Possibilities of Muon Beams at the J-PARC Hadron Experimental Facility

KEK / J-PARC Center / SOKENDAI
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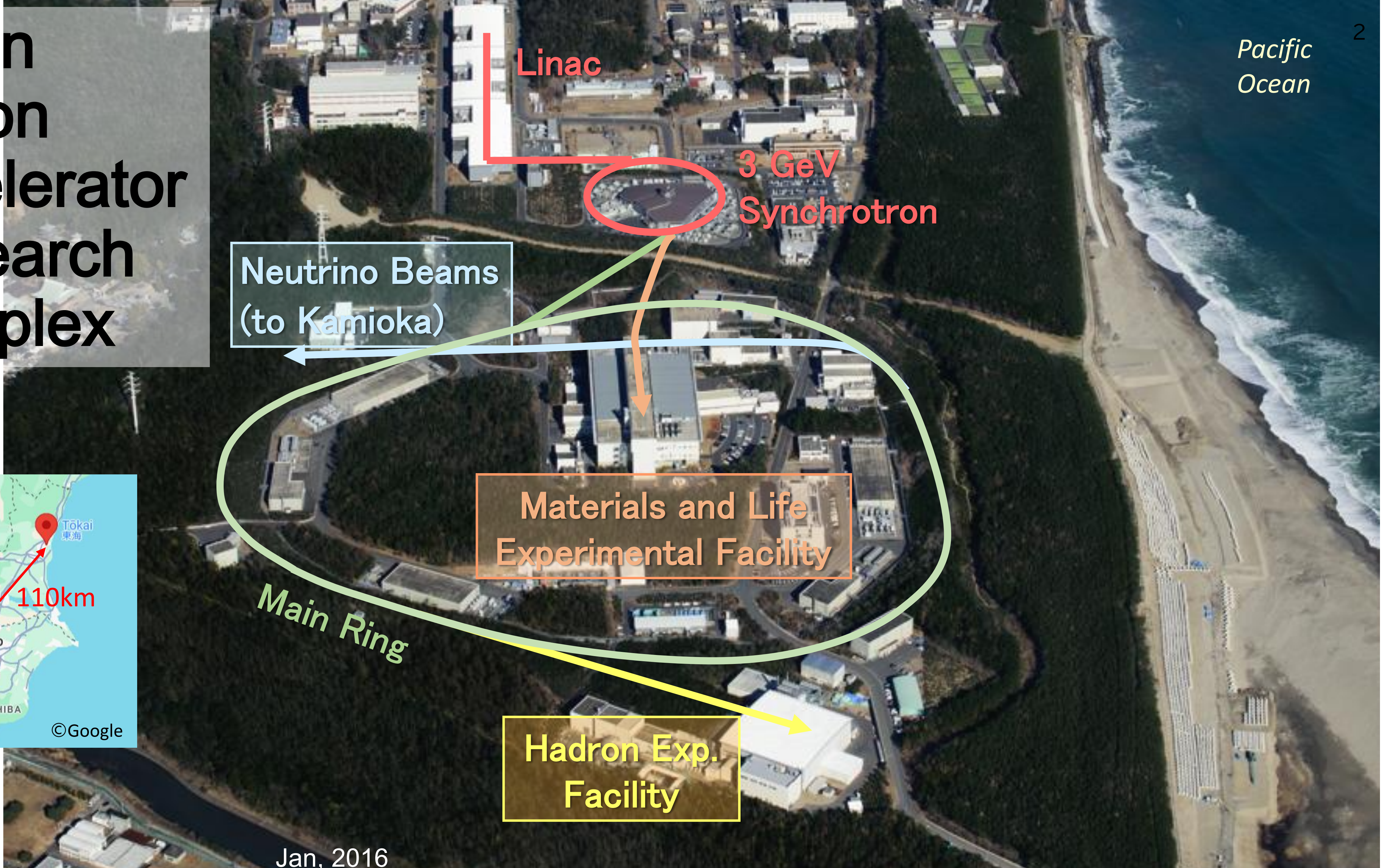
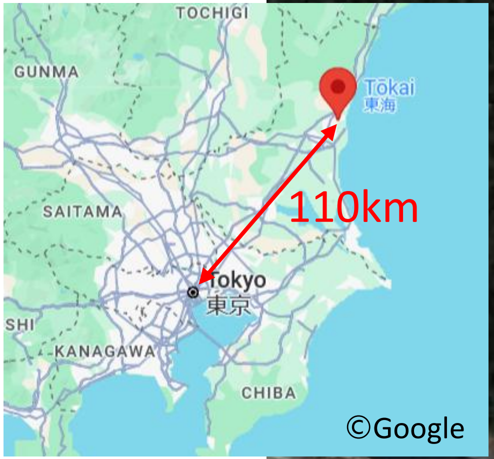
Acknowledgement:

This talk is based on research activities conducted by the COMET Group, T106 Group, and KOTO/KOTO-II Group.
I extend our deepest gratitude to all members of these groups.

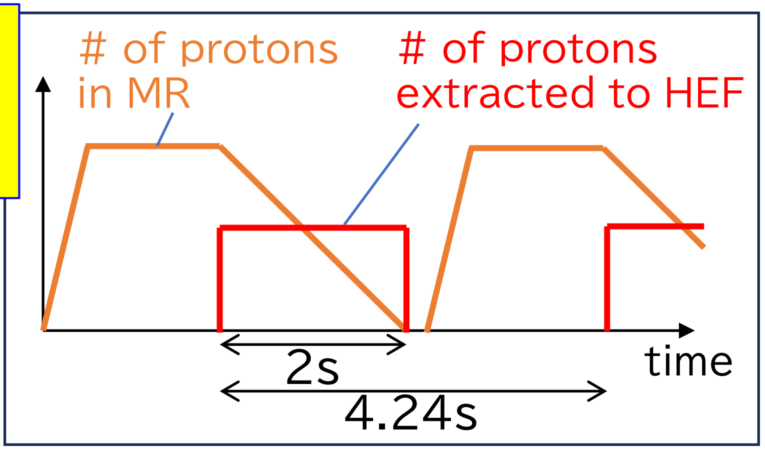
Japan Proton Accelerator Research Complex

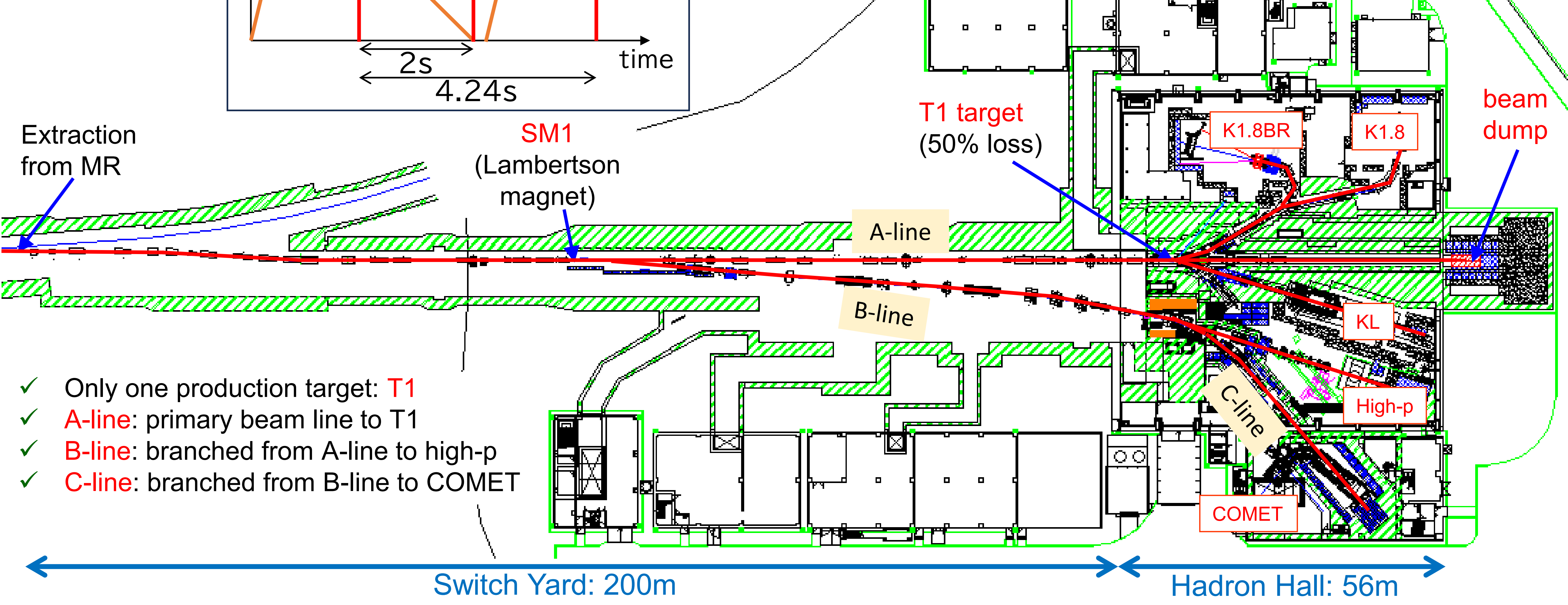




Hadron Experimental Facility (HEF)

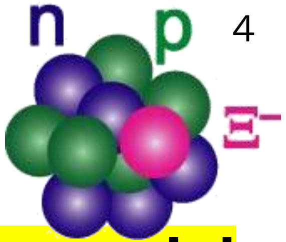
Slow-Extraction Beam



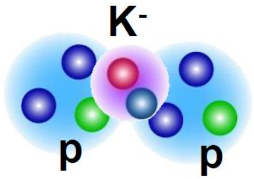


- ✓ Only one production target: T1
- ✓ A-line: primary beam line to T1
- ✓ B-line: branched from A-line to high-p
- ✓ C-line: branched from B-line to COMET

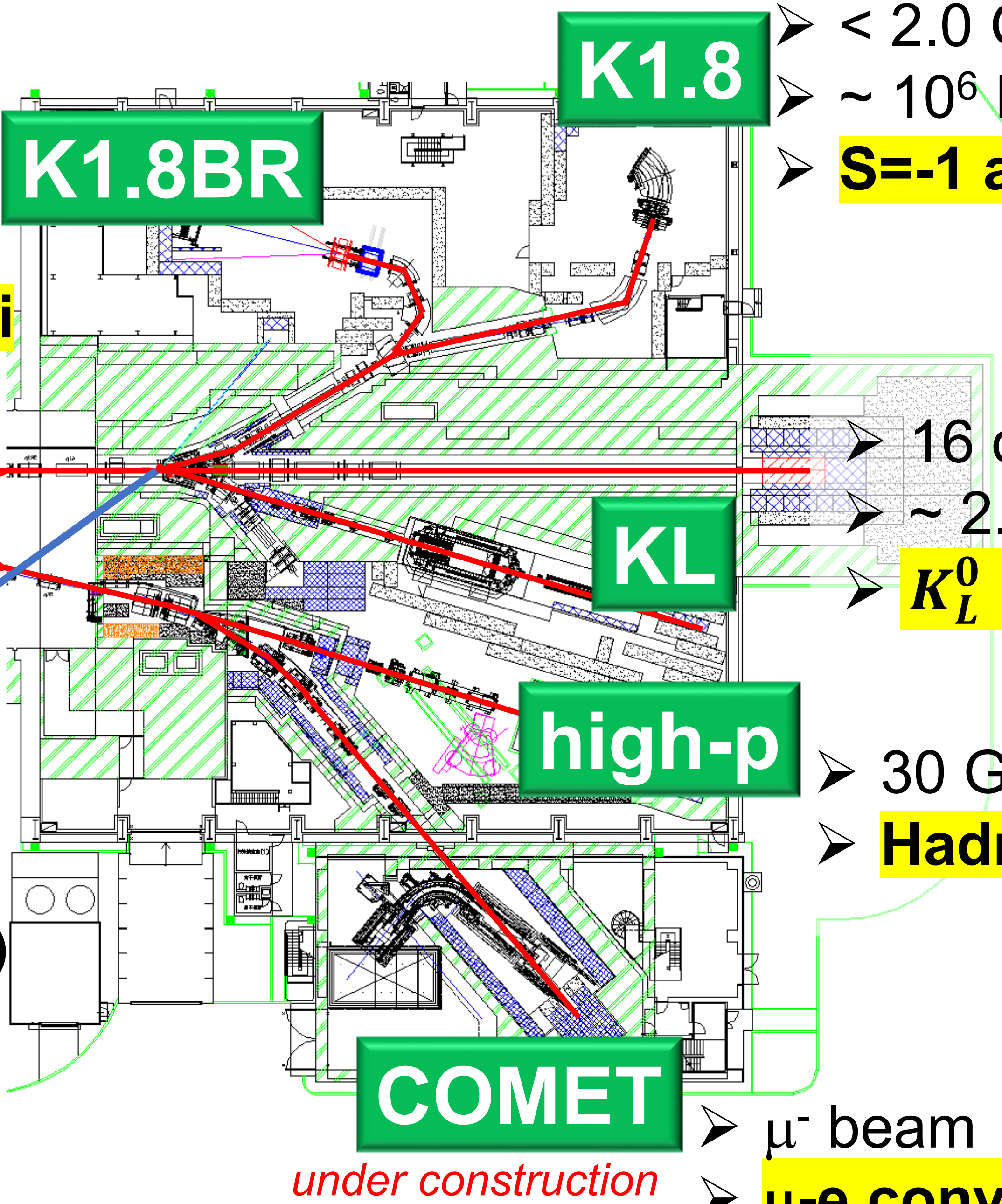
Current HEF

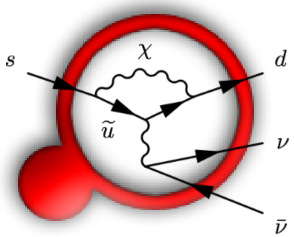


- < 2.0 GeV/c
- ~ 10^6 K^-/spill
- **S=-1 and S=-2 hypernuclei**



- < 1.1 GeV/c
- ~ 5×10^5 K^-/spill
- **Kaon in nuclei**

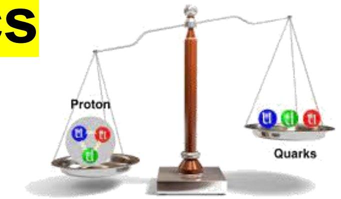




- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K^0_L \to \pi^0 \nu\bar{\nu}$

- Au Target
- Indirectly cooled
- max 115 kW (4.24s)
- 92-kW achieved

- 30 GeV proton ~ 10^{10}
- **Hadron physics**



- μ^- beam
- **μ-e conversion**

From Space to Muons: Advanced Experimental Approaches for New User Engagement

Toward Acquiring New Users

<u>Space Industry Sector</u>

- Utilization of proton beams:
- Radiation tolerance testing of commercial off-the-shelf (COTS) semiconductor devices, including measurements of bit-flip cross sections @ new test beam line (SP beamline)
  - Targeted especially at universities and startup companies developing small satellites.

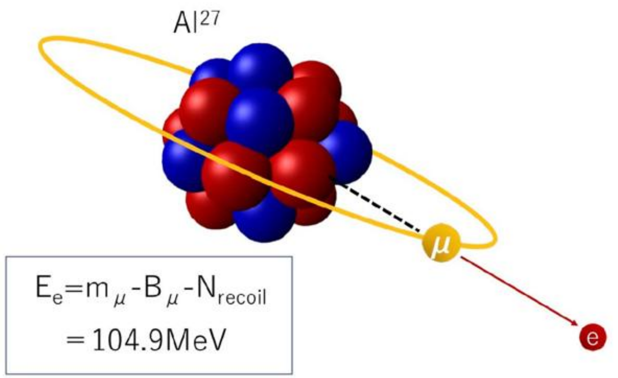
<u>Muon Science Sector</u>

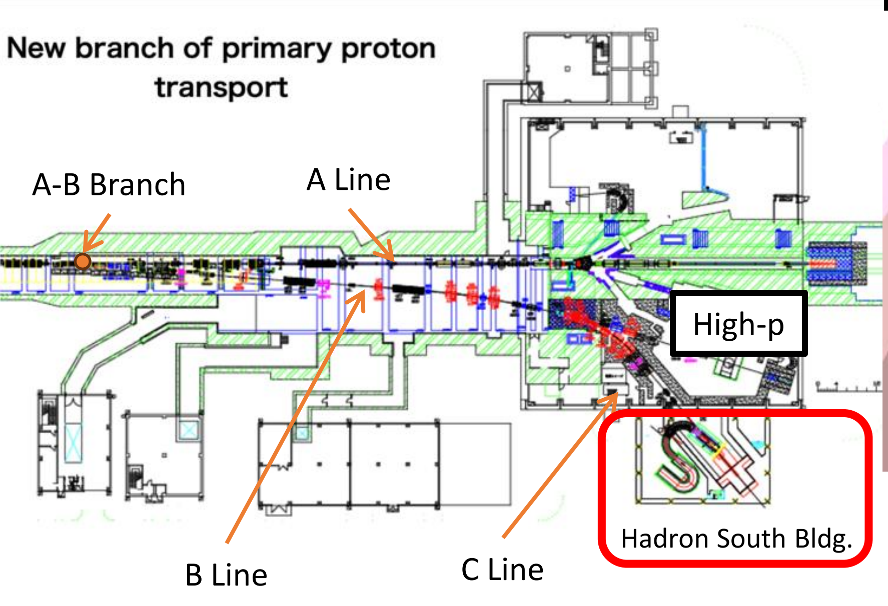
- Multi-purpose utilization of muon beams:
  - Muon-catalyzed fusion@ COMET experimental facility
  - Muography @ μ20 beam line, downstream of the beam dump

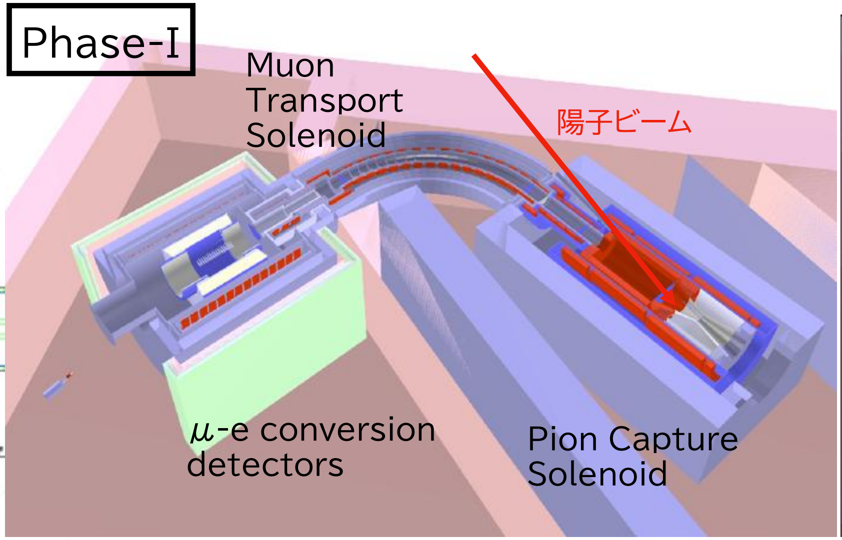
1 High-intensity low-momentum muon beam

Search for Muon-to-Electron Conversion: The COMET Experiment

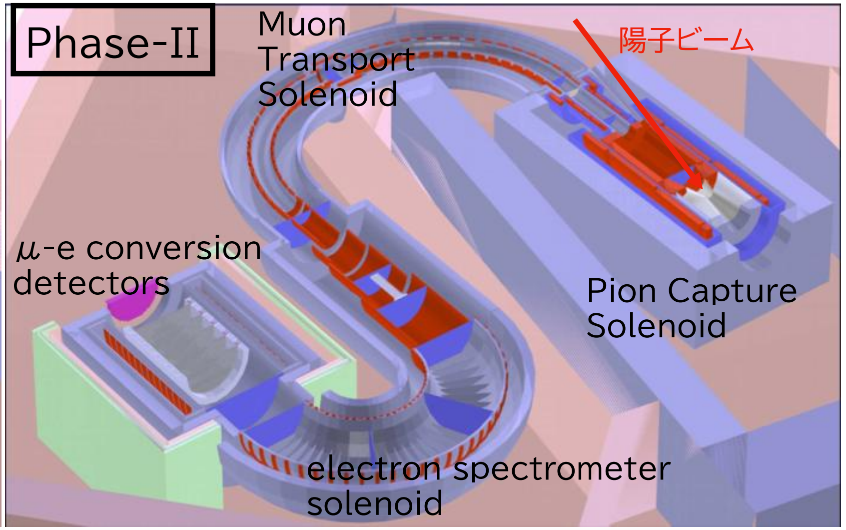
- The COMET experiment aims to search for muon-to-electron conversion without neutrino emission in the field of a nucleus.
  - This process is forbidden in the Standard Model, and its observation would be a clear signal of new physics beyond the Standard Model.
  - The experiment seeks to explore the origin of neutrino mass and other phenomena not explained by the Standard Model.
  - Current experimental upper limit:
    7×10^{-13} (90% Confidence Level) SINDRUM-II at PSI







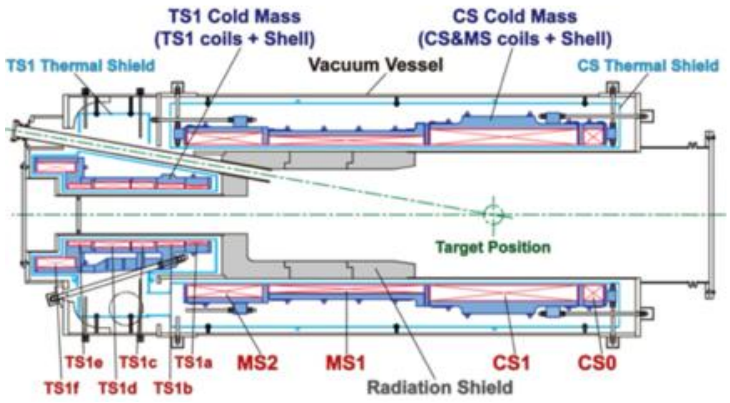
Target sensitivity: $<10^{-14}$
Proton beam power: 3.2kW

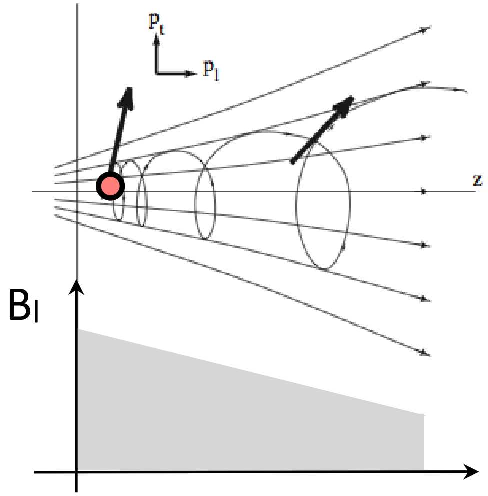


Target sensitivity: $<10^{-16}$
Proton beam power: 56 kW

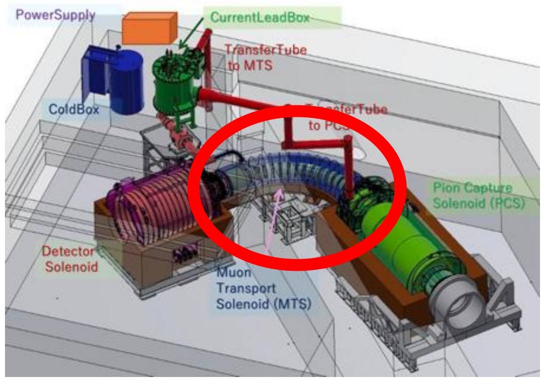
Muon Capture and Transport

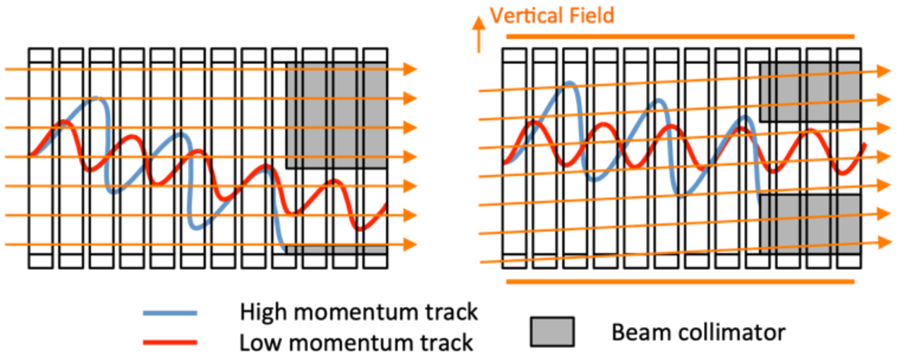
- Pion/muon capture using gradient magnetic field
  - Production target is located in high field region.
  - Alien the direction of secondary particles by a gradient field.





- Muon transport with curved solenoid magnet
  - momentum selection by dipole field and collimator





Muons stopped in exp target: > 10^9 muons/s (Phase-1)

※ Not only stopped muons but also muons with 100-150 MeV/c are available by changing collimator.

COMET Experimental Area

- Radiation shieldings
- Radiation control of exhaust air and wastewater
- Air conditioning (HVAC system)
- Various types of detectors available
  - gas detectors, scintillation detectors, semiconductor detectors, etc.

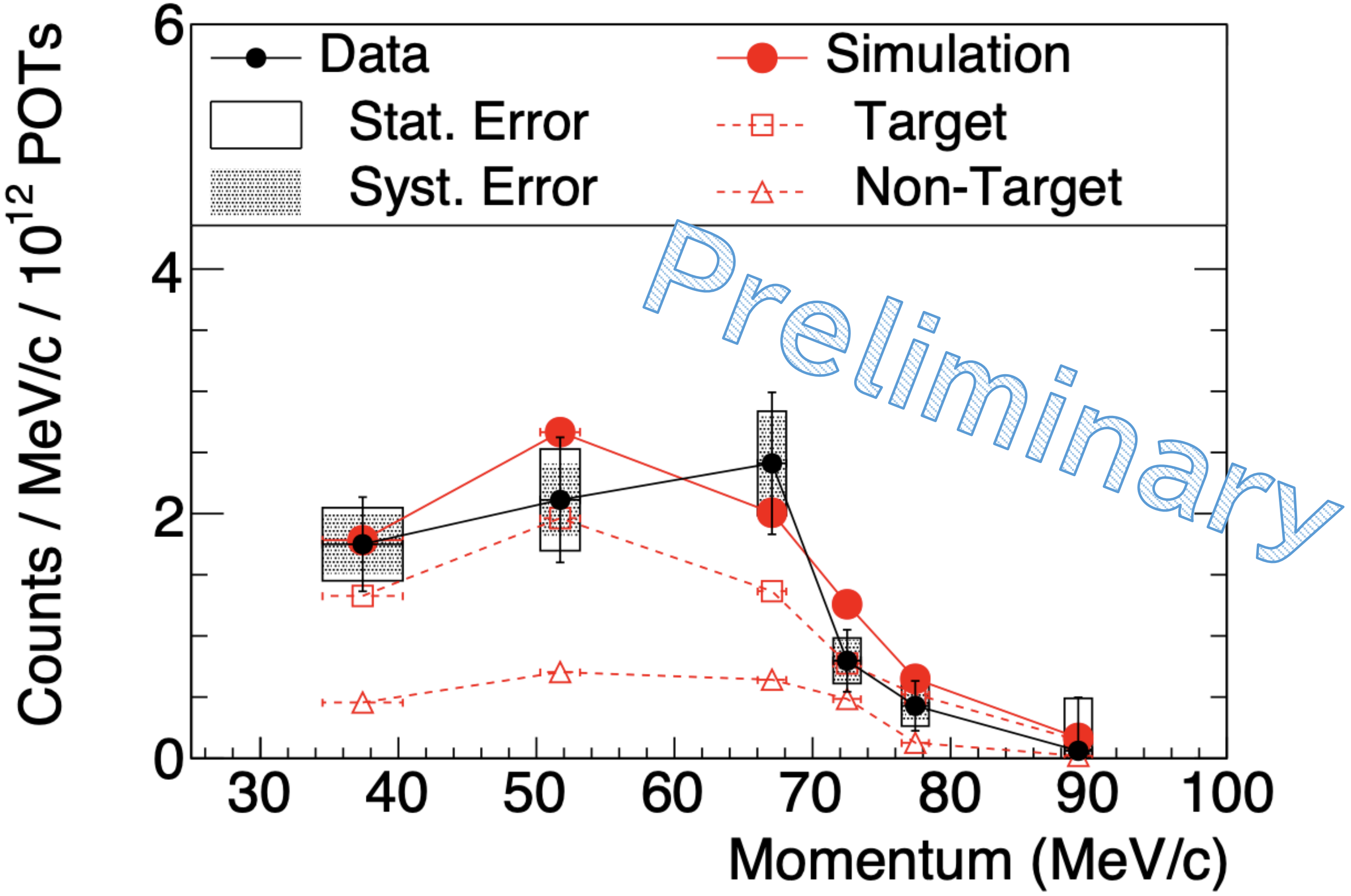
Ideal environment for proof-of-principle experiments on muon-catalyzed fusion

Additionally suitable for:

- Muon tomography for non-destructive imaging of internal structures
- Muonic X-ray elemental analysis for non-destructive compositional analysis of structures

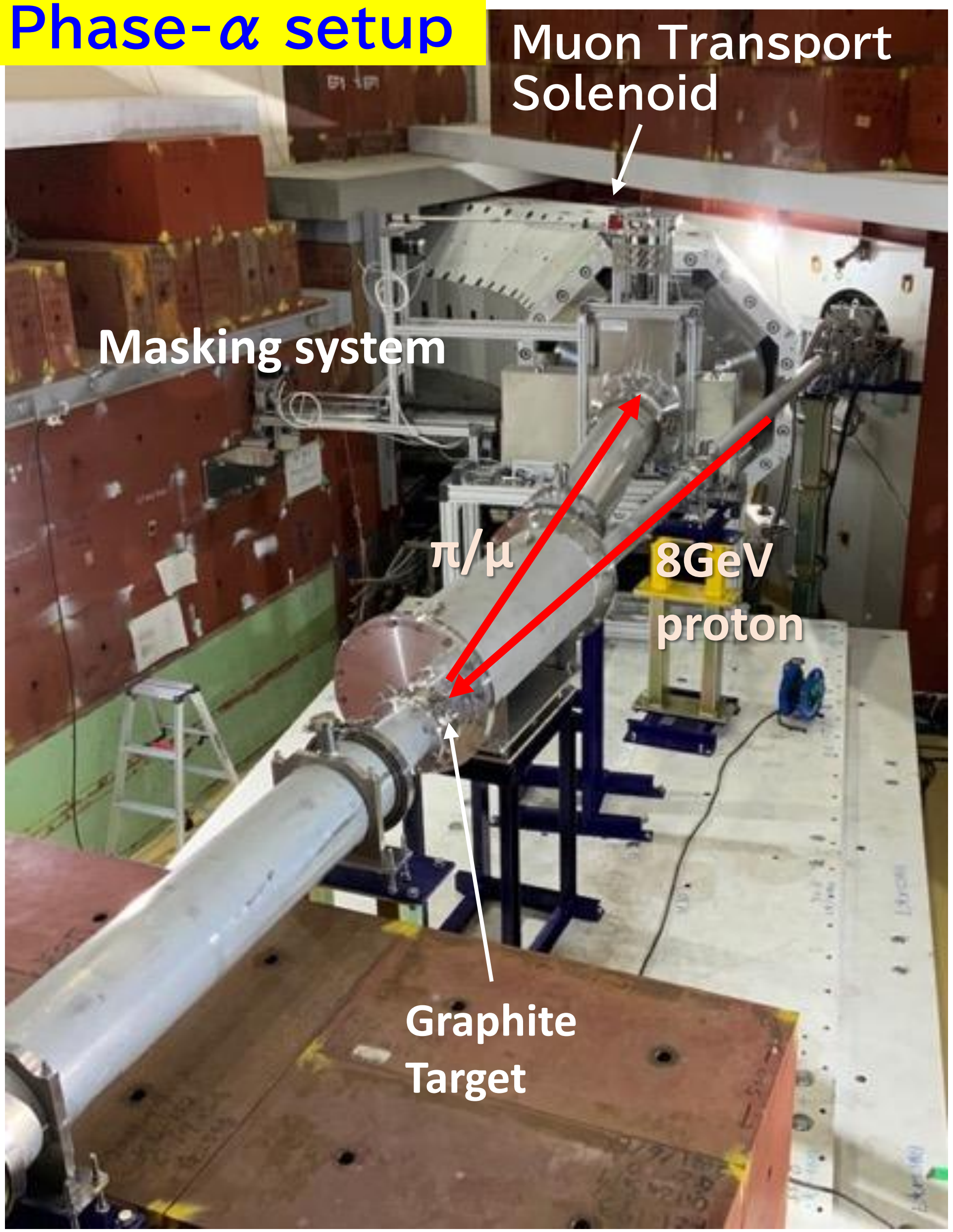
Multi-purpose utilization of muon beams at COMET experimental facility

Preliminary Result of COMET Phase-α



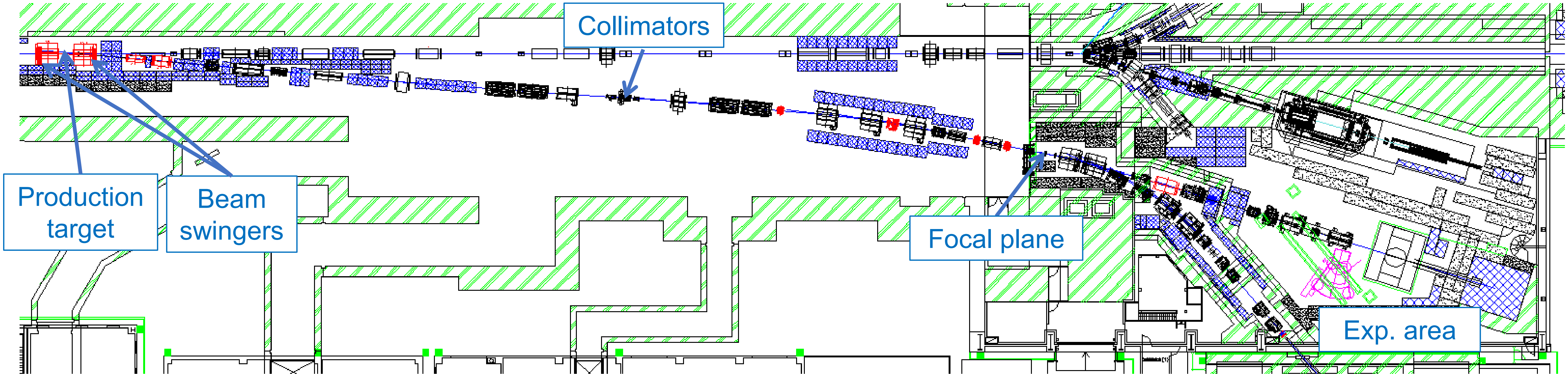
Muon beam has been obtained as expected.

Phase-α setup



2 High-momentum muon beam

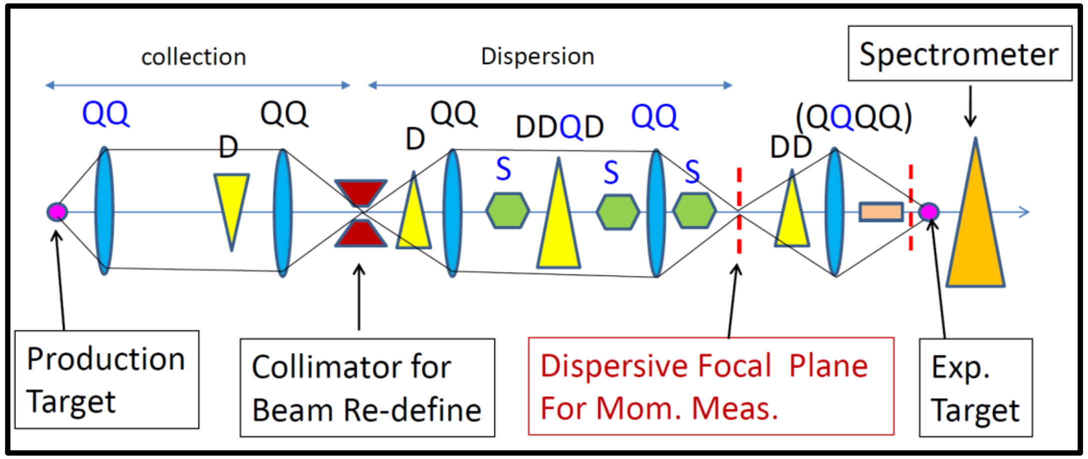
Upgrade Plan of B-Line



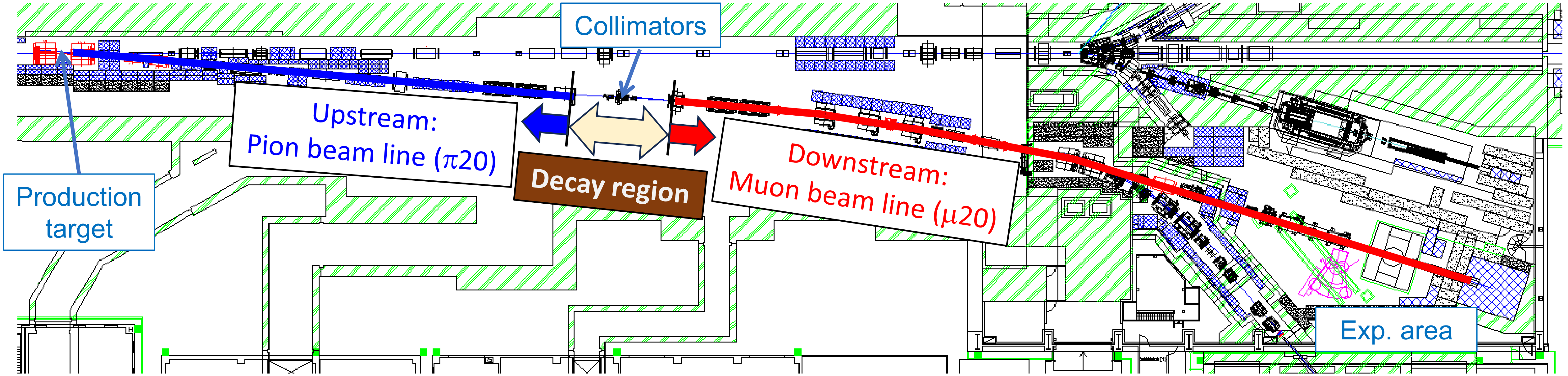
B-line is upgraded to a secondary beam line by adding a production target & some magnets

→ **π20 beam line**

- Momentum: < 20 GeV/c
- Intensity: ～10^8 π^-/spill @20GeV/c (15kW loss, 4.24s cycle)
- $\Delta p/p$: ~ 1/1000



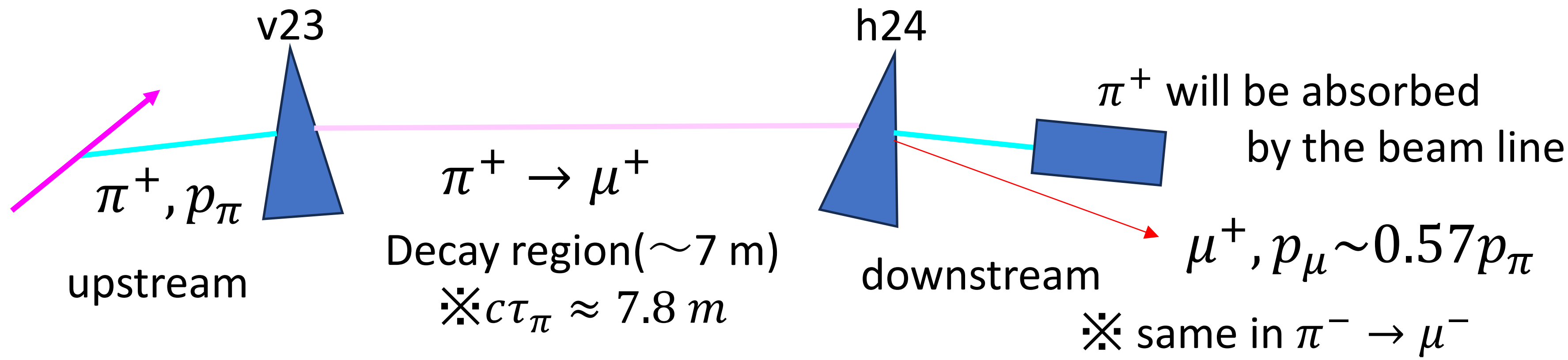
3rd Application of B-Line: μ20



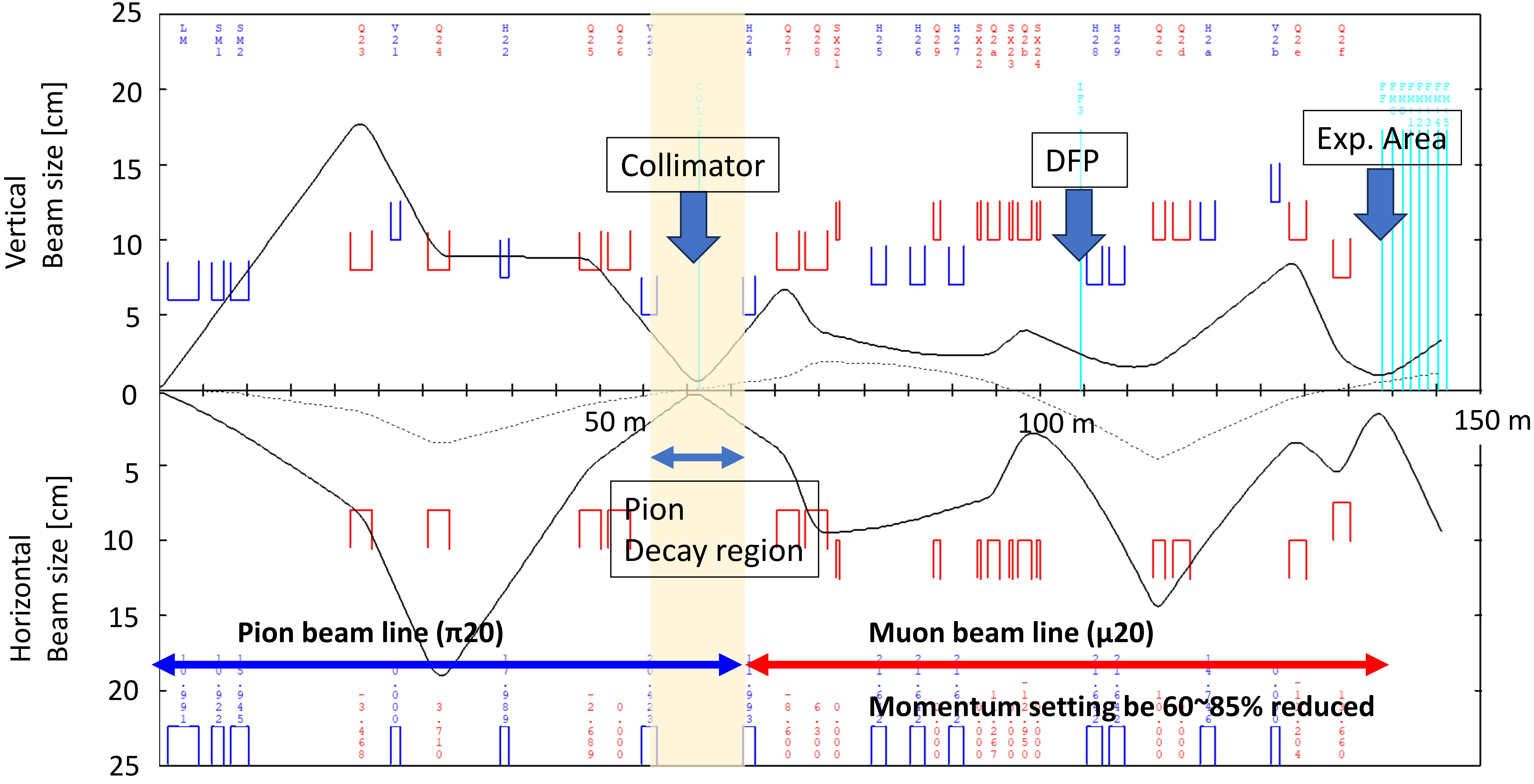
By changing the momentum settings downstream of decay region, only muons decayed from π are transported to exp. area.

→ **muon beam with GeV-region momentum**

Muon tomography of large objects, etc.



Beam Optics of μ20 Beam Line



Staging plan toward constructing π20

Phase 1: Minimum modification of beam line

- Only uses beam loss at Lambertson magnet (< 420W) for secondary-particle production.
  ⇒ ˜10^5 /spill π @ 2–20 GeV/c
- Equipment: polarity-change devices to deliver negatively charged beam.

Phase 2: High-intensity & high-momentum 2ndary beam line (for Ξ spectroscopy)

- Upgrade of A-B branching point (Several kW loss)

⇒ > Several 10^6 /spill π @ 2–20 GeV/c & ˜10^5/spill $K^-/\bar{p}$ @ 5–10 GeV/c

- Equipment: Thin prod. target, swinger magnet, radiation shield around SM and SY region

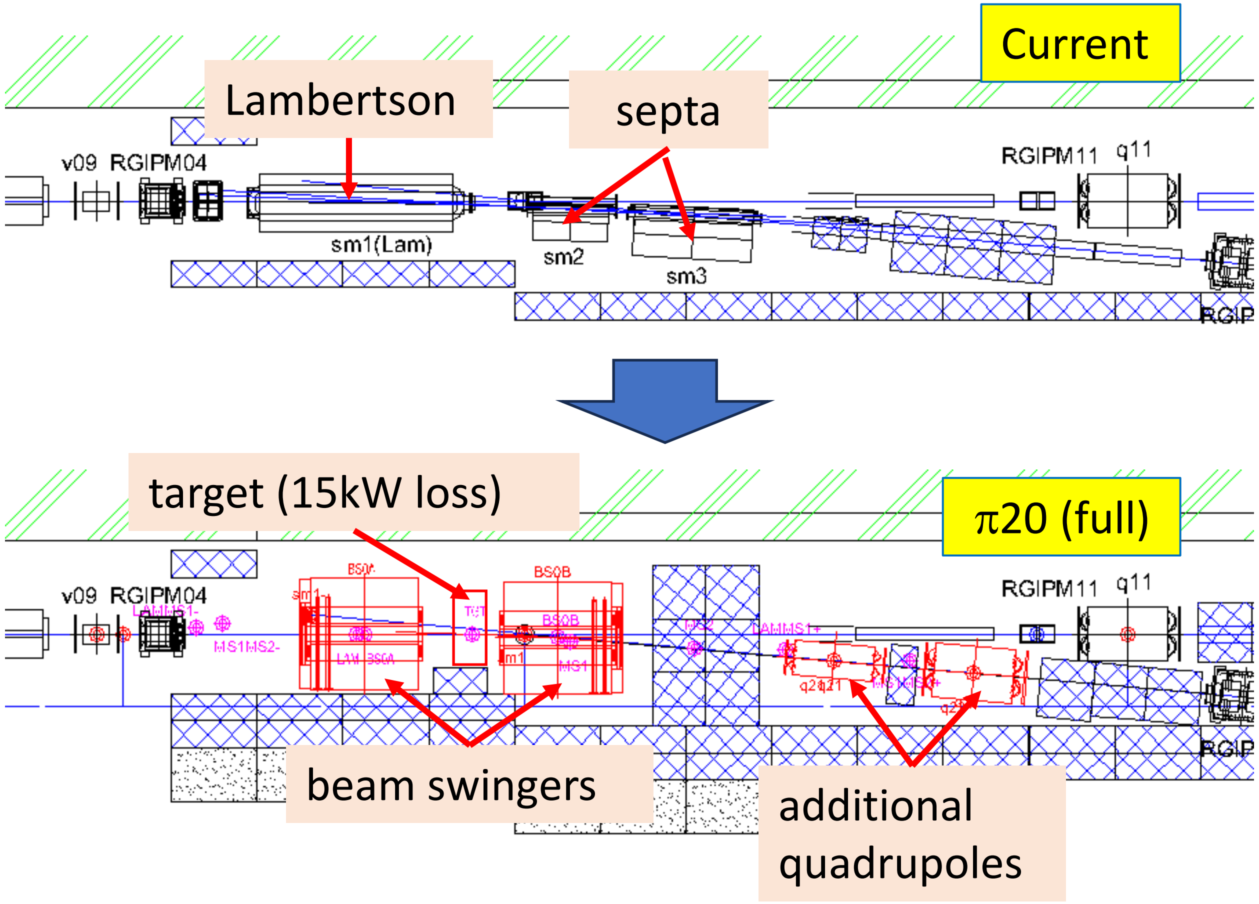
Phase 3: Full π20 beam line (for Charmed baryon and Ω spectroscopy)

- Full specification for 2ndary beam production (˜15 kW loss)

⇒ > 6.0×10^7 /spill π @ 2–20 GeV/c & Several 10^5/spill $K^-/\bar{p}$ @ 5–10 GeV/c

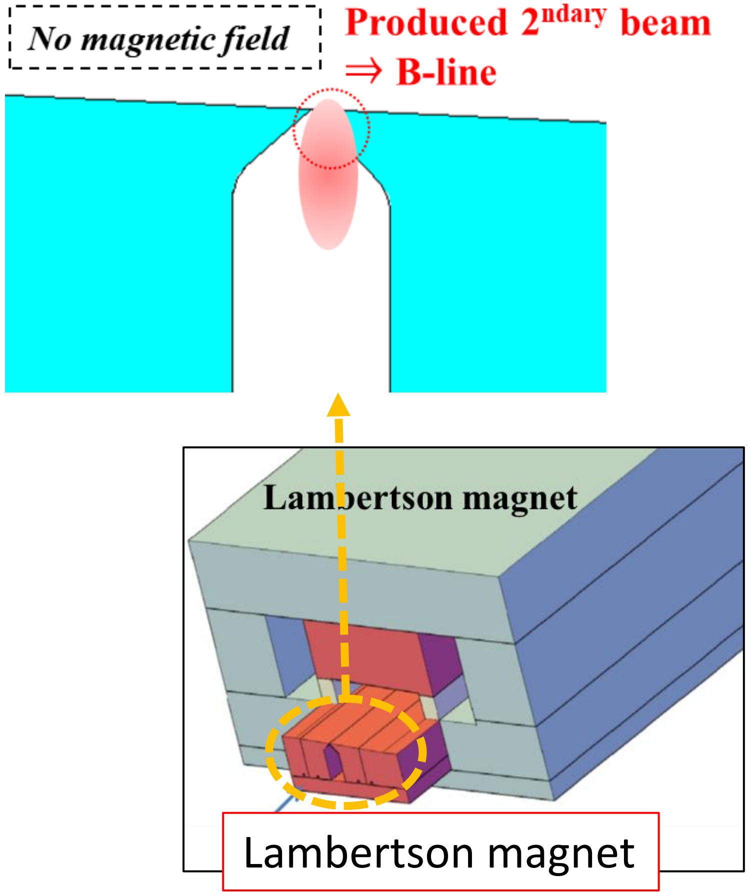
- Equipment: Gas tight prod. target, Completion of radiation shield and additional items

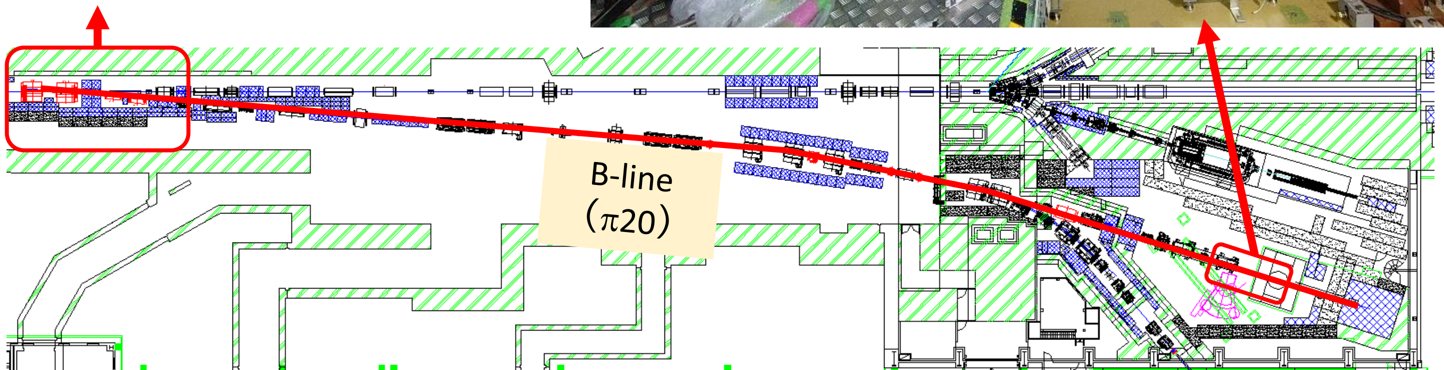
Layout in A-B branching section



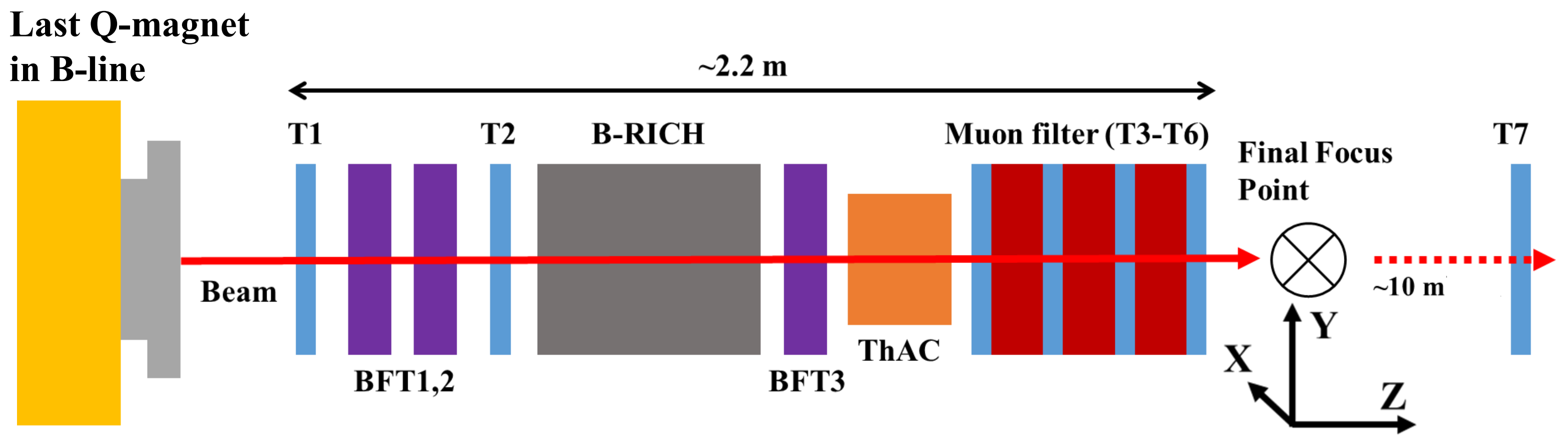
Toward π20/μ20

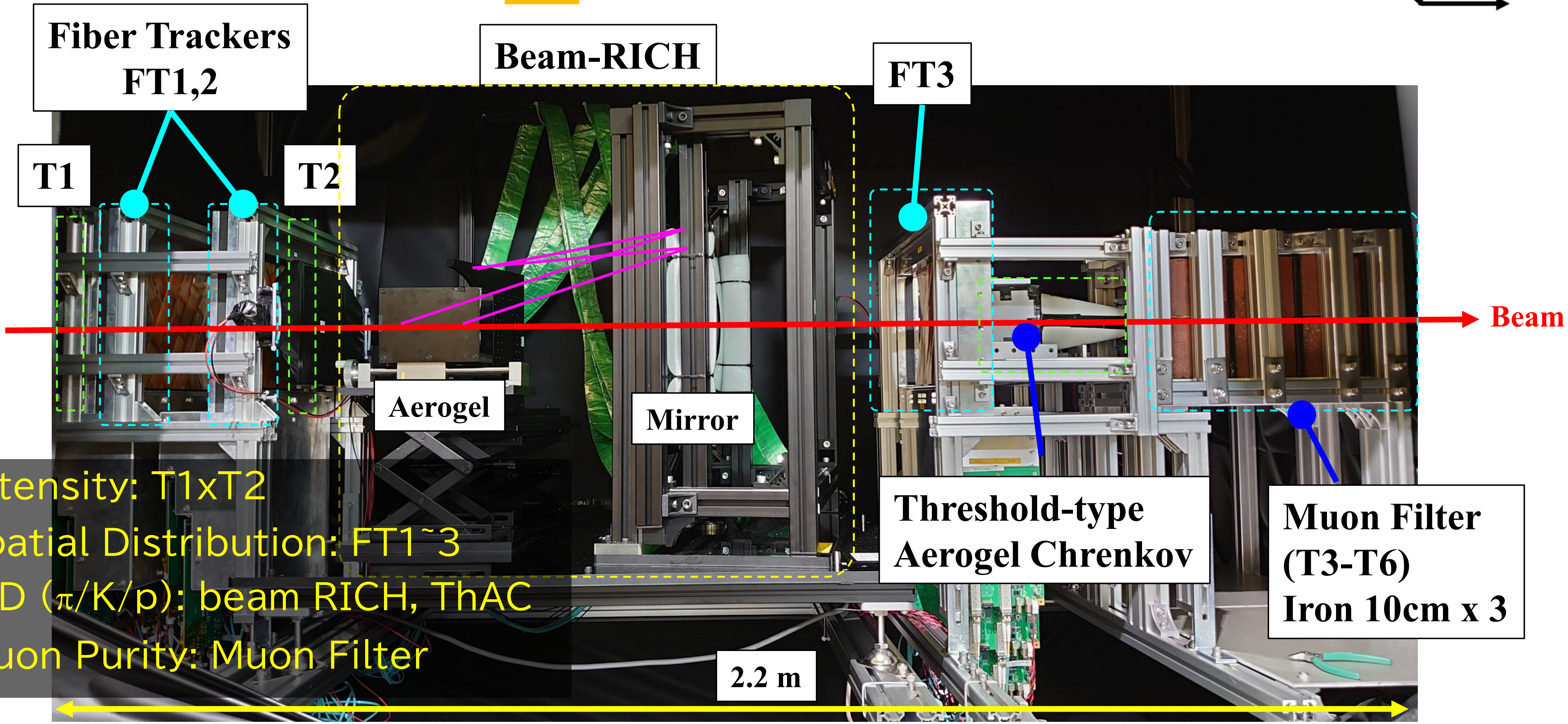
Test experiment **T106** has been carried out to measure positively charged secondary particles from the beam loss at the Lambertson magnet.





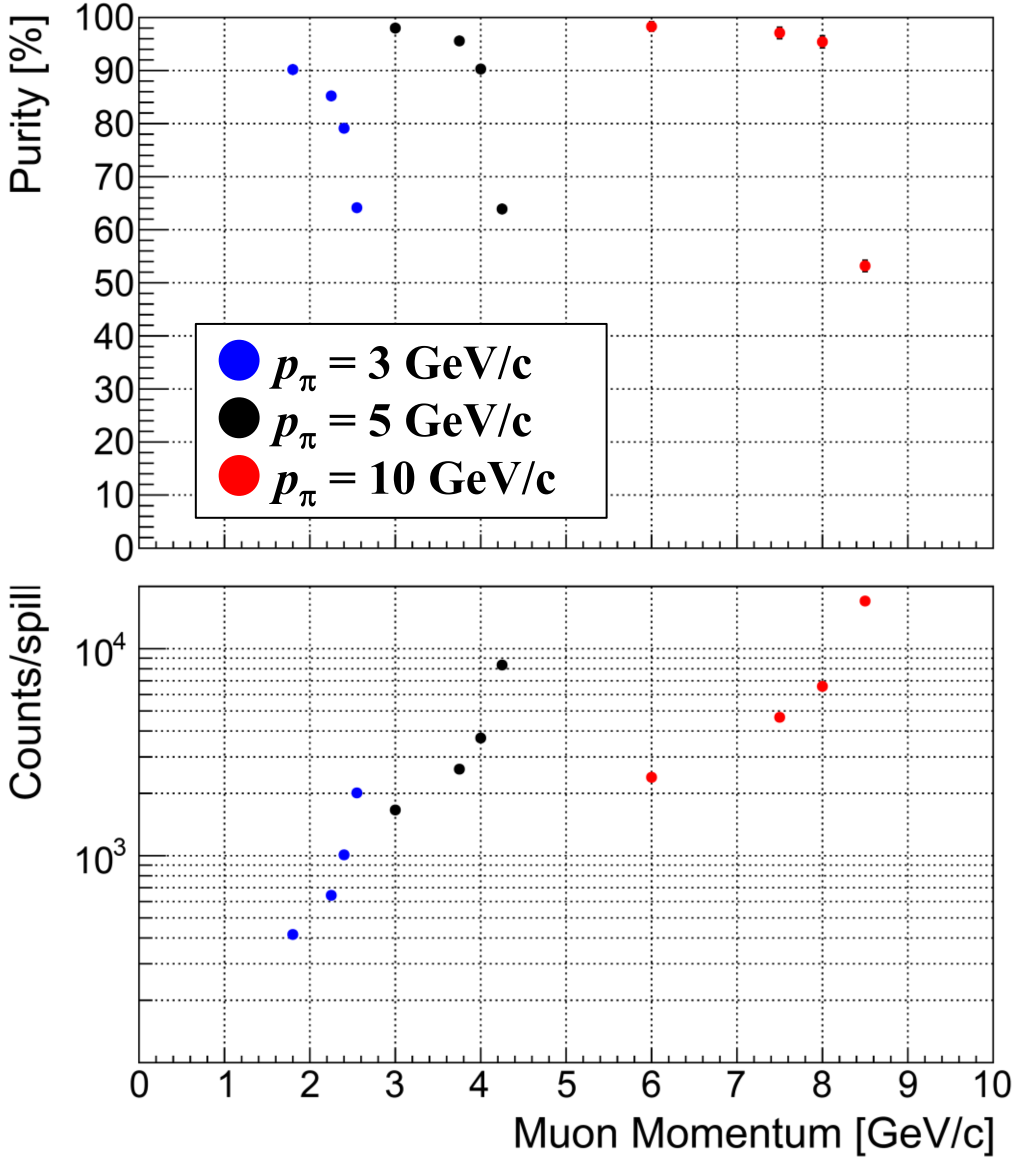
T106 Setup





- Intensity: T1xT2
- Spatial Distribution: FT1~3
- PID (π/K/p): beam RICH, ThAC
- Muon Purity: Muon Filter

Results of T106: Intensity/Purity of Muons



Beam loss at LM: 230 W
Spill repetition: 4.24 s

Several 100 ～ several 1000 muons/spill (= 100 ～ 1000 muons/s) with the purity of >90%

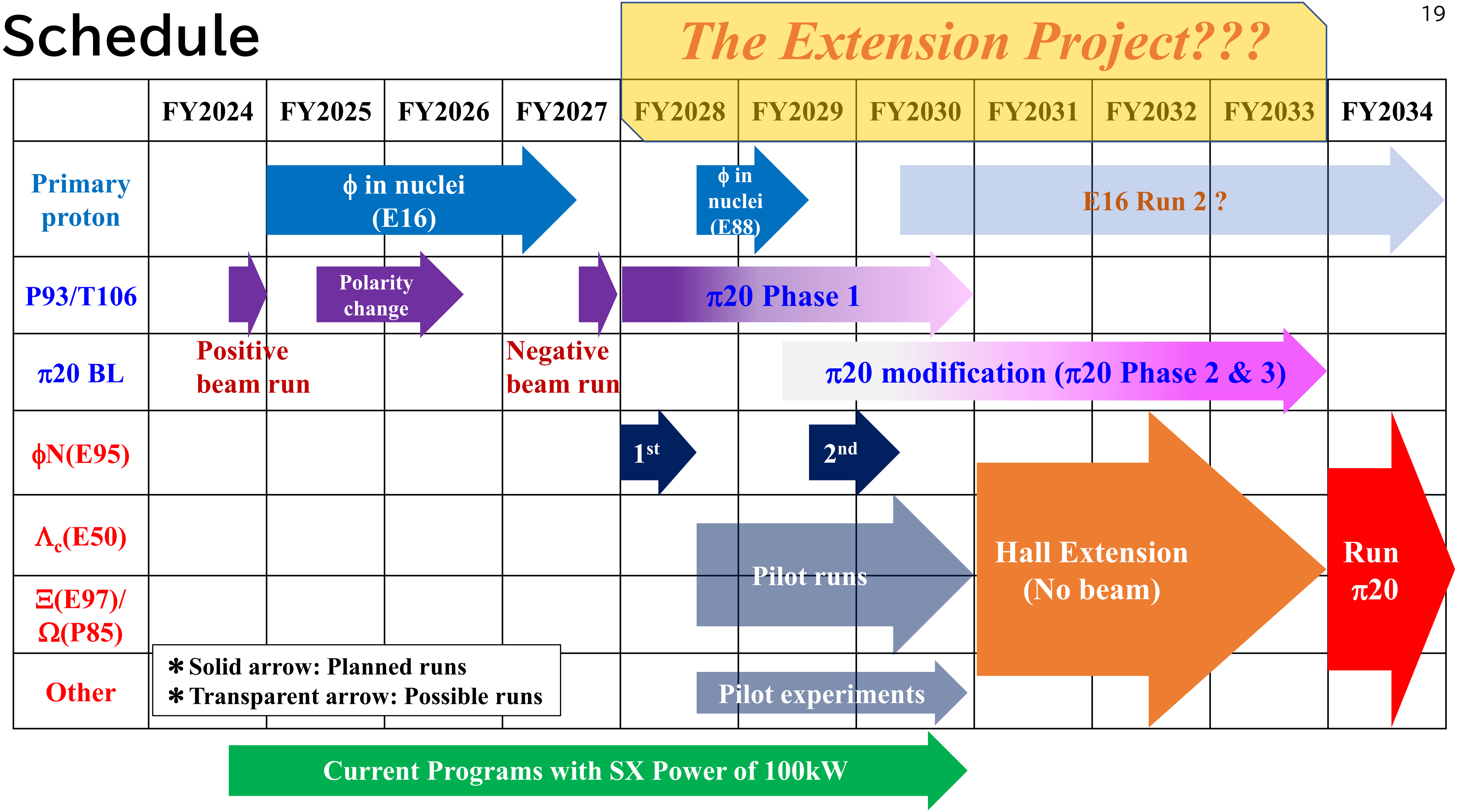
cf. π20 mode (hadron beam) intensity

3 GeV/c:	~200 k/spill
5 GeV/c:	~600 k/spill
10 GeV/c:	~1400 k/spill

π^+/p: ~ 1/1

※ Intensity will be increased by 2 orders of magnitude at Phase-3 (15kW-loss target)

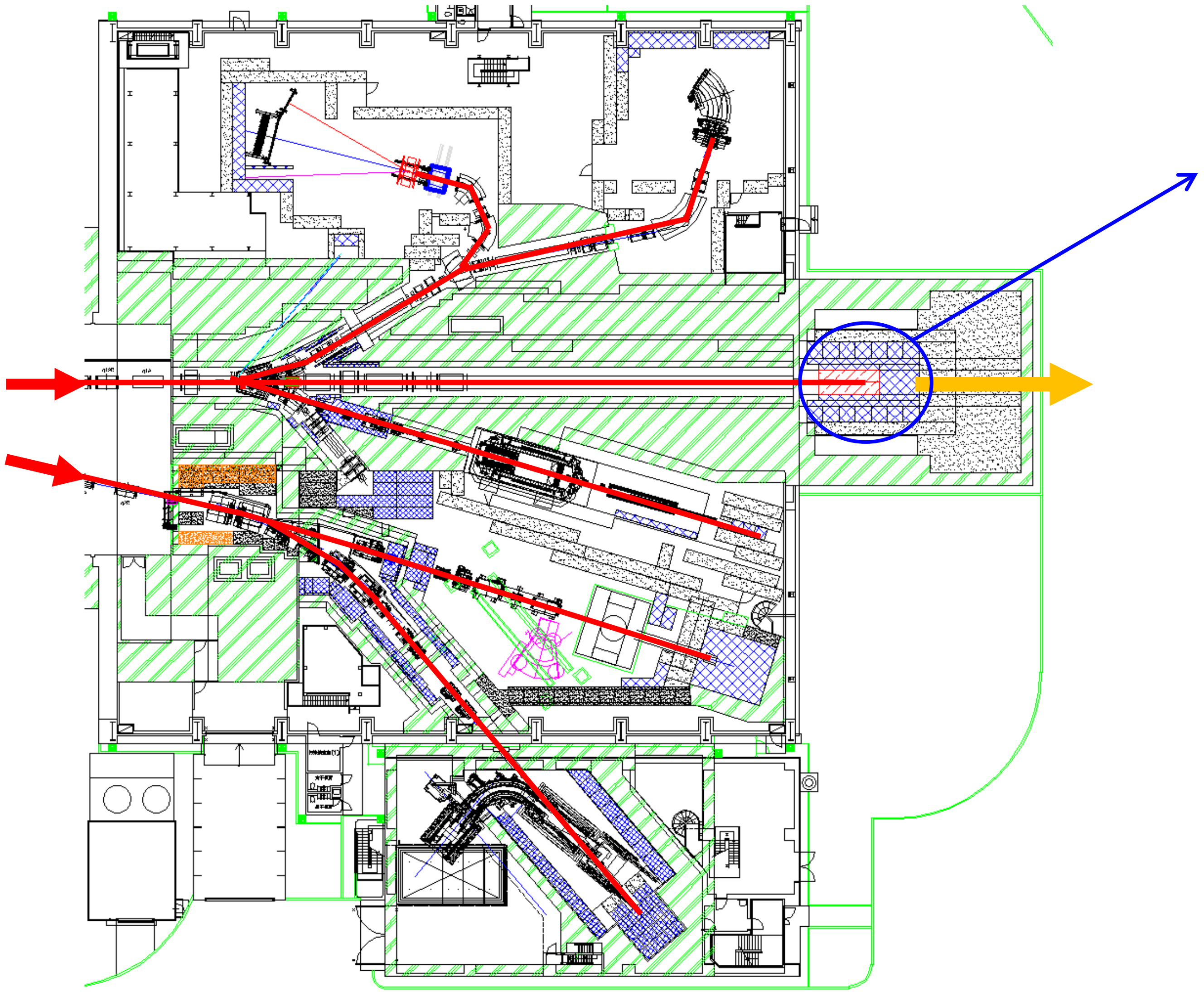
Schedule


The Extension Project???
FY2024
FY2025
FY2026
FY2027
FY2028
FY2029
FY2030
FY2031
FY2032
FY2033
FY2034
Primary proton
ϕ in nuclei (E16)
ϕ in nuclei (E88)
E16 Run 2 ?
P93/T106
Polarity change
π20 Phase 1
π20 BL
Positive beam run
Negative beam run
π20 modification (π20 Phase 2 & 3)
ϕN(E95)
1st
2nd
Λc(E50)
Ξ(E97)/ Ω(P85)
Pilot runs
Hall Extension (No beam)
Run π20
Other
Pilot experiments
✱Solid arrow: Planned runs
✱Transparent arrow: Possible runs
Current Programs with SX Power of 100kW

3. White muon beam

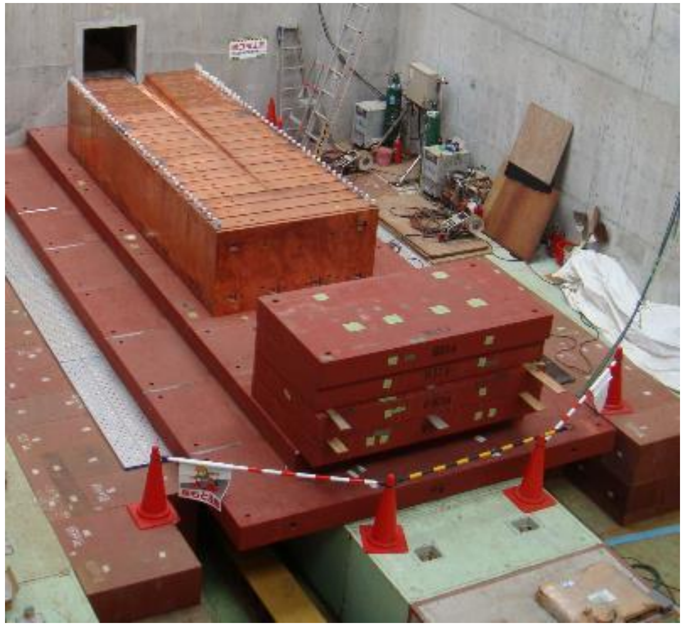
Muons from Primary Beam Dump

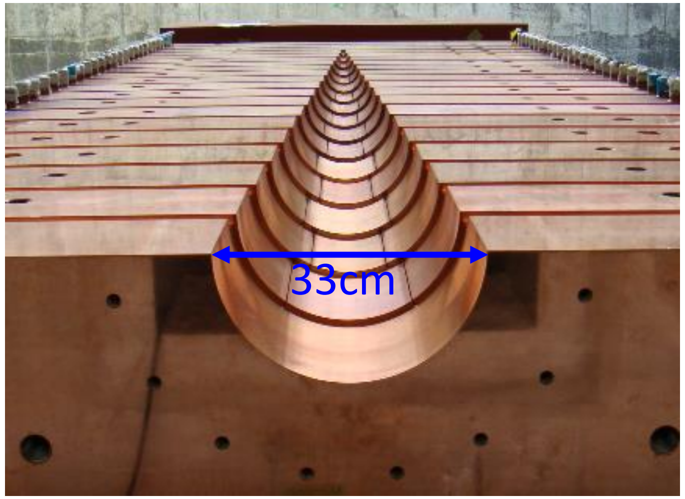
primary proton beams



Dump core (Cu, 2m*2m*5m)

※lower half



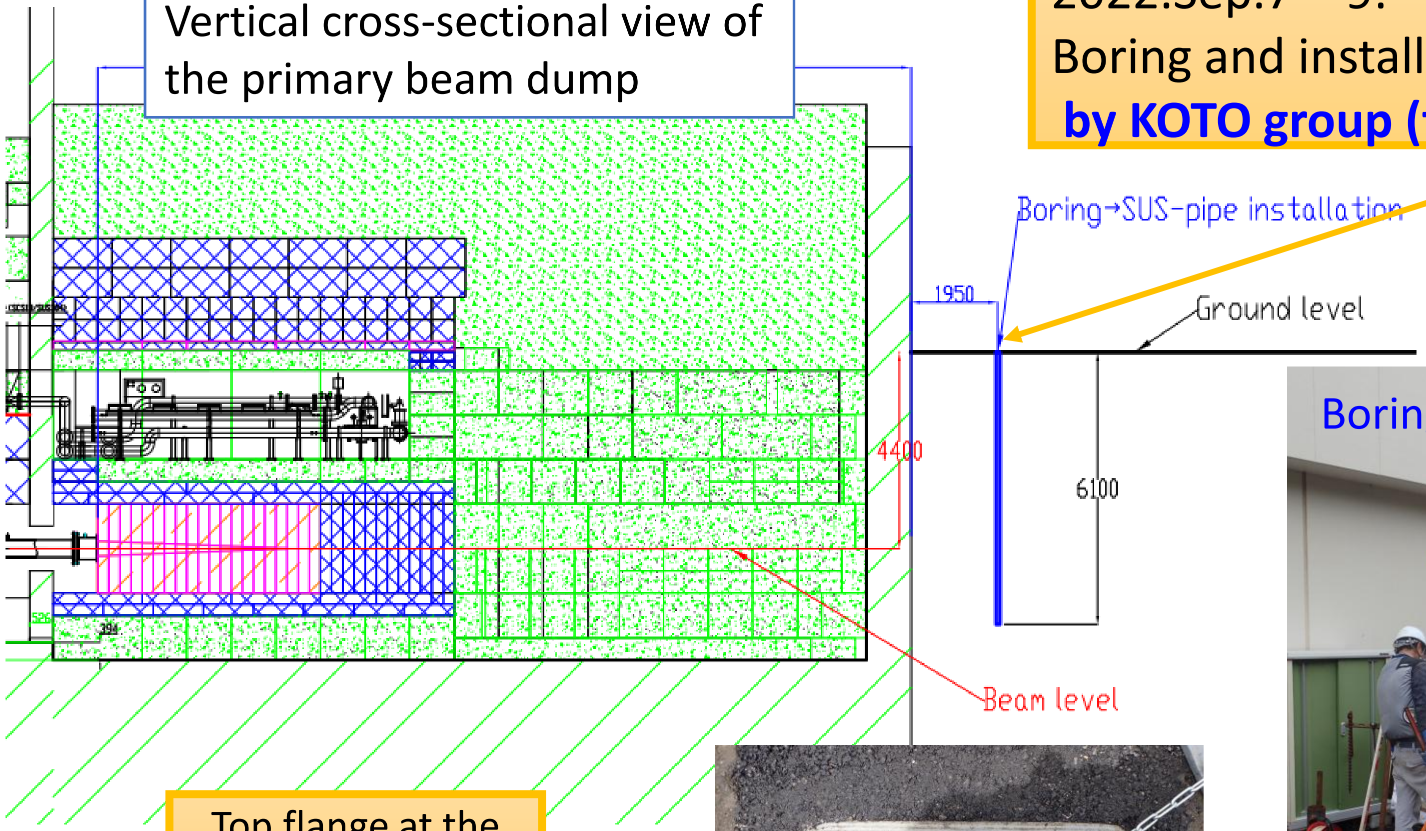


Preliminary measurement of radiation dose due to punch-through muon downstream of primary beam dump

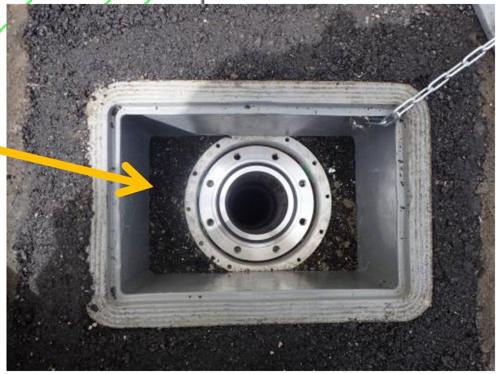
2022.Sep.7～9:
Boring and installing a 6.1m-long SUS-pipe
by KOTO group (for KOTO2 BG measurement).

Vertical cross-sectional view of the primary beam dump

Primary proton



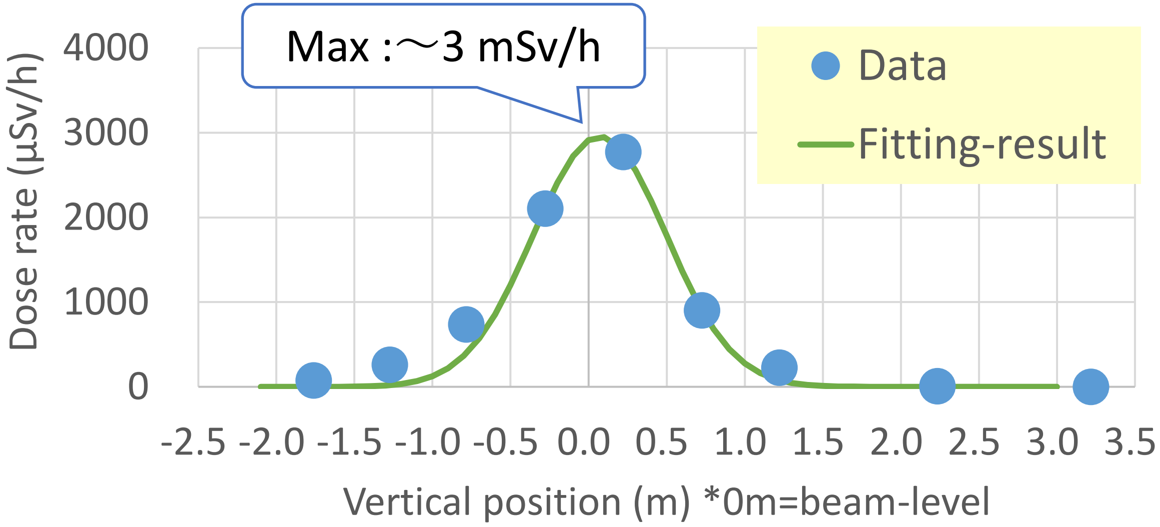
Top flange at the ground level



Muon Flux Downstream of Beam Dump

Measurement by personal dosemeters (50-kW x 8-hrs)

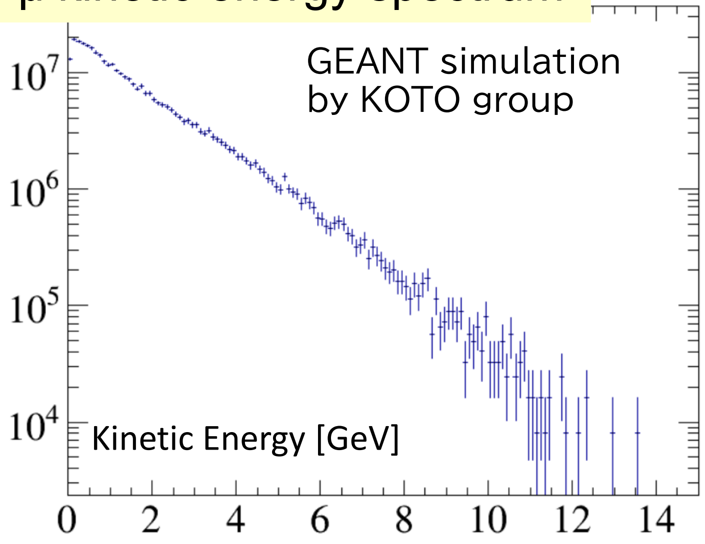
Data for 50-kW proton beam



- **Measured muon flux at a proton beam power of 50 kW: ~2.6 × 10^3 muons/cm²/s**
- Beam profile(FWHM) ≈ 1 meter
- No selection applied on charge or momentum

→ Resulting in a **white muon beam**

μ kinetic energy spectrum



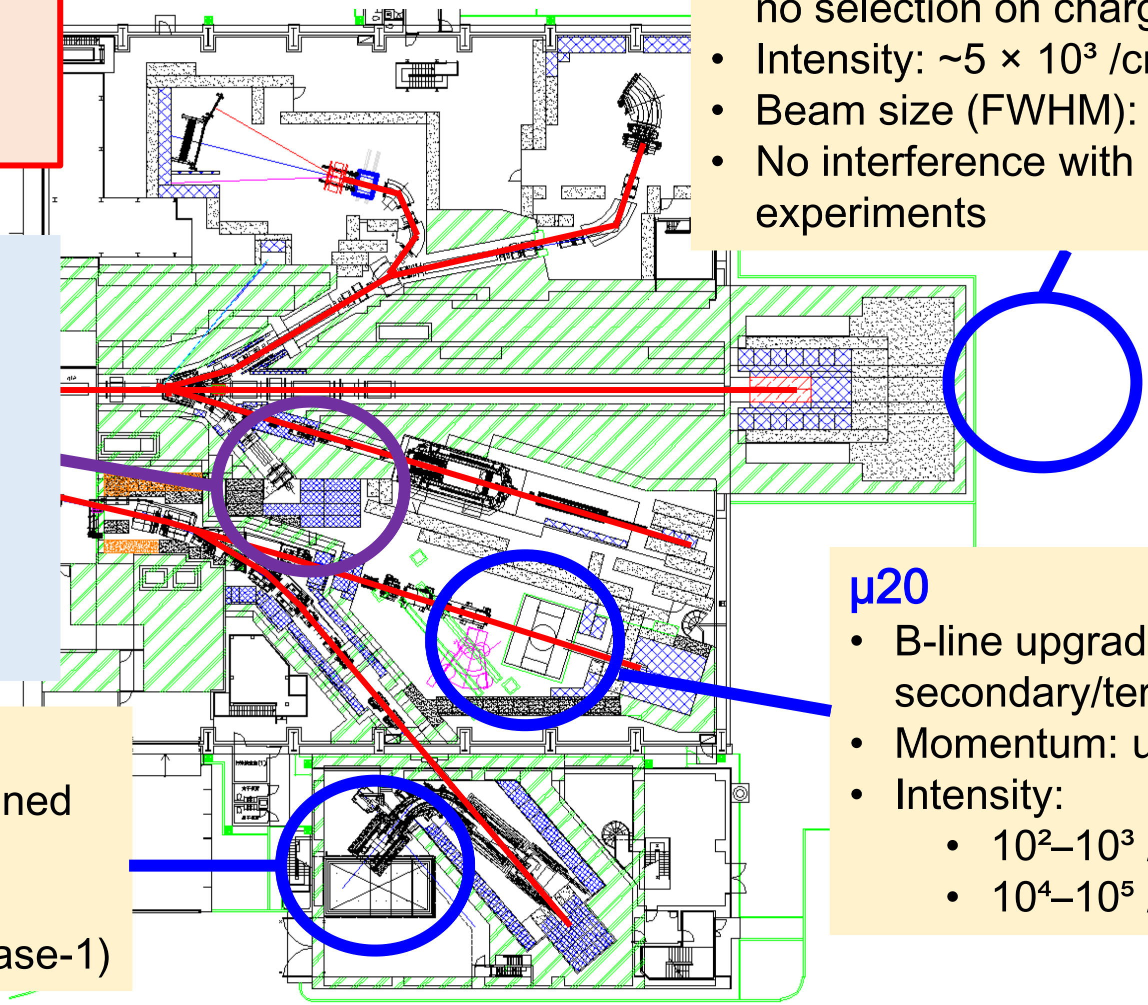
Potential Applications:
Muography, Soft Error Testing

This muon field provides a valuable resource for both fundamental research and practical applications without interfering with primary experimental programs.

Summary: Diverse Proton and Muon Beamlines for Fundamental and Applied Research

Common Features
- DC (Continuous) Muon Beam enabled by slow extraction
- Coincidence measurements possible

→ Clear differentiation from the MLF Muon Facility (optimized for pulsed beams)



Behind the Beam Dump
- White muon beam (broad spectrum with no selection on charge or momentum)
- Intensity: ~5 × 10^3 /cm²/s
- Beam size (FWHM): ~1 meter
- No interference with primary physics experiments

SP (Secondary proton beamline for space application)
- Separated charged secondary beamline capable of providing high-purity proton and meson beams
- Momentum: < 1.1 GeV/c
- Intensity: > 10^7 protons/s
- Beam size: σ_x = 2.2–5 cm, σ_Y = 0.5–5 cm

μ20
- B-line upgraded as a secondary/tertiary beamline
- Momentum: up to 16 GeV/c
- Intensity:
  - 10^2–10^3 /s (Phase-1)
  - 10^4–10^5 /s (Phase-3)

COMET
- Dedicated beamline specifically designed for the COMET experiment
- Momentum: < 150 MeV/c
- Intensity: > 10^9 stopped muons/s (Phase-1)