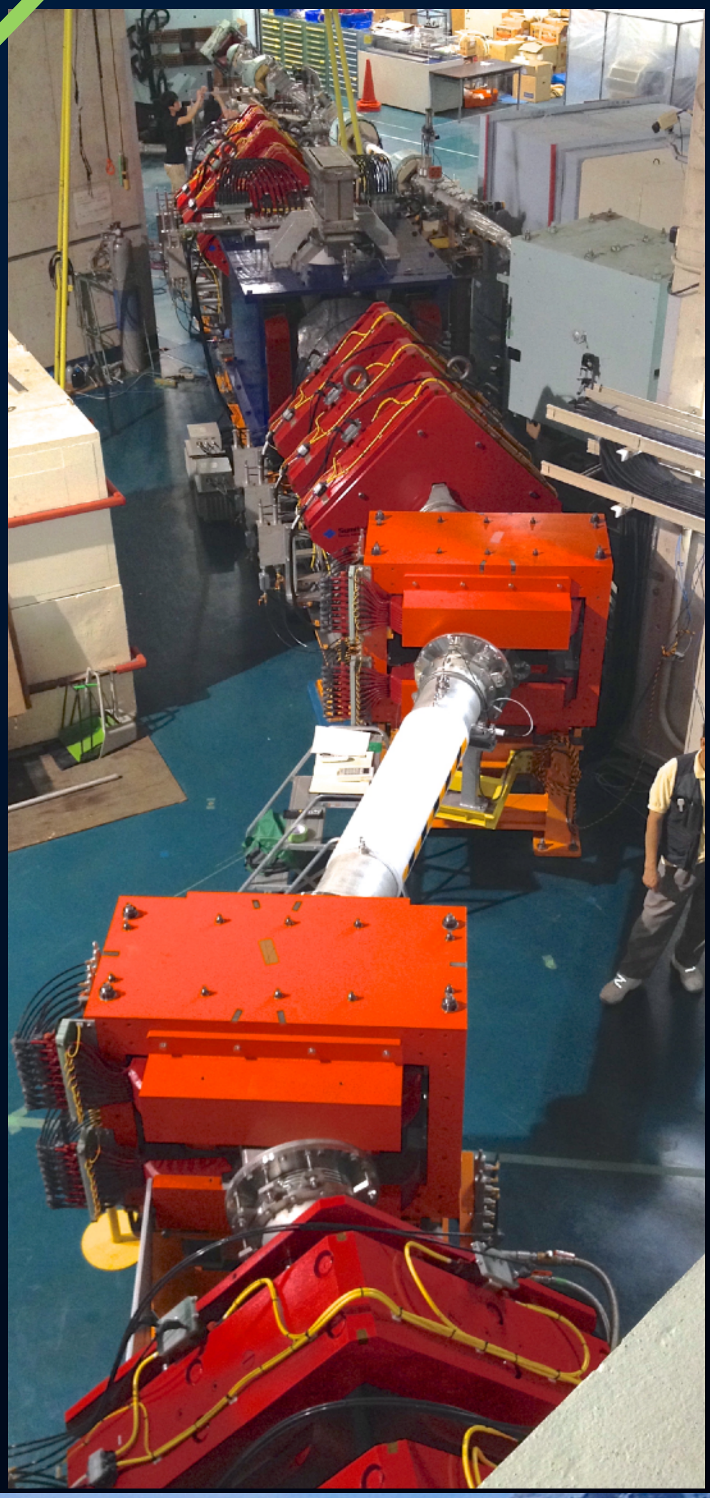
The DC muon beam line in Japan

RCNP-MuSIC-M1 constructed in 2013JFY

Goal of the beam performance

- **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：**$2x10^4$ ~$2x10^5$/sec**





Full operations started from 2017.

Examples of DC Muon Science at MuSIC

- **Particle Physics :**
  - **search for $\mu \to eee$ (muon LFV)** **$10^{8\text{-}9} \mu^+$/sec**
    - DC continuous beam is critical
- **Materials Science :**
  - μSR (a μSR apparatus is needed) **$10^{5\text{-}6} \mu^\pm$ /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**
- **Non-destructive element analysis**
  - archaeology, asteroid explorer (Hayabusa-2) **$10^{4\text{-}5} \mu^-$/sec**
- **Accelerator / Instruments R&D**
  - (for PRISM/neutrino factory/muon collider) :
    - Superconducting solenoid magnets
    - FFAG, RF
    - cooling methods
    - muon acceleration, deceleration, and phase rotation

Stage-2

Needs a long SC solenoid channel.

Stage-1

MuSIC-M1 beamline has been constructed!

16 user experiments have been performed already.

J-PARC at Tokai, Ibaraki

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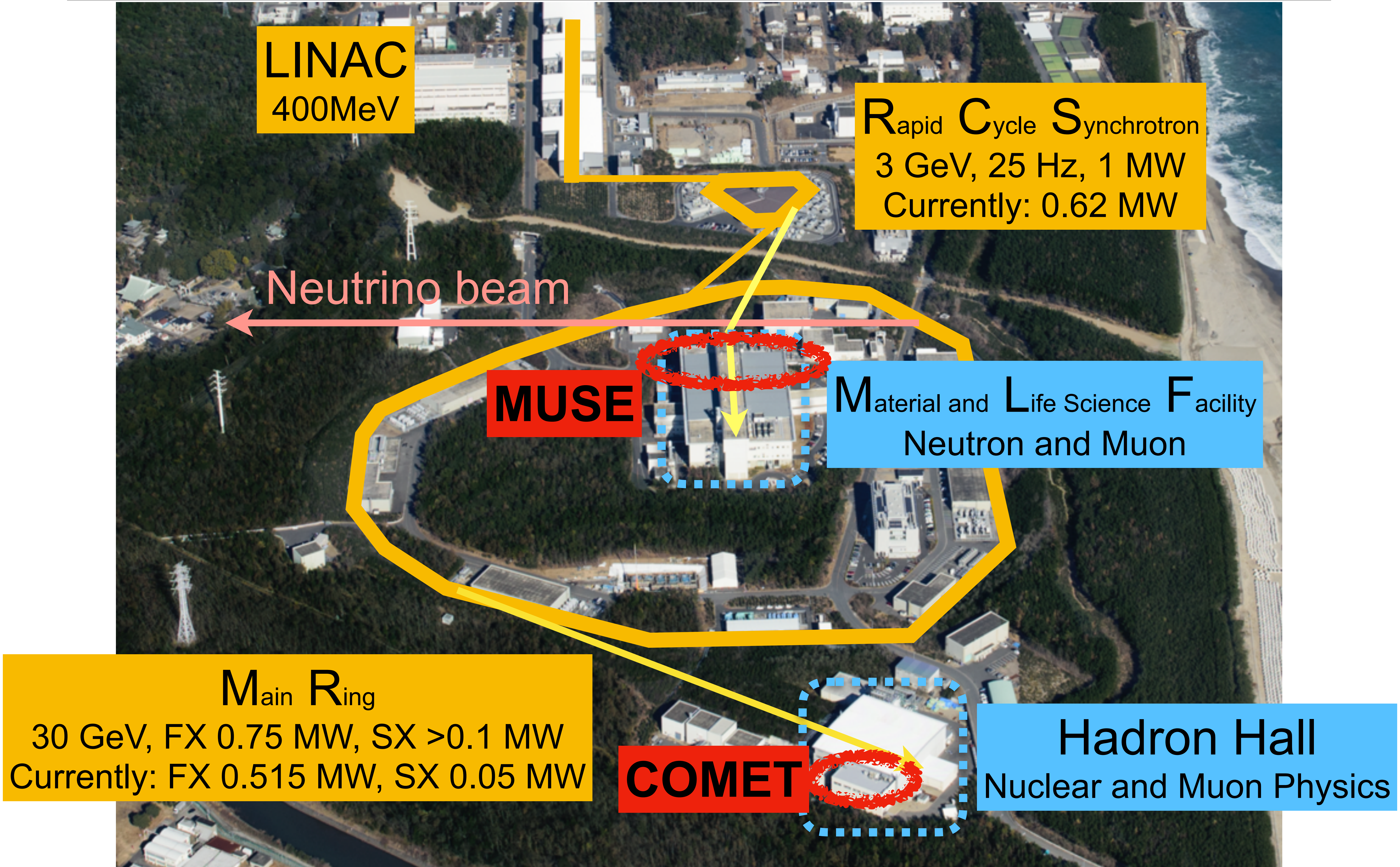

J-PARC: COMET

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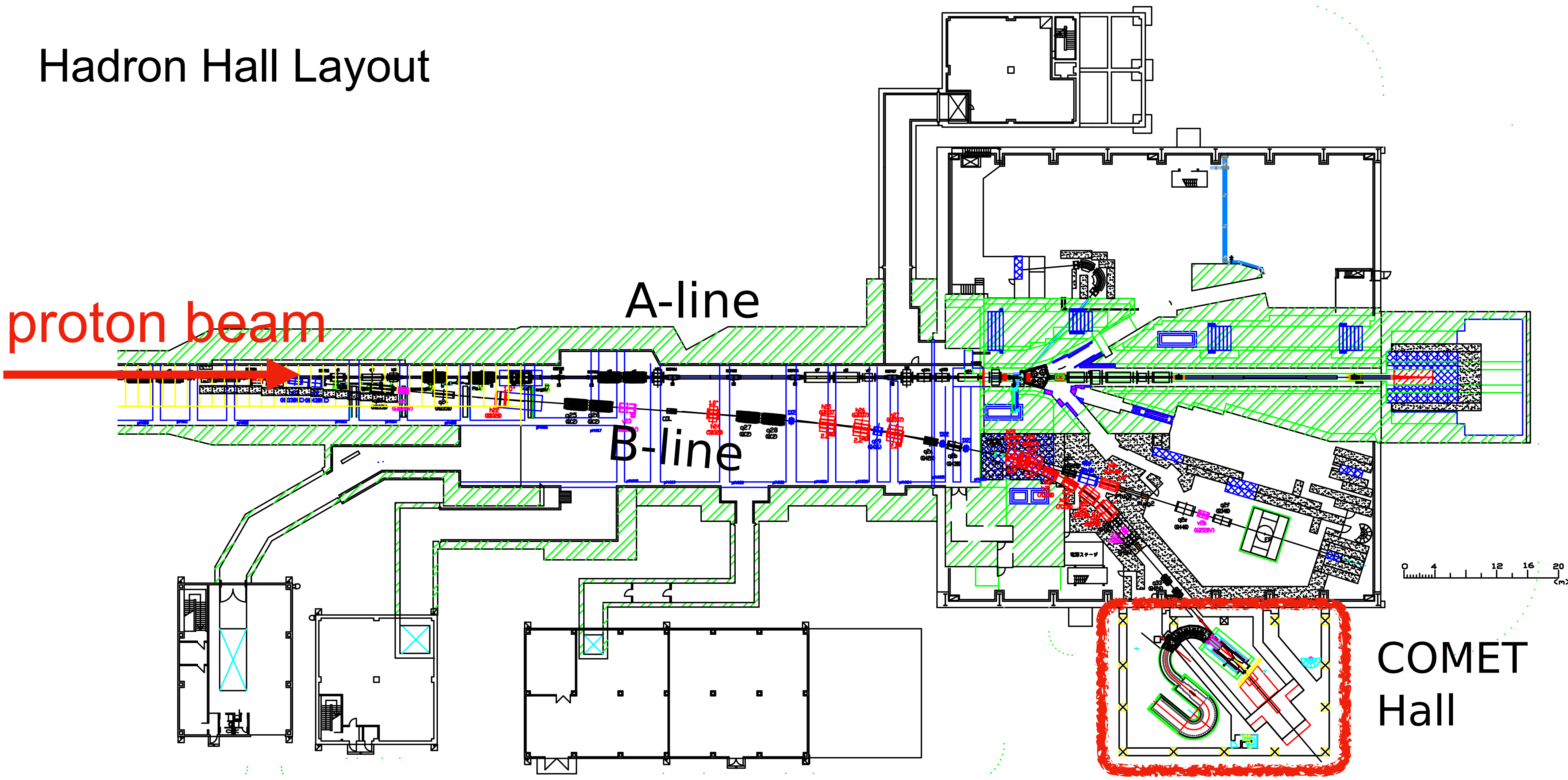
- COMET is an experiment to search for the μ-e conversion.
- Low energy muon beams are generated using a pulsed 8 GeV proton beam.
- We have built a special experimental hall and a beam line for it.

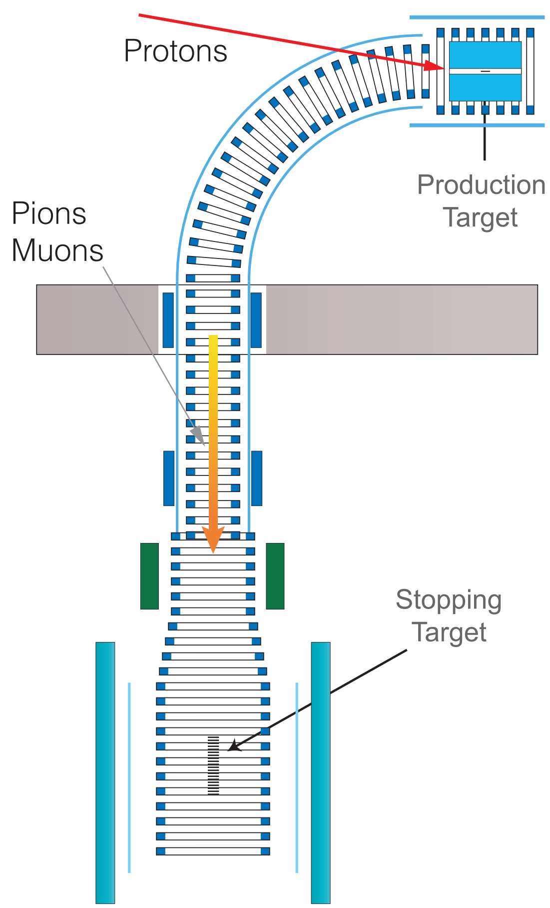


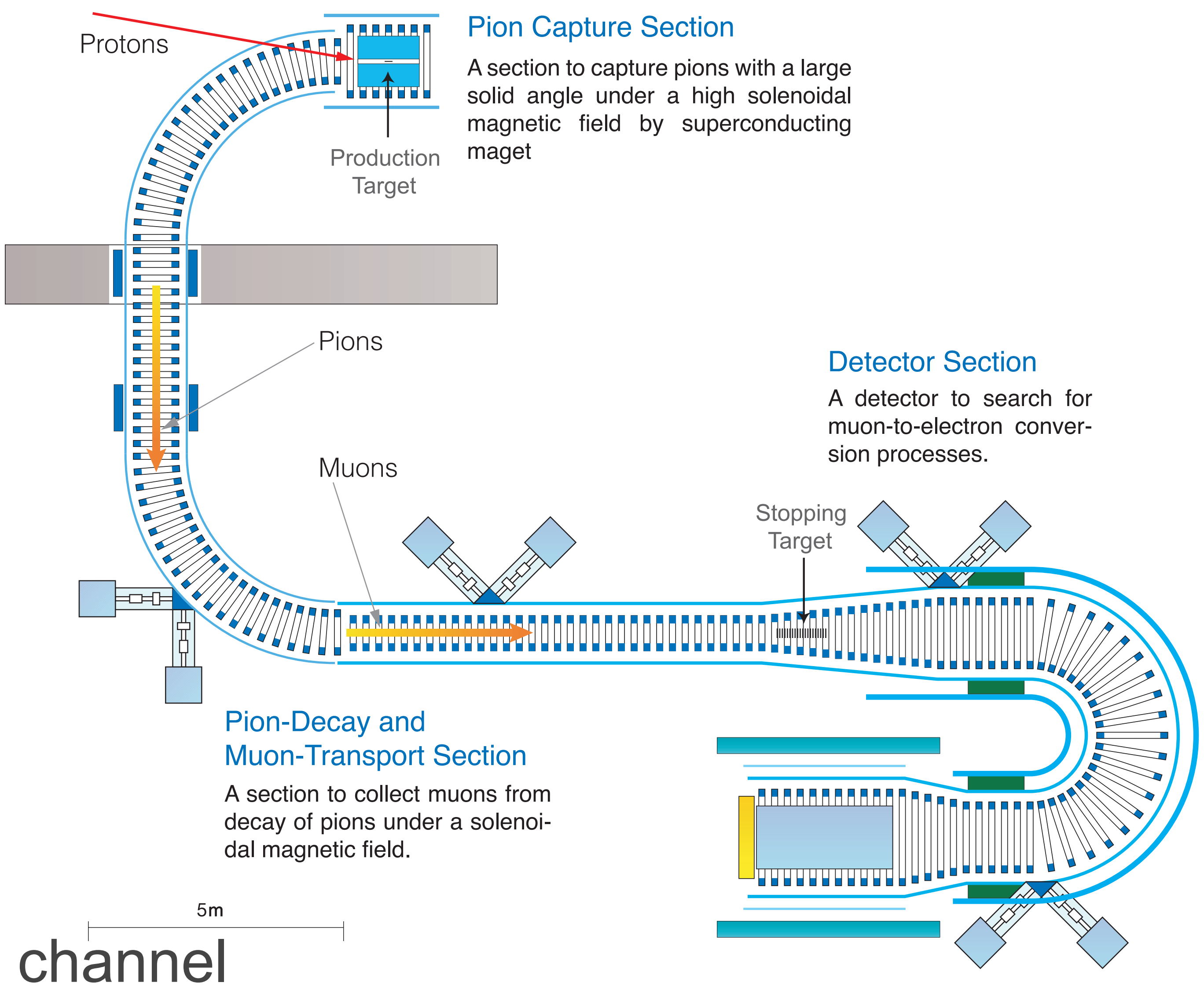
COMET

COMET Phase-I: SES: 3.1 x 10^{-15}

COMET Phase-II: SES: 2.7 x 10^{-17}

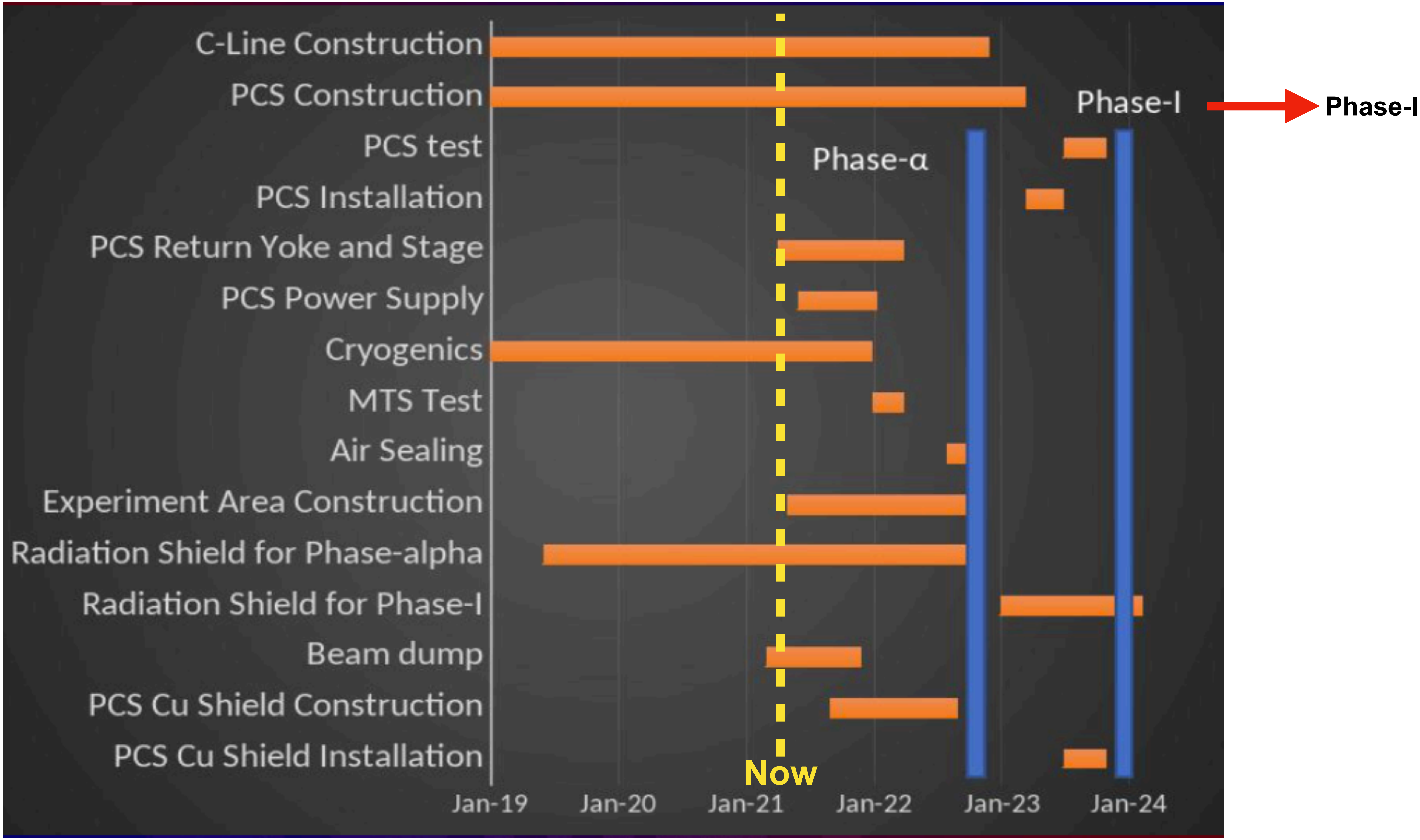
2023~





- A long superconducting solenoid channel
  - pion capture, μ transport, electron spectrometer and detector solenoid
- Stop negative muons at the Al stopping targets
- ID signal electrons emitted from the targets and measure their energy precisely

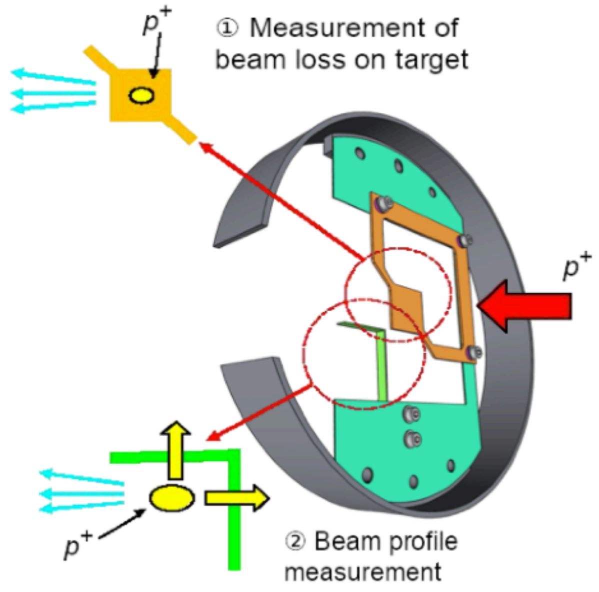
COMET: Schedule

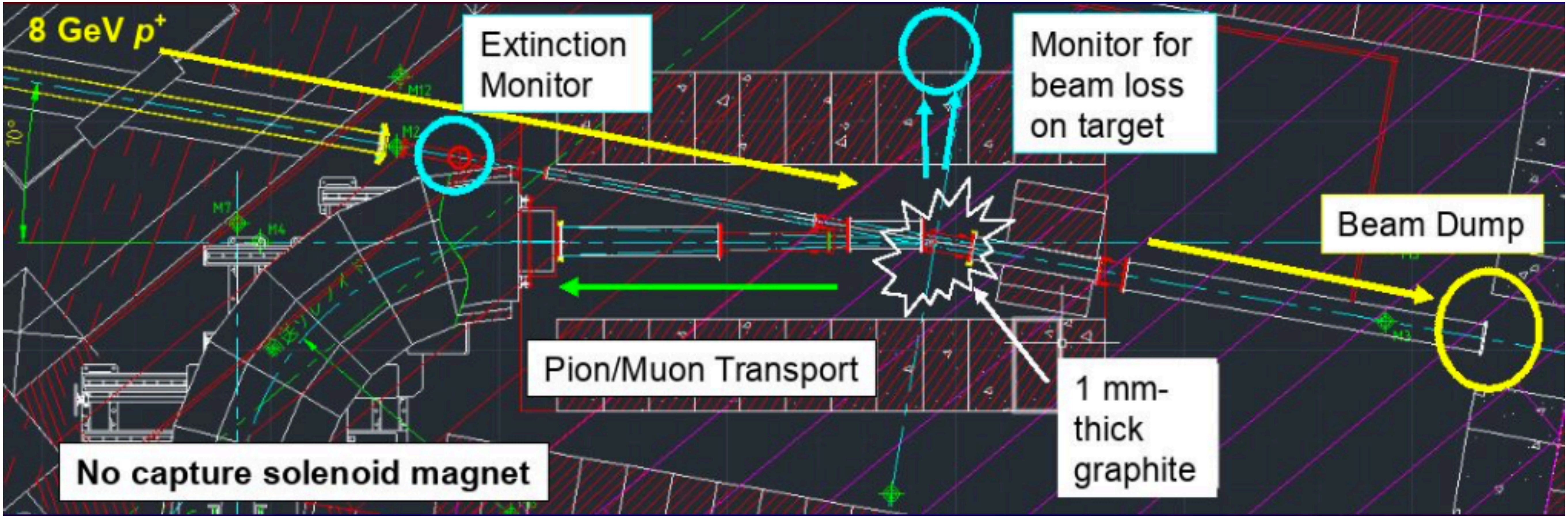


- For MC the Phase-α also would be a good chance to study secondary beams from proton beams.

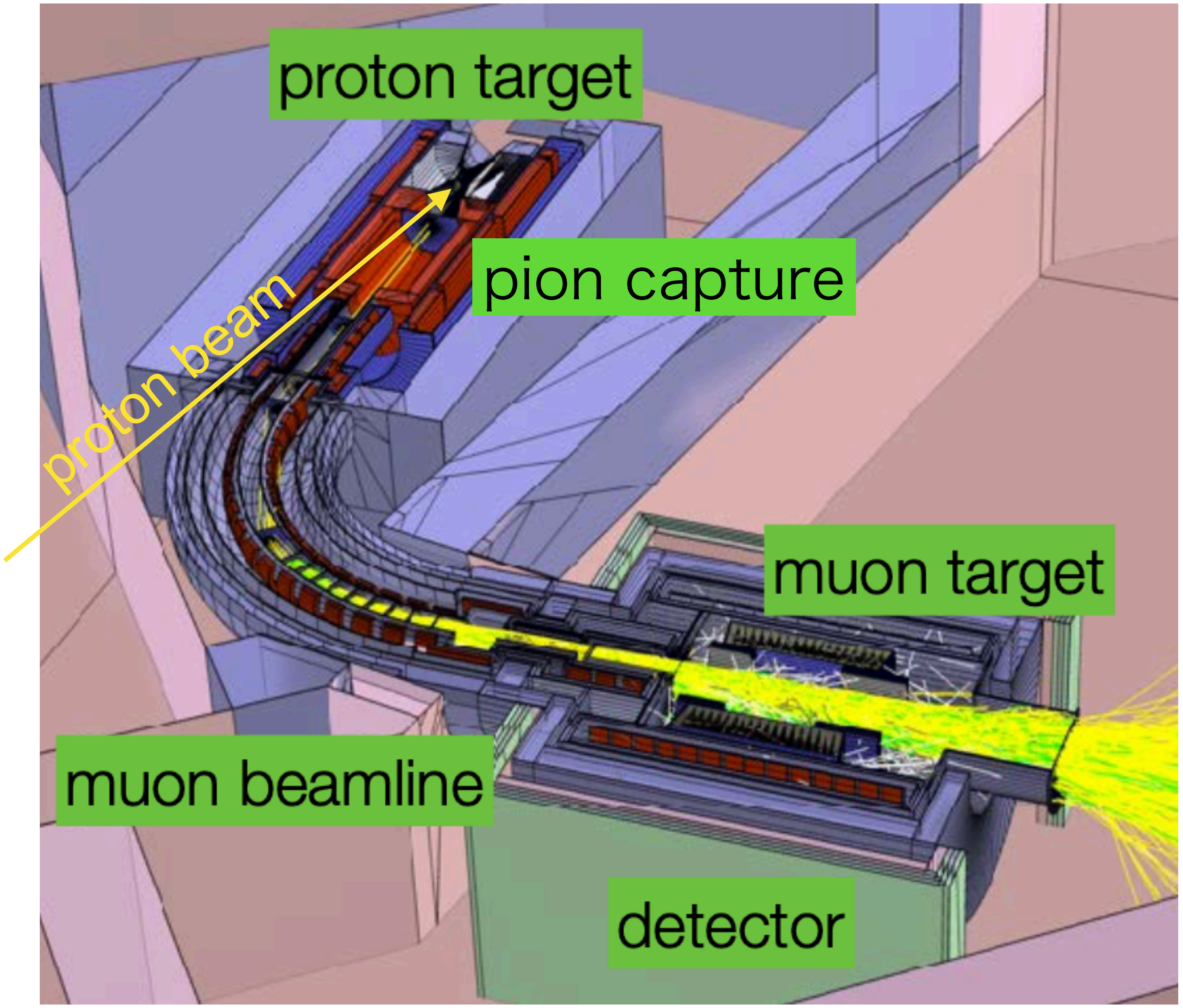
COMET: Phase-α in 2022

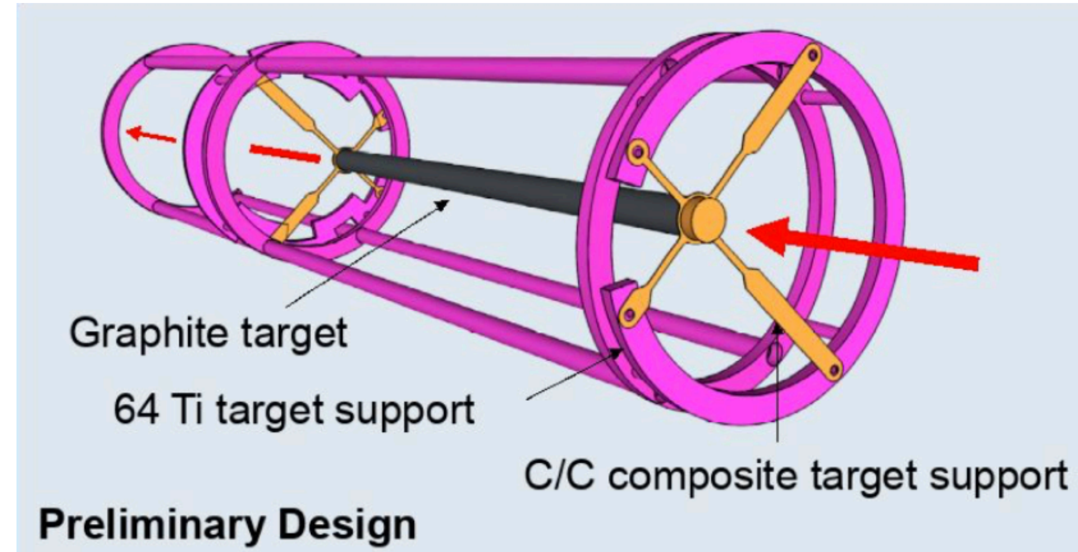
- Goal
  - Proton beam line commissioning
    Direct extinction measurements at the COMET area
  - Demonstration of the muon transport system
  - Estimation of backward pions/muons production yields
  - Measurements of yields of secondary particles, others
- Measurement conditions
  - Proton beam: 8GeV, 200W
  - Thin graphite target, no pion capture solenoid, w/ 90deg. transport solenoid

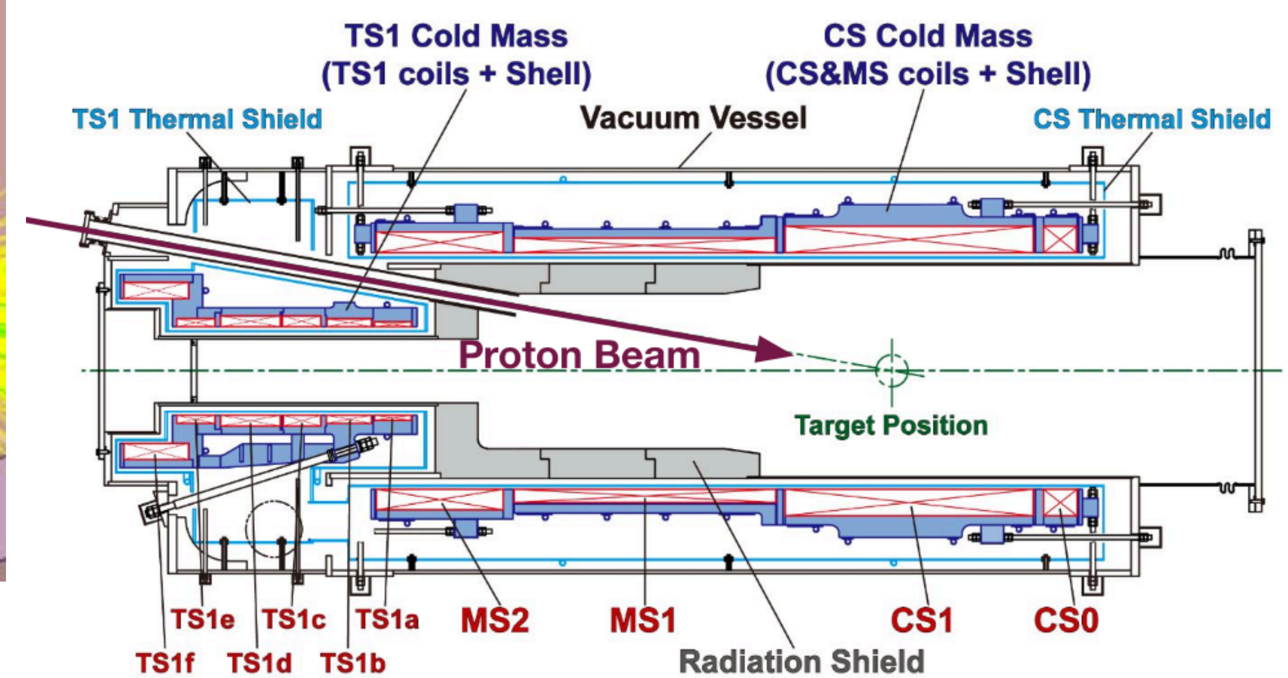




COMET Phase-I: 2023~

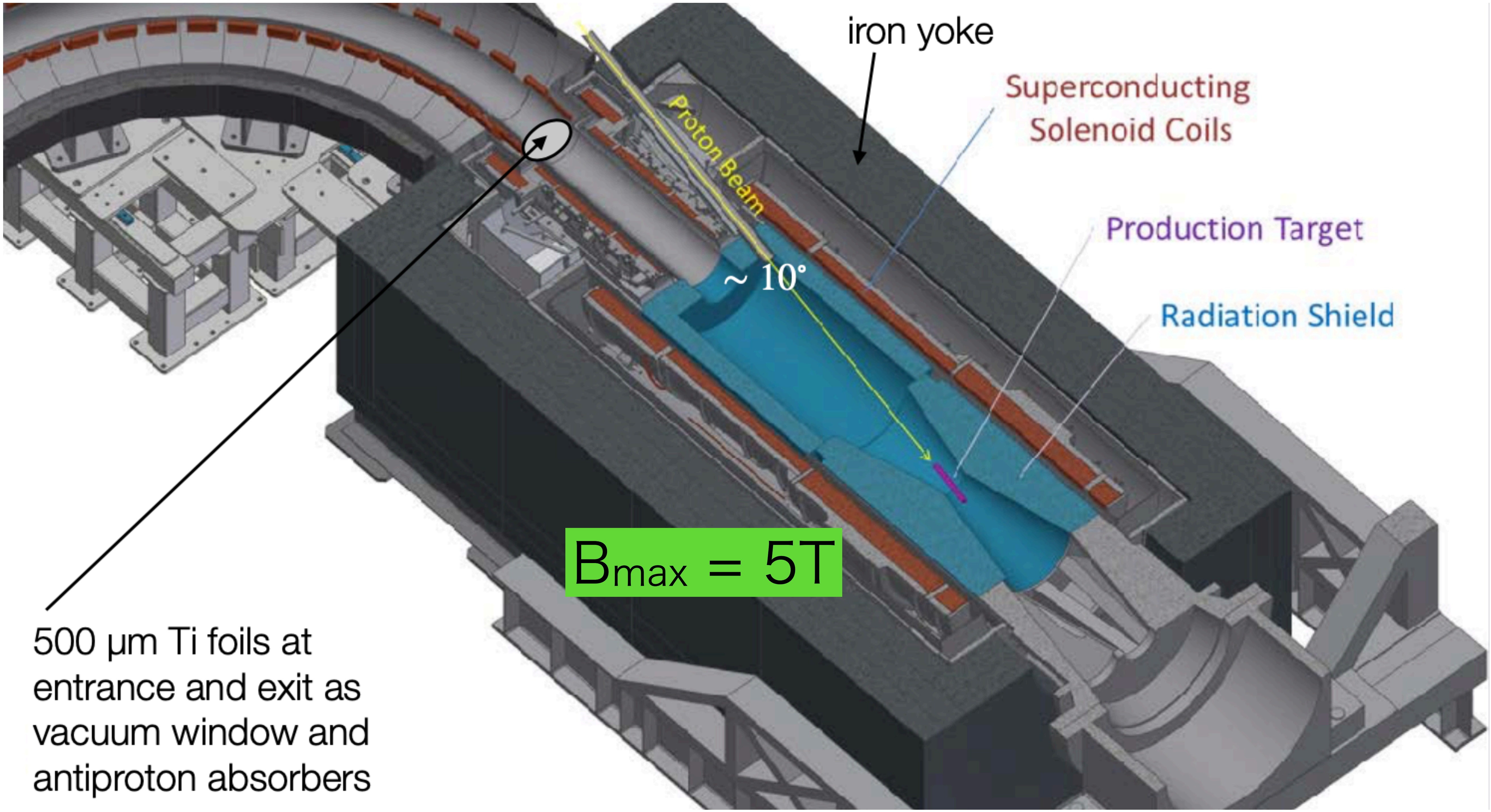






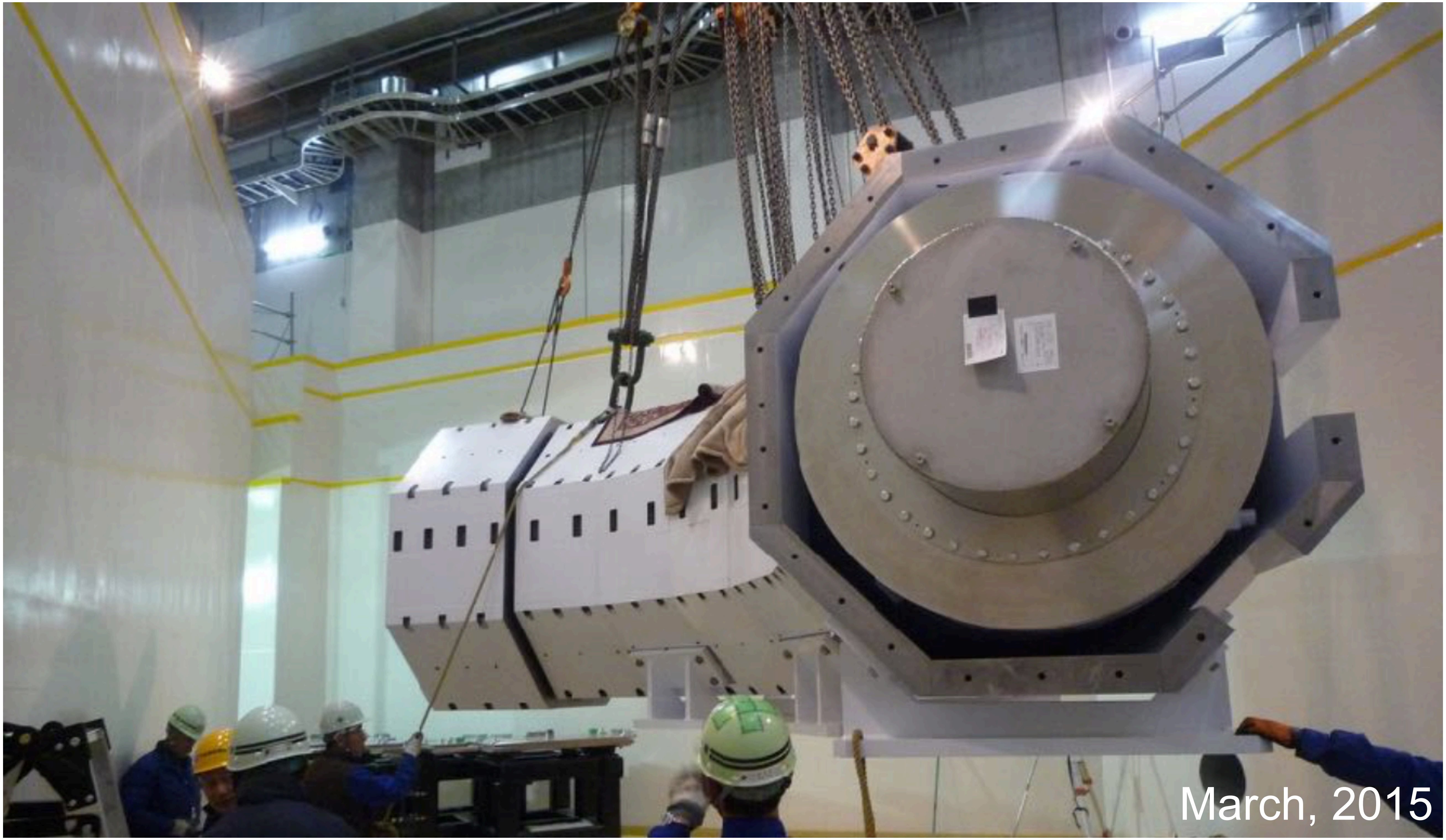
- (1) Beam measurements
- (2) Physics runs: 1.2 x 10^7 sec for SES of 3.1 x10^{-15}
  - Proton beam: 8 GeV, 3.2 kW
  - Pion production target: graphite rod, φ26 mm, L=700 mm
  - Muon beam: ~50 MeV/c, 1.2 x 10^9 stopped μ^-/s

COMET Phase-I: Pion Capture Solenoid



- Superconducting solenoid magnet

COMET Phase-I: Muon Transport



- Curved superconducting solenoid channel: ~ 3 Tesla

COMET Phase-I: Detectors

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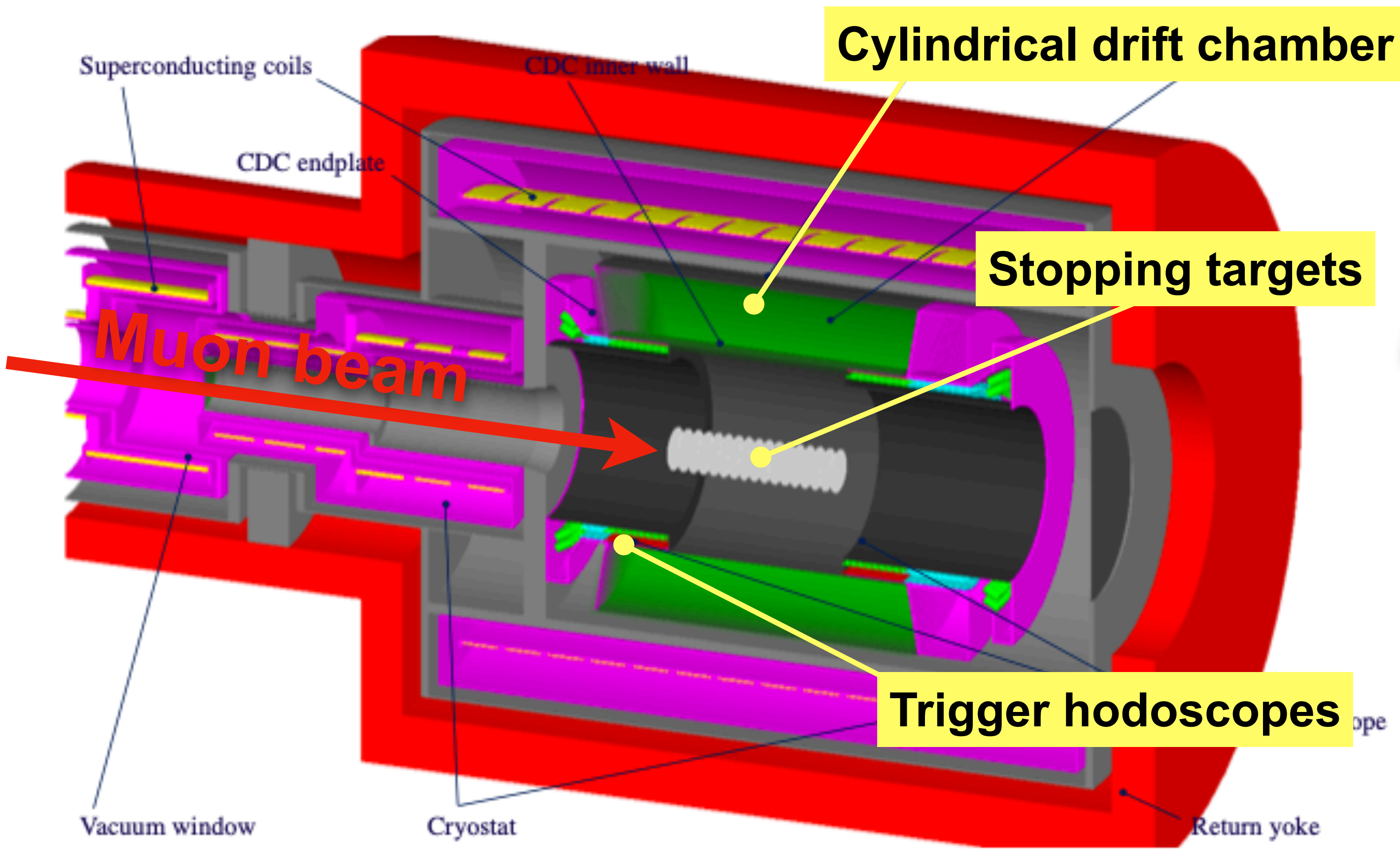
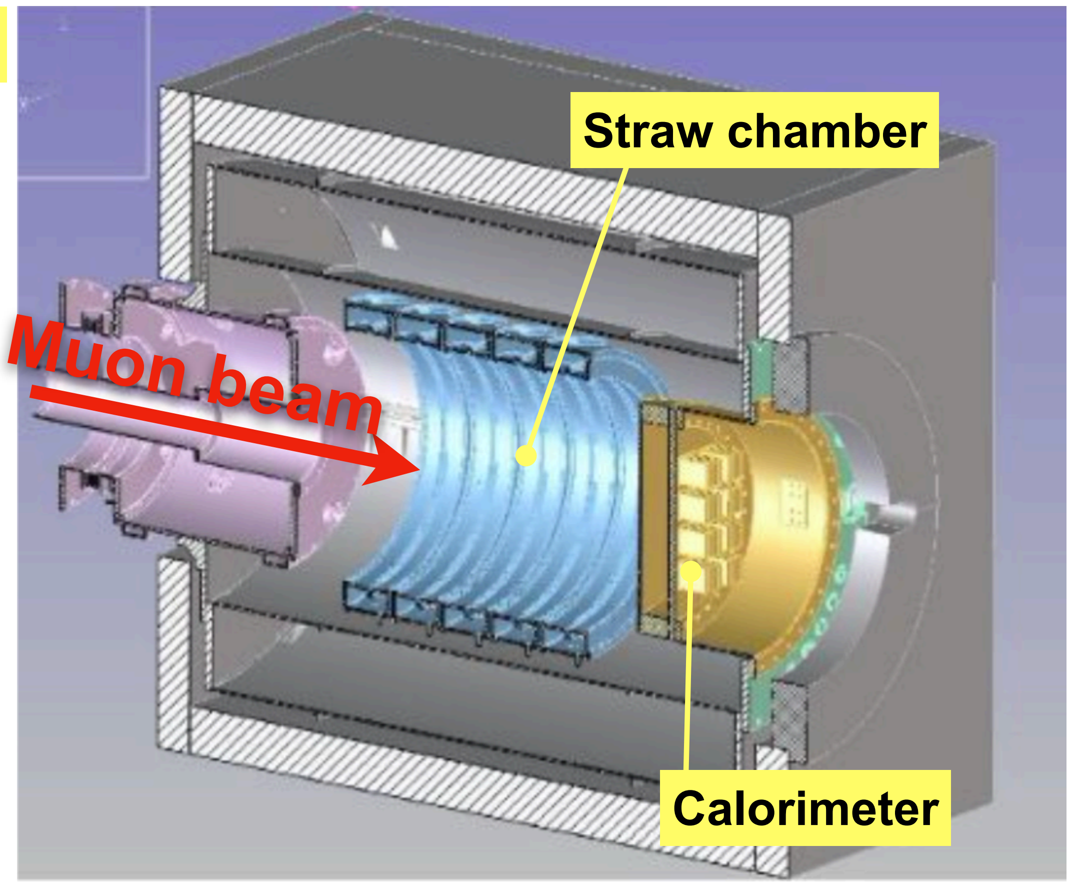
Physics run



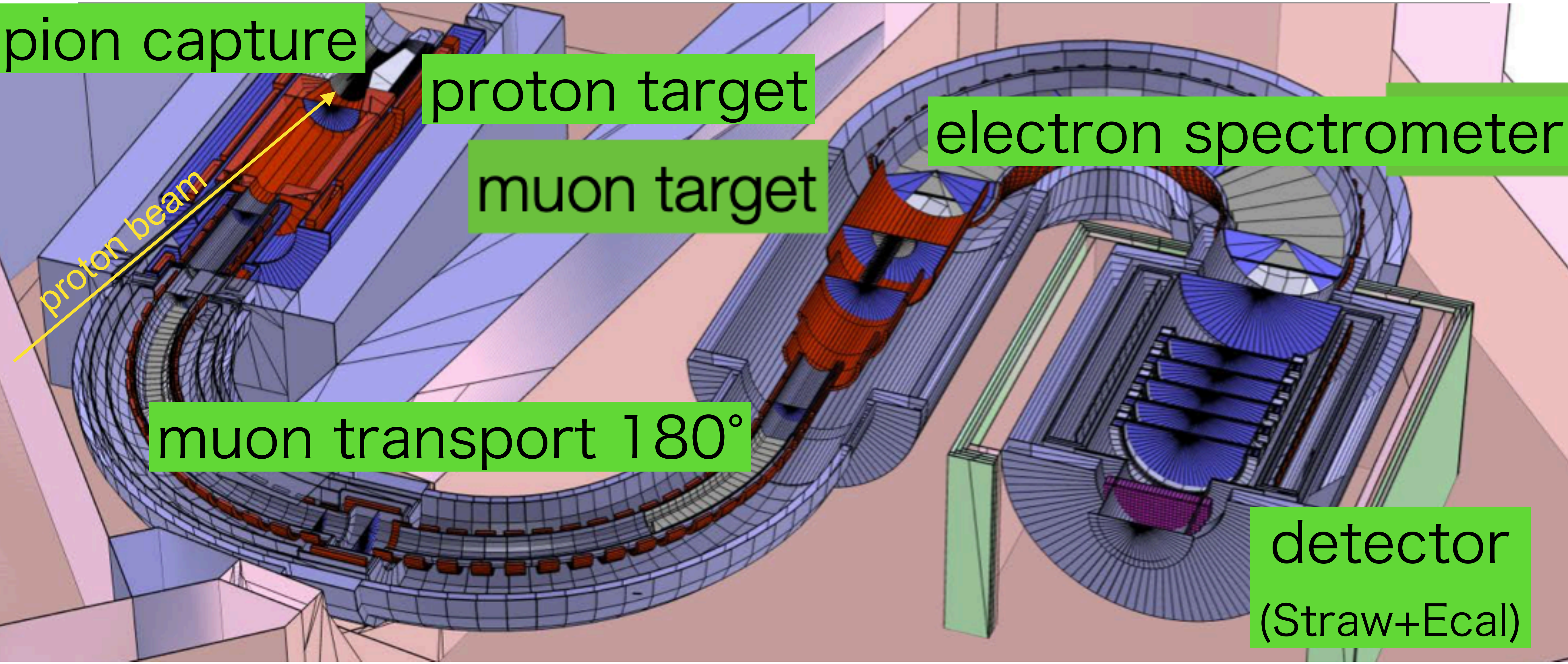
- Cylindrical drift chamber
- Trigger hodoscope
  - Scintillators
  - Cherenkov

Beam measurement



- Straw chambers
- Calorimeter
  - LYSO

COMET: Phase-II



- Physics runs: 2 x 10^7 sec for SES of 2.7 x10^{-17}
  - Proton beam: 8 GeV, 56 kW
  - Pion production target: Tungsten, φ10 mm, L=250 mm
    - water/He cooling
  - Muon beam: ~50 MeV/c, 2 x 10^{11} stopped μ^-/s

COMET for Muon Collider R&D

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- Possible R&Ds
  - Pion production targets
  - Secondary particles from 8 GeV proton beams
  - Pion capture solenoids, curved solenoids
  - Effects to superconducting magnets in a high radiation field
  - Study with muon beams
    - Detectors
    - Accelerator components
    - …

J-PARC at Tokai, Ibaraki

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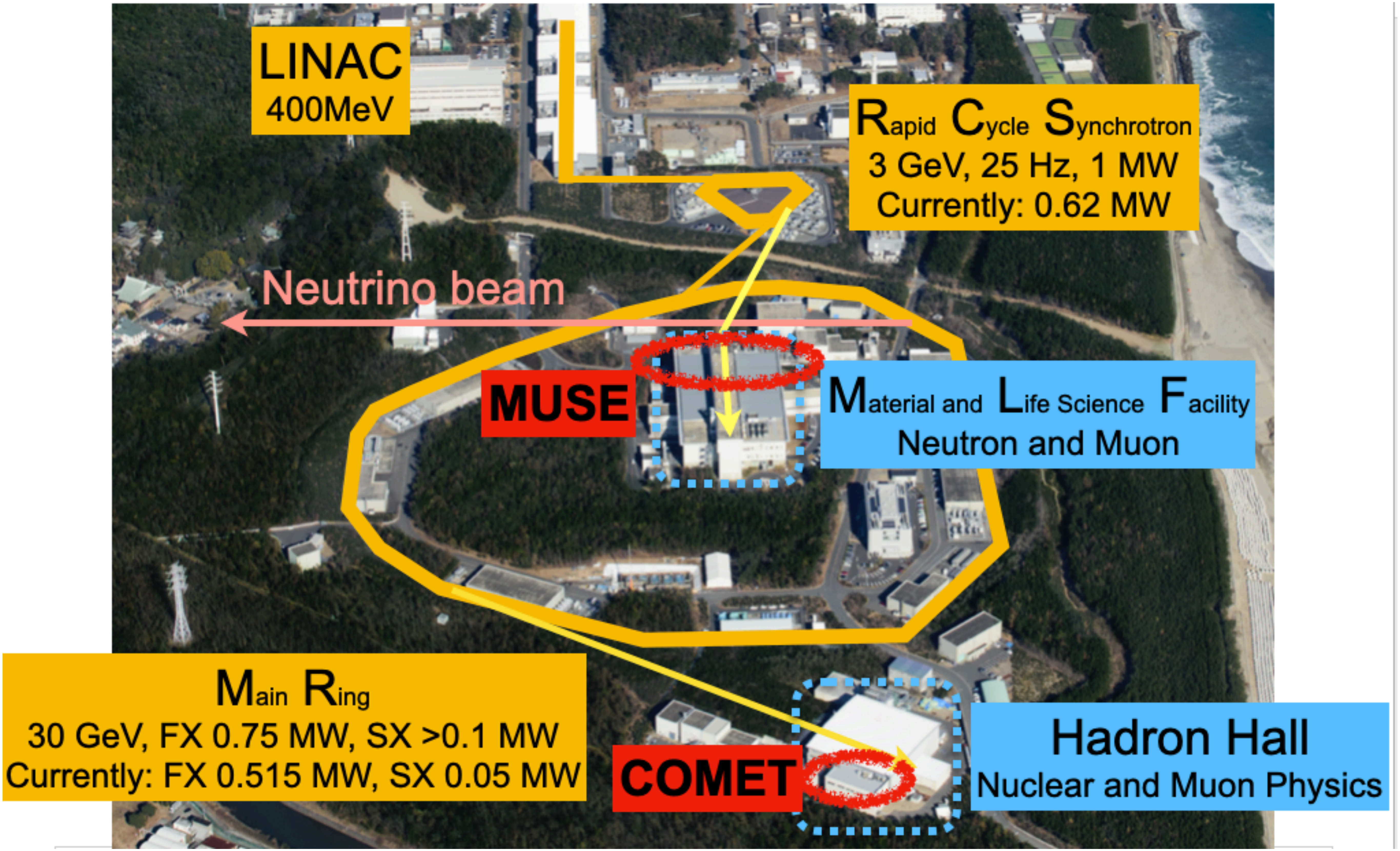
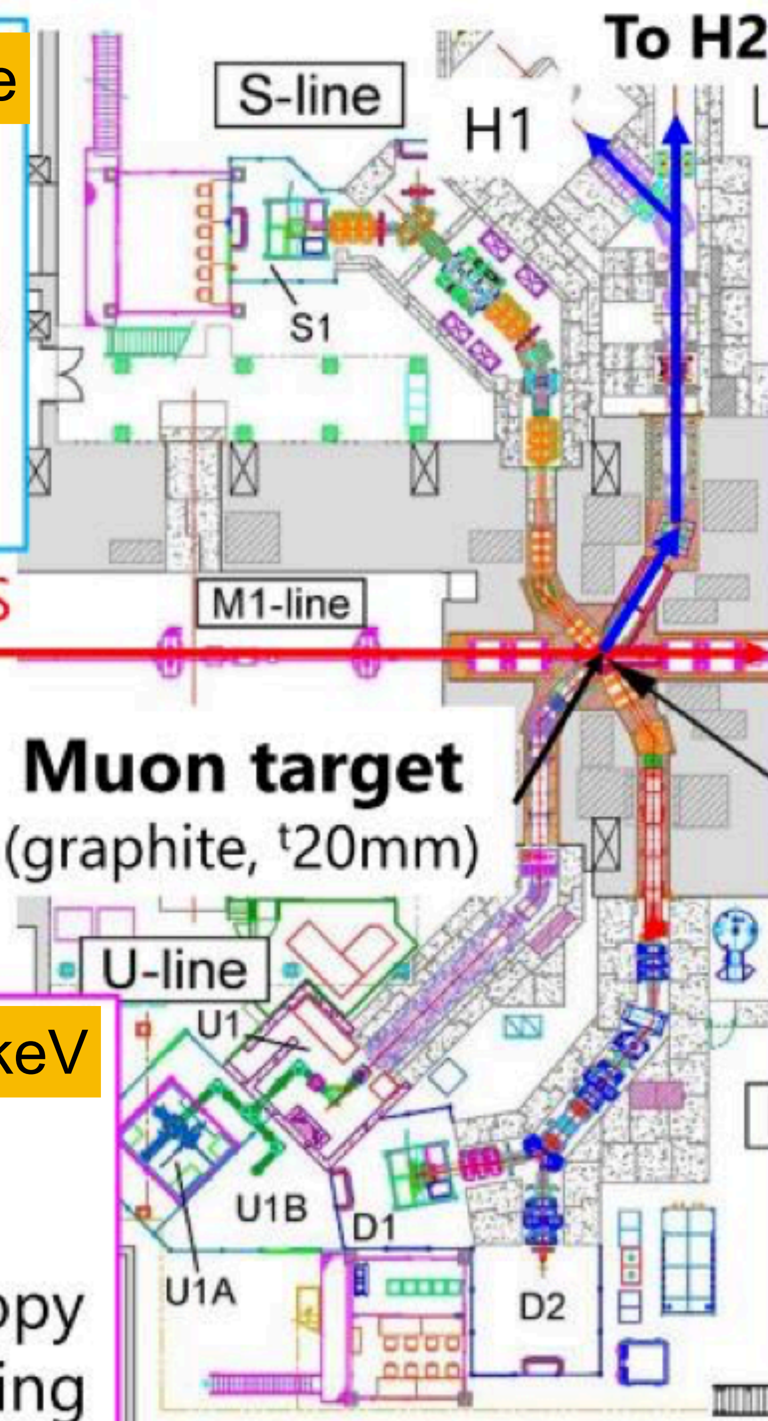


J-PARC MUSE

- MUSE (MUon Science Establishment) in the MLF

S-line Material science
- surface μ⁺
- dedicated to μSR
- S1 area is available
- S2/S3/S4 will be constructed

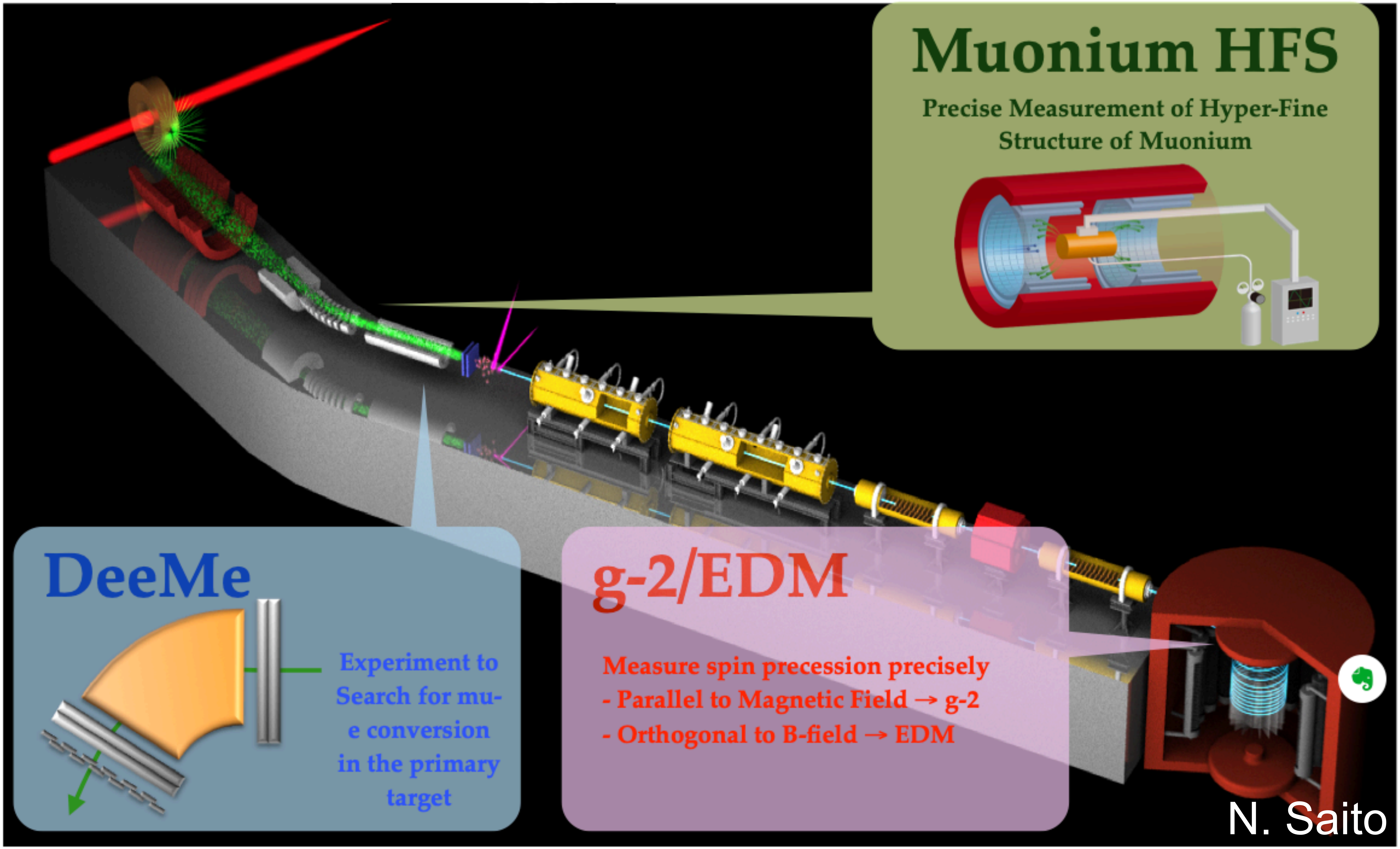
H-line Particle physics
- **surface μ⁺ (>10⁸ μ⁺/s)**, decay μ⁺/μ⁻, e⁻
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2** for **g-2/EDM** & transmission muon microscopy
- **under construction**



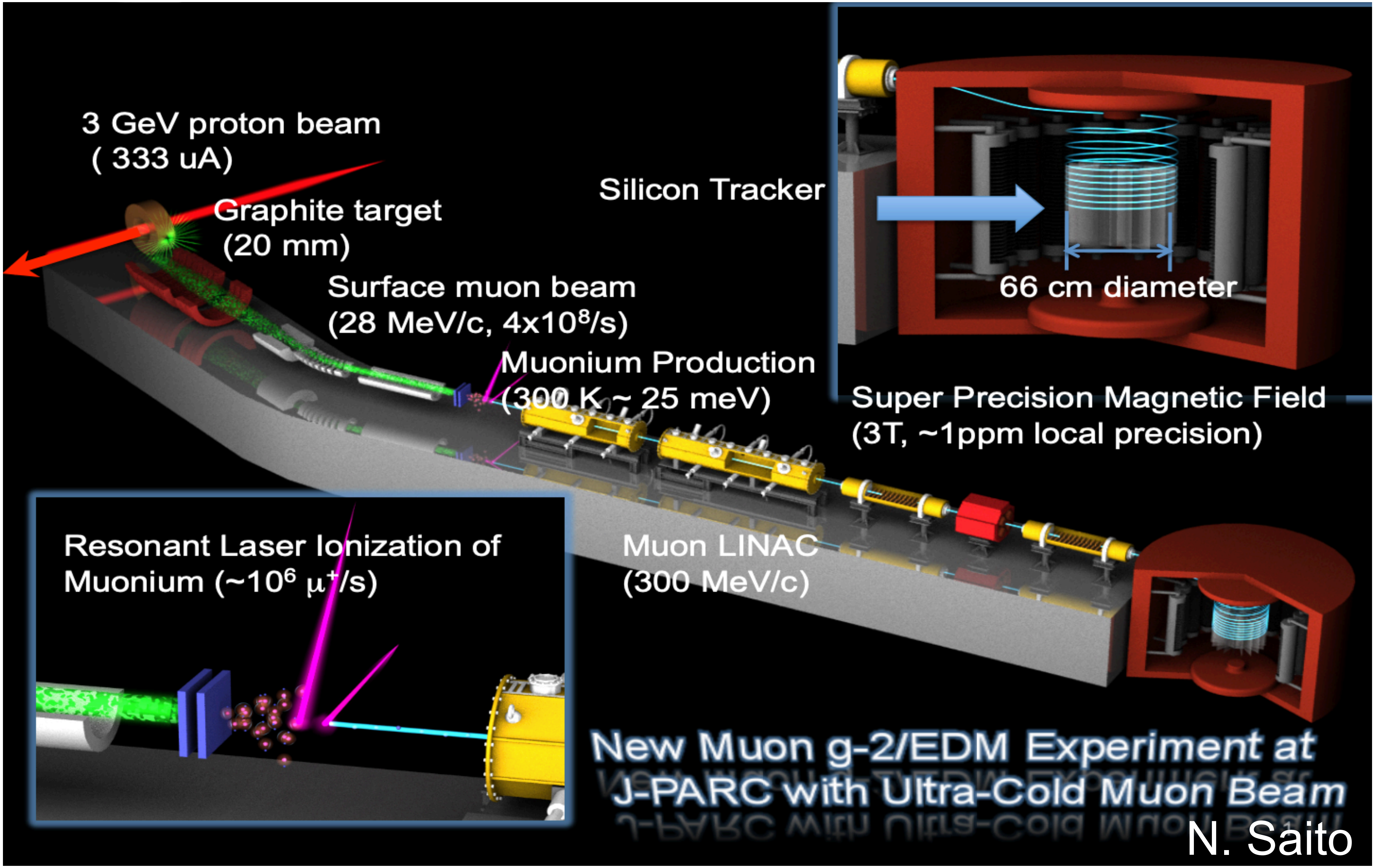
U-line 0.05 keV–30 keV
- ultra slow μ⁺
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

D-line multi purpose
- decay μ⁺/μ⁻, surface μ⁺
- D1 area for μSR
- D2 for variety of science

J-PARC MUSE: H-Line



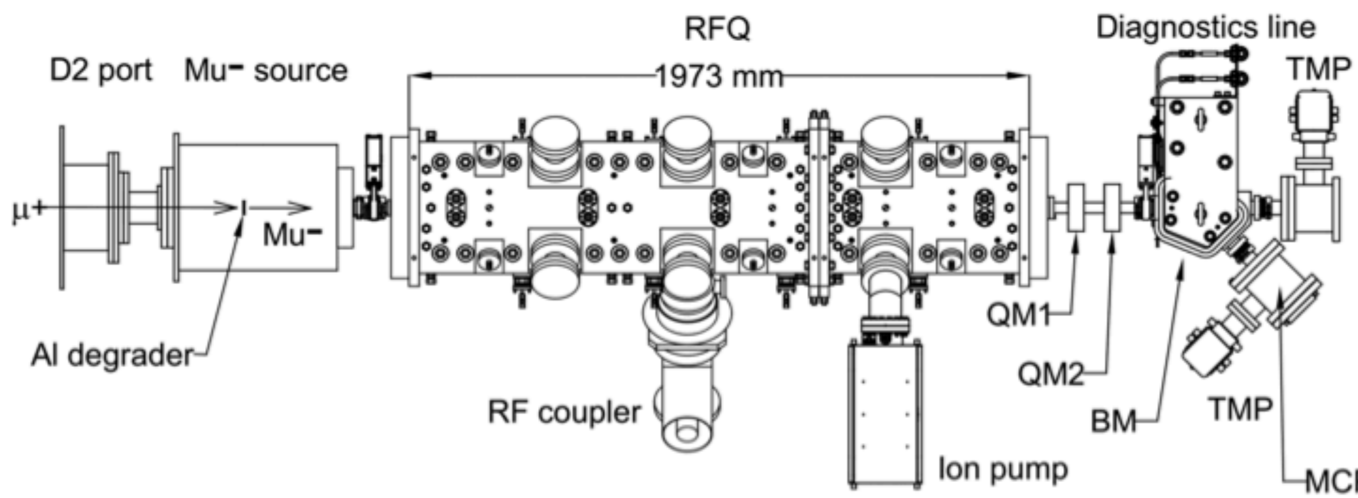
Muon g-2 @ H-Line

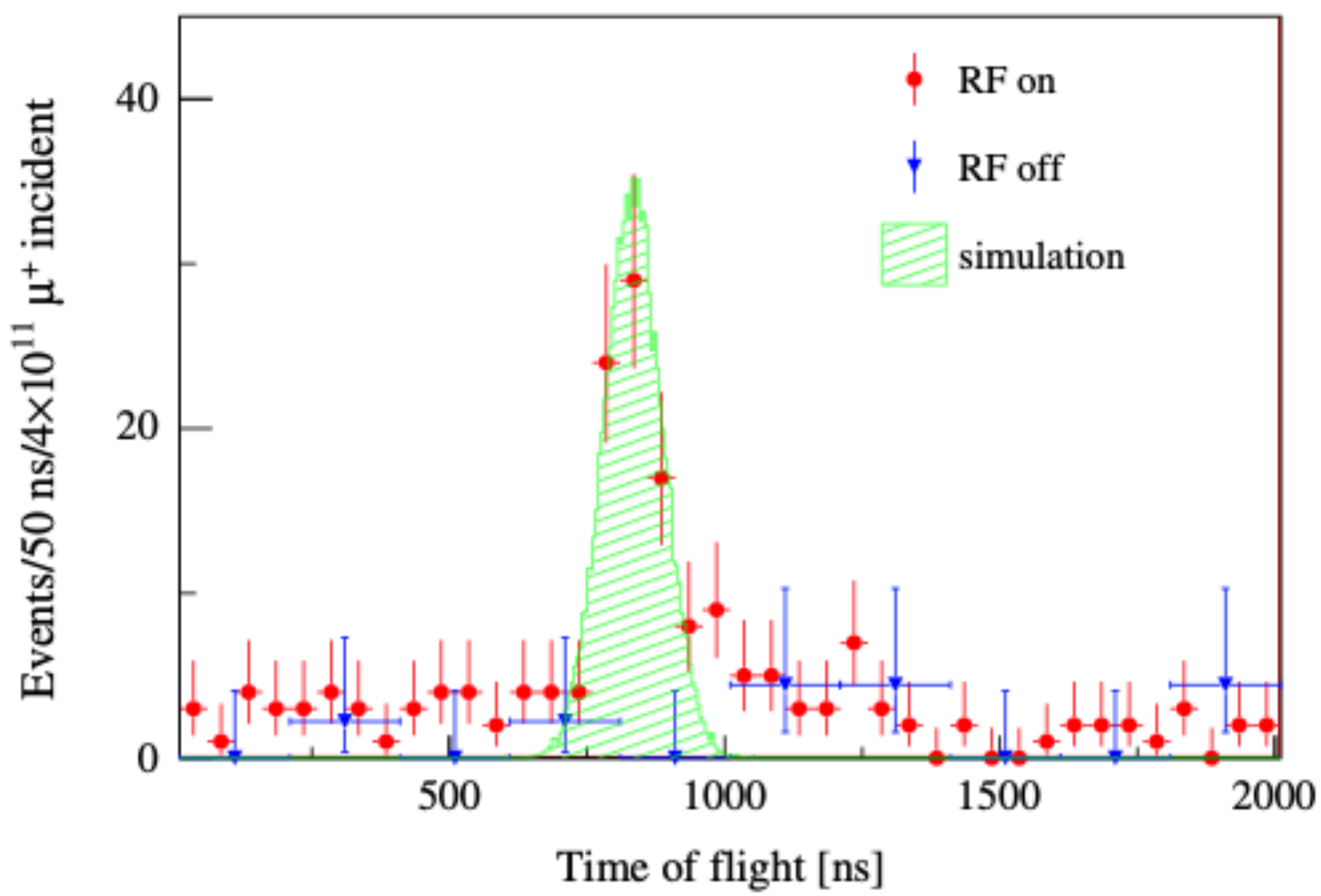


Mu⁻ accelerated

DOI: 10.1103/PhysRevAccelBeams.21.050101

- Negative muonium atoms ($Mu^- = \mu^+ e^- e^-$) were accelerated to 89 keV.
  - One of R&D items for the muon g-2 experiment
  - A μ^+ was converted to Mu^- by a Al degrader, then accelerated by an RFQ.
  - Time distribution of the Mu^-s was measured by a MCP.





MUSE for Muon Collider R&D

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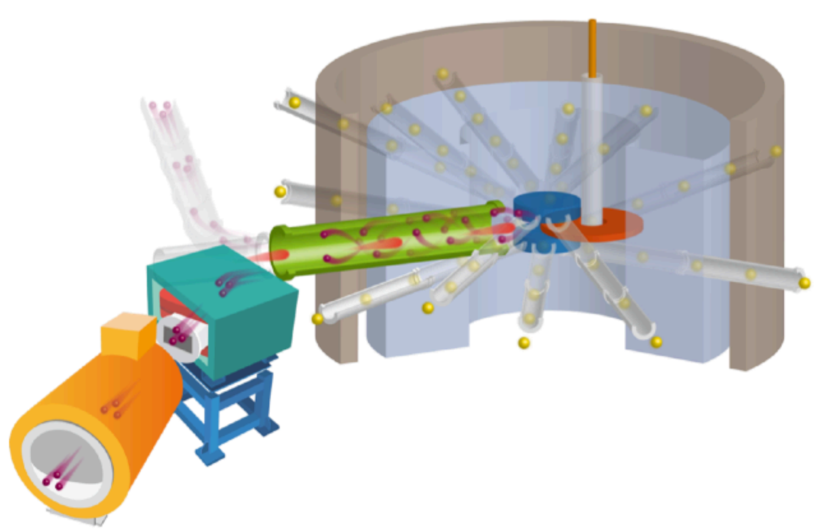
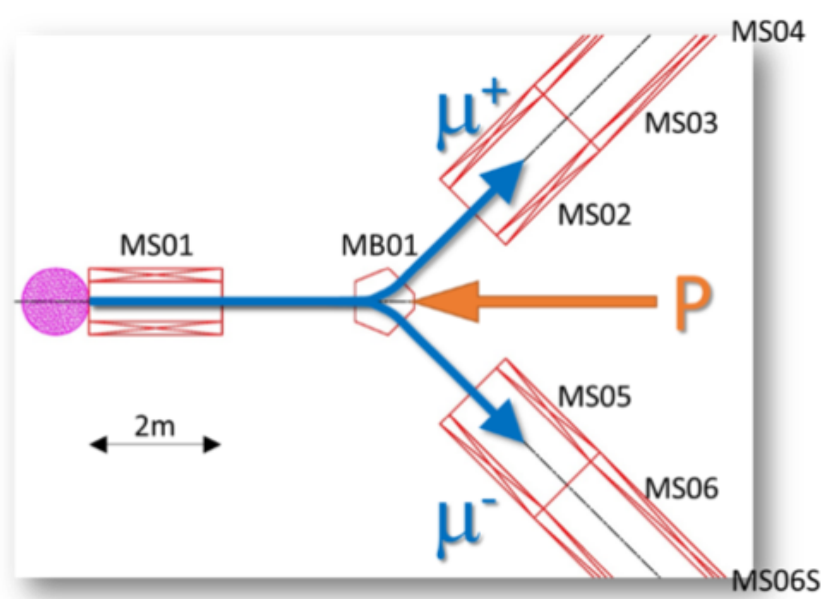
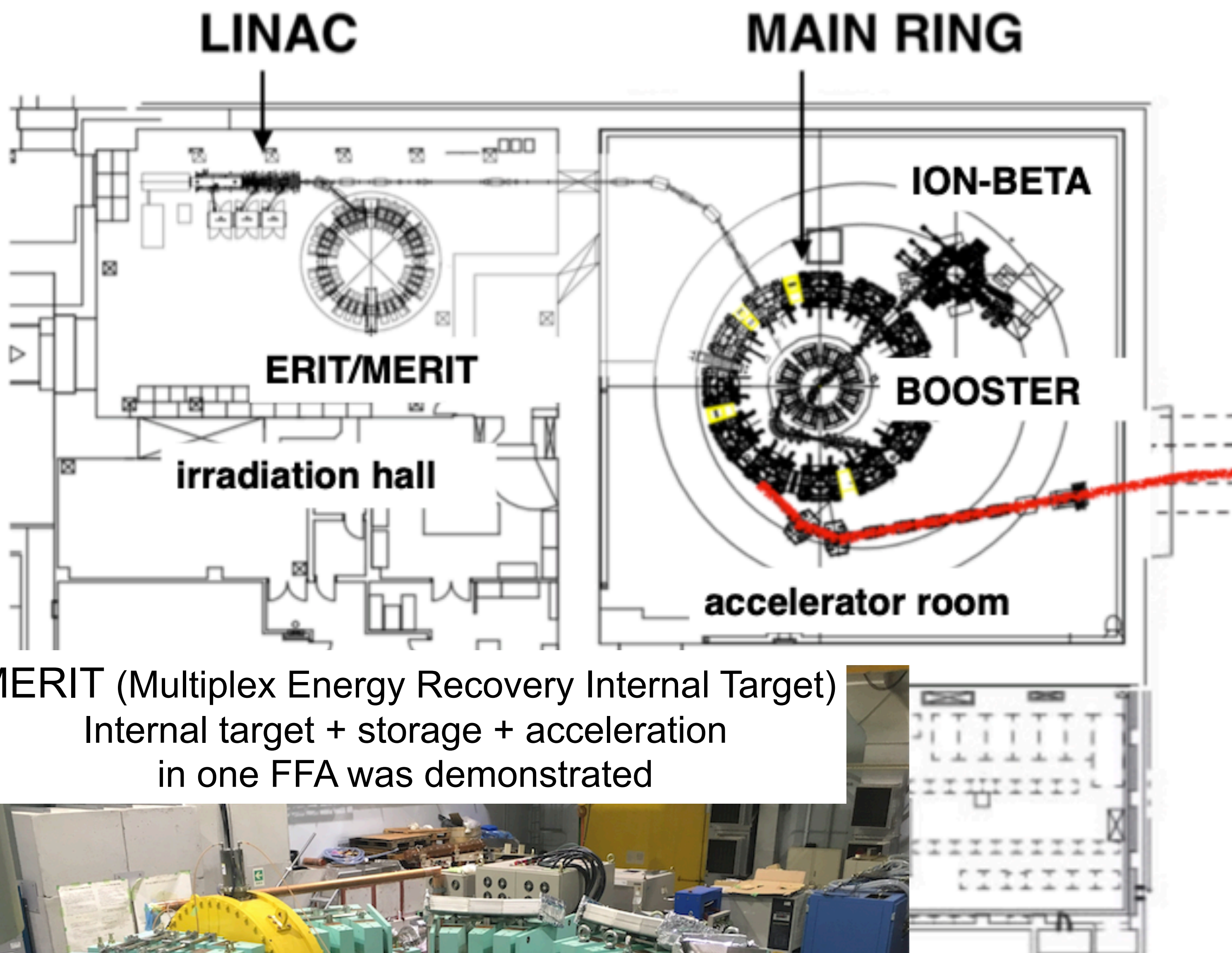
- Verity of pulsed muon beams is available.
  - Energy: 50 eV ~ 55 MeV
- Unique R&Ds are ongoing
  - Ultra cold muons
  - Muon acceleration by LINAC and cyclotron
- Design study for the 2nd target station is in progress
  - ~0.5 MW proton beam on W target
    - https://j-parc.jp/researcher/MatLife/ja/publication/files/TS2CDR.pdf

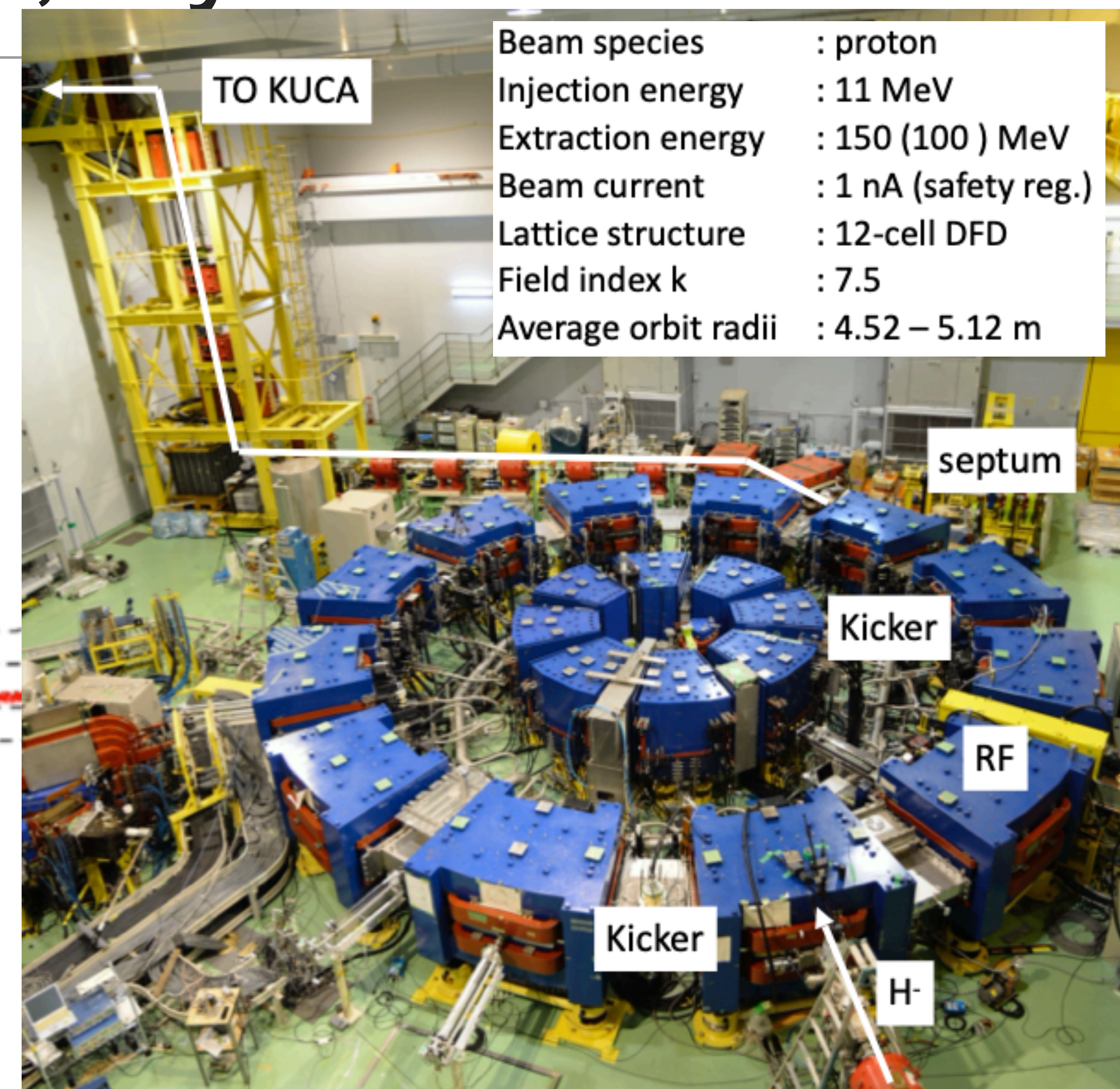




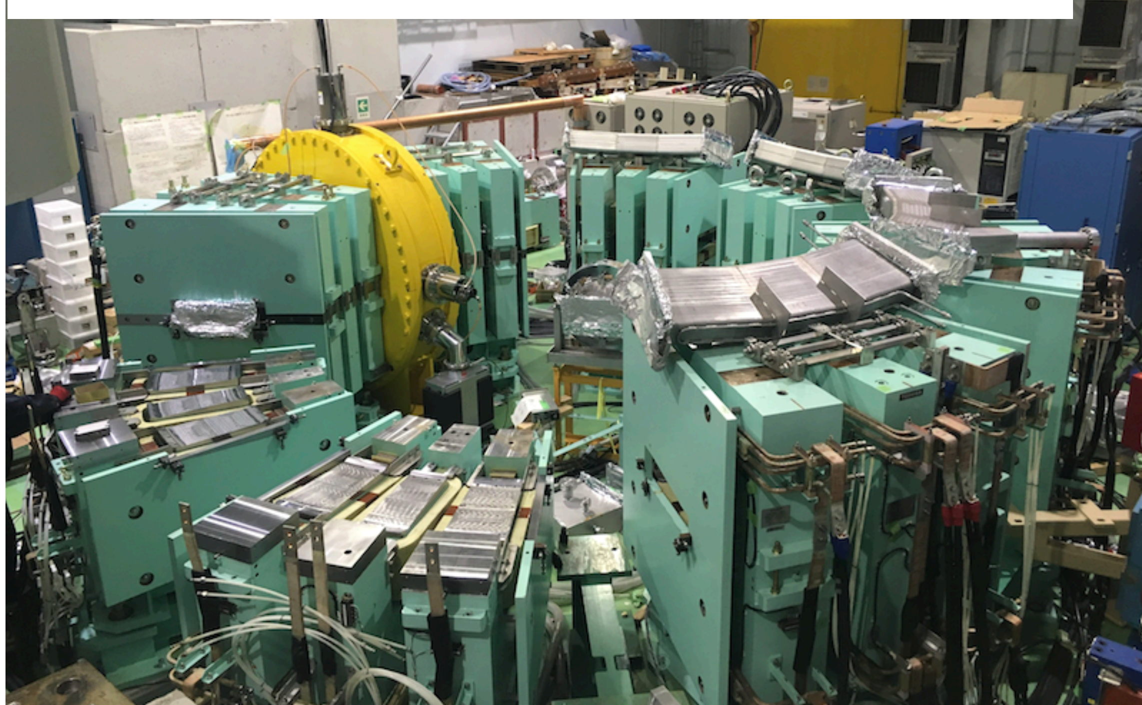
FFAs in Japan

FFA complex at KURNS, Kyoto U.



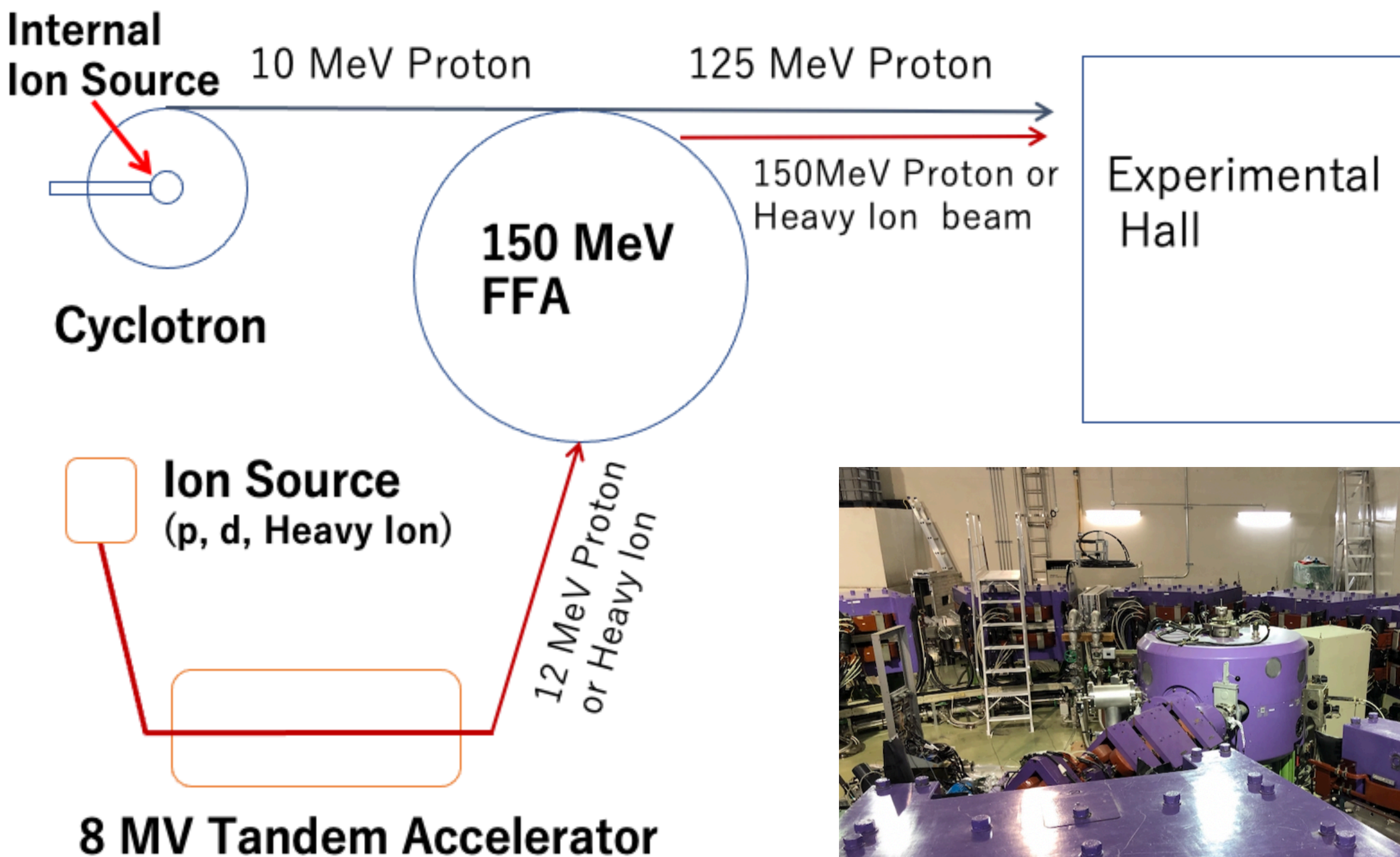


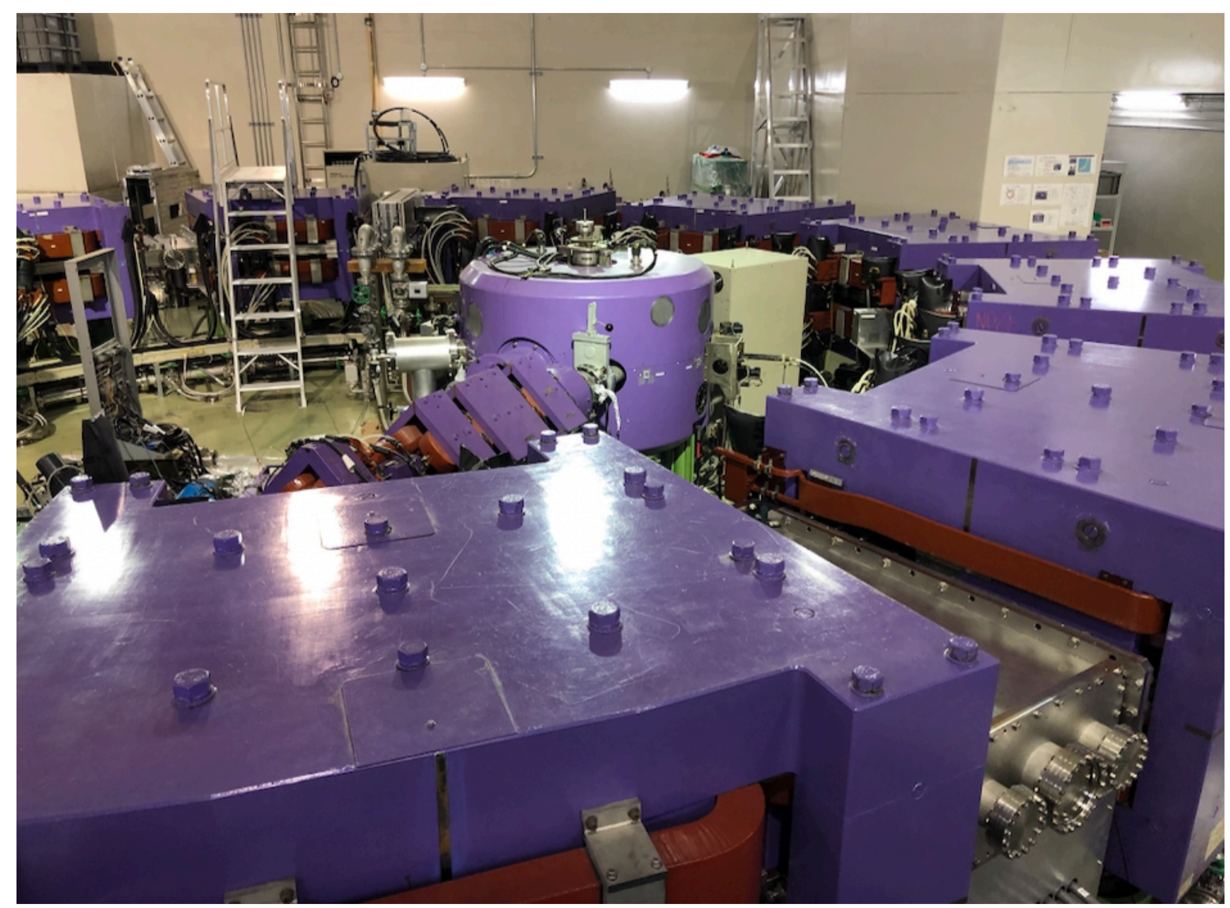
MERIT (Multiplex Energy Recovery Internal Target)
Internal target + storage + acceleration
in one FFA was demonstrated



- Three FFAs are in operation.
- We can study with the rings.

FFA at Kyushu U.

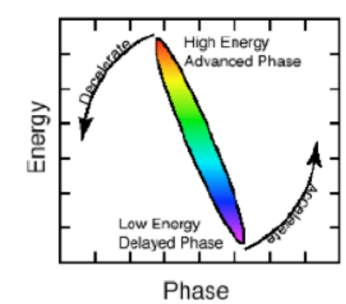


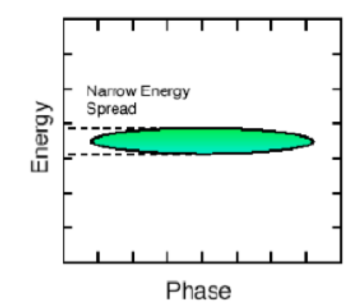


PRISM-FFAG

Demonstration of the phase rotation has been done.

- PRISM/PRIME
  - ultimate μ-e conv. search: BR ~10^{-19}
- μ beam
  - low energy ~ 60 MeV/c
  - small dp/p ~ 2%
  - pure (no pions)
- Can be achieved by an FFA storage ring
  - PRISM-FFAG



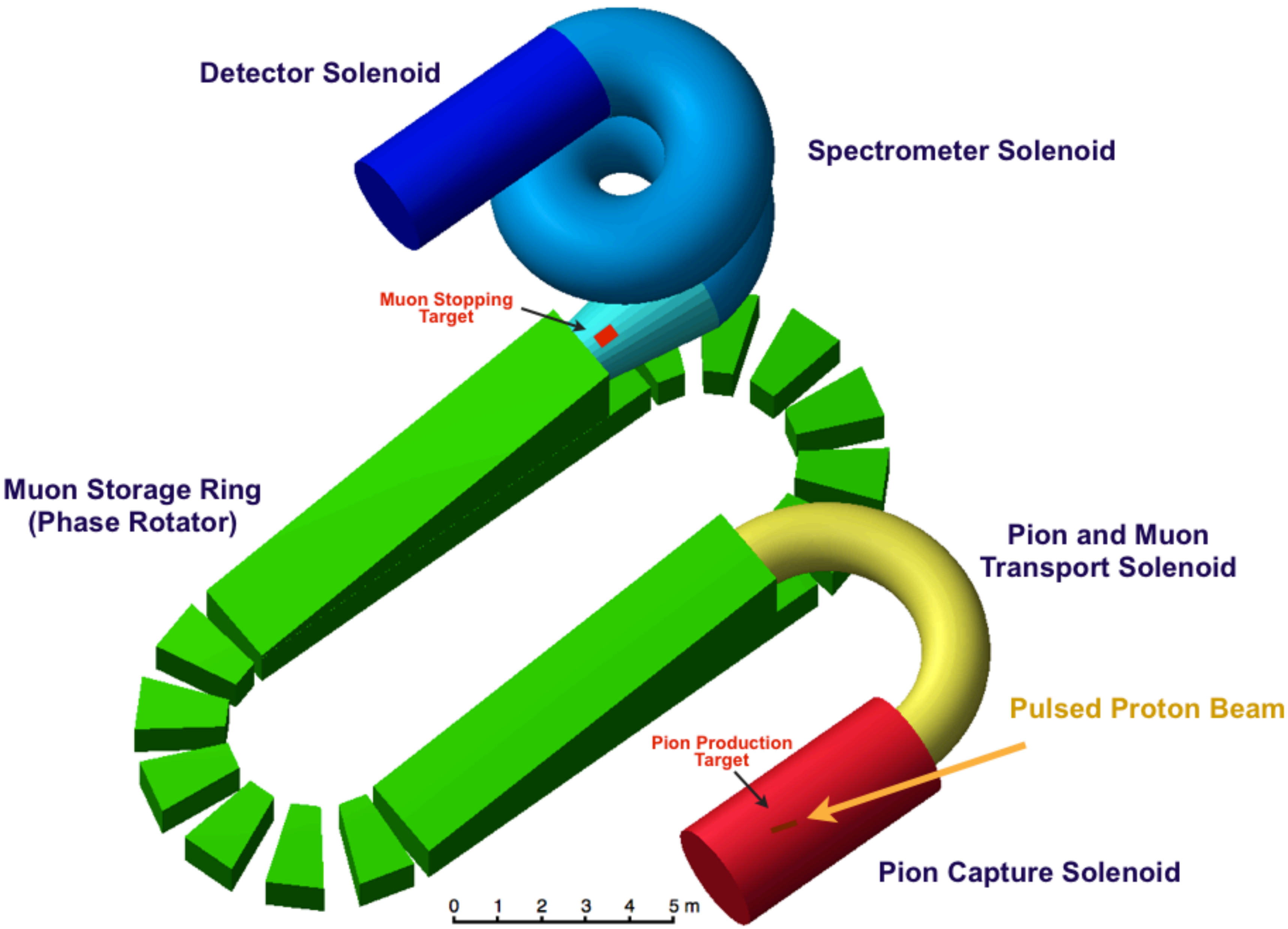


- The ring has been disassembled, but the magnets and the RF is still available.

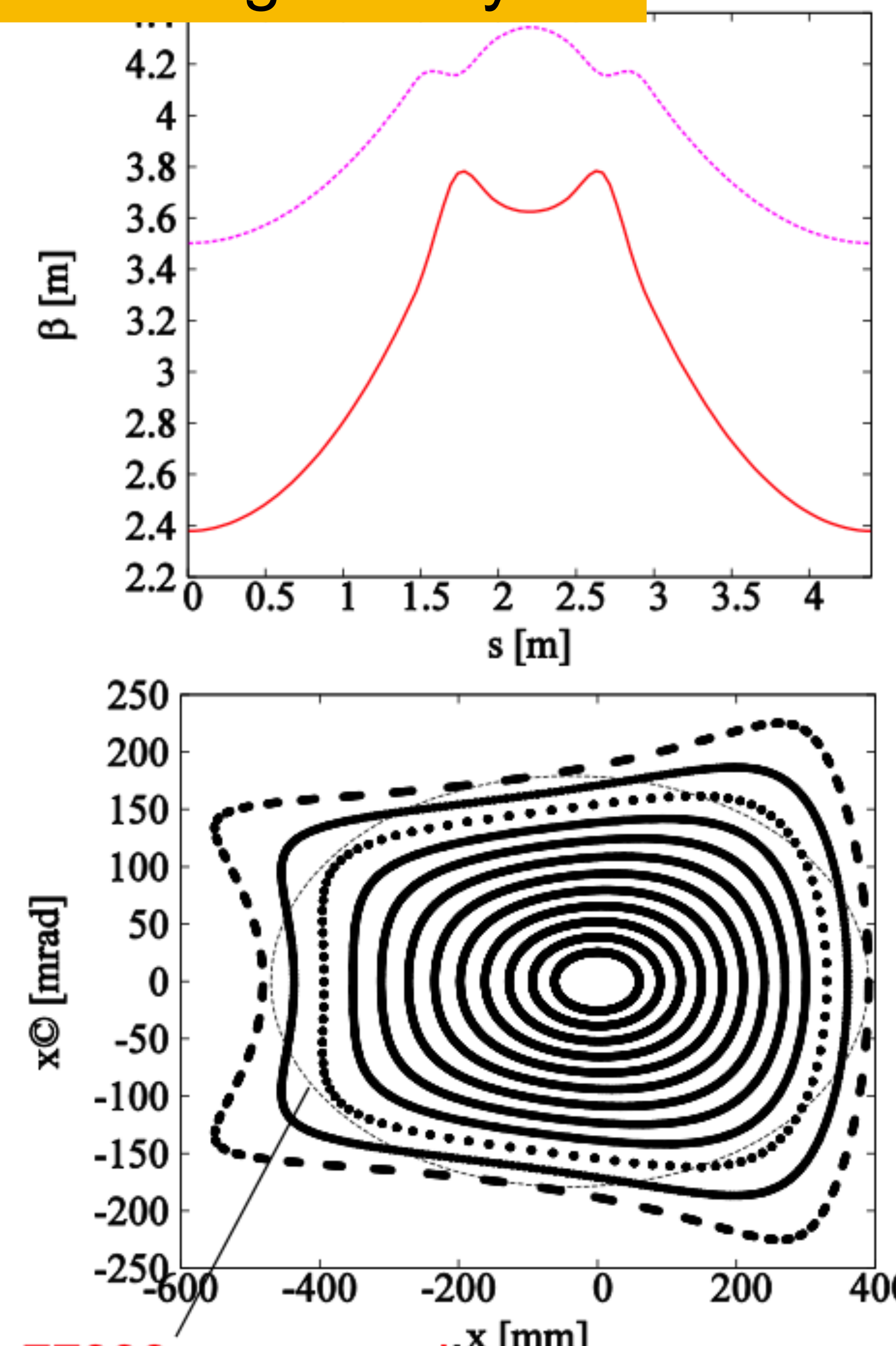
PRISM Task Force

- PRISM task force, lead by J. Pasternak, continues the PRISM-FFA study.

A new conceptual design



FDF scaling FFA by J.P



77000 π.mm.mrad!

Snowmass`21

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A Phase Rotated Intense Source of Muons (PRISM) for a $\mu \to e$ Conversion Experiment

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Muon to electron ($\mu \to e$) conversion in a muonic atom is an excellent laboratory to search for charged lepton flavor violation (CLFV). Its discovery would be a clear signature of physics beyond the Standard Model (BSM), and the current generation of experiments will probe 10^4 beyond current limits. In order to further improve the experiments by an additional factor of 100 and study potential signals, the use of a Fixed-Field Alternating gradient (FFA) ring has been proposed to create a Phase Rotated Intense Source of Muons (PRISM). Short, high intensity proton bunches are sent to a production target followed by a high acceptance capture/transport system, where the muon beam will be formed and subsequently injected into the FFA ring. PRISM will allow significant purification of the muon beam and suppression of a typically large momentum spread by the use of RF phase rotation in the ring, both reducing the backgrounds and increasing the number of stopped muons relative to other methods. PRISM requires a proton driver capable of producing short, intense proton bunches. New facilities, in particular PIP-II at Fermilab equipped with a dedicated accumulator ring, or upgrades of other accelerator facilities, such as J-PARC and ESS, offer promising opportunities for providing the required intensity and time structure of the proton beam. The FFA would provide the world's forefront facility to explore CLFV physics with high-brightness muon sources.

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf

Summary

- There are three muon facilities in Japan.
  - RCNP-MuSIC
  - J-PARC COMET
  - J-PARC MUSE
- We have a lot of muon project in Japan. They are mostly for low energy muon programs.
  - Some of technologies can be extended for the Muon Collider R&Ds.
- FFAs are also an attractive candidate for the MC; phase rotator, storage ring, accelerator …
- Future high intense muon beams are also very important for fundamental science with low energy muon beams. We should consider possibilities to add the low energy muon programs to the MC / nuSTORM.