



Report of electron beam acceleration with STF-2 cryomodules for the ILC

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ON BEHALF OF THE STF-2 COLLABORATION

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STF-2 Collaboration

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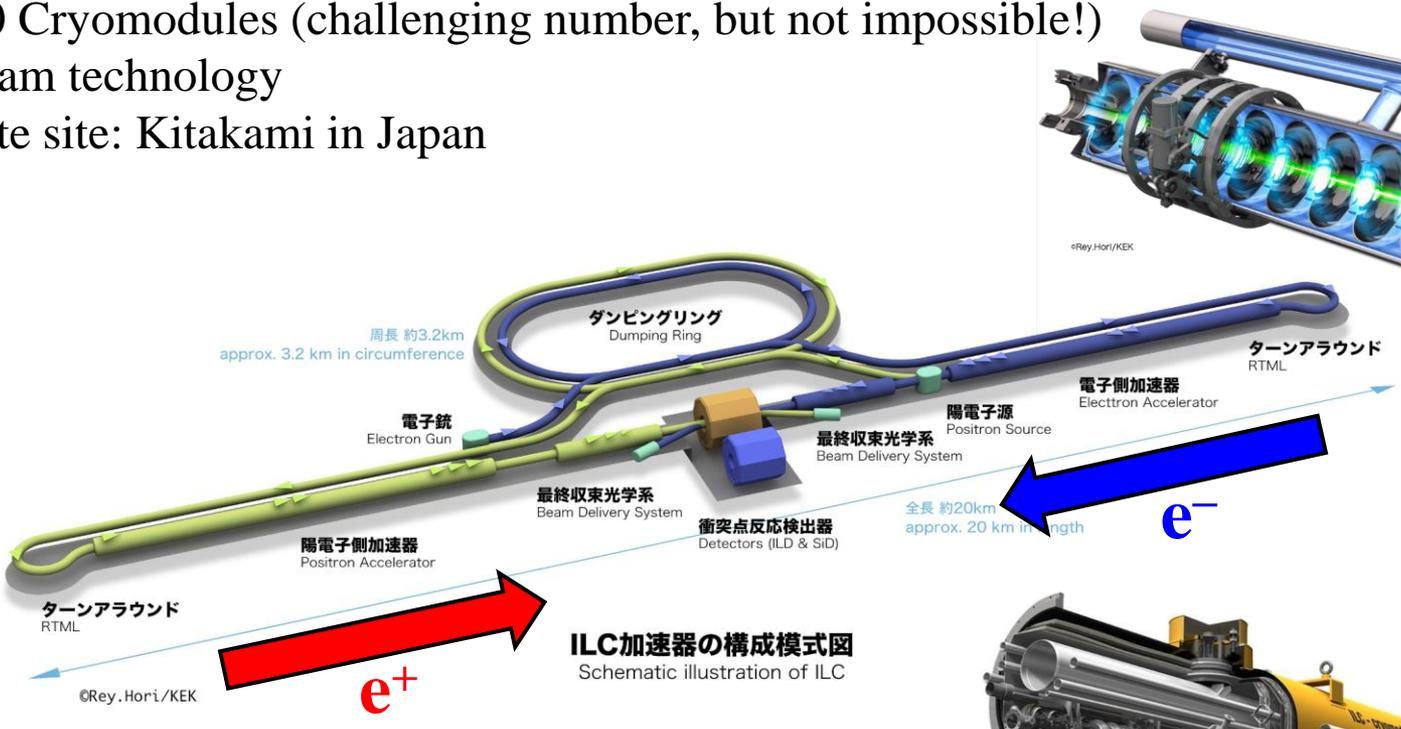


Introduction

- STF-2 have been developed to verify the technology of superconducting acceleration, which is the key towards realization of the International Linear Collider (ILC)
- Requirements for STF: Realization of ILC specification
 - High accelerating gradient operation
 - Long pulse, high current beam operation **without loss**
 - Beam quality: **Keeps emittance as designed**
- R&Ds have been proceeded to achieve those requirements
- We report the status of the studies at STF-2

ILC Project

- Higgs factory machine (250 GeV @ E_{CM})
- Superconducting cavity/cryomodule technology as mass production
 - ~750 Cryomodules (challenging number, but not impossible!)
- Nano beam technology
- Candidate site: Kitakami in Japan



ILC Spec.	E_{acc}	Q_0
Vertical Test	35 MV/m	0.8×10^{10}
Cryomodule test	31.5 MV/m	1.0×10^{10}

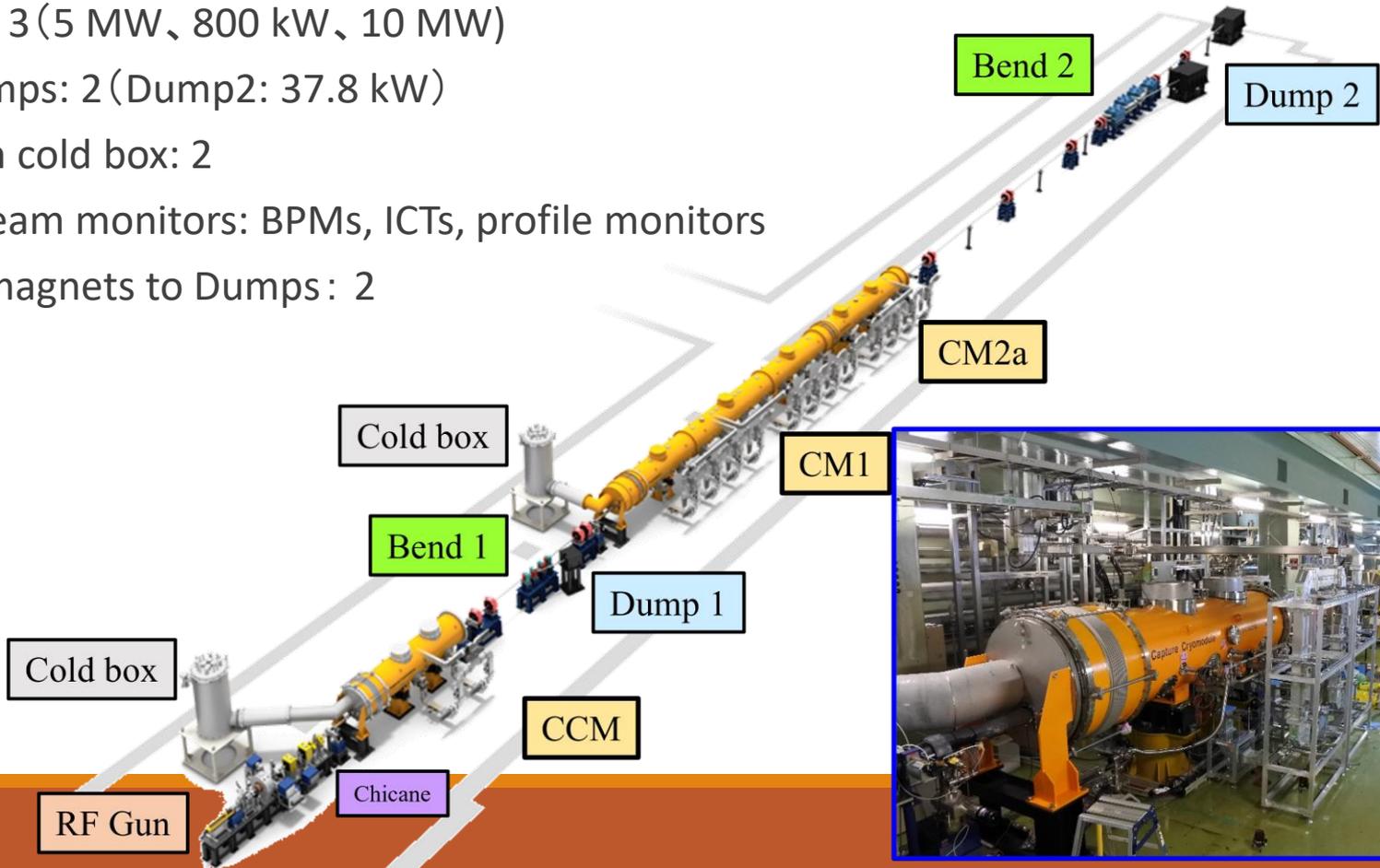
>90% (successful rate)

STF-2 accelerator

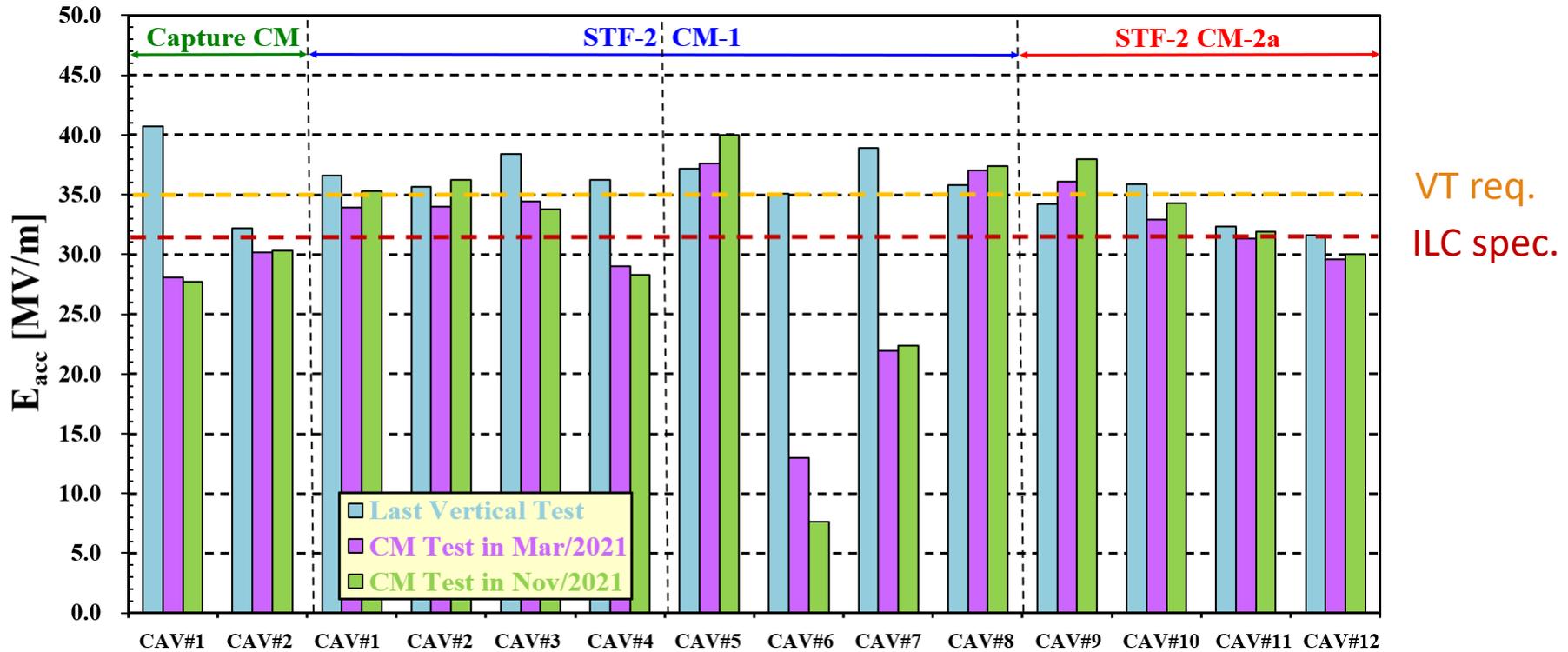
- ~70 m superconducting Linac (1.65 msec/5Hz)
- Superconducting cavities : 14 (1.3 GHz、9-cell)
- Cryomodules : CCM (2) CM1/CM2a (12)
- Photo cathode RF gun (Cs2Te、Q.E.~1%)
- Laser system : 162.5 MHz、1064 nm、12 W
- Klystrons : 3 (5 MW、800 kW、10 MW)
- Beam dumps: 2 (Dump2: 37.8 kW)
- 2K Helium cold box: 2
- Several beam monitors: BPMs, ICTs, profile monitors
- Bending magnets to Dumps : 2

- Specification since FY2020

Max. Energy [MeV]	500
Max. Beam Intensity [μA]	3.0
Max. beam power [kW]	1.35



Achievable Accelerating Gradient in CM1/2a in 2021



※ most of the cavities have same performance in FY2021

- In April 2021, beam operation with 14 cavities was successfully done
- 12 cavities have performance within $\pm 20\%$ of 31.5 MV/m
 - Some cavities have performance degradation due to
 - Abnormal heat load
 - Field emission

Max Average E_{acc} Operation

- In April 2021, beam operation with maximum averaged accelerating gradient using 9 cavities was performed
 - Averaged accelerating gradient:

	From beam	From RF
Averaged E_{acc} [MV/m]	32.9	33.0

- There is 5% margin from ILC specification
 - ILC specification: 31.5 MV/m

Cavity status monitor

The screenshot displays the 'Cavity Monitor (CM1, CM2a)' interface. At the top, it shows 'BEAM ON LINACモード' and the date/time '2021/04/12 17:45:58'. The main table lists parameters for 12 cavities (#1 to #12).

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Pf (W):	85.52kW	75.69kW	78.72kW	37.75kW	91.83kW	2.96kW	21.41kW	79.54kW	94.92kW	74.65kW	61.23kW	75.52kW
Pf Eacc(MV/m):	37.63	34.19	36.36	20.10	38.77	8.12	29.66	35.57	38.59	35.81	34.86	36.26
Pt(W):	11.78W	8.36W	7.38W	504.14uW	10.71W	341.25uW	1.20mW	11.64W	7.88W	7.48W	8.27W	5.98W
Pt Eacc(MV/m):	33.76	32.23	34.40	0.22	34.91	0.18	0.39	35.01	35.44	31.96	30.30	28.98
E-Pulse(mV):	329.000	244.000	298.000	103.000	219.000	151.000	128.000	187.000	882.000	691.000	197.000	-99.000
E-Charge(mV):	103.000	283.000	165.000	107.000	265.000	316.000	207.000	188.000	790.000	523.000	-707.000	50.000
Arc(mV):	196.000	191.000	200.000	191.000	200.000	214.000	217.000	198.000	134.000	180.000	131.000	171.000

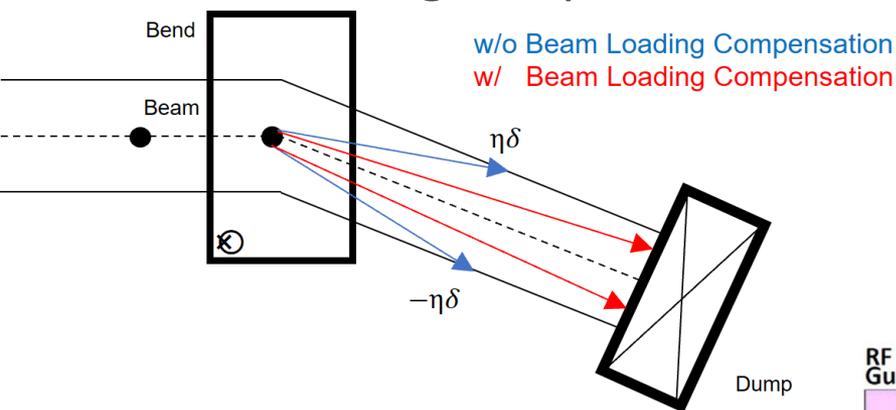
Below the main table are several monitoring panels:

- Heriumu:** flow rate 2K: 54.725 m³/hour, float rate 5K: -0.125 m³/hour, Heat Load 2K: 63.846 W, Pressure 2K: 3.01 kPa, Pressure 4K: 125.30 kPa, Level 4K: 51.21 %, Level 2K: 54.35 %, Level CM2a End: 22.90 %.
- Vacuum:** Capture Upstream: 2.35E-7 Pa, Capture Downstream: 1.78E-7 Pa, Capture Input coupler: 7.46E-7 Pa, Capture Inner conductor: 4.12E-8 Pa, CM1 Upstream: 1.41E-7 Pa, CM1 Input coupler: 5.44E-6 Pa, CM1 Inner conductor: 2.28E-8 Pa, CM2a Downstream: 2.24E-6 Pa, CM2a Input coupler: 5.44E-6 Pa, CM2a Inner conductor: 4.93E-8 Pa, CM1/CM2a Vessel: 1.01E-3 Pa.
- Power:** KLY3 上 Pf: 2.18MW, KLY3 下 Pf: 2.32MW, Pt Eacc sum: 297.78MV/m, Pt Eacc ave.: 24.81MV/m, Input Volt: 2.17V.
- Radiation:** Low/High values for Up, Mid, and Down detectors.
- Feedback:** Feedback: ON, Ref Power: 33.32.
- Beam:** Momentum and Energy values for BH1 and BH2.

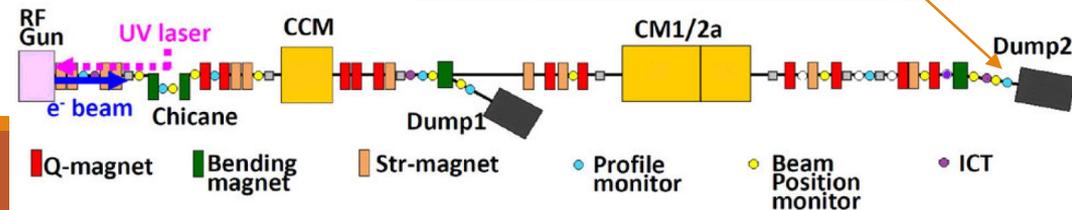
A red box highlights the 'Pt Eacc sum' (296.99MV/m) and 'Pt Eacc ave.' (33.00MV/m) values in the Power panel.

Middle pulse beam operation without loss

- At beam operation in April 2021, severe beam loss near Dump2 was a big problem for high current operation
- **Beam loading** makes energy spread in the pulsed beam
 - **Gradient drop** happens in the accelerating cavities
- Beam hits on the beam line due to dispersion
 - Electrons with different energy go through different orbits after bending magnet
- We would like to do long pulsed beam operation without loss
 - Beam loading compensation is indispensable



Signal of Cherenkov counter



Plan of STF-2 beam operation

We plan a beam operation with same pulse length as ILC specification

	F.Y.2019	F.Y.2020	F.Y.2021	F.Y.2022	ILC spec.
Item			Middle train	x 7 beam power	
Max. beam energy [MeV]	500	500	500	500	500 GeV
Max. beam intensity [μ A]	0.30	3.00	3.00	21.5	21.0
Max. beam power [kW]	0.135	1.350	1.350	9.675	14 MW
Max # of bunch / train	1000	1000	16260	118048	1312
Bunch spacing [nsec]	6.15	6.15	6.15	6.15	554 nsec
Max train length [μ sec]	6.15	6.15	100	726.00	726.848 μ sec
Max. RF repetition rate [Hz]	5	5	5	5	5 Hz
Bunch charge [pC]	60	600	36.90	35.66	3.21 nC
Bunch current [mA]	9.756	97.561	6.00	5.799	5.8 mA

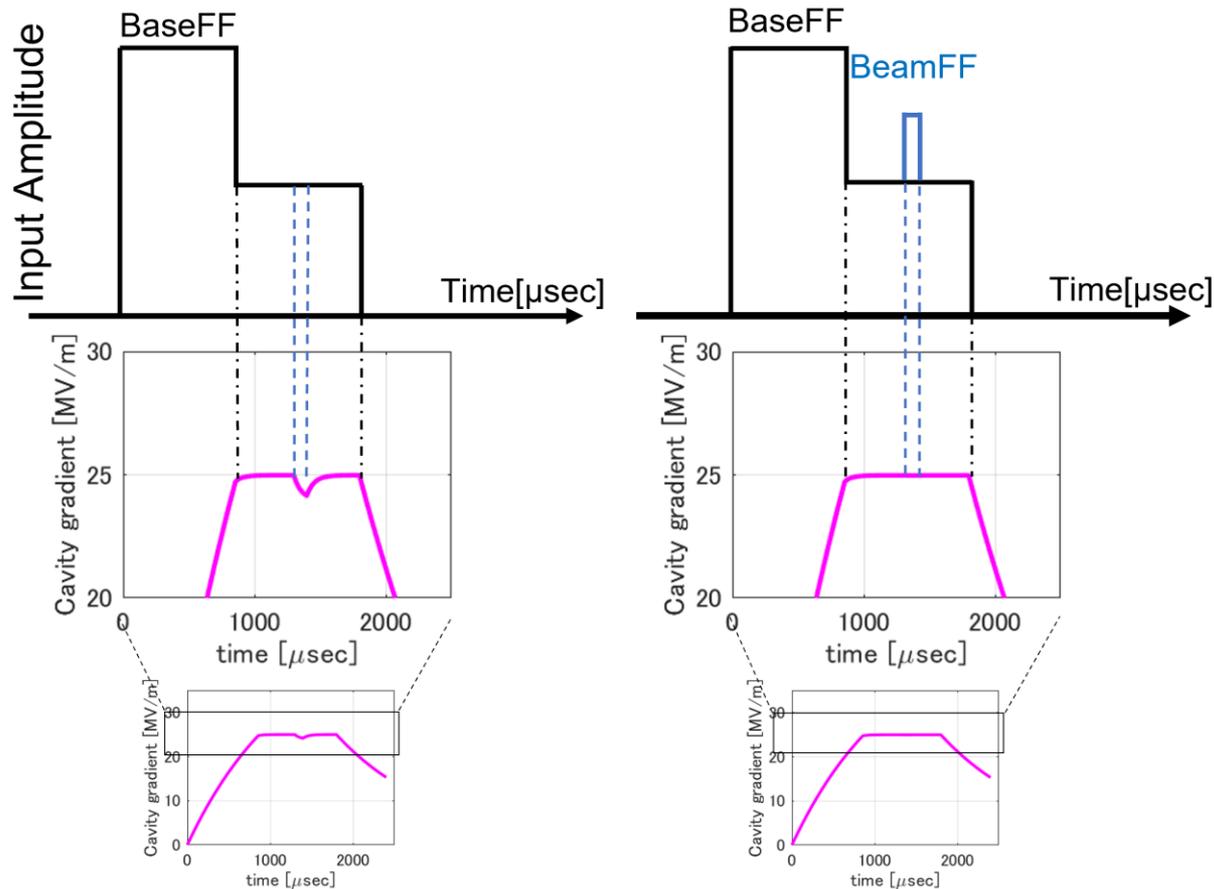
Comparison between the 2021 plan and middle pulsed beam operation in Dec. 2021

- Almost same pulse length as target

parameter	Beam Energy [MeV]	Pulse length [μ sec]	Bunch charge [pC/bunch]	Rep. rate [Hz]
Specification	500	100	36.9	5
Achievement	312	98.4	26	5

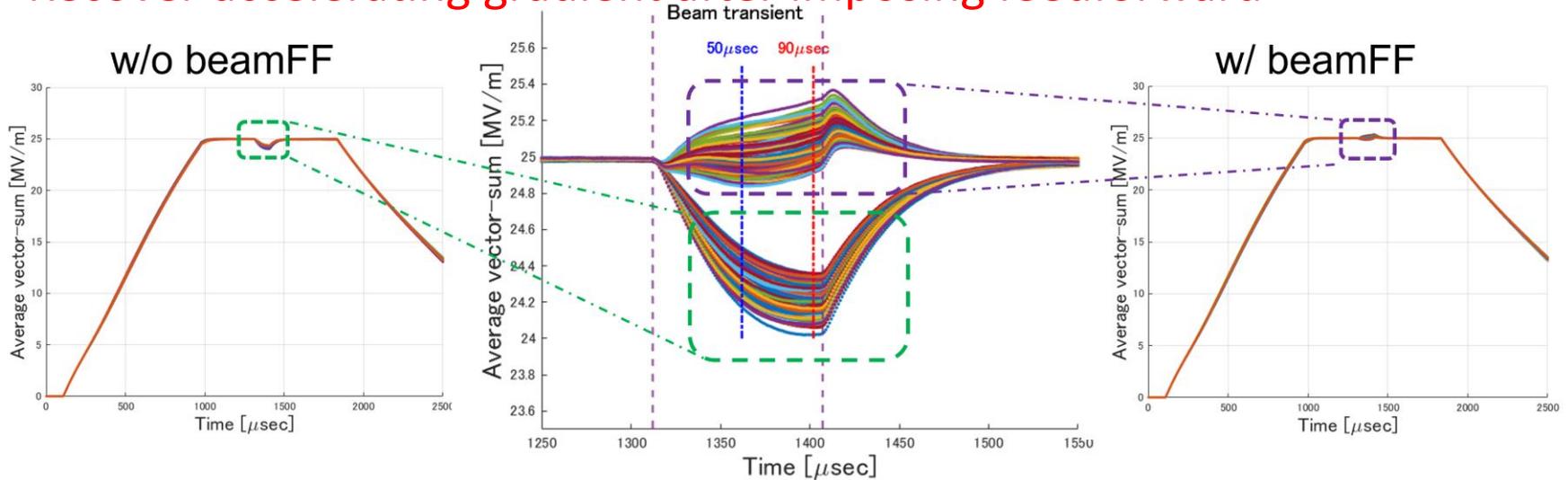
Beam Loading Compensation

- To achieve stable flattop accelerating field:
 - Unexpected disturbance: feedback
 - Repetitive disturbance: Feedforward – Additional driving power imposed
- ⇒ compensate gradient drop from beam loading



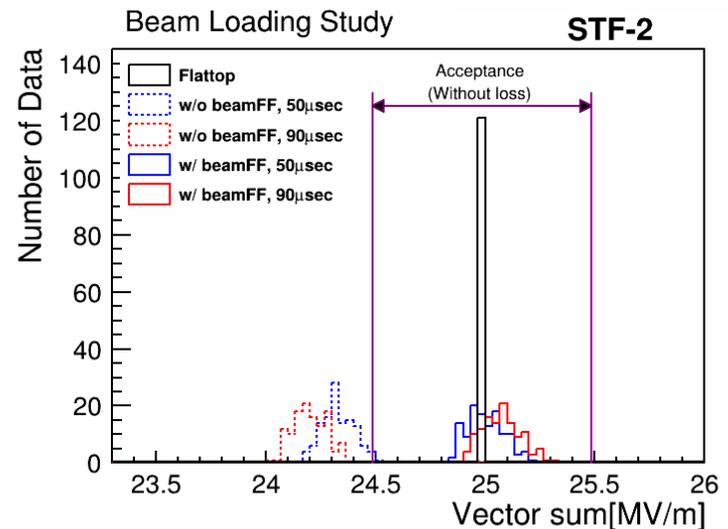
Middle pulse operation

- Averaged accelerating gradient
 - Clear Gradient drop can be seen without feedforward
 - Recover accelerating gradient after imposing feedforward



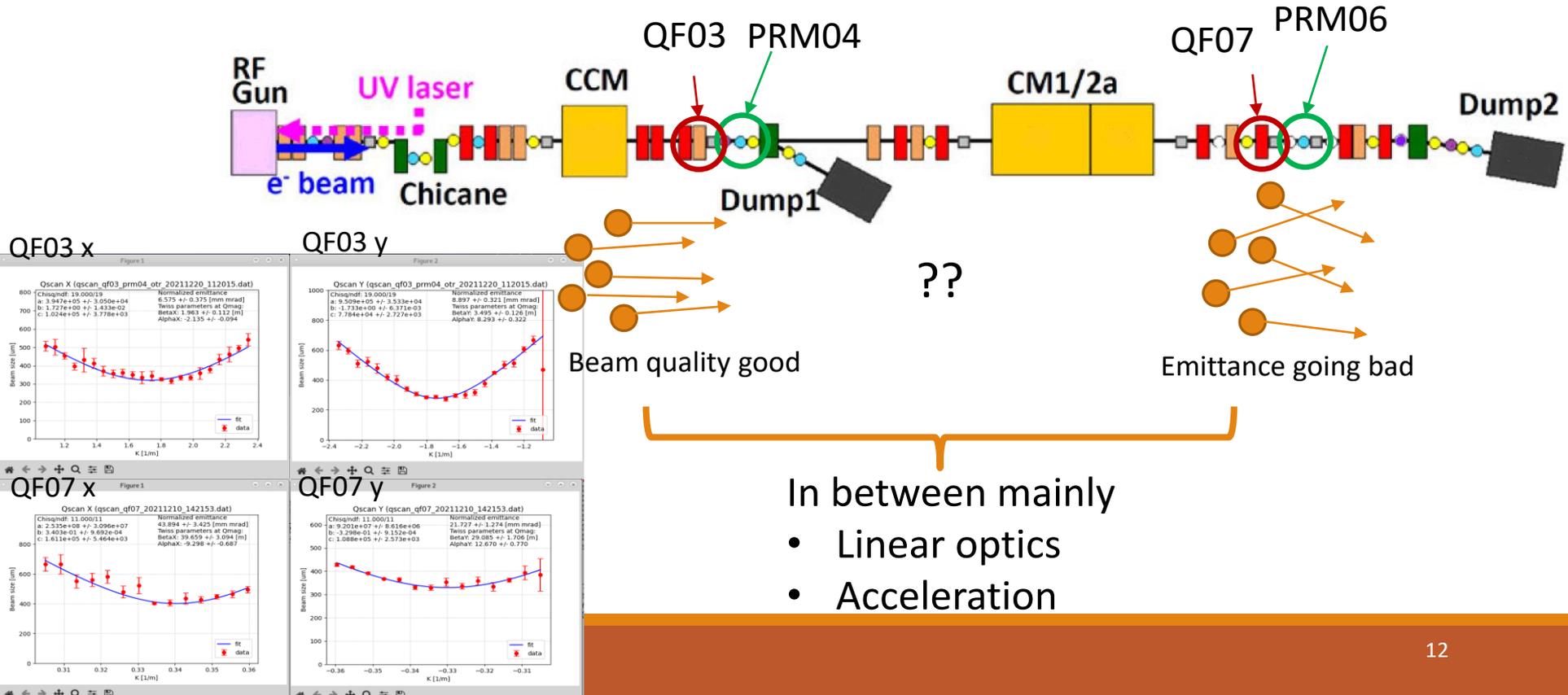
- All the data within the acceptance window without loss

⇒ It is considered that we have obtained a powerful finding for long pulsed beam operation



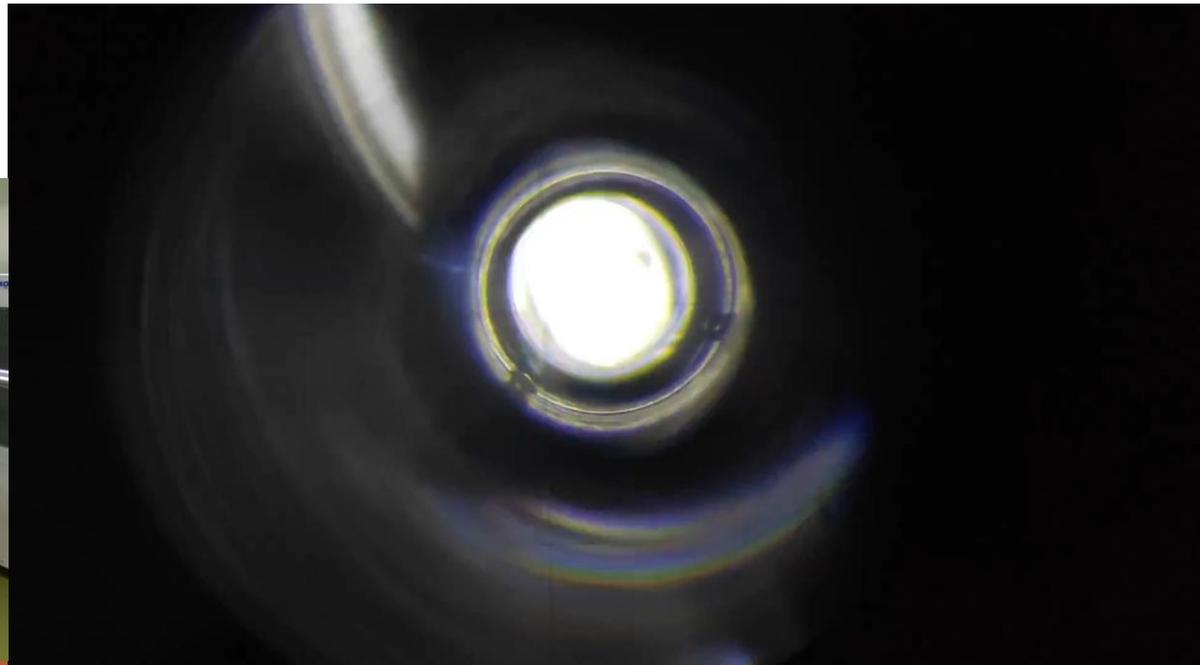
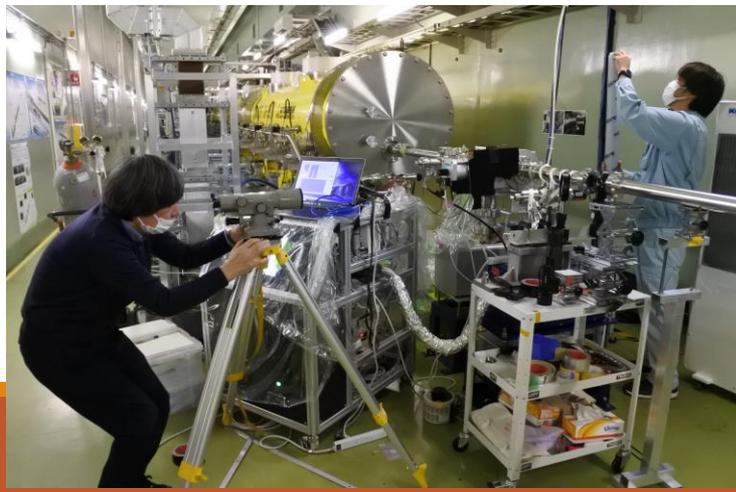
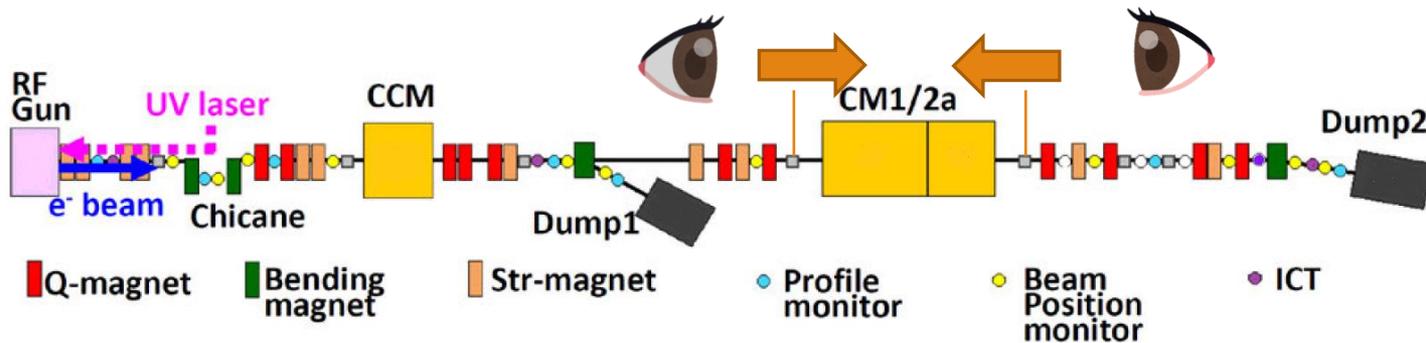
Anomalous emittance growth

- Since 2019, we found emittance varied before/after accelerating cavities
- Measure emittance before/after cryomodules by Q scan
 - Measure beam size changing Q magnetic field
- Emittance drastically grows: a few times larger than design ($O(1)$ [mm mrad])
 - ⇒ need to find out the source of this growth



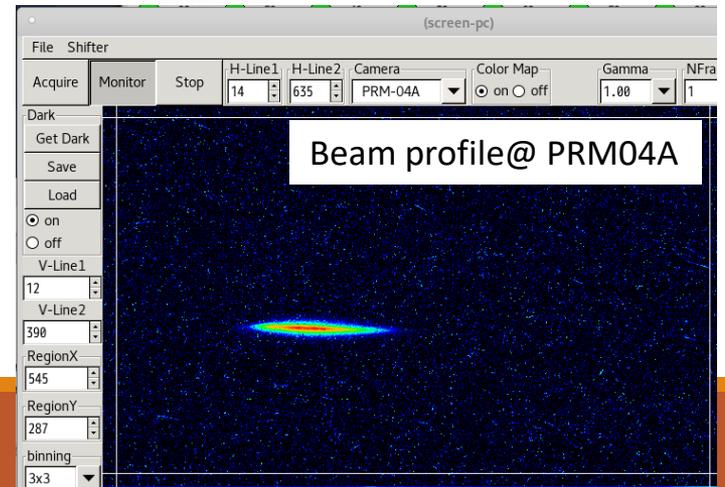
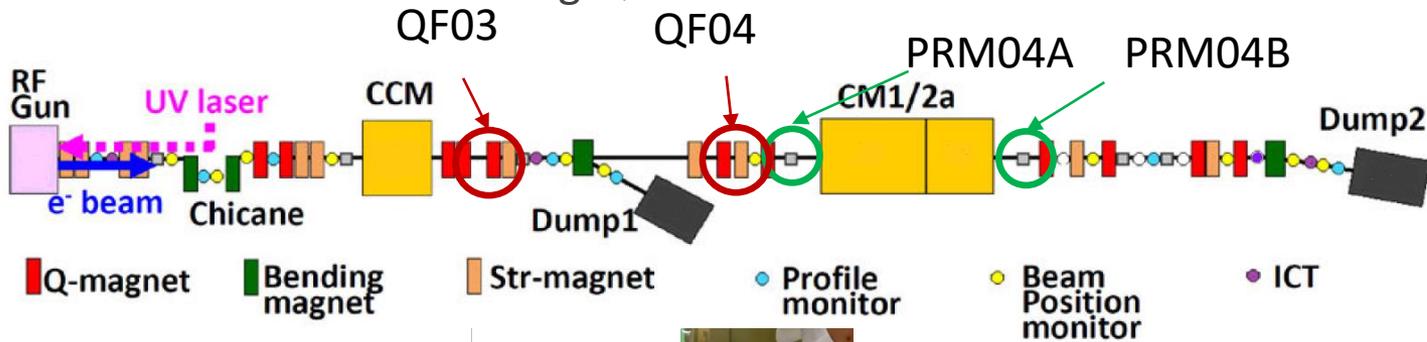
Observation inside the cavities

- In November 2021, to verify there is no obstacle as a source of emittance growth, we observed inside the accelerating cavities by eye
- Confirm nothing is there



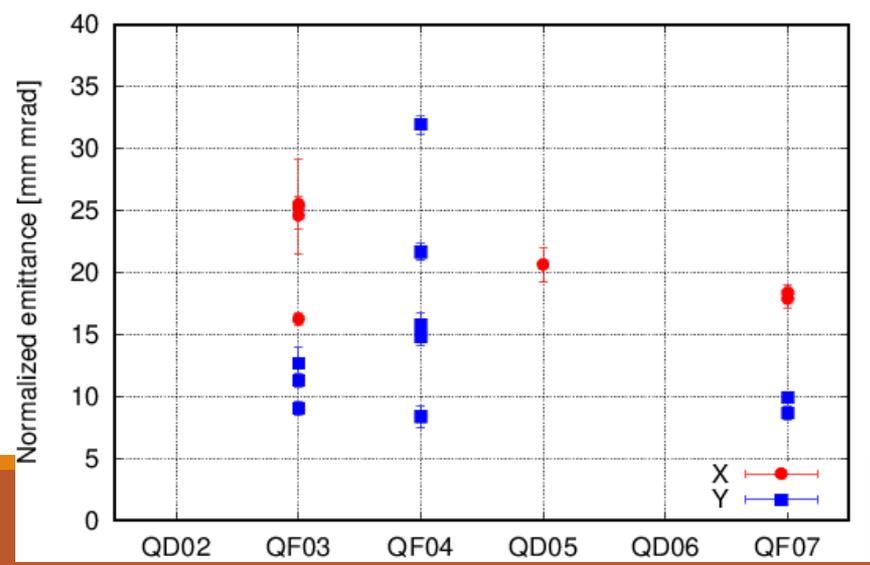
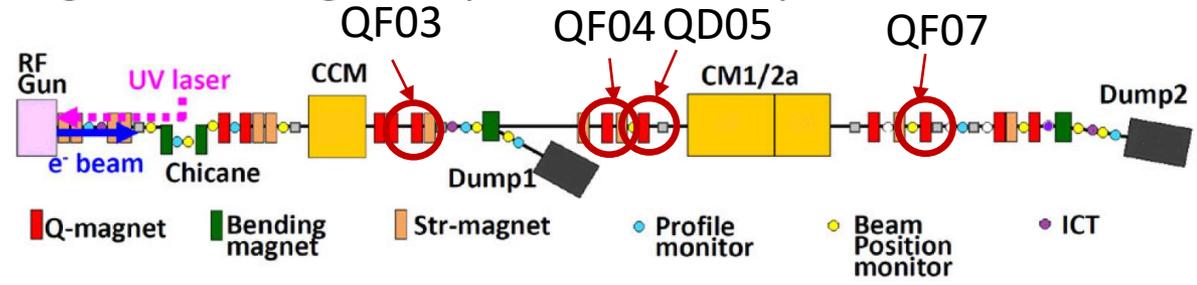
Status of the studies

- We checked several candidates of this emittance growth
 - Mainly focus on accelerating cavities
- In November 2021, we newly installed additional beam profile monitors immediately upstream/downstream cryomodules
 - We can check the accelerating cavity effect on emittance more precisely
 - Can measure the emittance using QF04-PRM04A



Re-estimate the emittance

- We checked the calculation of emittance
 - Latest changes of components on the beamline were not reflected correctly
- Re-estimate the emittance
 - **Emittance is already increased by the time reaching QF03: larger than design**
 - Emittance growth during acceleration by CM1/2a looks small
 - We are planning to investigate upstream components



Summary

- STF-2 aims to verify superconducting acceleration for the ILC
- Beam operation with 14 cavities was successfully done
- Acceleration gradient of 33 MV/m was achieved
 - 5% margin from ILC specification
- We plan the same long pulse operation as that of the ILC specification (726 μ sec). We have carried out 100 μ sec pulsed beam operation without loss at STF-2 in 2021.
- Anomalous emittance growth was observed. So far, no candidate of the source was found. However, it seems that the source(s) might be located at upstream components