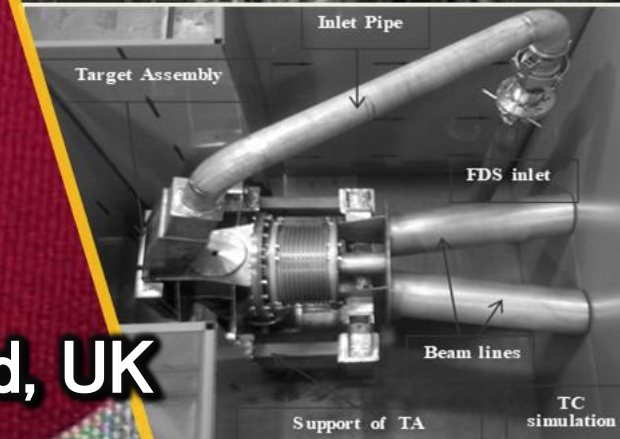


Reduction of longitudinal rms emittance through nonlinear space-charge forces

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Space Charge 2026 @ the University of Oxford, UK

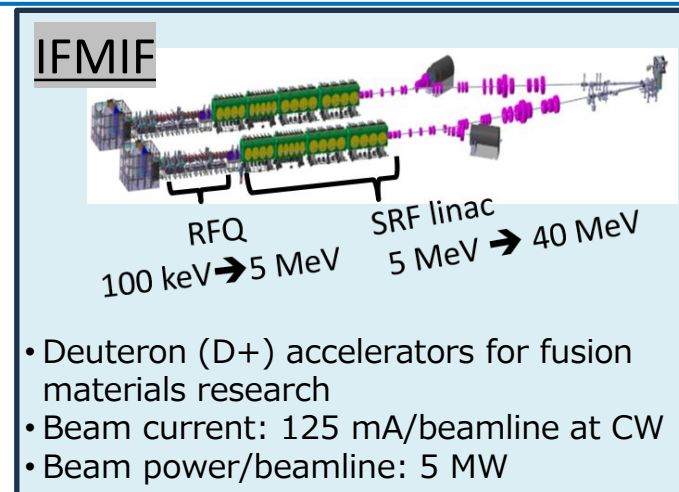




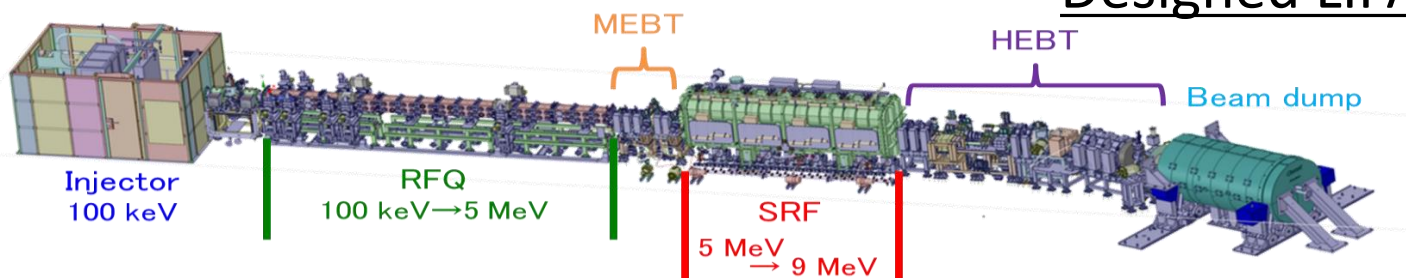
Linear IFMIF Prototype Accelerator (LIPAc)

LIPAc

- ✓ Demonstration of the low energy section of IFMIF accelerator.
- ✓ 125 mA CW deuteron (D^+) accelerator.
- ✓ Accelerating D^+ beam up to 9 MeV using an RFQ and a SRF linac.



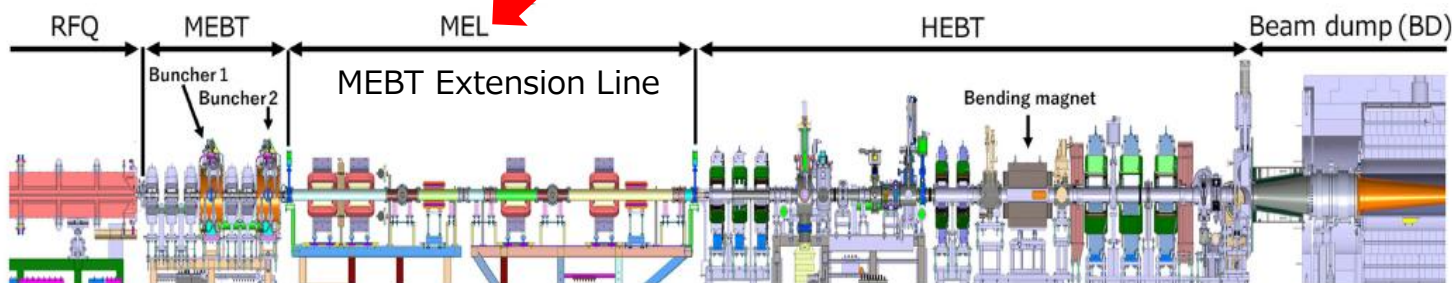
Designed LIPAc



- SRF linac under conditioning
- Beam operation planned for 2027

Temporary beamline (until June 2024)

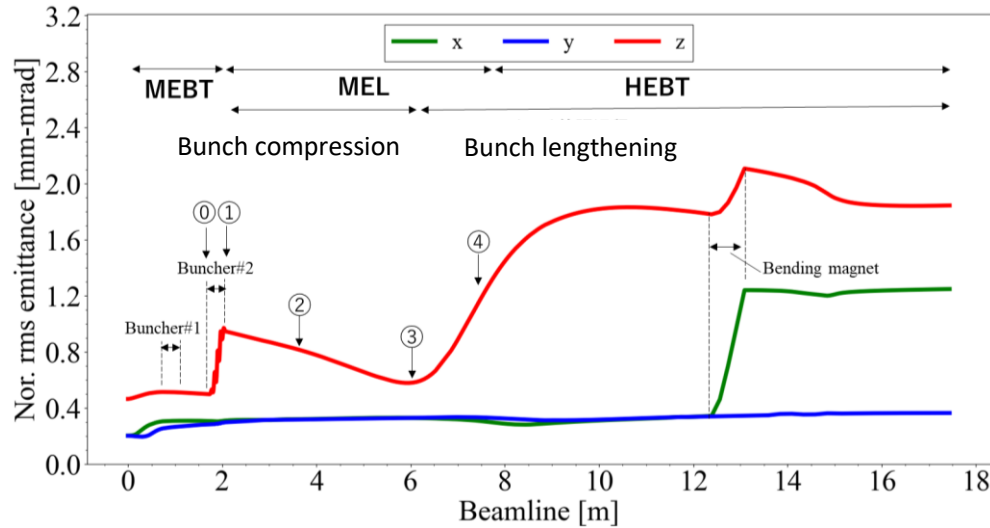
Beam conditions: 125 mA D^+ beam at 5 MeV



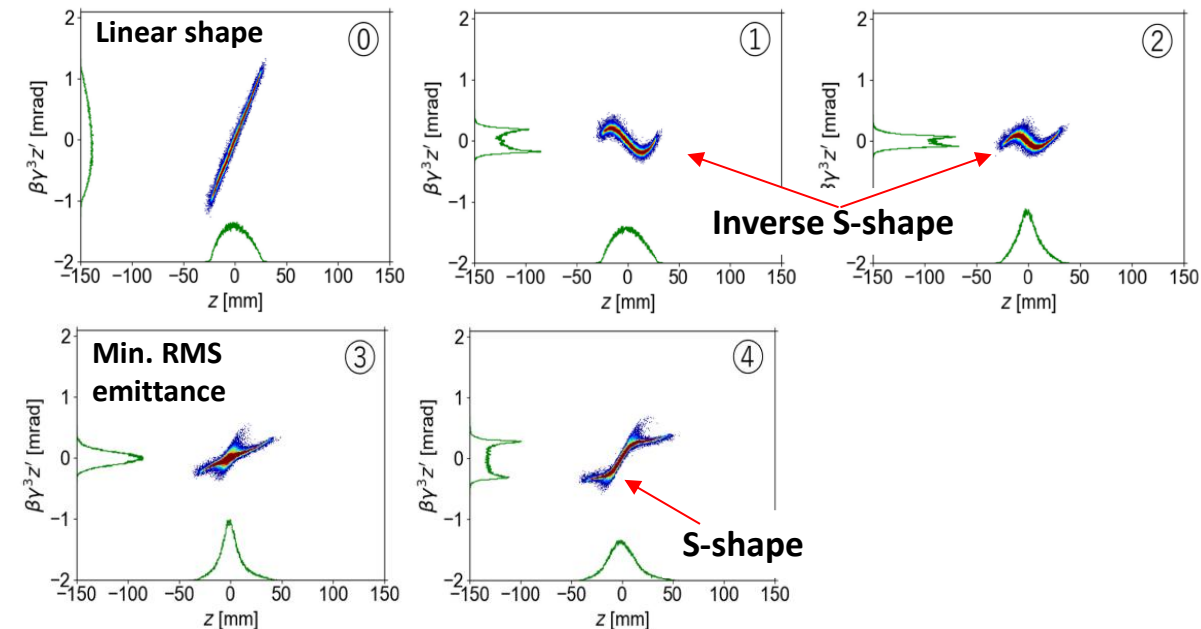
Unexpected observation in simulation*

Longitudinal RMS emittance decreases despite strong space-charge effects, where emittance growth is normally expected. *TraceWin is used for simulations

➤ This study aims to clarify the mechanism of this emittance reduction.



Longitudinal phase space distributions



- ①: RF nonlinearity in Buncher#2
- ②: Inverse S-shaped phase-space distortion
- ③: Bunch compression
- ④: Minimum longitudinal rms emittance
- ⑤: S-shaped phase space distortion

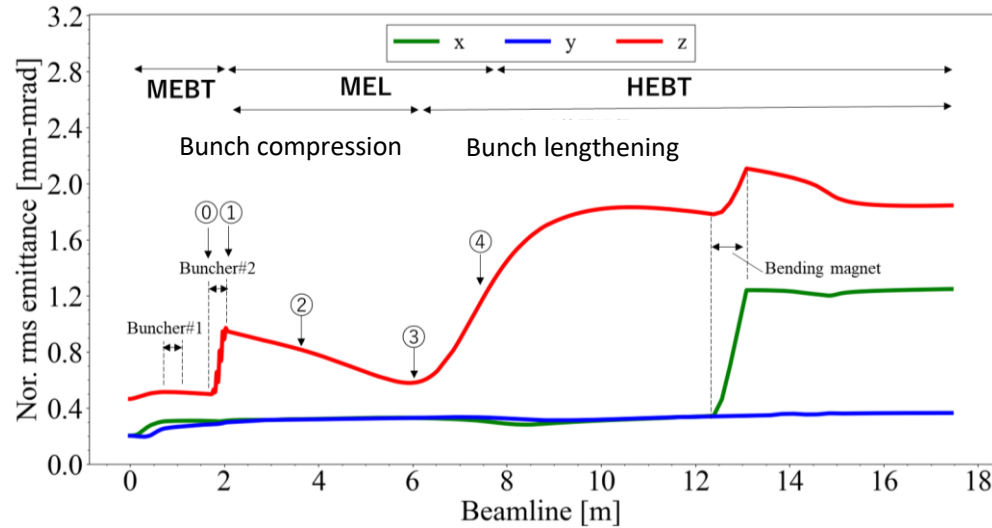
Note: the RMS emittance is the area of the 1σ ellipse in phase space. Unlike the Liouville-invariant phase-space area, it can decrease through phase-space redistribution.

Simulation results:

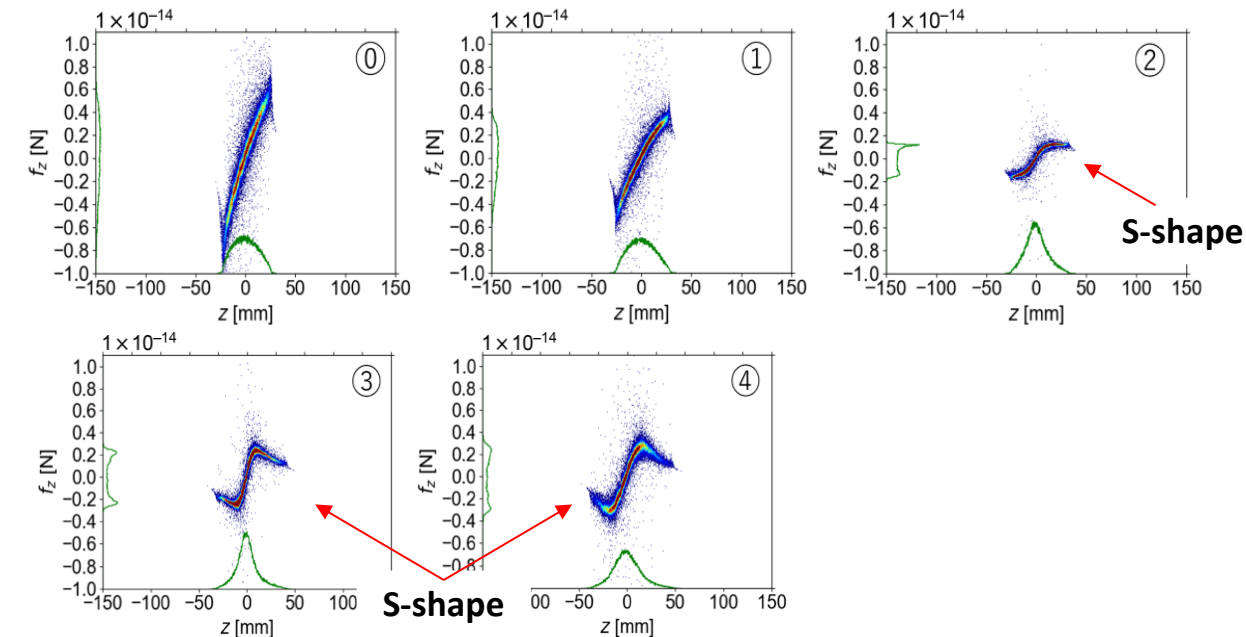
- Longitudinal RMS emittance decreases by $\sim 40\%$.
- No significant change in transverse emittances.
- The effect strongly depends on beam current.

Key observation:

- The strong beam-current dependence suggests that the mechanism is related to space-charge-driven effects.



Longitudinal space-charge force distributions



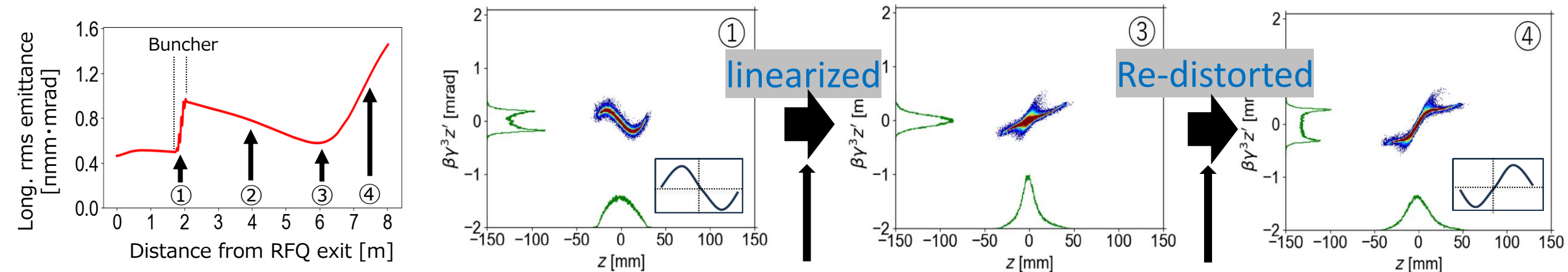
- Longitudinal force acting on a particle in a bunch

$$F_{sc,i} = qE(z_i) = \frac{qQ}{4\pi\epsilon_0 N} \sum_{j \neq i}^N \frac{z_i - z_j}{\gamma_j^2 \left[(z_i - z_j)^2 + \frac{1}{\gamma_j^2} [(x_i - x_j)^2 + (y_i - y_j)^2] \right]^{3/2}}$$

- The longitudinal space-charge force remains nearly linear up to Buncher#2 exit (① and ②).
- During bunch compression (①-③), the longitudinal force becomes increasingly S-shaped.
- After point ③, the bunch begins to debunch while maintaining the S-shaped profile.

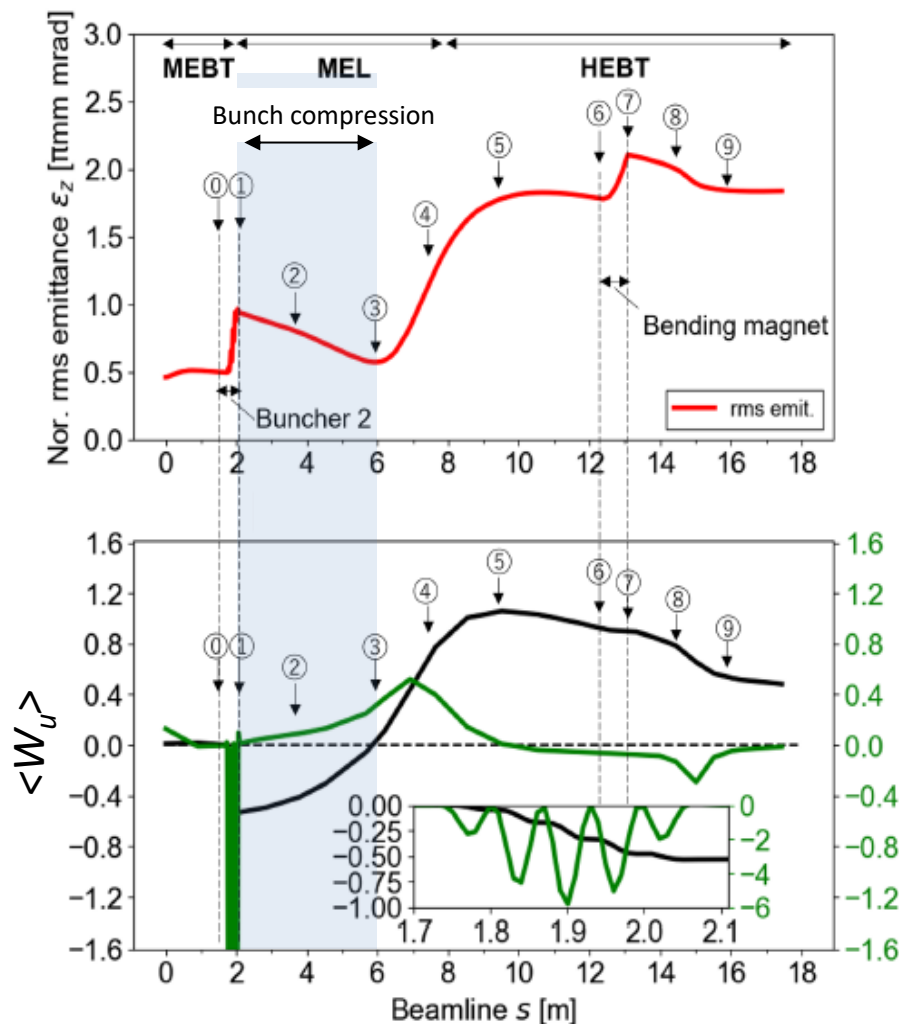
Observation:

- The longitudinal RMS emittance decreases while the force distribution becomes increasingly nonlinear.

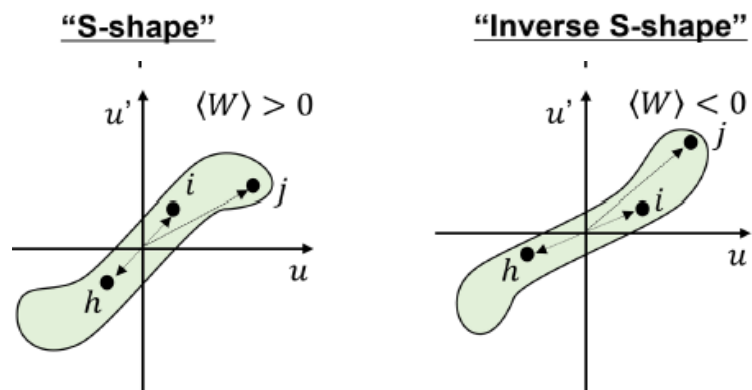


Mechanism:

- The buncher creates an inverse S-shaped phase-space distortion.
- During bunch compression, nonlinear longitudinal space-charge forces generate an S-shaped distortion.
- The two distortions partially cancel each other, resulting in a nearly linearized phase space and a reduction of the longitudinal RMS emittance.
- Further downstream, the space-charge distortion becomes dominant, re-distorting the phase space and increasing the RMS emittance.



Two physical parameters are introduced to quantify phase-space distortion and force nonlinearity.



For both $\langle W_u \rangle$ and $\langle W_F \rangle$:

- + $\rightarrow$ S-shape
- - $\rightarrow$ Inverse S-shape

- Phase-space distortion parameter: $\langle W_u \rangle$

$$W_{ij} = (u_i u'_j - u_j u'_i) \cdot \text{sgn}(|u_i| - |u_j|) \cdot \text{sgn}(u_i u_j)$$

- Force nonlinearity parameter: $\langle W_F \rangle$

$$W_{Fz,ij} = (z_i F_{zj} - z_j F_{zi}) \cdot \text{sgn}(|z_i| - |z_j|) \cdot \text{sgn}(z_i z_j)$$

*J. Hyun and A. Mizuno,
PRAB 28,094202 (2025)*

Key Result

- Opposite signs:
 $\langle W_u \rangle \cdot \langle W_F \rangle < 0$
 $\rightarrow$ RMS emittance reduction.
- Same signs:
 $\langle W_u \rangle \cdot \langle W_F \rangle > 0$
 $\rightarrow$ RMS emittance growth.



Key results:

- A ~40% reduction of longitudinal RMS emittance was observed in simulations of the LIPAc beamline.
- The reduction is driven by nonlinear longitudinal space-charge forces.
- The observed emittance evolution is quantitatively described by the phase-space distortion parameter $\langle W_u \rangle$ and the force nonlinearity parameter $\langle W_F \rangle$.

Challenge:

- The proposed mechanism has not yet been experimentally verified.

Open questions:

- Can the predicted emittance reduction be confirmed experimentally?
- Can this mechanism be applied for beam-quality control?
- Can the concept of the force nonlinearity parameter be extended to predict beam halo formation?



Thank you for your attention!

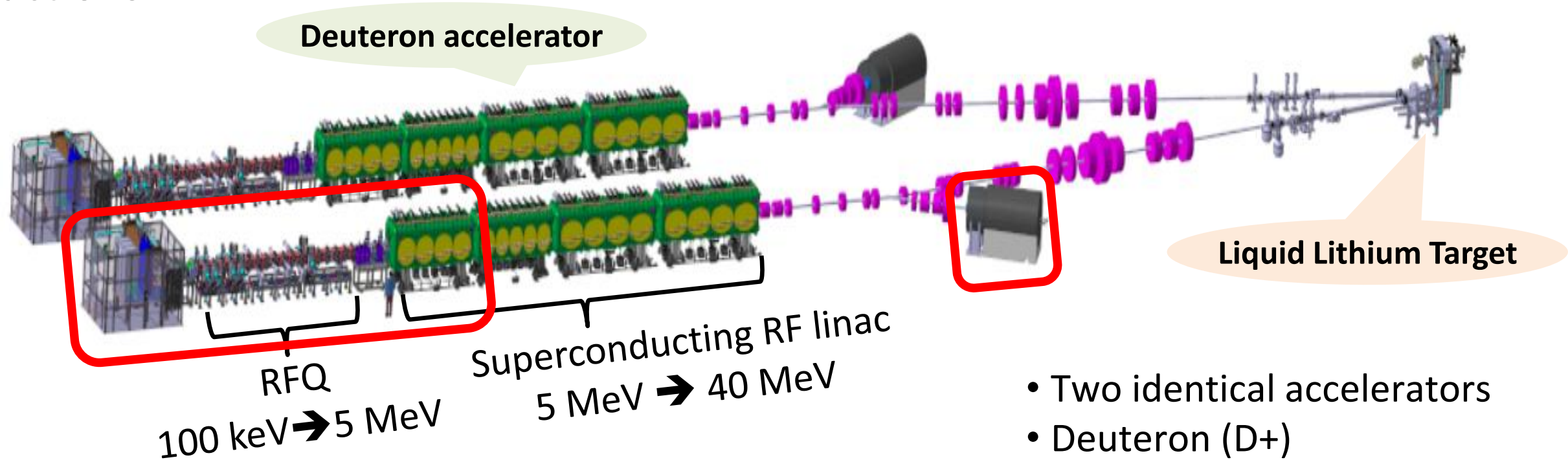
Nonlinear space-charge forces are not always detrimental to beam quality.



Backups

International Fusion Materials Irradiation Facility (IFMIF):

Accelerator-based neutron source facility for testing fusion materials using D-Li reactions.

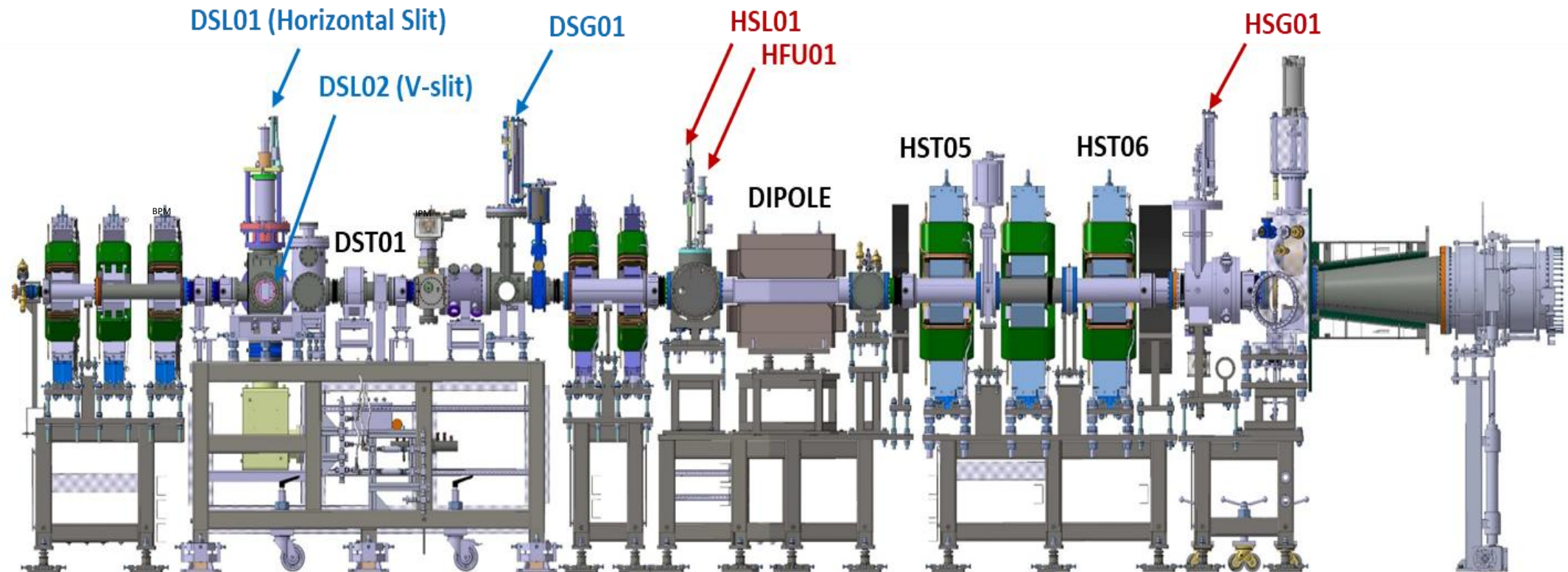


- Two identical accelerators
- Deuteron (D⁺)
- Beam current: 125 mA at CW
- Max. beam energy: 40 MeV
- Beam power/beamline: 5 MW

➤ To realize the IFMIF accelerator, it is essential to demonstrate beam acceleration in the low-energy section where space charge effects dominate.



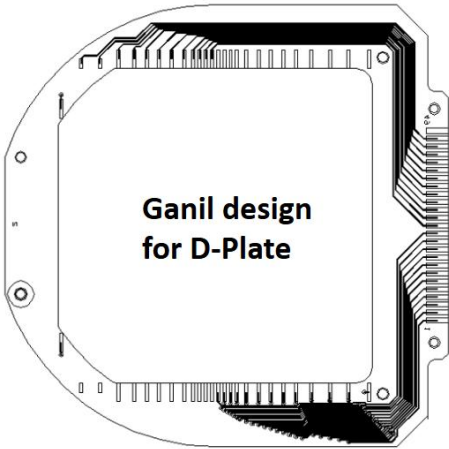
Interceptive profiler





Interceptive profiler: SEM-grid

- Secondary Emission Monitor grids
- Developed based on Spiral2 model (Ganil design & CEA design)



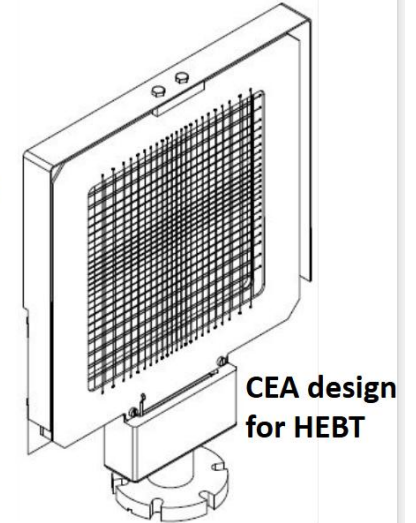
101 × 101 mm²

➤ Rackets

- 2 wire planes (vertical & horizontal), 47 wires / plane, ceramic frames
- Repeller: surrounding circuit at +100 V to avoid back-scattered electrons

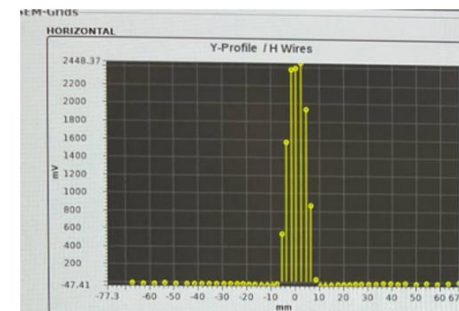
➤ Wires

- 47 Tungsten golden plated
- $\varnothing = 20 \mu\text{m}$ for D-Plate one, $100 \mu\text{m}$ for HEBT one,

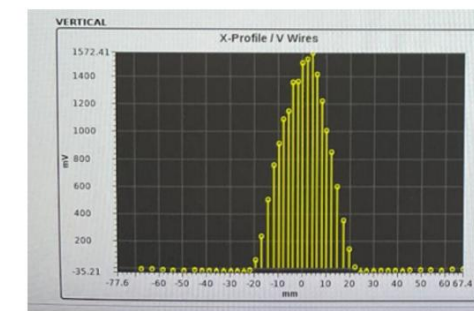


150 × 150 mm²

- Intuitive profile measurement directly
- Use only for low duty cycle, low beam current



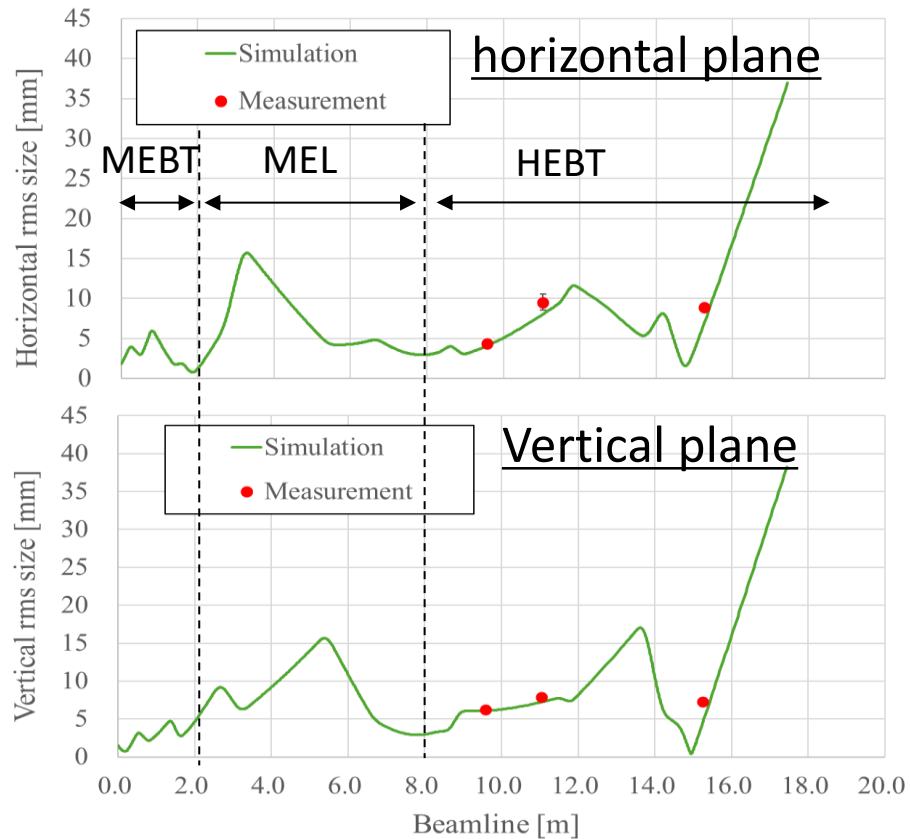
Y-profile/H wires



X-profile/V wires



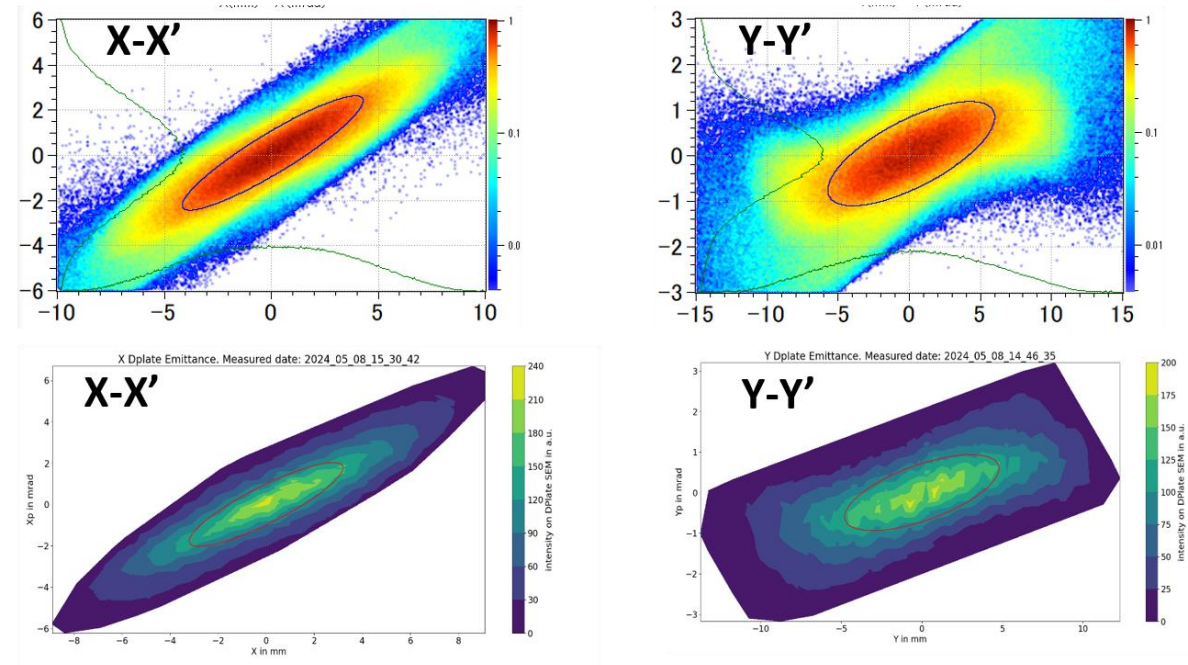
Comparison of measured and simulated beam sizes



Simulation

Measurement

Comparison of measured and simulated emittance

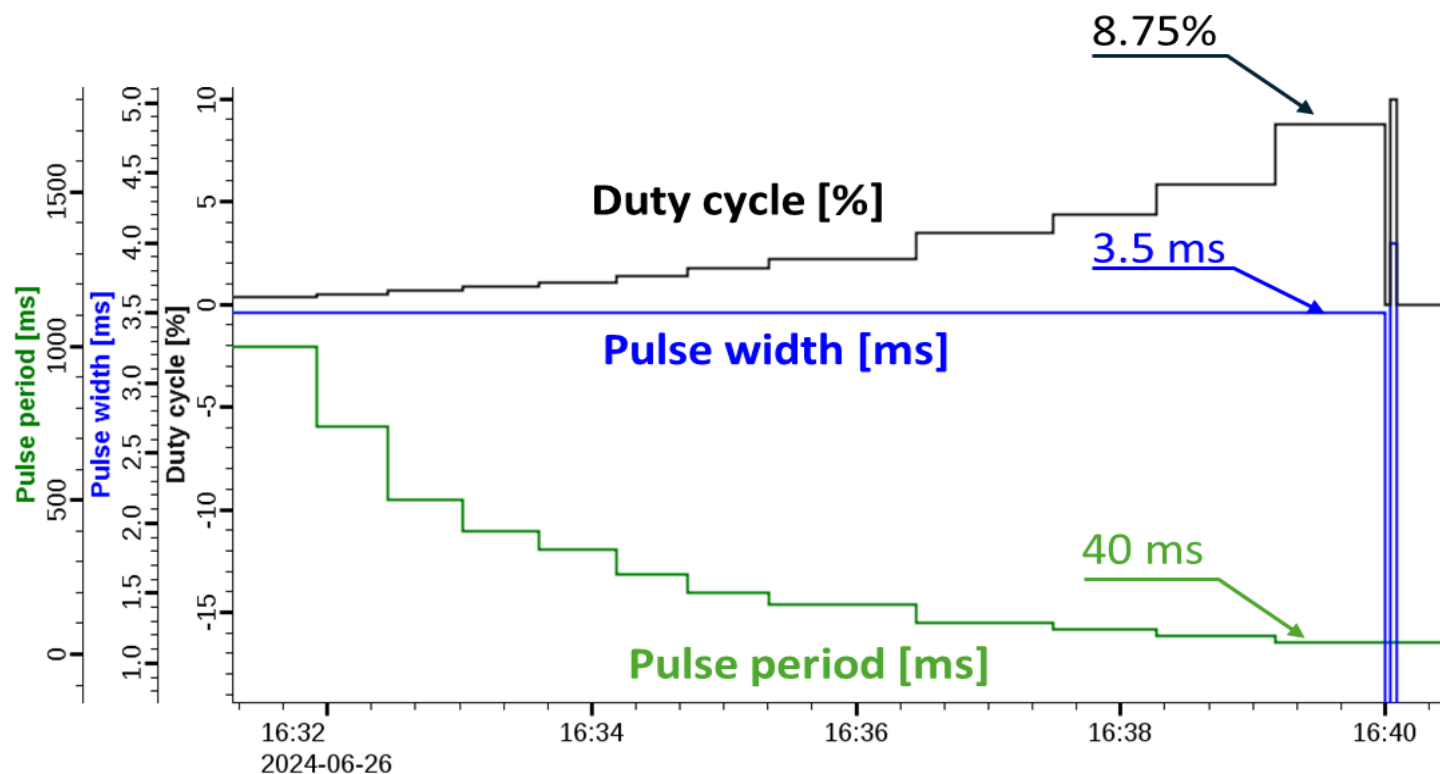


- The simulated and measured phase space distributions are almost agreed.
- The same result was obtained at an RFQ voltage of 137 kV

➤ The measured rms beam size and emittance agreed with the simulation results in different two optics.



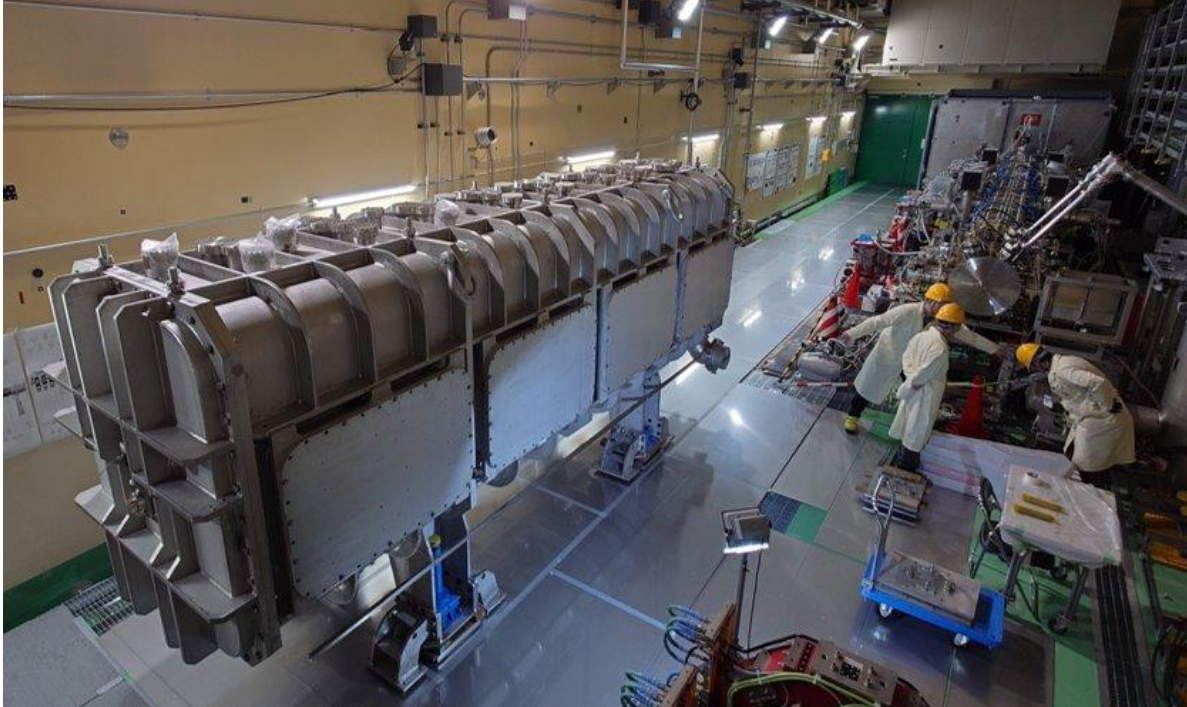
Duty cycle enhancement



- Operator tuning limited the duty cycle to $\sim 3.5\%$ due to vacuum interlock (particle losses).
- ML optimization improved vacuum conditions, enabling an 8.7% duty cycle at a $119\text{ mA}/5\text{ MeV}$ deuteron beam.
- Significant milestone in our beam commissioning, as it fulfils one of the core objectives of this beam commissioning phase.



SRF integration into the beamline

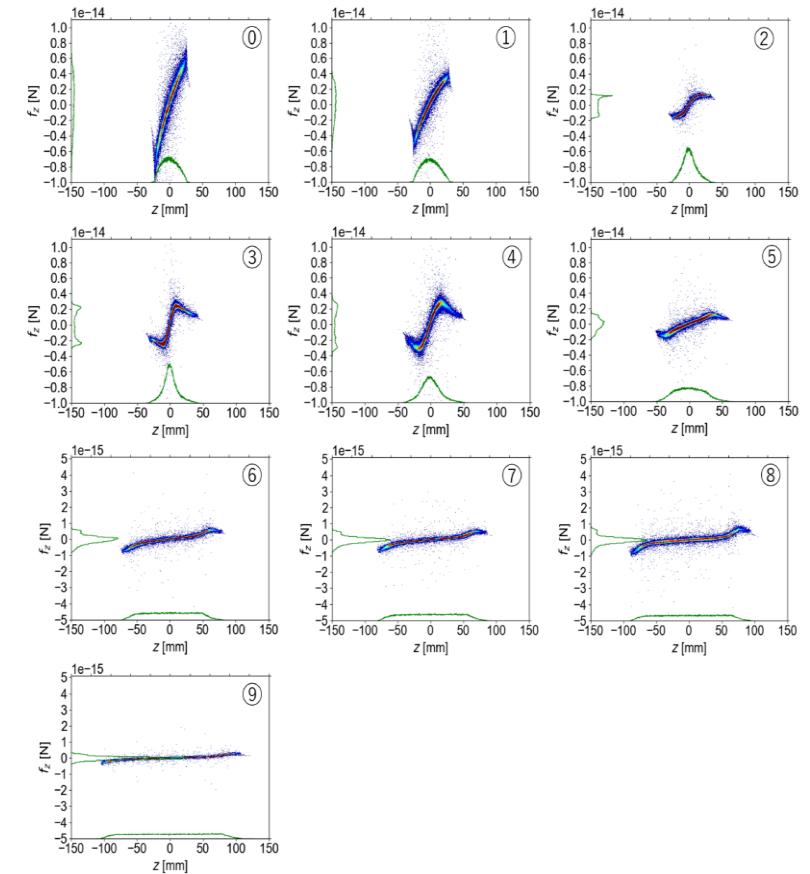
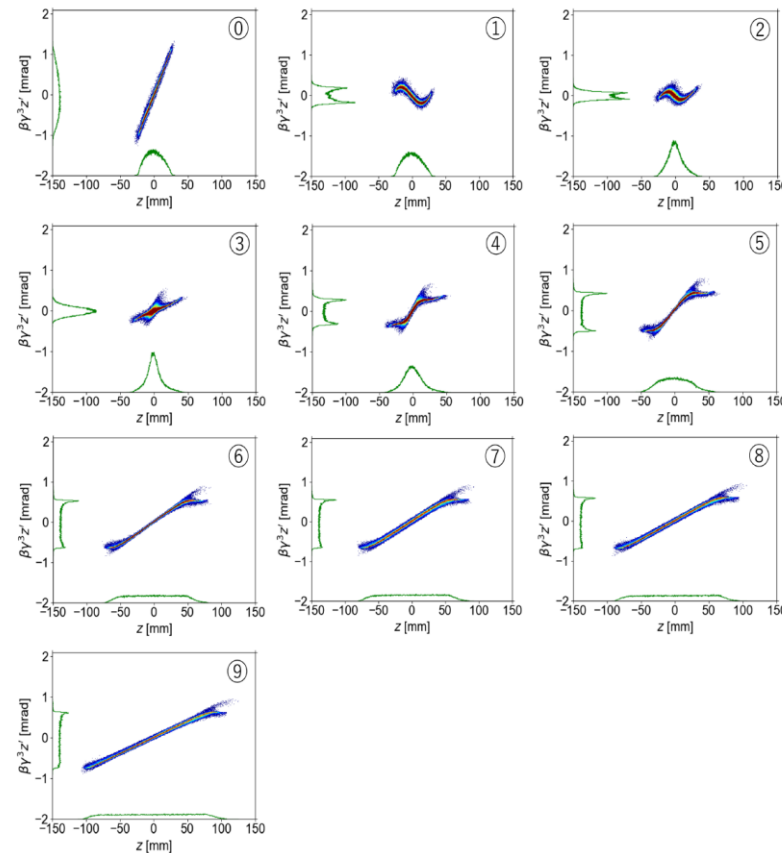
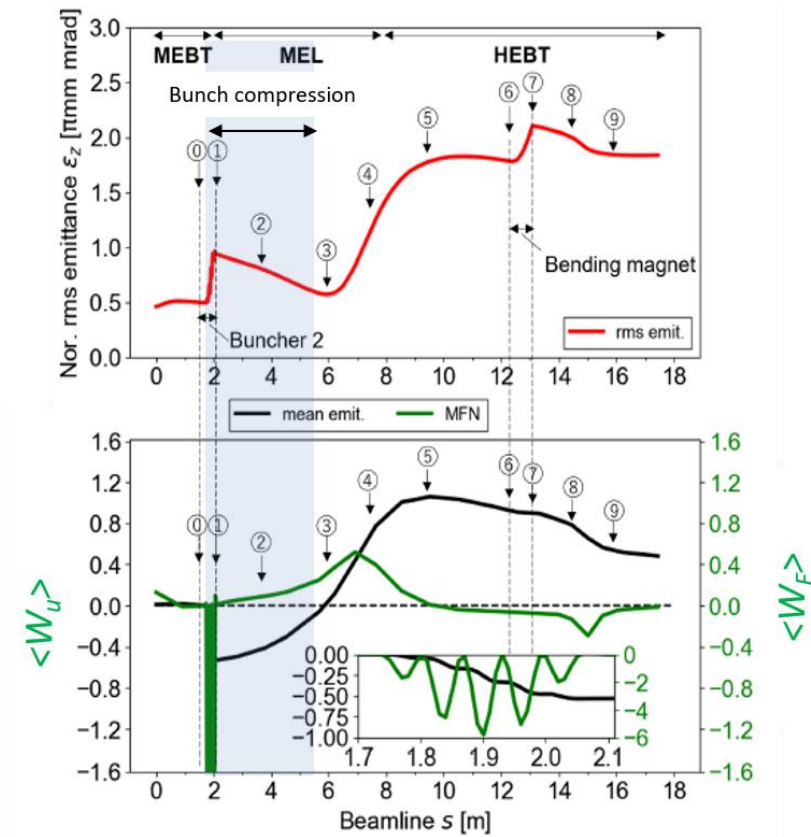


- The MEL section was removed in July 2024.
- Installation of the SRF linac into the beamline has begun, with beam operation scheduled to start in 2027.
- Particle losses in the SRF linac can cause quenching and equipment damage.
- Machine learning techniques will be applied to mitigate particle losses.



Phase space distributions

Force distributions



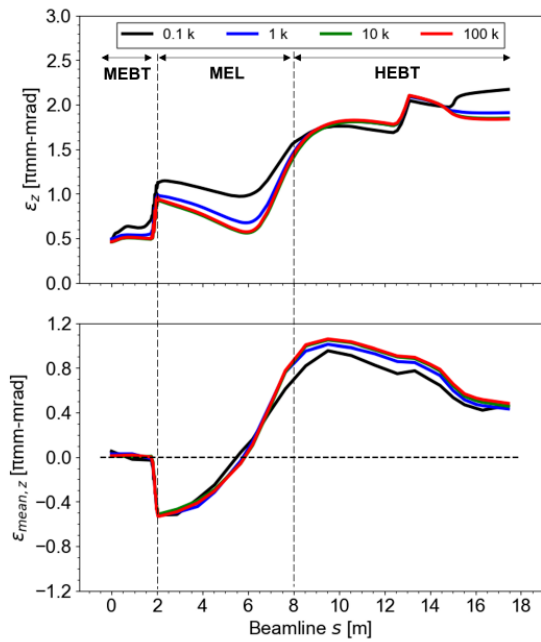


FIG. 11. Normalized longitudinal rms and mean emittances simulated along the beamline for 0.1 k, 1 k, 10 k, and 100 k. k stands for thousand.

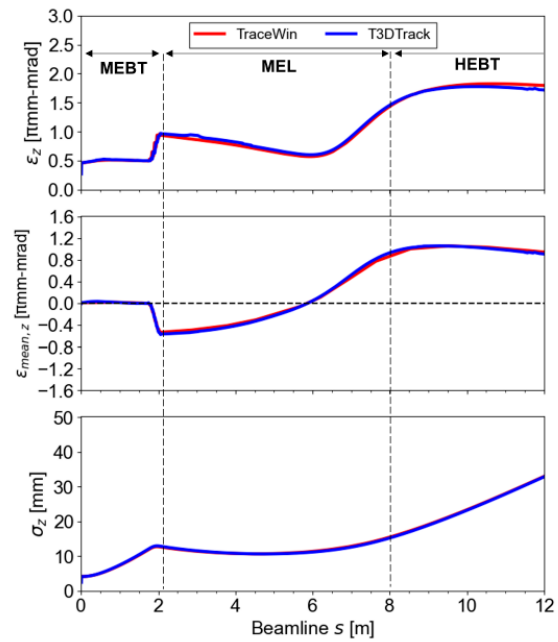


FIG. 12. Normalized rms emittance (top), normalized mean emittance (middle), and rms bunch length (bottom) in the longitudinal plane simulated using TraceWin and T3DTrack.

