Accelerator Technology

Superconducting RF Cavity

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The 2nd EUV-FEL Workshop

KEK, High Energy Accelerator Research Organization

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Accelerator Technology
Superconducting RF Cavity

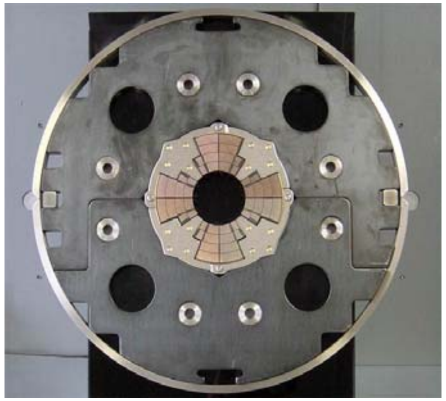
- Surface resistance of NC & SC
- Application of SC-RF
- Linear Acceleartors
- Summary

Surface resistance of NC & SC

Superconducting technology in accelerator

SC magnet

strong DC magnetic field
kicking beams
bending, focusing, undulator



SC RF cavity

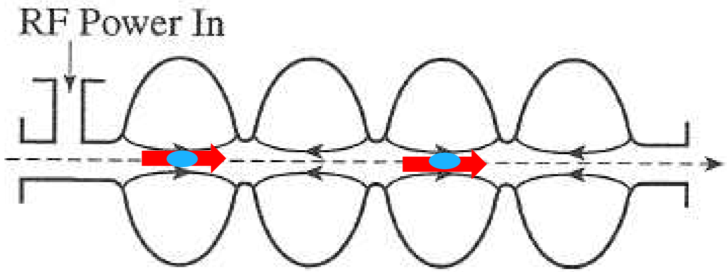
electro-magnetic field for beam acceleration
energy transfer to the beam
accelerating, deflection, RF separator

Surface resistance of NC & SC

Performance of RF Cavity

Shunt impedance : R_0
accelerating voltage: Vc
cavity wall loss: Pc
ohmic loss of surface current

$$R_0 = \frac{V_c^2}{P_c} = \frac{V_c^2}{\frac{1}{2}\int_s R_s H^2 ds}$$



R_s: has the material information
surface resistance (ohm)

Surface resistance of NC & SC

Normal conducting cavity

$$R_s = \frac{1}{\delta\sigma} = \sqrt{\frac{\omega\mu}{2\sigma}}$$

(δ: skin depth, σ: conductivity)

$$R_0 = \frac{V_c^2}{P_c} = \frac{V_c^2}{\frac{1}{2}\int_s R_s H^2 ds}$$

R_s depends on both frequency and cavity material.

For Cu cavity of 1.3 GHz

σ=0.58×10⁸ mho/m

R_s=9 mΩ

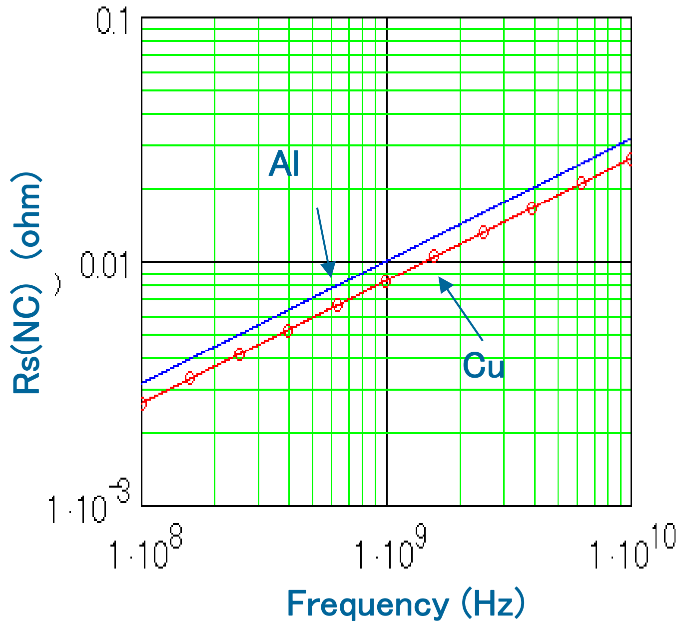
huge wall loss of

8 MW/m at 20 MV/m

32 MW/m at 40 MV/m

→pulse operation with high gradient

→continuous wave with low gradient



Surface resistance

Surface resistance of NC & SC

Superconducting cavity

$$R_s = R_{BCS} + R_{res} ,$$

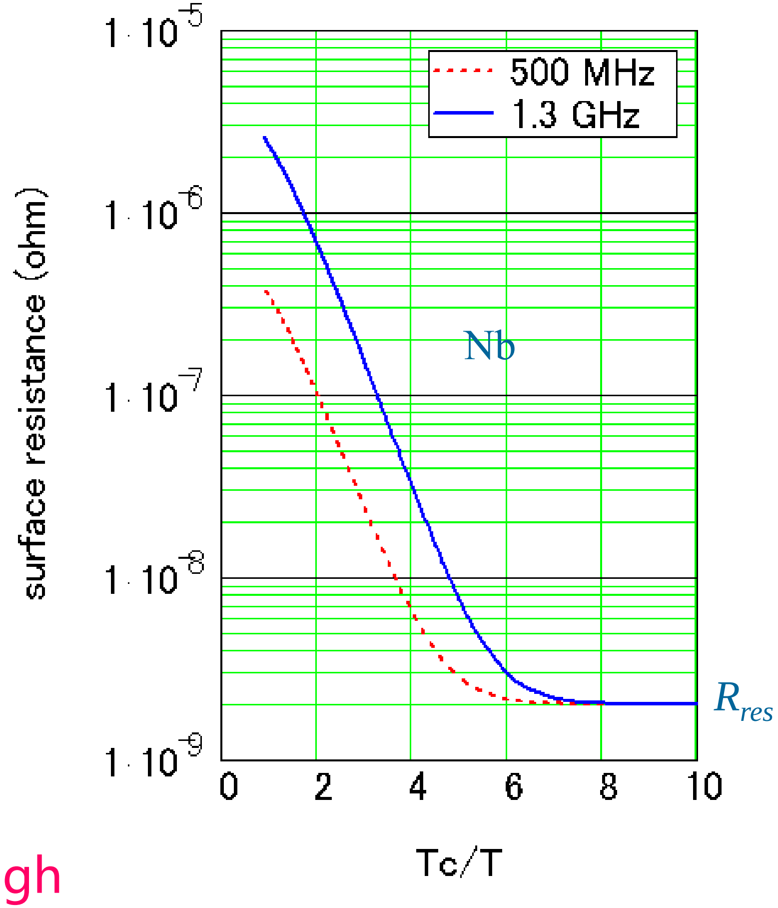
R_{BCS}: theoretical; R_{res}: residual resistance

$$R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta(0)}{k_B T_c}\cdot\frac{T_c}{T}\right)$$

For Nb cavity of 1.3 GHz
4×10^{-7} ohm at 4.2K,
6×10^{-9} ohm at 1.8K.

negligible small wall loss of
1.3W/m at 10MV/m,
5.4W/m at 20MV/m.

SC-RF provides CW operation at high gradient, but needs extremely clean work.

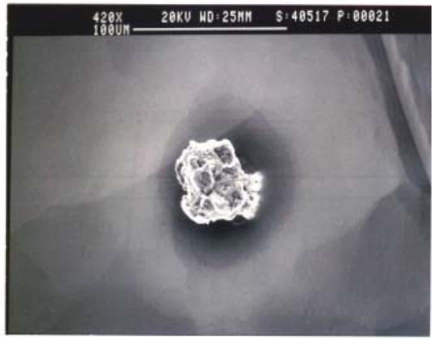


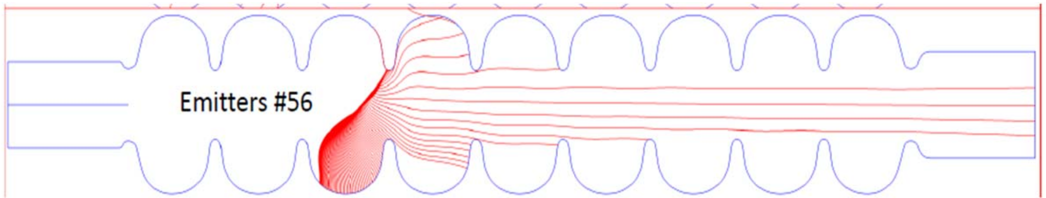
Surface resistance

Surface resistance of NC & SC

Field limitation of SC-RF

1. Critical magnetic field of Superconductivity
   When magnetic field in the cavity exceeds Hc.
   In typical Nb cavity, Hc1 of 0.2 T corresponds to 50 MV/m.
2. Local heating and quench due to the surface defect
   1) inpurity
   2) trapped flux of residual magnetic field
   3) Multipacting discharge
   4) field emission
   5) Q-disease
3. Cryogenic capacity
   Cavity loss is proportional with $(\text{gradient})^2$.
   Loss of 1 W at 2 K needs primary electric power of ~3 kW.



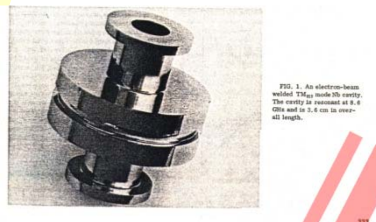


Application of SC-RF

History of SC-RF application

Circular accelerator

Linear accelerator


1965 HEPL the first beam

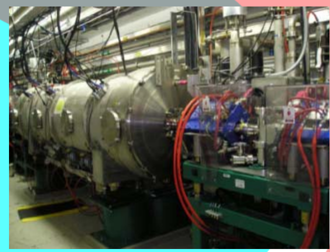

1988 KEK-TRISTAN

1991 CERN LEP

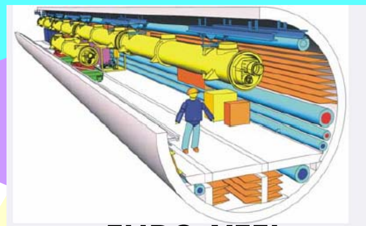

Light source


ANL ion acc.(1978)


CEBAF(1992)


SNS


KEKB(1998)


EURO-XFEL


ILC · ERL · LCLS-II


LHC(2009)

Application of SC-RF

SR rings using SC-RF

	TLS	CLS	Diamond	SSRF	BEPC-II	SOLEIL	NSLS-II	TPS	PLS-II
Energy (GeV)	1.5	2.5	3.0	3.5	2.5	2.75	3.0	3.0	3.0
Current (mA)	350	250	300	200	250	500	300	400	400
frequency (MHz)	500	500	500	500	500	352	500	500	500
Cavity type	CESR	CESR	CESR	CESR	KEKB	SOLEIL	CESR	KEKB	CESR
Number of cavity	1	1	2	3	2	4	2	3	3
Voltage (MV/cav)	1.6	2.4	2.0	2.0	1.5	1.5	1.7	1.6	1.5



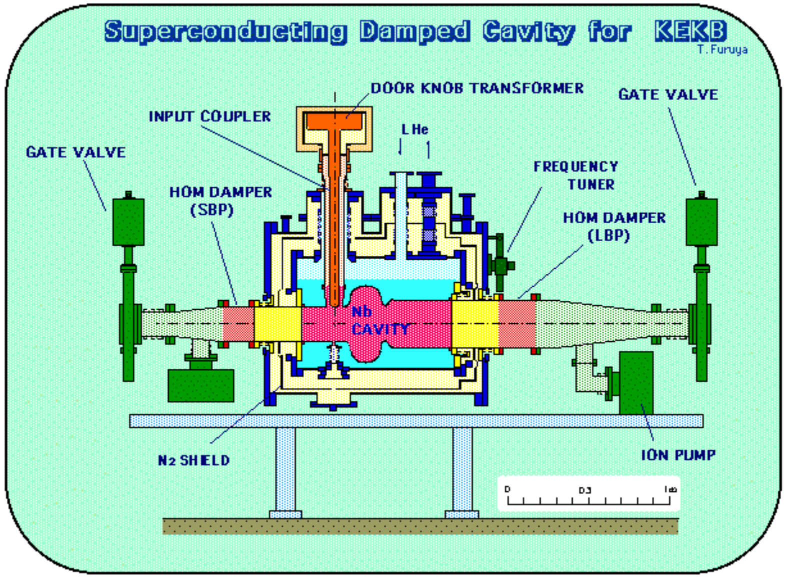


SC-RF provides a stable operation of 5 ~ 10 MV/m.
Minimize the RF space so as to increase the number of insertion.

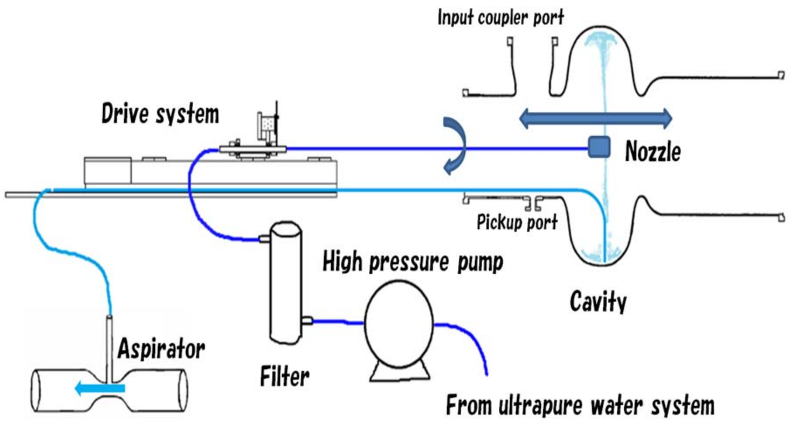
Application of SC-RF

SC-RF of SuperKEKB

- Challenge to a 2.6 A beam. Commissioning of SuperKEKB starts in 2018.
- performance recovery by horizontal high-pressure rinsing. Degraded gradient and Q0 were recovered.



SuperKEKB-SCC Design Parameters	
Number of Cavities	8
Max. Beam Current [A]	2.6
RF Voltage [MV/cav.]	1.5
External Q	5E+4
Unloaded Q at 2MV	1E+9
Beam Loading [kW/cav.]	400
HOM Loading [kW/cav.]	37



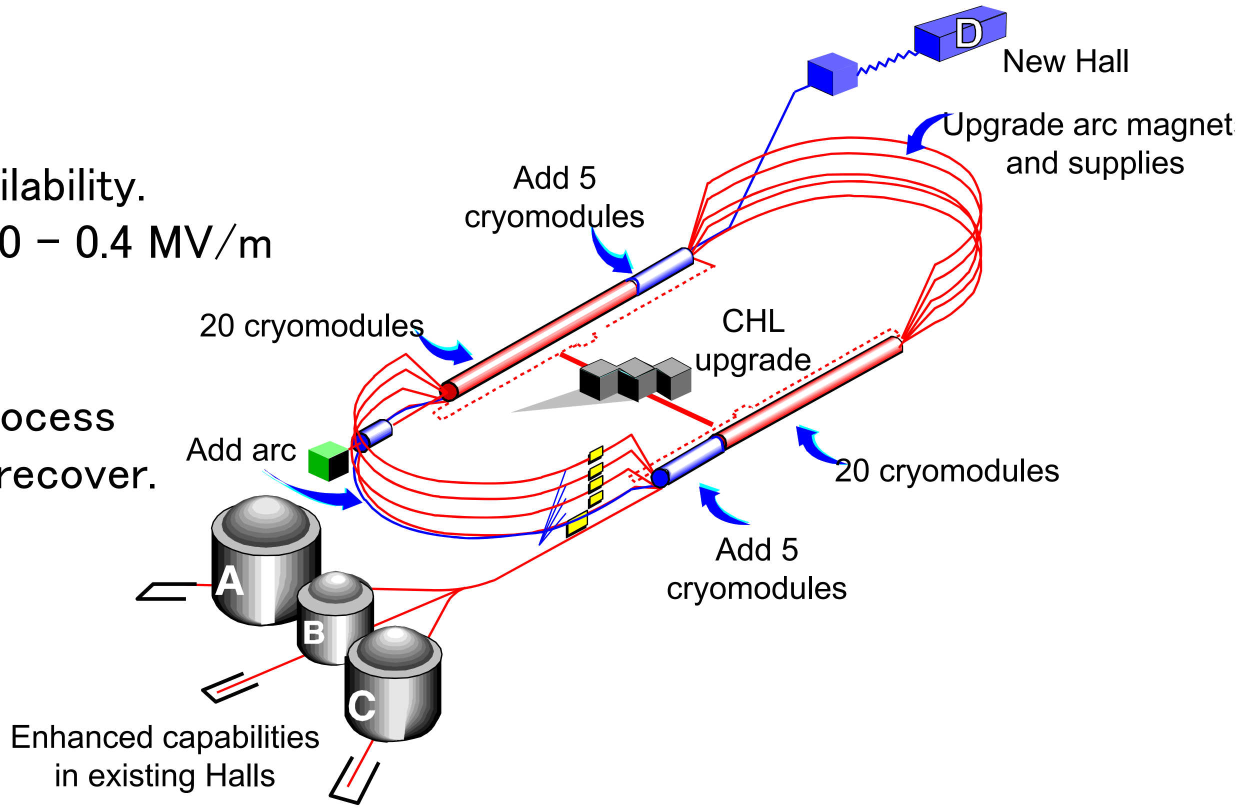
SC-RF Linear Accelerators

CEBAF (1992 –)

CW electron linac for nuclear physics
Five turns of the SC-RF of 80m × 2 provides 12 GeV electrons.
1.5 GHz 0.5m × 418 cavities generates 2.2 GV
Accelerating gradient of 5 – 18 MV/m

- strong field emission
- trip rate of 15/hr reduces the beam availability.
- gradient degradation of 0 – 0.4 MV/m per year. (1.5%/year)

- need to establish the process of maintenance & recover.
  Plasma processing
  He processing

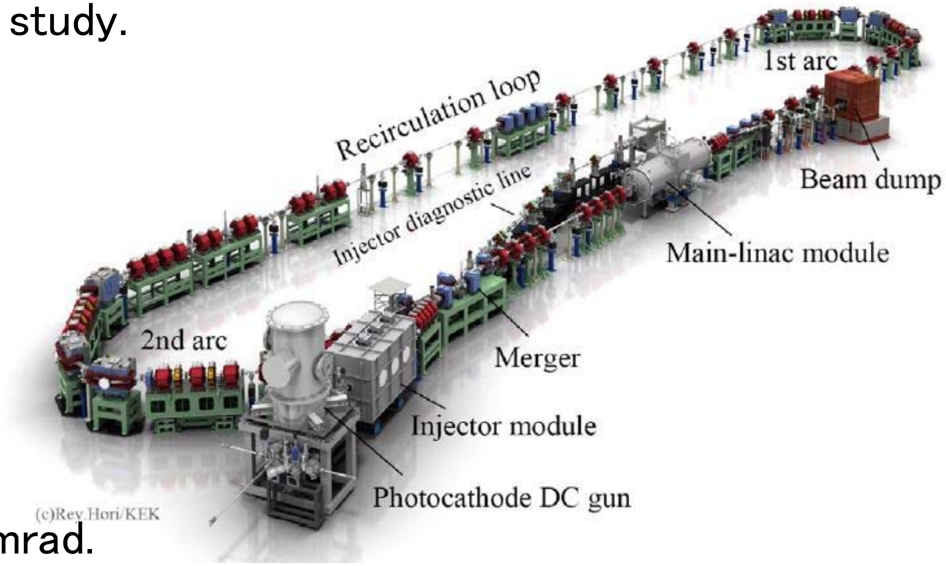


Application of SC-RF

KEK-cERL (2013 –)

CW electron linac for ERL feasibility study.
35 MeV ERL with 5.5MeV injection.
RF system
- ・500 kV photocathode gun
- ・injector linac: 1.3 GHz 2-cell × 3
- ・main linac: 1.3 GHz 9-cell × 2

Stable operation at 20 MeV.
Demonstrate the basic functions of
energy recovering
normalized emittance of 0.14mm・mrad.
stable operation at 8.2 MV/m



- ・Since the strong field emission electron in the cavity increased the cryogenic load, accelerating gradient had to be reduced.
- ・The source of FE is the dust particle during the final assembly process and also by the dust particle penetrate into the cavity during operation.
- ・Still need the establishment of a clean assembling process.
- ・It seems that manufacturing method of the cavity itself has been established.

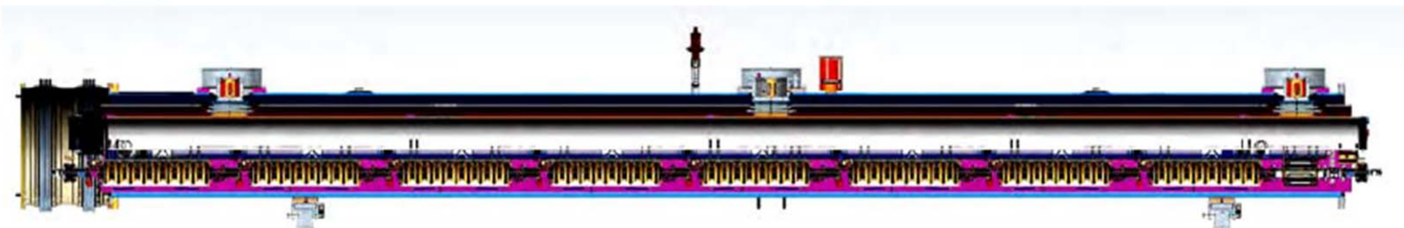
Application of SC-RF

LCLS-II (2020? –)

CW linac of 4 GeV, with an average current of 62 μA.
1.3 GHz, 9-cell × 280, 16 MV/m with Q0 of 2.7E+10.
Manufacturing and installation of the cavity modules will finish in 2019.

- low-loss cavity surface treated by N-dope technology.
- following the mass production technology of Euro-XFEL.
- under the collaboration with FNAL & JLAB.
- Cryoplant of 18 kW @4.5K. (4 kW @2K)

AVG gradient of 144 cavities achieved 22.6 MV/m. (Q0 of 3×10^{10})
Completed 6 modules have an average gradient of 19 MV/m (Q0 of 2.5×10^{10})



8 cavities (End Tuner) + 1 Splittable Quad (V. Kashikhin), 6 Current Leads ~50A

Application of SC-RF

Euro-FEL (2016 –)

17.5 GeV electron linac.
pulse of 1.4 ms with a rep rate of 10 Hz
1.3 GHz, 9-cell × 768,
24 MV/m with Q of 1E+10

All cavities were completed and installed.
Machine commissioning is in progress.
Produces X-ray up to 24.8 keV.
Produces bright and very short light pulses up to 27000 pps.

Construction in 2008 – 2015 gives a lot of information about mass production.

Summary

- The most important characteristic of SC-RF is that it can provide high field gradient in CW mode or a very high duty factor.

- In circular machine, HOM damped SC-RF accelerates a ampere class beam. The SC-RF of SuperKEKB will challenge a 2.6 A beam.

- In SC-RF linac, it is a very exciting time now.
  Large scale SC-RF linacs are
  CEBAF is accumulating the operation data of high gradient cavities.
  Euro-XFEL has just started commissioning.
  LCLS-II will complete in 2019, and will commission in 2020.

・Manufacturing process of SC-RF of 20 MV/m has been established.
The next problem is maintenance and performance recovering.
Especially, measures against FE is an urgent issue.

Thank you for your attention.