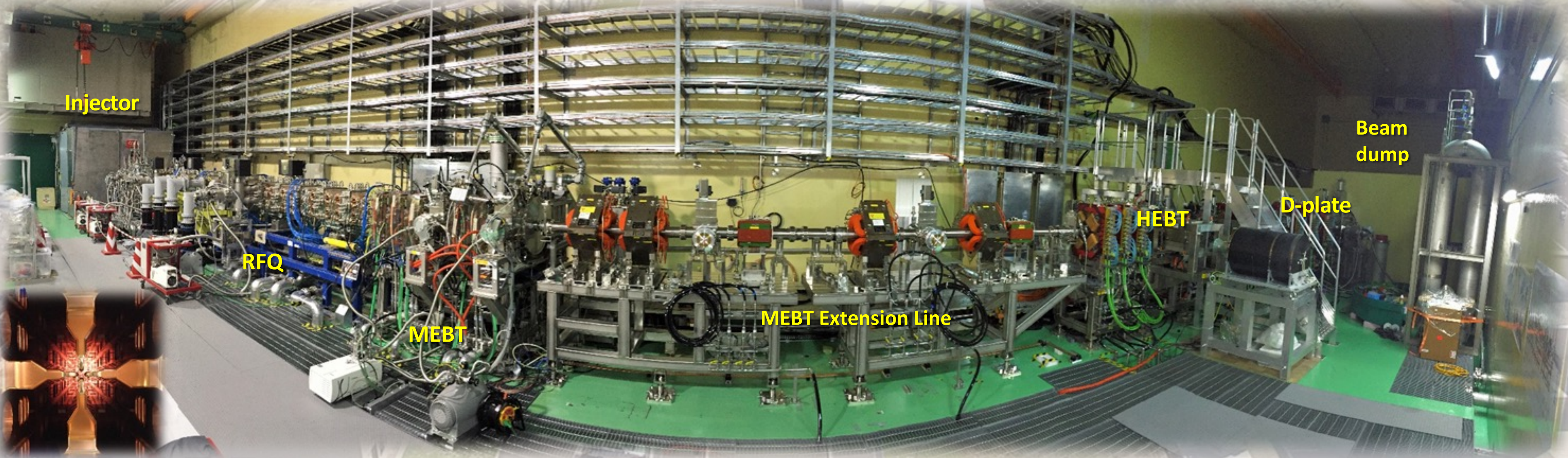
High beam current operation with beam diagnostics at LIPAc

Saerom Kwon[1], A. De Franco[1], K. Masuda[1], K. Hirosawa[1], T. Akagi[1], K. Kondo[1], M. Ohta[1], F. Benedetti[2,3], F. Cismondi[2], D. Gex[2], Y. Carin[2], J. Marroncle[3], B. Bolzon[3], N. Chauvin[3], D. Jimenez[2,4], I. Podadera[4,6], V. Villamayor[4], A. Rodriguez[4], M. Poggi[5], J. C. Morales Vega[6], L. Maindive[7]

[1]QST, [2]F4E, [3]CEA, [4]CIEMAT, [5]INFN, [6]IFMIF-DONES Spain, [7]UGR

9-13 Oct. 2023

HB2023@CERN, Switzerland



Linear IFMIF Prototype Accelerator (LIPAc)

Paper ID: FRC1I2

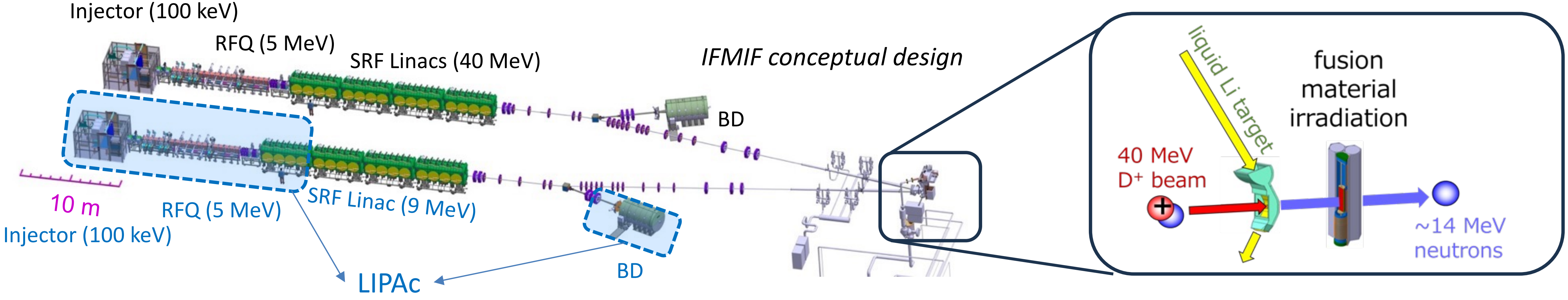
Working Group E: Beam Instrumentation and Intercepting Devices

Rokkasho Fusion Institute (BA Site)

OUTLINE

International Fusion Materials Irradiation Facility (IFMIF)

The IFMIF will address the need of a high energy fusion-like neutron (14.1 MeV) source for material tests toward future Fusion Power Plant (DEMO or beyond DEMO)



engineering validation ongoing (under EU-Japan collaboration)

Common primary parameter: CW, D+, 175 MHz RF

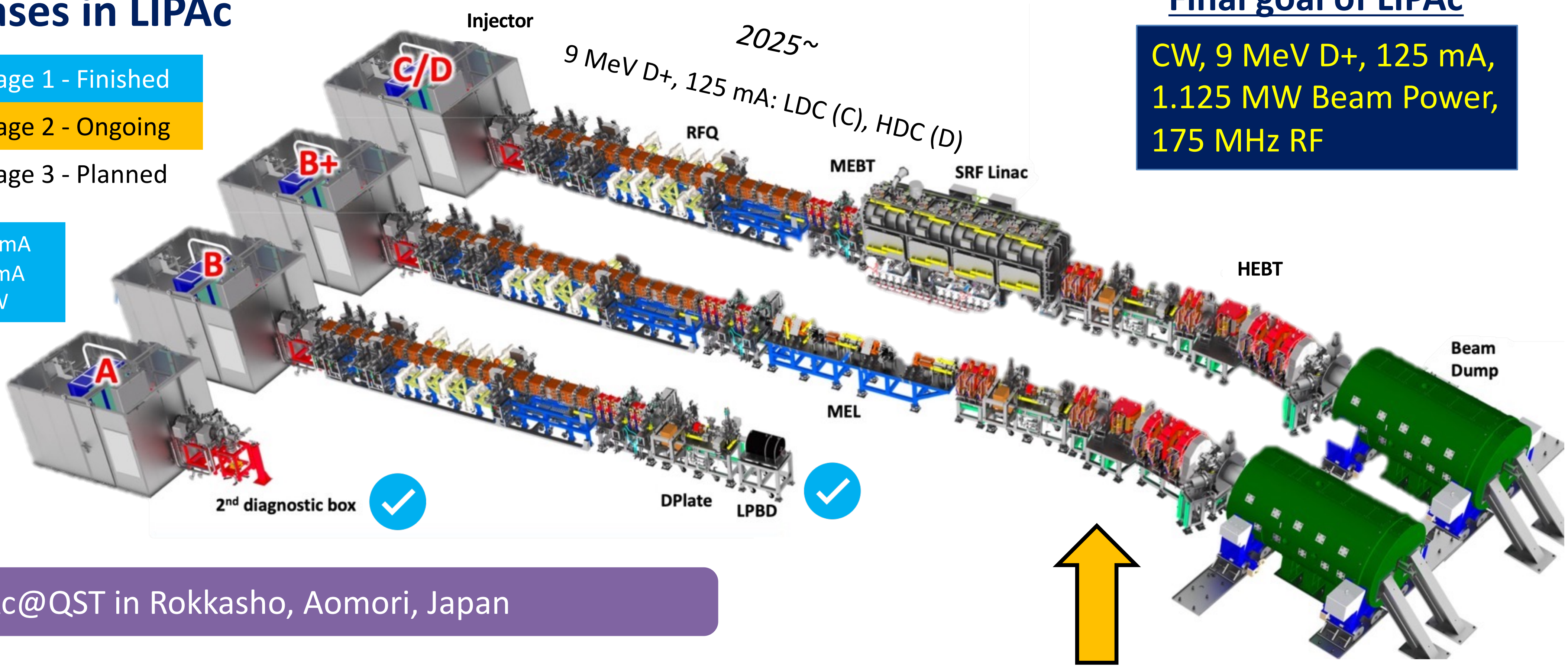
→ All results, experiences and lessons learned & to be learned from LIPAc will be used for further designs of the accelerators.

	IFMIF	LIPAc
Number of Linacs	2	1
Intensity (mA)	2 x 125	125
Energy (MeV)	40	9
Number of cryomodules	2 x 4	1
Beam power (MW)	2 x 5	1.125

Linear IFMIF Prototype Accelerator (LIPAc)

4 operation phases in LIPAc

B+	Stage 1 - Finished Stage 2 - Ongoing Stage 3 - Planned
B	H+ 2.5 MeV 57 mA D+ 5 MeV 127 mA <1% DC, 625 kW
A	H+, 100 mA D+, 170 mA 100 keV, CW 12.5 kW



Final goal of LIPAc

CW, 9 MeV D+, 125 mA,
1.125 MW Beam Power,
175 MHz RF

now we are here, Phase B+

LIPAc@QST in Rokkasho, Aomori, Japan

Key dates for the first achievement so far (Phase A & B),

- 4 Nov. 2014: 1st H+ beam extracted from injector
- 7 Jul. 2015: 1st D+ beam extracted from injector
- 13 Jun. 2018: 1st H+ beam into the RFQ
- 24 Jul. 2019: 1st Successful acceleration of 125 mA, 5 MeV D+

More details?
https://www.ifmif.org/archive-newline/

LIPAc now… Phase B+ Stage 2

- **Summer 2019**: Move to Phase B+
- **Summer 2021**: Start of Phase B+
- **Winter 2021**: End of stage 1: D+ beam until Beam Dump
- **Spring 2022**: Failure of RFQ RF circulator & RF couplers
- **Summer 2023**: Start of Phase B+ Stage 2
- **Sep. 2023**: 125 mA D+ beam at HEBT @150us/1Hz at 90% of transmission
- **Autumn 2023**: Resume Stage 2 after 4.0 weeks of Summer maintenance

B+	H+, 2.5 MeV D+, 5 MeV 625 kW	Stage 1	H+, 10 mA D+, 20 mA	<0.1% duty cycle
		Stage 2	D+, 125 mA	<1% duty cycle ⇦ now
		Stage 3		high duty cycle

LIPAc beam diag.

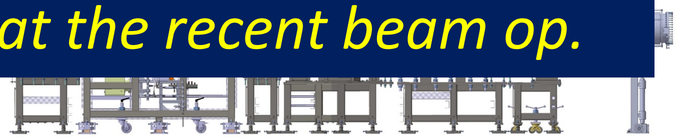
- **LIPAc Beam Diagnostics – From exit of RFQ to Beam Dump: understand/measure beam characteristics**
- **Divide into "Interceptive devices" / "Non-interceptive devices"**

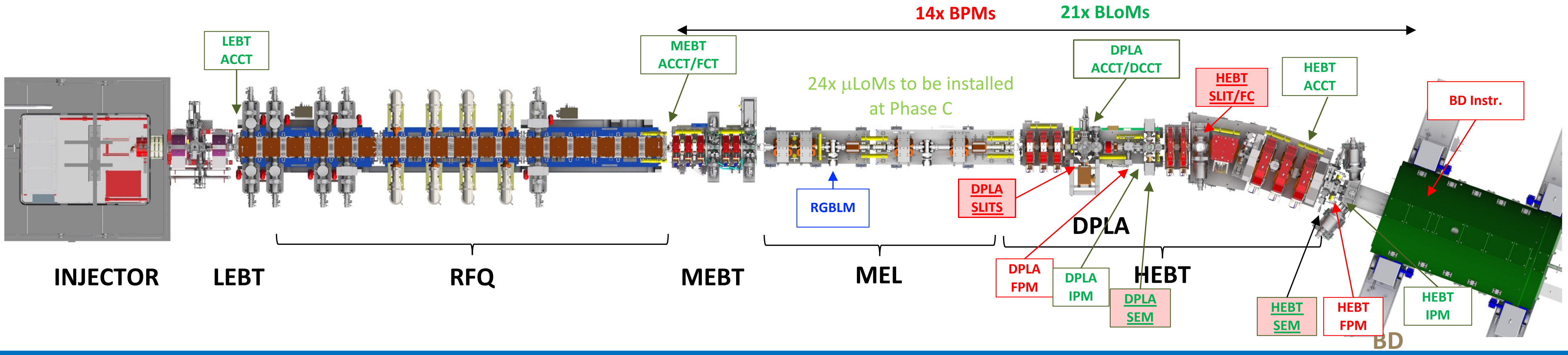
CT: Current Transformer
BPM: Beam Position Monitor
SEM: Secondary Emission Monitor
IPM: Ionization Profile Monitor

RGBLM: Residual Gas Bunch Length Monitor
BLoM: Beam Loss Monitor
µLoM: Micro Loss Monitor
IC: Ionization Chamber

Current measurement: 3 ACCT, 1 DCCT, 1FCT
Position, phase & energy: 14 BPMs
Transverse profile: 2 SEM-grid (pulsed), 3 IPMs (CW), 4 FP
Transverse emittance: Slits + SEM-grids
Longitudinal emittance: 1 RGBLM
Losses: 21 BLoMs + 24 µLoMs
Beam Dump instrumentation: 6 ICs, 3 Accelerometers

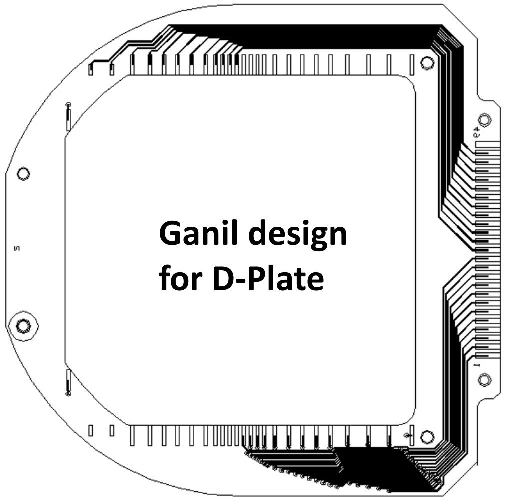
today's main topic
: Interceptive devices & few other devices &
Some results we got at the recent beam op.





Interceptive profiler: SEM-grid

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



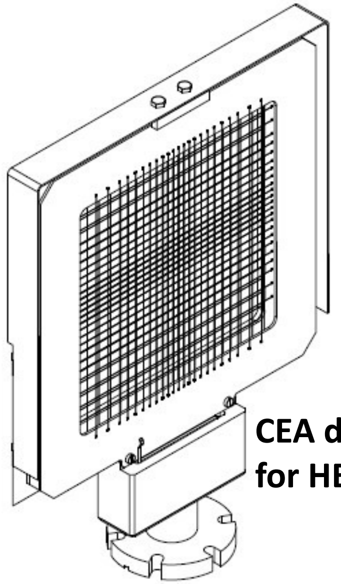
101 × 101 mm^2

➢ Rackets

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

➢ Wires

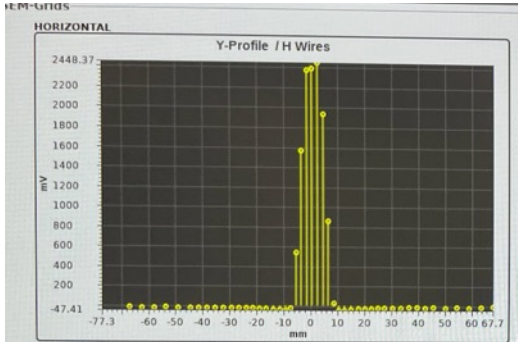
- 47 Tungsten golden platted
- Ø = 20 µm for D-Plate one, 100 µm for HEBT one,



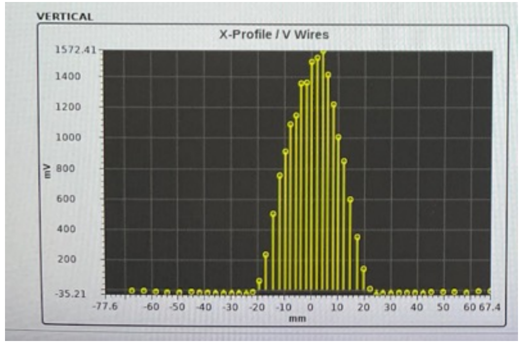
CEA design
for HEBT

150 × 150 mm^2

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



Y-profile/H wires

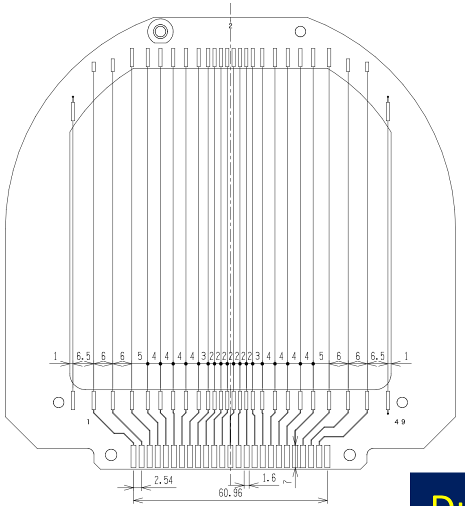


X-profile/V wires

Measurement by SEM-grid

- SEM-grids are actuated by a pneumatic actuator
- D-Plate SEM-grid (DSG) for transversal profile and Emittance measurement
- HEBT SEM-grid (HSG) for transversal profile and Energy spread measurement
- Water cooled Slits protect SEM-grids (two slits (vertical and horizontal) in D-Plate, one slit (vertical) in HEBT)

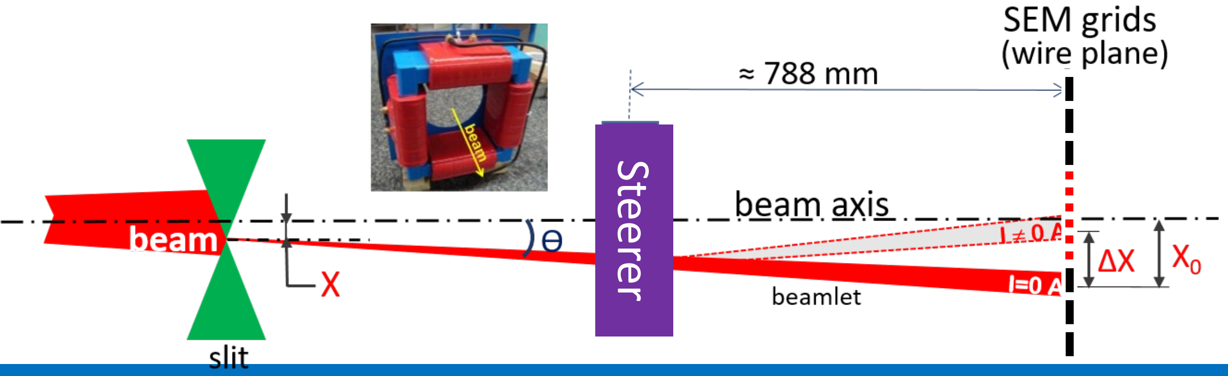
12-July 2022 replaced from horizontal slit to vertical one

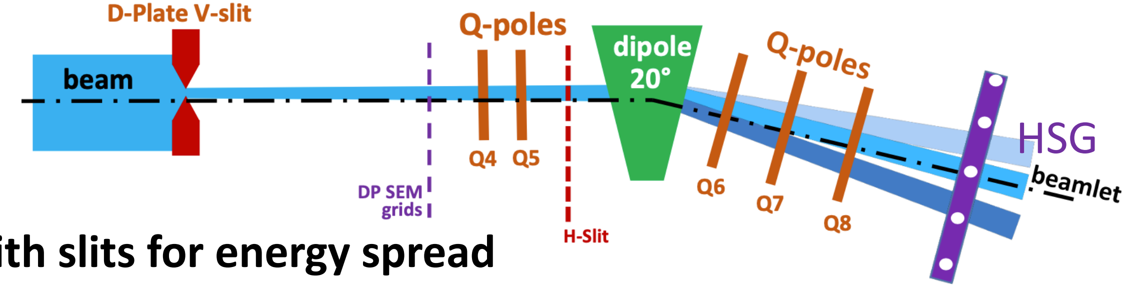


- Fine wire density on center
- Gaps between wires
  - D-Plate one: 1 / 2 / 3 mm
  - HEBT one: 2 / 2.5 / 3 / 4.5 mm

Due to the large wire gaps in the extreme, it cannot be possible to use a normal technique of an emittance measurement (slit + SEM-grid). The steerer has been installed.

DSG with slits & steerer for emittance

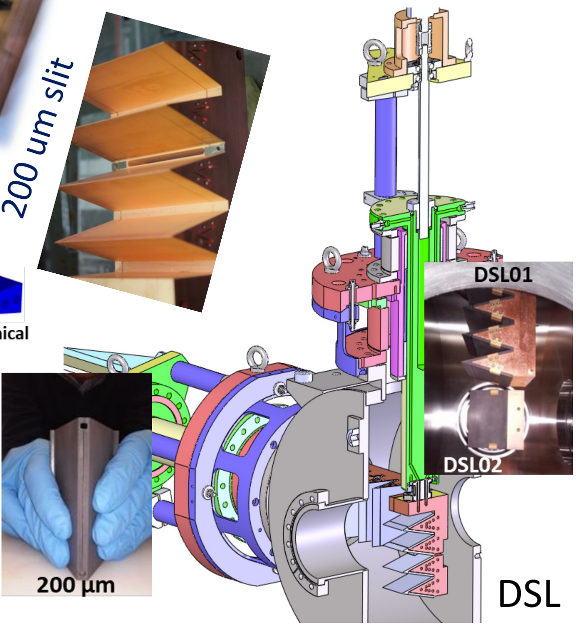




HSG with slits for energy spread

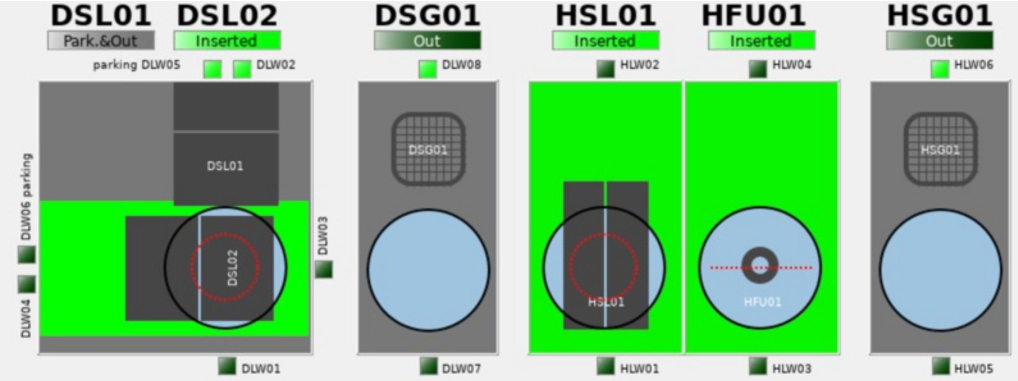
Other Interceptives: Slits & faraday cup

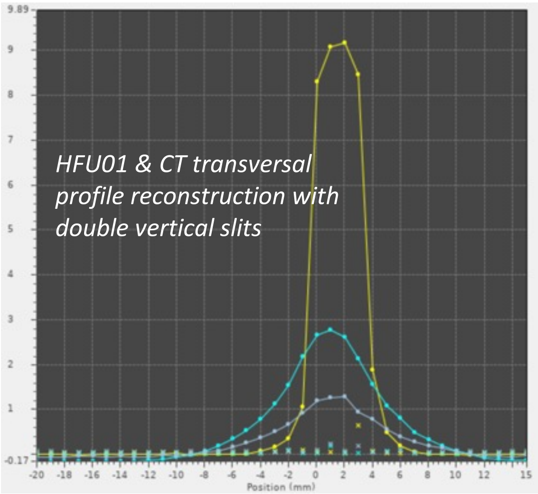
- 2 slits (vertical & horizontal) in D-Plate (DSL) and 1 slit in HEBT (HSL) with FC
- DSL: Copper + Graphite <-- water cooling system implemented
- HSL: 2.5 mm thickness of Tungsten alloy
- Slits scan motion up to 160 mm actuates by a Phytron motor (1 um motion precision)
- Operation validated up to 2 ms/1Hz with d+@5 MeV_125 mA

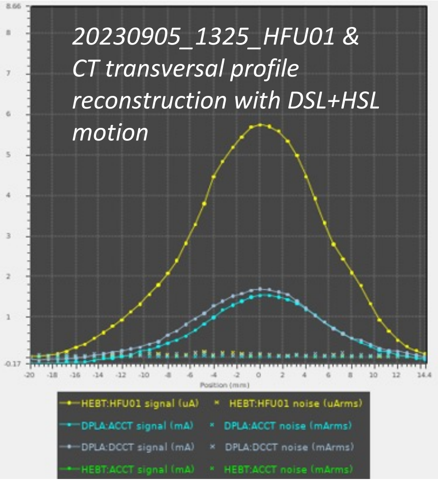


DSL

3 mm graphite pyrolytic-cut Z-axis plate for improve thermal transmission

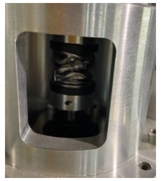




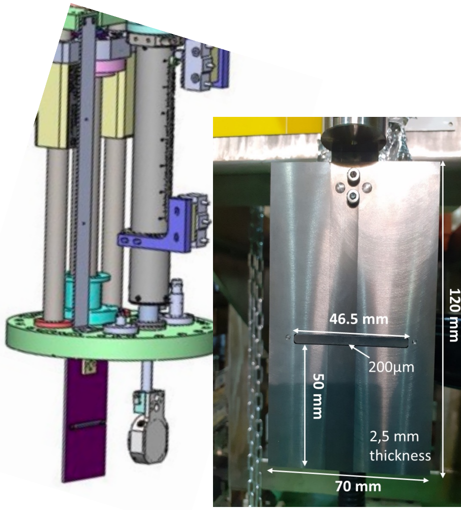


<Features>

- Easy OPI to know the status
- Auto-scan mode implemented with CTs/FC for quick beam profile check (like another profiler)
- Another automatic function to be added for the emittance measurement



everyday is not a good day…
motor coupling of one DSL damaged without anyone knowing
→ noticed at annual maintenance

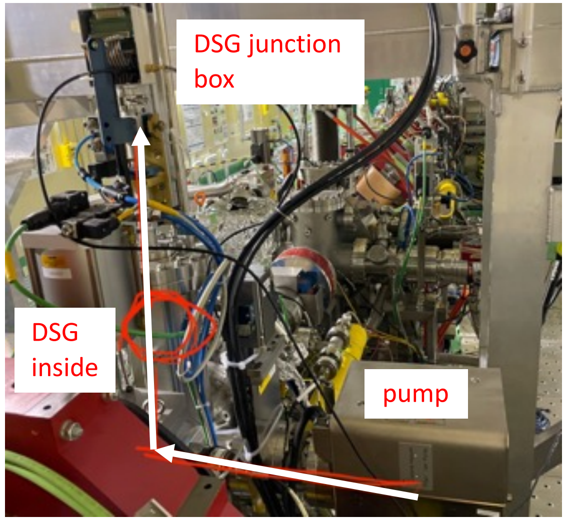


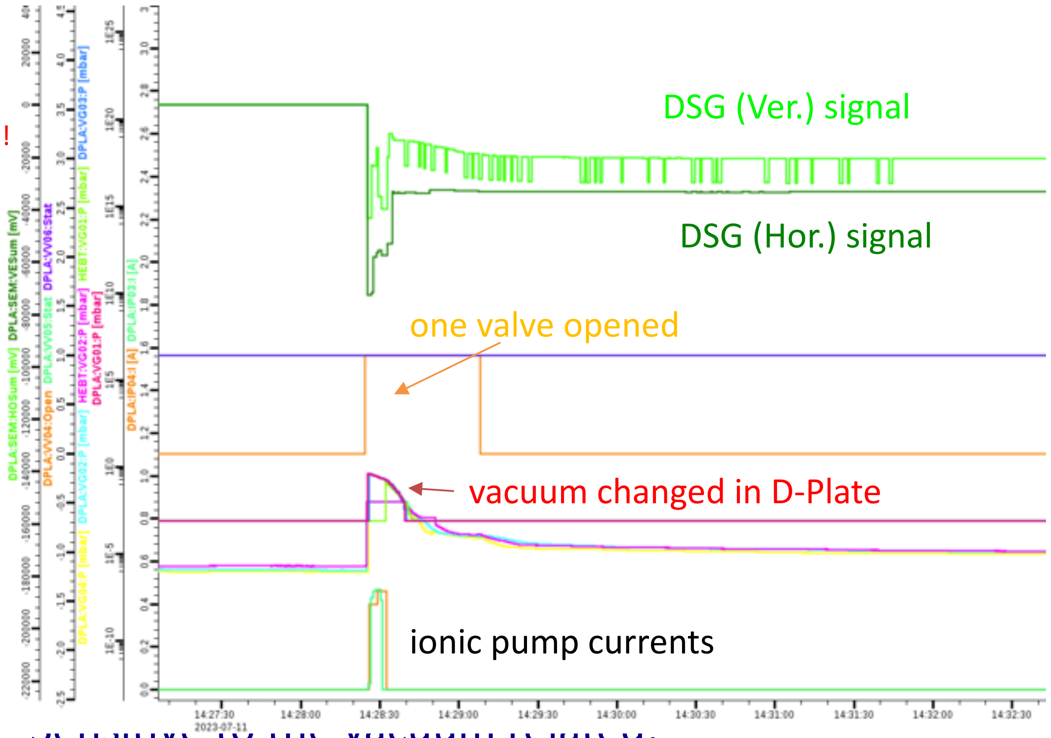
HSL & HEBT Faraday cup

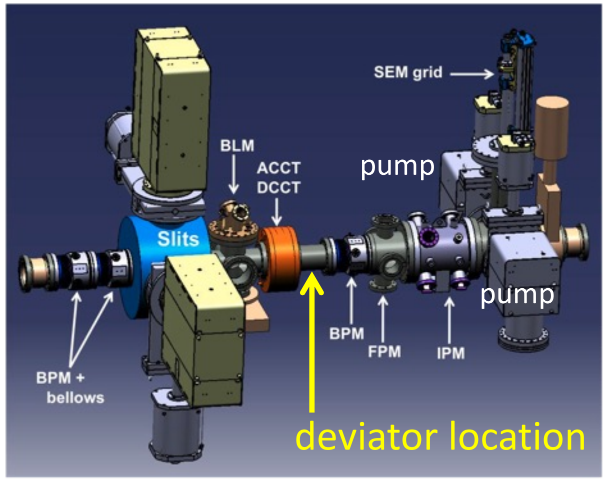
Issues of SEM-grid

a few current to FEE?

And up to 30 m to the pre-amplifier!!





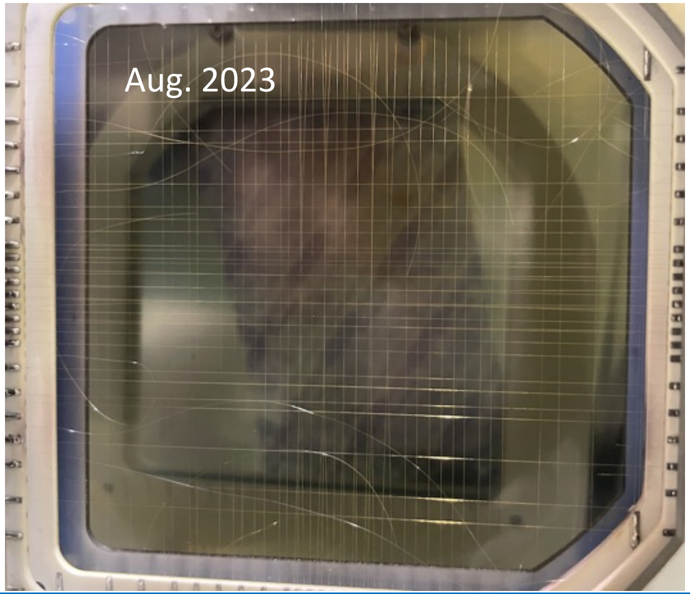


Sensitive to the vacuum related,

(1) Vacuum chamber shared with 2 horizontal ionic pumps -> some arcs were in the chamber, it destroyed the DAQ.

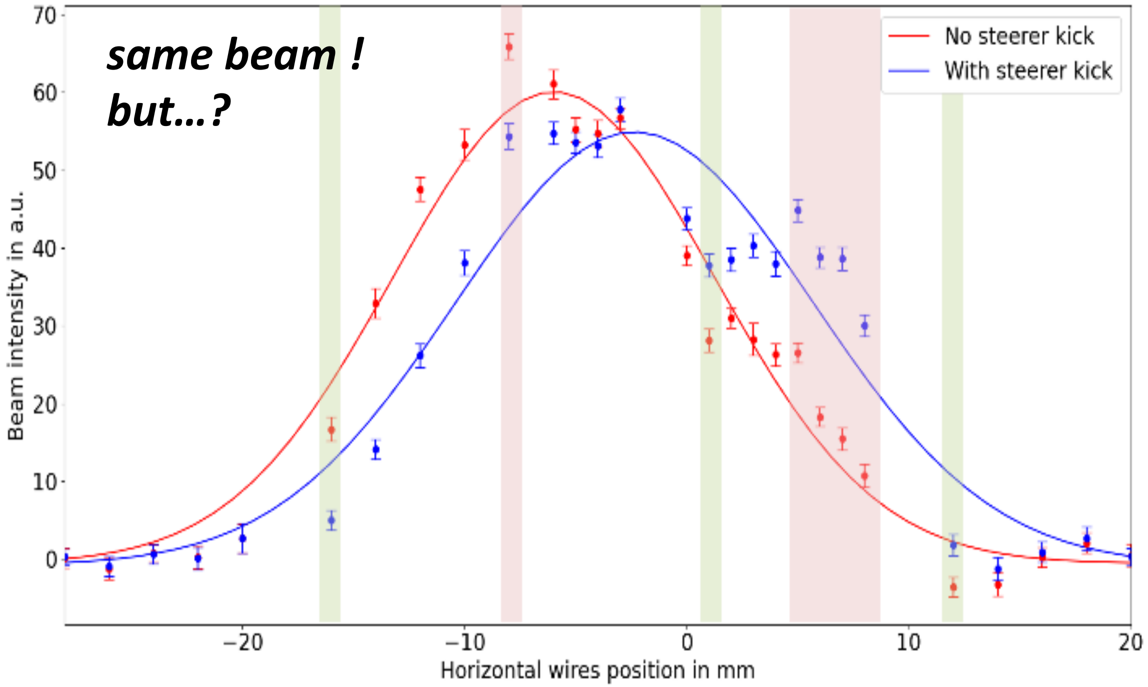
(2) Sudden “big” vacuum changed by the system error, and/or human error, wires damaged two times even there’s no beam operation.

→ Maintenance procedure updated to avoid the failure



Gain correction of SEM-grid

Previous beam op. Stage 1…



Wire degradation …?

Signal seems systematically

Higher than profile

Lower than profile

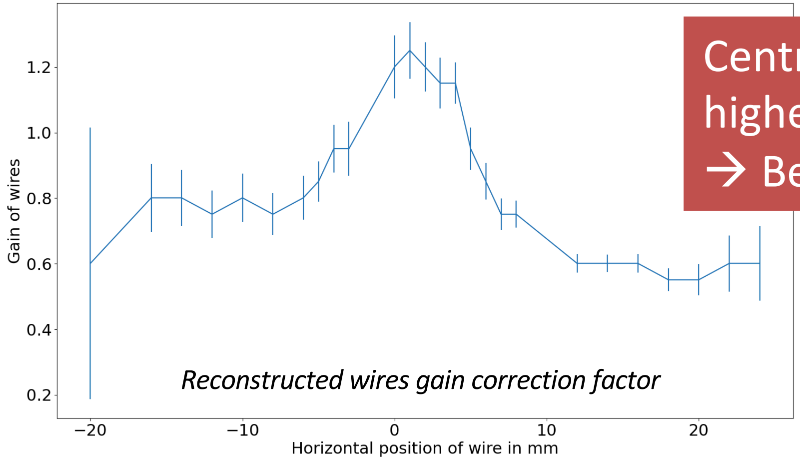
Due to the high beam current, the thermo-ionic effect of the beam power, the secondary emission of some wires is reduced, and the traversal beam profile signal is inhomogeneous with the beam operation

- Acquisition chain gain is very even
- Profile measured with slit/ACCT is Gauss down/upstream

→ Uneven wire gain?

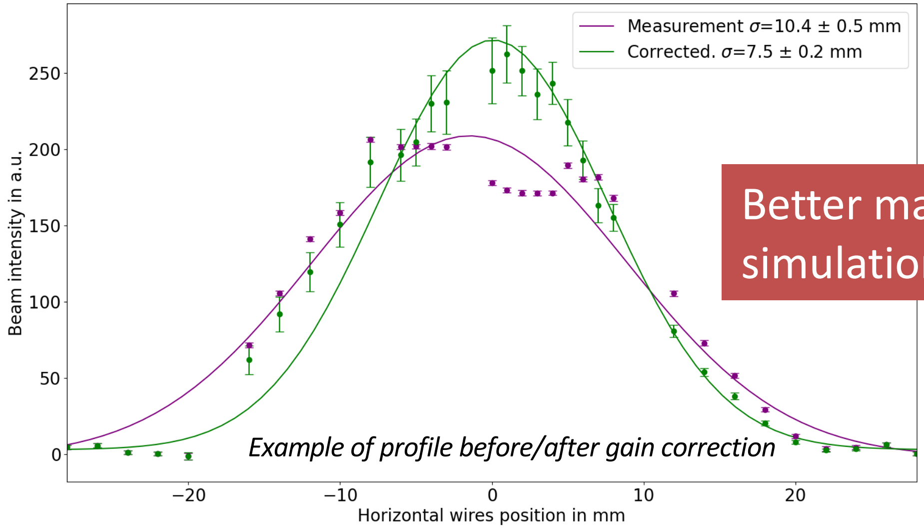
We apply gain correction from analysis of emittance measurement

→ **Useful for the further beam operation results**



Reconstructed wires gain correction factor

Central wires require higher correction factor
→ Beam induced damage?



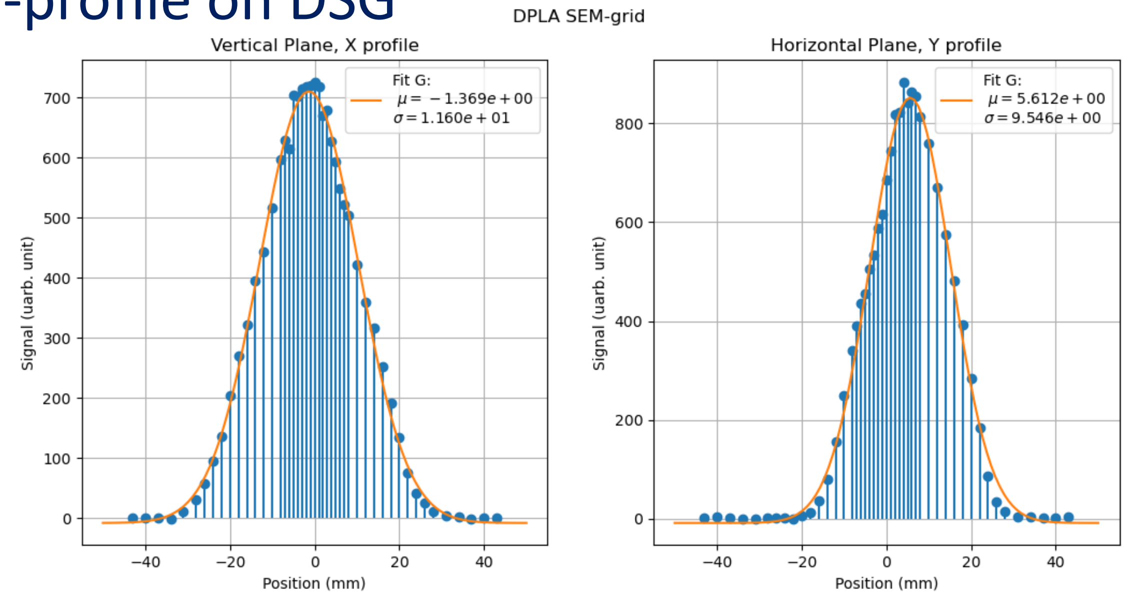
Example of profile before/after gain correction

Better match to simulation (σ=6.1 mm)

A. De Franco et al., "Beam based gain flattening of secondary emission grid profile monitors at the Linear IFMIF Prototype Accelerator, AESJ2023Fall

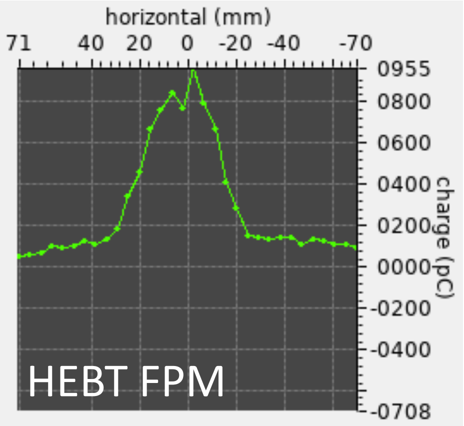
Some Results on interceptive devices - 1

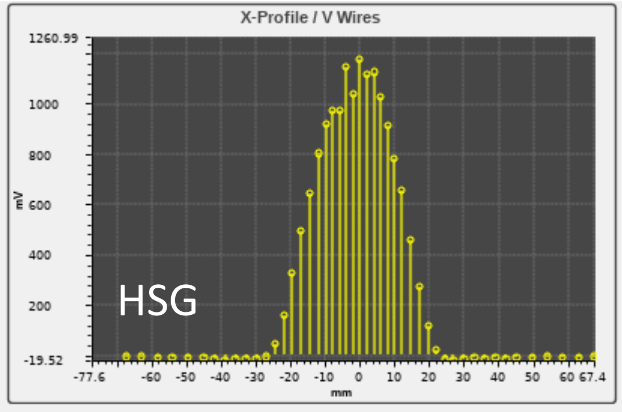
- Full-profile on DSG



Full beam profile on the SEM-grid
→ It provides beam size, position, shape
→ It could be a 1st proof of the beam

- Horizontal profile on HSG and another profile monitor (FPM)





→ ”Reference” for other non-interceptive profile monitors

Some Results on interceptive devices - 2

Beam tuning using the measurement data

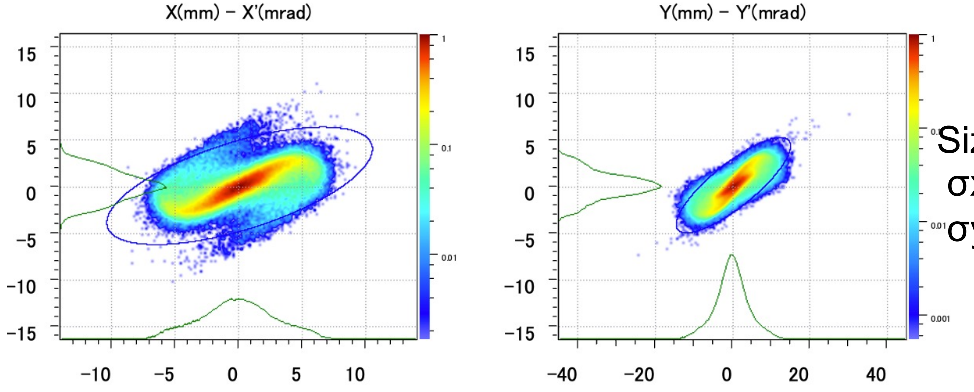
- Beam simulation results were ready (prediction)
- Real measurement could not be matched (even qualitatively…)

→ Difficult to predict the real beam

- The real measurement data INTO the simulation

→ **Feedback to the simulation (high accuracy tracking calculation is possible after the monitor)**

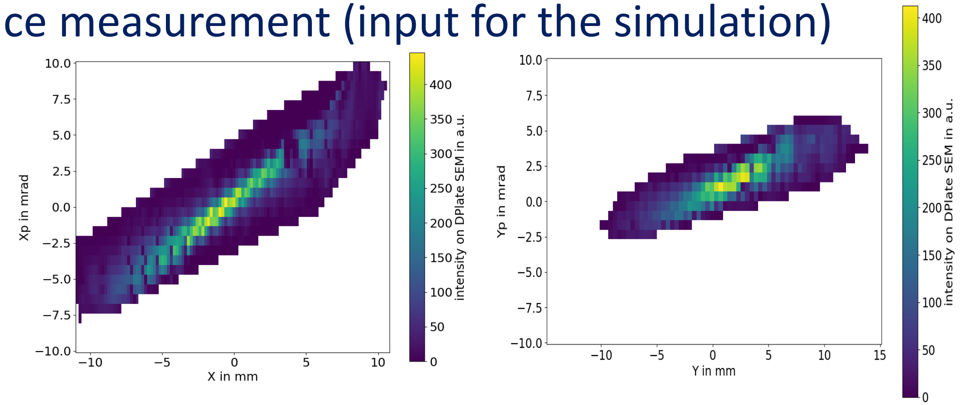
One example: Transverse phase space at DSL



Size @DSL (TraceWin)
σx [rms] = 2.8182 mm
σy [rms] = 4.1896 mm

- Emittance measurement (input for the simulation)

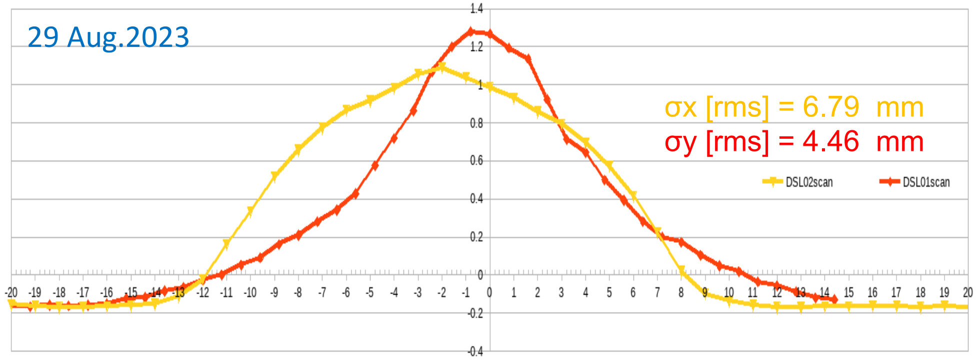
30 Aug.2023

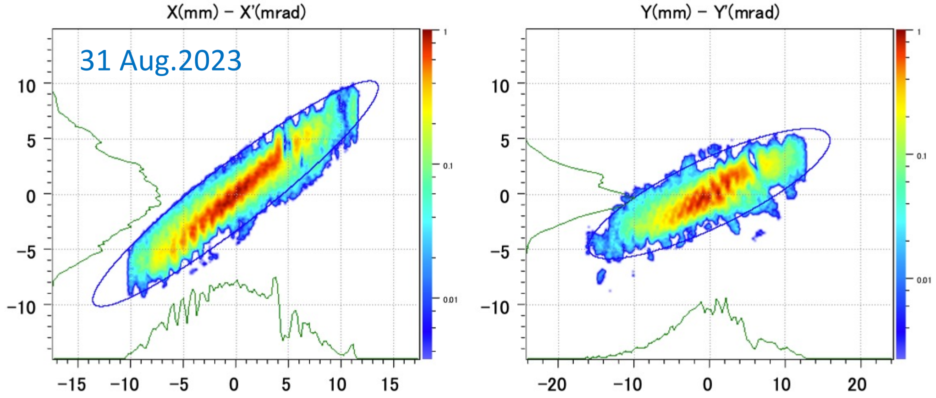


- Created data for TraceWin from the above measured one

Size at DSL (measured)
σx [rms] > 6 mm
σy [rms] > 4 mm

→ Not matched at all…





σx [rms] = 4.4327 mm, σy [rms] = 4.9488 mm

Beam Position Monitor (BPM)

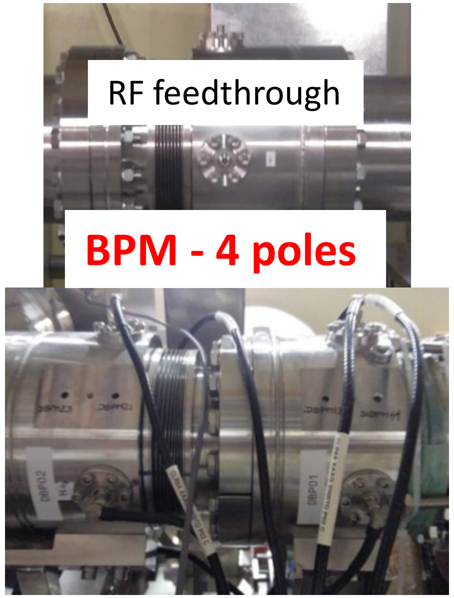
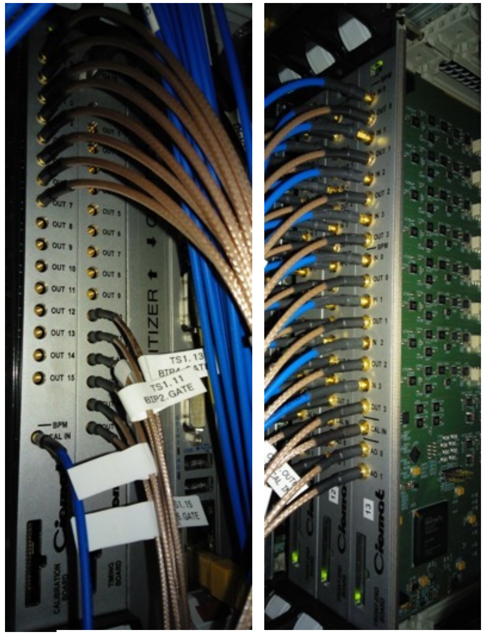


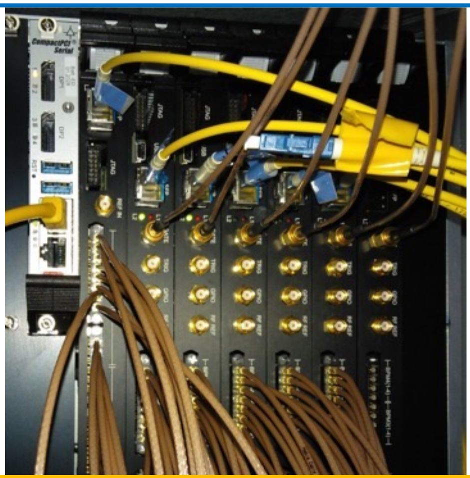
Image current

Image current



Analog Front End

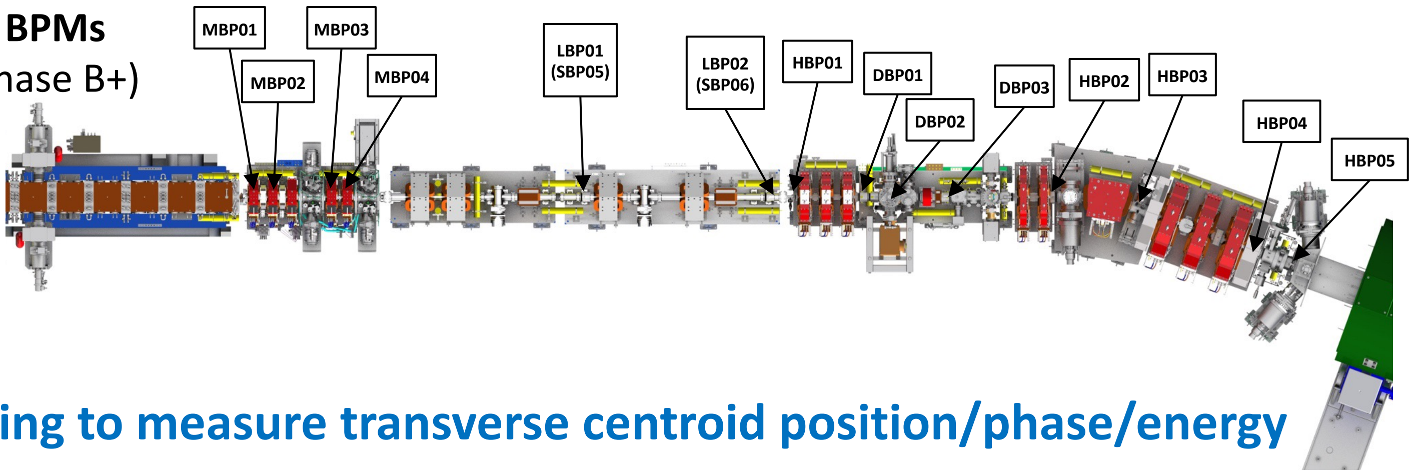
IF signal



synchronized with RF
by white rabbit (WR) system

Digitizer（DAQ+FPGA）

14x BPMs
(for Phase B+)



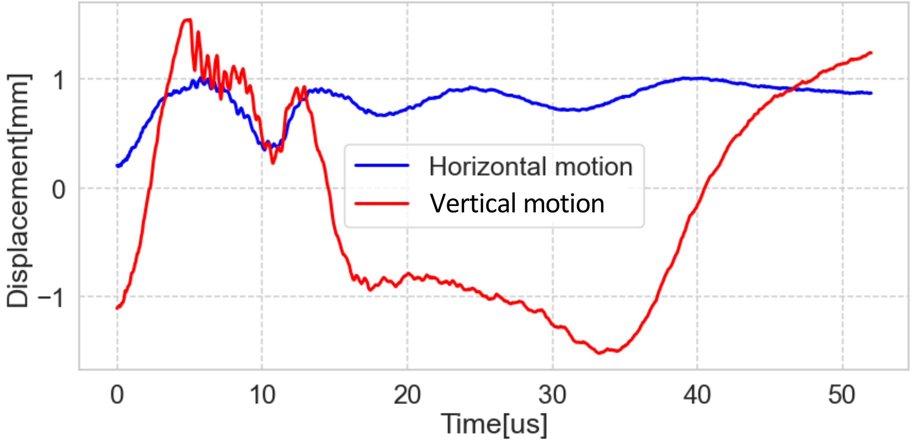
BPM	Quantity	Range	Accuracy	Resolution
MEBT	Position	0 to 5 mm	0.1 mm	0.01 mm
	Mean Energy	5MeV±10%	0.05MeV	0.05MeV
Cryomodule	Position	0 to 5mm	0.25 mm	0.025mm
	Phase		2 deg	0.3deg
D-plate, HEBT	Position	0 to 5 mm	0.3 mm	0.01 mm
	Mean Energy	4 to 10 MeV	0.05 MeV	0.05 MeV

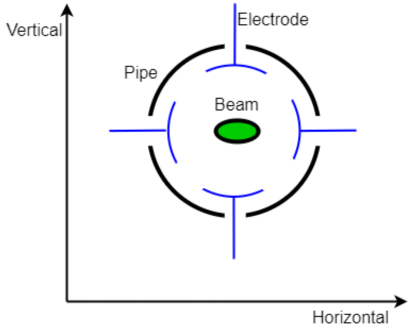
Devoting to measure transverse centroid position/phase/energy

Measurement example of BPMs

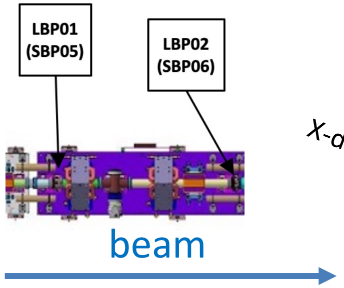
Details presented by K. Hirosawa on Tuesday (TUA3I2)

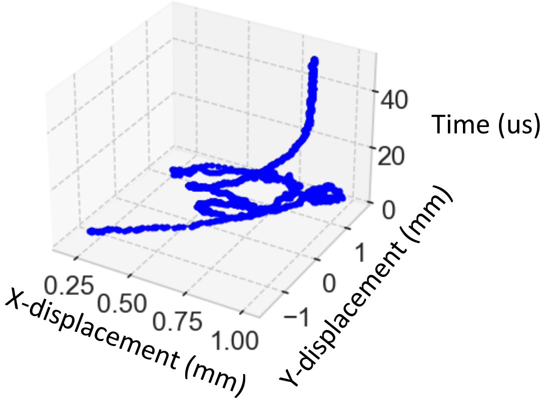
- Beam positions (by raw data logger, 6-Sep.2023)

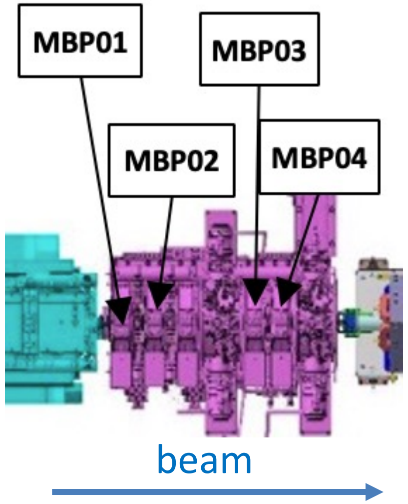




averaged 30 samples in the MEL

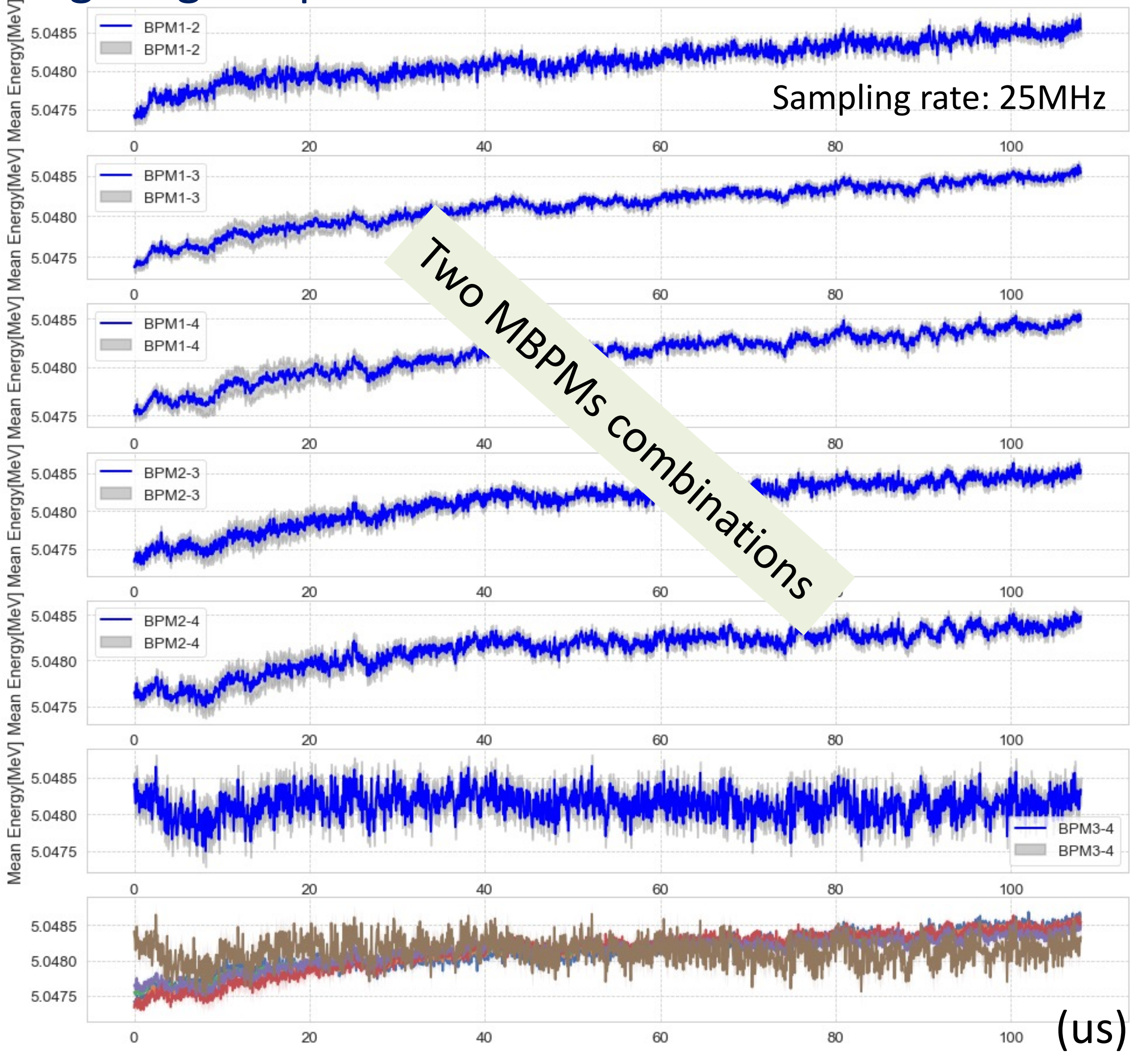






- Energy by TOF method (7-Sep.2023)

→ gating the plateau from the waveform in MEBT



→ Provides the important information properly for tuning and checking the beam status

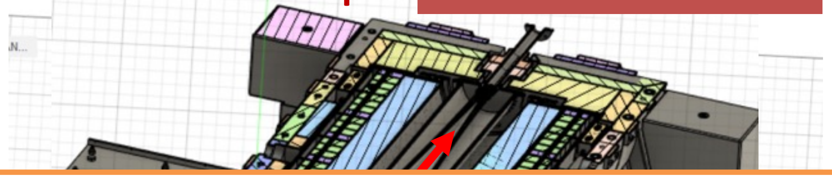
BD instrumentation

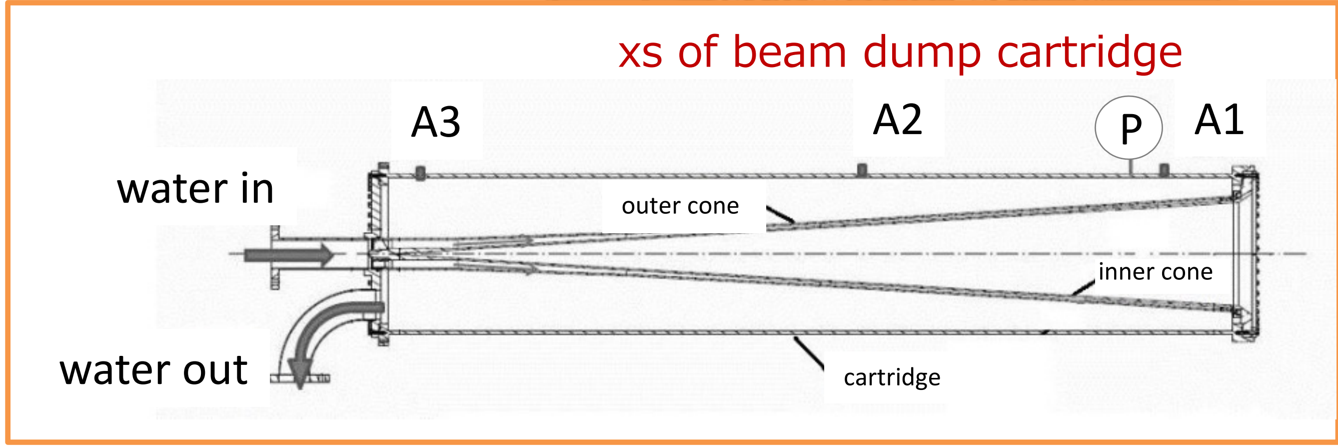
- In the beam dump shield, 6 ICs and 3 Accelerometers as the BD instr.
- Checking beam center w/ signal ratio of ICs
- Vibration from water bubble by high temperature detect by accelerometers

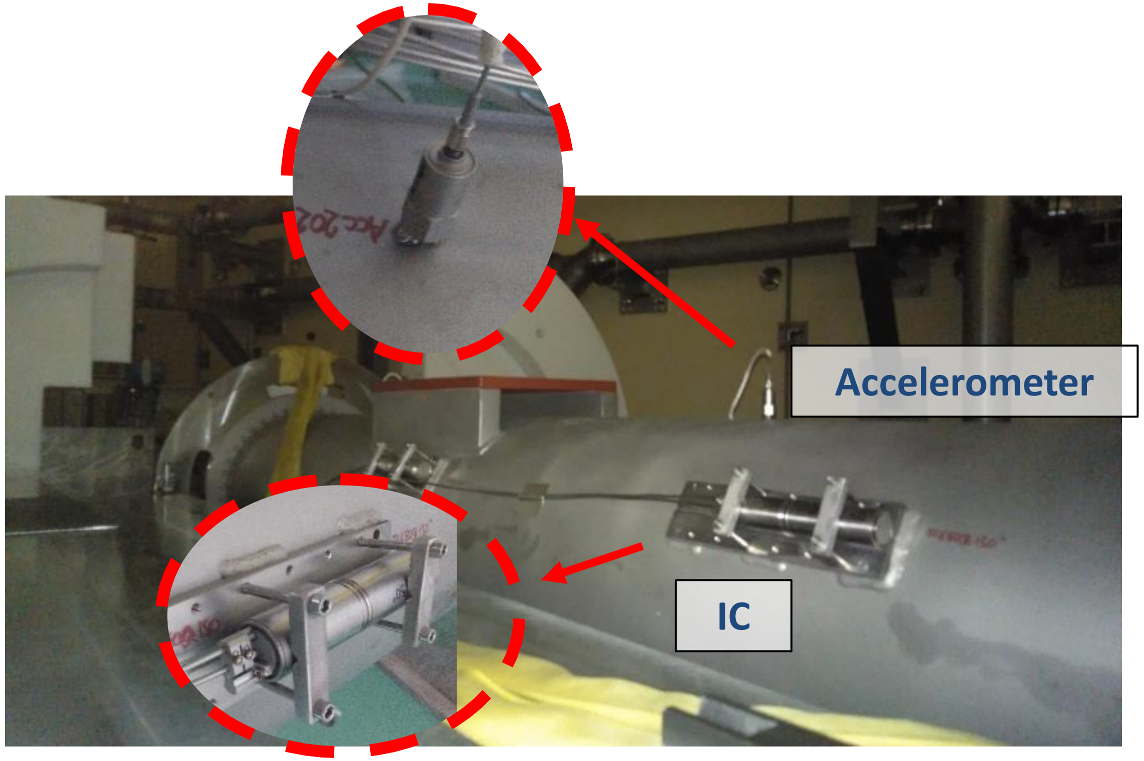
(localized overheating (or hot spots) by incorrect beam focusing (or overfocus) in the BD)

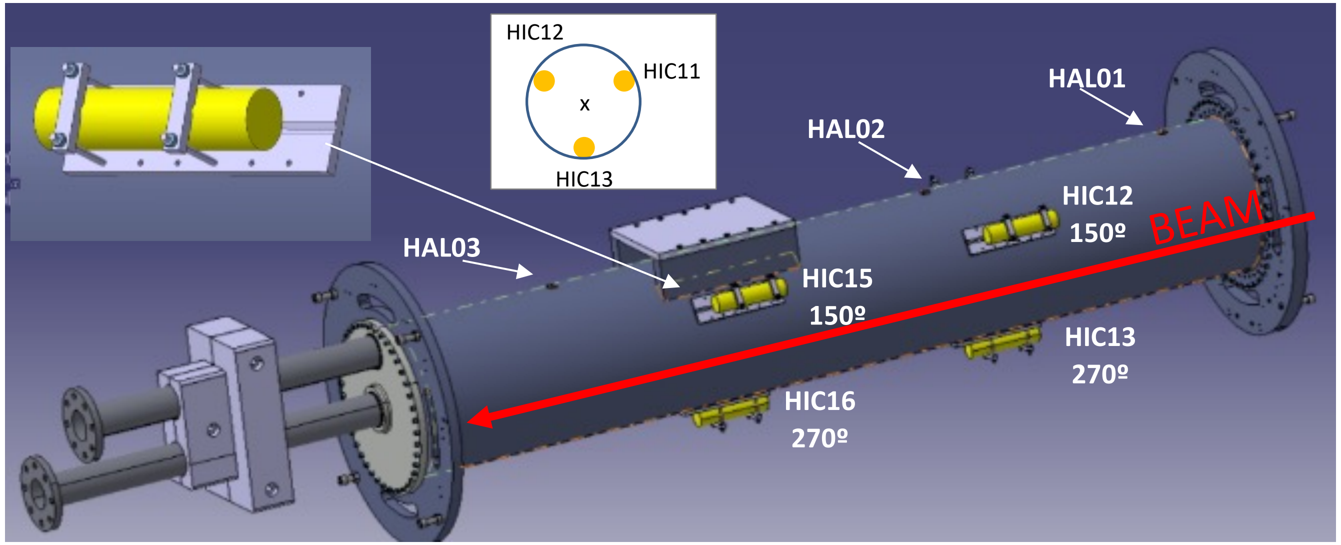
Beam Dump

1.125 MW Beam Power







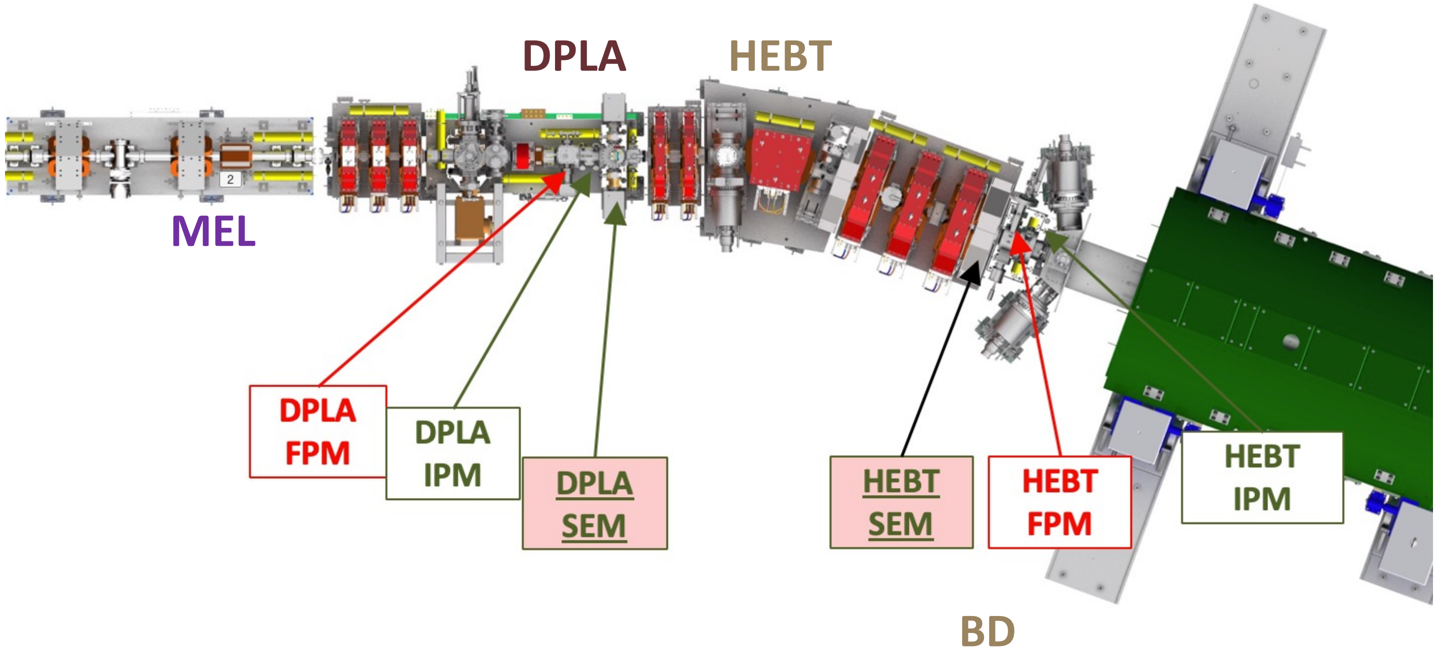


Non-interceptive profilers: IPM and FPM

- LIPAc's goal: Stable 125 mA CW D+ beam operation (up to 1.125 MW)

→ Interceptive devices cannot be used at that time.

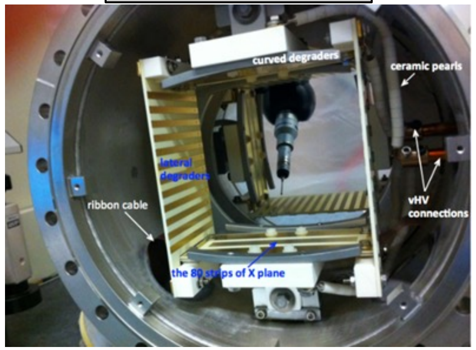
- IPM and FPM have a quite important role for study the vertical-horizontal transversal beam profile
- 2 FPMs and 2 IPMs near DSG in D-Plate, 2 FPMs and 1 IPM near HSG in HEBT



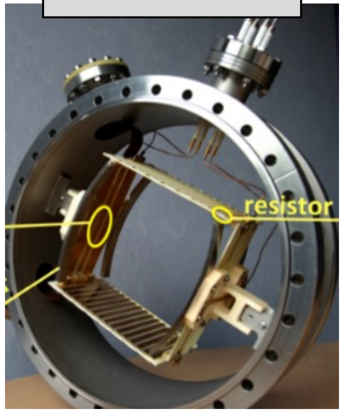
IPMs

- One-set for D-Plate (horizontal, vertical), another (only one direction) for HEBT due to the limit of the space
- Stand-alone tested for both IPMs before the pandemic
- So far, we could not see the "profile" yet at LIPAc (Not ready)

D-Plate IPM



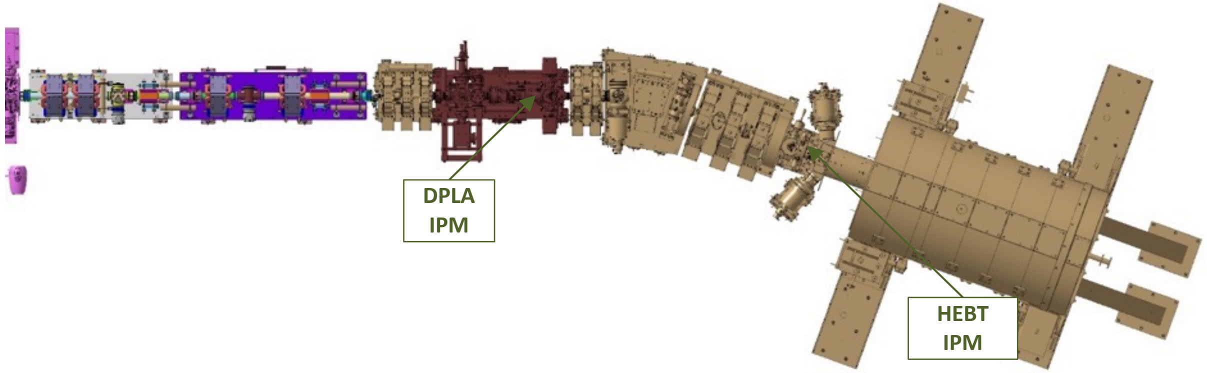
HEBT IPM

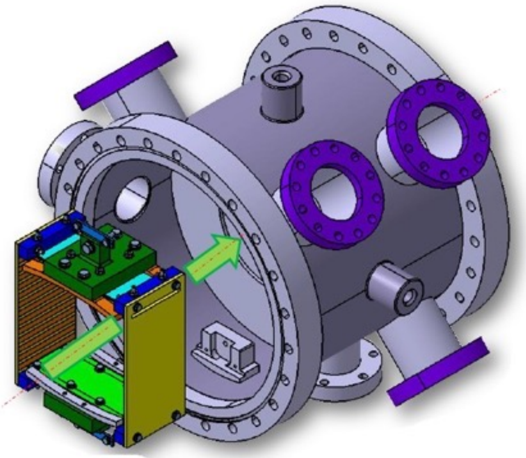


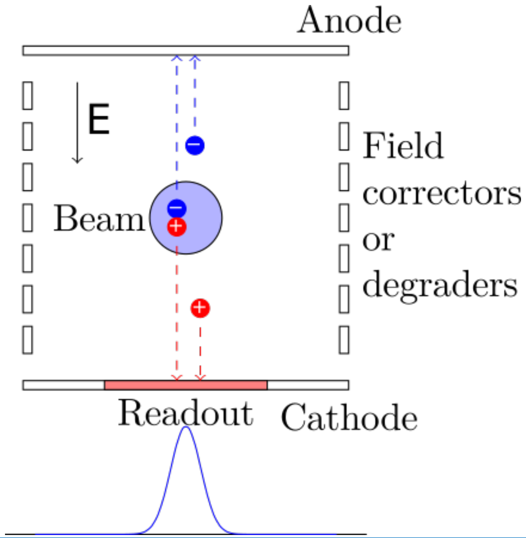
- Simple checkout has been performed for being ready at HDC

→ Found wrong channel assignment: solved

→ Raw signal checks injecting signal: a few channel "dead", SAMTEC connector?







FPMs

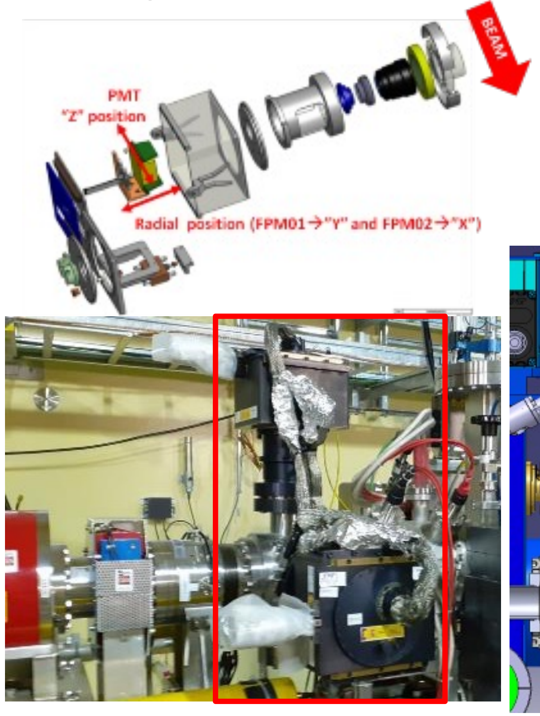
- Based on PMT arrays: (2) 64 ch Vertical-Horizontal for D-Plate, (2) two 32 ch Vertical-Horizontal for HEBT
- Since the Stage 1 op., there's "something" but not clear to see tendencies.
- The Channels "gain calibration" & Ch/mm calibration have been performed in the optical workshop
- Careful light & radiation shielding has been needed
- Now FPMs have high sensitivity even at LDC and UHV (1e-8 mbar)

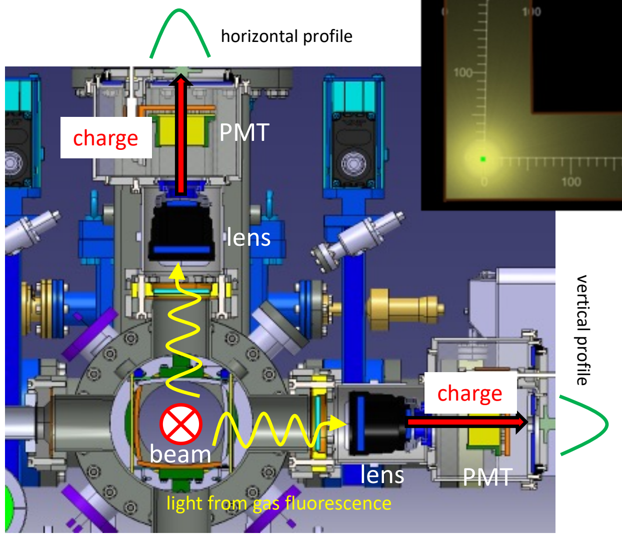
Photon emission efficiency

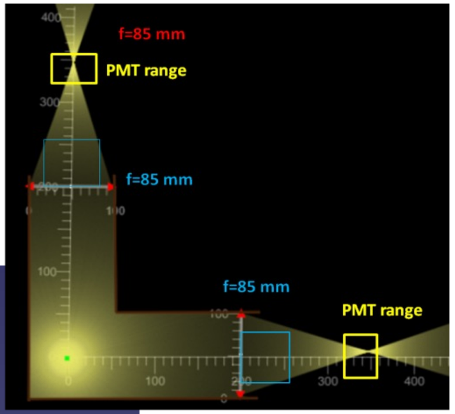
$$\varepsilon \sim \sigma^{eq} \left(P_{gas} \cdot I_{beam}\right) \cdot d_{path}$$

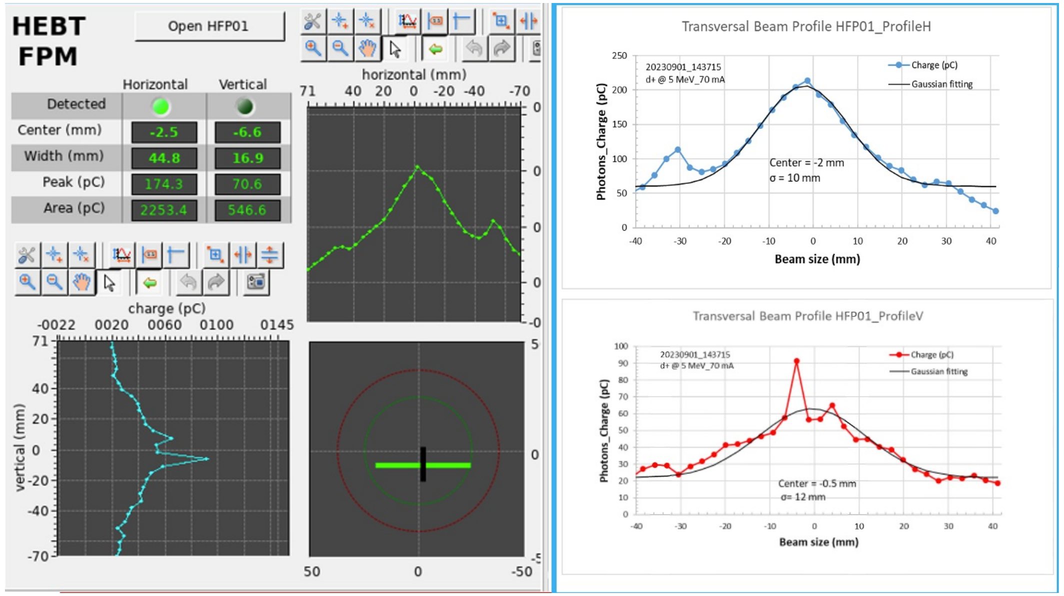
$$N \sim \varepsilon \cdot \Omega \cdot \tau \cdot \chi^{sist}$$

residual gas fluorescence originated by the beam-gas interaction





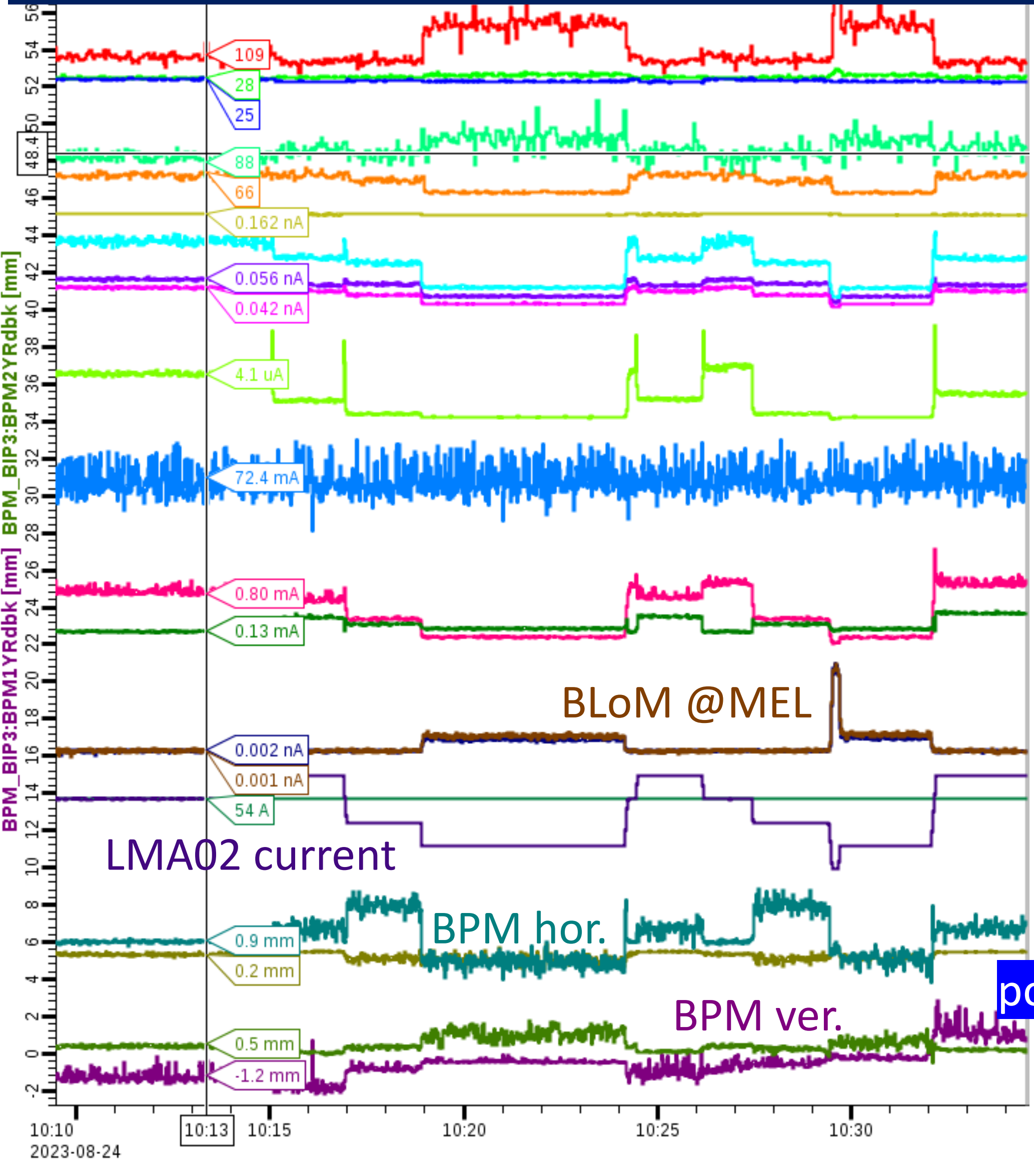




20230901-1437-Transverse profile on HFPMs

Other Results (CT, HFU, BLoM, N-det. & BPM)

when BBA (beam-based alignment) performed



in front of BD

exit of MEBT

middle of MEL

LOSS: N-Det.

Beam current

HEBT Faraday cup (< 8 uA)

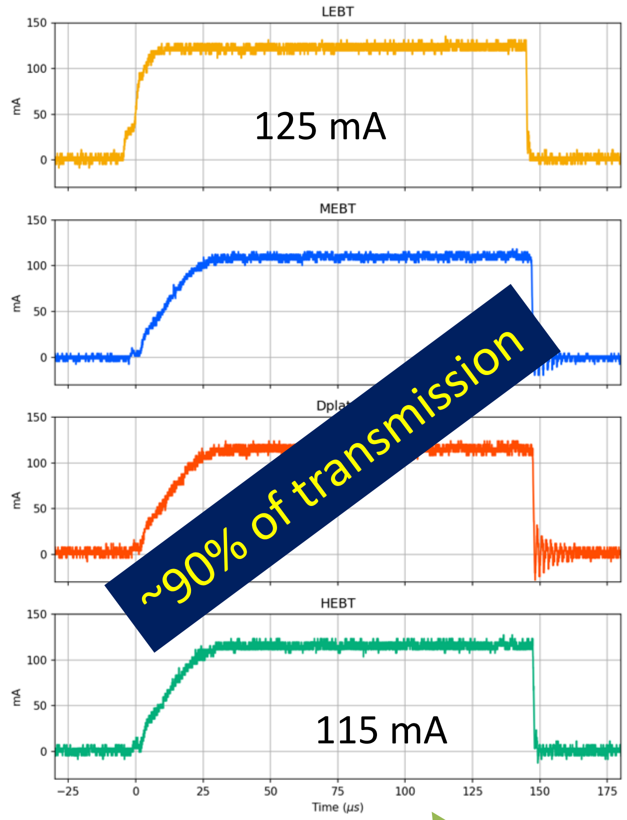
MEBT:ACCT (~70 – 75 mA)

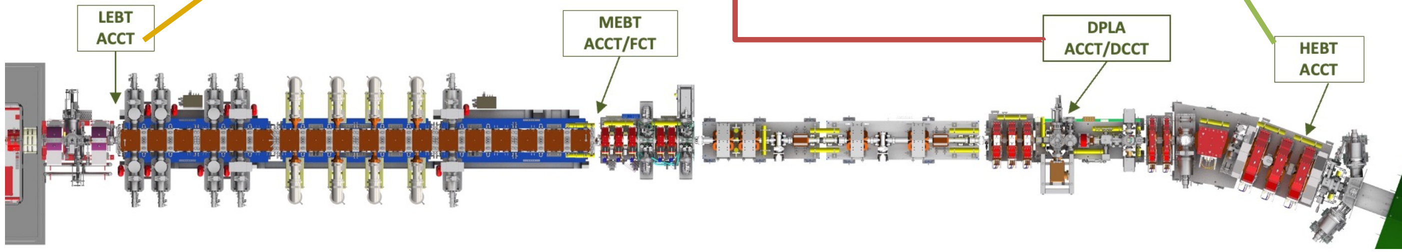
DPLA:ACCT and HEBT:ACCT

Loss

position

125 mA/150 us, 7-Sep. 2023





Summary

- LIPAc operation Phase B+ is ongoing at Rokkasho, Japan.

- We reached a high current beam operation (~125 mA) with LDC.
- Most of diagnostics we installed are somehow working, even with issues.

- Interceptive devices are fully available for the LDC operation.
- Non-interceptive devices are partly ready before the HDC operation.

- Phase B+ will be continued toward the HDC operations until end of this fiscal year (Mar. 2024).
- Some upgrades of LIPAc beam diagnostics has been started for further operation phases.

Thank you for your attention!

contact: kwon.saerom@qst.go.jp