MOOP011

Generative Phase-Space Reconstruction for Low-Intensity Beam Characterization in the J-PARC Muon Linac MEBT Line

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High Energy Accelerator Research Organization (KEK)

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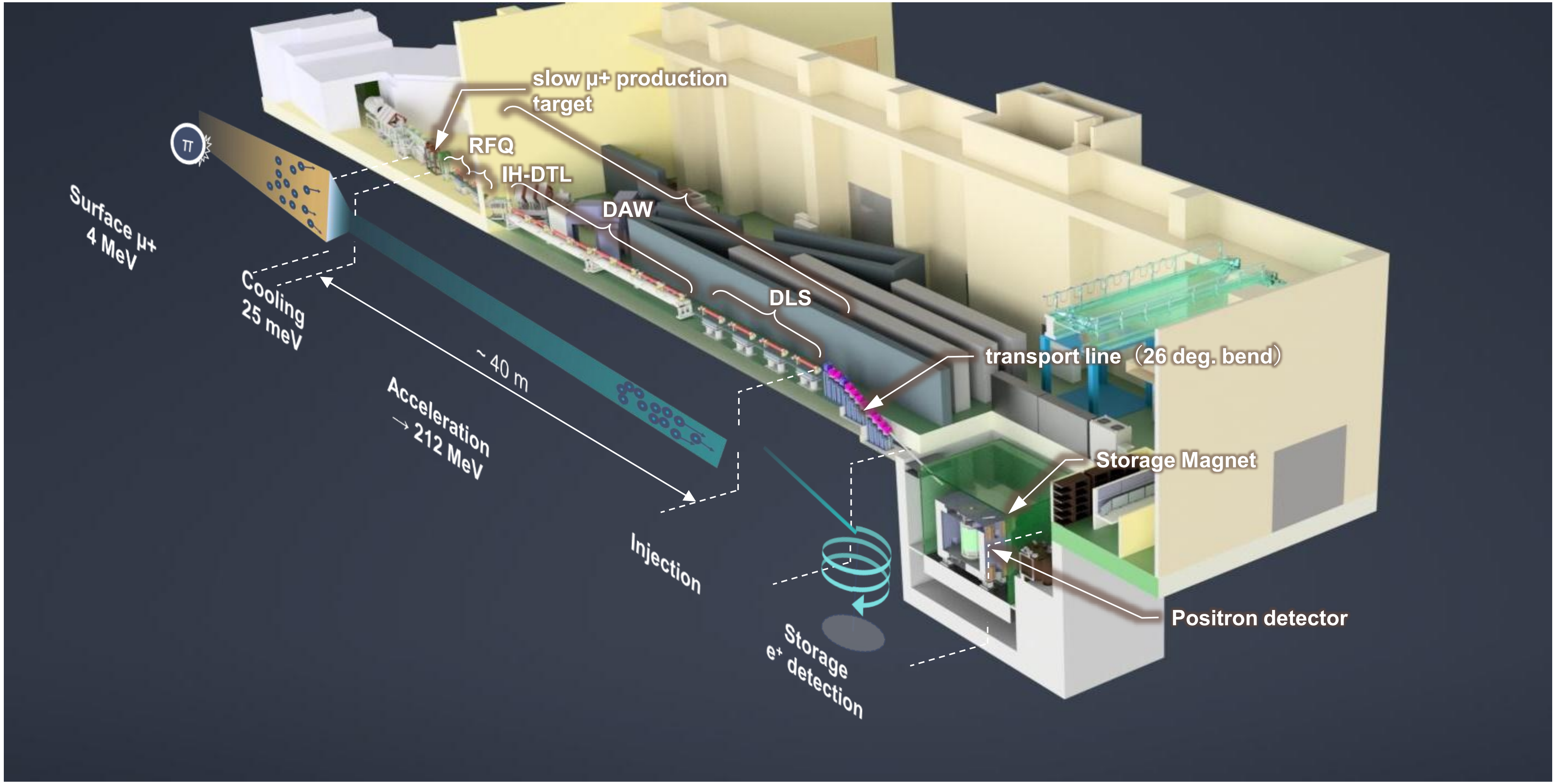
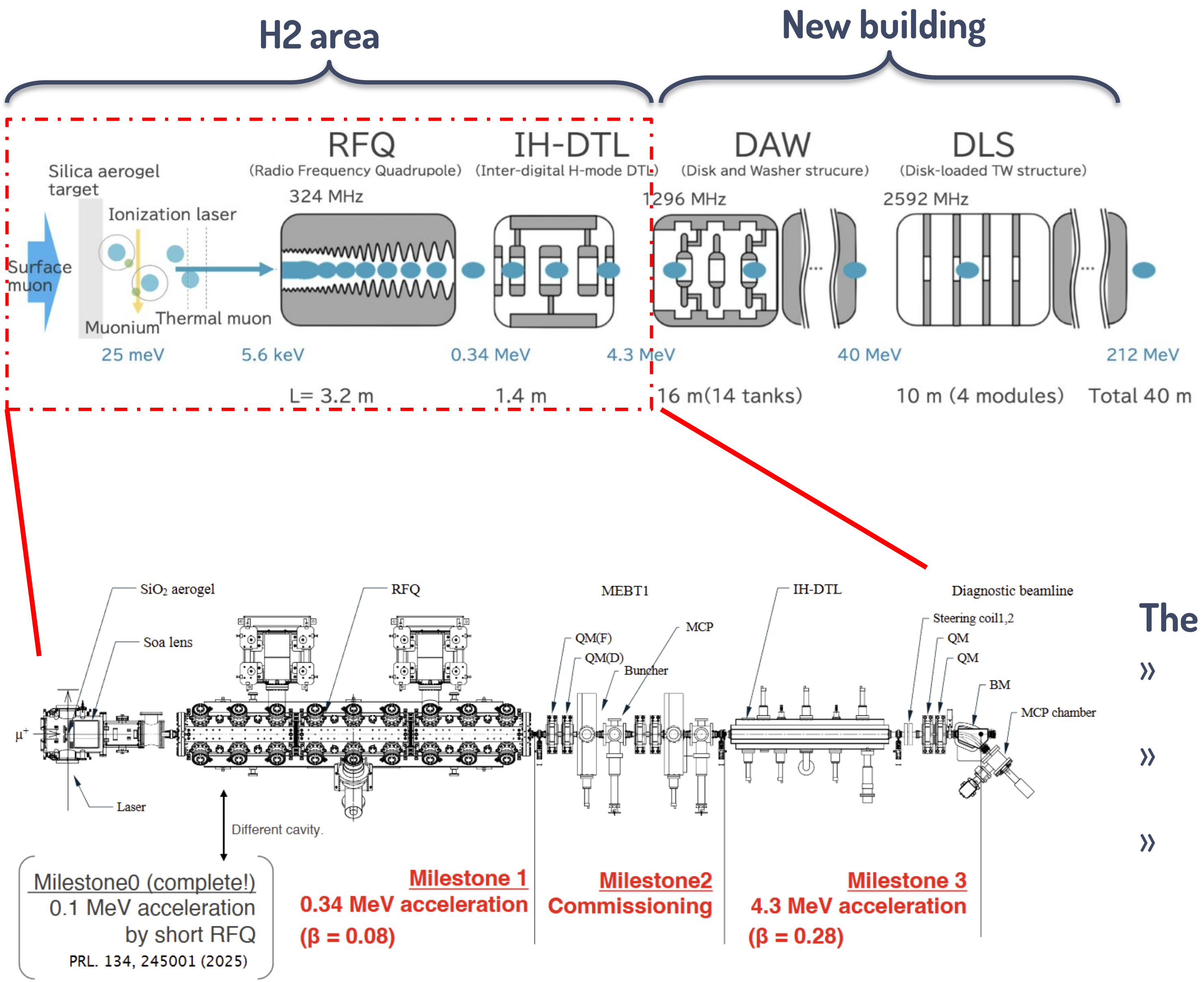
Table of Contents

Layout of muon g-2/EDM experiment



Latest Commissioning results: **FR1A002**, Low-emittance muon beam acceleration using a radio frequency quadrupole for the J-PARC muon g−2/EDM Experiment
Aug 21, 2026, 8:50 AM, **Yuga Nakazawa (High Energy Accelerator Research Organization)**

Muon Linac (& H2 area)



Energy [MeV]	212
Intensity[/s]	10^6
Repetition [Hz]	25
Pulse length [nsec]	~10
Normalized ε_t [π mm mrad]	~1.5
Δp [%]	~0.1

The H2 area

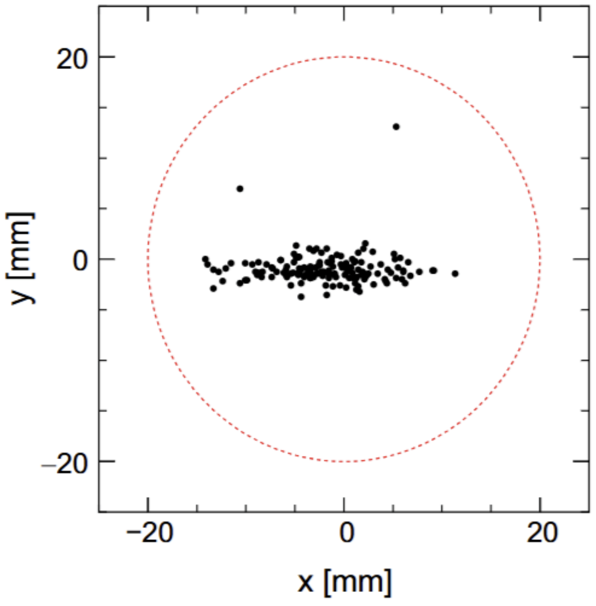
- The H2 area covers the front-end part of the muon linac, from ultra-slow muon generation to IH-DTL acceleration.
- The beam is accelerated by the RFQ to 0.34 MeV and then by the IH-DTL to about 4.3 MeV.
- MEBT-I connects the RFQ and IH-DTL, providing beam transport, matching, and diagnostics before IH-DTL injection.

Generative Model for Muon Linac

- Muon beam intensity is very low.
- Destructive / slit-based diagnostics are impractical.
- Conventional quad-scan only gives 2D phase space RMS information, not full 4D beam structure.
- Can machine-learning-assisted reconstruction recover the initial 4D/6D beam distributions?

- **Generative Phase Space Reconstruction** uses a **neural-network beam generator** and **differentiable particle tracking** to infer the full 4D/6D initial beam distribution from downstream screen images.
- This method does not require any novel slit (or pepper-pot) technique.
- It only rely on the beam projection to reconstruct phase space distribution.

March and April of 2024 test:



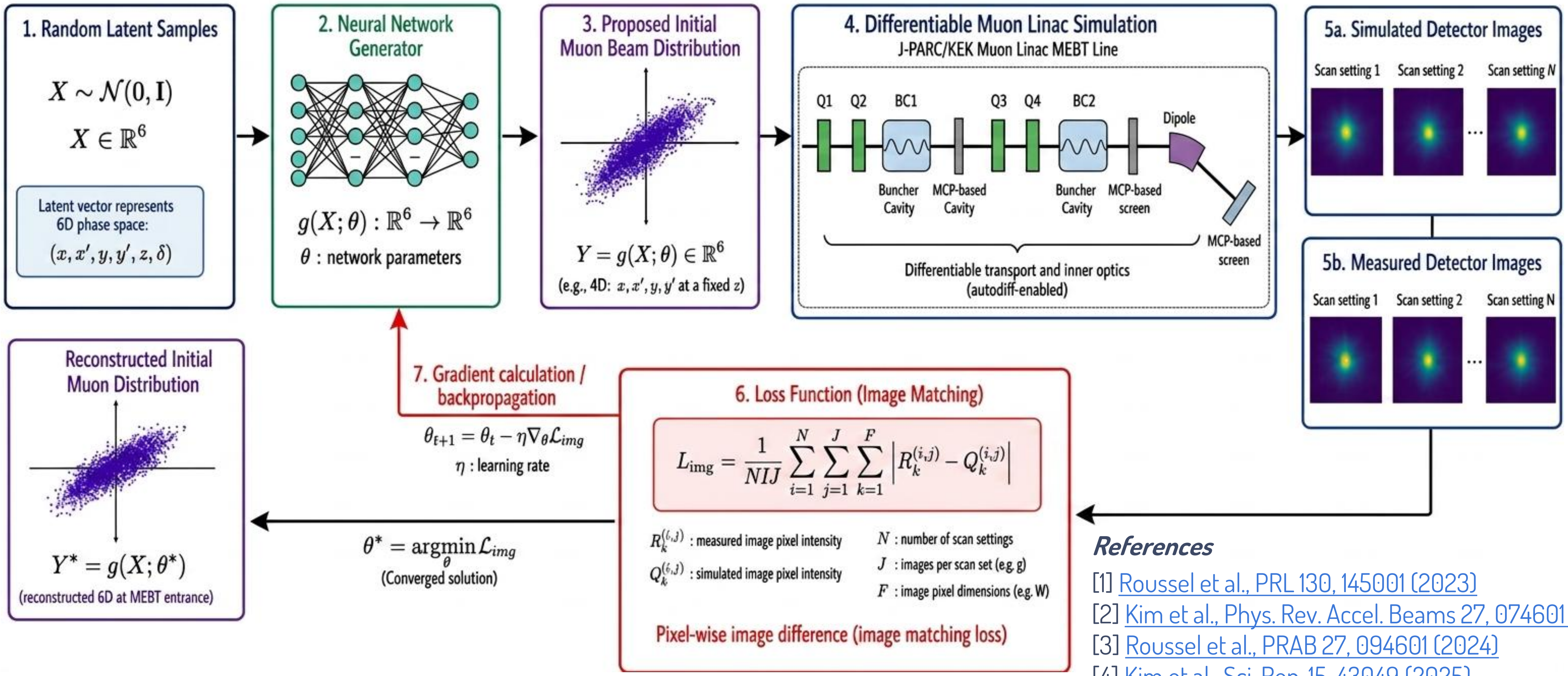
Aritome, S., et al. "Acceleration of positive muons by a radio-frequency cavity." Physical review letters 134.24 (2025): 245001.

FIG. 3. Beam profile measured using a BPM at the end of the diagnostics line. The circle drawn with a dashed line is the BPM's sensitive area, $\phi 40$ mm. The currents of the quadrupole magnets were $I_1 = 0.90$ and $I_2 = -0.75$ A.

Latest achieved intensity results:

FR1A002, Aug 21, 2026, 8:50 AM, **Yuga Nakazawa**

Generative model - *workflow*



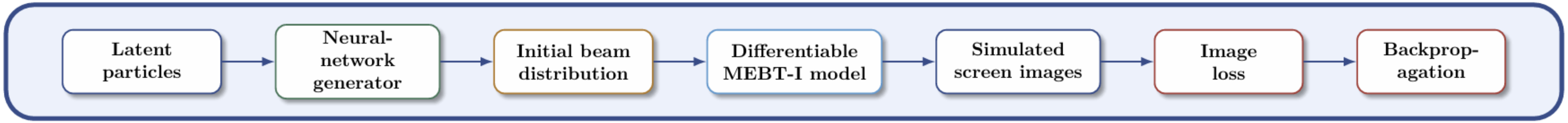
References

[1] Roussel et al., PRL 130, 145001 (2023)

[2] Kim et al., Phys. Rev. Accel. Beams 27, 074601 (2024).

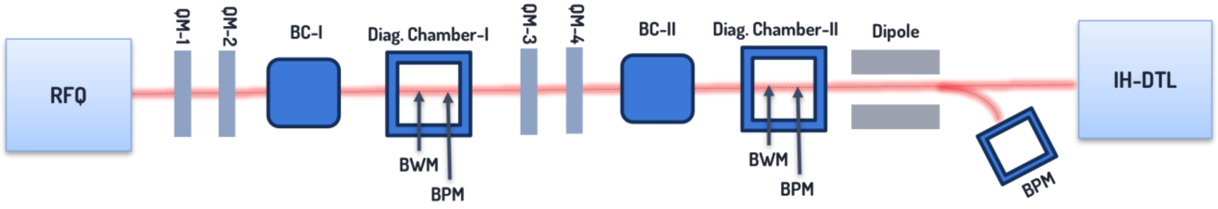
[3] Roussel et al., PRAB 27, 094601 (2024)

[4] Kim et al., Sci. Rep. 15, 43049 (2025)

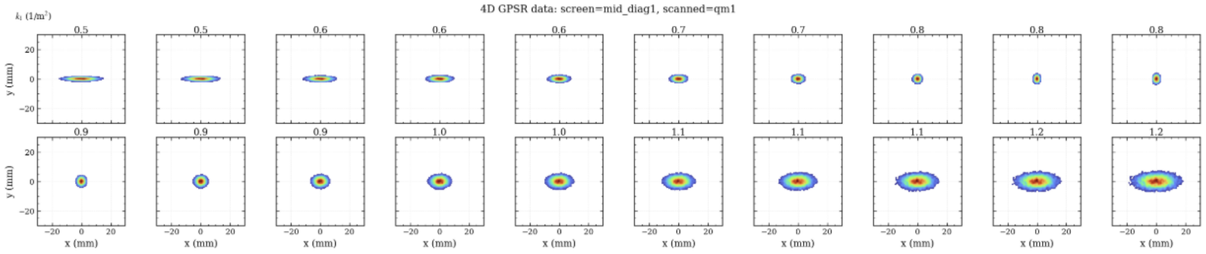


4D GPSR - *Synthetic Data reconstruction*

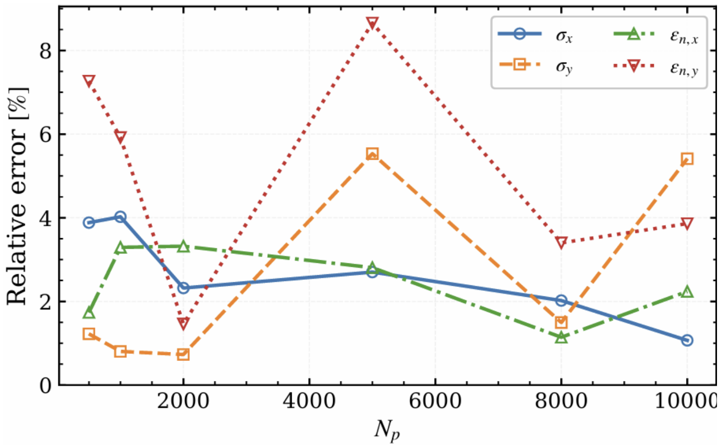
Muon Linac MEBT-I beamline



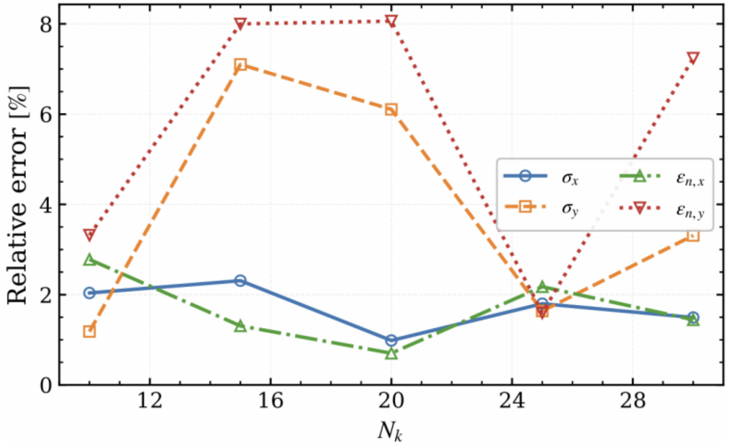
Synthetic data in Diagnostic Chamber-I



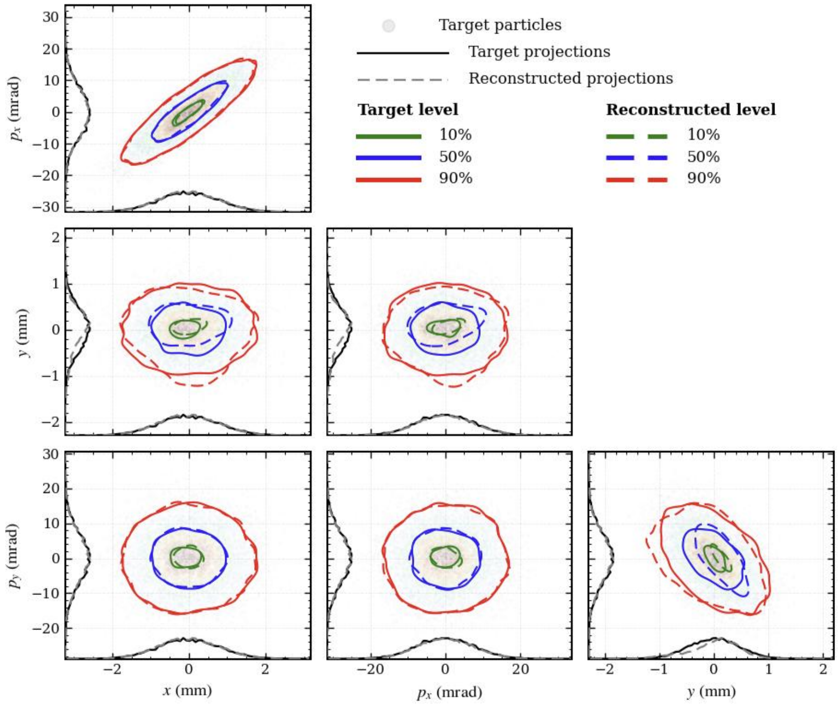
of particles relative error to ground truth



of dataset relative error to ground truth

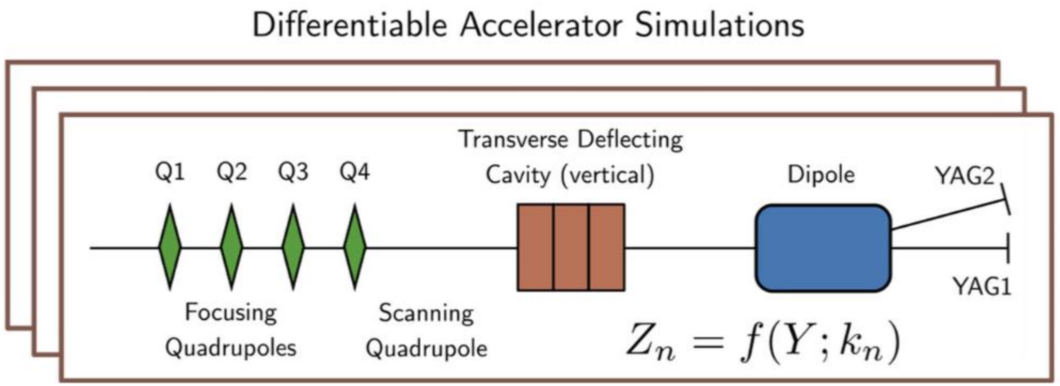


4D reconstructed and ground truth phase space

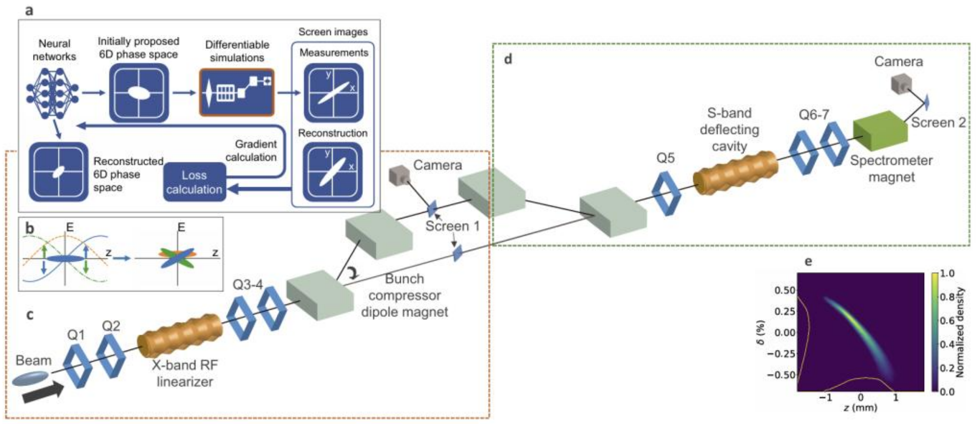


6D GPSR - *Previous Studies*

1. Argonne Wakefield Accelerator (AWA)



2. Pohang Accelerator Laboratory (PAL)-XFEL



AWA: TDC + Dipole 6D GPSR

Roussel et al., *Phys. Rev. Accel. Beams* **27**, 094601 (2024)

TDC: longitudinal position → vertical angle

$$y' \to y' + K_{\text{TDC}} z$$

$$y_{\text{scr}} \simeq R_{33} y + R_{34} y' + R_{34} K_{\text{TDC}} z$$

Dipole: energy deviation → horizontal position

$$x_{\text{scr}} \simeq R_{11} x + R_{12} x' + R_{16} \delta$$

$$\boxed{z \to y_{\text{scr}}, \qquad \delta \to x_{\text{scr}}}$$

PAL-XFEL: Cavity + Dipole 6D GPSR

Kim et al., *Scientific Reports* **15**, 43049 (2025)

Accelerating cavity: longitudinal position → energy

$$\delta \to \delta + hz$$

Dipole: energy deviation → horizontal position

$$x_{\text{scr}} \simeq R_{11} x + R_{12} x' + R_{16} \delta$$

$$\boxed{z \to \delta \to x_{\text{scr}}}$$

No transverse deflecting cavity is required.

6D GPSR for Muon Linac: ***Low-β Buncher Model***

Standard-element 6D concept

$$\tau \to \Delta W \to \delta \to x_{\rm scr}$$

$$x_{\rm scr} \simeq R_{11}x + R_{12}p_x + R_{16}\delta$$

The buncher phase scan converts longitudinal position into energy variation, and the dispersive section converts this energy variation into horizontal screen displacement.

Why the standard cavity model is not enough

$$K_\mu \simeq 0.34\ \text{MeV}, \qquad \beta_0 \simeq 0.08, \qquad V_{\rm BC} \sim 14\ \text{kV}$$

At this low velocity, muons experience significant RF phase advance while passing through the finite-length buncher. Therefore, an instantaneous thin-gap or standard cavity kick cannot reproduce the correct buncher response.

Sliced field-map buncher model

$$\Delta W_i \simeq q \int E_z(s)\cos\left[\phi_{\rm RF} + k_{\rm RF}\tau_i + \frac{k_{\rm RF}s}{\beta_0}\right] ds$$

The finite-length field map gives the phase-dependent longitudinal energy kick. The same longitudinal field variation also produces transverse RF focusing:

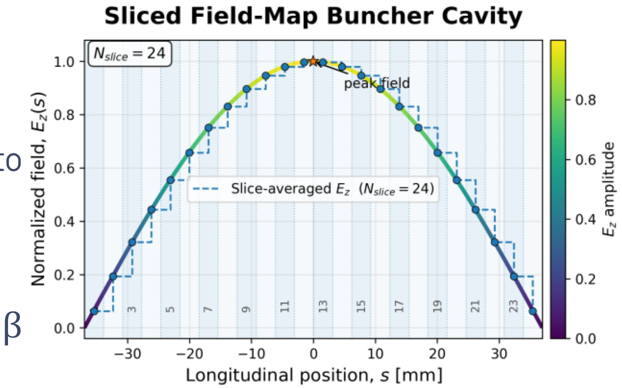
$$E_x \simeq -\frac{x}{2}\frac{\partial E_z}{\partial s}, \qquad E_y \simeq -\frac{y}{2}\frac{\partial E_z}{\partial s}$$

$$\boxed{\text{slice} = \text{drift} + \text{RF energy kick} + \text{transverse RF kick}}$$

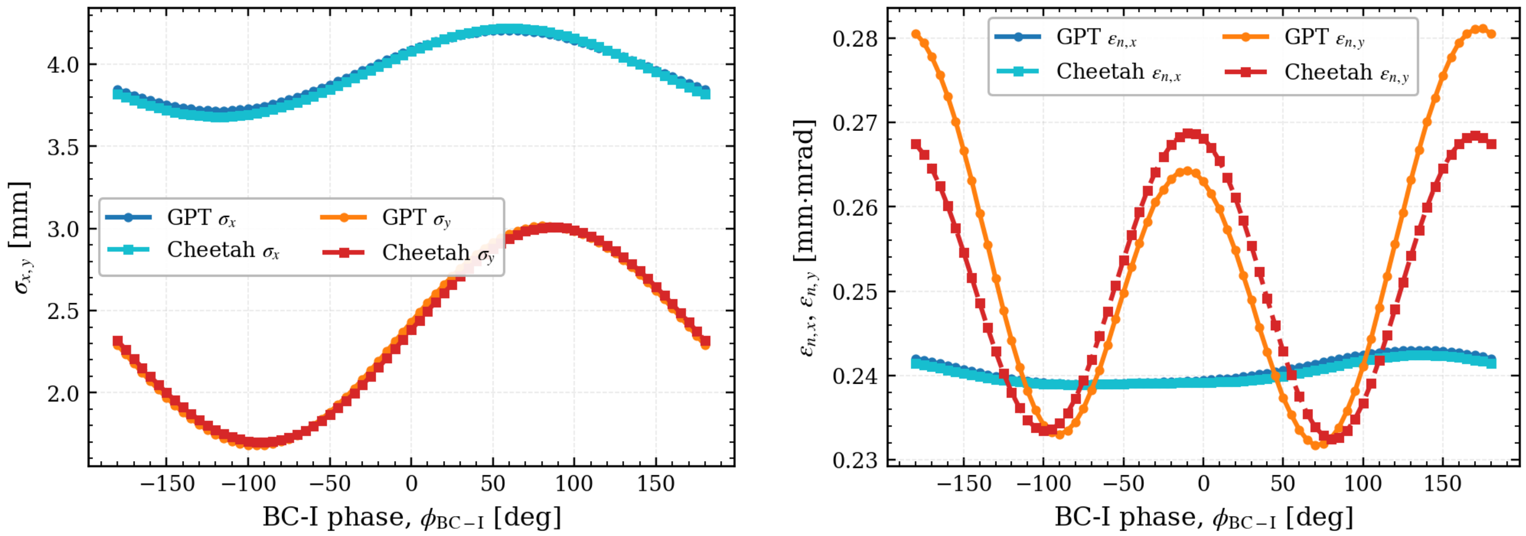
This GPT-like sliced model keeps the essential low-β buncher physics while remaining differentiable for GPSR optimization.

SlicedEzCell Cavity Class in Cheetah

- GPT-like differentiable model of the MEBT buncher cavity.
- Uses the single-cell longitudinal field map, Ez(s), divided into short slices.
- Each slice applies: drift + RF energy kick + transverse RF kick
- Includes finite RF transit-time effect, important for low-β muons: β ≈ 0.08.
- Enables realistic buncher-phase scans for GPSR.

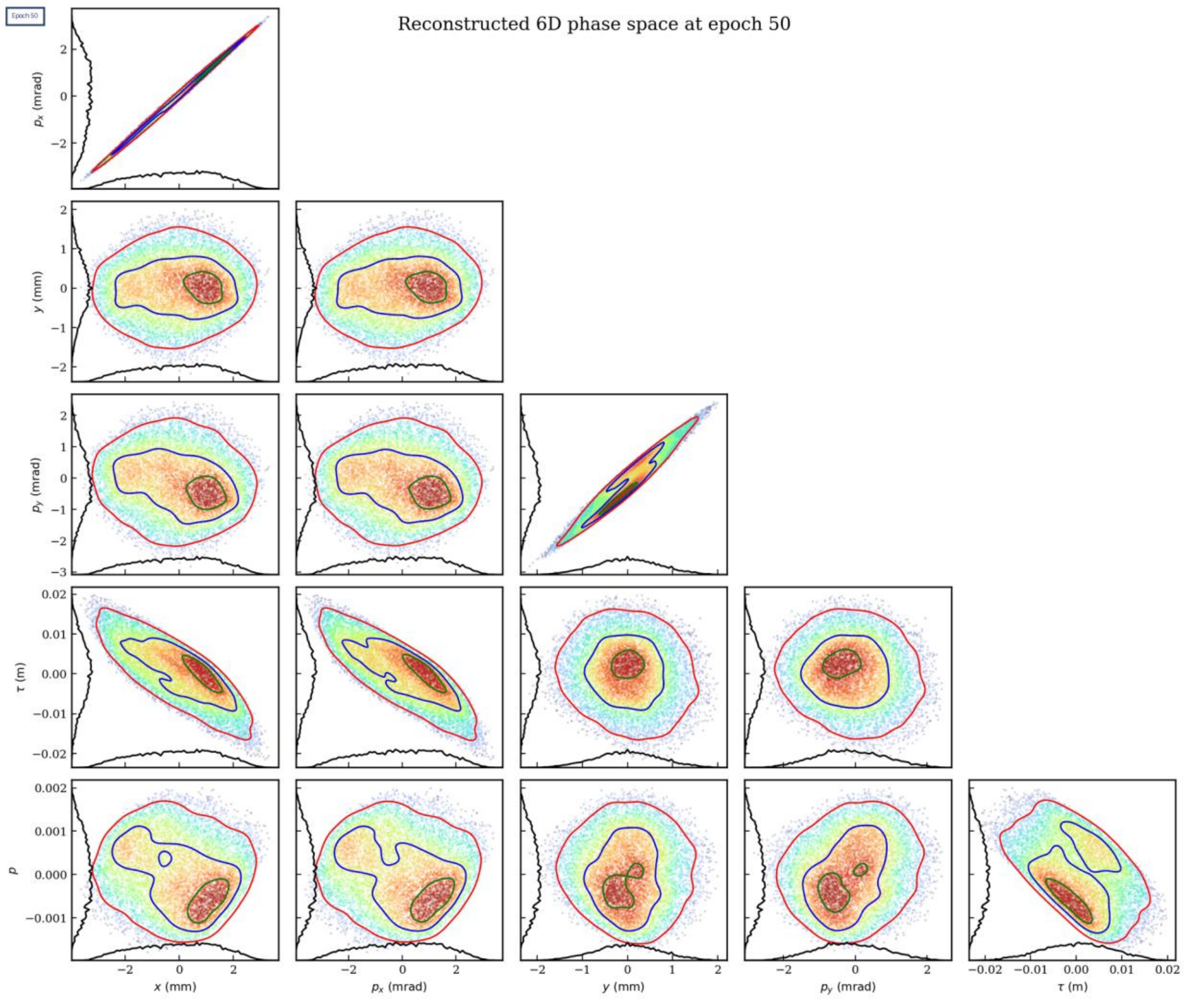


Benchmark: SlicedEzCell model vs. GPT phase scan



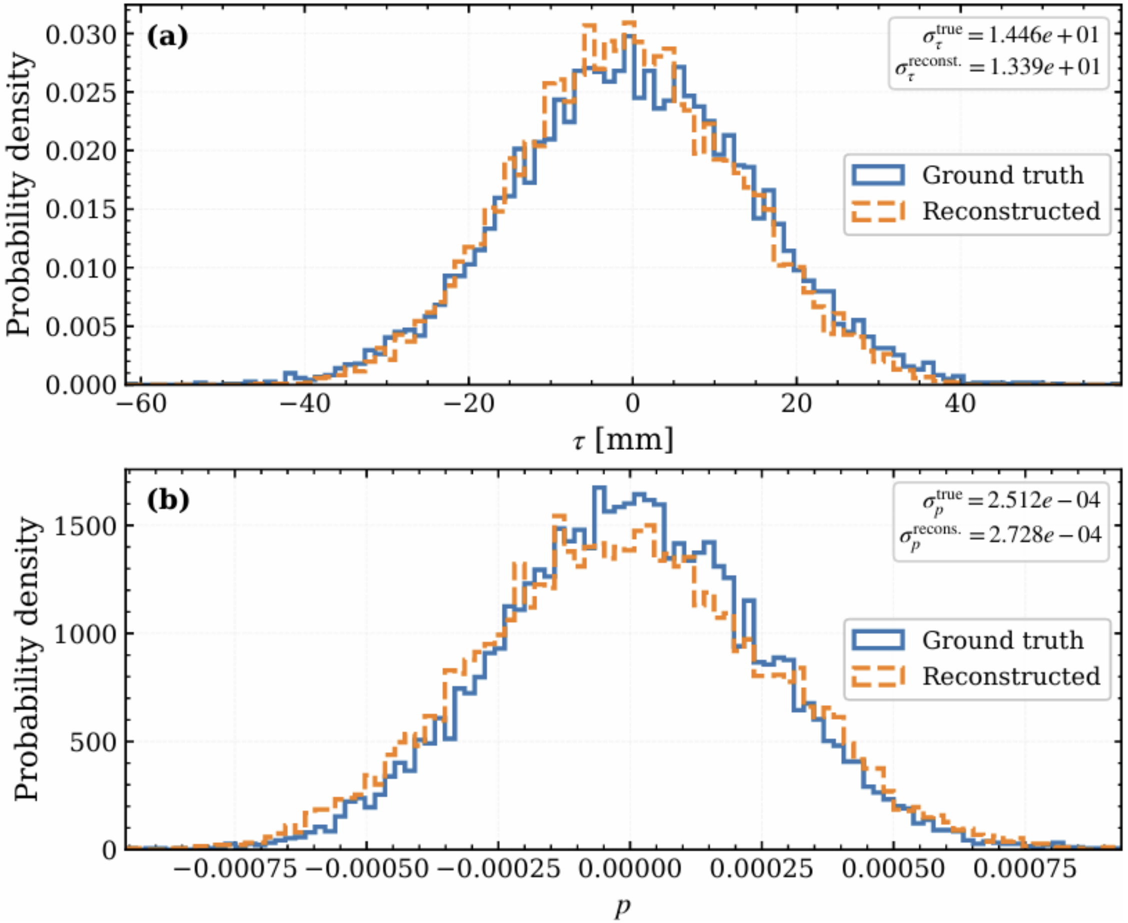
6D GPSR Results: ***Longitudinal Projections***

Training Progress



.gif image

Comparison of Ground truth and Reconstructed beam LPS projections



Conclusion

- Generative model is a promising tool for ***low-intensity beam*** characterization in the J-PARC Muon Linac MEBT-I.
- 4D transverse phase space can be reconstructed from quadrupole-scan profile images, even with ***limited particle statistics***.
- The method can reduce the required number of measurements, which is important because one MCP profile can take ***about 20-30 min***.
- 6D reconstruction is possible using ***buncher-phase scans*** and a downstream dispersive screen.
- A ***sliced field-map buncher model*** was implemented to reproduce the low-β cavity response needed for realistic 6D GPSR.
- Different diagnostic tools, including the Beam Width Monitor ***(BWM)*** and MCP-based Beam Profile Monitors ***(BPM)***, will be installed at several locations along the MEBT-I line.
- MEBT-I commissioning is planned for ***FY2027***, with complementary diagnostic approaches: ***bunch-width measurement***, ***quadrupole-scan phase-space characterization***, and ***generative model-based reconstruction***.

Detailed Discussion: MOOP011