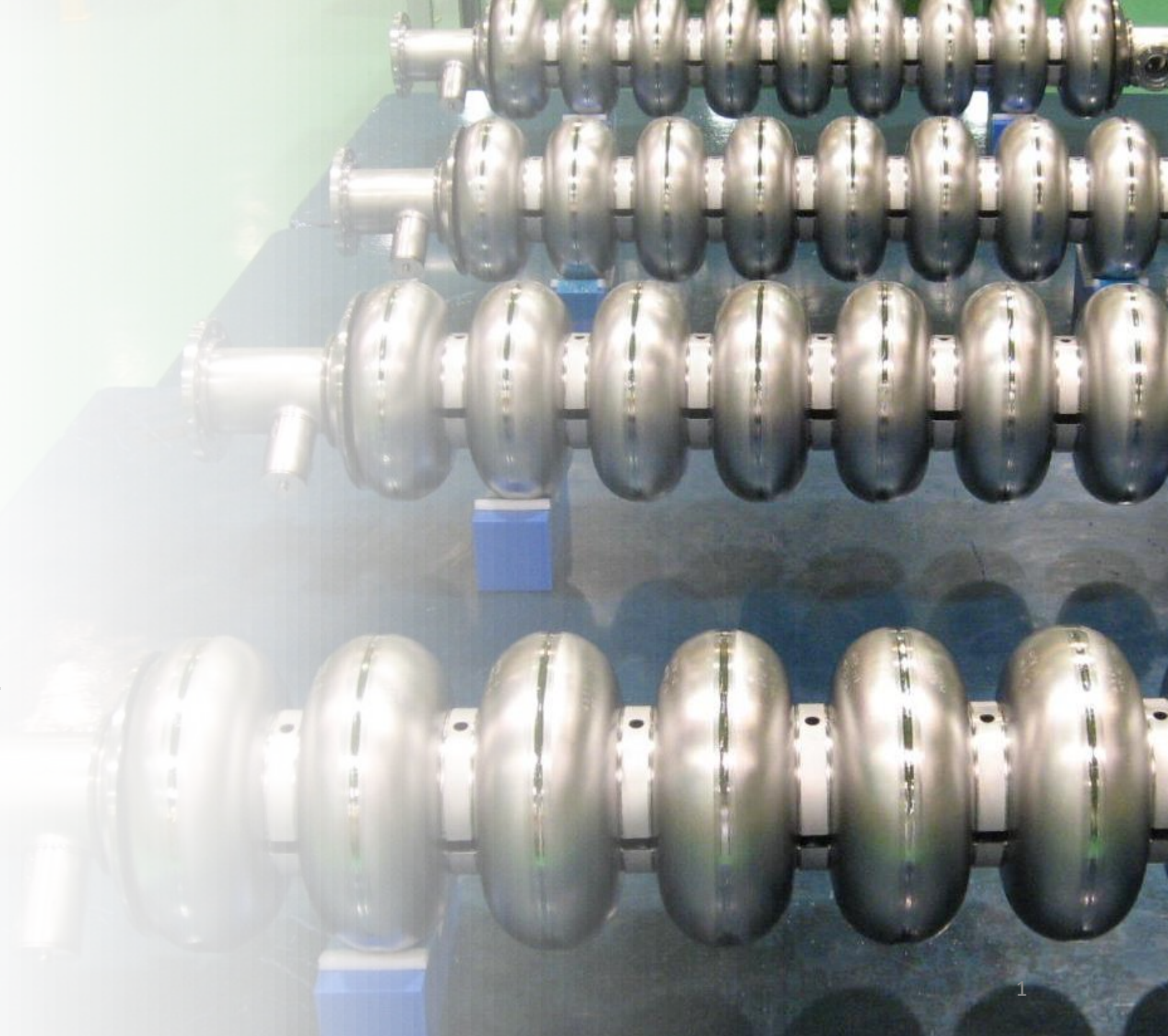
ILC SRF technology development at KEK

The 2021 International Workshop on the High Energy Circular Electron Positron Collider

2021/11/9

KEK CASA Kensei Umemori

(on behalf of KEK CASA-SRF)



Contents

- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

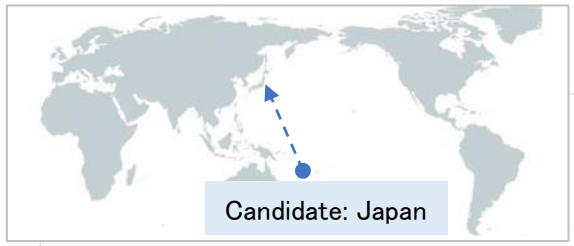
Contents

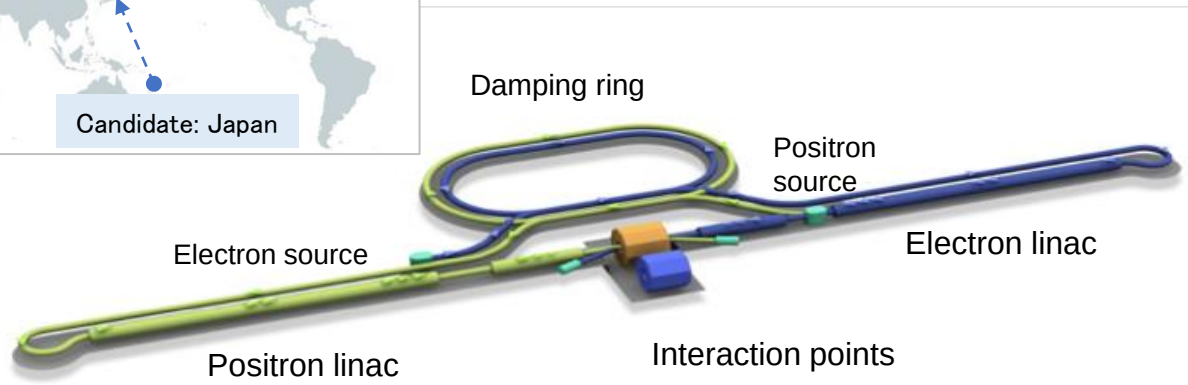
- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

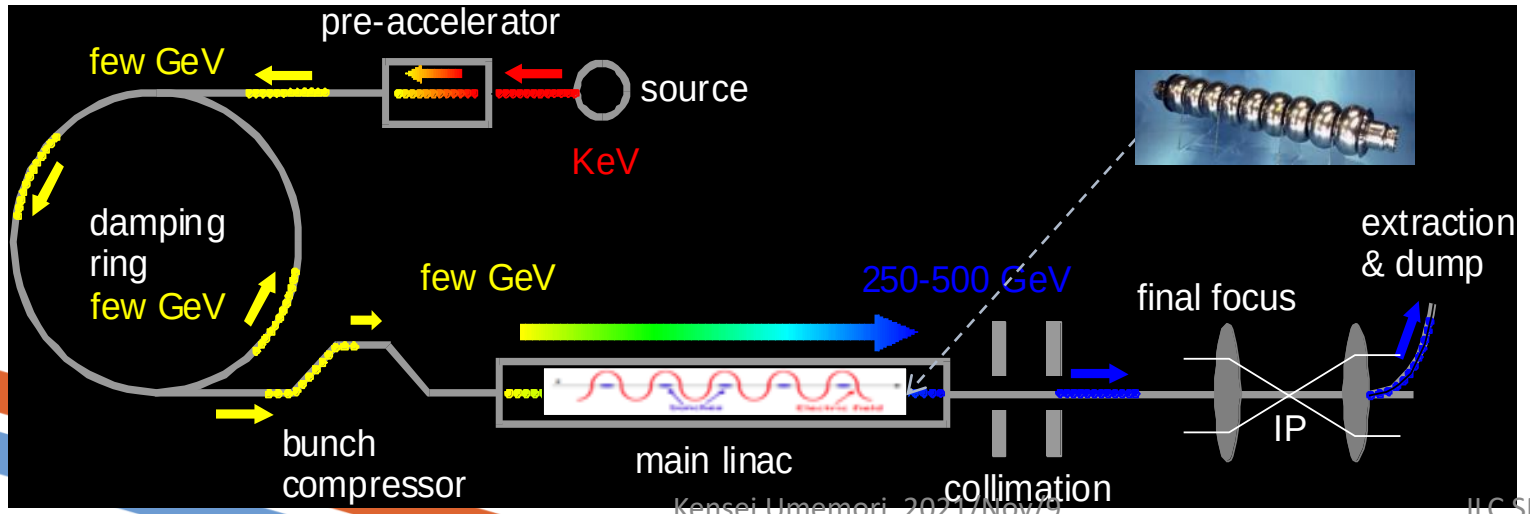
ILC (International Linear Collider)

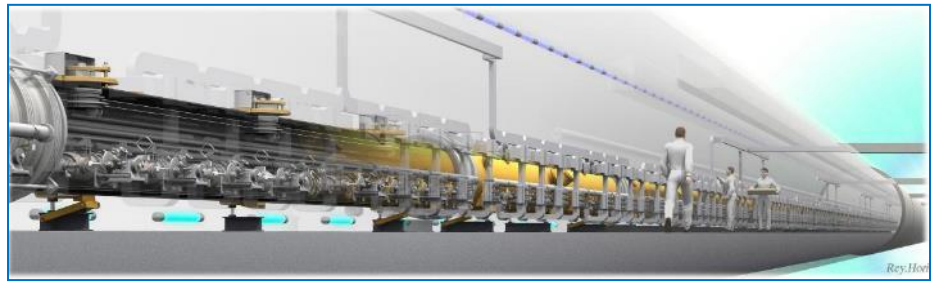
Shin Michizono

CASA Center for Applied Superconducting Accelerator 応用超伝導加速器センター









Item	Parameter
Electron-positron energy	125+125 GeV
Repetition rate	5 Hz
Beam pulse time	0.73 ms
Accelerating gradient Q-value	31.5 MV/m(+/-20%) Q_0 = 1E10
9-cell SRF cavities	**~ 8,000 (x 1.1)**
Cryomodule	**~ 900**

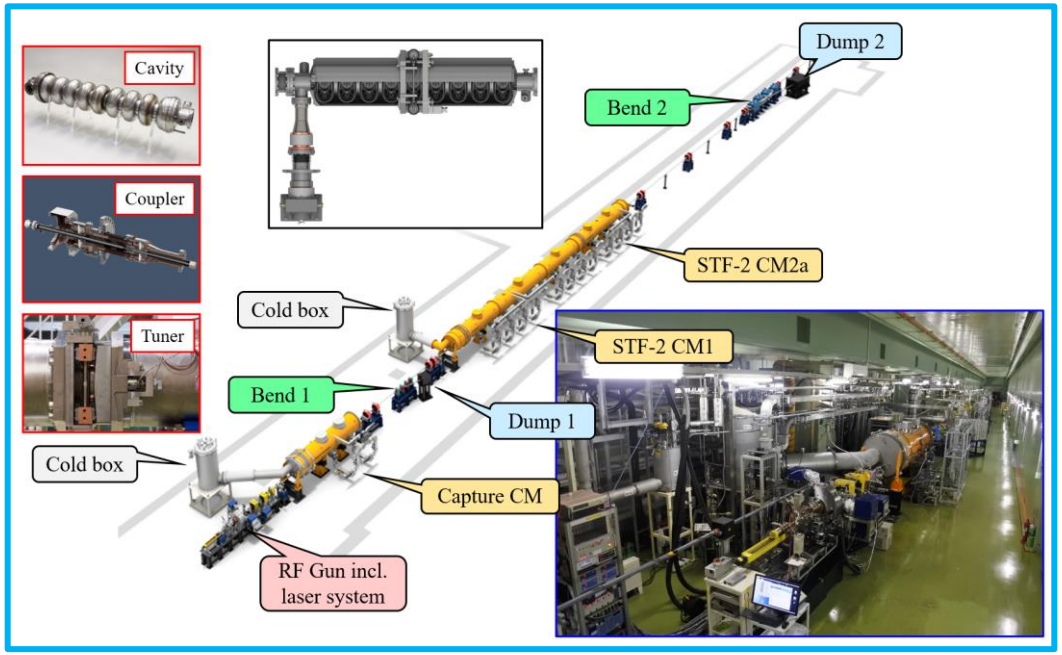
Contents

- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

STF-2 accelerator

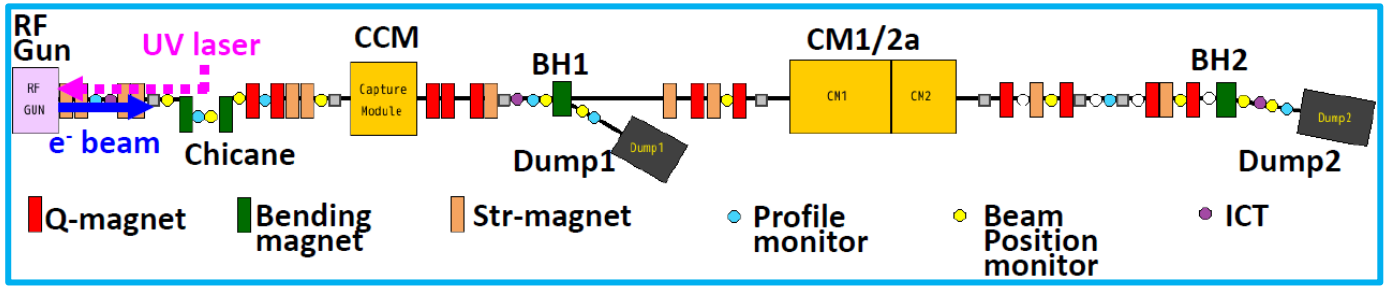
Kirk Yamamoto

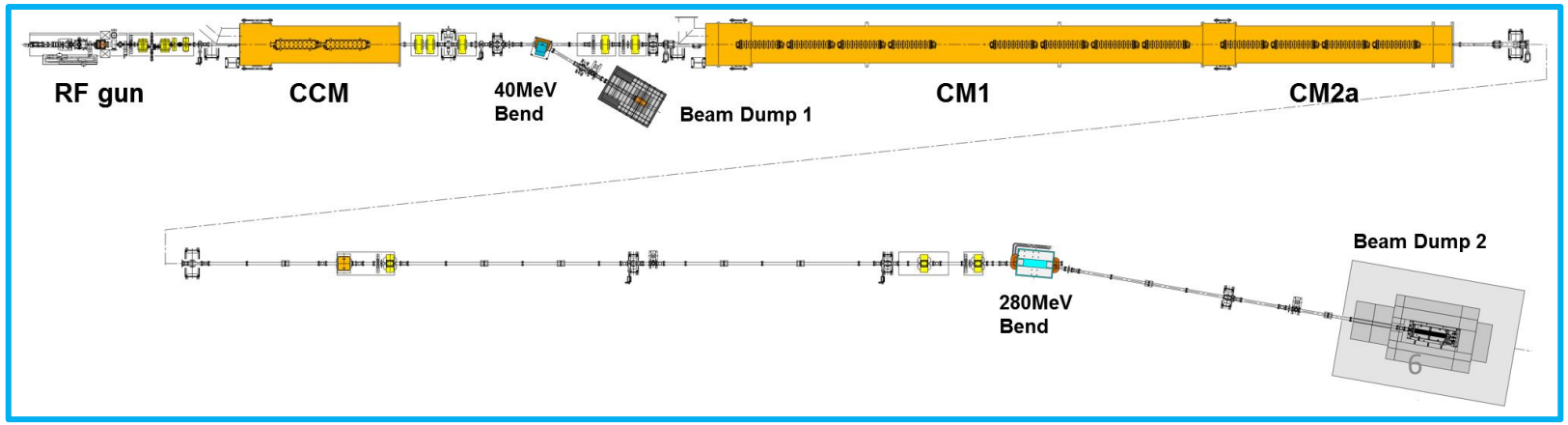
- ~70 m Superconducting linac（1.65 msec/5Hz）
- SC cavities：Total 14 cavities（1.3 GHz、9-cell）
- Cryomodule：CCM（2 cavities）とCM1/CM2a（8+4 cavities）
- Photocathode RF gun（Cs_2Te、Q.E.~1%）
- Laser system：162.5 MHz、1064 nm、12 W
- Klystron：3（5 MW、800 kW、10 MW）
- Beam dump：2（Dump2: 37.8 kW）
- 2K He refrigerator
- Beam monitor：Position, current, beam profile
- Bending magnet：2



History on STF-2		# of cavities
F.Y.2014	Low power test	---
F.Y.2015	High power test	1 cavity
F.Y.2016	High power test	8 cavities
F.Y.2018	High power + beam test	7+2 cavities
F.Y.2020	Low power test	---
F.Y.2020~2021	High power + beam test	12+2 cavities

Specification in application (radiation safety)
- Max beam energy：500 MeV
- Max beam current：3.0 μA
- Max beam power：1.35 kW



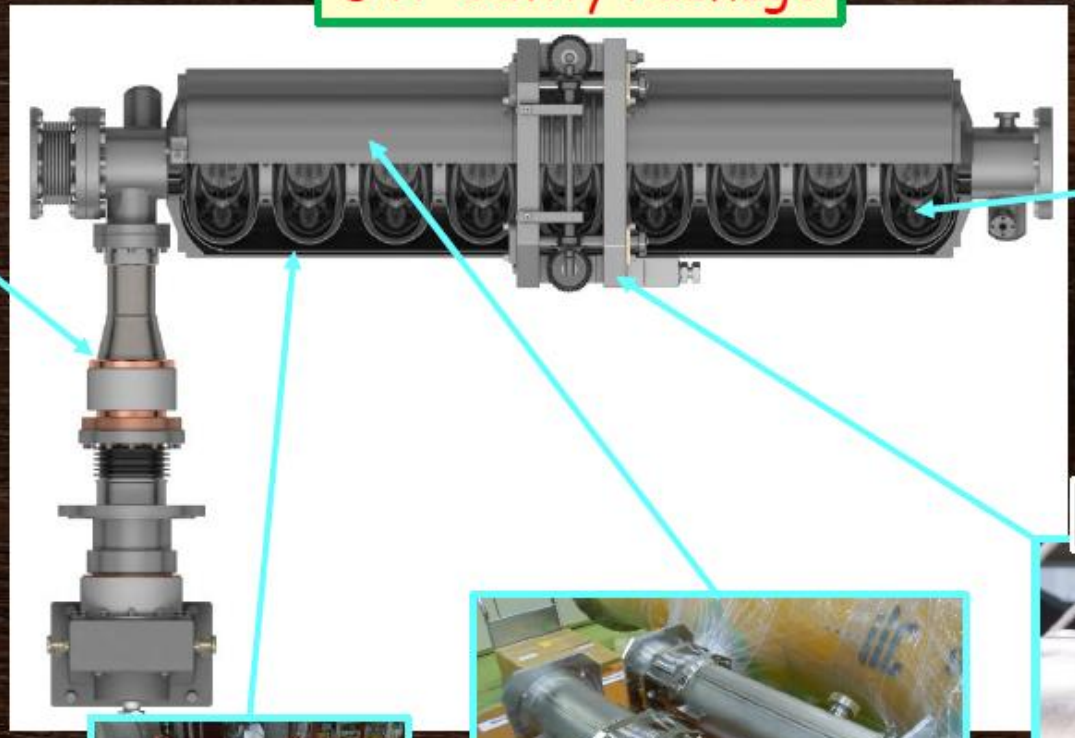


Cavity Package

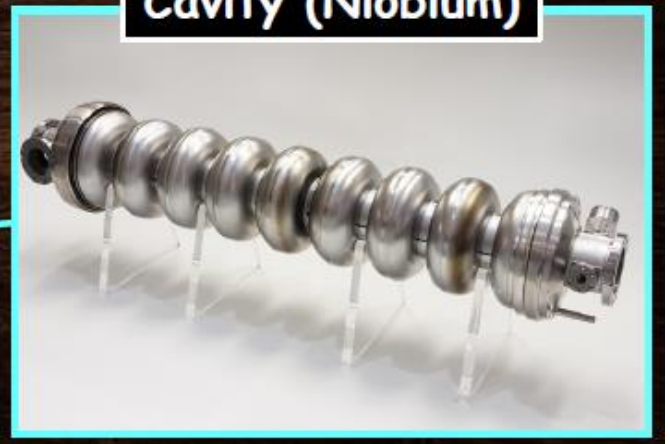
Kirk Yamamoto

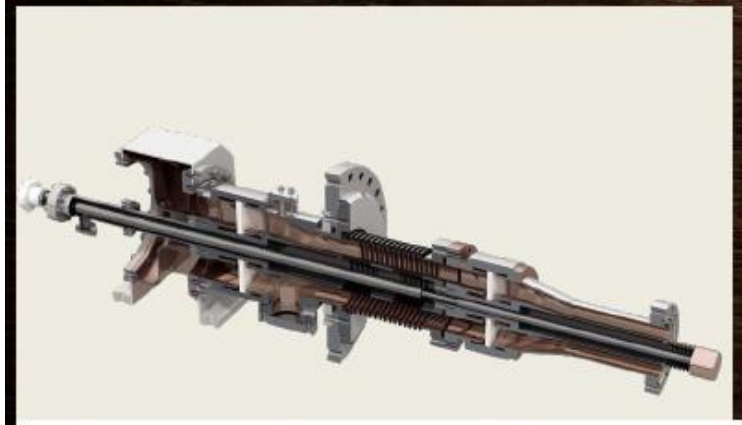
Power coupler
(Copper plating on SUS316L)

STF Cavity Package



Cavity (Niobium)



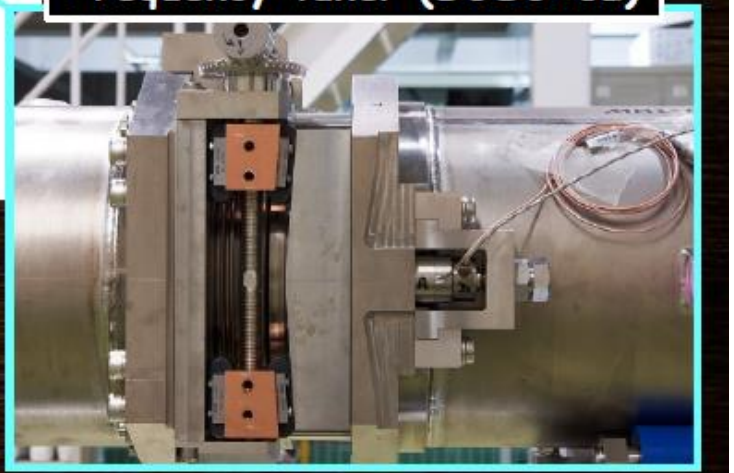


Cross-sectional view of power coupler
(double ceramic windows w/ TiN coating)

Magnetic shield (Permalloy)

Helium tank (Titanium)

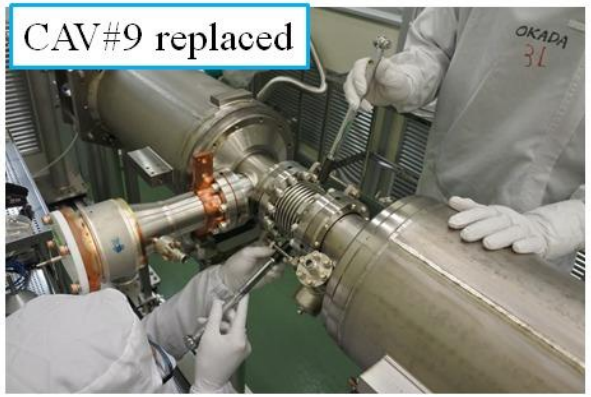
Frequency tuner (SUS316L)



Cavity replacement work from 2019 to 2020

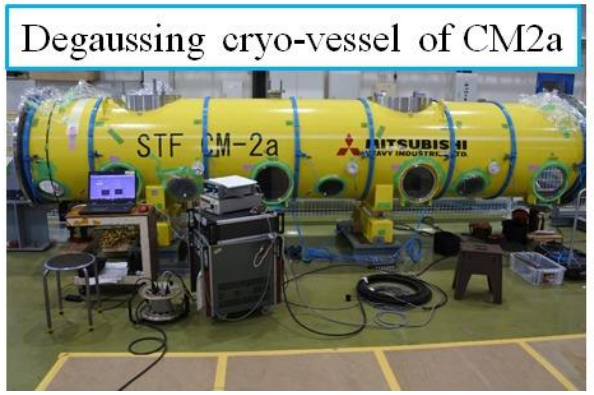
Kirk Yamamoto

CAV#9 replaced



Tuner drive and HOM tuning

Degaussing cryo-vessel of CM2a



Cold mass of CM2a

Installing into beamline

Alignment of CM2a

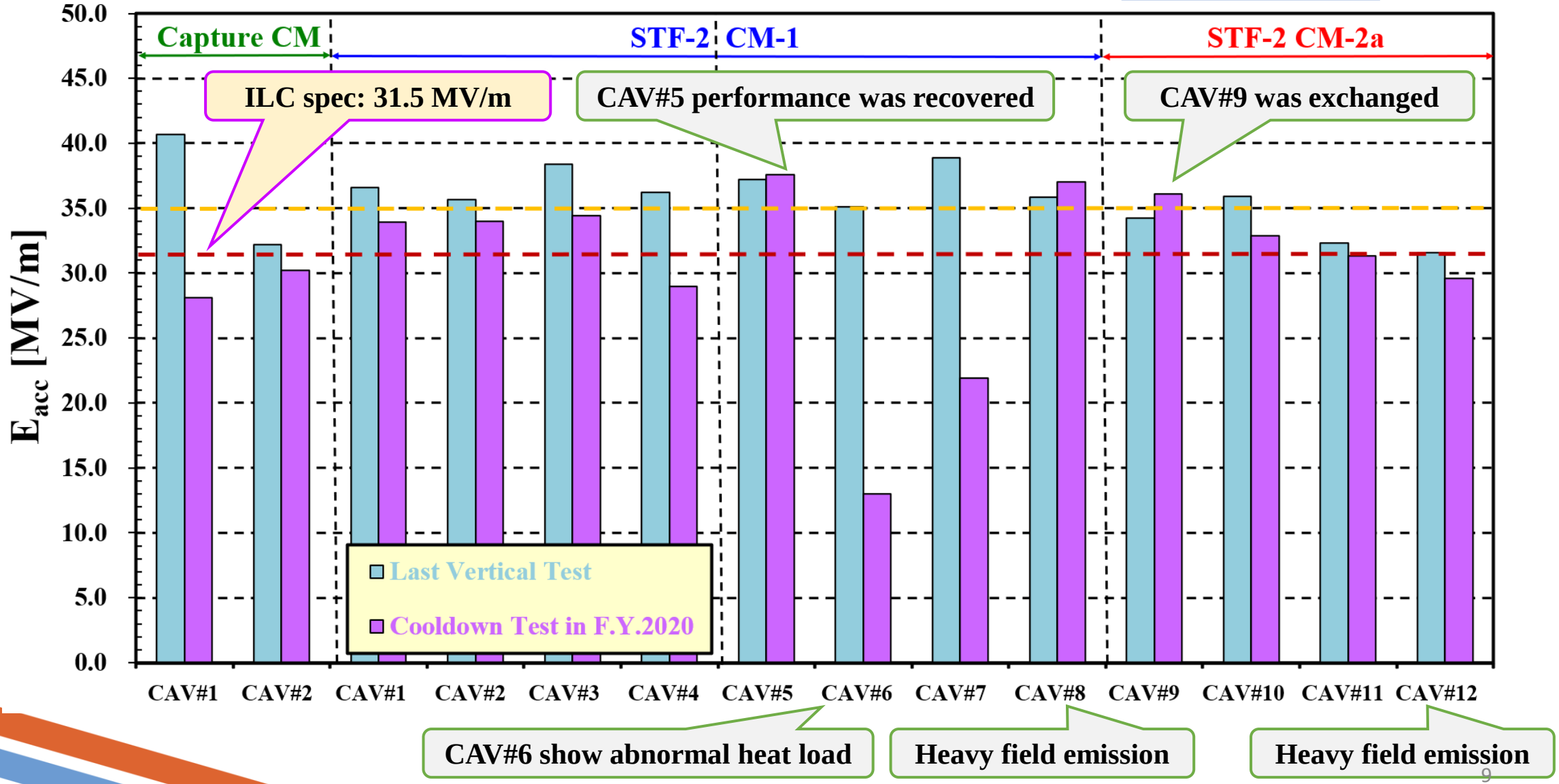
Beamline connection

Completion inspection

CAV#9 was replaced by the N-infusion cavity, in order to improve the accelerator performance.

Cavity Performance in VT and CM

Kirk Yamamoto

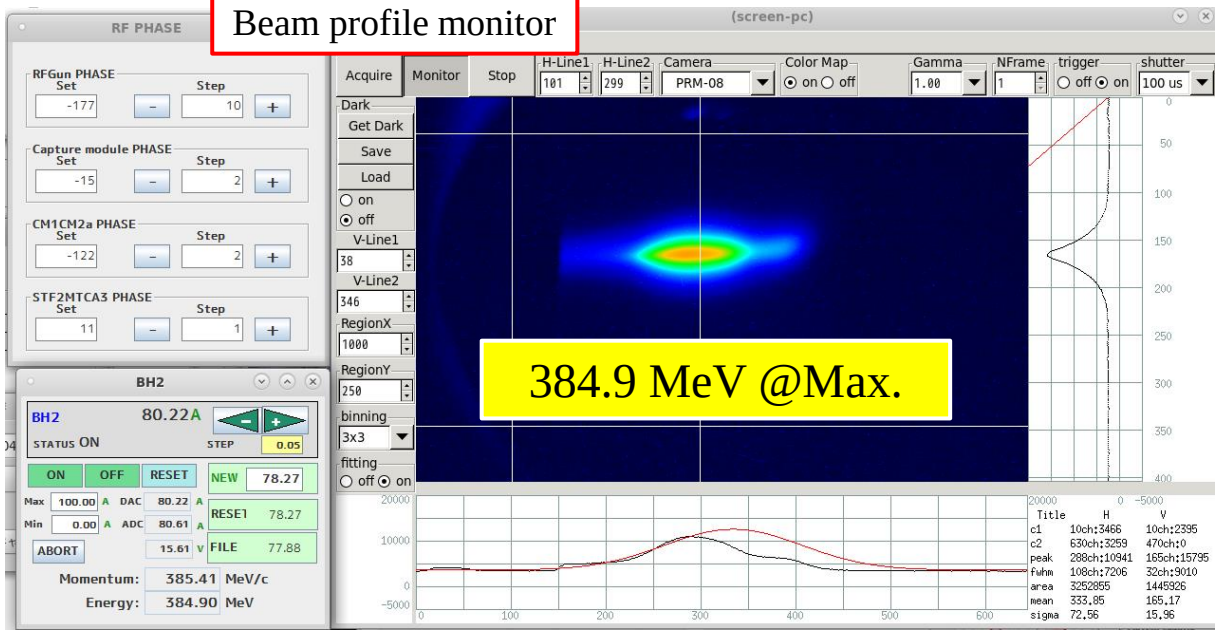


Max. Beam Energy Operation

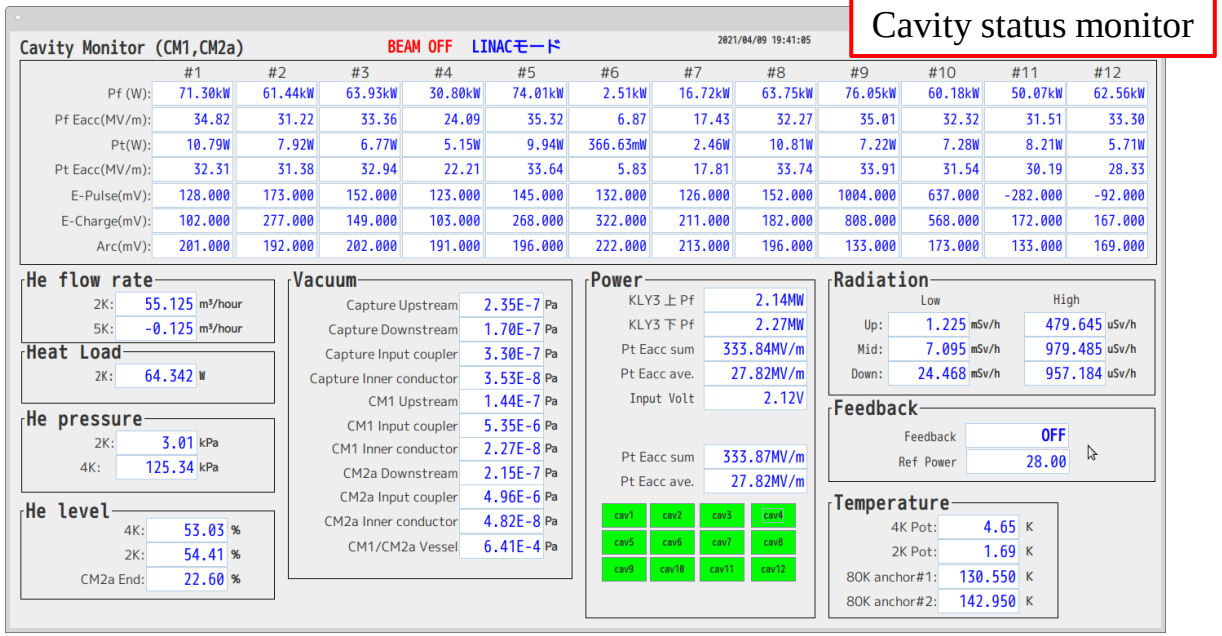
Kirk Yamamoto

4/9 Tried to Max. beam energy operation by adjusting cavity phase, while looking at beam plofile.

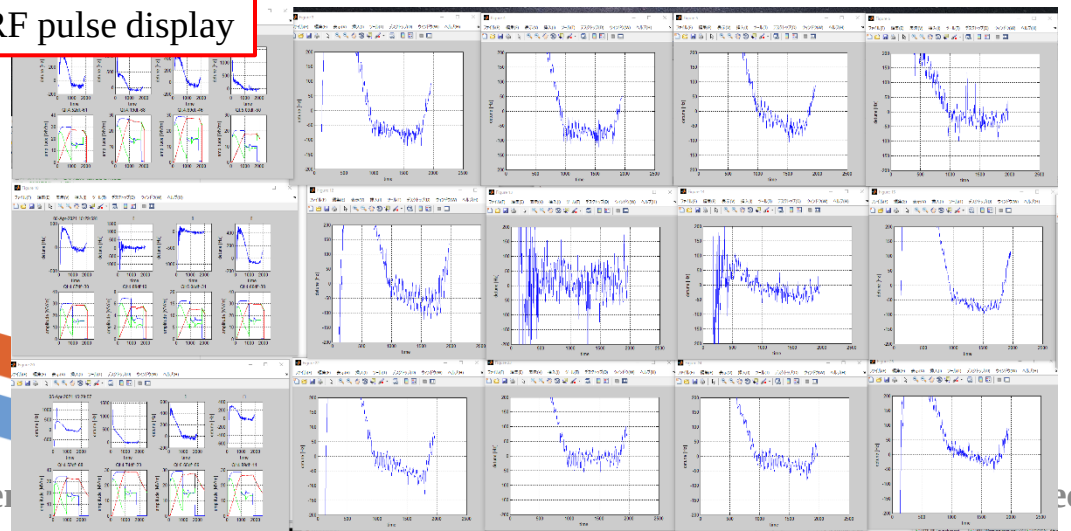
Beam profile monitor



Cavity status monitor



RF pulse display



- Maximum beam energy of 385 MeV was observed after adjustment of cavity phase.
- Maximized cavity performance was difficult, because of spread of cavity performance.
- After quenches at max. field, cavity performance sometimes became unstable, probably due to heat up of somewhere.
- All of electron-gun, He refrigerator, LLRF/HLRF, cryomodule were stable.

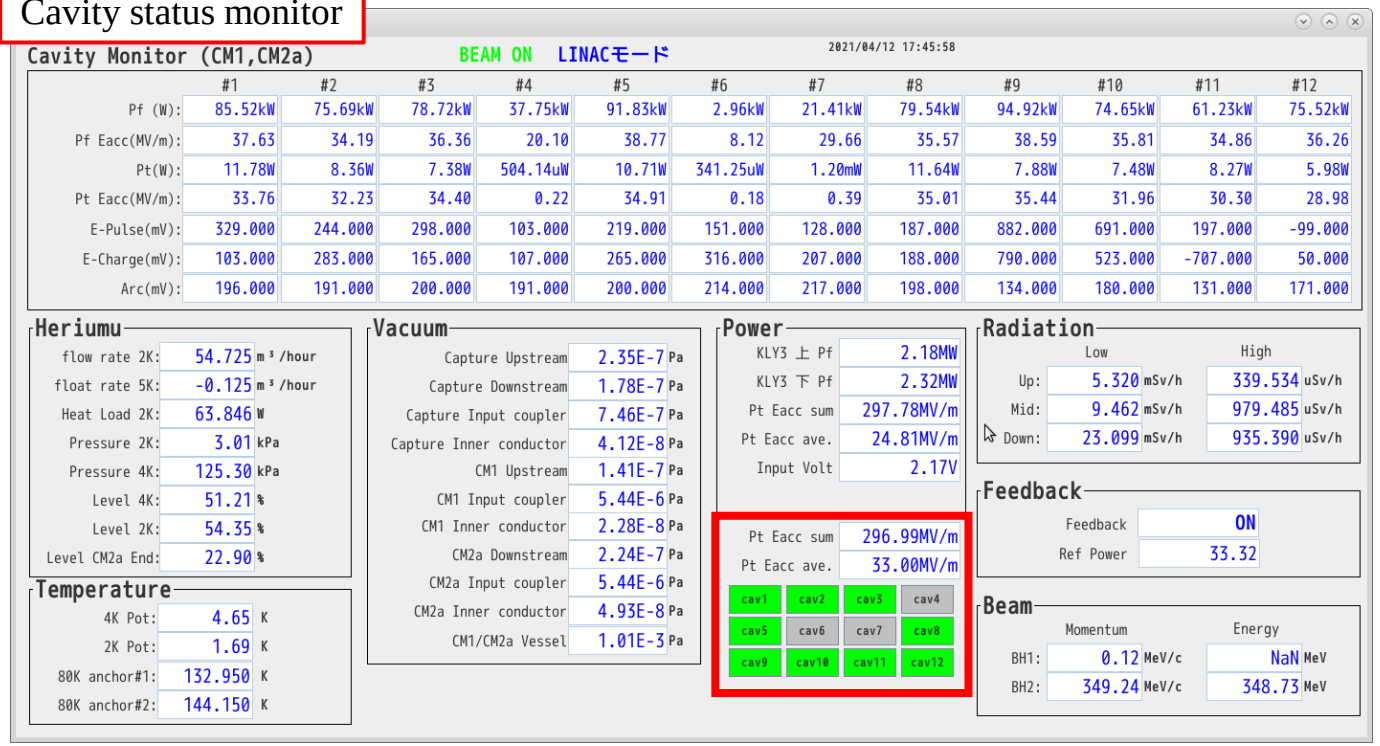
Max. Average E_{acc} Operation

Kirk Yamamoto

Center for Applied Superconducting Accelerator

2021/4/12 Max. average Eacc operation was performed for 9 cavities (3 cavities were detuned).

Cavity status monitor



	#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

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	%

Temperature

4K Pot:	4.65	K
2K Pot:	1.69	K
80K anchor#1:	132.950	K
80K anchor#2:	144.150	K

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-7	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
Pt Eacc sum	296.99MV/m
Pt Eacc ave.	33.00MV/m

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

Radiation

	Low		High	
Up:	5.320	mSv/h	339.534	uSv/h
Mid:	9.462	mSv/h	979.485	uSv/h
Down:	23.099	mSv/h	935.390	uSv/h

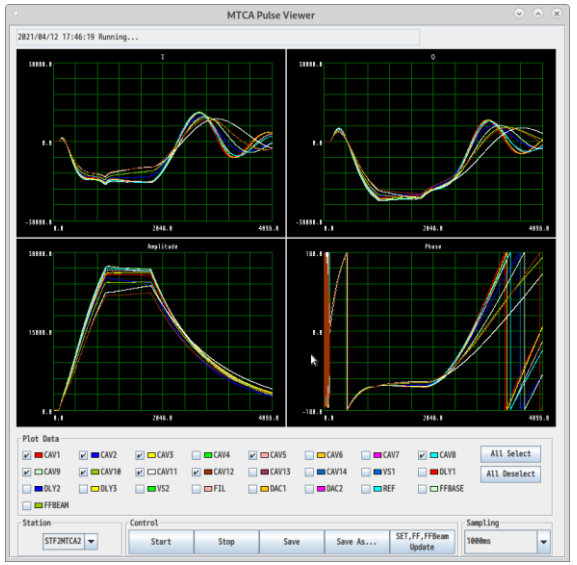
Feedback

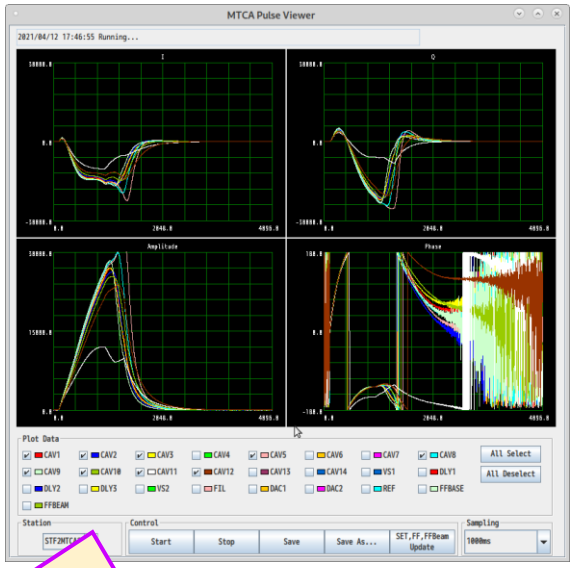
Feedback	ON
Ref Power	33.32

Beam

	Momentum		Energy	
BH1:	0.12	MeV/c	NaN	MeV
BH2:	349.24	MeV/c	348.73	MeV

Pulse Viewer





Waveform when quench happened

- Average accelerating gradient estimated from beam energy was 32.9 MV/m, and estimated from RF measurement was 33.0 MV/m. Both showed very good agreement.
- 5% margin exists against ILC specification of 31.5 MV/m.
- Sometimes quenches happed during adjustment. We had to re-start.
- Beam was stable during operation.

Achievements in 2019 and 2021

Kirk Yamoto

- **Successful beam acceleration at STF-2 by 14 cavities.**
- Average accelerating gradient estimated from beam energy was 32.9 MV/m, and estimated from RF measurement was 33.0 MV/m. Both showed very good agreement.
- Emittance growth observed after passing through CM1/2a is under investigation.

Parameters	Mar/2019	Apr/2021
Number of cavities incl. CCM used for operation	7 + 2	12 + 2
Beam energy	280 MeV (40 MeV @CCM)	384 MeV (40 MeV @CCM)
Beam intensity	0.28 μA	1.8 μA
Beam power	78 W	677 W
Total charge per pulse	56 nC	360 nC
RF power @RF Gun	2.5 MW	4.0 MW
Normalized emittance @CCM	~10 / ~10 mm mrad	1.93 / 1.44 mm mrad
Normalized emittance @CM1/2a	70~90 / 35~53 mm mrad	18.9 / 26.2 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)

Contents

- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

2-step baking

Ryo Katayama, SRF2021

	VT	EP	Bake	Cooling
MT3	VT4 (Baseline)	KEK-STD (20 um)	120 °C 48 h	KEK-STD
	VT5	KEK-cold (20 um)	75 °C 2h (cell1) / 75 °C 4 h (others) + 120 °C 48 h	KEK-STD
MT5	VT1 (Baseline)	KEK-STD (20 um)	120 °C 48 h	KEK-STD
	VT2	KEK-cold (20 um)	75 °C 4 h + 120 °C 48 h	KEK-STD
	VT5	KEK-cold (10 um)	75 °C 4 h + 120 °C 48 h	KEK-STD
	VT6	KEK-cold (20 um)	70 °C 4 h + 120 °C 48 h	KEK-STD w/ additional cooling
MT6	VT5 (Baseline)	KEK-STD (30 um)	120 °C 48 h	KEK-Fast w/ additional cooling
	VT6	KEK-cold (10 um)	70 °C 4 h + 120 °C 48 h	KEK-Fast w/ additional cooling

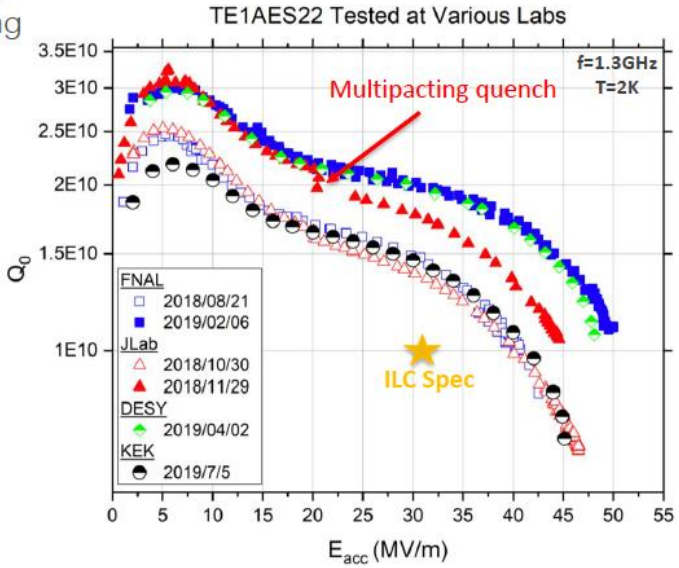
Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

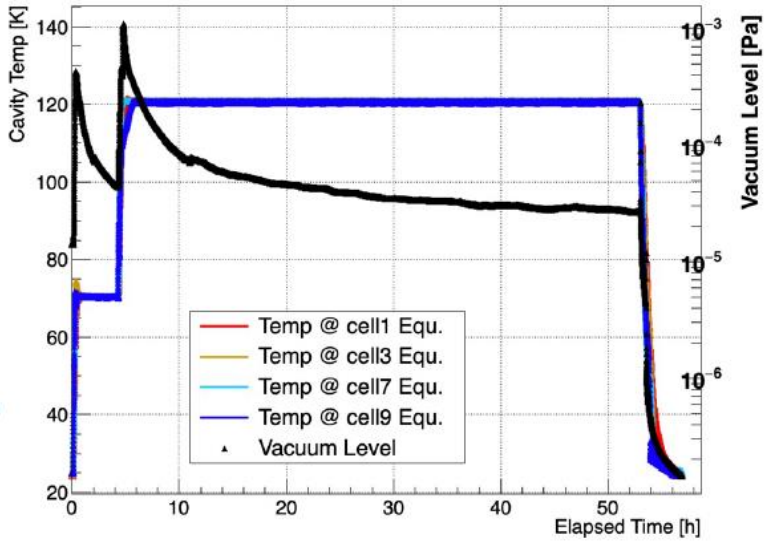
FNAL – Batavia, IL
- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia
- Lower and Upper branch obtained

DESY – Hamburg, Germany
- Upper branch: +48MV/m confirmed

KEK – Tsukuba, Japan
- Lower Branch: +45MV/m confirmed





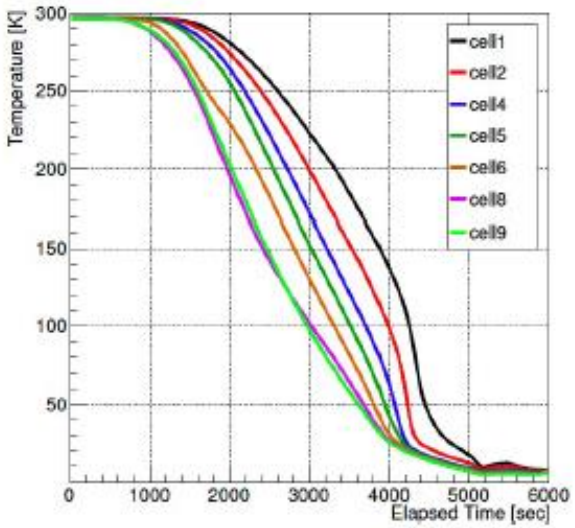
2-step baking (70-75C, 4h + 120C, 48h) was applied to TESLA-type 9-cell cavities, in order to investigate improvement of cavity performance.

Fast cool-down

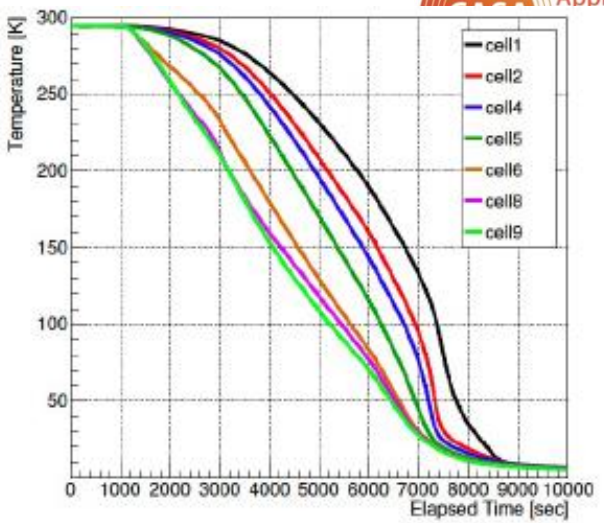
Fast cool-down was tried at KEK. VT pit was pumped during He transfer from the dewar.

Ryo Katayama, SRF2021

Fast cool-down



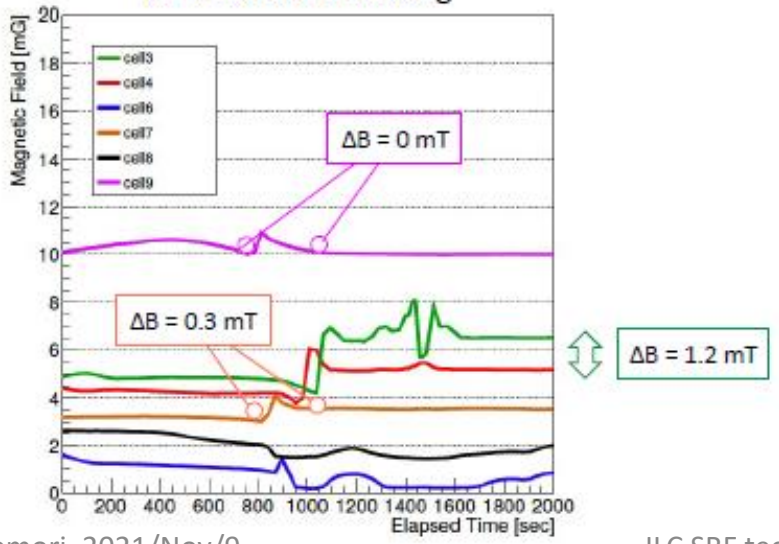
Standard cool-down



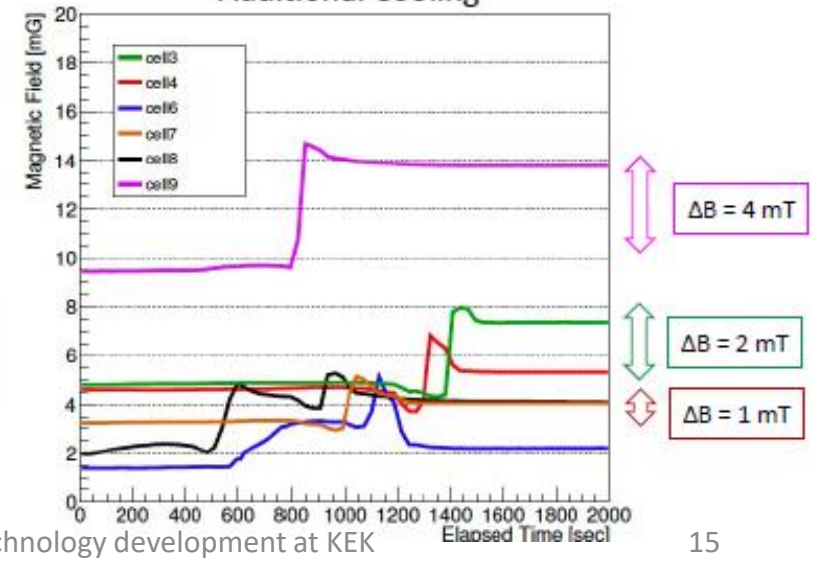
cell	Δt from 200 K to 100 K
1	1593 s for STD
	924 s for Fast
5	1782 s for STD
	952 s for Fast
9	2025 s for STD
	952 s for Fast

Flux expulsion during KEK-STD cooling and the additional cooling as a function of time are shown in the following figures.

KEK-Standard Cooling



Additional Cooling

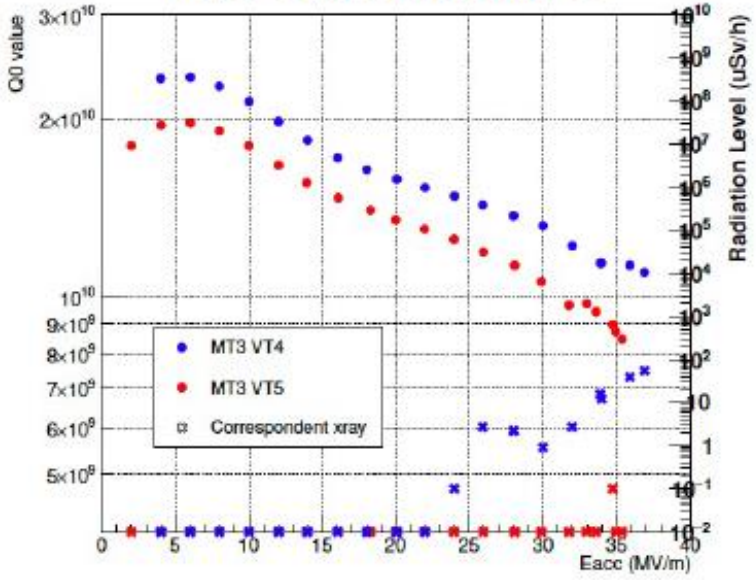


Results of 2-step baking

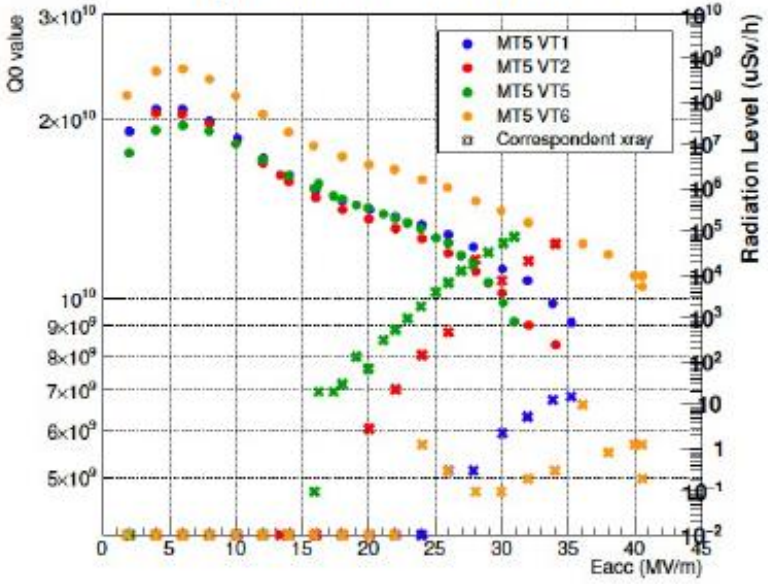
Blue: 120C, 48h baking
Others: 2-step baking

Ryo Katayama, SRF2021

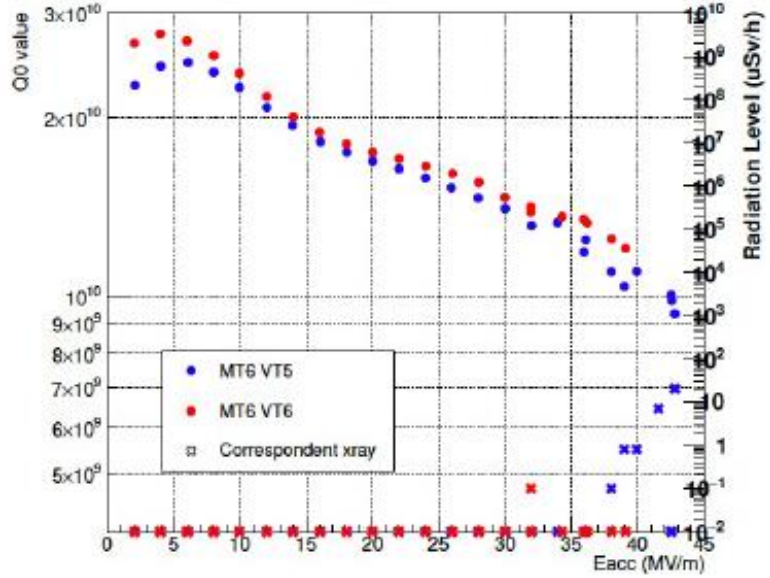
Q-E curve for MT-3



Q-E curve for MT-5



Q-E curve for MT-6



Cell	MT3 VT4	MT3 VT5	MT5 VT1	MT5 VT2	MT5 VT5	MT5 VT6	MT6 VT5	MT6 VT6
1 & 9	36.9	36.6	36.3	36.3	35.7	40.7	>42.8	39.5
2 & 8	42.0	36.6 (F.E.)	>40.4	40.2	40.2	>40.7	>42.8	>43.6
3 & 7	43.8	>38.9	41.0	>39.6	>34.7	>40.7	>42.8	43.5
4 & 6	45.1	>40.5	39.0	40.0	31.1 (F.E.)	>40.7	>42.8	41.2
5	43.0	>41.9	40.4	40.6	>40.2	>40.7	>42.8	43.6

Unit: MV/m

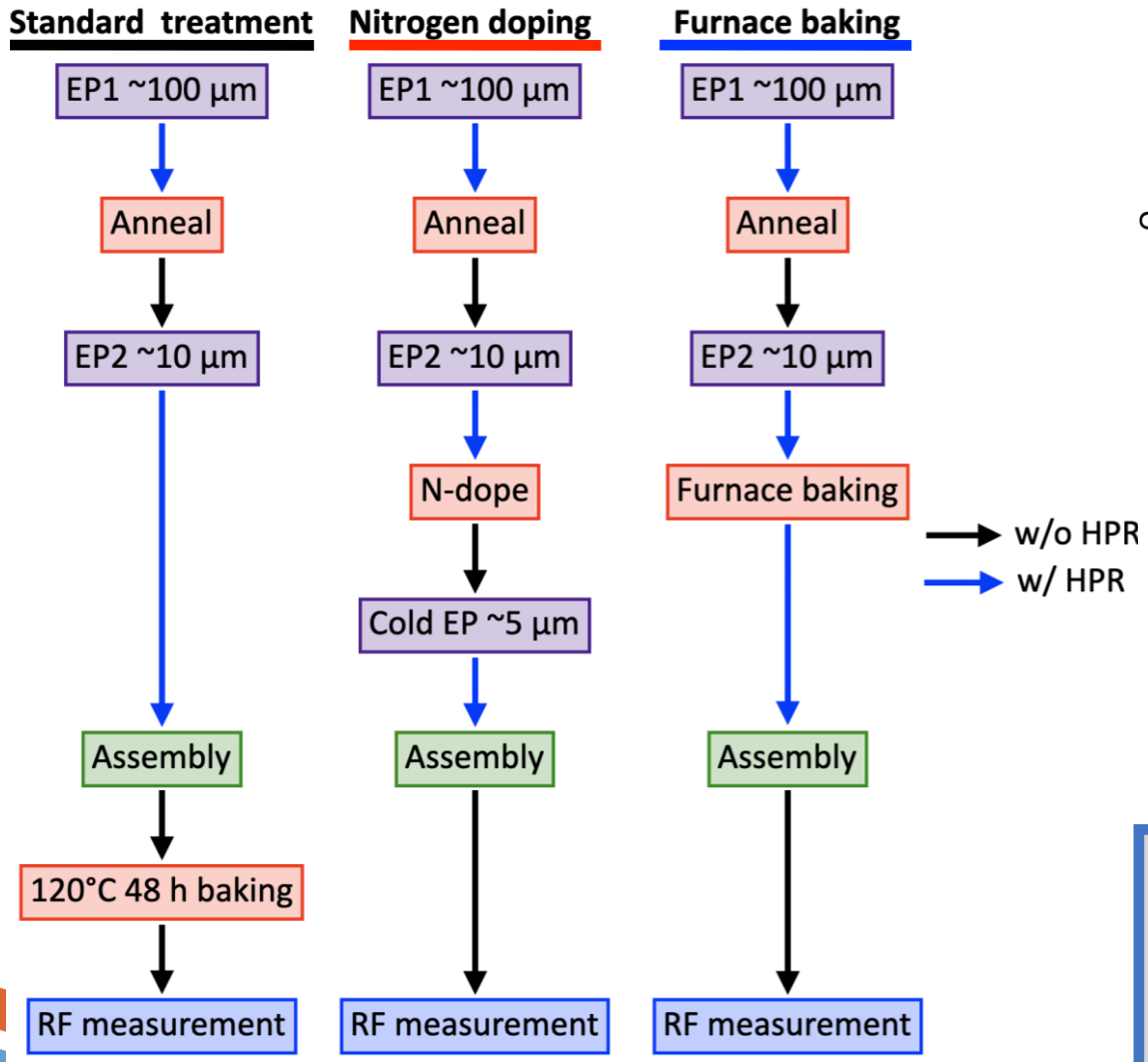
- Some improvement was observed for Q-values. But fast-cool down might be important factor.
- No improvement of Eacc was observed.
- Both of normal baking/2-step baking show good results.

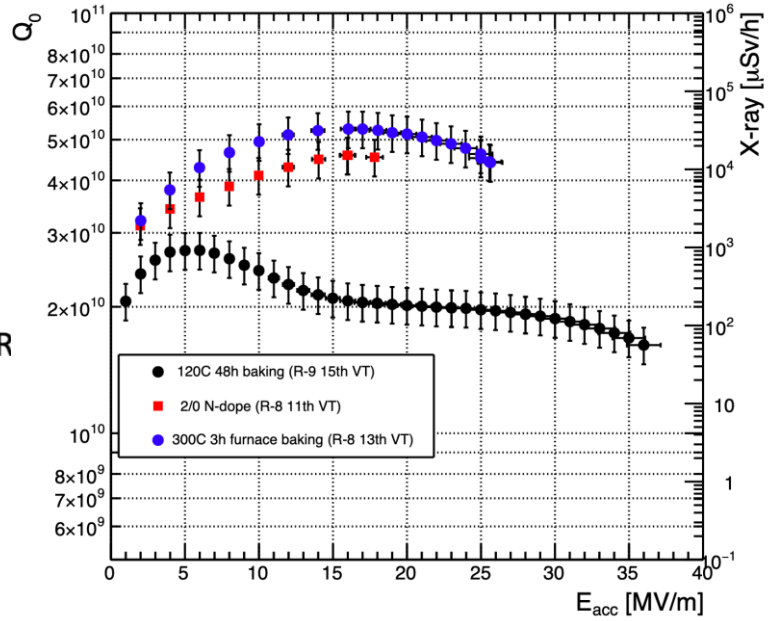
Contents

- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

Mid-T furnace baking method

Hayato Ito, SRF2021





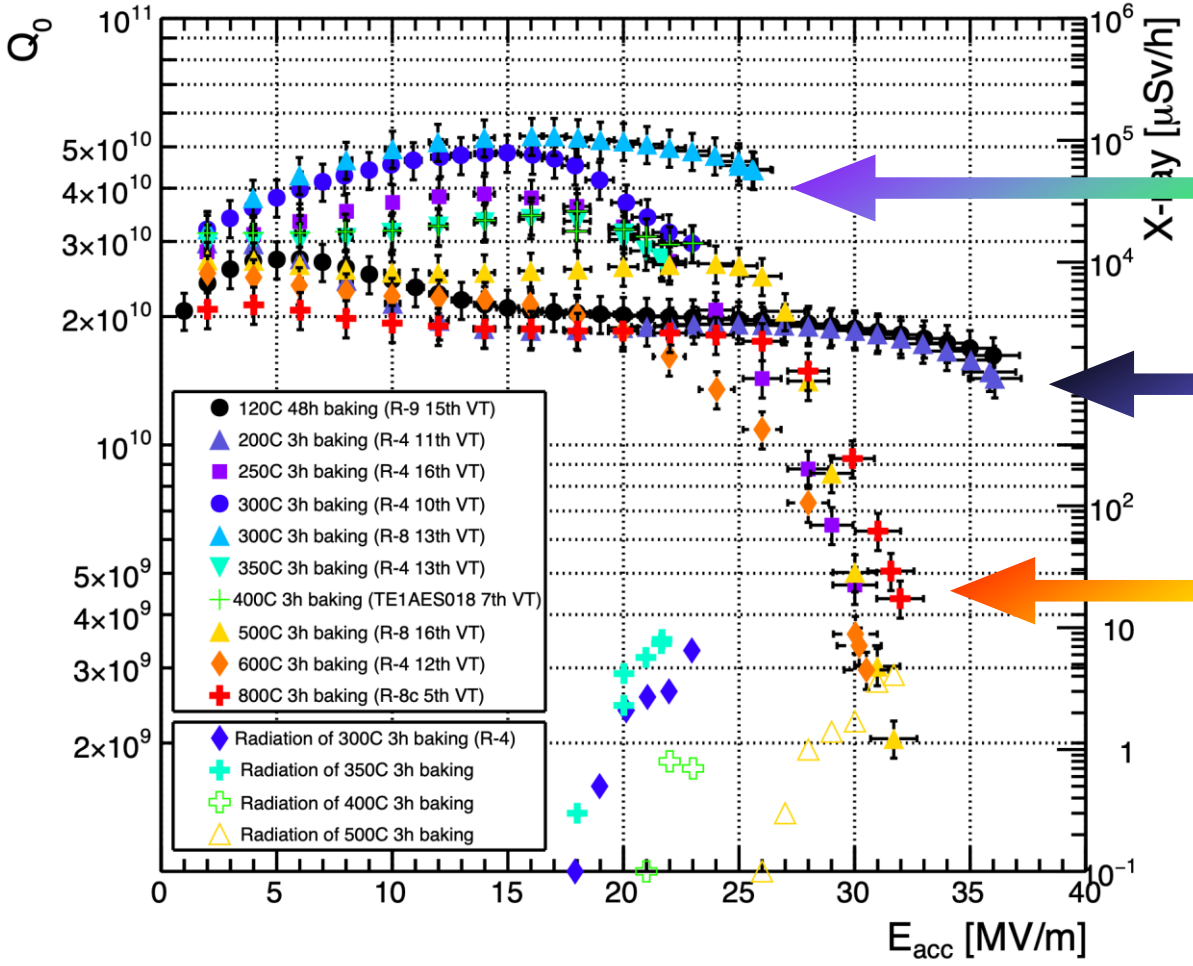
We can achieve high-Q value with a simpler process by furnace baking.

Comparison of Q-E curve

Hayato Ito, SRF2021

Center for Applied Superconducting Accelerator 応用超伝導加速器センター

Cavity temperature during measurement
- 120 ~ 600°C baking … at 2.0 K (2.00~2.01 K)
- 800°C baking … at 2.1 K (2.07K)



250 ~ 400°C 3 h
- Extremely high Q value and anti-Q slope are observed
- Highest Q value at 2.0 K is ~ 5E10 for 300°C baked cavity
- Magnetic field was trapped before 2 K measurement of 350°C baked cavity -> Q value is Essentially a bit higher

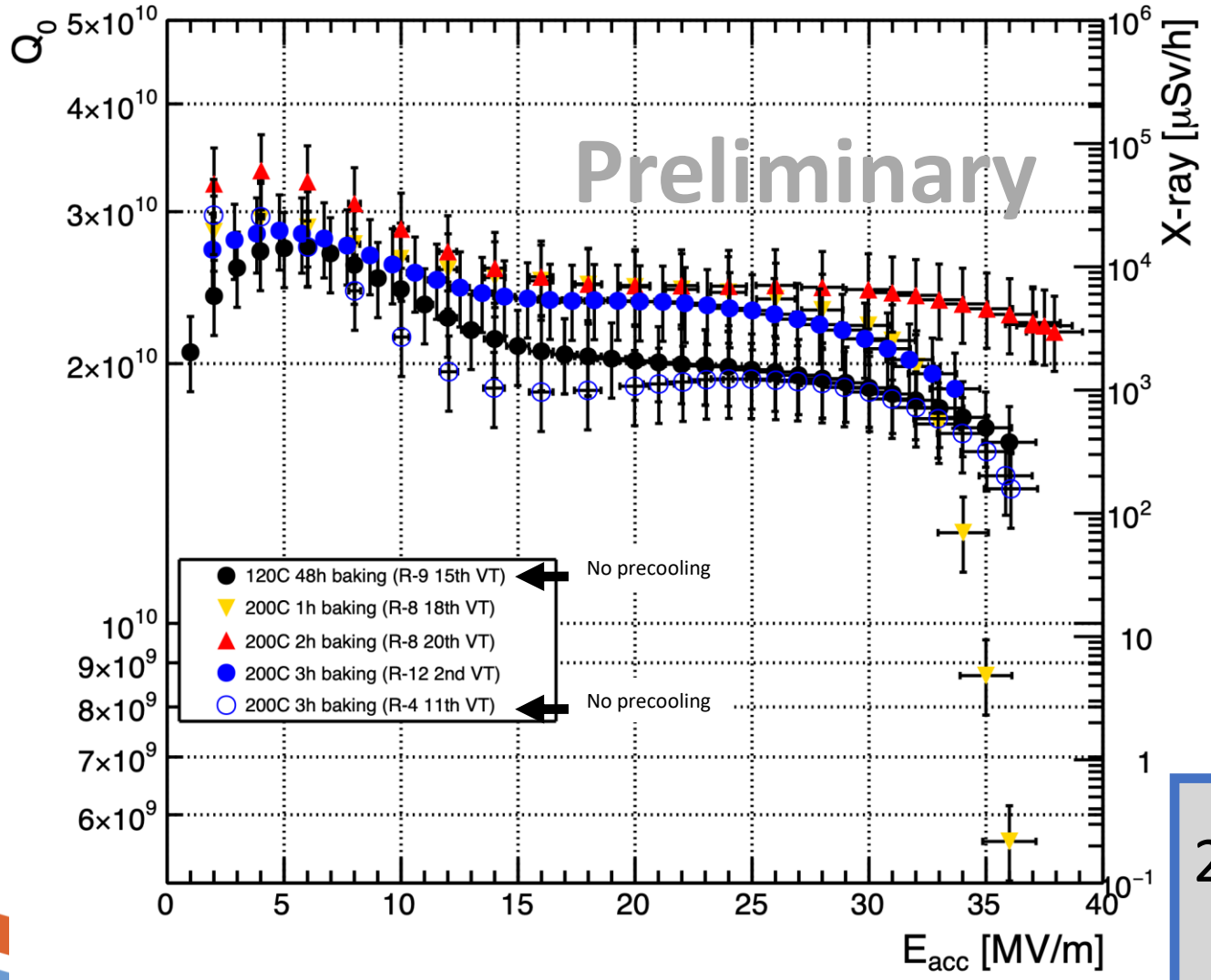
Standard recipe (120°C 48 h), 200°C 3 h
- 200°C baked cavity follows the standard recipe (120°C 48h)
- Q-E behavior at low E_{acc} is slightly different

500 ~ 800°C 3 h
- High Q value wasn't observed
- HFQS occurred

- Varying the temperature of furnace baking varies Q-E behavior drastically
- In 300 ~ 400°C furnace baking, the cavity is limited at around 25 MV/m?

Changing baking time for 200C furnace baking

Hayato Ito, SRF2021



- Onset of HFQS for 200°C 1 h cavity was overcome by 200°C 2 h furnace baking

->Q exceeded 2E10 at 35 MV/m

- The effect of precooling needs to be considered
- Or is there a cavity dependence?

200C furnace baking is a good candidate for high-Q/high-G ILC cavities.

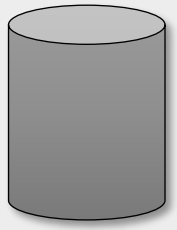
Contents

- ILC
- Operation of STF-2 accelerator
- High-Q/high-G R&D
  - 2-step baking
  - Furnace baking
- LG cavity fabrication
- Summary

Manufacture method of Large and Medium-Grain Nb discs

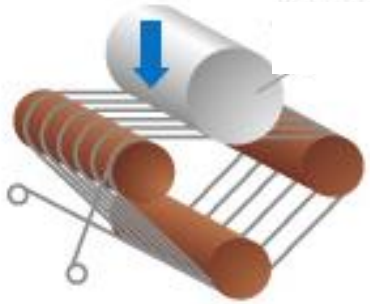
Takayuki Saeki & K. Umemori, SRF2021

Nb melting

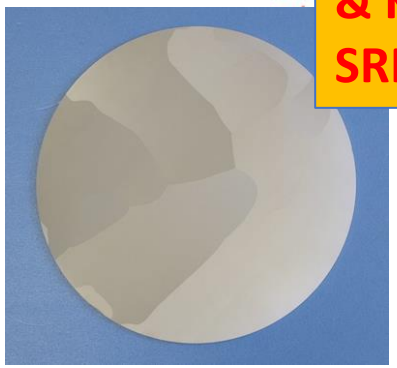


Niobium ingot
(Raw material)

Direct slice of LG ingot



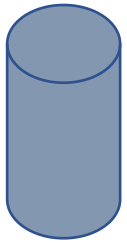
Slicing image
by wire-saw



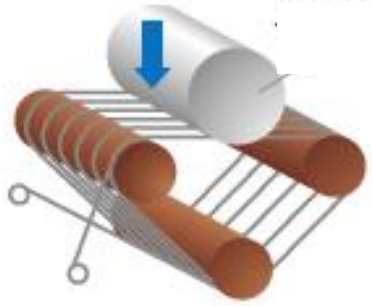
Large Grain (LG) Disc
Grain Size >> 1 cm

- Aiming for clean, mechanically stable, and cost-effective SRF cavity production.

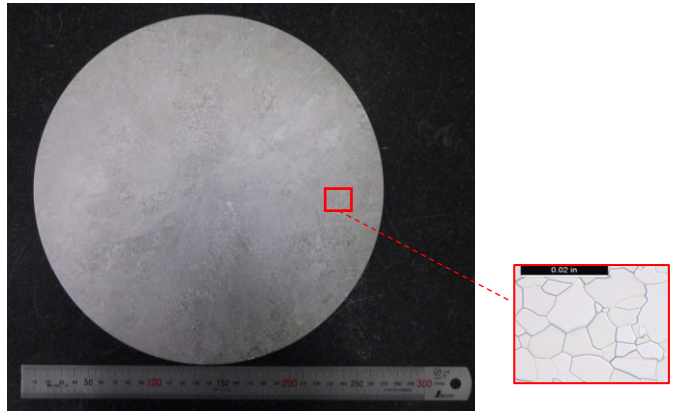
Direct slice of MG ingot



Ingot, forged and annealed



Slicing image
by wire-saw

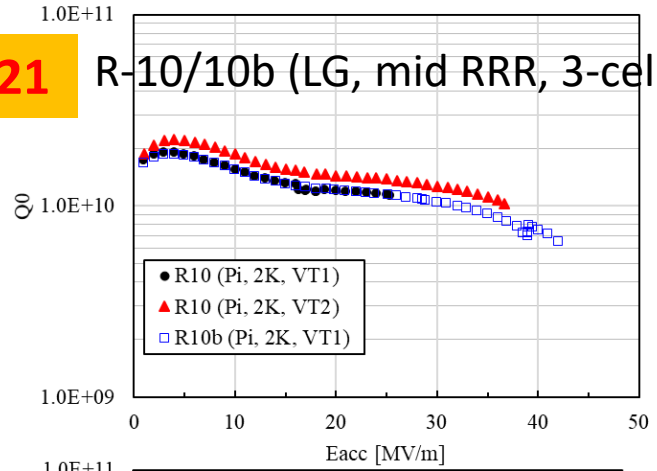


A New Approach:
Medium Grain (MG) Disc
Average Grain Size **< 1 mm**

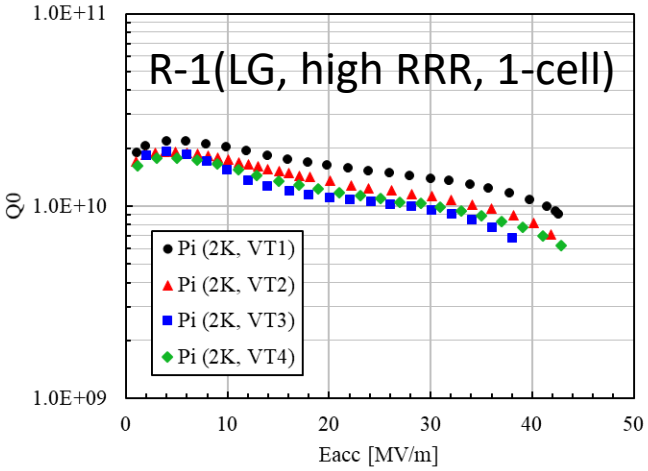
* The “Nb forged ingot” technology originated by **ATI**, and SRF (GHz) cavities were fabricated and RF tested by **KEK** and **JLab**, to qualify this approach, in collaboration of **ATI, ODU/BSCE, JLab, and KEK.**

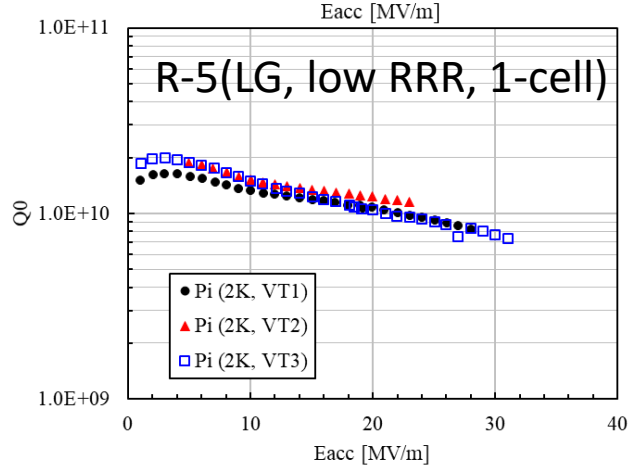
Takeshi Dohmae & K. Umemori, SRF2021

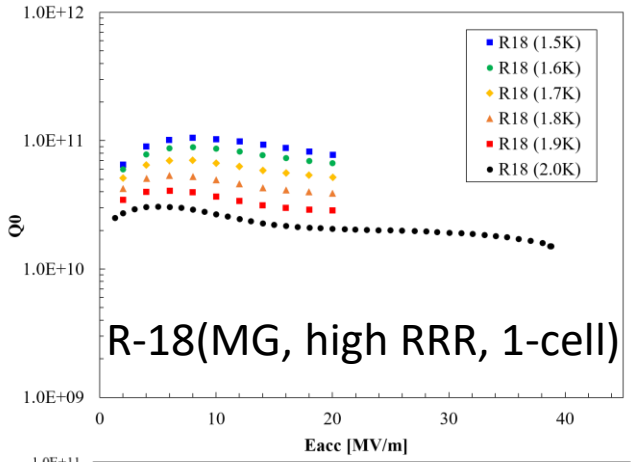
Results of LG cavities

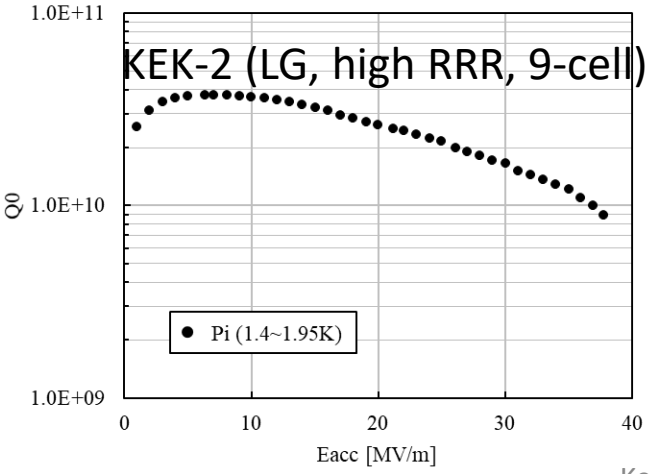


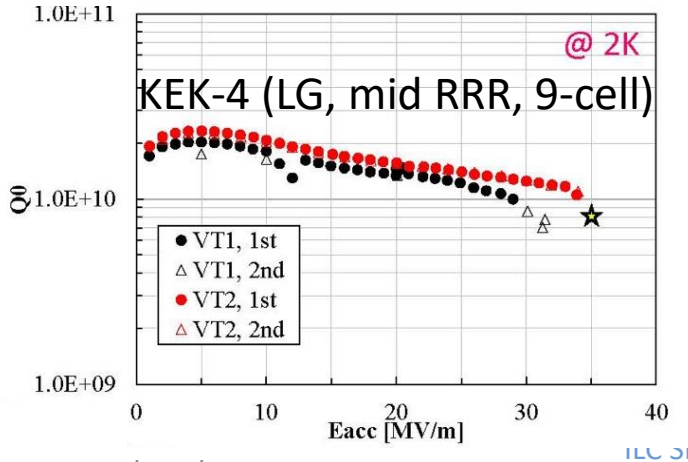
High RRR LG: Eacc = 38 ~ 42 MV/m
Mid RRR LG: Eacc = 32 ~ 42 MV/m
KEK selected high RRR LG for further study.

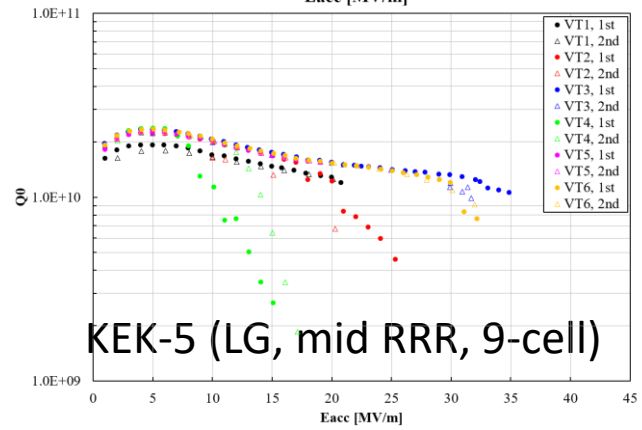












Results of KEK LG/MG cavities

K. Umemori, SRF2021

	R1	R5	KEK-2	R10/ R10b	KEK-4/ KEK-5	R-16/ R16b	R-17/ R-17b	R-18/ R-18b
Supplier	Tokyo Denkai	CBMM	Tokyo Denkai	CBMM	CBMM	ULVAC	ULVAC	ATI
Grain size	LG	LG	LG	LG	LG	LG	LG	MG
# of cells	Single	Single	9-cells	3-cells	9-cells	3-cells	3-cells	Single
RRR (RT/Tc)	496	107	496	242 ～ 298	242 ～ 298	500	363	494
Ta-content	Low	High	Low	High	High	Low	High	Low
Results (π-mode)	42 MV/m	31 MV/m	38 MV/m	38 / 42 MV/m	34 / 32 MV/m	-- / -- MV/m	-- / -- MV/m	39 / -- MV/m

※ Study on LG/MG cavities on-going. 9-cell cavities are under fabrication.

Summary

- SRF technology has been developed at KEK, toward ILC.
- STF-2 accelerator was successfully operated with 2 + 12 cavities.
- Average gradient from 9-cavity operation achieved 33 MV/m.
- Study on high-Q/high-G is on-going.
- Two step baking and furnace baking have been investigated to improve cavity performance. Promising results were observed.
- LG and MG Nb materials are under study. They show promising performance from single-cell cavity results.

Acknowledgement

Thank you very much for your help.

- Kirk Yamamoto
- Ryo Katayama
- Hayato Ito
- Takeshi Dohmae
- Takayuki Saeki

Thank you very much for your attention.