CW operation of high-current deuteron injector for the Linear IFMIF Prototype Accelerator (LIPAc)

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On behalf of the LIPAc Injector team

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Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

Outline

- Introduction to IFMIF and LIPAc
- LIPAc Injector and commissioning overview
- Achievement of CW operation
- Investigation of BN disks degradation

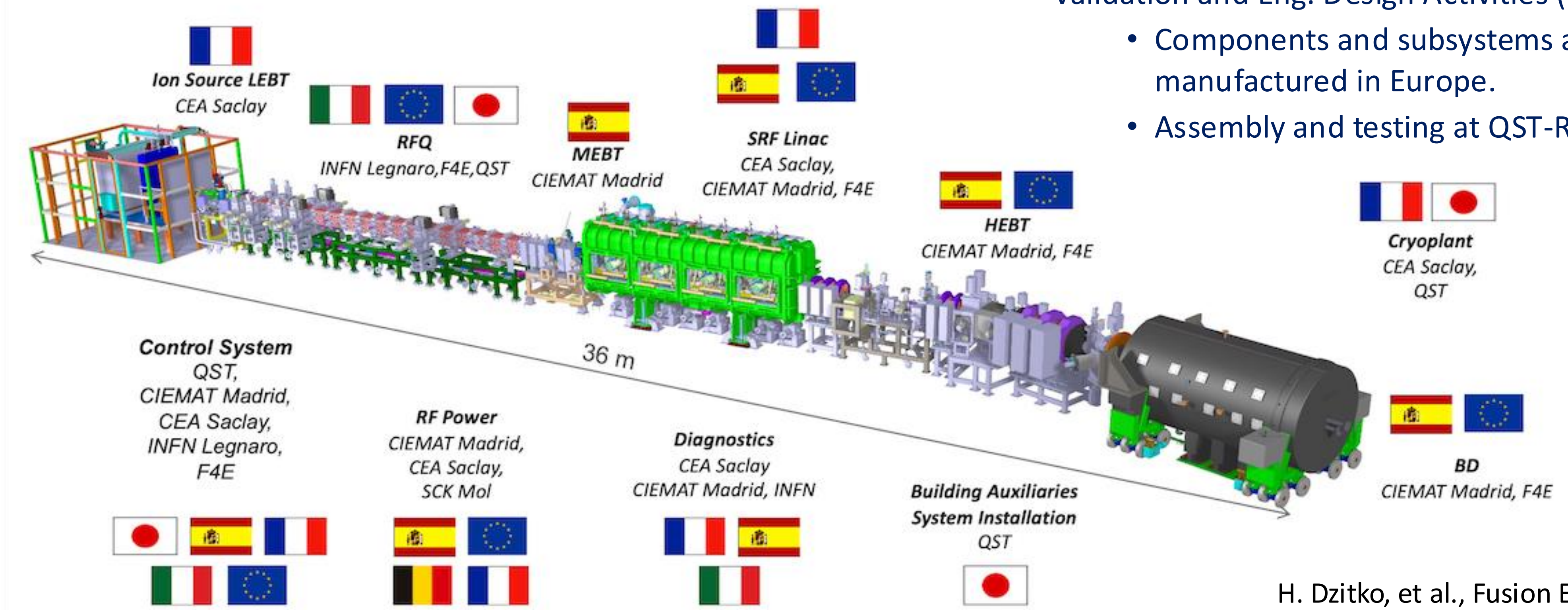
IFMIF, LIPAc, and DONES

IFMIF – International Fusion Materials Irradiation Facility: 40 MeV, 2×125 mA, CW

- Intense neutron source (using D+ accelerator & Li target) for fusion materials research.

LIPAc – Linear IFMIF Prototype Accelerator: 9 MeV, 125 mA, CW

- Demonstration of the low-energy section of the IFMIF accelerator.



- 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 at QST-Rokkasho.

H. Dzitko, et al., Fusion Eng. Des. **201** (2024) 114259.

DONES – DEMO* Oriented Neutron Source: 40 MeV, 125 mA, CW

- Full-scale IFMIF neutron source (one branch) being in construction in Granada.
- User facility – i.e., very high operational availability of 87%.

*DEMO: future DEMOnstration D-T fusion reaction power plant.

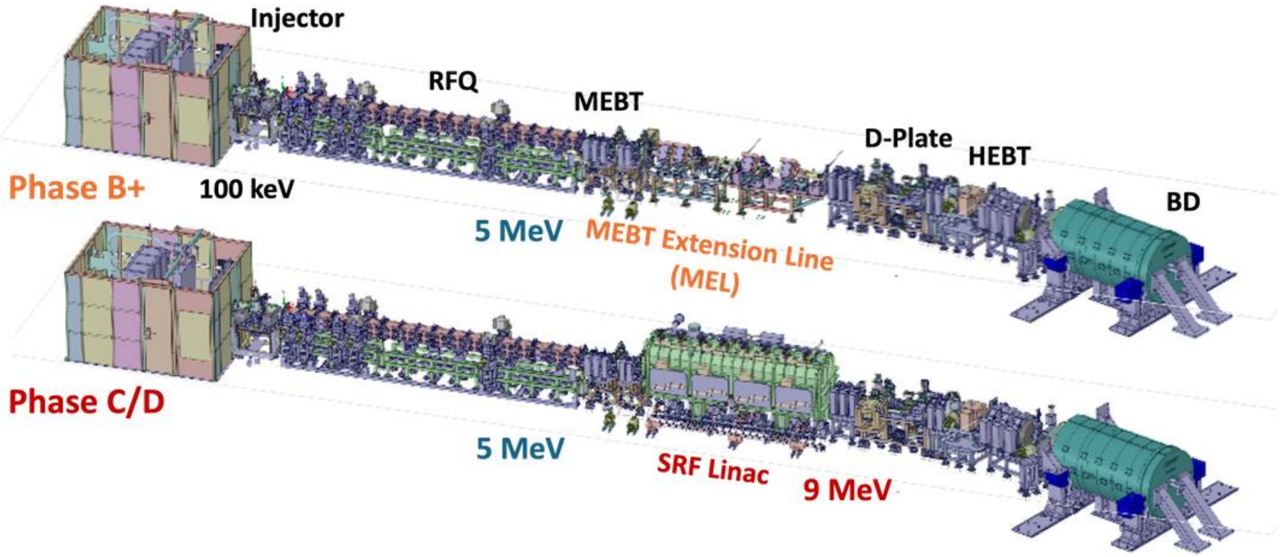
Commissioning phases of LIPAc

Phase A & Phase B: Commissioning of Injector & RFQ with low-power beam dump. **Completed in June 2019.**

- 125 mA D^+ pulse beam acceleration was achieved in the Phase B.

Phase B+: Started in July 2021. **Completed in June 2024.**

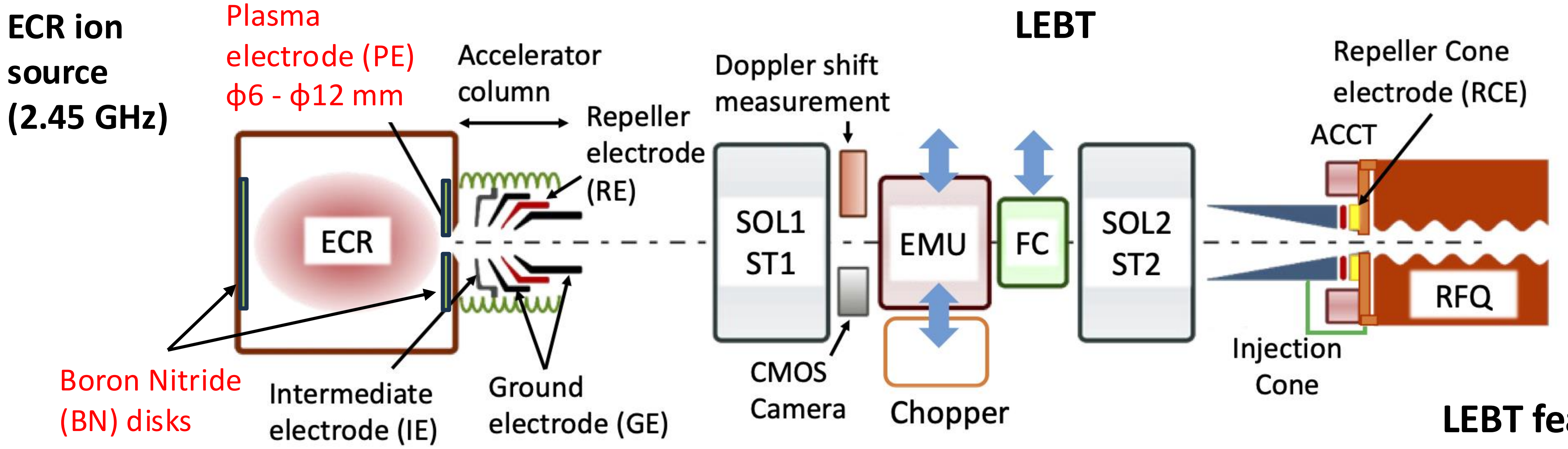
- Goals:
  - Demonstration of high duty cycle deuteron beam acceleration by RFQ (5 MeV, 125 mA, up to CW)
  - Characterization of beam to be injected into SRF in subsequent Phase C/D.
- Achievements:
  - Successful commissioning of components and diagnostics
  - Validation of beam transport simulations by comparing them with experimental measurements
  - Transport of ~119 mA deuteron beam to beam dump with RFQ transmission of 90.1% (consistent with RFQ design)
- Challenges:
  - Maximum duty cycle limited to **8.75 %** (pulse width 3.5 ms, rep. period 40 ms) due to RFQ RF coupler issue.



Phase C/D: Acceleration up to 9 MeV by SRF Linac.
Target to start in 2027.

- SRF Linac installation ongoing.

LIPAc Injector hardware overview

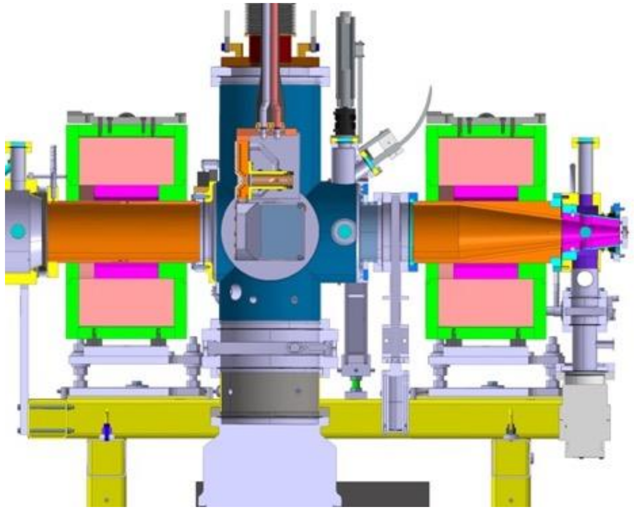


Injector designed by CEA/Saclay based on the SILHI source.

LIPAc Injector main requirements

Particle type*	D^+
Beam energy	100 keV
D^+ Beam current (@ RFQ entrance)	140 mA
Beam current noise	1% rms
Normalized rms emittance	0.25 π mm mrad
Operation mode	Pulse/CW

* H^+ beam is also used for beam commissioning to minimize machine activation.



LEBT features

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

Injector beam commissioning overview

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025

LIPAc operation:

Phase B: B0, B1.1, B1.2, B2

Phase B+: Stage 1, Stage 2, Stage 3

Injector "standalone" operation:

PE(mm) = 9

PE(mm) = 10

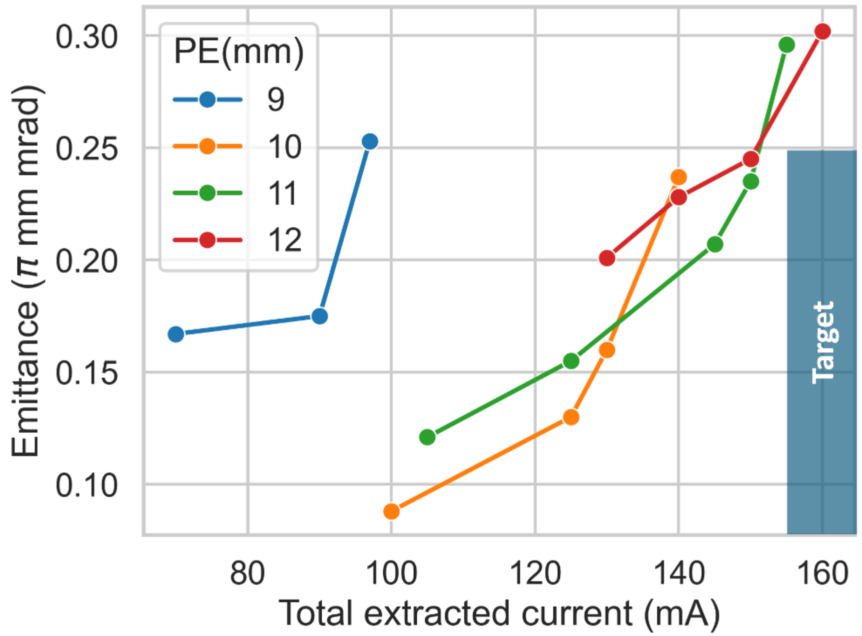
PE(mm) = 11

PE(mm) = 12

PE(mm) = 11.5

PE(mm) = 11.25

PEs of various aperture diameters (9, 10, 11 and 12 mmϕ) were experimentally studied in terms of stability, emittance, and extracted current.

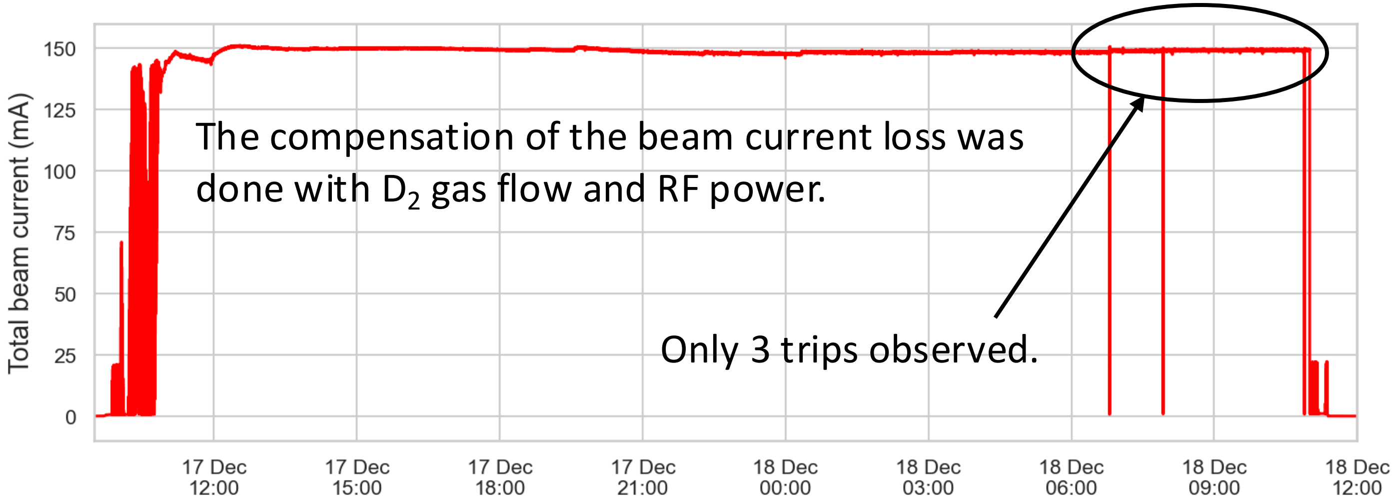


- To allow for a margin of D^+ beam current, we decided to explore the range between ϕ11 and ϕ12 mm PE.
- Last campaign with ϕ11.25 focused on analysis of BN disks lifetime (see next slides).

Achievement of CW operation (Oct-Dec 2024)

CW 24-hour-long run with ϕ11.25-mm PE:

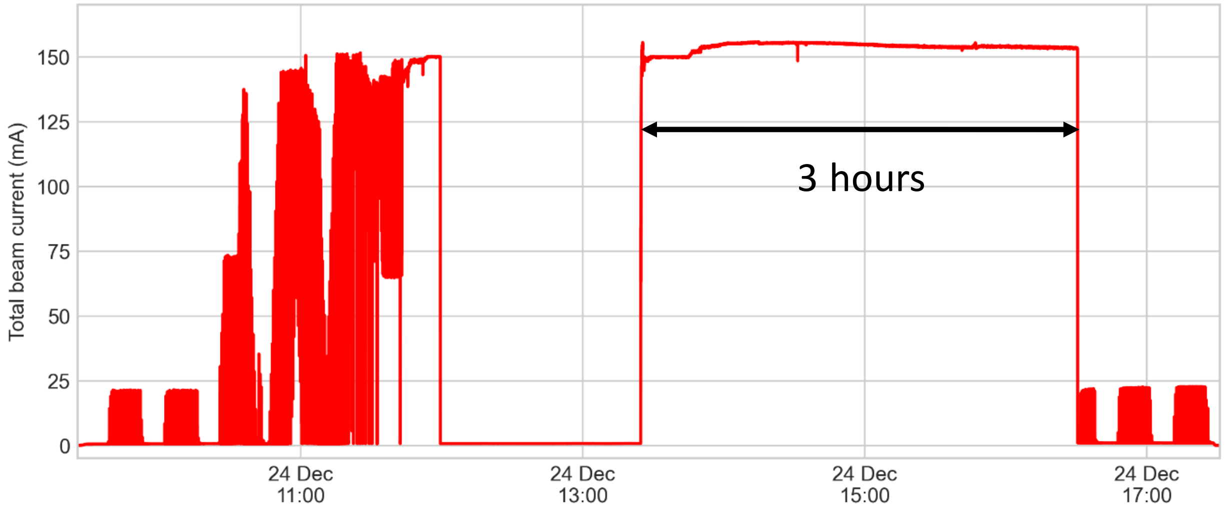
Initial total extracted current 150 mA.



Beam parameters:

- $\varepsilon_{rms,n}$ = 0.18 π·mm·mrad
- I_{ext} = 148 mA
- $\langle I_{FC} \rangle$ = 142 mA
- rms noise = 3.5%
- Species fraction = 92%

The total extracted current at CW was gradually increased up to 155 mA.



Beam parameters:

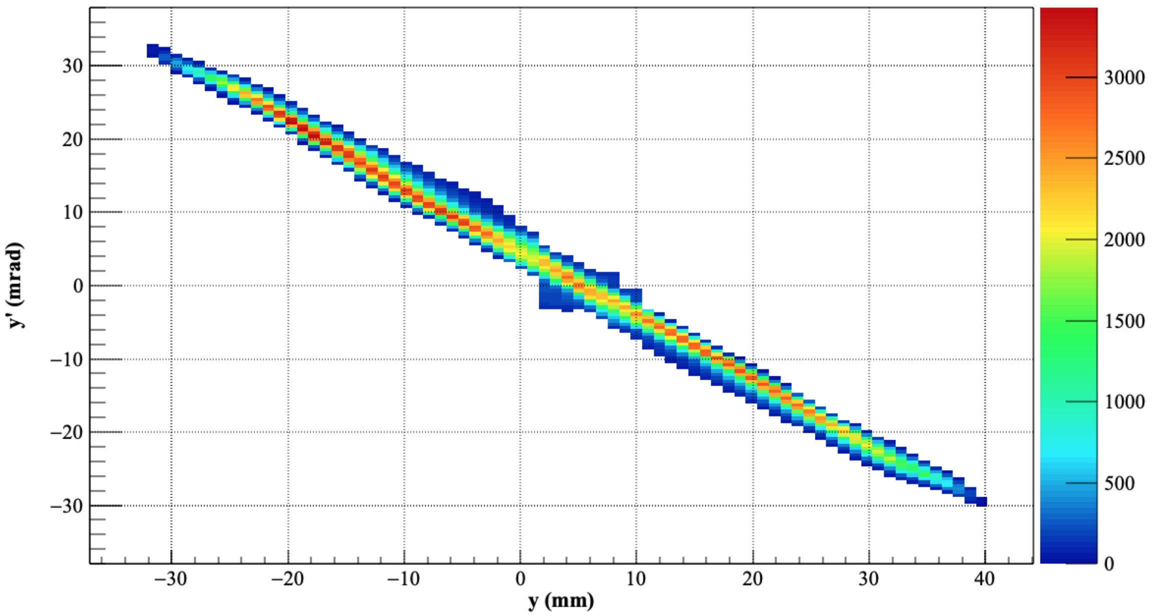
- $\varepsilon_{rms,n}$ = 0.18 π·mm·mrad
- I_{ext} = 155 mA
- $\langle I_{FC} \rangle$ = 148 mA
- rms noise = 1.7%
- Species fraction = 92%

✓ **Meets LIPAc requirements**

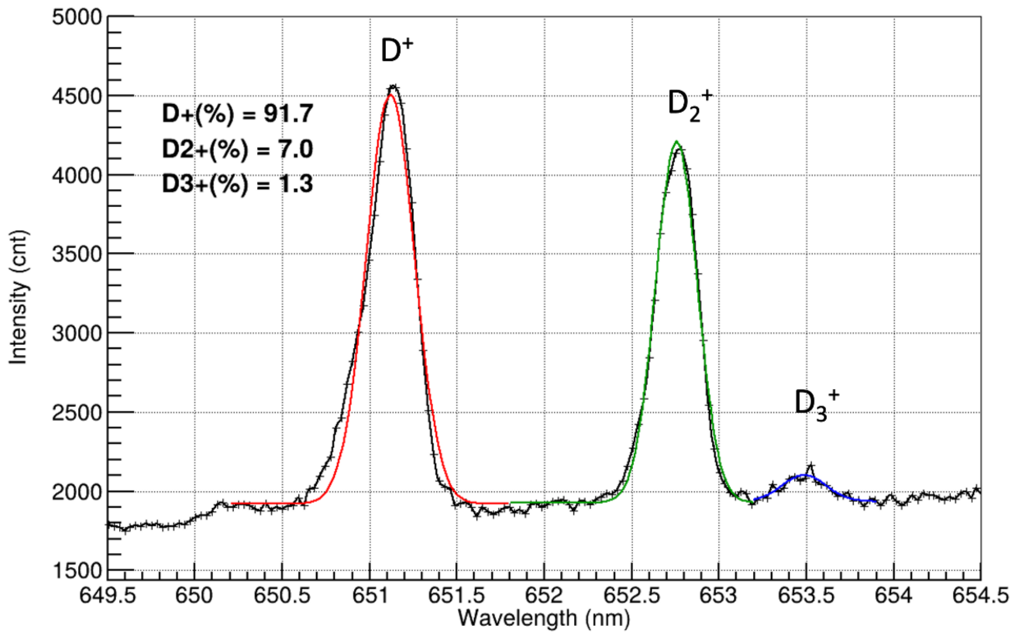
Achievement of CW operation (Oct-Dec 2024)

CW 24-hour-long run with ϕ11.25-mm PE: measurement of key beam parameters

Emittance measurement with 3% duty cycle
Total extracted current **156 mA**
Normalized RMS emittance 0.18 π mm mrad



Species fractions obtained with Doppler shift method
D+ fraction 91.7% with total current **156 mA at CW**
D^+ current of 143 mA (meets LIPAc requirement)



Observation of BN disks degradation

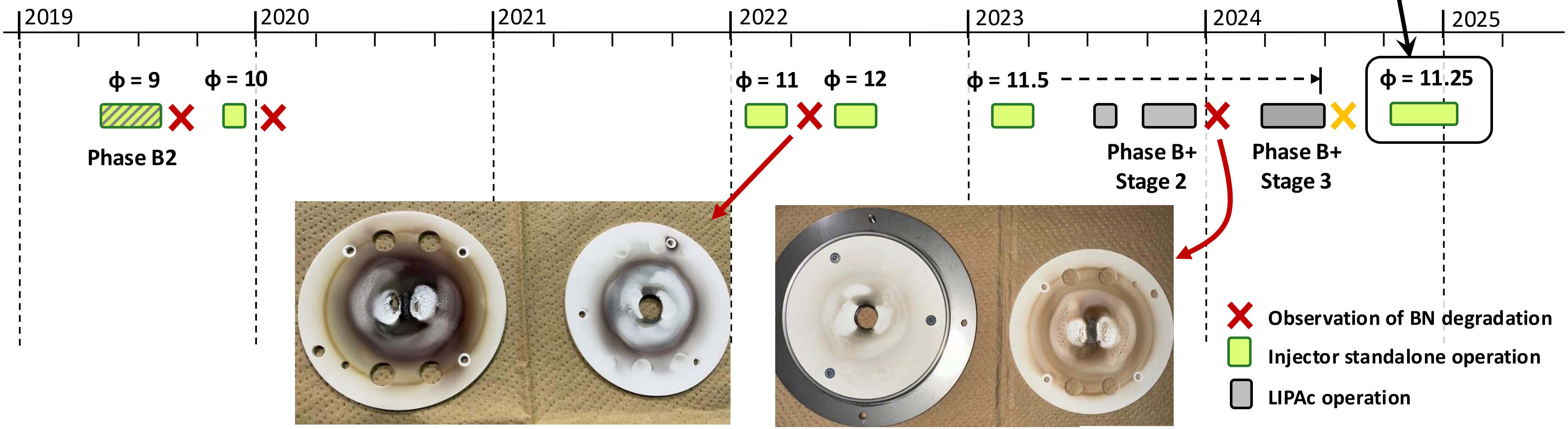
Role of BN disks in ECR ion sources

The use of insulator materials (BN, SiN, Al203) in the form of disks at the RF source side and PE side and/or covering the walls of the plasma chamber (coating like) improves the performances in terms of:

- total extracted current,
- species fraction (larger H+/D+ fraction over molecular species),
- stability of the extracted beam (beam ripple).

The investigation of BN disks degradation motivates the campaign of Oct-Dec 2024.

Observation of BN disks degradation at LIPAc

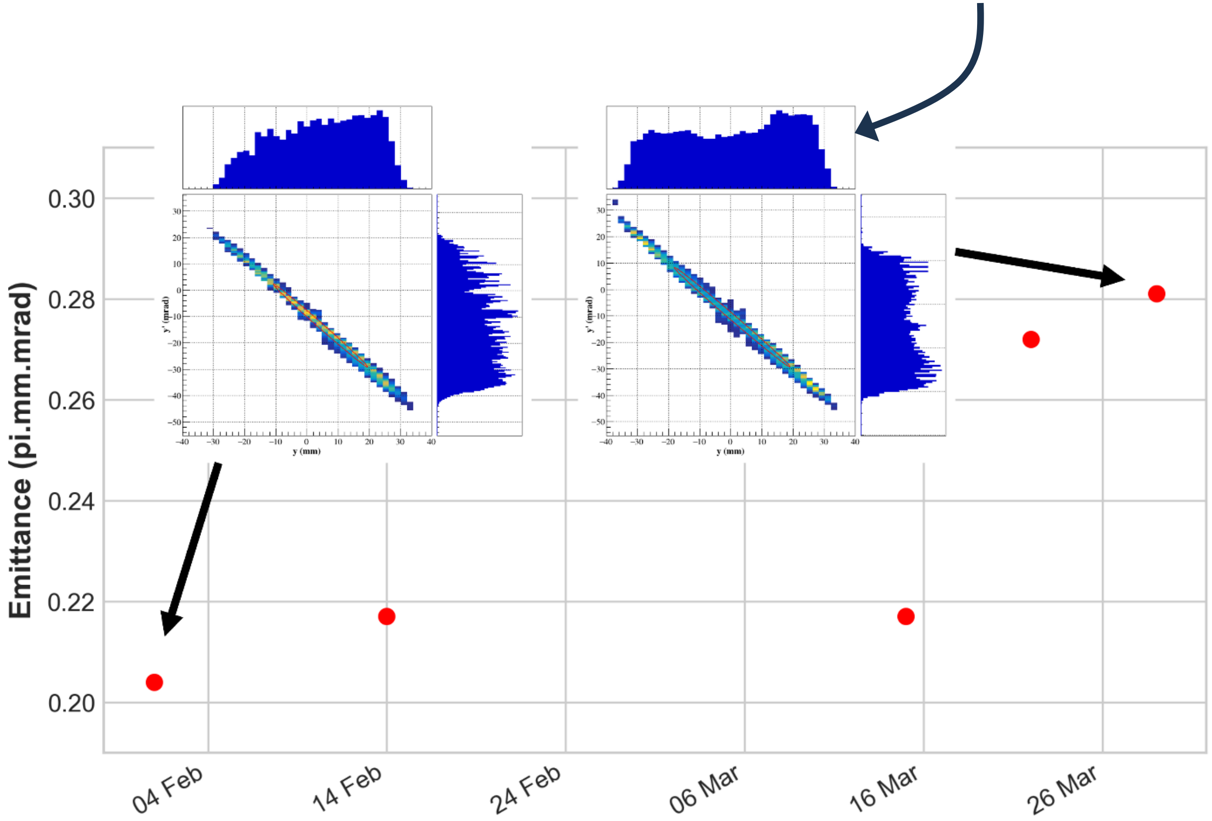


Observation of BN disks degradation

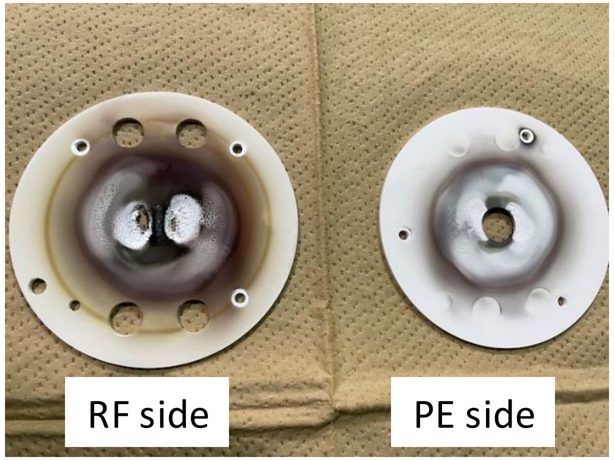
Observation of beam degradation along with BN disks degradation

During beam commissioning with ϕ11-mm PE (March 2022) a substantial **emittance increase** is observed at the end of the campaign – even if the ion source parameters are kept constant.

Also, the beam distribution tends to develop a **hollow core**.



After the beam commissioning was completed, the inside of the ion source was inspected and damage to the Boron Nitride (BN) disks was confirmed.



This is a concern for facility like IFMIF-DONES that need to maintain nominal conditions for 6 months.

Causes of BN disks degradation

Investigation of BN disk degradation

The investigation of the cause of the BN disk degradation is addressed with two main actions:

1) Identify the source parameters that correlate with the degradation level.
2) Try to understand the underlying mechanism of the degradation process by means of detailed surface analysis of the BN disks.

1) Identification of source parameters that correlate with the degradation level

Initial guess of possible parameters that could lead to BN disks degradation:

- Total amount of extracted charge from the source
- Cumulated hours of plasma in the source
- Total number of plasma ignition and afterglow events

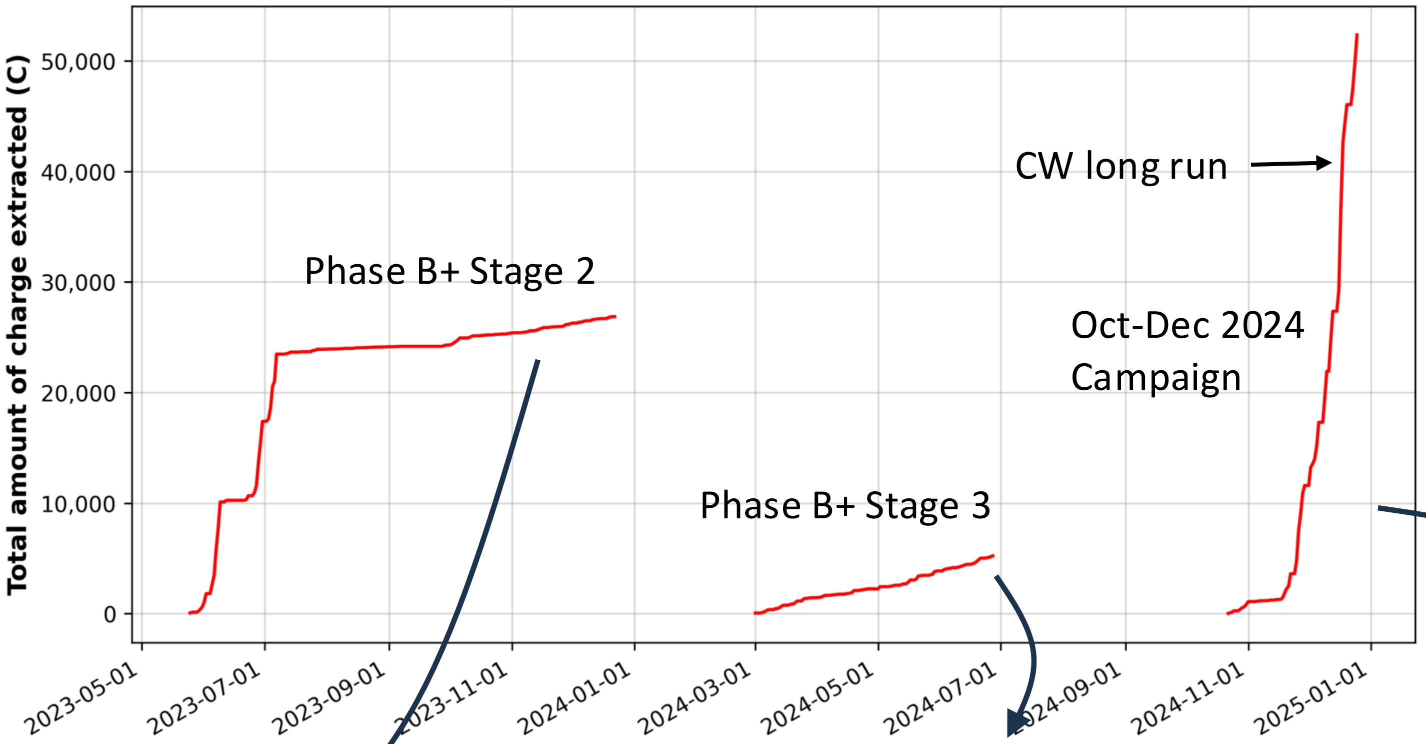
} **Analysis relatively straightforward**

- Stability of the plasma heating process
- Power and/or frequency stability of the high-power microwave source
- Magnetic field configuration and location of ECR regions
- …

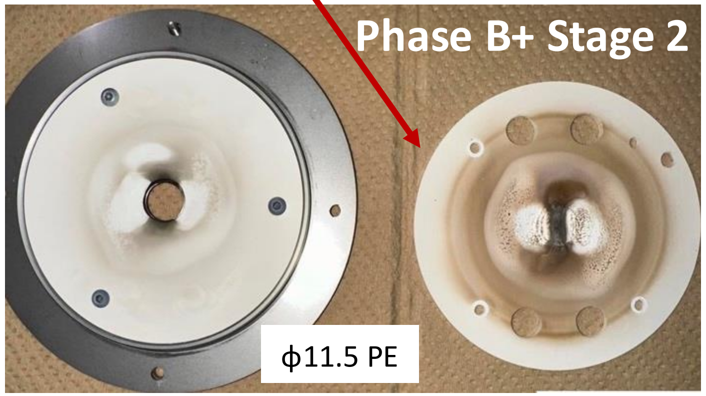
} **Not trivial to analyse…**

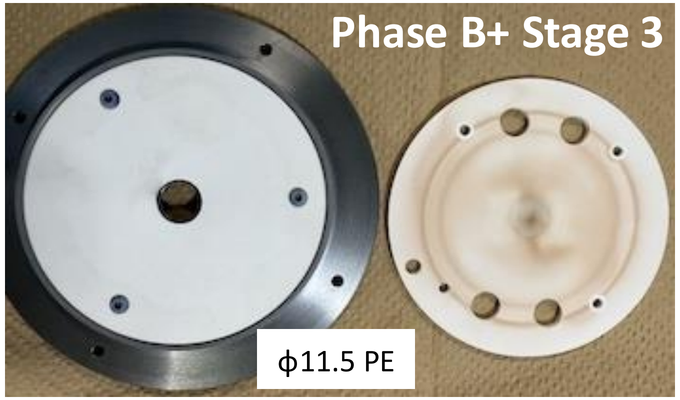
Causes of BN disks degradation

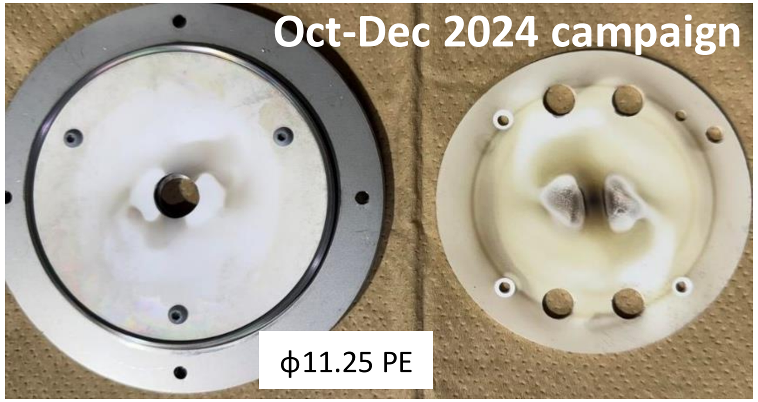
Total amount of extracted charge from the source



Most severe level of degradation

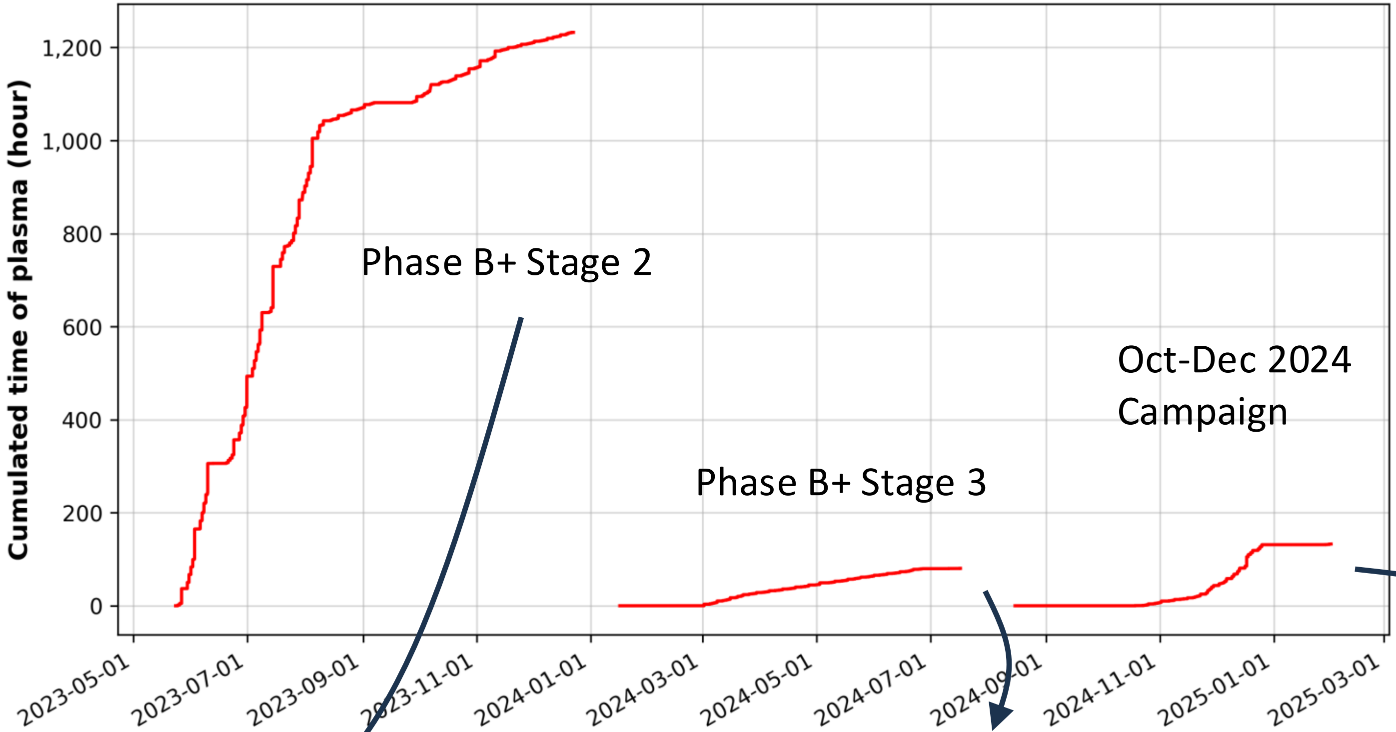






Causes of BN disks degradation

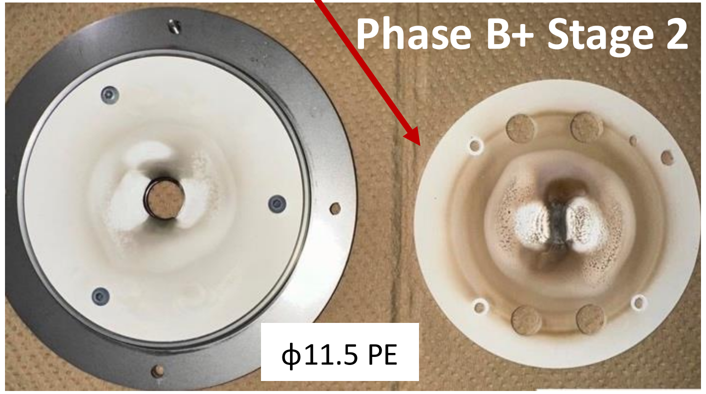
Cumulated time of plasma in the source with the BN disk degradation level

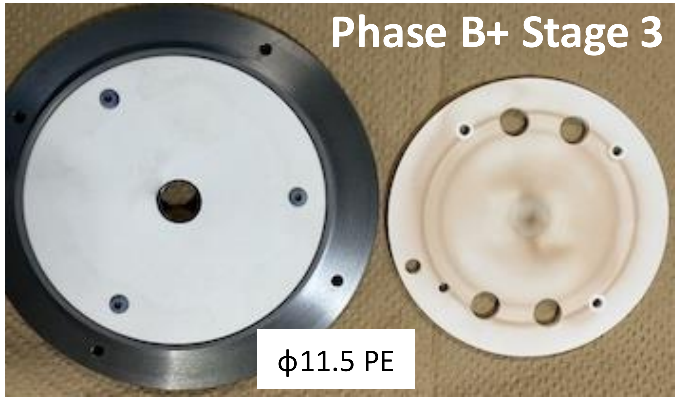


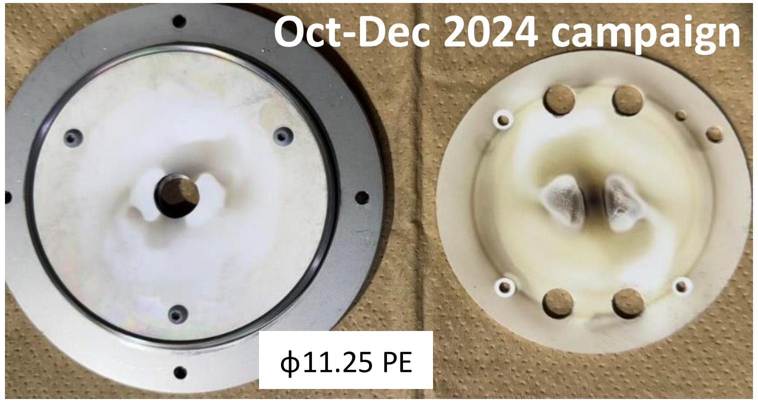
At LIPAc, the beam is typically not extracted during night. Instead, "plasma conditioning" is performed.

The significant difference in the cumulated time of plasma is due to differences in the duty cycles of the plasma conditioning.

Most severe level of degradation

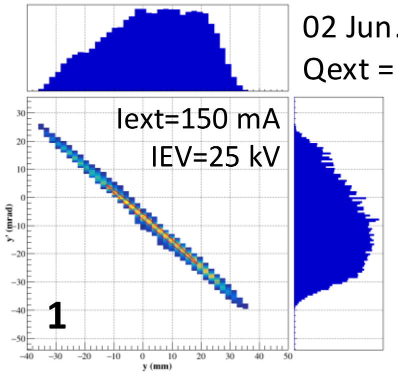




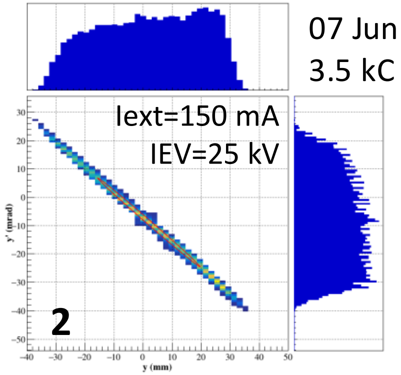


Effects of BN disks degradation

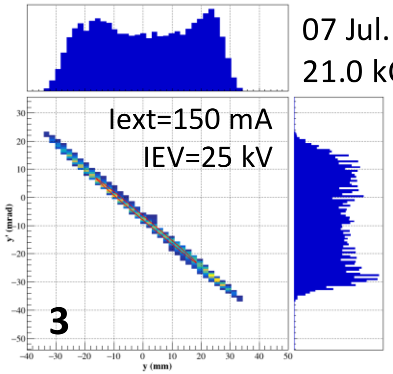
Cumulated plasma time also correlates with the degradation of beam quality



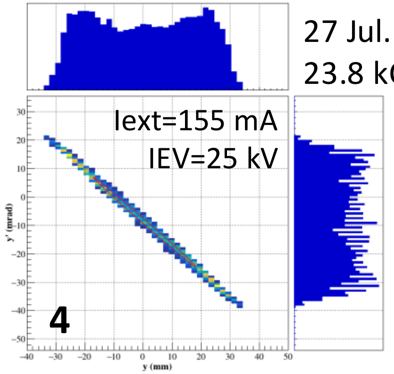
02 Jun. 2023
Qext = 1.0 kC



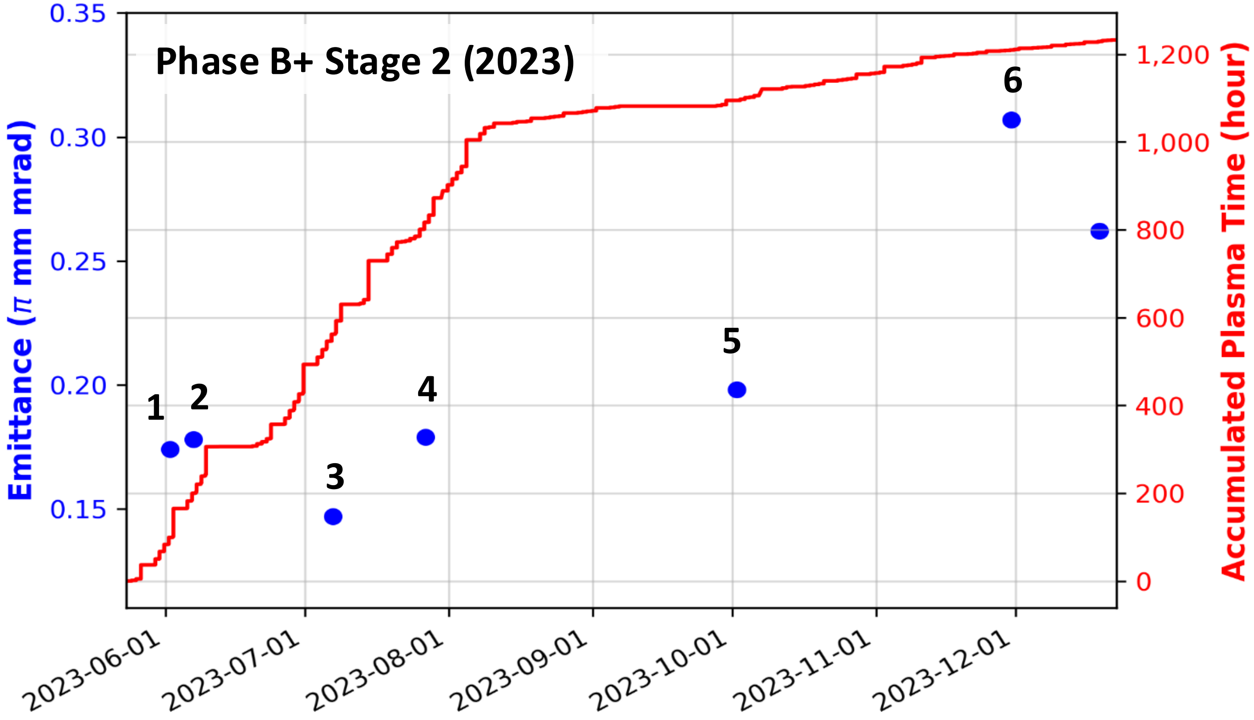
07 Jun. 2023
3.5 kC

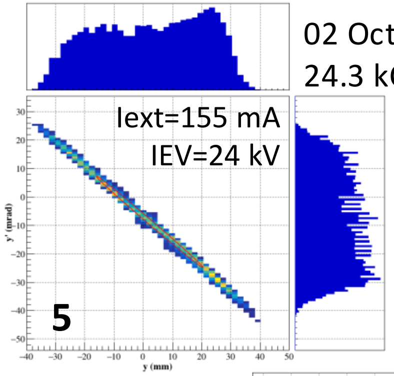


07 Jul. 2023
21.0 kC

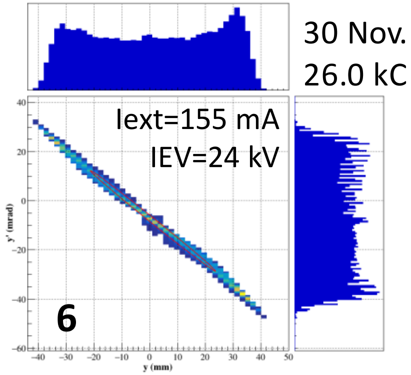


27 Jul. 2023
23.8 kC





02 Oct. 2023
24.3 kC



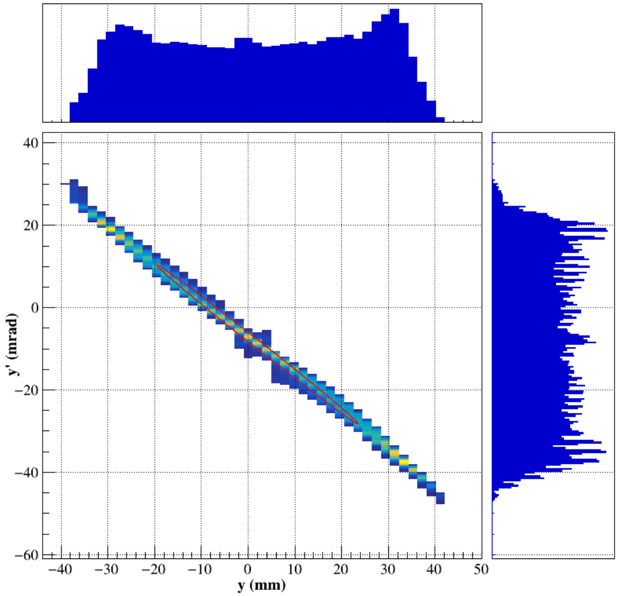
30 Nov. 2023
26.0 kC

Effects of BN disks degradation

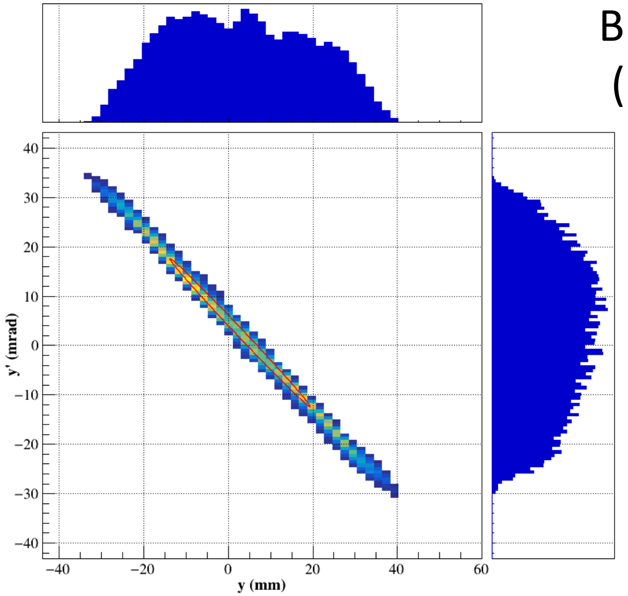
Experimental confirmation of correlation of BN disks degradation vs. beam quality

- During Oct-Dec 2024 campaign, additional measurements were conducted by replacing the BN disks with the severely degraded ones used during Phase B+ Stage 2.
- The phase space distribution and the emittance are well reproduced by using the degraded BNs.
- **These results allow to conclude that the degradation of beam quality is directly related to the condition of the BN disks.**

Dec. 2023
0.26 π mm.mrad
Iext = 150 mA

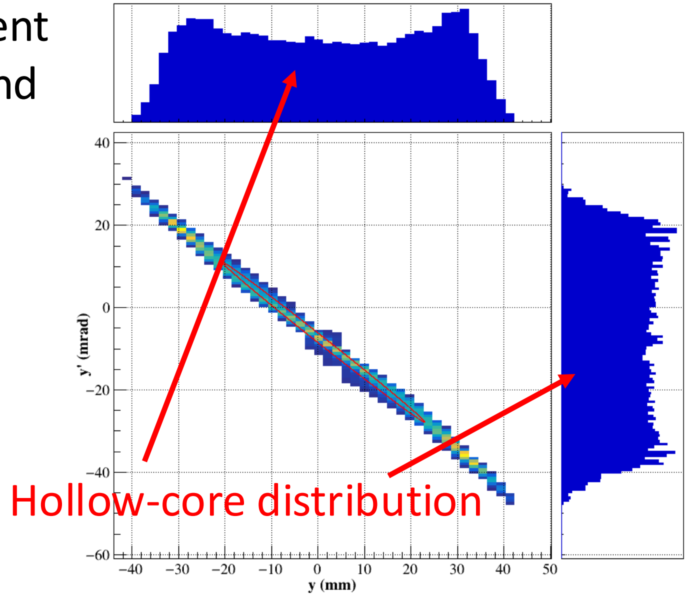


Jan. 2025
0.19 π mm.mrad
Iext = 156 mA



BN disks replacement (RF and PE side) and operation with identical source parameters

Jan. 2025
0.27 π mm.mrad
Iext = 151 mA



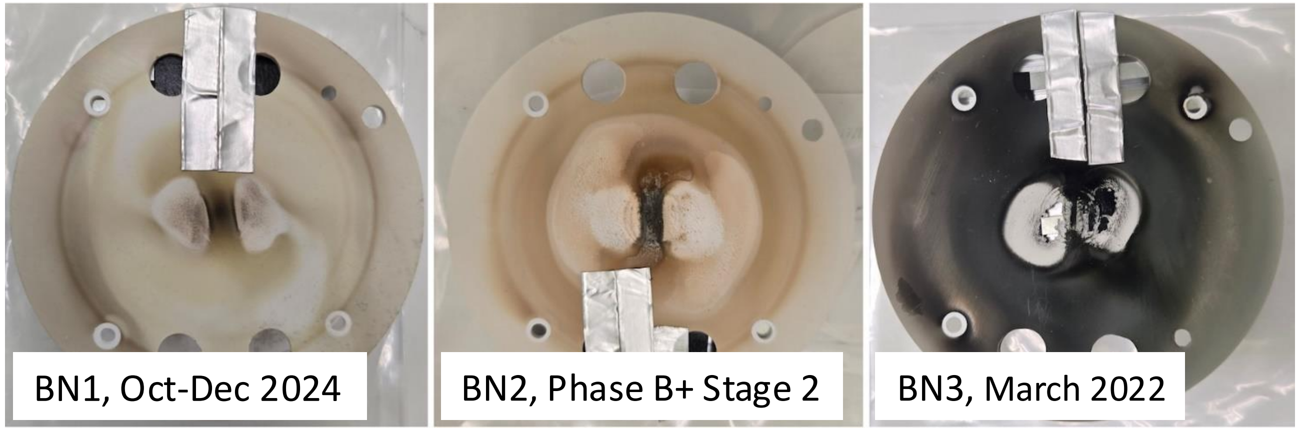
Surface analysis of degraded BN disks

2) Investigation of underlying mechanism of degradation: BN disks surface analysis

Results of the EDS analysis show presence of contaminants:

Disk	Degradation Level	Detected Elements	Comment
BN1	Least	B, N, Fe, Ni, O	Screws, H_2O
BN2	Moderate	+ C	Increased contamination
BN3	Severe	+ Cu	Cu exposure due to perforation

Cumulated plasma time: 130 hour 1200 hour 4400 hour

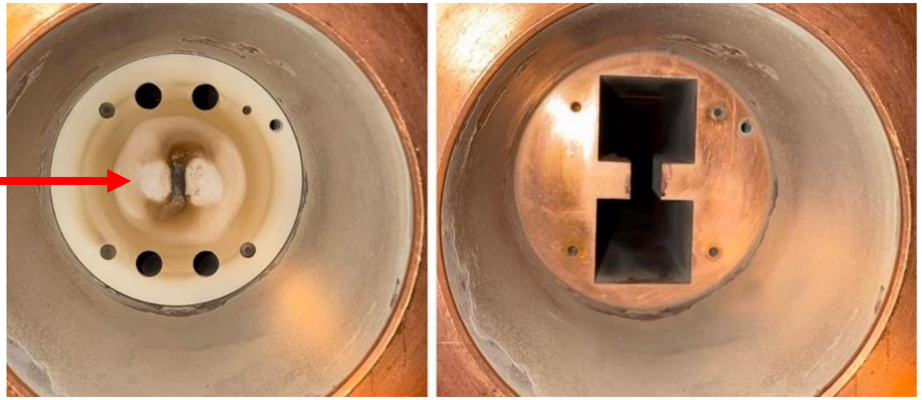


Preliminary conclusions and corrective actions:

- Some contaminants come from screws → cover screw heads with ceramic caps.
- Contaminated layer might absorb RF power → monitor temperature of the plasma chamber in future campaigns.

Further investigation is needed to determine:

- How contaminants impact BN disk performance (e.g., SEE, conductivity of BN disks, change of diffusion regime, …).
- Why some areas degrade mainly by sputtering, while others by contaminant adhesion. An observation and some hypotheses:
  - The areas of severe BN disk degradation (sputtering) correspond to locations where Cu (ridged waveguide) is present behind it. Why is that?
    1) Different charge-up due to conductivity change (e.g., with temperature)?
    2) RF modes & plasma heating process?
    3) ???



Summary

- **Achievements:**
  - LIPAc Phase B+ commissioning completed: acceleration of a 5 MeV deuteron beam at 9% duty cycle.
  - The LIPAc injector achieved CW operation of a low-emittance D^+ beam for 24 hours with a total current of 150 mA during conditioning. Also, for several hours with 155 mA.

- **Challenges:**
  - BN disk degradation observed, impacting beam quality.
  - Level of BN disks degradation correlates with cumulated time of plasma.

- **Next step:**
  - Assessment of lifetime and develop strategies to extend it (≥6 months).

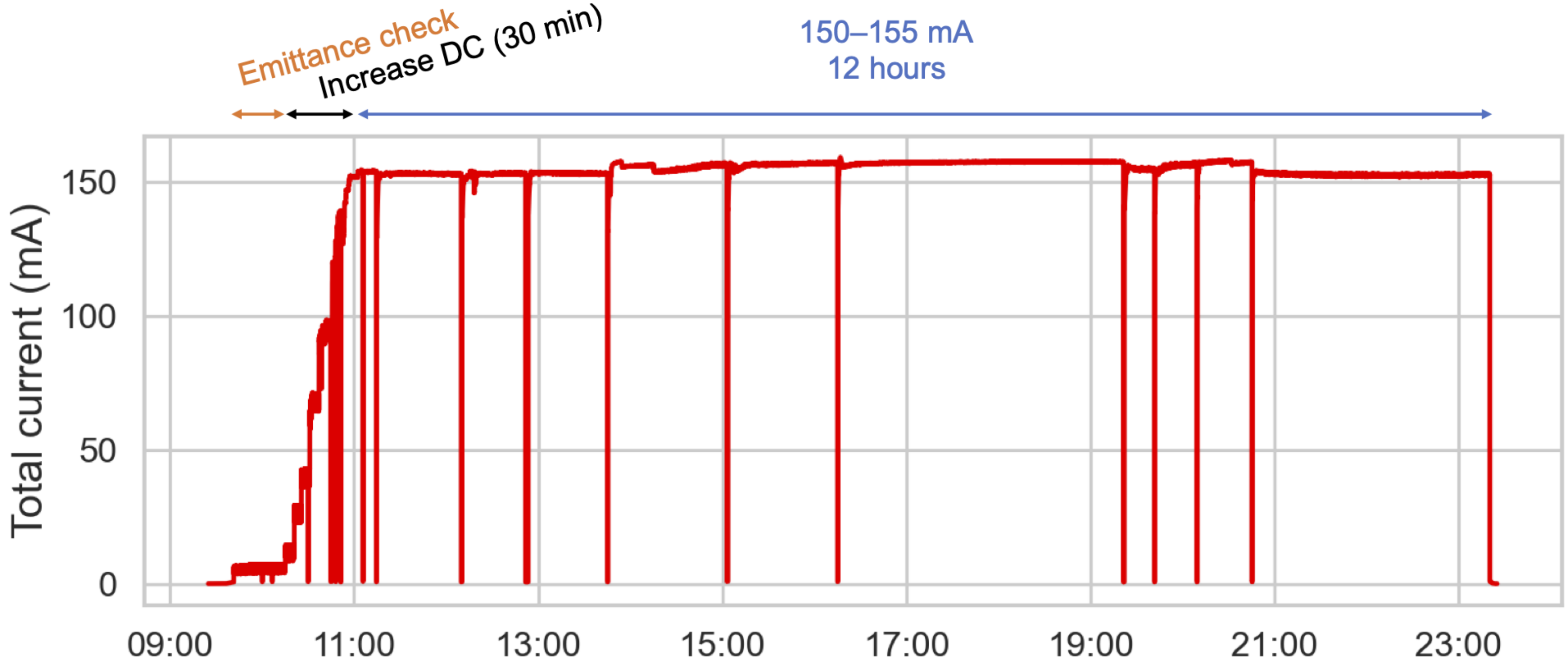
This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.

Backup Slides

Achievement of CW operation (March 2022)

CW 12-hour-long run with ϕ11-mm PE:

- Total extracted current 150 mA, D+ fraction fraction 91%, emittance 0.24 π mm mrad.
- CW long run operation with this beam condition.



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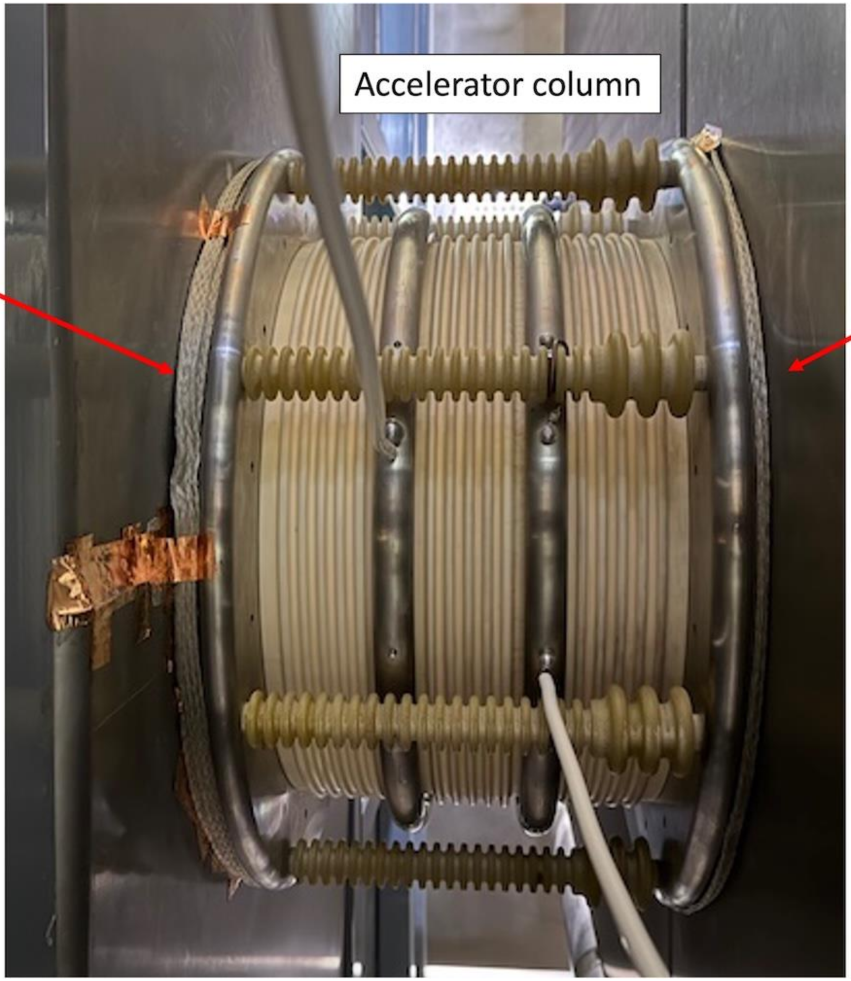
Additional improvements/Investigations

Corrective action for the sparks issue was conducted before CW long run.

Flat Braided wire



Flat Braided wire (HV potential)

Installation of braided wires has eliminated sparks that occurred on the outside.

It's important to eliminate empty spaces, even if two parts have the same potential.

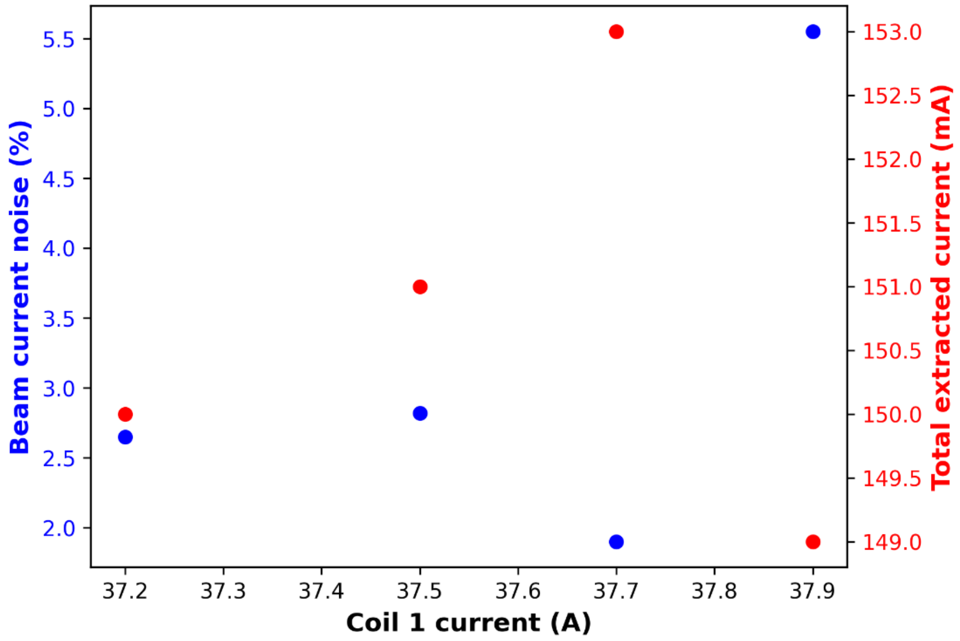
Location of sparks were identified with camera.

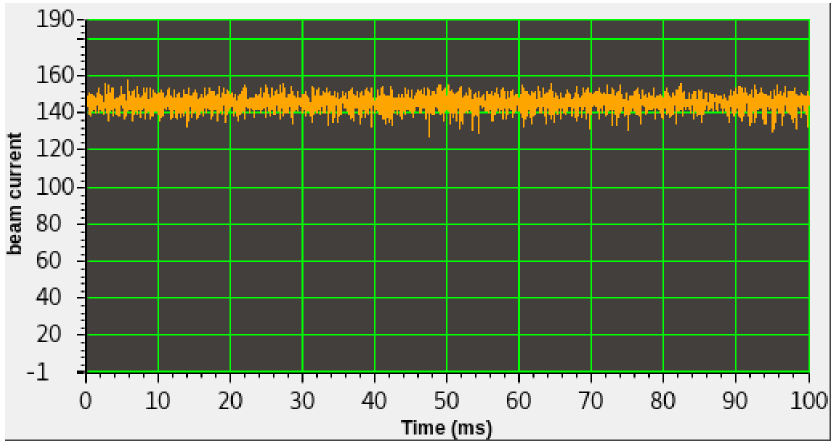
Additional improvements/Investigations

Beam current noise optimization

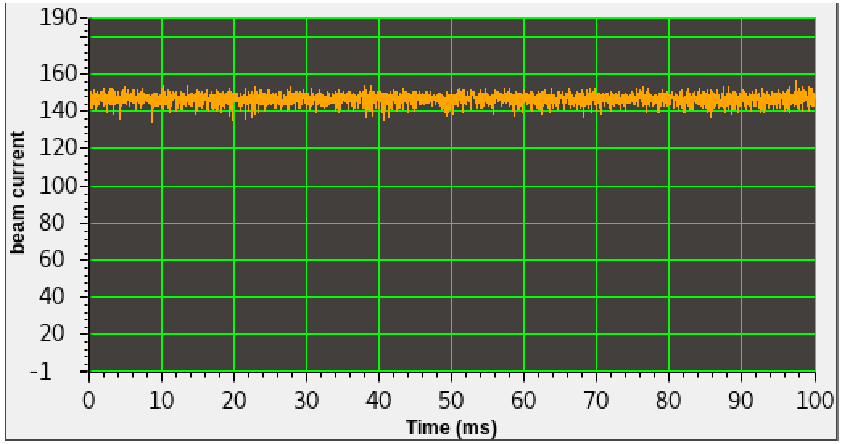
Source coil 1 current has large impact on the total extracted current and beam current noise.

Coil 1 current (A)	37.2	37.5	37.7	37.9
I_ext (mA)	150	151	153	149
I_FC (mA)	144	145	146	143
I_FC rms noise (%)	2.65	2.82	1.90	5.55

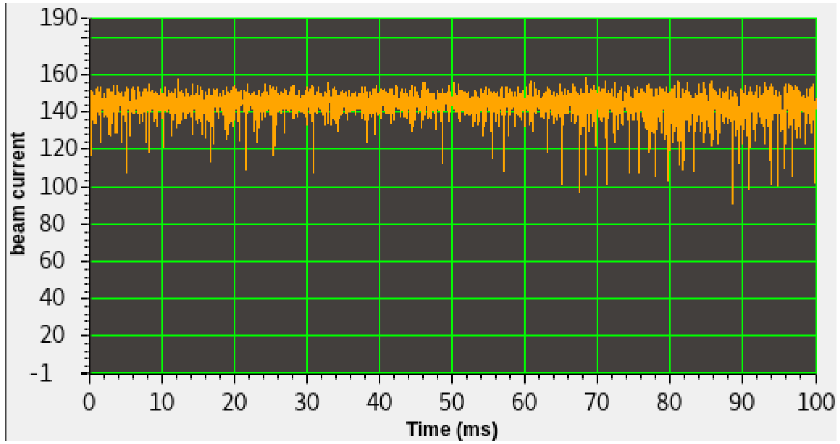




Coil 1 = 37.5 A



Coil 1 = 37.7 A



Coil 1 = 37.9 A