超伝導空洞開発
High-Qの実現と窒素ドープ

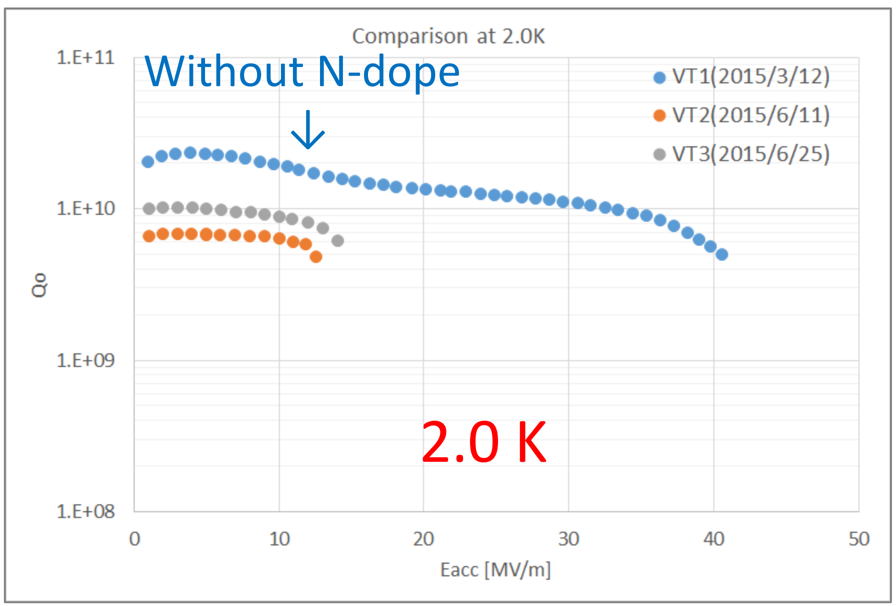
2017年6月8日

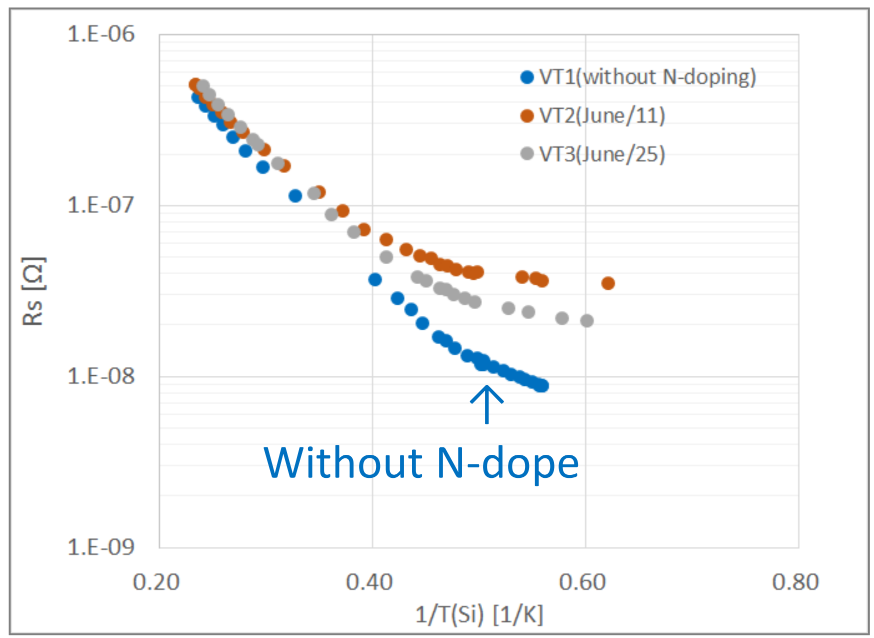
ERL検討会

梅森　健成（SCRFグループ）

はじめに

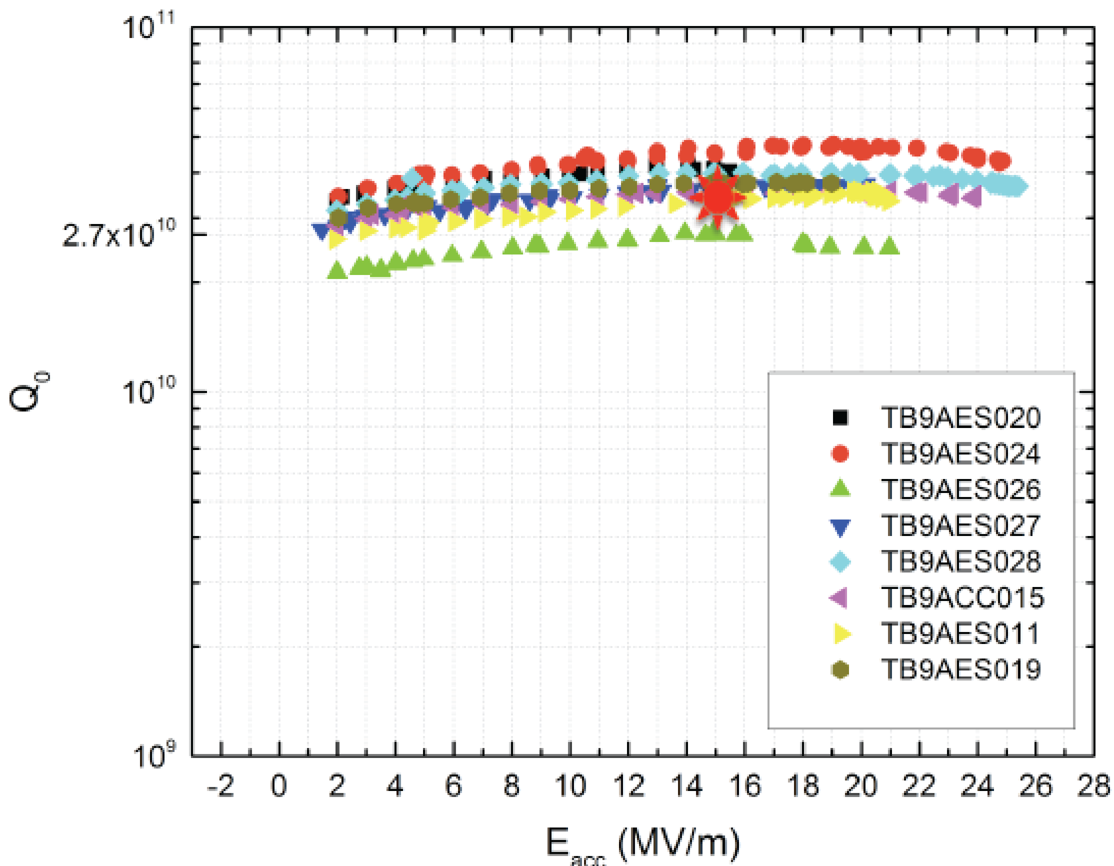
- LCLS-IIをはじめ、high-Qでの超伝導空洞の運転にむけた計画が、世界各国で行われている。
- KEKにおいても、ここ２～３年研究を進めている。
- 以前、2015年9月のERL検討会にて「High-Qを目指した窒素ドープの試み」として、KEKでの窒素ドープはうまくいっていない旨の報告。





TTC meeting（2014/12月） Alex Melnychuk 「Update on N doping at Fermilab」より

One cryomodule milestone – avg Q (2K, 16 MV/m)~3.75e10, avg quench field ~22 MV/m



Best N doping recipe so far (high Q and highest gradients achieved on nine cells) is the one known as "Fermilab 2/6": 800C 3 hrs in HV, then 2 min @ 800C with ~ 25 mTorr N2, then 6 min @ 800C in HV + 5 microns EP

Fermilab

Why N-doping does not work?

Possible reason of bad results are followings.

1. Nb surface was not N-doped correctly.

真空炉？？

- Something wrong?
- Difference of vacuum system? (Cryopump or diffusion pump, oil-free?)
- Difference on N-doping system?

2. Effect due to remnant field on vertical test cryostat.

- Trapping of magnetic field on N-doped surface is more sensitive to remnant field on vertical test cryostat.(More than a few 〜 several times sensitive?)
- KEK's VT cryostat has more than 10 mG.

縦測定での磁場環境？？

- Also depend on cooling procedure.

3. Cavity or material is wrong?

- Cavity is made at KEK-CFF.
- Nb supplier is ULVAC and Tokyo-Denkai.

材料または製法？？

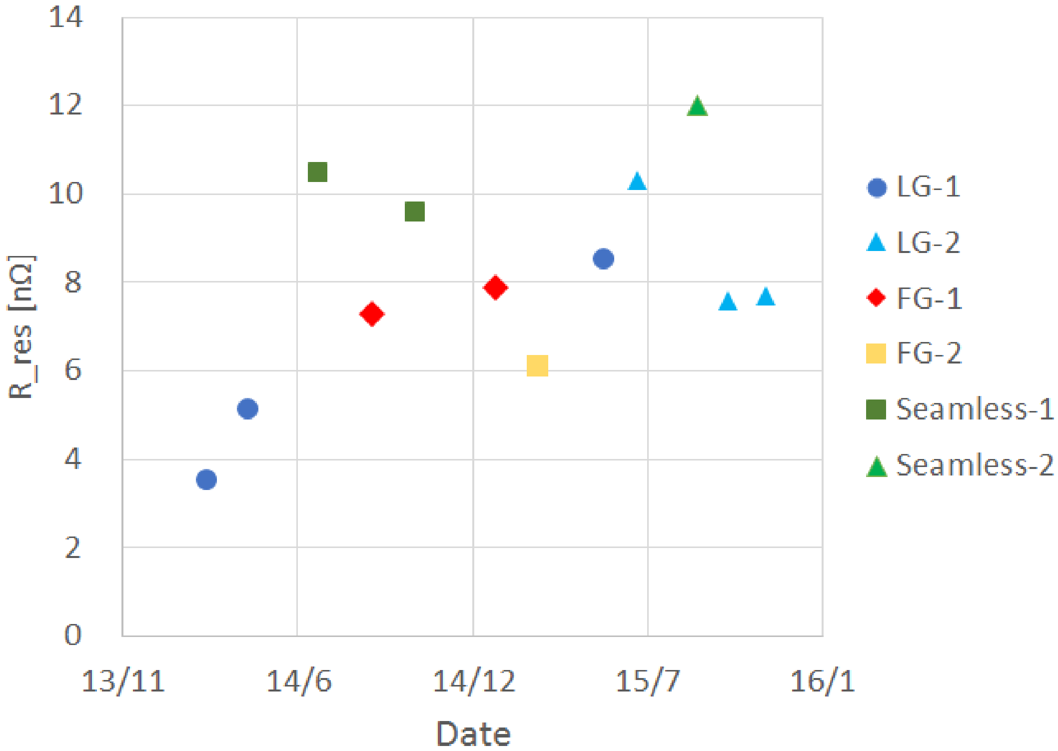
今回の報告

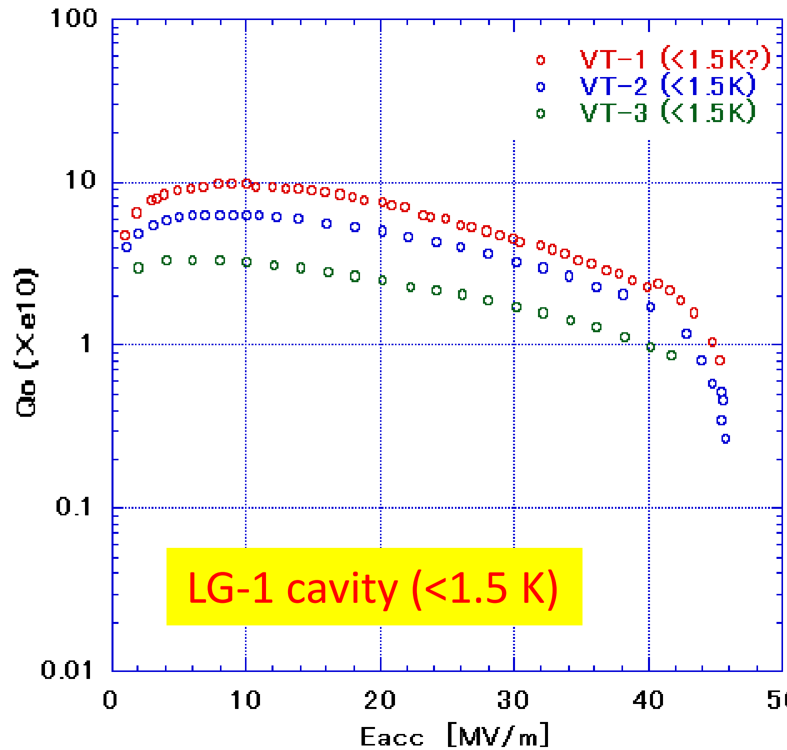
1. **High-Qの測定に向けたKEK-STFの縦測定クライオスタット磁場環境の改善**

2. **FNALおよびJ-PARCとの協力のもとでの窒素ドープの結果**

High-Q study

Rres history of single-cell cavity vertical tests





- R_res gradually increase?
- Q-values of LG cavity were gradually decrease.

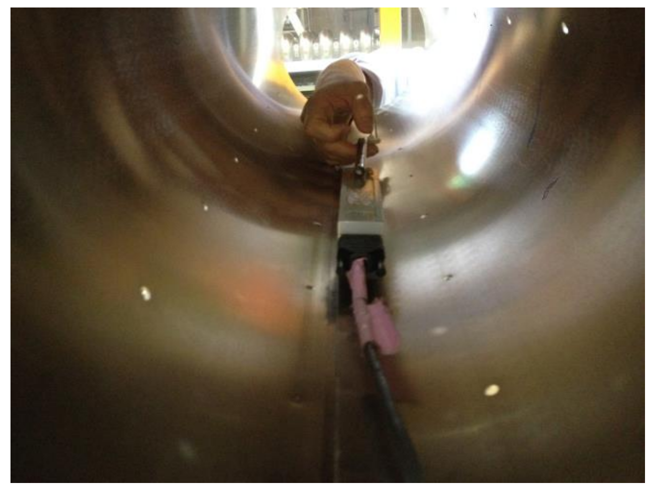
Degradation of R_res?

Check magnetization for most of all the components of vertical test

Study on magnetized components (example)

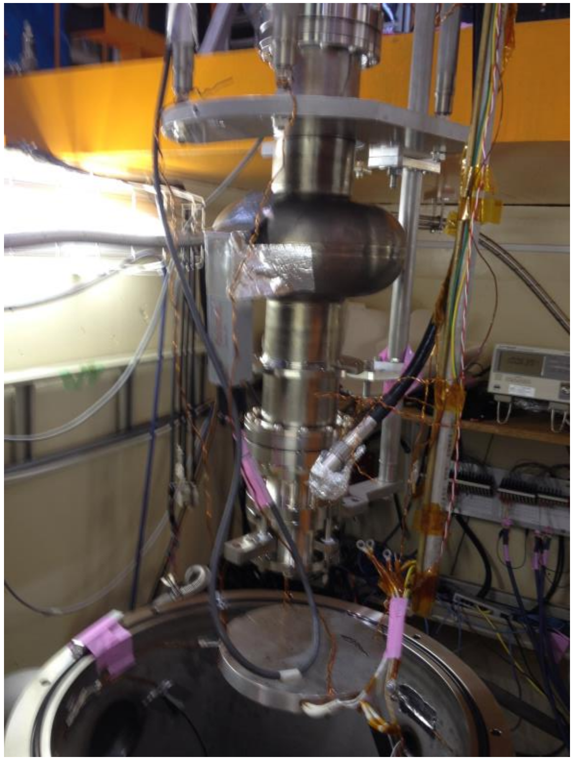
From T. Yanagimachi(9/26)

No.	name	Magnetic field [mG]
14	Φ034 metal valve ①	430
15	Φ034 metal valve (which observed vacuum leak)	80
19	Φ034 metal valve ②	59
25	Volts and washers for support of input coupler shaft	140
28	Nuts and washers for hanging cavity	110
29	Stat-volts, nuts and washers for hanging cavity	300



Measure inside magnetic shield by using 3-axis flux gate sensor.

Effects of SUS shafts



SUS shafts for variable coupler were highly magnetized.
More than 1 G!!

Magnetic field with shafts inside vertical test dewar

Angle	Bx [mG]	By[mG]	Bz[mG]	B[mG]
0	-7	-11	-6	15
90	-6	2	-9	11
180	6	-11	-7	15
270	8	130	-49	139

If both shafts were removed
B ≦ 2mG for any positions.

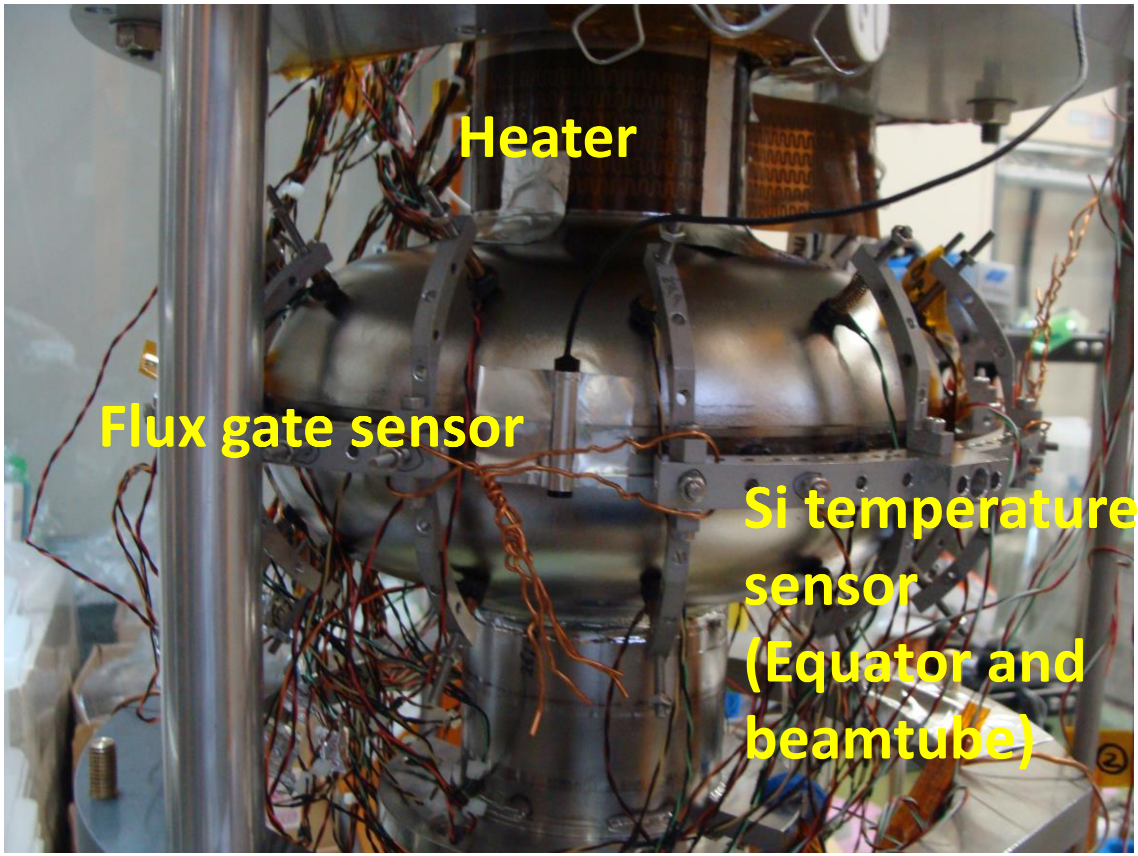
Then…

- ◆Exchange SUS shafts to Ti
- ◆Exchange or remove SUS components as much as possible
- ◆Exchange metal valve to less magnetized one

And vertical tests were carried out.

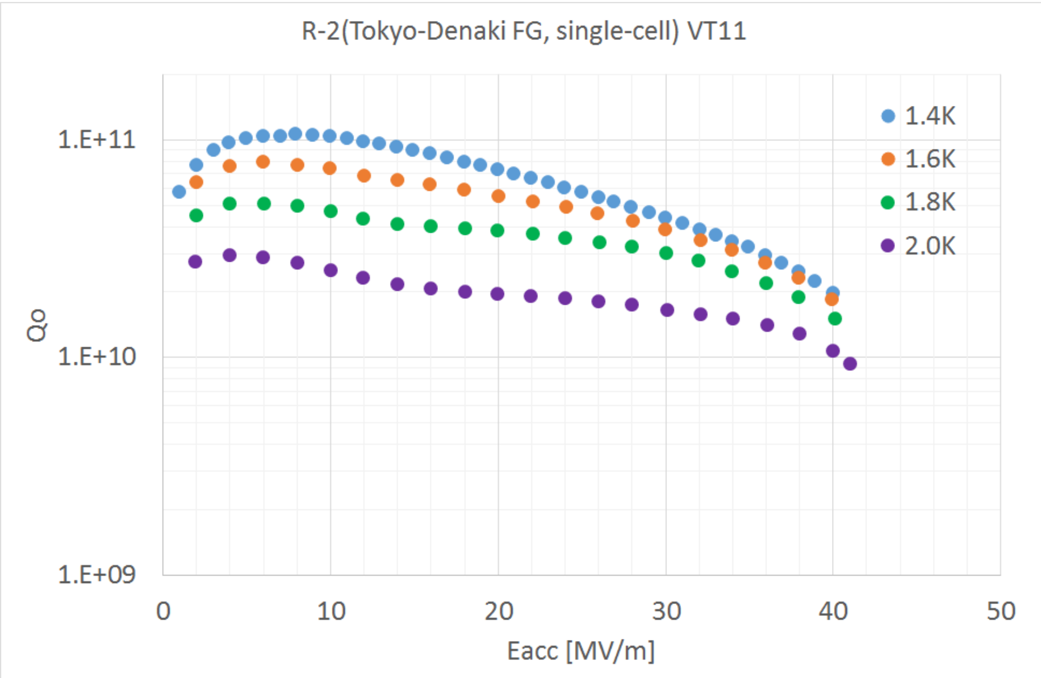
Typical vertical test setup

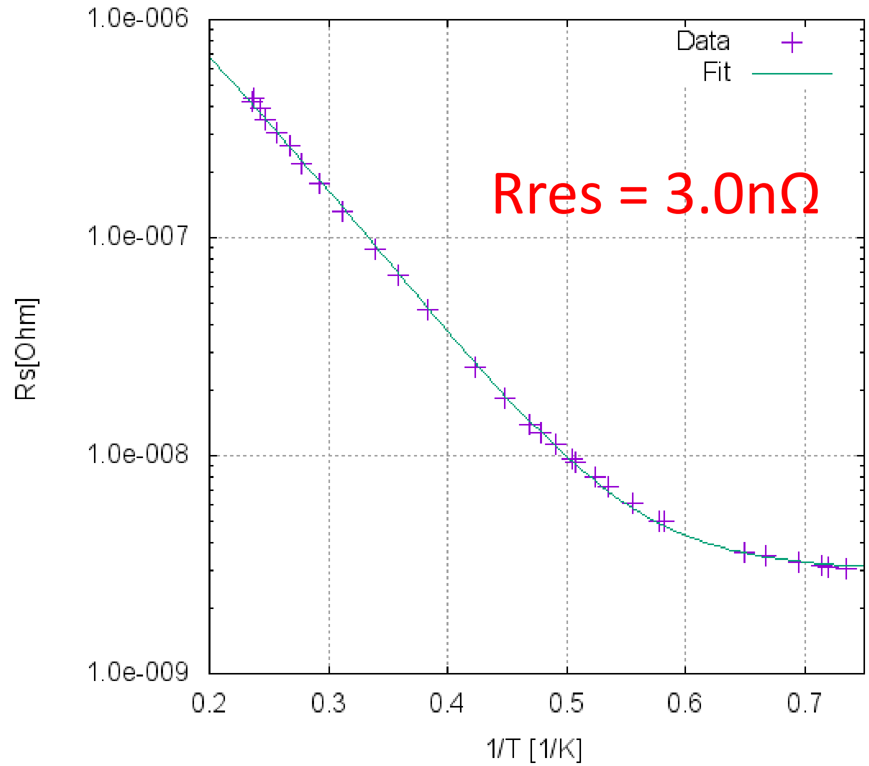
※ Pictures are for different measurement.
※ But setup of sensors and coil are same.



Flux gate sensor, Si temperature sensor, heater and solenoid coil were used.

Vertical test results after demagnetization effort

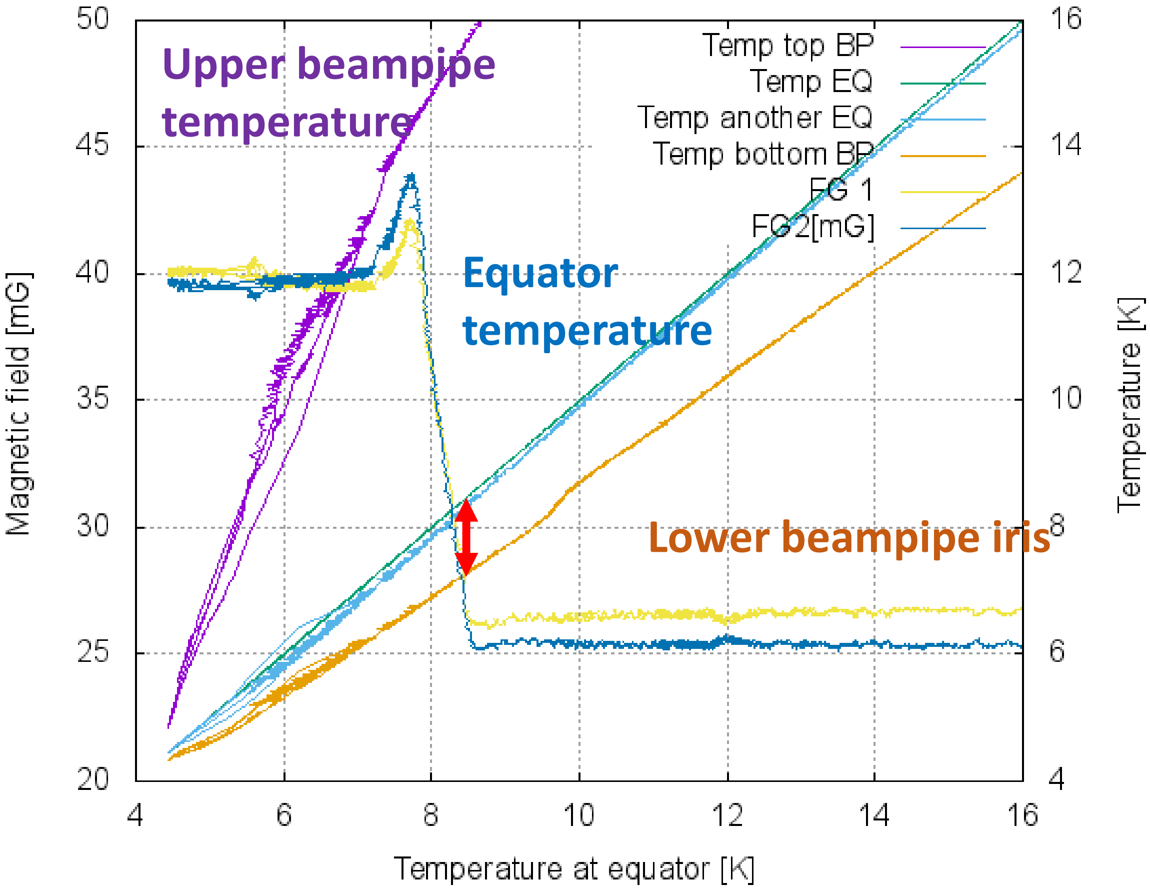




- FG single-cell cavity (Tokyo-Denkai)
- Nominal recipe (Not N-doping)
- With cancelling coil
- With thermal gradient by heater

Very high-Q was observed after the effort for demagnetization

Flux expulsion during cool-down(add 16mG with coil)



- FG single-cell cavity (ULVAC)
- Nominal recipe (Not N-doping)
- 900 degree heat treatment applied
- Add +16mG with coil (Total 9 + 16 = 25mG)
- With thermal gradient by heater

- Clear flux expulsion(~90%) can be observed.
- Temperature gradient of more than 1 degree between equator and lower beampipe iris.

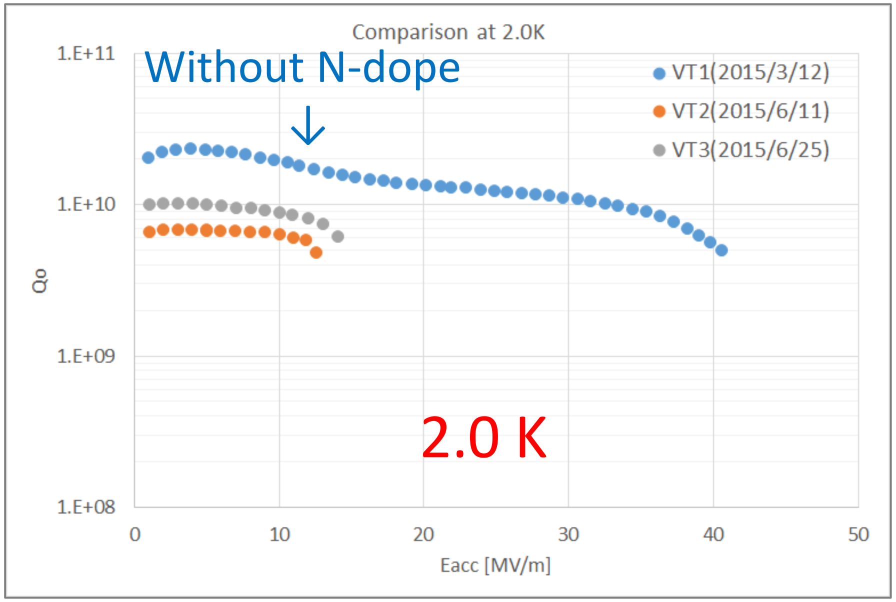
Summary (High-Q study)

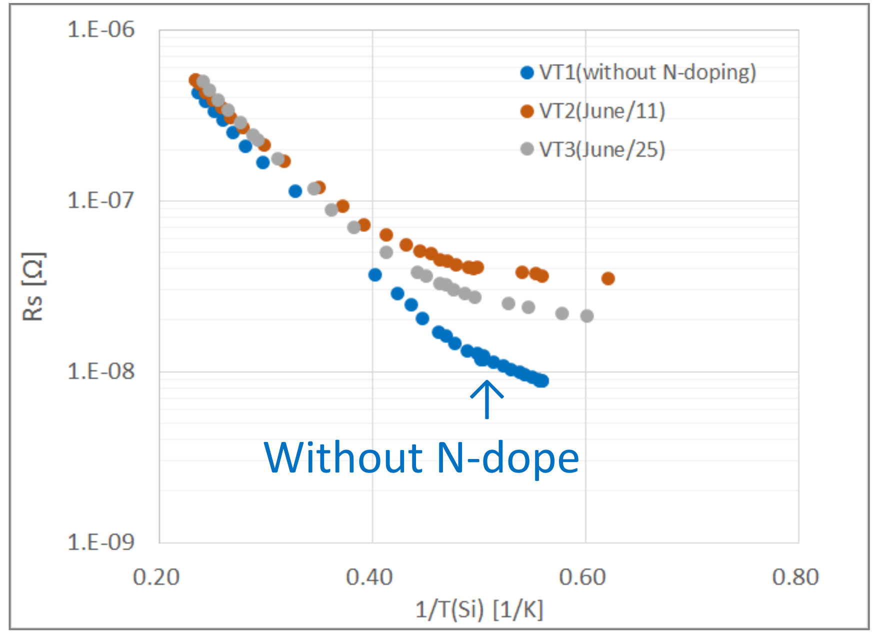
- It was difficult to achieve high-Q at KEK-STF vertical test.
- Magnetization was investigated for each components of vertical tests.
- Some components were highly magnetized. One of highest was shaft for variable coupler.
- Magnetized components were removed or exchanged. Also solenoid coil was prepared.
- After these effort, high-Q could be measured and clear flux expulsion signal was observed.

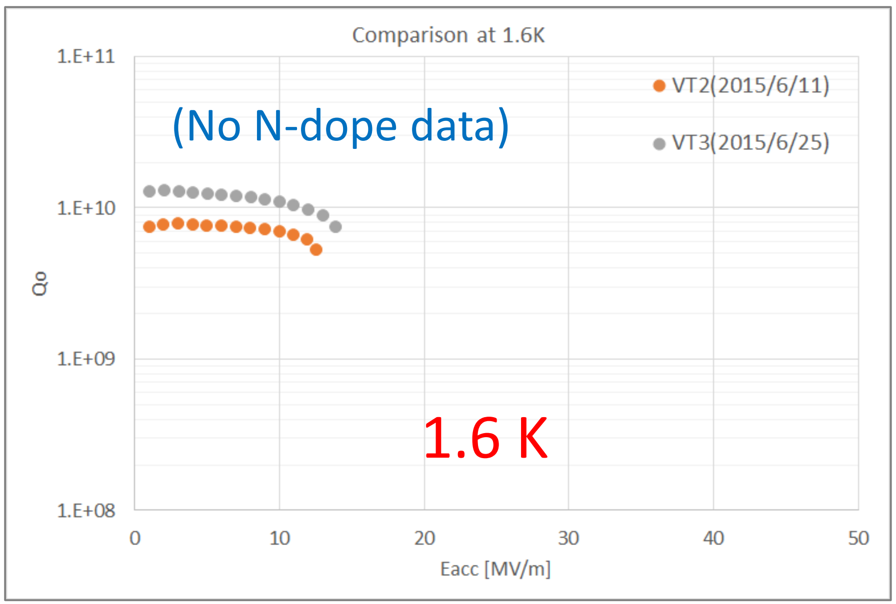
Nitrogen doping

KEK真空炉での窒素ドープの一例（2015年9月のERL検討会スライドより）

縦測定結果







・窒素ドープの後、15um + 15umのEP-2をして2回の縦測定を行った。
・今回は更にひどくQ値が劣化。$1x10^{10}$に届くか届かないか。
・Quench fieldは13MV/m。
・2回目のEPで、Q値、quench fieldともに少しだけ回復。
・Quenchの場所は、今回はほぼ同じ。

Why N-doping does not work?

Possible reason of bad results are followings.

1. Nb surface was not N-doped correctly. ⇒ N-dope@FNAL and J-PARC
   - Something wrong?
   - Difference of vacuum system? (Cryopump or diffusion pump, oil-free?)
   - Difference on N-doping system?

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2. Effect due to remnant field on vertical test cryostat. ⇒ VT@FNAL(March)
   - Trapping of magnetic field on N-doped surface is more sensitive to remnant field on vertical test cryostat.(More than a few 〜 several times sensitive?)
   - KEK's VT cryostat has more than 10 mG.
   - Also depend on cooling procedure.

縦測定での磁場環境？？

3. Cavity or material is wrong? ⇒ N-dope@FNAL and VT@FNAL(October)
   - Cavity is made at KEK-CFF.
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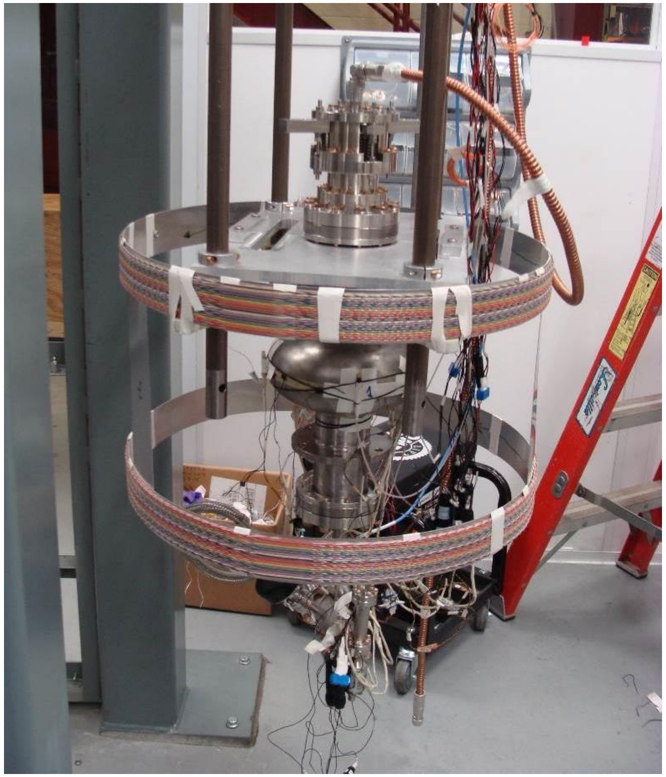
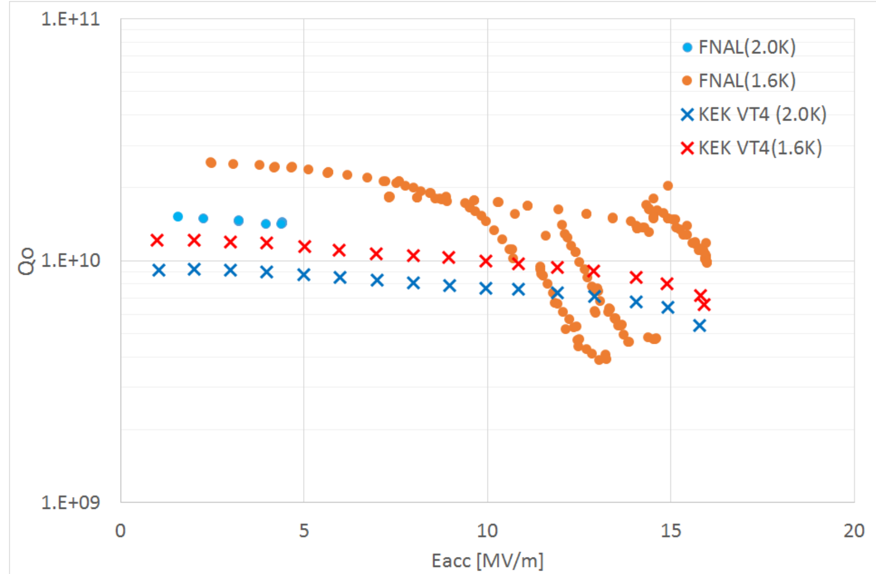
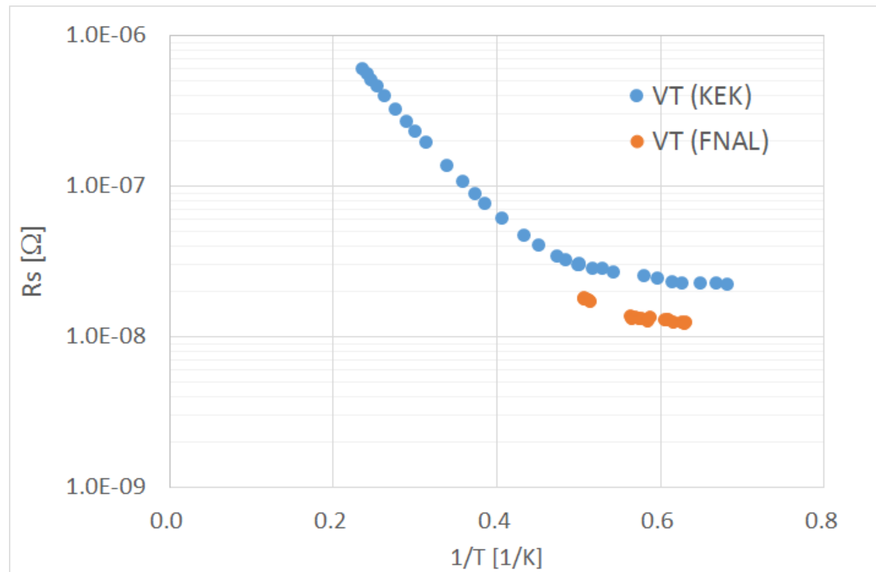
材料または製法？？

Vertical test of KEK doped cavity at FNAL







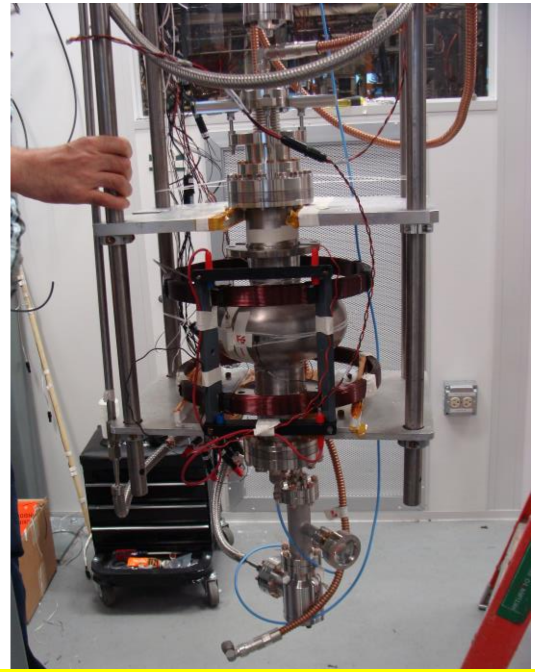
- Vertical test of KEK N-doped cavity was carried out at FNAL, where magnetic field inside VT dewar is very small.
- However, Q-value was not good as nominal N-doping cavity.

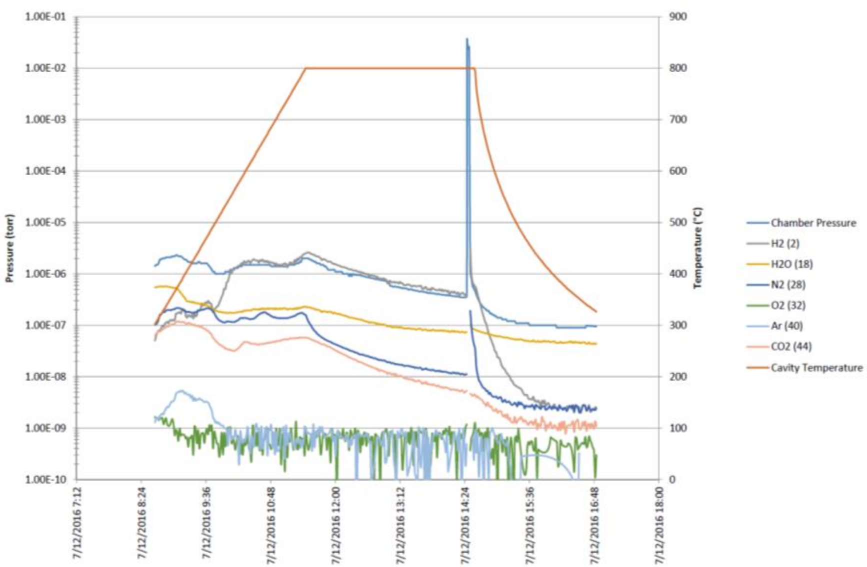
Even in zero magnetics field, still Rres was too large.

N-dope and VT of KEK cavity @FNAL

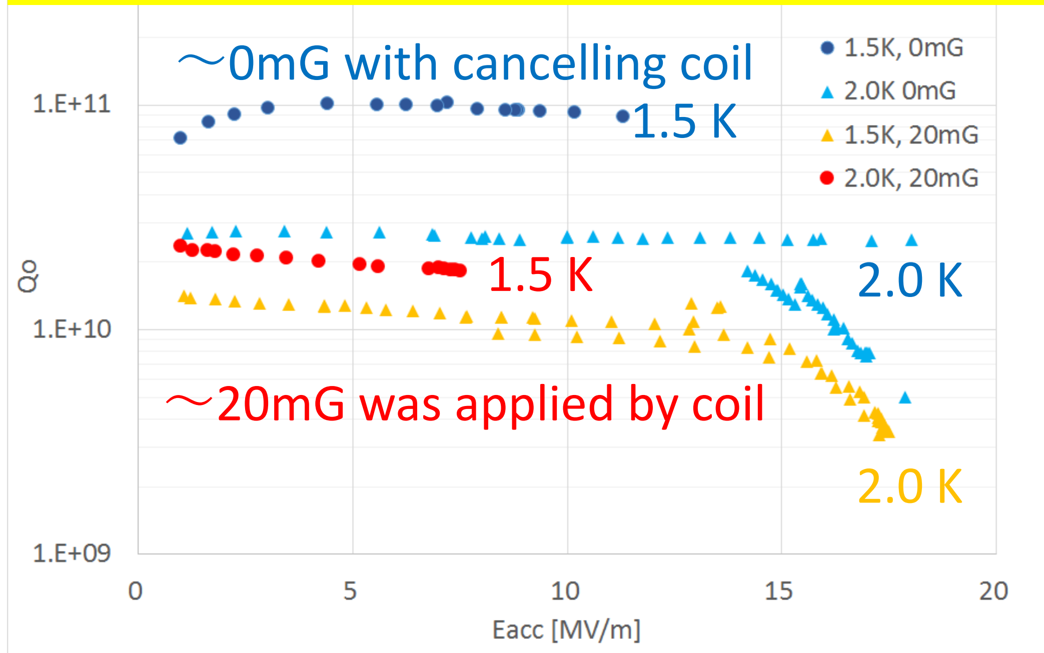
- 2016/7/9 EP 60um
- 2016/7/12 N-doping (FNAL standard recipe 2/6)
- 2016/9/13 EP 6um
- 2016/10/25, 26 VT

- KEK cavity was doped at FNAL and also tested.
- It showed successful doped performance.





N-doping successful !! Thanks for FNAL-SRF group!!



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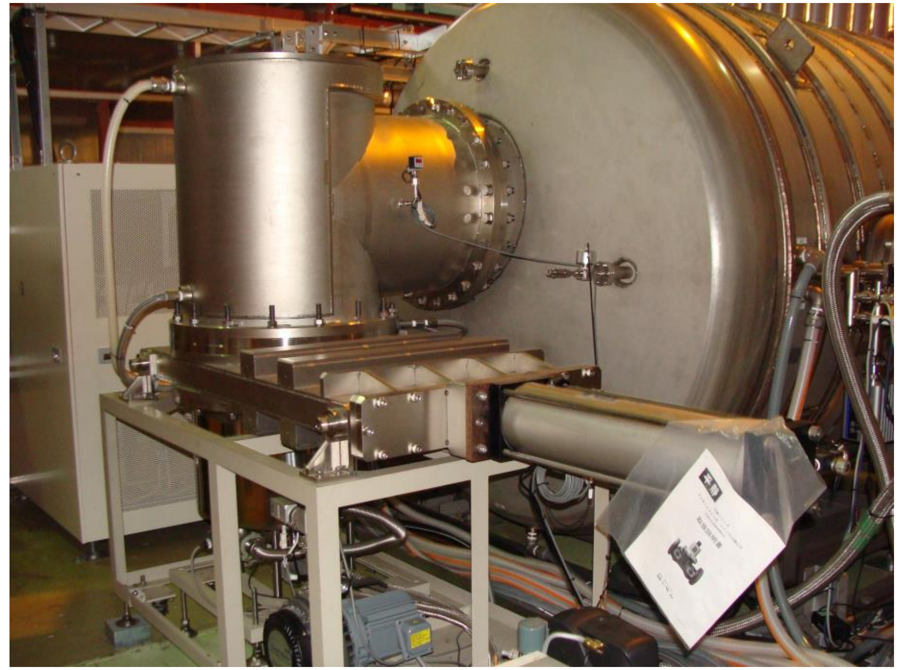
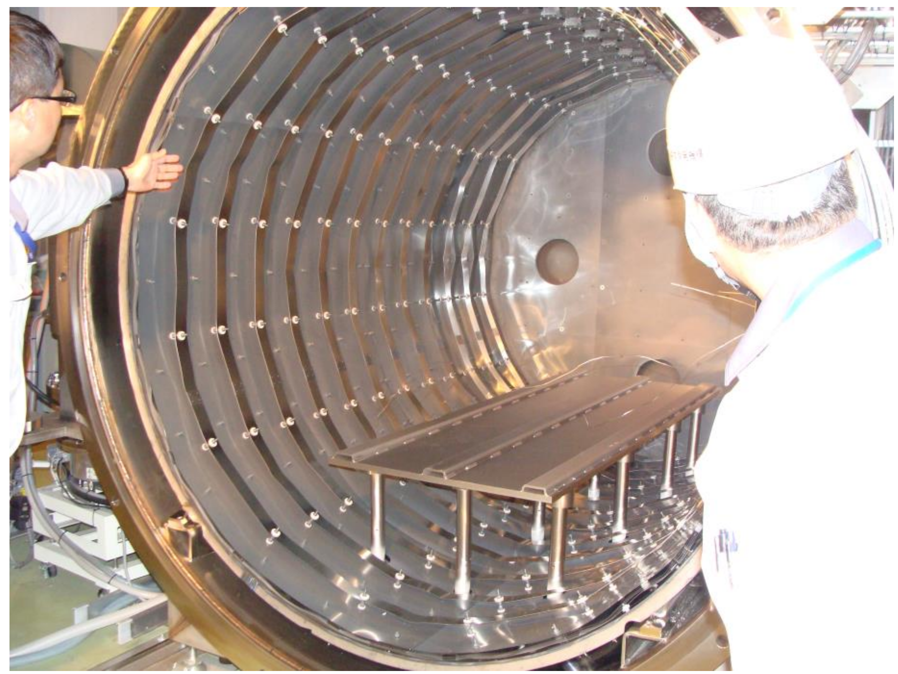
材料または製法？？

Furnace at J-PARC



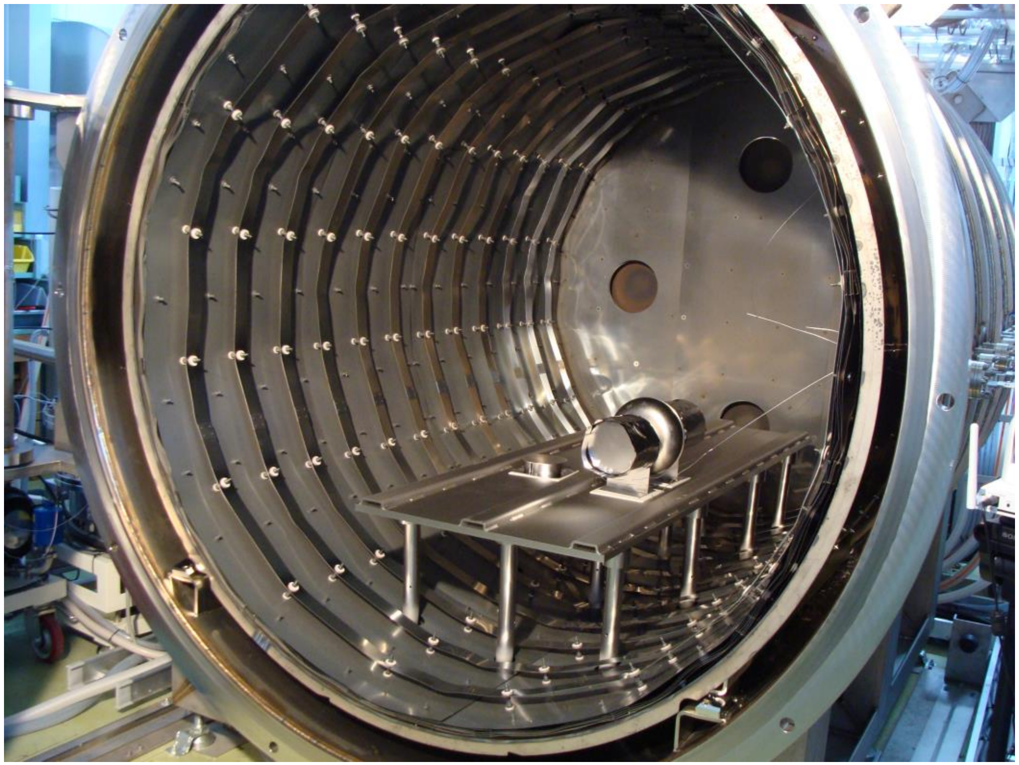


- J-PARC has oil-free furnace with cryo-pump and TMP.
- We try to use it for N-doping / N-infusion.
- Normally used for degassing of beam-ducts and components.

N-doping@J-PARC furnace

N-doping at 2017/May/11

800 deg, 3 hours
800 deg, 20 min, N 2.7Pa
800 deg, 30 min
Cooldown

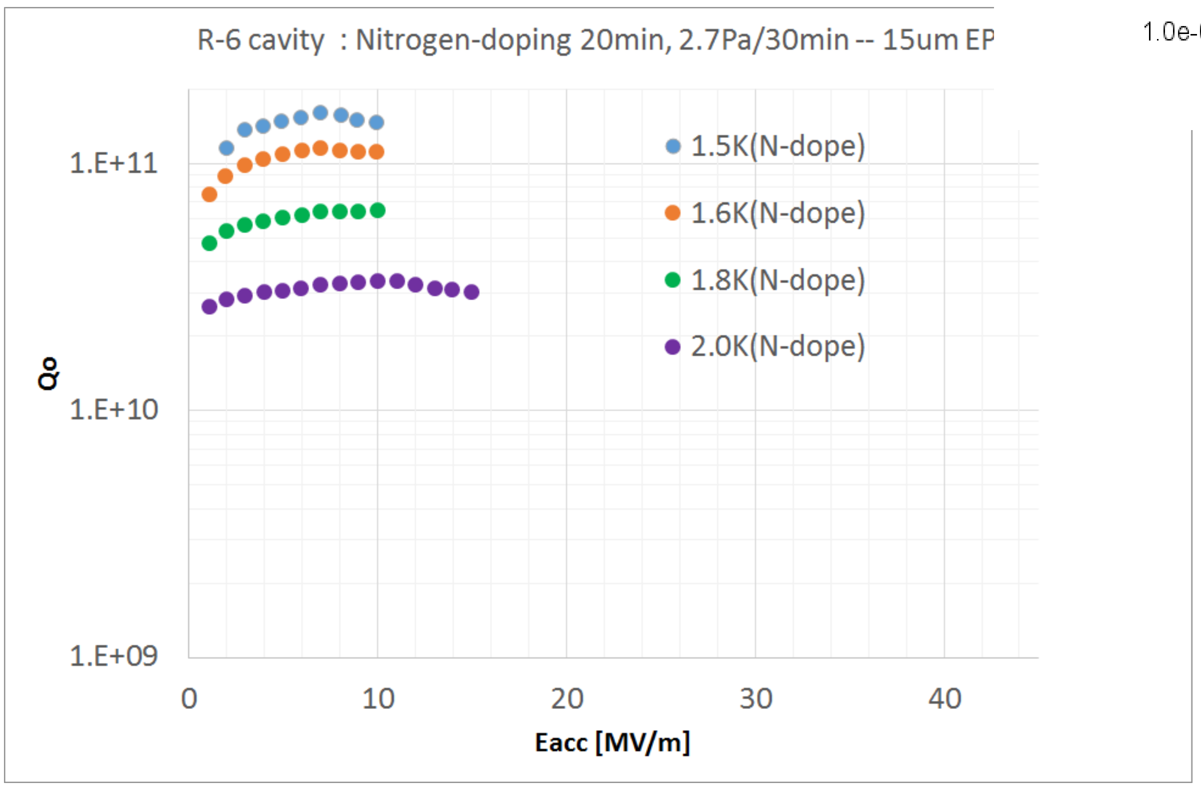


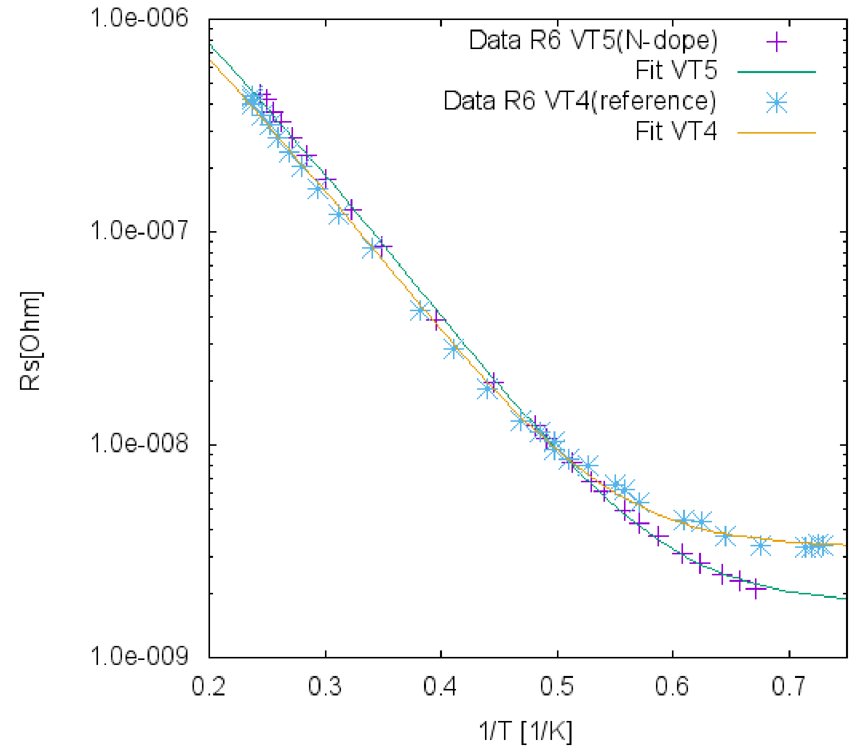
Pumping system of J-PARC furnace
-- Cryopump + TMP (+ scroll)
-- reach to 1e-6 Pa after cool-down

VT results of N-doping

15um EP
HPR (total) 3~4hours
Dry assembly (No baking)

- Magnetic field canceled with solenoid coil. (< 1mG)
- Cooled down with thermal gradient by heater

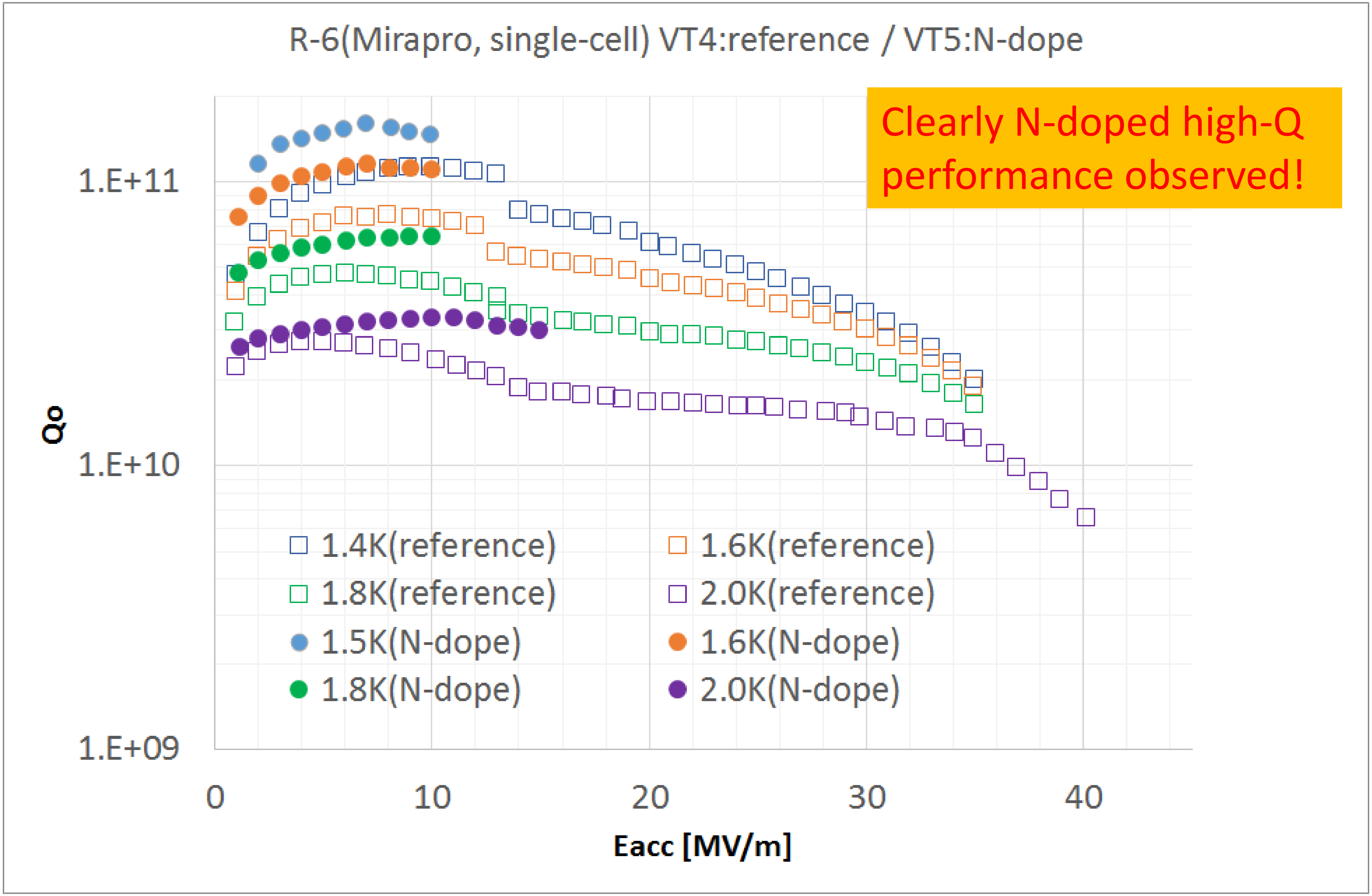




VT4(reference) Rs=3.3nΩ
VT5(N-dope) Rs=1.8nΩ

- Very high Q up to high field
- Q = 1.6e11@7MV/m, 1.47K
- Q = 3.0e10@15MV/m, 2K
- Quench at 16MV/m
- No field emission

Comparison with previous measurements



Summary (N-dope)

- In KEK, study on N-doping have been continued under collaboration with FNAL and J-PARC.
- N-doping was tried using J-PARC furnace, which has oil-free pumping system, consists of a cryopump and TMPs.
- After removable of 15um by EP, vertical test showed good performance: 1.6e11 at 7MV/m(@1.47K) and 3.0e10 at 15MV/m(@2.0K).
- This is first successful N-doped results in Japan.
- Clean furnace seems to be essential for N-doping. Details of reason is under investigation.

物構研・加速器合同セミナーのお知らせ

日時：7月4日（火）15時から16時30分

場所：4号館1階セミナーホール

講師：許斐太郎氏（加速器第六研究系　助教）

題目：**超伝導RF加速空洞のHigh-Q, High-Gの最近の動向とKEKでの展開**

（Recent world wide research and KEK activities of the Superconducting RF cavity for High-Q, High-G）

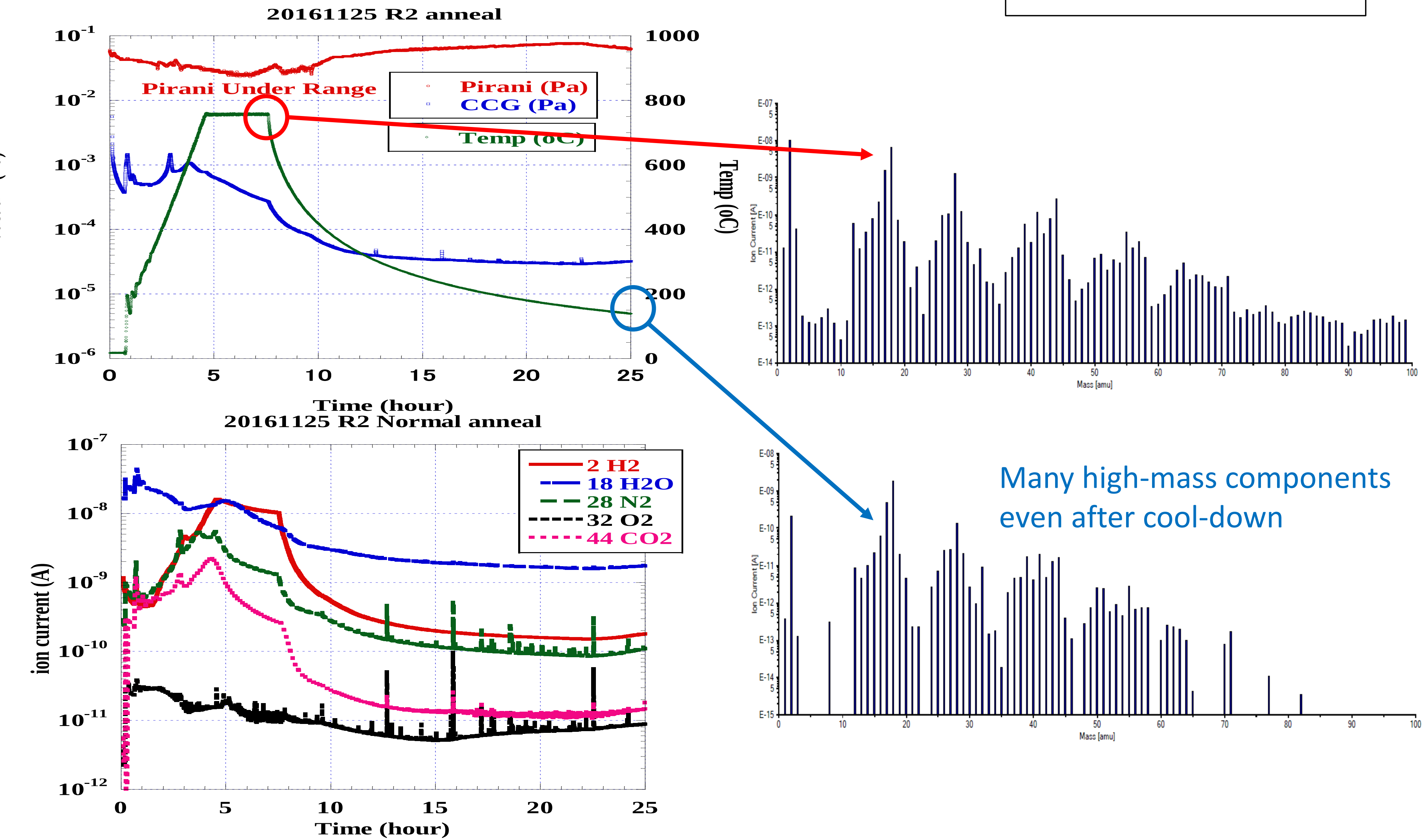
要旨：超伝導RF加速空洞には一般的に加工性が良くかつ超伝導転移温度が比較的高いニオブが使用されている。長年の研究により高電界が印加されるRF環境下であってもニオブの臨界磁場近くの性能を安定して引き出すことができるようになってきている。近年はニオブの限界性能を超えるためにNb3Sn、MgB2、窒素処理などによる薄膜コーティングに関する研究も盛んとなってきている。
一方、昨年、米国フェルミ研究所の研究者により、空洞の熱処理中に窒素を導入することにより空洞の低損失・高電界化（High-Q, High-G）を実現する新技術が開発された。ILC（国際リニアコライダー）のコスト削減を目指したR&Dを日米で始めることになったが、この低損失・高電界化はR&Dの重要なテーマとなっており、KEKでもこの処理についてR&Dを開始しつつある。本セミナーでは、超伝導空洞の最近の動向を説明した後、KEKでの展開を報告する。

世話人　村上洋一（物構研）、道園真一郎（加速器）

Backup slide

RGA spectrum of KEK big furnace

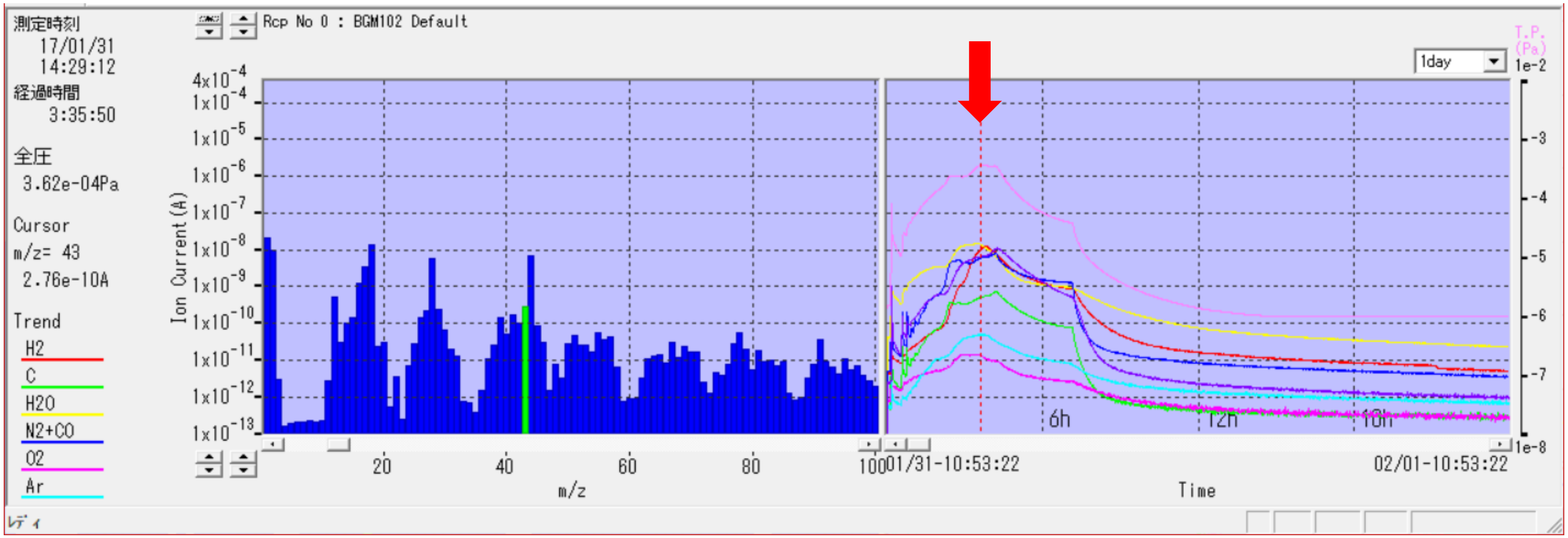
No RGA data for KEK small furnace

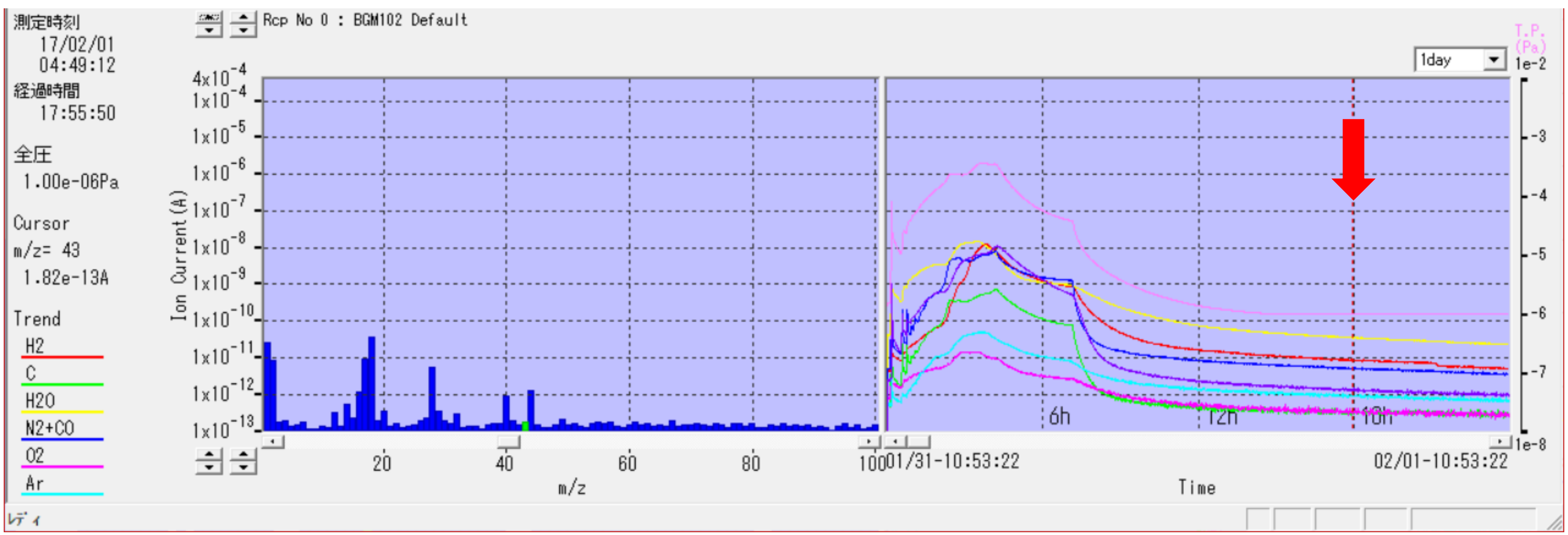


Many high-mass components even after cool-down

RGA spectrum of J-PARC furnace

750deg, 3hour annealing (No doping)
No cavity. Jigs and Nb samples.

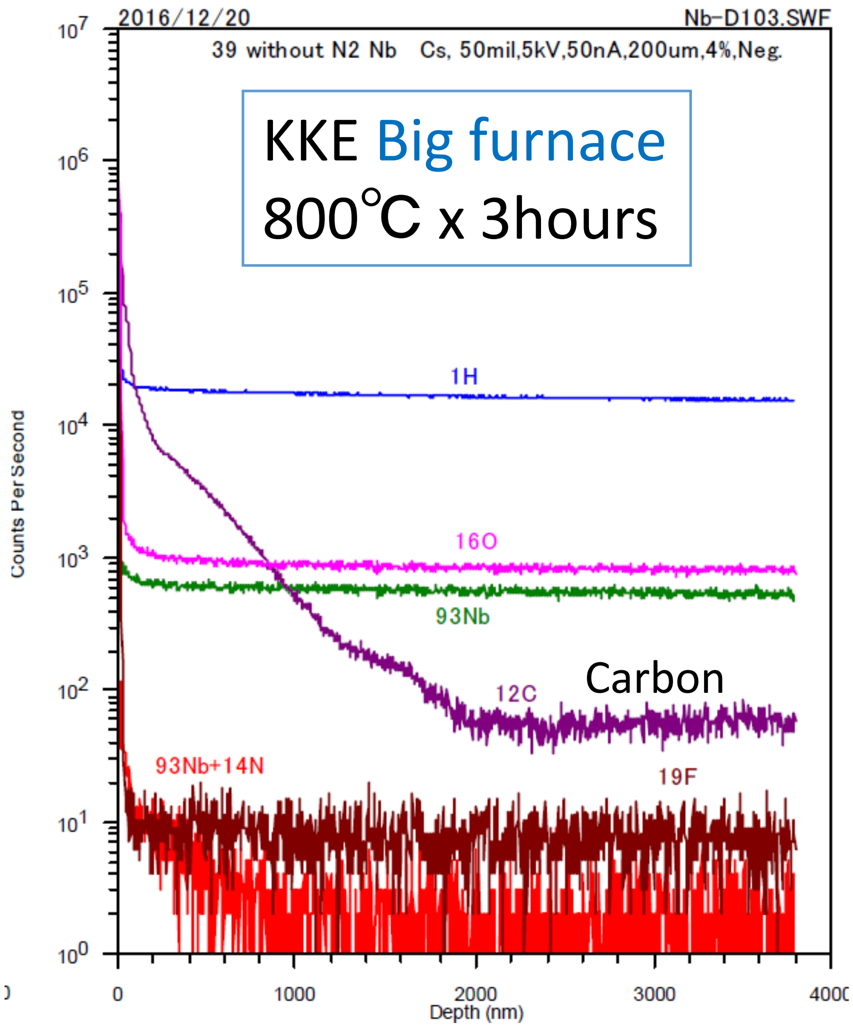


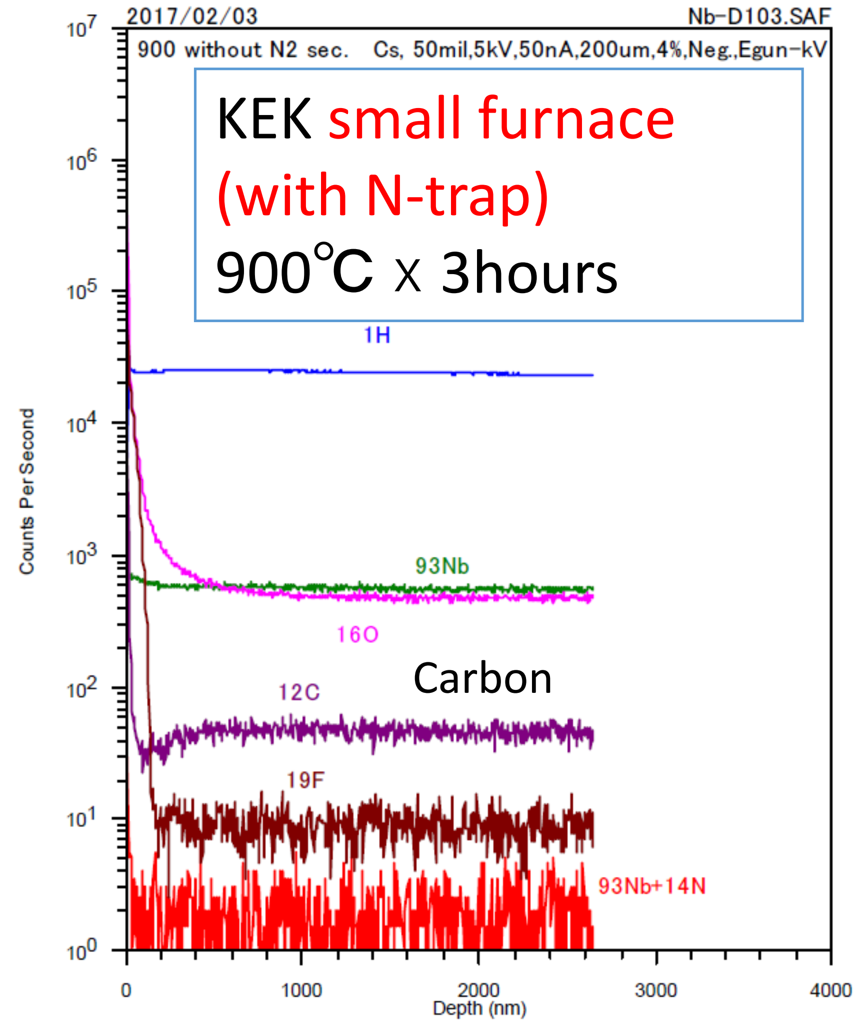


Nb sample analysis for KEK big/small furnace (Heat treatment without N-dope)

Analyzed by ULVAC

ULVAC, Inc.





Each figures are up to 4um.

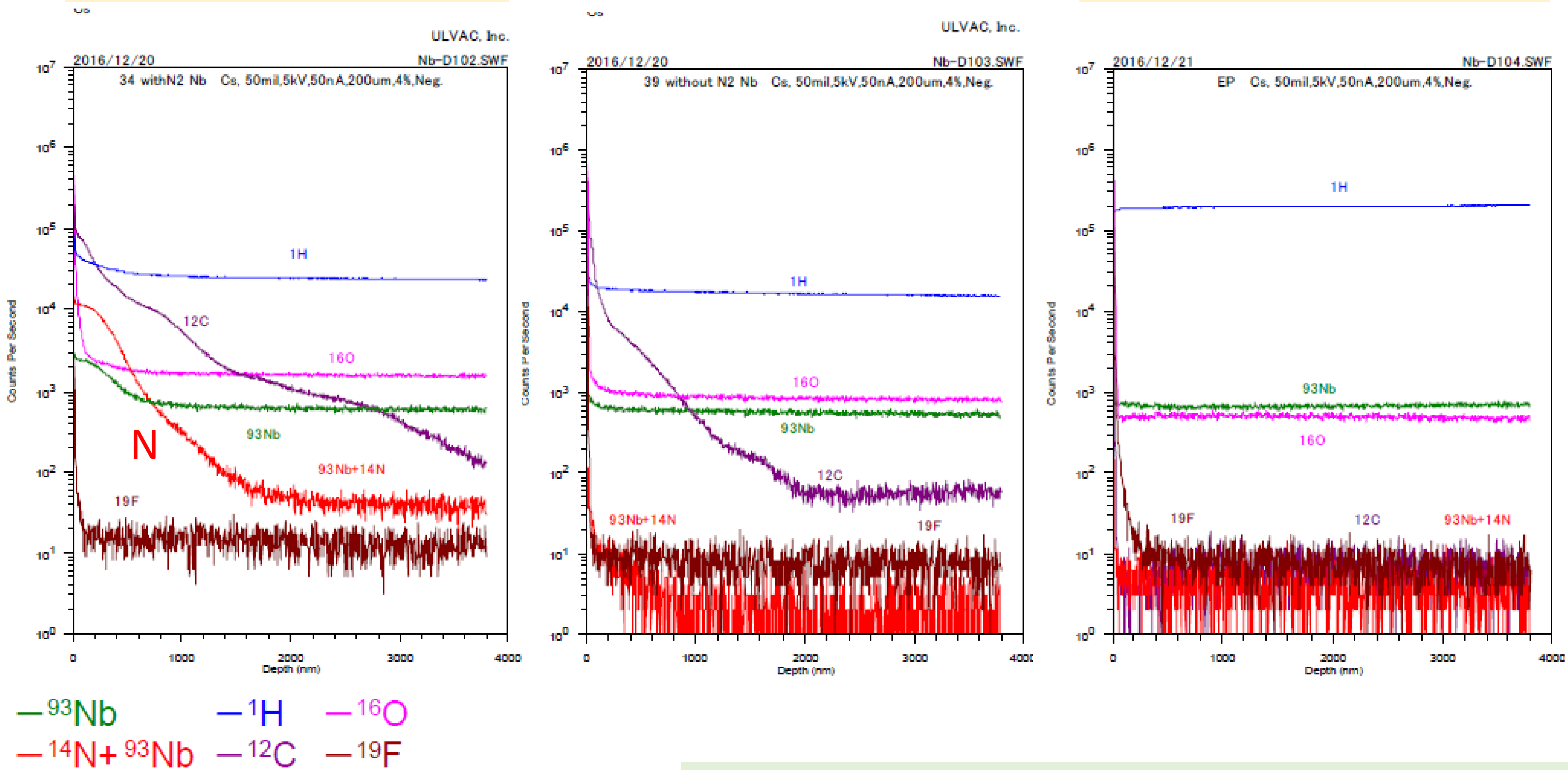
Nb sample analysis for KEK big furnace

Analyzed by ULVAC

Heat treatment with N-doping

Heat treatment No N-doping

No heat treatment (only EP)



Each figures are up to 4um.

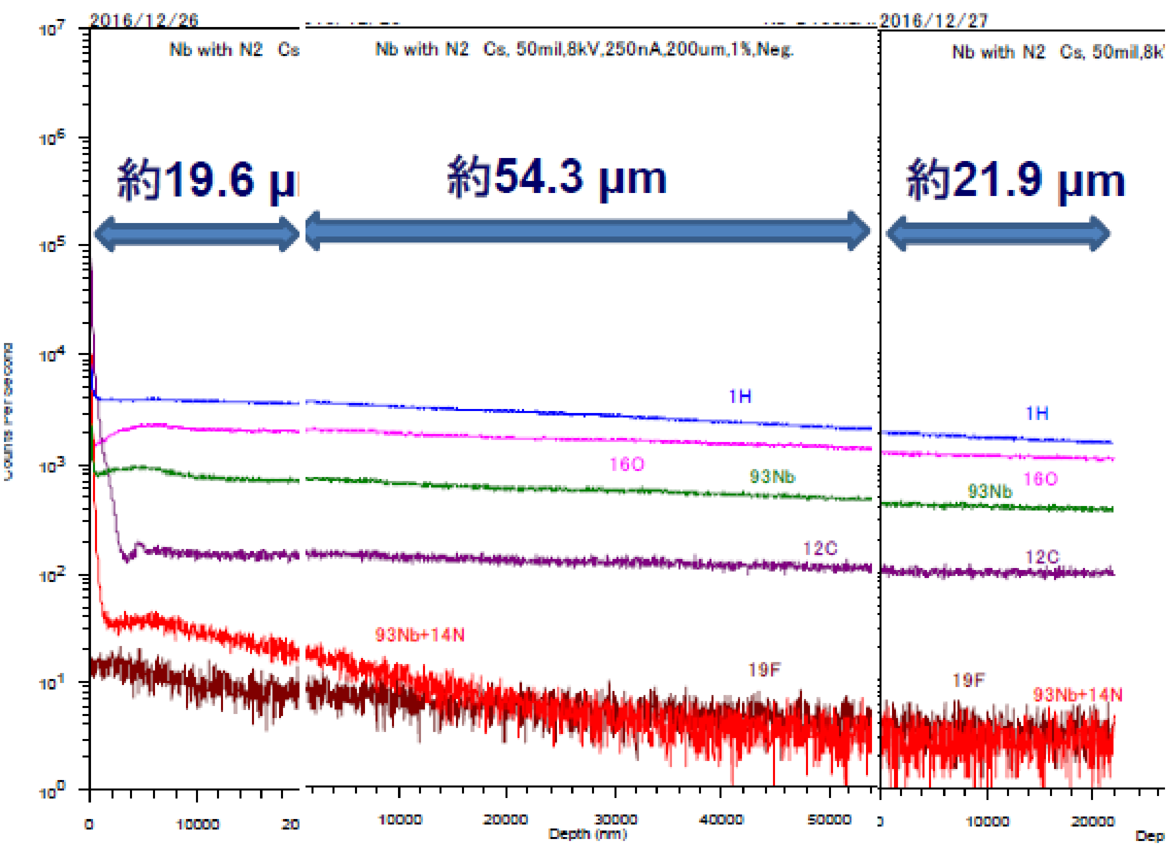
N is observed for N-doped sample

C is observed for heat treated samples.

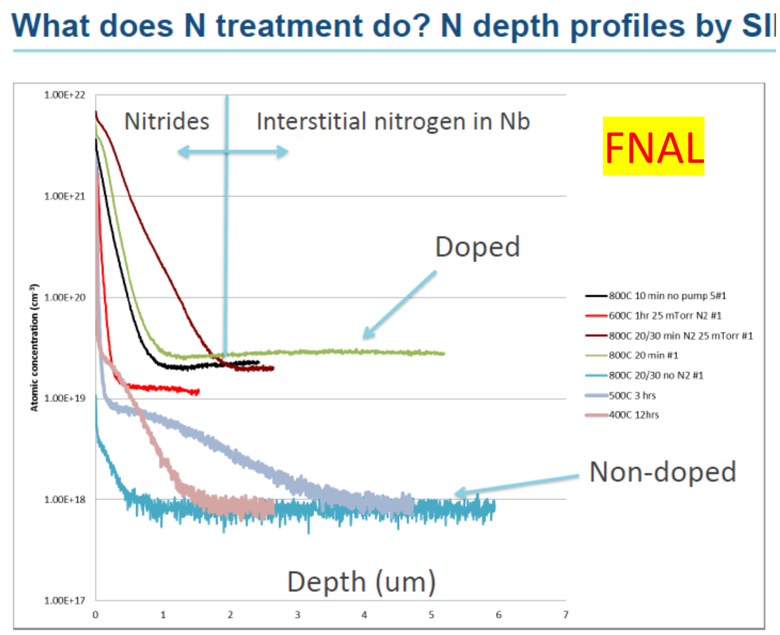
SIMS for N-doped sample(~100um)

Analyzed by ULVAC

Total of three measurements



- Rapidly decrease until ~1um
- Flat up to ~10um
- Then gradually decrease (down to lower limit)
- N behavior seems to be similar



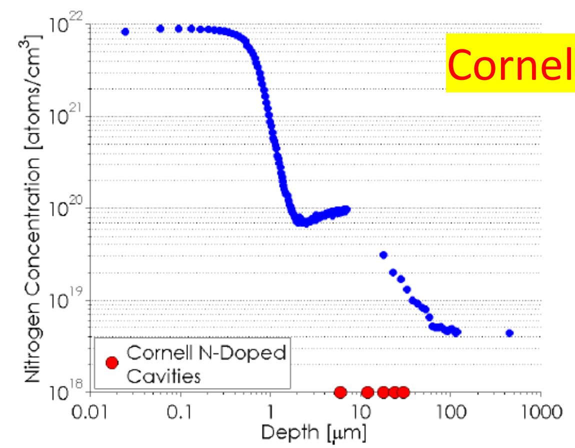


Figure 6: SIMS results from a sample treated with TE1-4 and TE1-5. Single-cell cavities are also included for reference.