High beam current operation with beam diagnostics at LIPAc

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Working Group E: Beam Instrumentation and Intercepting Devices

Linear IFMIF Prototype Accelerator (LIPAc)

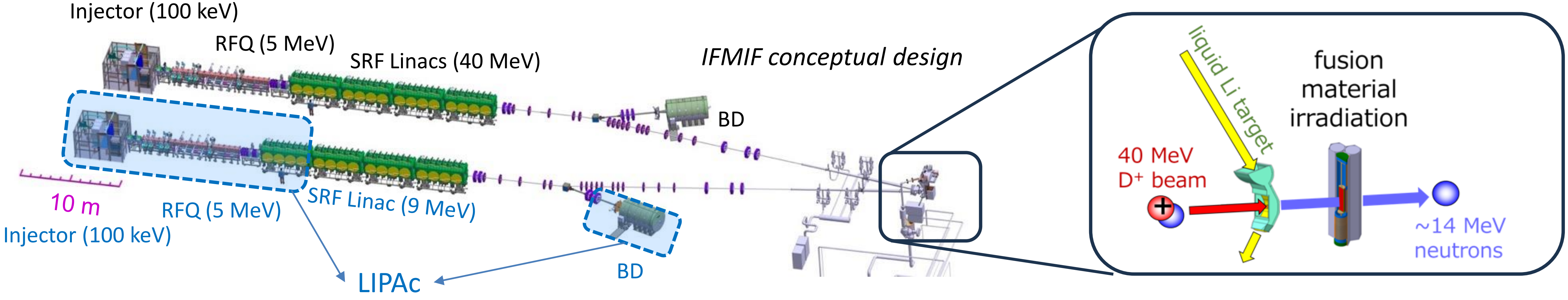
Rokkasho Fusion Institute (BA Site)

OUTLINE

- Introduction: IFMIF & LIPAc
- Status of LIPAc
- LIPAc beam diagnostics: Interceptive devices
- LIPAc beam diagnostics: Others
- Summary

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

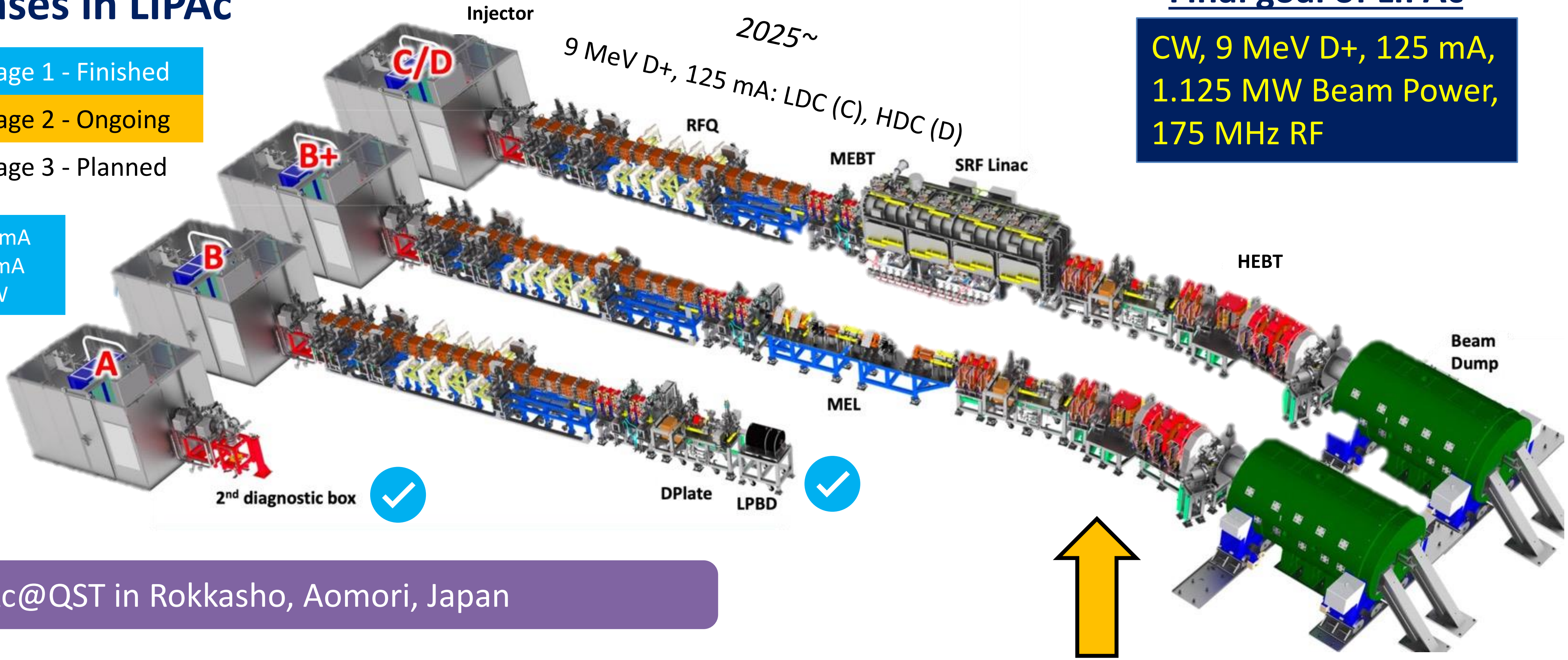
→ All results, experiences and lessons learned & to be learned from LIPAc will be used for further designs of the accelerators.

	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

125 mA D+ beam at HEBT @150us/1Hz at 90% of transmission — Sep. 2023

- **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
		Stage 3		high duty cycle

← now

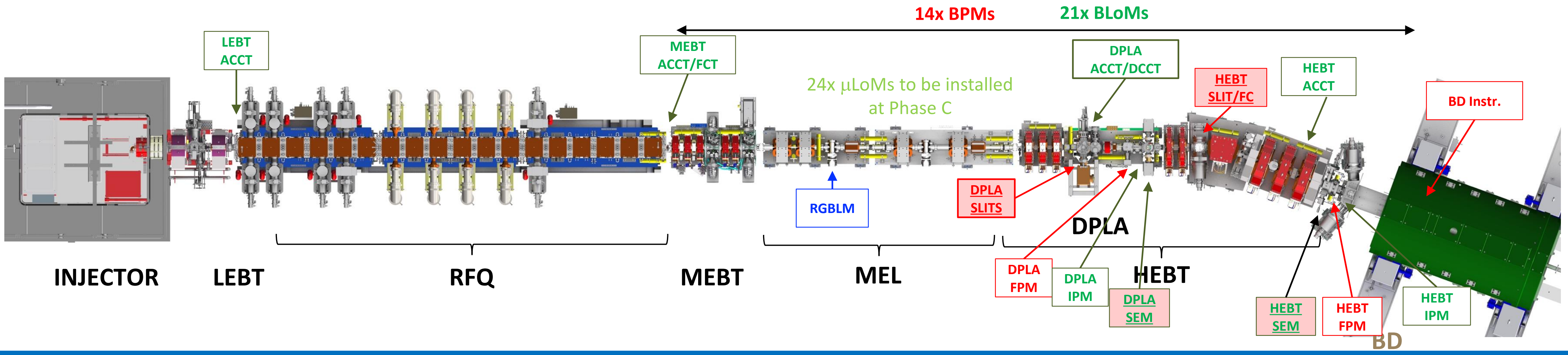
LIPAc beam diag.

- 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
FPM: Florescence Profile Monitor
RGBLM: Residual Gas Bunch Length Monitor
BLoM: Beam Loss Monitor
µLoM: Micro Loss Monitor
IC: Ionization Chamber

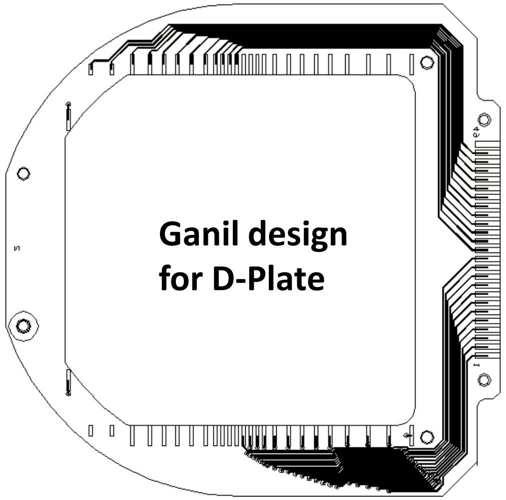
Current measurement: 3 ACCT, 1 DCCT, 1FCT
Position, phase & energy: 14 BPMs
Transverse profile: 2 SEM-grid (pulsed), 3 IPMs (CW), 4 FP
Transverse emittance: Slits + SEM-grids
Longitudinal emittance: 1 RGBLM
Losses: 21 BLoMs + 24 µLoMs
Beam Dump instrumentation: 6 ICs, 3 Accelerometers

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)



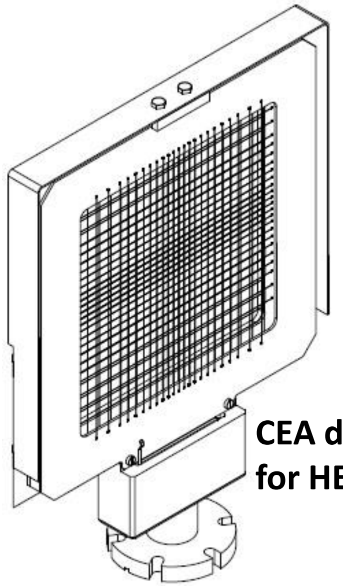
101 × 101 mm^2

➢ Rackets

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

➢ Wires

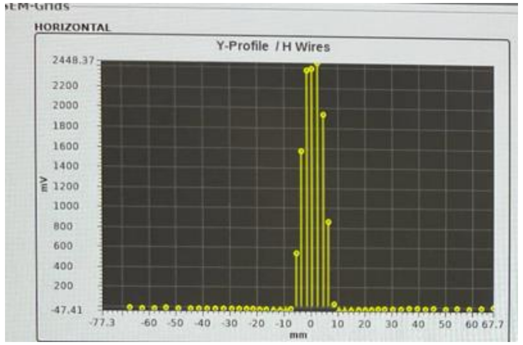
- 47 Tungsten golden platted
- Ø = 20 µm for D-Plate one, 100 µm for HEBT one,



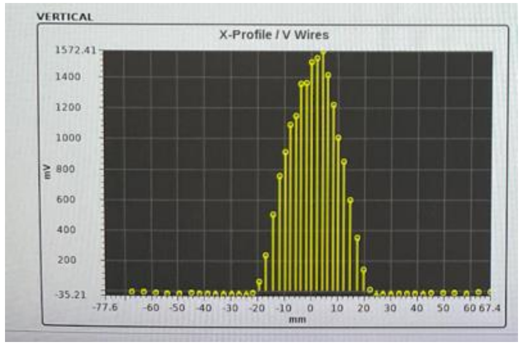
CEA design for HEBT

150 × 150 mm^2

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



Y-profile/H wires

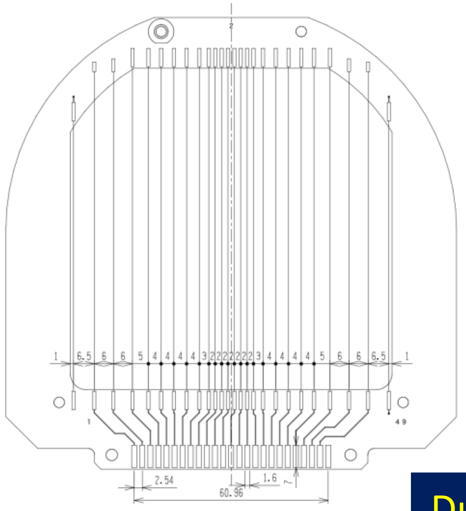


X-profile/V wires

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)

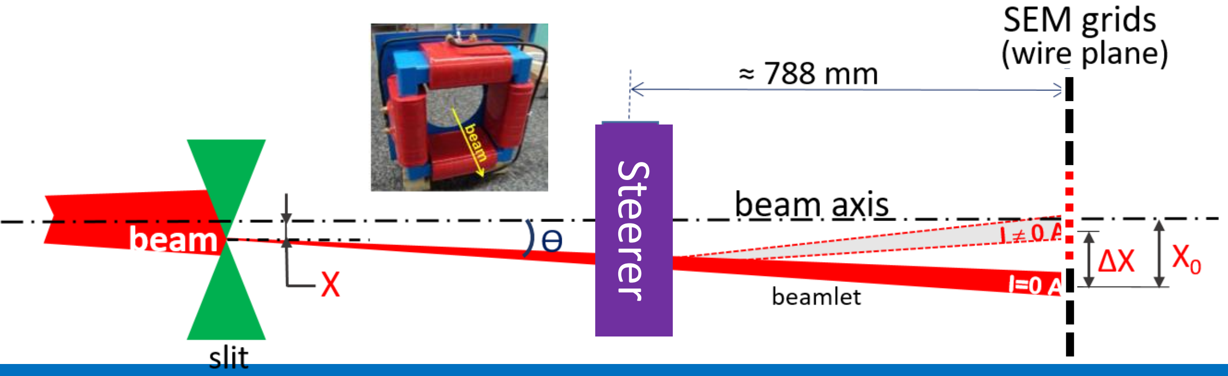
12-July 2022 replaced from horizontal slit to vertical one

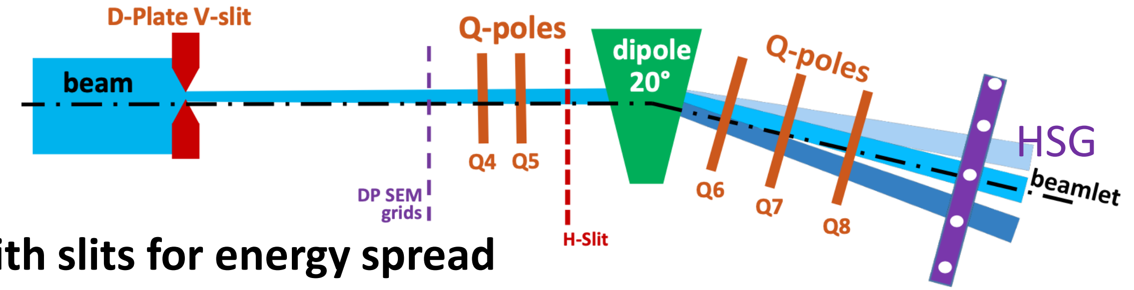


- Fine wire density on center
- Gaps between wires
  - D-Plate one: 1 / 2 / 3 mm
  - HEBT one: 2 / 2.5 / 3 / 4.5 mm

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

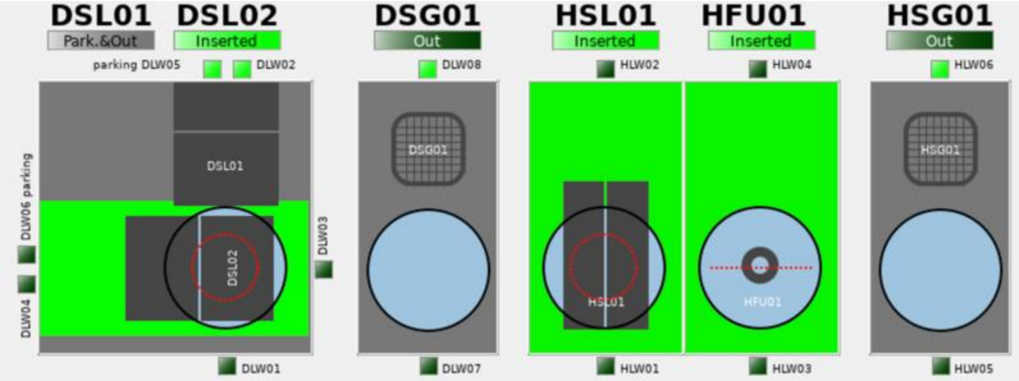


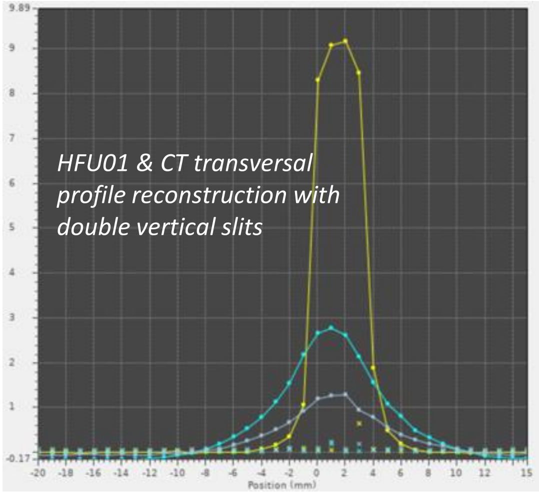


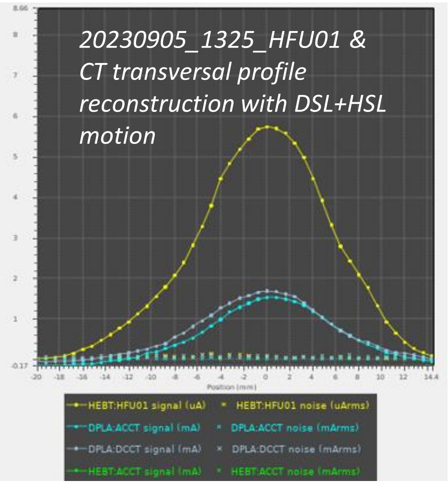
HSG with slits for energy spread

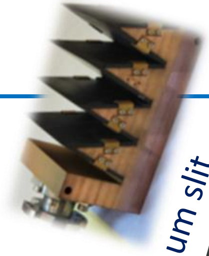
Other Interceptives: Slits & faraday cup

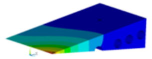
- 2 slits (vertical & horizontal) in D-Plate (DSL) and 1 slit in HEBT (HSL) with FC
- DSL: Copper + Graphite <-- water cooling system implemented
- HSL: 2.5 mm thickness of Tungsten alloy
- Slits scan motion up to 160 mm actuates by a Phytron motor (1 um motion precision)
- Operation validated up to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



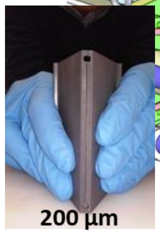


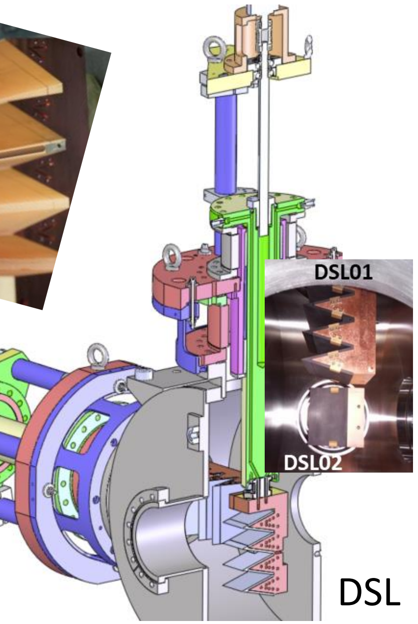






thermo-mechanical simulations

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



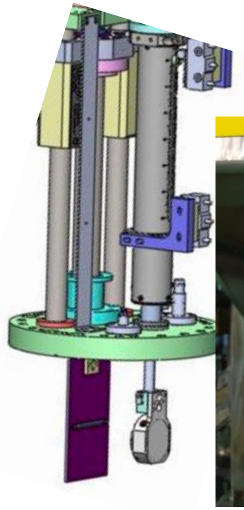


DSL

<Features>

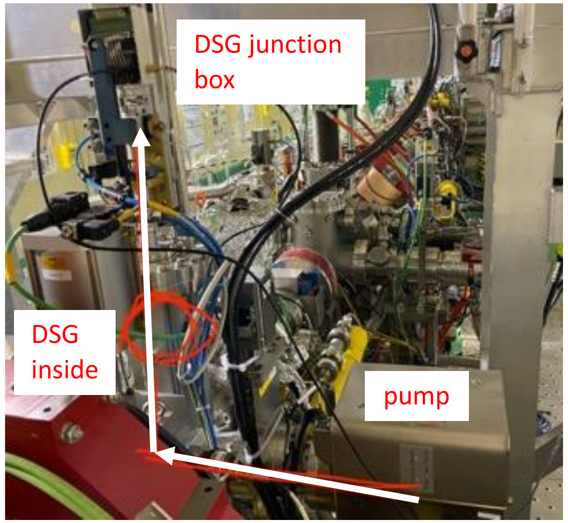
- Easy OPI to know the status
- Auto-scan mode implemented with CTs/FC for quick beam profile check (like another profiler)
- Another automatic function to be added for the emittance measurement

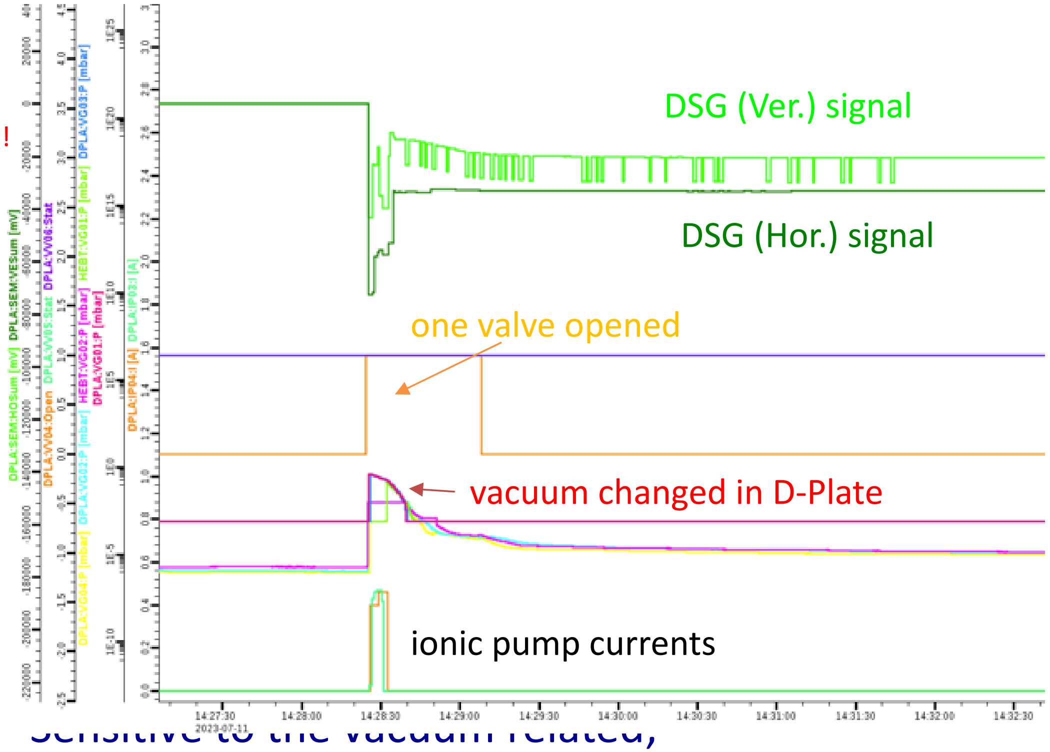

everyday is not a good day…
motor coupling of one DSL damaged without anyone knowing
→ noticed at annual maintenance

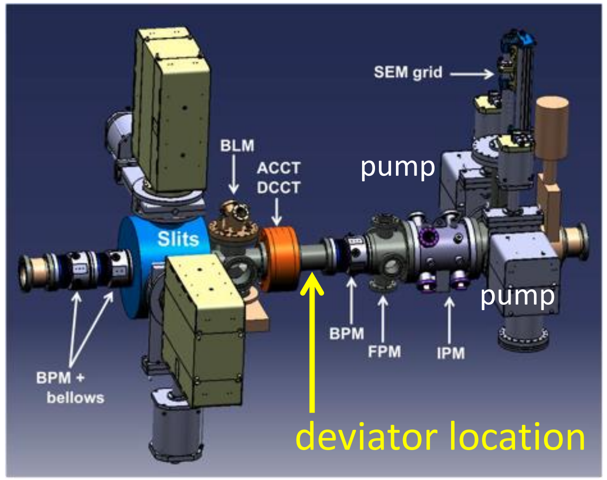



HSL & HEBT Faraday cup

Issues of SEM-grid







Sensitive to the vacuum related,

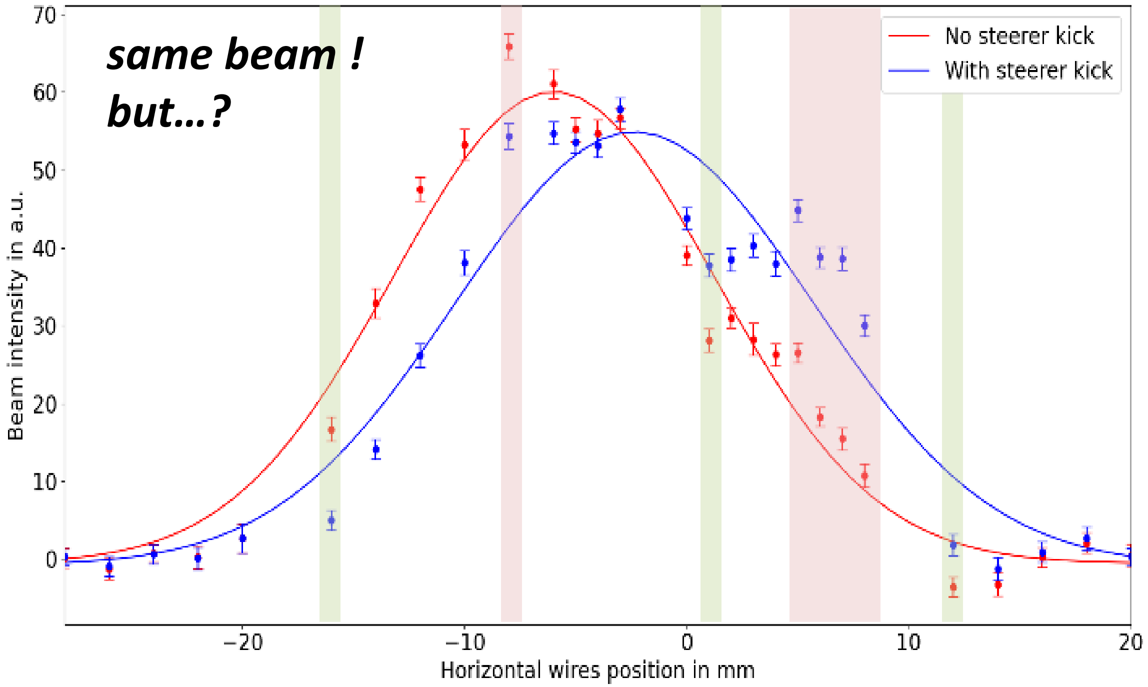
(1) Vacuum chamber shared with 2 horizontal ionic pumps -> some arcs were in the chamber, it destroyed the DAQ.

(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 …?

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

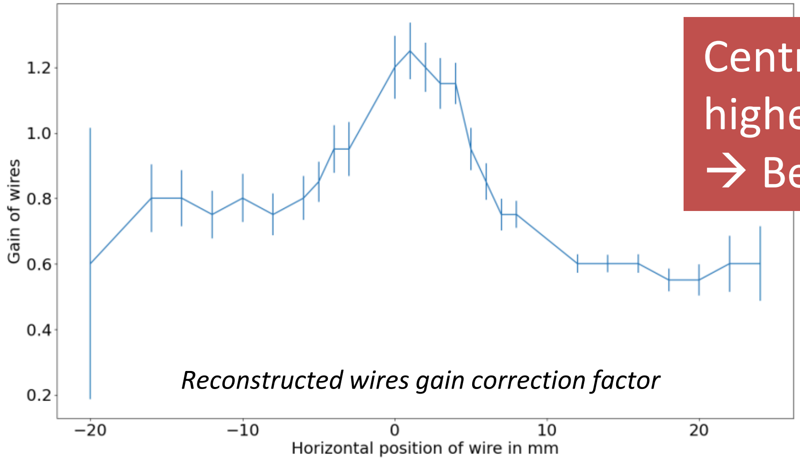
Signal seems systematically
- Higher than profile
- Lower than profile

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

→ Uneven wire gain?

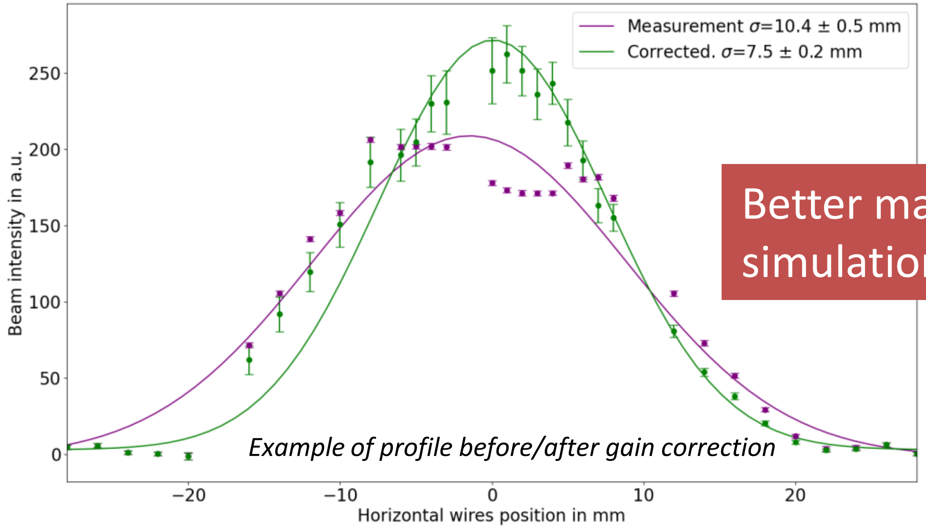
We apply gain correction from analysis of emittance measurement

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



Reconstructed wires gain correction factor

Central wires require higher correction factor
→ Beam induced damage?



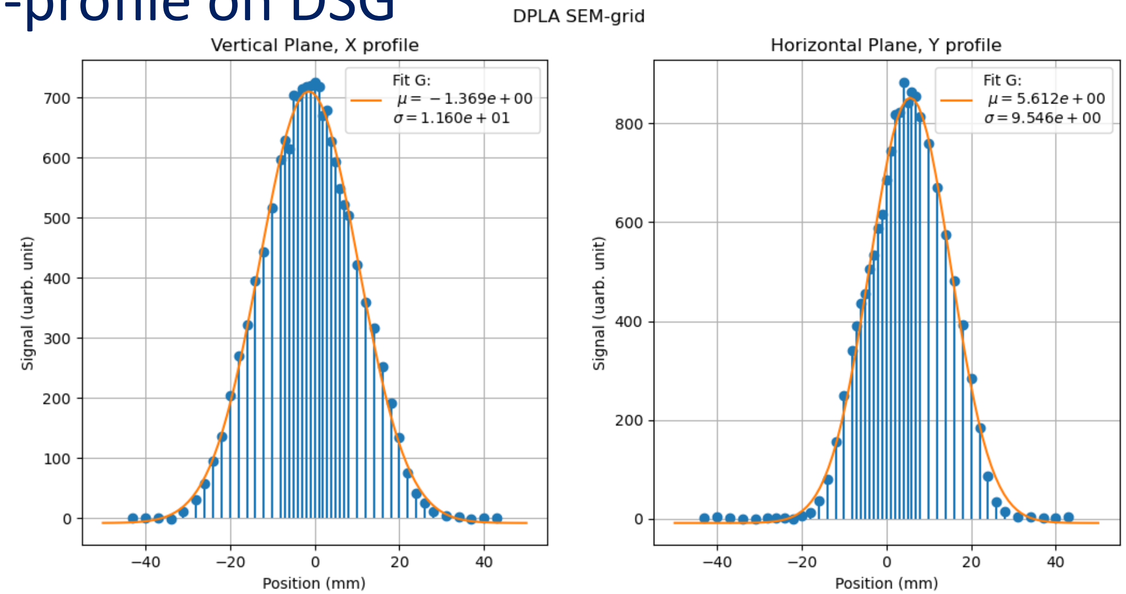
Example of profile before/after gain correction

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

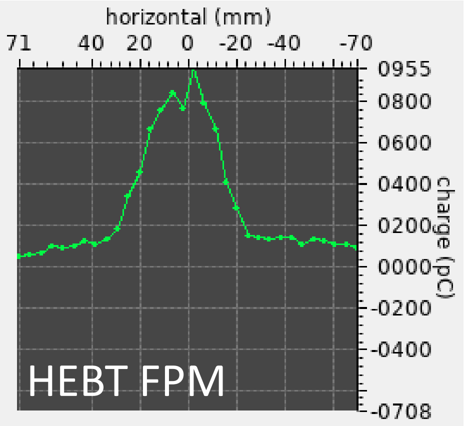
Some Results on interceptive devices - 1

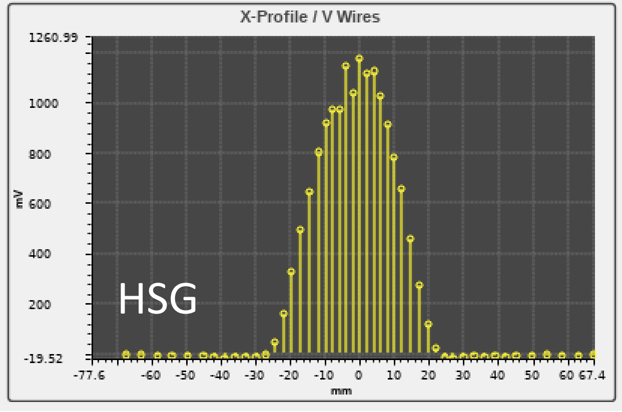
- Full-profile on DSG



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

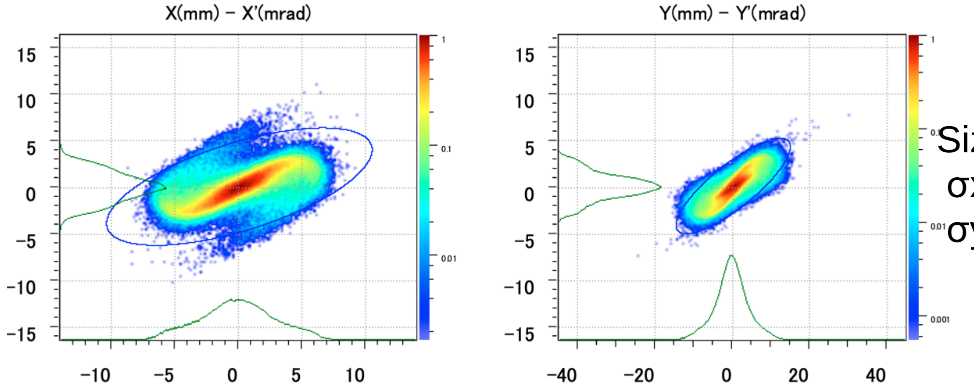
- Beam simulation results were ready (prediction)
- Real measurement could not be matched (even qualitatively…)

→ 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)**

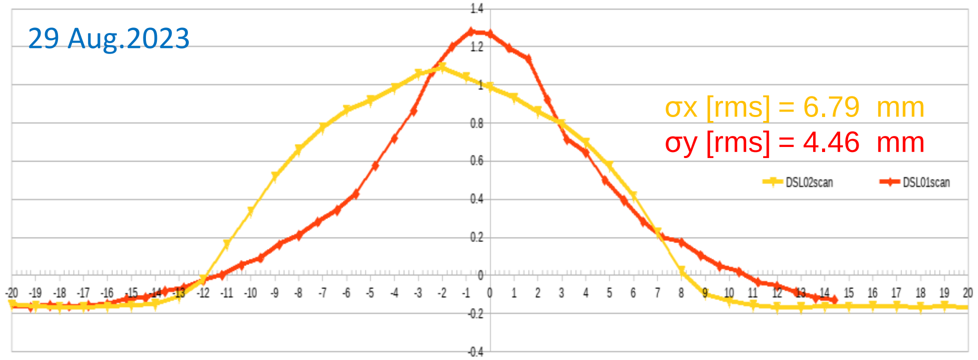
One example: Transverse phase space at DSL



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

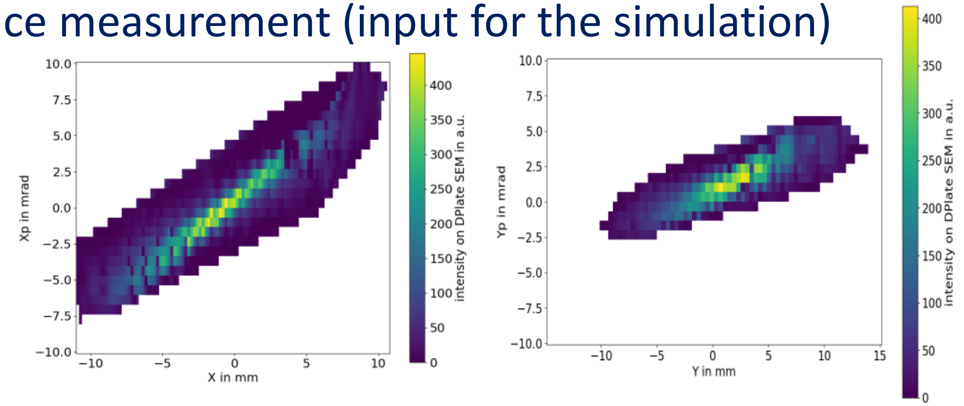
Size at DSL (measured)
σx [rms] > 6 mm
σy [rms] > 4 mm

→ Not matched at all…

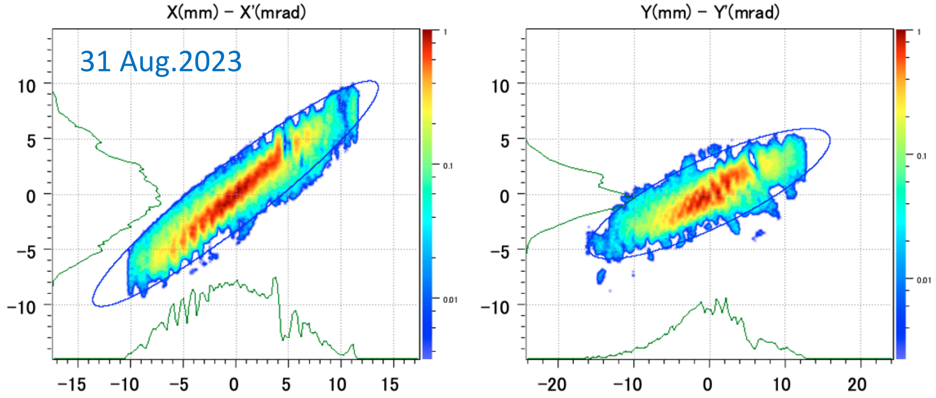


- Emittance measurement (input for the simulation)

30 Aug.2023



- Created data for TraceWin from the above measured one



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

Beam Position Monitor (BPM)

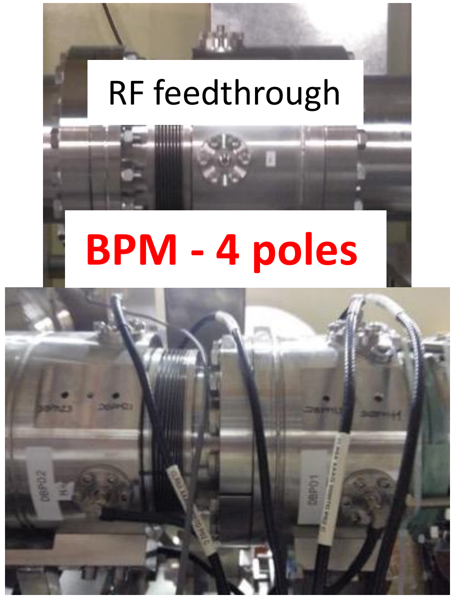


Image current

Image current

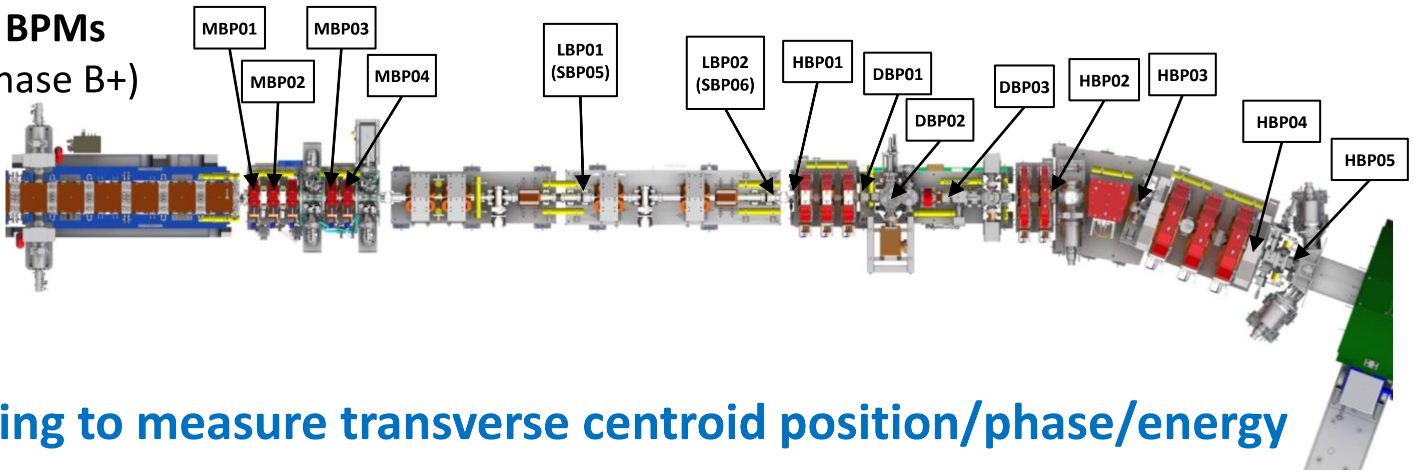
Analog Front End

IF signal

synchronized with RF
by white rabbit (WR) system

Digitizer（DAQ+FPGA）

14x BPMs
(for Phase B+)



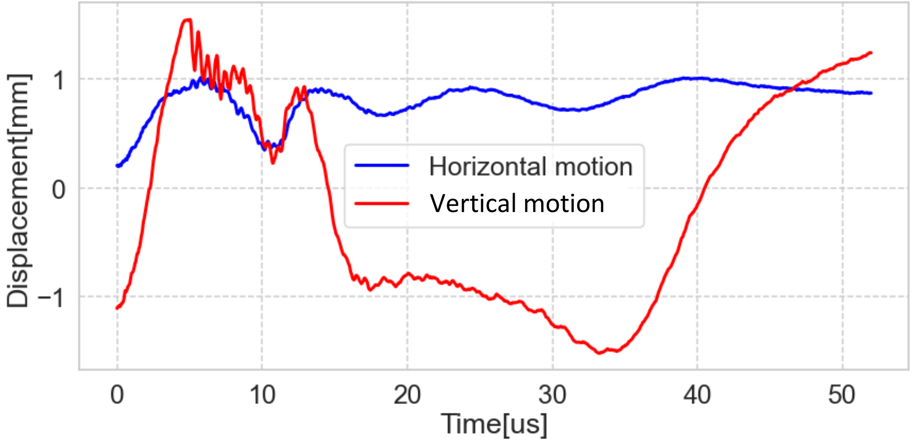
BPM	Quantity	Range	Accuracy	Resolution
MEBT	Position	0 to 5 mm	0.1 mm	0.01 mm
	Mean Energy	5MeV±10%	0.05MeV	0.05MeV
Cryomodule	Position	0 to 5mm	0.25 mm	0.025mm
	Phase		2 deg	0.3deg
D-plate, HEBT	Position	0 to 5 mm	0.3 mm	0.01 mm
	Mean Energy	4 to 10 MeV	0.05 MeV	0.05 MeV

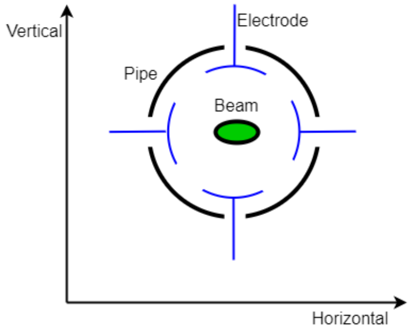
Devoting to measure transverse centroid position/phase/energy

Measurement example of BPMs

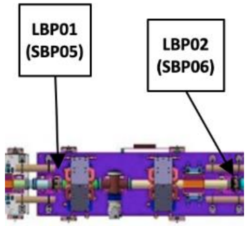
Details presented by K. Hirosawa on Tuesday (TUA3I2)

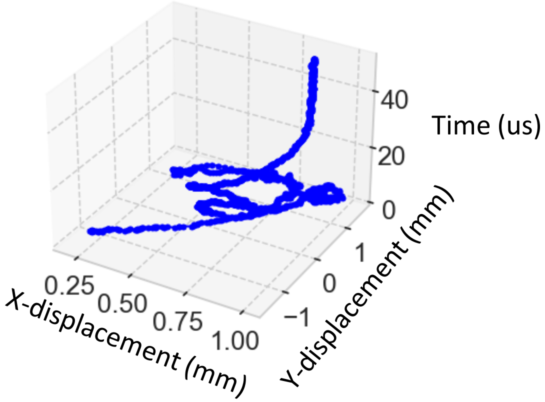
- Beam positions (by raw data logger, 6-Sep.2023)

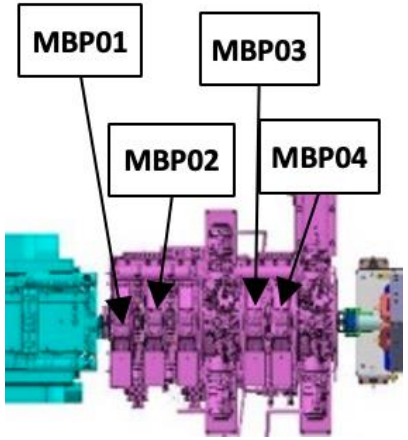




averaged 30 samples in the MEL

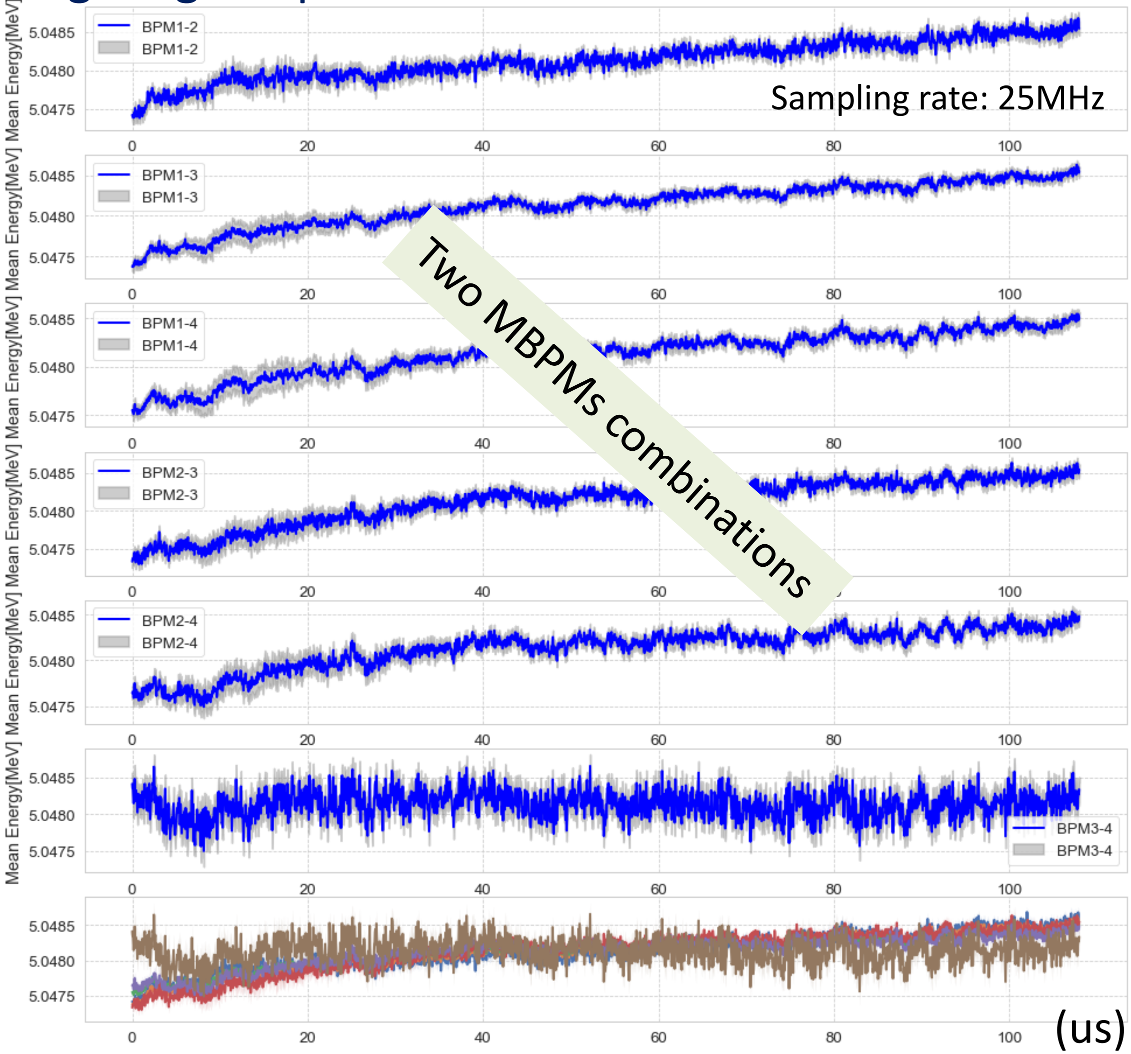






- Energy by TOF method (7-Sep.2023)

→ gating the plateau from the waveform in MEBT

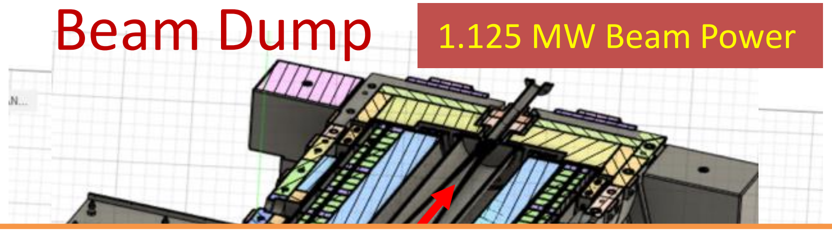


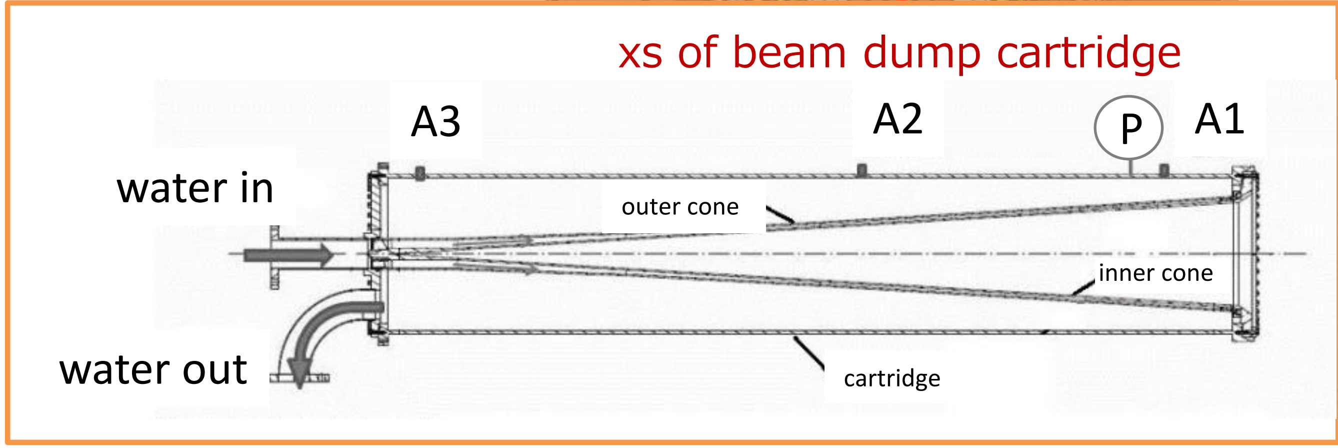
→ Provides the important information properly for tuning and checking the beam status

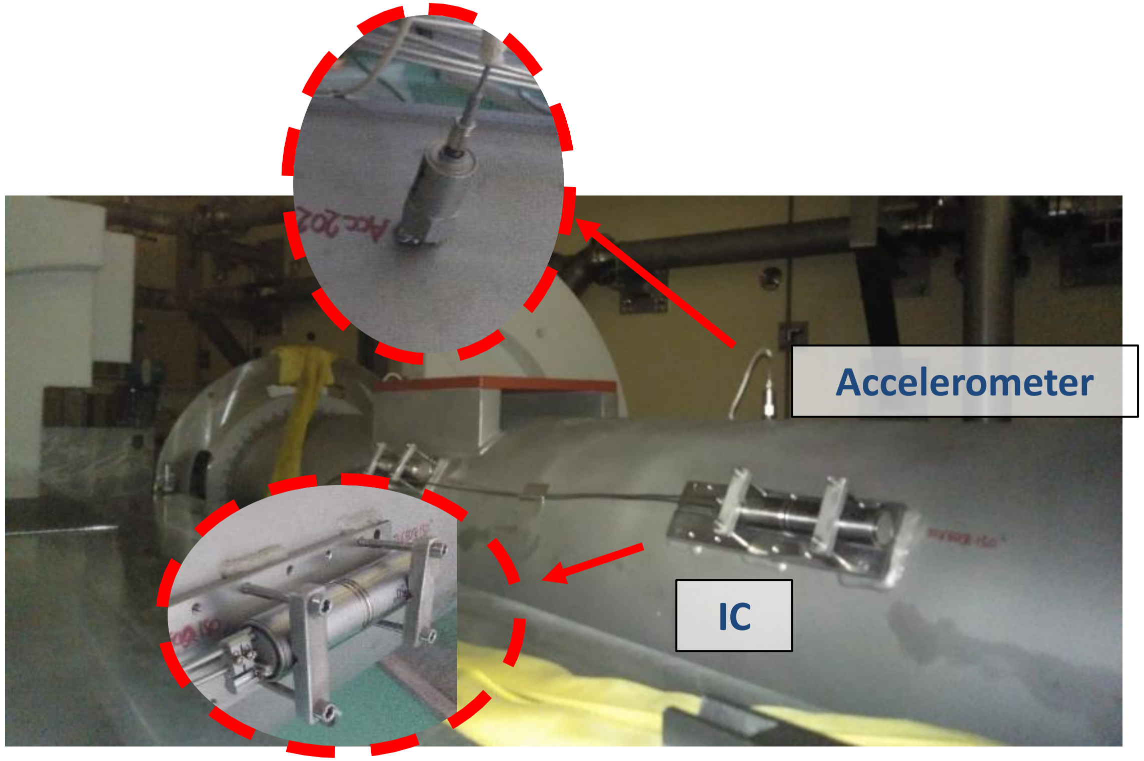
BD instrumentation

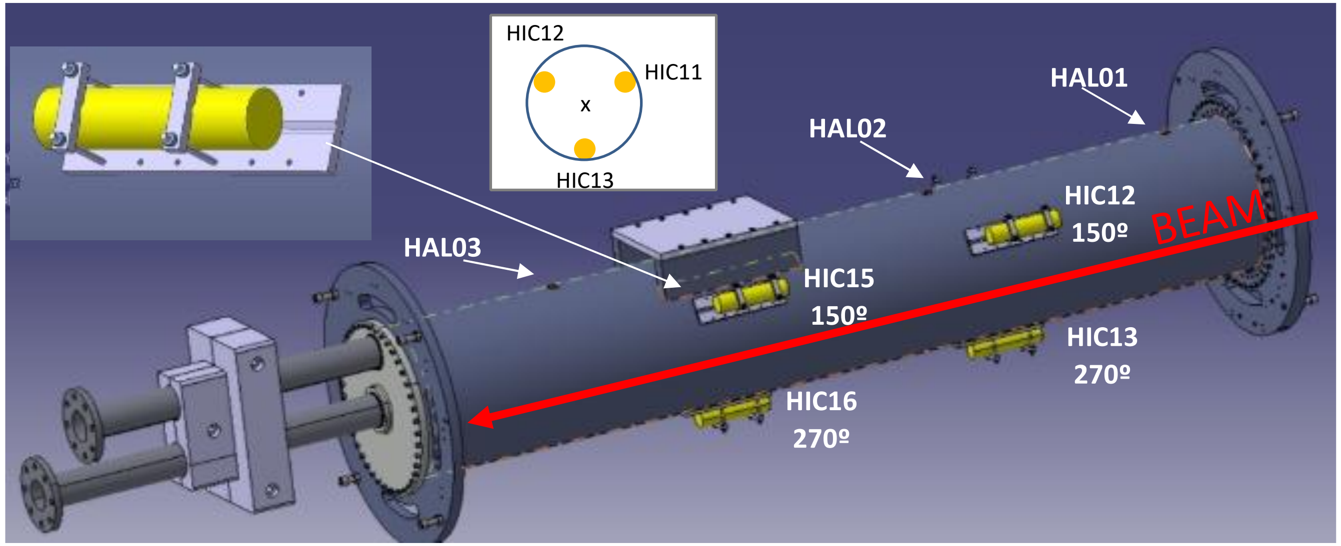
- In the beam dump shield, 6 ICs and 3 Accelerometers as the BD instr.
- Checking beam center w/ signal ratio of ICs
- Vibration from water bubble by high temperature detect by accelerometers

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







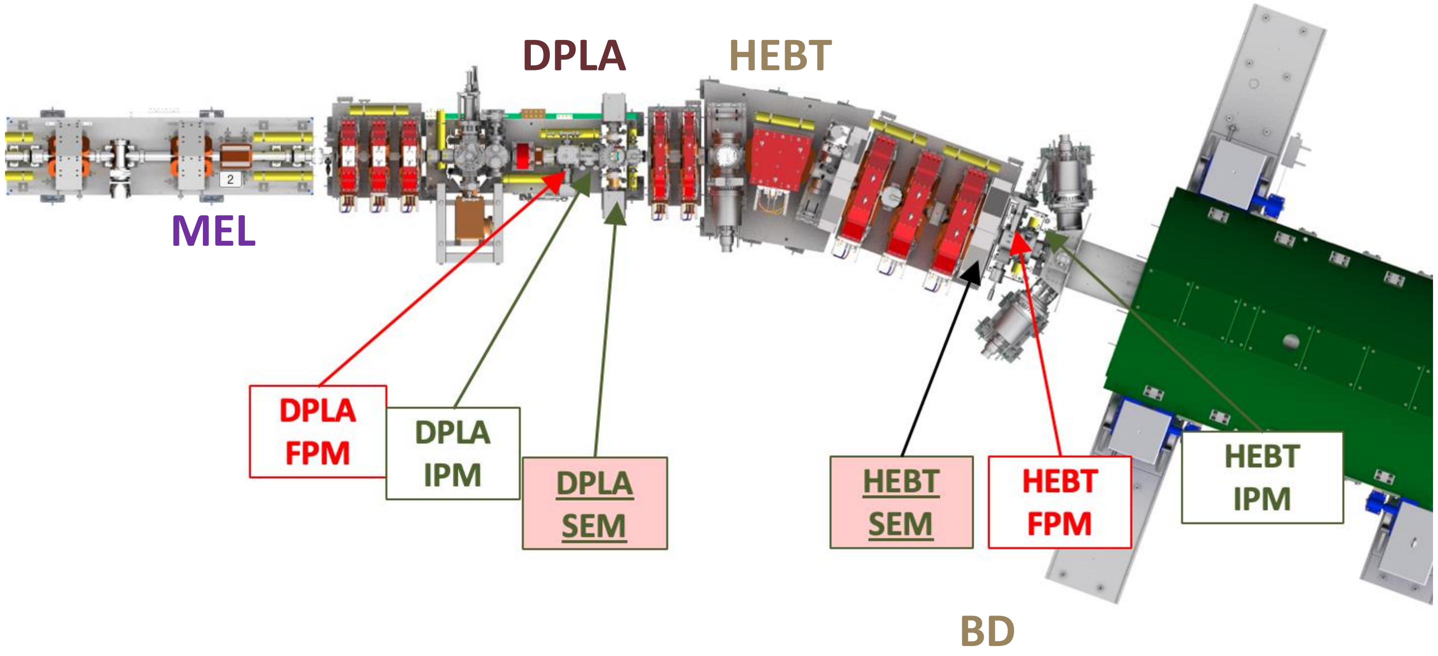


Non-interceptive profilers: IPM and FPM

- 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

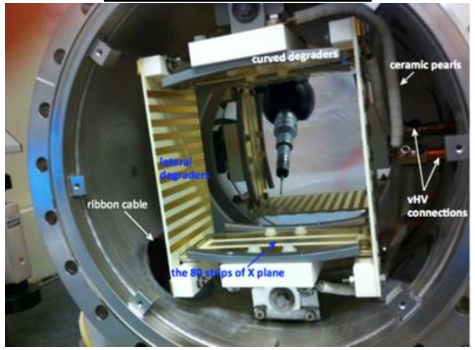
- One-set for D-Plate (horizontal, vertical), another (only one direction) for HEBT due to the limit of the space
- Stand-alone tested for both IPMs before the pandemic
- So far, we could not see the “profile” yet at LIPAc (Not ready)

- Simple checkout has been performed for being ready at HDC

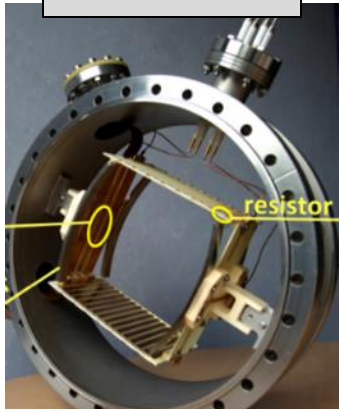
→ Found wrong channel assignment: solved

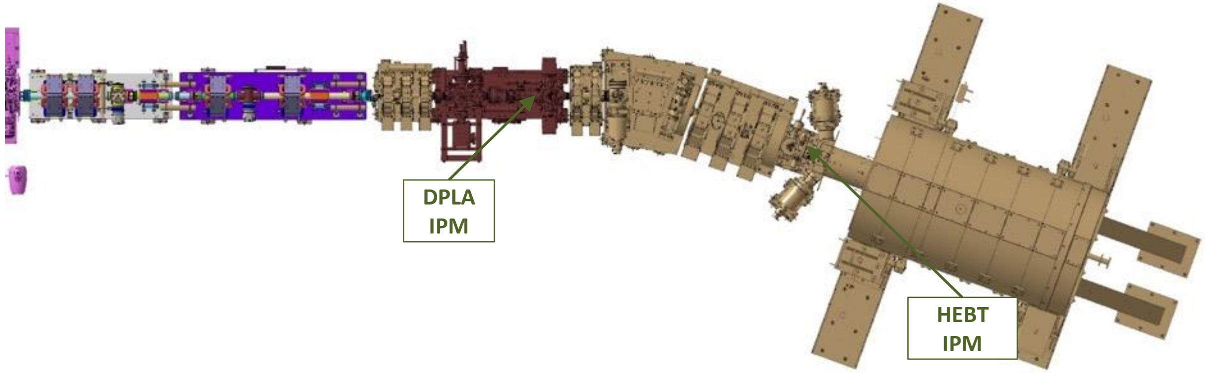
→ Raw signal checks injecting signal: a few channel “dead”, SAMTEC connector?

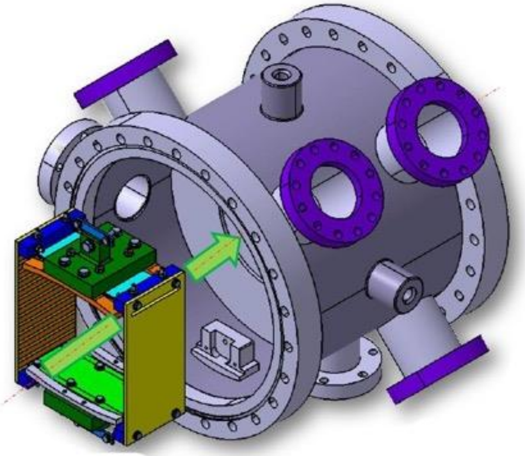
D-Plate IPM

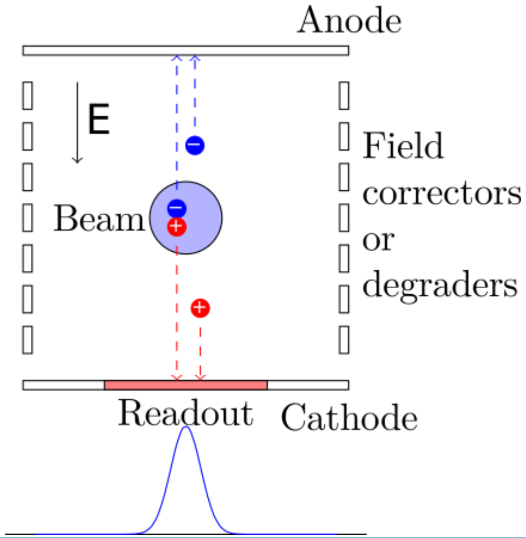


HEBT IPM









FPMs

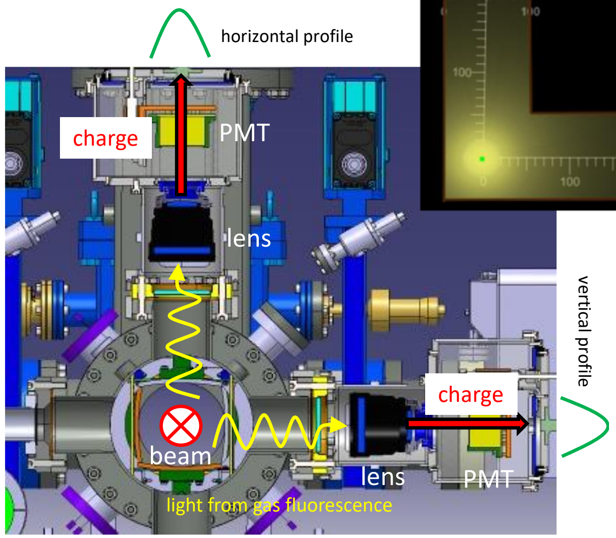
- Based on PMT arrays: (2) 64 ch Vertical-Horizontal for D-Plate, (2) two 32 ch Vertical-Horizontal for HEBT
- Since the Stage 1 op., there's "something" but not clear to see tendencies.
- The Channels "gain calibration" & Ch/mm calibration have been performed in the optical workshop
- Careful light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

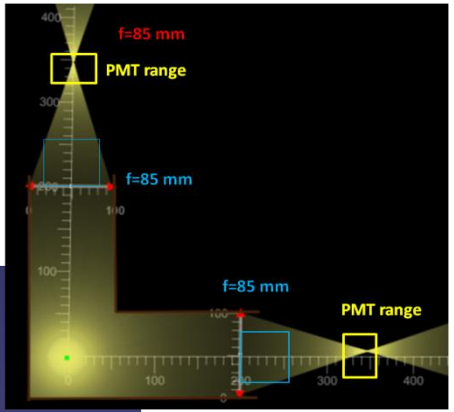
Photon emission efficiency

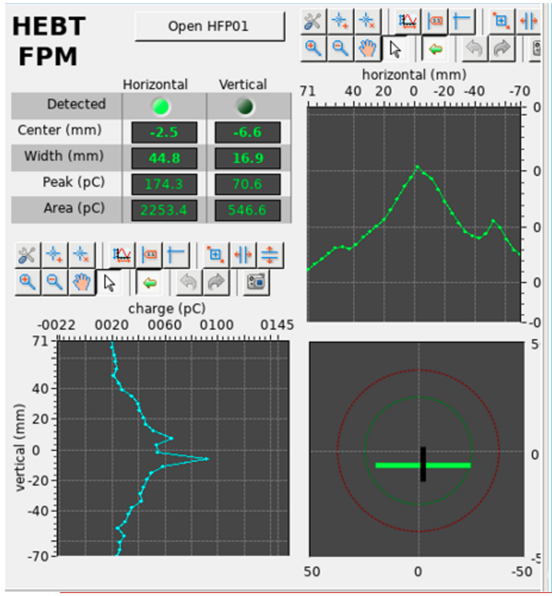
$$\varepsilon \sim \sigma^{eq} \cdot (P_{gas} \cdot I_{beam}) \cdot d_{path}$$

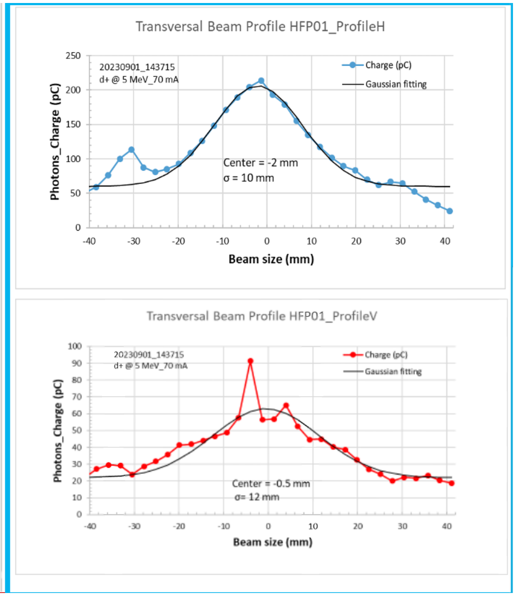
$$N \sim \varepsilon \cdot \Omega \cdot (\tau) \cdot \chi^{sist}$$

residual gas fluorescence originated by the beam-gas interaction





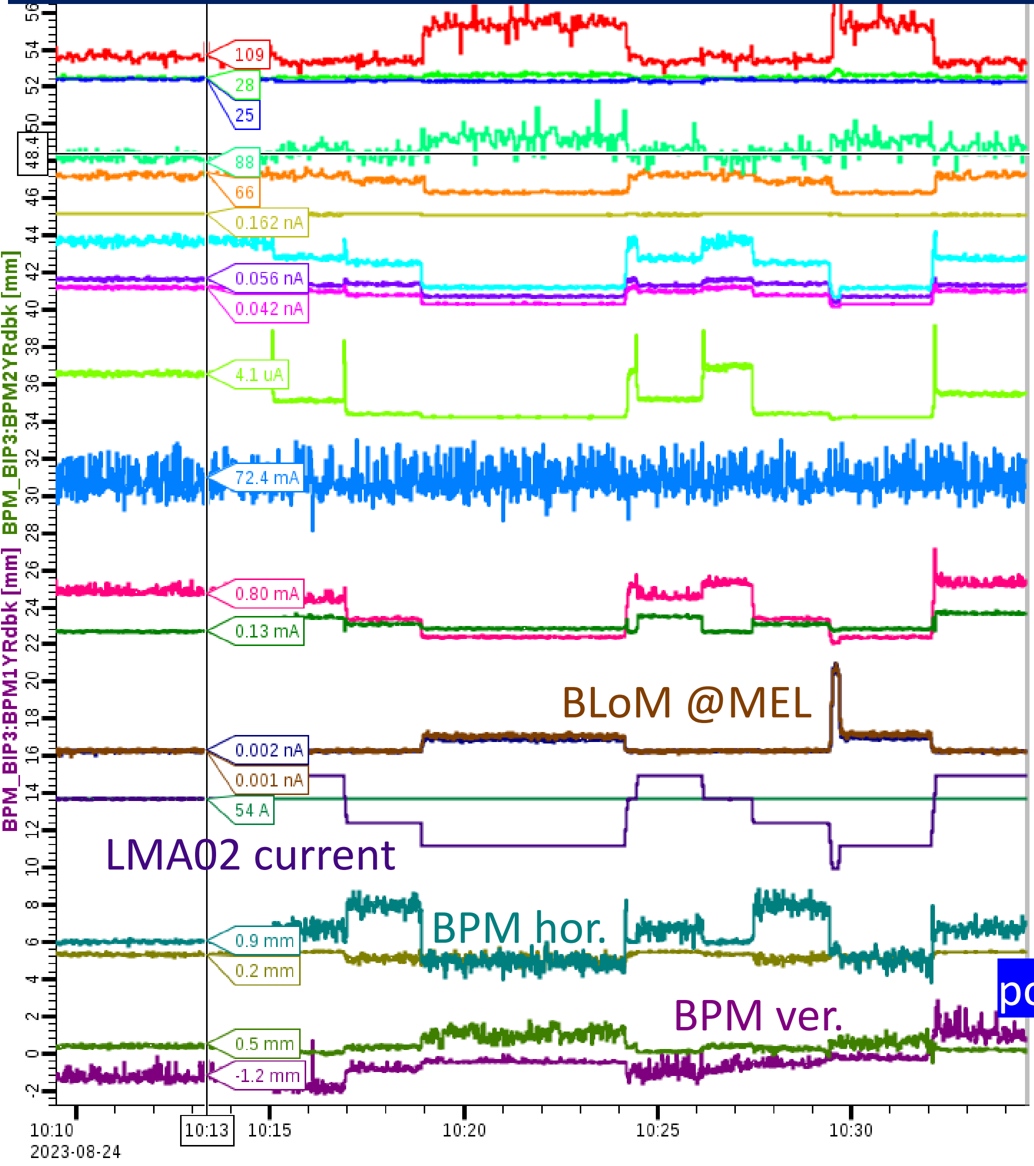




20230901-1437-Transverse profile on HFPMs

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)

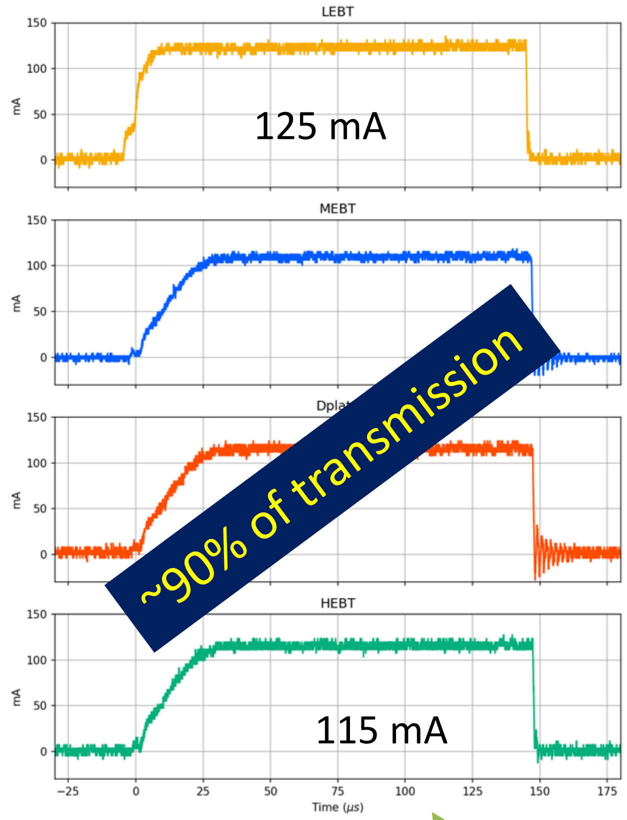
MEBT:ACCT (~70 – 75 mA)

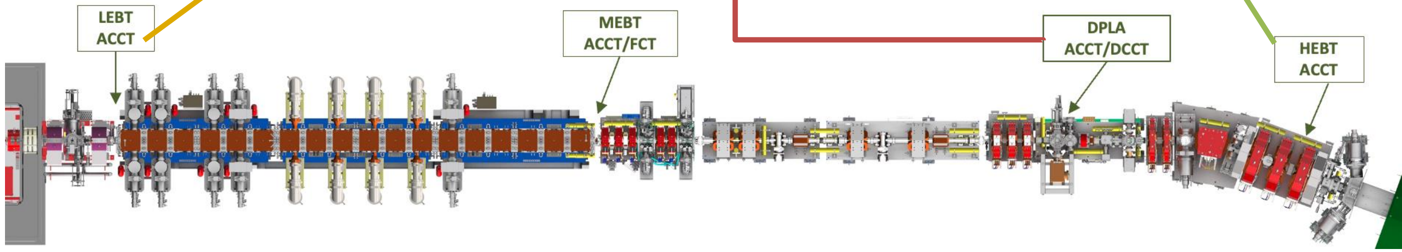
DPLA:ACCT and HEBT:ACCT

Loss

position

125 mA/150 us, 7-Sep. 2023





Summary

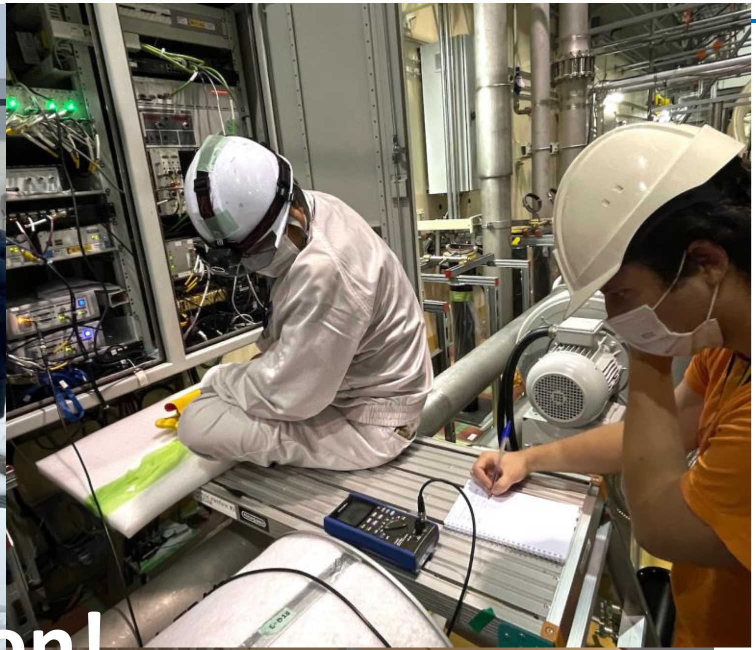
- LIPAc operation Phase B+ is ongoing at Rokkasho, Japan.

- 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.



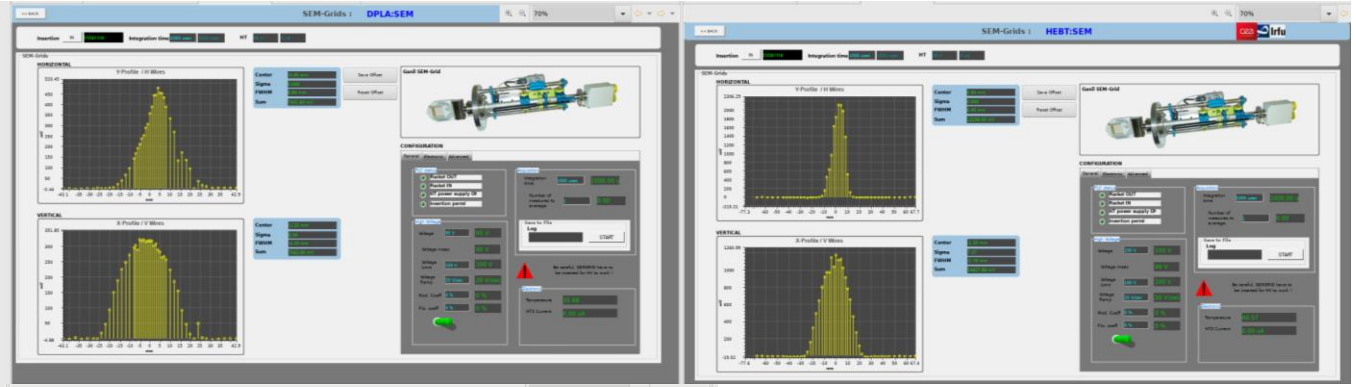


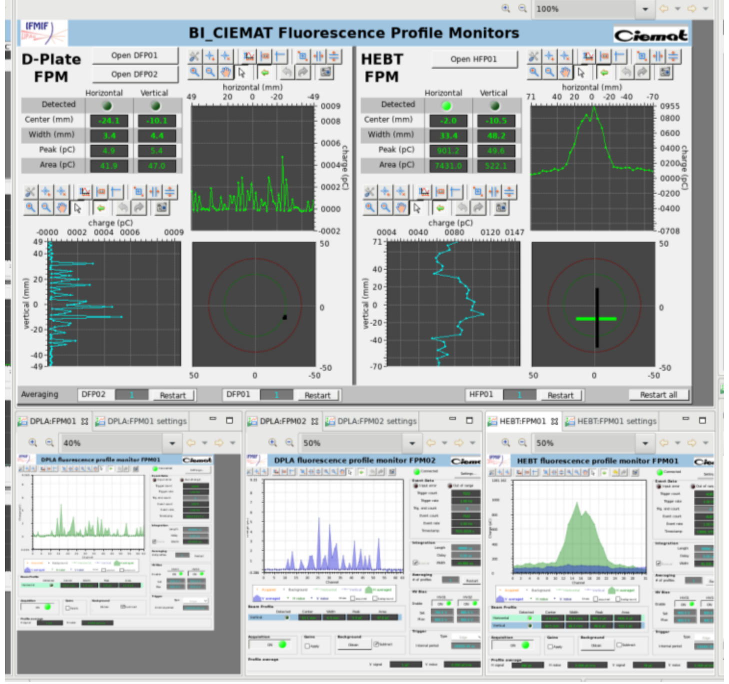
Thank you for your attention!

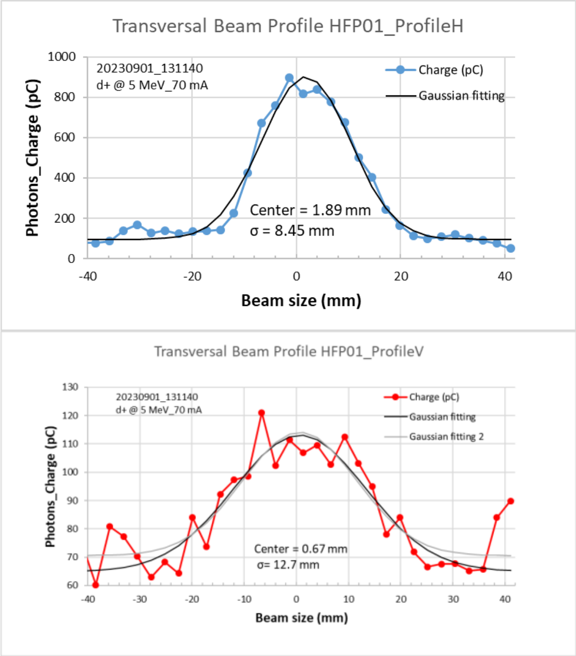
contact: kwon.saerom@qst.go.jp


backup slides

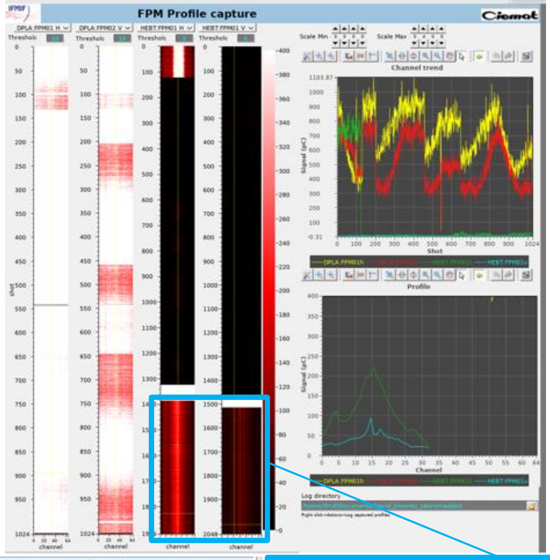
FPMs – results under analysis

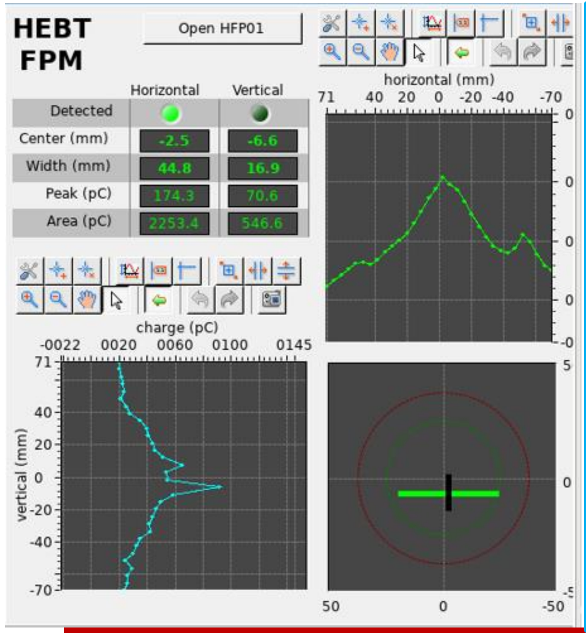


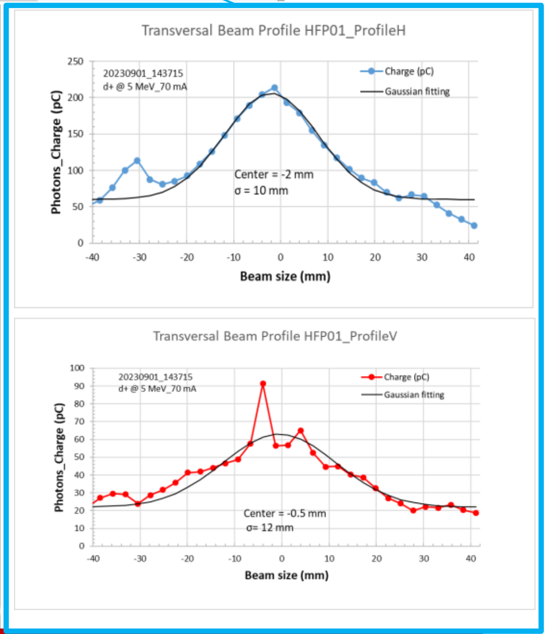




Beam transversal profile in DSG-HSG at the same time and H-FPM (20230901-1310-DSG01-HSG01-HFPMs)

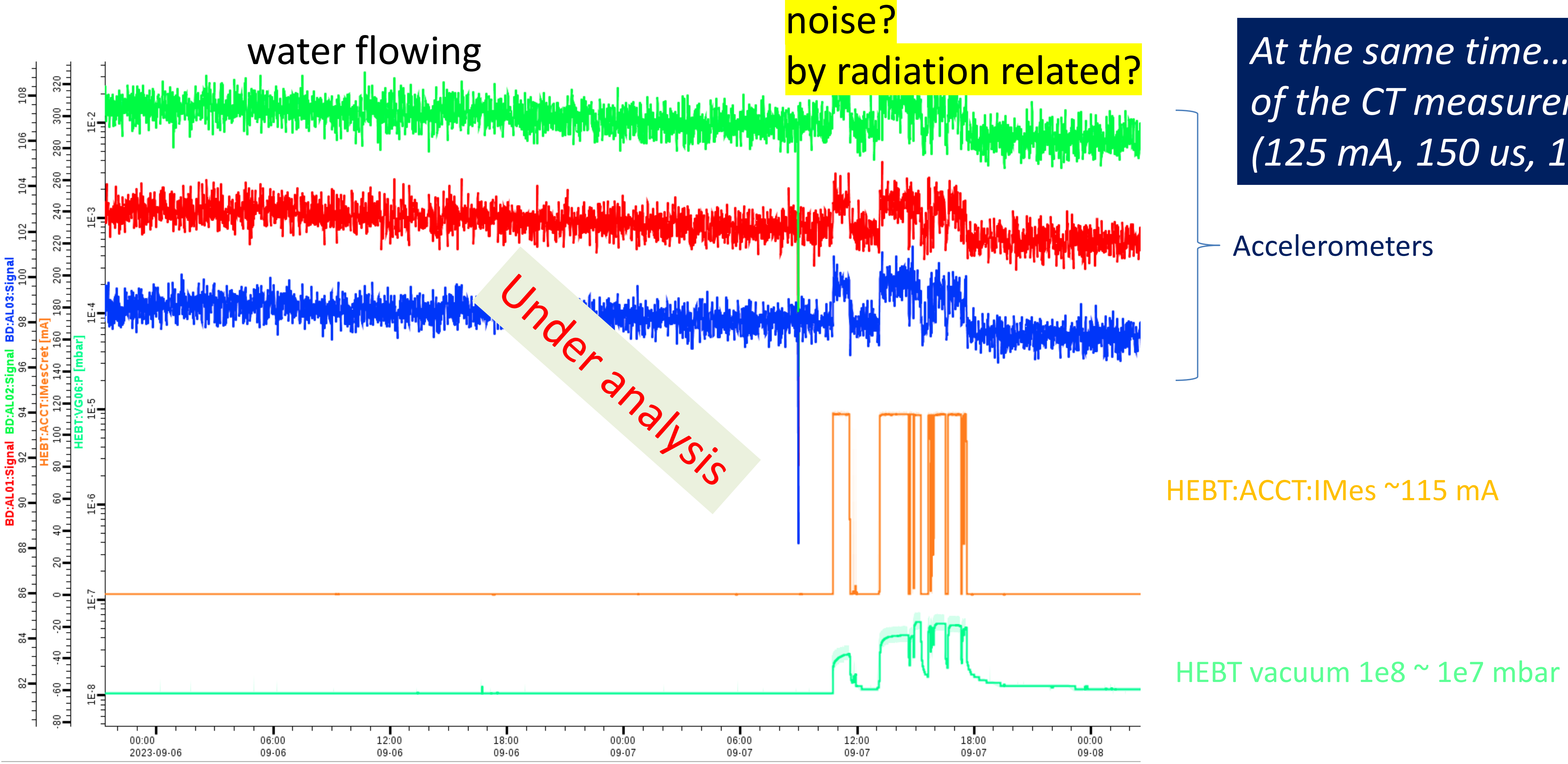






20230901-1437-HFPMs visualization in the new waveform OPI

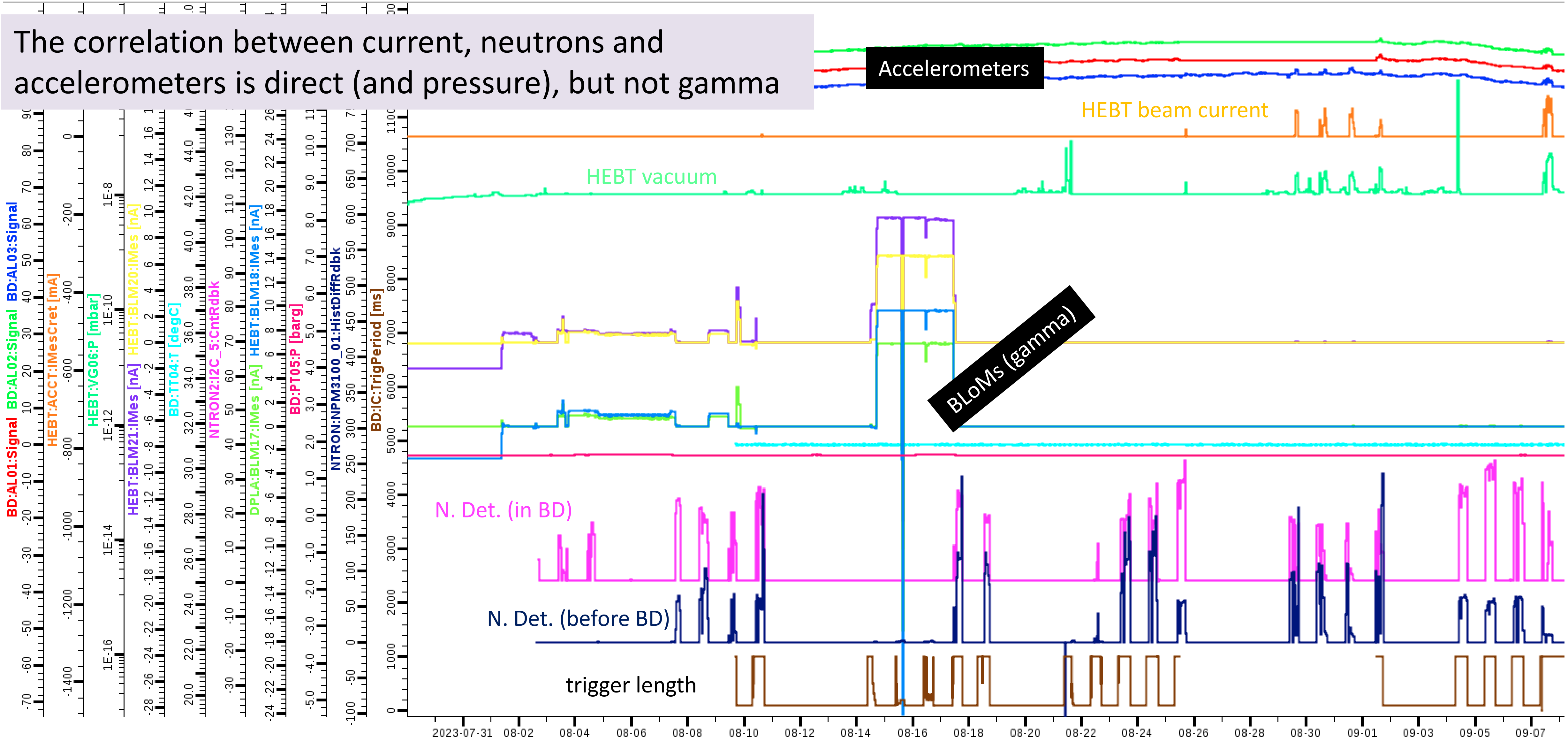
Results (BD inst.: accelerometers)



At the same time… of the CT measurement (125 mA, 150 us, 1 Hz)

Results (BD inst.: accelerometers)

The correlation between current, neutrons and accelerometers is direct (and pressure), but not gamma

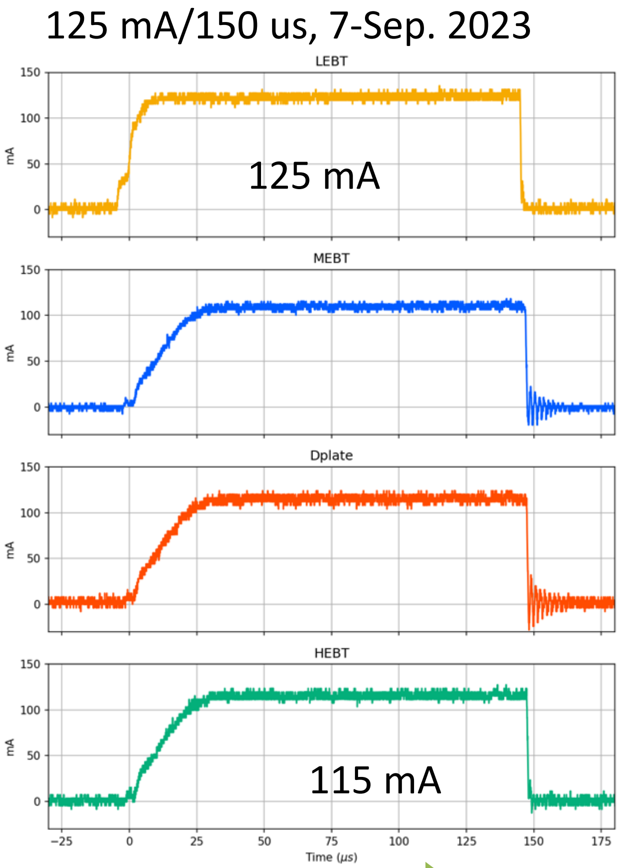


Ready for the beam operation

<Ready>

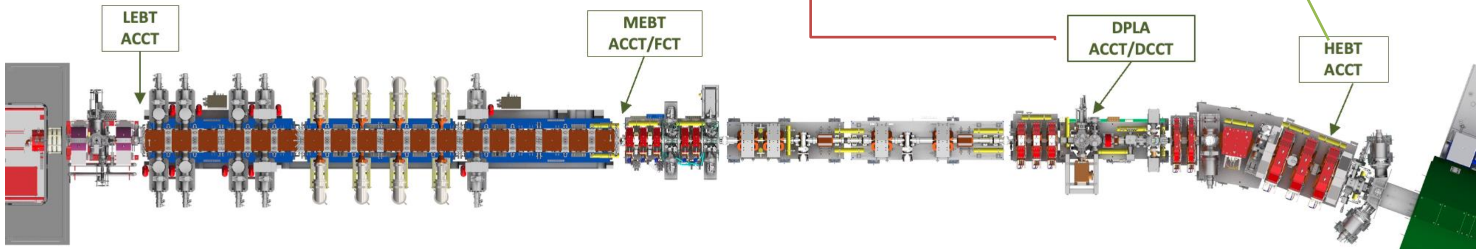
- ✓ Beam monitoring, index of Transmission, MPS interlock by CTs
- ✓ Profile + Emittance by interceptive devices (SEM-grid, slits)
- ✓ Profile by FPM
- ✓ Positions by BPMs
- ✓ Beam inside the BD by IC & Accelerometers
- ✓ Loss by BLoM & neutron detectors

Almost Fully Available for Phase B+ operation?!

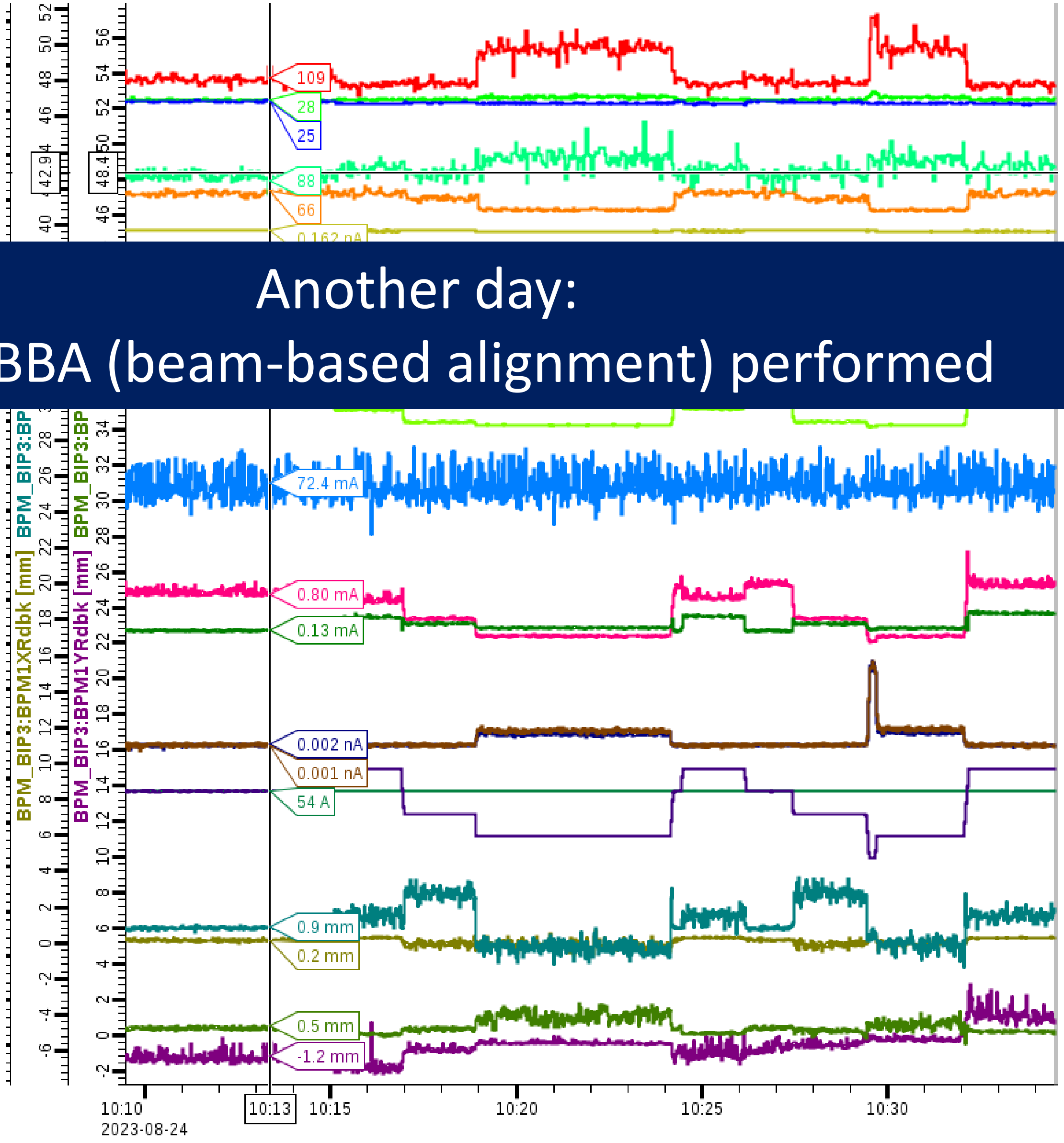


<To be ready>

- ❑ Profile by IPMs
- ❑ Bunch length by RGBLM



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



Another day:
when BBA (beam-based alignment) performed

in front of BD
exit of MEBT
middle of MEL
LOSS: neutron counter

HEBT Faraday cup (< 8 uA)
MEBT:ACCT (~70 – 75 mA)
DPLA:ACCT and HEBT:ACCT
Beam current

BLoM @middle of MEL — Beam loss

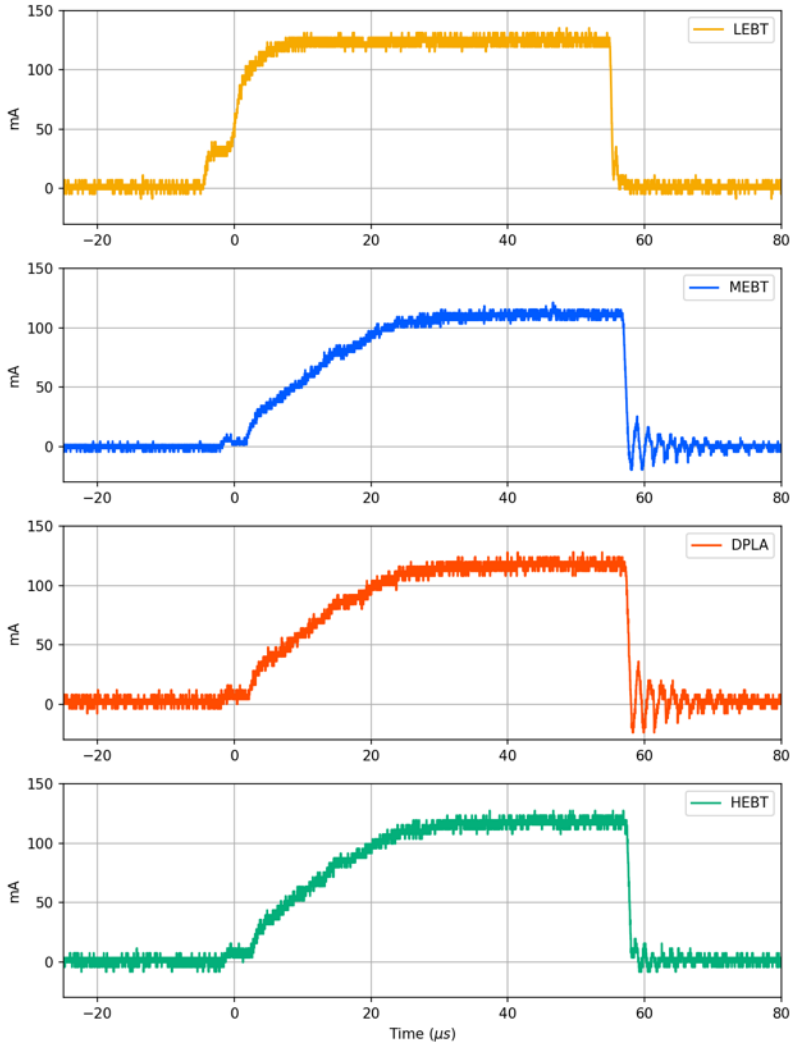
LMA02 current — magnet setting

MEL BPM horizontal position
MEL BPM vertical position
Beam position

Results (Bergoz ACCTs)

125 mA/60 us

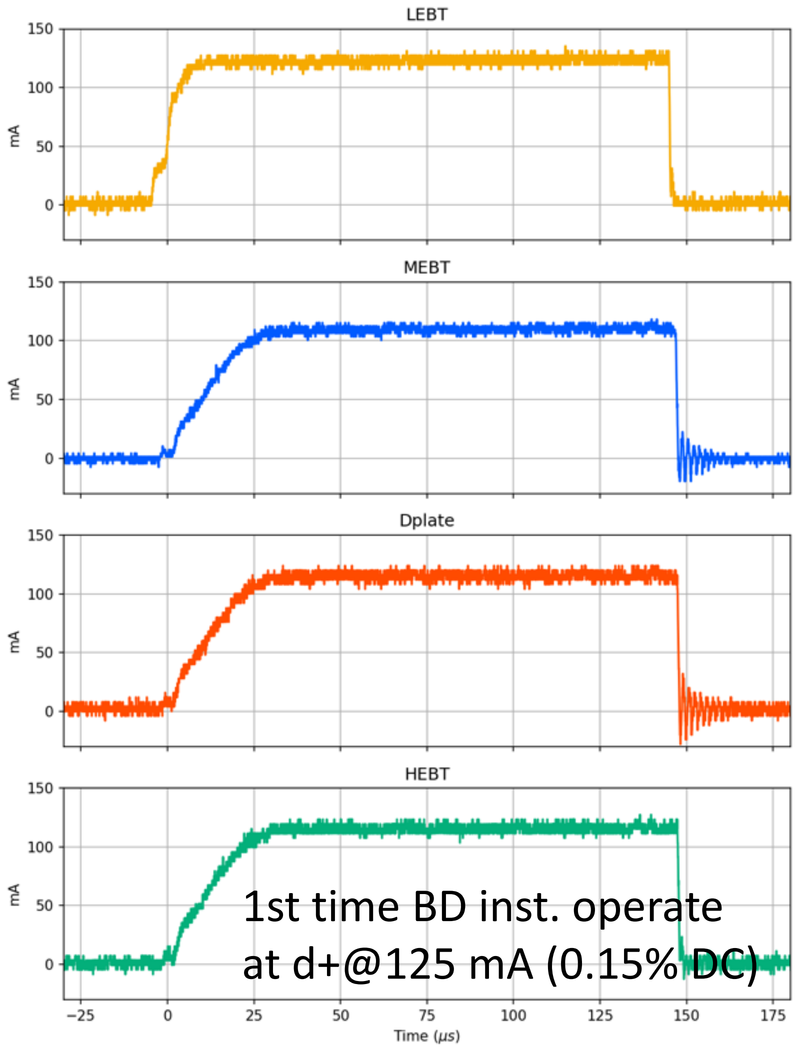
10:48
7-Sep,2023



125 mA/150 us

14:59
7-Sep,2023

increasing the pulse length for HDC (Stage 3)



1st time BD inst. operate at d+@125 mA (0.15% DC)

90% transmission confirmed from Upstream (LEBT) to Downstream (HEBT)

The beam was stable just before the summer maintenance period (8-Sep. – 22-Sep.)

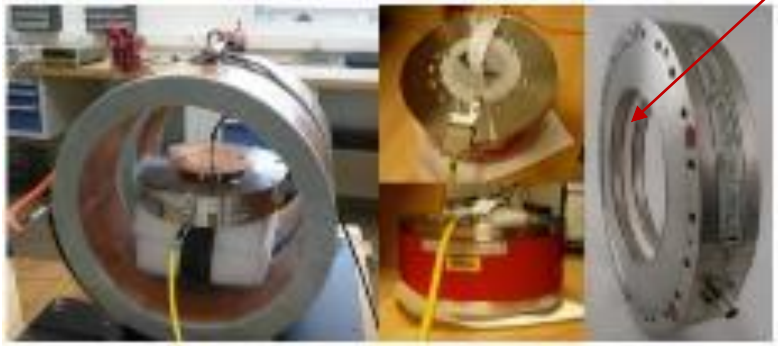
CTs - 1

- Dynamic range: 1-150 mA (resolution < 0.15 mA)
- Available to use duty cycle: 10^{-4} – CW (pulse: ACCTs, CW: DCCT, FCT)
- Beam monitoring, index of Transmission, MPS interlock…

Archiving the current values averaged (plateau)

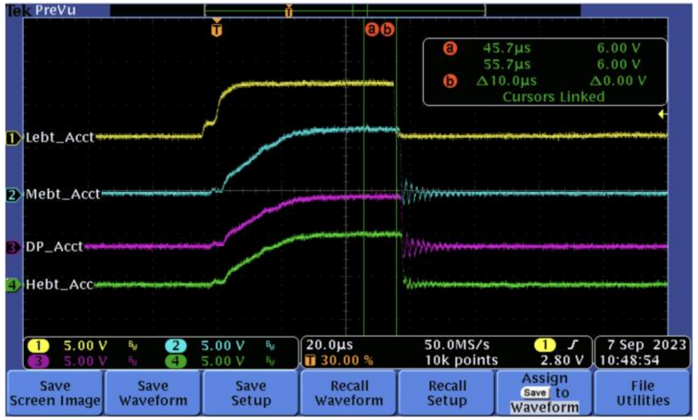
in-flange model (Bergoz)

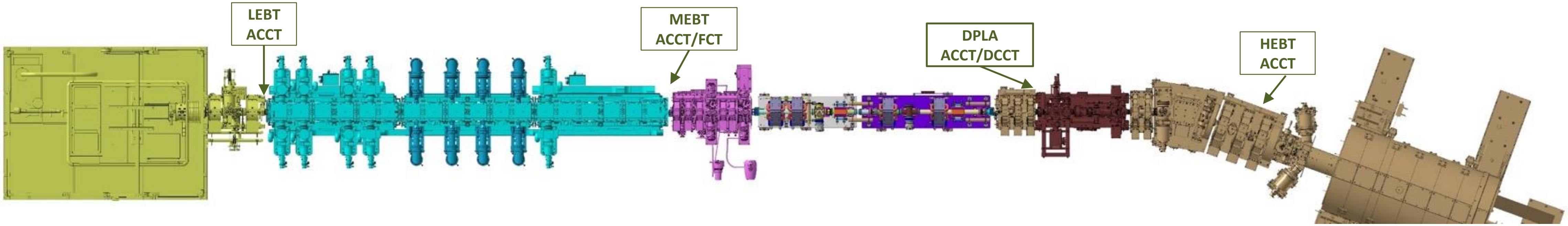
ceramic (to stop the wall current)



Location	Type	Band width
LEBT	ACCT	5 Hz – 326 kHz
MEBT	ACCT	2.4 Hz – 350 kHz
MEBT	FCT	14 kHz – 266 MHz
D-Plate	ACCT	2.8 Hz – 340 kHz
D-Plate	DCCT	0 – 12.6 kHz
HEBT	ACCT	2.7 Hz – 330 kHz

Recorded Waveform by Osc.





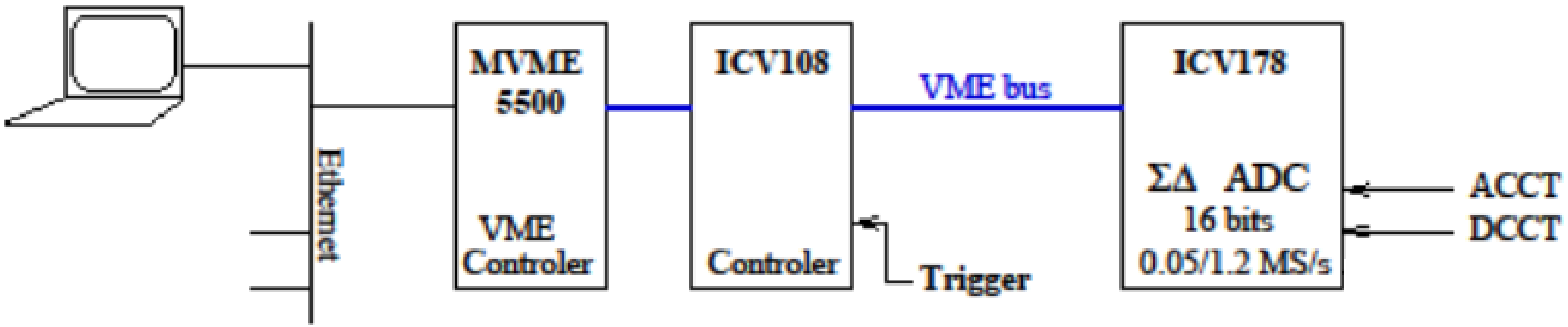
CTs - 2

- Same data acquisition system of Spiral2 Beam diagnostics (CEA)

- Process with two VME boards in DCU07 → So far frequently "frozen" in LIPAcNet due to too much data loading with waveform data archiving → stopped archiving except scalar PVs
- "PV gateway system" prepared to avoid the heavy loading

- A plan to change VME to another system

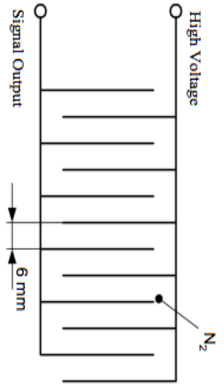
LCR/CCR DCU07 (one cubicle for diagnostics)



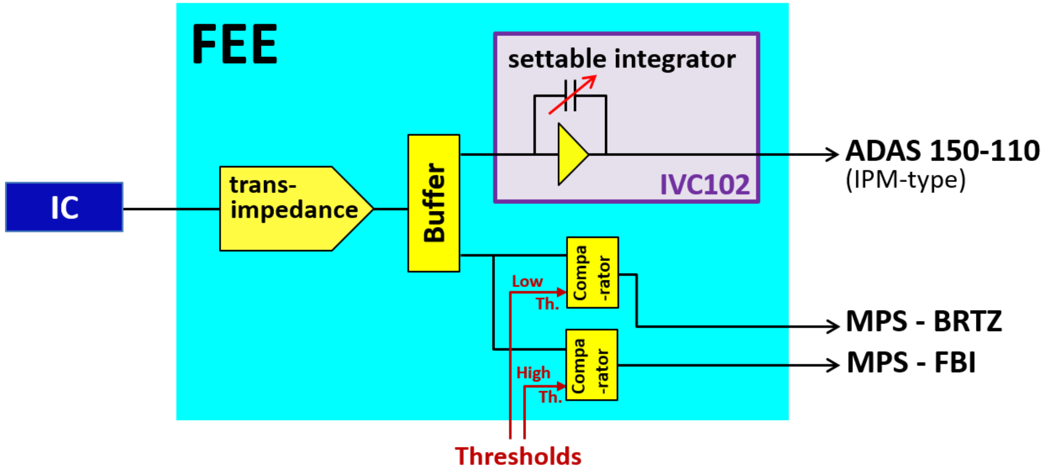
BLoMs

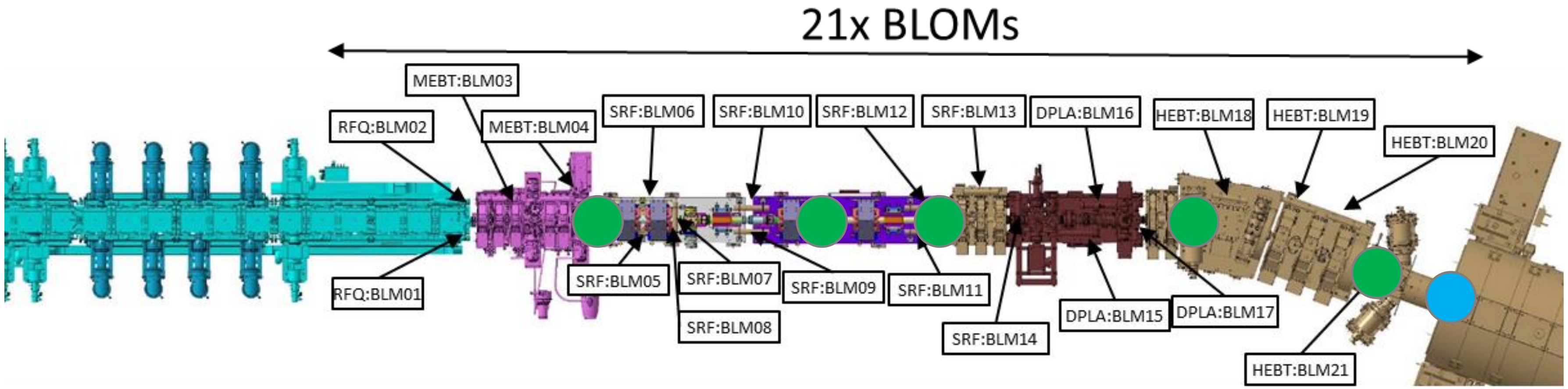
- Design based on the ion chamber used in CERN (LHC IC)
- To detect beam losses for monitoring & MPS by setting the threshold then trigger interlock (beam stop)

LHC IC characteristics	
L (cm)	50 (37.5)
Ø (cm)	9 (7.5)
electrodes	61
$Space_{elect}$ (mm)	5.75
N_2 (bar)	1.1
V (kV)	+1.5 (0 < HV < +1.6)
Capacitor (nF)	470
Resistor (MΩ)	10
IC thickness (mm)	
tube	2
top	5
bottom	4



8 settable integration time durations:
74 µs, 234 µs, 893 µs, 3.6 ms, 14.7 ms, 60 ms, 250 ms, 1.15 s

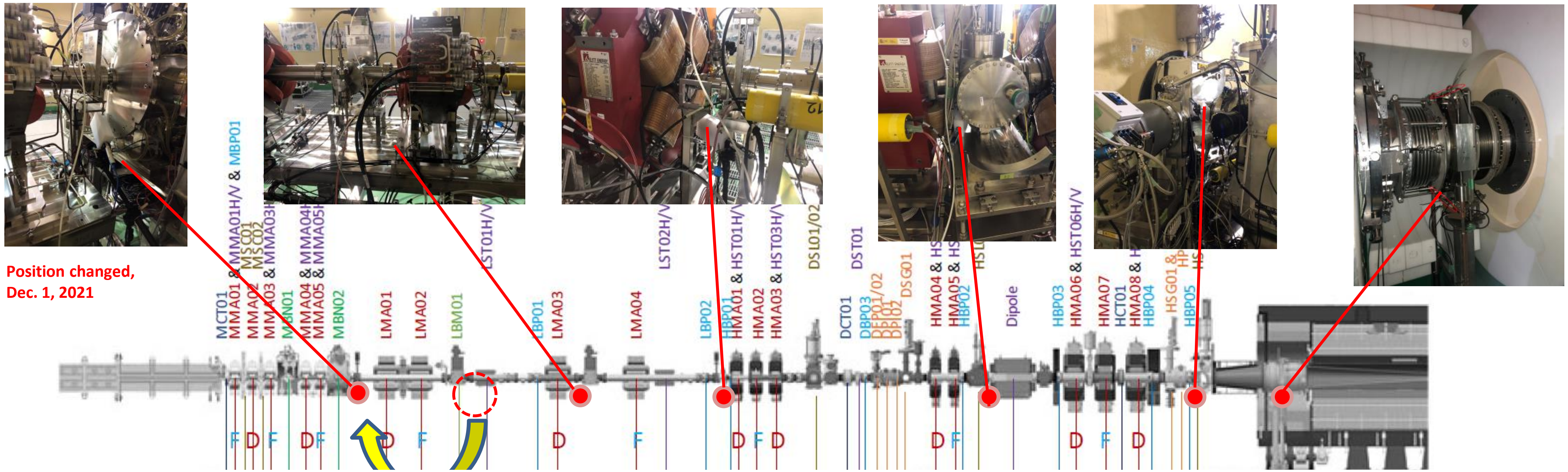


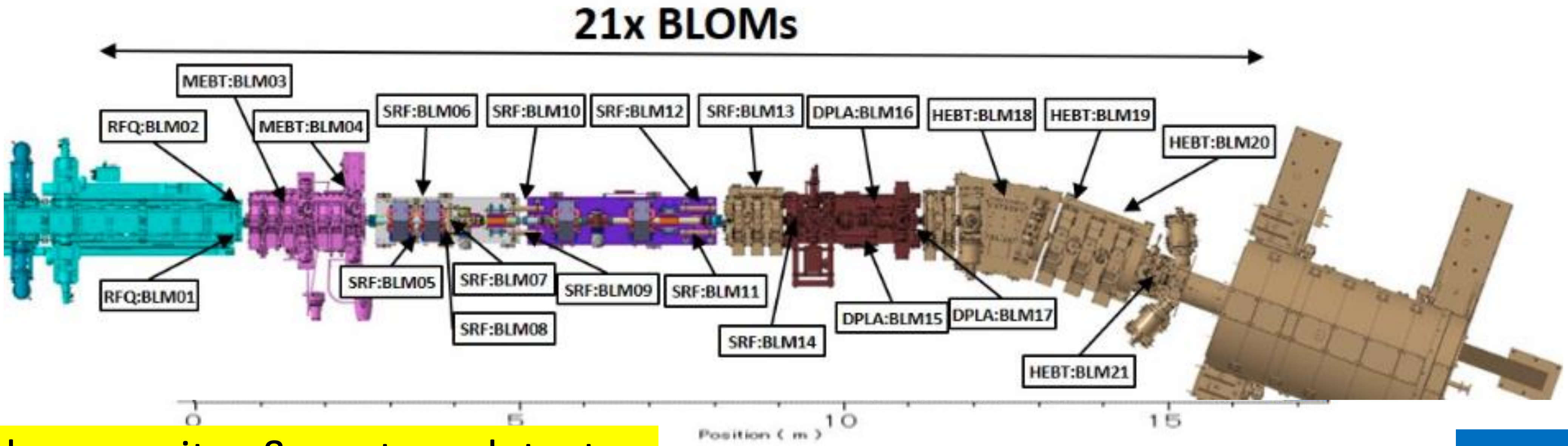


A few neutron detectors installed to intercompare the results from BLoMs

NPM3100 (^{3}He det.)

Another ^{3}He



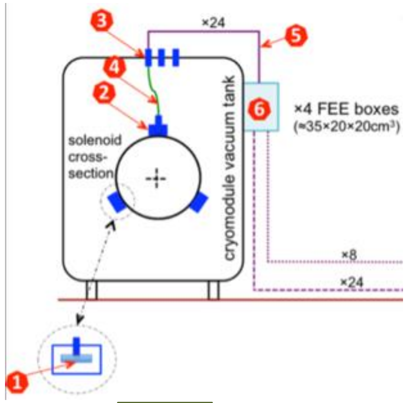


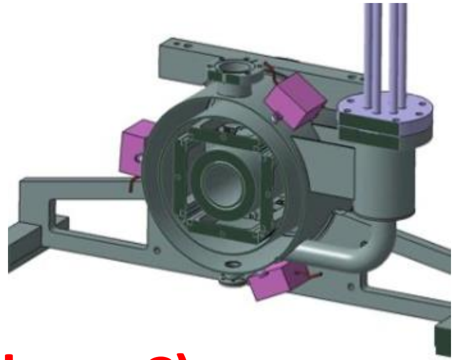
Beam loss monitor & neutron detectors

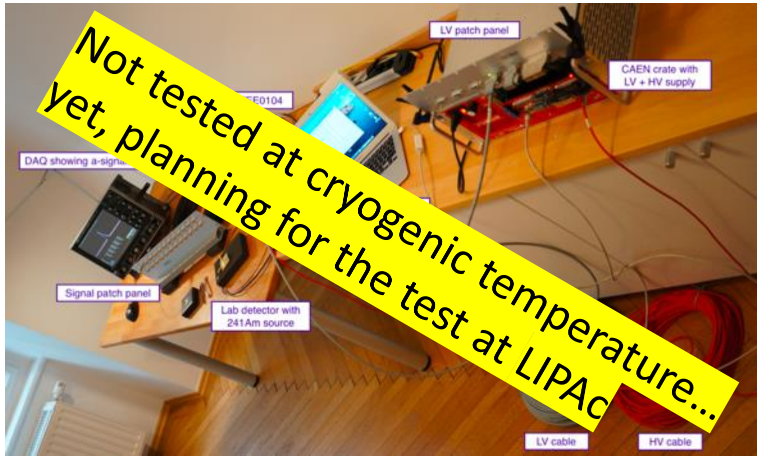
µLoMs - 1

- To be used from Phase C (MEL → SRF linac)
- 3 sCVD diamond detectors (CIVIDEC) to be installed in each 8 solenoids of SRF Linac
- Winter 2022, all devices delivered onsite. When SRF assembles, uLoMs are going to be installed at the same time.

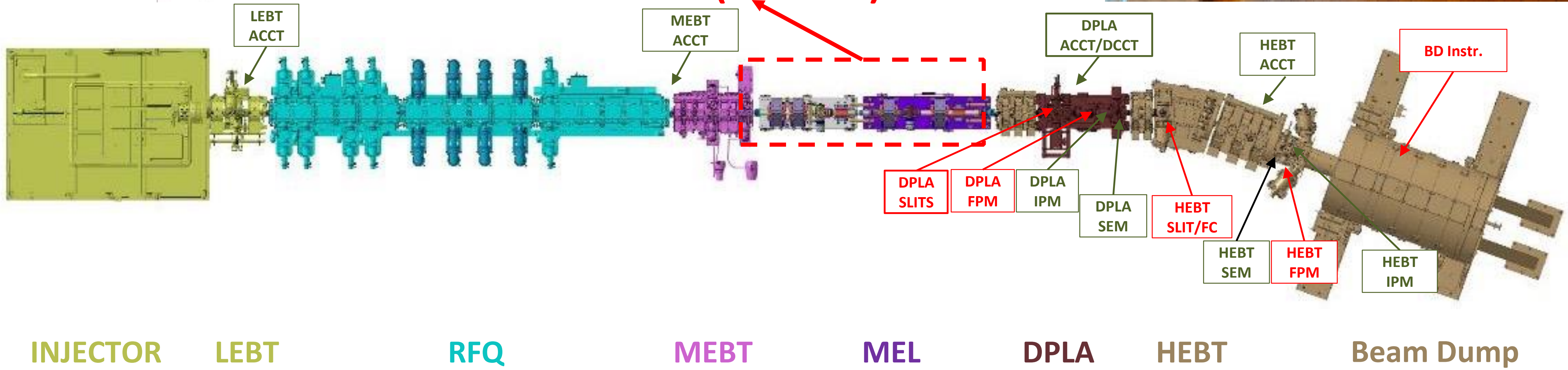
1 detector
2 support
3 feedthrough
4 cable (cryogenic)
5 cable (room temp.)
6 FEE



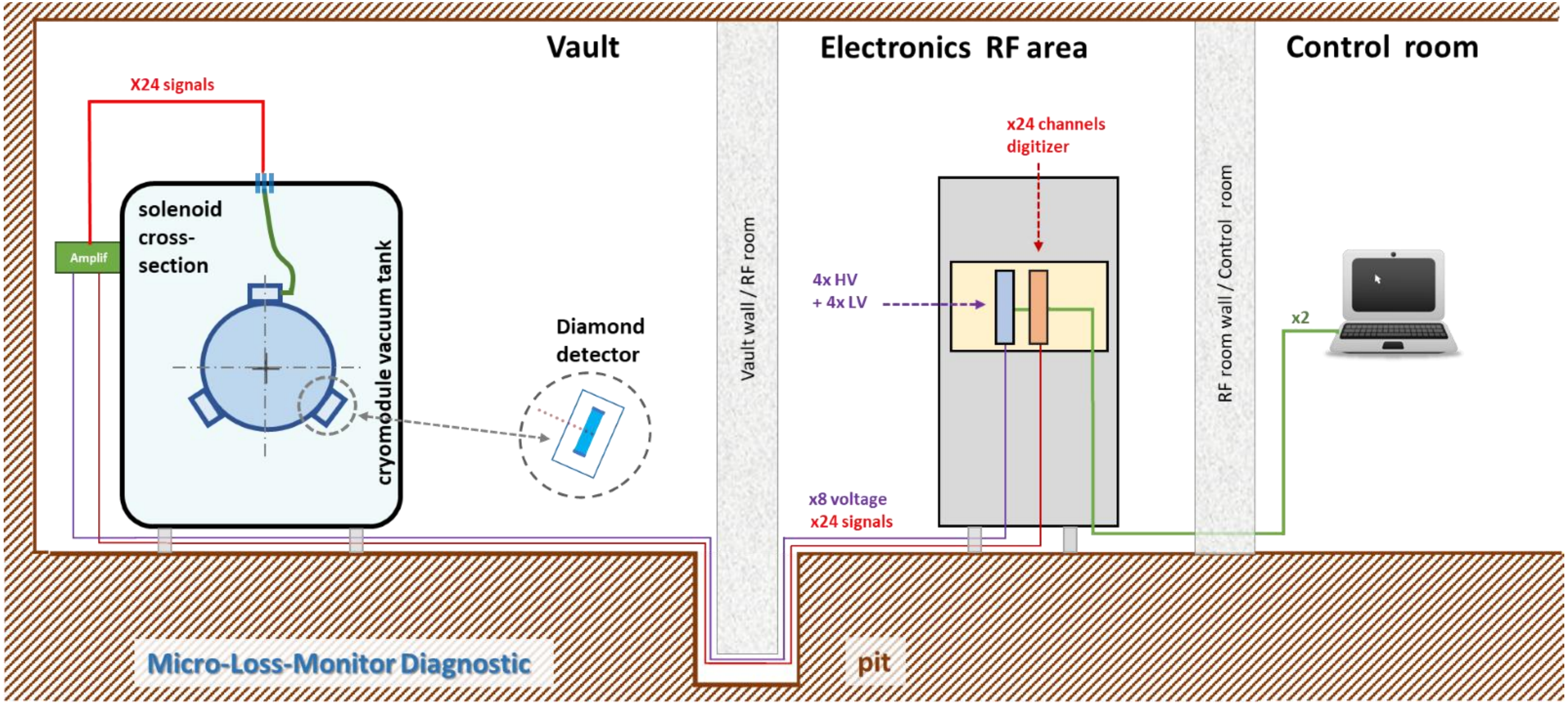




SRF Linac (Phase C)



µLoMs - 2

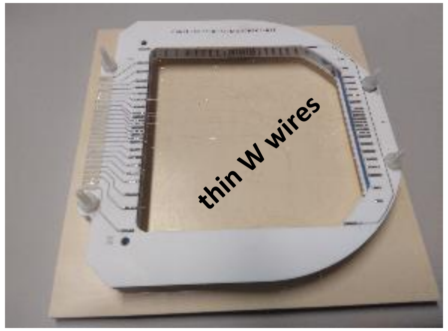


- no LCS yet
- cables to be installed through pits
- HV/DAQs to be installed in RF area

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



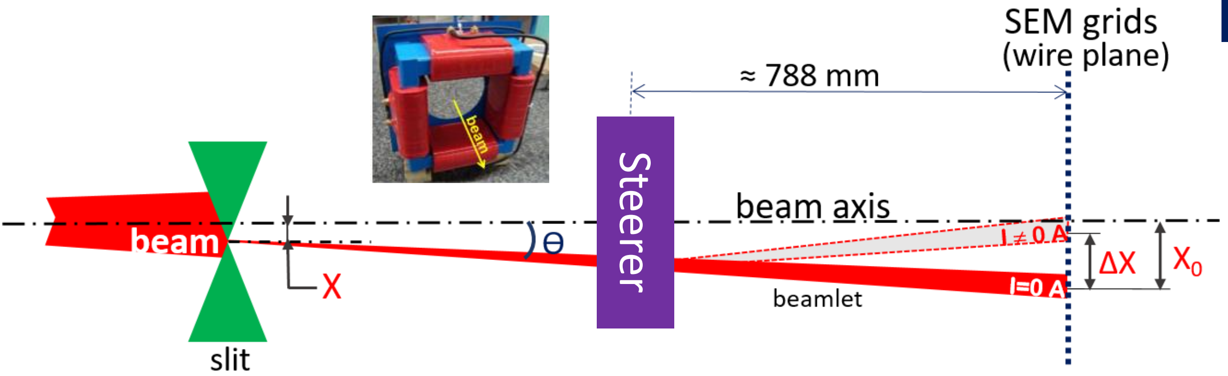
Gaps between wires

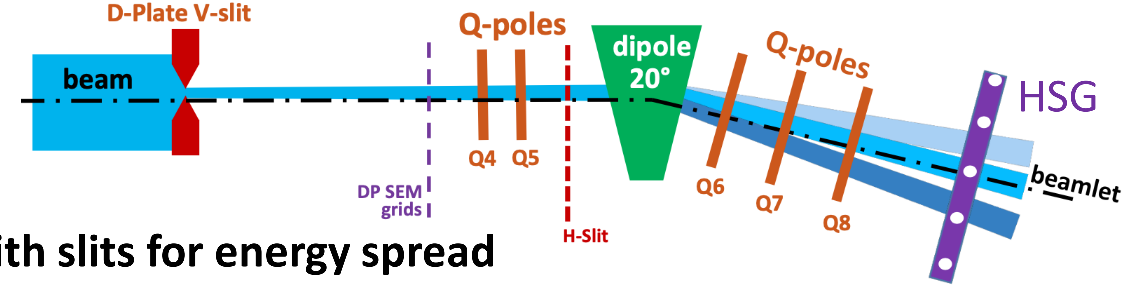
Diagnostic Plate					
Wire number	1 to 5	6 to 15	16 to 32	33 to 42	43 to 47
Gap (mm)	3	2	1	2	3

HEBT							
Wire number	1 to 5	6 to 11	12 to 17	18 to 30	31 to 36	37 to 42	43 to 47
Gap (mm)	4.5	3	2.5	2	2.5	3	4.5

LIPAc's SEM-grid monitors have large wire gaps in the extreme: 1, 2 and 3 mm, often larger than the beamlet. Thus 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