High Energy Physics related SRF in Japan

Snowmass 2021 Accelerator frontier

AF07 Accelerator Technology R&D: RF

2020/Aug/3

KEK CASA Kensei Umemori

Target of HEP accelerator

- Higher beam energy
- Higher luminosity
- Higher flux

Target of SRF cavity

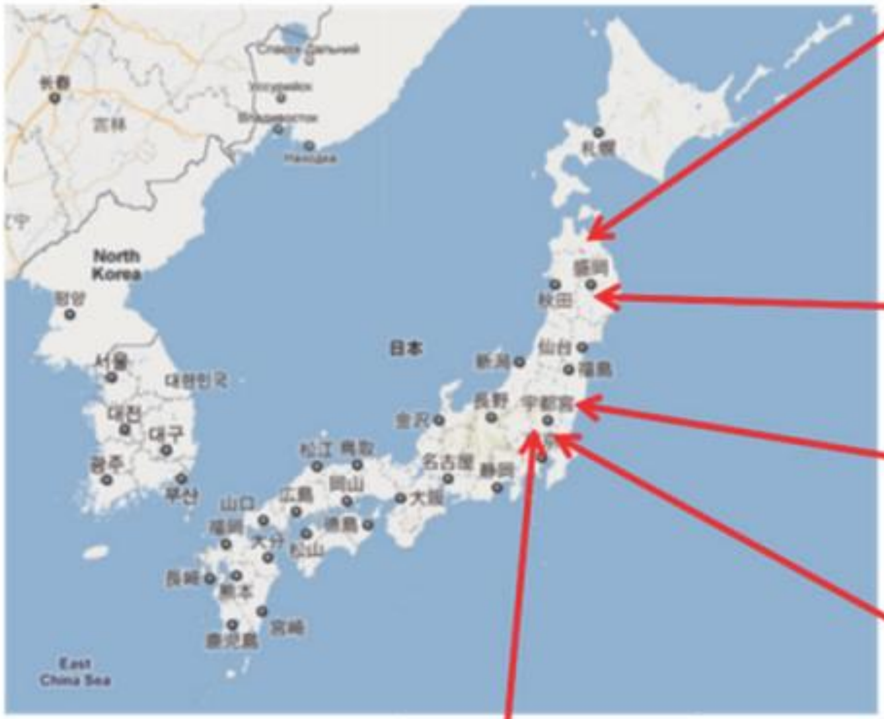
- Higher accelerating gradient
- Higher beam current
- Higher Q values (lower surface loss)
- CW or higher duty operation

In this talk, I present current SRF activity in Japan and on-going R&Ds toward future SRF accelerators.

Contents

- SRF accelerator activity in Japan
  - KEKB
  - Compact ERL (cERL)
  - STF
- High-Q/high-G R&D
  - N-infusion
  - 2-step baking
  - N-dope
  - Mid-T furnace baking
- Nb3Sn cavity R&D
- Layered structure
- Summary

SRF Accelerator in Japan



QST-Rokkasho
- ● IFMIF-LIPAc (deuterons)
  8 : 175MHz, HWR
- A-FNS (deuterons)
  8+10+12+12 : 175MHz, HWR

ILC (e⁻ e⁺ collider)
8000 : 1.3GHz, 9-cell cavity

JAEA-Tokai
ADS (protons)

KEK-Tsukuba
- ■ SuperKEKB (e⁻ e⁺ collider)
  8 : 508MHz, 1-cell cavity
- ■ cERL (elecrons)
  3 : 1.3GHz, 2-cell cavity
  2 : 1.3GHz, 9-cell cavity
- ■ STF2 (electrons)
  2+12 : 1.3GHz, 9-cell cavity
- Multi-MW SC Proton Driver (protons)

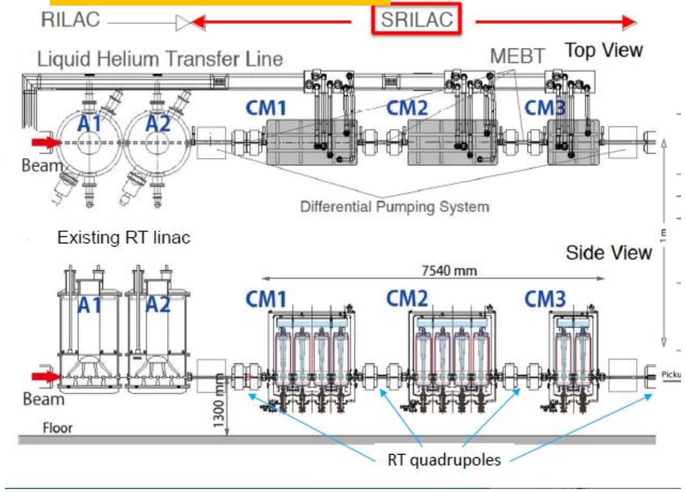
RIKEN-Nishina
- ● SRILAC (heavy ions)
  4+4+2 : 73MHz, QWR

■ operation
● under construction
No. of cavity : frequency : cavity structure
underline: future project

Eiji Kako, Journal of Cryogenics and Superconductivity Society of Japan (2019)

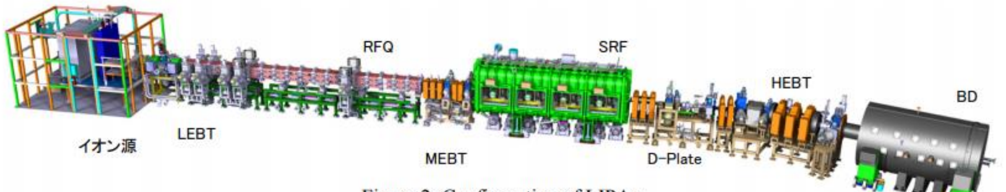
RIKEN SRILAC

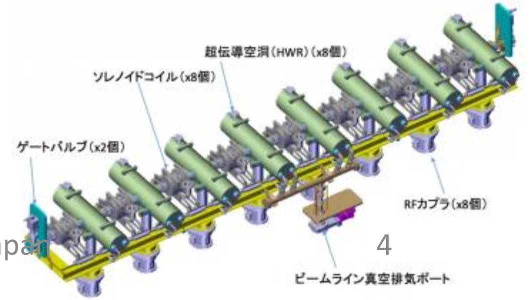
Yamada, Sakamoto @TTC(CERN)



QST IFMIF-LIPAc

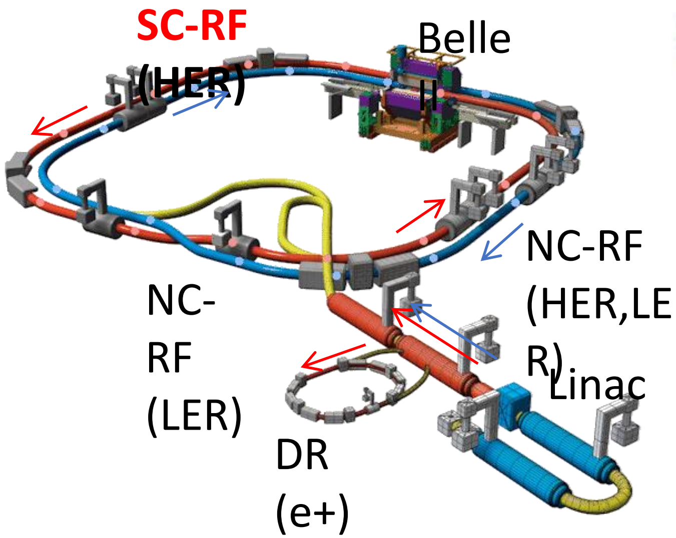
Kasugai, 14th Particle Accelerator Society of Japan (2017)



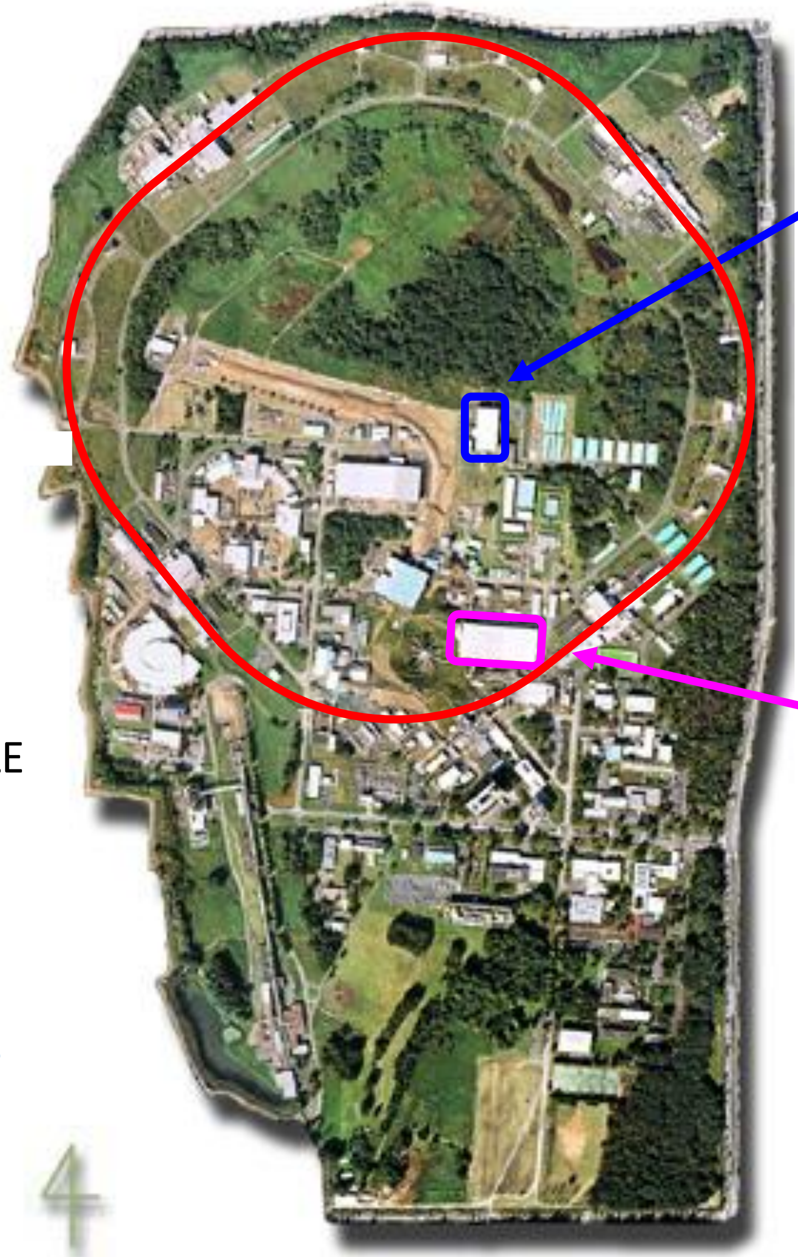


SRF Accelerator in KEK

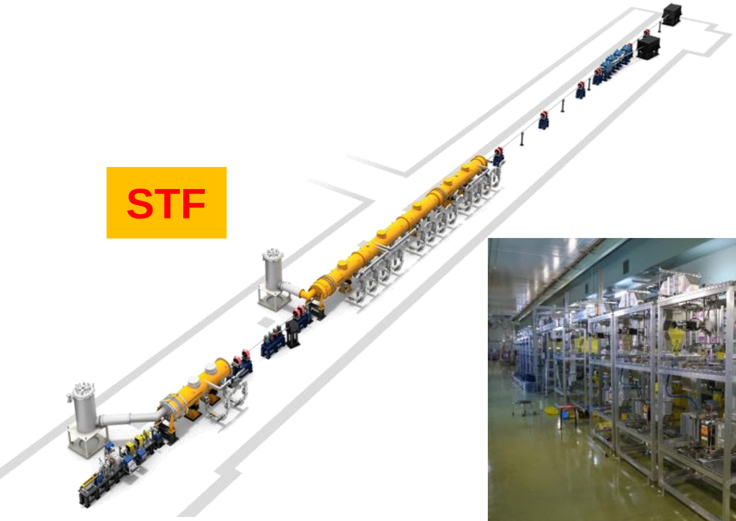
Super KEKB



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

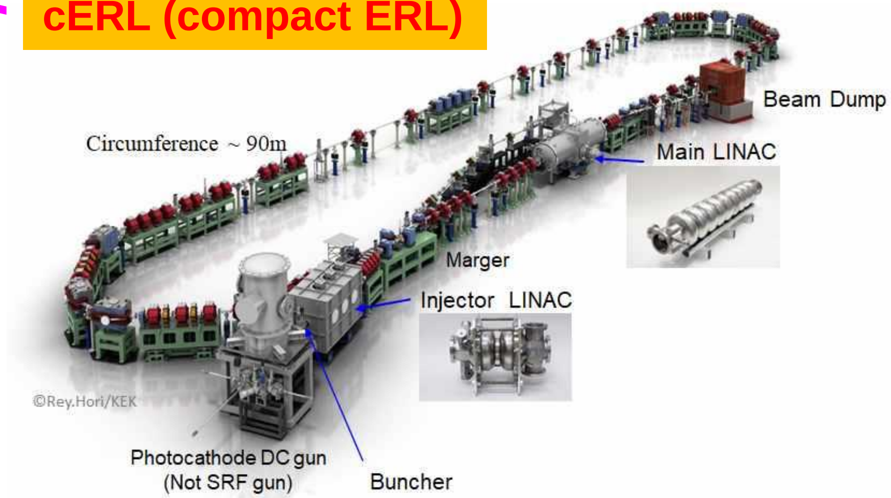


STF



Prototype cryomodule for ILC, pulse operation with high gradient

cERL (compact ERL)



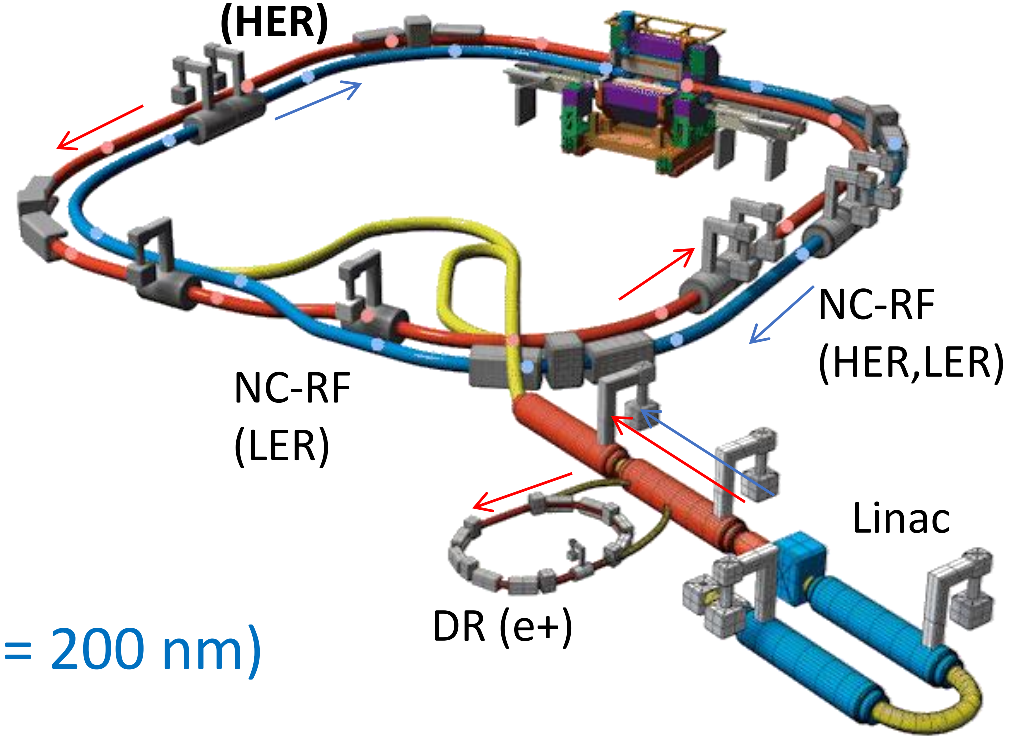
Test facility for Energy Recovery Linac, CW operation

Super KEKB

SuperKEKB (Successor to KEKB)

SKEKB-SRF team

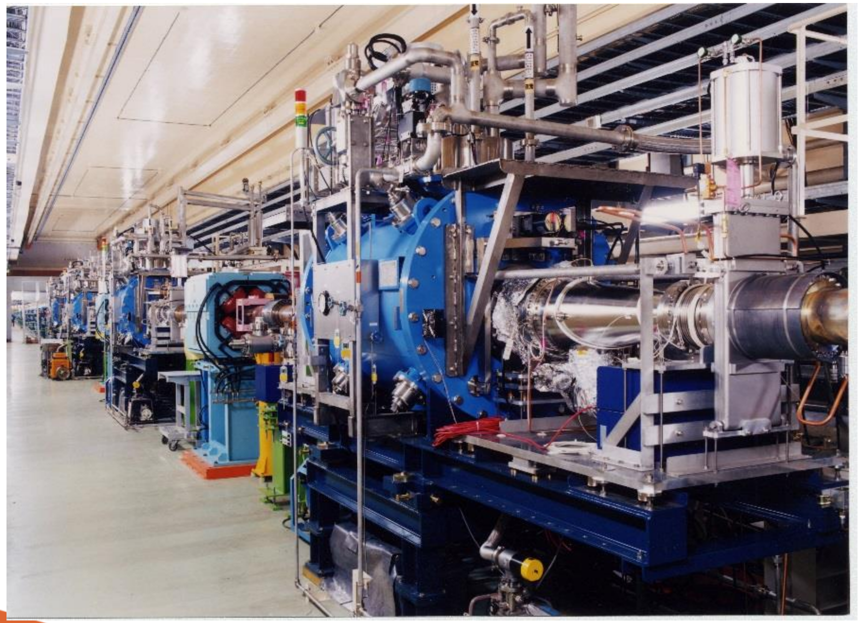
- e^+/e^- collider with target luminosity of
  - 8 × 10^{35} /cm^2/s = 800 /nb/s
  - using nano beam scheme
- Beam : LER(e^+): 4 GeV × 3.6 A
  HER(e^-): 7 GeV × 2.6 A
- Beam size : σ_x^*/σ_y^* = 10 μm/50 nm (β_y^*= 0.3 mm)
  & crab-waist
- Operation: Physics Run since Mar. 2019
  current: 2.4 × 10^{34} /cm^2/s with 0.7 A × 0.6 A (σ_y^* = 200 nm)
  Challenging to 50 nm & full intensity



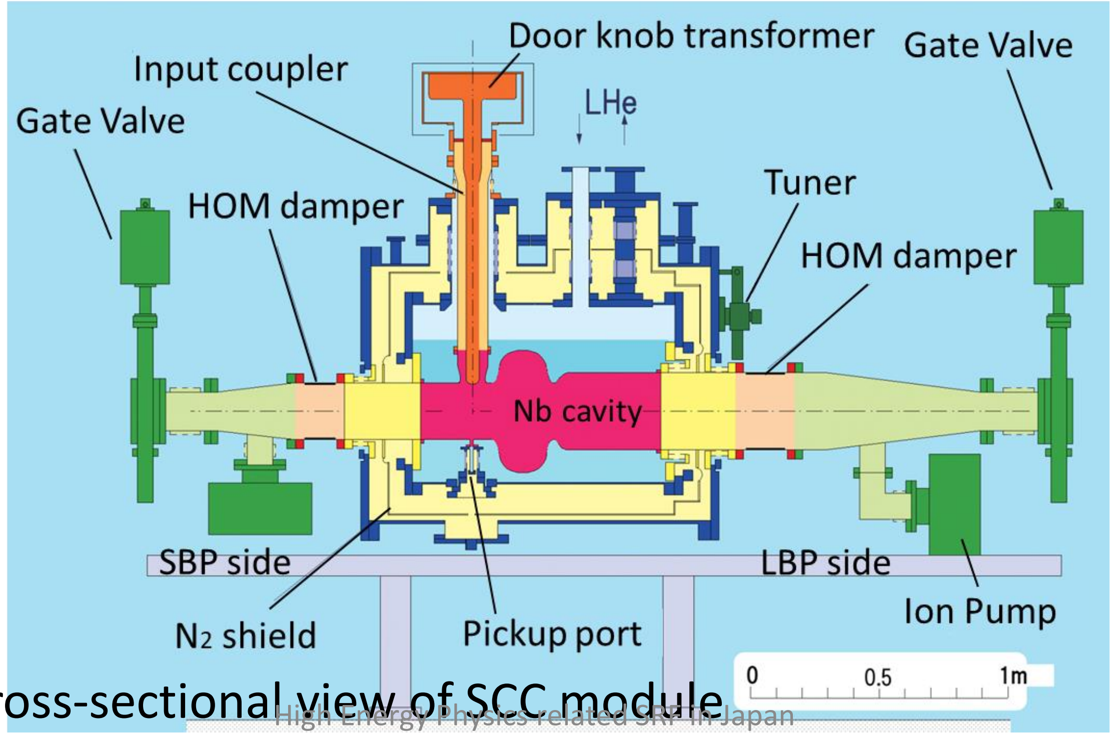
High current SRF operation in storage ring

SRF System in SuperKEKB (HER)

- Hybrid RF System of 8 SCRF & 8 NCRF(ARES) for HER to allow sharing beam power & voltage.
- 509 MHz Nb single-cell Cavity, 4.4 K Operation.
- Re-use of existing SRF system for KEKB (since 1999).
- SRF providing the max power & voltage of 3.2 MW and 16 MV in cw.



SCC Modules in SuperKEKB Tunnel



Cross-sectional view of SCC module

Issues in High-Current Beam Operation

- Stable operation: Slight conditioning every two weeks suppresses sc trips.
- In situ cleaning: Performance recovering by horizontal HPR. Lab. test gave satisfied results.
- HOM Power : Estimated HOM power dissipated in one SC is 37 kW at 2.6 A.

SCC Operation Parameters	KEKB (achieved)	SuperKEKB (design)
Number of Cavities	8	8
Max. Beam Current [A]	1.4	**2.6**
RF Voltage [MV/cav.]	6	**5**
RF Voltage [MV/cav.]	1.0-1.5	1.5
External Q	5E+4	5E+4
Unloaded Q at 2MV	1E+9	1E+9
Beam Loading [kW/cav.]	350-400	400
HOM Loading [kW/cav.]	**16**	**37**

Measure against HOM Power

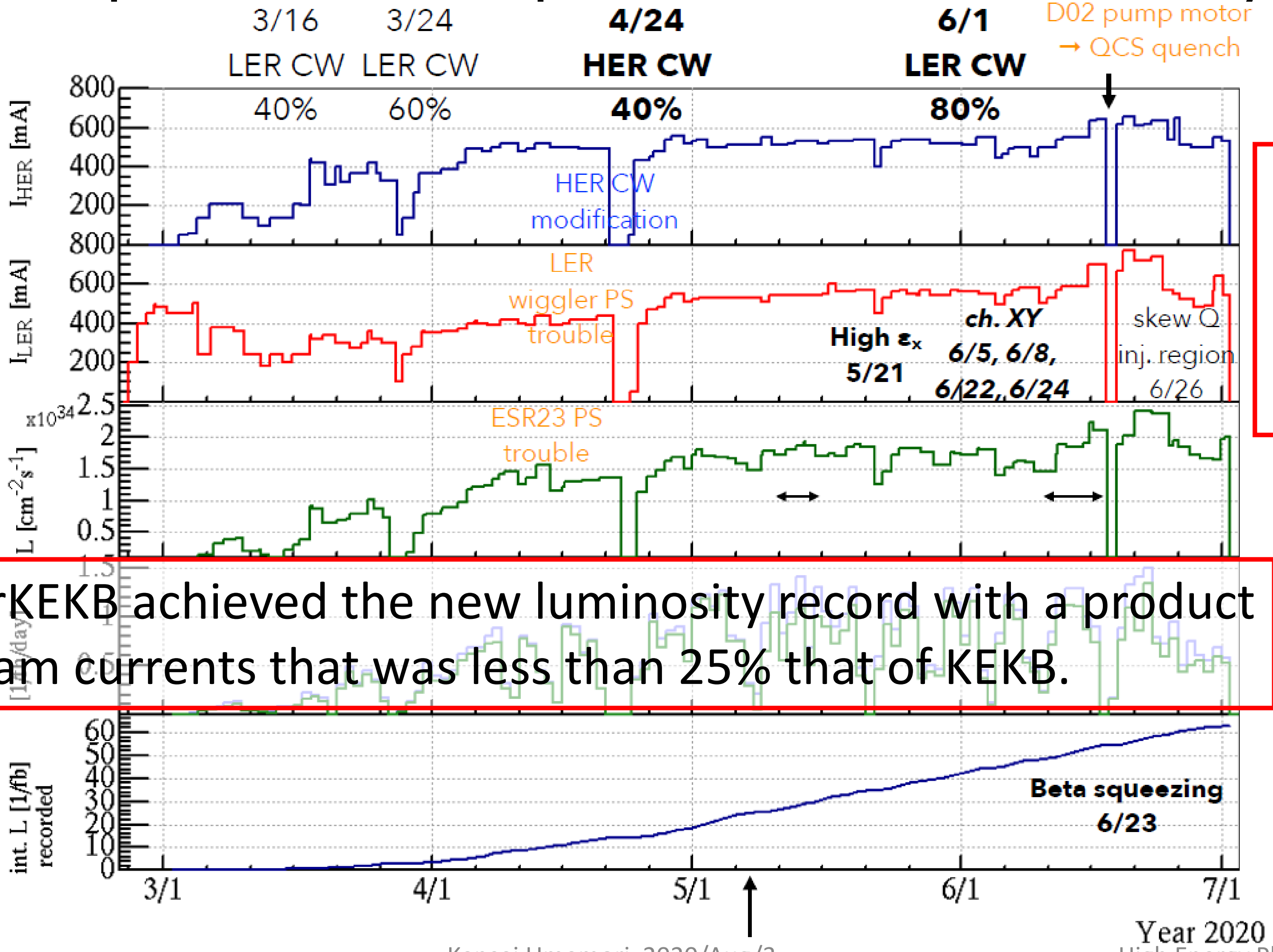
A half of the HOM power will be absorbed by a pair of HOM dampers attached in the SCC module and the other half will emit through the beam pipe. The emitting power becomes additional load to SCC module in the downstream.

To reduce the HOM power emission, an additional SiC damper has installed in the beam pipe.

A 20% reduction of HOM power was observed at the SC module of downstream.

SuperKEKB Operation Summary (2020/3-6)

Y.Ohnishi



LER started on Feb. 25

HER started on March. 2

Max. current
LER : 770 mA
HER : 660 mA

Peak luminosity : 2.4 x 10^{34} $cm^{-2}s^{-1}$

Int. luminosity/day : 1.346 / 1.498 fb^{-1}

5/11-5/14 off-resonance

6/10-6/17 off-resonance

SuperKEKB achieved the new luminosity record with a product of beam currents that was less than 25% that of KEKB.

LER :

$$\beta_x^*/\beta_y^* = 80\ mm/1\ mm \rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

HER :

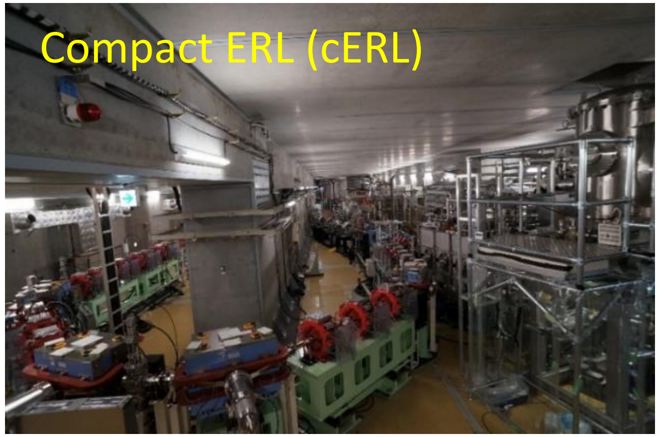
$$\beta_x^*/\beta_y^* = 60\ mm/1\ mm \rightarrow \beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$$

Remarks : ECL online luminosity does not include trigger veto dead time before May 7.

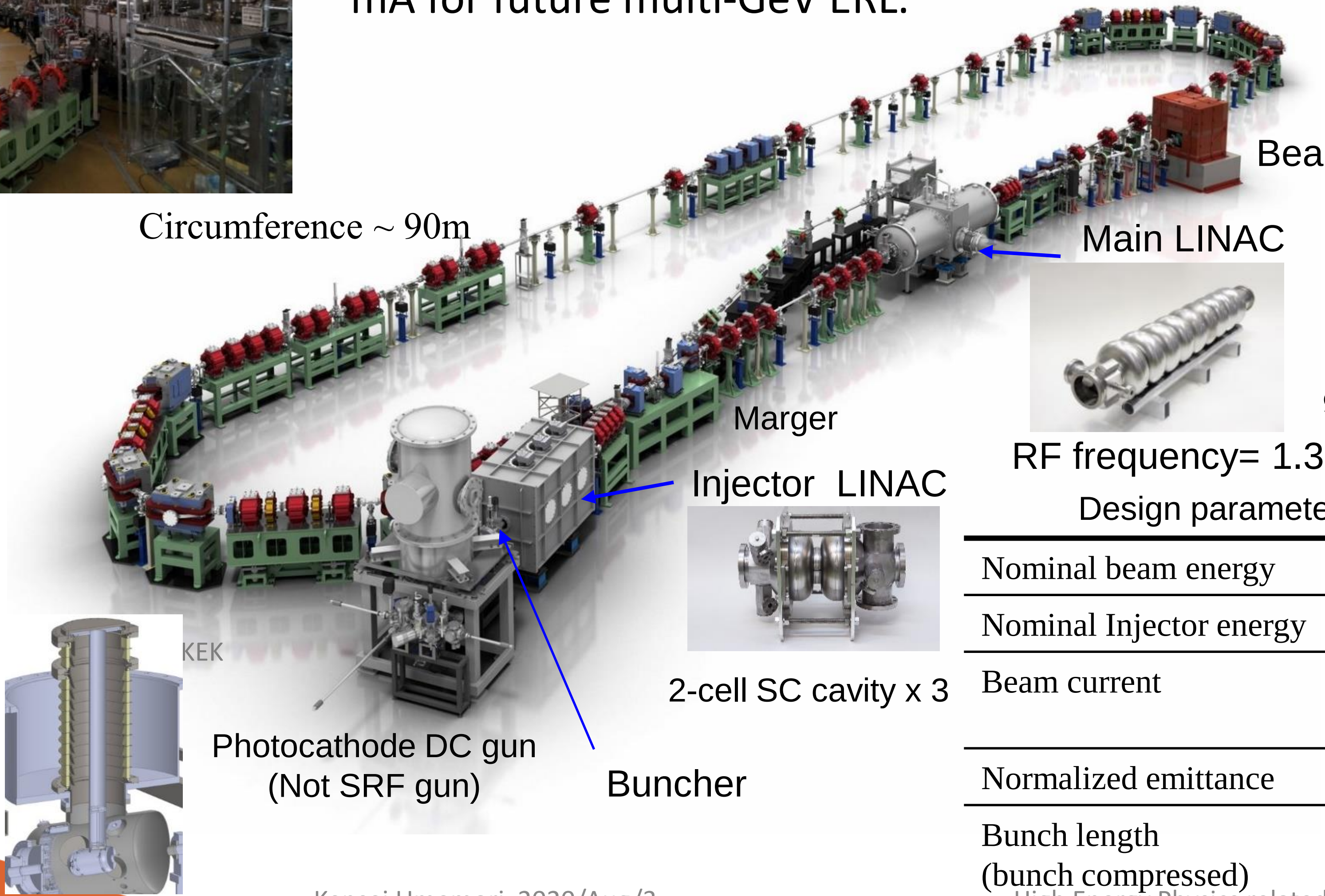
cERL

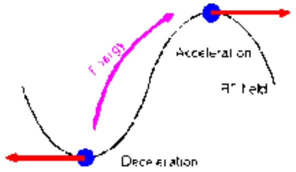
Compact ERL (cERL) in KEK

Target: High current SRF operation in linac with energy recovery



Compact ERL (**cERL**) has been constructed in 2013 at KEK to demonstrate energy recovery with low-emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL.





9-cell SC cavity x 2

RF frequency= 1.3 GHz

2-cell SC cavity x 3

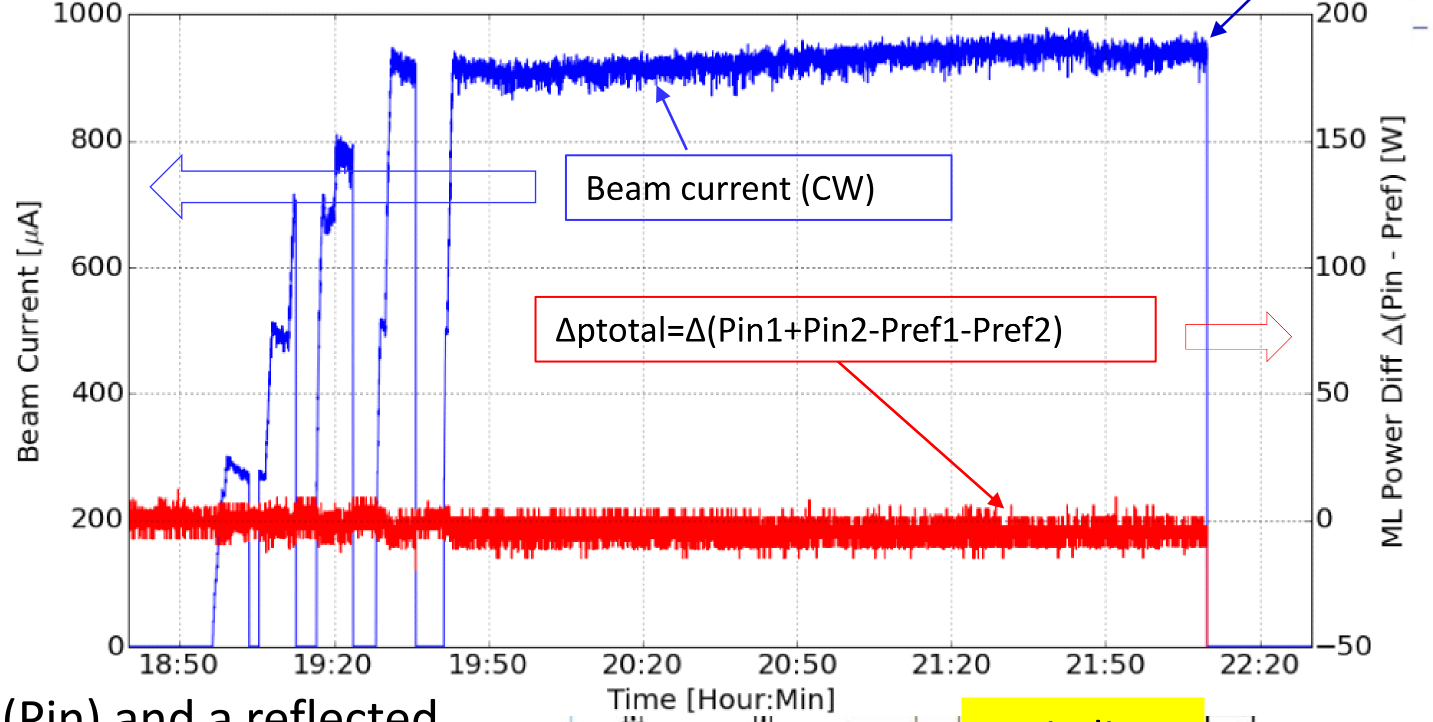
17.7 MeV

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)

Successful ~ 1mA CW beam operation with energy recovery

Change CW mode and increase the beam current: Reach 0.9 mA after the 1mA approval from the government at 8th/Mar/2016.

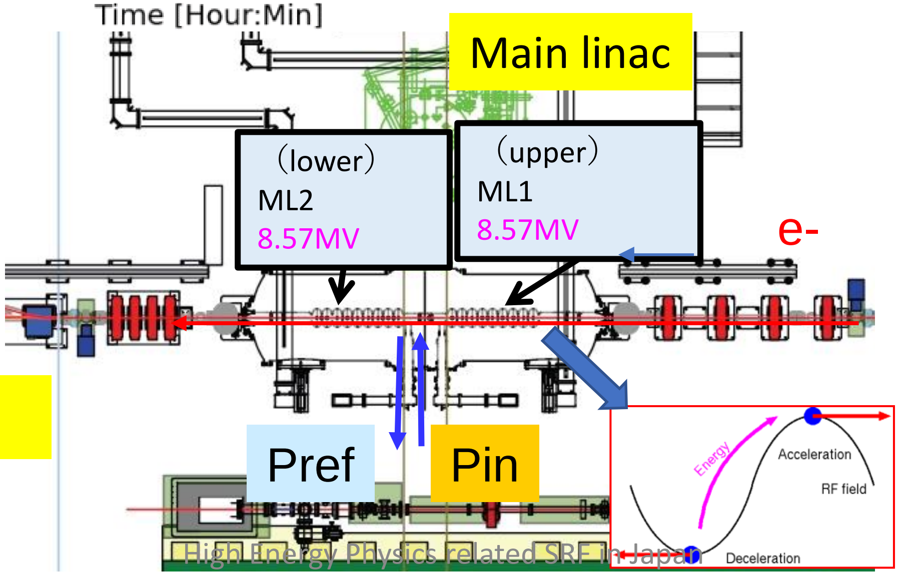


No HOM-BBU was observed.

red : Difference between an input (Pin) and a reflected (Pref) power of the ML. Energy loss measured from the graph = 4 W. (error +-4W)

Required power without recovery is :

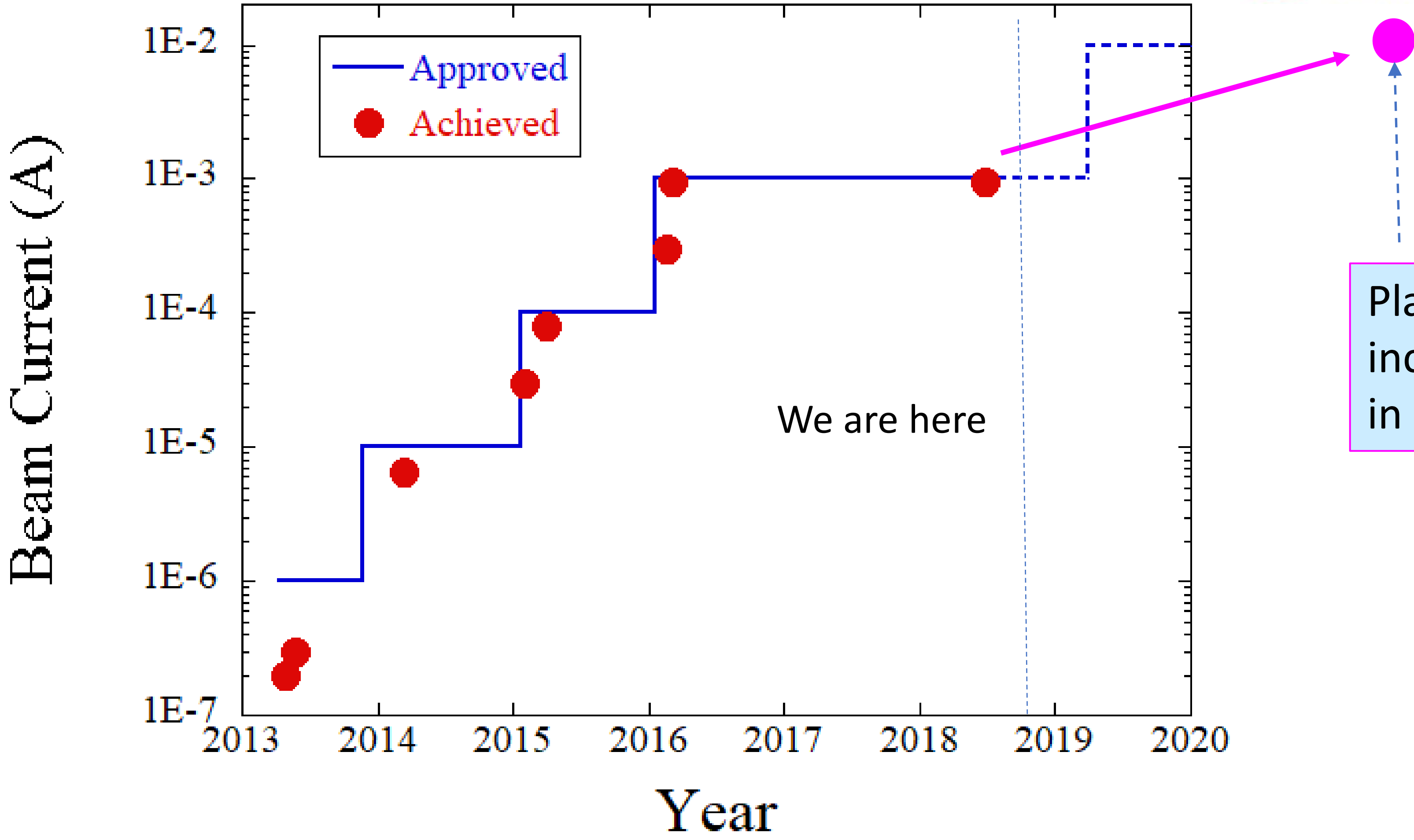
17.14 MV x 900 uA = 15.4 kW



Energy Recovery is almost 100.0% (error +-0.03%)

This measurement agree well with beam loss measurement of less than 0.01%

Beam Currents: Achievement and Prospect



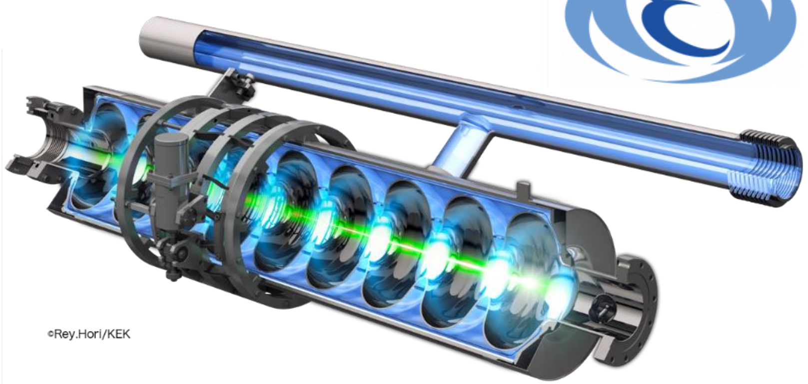
Plan to increase 10 mA in 2021.

By achieving low loss beam operation and high charge low emittance beam generation of 7.7pC. 10 mA operation is within target.

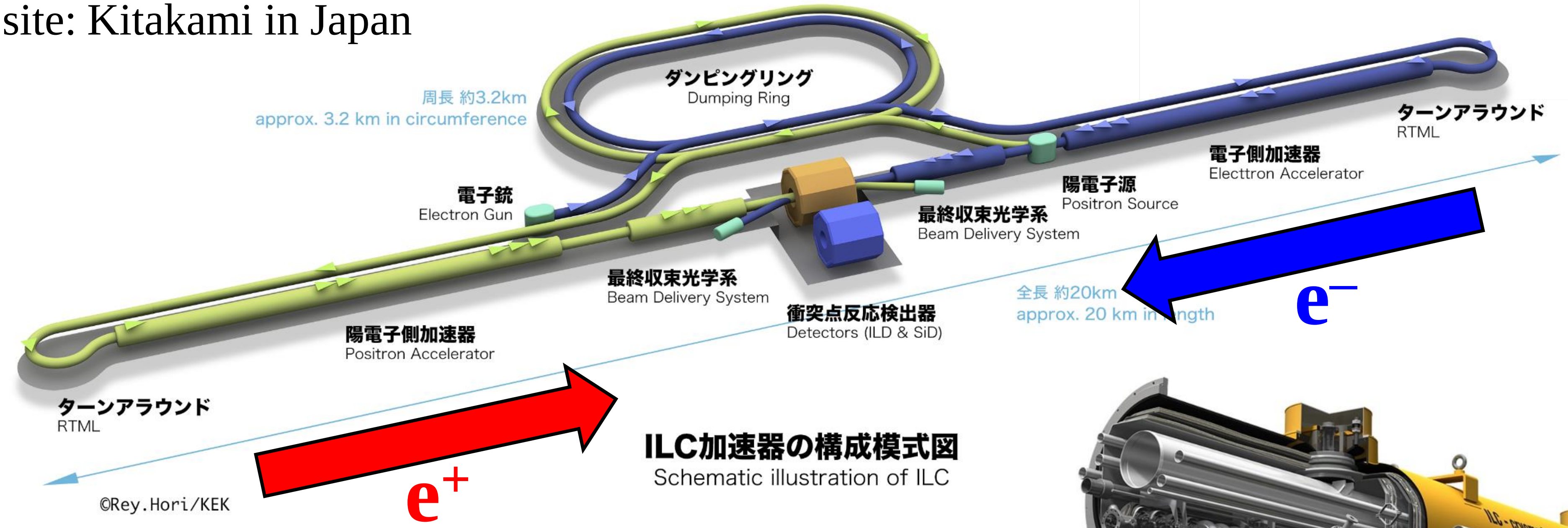
ILC

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
- Candidate site: Kitakami in Japan



岩手県一関市の資料をもとに作製



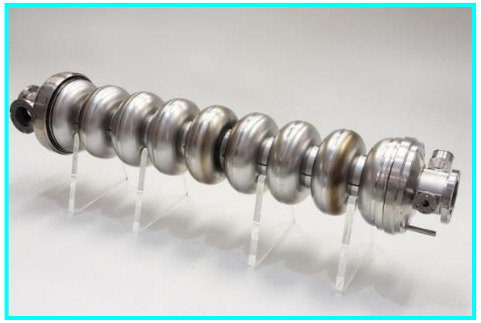
ILC Spec.	E_{acc}	Q_0
Vertical Test	35 MV/m	0.8×10^{10}
Cryomodule test	31.5 MV/m	1.0×10^{10}

>90% (successful rate)

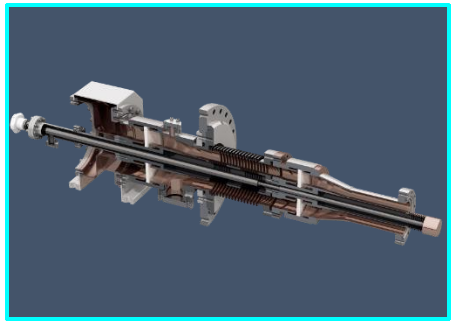
STF

STF-2 project and STF-2 accelerator

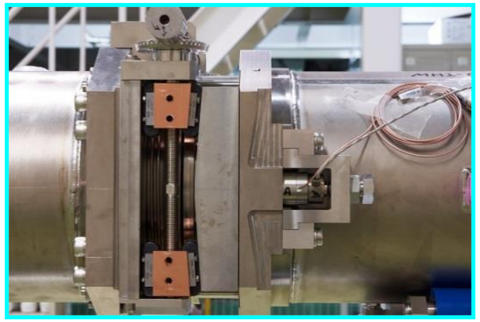
STF Cavity

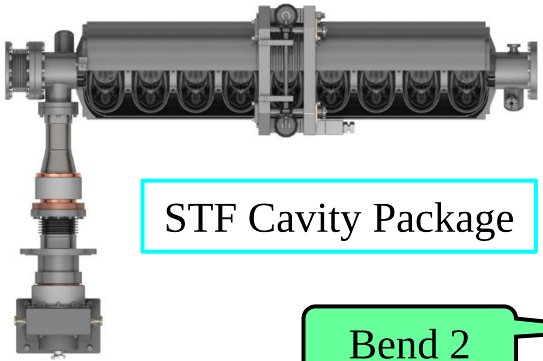


STF-II power coupler

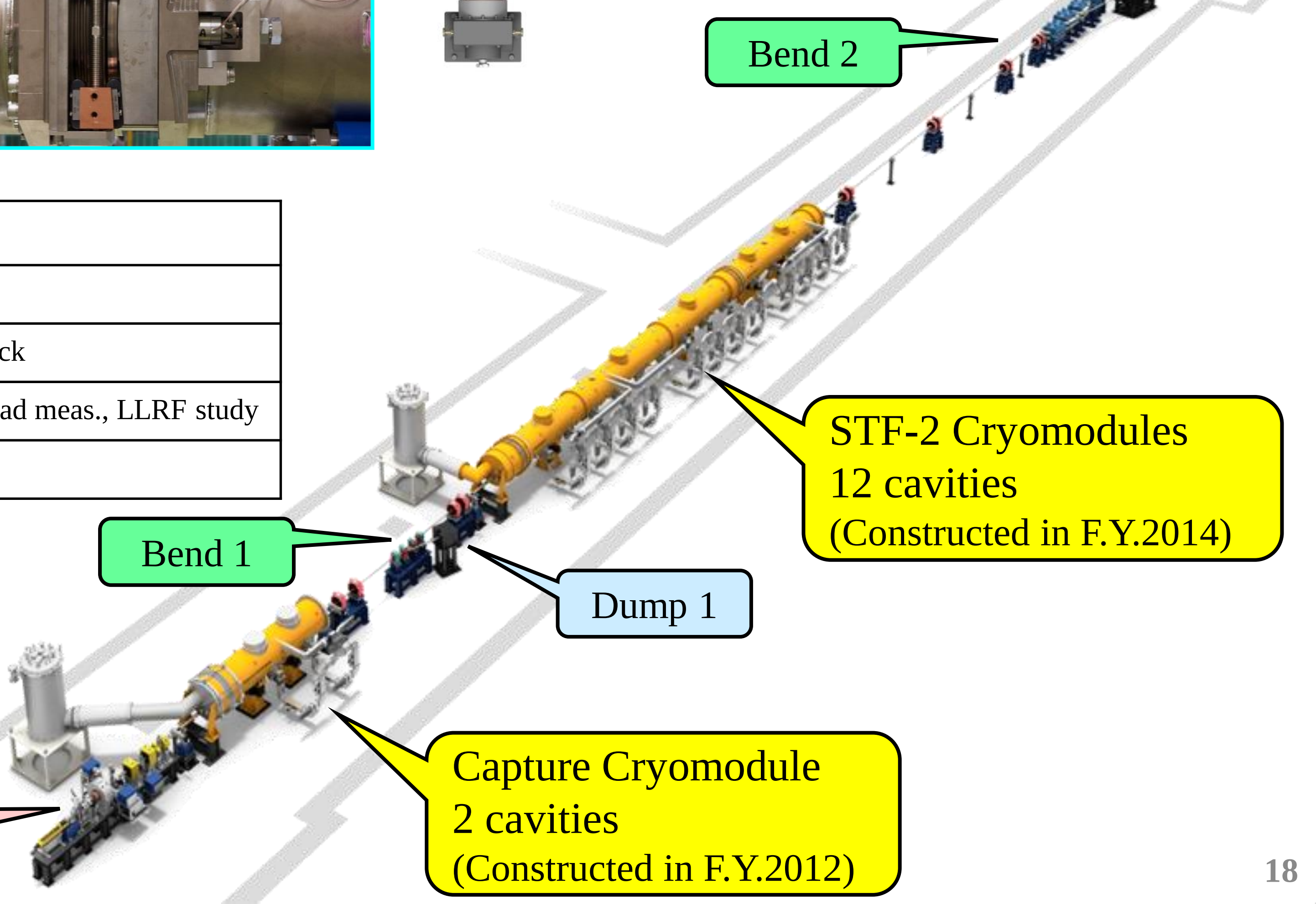


Slide-jack tuner





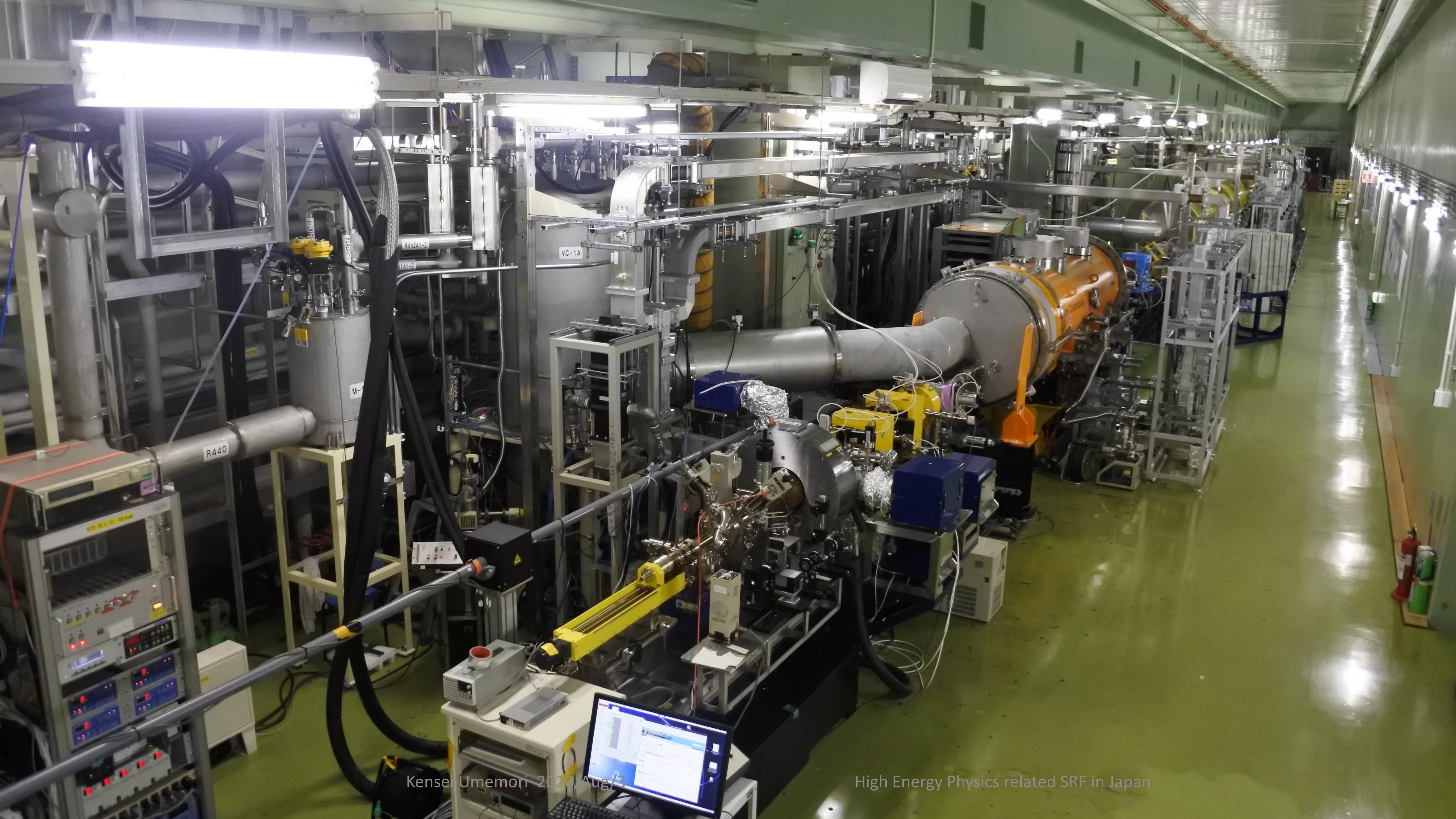
STF Cavity Package



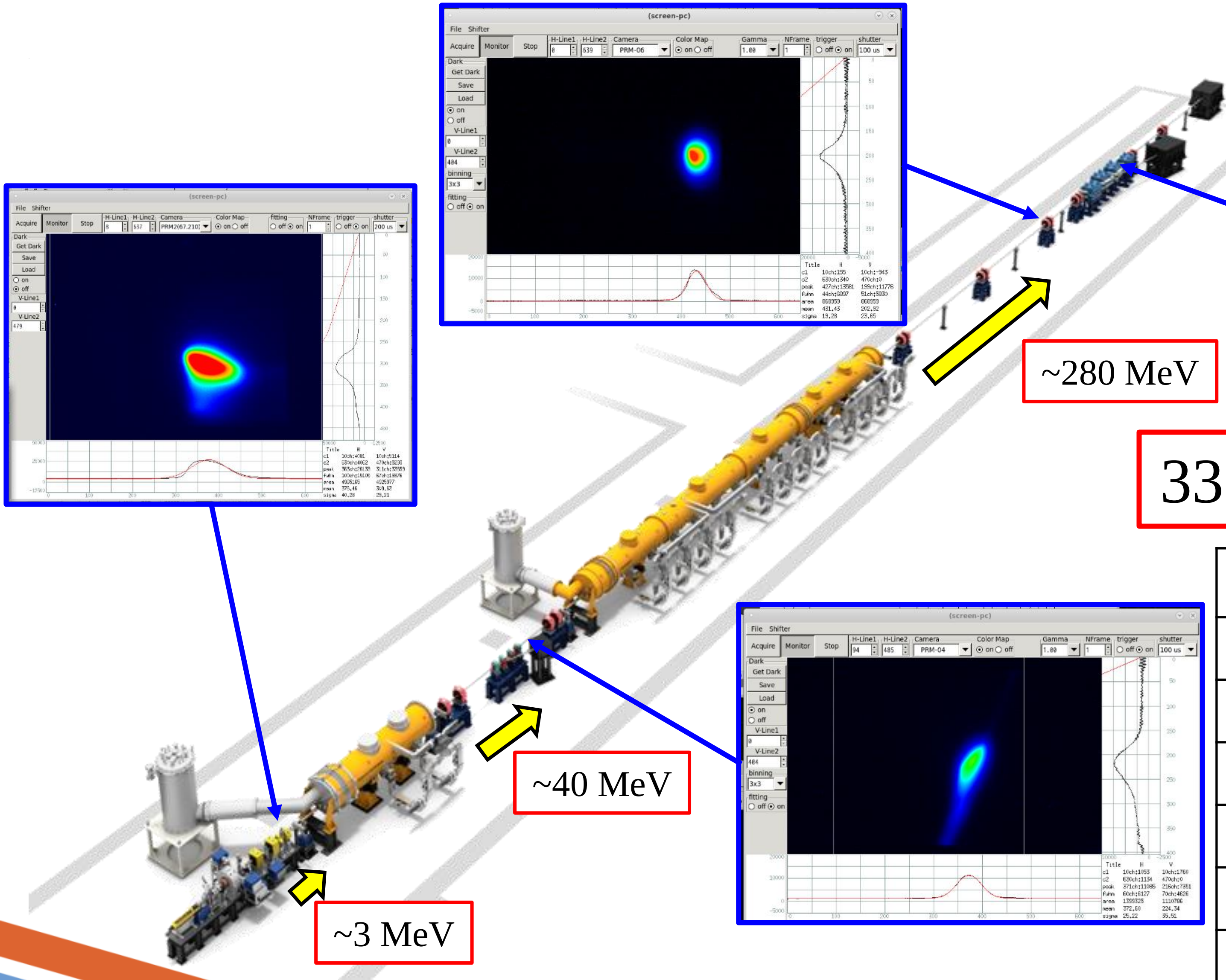
Cooldown	Date	Content
1	Oct/2014 ~ Dec/2014	Low power test
2	Oct/2015 ~ Dec/2015	Single cavity operation, performance check
3	Sep/2016 ~ Nov/2016	Eight cavities operation, LFD and heat load meas., LLRF study
4	Jan/2019 ~ Mar/2019	Beam commissioning, Machine study

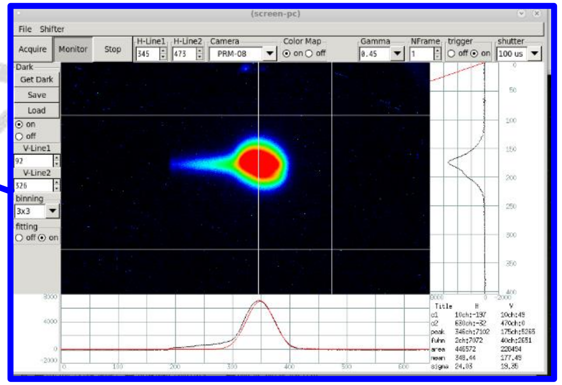
Operational condition

- RF: 1.65 msec/5 Hz (ILC/TDR)
- Temperature: 2K in liq. Helium
- As max. E_{acc} as possible for STF-2 CM

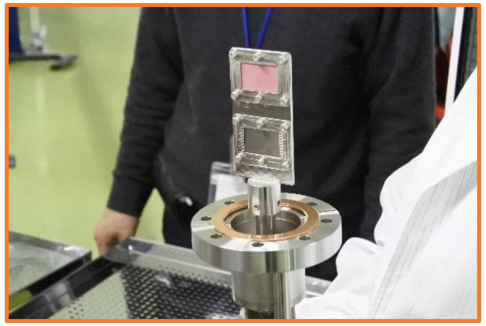

VC-1A
R440

Accelerating gradient estimated from beam energy





Beam profile monitor



33.1 MV/m (averaging for 7 cavities)

Achievements in STF-2 beam commissioning	
Beam energy	280 MeV
Beam power	75 W
Beam current	275 nA
Charge	55 nC/pulse
# of bunches	1000 / pulse
Average gradient estimated from beam energy	33.1 MV/m
Average gradient measured by power meter	33.8 MV/m

Consistent within 2%!

R&D for high-Q/high-Gradient

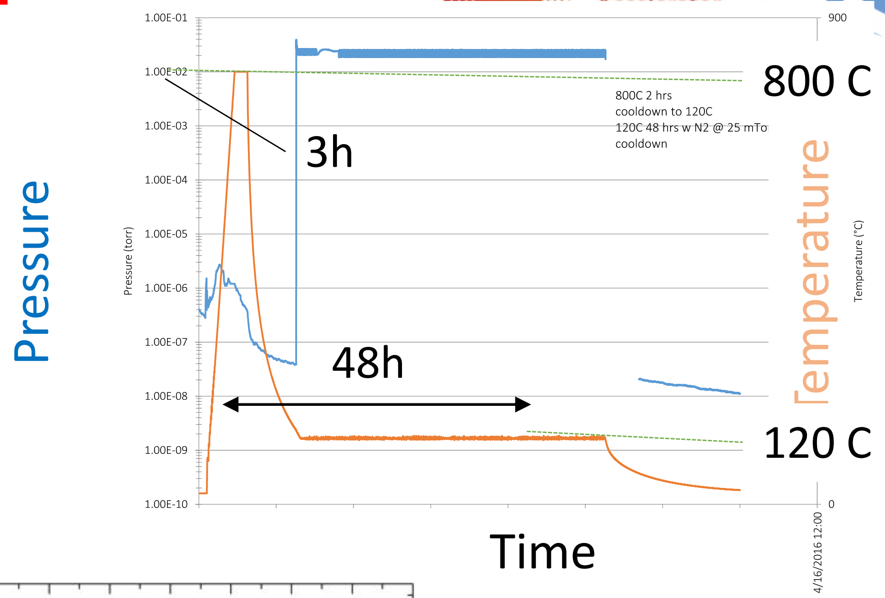
- N-infusion
- 2 step (75C + 120C) baking
- N-dope
- Mid-T furnace baking

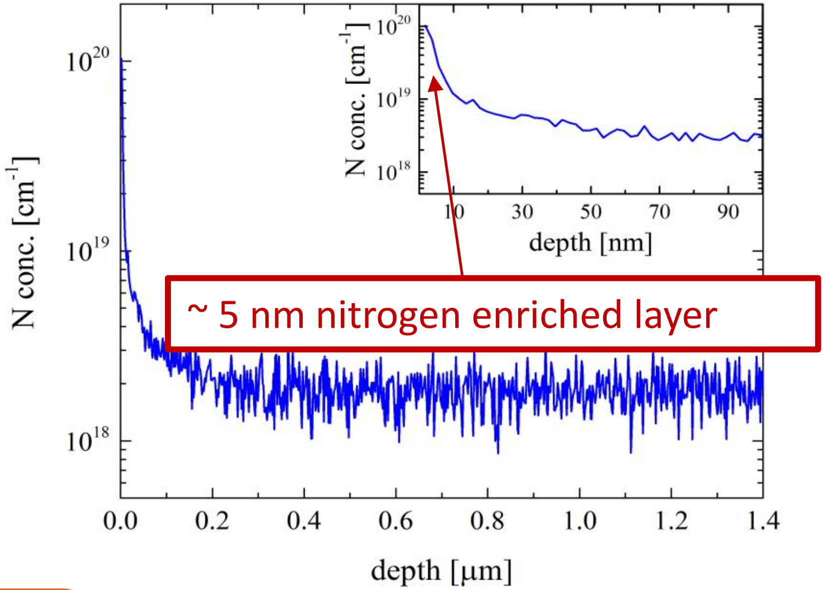
N-infusion

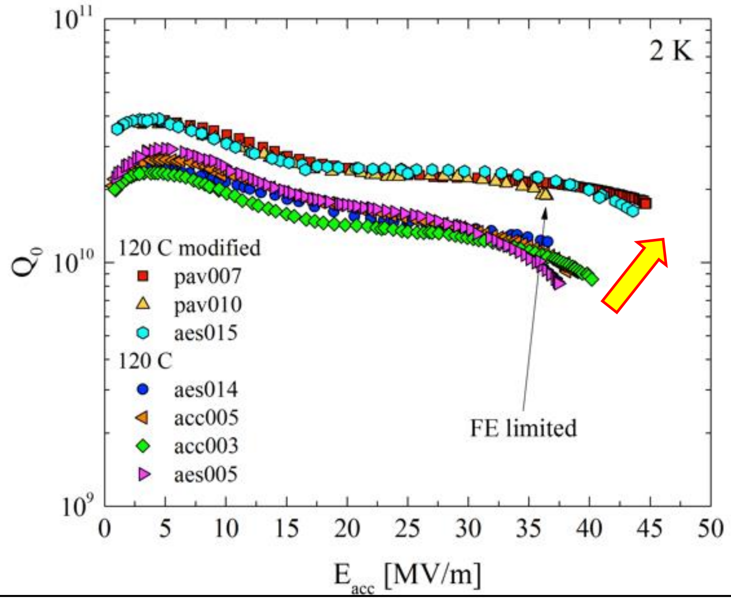
Nitrogen-infusion (N-infusion)

After high temperature heat treatment, ~Pa of N2 is fed into the furnace at ~120C for several 10 hours.

Nitrogen goes into depth of ~ 10 nm.
No need of additional EP after N-infusion.
Achieve better-Q
Also can get better Eacc







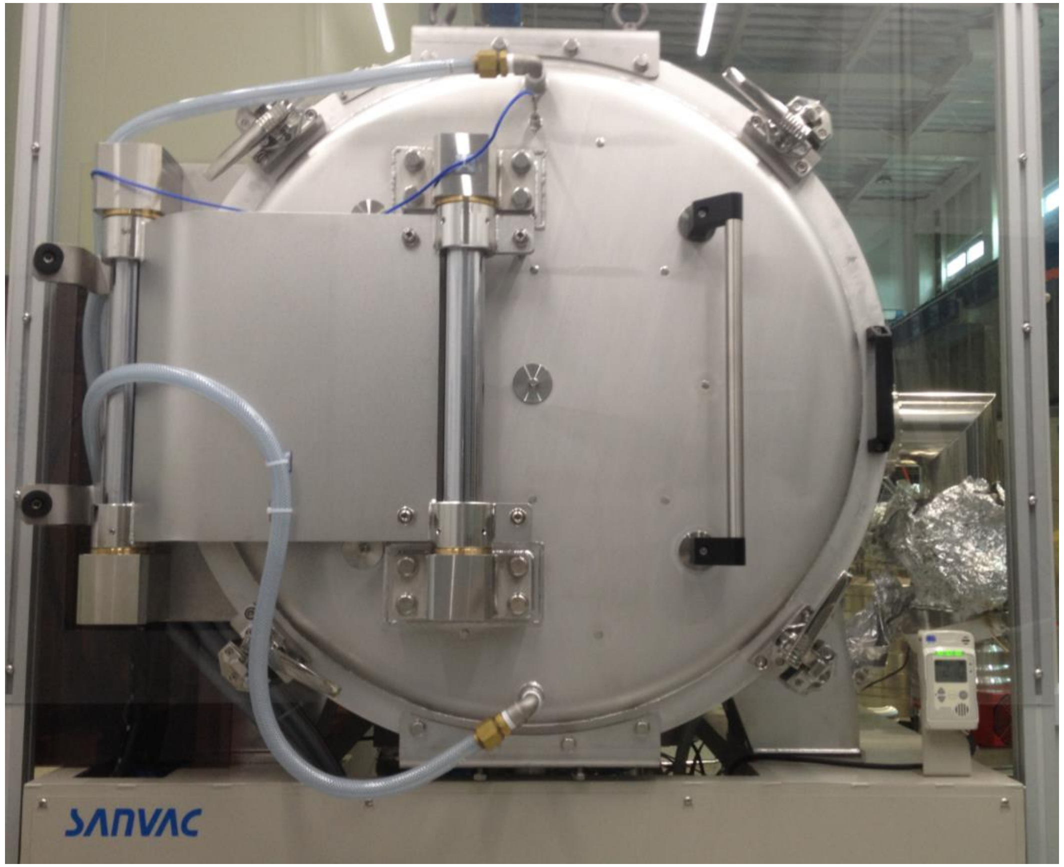
Sebastian Aderhold / Anna Grassellino (TTC@Saclay)

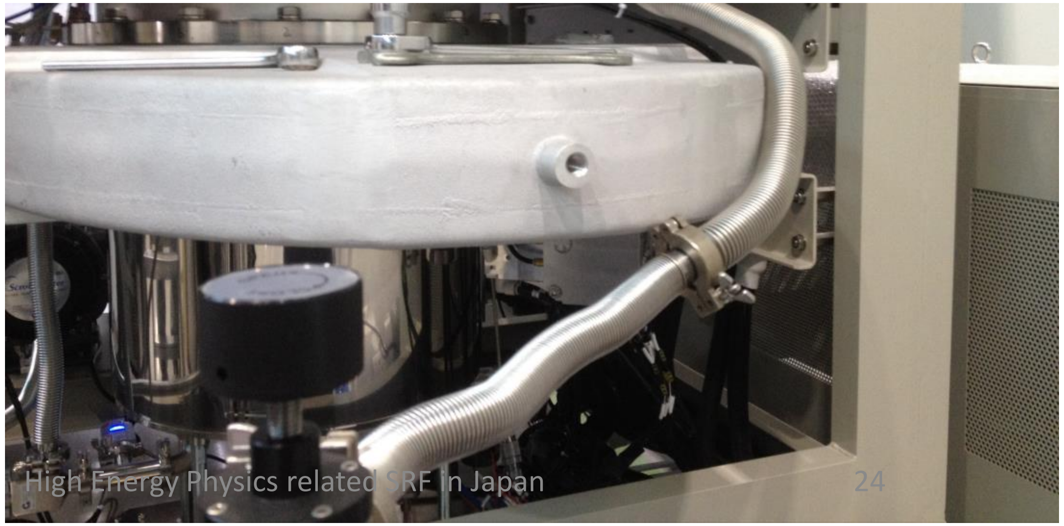
N-infusion can improve acceleration gradient.

KEK furnace

- Completed at the end of FY2017
- Cryopump for main pump, oil-free pumping system.
- Molybdenum is used for heater, reflector, table etc.
- TMP is used during N-injection, can reach ~2e-5Pa.
- Clean-booth surround entrance door.

Clean furnace is important equipment.

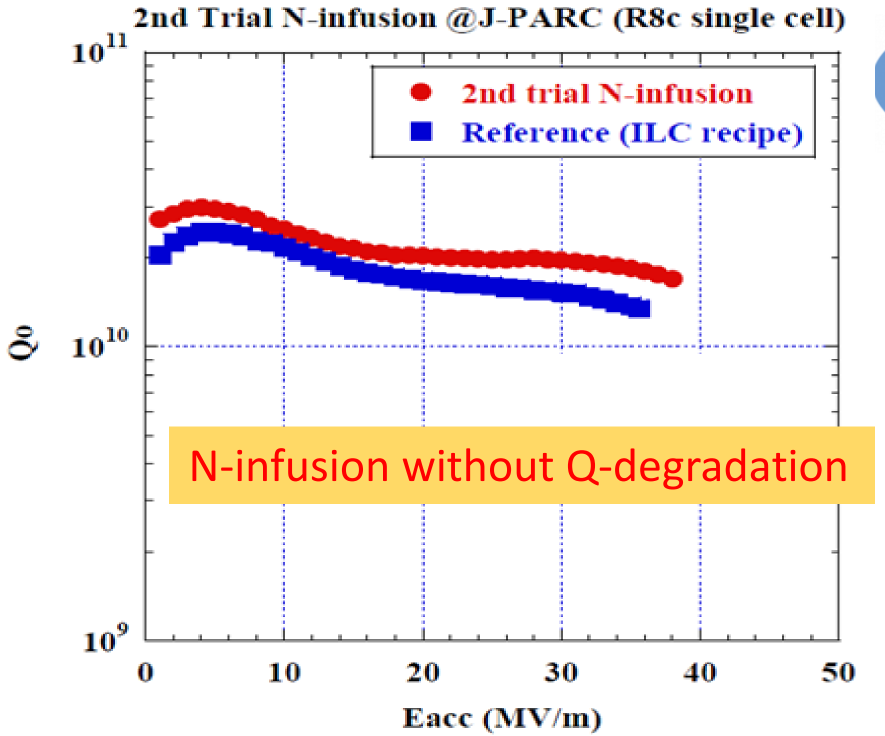


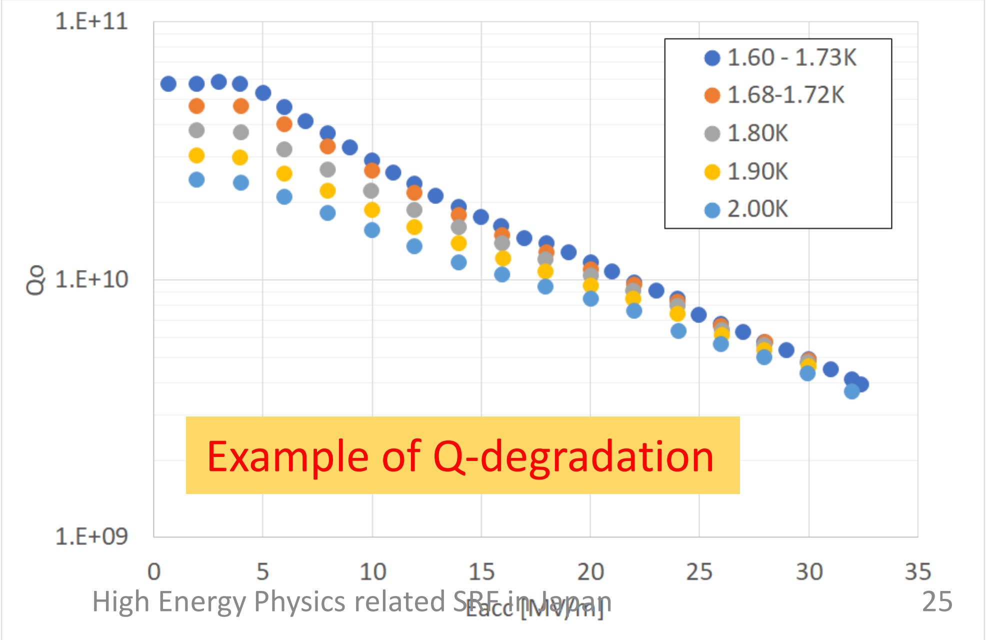


N-infusion results

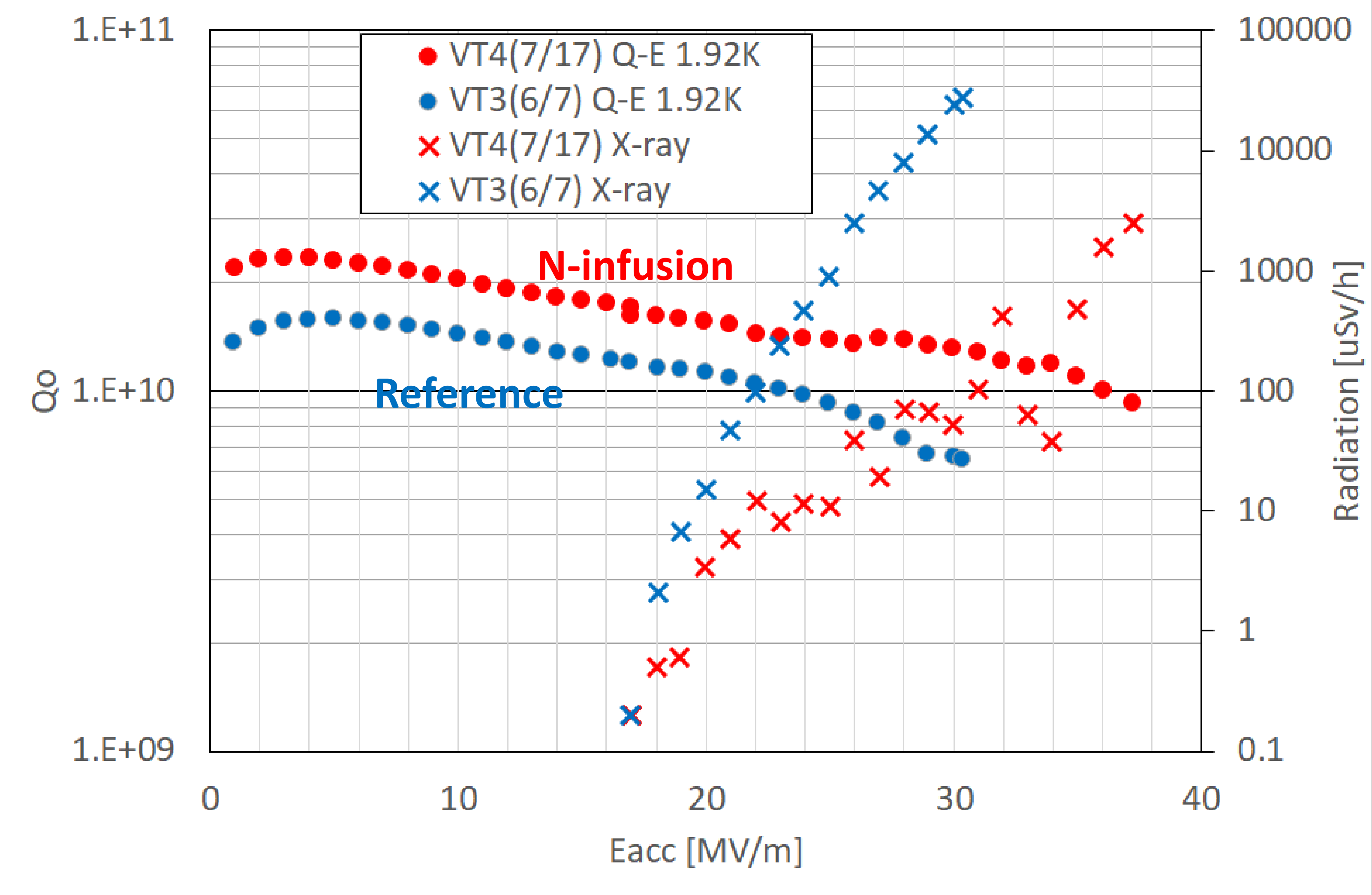
#	Day (N-inf / VT)	Cavity name	# of cell	Nb	Treatment	Results	Eacc (MV/m)	Comment
1	2018/Jun	R-6	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	35	
2	2018/Jun, Jul	R-9b	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	26	Defect limited
3	2018/Jun, Jul	R-10	3	LG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	27	F.E. limited
Summer shutdown								
4	2018/Sep, Oct	R-2	1	FG	800C, 3h + 160C, 48h, 3.3Pa N2	Q-degradation	19	No defects found
5	2018/Oct	R-6	1	FG	800C, 3h + 120C, 48h (without N2)	Q-degradation	32	
Apply dedicated burning run after this period								
6	2018/Nov, Dec	R-8	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Better Q than reference	36	
Improve cooling of cryo-pump by adding cooling-water type shielding plate								
7	2018/Dec 2019/Jan	R-9b	1	FG	800C, 3h + 800C, 2h + 160C, 48h, 3.3Pa N2	Q-degradation	24	Defect limited
8	2019/Jan, Feb	AES18	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	No Q-degradation	38	
Modify N2 injection line								
9	2019/Apr	R-4	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	Q-degradation	39	
10	2019/May	AES18	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	Q-degradation	31	
Remove cooling-water type shielding plate due to water leak trouble								
11	2019/Jun, Jul	MHI31	9	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Better Q than reference	37	
12	2019/Sep	R-4	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Q-degradation	36	

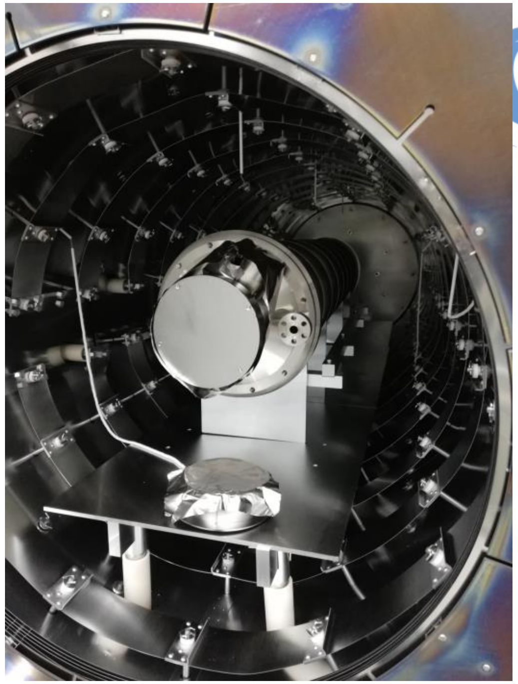
- Half of N-infusion at KEK / J-PARC showed Q-degradation due to the furnace contamination.
- Some successful results showed improvement of Q-values, which is caused by lower R_res.
- No cavity showed improvement of accelerating gradient.





N-infusion results for 9-cell cavity





- **Max Eacc = 37MV/m**
- **Magnetic field inside VT dewar was not controlled for 9-cell cavities.**
- **This cavity was installed to STF-2 CM, waiting beam operation.**

※ **Eacc for reference measurement was limited by F.E.**

2-step (75C + 120C) baking

2-step baking (75 C + 120 C)

A. Grassellino et al.,「Accelerating fields up to 49 MV/m in TESLA-shape superconducting RF niobium cavities via 75C vacuum bake」

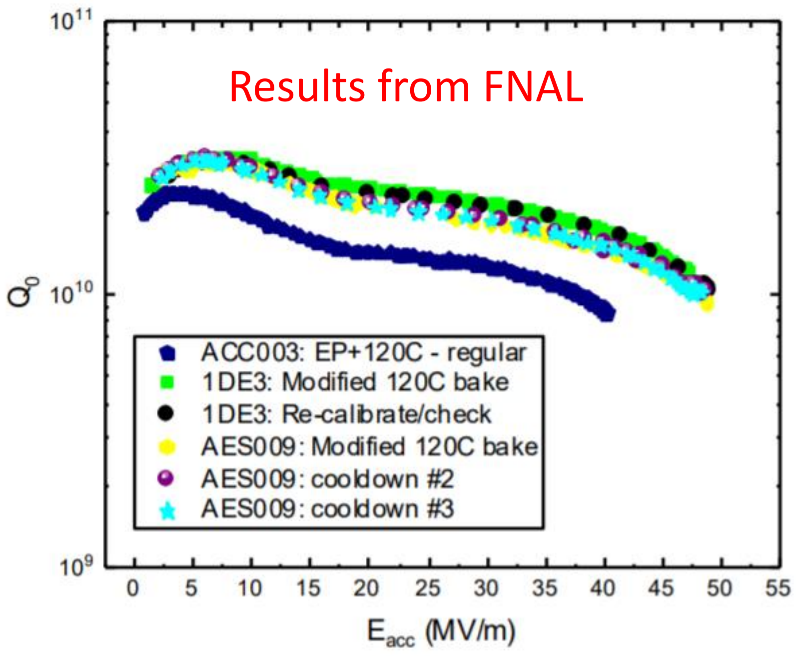
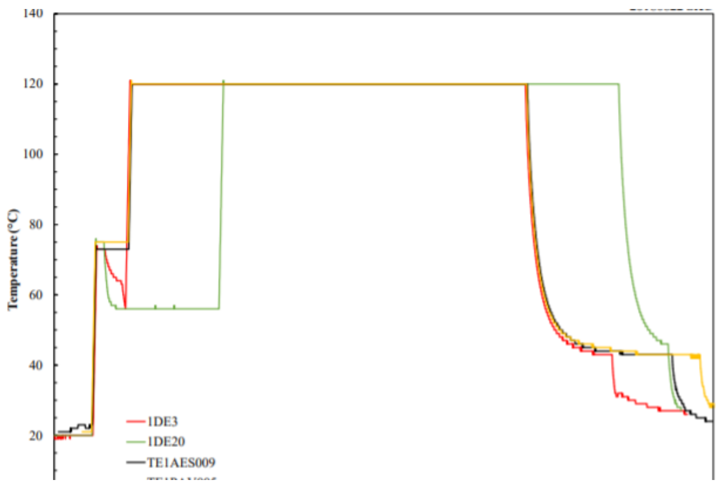
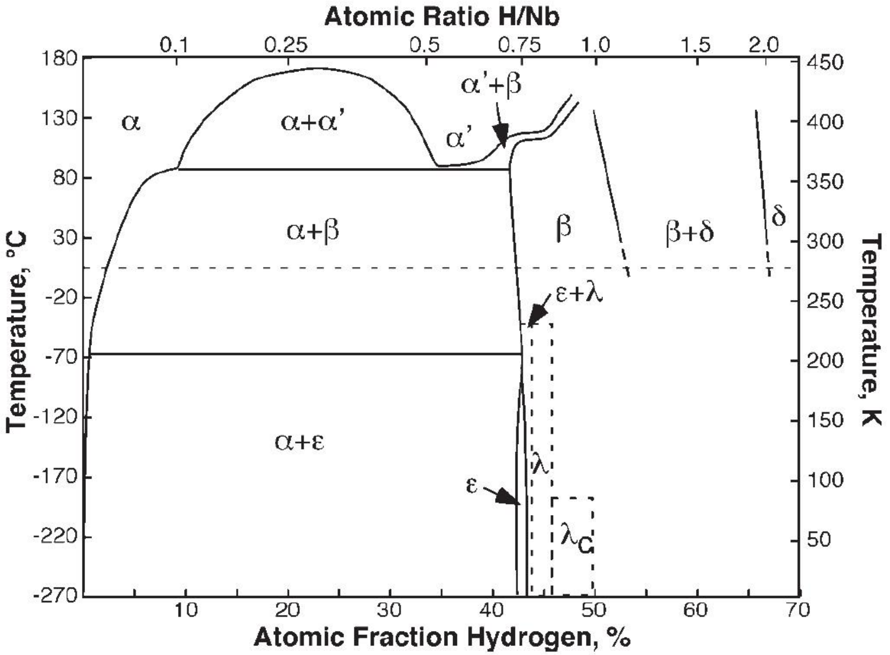


Figure 3: Comparison of 1DE3 for regular 120°C bake and for 75°C+120°C bake.

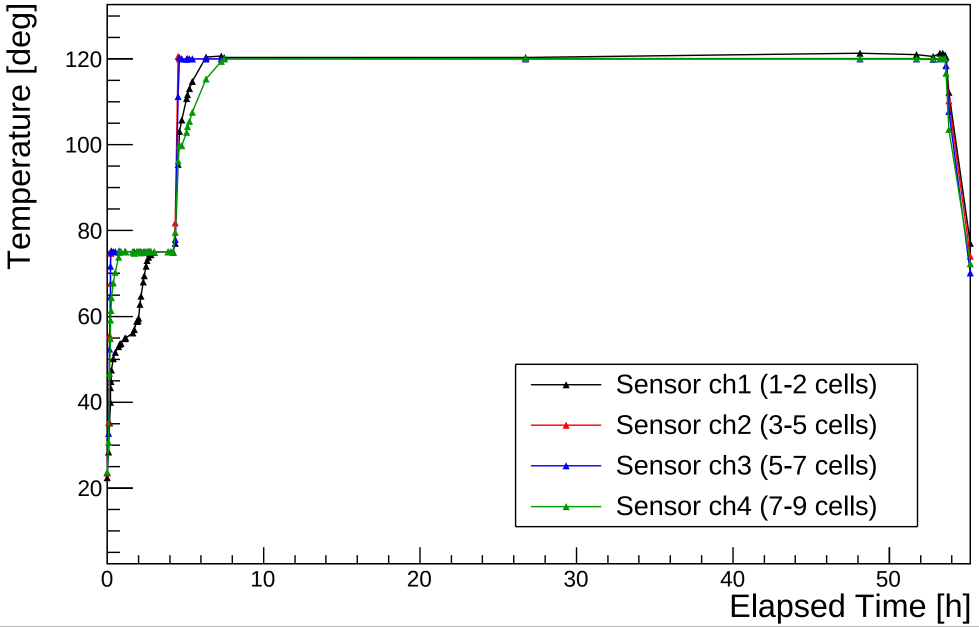




2-step baking was proposed by FNAL, which can improve Eacc up to 49 MV/m.

Manchester F D and Pitre J M 2000 *Phase Diagrams of Binary Hydrogen Alloys* ed F D Manchester (Materials Park, OH: ASM International) pp 115–37

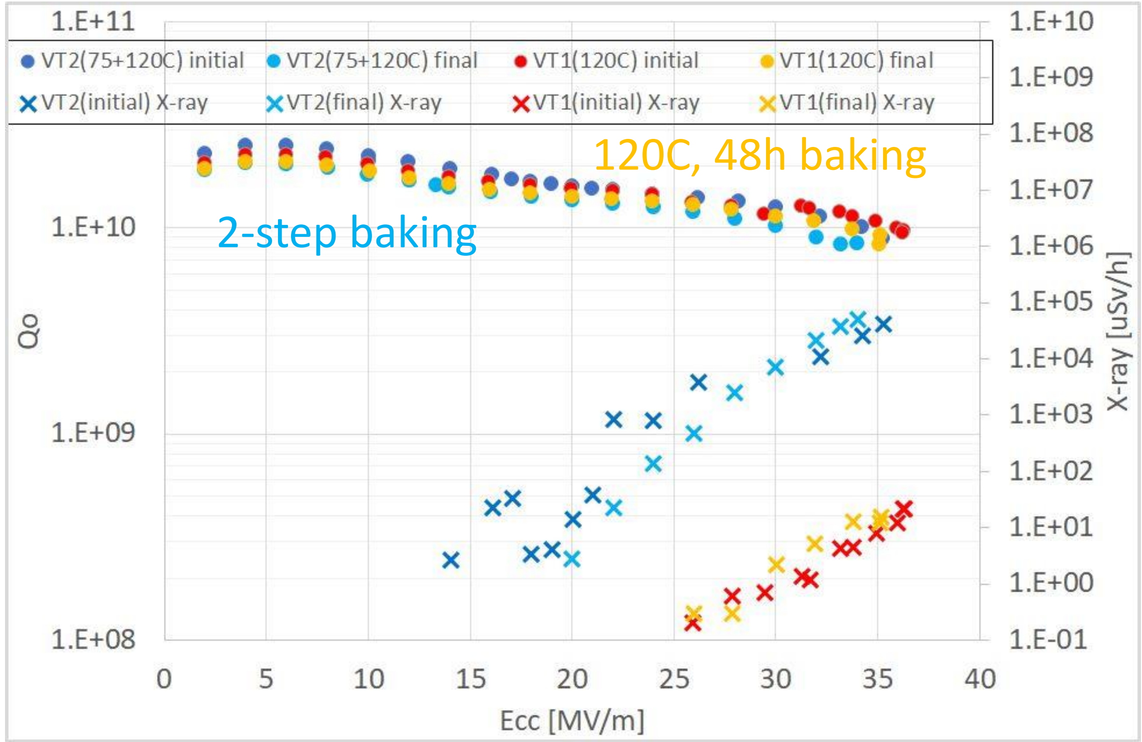
2-step baking trial for 9-cell cavities at KEK



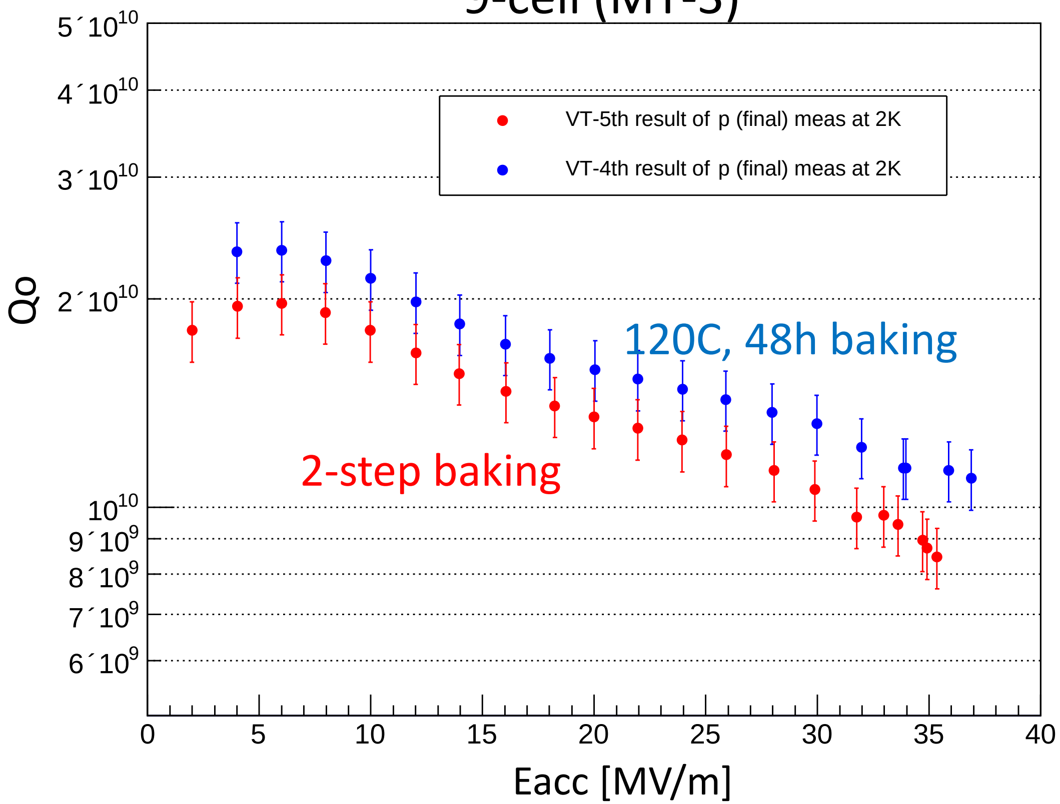
- 2-step (75C,4h + 120C,48h) baking was applied for 9-cell cavities at KEK.
- Cold EP (14 C) was applied for the cavities before 2-step baking.
- Cool down was done by filling He from dewar. (Not so fast cooling.)

2-step (75C + 120C) baking results on two 9-cell cavities

9-cell (MT-5)



9-cell (MT-3)



- VT results are very similar between 2-step baking and 120C baking.
- No improvement on gradient was observed, including pass-band analysis.

N-doping

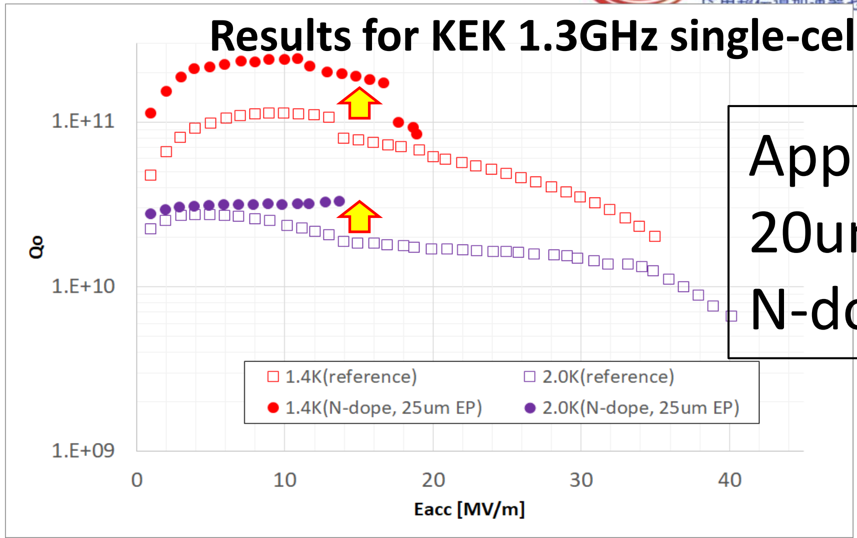
N-doping (Nitrogen-doping)

During high temperature heat treatment, ~Pa of N2 is fed into the furnace for a few to a few 10 min.

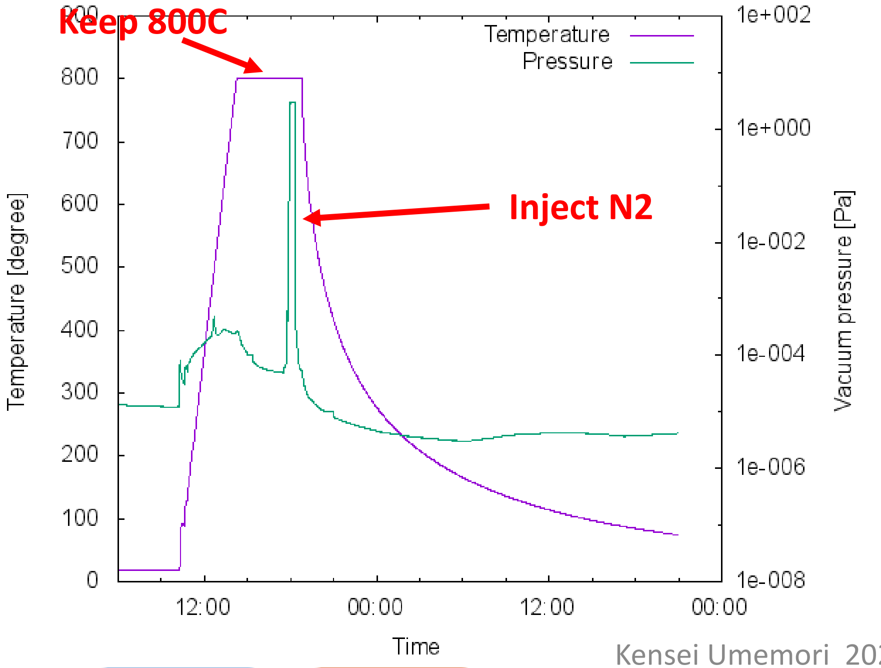
Nitrogen goes into depth of several 10 um.

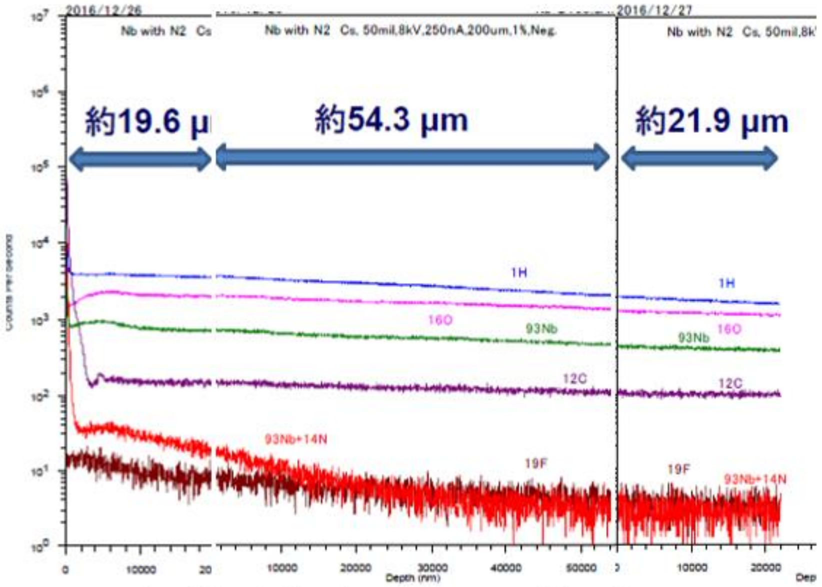
Achieve high-Q

But Eacc decrease



Apply several ~ 20um EP after N-doping





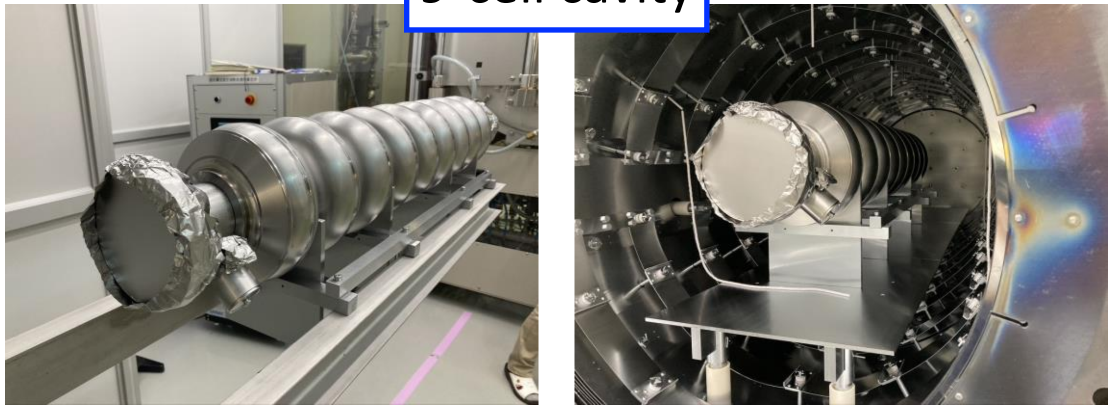
Furnace with diffusion pump did not work.
Furnace with cryopump work well.

"2/0" N-doping at KEK

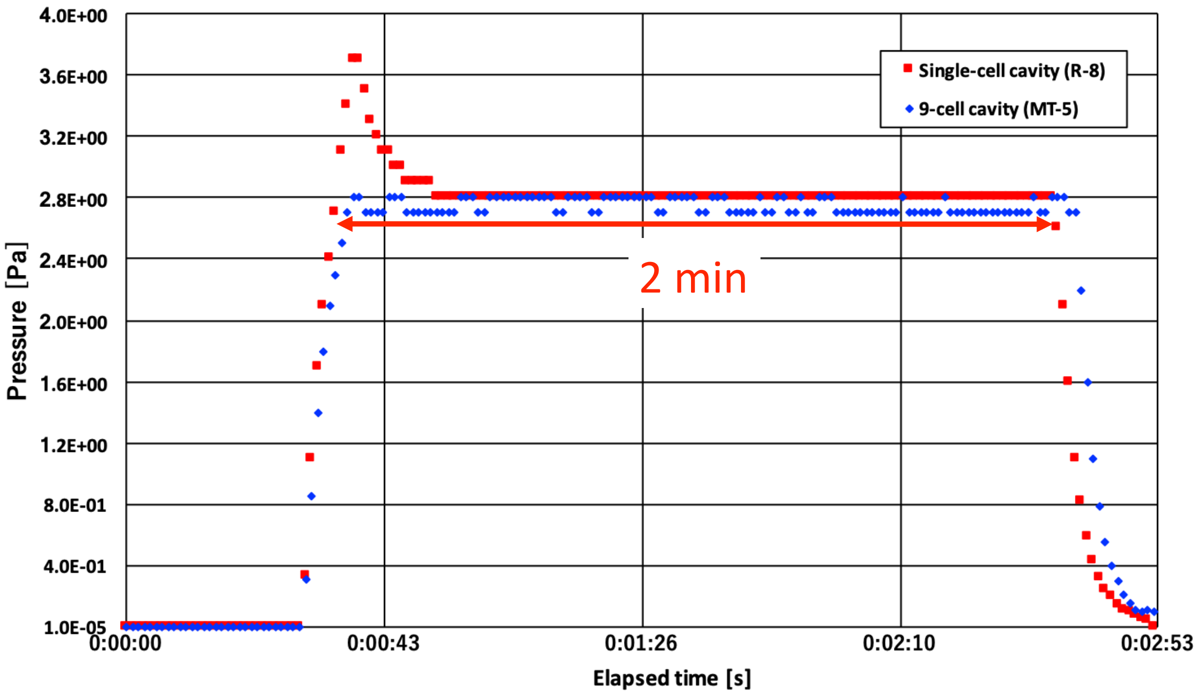
- 2 min 3.3 Pa of N_2 at 800 C + 5 μm cold EP

Single-cell cavity

9-cell cavity



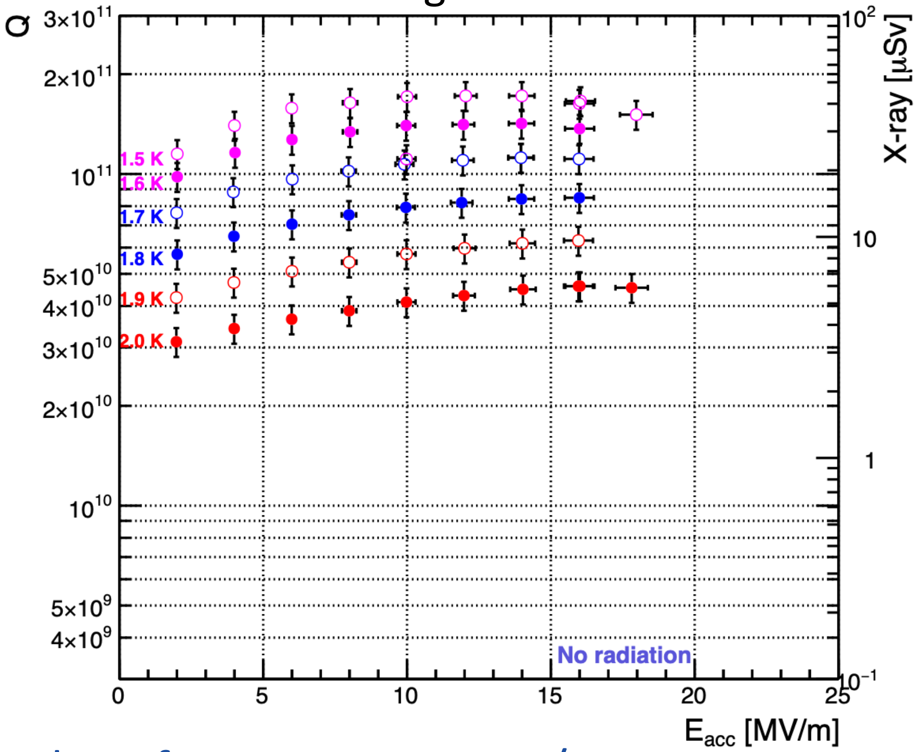
"2/0" N-doping was performed to one single-cell cavity and one 9-cell cavity.



*Monitored pressure was slightly different from the set pressure of 3.3 Pa due to differences in the position of the pressure gauges.

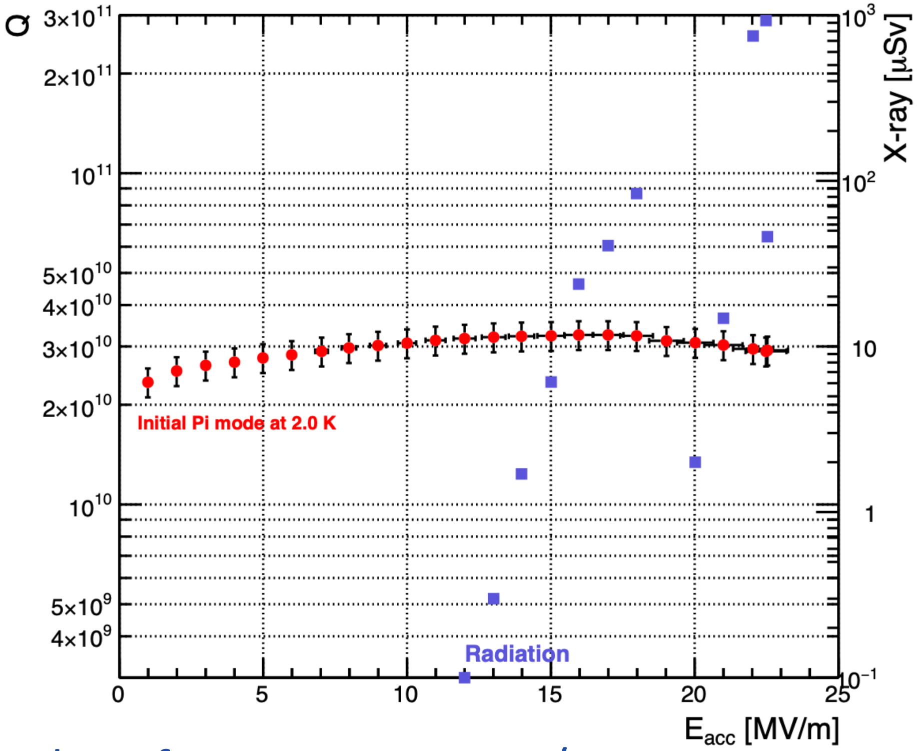
VT result of “2/0” N-doped cavities

Single-cell



- Q value of 4.6E+10 at 16 MV/m.
- Quench at 18 MV/m (heating at Not the equator)

9-cell

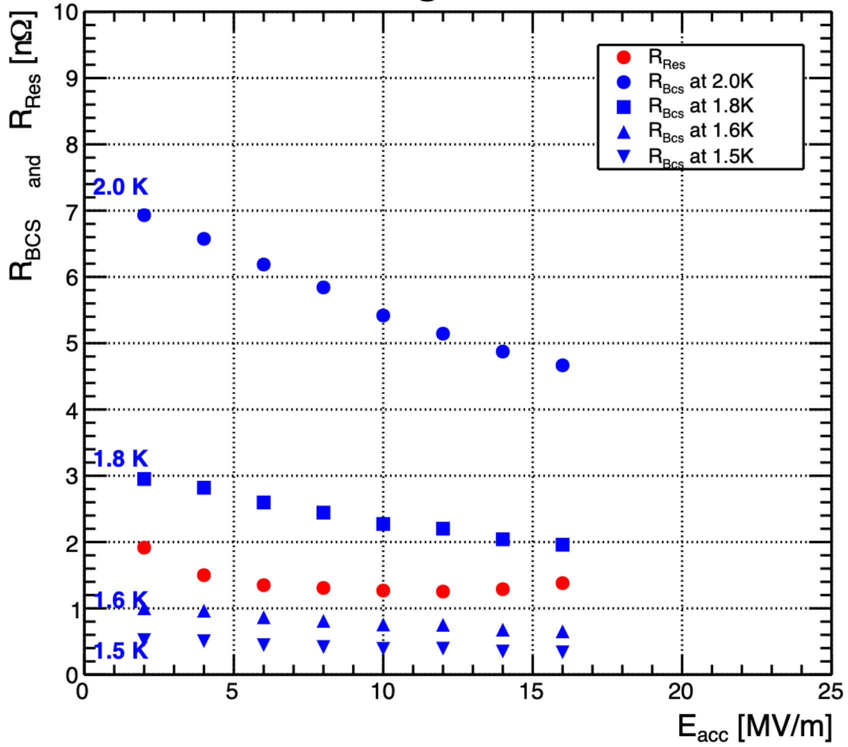


- Q value of 3.3E+10 at 16 MV/m.
- Quench at 22 MV/m (heating at cell-6 equator)

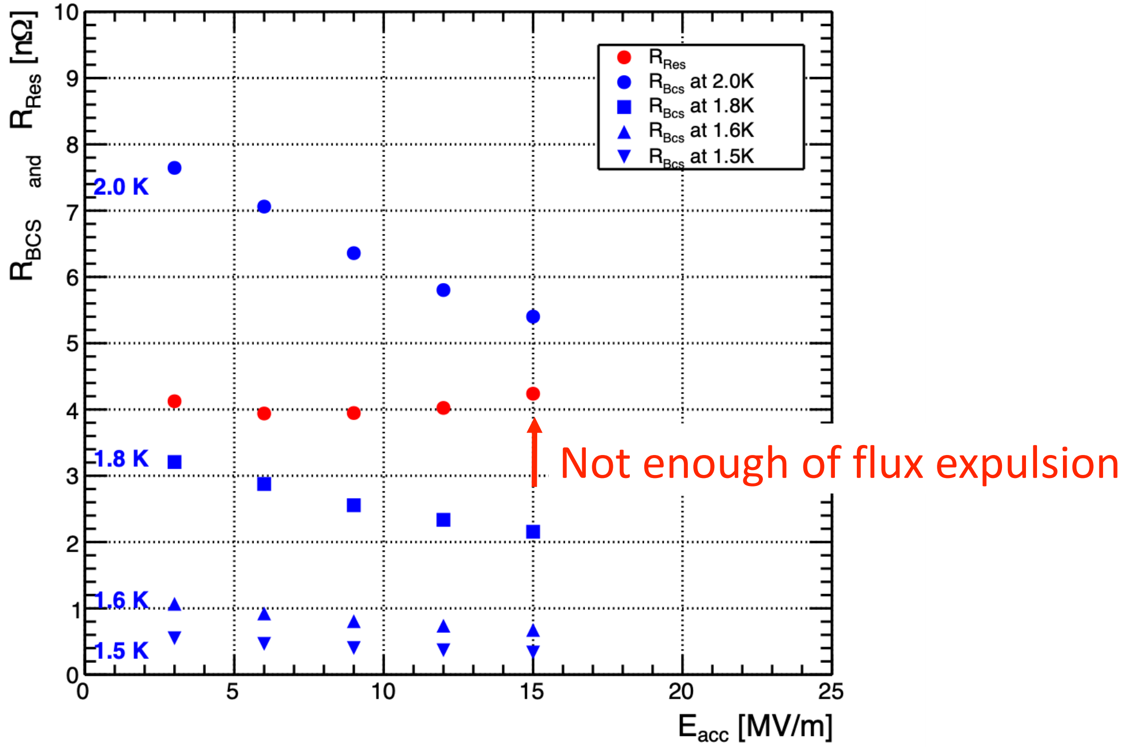
	Cells 1&9	Cells 2&8	Cells 3&7	Cells 4&6	Cell 5
Eacc,max [Mv/m]	26.55	28.04	22.68	22.50	28.04
Heating	cell-9 upper iris	cell-2 equator	cell-7 upper iris	cell-6 equator	

comparison of R_{BCS} and R_{Res}

Single-cell



9-cell



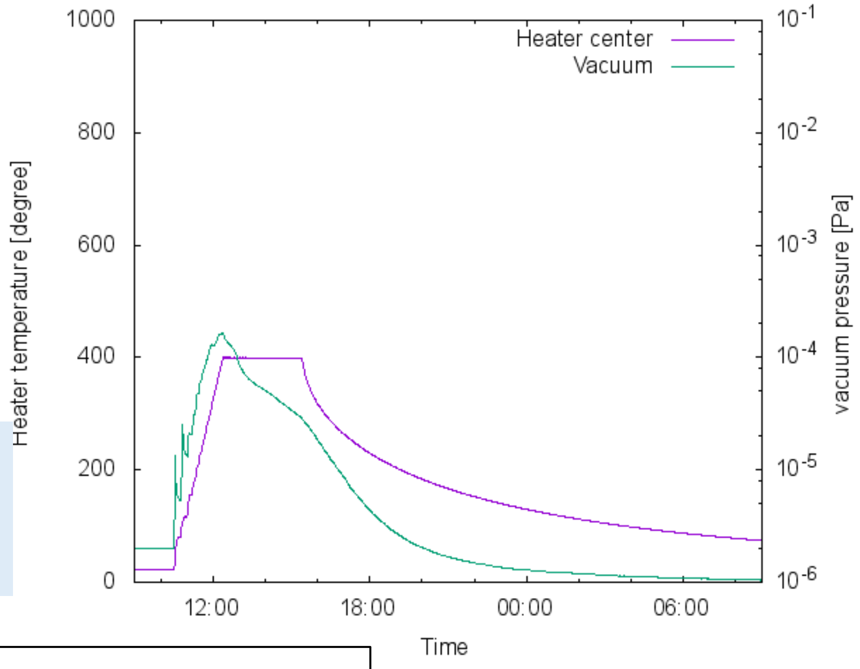
R_{BCS} has similar behavior on both cavities.

*For the single-cell cavity, demagnetization was performed using a coil and cooling was performed with a temperature gradient using a heater, so that the flux expulsion is sufficient, while that for the 9-cell cavity was not sufficient because of cooling without a coil or a heater.

Mid-T furnace baking

Medium-T furnace baking

Mid-T baking change oxide components on Nb surface



R-8 cavity (single cell)

- N-infusion at KEK furnace
- HPR, Assembly
- VT
- Disassembly

↓

- HPR
- **Heat treatment (400C, 3h) at KEK furnace**
- HPR, Assembly(No baking)
- **VT**

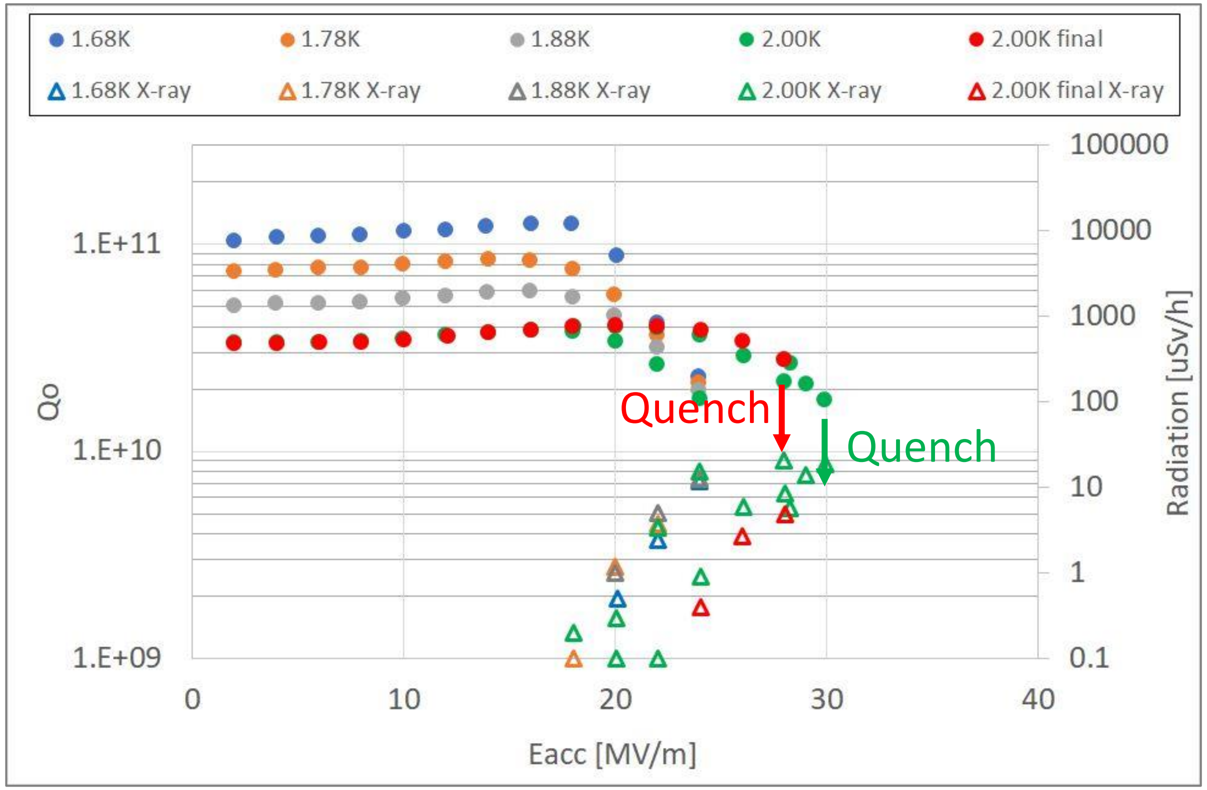
R-4 cavity (single cell)

- Refresh cold EP(10um)

↓

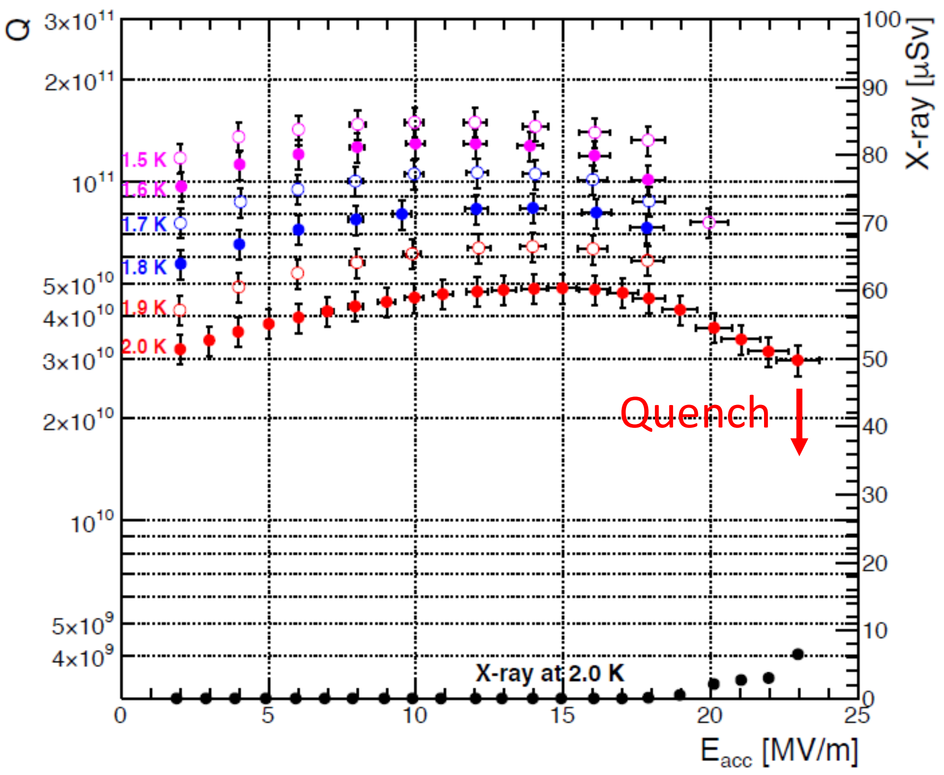
- HPR
- **Heat treatment (300C, 3h) at KEK furnace**
- HPR, Assembly(No baking)
- **VT**

R-8 cavity (400 C)



- high-Q (> 3e10) with slight anti-Q slope.
- Qo ～ 4e10 (@20MV/m, 2.0K)
- No HFQS(high field Q-slope) was observed up to 30 MV/m.
- Quench field was 30 MV/m

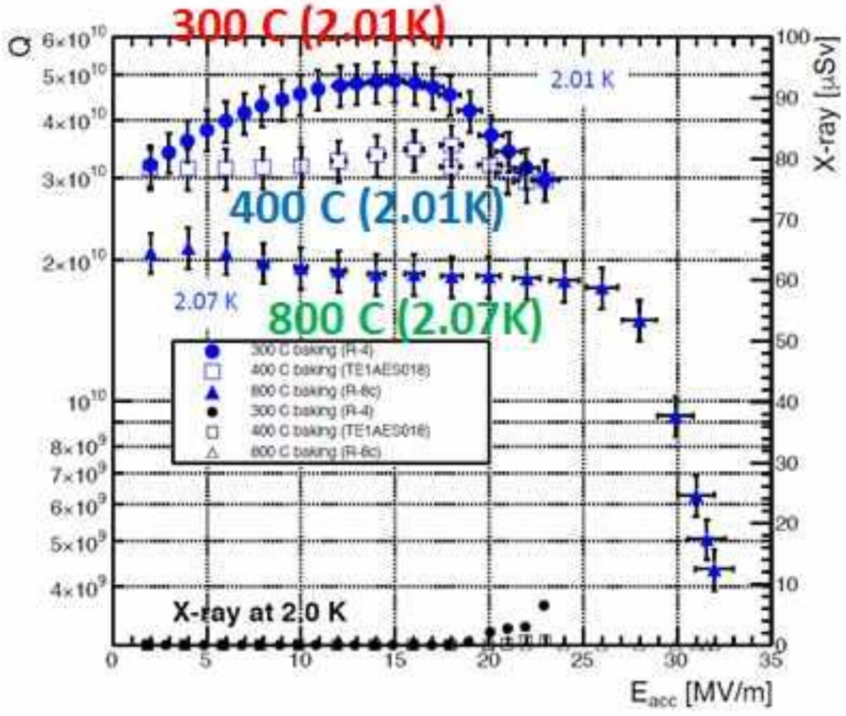
R-4 cavity (300 C)



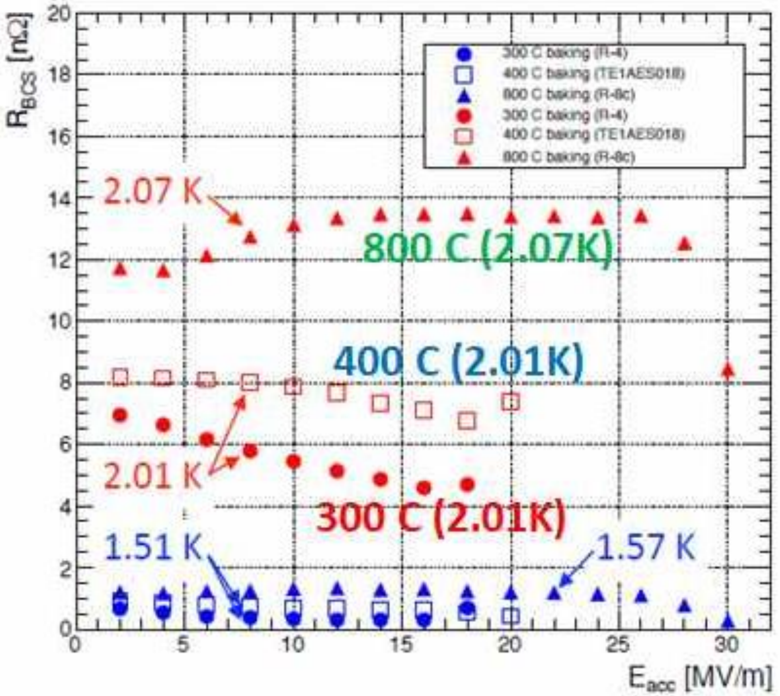
- high-Q (> 3e10) with anti-Q slope.
- Qo ～ 5e10 (@15MV/m, 2.0K)
- No HFQS(high field Q-slope) was observed up to 23 MV/m.
- Quench field was 23 MV/m

Comparison with different temperature for the furnace baking

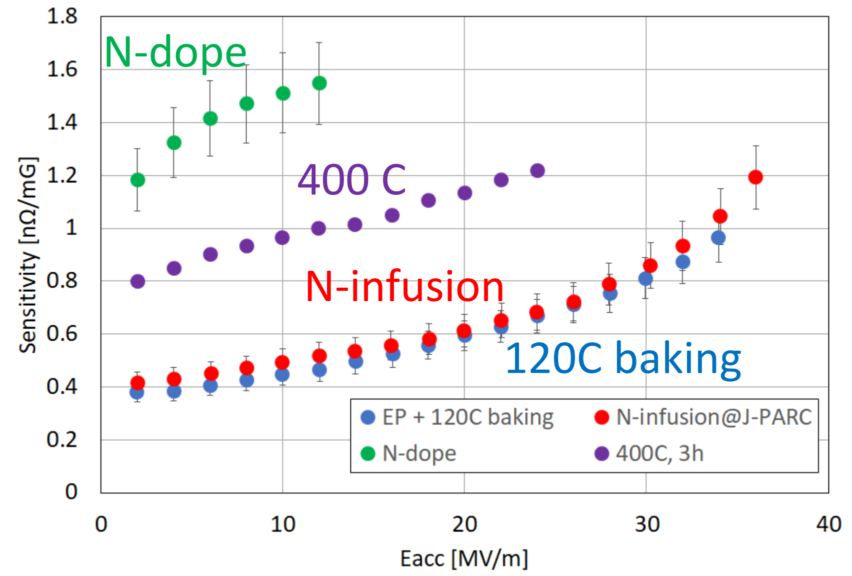
Q-E @ 2.0 – 2.1K



BCS resistance vs Eacc



Sensitivity, Rres/Btrap

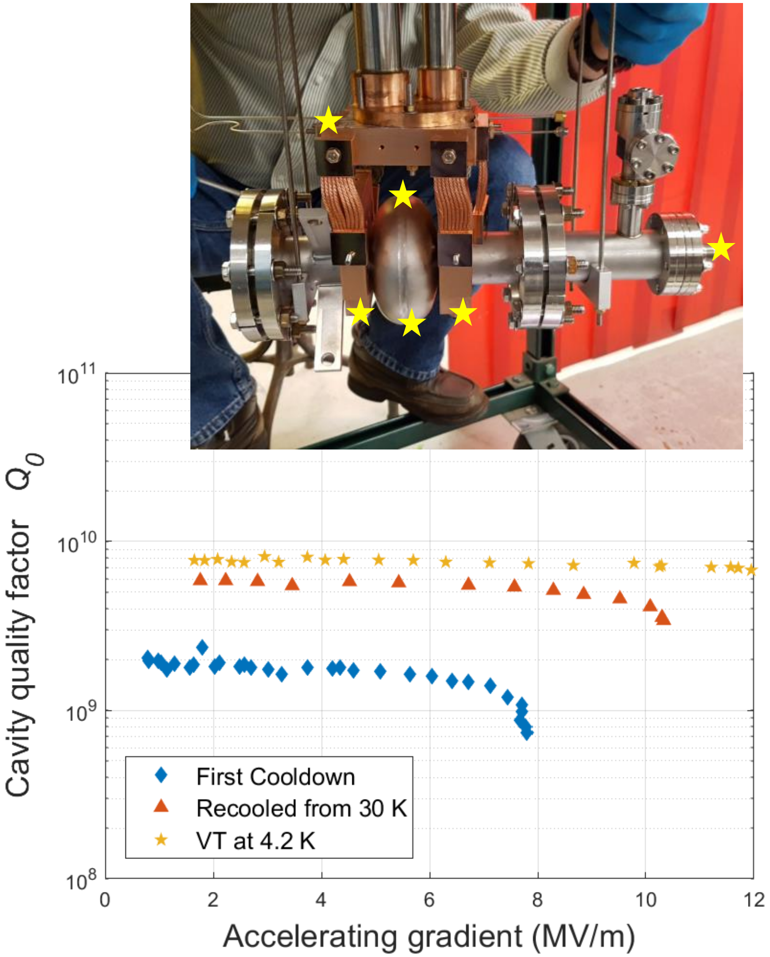


- Mid-T furnace baking shows high-Q performance of SRF cavities.
- Performance of 300C furnace baked cavity is very similar to N-doped cavity.
- Mid-T baking is one way to achieve high-Q performance, without N2.

Development for Nb3Sn cavity

Nb3Sn cavity development

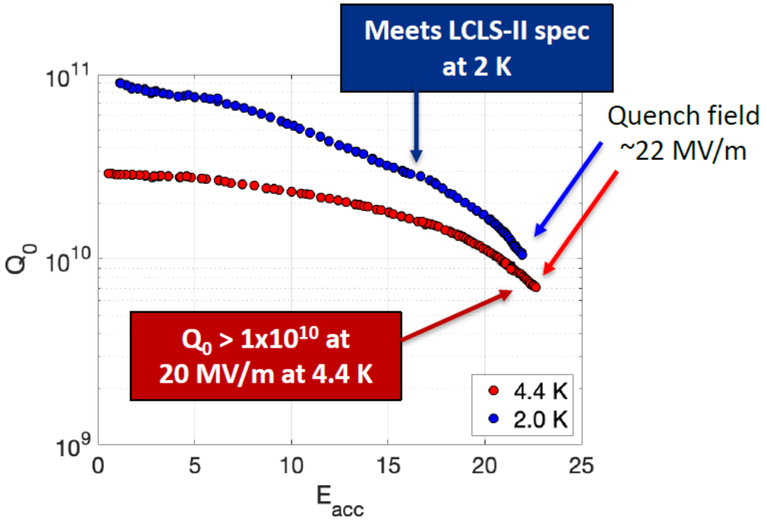
10MV/m operation by cryo-cooler



R. Portar (TTC@CERN)

※ FNAL, JLAB also did successful operation by cryo-cooler

> 20MV/m performance of Nb3Sn cavity

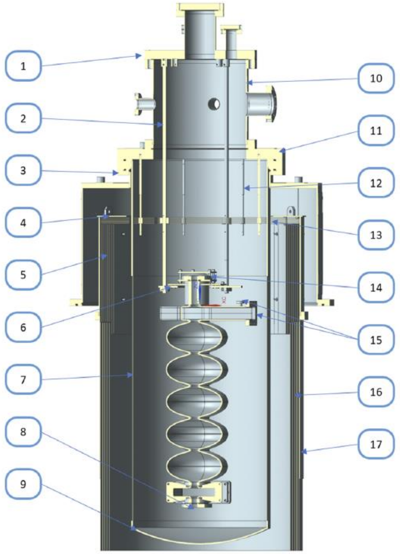


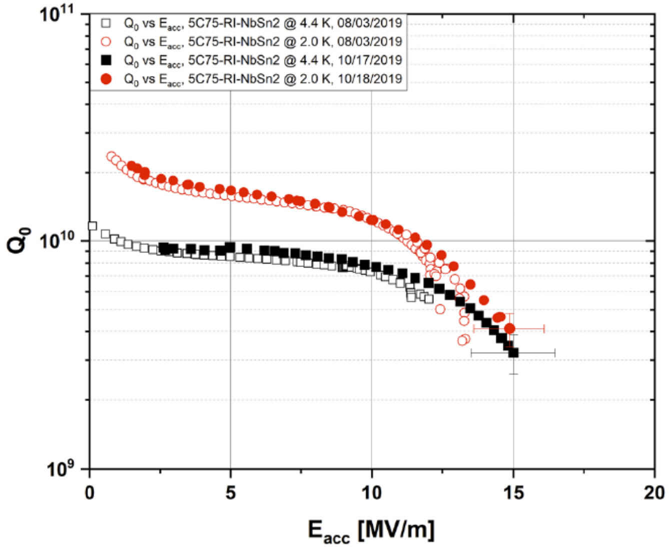
World record CW gradient for Nb_3Sn accelerator cavities!

Fermilab

S. Posen (TTC@CERN)

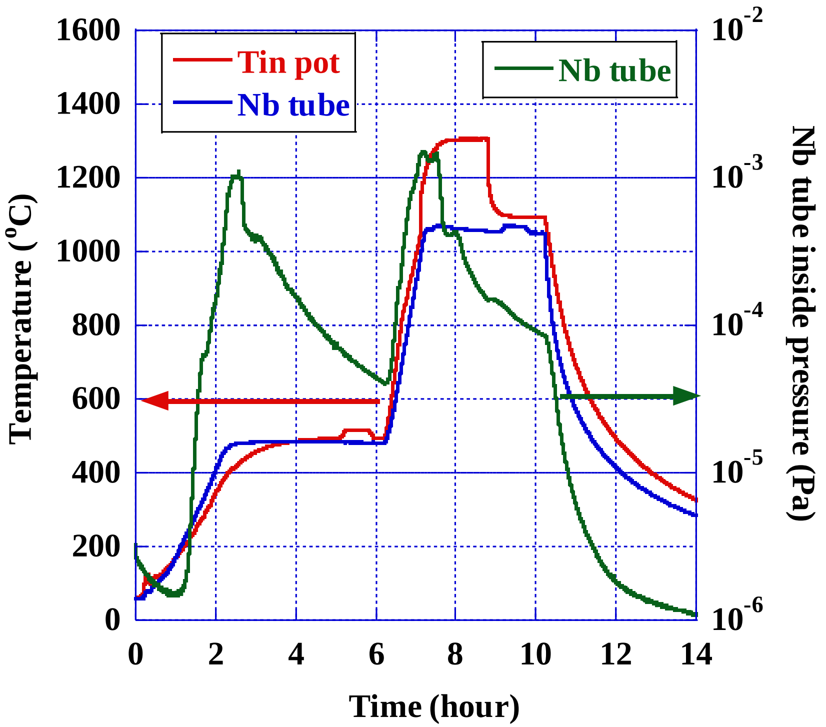
Nb3Sn multi-cell (5-cell) cavity

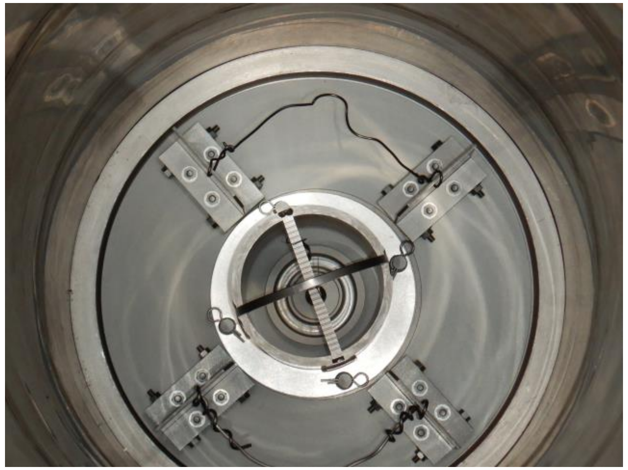




G. Eremeev et al., Rev. Sci. Instrum. 91, 073911 (2020)

Nb3Sn cavity R&D at KEK





- Nb3Sn furnace was constructed at KEK.
- First trial for Nb3Sn coating on Nb films was just carried out.
- We will try to coat Nb3Sn on single-cell Nb cavity soon.
- We will develop Nb3Sn cryomodule for the future.

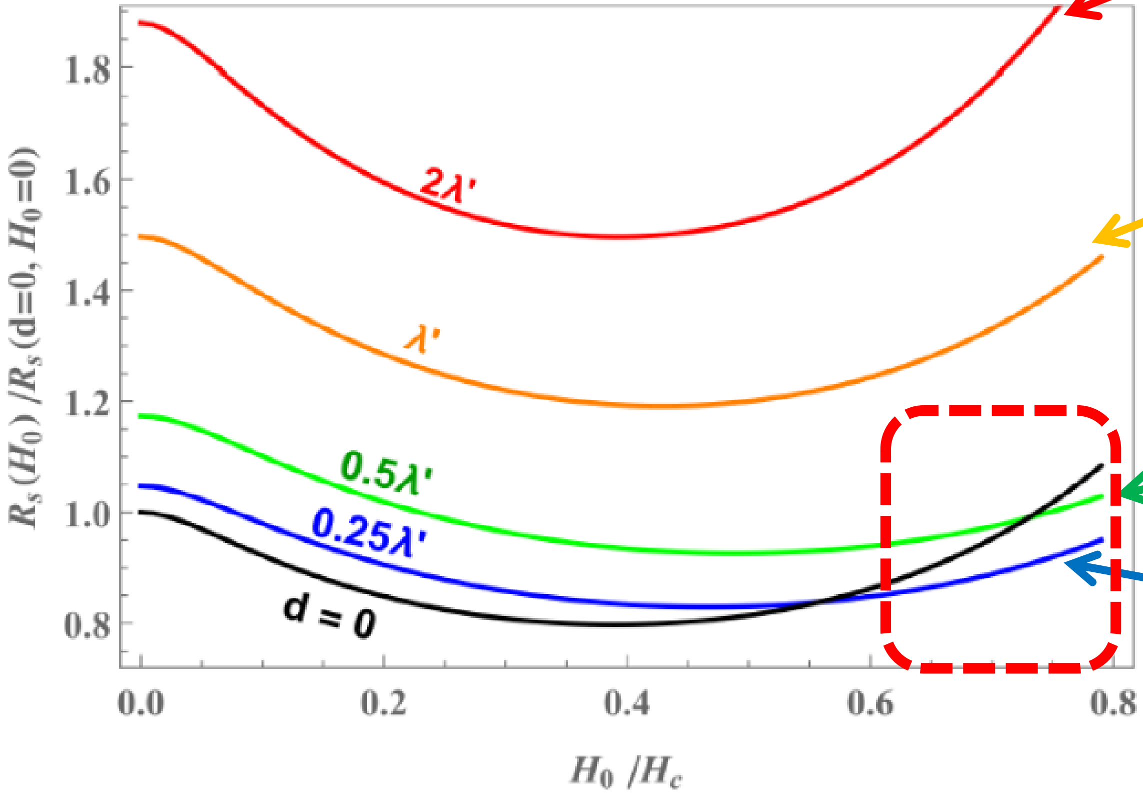
Nb3Sn should be next standard (at least) for CW SRF.

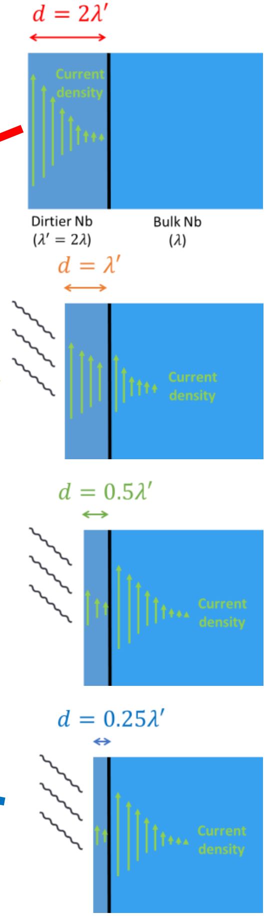
SRF cavity development beyond Nb/Nb3Sn

Layered structures: **Theoretical studies**

(1) A dirty layer mitigates the high-field Q slope

T. Kubo and A. Gurevich, Phys. Rev. B **100**, 064522 (2019)
(See also the presentation at SRF2019)

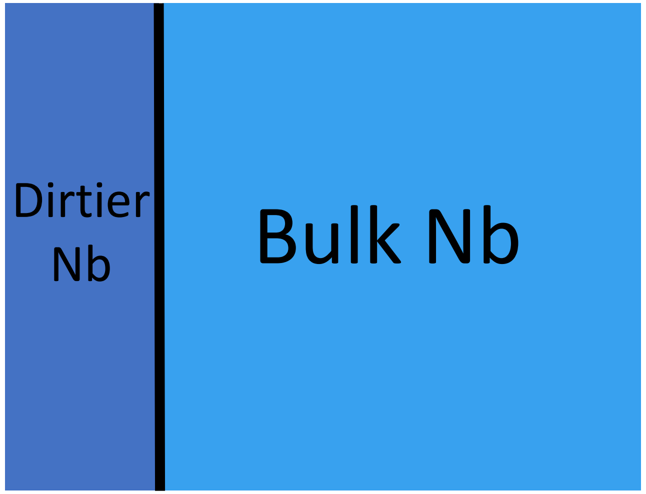


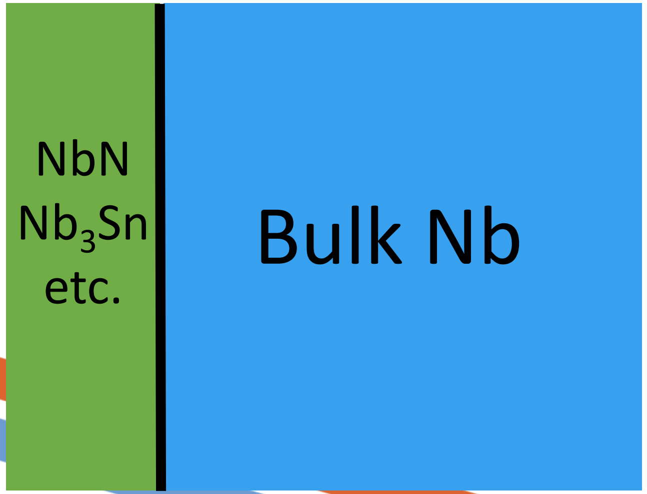


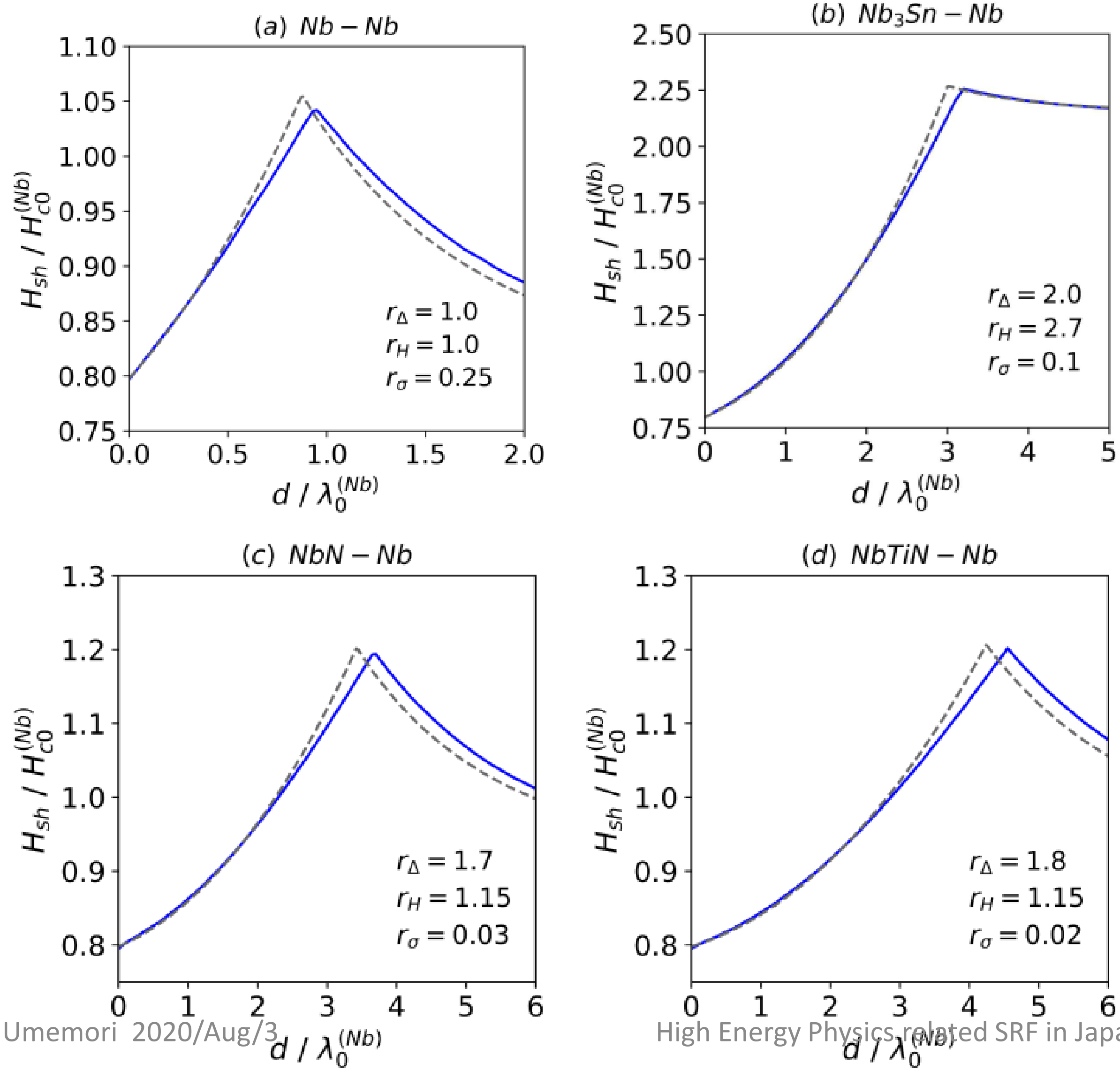
According to the BCS theory, appropriate thicknesses of the dirty layer can cure the Q drop!

Layered structures: **Theoretical studies**

(2) Enhance the theoretical field-limit

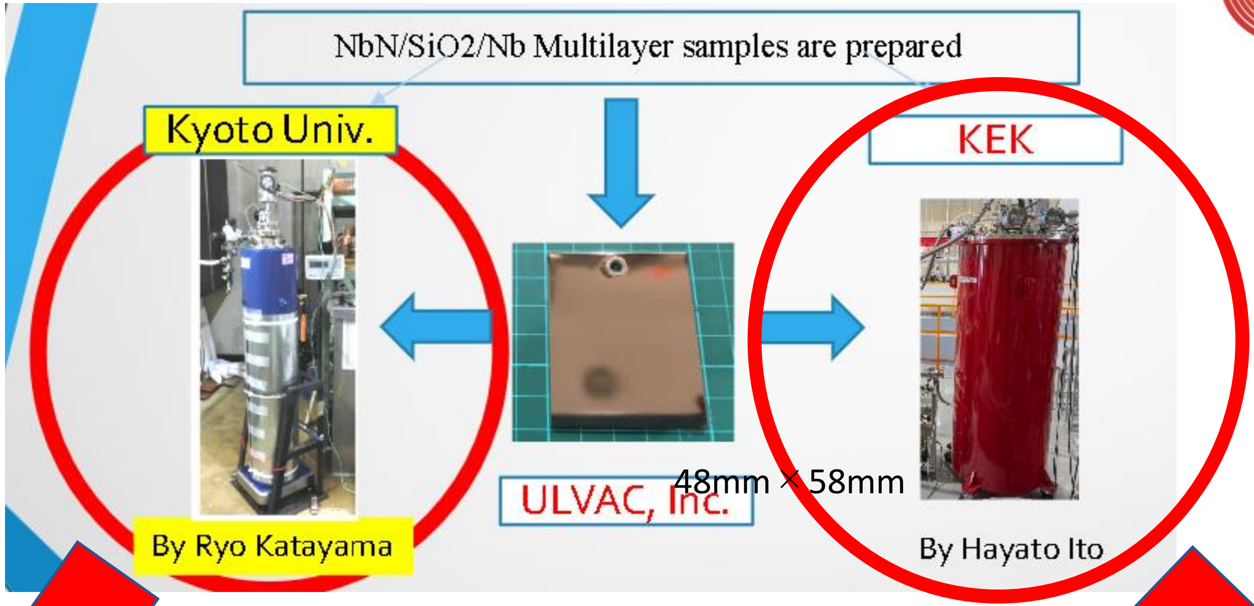




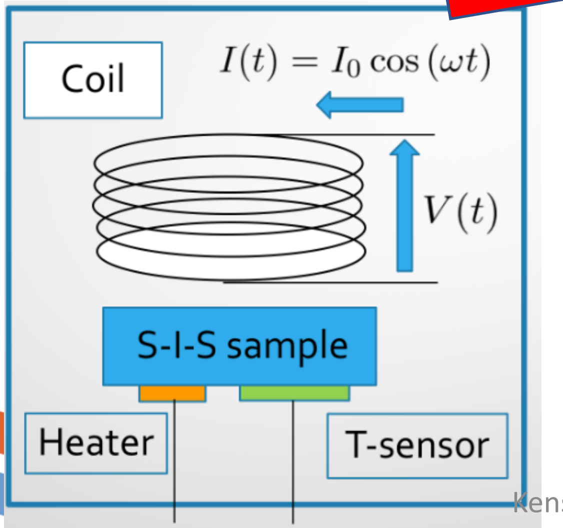


- A. Gurevich, Appl. Phys. Lett. **88**, 012511 (2006).
- T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. **104**, 032603 (2014).
- A. Gurevich, AIP Adv. **5**, 017112 (2015).
- S. Posen et al., Phys. Rev. Applied **4**, 044019 (2015).
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017).
- V. Ngampruetikorn and J. A. Sauls, Phys. Rev. Research **1**, 012015 (2019).
- T. Kubo, arXiv:2006.12003

Layered structures: Sample experiments

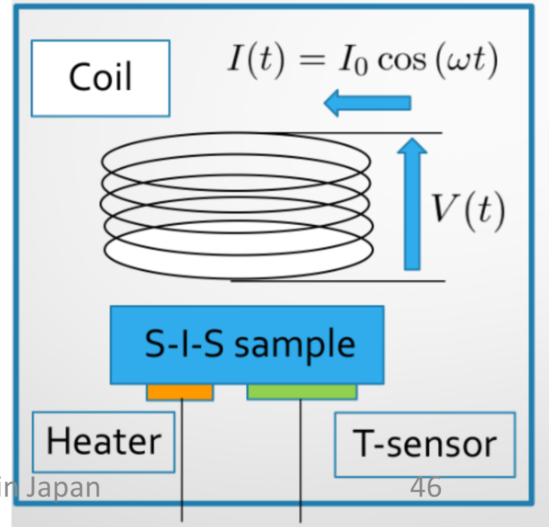


@Kyoto



Independently start up two experimental devices

@KEK

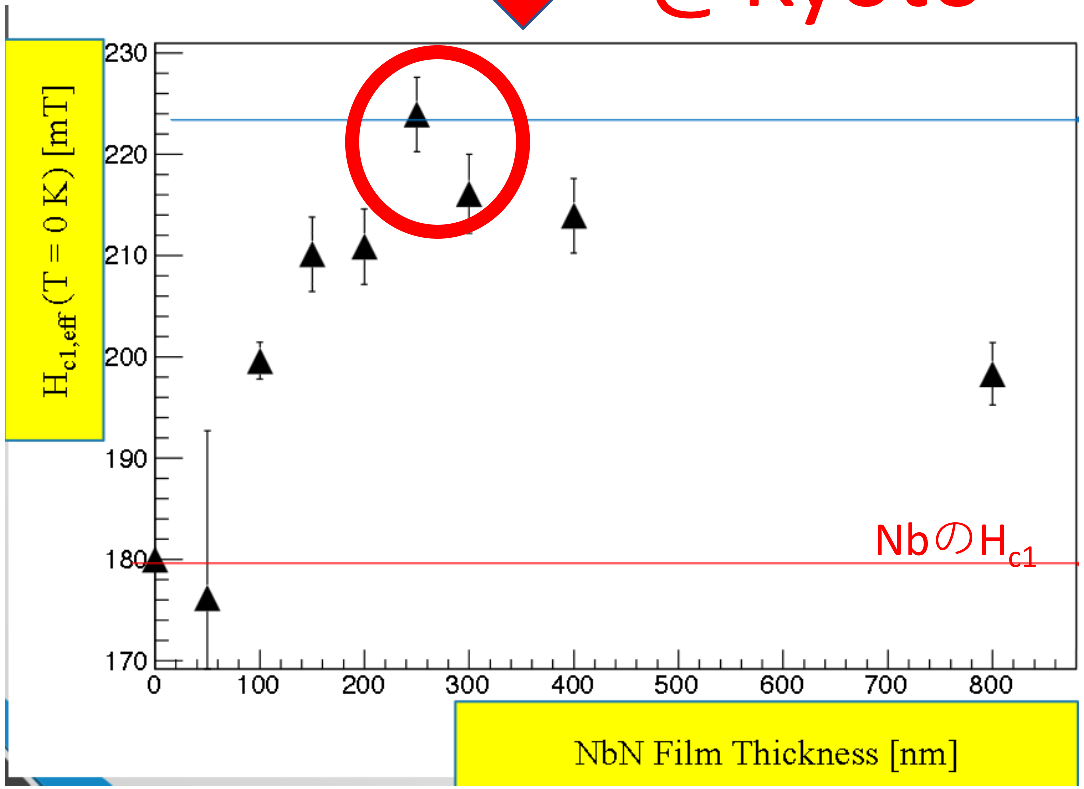


Apply the magnetic field to NbN-I-Nb samples and measure the field of vortex penetration.

R. Katayama, H. Hayano, T. Kubo, T. Saeki, C.Z. Antoine, H. Ito, R. Ito, Y. Iwashita, H. Tongu, and T. Nagata, In proceedings of SRF2019, Dresden Germany (2019) , THFUA2.

Layered structu : Sample experiments

@Kyoto



R. Katayama, H. Hayano, T. Kubo, T. Saeki, C.Z. Antoine, H. Ito, R. Ito, Y. Iwashita, H. Tongu, and T. Nagata, In proceedings of SRF2019, Dresden Germany (2019), THFUA2.

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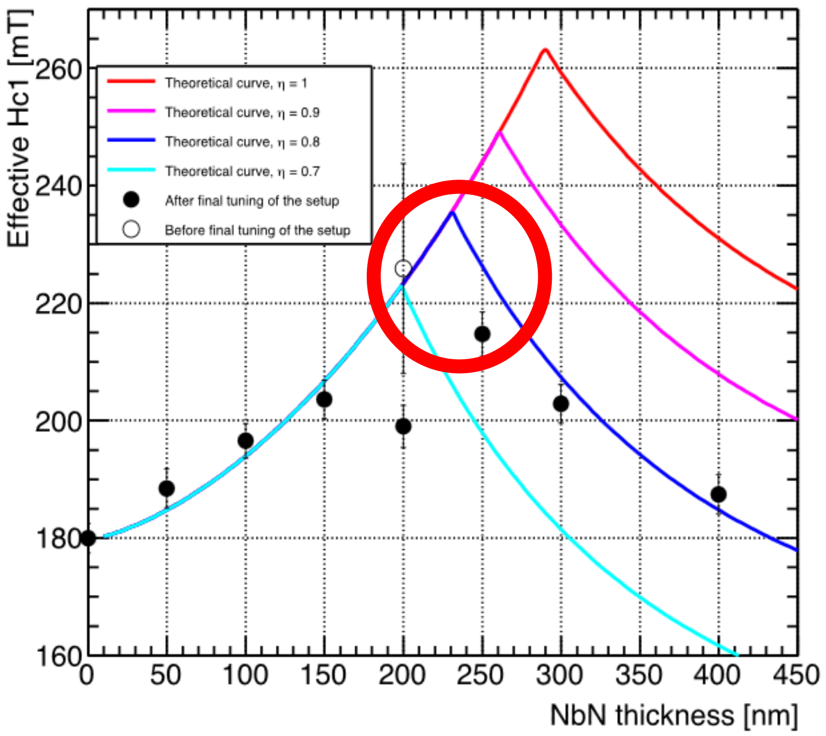
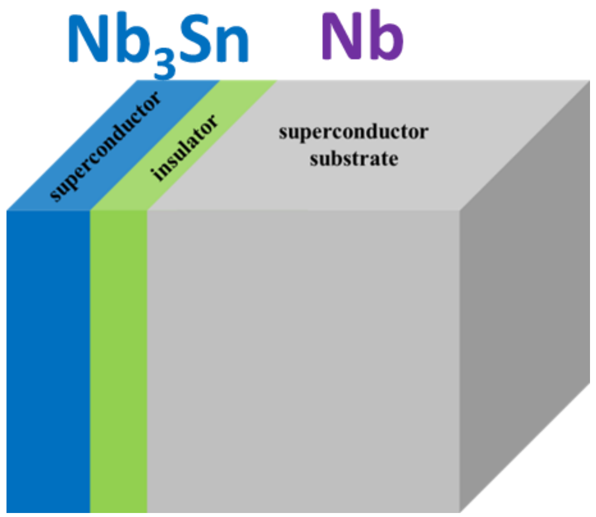


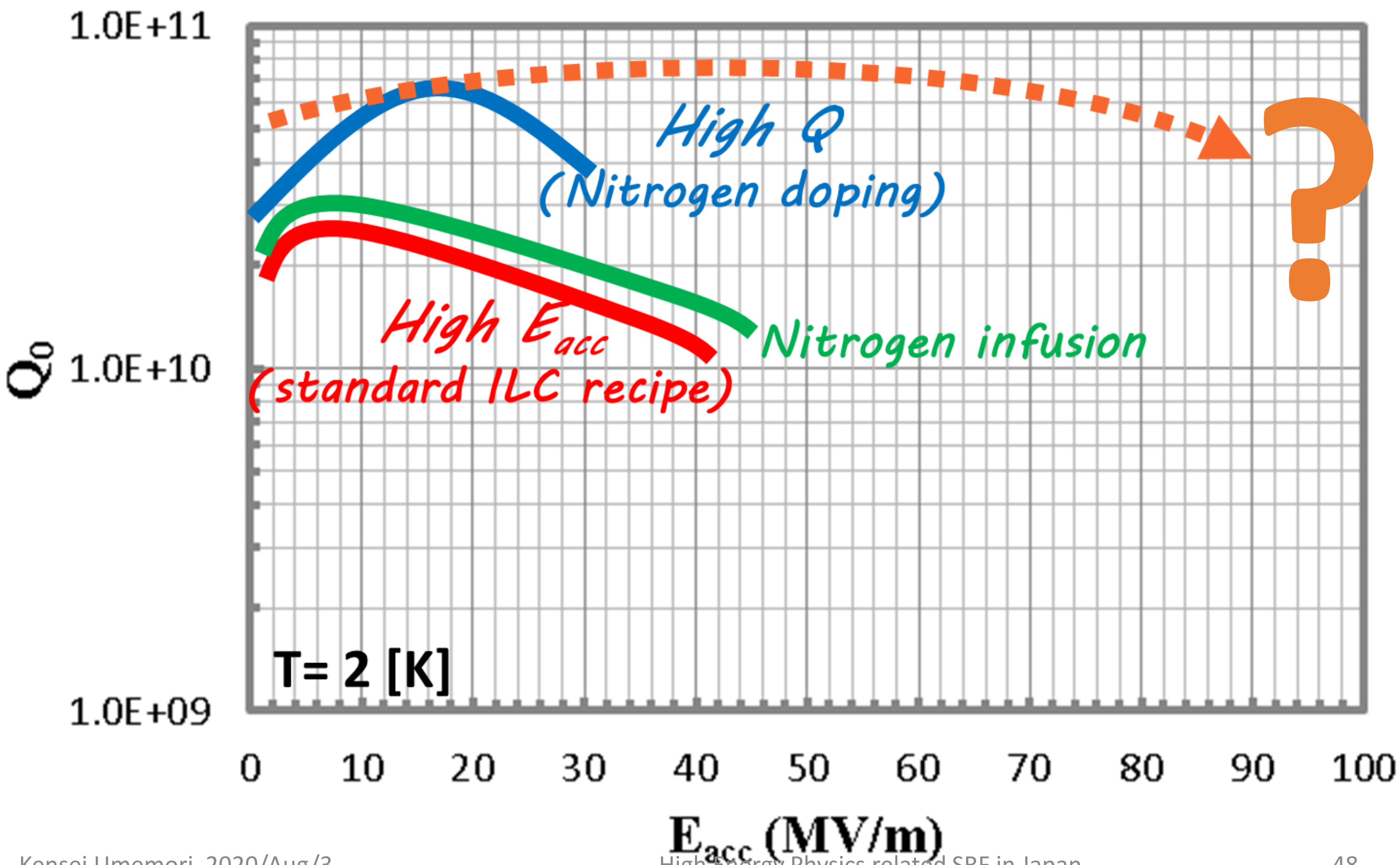
H. Ito, C.Z. Antoine, H. Hayano, R. Katayama, T. Kubo, T. Saeki, R. Ito, T. Nagata, Y. Iwashita, and H. Tongu, In proceedings of SRF2019, Dresden Germany (2019) , . TUP078

The two independent experiments found that there exist the optimum thickness.
These finding are consistent with the theoretical prediction.

Layered structures: Next

Demonstrate the field-limit enhancement using cavities.
Stay tuned!





Summary

- Introduced SRF activities in Japan
- Keyword for current and future SRF development
  - Higher accelerating gradient
  - Higher beam current
  - Higher Q values (lower surface loss)
  - CW or higher duty operation
- High-Q technology is recently well established.
- High gradient technology is, at moment, bit difficult for reproducibility and reliability.
- Nb3Sn SRF cavity is expected to be next standard for CW operation.
- Layered structure has a key to improve gradient.

Discussion ~toward perfect performance of SRF cavity~

Target: Reliable SRF operation above 40 MV/m, possibly > 45 MV/m.

【Material / Fabrication】

- What is limitation above 30 MV/m?
- Is this fabrication issue? Or material? Treatment?
- How can we achieve “defect free” cavity?

【Surface treatment】

- What is the best surface treatment?
- What is optimum conditions for oxide, hydride? How about for N, C etc.?

【Assembly】

- How do we achieve “field emission free” assembly?
- Robotics/automation will help?
- Need new breakthrough instead on HPR?

These are open questions for SRF communities for future improvement of SRF cavity performance.

Acknowledgement

Thank you very much for your supports.

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S. Michizono

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H. Araki, T. Dohmae, M. Egi, H. Hayano, H. Itoh, E. Kako, R. Katayama, T. Konomi, T. Kubo, T. Okada, M. Omet, T. Saeki, H. Sakai, T. Shishido, K. Takahashi, Y. Yamamoto

KEK KEKB-SRF team
T. Furuya, Y. Morita, M. Nishiwaki