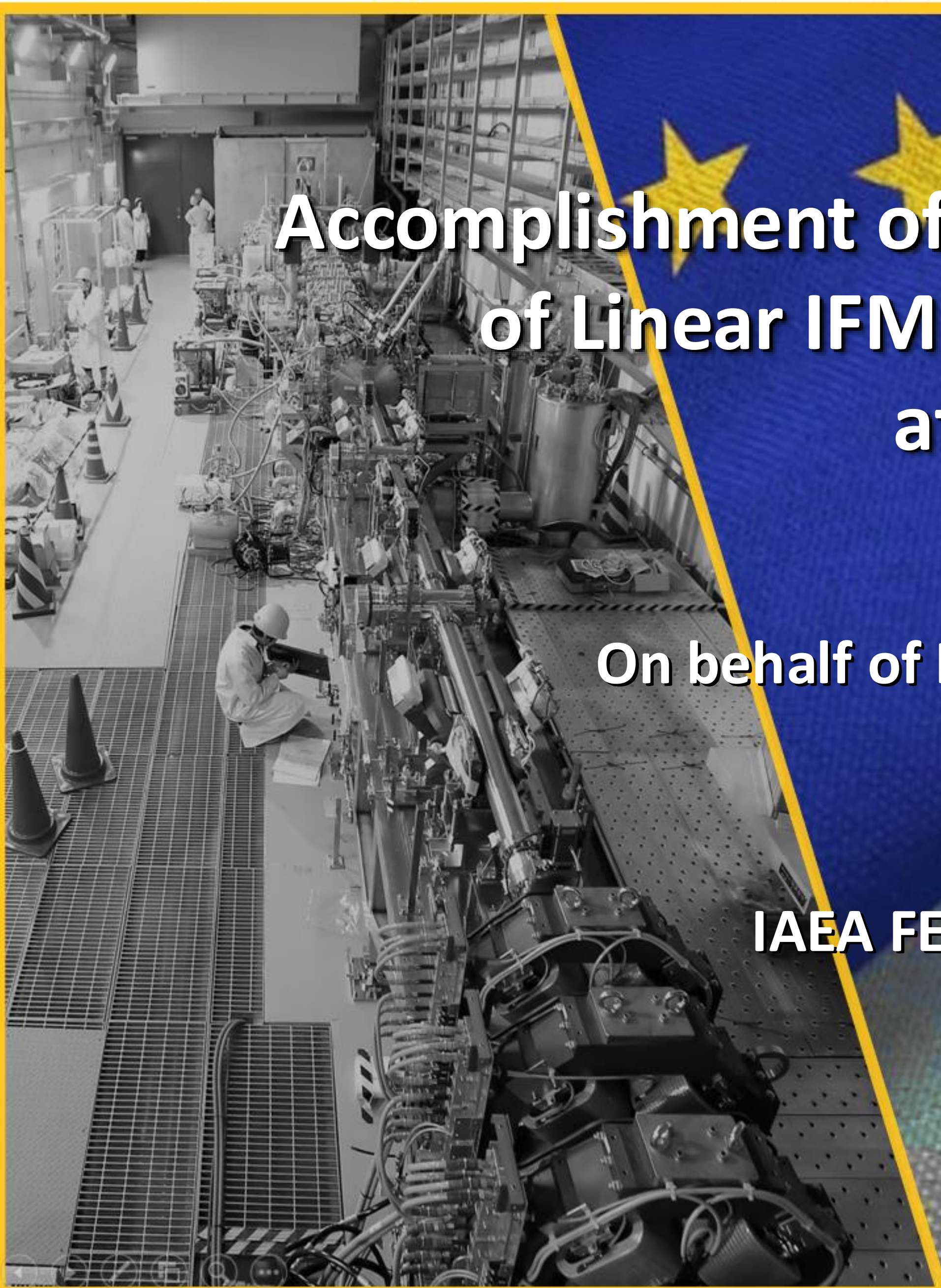
IFMIF/EVEDA
BA-Engineering Validation and Engineering Design Activities for the Fusion Materials Irradiation Facility

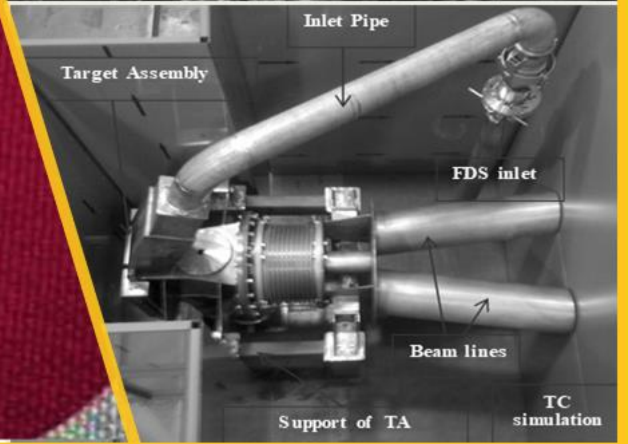


Accomplishment of high duty cycle beam commissioning of Linear IFMIF Prototype Accelerator (LIPAc) at 5 MeV, 125 mA D+

Tomoya Akagi (QST)
On behalf of IFMIF/EVEDA Integrated Project Team

IAEA FEC 2025 IFMIF/EVEDA Workshop

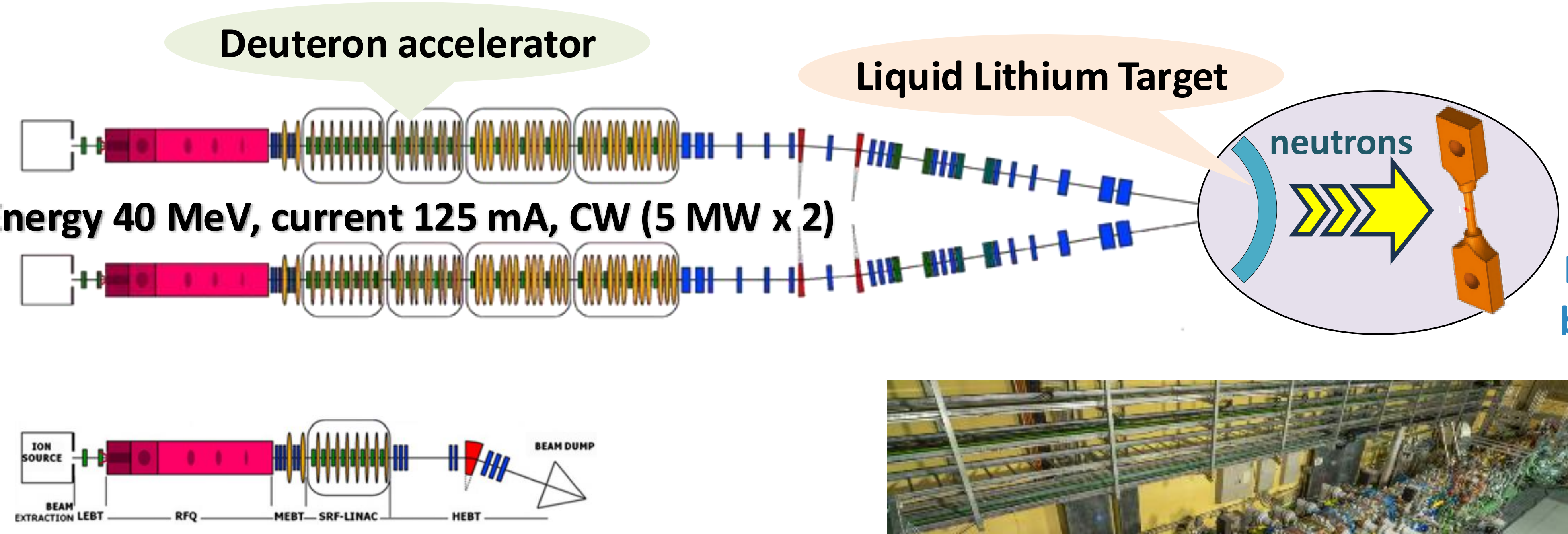
17 September 2025



Outline

- Introduction
- High duty D+ beam commissioning
- Challenges in high-duty operation
- Summary

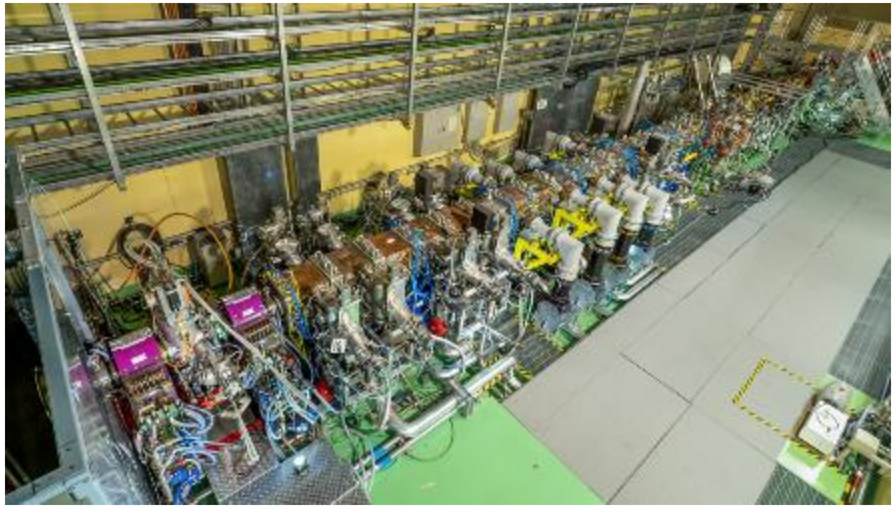
IFMIF (International Fusion Materials Irradiation Facility)
Accelerator-driven powerful neutron source facility using D-Li reaction.



Equivalent to DEMO reactors neutron fluence (up to 20 dpa/y)

Long-term materials behavior verification for DEMO

Linear IFMIF Prototype Accelerator (LIPAc)
Energy 9 MeV, current 125 mA, CW (1.125 MW)



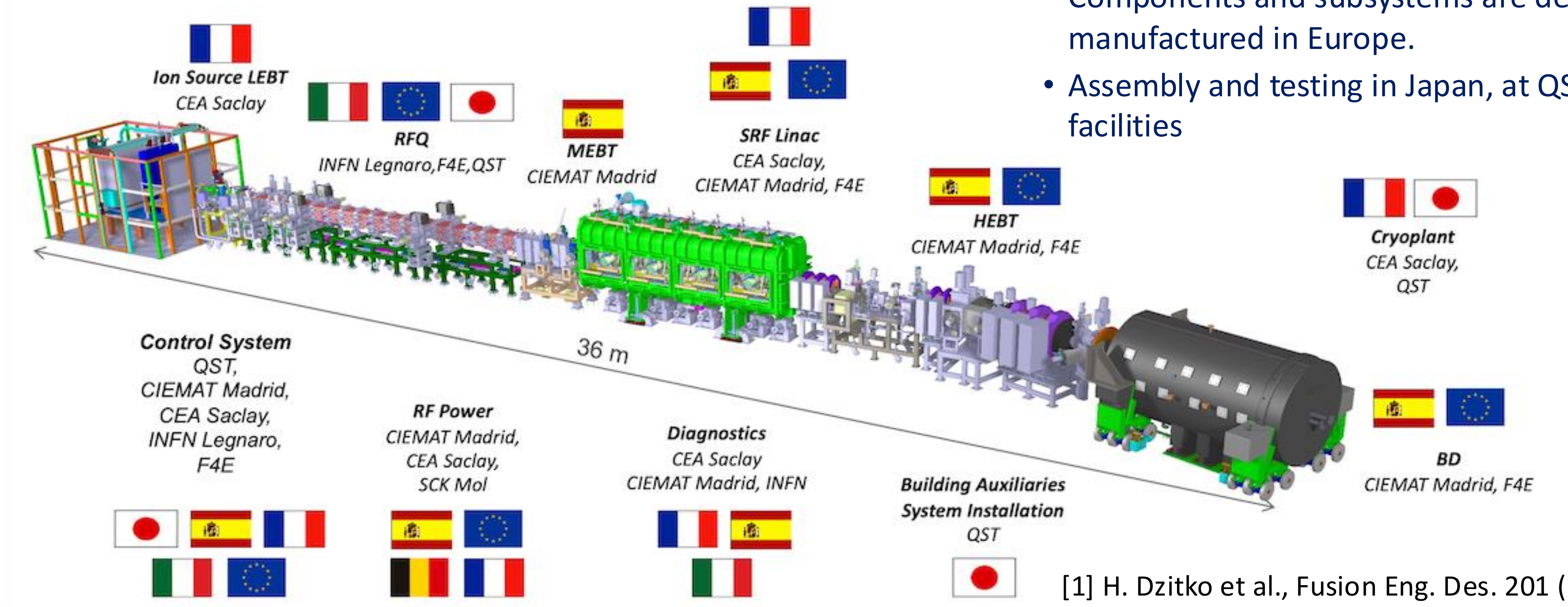
Linear IFMIF Prototype Accelerator (LIPAc)

LIPAc – Linear IFMIF Prototype Accelerator:

- Demonstration of the low-energy section of the IFMIF accelerator.
- Commissioning is being conducted in Rokkasho, Japan, jointly between Europe and Japan.
- Target is to accelerate a deuteron beam of 125 mA to 9 MeV and demonstrate CW operation.

IFMIF: 40 MeV, 2×125 mA, CW
LIPAc: 9 MeV, 125 mA, CW

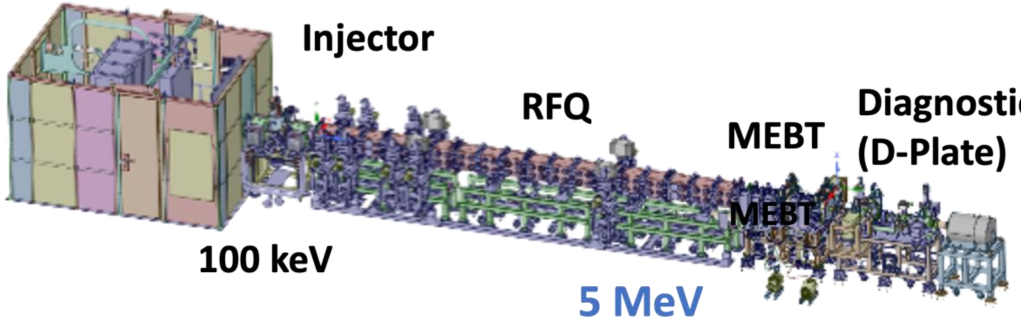
- Part of Broader Approach since 2007, focusing on Eng. Validation and Eng. Design Activities (IFMIF/EVEDA):
  - Components and subsystems are designed and manufactured in Europe.
  - Assembly and testing in Japan, at QST-Rokkasho facilities



[1] H. Dzitko et al., Fusion Eng. Des. 201 (2024) 114259.

LIPAc commissioning phases

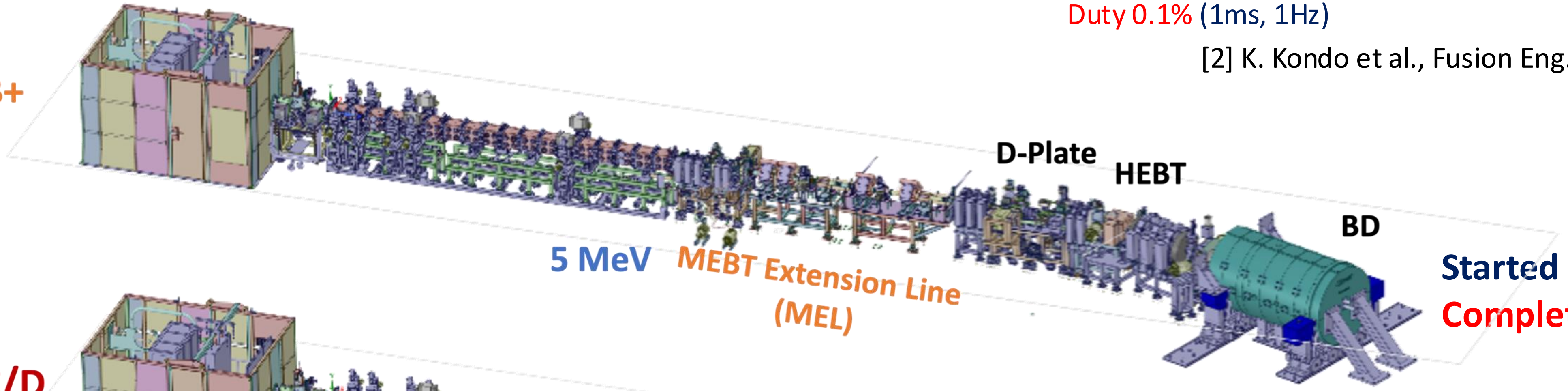
Phase B



Started in June 2018, completed in August 2019.
Successful acceleration of 125 mA deuteron pulsed beam by RFQ.
Duty 0.1% (1ms, 1Hz)

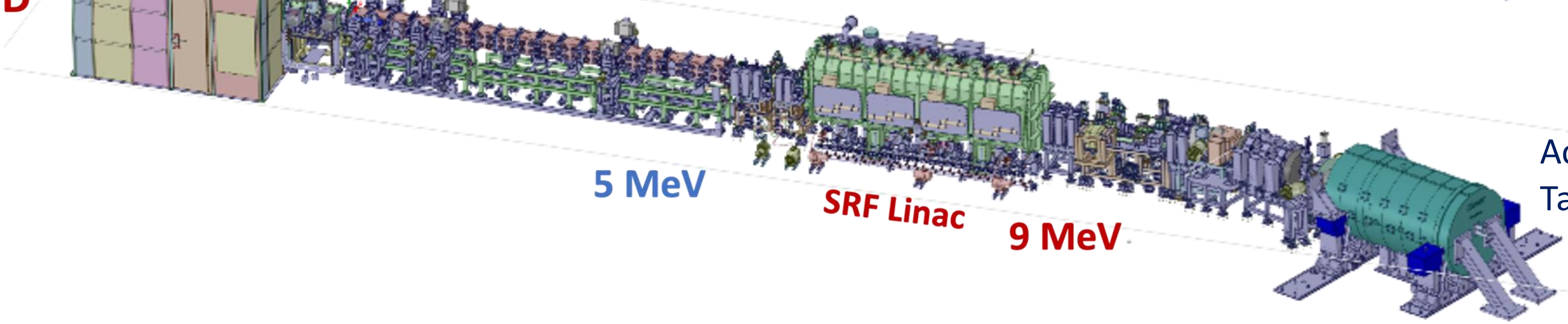
[2] K. Kondo et al., Fusion Eng. Des. 153 (2020) 111503.

Phase B+



Started in July 2021.
Completed in June 2024.

Phase C/D



Acceleration up to 9 MeV by SRF.
Target to start in 2027.

Phase B+: High-duty deuteron beam test

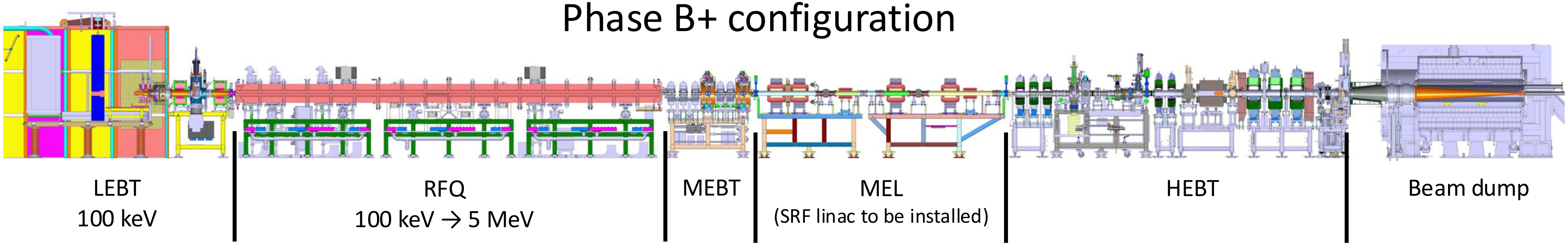
Objectives of Phase B+

- Demonstration of high duty cycle deuteron beam acceleration by RFQ (5 MeV, 125 mA, up to CW).
- Validation of the HEBT and the Beam dump (first time in operation).
- Characterization of beam to be injected into SRF in subsequent Phase C/D.

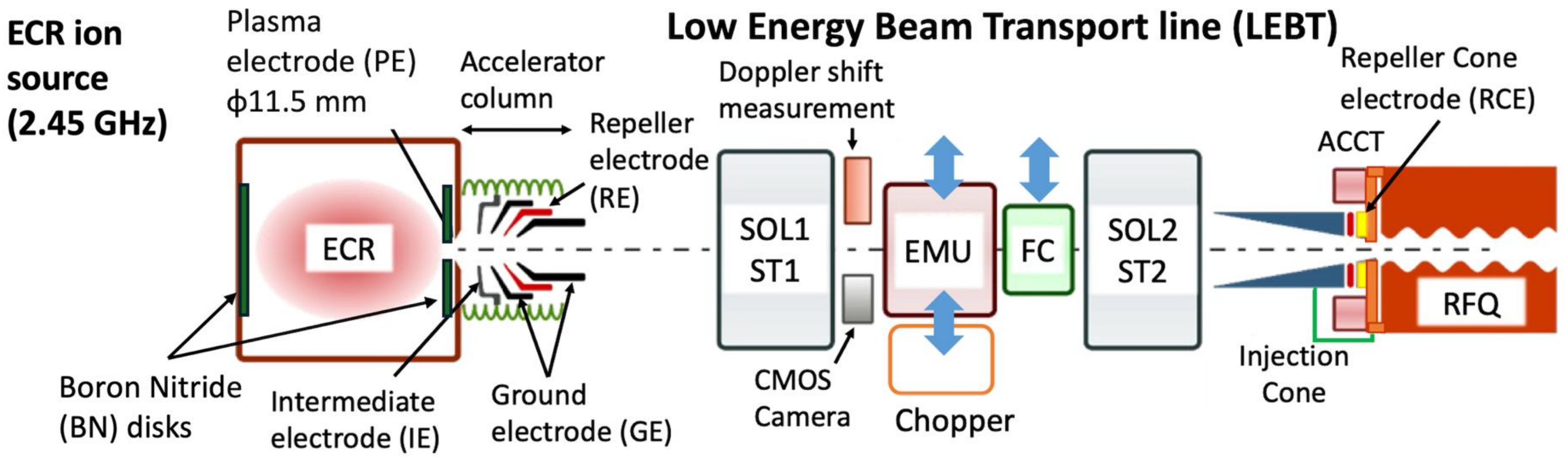
Phase B+ consists of three stages:

- Stage1: Low current, low duty. **Reported at FEC2023.**
  - the pilot beam (10 mA H+, D+ 20 mA D+)
  - beam pulse 100 μs/1 Hz (non interceptive devices are available)
- Stage2: Nominal current (125 mA), low-duty D+ beam
- Stage3: Nominal current (125 mA), high-duty D+ beam (up to CW)

Phase B+ configuration



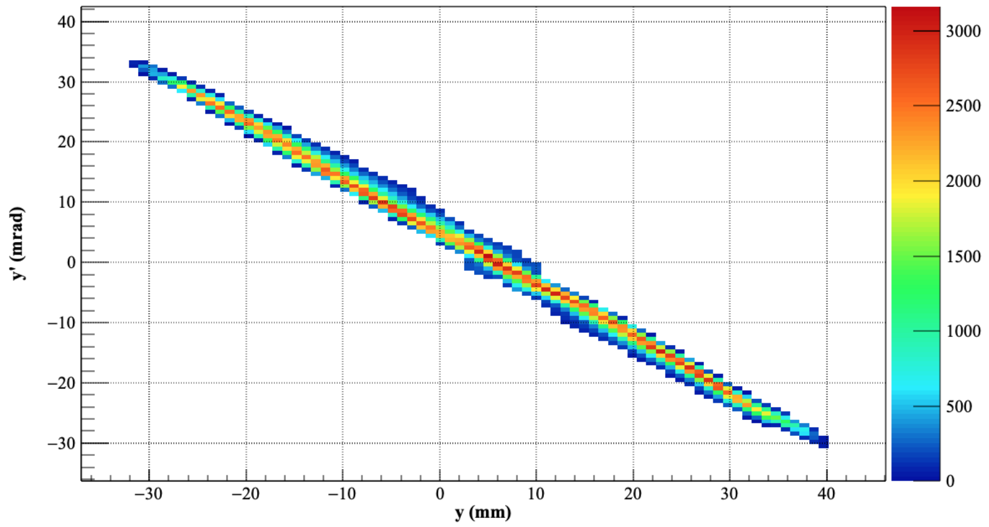
Injector beam commissioning



LEBT features

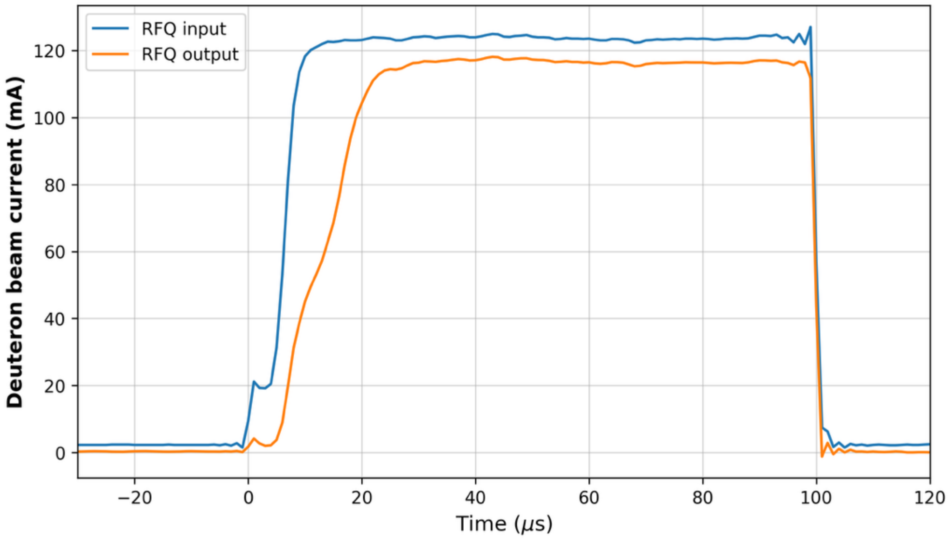
- 2 solenoids with integrated H/V steerers
- Emittance Measurement Unit (EMU
- FC – Faraday cup (beam stopper)
- Species fraction measurement with Doppler-shift spectrometer
- Kr gas injection for SCC
- Chopper to produce short, low-power beams

Emittance measurement with 3% duty cycle
Total extracted current **158 mA**
Normalized RMS emittance 0.18 π mm mrad



~120 mA D+, 100 µs beam pulse with chopper

- Short pulse beam that allow the use of interceptive diagnostics



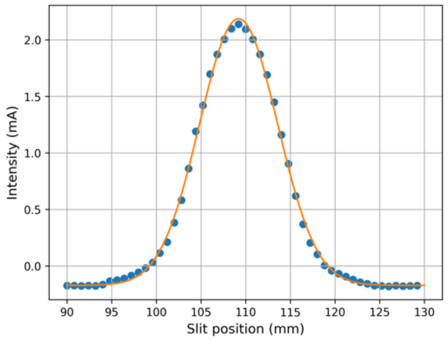
Commissioning of Beam Diagnostics

Transverse beam profiles measured by the interceptive diagnostics.

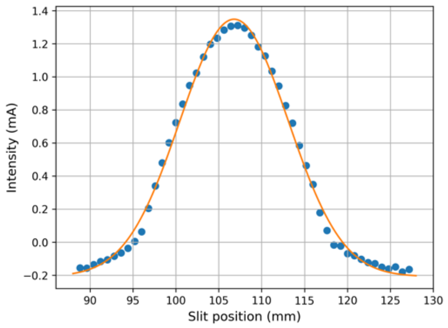
- Interceptive diagnostics worked as expected.
- These were used for beam characterization at low duty cycle.

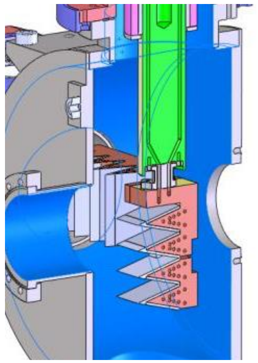
DPlate SLITs (H/V) + CT

Horizontal



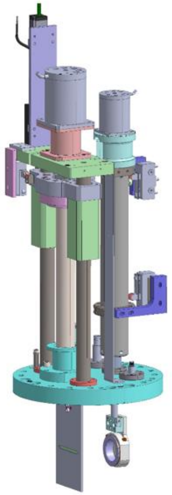
Vertical



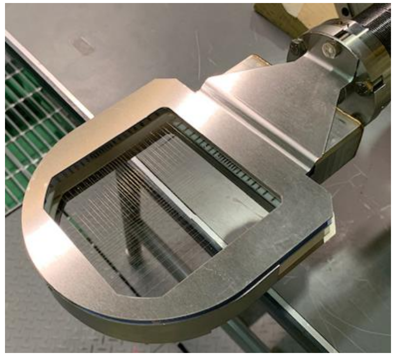


DPlate SLITs

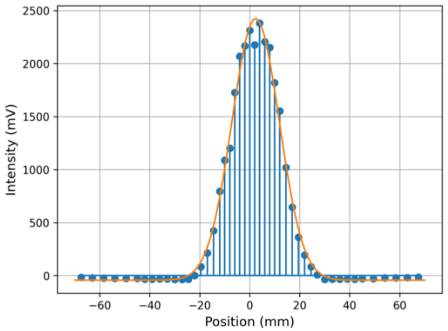
HEBT SLIT + FC



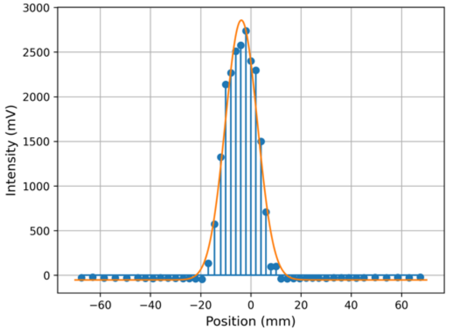
Secondary Emission Monitor (SEM) grid

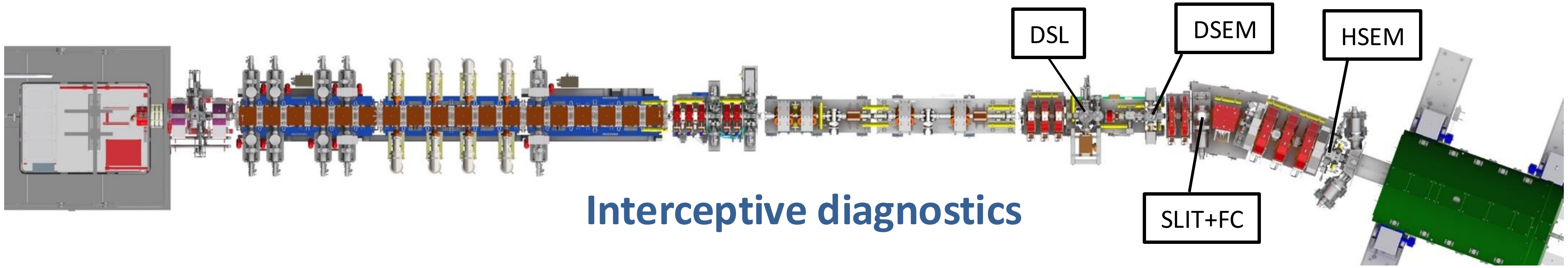


HSEM Horizontal



HSEM Vertical





Interceptive diagnostics

CT: Current Transformer
FC: Faraday Cup

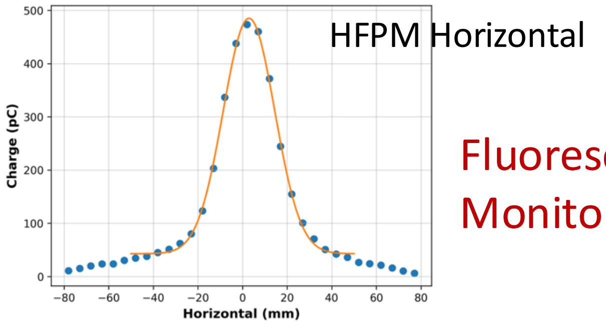
Commissioning of Beam Diagnostics

Transverse beam profiles measured by the non-interceptive profiler.

Basic test of non-interceptive diagnostics was done.

Challenges:

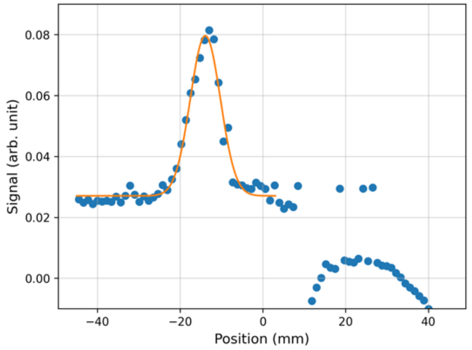
- High sensitivity to vacuum and radiation (FPM)
- HVs were sensitive to the beam/vacuum (IPM)
- Need to investigate electronics setup (IPM)



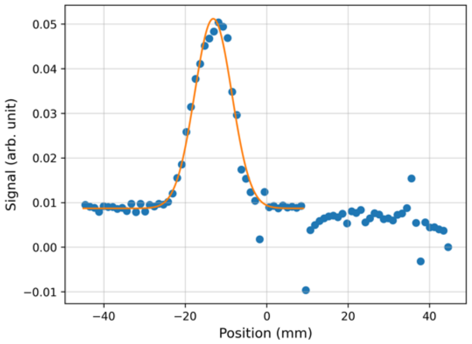
Fluorescence Profile Monitor (FPM)

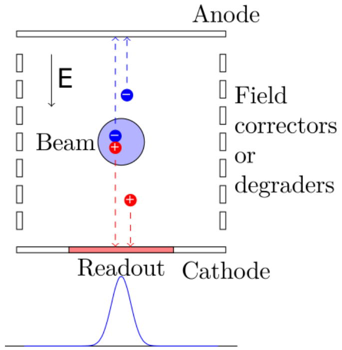
Ionization Profile Monitor (IPM)

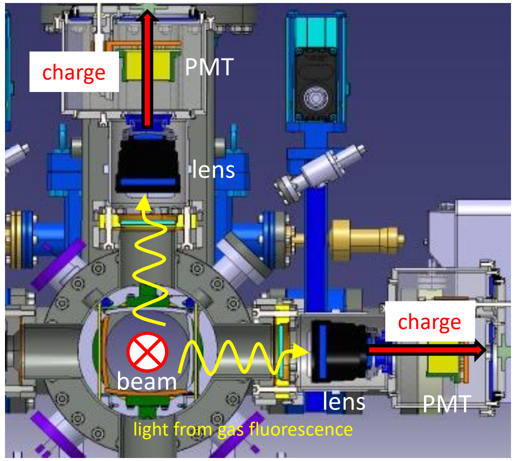
DIPM Horizontal

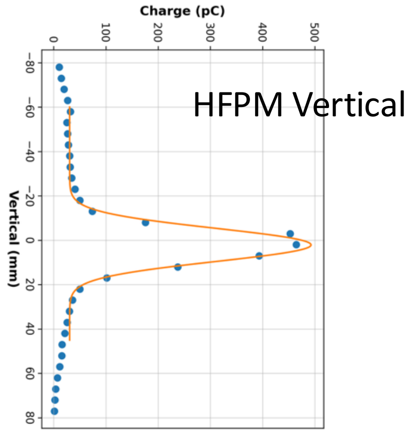


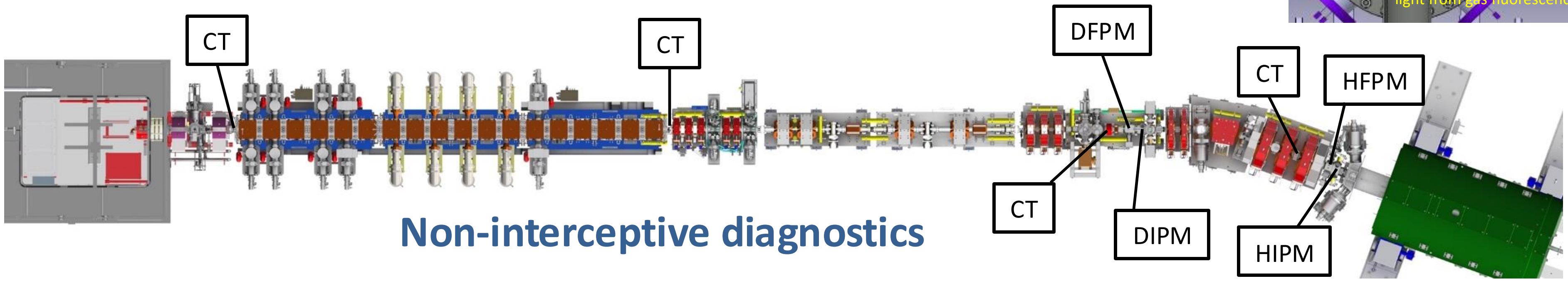
DIPM Vertical











Non-interceptive diagnostics

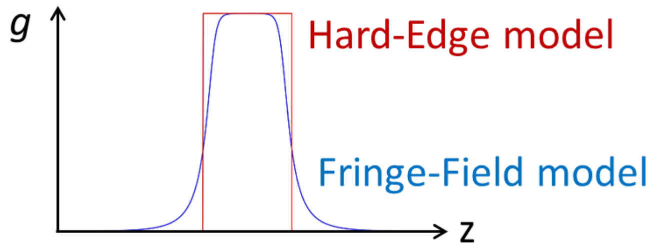
CT: Current Transformer

Validation of beam transport simulation

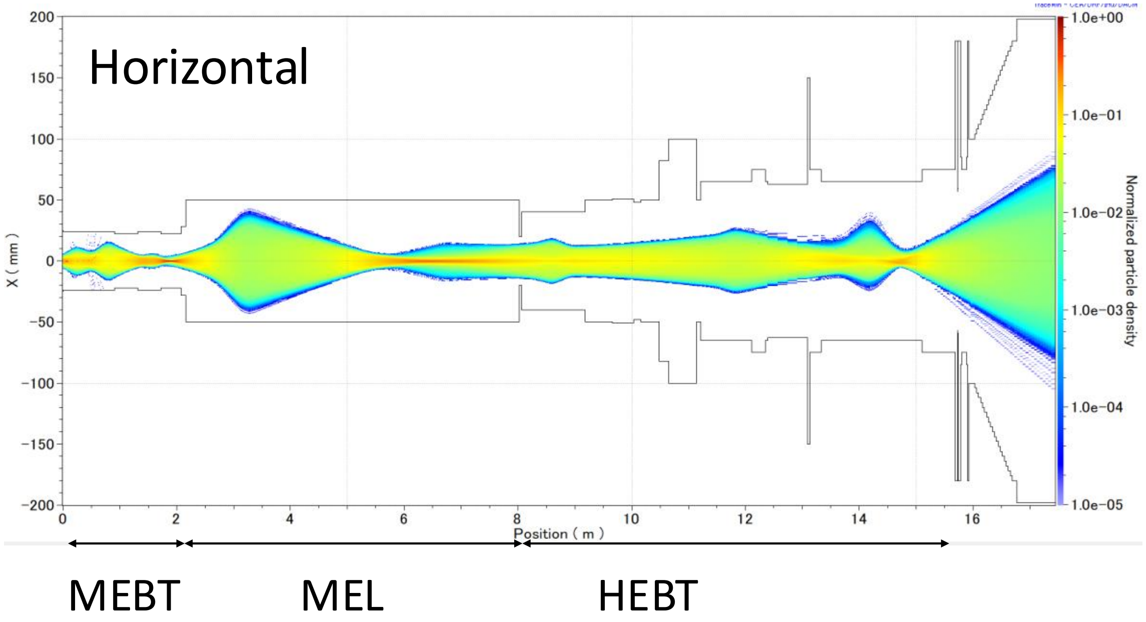
Following the observation of unexpected particle loss, the beam modeling was improved.

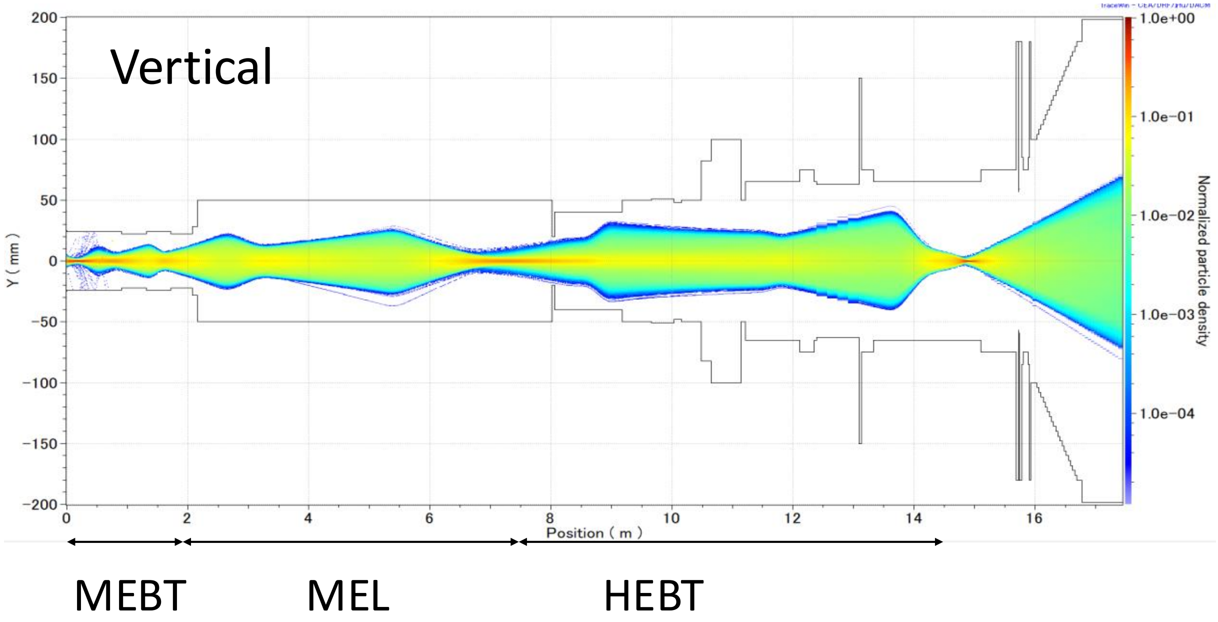
- Simulation using the exact quad field distribution, fully implementing fringing fields instead of the hard-edge model.
- Beam-based calibration of quadrupole magnet *g* (T/m) to *I* (A).

[3] J. Hyun et al., 15th International Particle Accelerator Conference (IPAC'24)



Updated beam optics with calibrated conversion factor and Fringe Field model

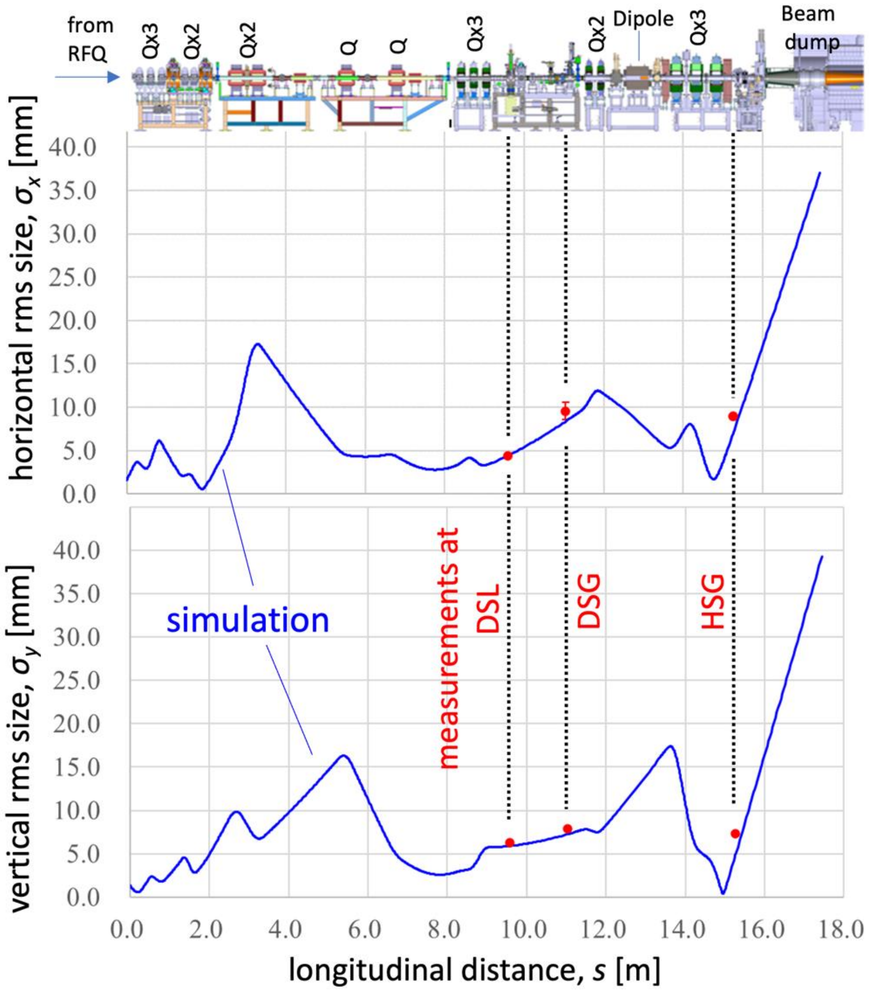




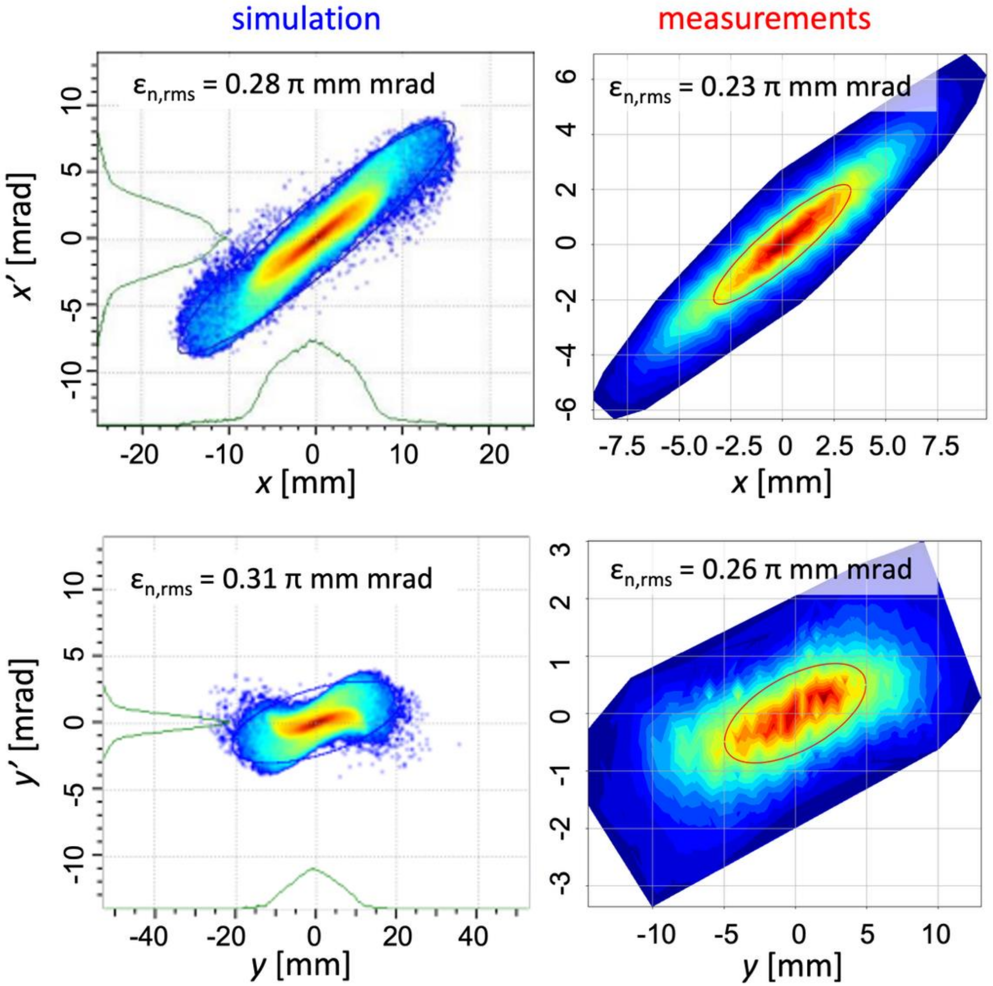
Validation of beam transport simulation

Good agreement between measurements and simulations.

Beam losses are significantly reduced.

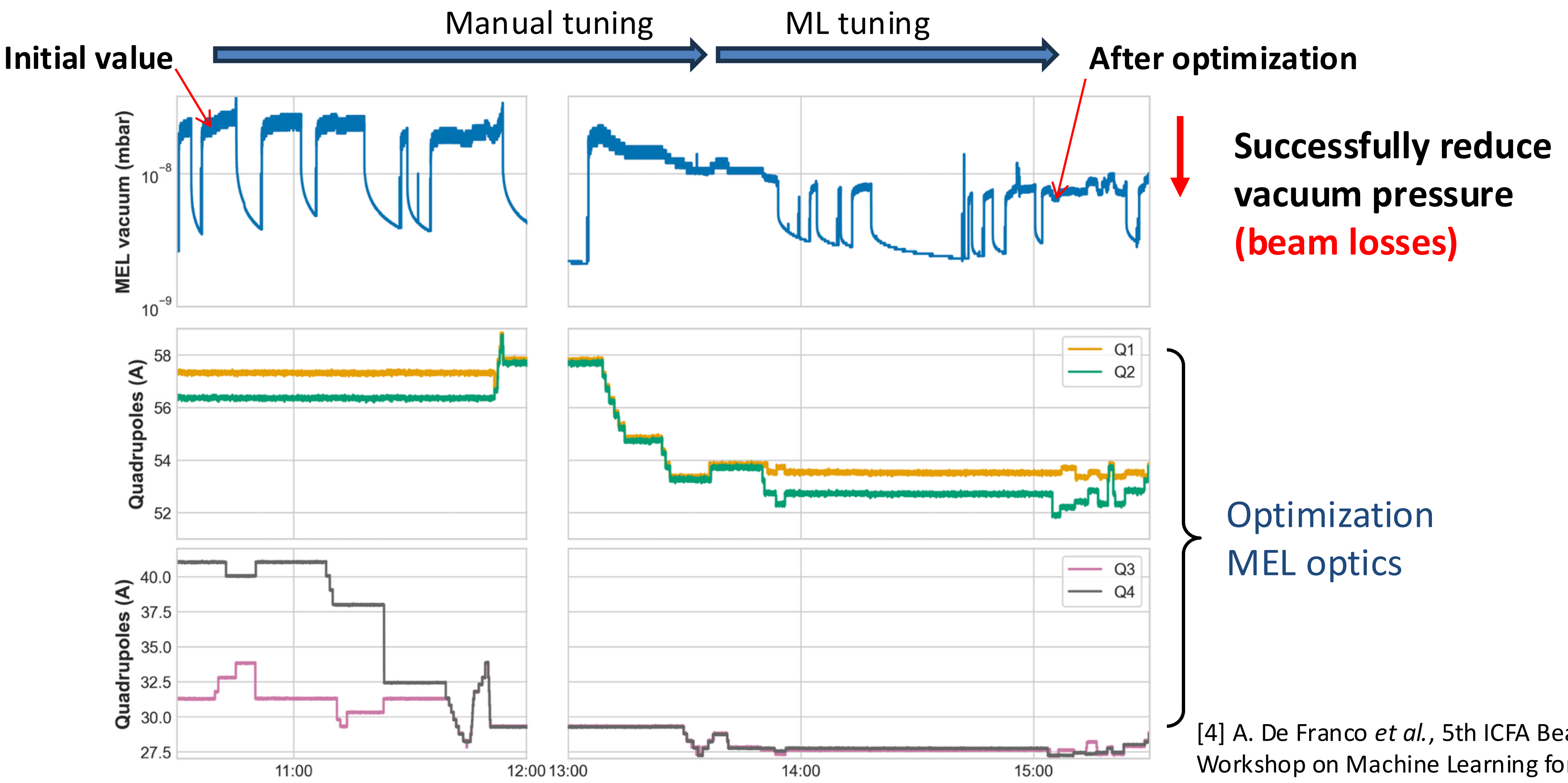


Emittance measurement achieved with DSL-DSG



Beam losses optimization by ML

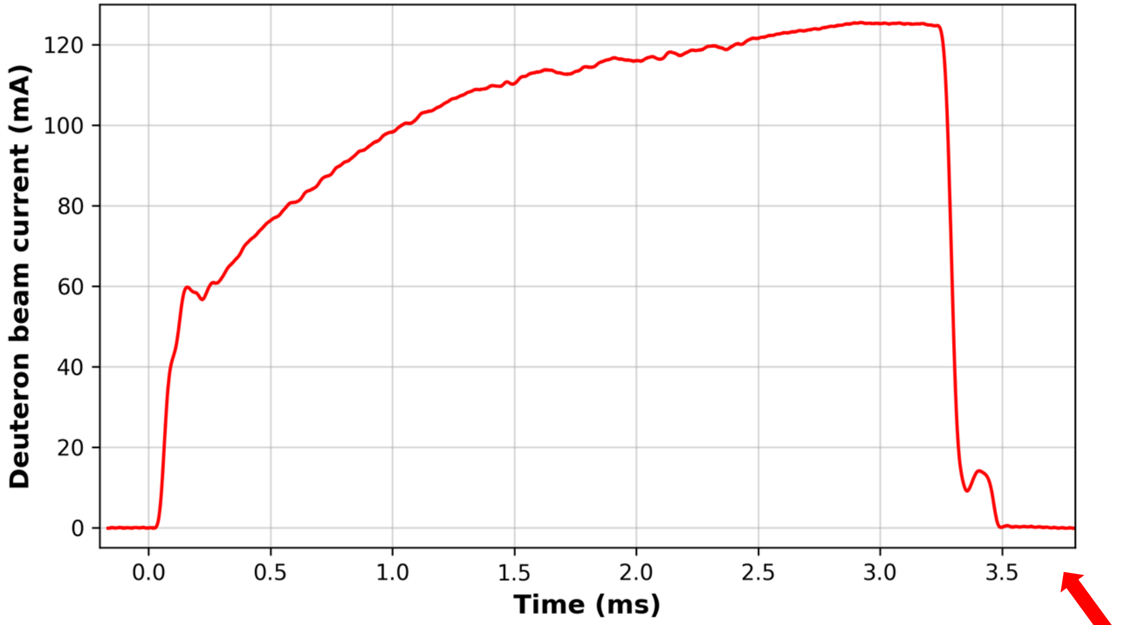
- When increasing duty cycle (~3%), vacuum pressure in MEL approached interlock level due to beam-halo losses.
- Optimization MEL optics (4 quadrupoles + 2 H/V steerers) to minimize beam losses (to reduce vacuum pressure) was performed using Machine Learning (ML).

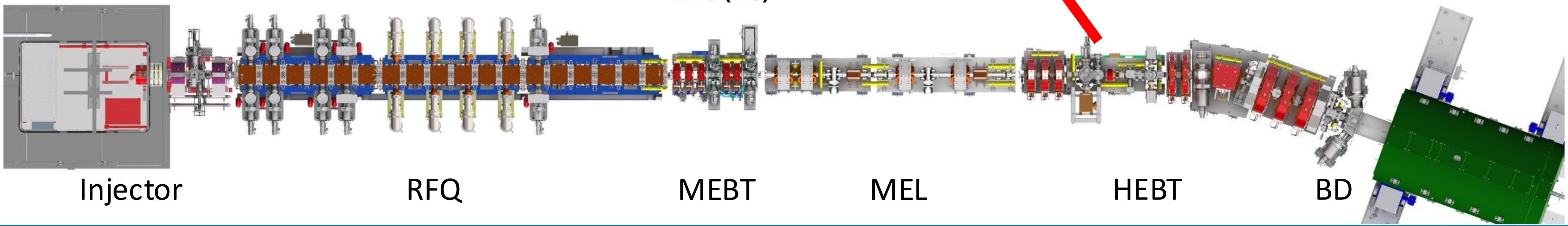


[4] A. De Franco *et al.*, 5th ICFA Beam Dynamics Mini-Workshop on Machine Learning for Particle Accelerators.

Target D+ beam current was achieved.

125 mA D+, 5 MeV, Duty Cycle 1% (pulse width: 3.2ms, repetition period: 300ms)





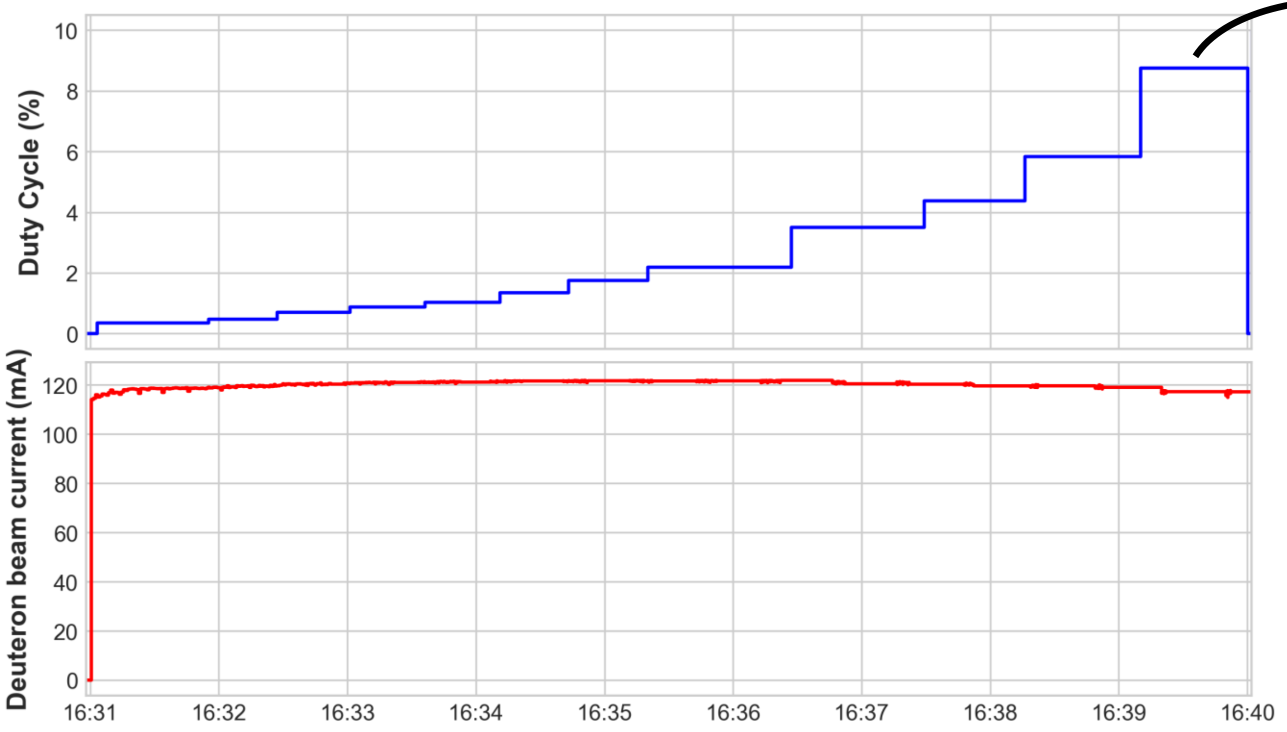
High duty operation: duty 10% operation

Maximum duty cycle of 8.75% (pulse width: 3.5 ms, repetition period: 40 ms)

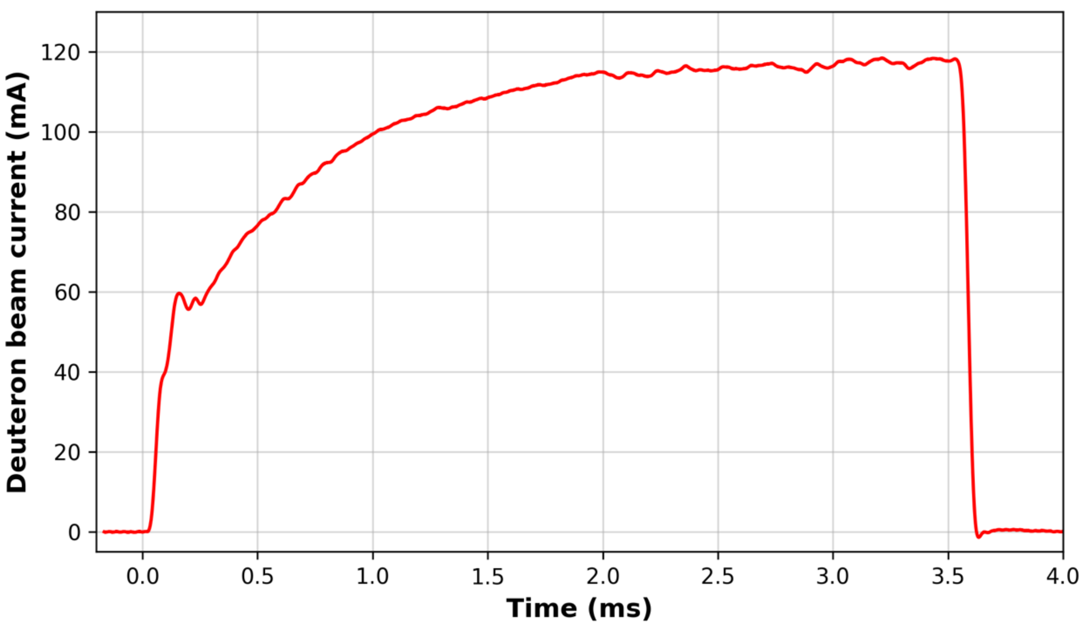
About 119 mA at HEBT, RFQ beam transmission is ~90% (consistent with RFQ design)

RFQ average beam power: 40-45 kW

The world's highest beam power among operational RFQs



Beam current waveform at duty 8.75%



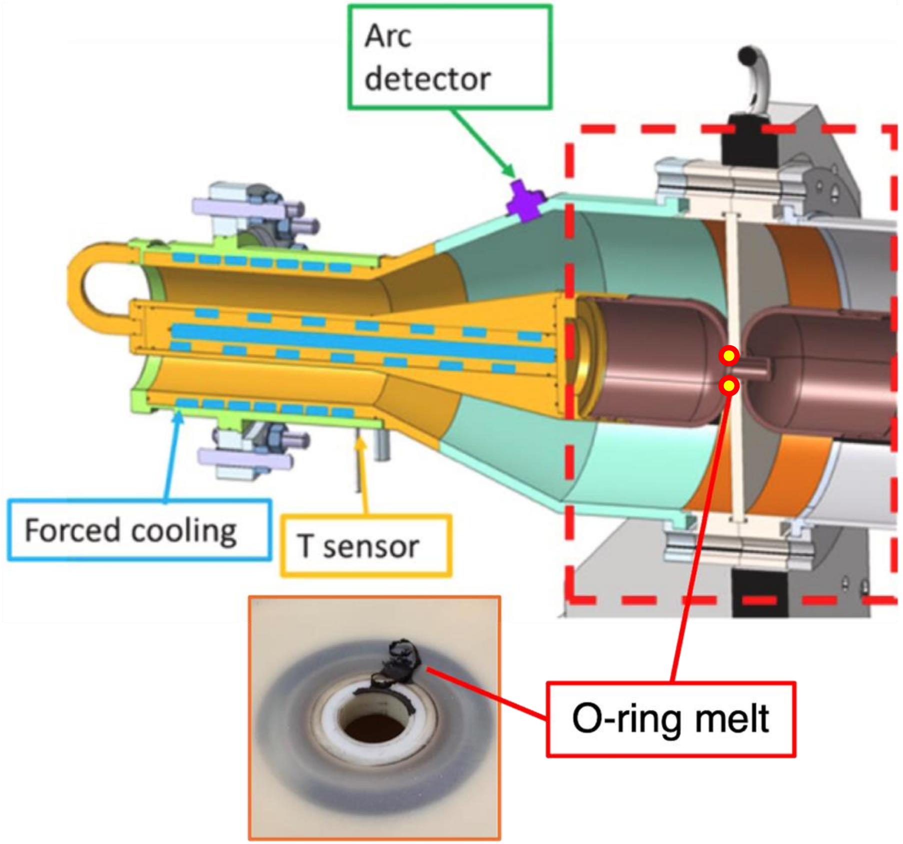
Challenge: RFQ RF couplers

RFQ-RF system: 175 MHz, 200 kW (design) x 8 chains
Nominal RFQ cavity voltage: 132 kV

Achieved CW RF injection at 80% of nominal voltage (105 kV)[5]
But vacuum leak event occurred in March 2022
Viton O-rings were melted/deformed in 5 out of 8 couplers

Identified multipacting as the cause of O-ring overheating.
As a short-term solution, inner conductors with enhanced cooling were installed[6]. **However, the duty cycle was limited to 10% max in Phase B+ to avoid RFQ coupler damage.**

Present coupler (using EPDM O-ring)

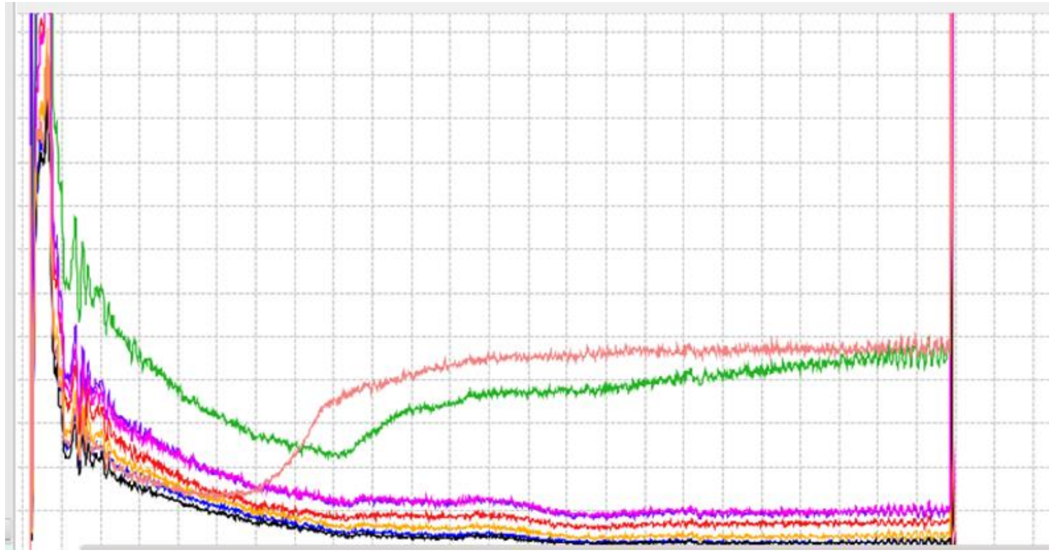


[5] A. De Franco et al., IPAC'23.
[6] F. Scantamburlo et al., Fusion Eng. Des. 204 (2024) 114508.

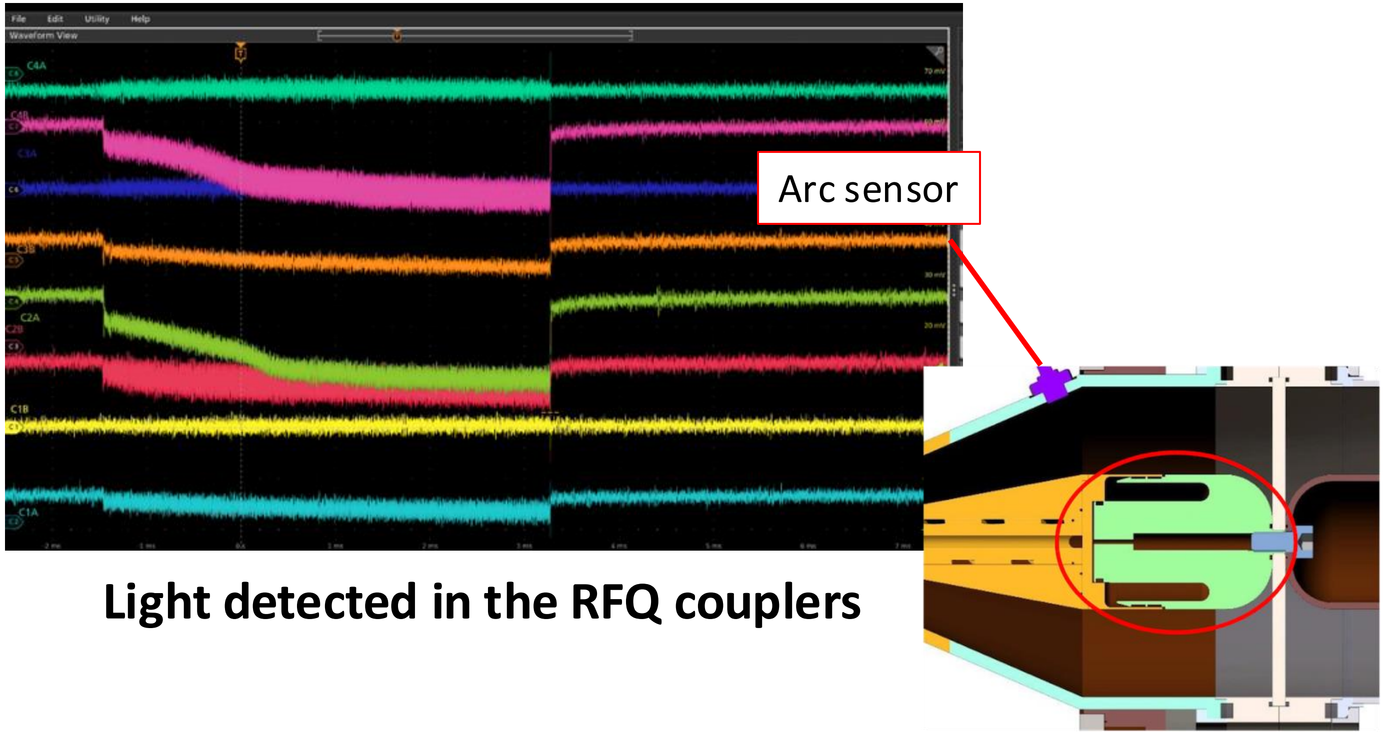
Present coupler behavior at high-duty operation

- Confirmation that a duty increase of up to 10% is difficult with current RFQ O-ring couplers.
- At long-pulse, high-duty, multipacting varies at different ways between couplers, resulting in an imbalance in each RF chain. Consequently, the RF interlock stops before the cavity temperature and vacuum level reach steady state.

→ Preparation of high-duty couplers (brazed couplers) for high-duty operation was carried out in parallel with beam commissioning.



Reflected power in the RFQ-RF chains

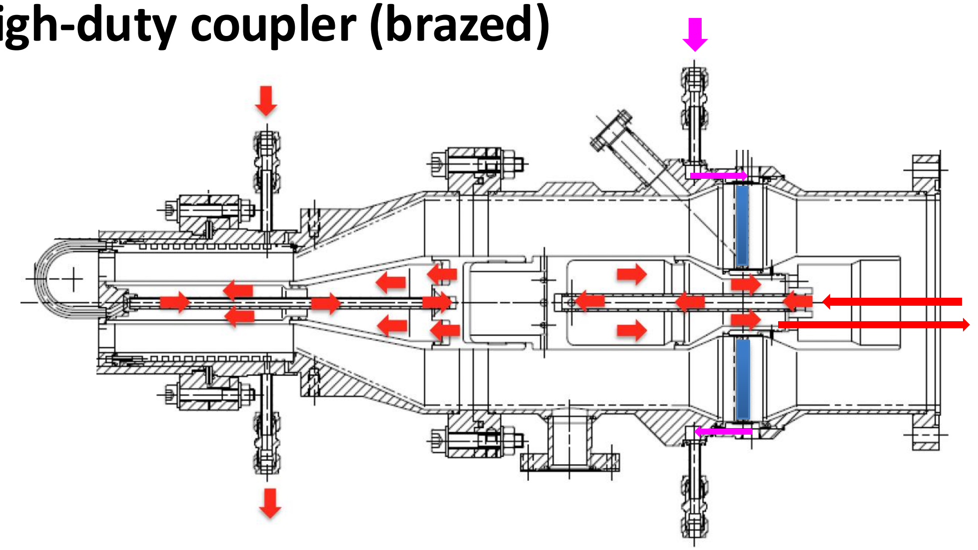


Light detected in the RFQ couplers

RFQ high-duty coupler testing

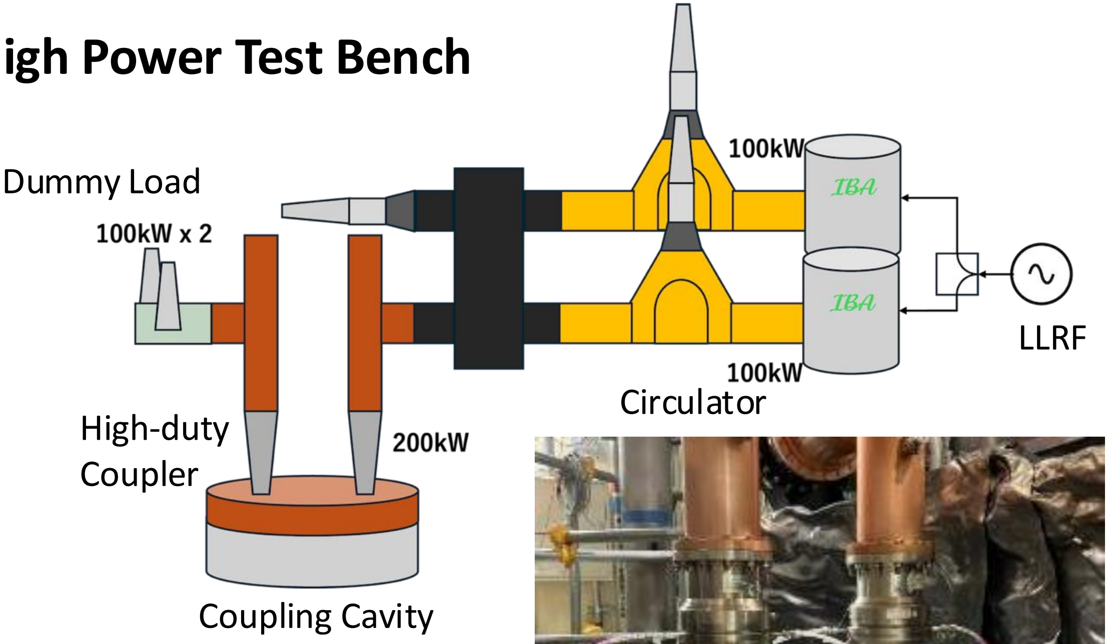
RFQ couplers with the inner conductor brazed to the vacuum window

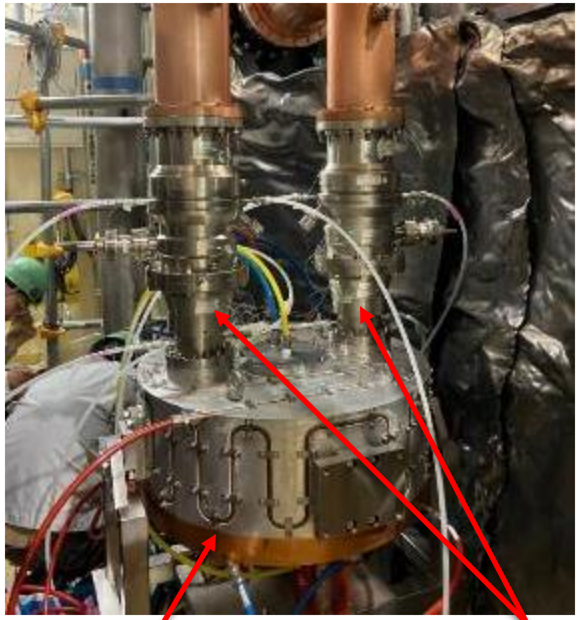
High-duty coupler (brazed)



Red arrows indicate the cooling water flow.

High Power Test Bench





Coupling cavity

High-duty couplers

Status of the high-power test:

- 4 couplers have achieved CW at 190 kW. Promising result for next high-duty operation.
- The remaining couplers are under preparation, aiming for installation in RFQ cavities and RF conditioning.
- As a mitigation plan, another set of high-duty couplers is under production.

Assembly of SRF Linac

- Clean room assembly was completed in September 2024.
- Cold mass was inserted into the vacuum vessel in January 2025.
- Transport to the vault in March 2025.
  - Assembly in the vault is ongoing

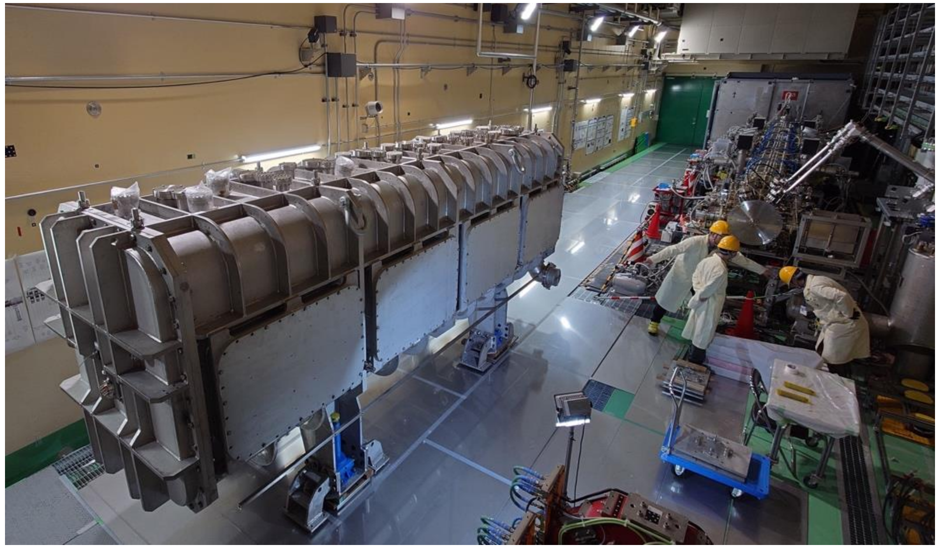
Next steps:

- Installation of the cryomodule to the final position.
- Warm conditioning and first cooldown.
- Phase C beam test is target to start in 2027.


Cavities and solenoids


Insertion of cold mass

Transportation of cryomodule to the vault



Summary

- Successfully demonstrated high-duty cycle operation of the LIPAc, achieving a maximum duty cycle of 8.75% and a beam current of 119 mA.
- Newly installed components, HEBT and BD, were successfully validated.
- These achievements establish a solid foundation for future progress towards CW operation to demonstrate the IFMIF accelerator concept.
- RF couplers are identified as critical components requiring improvement to achieve CW operation.
- Installation of the SRF Linac is ongoing. Phase C is targeted to start in 2027.

This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.