

Measurement of Momentum Halo Due To the Reduced RFQ Voltage During Beam Commissioning of LIPAc

Kouki Hiroswawa¹, A. De Franco¹, K. Masuda¹, A. Mizuno¹,
S. Kwon¹, K. Kondo¹, M. Sugimoto¹, K. Hasegawa¹,
I. Moya², F. Scantamburlo², F. Benedetti^{2,3}, D. Gex², H. Dzitko², Y. Carin²,
I. Podadera^{4,5}, J. C. Morales Vega⁵

¹QST, ²F4E, ³CEA, ⁴CIEMAT, ⁵IFMIF-DONES España

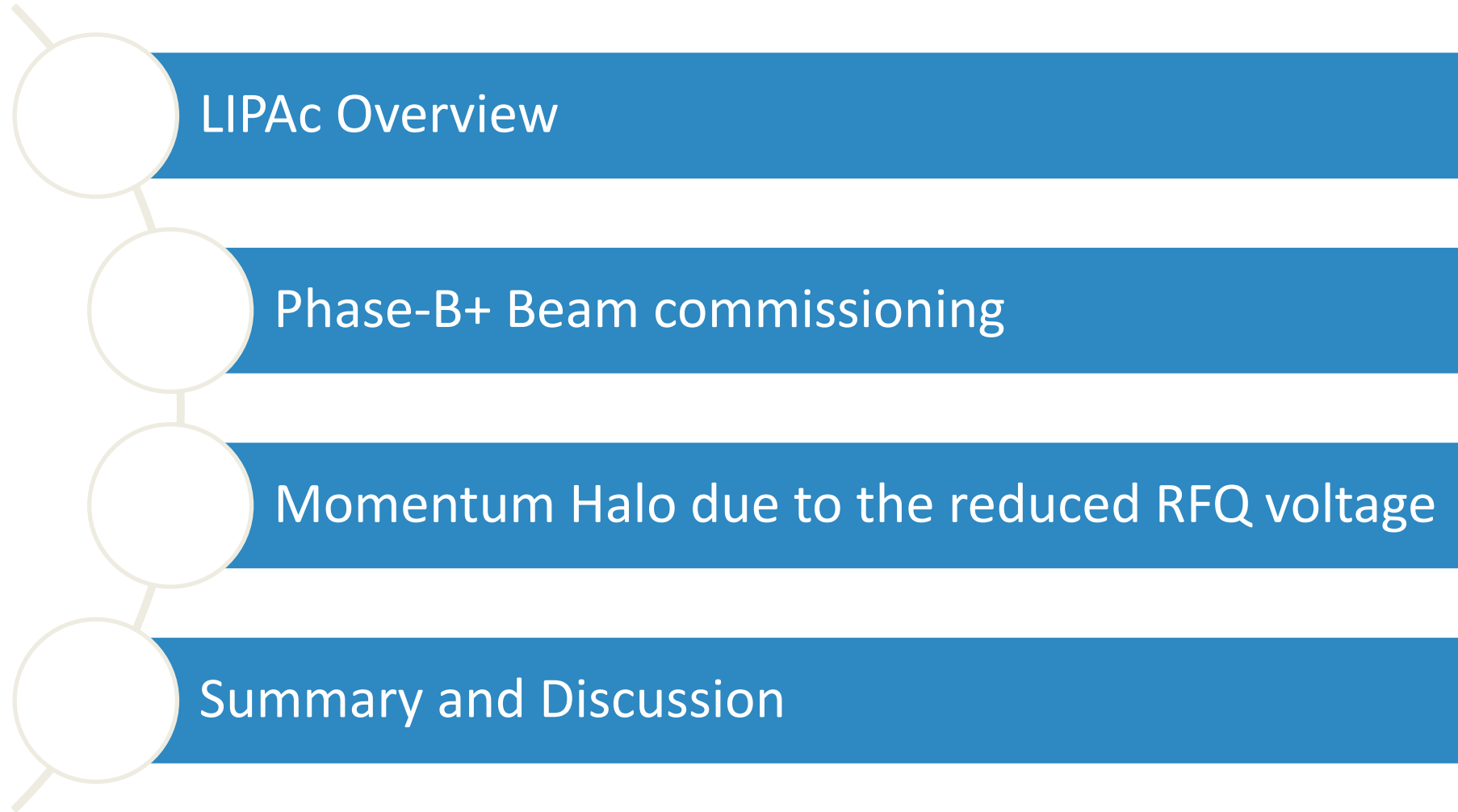
9-13 Oct. 2023
HB2023@CERN, Switzerland

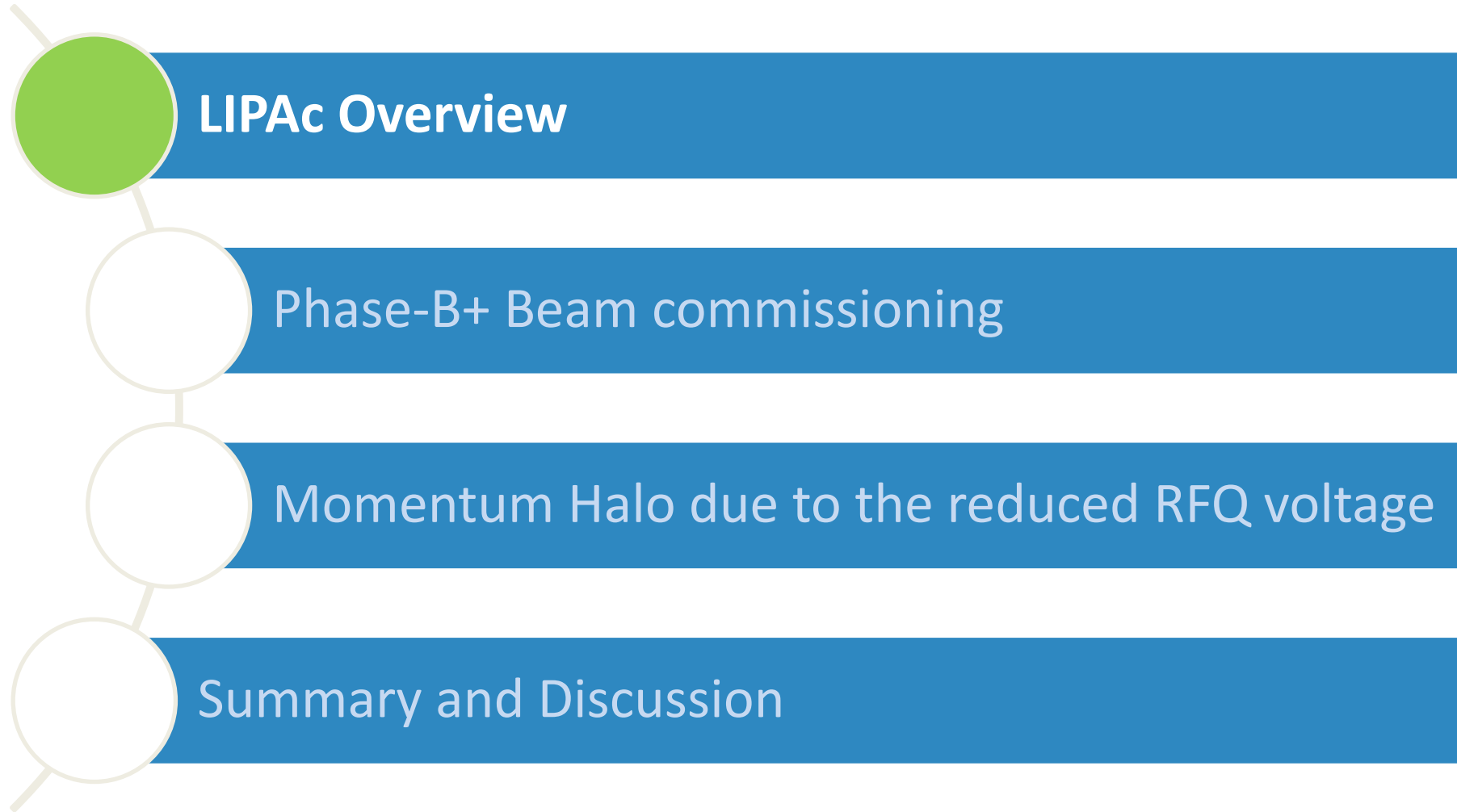


Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

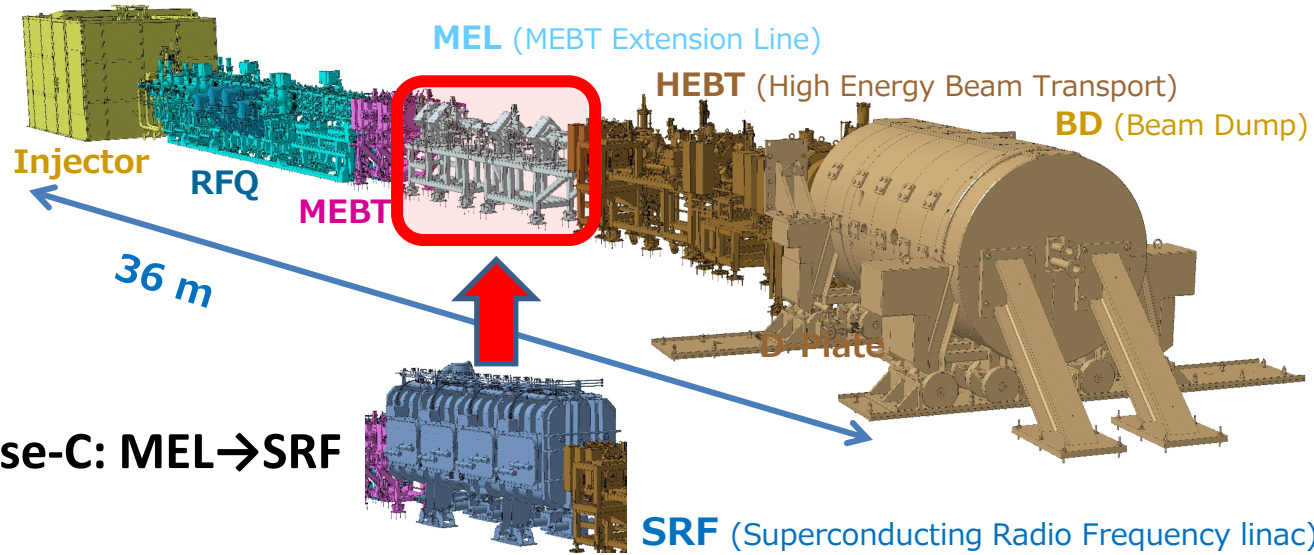
TUA312





To validate low energy part ($\leq 9.0\text{MeV}$) of the IFMIF accelerator for testing material for the fusion power plant.

Phase-B+ Layout

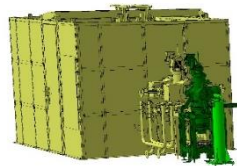


Phase-C: MEL→SRF

Ion species	D ⁺ (H ⁺ for start-up/tuning)
Peak current	Up to 125 mA
RFQ output energy	5 MeV
SRF output energy	9 MeV
RF frequency	175 MHz
Bunch width	0.1–0.7 ns (sim.)
Duty factor	10 ⁻² – CW
Pulse length	10 ² μs – CW
Beam power	Up to 1.125 MW

Previous Phases

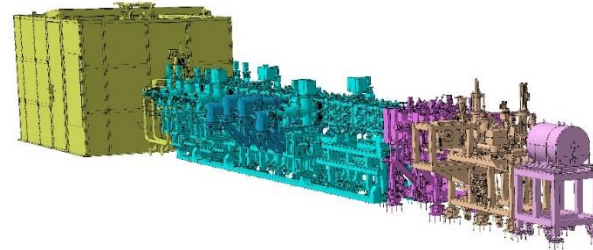
Phase-A (Apr. 2015 - Aug. 2017)



Injector + Diagnostic box

100keV, -125 mA, 12.5kW, CW beam

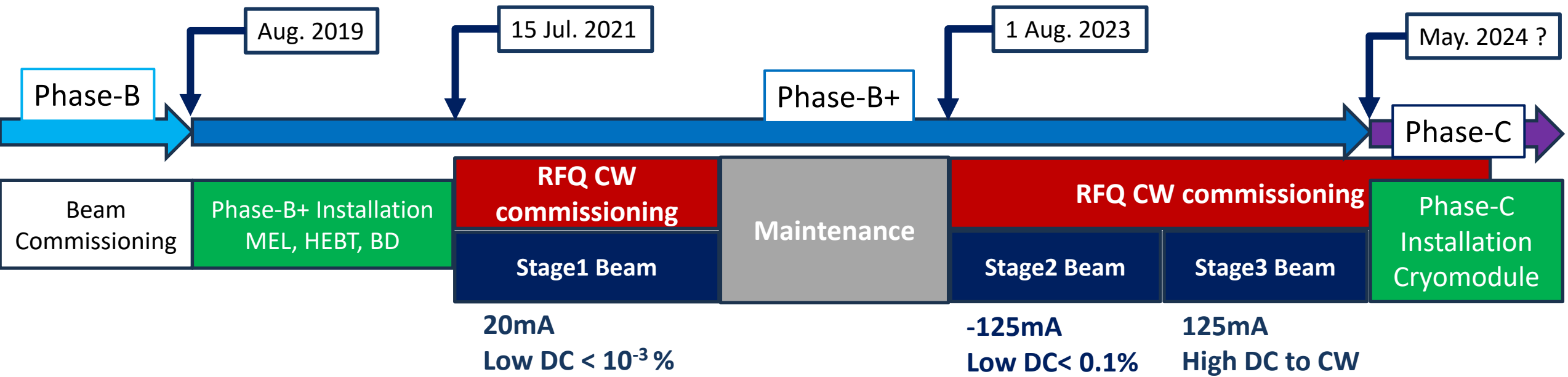
Phase-B (Jun. 2018 - Aug. 2019)



Injector + RFQ + MEBT + D-Plate + LPBD

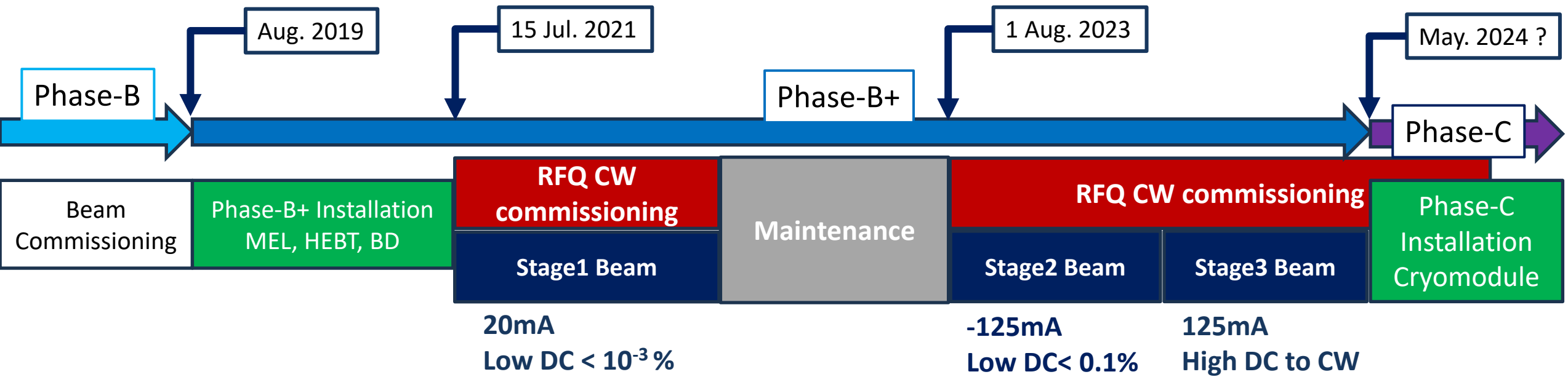
5MeV, -125mA, 625kW, Pulsed beam

1. K. Kondo et al., Fusion Eng. Des. 153 (2020) 111503.
2. H. Dzitko et al., Fusion Eng. Des. 168 (2021) 112621.
3. K. Kondo et al., Nucl. Fusion 61 (2021) 116002.
4. L. Bellan et al., the Proc. of ICFA HB2021 (2021).



Phase-B+ Mission

- Injector CW operation
 - RFQ CW operation
 - 125mA 5MeV D⁺ beam in high DC
- {
 - To Validate diagnostics
 - Preparation for Phase-C

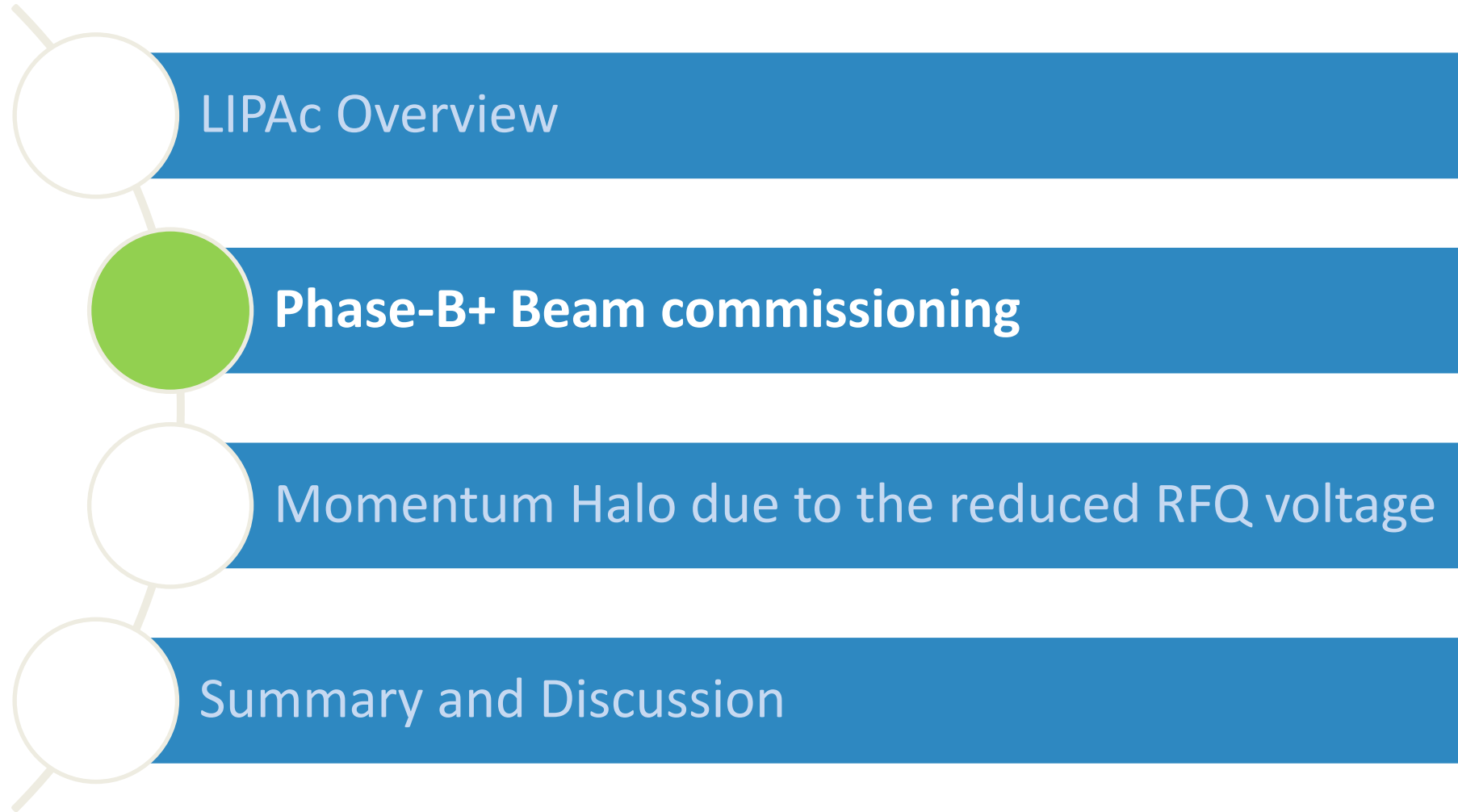


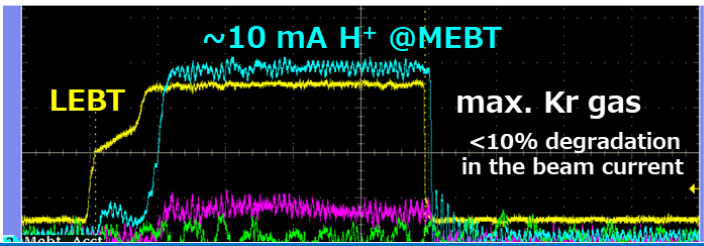
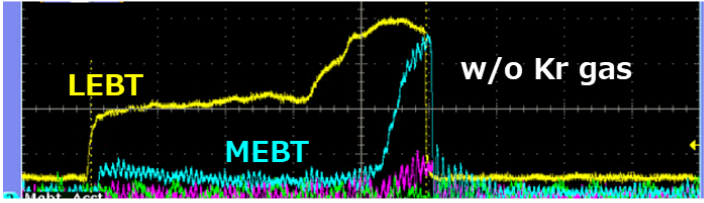
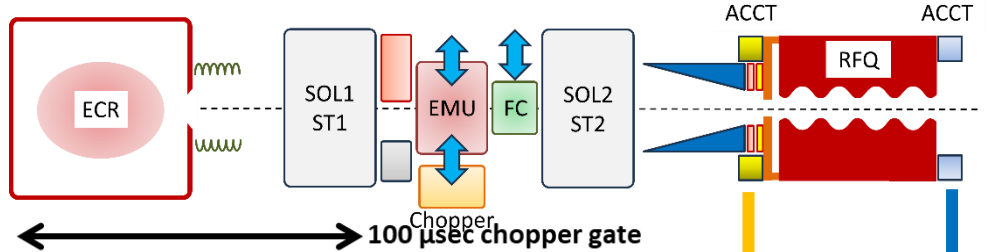
Phase-B+ Mission

- Injector CW operation
- RFQ CW operation
- 125mA 5MeV D⁺ beam in high DC

↑
Now

- To Validate diagnostics
- Preparation for Phase-C





Stage-1 (Jul. 2021 – Dec. 2021)

- ✓ The Pilot beam (10mA H⁺ and 20mA D⁺) were tested.
- ✓ Chopper pulsing has been confirmed.
- ✓ Alignment of full beam transport was check in beam-based method.
- ✓ Newly installed components were checked.
 - ❑ Validation of diagnostics → Stage-2 and -3 in high current and DC.
- ✓ Measured beam size could be reproduced by the simulation.
- ✓ Evaluation of space charge compensation degree.

Interesting topics observed from this stage

- ❑ Transient of chopper and space charge compensation.

1. K. Masuda, the Proc. of LINAC2022 (2022).

Stage-2 (Aug. 2023 –)

Developed point – Learnt from Stage-1, Alignment corrected, Injector CW commissioning completed.

Objective and Results:

- ❑ Recheck what we confirmed during stage-1, in the high current operation.
 - ✓ Chopper worked well.
 - ✓ Beam-based alignment was performed.
- ❑ Transport the 5MeV 125mA D⁺ beam to the BD.
 - ✓ Beam transported to the BD (112mA D⁺ 150us with 120us plateau, 1Hz).
- ❑ Validation of the Interceptive/non-interceptive diagnostics.
 - ✓ Interceptive devices worked well. [Details](#) → [Oral session by S. Kwon \(FRC1I2\)](#)
 - ✓ Visibility of all BPMs has been confirmed by steering scan.
- ❑ Study dynamics of space charge compensation degree.
 - Testing the effect of Kr gas flow rate to the transient

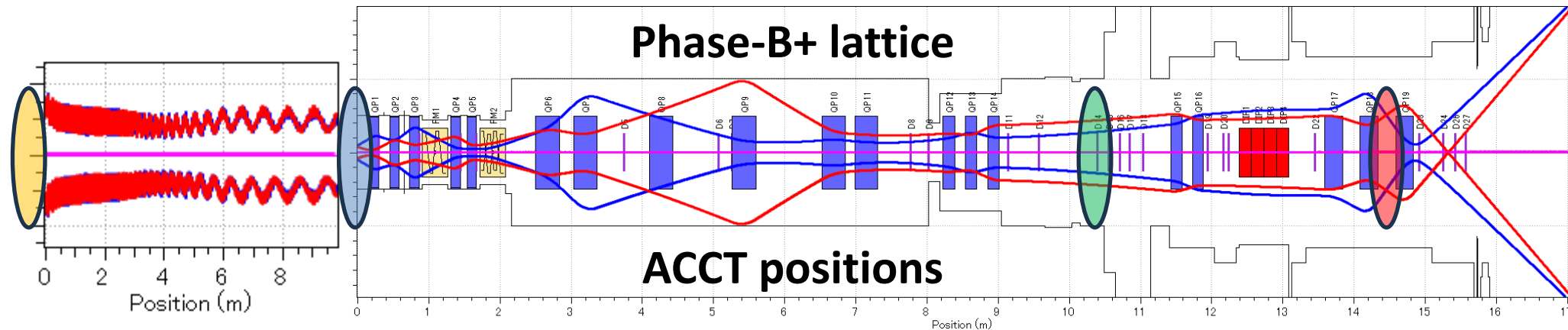
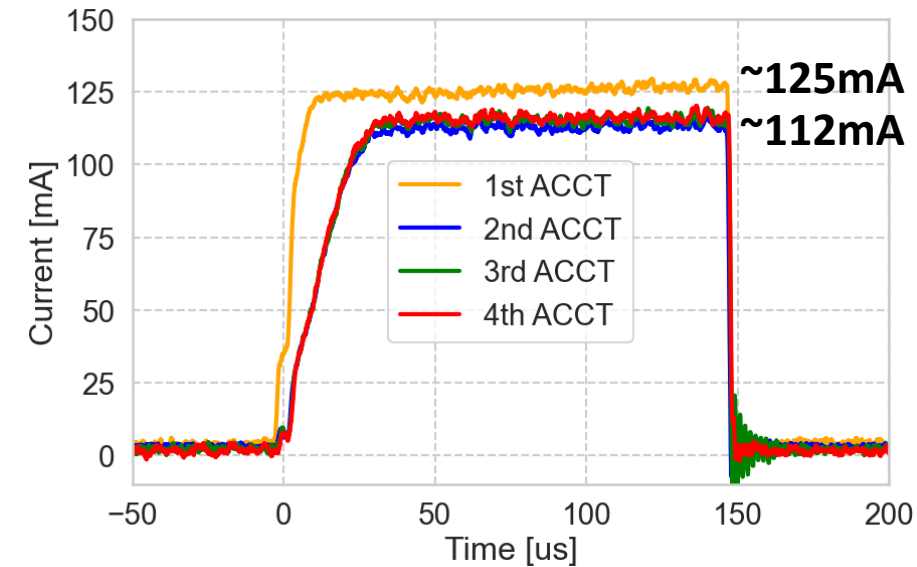
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Measurement by ACCTs (7th / Sep. 2023)



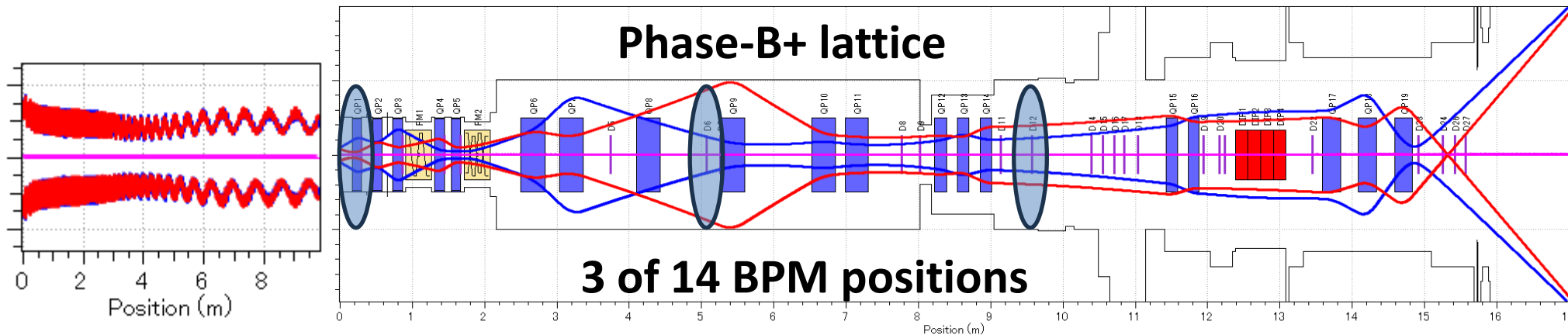
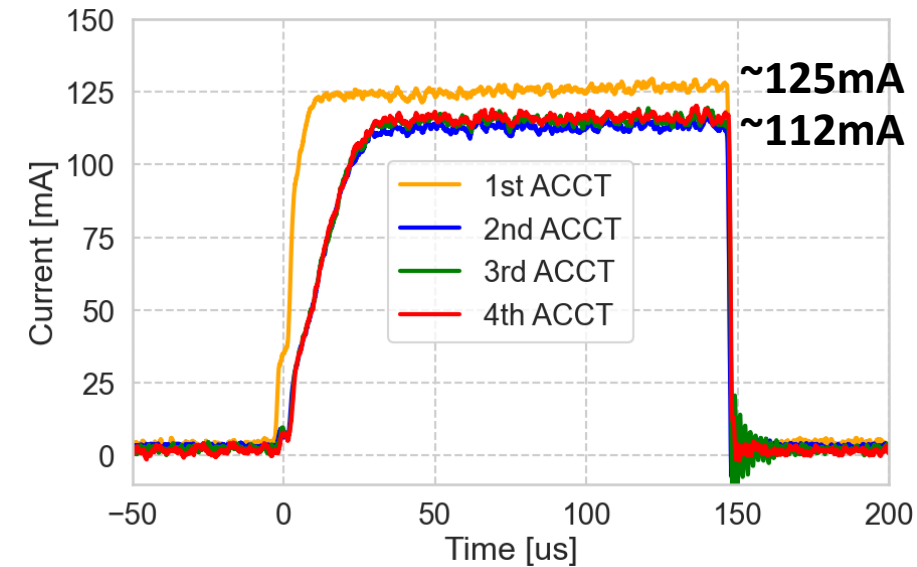
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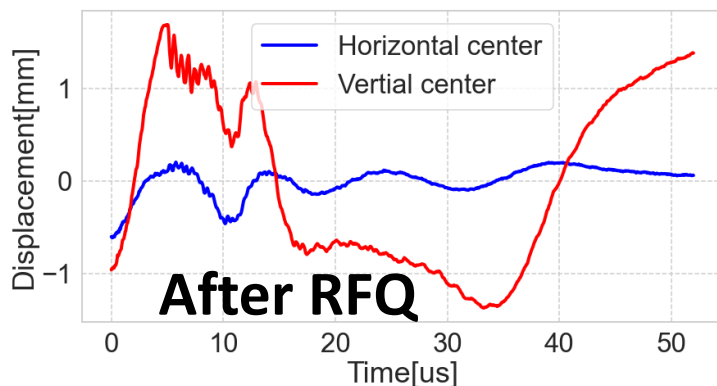
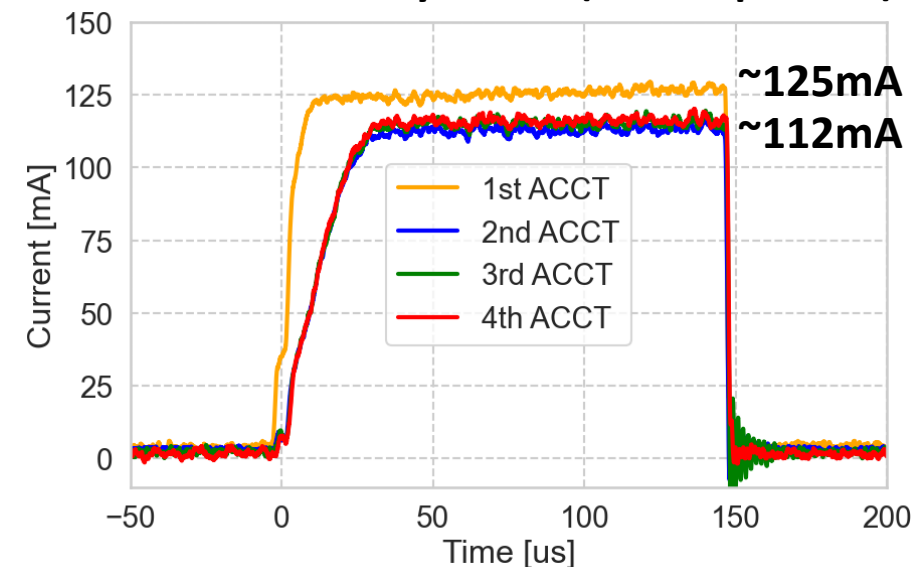
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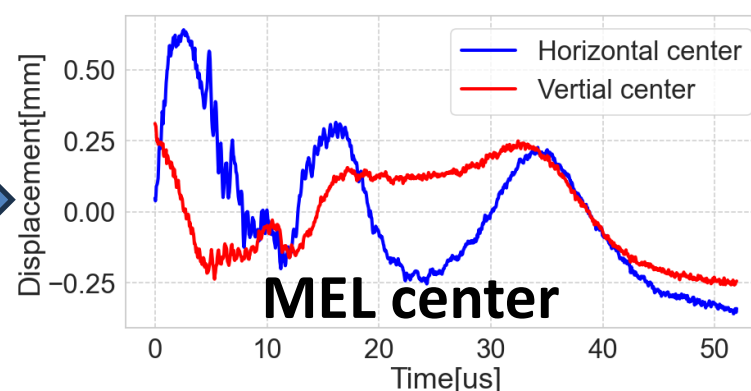
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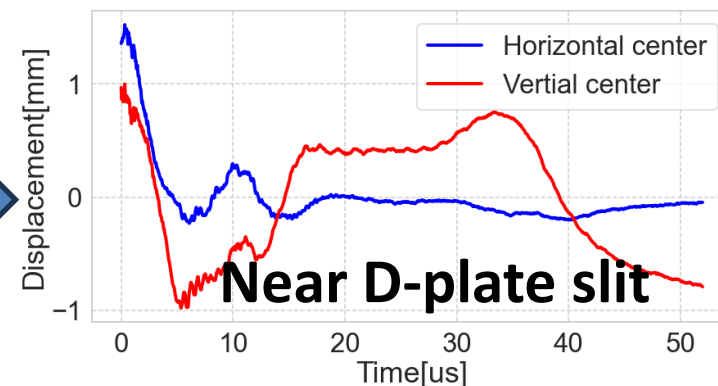
Measurement by ACCTs (7th / Sep. 2023)



7 Quads

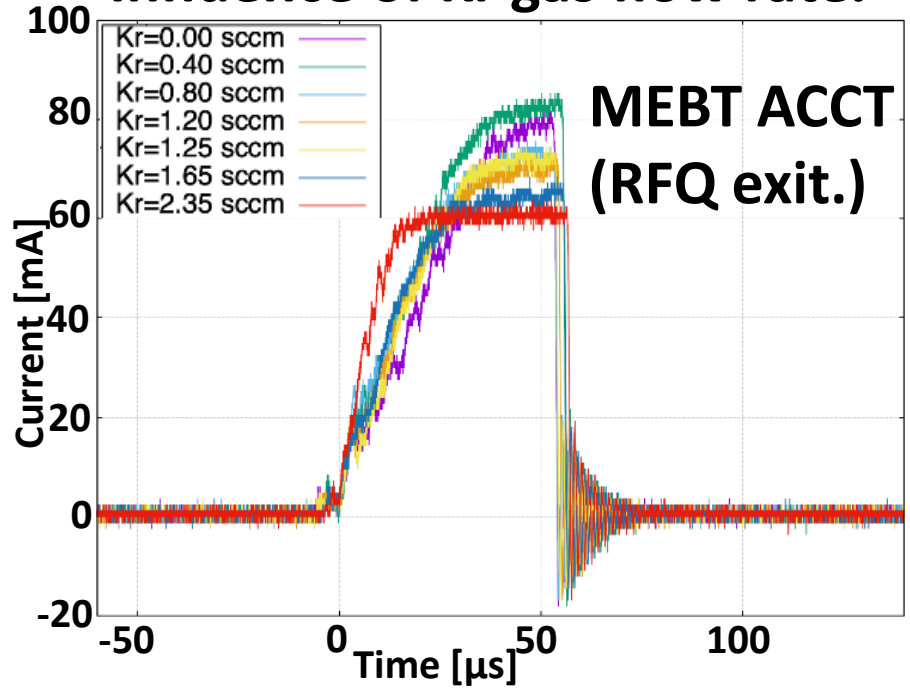


6 Quads



Centroid motion in a pulse measured by BPM.

Influence of Kr gas flow rate.

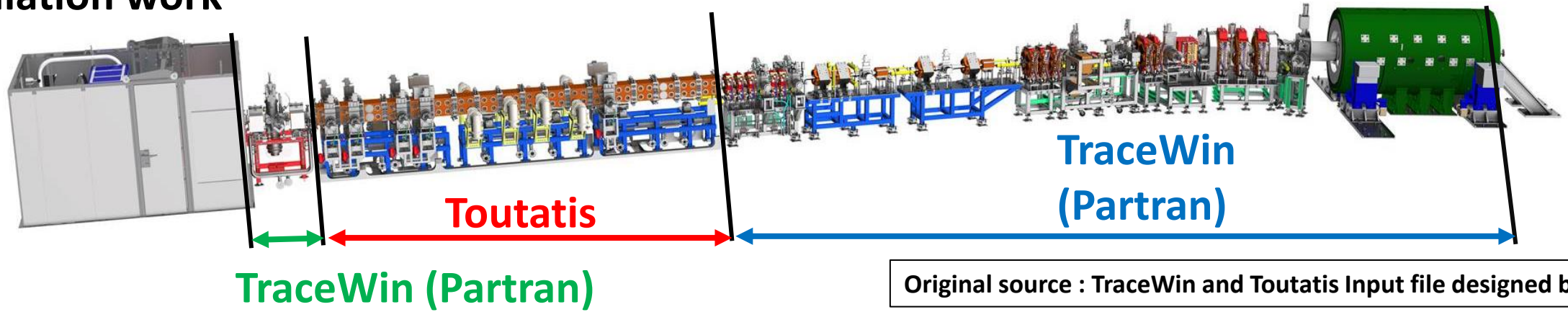


LIPAc RFQ (4 vanes type) spec.

- Length : 9.8m consists of 18 modules
- RF Frequency : 175MHz
- **RFQ vane voltage : 132kV → 137kV (new nominal)**
- Kilpatrick : 1.8
- RF source : 8 chains, 200kW / chain

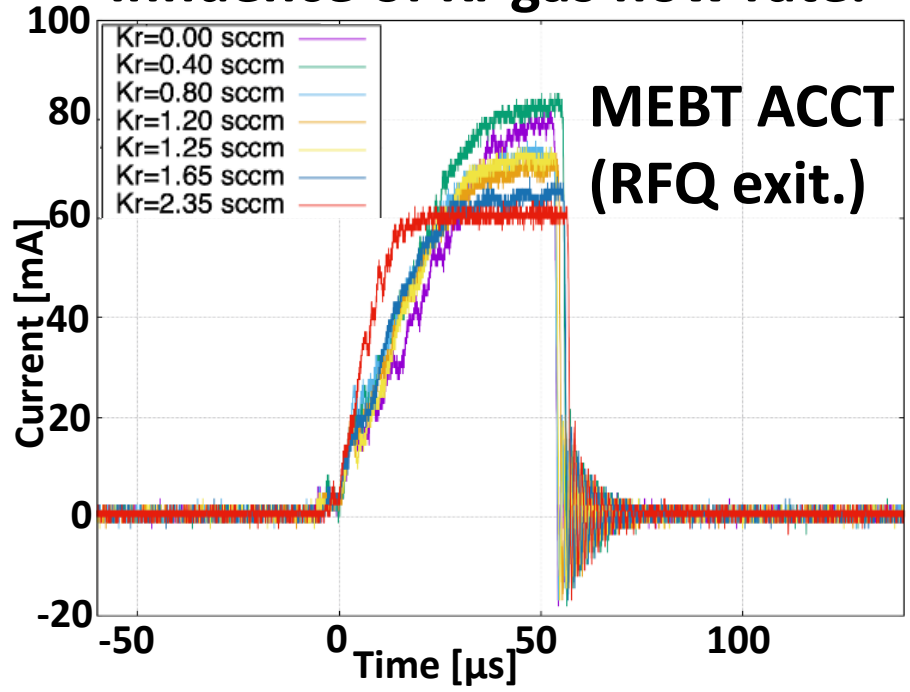
Coming from Luca's work.
(L. Bellan, 2nd CBO workshop)

Simulation work



Original source : TraceWin and Toutatis Input file designed by L.Bellan

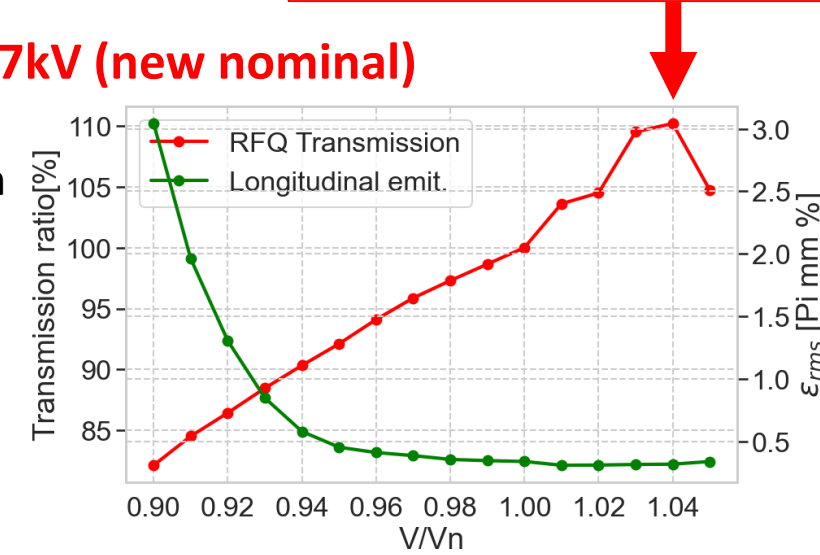
Influence of Kr gas flow rate.



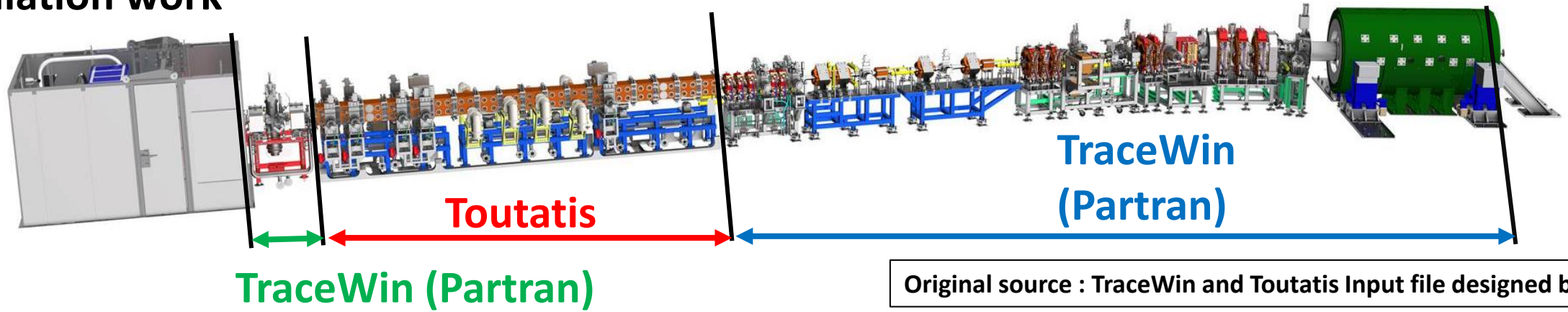
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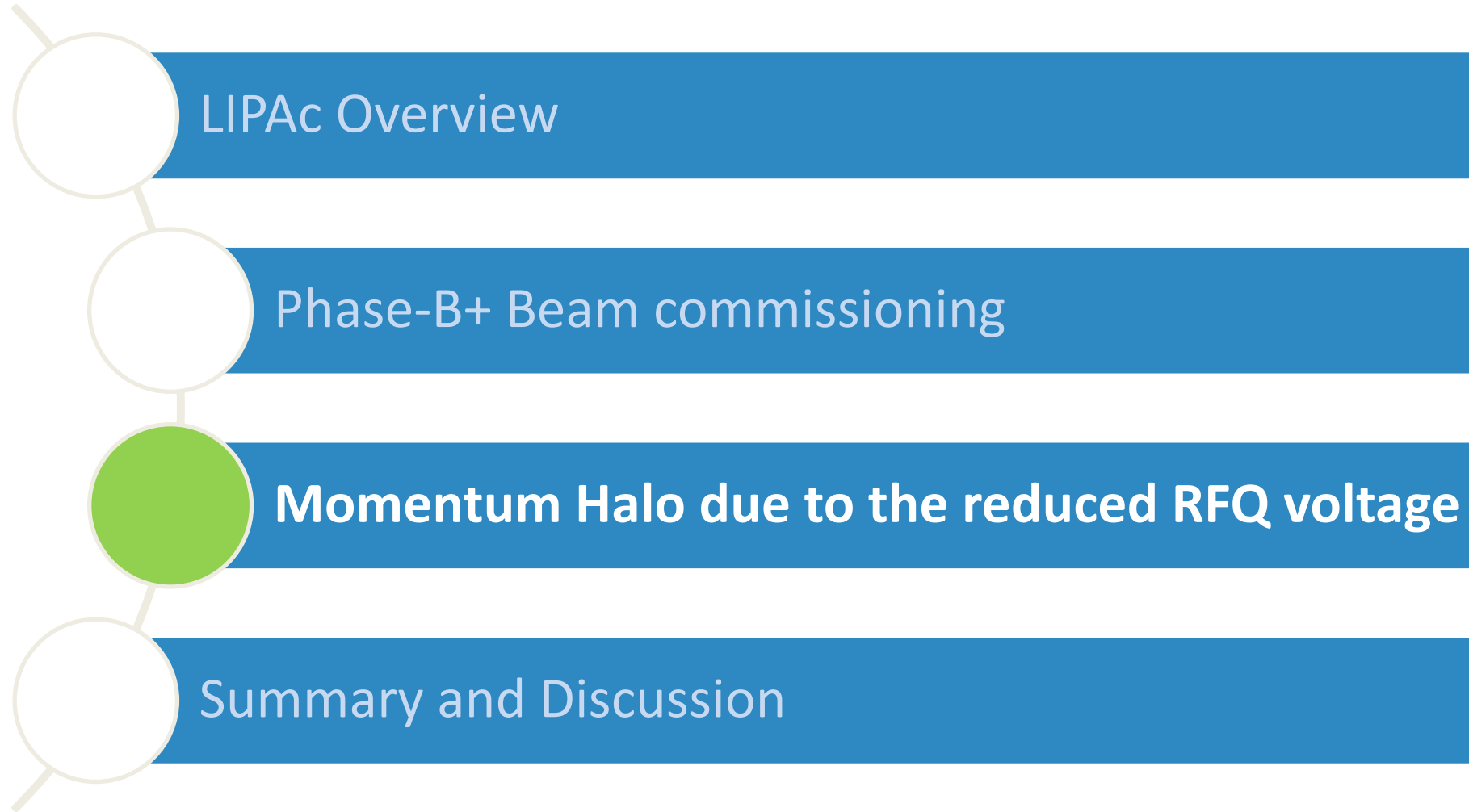
104% (137kV) is better.



Simulation work

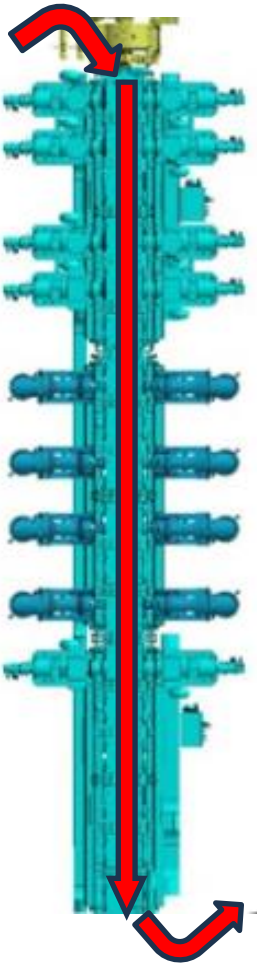
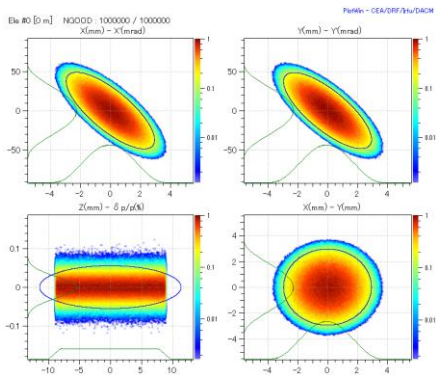


Original source : TraceWin and Toutatis Input file designed by L.Bellan

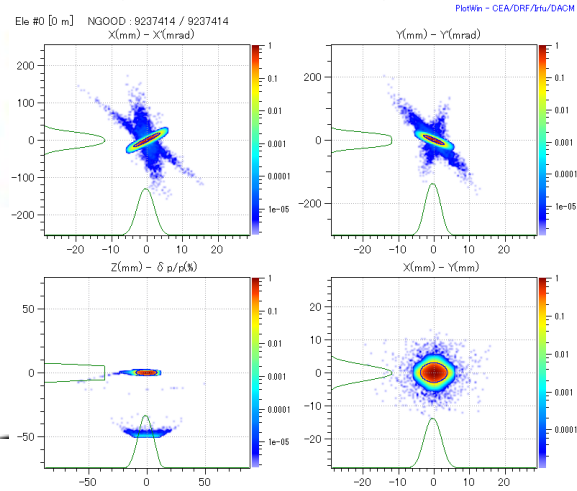


- Reduced RFQ voltage induces spreading distribution following discrete energy levels.
- Phase-C configuration has a **cryomodule LINAC** with 8 superconducting solenoids and cavities, which has **10W margin** of the heat as the whole helium tank.
- Phase-B+ is a good chance to test beam dynamics depend on RFQ voltage, aggressively.
- By testing it in this phase, we are **considering to prepare a kind of Interlock for losses in the cryomodule.**

RFQ simulation: applied vane voltage = 90% (119kV) - 105% (138kV)

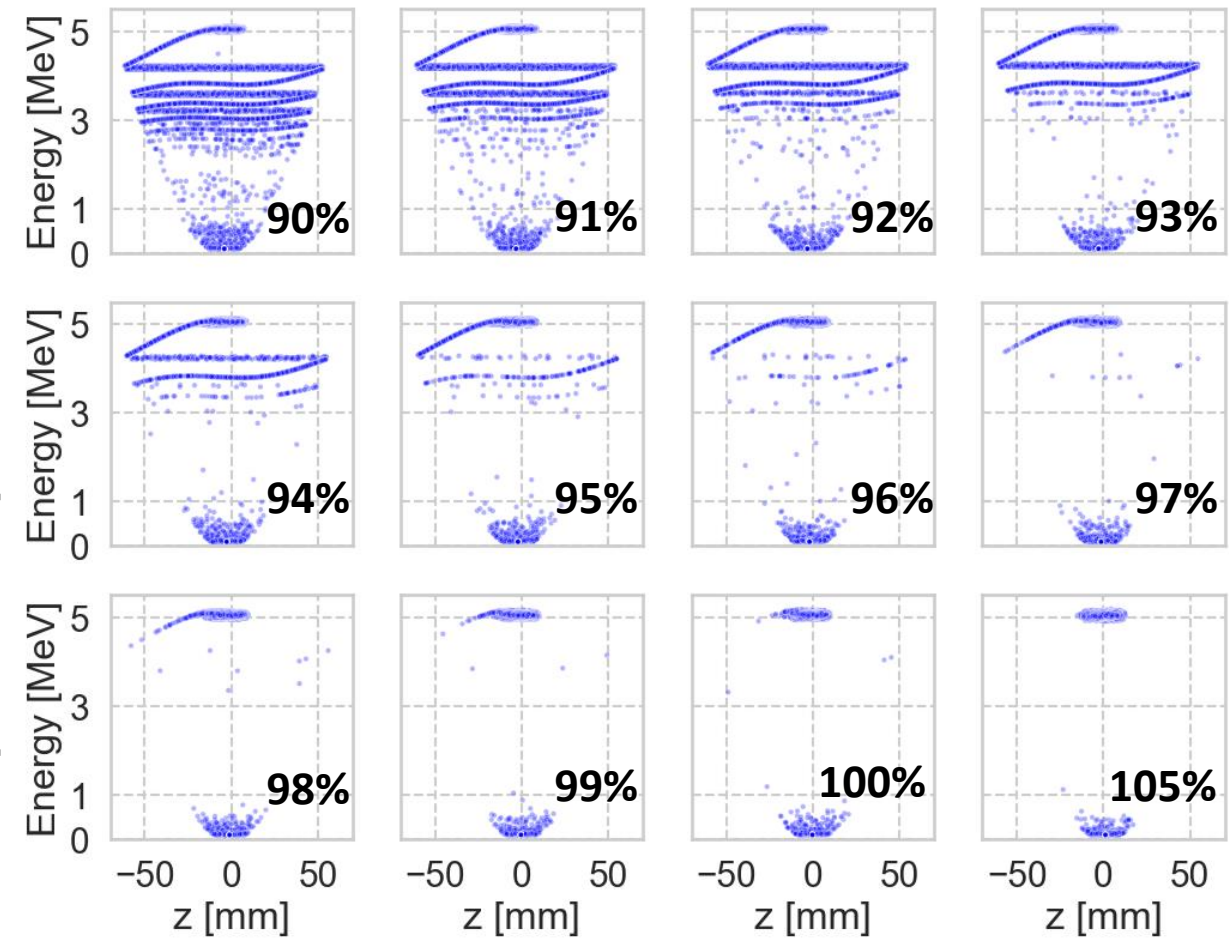


Output distribution (10M particles for design voltage)

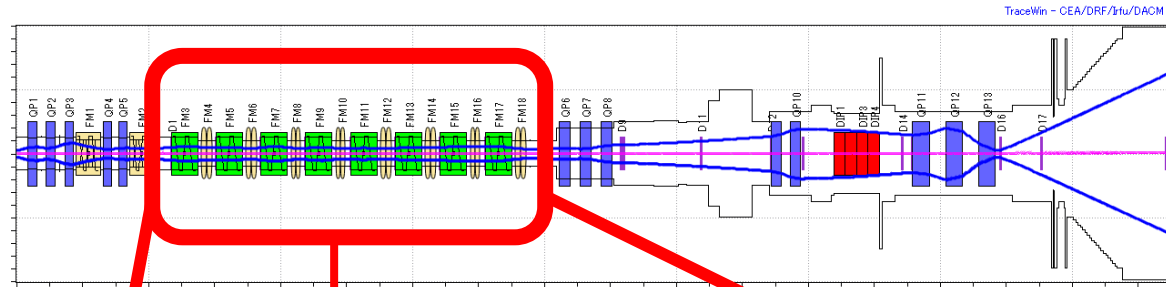


Not properly accelerated particles, called “Momentum Halo”, are included in the same duration just after RFQ.

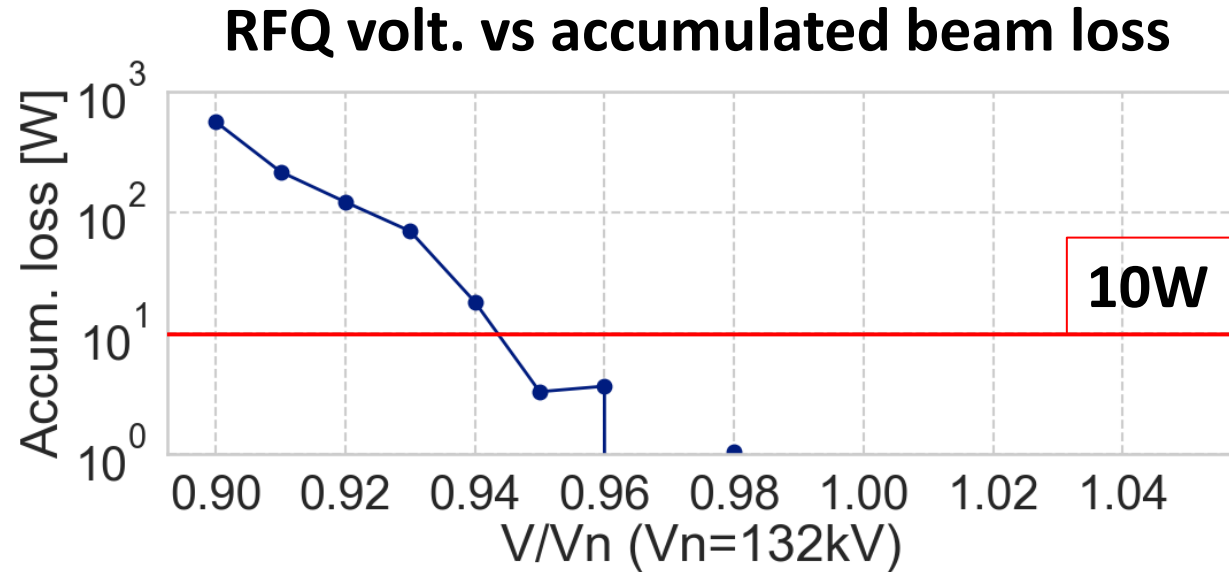
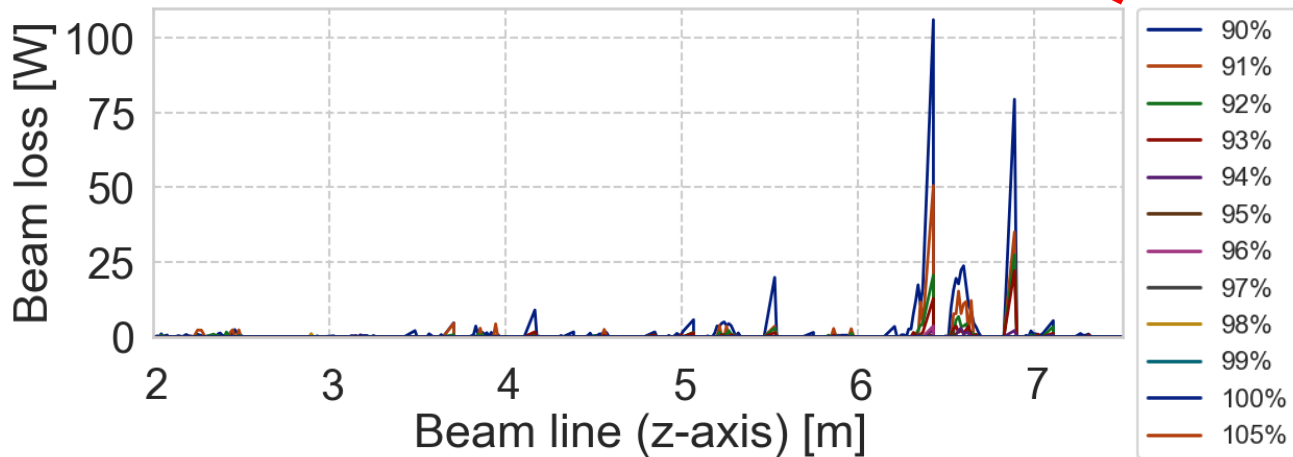
Particle distributions for longitudinal phase space



Beam loss in the cryomodule was checked by particle tracking simulation.



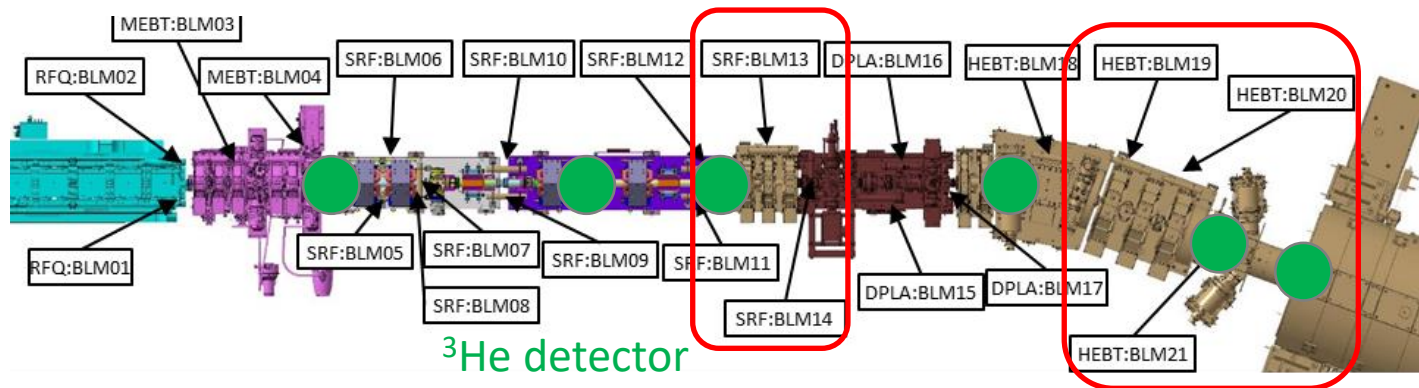
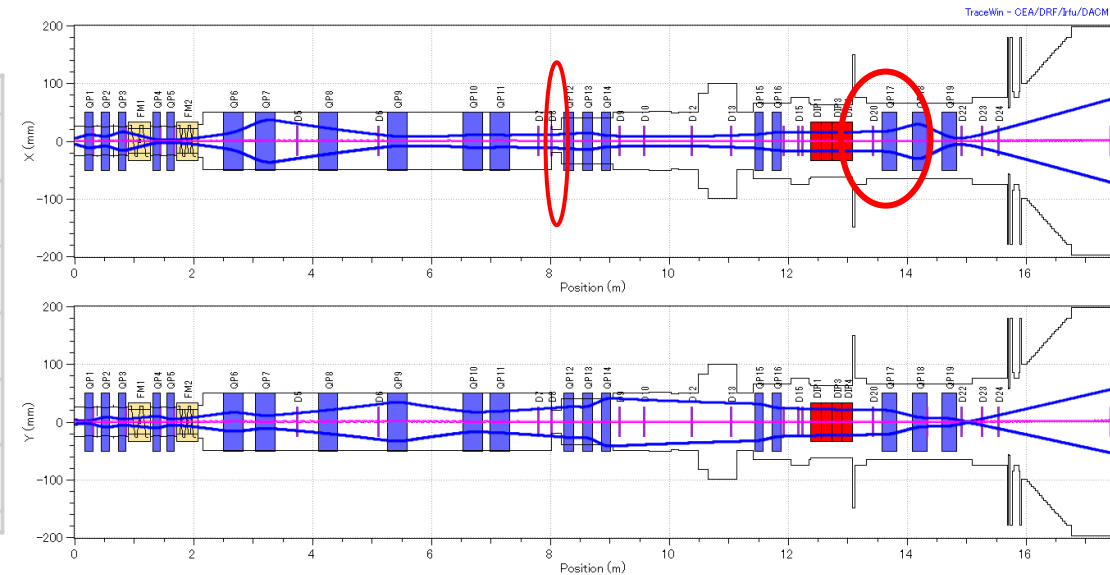
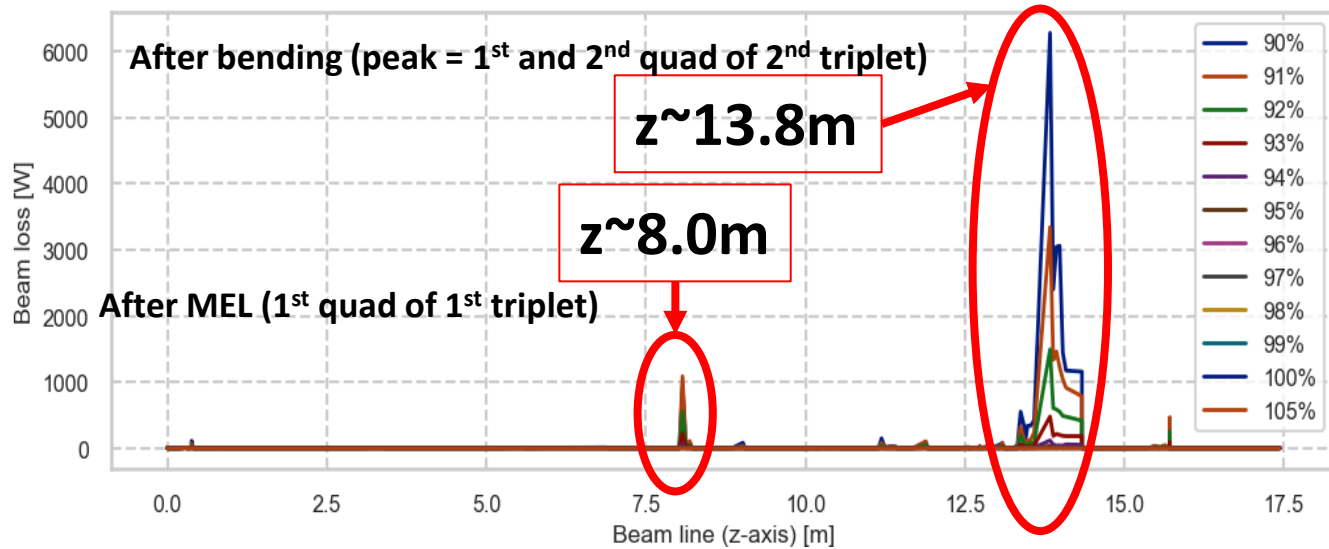
Z = 2m – 8m is the section of Cryomodule



Less than 94% can produce beam loss > 10W in the simulation (1M pt.), without error study.

At least, 95% is one threshold.

Estimation by tracking simulation was done to know good monitoring position if we can detect the effective beam loss along the downstream BT.

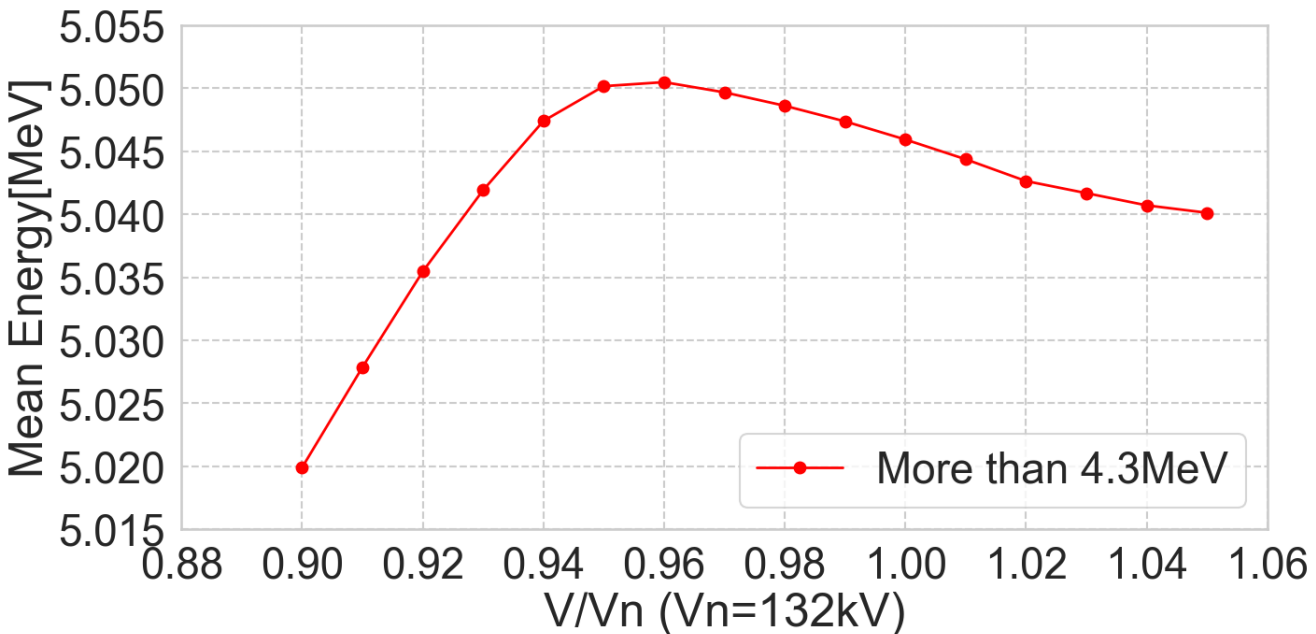


Effective beam loss can be detected by:

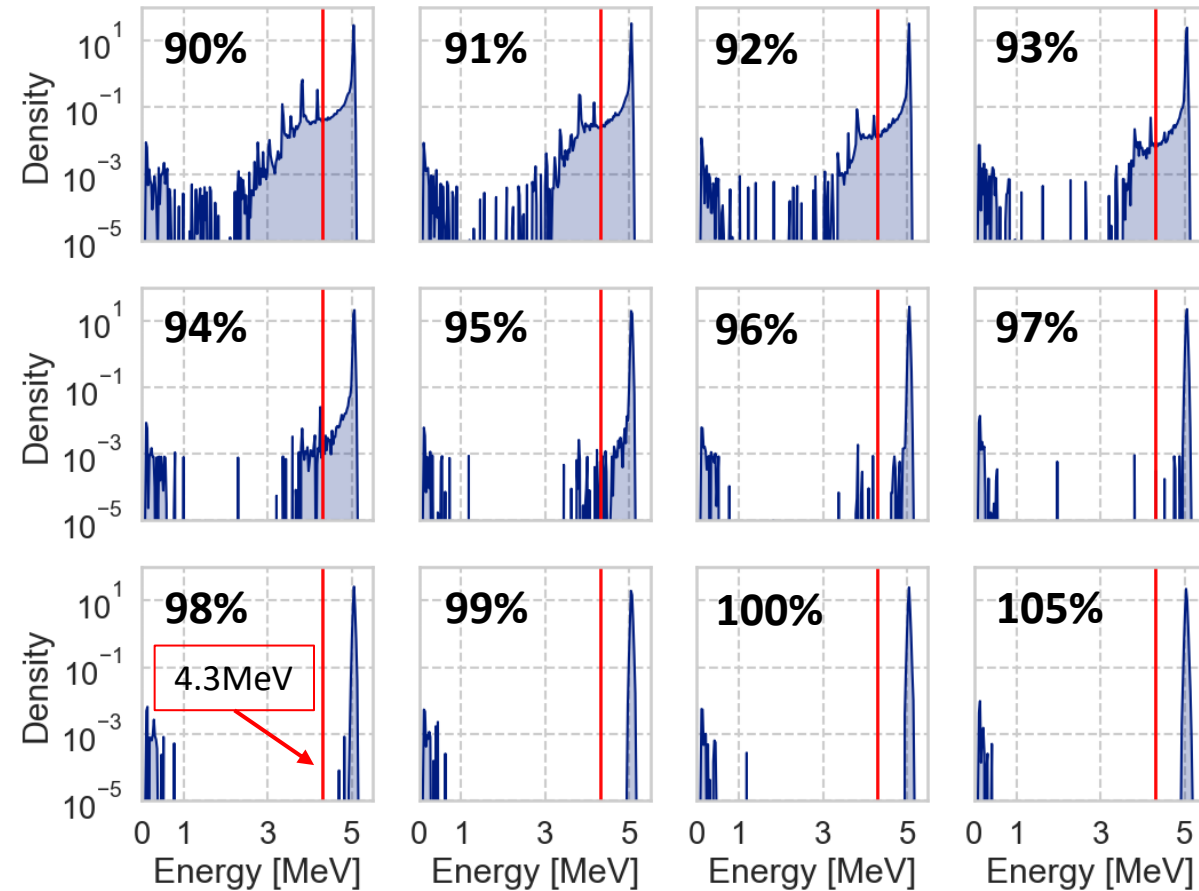
- BLM13 and 14, and 3rd ³He detector (Beam loss around z~8m)
- BLM 19, 20, and 21, an 5th and 6th ³He detectors (Beam Loss around z~13.8m)

As a measurable value for our system, mean energy of each bunch is one candidate.

For the RFQ exit beam,
 Not accelerated particles → Not detectable in BPM
 Only core and its tail → Maybe measurable by ToF
 (4.3MeV- particles)



Energy distribution (Logscale)



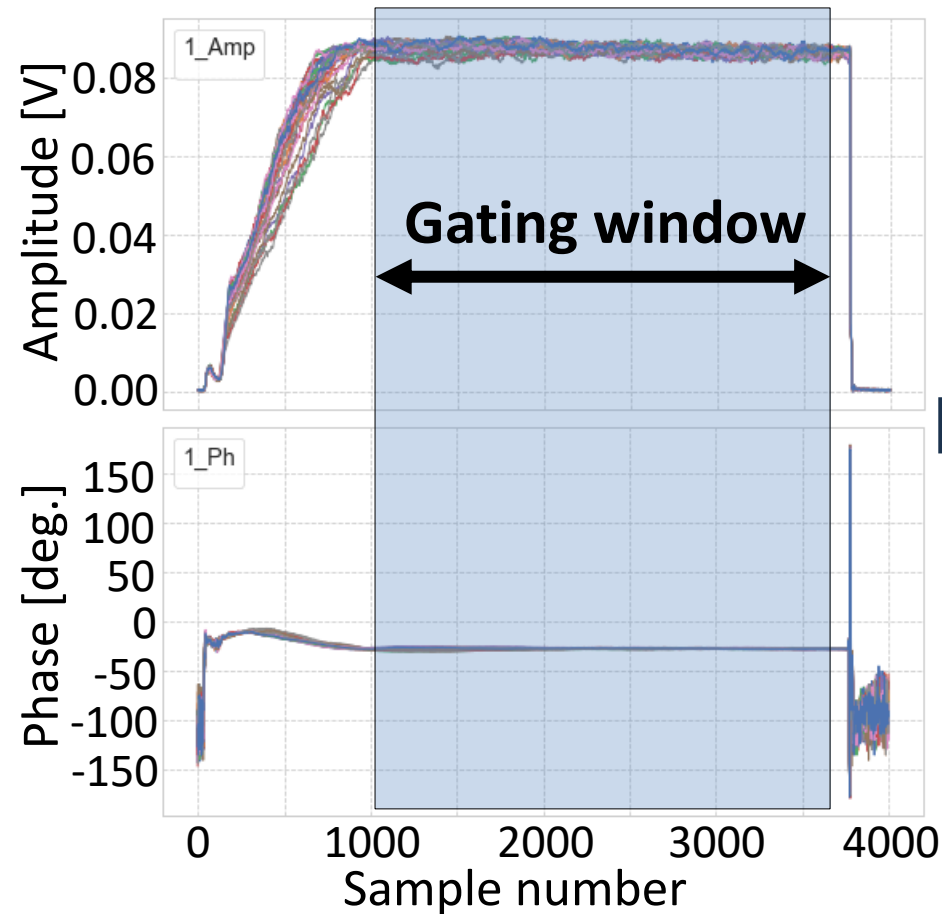
Less than 95%, ~ 5keV resolution is good to distinguish distributions of several RFQ voltages.

Upper region requires ~1keV resolution.

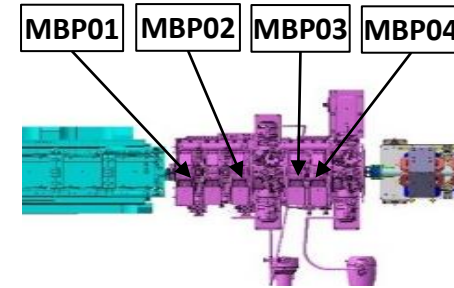
Previous results of BPM
 1. I. Podadera, the Proc. of IBIC2019 (2019).

Evaluation of visibility of BPM phase measurement in a pulse.
 150 μ s pulse, 1Hz, 112mA at RFQ exit ACCT

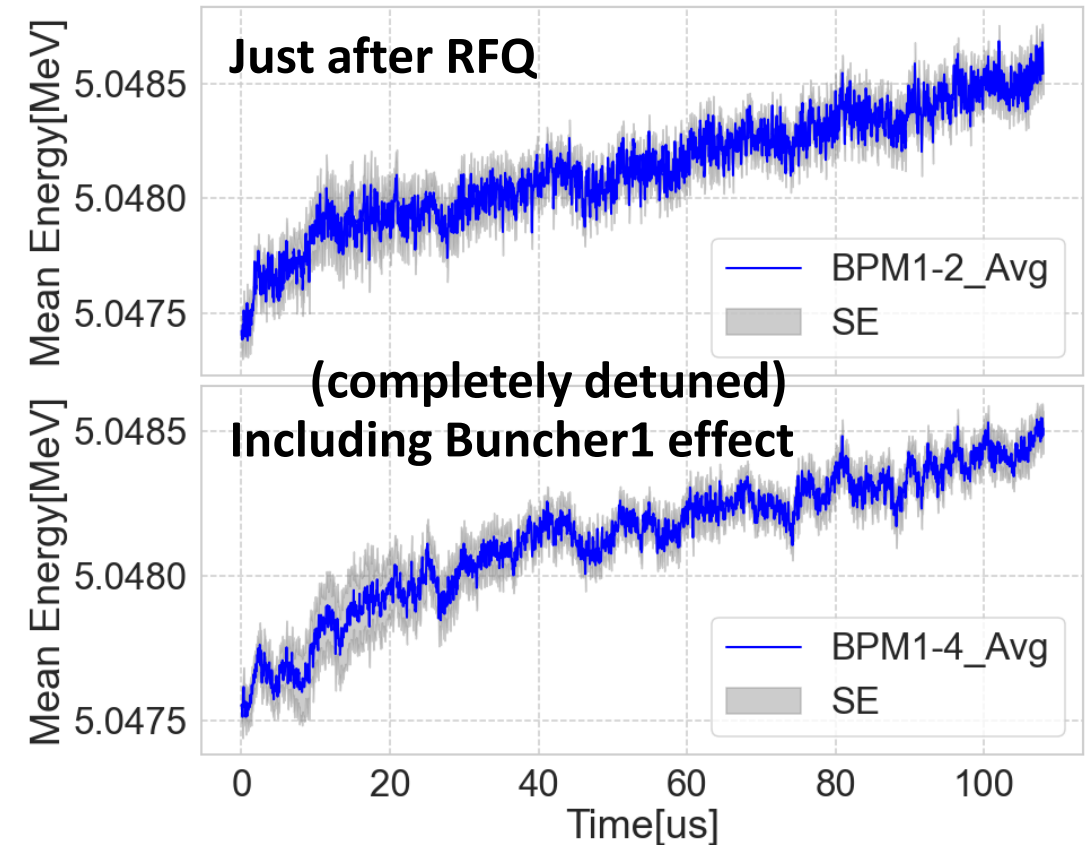
50 pulses raw data: BPM MBP01 electrode-L (+x)



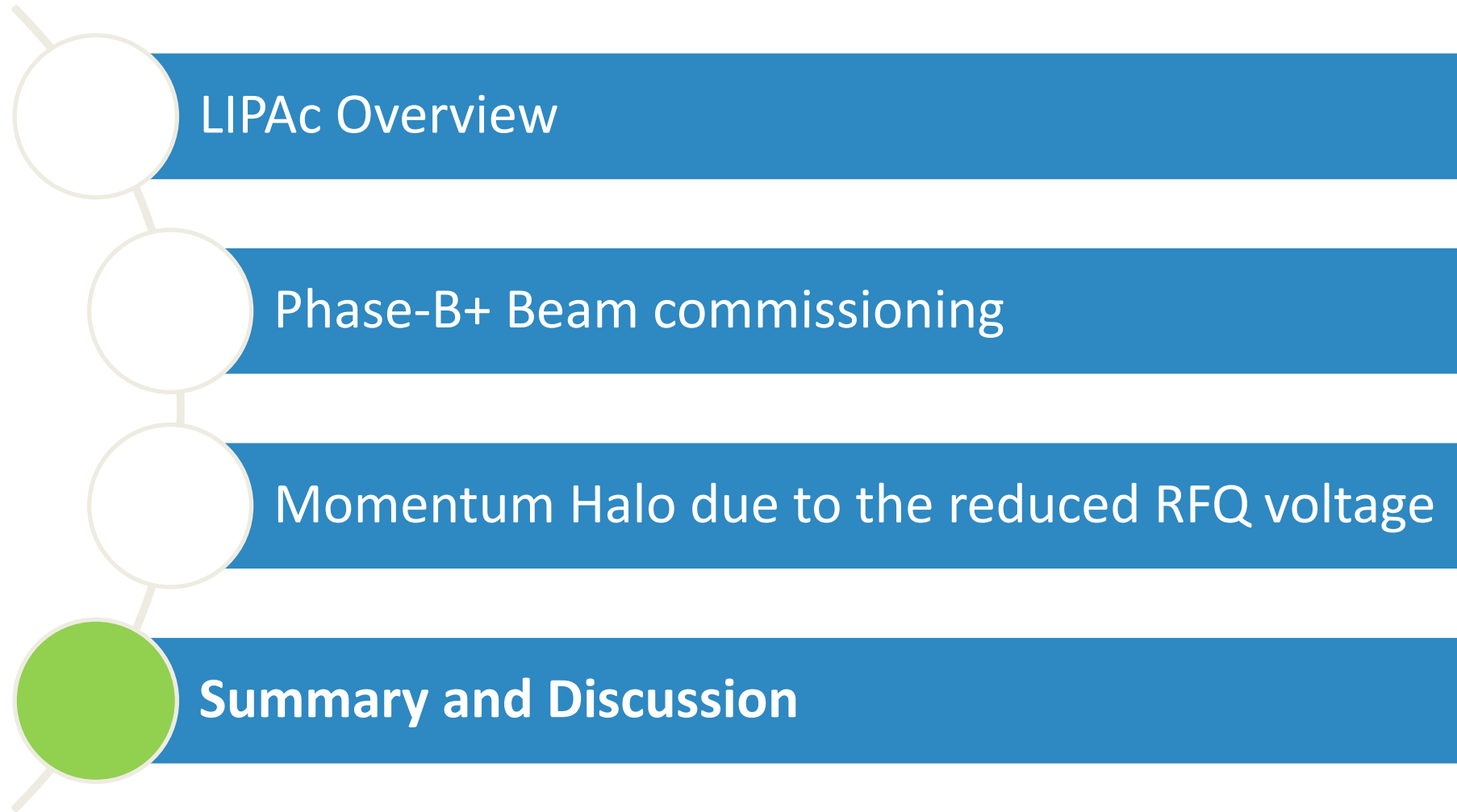
Analyzed (ToF)
 Statistics : 50 pulses



Blue : average over 50 samples
 Gray area : Standard error



As the mean energy resolution, < 0.5keV for 350MHz can be expected. \rightarrow Enough to see 1% difference.

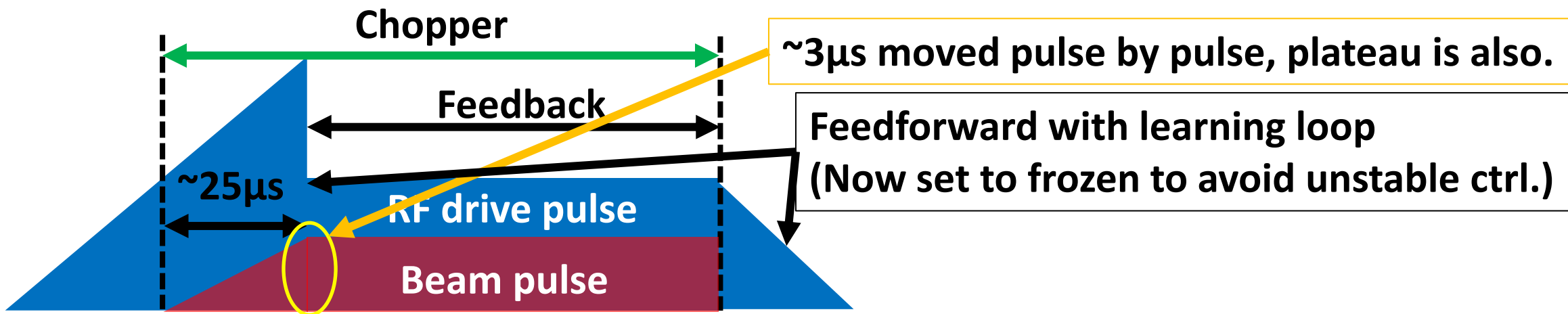
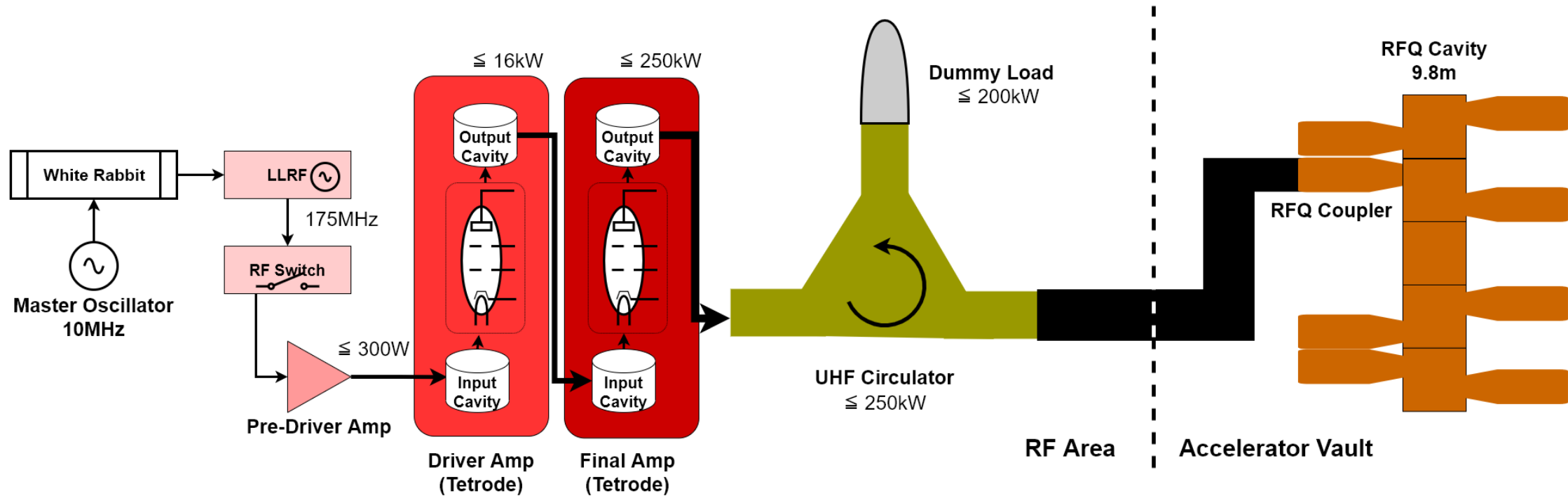


- **LIPAc is now in the beam commissioning Phase-B+.**
 - **Aims to High current, High DC**
- **Beam to the BD : 5MeV-112mA D⁺ beam in 150us-1Hz DC.**
- **Good agreement between sim. and meas. for the pilot beam.**
- **Study of the space charge compensation is being proceeded.**

- **For momentum halo due to the reduced RFQ voltage,**
 - **Loss monitor approach near bend is planned in the Phase-B+.**
 - **Resolution of BPM-ToF looks enough (< 0.5keV) to draw the energy carve.**

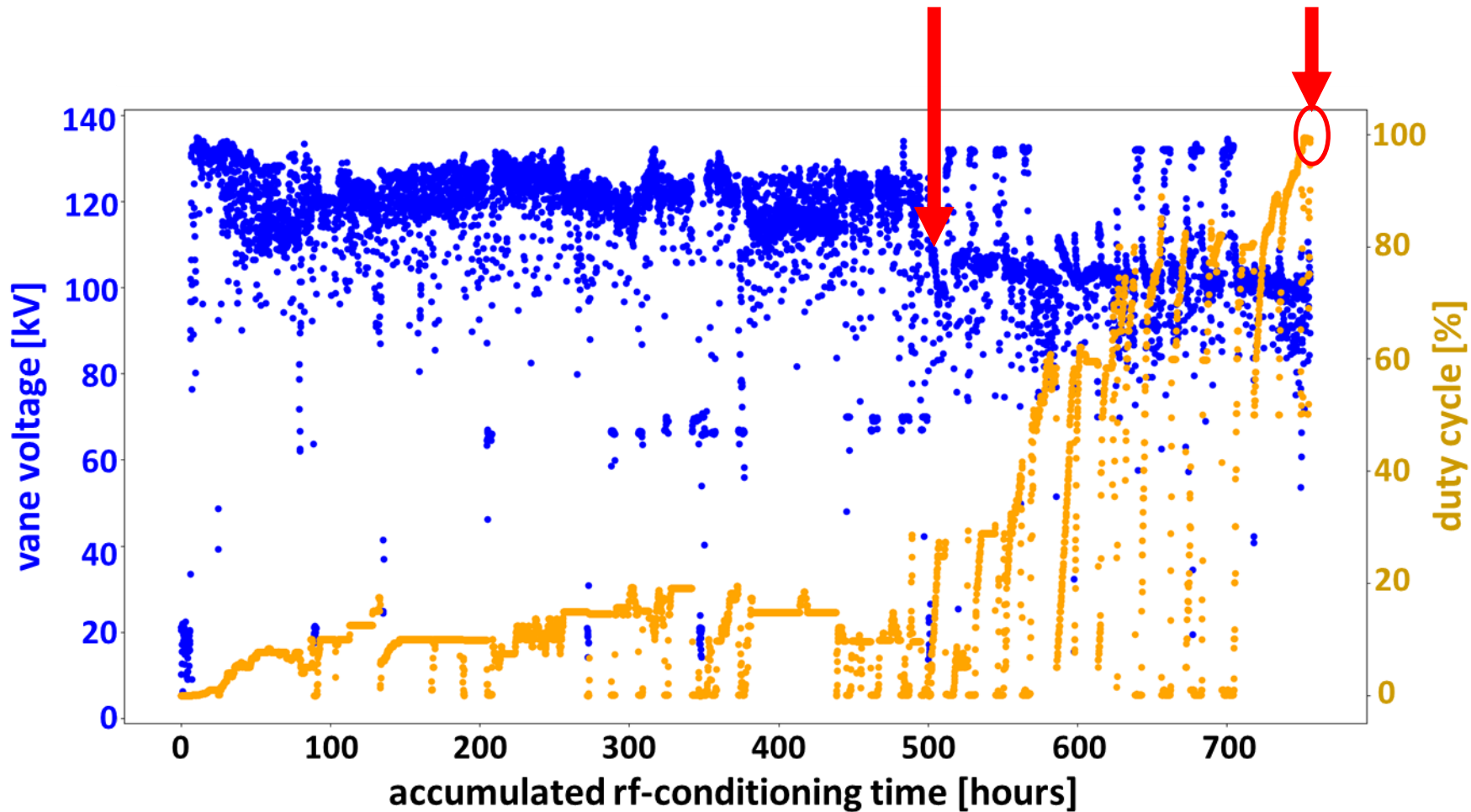
Thank you for your attention!

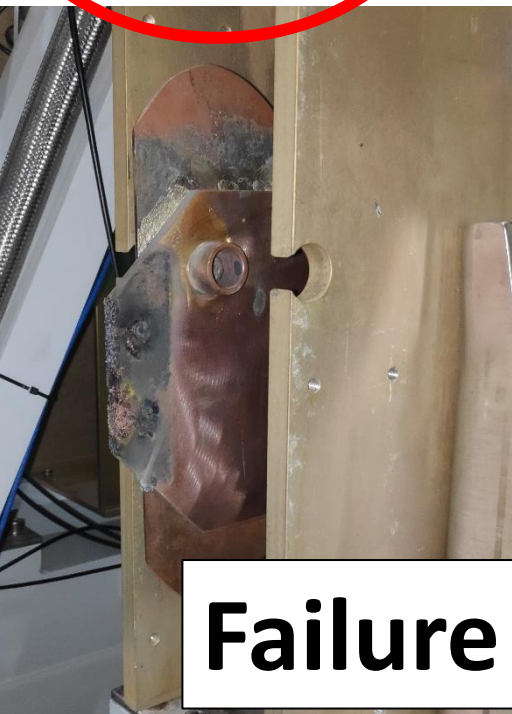
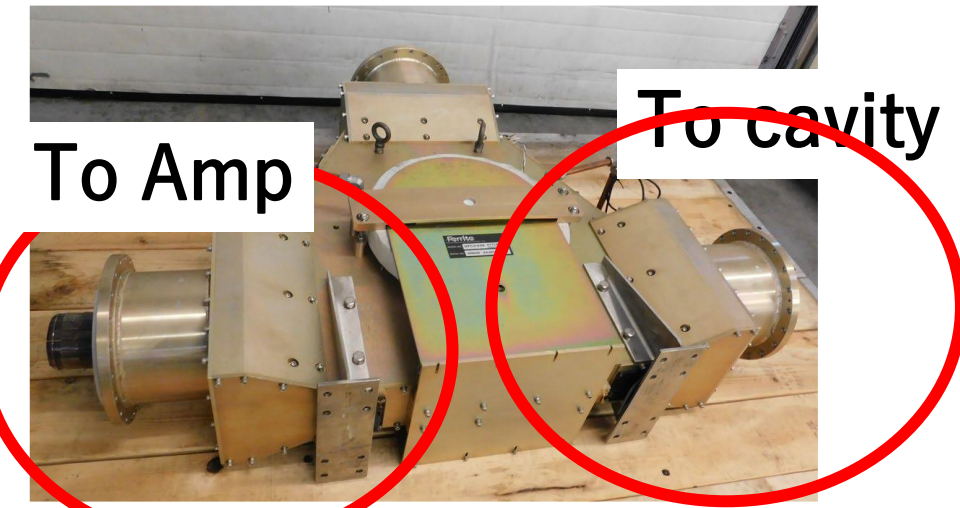
Backup slides



17, Dec., 2021. We reached to CW with 108kV (80% of design).

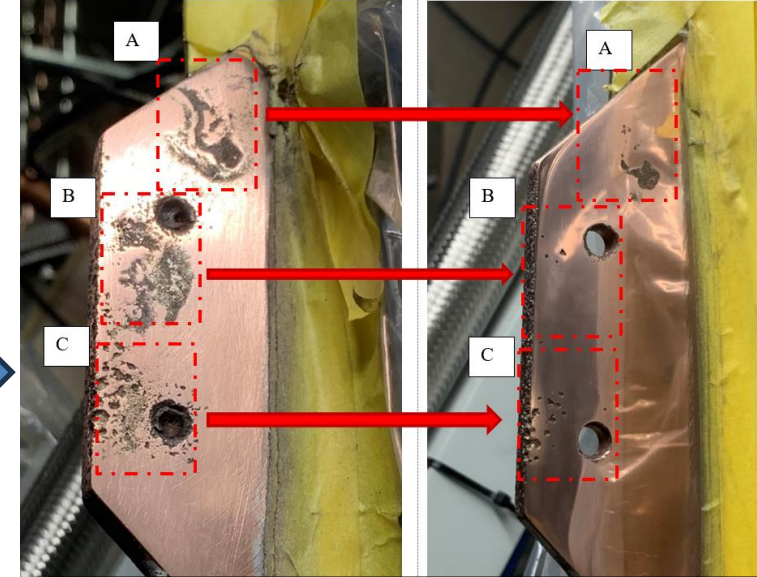
Reduced the voltage to 80% CW



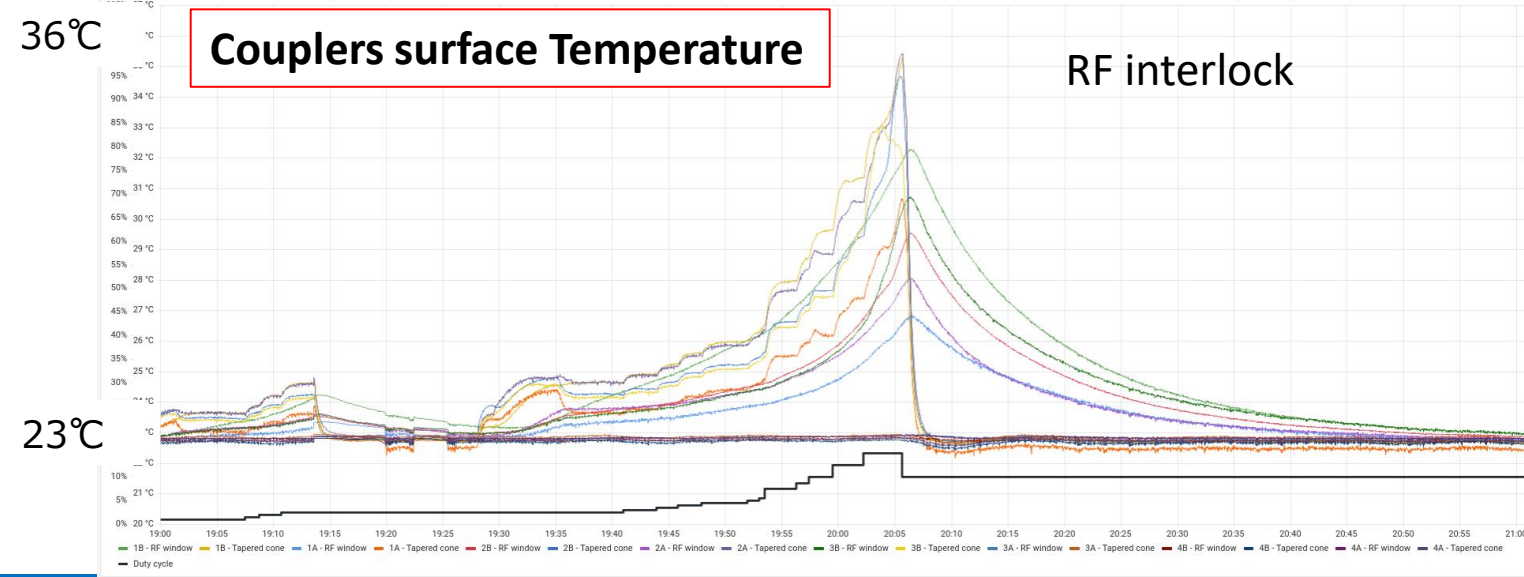
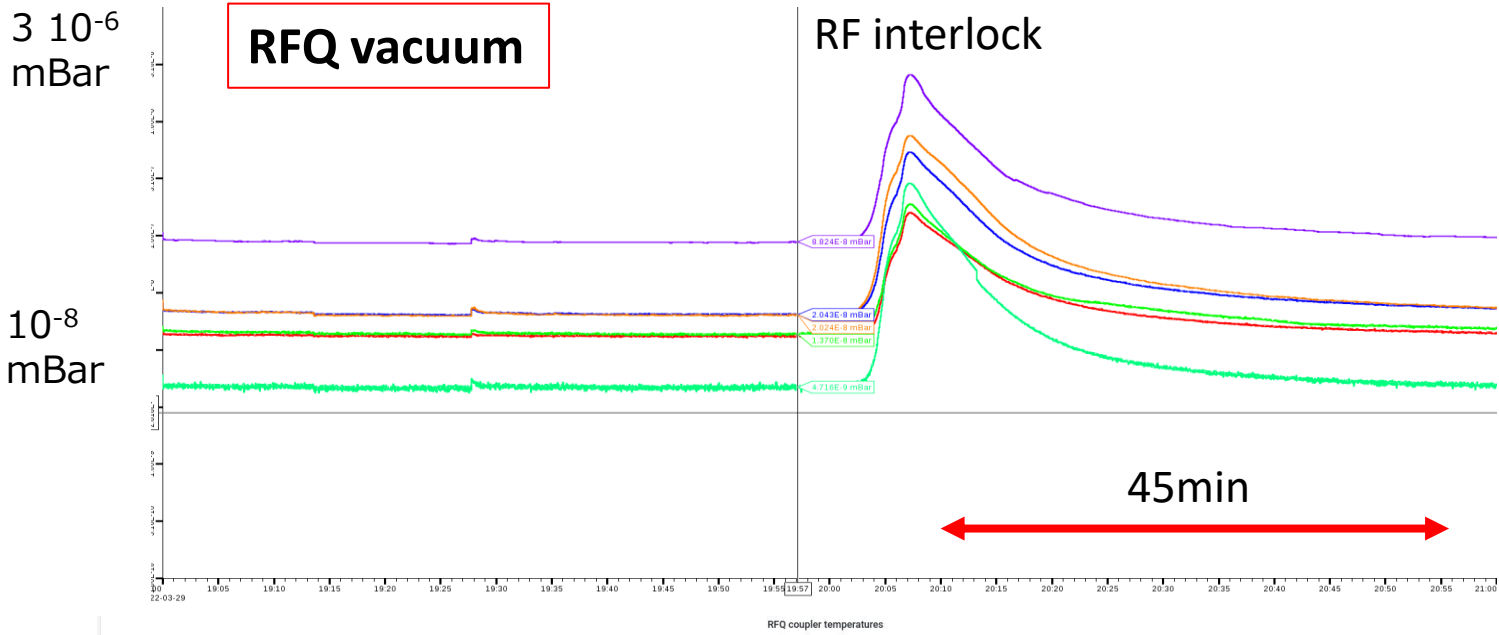


Failure Jan/2022

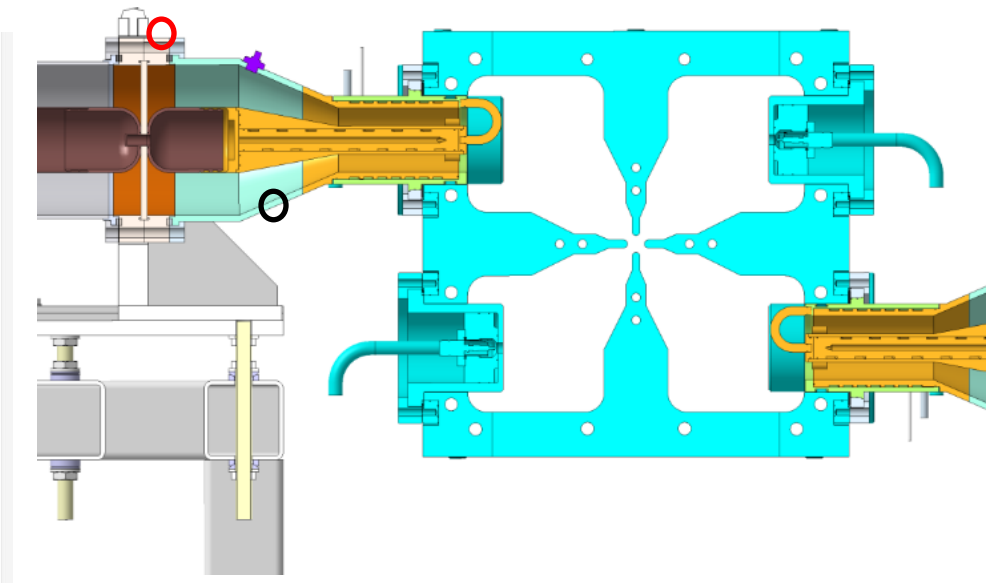
repair
→



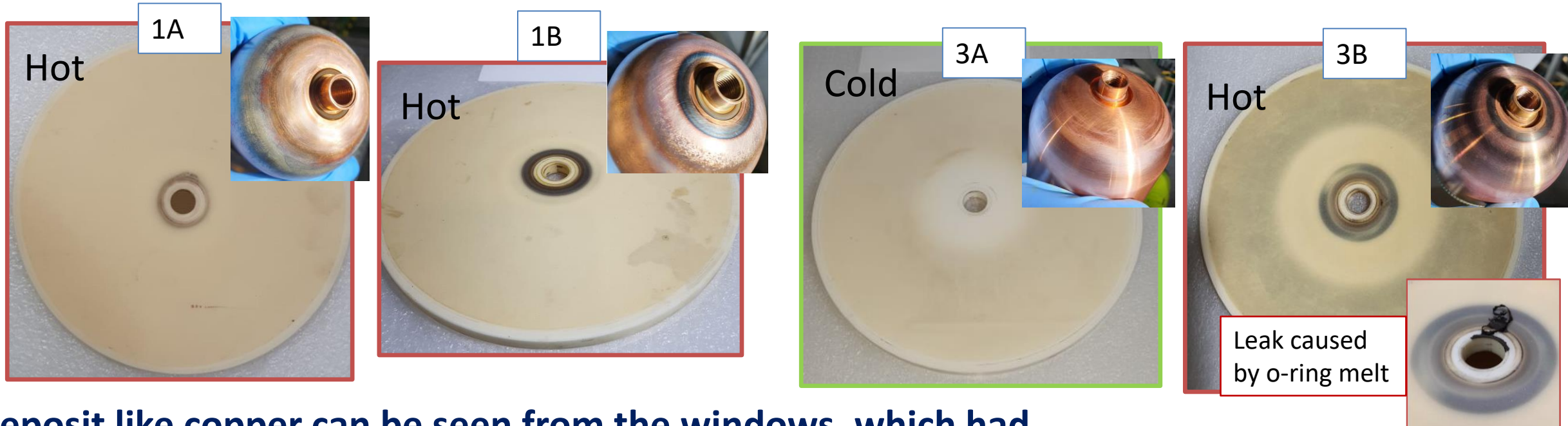
on-site repair June/2022



Measurement points

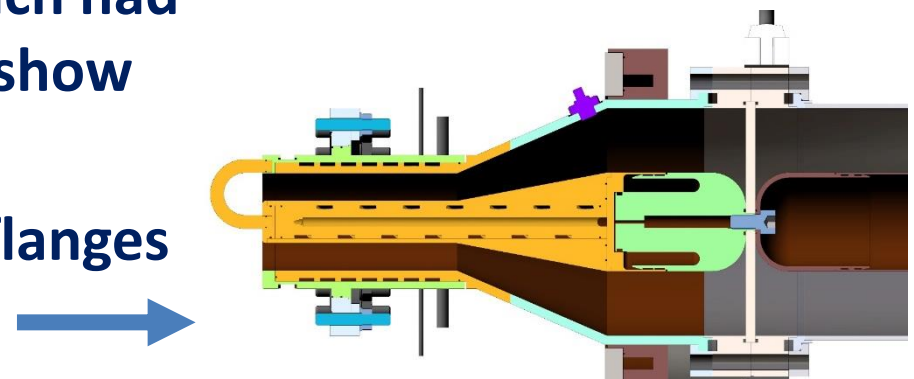


Vacuum leak were happened from two RFQ input couplers, so we disassembled all couplers and checked it. Bellow 4 pictures are typical windows dismantled from the coupler.



Deposit like copper can be seen from the windows, which had high temperature during the test. Cold windows never show effective temperature increasing.

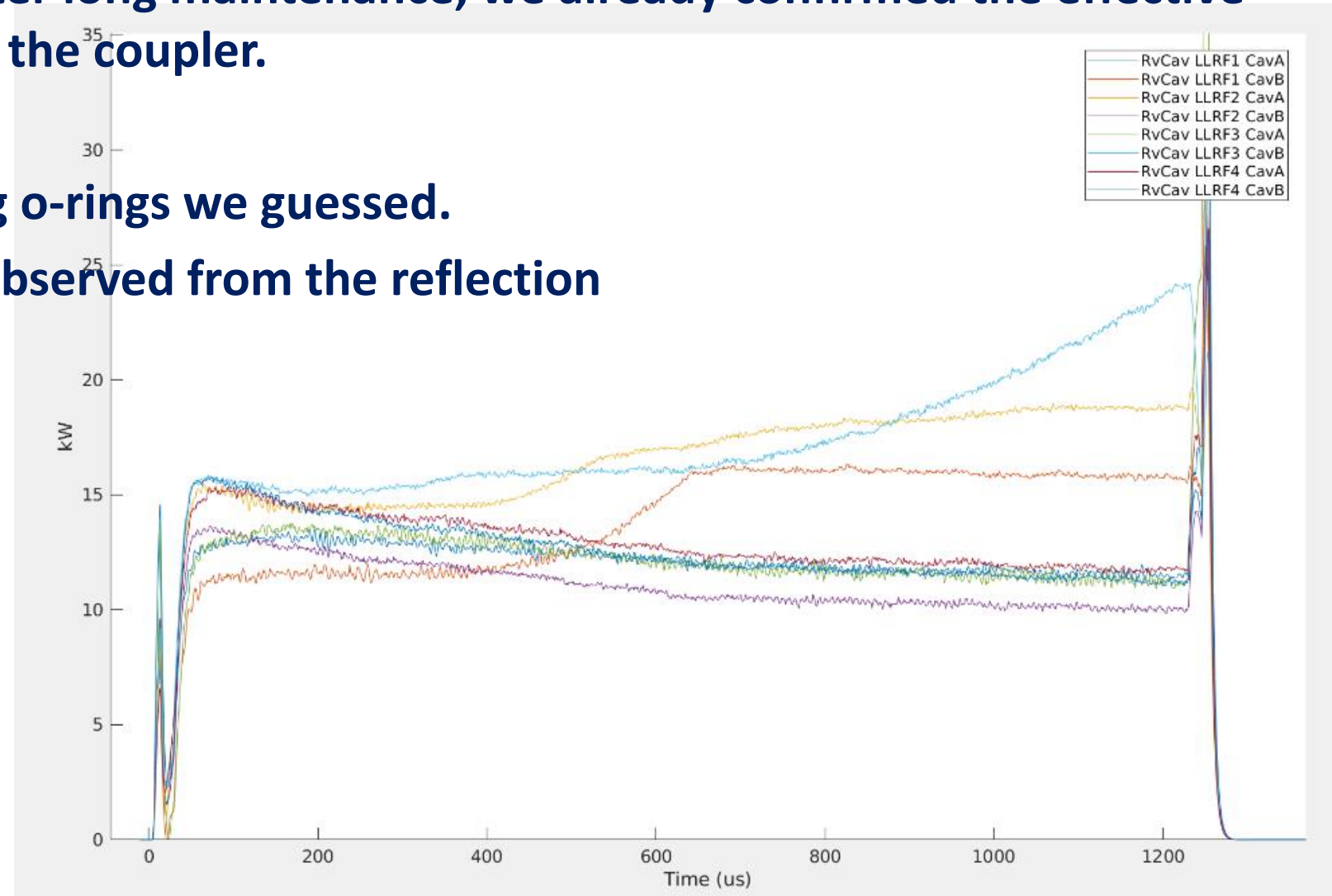
We modified the inner conductor of vacuum side, and flanges to enhance cooling efficiency.



RFQ CW commissioning after long maintenance, we already confirmed the effective temperature increasing on the coupler.

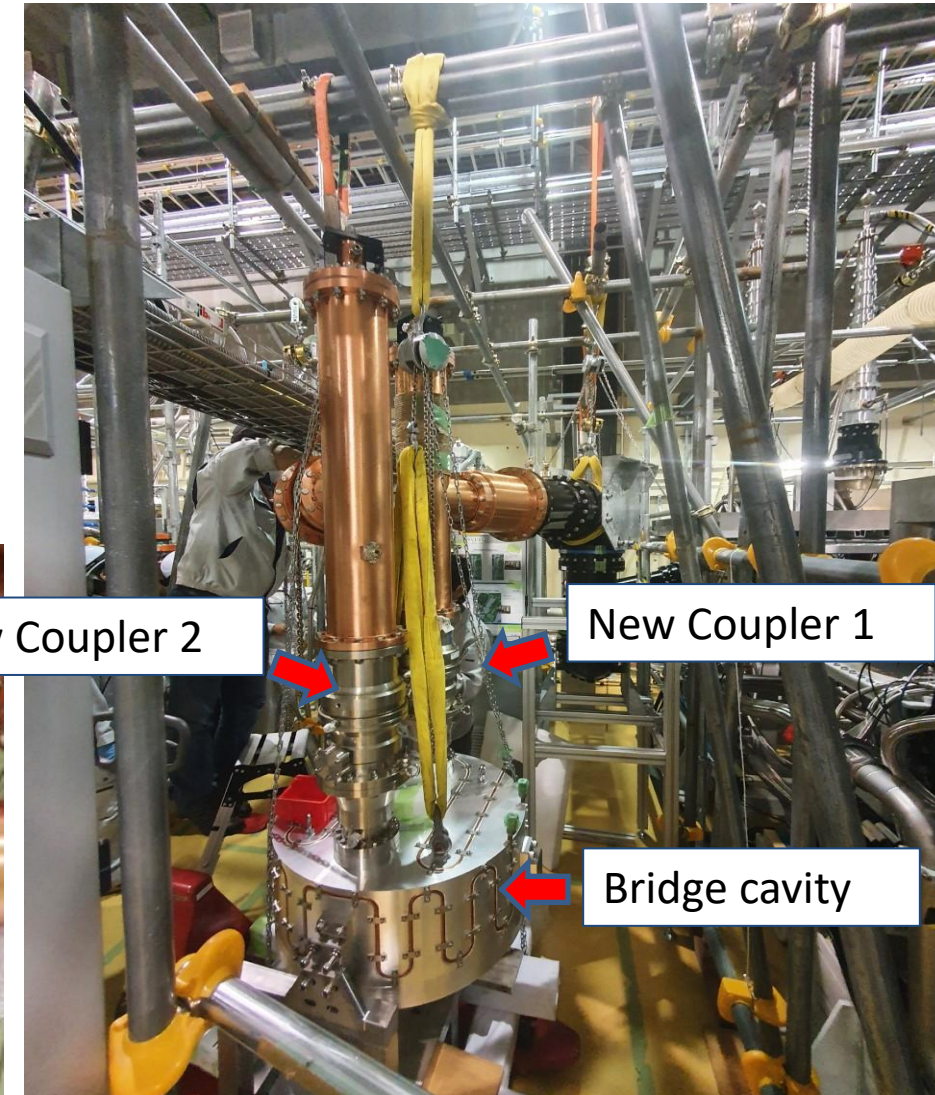
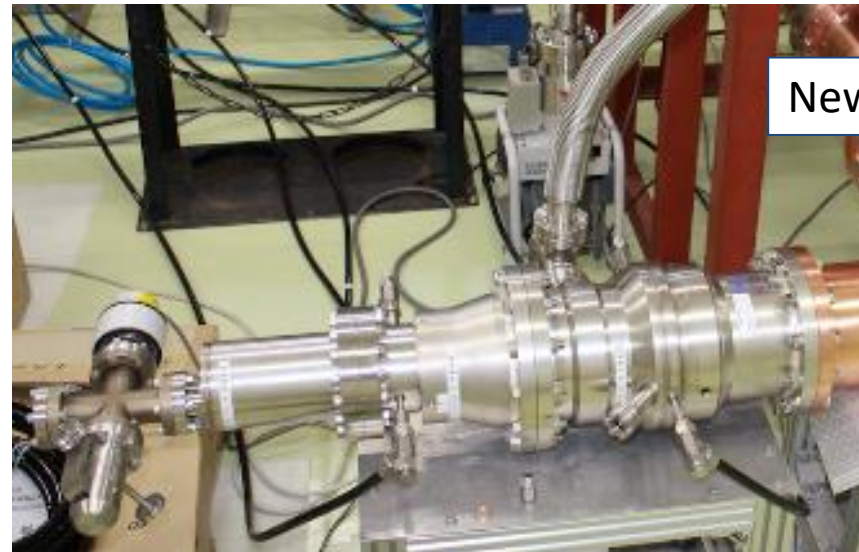
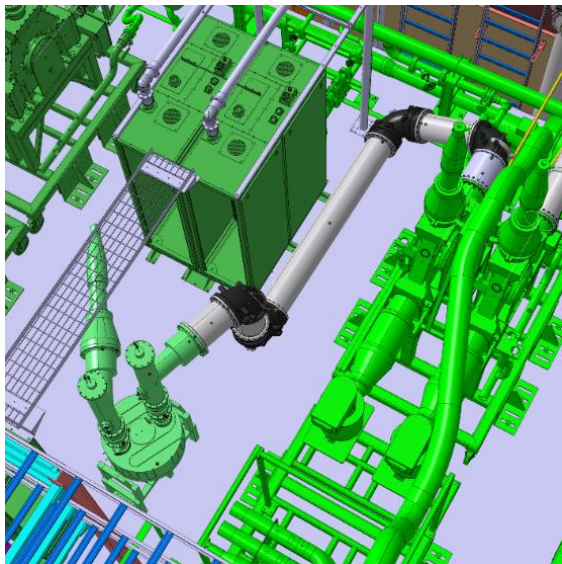
This is the cause of melting o-rings we guessed.

Interesting transient was observed from the reflection



As a different solution, brazed type without curvature at the window part is now tested.

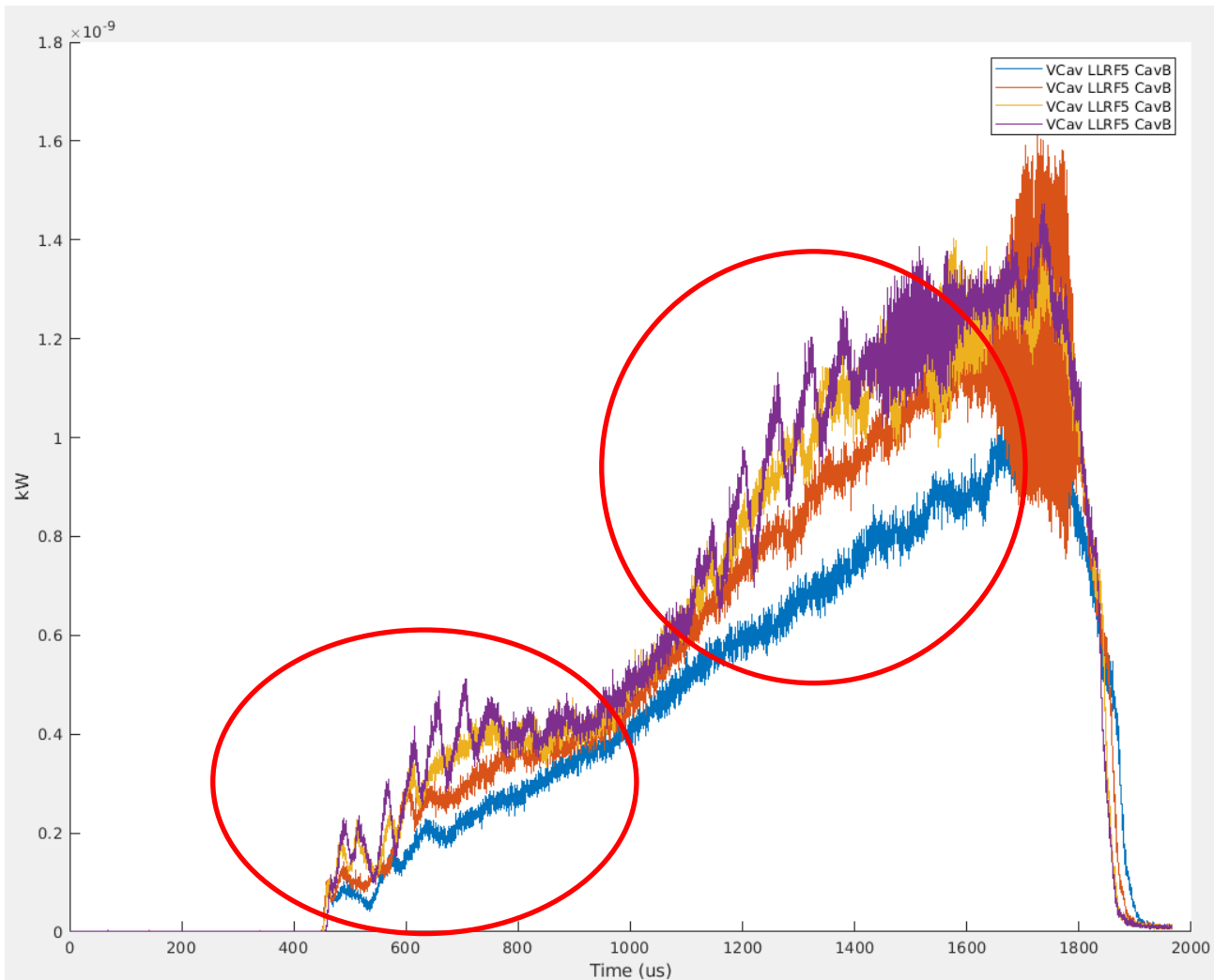
Because of vacuum quality of bridge cavity, in our guessing, was observed during the test, so we plan to modify the cavity.



New Coupler 2

New Coupler 1

Bridge cavity



H+ beam 26/Nov, 2021 without chopper

Beam induced voltage in the detuned buncher in presence of Kr Gas flow

Blue = 1.4 sccm

Red = 0.85 sccm

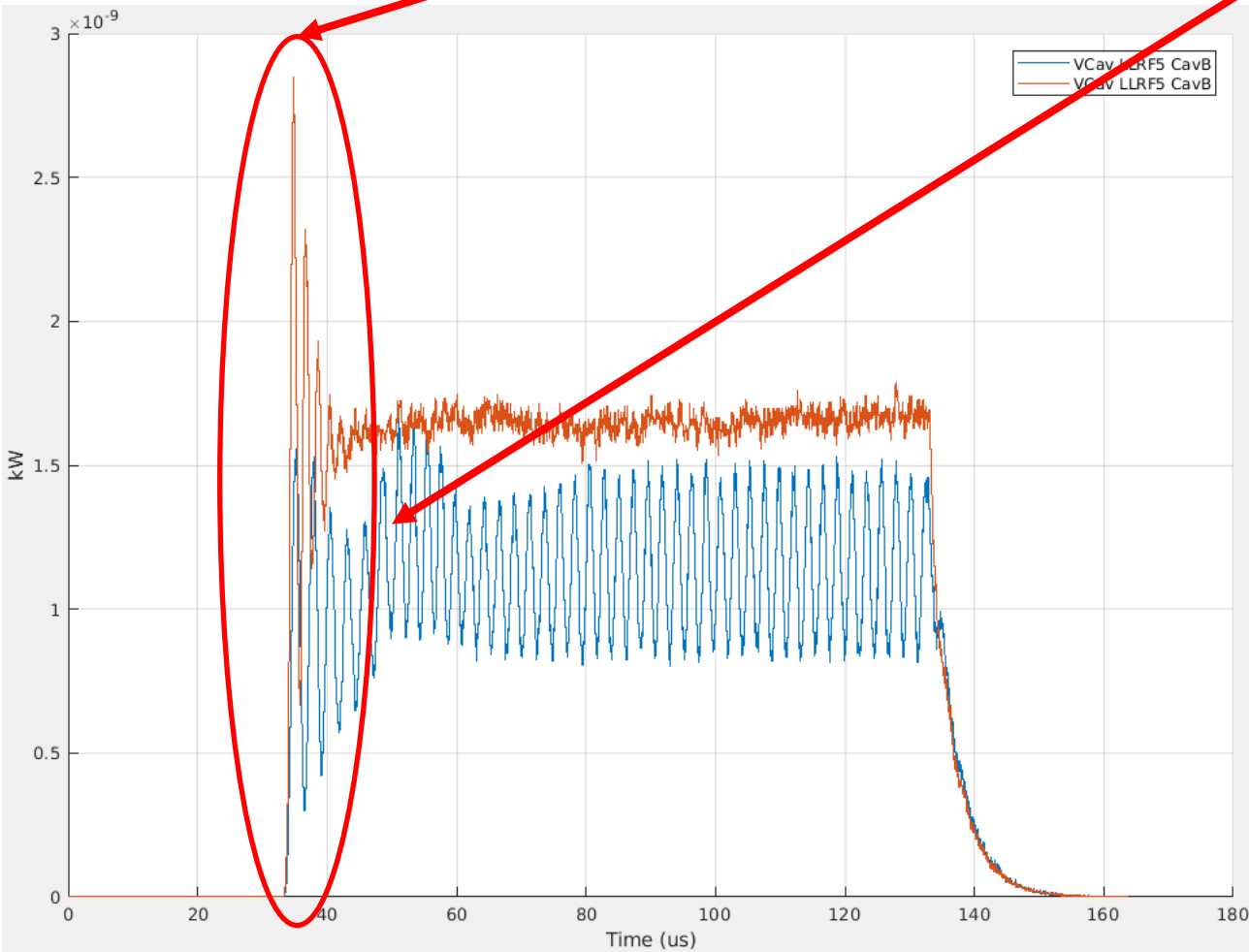
Yellow = 0.38 sccm

Violet = 0 sccm

As increasing Kr gas flow, zigzag shape is disappeared.

Because of detuning

Oscillation period switched here.



D+ beam 07/Dec, 2021, chopped

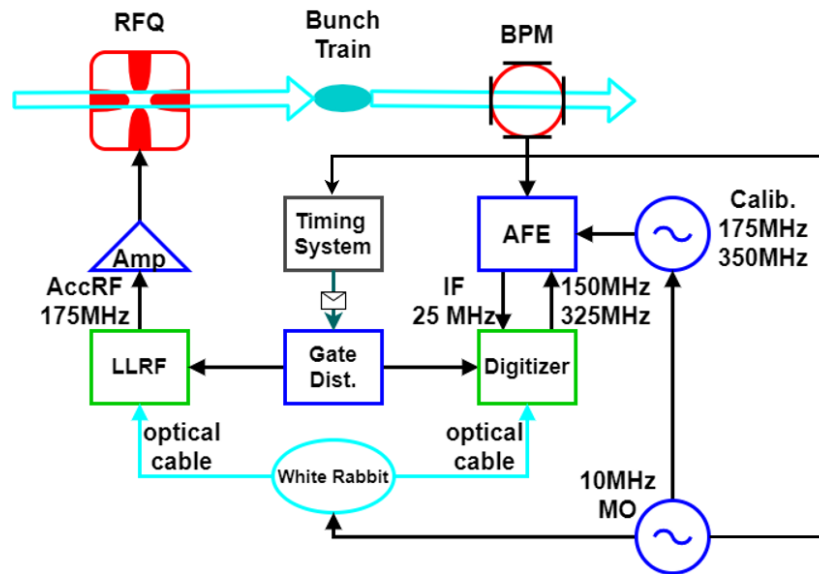
Beam induced voltage in the detuned buncher in presence of Kr Gas flow

Blue = 2.36sccm, 6.9E-5mbar

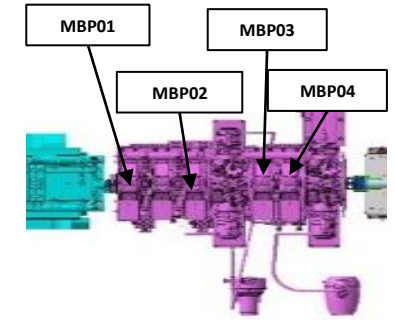
Red = 0.0sccm , 6.9E-5mbar

With Kr gas SCC, large amplitude oscillation was observed.

Mean Energy can be measured by beam position and phase monitor.



4 BPMs implemented in the MEBT is good to use for voltage calibration of the RFQ of Phase-C/D.



One phase locked clock by White Rabbit is shared among **4 BPMs**.
 → **Relative phase offset can be frozen among them.**

Data type of this measurement:
 Max 25MS/s for 1 channel. Output rate (memory storage rate) is 100MS/s.

To focus on the relative change of mean energy, offset value to the phase calibrated by beam.