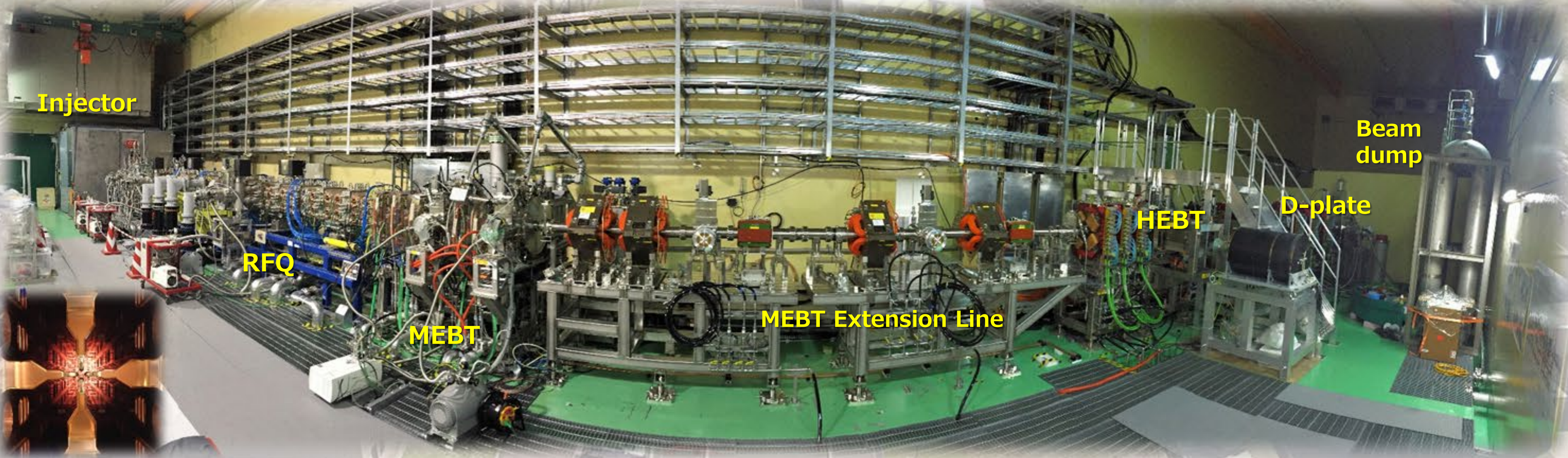
Commissioning of IFMIF Prototype Accelerator towards CW operation

Kai Masuda

The 31st Linear Accelerator Conference (LINAC 2022)

Liverpool, UK – 30/Aug/2022



Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

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And many not shown above have contributed and supported the LIPAc activities.

Contents

IFMIF Concept and LIPAc

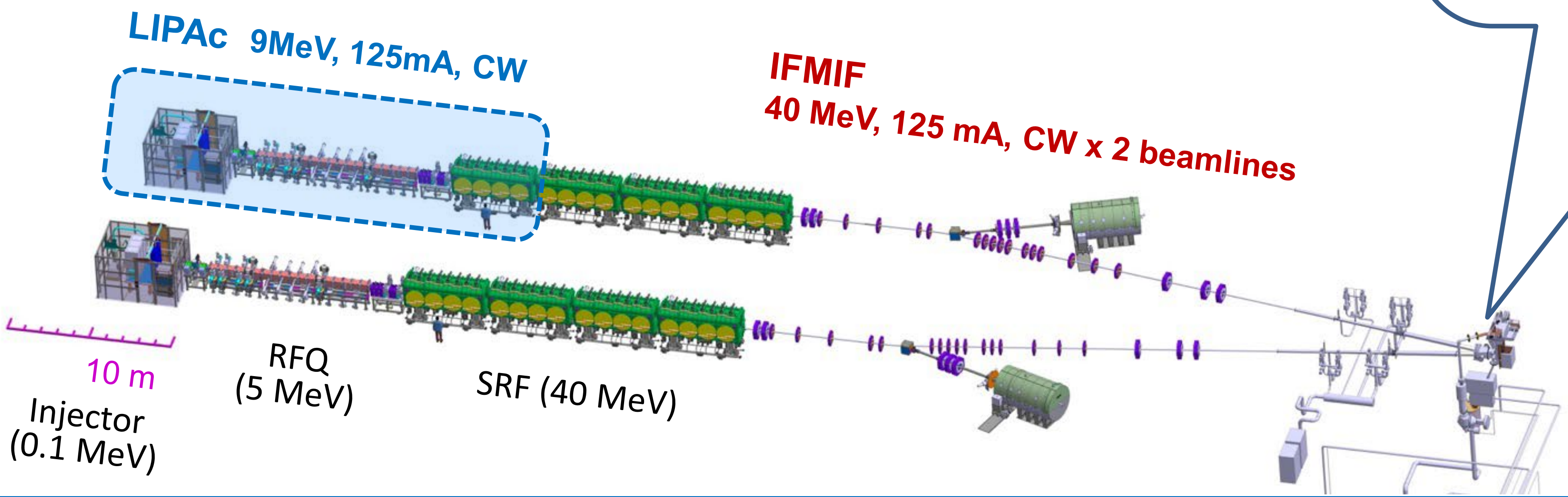
International Advisory Panels pointed out Fusion Neutron Source as essential need toward Fusion Power Plant

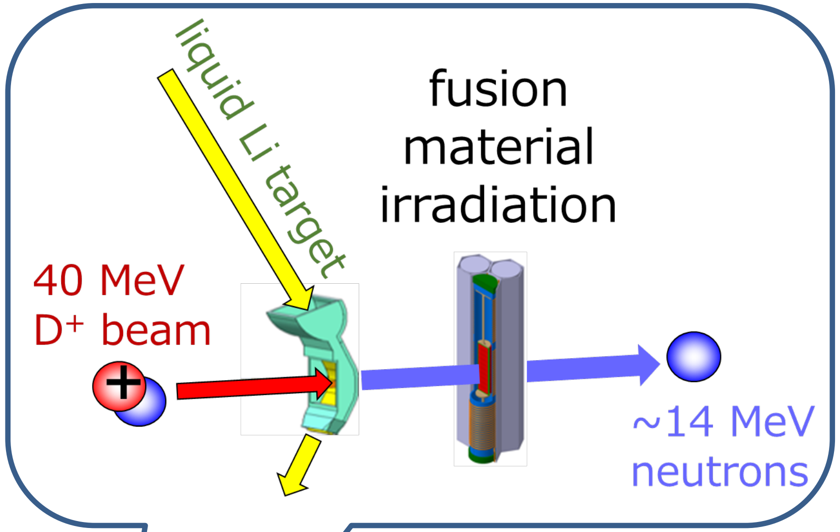
→ best fulfilled with a D-Li stripping source

→ IFMIF concept, requiring a challenging accelerator

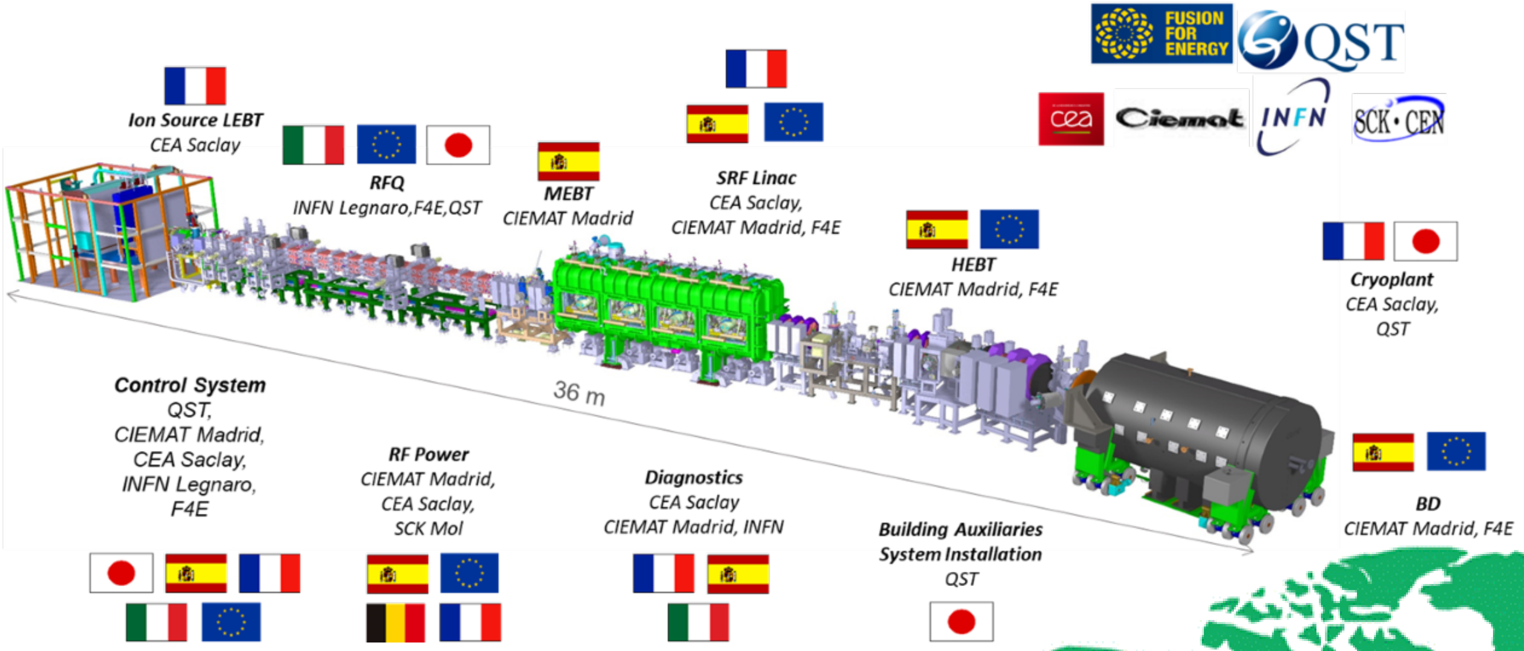
- ☐ World's highest D^+ beam current and beam perveance,
- ☐ World's longest RFQ,
- ☐ World's record of hadron current through SC cavities,
- ☐ **Beam availability in CW > 87 %.**

→ **L**iner **I**FMIF **P**rototype **Ac**celerator (**LIPAc**) **for the engineering validation**



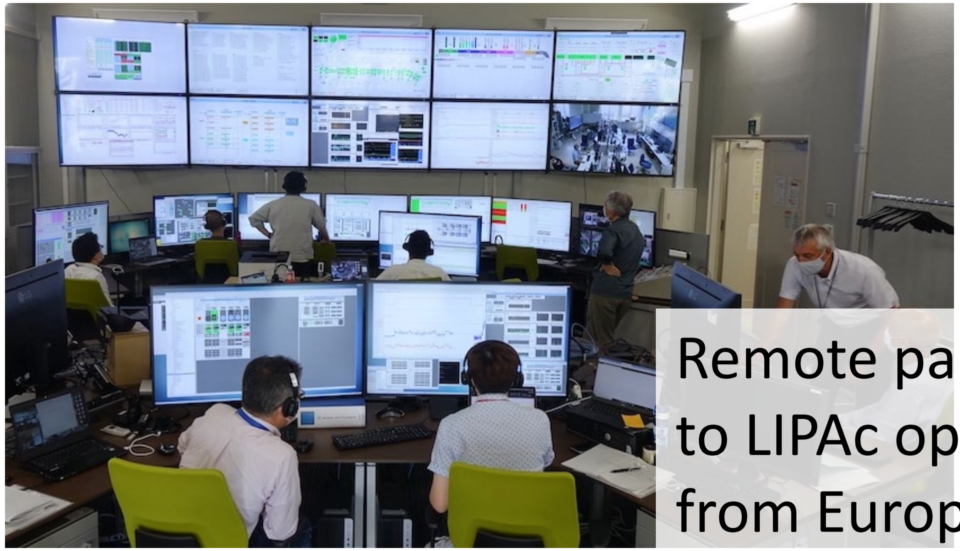


LIPAc – EU/JA Scientific Collaboration



Equipment designed and constructed in Europe,

installed and commissioned in Rokkasho.

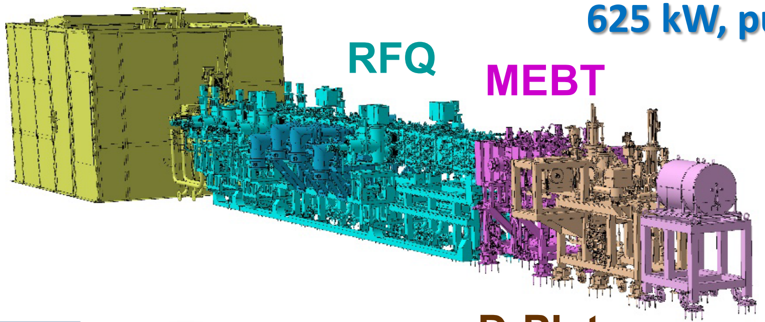


Remote participation to LIPAc operation from Europe

Contents

Stepwise Installation and Beam Commissioning

Phase B completed in Aug. 2019.



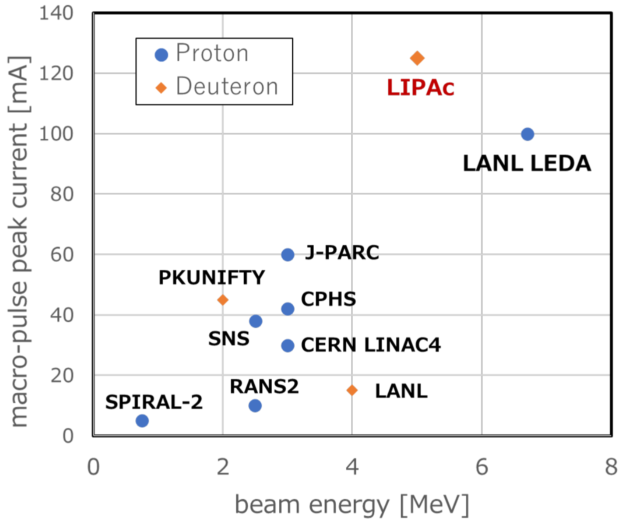
5 MeV - 125 mA
625 kW, pulsed (up to 0.1 % duty)

Injector | CW

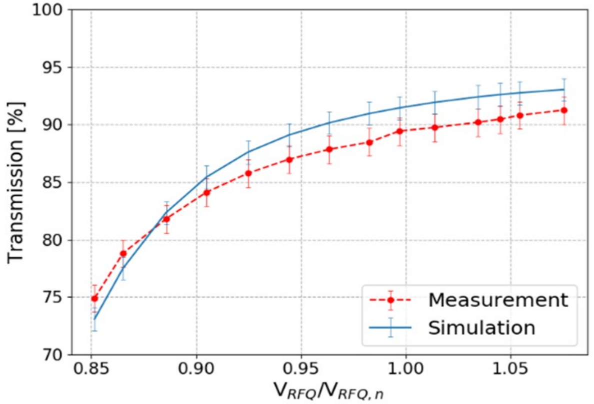
Phase A *(Apr.2015 - Aug.2017)*

Injector | RFQ + MEBT | D-Plate | pulsed

Phase B *(Jun.2018 – Aug.2019)*



- 125 mA D^+ (macro-pulse peak) through RFQ reached on 9th Aug 2019 [1,2].



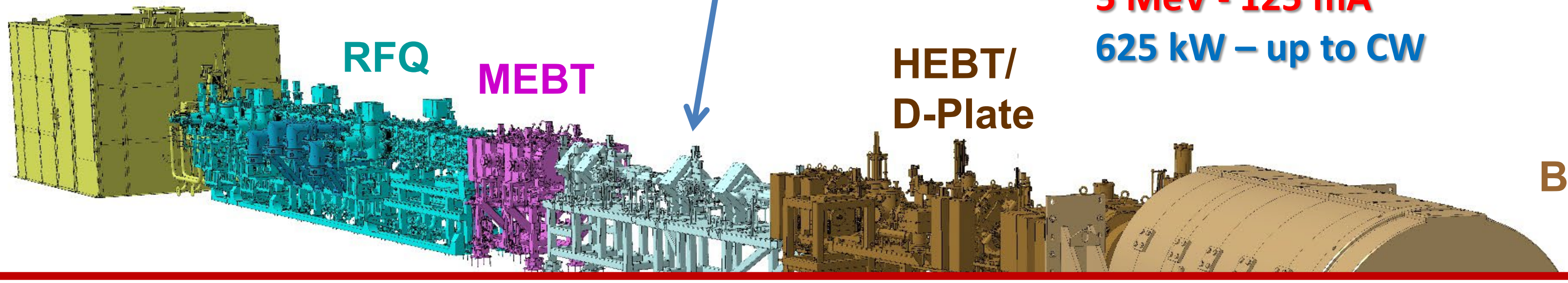
- Confirmation of designed beam dynamics in terms of beam transmission through RFQ [3].
- No significant trace of unexpected beam loss [4].

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

Stepwise Installation and Beam Commissioning

Phase B+ started last July and ongoing.

MEBT Extension Line temporarily placed in the position of SRF linac.



Major Goals of Phase B+

- To validate Injector, RFQ and MEBT (incl. bunchers) up to CW with the nominal 125 mA D^+ beam.
- To validate BD up to 0.625 MW CW (5 MeV instead of 9 MeV D^+ beam).
- To validate beam diagnostics for both low and high duty operations.
- To characterize the beam properties to be injected into SRF linac in the following Phase C.

Injector | RFQ + MEBT | MEL | HEBT/D-Plate + BD | CW

Phase B+ (Jul.2021 –)

Injector | RFQ + MEBT | SRF | HEBT/D-Plate + BD | CW

The final configuration.

Phase C will start after completion of Phase B+

Strategy and Timeline of Phase B+

Ion source extraction aperture:
6 mmϕ PE

the present (Aug 2022)

Now in a 2-month break for scheduled maintenance

Phase B completed Aug 2019

Phase B+ Installation
MEL
HEBT
BD

Stage 1 of Phase B+ completed in Dec 2021
7 weeks, 10 mA H^+ and then 20 mA D+, $<10^{-3}$ duty

Injector CW Campaign
Optimization for 125 mA D^+ CW

RFQ & RFPS CW Campaign
RF conditioning towards CW

- RFQ validation with pulsed beams by use of LPBD
- BD to accept CW
- Tests and alignment checks of newly installed components with the "pilot" beams
- **Characterization of the Pilot beams**
- Verification of beam transport simulation
- Commissioning of the subsystems in preparation to the nominal 125 mA D+ beam operations in CW

TBD

in Injector CW Campaign

11-12 mmϕ PE

Stage 2 of Phase B+ planned to start in Spring 2023
12 weeks
~50 mA D^+ → 125 mA D^+
<5% duty

- **Beam characterization** with applicability of interceptive diagnostics

11-12 mmϕ PE

Stage 3 of Phase B+ will follow stage 2
12 weeks
125 mA D^+
5 % → CW

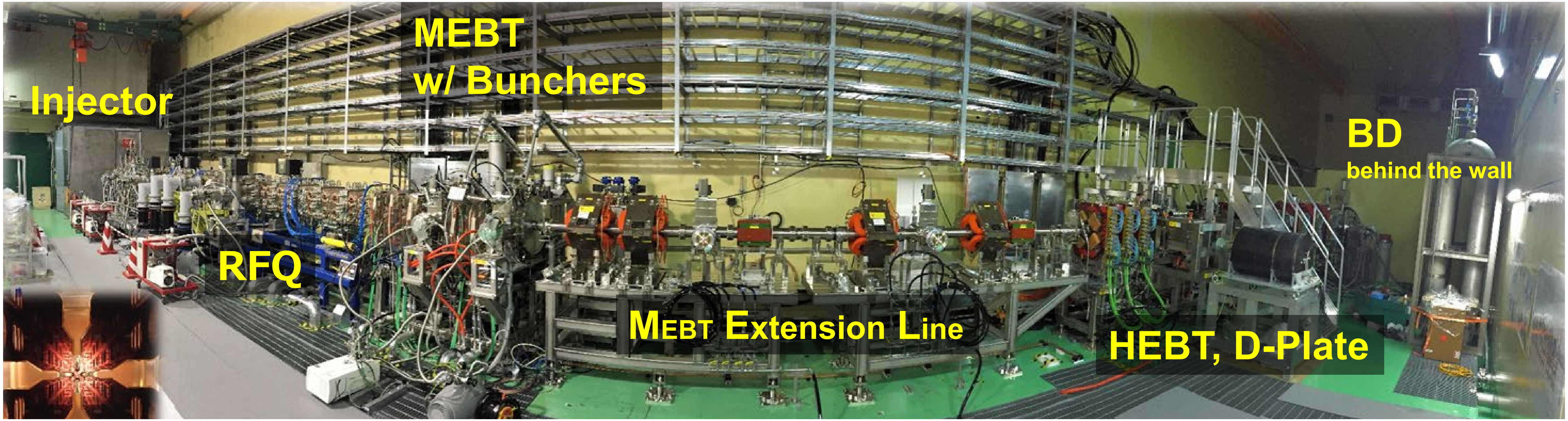
- **Beam commissioning towards CW** with non-interceptive diagnostics

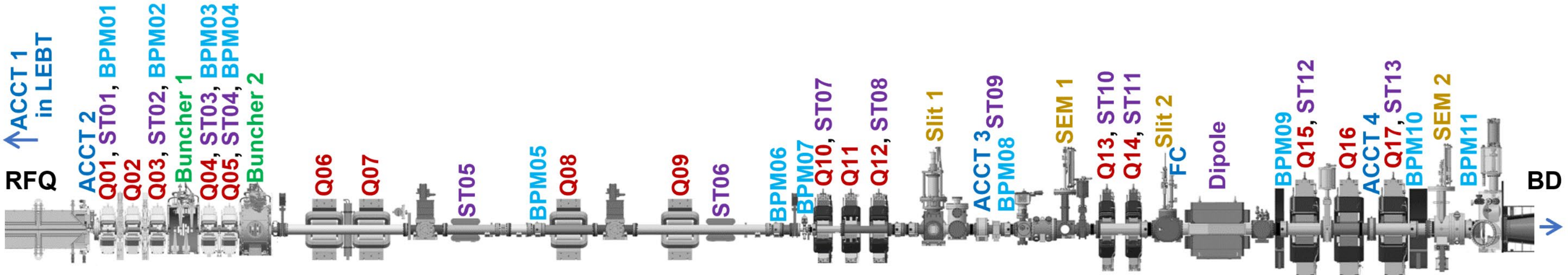
6 mmϕ PE, then **11-12** mmϕ PE

Phase C
SRF Installation.
Beam commissioning will **start with the pilot beams** (10 mA H^+ and then 20 mA D^+).

Contents

Experimental Layout



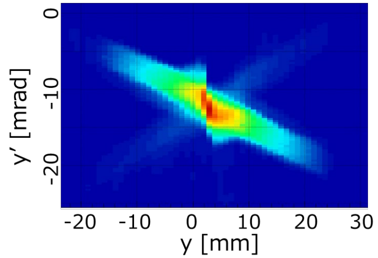


Non-interceptive diags. for use in the later Stages 2&3 are not shown for simplicity.

Results from Beam Commissioning Stage 1

– Injector –

- The Pilot beams = ~10 mA H^+ & ~20 mA D^+ @ **MEBT ACCT** (RFQ exit)
  - ✓ Use of **6 mmϕ PE** for the Pilot beams (cf. 11-12 mmϕ for 125 mA)
  - ✓ Determination of **ECR** power, **IE** bias, **SOL**enoids, **ST**eerings, Kr gas flow etc.
  - ✓ Beam characterization by use of **EMU** (Allison scanner).



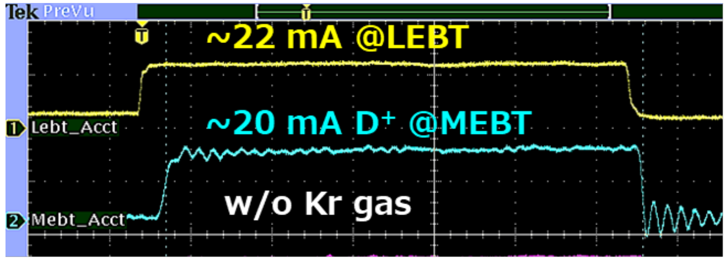
~22 mA D^+ @LEBT

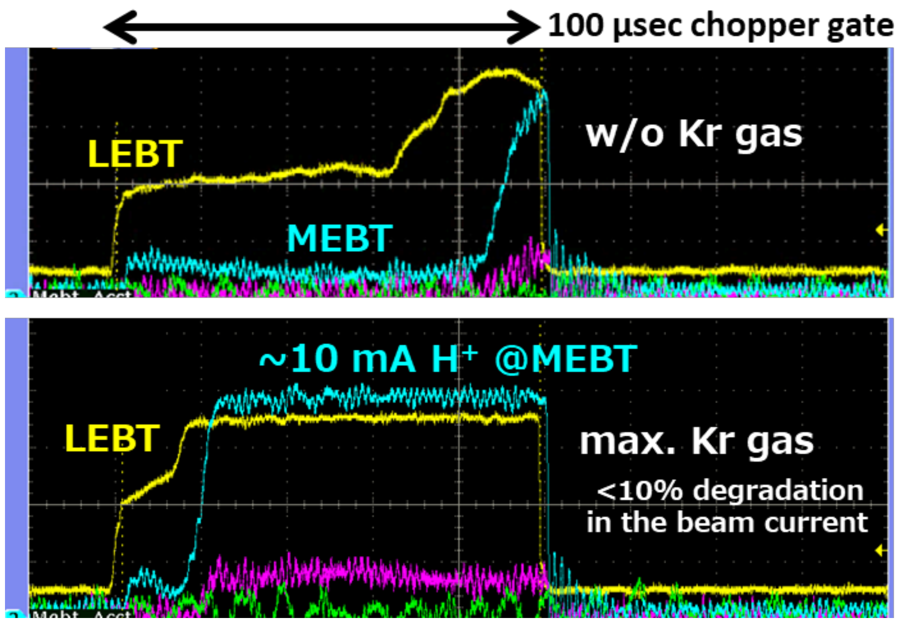
$\varepsilon_{n,y}$ = 0.095 [π mm mrad]

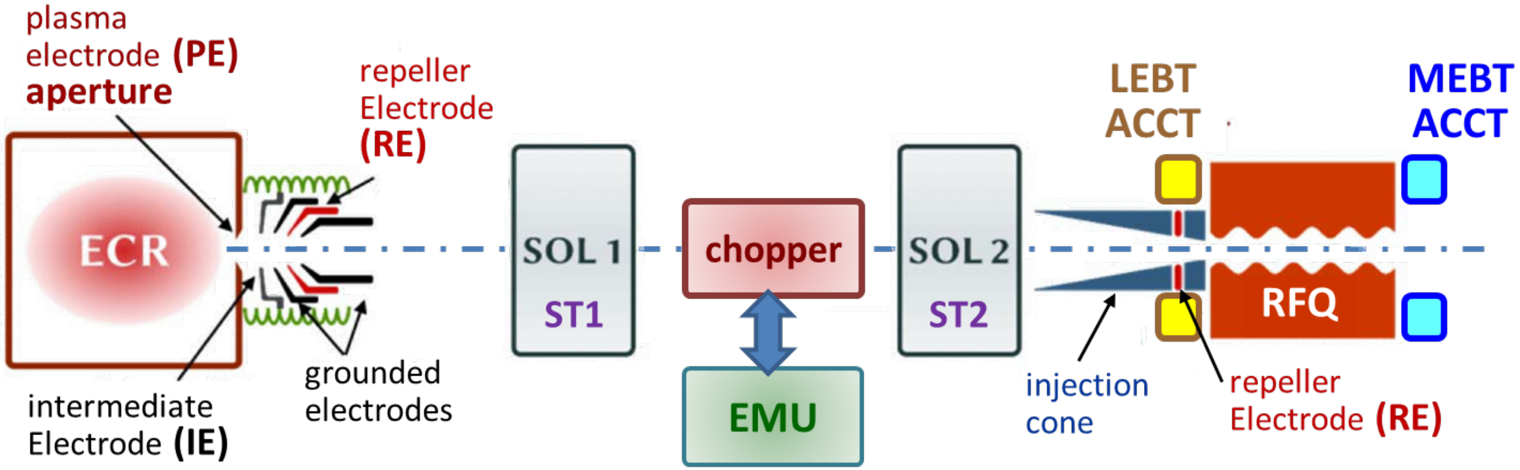
β_y = 5.5 [mm / πmrad]

α_y = 1.9

- Pulsing by **Chopper**
  - ✓ No issue confirmed for ~20 mA D^+. (To be tested up to 125 mA in Stage 2)
  - ✓ Significant delay / transient at the rising edge for ~10 mA H^+.
    Probably Space Charge Compensation (SCC) build-up process following the Chopper gate opening (details to be published later).







Results from Beam Commissioning Stage 1

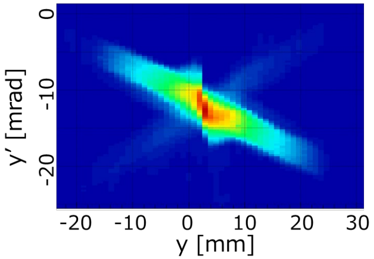
– transverse profiles and comparisons with simulations (1/5) –

Beam transport simulations

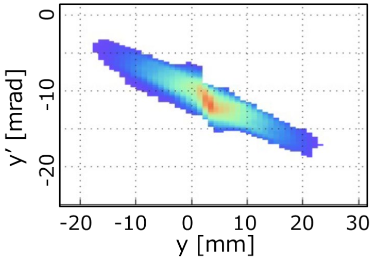
1. Start at EMU position with the measured y-y’ profile.
2. Determine the SCC degree (SCCD) between EMU and RFQ entrance.

   Uniform SCCD was assumed (though strong s-dependence is known[2]), and

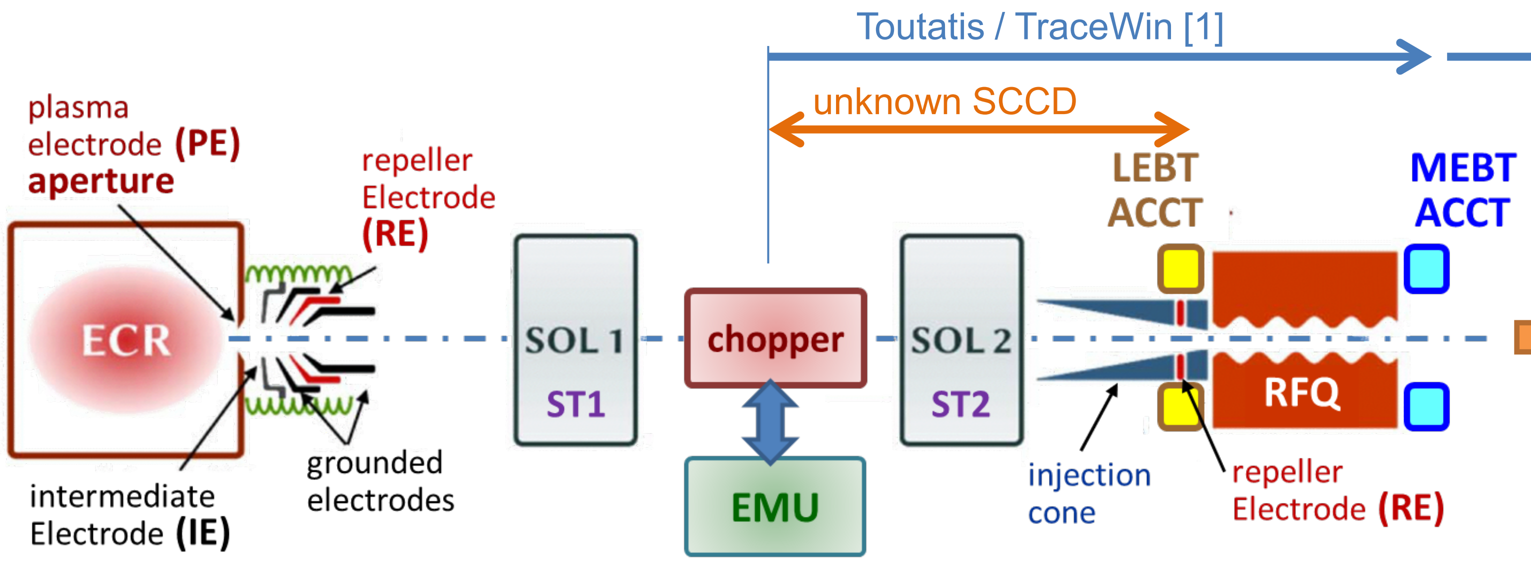
   was determined so as to reproduce experimental dependence of beam transmission to MEBT ACCT on SOL2 current



EMU measurement



Simulation input.
- 10^6 particles.
- Cylindrical symmetry was assumed.



3. Transport down to BD.
   - 2 bunchers in MEBT (one not in use this time).
   - 17 quads, 1 bending, (13 steering magnets).

4. Comparison with measurements.

   3 transverse **profile monitors** along the beam line to be compared with simulations.

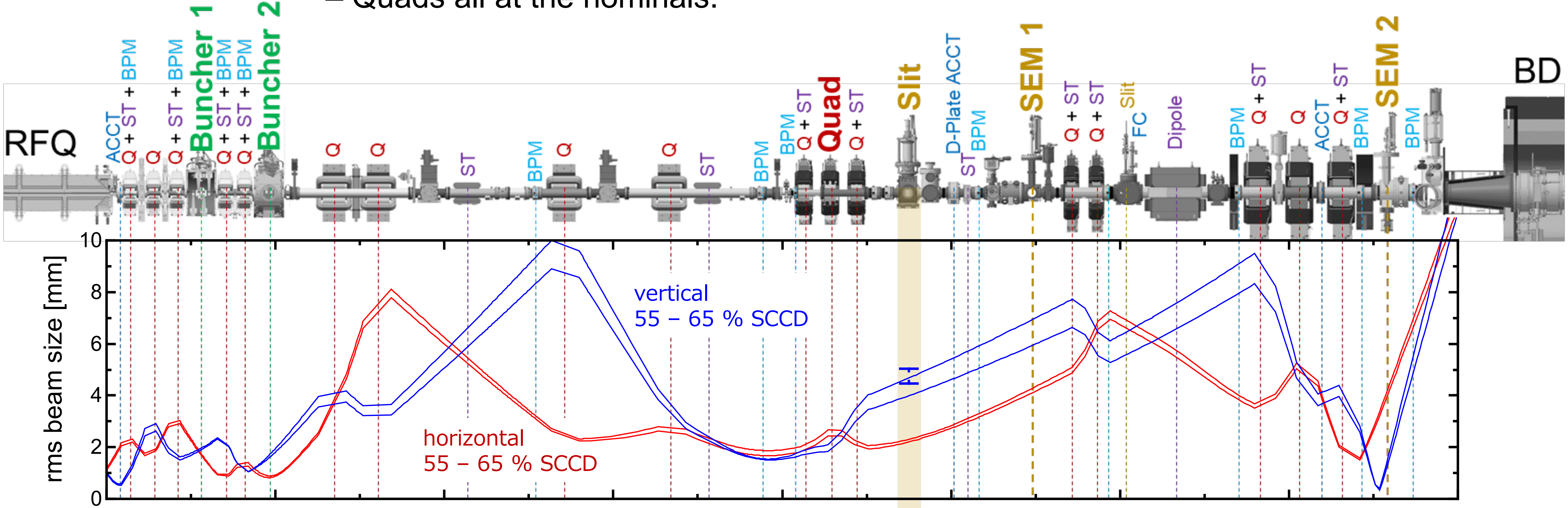
[1] https://dacm-logiciels.fr/
[2] L. Bellan et al., ICIS2021.

Results from Beam Commissioning Stage 1

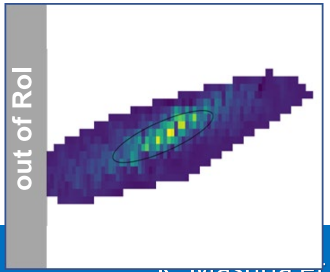
– transverse profiles and comparisons with simulations (5/5) –

Case 3 – w/o Buncher (both Bunchers 1 & 2 at 0 kV)

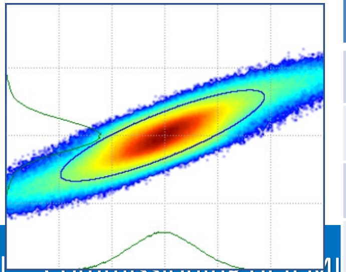
– Quads all at the nominals.



measurement



simulation (60% SCCD)



	measurement with 1σ error	simulation 55–65 % SCCD
$\sigma_{y'}$	1.96 ± 0.21	1.63 – 1.42
$\varepsilon_{n,y}$	0.44 ± 0.14	0.28 – 0.23
$-\alpha_y$	1.30 ± 0.43	1.82 – 1.59
γ_y / β_y	0.17 ± 0.06	0.12 – 0.12

within 1 σ
2 σ
3 σ
beyond 3 σ

⇗ SEM measurements were not done in this case.

⇖ **Slit** measurements agree well with simulation.

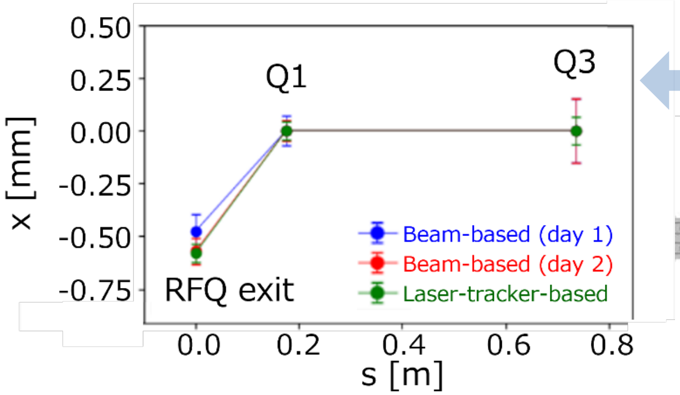
⇐ Agreement looks good enough.

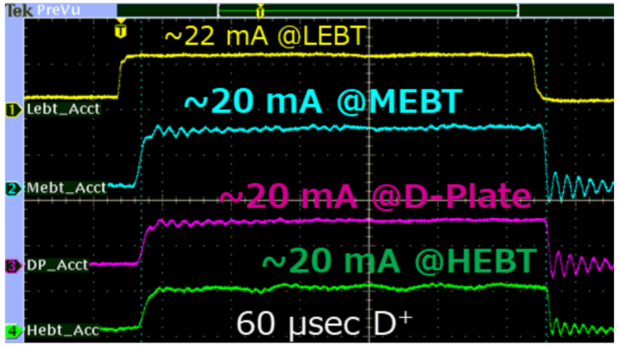
Results from Beam Commissioning Stage 1

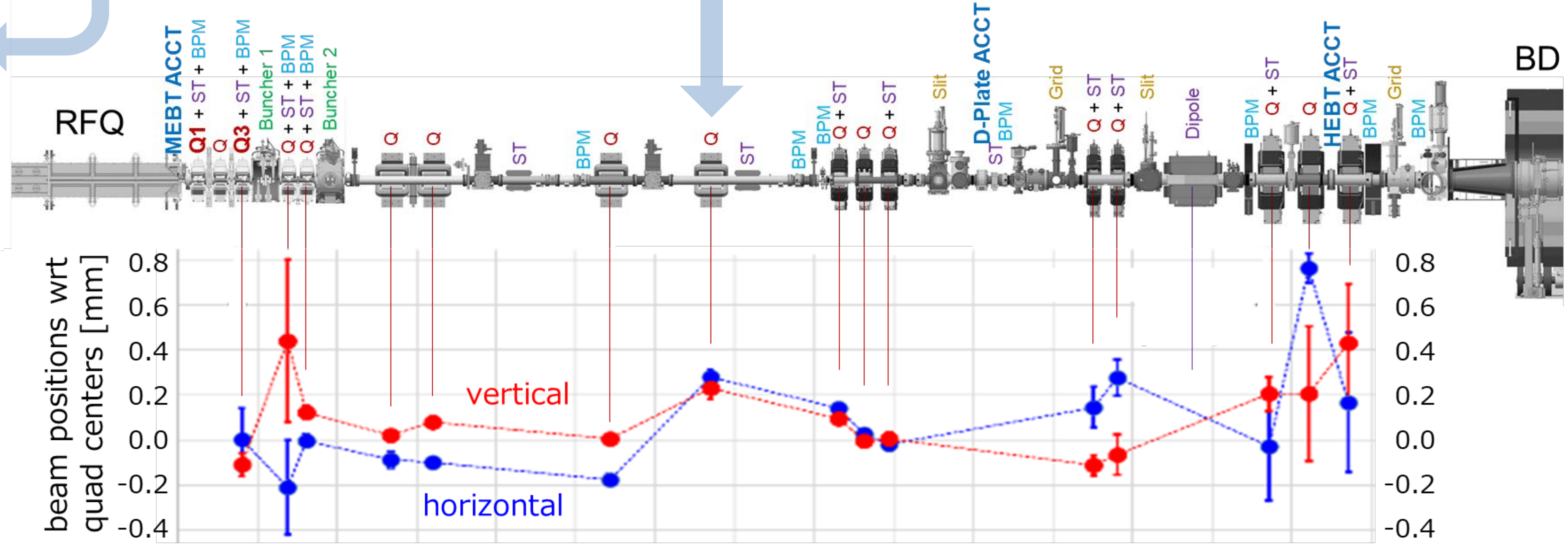
– beam transport and alignment checks [1]–

- ☑ Beam-based alignment of beam to selected **Q**uads (tuning of **ST**eerings).
- ☑ Beam-based determination of beam positions with respect to **Q**uads.
- ☐ Beam-based calibration of **BPM** centers with respect to **Q**uad centers
  → Postponed. RF noise and other issues in **BPMs** are being coped [2].
- ☑ Beam-based alignment checks of **Q**uads (evaluated from the **ST**eering angles).
  → ~0.5 mm horizontal misalignment was confirmed.

- ☑ 20 mA D^+ beam was transported down to the BD without significant beam loss.
- ☑ The use of a buncher made the beam visible in all the **BPMs** down to the BD as expected.





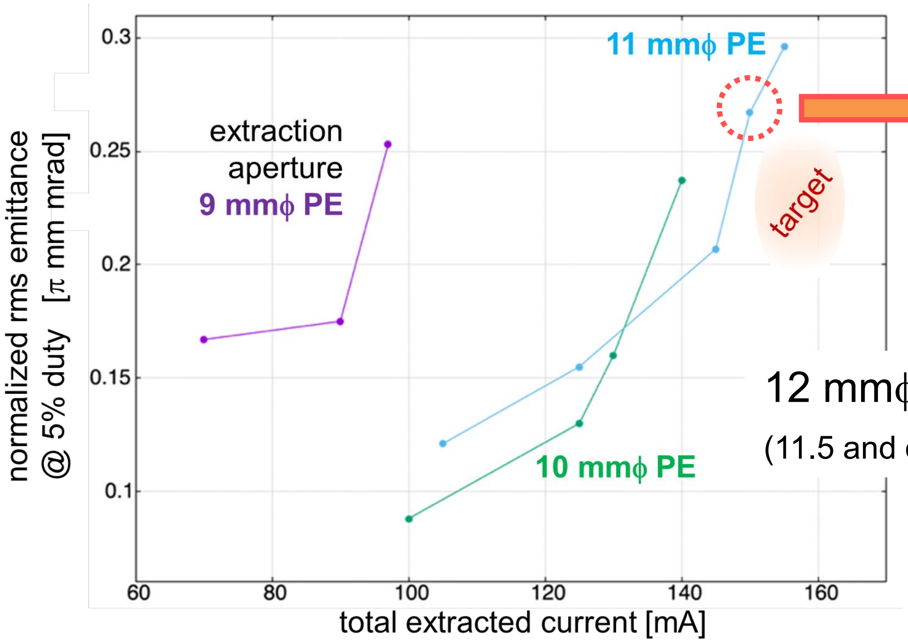


[1] J. Hyun et al., Proc. Annual Mtg. Particle Accel. Society Jpn., 2022.
[2] K. Hirosawa et al., ibid. (in Japanese).

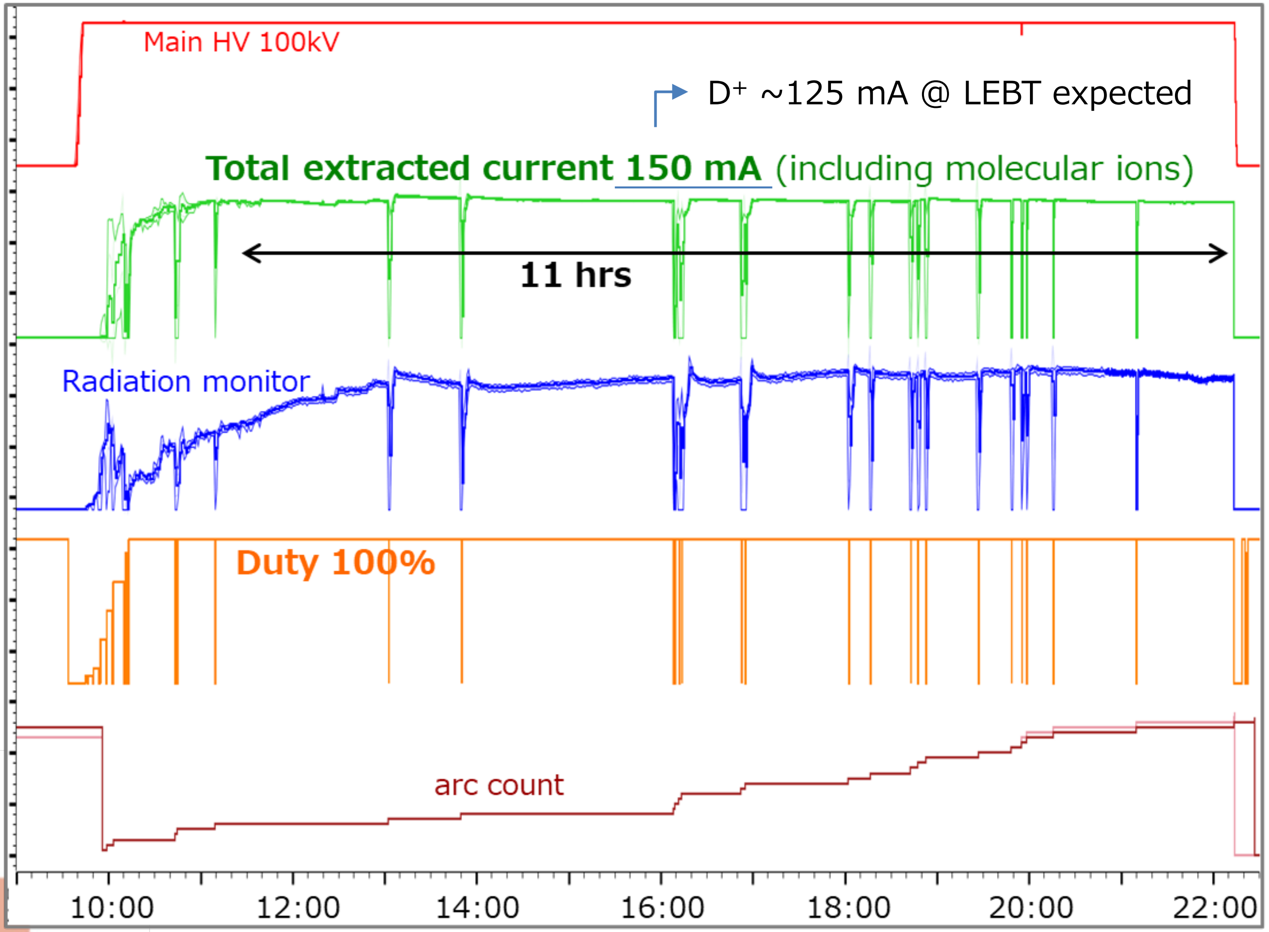
Contents

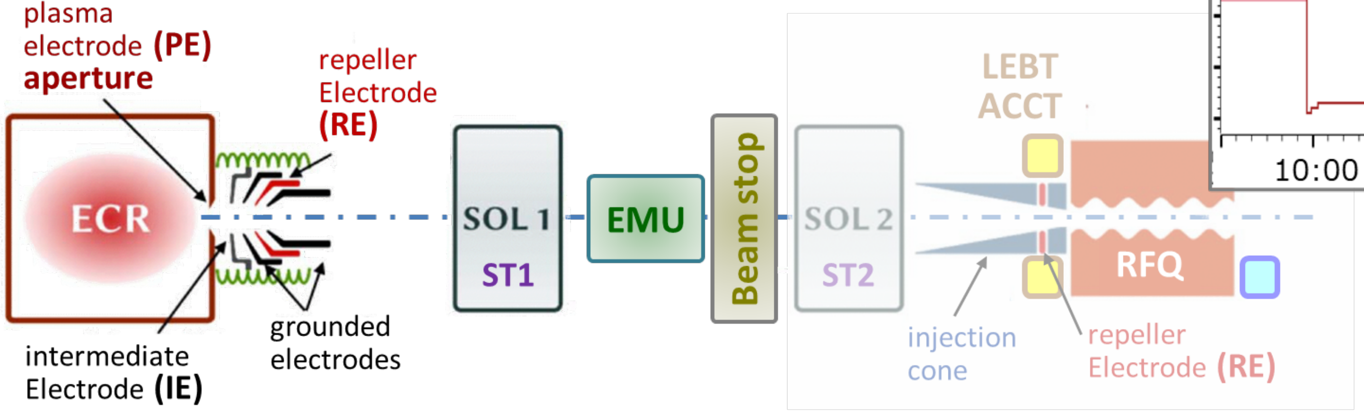
Injector CW Campaign

stably operational ε_n vs. I_{total} with different PE diameters



Injector CW long run with 11 mmϕ PE at I_{total} = 150 mA





The experimental survey will continue targeting at;

- I_{total} ~ 160 mA CW (to meet D^+ 125 mA @ MEBT)
- a better emittance

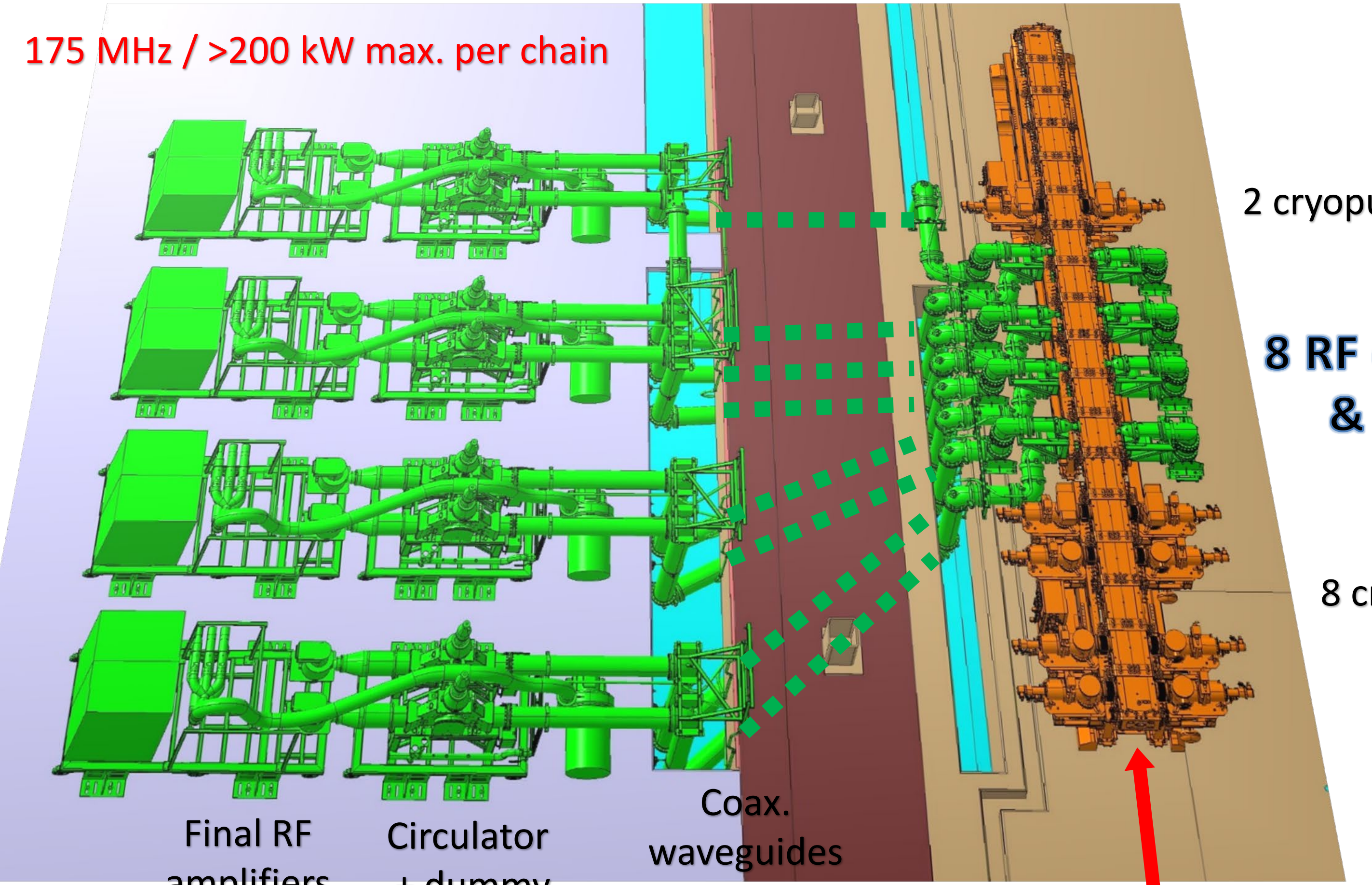
LIPAc RFQ & RF Power Supply

8-chain RFPS system [1,2]

1.5 m wall

RFQ consisting of 18 modules [3-6]

175 MHz / >200 kW max. per chain



2 cryopumps

8 RF couplers & windows

8 cryopumps

designed beam loss at low energy section [5,6]

Final RF amplifiers (tetrodes)

Circulator + dummy load

Coax. waveguides

Many components are not shown in this drawing.

from Injector

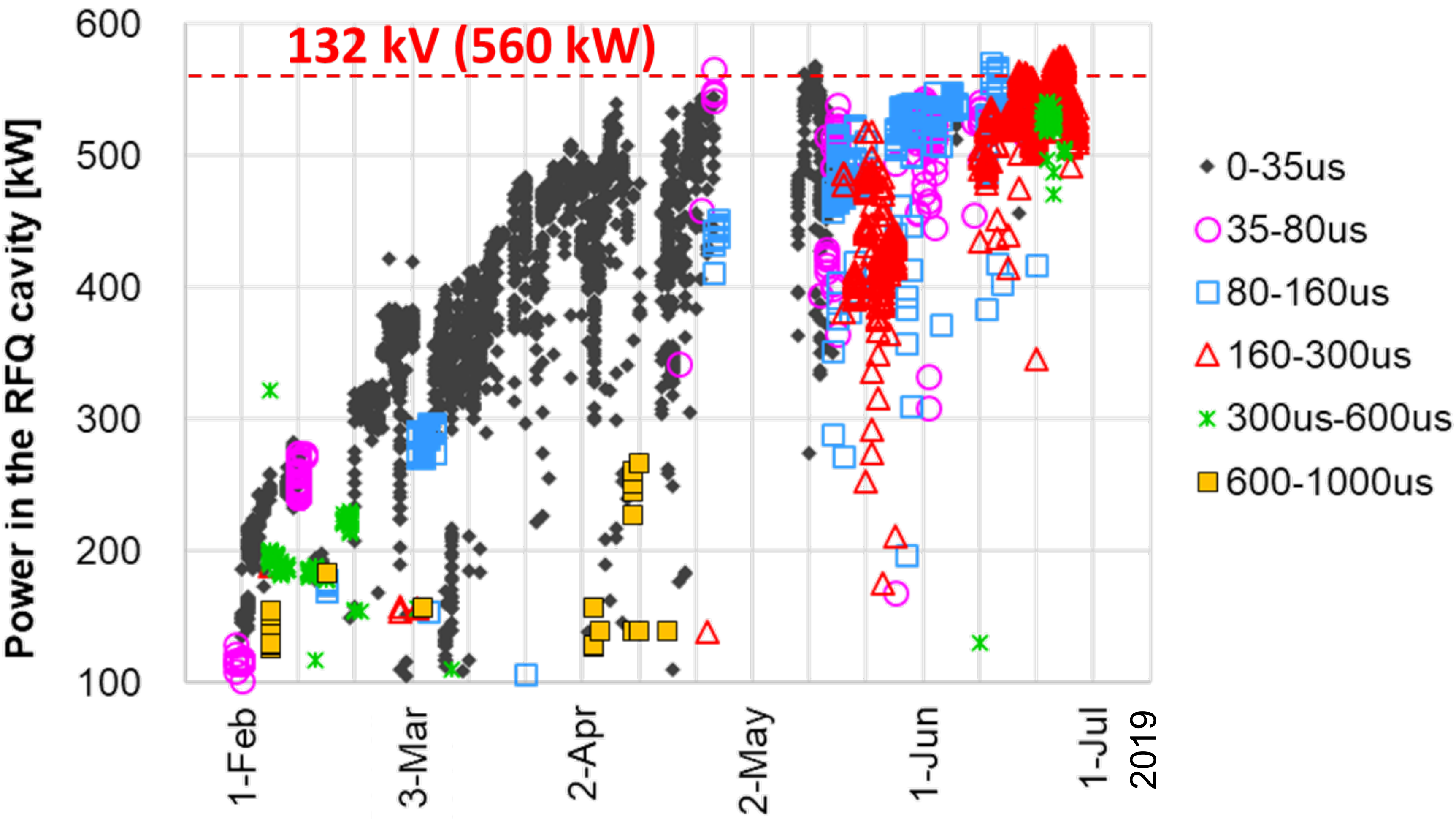
Tuning after assembly in Rokkasho

Baking (100 deg. C, 100 hrs)

[1] P. Mendez et al., Fusion Eng. Des. 165 (2021) 112226.
[2] M. Weber et al., IEEE Trans. Plasma. Sci. 49 (2021) 2987.
[3] A. Piesent et al., EPAC08, THPP078.
[4] F. Grespan et al., LINAC08, MOP037.
[5] M. Communian et al., EPAC08, THPP075.
[6] M. Communian et al., LINAC08, MOP036.

RF Conditioning of RFQ

up to the nominal vane voltage in pulsed mode reached in 2019 [1,2]



[1] K. Kondo et al., Fusion Eng. Des. 153 (2020) 111503.
[2] F. Grespan et al., IPAC2020.

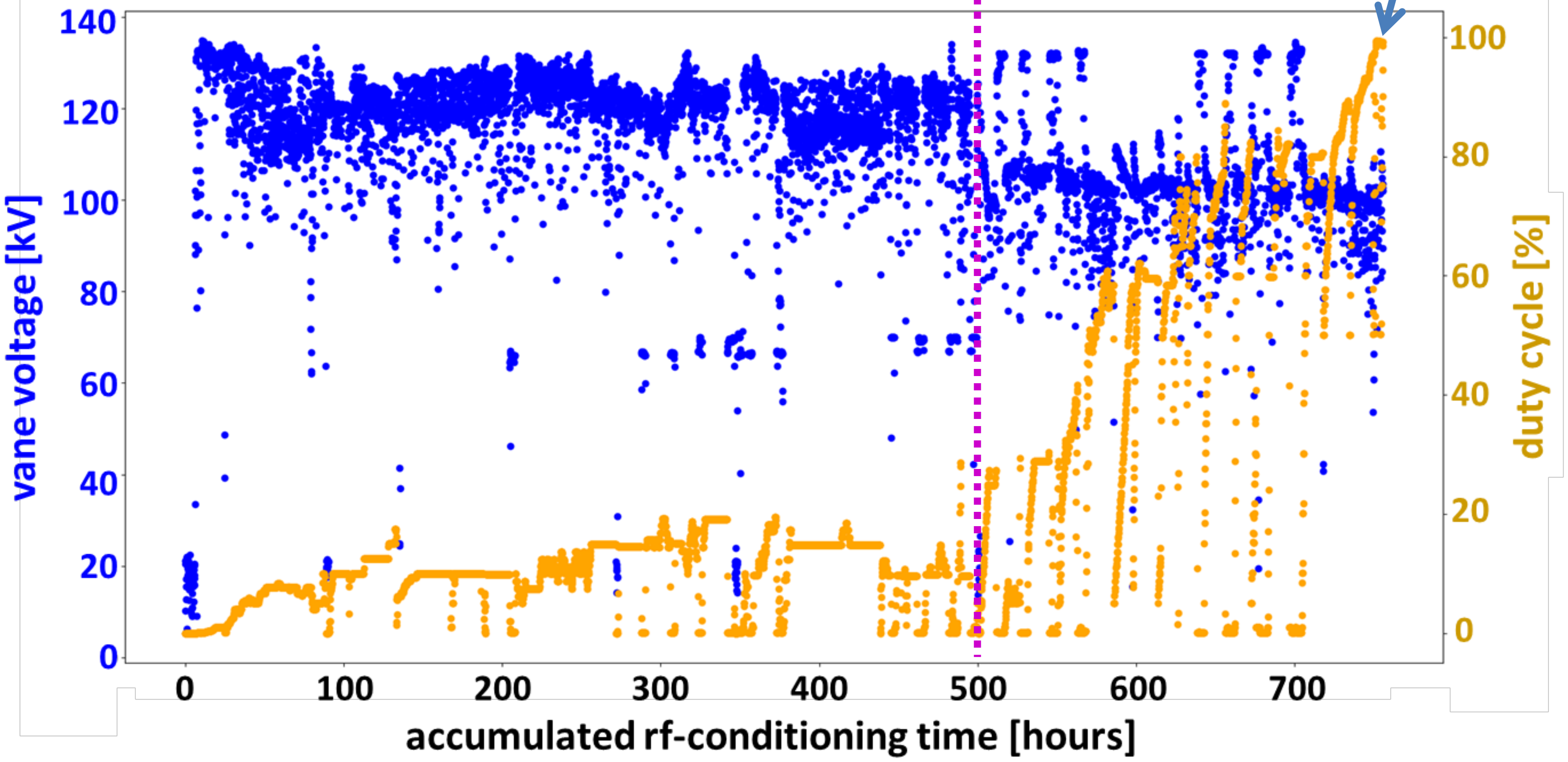
RF Conditioning of RFQ towards CW

Suffered from interlock events at ~25 % duty.

- Mostly voltage drop by LLRF control and rf reflection.
- Vacuum was OK.

Changed strategy to reach CW first and then increase voltage.

Reached CW at 80 % voltage.



RFQ RF-Conditioning Comparisons

The progress speed seems comparable to LEDA with a similar Kilpatrick,

though we don't know how intensive the RF conditioning in LEDA was.

In LIPAc, RF conditioning sometimes ran only during night shift in parallel to other day-time activities.

	type / length	Freq. [MHz]	Kilpatrick	Conditioning	
				period	achievement
LIPAc	4-vane 9.8 m	175	1.8	4.5 months	<1 msec, <20 pps (as of Jul. 2019)
				+1.5 months	CW at 80% voltage
LEDA [1,2]	4-vane 8 m	350	1.8	2.5 months#	CW
SARAF [3]	4-rod 3.8 m	176	1.5	< 1 day	<1 % duty
				5 days (36 net hrs.)	CW

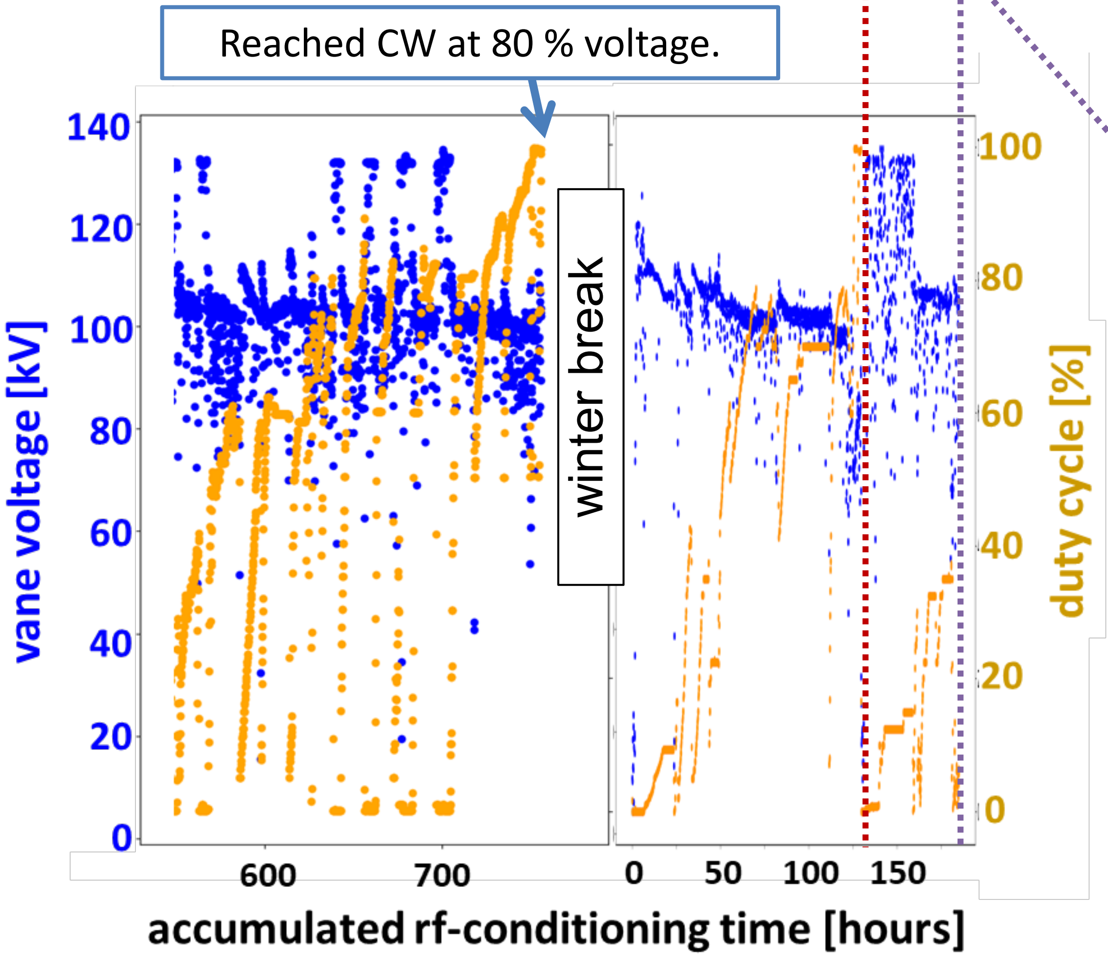
[1] L.M. Young et al., PAC1999.
[2] H.V. Smith et al., EPAC2000.
[3] A. Perry et al., LINAC2018.

excluding recovery work from coupler iris melting.

→ Major troubles we met in the next slide.

Major troubles we met

- ➢ **Recovery works are ongoing.**
- ➢ **RF conditioning to resume early next year.**



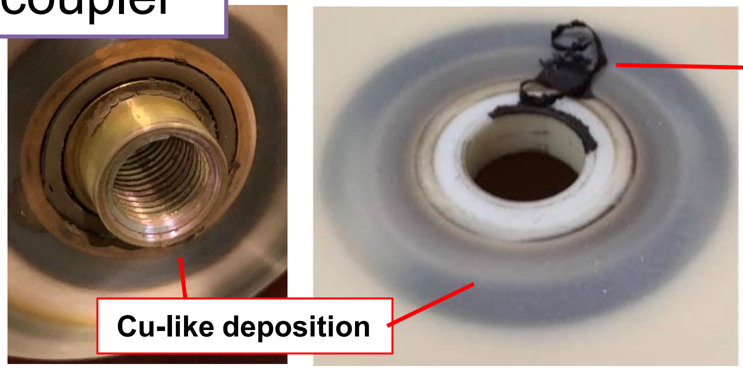
circulator

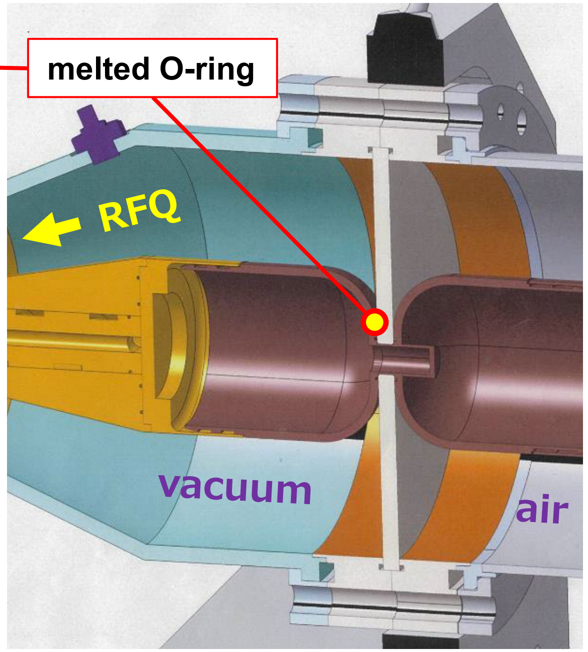
(Incident) Arcing due to a loose contact between coax. inner electrodes.

(Cause) Bolt loosening probably because of heat cycles.

(Measures) Use of brass bolts, regular checks. Under repairment in a factory of the provider.

rf coupler





(Incident) Viton O-rings were melted or deformed in 5 out of 8 rf couplers.

(Cause) Under investigations.

(Measures) Two ongoing in parallel;

- ➢ design work to improve the cooling of the inner conductor, and
- ➢ high power test of backup brazed and water-cooled couplers.

Contents

Conclusions

- Stage 1 beam commissioning – *completed*
  - The Pilot H^+ & D^+ beams (10 mA H^+ and 20 mA D^+) were tested and characterized.
  - The simulations could reproduce the measured beam sizes, and phase space profiles with satisfaction.
  - Newly installed components were mostly checked and validated.
    - Some needs of improvements were identified and are being coped with.
    - Checks of non-interceptive diagnostics should wait for a higher current & higher duty operation in Stage 2.
- Injector CW campaign – *ongoing*
  - Different dia. PEs were and are being studied in terms of stability, emittance, and extraction current.
  - I_{total} = 150 mA, CW (>11 hrs), $\varepsilon_{n,rms}$ = 0.27 π mm mrad were achieved by use of 11 mmϕ PE.
  - I_{total} ~ 160 mA is being targeted with a larger 12 mmϕ PE, or an intermediate one.
- RFQ RF-conditioning towards CW – *ongoing*
  - Achieved so far are;
    - ✓ CW at a reduced 80 % voltage, and
    - ✓ 25 % duty at the nominal voltage.
  - Recovery works from the coupler and circulator incidents are ongoing. RF conditioning is planned to resume early next year.

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.