Asian Forum for Accelerators and Detectors 2023

Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Development of SRF technology at KEK-iCASA

Asian Forum for Accelerators and Detectors 2023 WG3

2023/4/13

KEK iCASA (innovation Center for Applied Superconducting Accelerator)

Kensei Umemori

Outline

- SRF activity at KEK
- ILC / STF-2
- Surface treatment for high-Q/high-gradient
  - 2 step baking
  - Mid-T furnace baking
- cERL and its application
- Nb3Sn development
- Summary

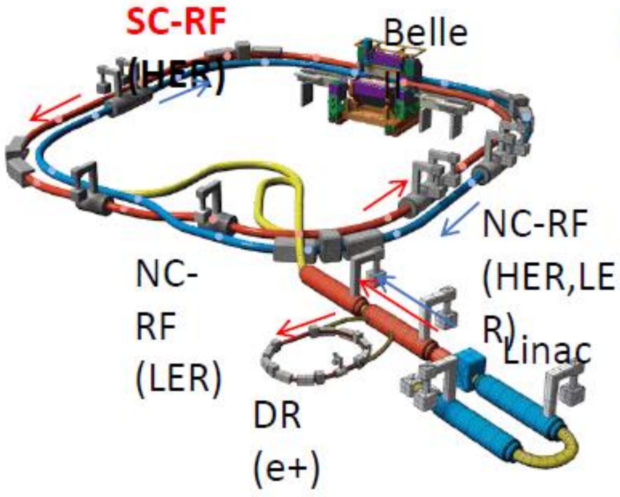
Target of R&D

Production of SRF accelerator
- High gradient pulse accelerator
- High Q CW accelerator

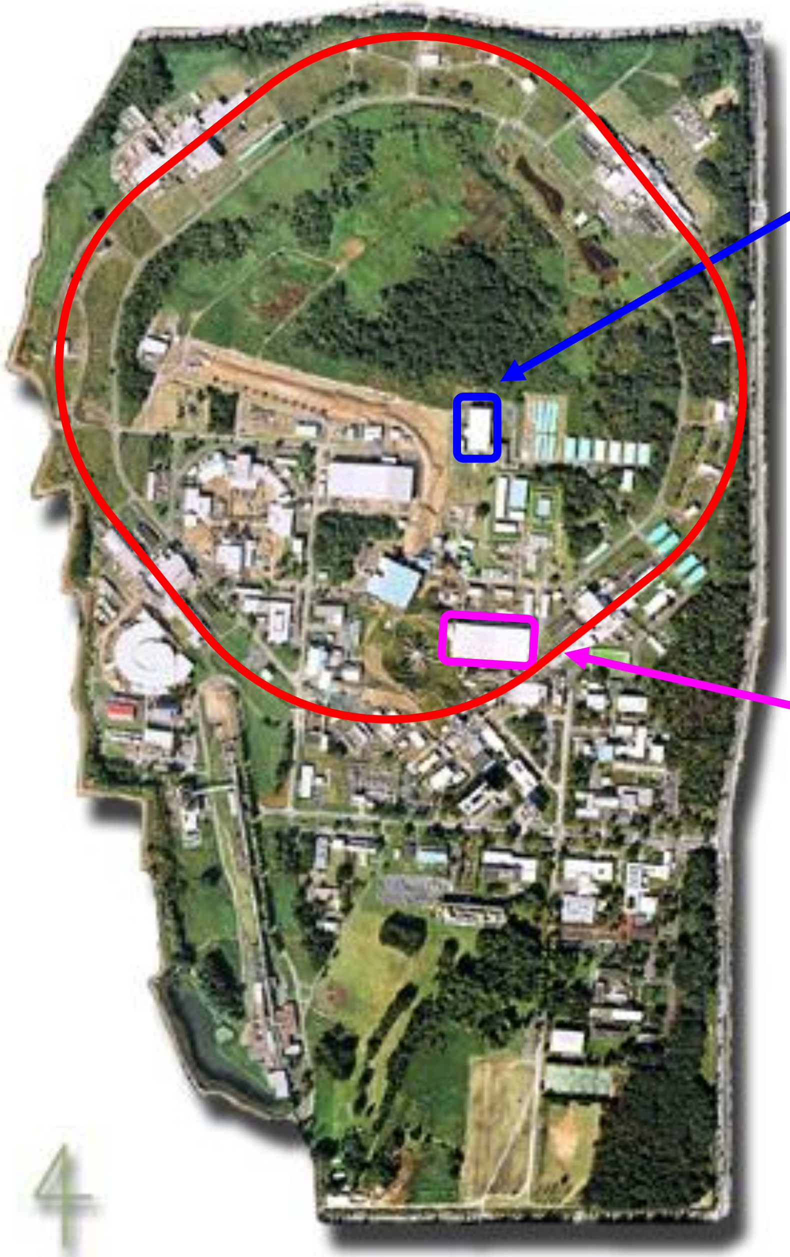
Surface treatment for high-Q/high-gradient

SRF Accelerator in KEK

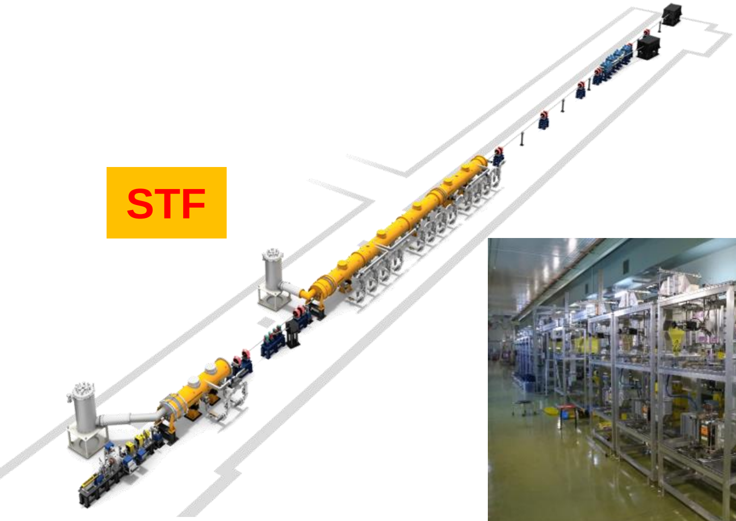
Super KEKB



A~class high current CW storage ring for e+e- collision

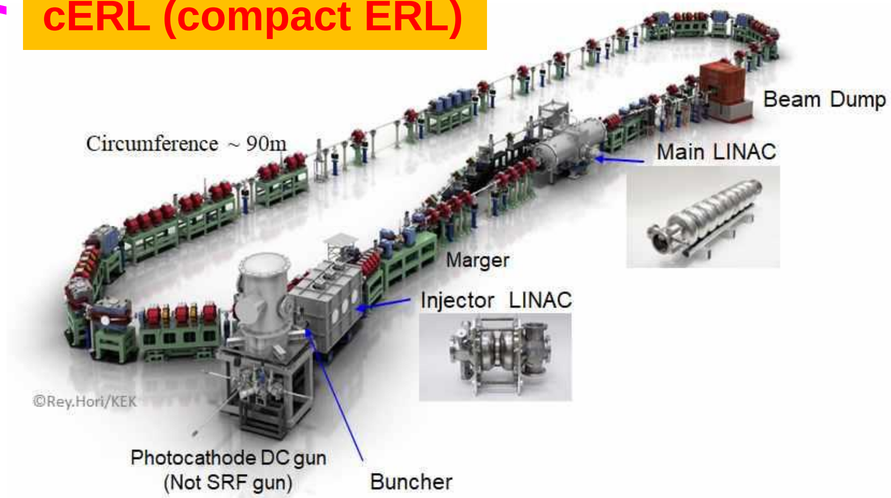


STF



Prototype cryomodule for ILC, pulse operation with high gradient

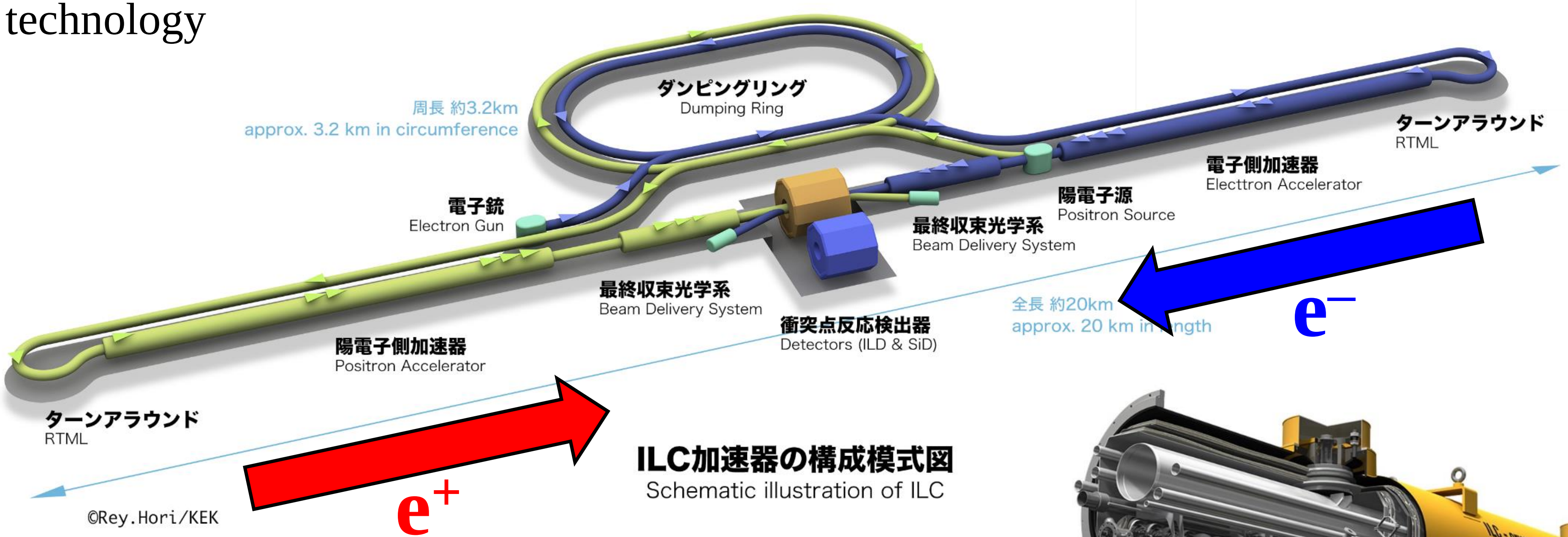
cERL (compact ERL)

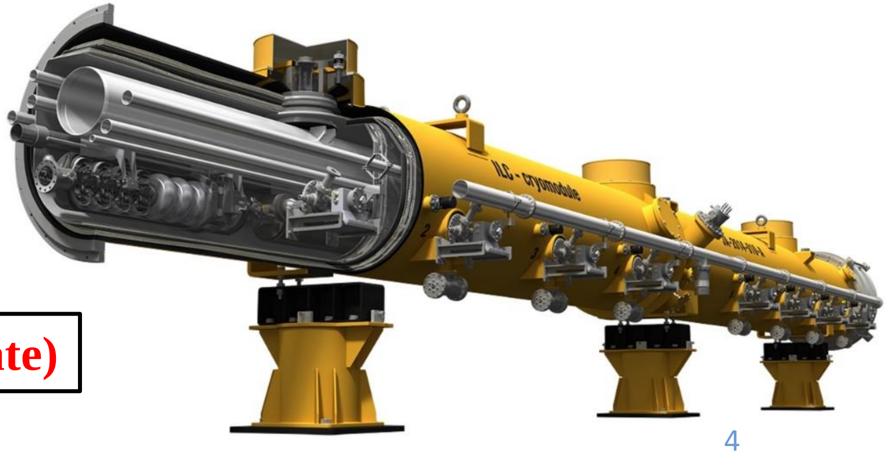


Test facility for Energy Recovery Linac, CW operation

ILC project

- Higgs factory machine (250 GeV @E_{CM})
- Superconducting cavity/cryomodule technology as mass production
  - Based on TESLA technology
  - ~900 Cryomodules (challenging number, but not impossible!)
- Nano beam technology





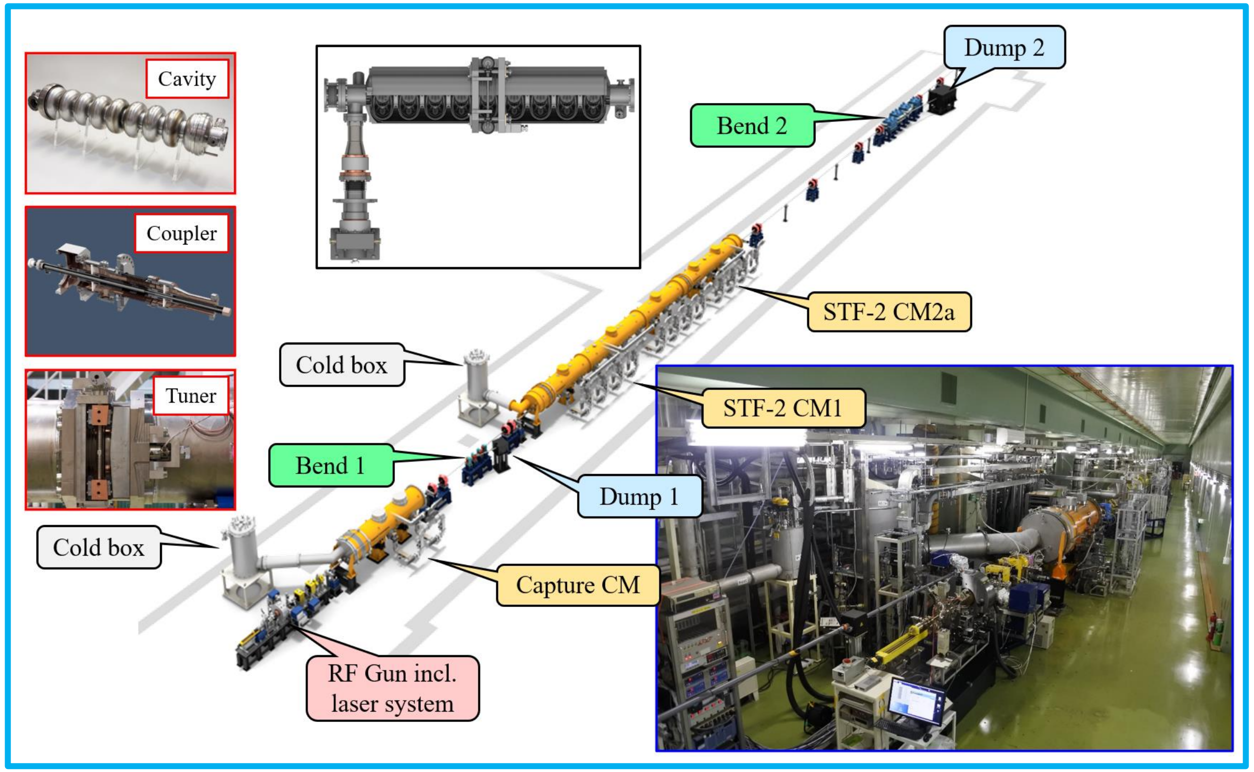
ILC Spec.	E_{acc}	Q_0
Vertical Test	35 MV/m	0.8 x 10^{10}
Cryomodule test	31.5 MV/m	1.0 x 10^{10}

>90% (successful rate)

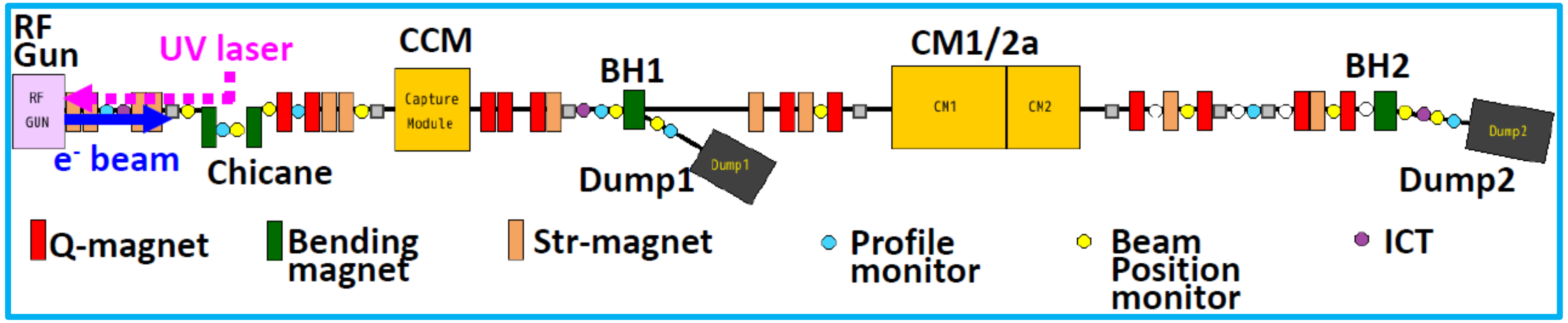
Features of STF-2 Accelerator

Kirk Yamamoto, LINAC2022

- ~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

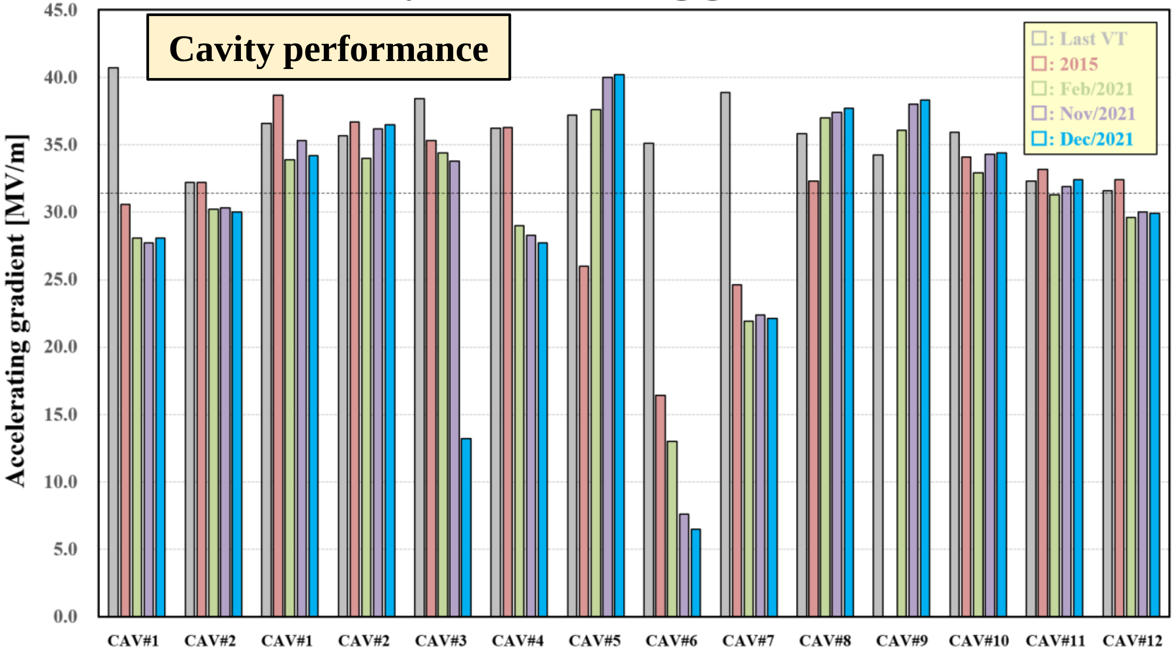


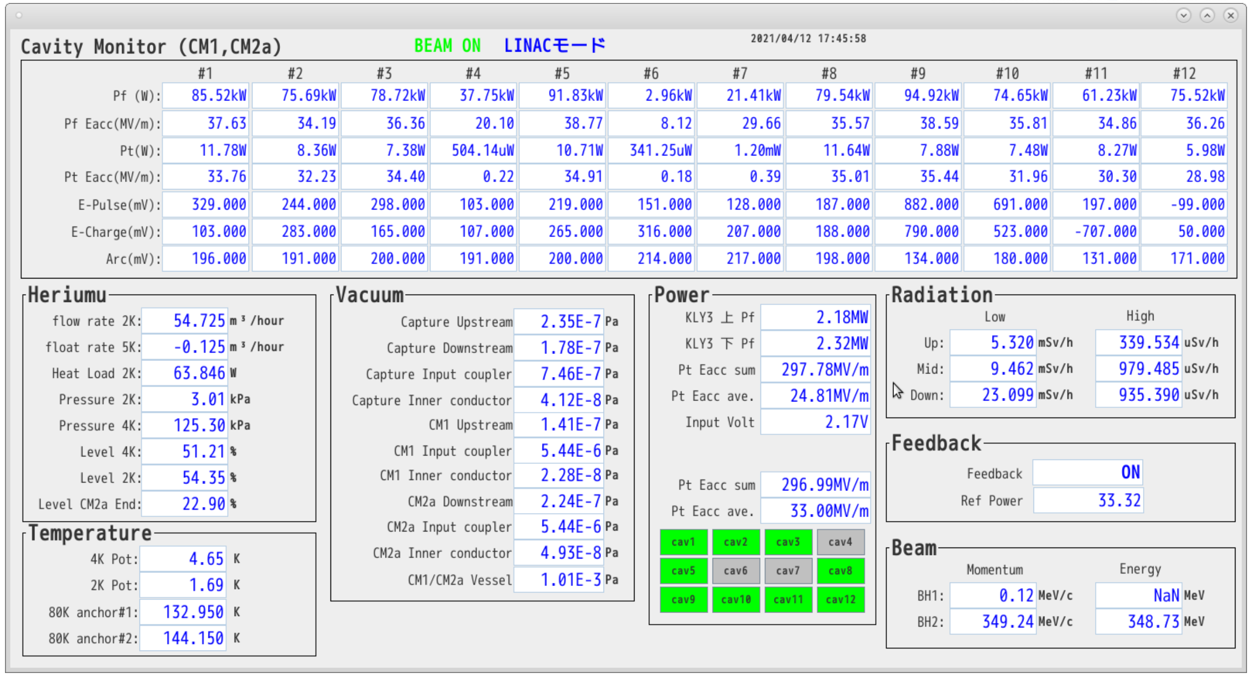
Achievements

Kirk Yamamoto, LINAC2022

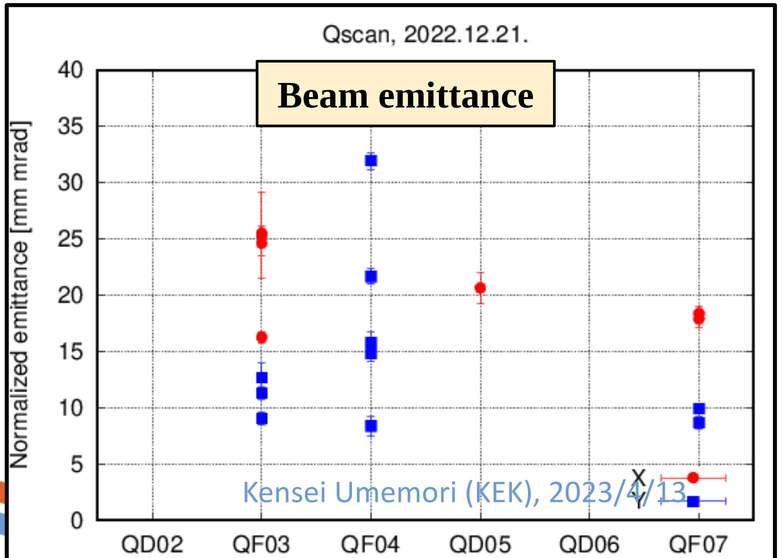
Beam acceleration at 33 MV/m

Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

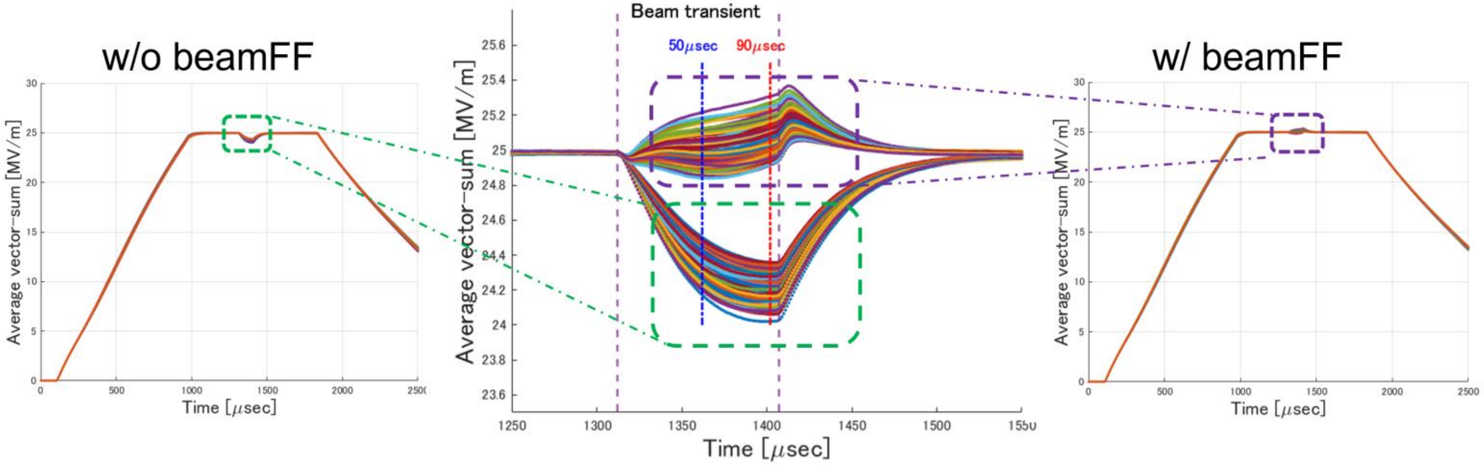




	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Pf (W):	85.52kW	75.69kW	78.72kW	37.75kW	91.83kW	2.96kW	21.41kW	79.54kW	94.92kW	74.65kW	61.23kW	75.52kW
Pf Eacc(MV/m):	37.63	34.19	36.36	20.10	38.77	8.12	29.66	35.57	38.59	35.81	34.86	36.26
Pt(W):	11.78W	8.36W	7.38W	504.14uW	10.71W	341.25uW	1.20mW	11.64W	7.88W	7.48W	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



Compensation for beam loading



Beam Parameters in 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!

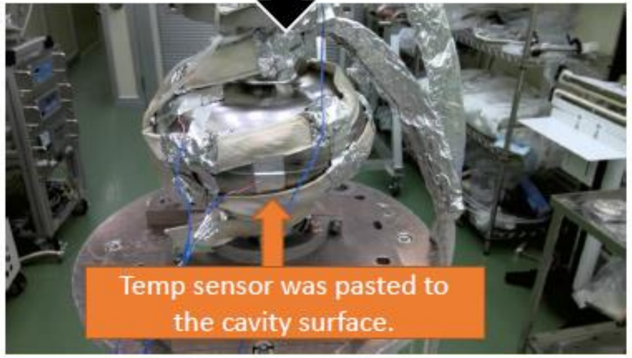
Target of FY2022: Increase beam current. Achieve ILC specification.

Surface treatment:
2-step baking

Ryo Katayama, TTC high-Q/high-G WG, 2022/Sep

- From the combination of cold EP + 2-step baking + fast cooling showed higher-Q performance.
- Improvement of gradient is not observed.

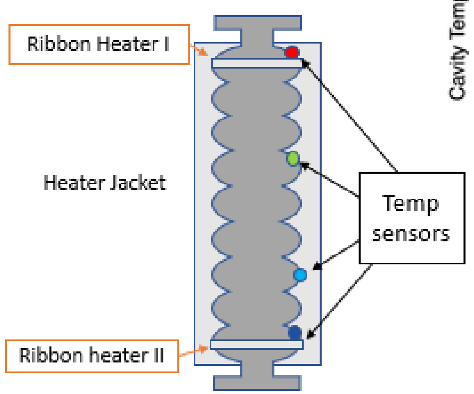
The cavity is wrapped around a ribbon heater.

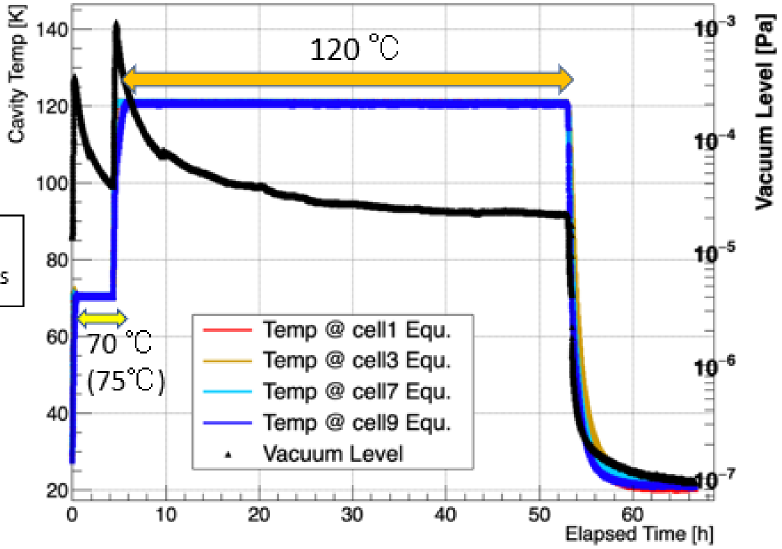


Additionally, 9-cell cavity wear a heater jacket.

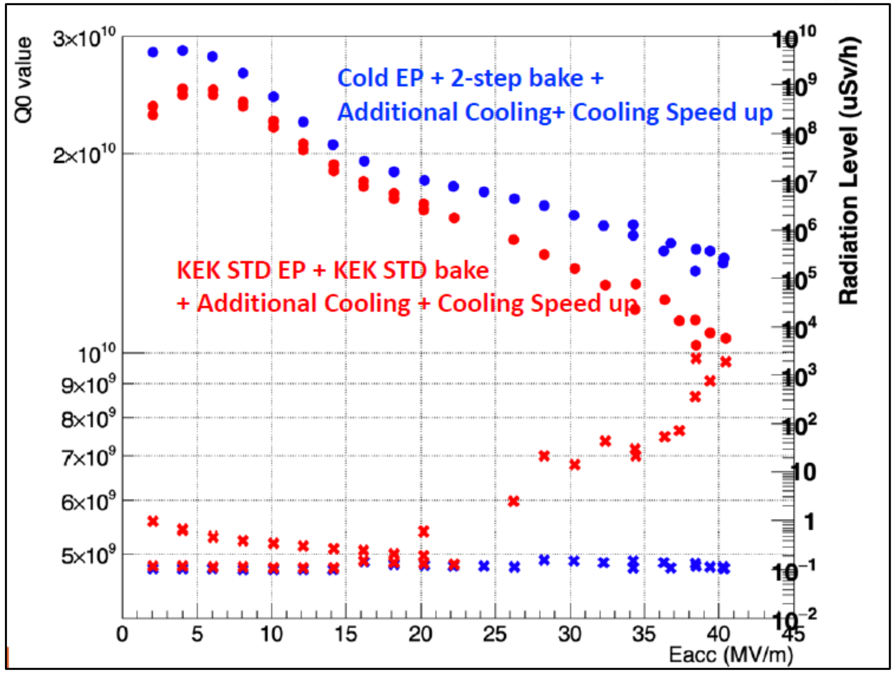
Q. Temperature just behind the ribbon heater and/or heater jacket may be deviated from the value indicated by temperature sensors?

baking temperature was modified by -5 ℃ to prevent localized overheating.



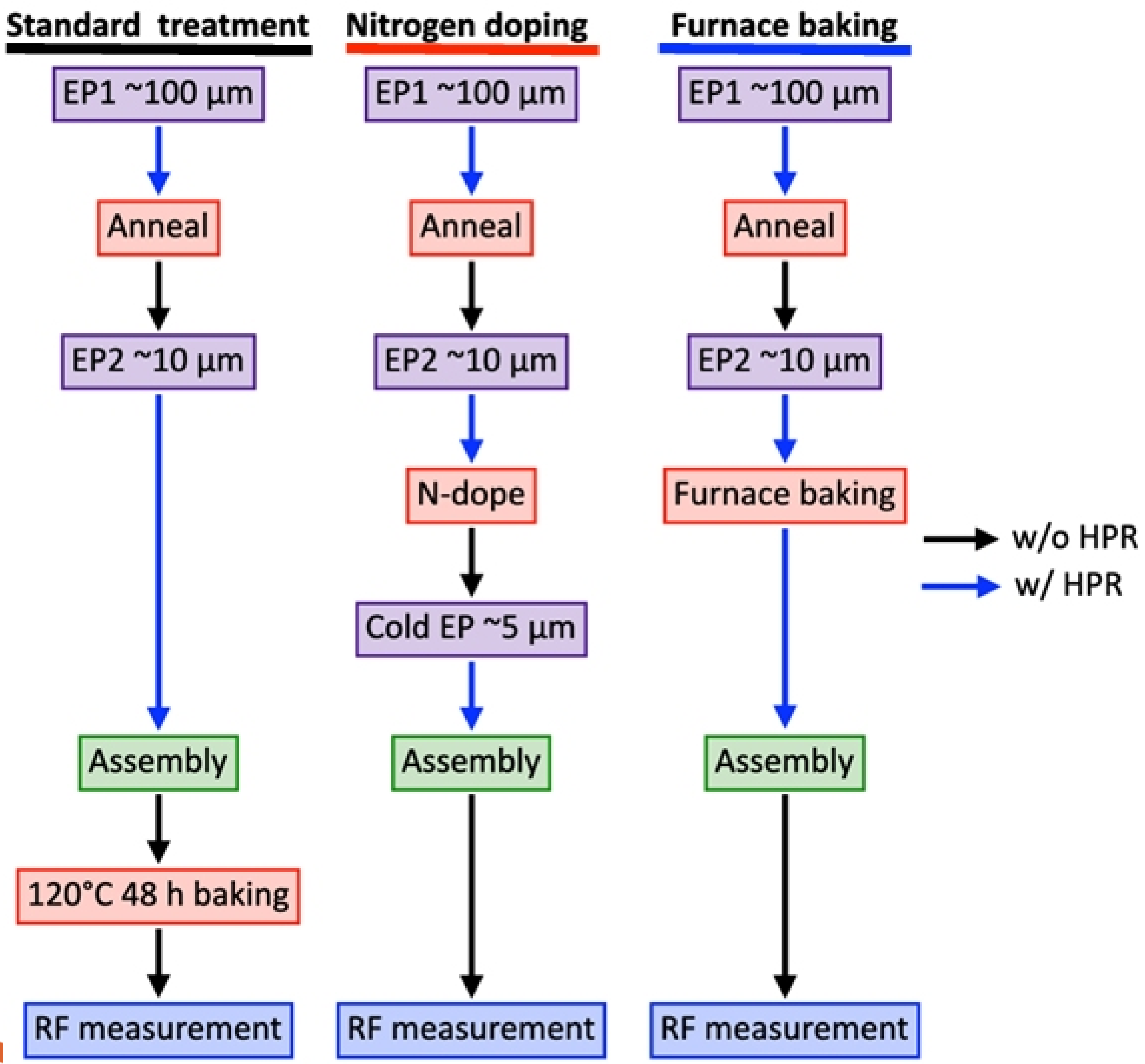


2-step baking for 9-cell cavity



Surface treatment:
Mid-T furnace baking

Hayato Ito, SRF2021

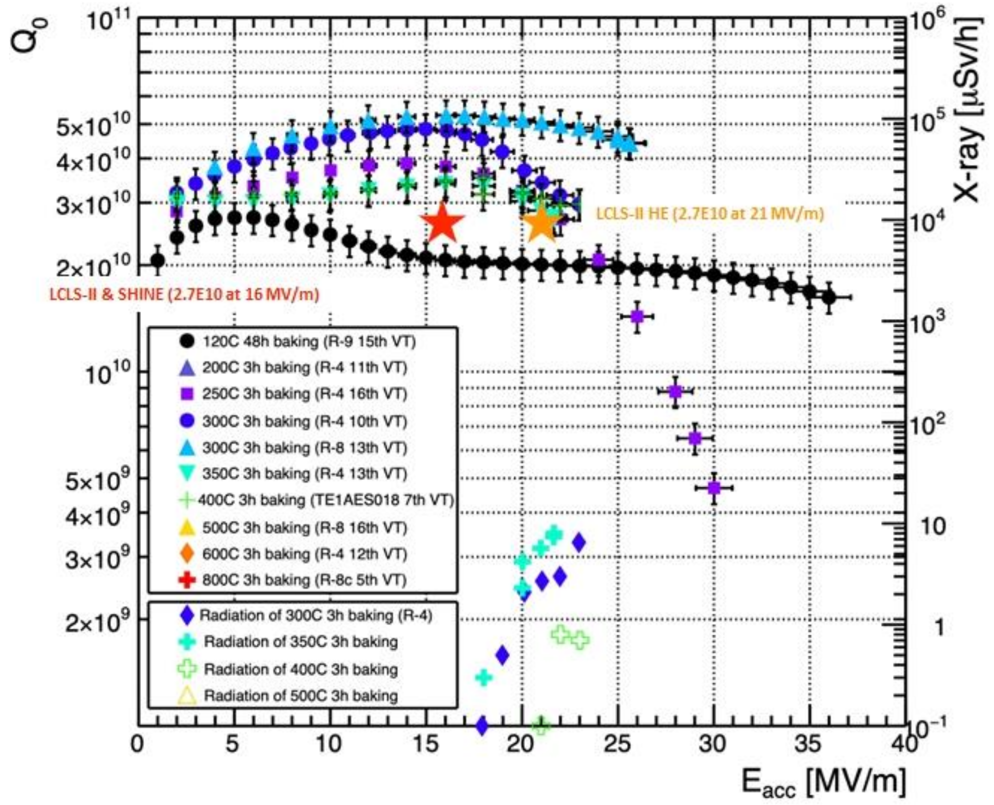


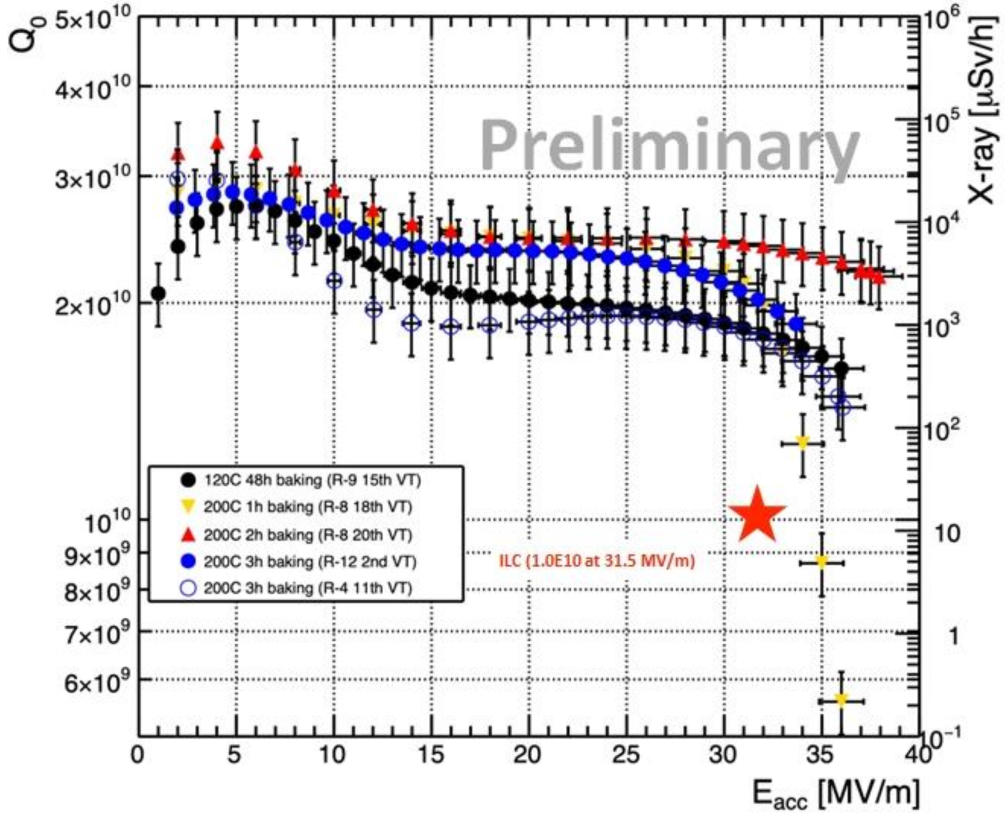
Mid-T furnace baking is simple process

- Easy to achieve high-Q
- Oxygen diffusion is important process to control the performance of Nb cavity.
- Suppression of HFQS is important to reach high gradient.

Mid-T furnace baking for single-cell cavity

Hayato Ito, SRF2021





300°C furnace baking

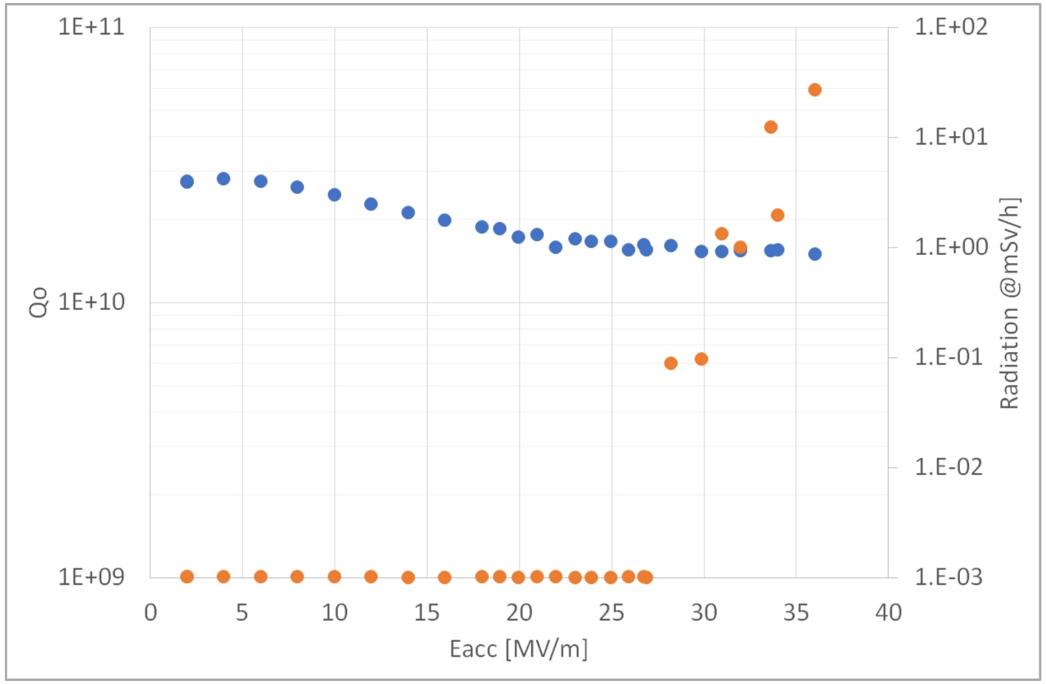
2~3 times higher Q value than standard treatment

-> 1/2~1/3 times higher heat load

200°C furnace baking

Higher Q-value than standard treatment, and E_{acc} performance comparable to standard treatment.

Horizontal test of Large Grain 9-cell TESLA cavity



- First horizontal test(HT) was performed for LG 9-cell TESLA cavity at KEK.
- He jacket was successfully welded after VT.
- Components, including magnetic shield, were prepared.
- Results of HT showed high performance of cavity.

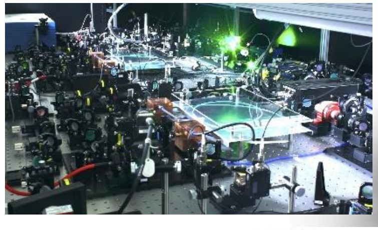
Compact ERL (cERL) in KEK

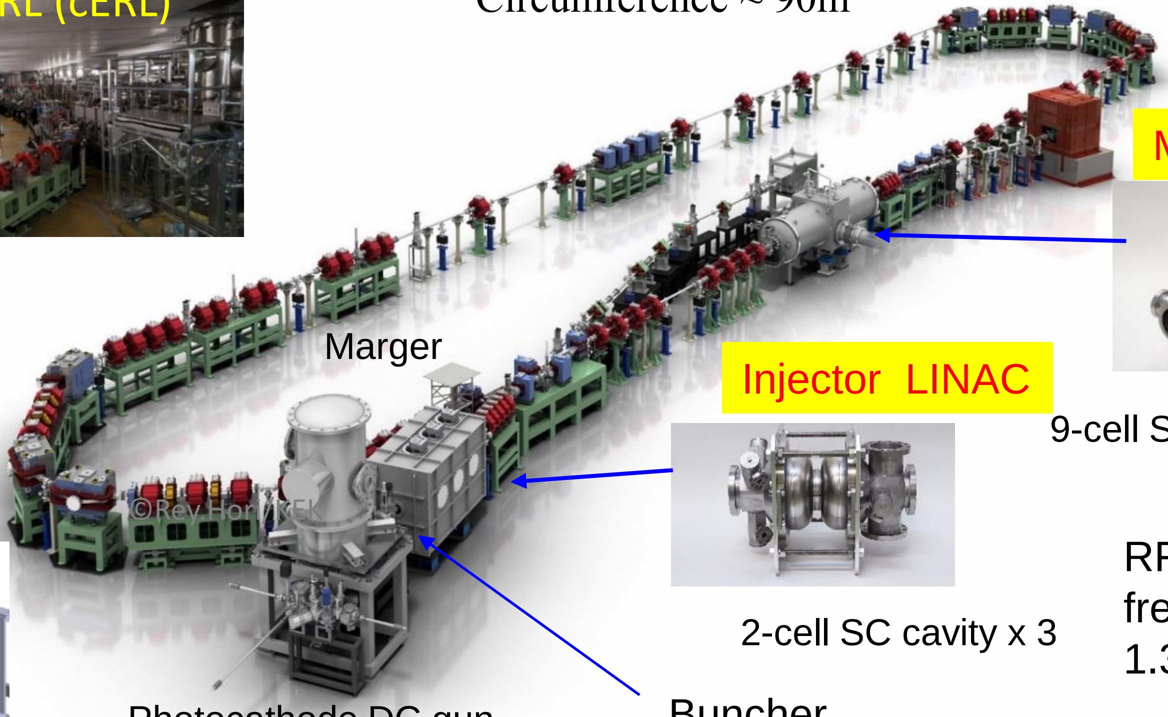
cERL developed the following key technologies and was constructed in 2013.

- **High current and high brightness** photo cathode DC gun.
- **CW superconducting cavity** for the high current beam operation.
- High current CW **energy recovery operation** achieved 1 mA ERL operation in 2016.

Recently, cERL was used for **industrial application** by using stable high current beam.

CW laser



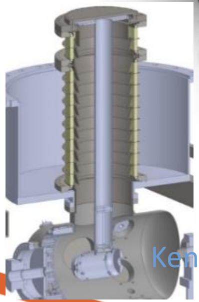


9-cell SC cavity x 2

2-cell SC cavity x 3

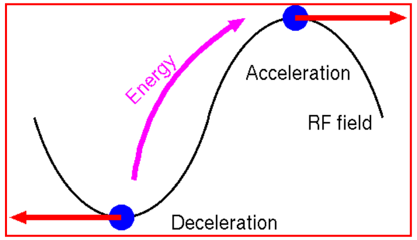
Buncher

RF frequency= 1.3 GHz



Photocathode DC gun (Not SRF gun)

500kV DC Gun (highest DC voltage in the world)



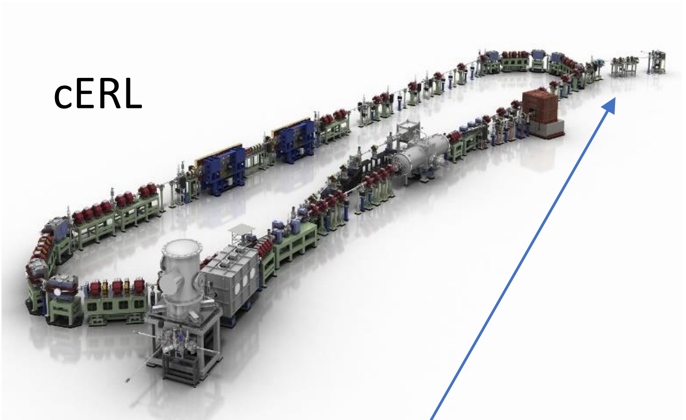
17.7 MeV

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV → 2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

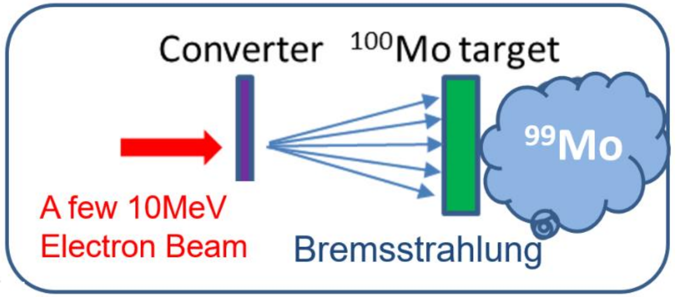
cERL – irradiation beam line

Courtesy of Y.Morikawa, N.Higashi, K.Harada, M. Yamamoto, H.Matsumura and A. Toyoda



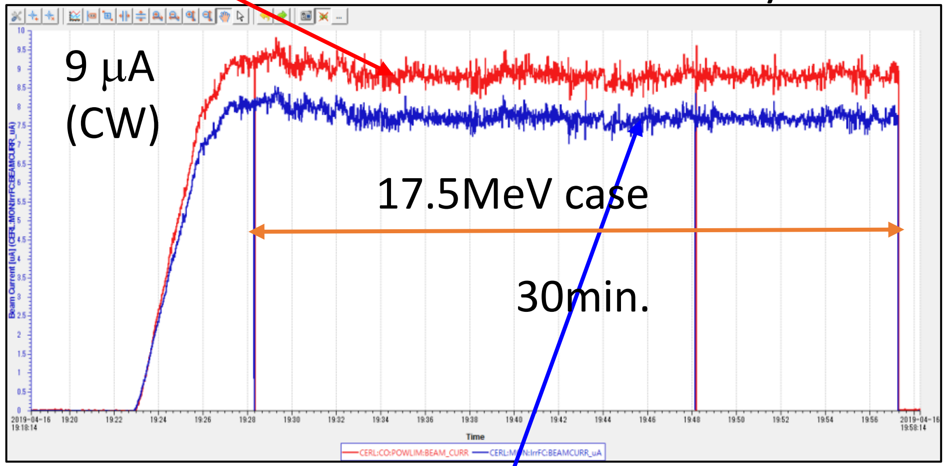
99Mo production was already shown in ERL2019

Development of RI manufacturing (^{99}Mo / ^{99m}Tc) by using accelerator for stable supply

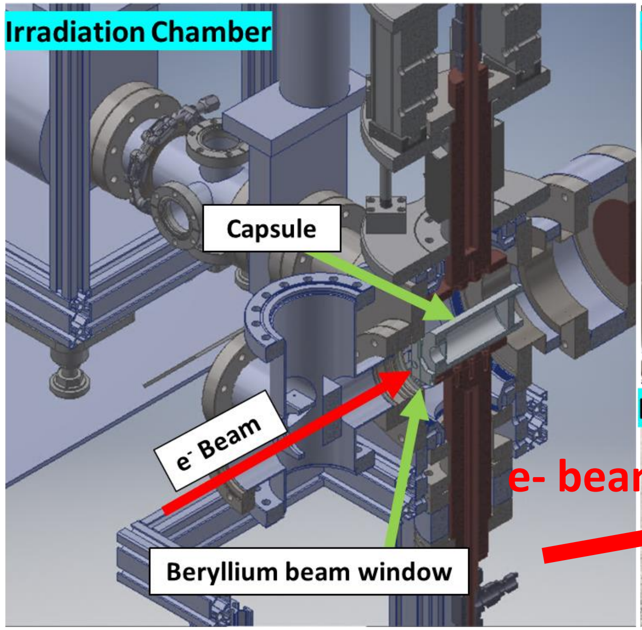


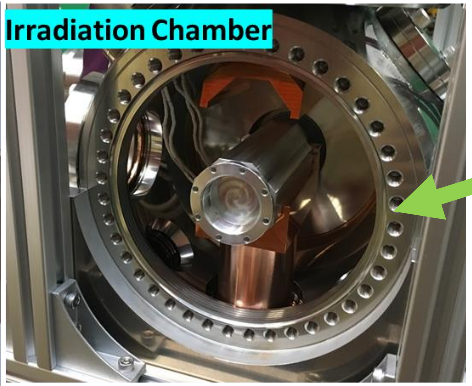
Gun current

Beam current is very stable



Typical trend of beam current
(faraday cup set on the same position of target)

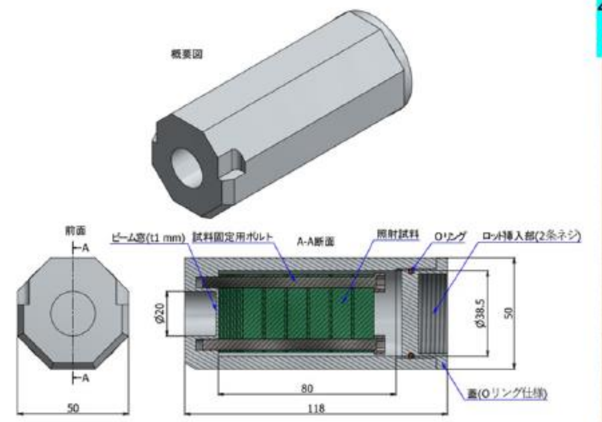




Aluminum capsule target holder

e- beam

For another RI production



100Mo targets with 1mm disks and 9mm disks in target folder

Higher energy was needed for 67Cu production from 68Zn. We operate the long pulsed operation to increase beam energy.

Y. Morikawa, *et al.*, “New Industrial Application Beamline for the cERL in KEK”, Proc. of IPAC2019, (Melbourne, Australia) p3475-3477, (2019)

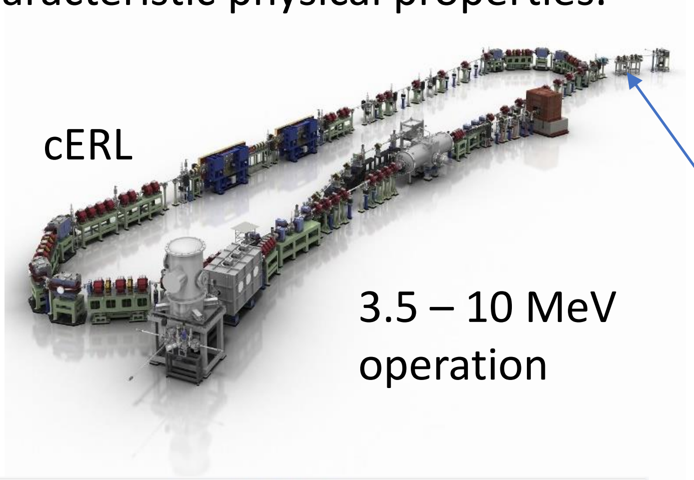
Nanocellulose (CNF) production by irradiation (FYI 2021)

Courtesy of T.Endo (AIST)

Nanocellulose, (cellulose nanofibers(CNF)) is expected to be used in various applications due to its characteristic physical properties.

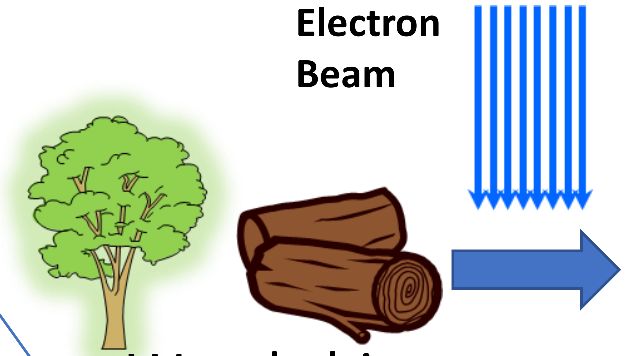
Motivation of irradiation of woods

A new electron beam irradiation system is applied instead of the conventional treatments to reduce the cost.

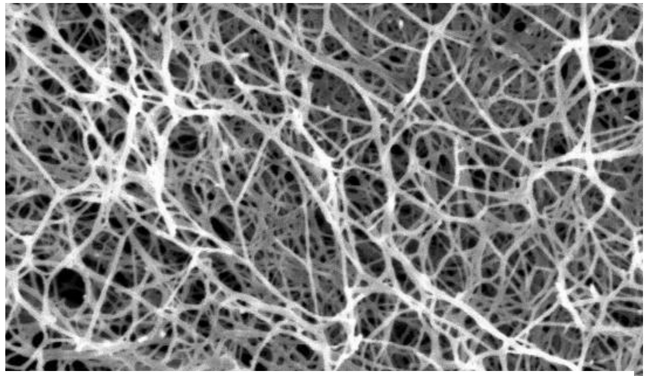


cERL

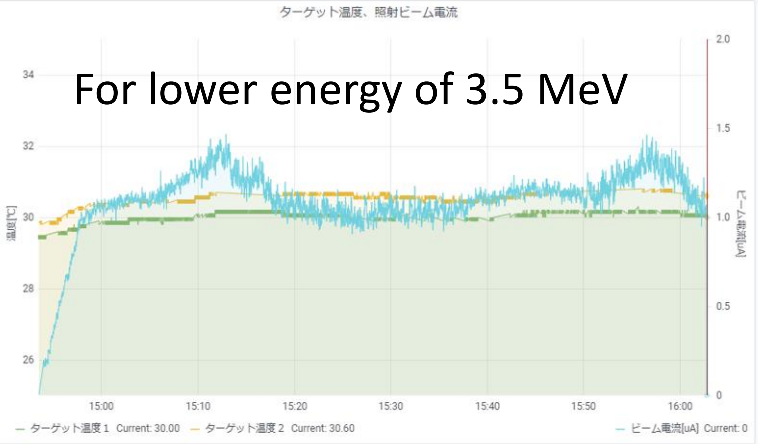
3.5 – 10 MeV operation



Woody biomass



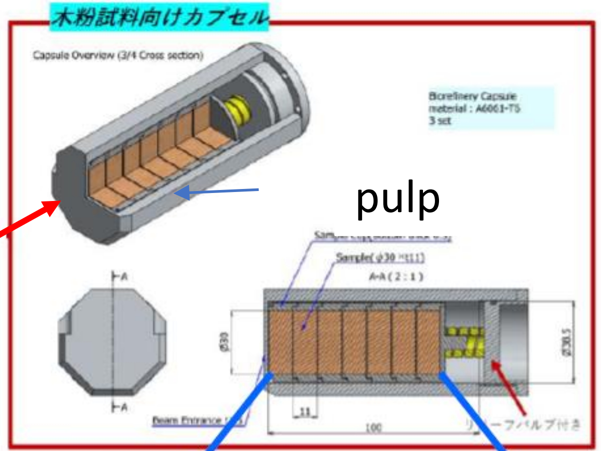
Cellulose nanofibers (CNF)



For lower energy of 3.5 MeV

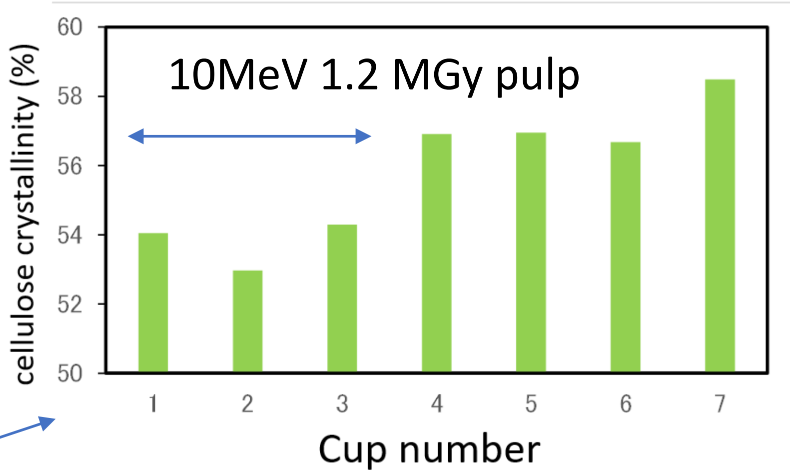
Stable CW beam operation was achieved.

CW e- beam



pulp

Cup number ①②③④⑤⑥⑦



Irradiation area much reduced the cellulose crystallinity →CNF produced on irradiation area

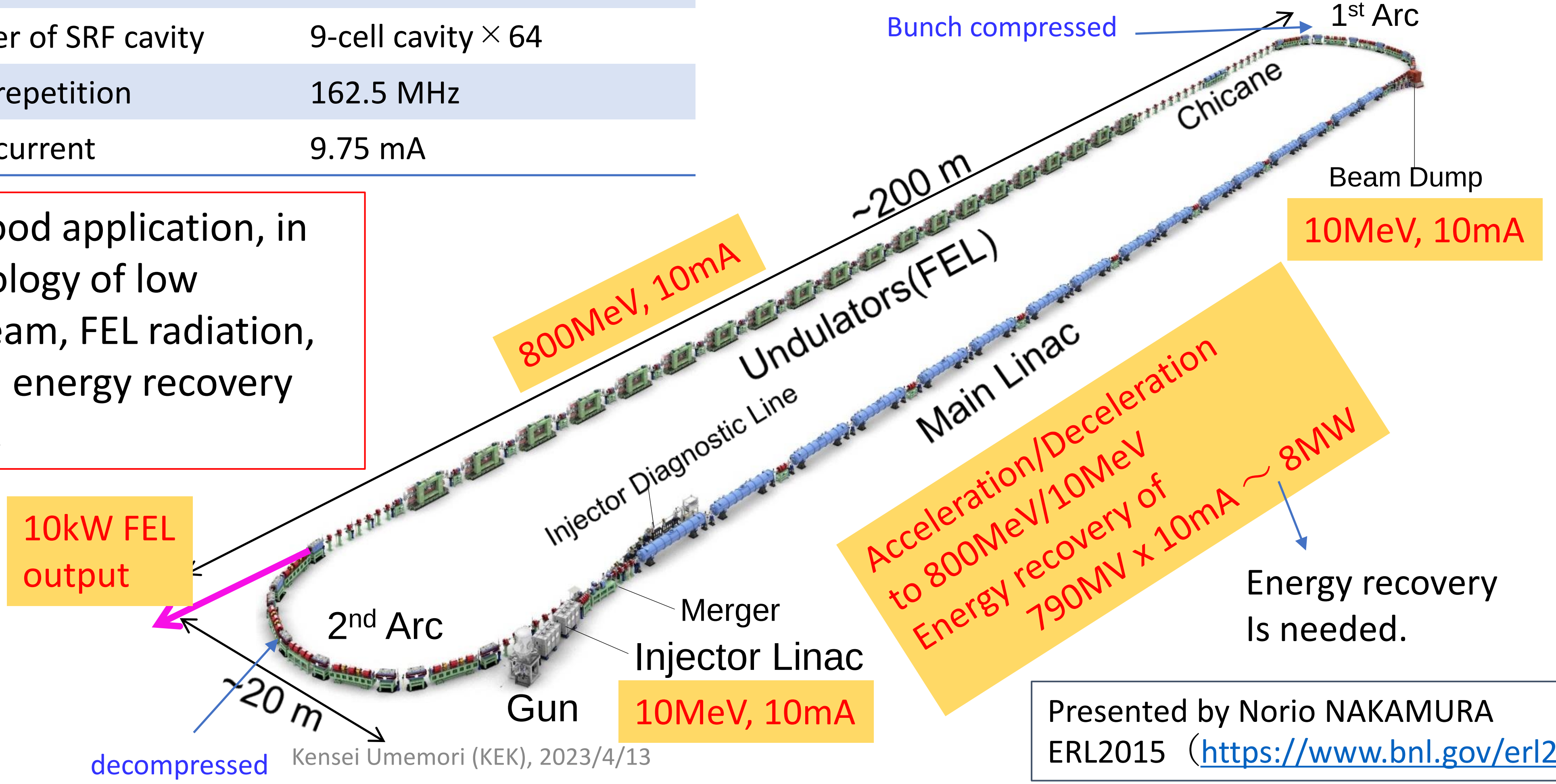
We now try to solve the mechanism of CNF production by irradiation.

Proposal of 10kW class ERL based EUV-FEL

Parameter	Specification
Wavelength	13.5 nm
Output power	10 kW
Bunch chare	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m (main linac)
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 MHz
Beam current	9.75 mA

cERL has been operated to realize proof-of-principle of ERL-SASE-FEL for EUV-FEL machine.

EUV-FEL is good application, in which technology of low emittance beam, FEL radiation, SRF linac and energy recovery are essential.



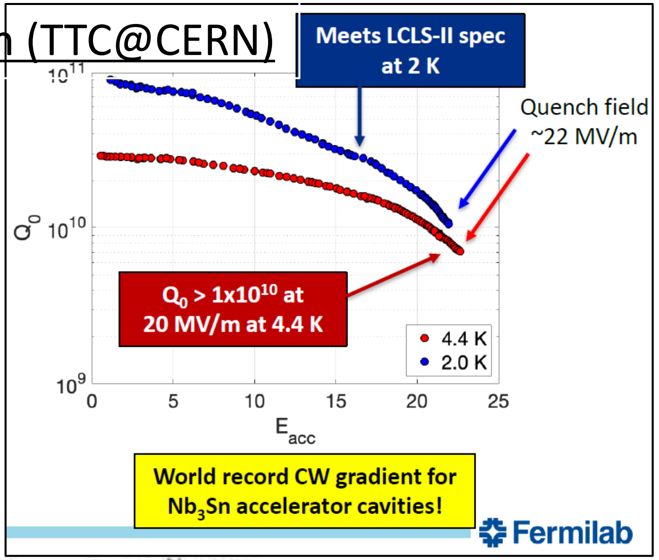
Presented by Norio NAKAMURA
ERL2015 （https://www.bnl.gov/erl2015/）

Design of compact Nb3Sn accelerator for irradiation experiment

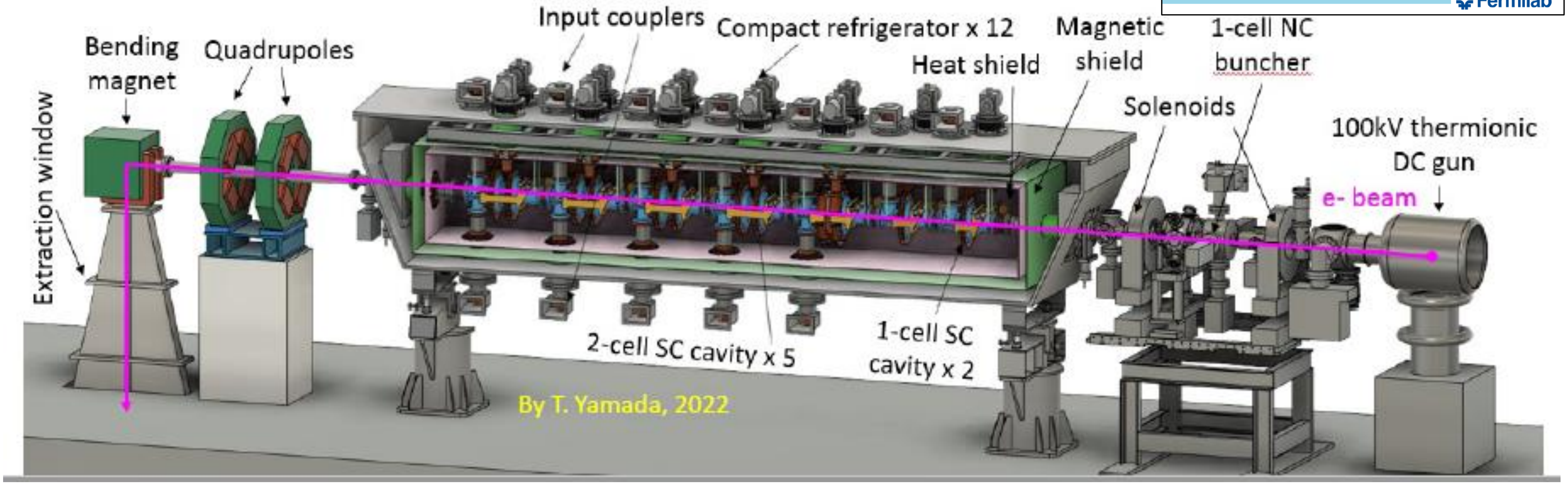
- Nb3Sn SRF cavity can achieve Q > 1e10 at 4K.
- Conduction cooling by cryo-cooler can be possible.

→ He free compact SRF accelerator

S. Posen (TTC@CERN)

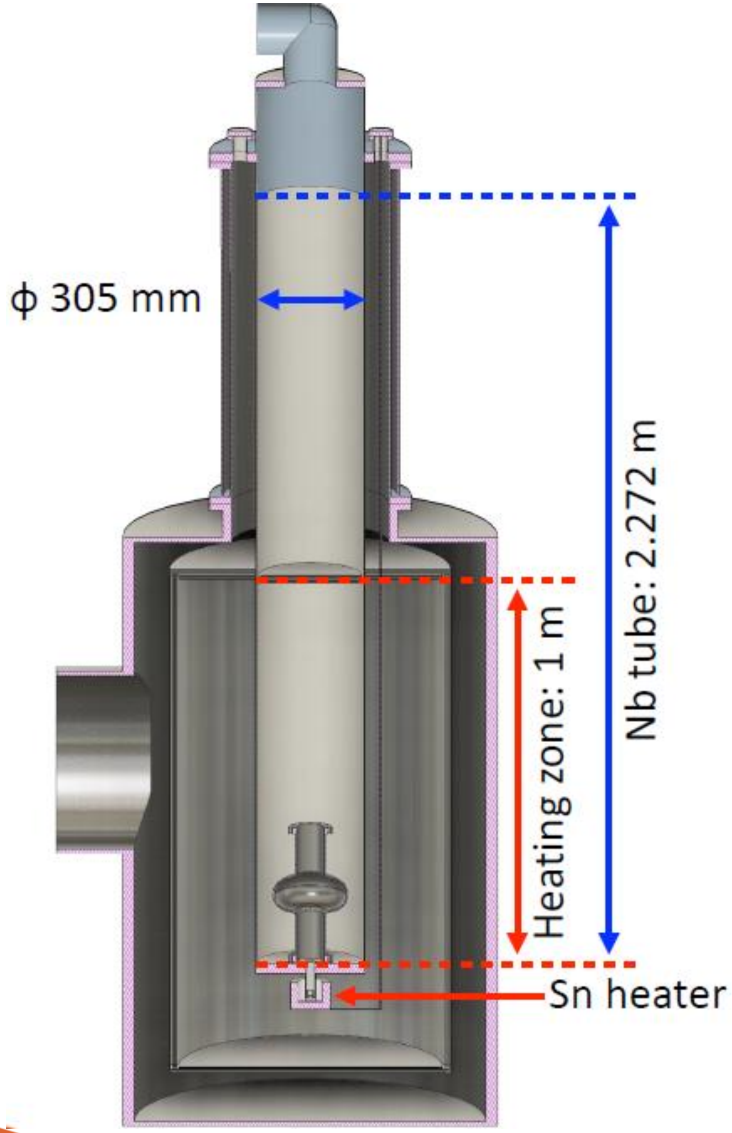


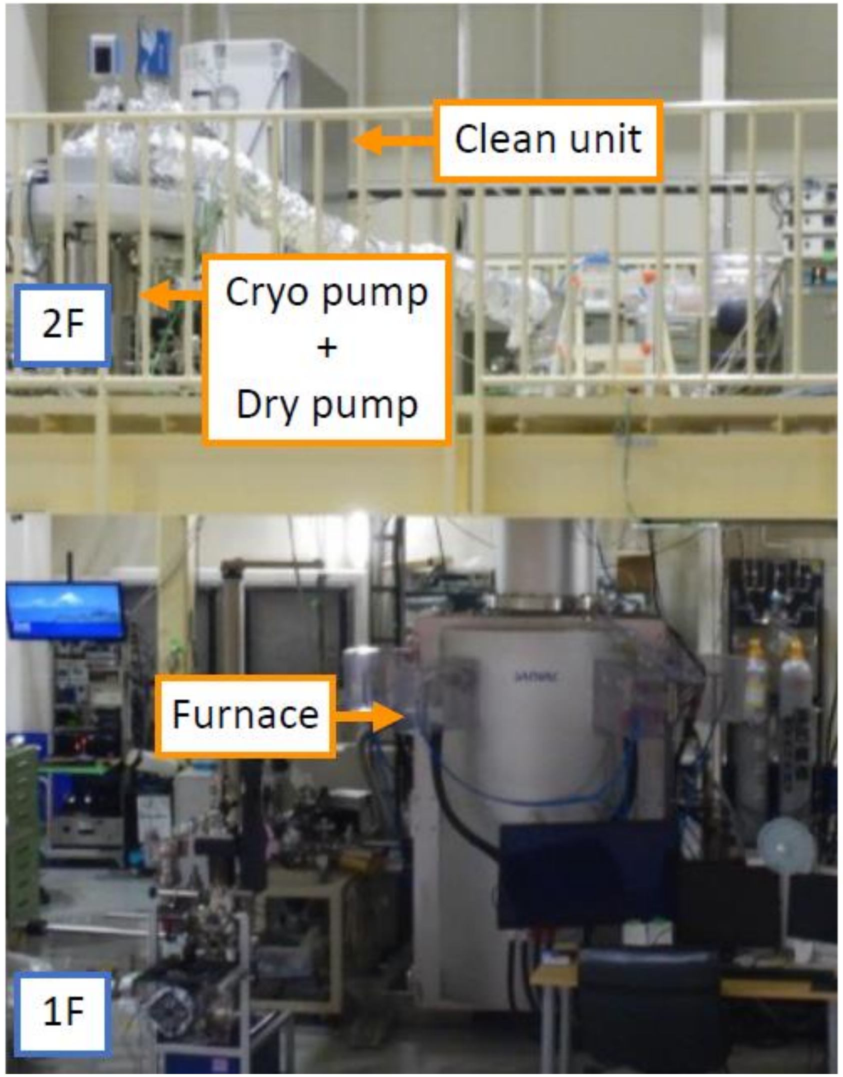
Oliga Tanaka, TTC meeting at Aomori



Nb3Sn coating furnace at KEK

Hayato Ito, TTC meeting at Aomori





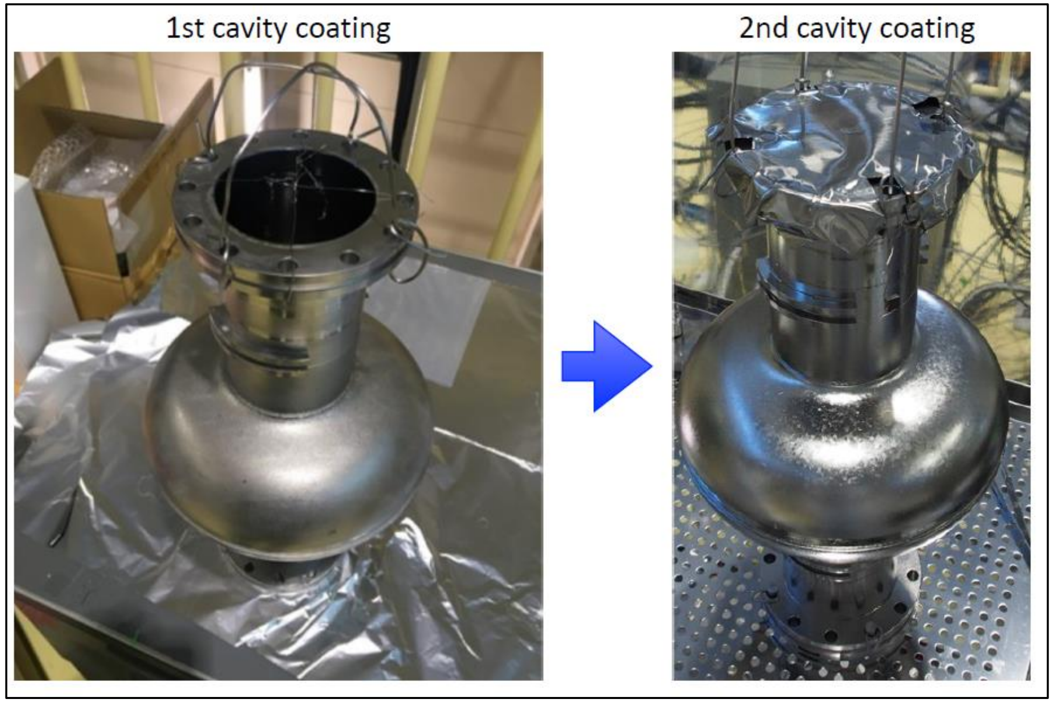
- Two independent vacuum systems
- Heaters
  - Furnace: Max 1200°C
  - Sn crucible: Max 1500°C
- Nb tube is evacuated during coating

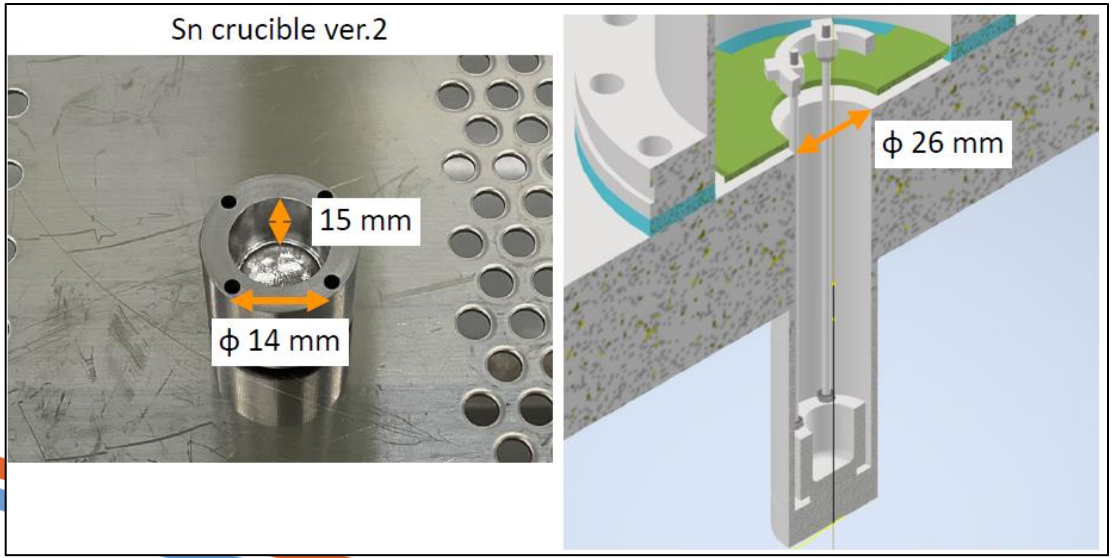
Modification of system

Hayato Ito, TTC meeting at Aomori

- KEK have been developing the Nb3Sn coating SRF cavity.
- Q-value of 1st coated cavity was 3.7e9(@1 MV/m, 4.2K).
- Q-value of 2nd coated cavity was 5e8(@1 MV/m, 4.2K)

- Our current big target is improvement of Q-value.





Modification of Nb3Sn coating procedure

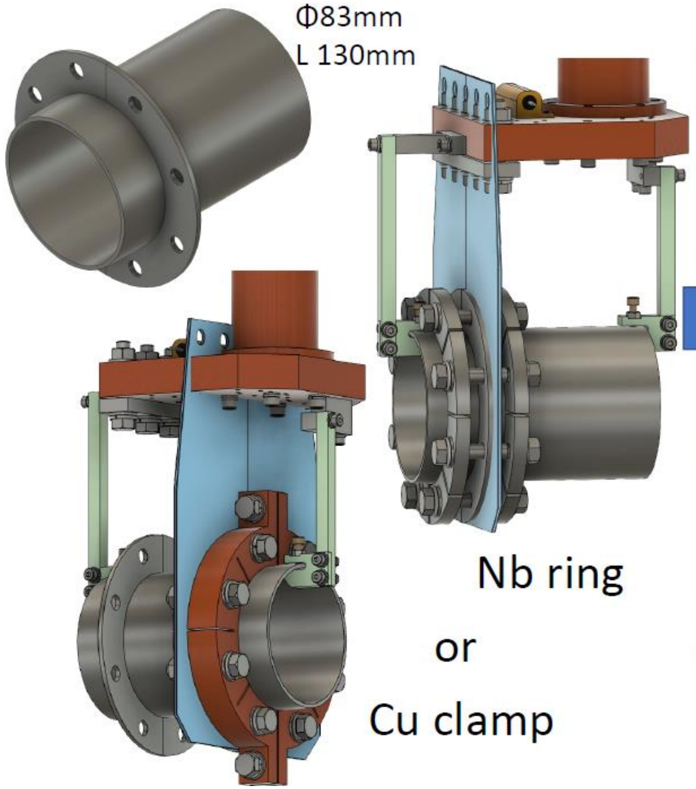
1. New Sn Crucible with bigger aperture to get enough Sn evaporation
2. Clean room to prevent contamination
3. Applying Nb foil on the top flange to increase Sn vaper pressure

Recent results shows Q>1e10 at low field at 4.2K.

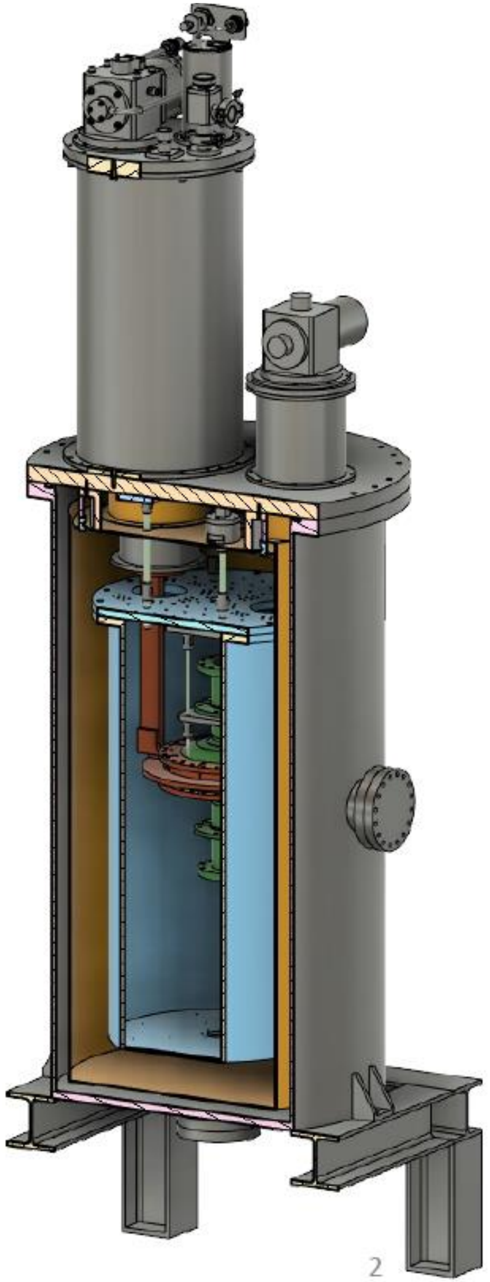
Conduction cooling test for Nb3Sn CM

Tomohiro Yamada, TTC meeting at Aomori

- KEK started the conduction cooling experiment using GM cryocooler.
- We have a plan to perform Nb3Sn cavity test within this FY.



Experimental photo of Nb ring test



High power test of single-cell Nb3Sn cavity via conduction cooling by cryo-cooler is planned at this April/May.

Summary

- KEK-iCASA has been actively developing the SRF technology for high performance accelerator.
  - ILC / STF-2 for high gradient accelerator
  - cERL and Nb3Sn for CW accelerator
- Surface treatment is key to achieve high performance of SRF cavities. Several treatment technique has been applied to the cavities.
- Several irradiation experiments have been carried out at cERL.]
- Essential technology for EUV-FEL will be realized throughout the cERL development.
- Nb3Sn coating technique is important for future compact SRF accelerator.

Backup slide

History of construction and Commissioning of cERL

Laser Compton scattering experiment in ERL

T. Akagi, et., al. "Narrow-band photon beam via laser Compton scattering in an energy recovery linac" Phys. Rev. Accel. Beams 19, 114701 (2016)

(Published) M. Akemoto *et al.*, "Construction and commissioning of the compact energy-recovery linac at KEK" Nucl. Instrum. Method A 877 p.197-219 (2018).

Commissioning started

R&D for Industrial application

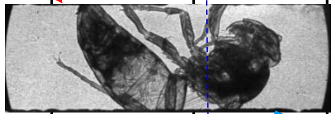
Beam operation

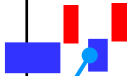
here

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

Construction

Commissioning/Operation





Refurbishment of building

Clearing radioactive materials

Construction of radiation shielding

Construction of injector

Commissioning of injector

Construction of recirculation loop

Commissioning of cERL (with loop)

Construction of LCS system

Commissioning of LCS system

Increasing the beam current

RI beam test & production

High bunch charge & THz study

1mA again

Construction of RI beamline

Construction of IR-FEL

FEL produced

0.3 mA CW beam with undulator

1mA CW ERL achieved

We will talk **latest three years status** of beam operation and hardware issues after ERL2019.

Related ERL22 presentation of cERL operation (details)

- M. Shimada, "Beam tuning for IR-FEL and industrial application at the compact ERL" (focus on development of beam simulation & operation)
- H. Sakai, "SRF performance on the cERL at KEK" (focus of development of SRF performance during beam operation)

ERL2019 (Sep.2019)

Construction started in 2009 and commissioning start in 2013.

Now we continue beam operation in 2022