Achievement of the ILC Milestone by Beam Operation of STF-2 Accelerator at KEK

Yasuchika Yamamoto, on behalf of STF group

Kirk

STF-2 Collaboration

Y. Yamamoto, Eiji Kako, Kensei Umemori, Hiroshi Sakai, Takayuki Saeki, Takeshi Dohmae, Mathieu Omet, Ryo Katayama, Hayato Ito, Hayato Araki, Toshihiro Matsumoto, Shinichiro Michizono, Masato Egi, Mitsuo Akemoto, Dai Arakawa, Hiroaki Katagiri, Masato Kawamura, Hiromitsu Nakajima, Hitoshi Hayano, Masafumi Fukuda, Yosuke Honda, Alexander Aryshev, Masao Kuriki, Zachary Liptak, Kazuyuki Sakaue, Hirotaka Nakai, Yuuji Kojima, Kazufumi Hara, Teruya Honma, Kota Nakanishi, Hirotaka Shimizu, Yoshinari Kondou, Akira Yamamoto, Nobuhiro Kimura, Sakae Araki, Yu Morikawa, Takahiro Oyama, Shin-ichi Takahara, Mika Masuzawa, Ryuichi Ueki, Masakazu Kurata, Miho Shimada, Yoshihisa Iwashita

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- ILC project
- STF/STF-2 accelerator
- Cavity performance
- Beam operation & High current operation
- Earthquake
- Achievements
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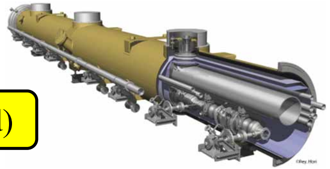
International Linear Collider (ILC)

- Higgs factory machine
- Staging scenario (250 → 500 → 1000 GeV)
- SRF technology for beam acceleration
- Nano-beam technology for high luminosity

x ~8000

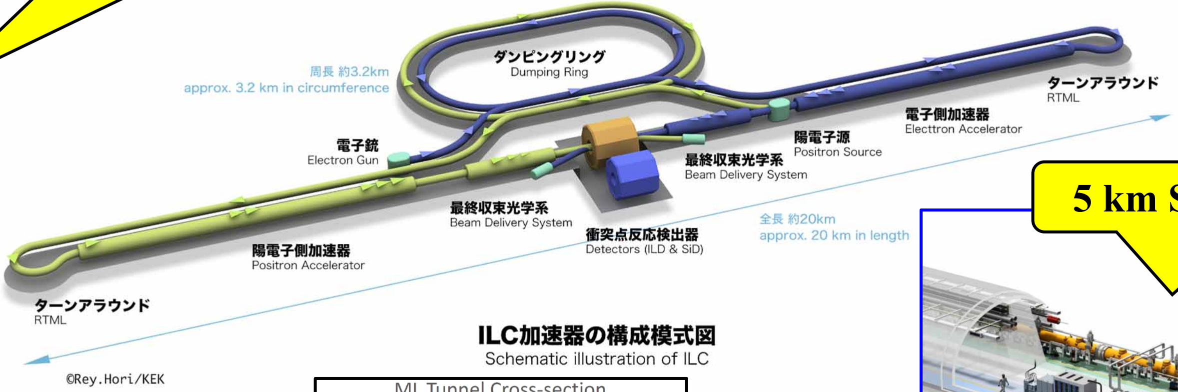


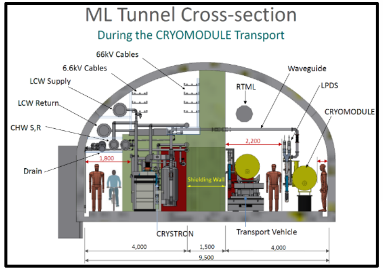
x ~750

	VT	CM
E_{acc}	35.0 MV/m	31.5 MV/m
Q_0	0.8×10^{10}	1.0×10^{10}
Yield	≥ 90%	~100%

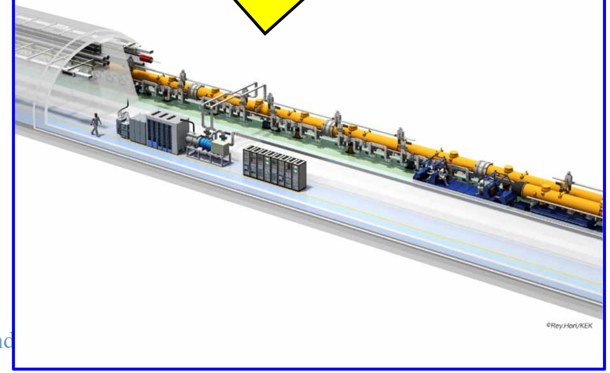
Candidate site (geologically suited)

岩手県一関市の資料をもとに作製





5 km SRF linac for each!



Recent status:

- ☐ Foundation of ILC Japan
- ☐ International Expert Panel
- ☐ Time critical WPs

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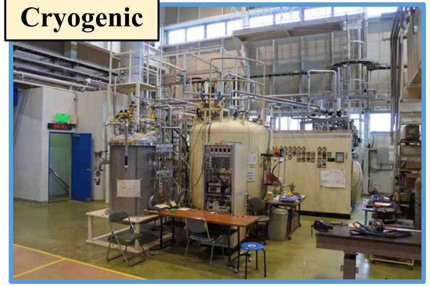
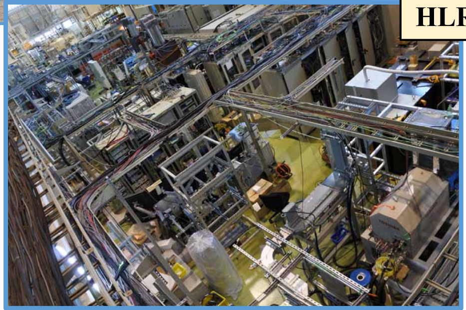
Superconducting RF Test Facility (STF)


Cryogenic

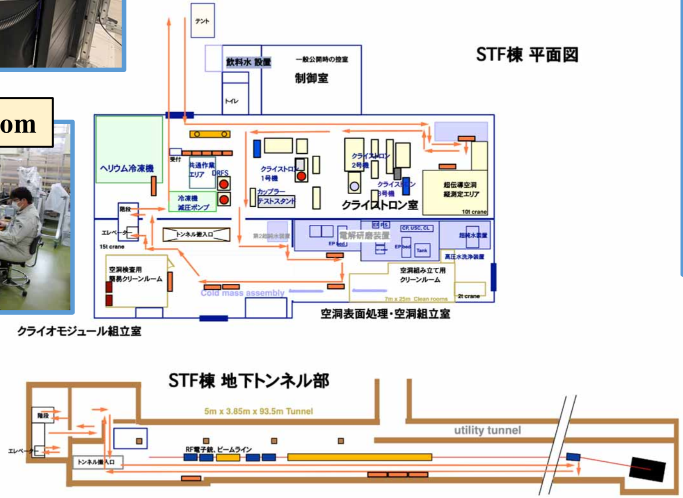

Control room


outside


HLRF


CM assembly area


Cavity inspection room




Accelerator tunnel

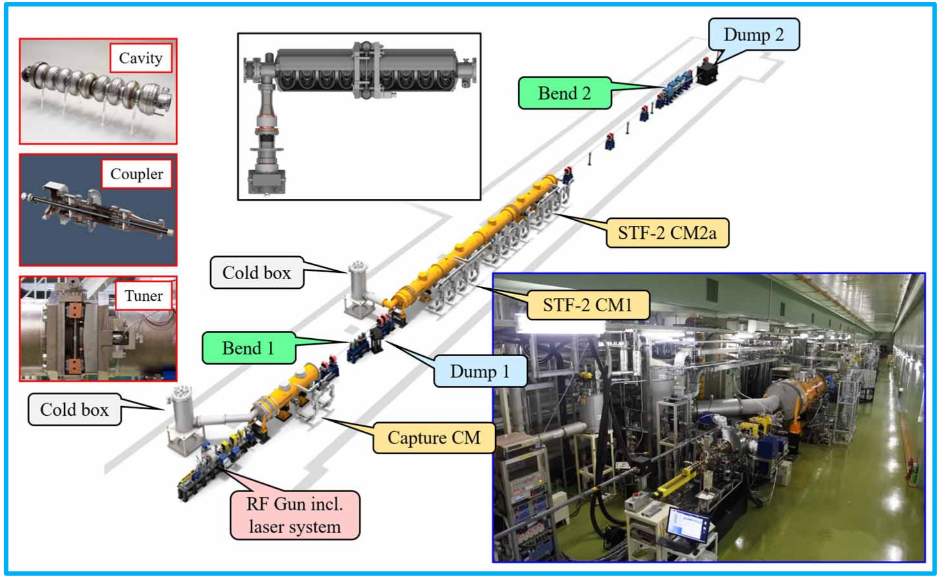

Clean room


EP

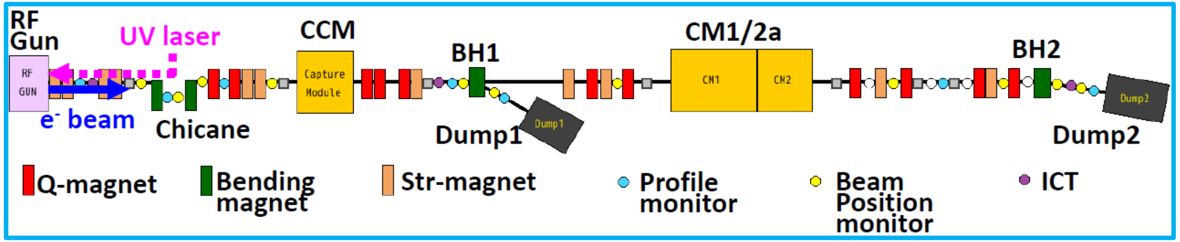

VT

Features of STF-2 Accelerator

- ~70 m superconducting linac (1.65 msec/5Hz)
- Superconducting cavities: 14 (1.3 GHz, 9-cell)
- Cryomodules: CCM, CM1/CM2a
- 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



History of cooldown test at STF-2		RF system
F.Y.2014	Low power test	
F.Y.2015	High power test	Single cavity
F.Y.2016	High power test	8 cavities
F.Y.2018	High power test + Beam	7 + 2 cavities
F.Y.2020	Low power test	
F.Y.2020~2021	High power test + Beam	12 + 2 cavities
F.Y.2021	High power test + Beam	12 + 2 cavities
F.Y.2022	High power test + Beam	12 + 2 cavities



Upgrading Beam Parameters of STF-2 Accelerator

Specifications to be reported to nuclear regulatory agency

1st upgrade (F.Y.2018 → F.Y.2020)

2nd upgrade (F.Y.2021 → F.Y.2022)

	F.Y.2018	F.Y.2020	F.Y.2021	F.Y.2022	ILC spec.
Max. beam energy [MeV]	500	500	500	500	500 GeV
Max. beam intensity [μA]	0.30	3.00	3.00	21.05	21.0
Max. beam power [kW]	0.135	1.350	1.350	6.750	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

We are approaching our goal!

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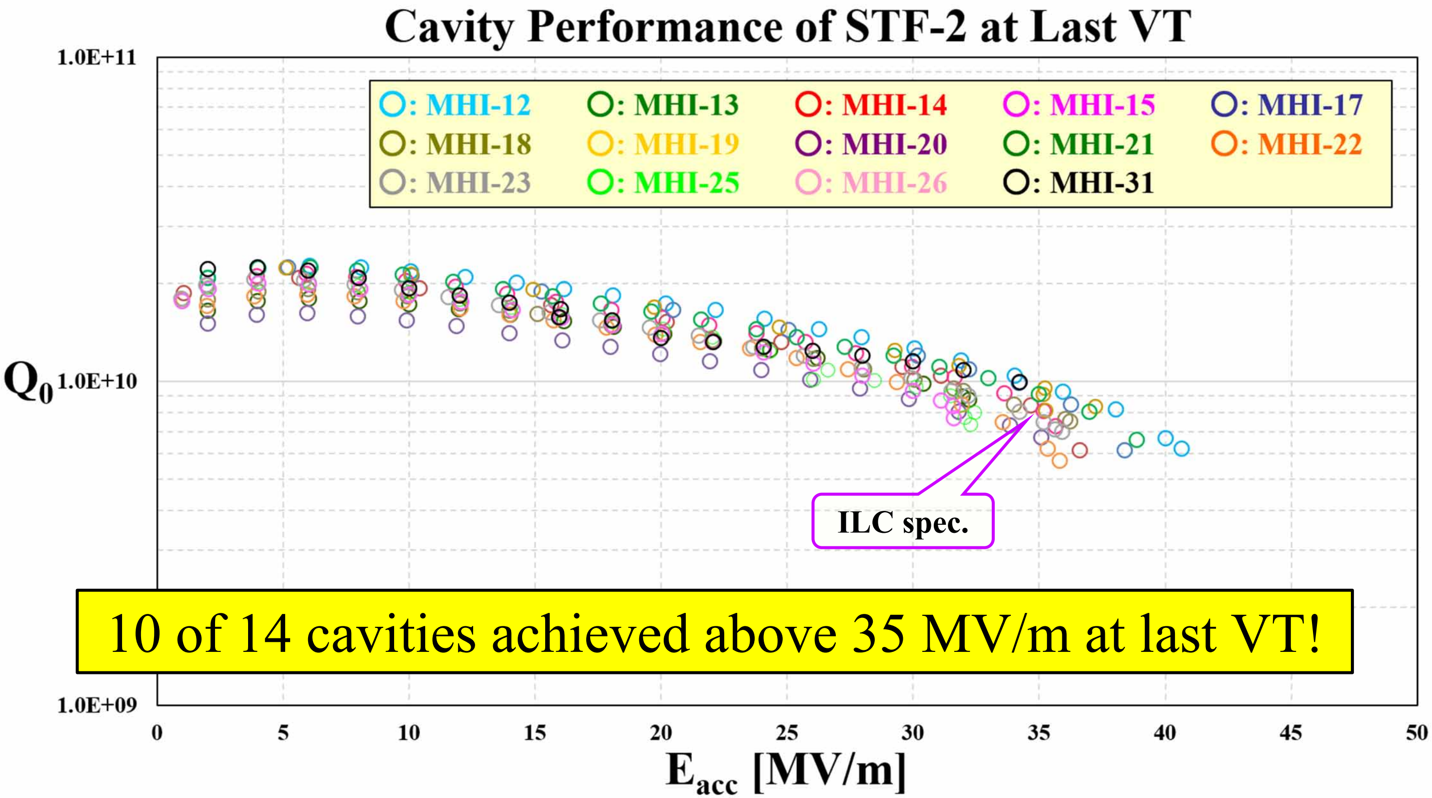
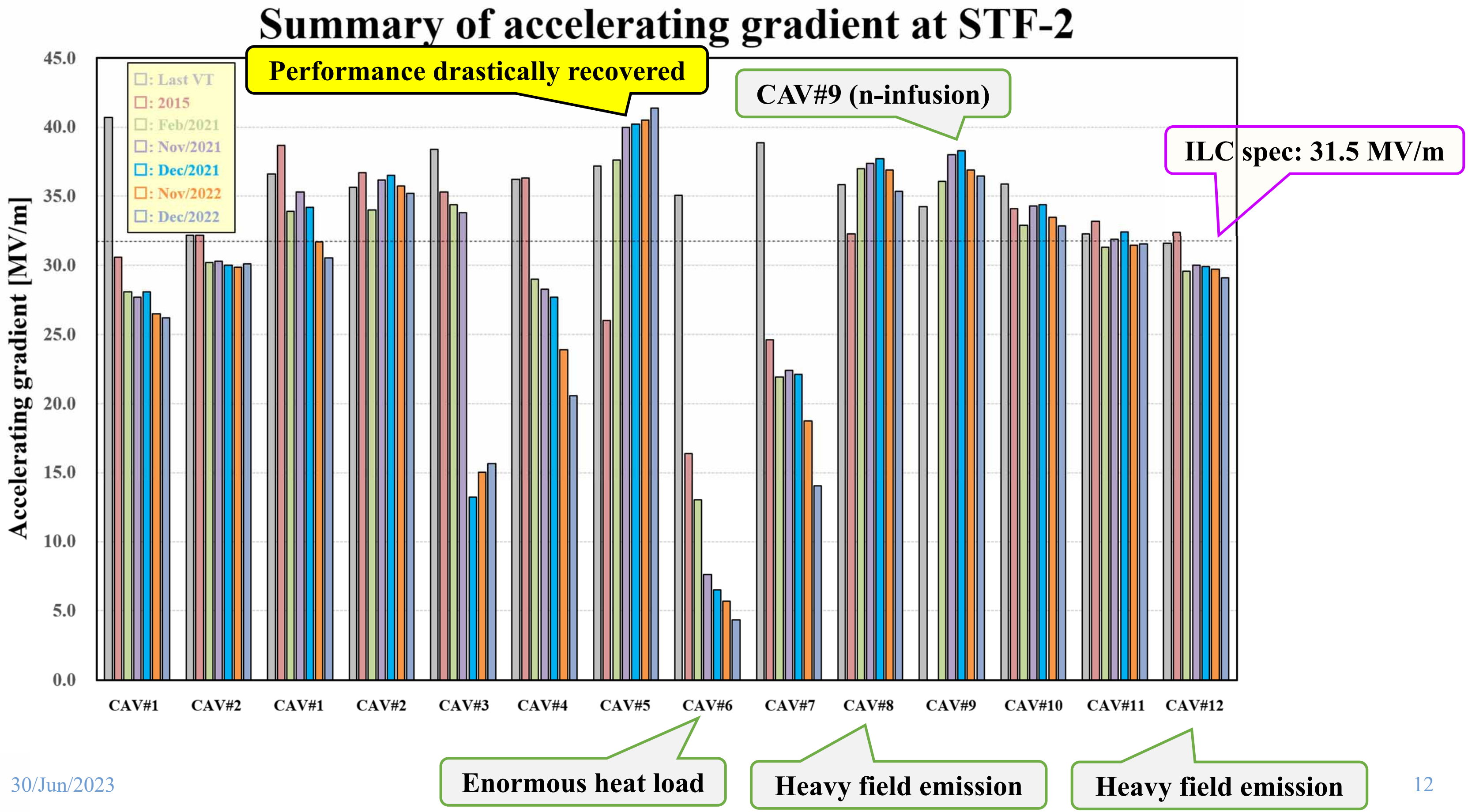
Cavity Performance at last VT



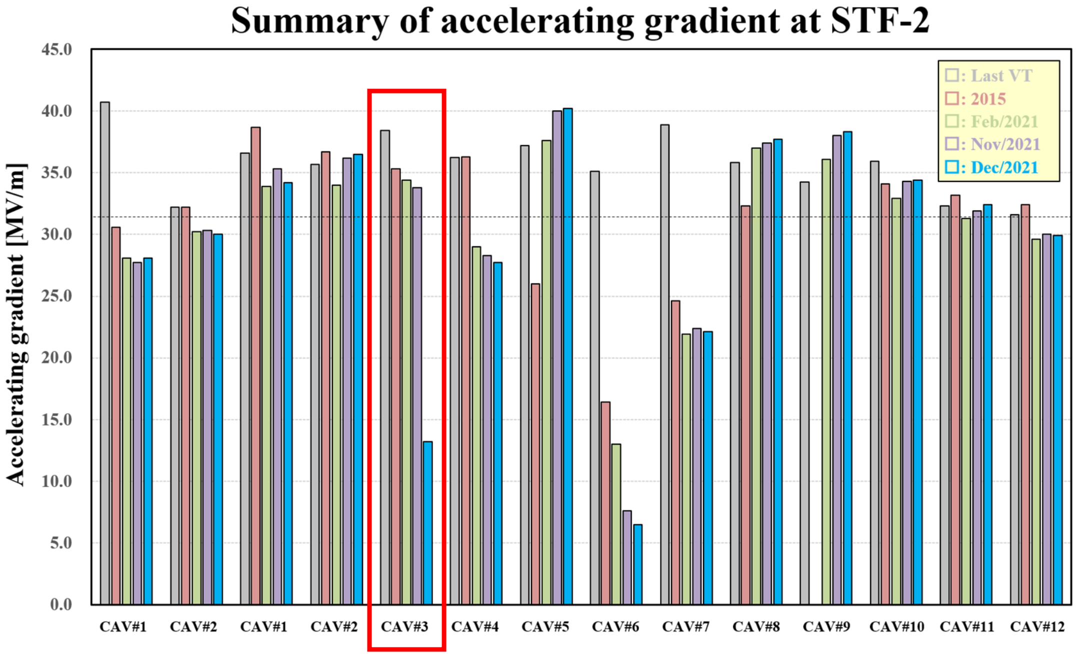
10 of 14 cavities achieved above 35 MV/m at last VT!

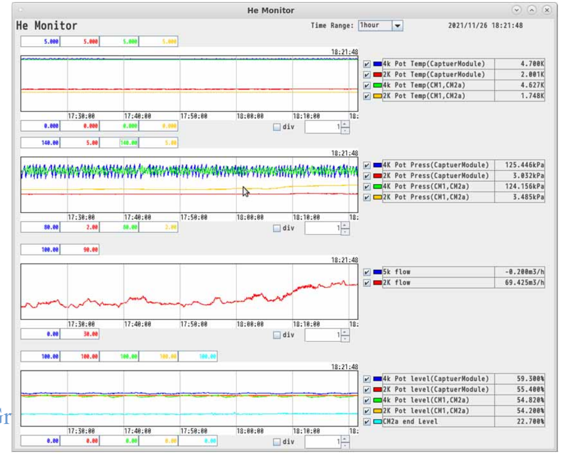
History of Cavity Performance



Unexpected performance degradation

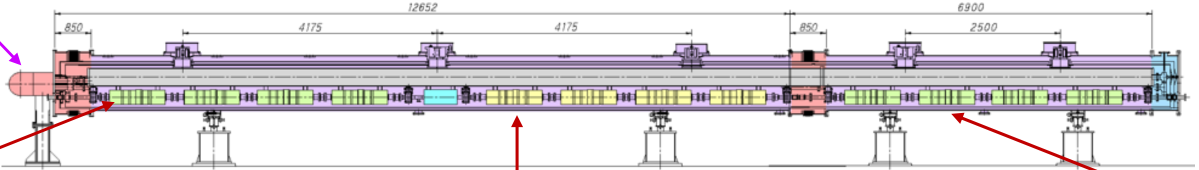
CAV#3 performance suddenly dropped during radiation measurement in 2021.
After strange quench, enormous heat load occurred same as CAV#6.

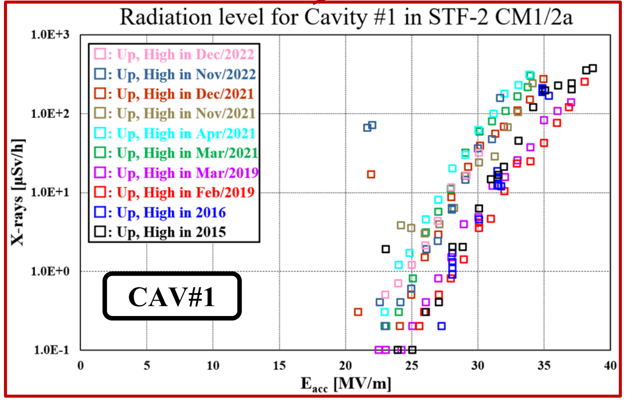


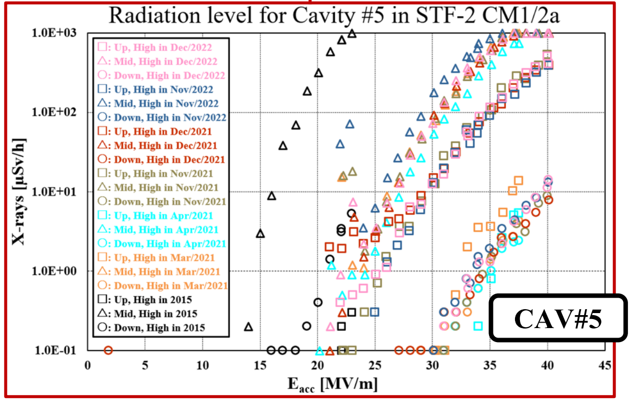


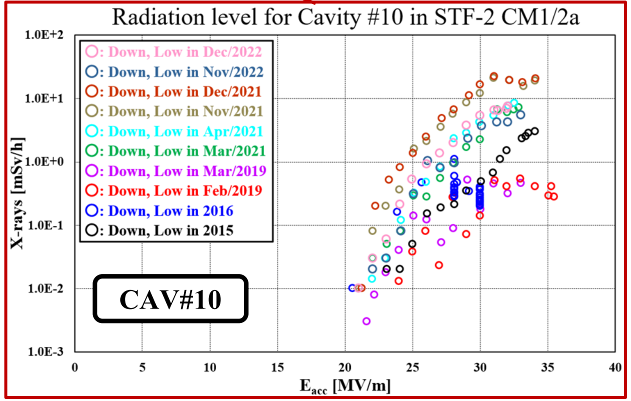
Change of Radiation in cavities

We have measured the radiation level each cold test since 2015.
The radiation sensors are installed at upstream, downstream and below cavity.
Fixed-point observations of radiation over a long period of time provides information on the status of the cavity.









Fortunately, we did not observe any increase in radiation for all cavities in this cooldown test!

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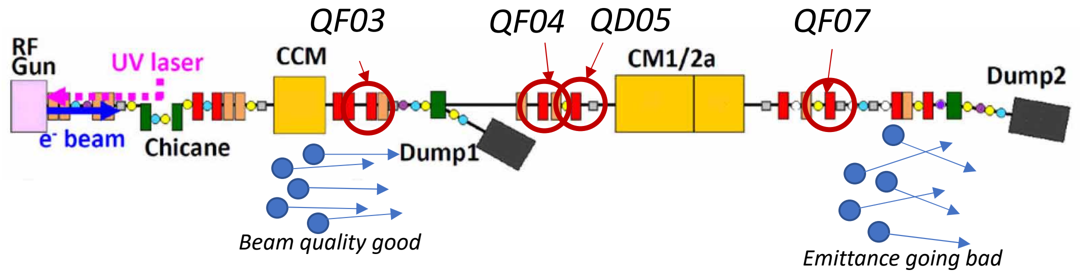
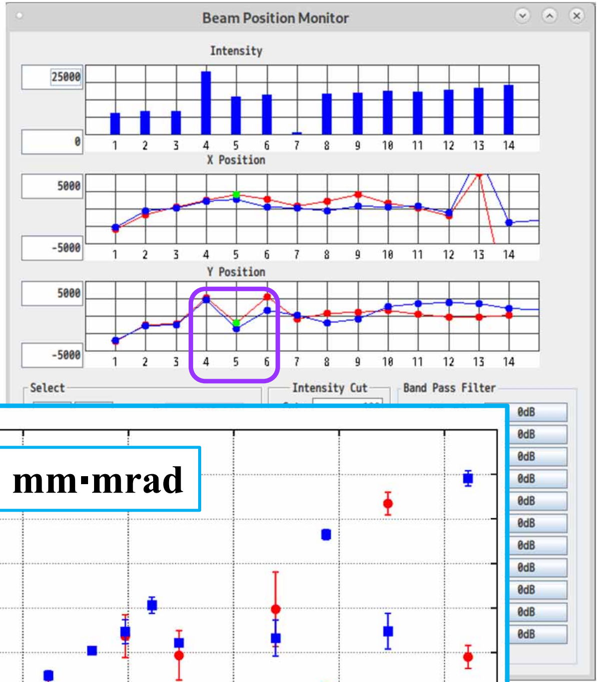
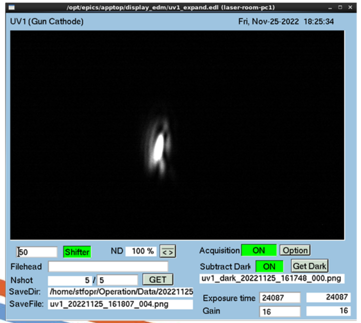
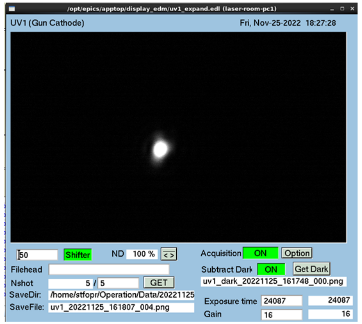
History of Emittance Improvement

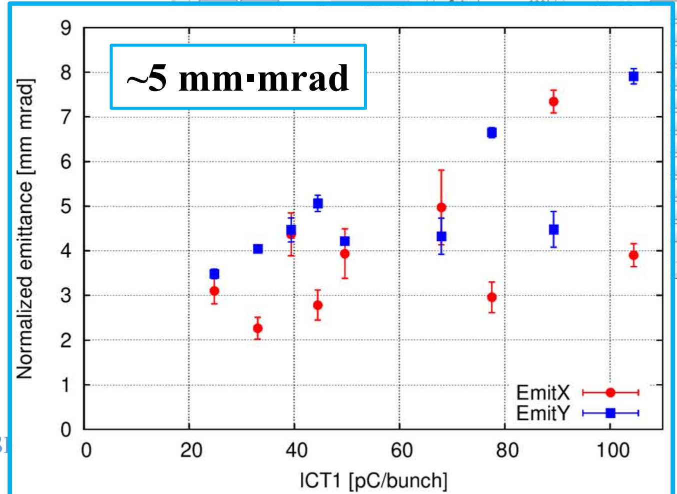
- Beam emittance was much worse than expected value by simulation since the commissioning
  - Meas.: >10 mm·mrad, Simulation: ~1 mm·mrad
- The STF team has considered this cause by various tests
- Fortunately, they found some solutions to improve in recent operation
  - Beam orbit correction by detuned cavities in CCM
  - Optimization of magnetic field by solenoid
  - Tuning the laser profile





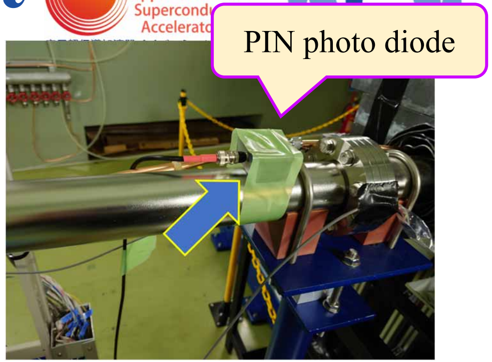


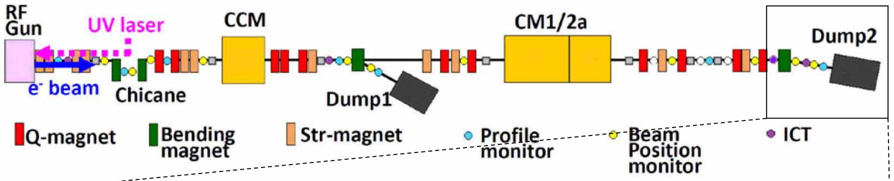


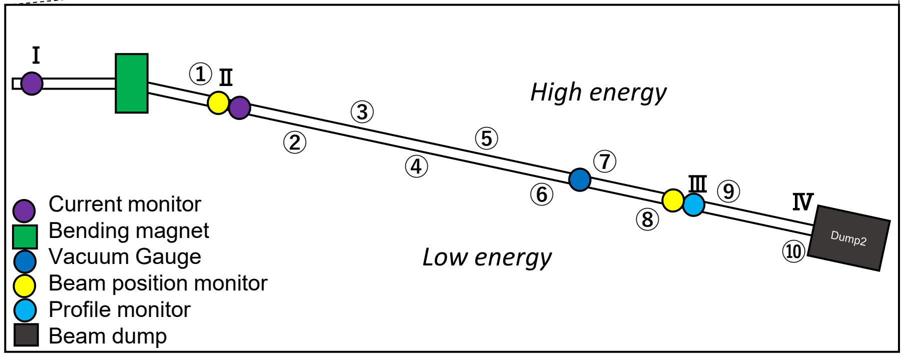


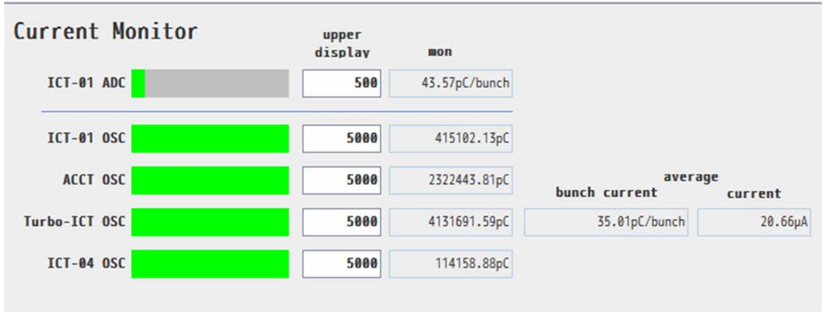
Long pulse operation for high current

- The STF team has aimed for high current operation same as the ILC specification
- They installed a lot of photo diodes as beam loss monitor
- They also installed Čerenkov detector near the beam dump
- Finally, they have successfully done this operation at 5.2 kW, 292 MeV, 20.7 μA





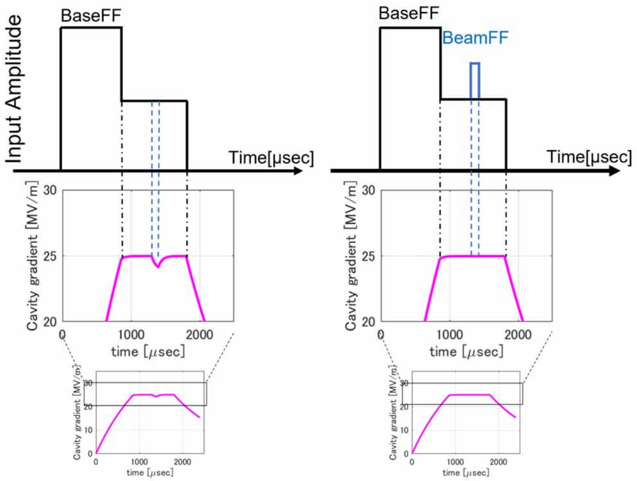


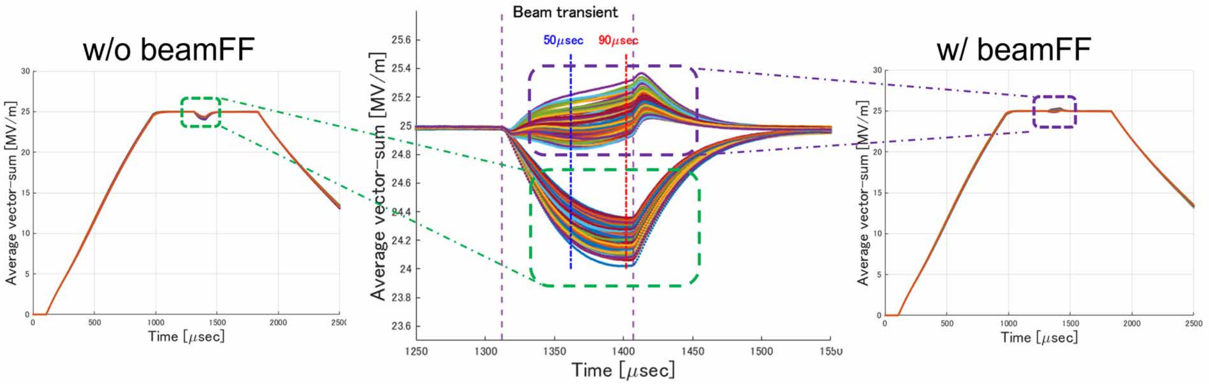


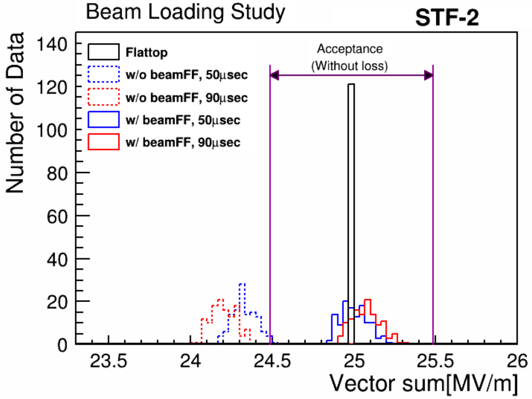
Compensation of Beam Loading

For high intensity beam, power loss by beam loading should be compensated by feed-forward control.

Schematic view of beam loading







Feed-forward control worked well to compensate beam loading!

High current/High gradient operation

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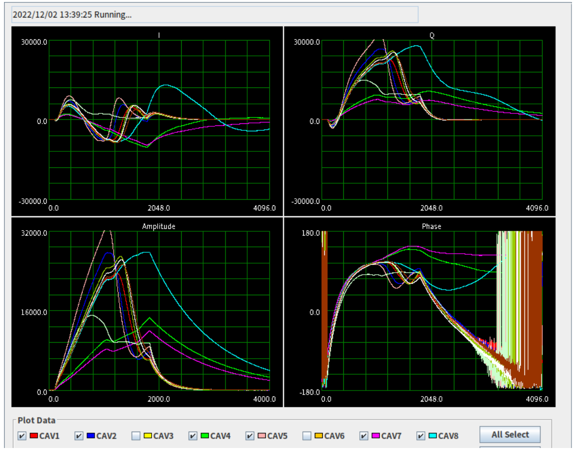
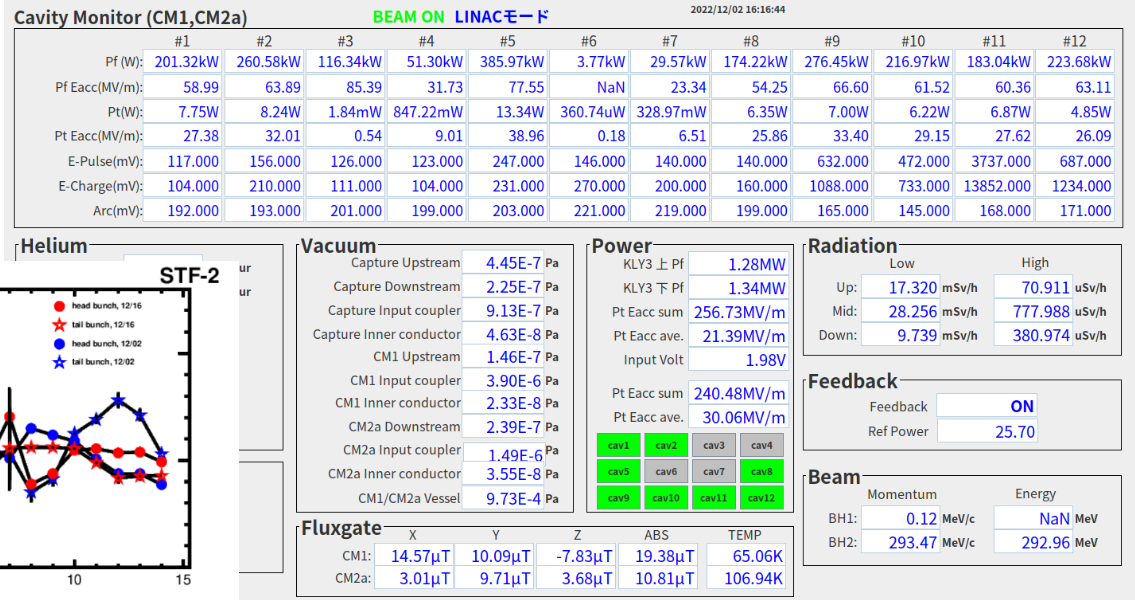
- The STF team observed a lot of quenches at high current (19 µA as average)/high gradient operation (~30 MV/m)
- When they tuned each cavity phase, the beam orbit was drastically improved without quench



Probably, the beam tail hit somewhere in the cavity!


Cavity Monitor (CM1,CM2a) BEAM ON LINACモード 2022/12/02 16:16:44

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Pf (W):	201.32kW	260.58kW	116.34kW	51.30kW	385.97kW	3.77kW	29.57kW	174.22kW	276.45kW	216.97kW	183.04kW	223.68kW
Pf Eacc(MV/m):	58.99	63.89	85.39	31.73	77.55	NaN	23.34	54.25	66.60	61.52	60.36	63.11
Pt(W):	7.75W	8.24W	1.84mW	847.22mW	13.34W	360.74uW	328.97mW	6.35W	7.00W	6.22W	6.87W	4.85W
Pt Eacc(MV/m):	27.38	32.01	0.54	9.01	38.96	0.18	6.51	25.86	33.40	29.15	27.62	26.09
E-Pulse(mV):	117.000	156.000	126.000	123.000	247.000	146.000	140.000	140.000	632.000	472.000	3737.000	687.000
E-Charge(mV):	104.000	210.000	111.000	104.000	231.000	270.000	200.000	160.000	1088.000	733.000	13852.000	1234.000
Arc(mV):	192.000	193.000	201.000	199.000	203.000	221.000	219.000	199.000	165.000	145.000	168.000	171.000

Helium

Vacuum

Capture Upstream	4.45E-7	Pa
Capture Downstream	2.25E-7	Pa
Capture Input coupler	9.13E-7	Pa
Capture Inner conductor	4.63E-8	Pa
CM1 Upstream	1.46E-7	Pa
CM1 Input coupler	3.90E-6	Pa
CM1 Inner conductor	2.33E-8	Pa
CM2a Downstream	2.39E-7	Pa
CM2a Input coupler	1.49E-6	Pa
CM2a Inner conductor	3.55E-8	Pa
CM1/CM2a Vessel	9.73E-4	Pa

Power

KLY3 上 Pf	1.28MW
KLY3 下 Pf	1.34MW
Pt Eacc sum	256.73MV/m
Pt Eacc ave.	21.39MV/m
Input Volt	1.98V
Pt Eacc sum	240.48MV/m
Pt Eacc ave.	30.06MV/m

cav1 cav2 cav3 cav4 cav5 cav6 cav7 cav8 cav9 cav10 cav11 cav12

Radiation

	Low	High
Up:	17.320 mSv/h	70.911 uSv/h
Mid:	28.256 mSv/h	777.988 uSv/h
Down:	9.739 mSv/h	380.974 uSv/h

Feedback

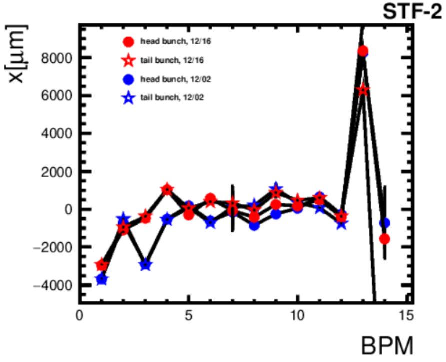
Feedback	ON
Ref Power	25.70

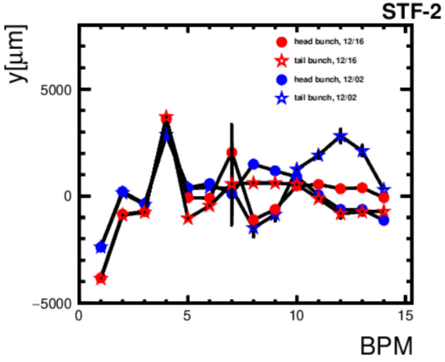
Beam

	Momentum	Energy
BH1:	0.12 MeV/c	NaN MeV
BH2:	293.47 MeV/c	292.96 MeV

Fluxgate

	X	Y	Z	ABS	TEMP
CM1:	14.57µT	10.09µT	-7.83µT	19.38µT	65.06K
CM2a:	3.01µT	9.71µT	3.68µT	10.81µT	106.94K





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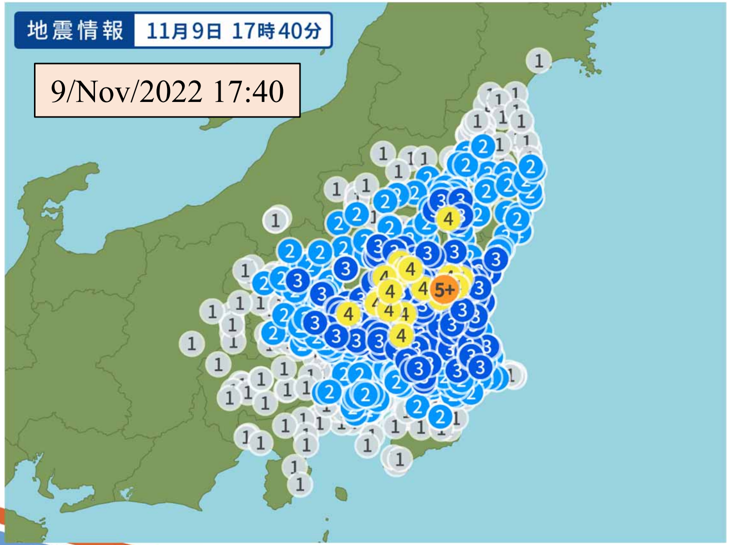
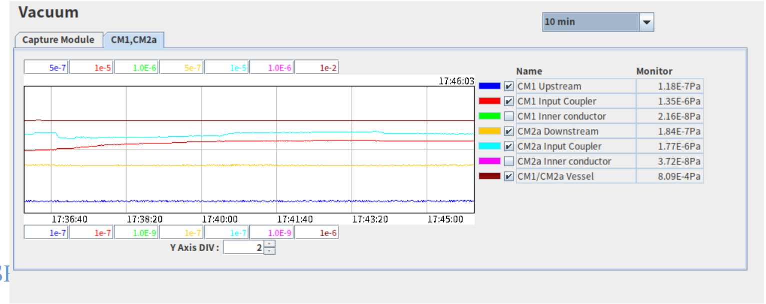
Earthquakes affect cavity performance?①

After the biggest earthquake in 2011, we have some big earthquakes every year.
In Japan, we have seven levels to identify each earthquake from Level 1 at min. to Level 7 at max.
In this case, Level 5 occurred near KEK during RF conditioning, but we just observed fluctuating helium flow, and all vacuum were stable.
Also, the performance for all cavities never changed.





Earthquakes affect cavity performance?②

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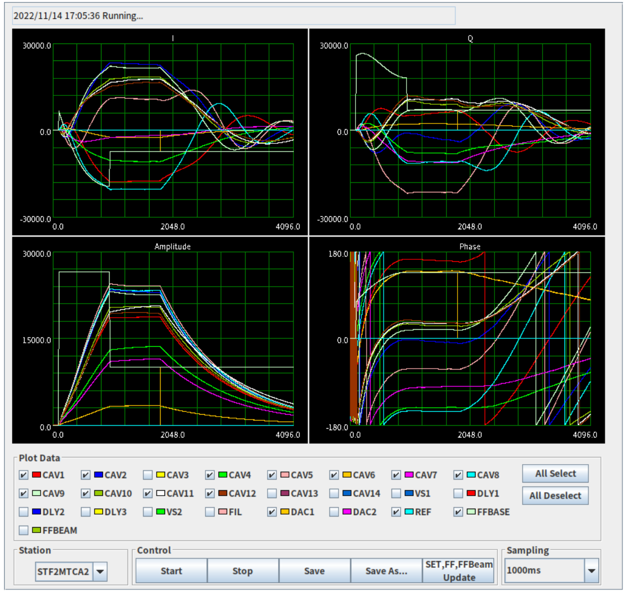
When this earthquake occurred, we were in the middle of the feed-back loop operation for all cavities.
The feed-back loop operation needs more stable cavity phase.
Fortunately, we never had any quench in all cavities.

14/Nov/2022 17:09

発生時刻	2022年11月14日 17時09分ごろ
震源地	三重県南東沖
最大震度	4
マグニチュード	6.1
深さ	350km
緯度/経度	北緯33.8度/東経137.5度
情報	この地震による津波の心配はありません。

震度4	福島県	双葉町 浪江町
	茨城県	つくばみらい市
震度3	宮城県	岩沼市 丸森町
	福島県	いわき市 白河市 須賀川市 田村市 南相馬市 泉崎村 中島村 玉川村 古殿町 福島 広野町 楢葉町 川内村 大熊町
	茨城県	水戸市 日立市 土浦市 茨城古河市 石岡市 下妻市 常総市 常陸太田市 北茨城市 笠間市 取手市 つくば市 守谷市 筑西市 坂東市 稲敷市 かすみがうら市 桜川市 行方市 鉾田市 小美玉市 茨城町 城里町 東海村 河内町 利根町
	栃木県	宇都宮市 栃木市 佐野市 鹿沼市 小山市 下野市 益子町 壬生町 野木町 高根沢町
	群馬県	板倉町

Pulse viewer



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Achievements at KEK/STF

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We have achieved two important milestones related to the ILC specifications at STF!

Parameters	Mar/2019	Apr, Dec/2021	Dec/2022
Number of cavities incl. CCM used for operation	7 + 2	12 + 2	12 + 2
Beam energy	280 MeV (40 MeV @CCM)	384 MeV (40 MeV @CCM)	293 MeV (40 MeV @CCM)
Beam intensity	0.28 μA	1.8 μA	21.0 μA
Beam power	78 W	~700 W	~6 kW
Total charge per pulse	56 nC	360 nC	4200 nC
# of bunch / train	1000	15000	118000
RF power @RF Gun	2.5 MW	4.0 MW	4.0 MW
Normalized emittance @CCM	10~20 mm mrad	10~20 mm mrad	4~6 mm mrad
Normalized emittance @CM1/2a	10~20 mm mrad	10~20 mm mrad	5~7 mm mrad
E_{acc} from beam energy	33.1 MV/m (7 cavities)	32.9 MV/m (9 cavities)	
E_{acc} from RF power (P_{tra})	33.8 MV/m (7 cavities)	33.0 MV/m (9 cavities)	27.7 MV/m (10 cavities)

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- What's the next?

Summary

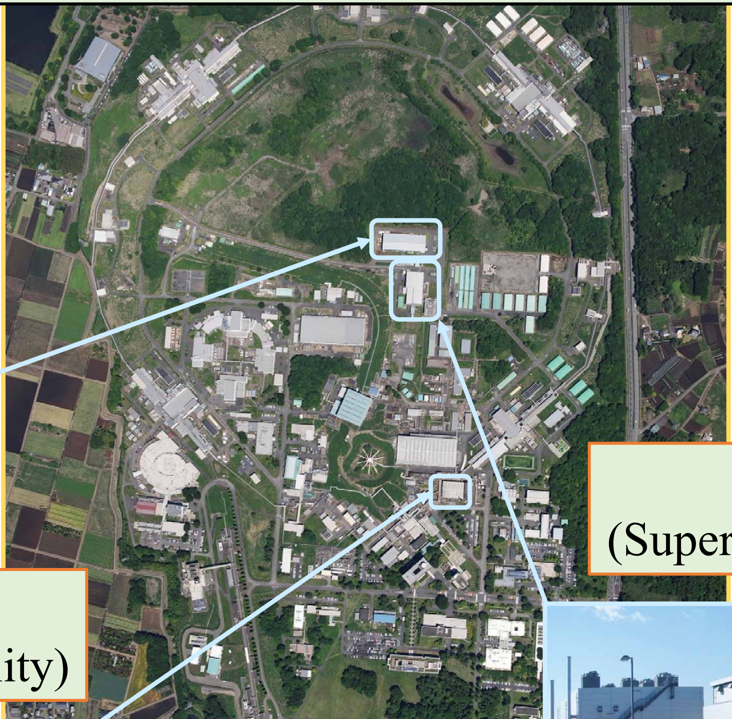
- SRF is the key technology for ILC
- STF is the center of R&D related to SRF for ILC
- The cavity performance achieved above the ILC specifications
- The beam operation satisfied with the ILC specifications was successfully done

What's the next?

Contents

- ILC project
- STF/STF-2 accelerator
- Cavity performance
- Beam operation & High current operation
- Earthquake
- Achievements
- Summary
- What's the next?

SRF facilities at KEK



COI
(Center of Innovation)

CFF
(Cavity Fabrication Facility)

STF
(Superconducting RF Test Facility)

応用超伝導加速器イノベーションセンター

COI infrastructures

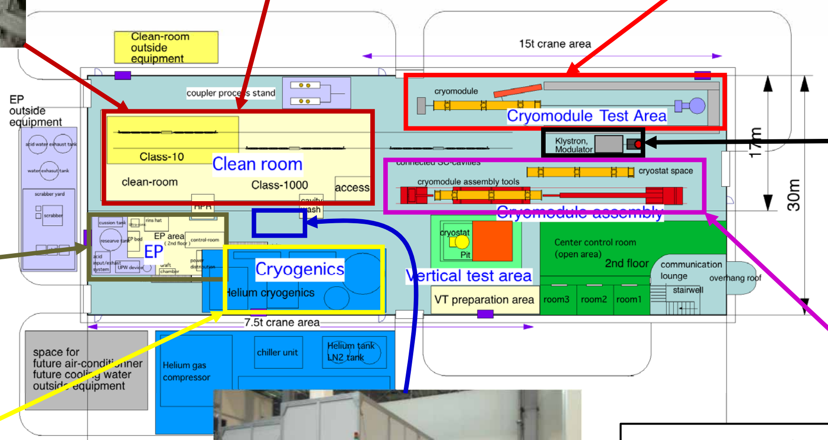
Rail system for cavity string

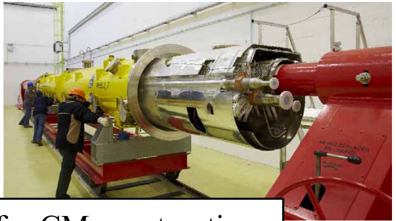
Robot arm for auto cleaning

Cryomodule test cave

High level RF system for CM test

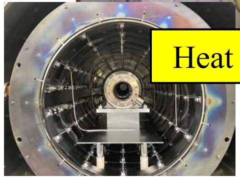
R&D for vertical EP





Hanger and rail system for CM construction

Cryogenics upgrade for CM test



Heat furnace upgrade

Thank you very much for your attention!