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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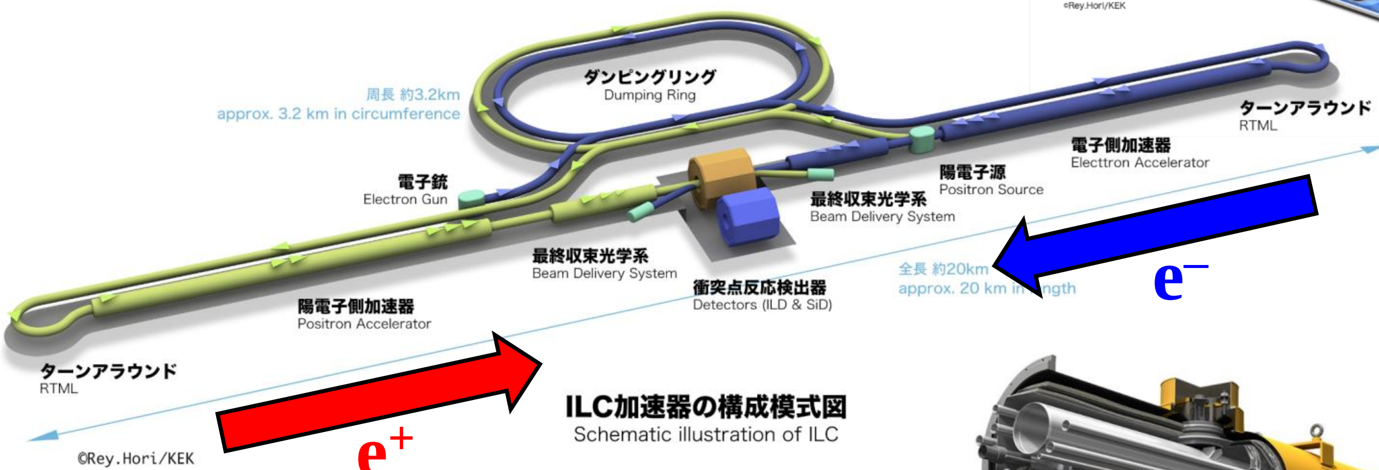
Introduction

- 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

岩手県一関市の資料をもとに作製



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}

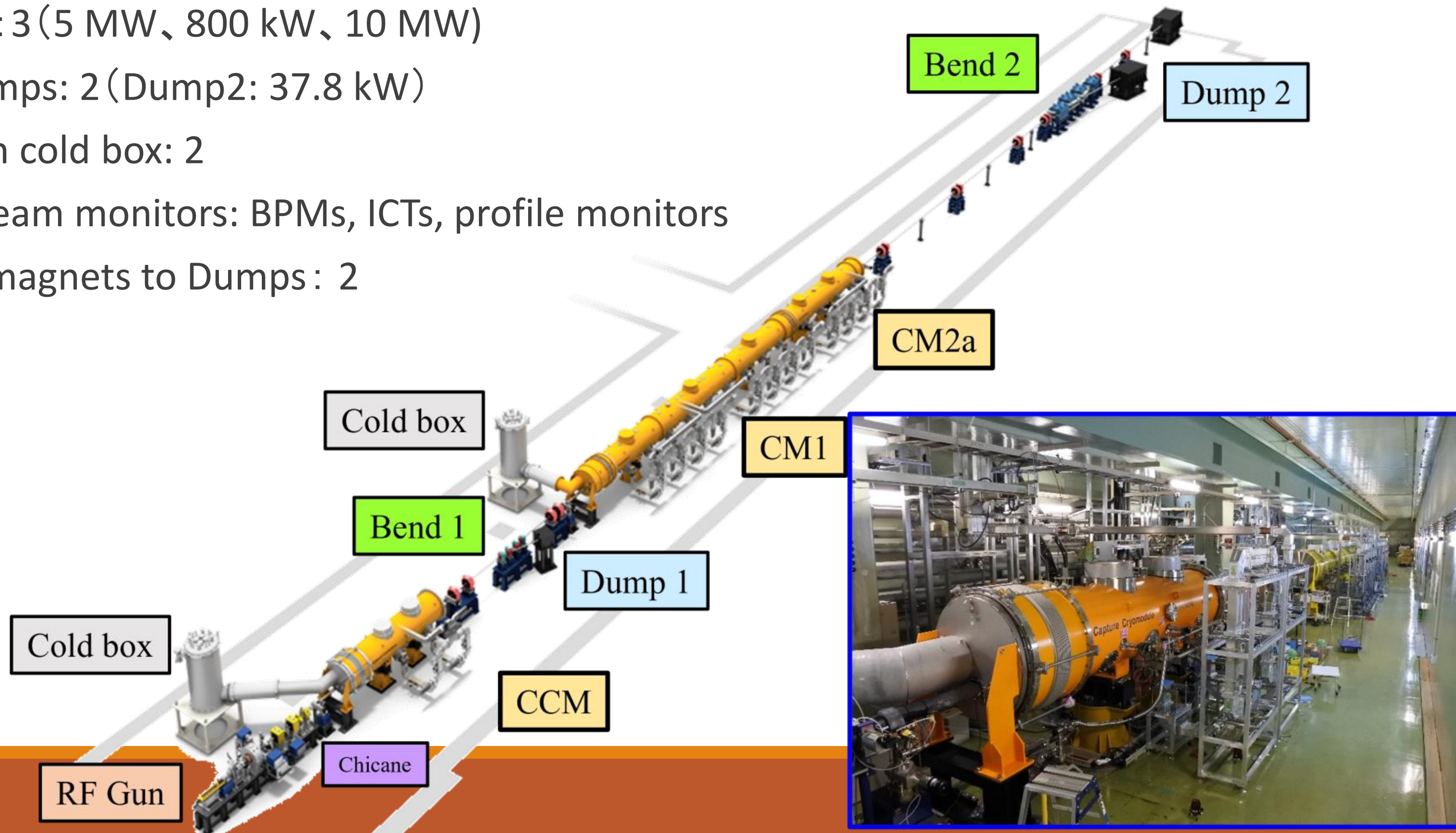
>90% (successful rate)

STF-2 accelerator

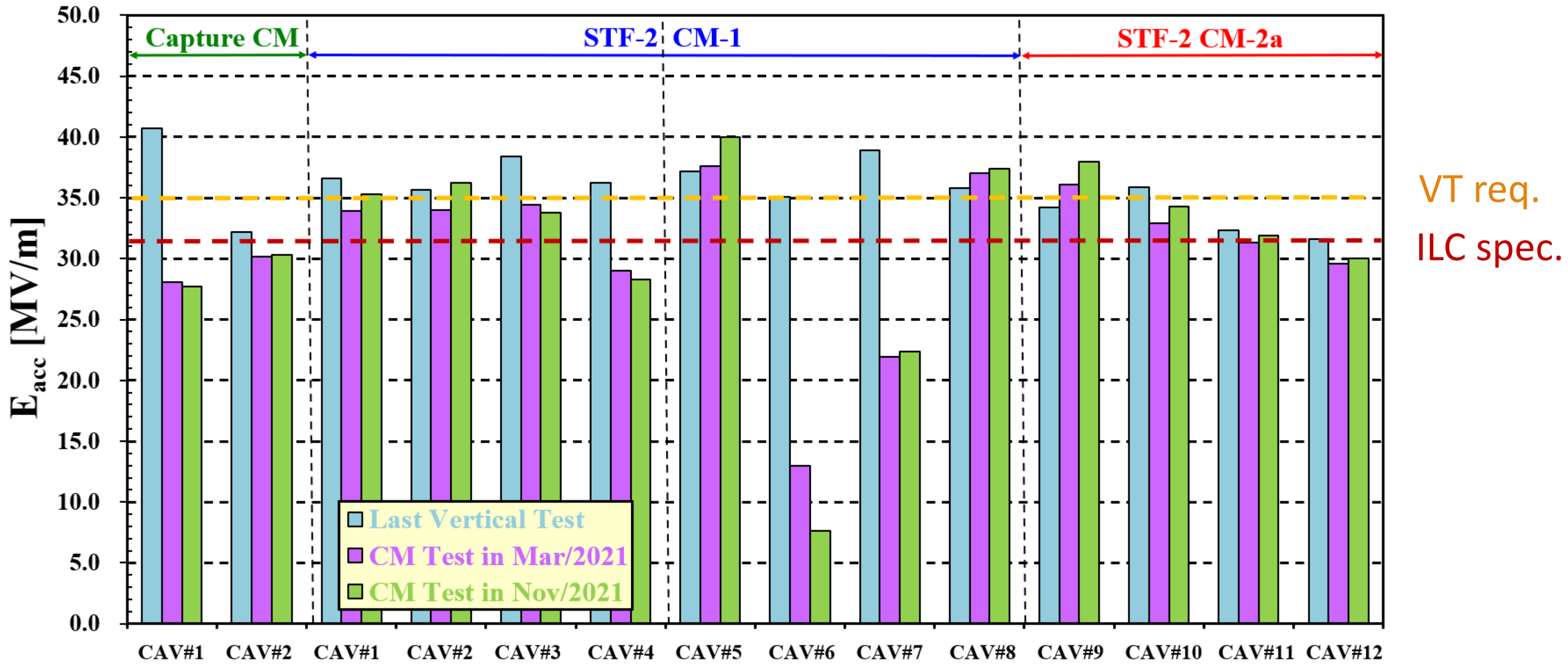
- ~70 m superconducting Linac（1.65 msec/5Hz）
- Superconducting cavities：14（1.3 GHz、9-cell）
- Cryomodules：CCM（2） CM1/CM2a（12）
- Photo cathode RF gun （Cs2Te、Q.E.~1%）
- Laser system：162.5 MHz、1064 nm、12 W
- Klystrons：3（5 MW、800 kW、10 MW)
- Beam dumps: 2（Dump2: 37.8 kW）
- 2K Helium cold box: 2
- Several 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 ±20% of 31.5 MV/m
  - Some cavities have performance degradation due to
    - Abnormal heat load
    - Field emission

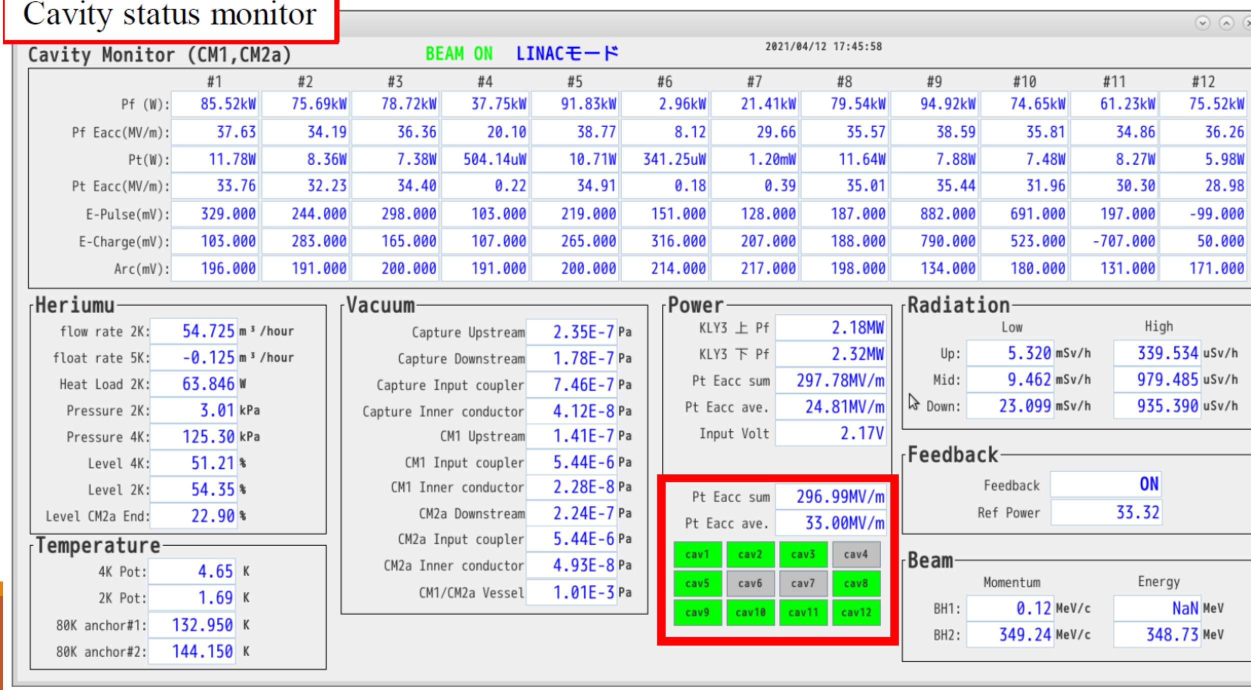
Max Average E_{acc} Operation

- 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

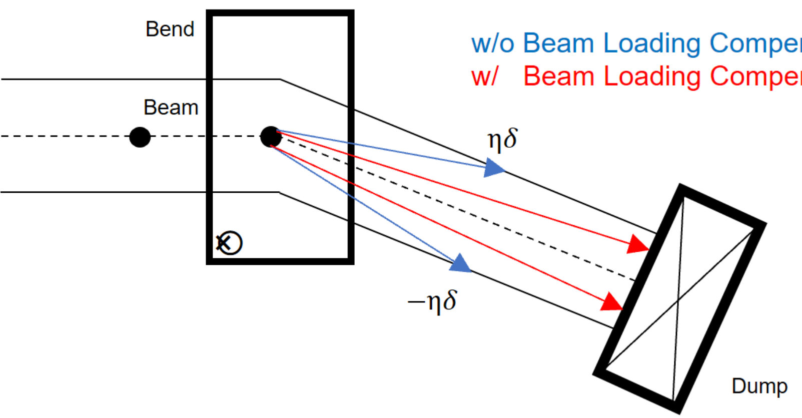
- **There is 5% margin from ILC specification**
  - ILC specification: 31.5 MV/m

Cavity status monitor

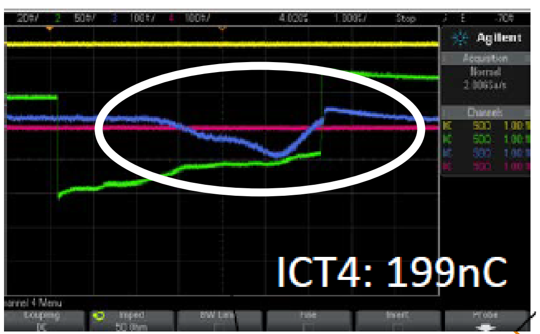


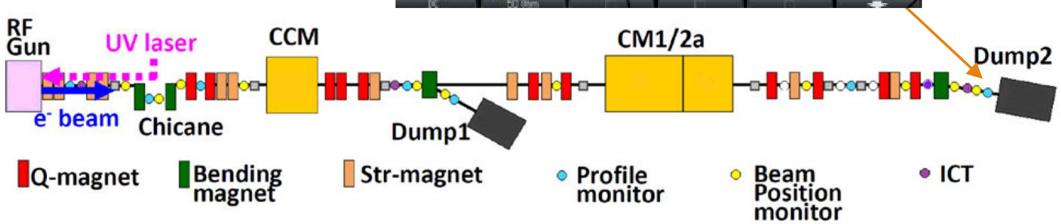
Middle pulse beam operation without loss

- 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 [μA]	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 [μsec]	6.15	6.15	100	726.00	726.848 μsec
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

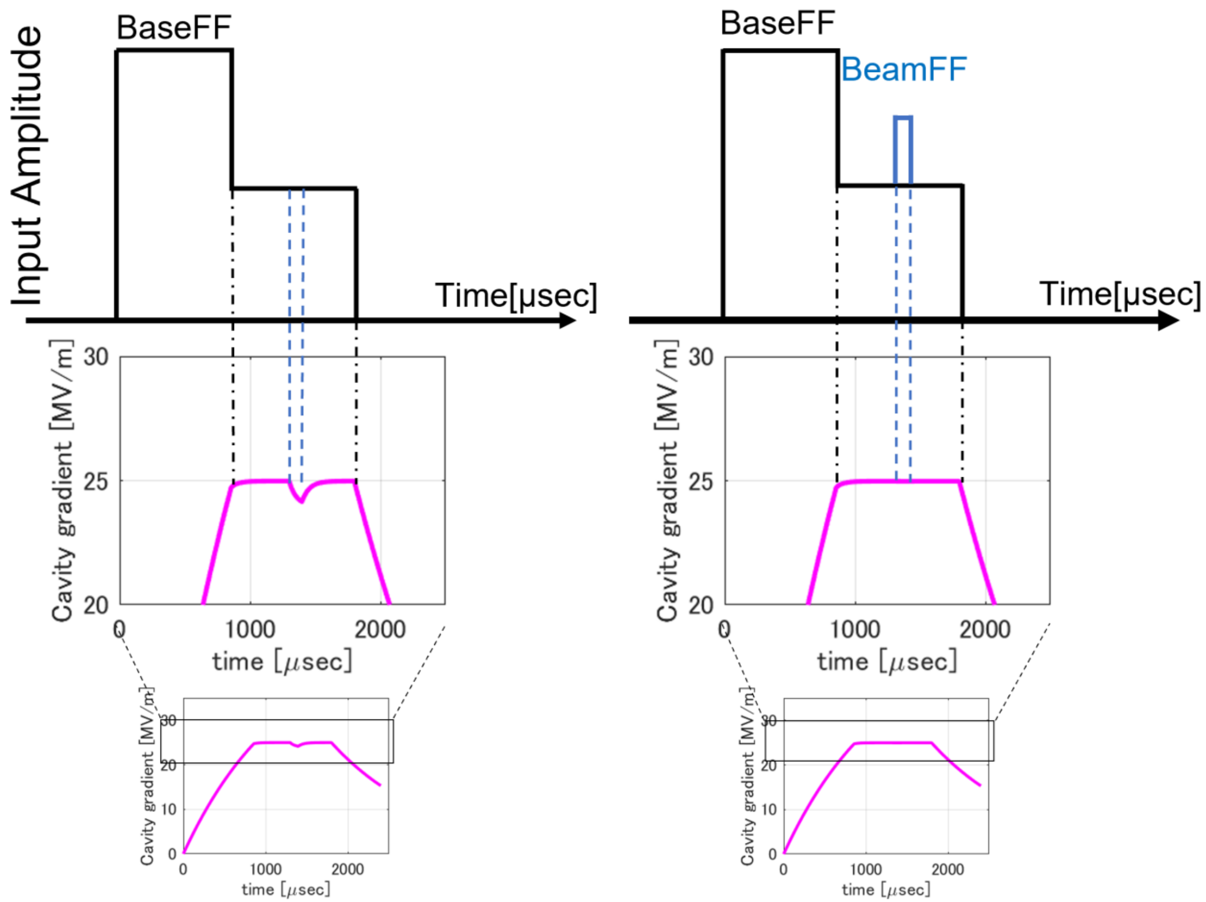
- Almost same pulse length as target

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

Beam Loading Compensation

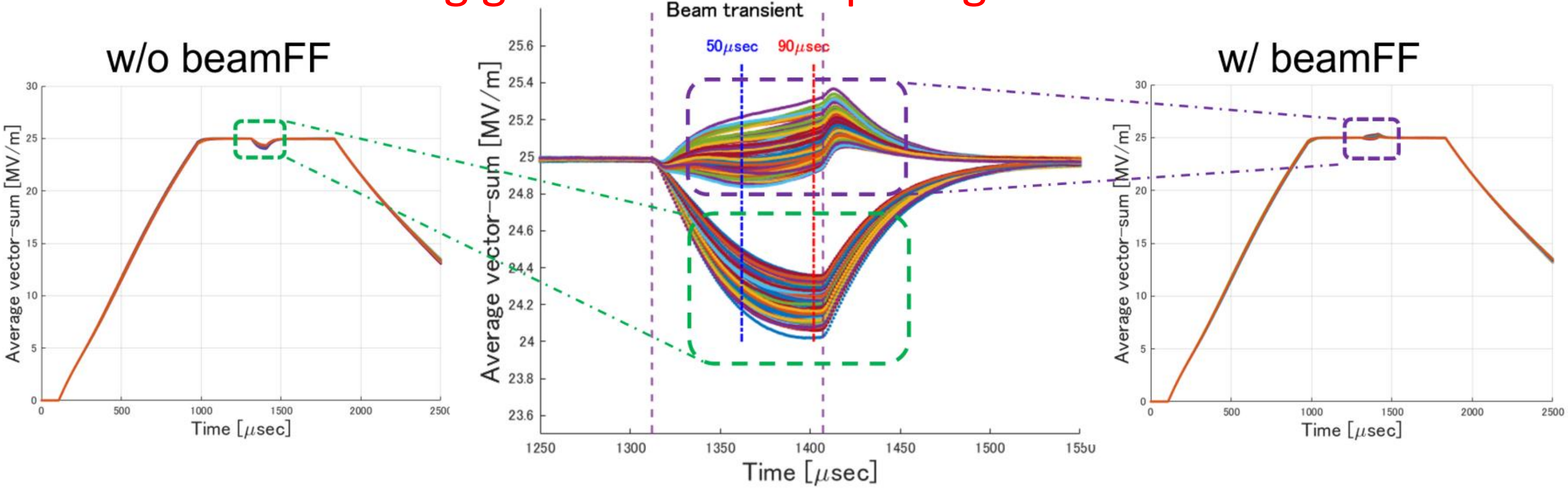
- To achieve stable flattop accelerating field:
  - Unexpected disturbance: feedback
  - Repetitive disturbance: Feedforward – Additional driving power imposed

⇒ compensate gradient drop from beam loading



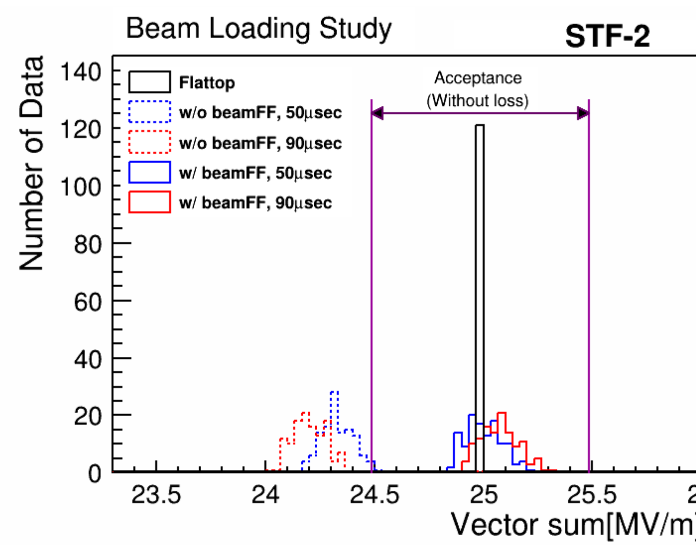
Middle pulse operation

- 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

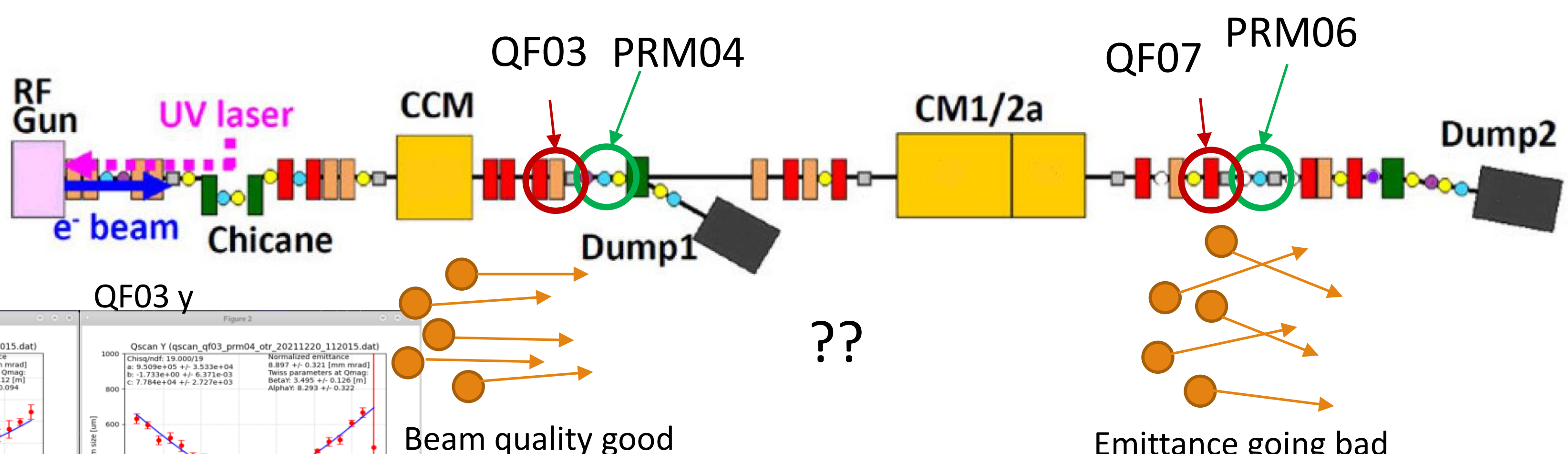
⇒ It is considered that we have obtained a powerful finding for long pulsed beam operation

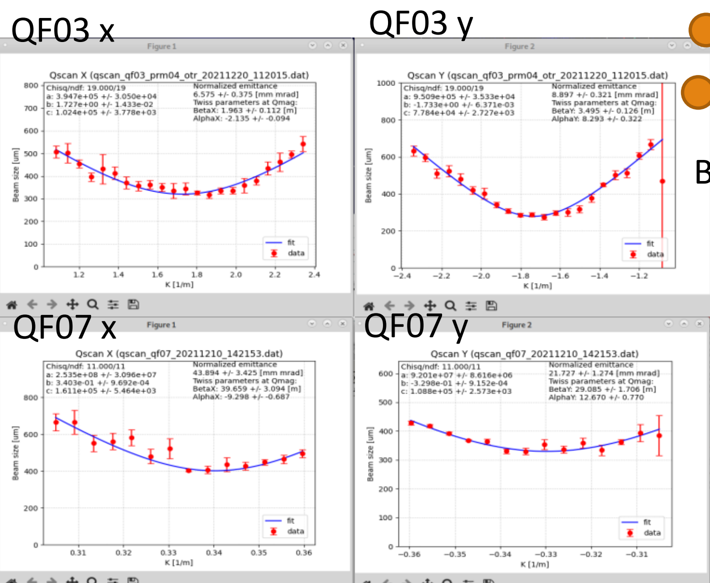


Anomalous emittance growth

- 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

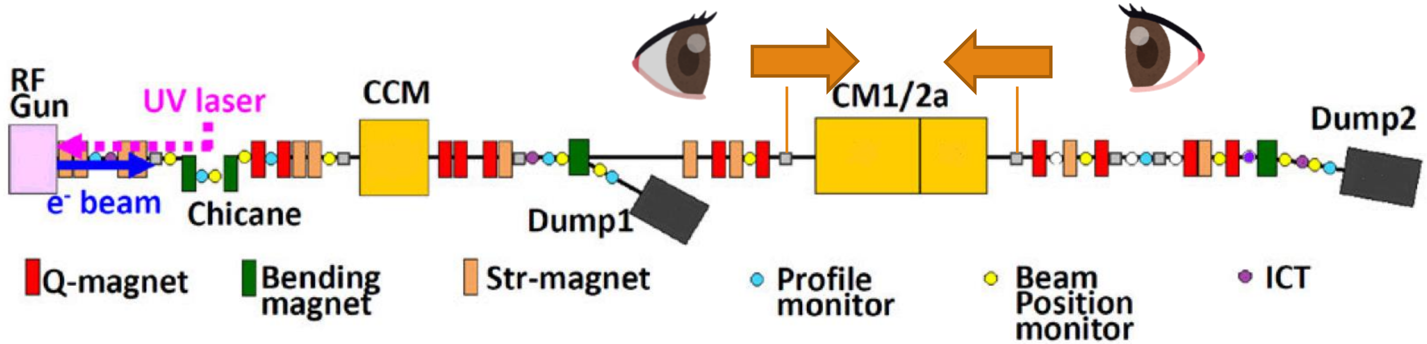


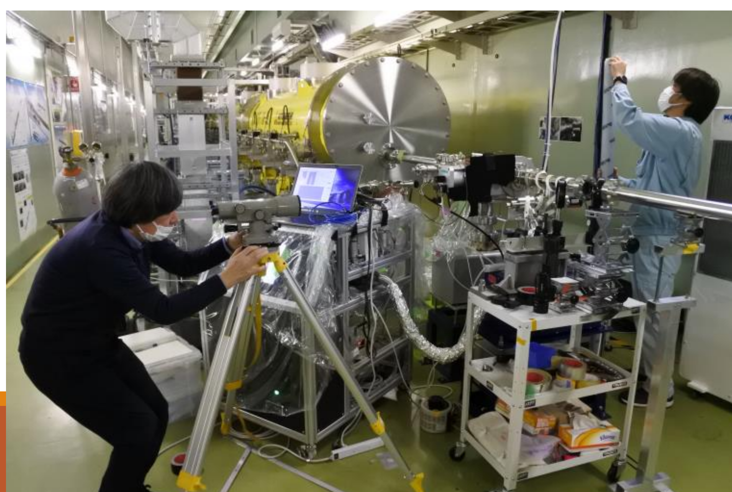


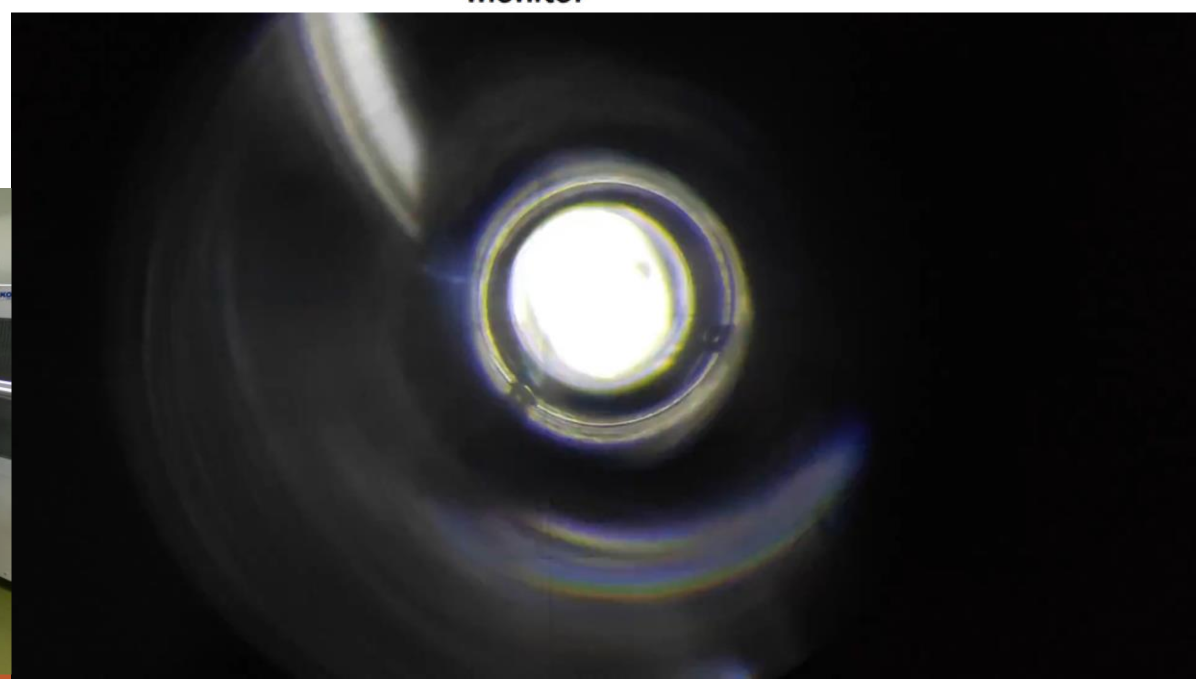
In between mainly
- Linear optics
- Acceleration

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

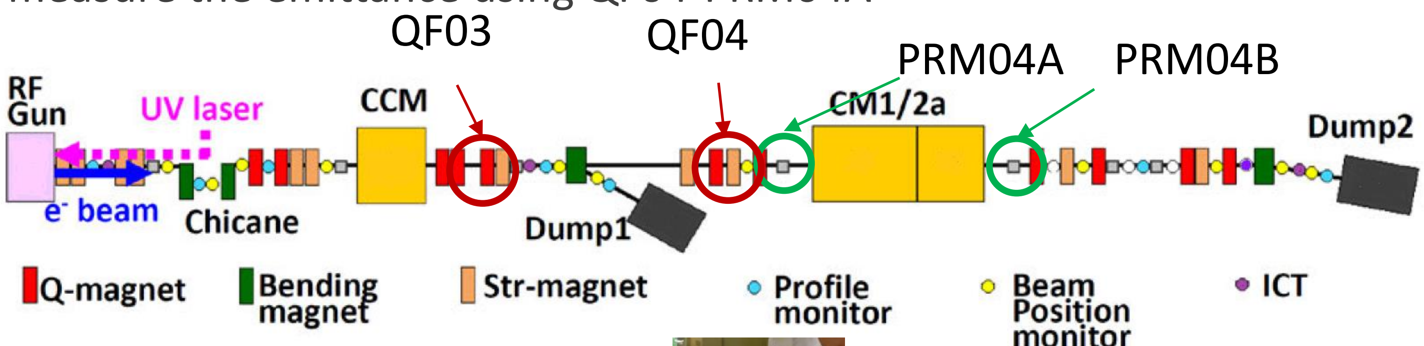


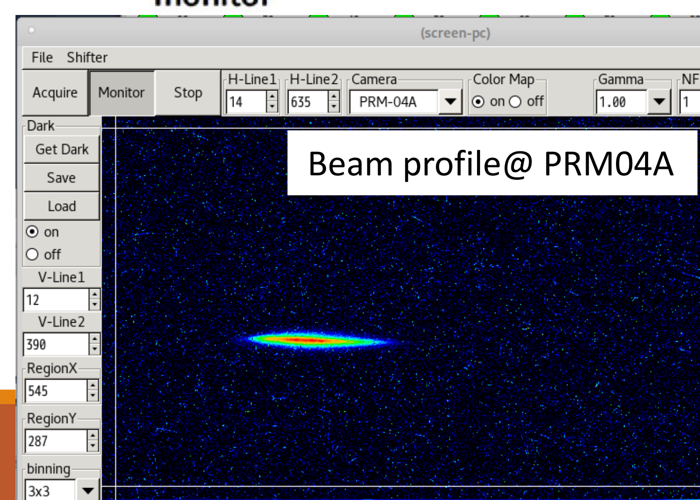




Status of the studies

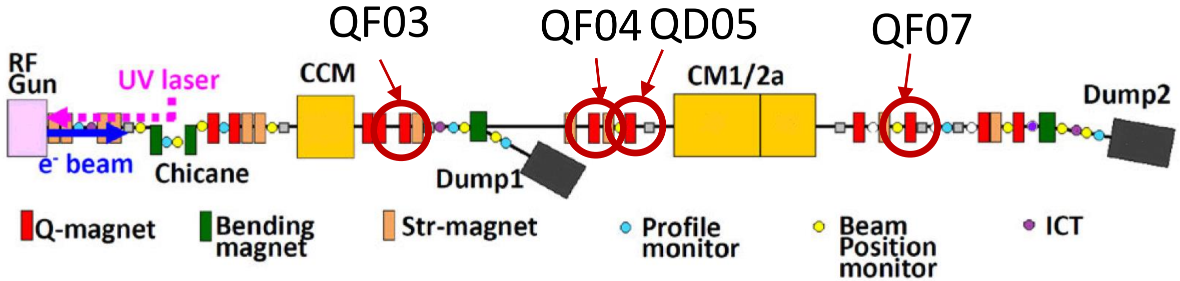
- We checked several candidates of this emittance growth
  - Mainly focus on accelerating cavities
- In November 2021, we newly installed additional beam profile monitors immediately upstream/downstream cryomodules
  - We can check the accelerating cavity effect on emittance more precisely
  - Can measure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

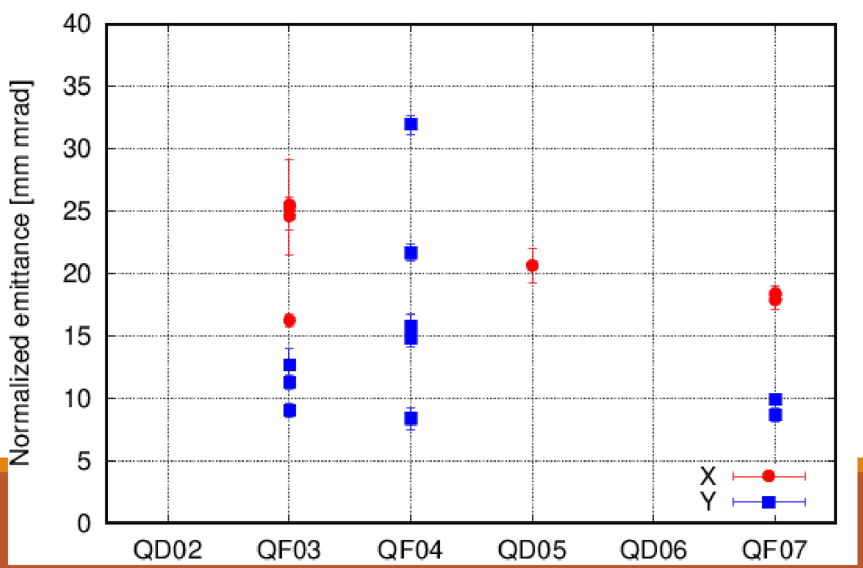




Re-estimate the emittance

- 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 μsec). We have carried out 100 μsec 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