

# WE03T03 A PORTABLE MUON SOURCE FOR ARTIFICIAL MUON MUOGRAPHY

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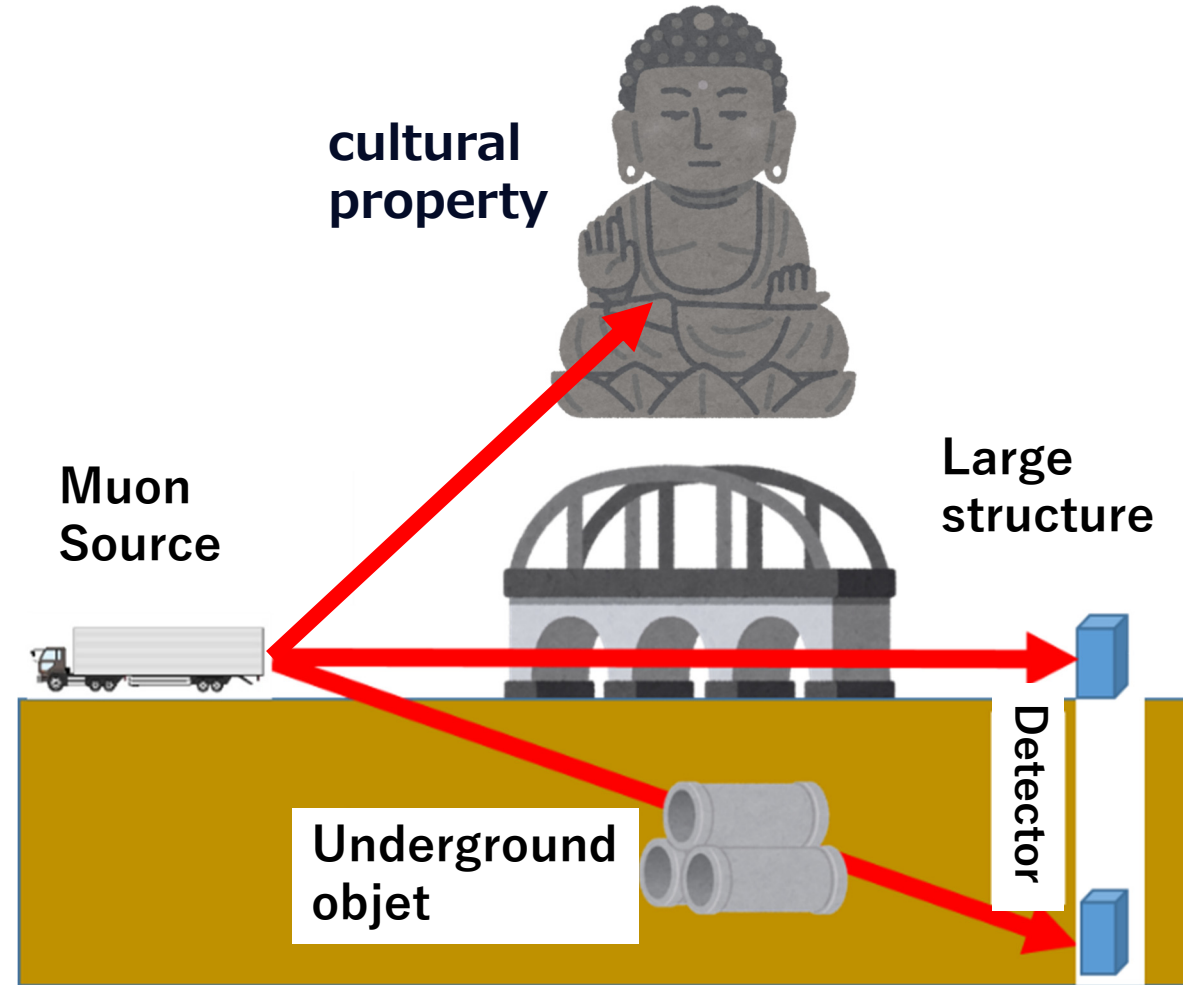


# Introduction

- A muon is a light particle with a mass of  $105.6 \text{ MeV}/c^2$  (207 times that of an electron).
- They are produced by the decay of pions:  $\pi \rightarrow \mu + \nu$ .
- Due to their greater mass, they are less prone to Bremsstrahlung than electrons. Ionization is the primary mechanism.
- Consequently, muons travel farther through matter than electrons, making them suitable for imaging large objects.
- Muon-induced X-rays are high-energy and easy to detect. Furthermore, since depth can be controlled by energy, it is possible to measure depth-dependent distributions of elements.

# A Portable Muon Source

- Currently, research focuses primarily on natural (low rate) and artificially generated muons produced in laboratories (less availability).
- Portable muon sources will make it possible to use high-intensity artificial muon beams even outdoors.
- Non-destructive inspection: infrastructure, cargo containers, nuclear reactors, and other large structures.
- Elemental analysis using muon-induced X-rays: cultural properties, works of art, and historical artifacts.



# Preventive Maintenance Using Muons

- The aging of social infrastructure built worldwide in the 1950s and 1960s is a major challenge.
- There is a shortage of the funds, personnel, and materials needed for renewal, making a blanket replacement impossible.
- It is essential to assess the condition of infrastructure and carry out efficient maintenance and renewal (preventive maintenance).
- The Ministry of Land, Infrastructure, Transport and Tourism estimates that preventive maintenance can reduce maintenance costs by 30% to 50%.
- Muon non-destructive inspection, in addition to X-rays and neutrons, contributes to the implementation of preventive maintenance.



## Minneapolis Highway Collapse

**Opened in 1967, the highway collapsed during the evening rush hour, killing 13 people and injuring 145.**

# Configuration of a Portable Muon Source

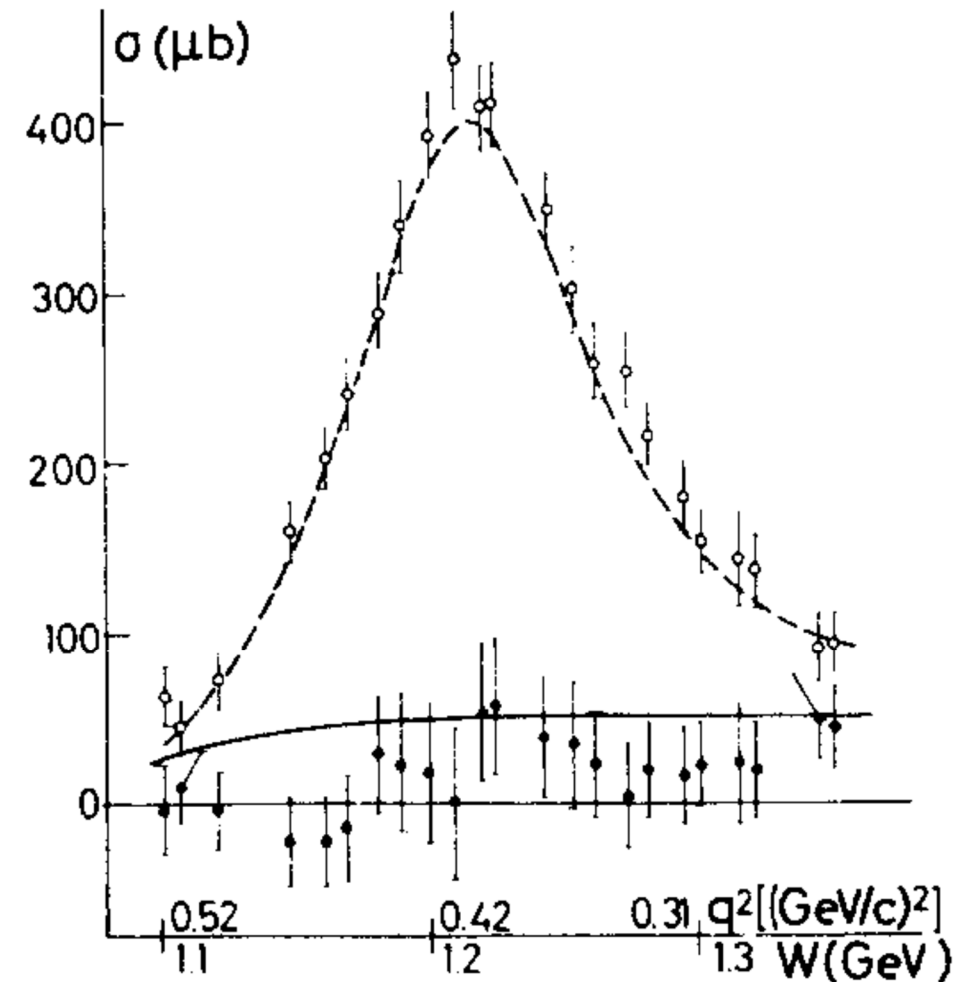
**Muon Driver**  
400 MeV 10 $\mu$ A  
Electron Accelerator

**Muon Target**  
 $e p \rightarrow \Delta \rightarrow \pi \rightarrow \mu$

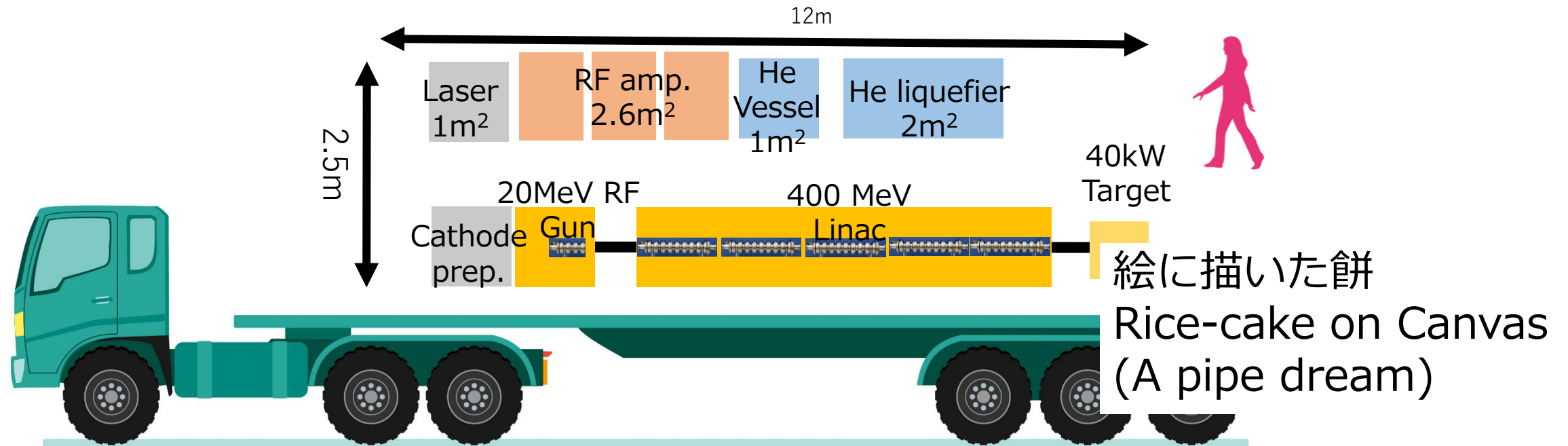
**Muon Accelerator**  
400 MeV

# Muon Generation

- For portable systems, muon production using an electron beam—which is easy to accelerate—is advantageous.
- Generally, the number of muons produced increases as energy rises, but efficient muon production is possible by utilizing the Delta resonance (1232 MeV).
- The threshold for electron beam energy is  $\sim 259$  MeV. Efficient muon production occurs around 400 MeV.
- A  $100 \mu\text{A}$ , 400 MeV electron beam is assumed.



# ASLMG Advanced SC Linac Muon Generator

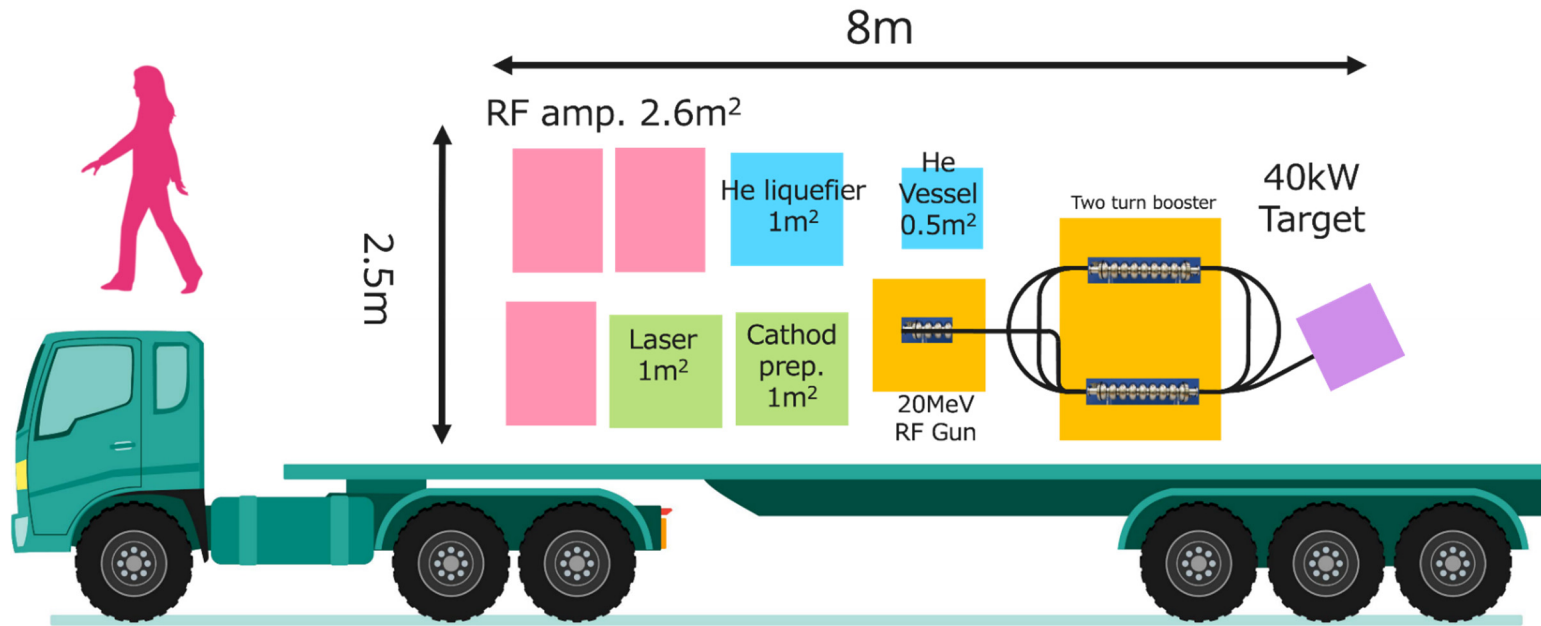


- Operating a superconducting accelerator with an effective length of 5 m at 80 MV/m yields 400 MeV.
- This high gradient is made possible by a multilayer structure consisting of Nb<sub>3</sub>Sn and an insulator.
- This technology has not yet been demonstrated.



# DSMMG

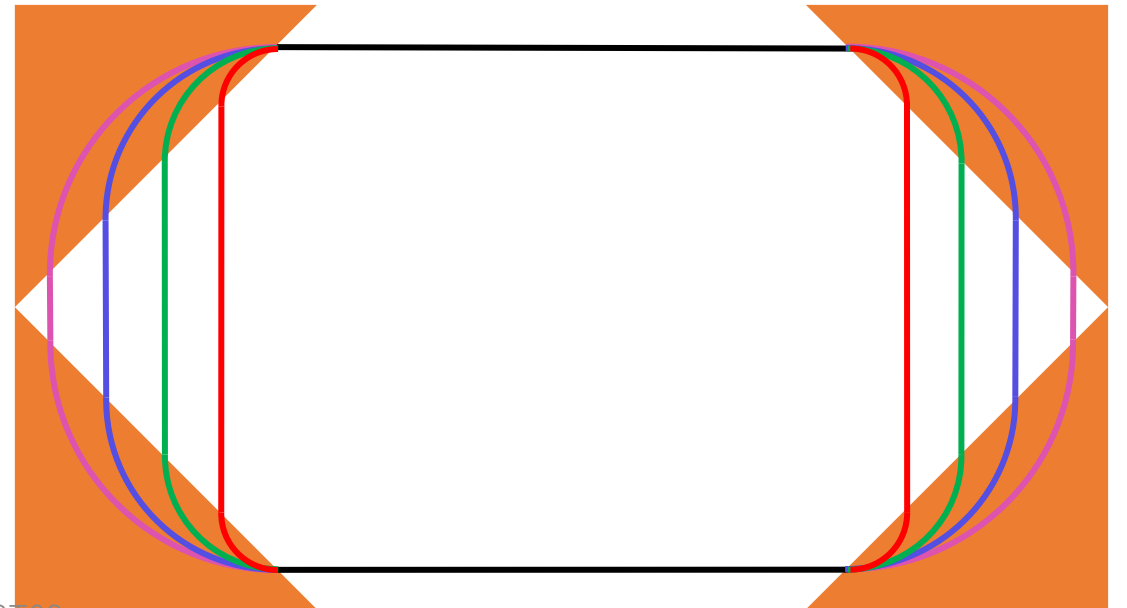
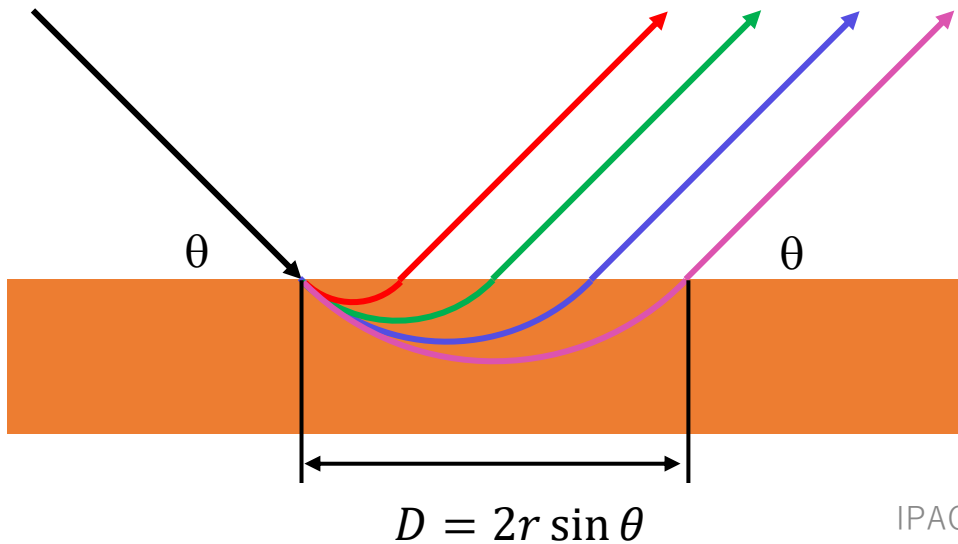
## Double-Sided Microtron Muon Generator



- This method is based on established technology.
- It allows for a shorter length than the previous ASLMG.

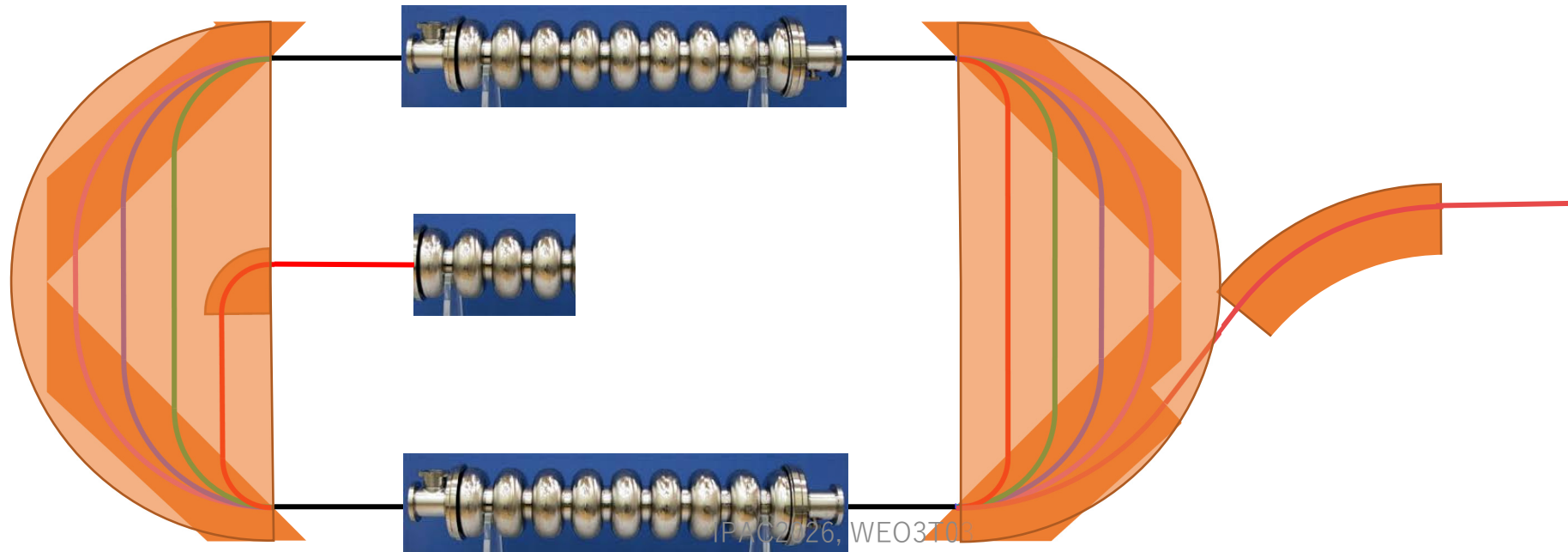
# Single-side bending

- Consider a particle entering a dipole magnet at an angle and exiting on the same side.
- Regardless of the energy, the angle of incidence equals the angle of reflection. The orbits shift parallel to each other depending on the energy.
- By combining four deflection fields that bend the particle by  $90^\circ$  (with an angle of incidence of  $45^\circ$ ), a circular orbit can be created. On two sides, all orbits coincide; on the remaining sides, the orbits shift depending on the energy.

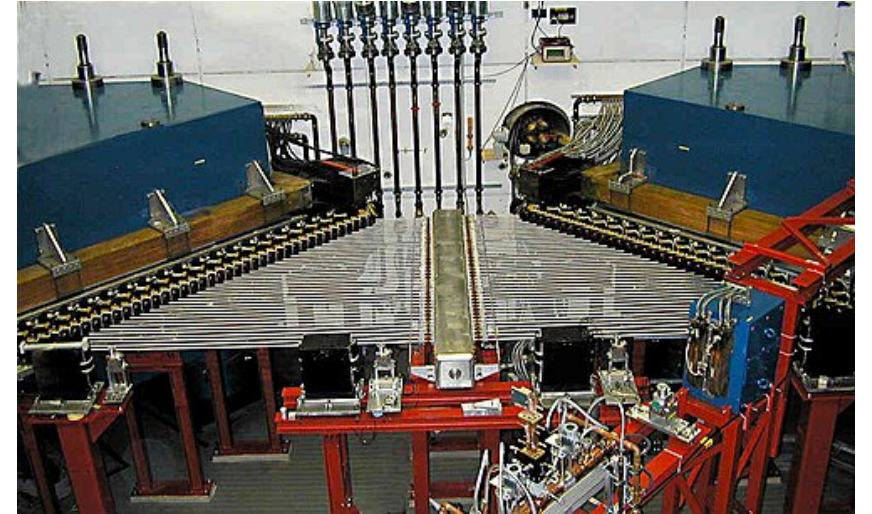
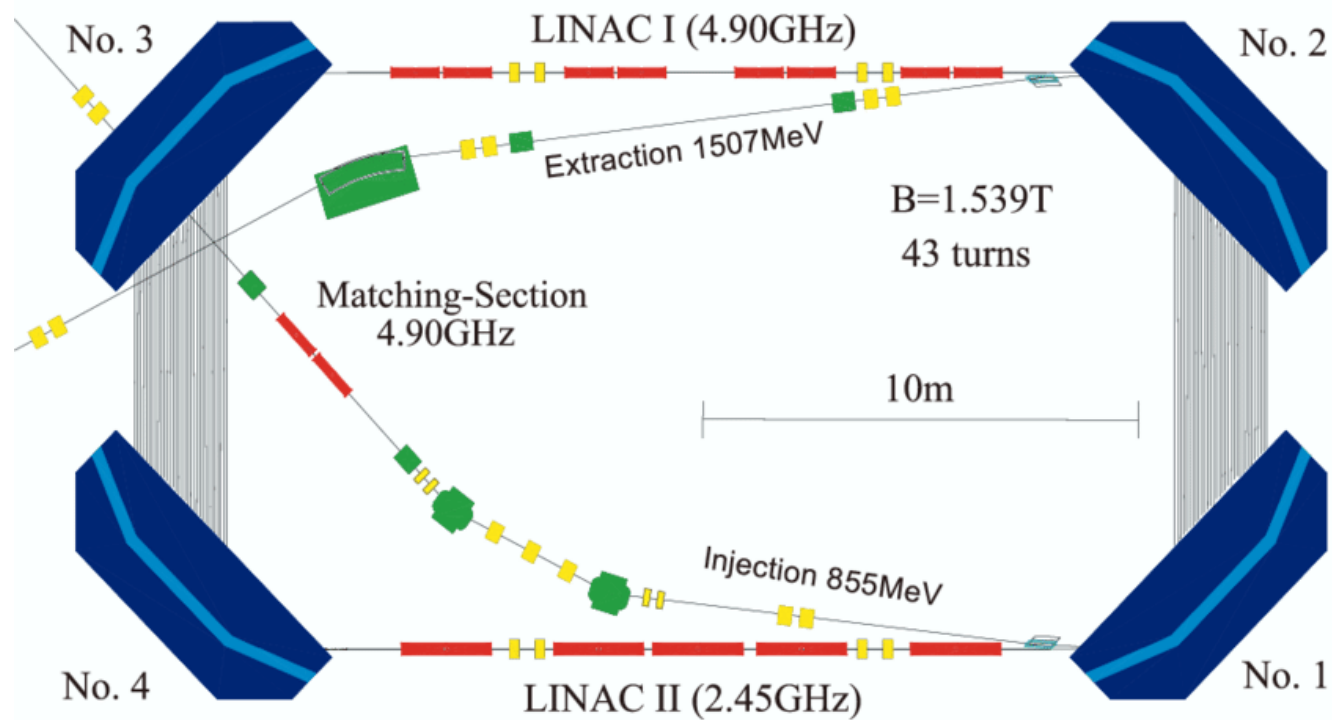


# Double-Sided Microtron

- Four p/4 single-sided bending magnets form a circular track. Superconducting accelerating cavities are installed in the two straight sections.
- An RF electron gun is positioned inside the circular track, with the beam injected from the inside.
- This design significantly reduces the mass of the magnets and the volume of the vacuum chamber, making it ideal for portable applications.



# Mainz Double Sided Microtron MAMI C



# Microtron Condition

Although the orbital period changes with acceleration, it must always be quantized in terms of the RF wavelength.

Orbit circumference:  $C$

$$C = 2L_s + 2\pi\rho + 4(R - \rho) = \frac{p}{eB} (2\pi - 4) + 4R + 2L_s$$

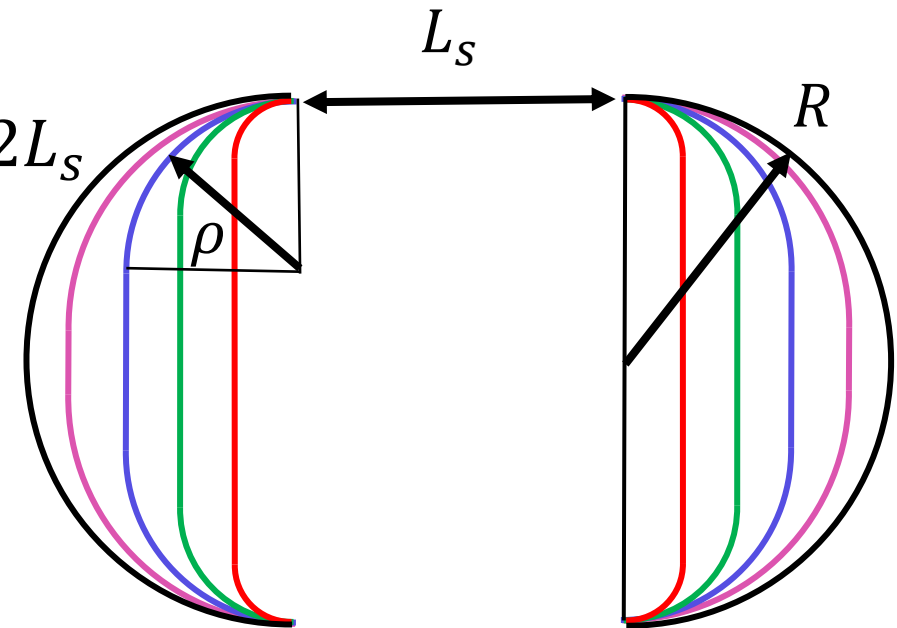
$R$ : Largest orbit radius

$\rho$ : Instantaneous orbit radius

$L_s$ : Straight section length

Variation on  $C$

$$dC = \frac{dp}{eB} (2\pi - 4) = n\lambda$$

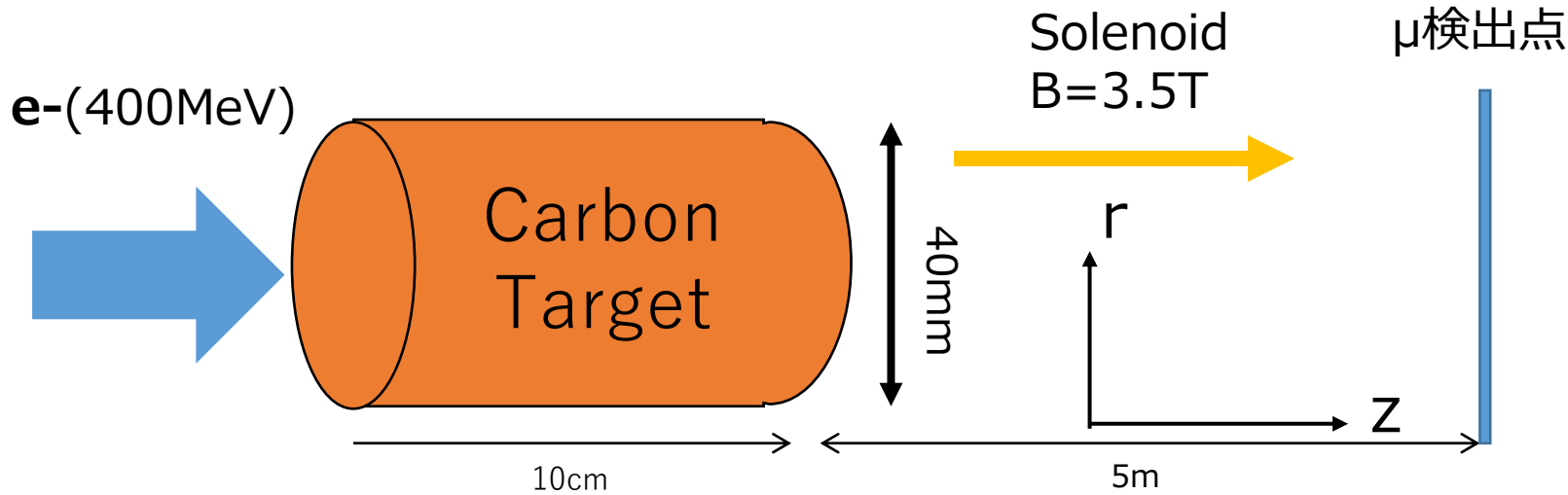


# Numerical Example

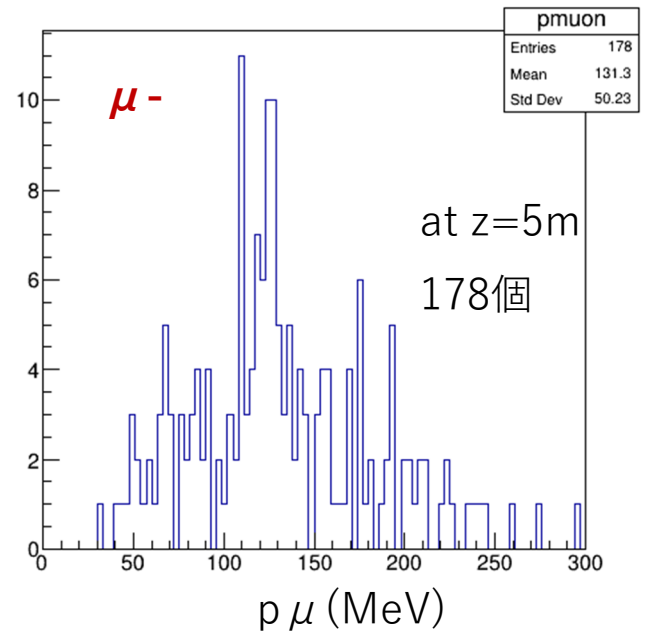
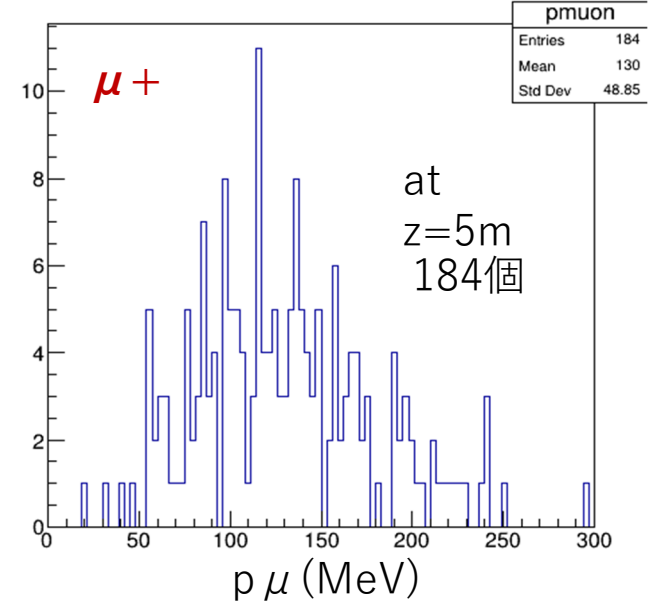
Parameter	Number	Unit
<b>B</b>	<b>1.336</b>	<b>T</b>
<b>cp (max)</b>	<b>400</b>	<b>MeV</b>
<b>R</b>	<b>1.0</b>	<b>m</b>
<b>dcp</b>	<b>41n</b>	<b>MeV</b>

- If the particles are accelerated by  $dcp = 41n$  (MeV) per orbit, the difference in orbital periods will be exactly an integer multiple of the wavelength.
- Assuming an acceleration of 41 MeV across the two cavities, the acceleration voltage per cavity can be set to 20.5 MeV.

# Muon Target

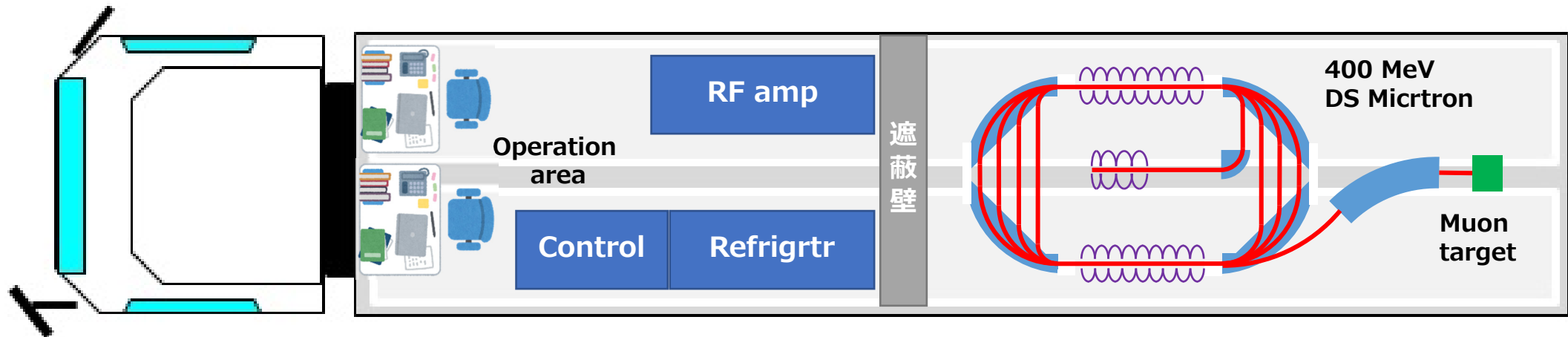


- 400 MeV、 $100\mu\text{A}$  electron on Graphite Target
- $1.4 \times 10^8 \mu^+ / \mu^-$  are obtained.
  - $8 \times 10^8$  400MeV  $e^-$  GEANT4, Shielding.
  - $\phi 40 \times 100\text{mm}$  carbon target.
  - 5m drift in 3.5 T solenoid field.



# Portable Muon Source

- Two TESLA cavities are driven at 20.5 MV/m, and a 100  $\mu\text{A}$  electron beam is accelerated to 414 MeV over 10 revolutions in a double-sided Microtron.
- The Microtron orbit is 2.0 m wide. It can be mounted on a 2.5 m-wide trailer.



# Summary

- We investigated portable muon sources.
- DSMMG: A compact muon generation system using a vehicle-mounted double-sided Microtron.
- A graphite target can generate  $1.4 \times 10^8 \mu^+/\mu^-$ .
- Radiation shielding is the primary challenge for outdoor use.
- To re-accelerate muons, an accelerator design for muon capture and re-acceleration is required.

# Acknowledgement

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