High-Q R&D for SRF challenge

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ERL2015, 7-11June2015, Stony Brook

Introduction

High-Q cavity

Why we need ?

$$P_{diss} = \frac{V^2}{R_{sh}} = \frac{V^2}{\left(R_{sh}/Q_o\right) Q_o}$$

↑ *Determined by cavity shape*

High-Q provides lower cryogenic load for future CW SRF machines.

How to achieve?

$$Q_0 = \frac{\Gamma}{R_s}$$

← *Determined by cavity shape*

$$R_S = R_{BCS}(T) + R_{residual}$$

Minimizing Rs is the Key for future High-Q applications.

Low Rs

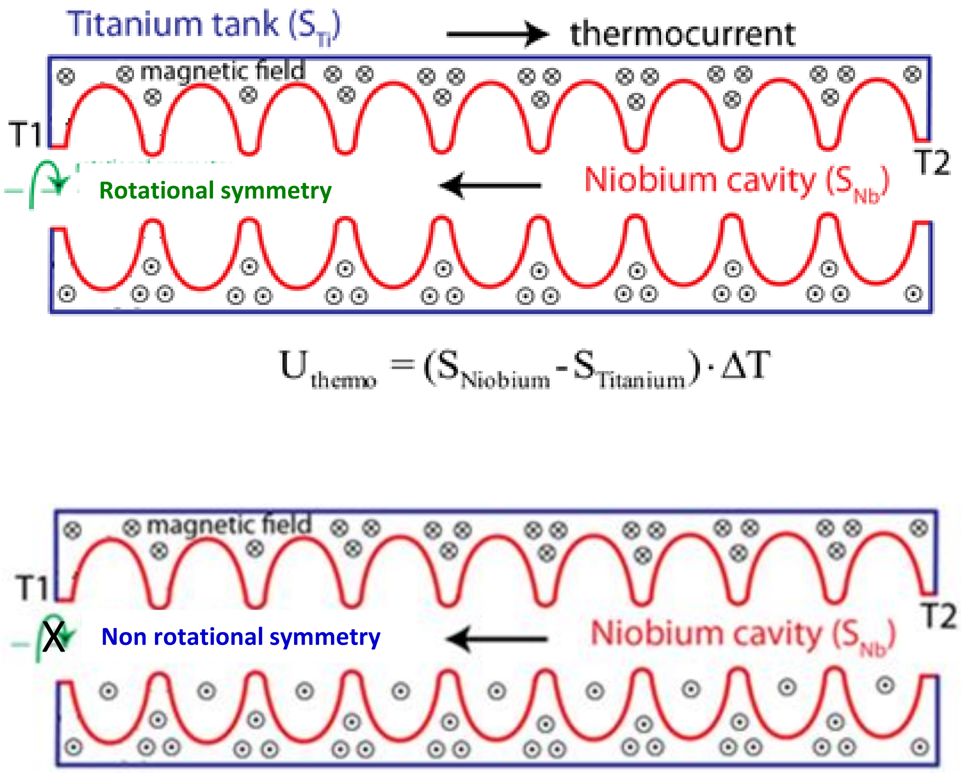
$$R_S(T,B) = R_{BCS}(T,B) + R_{residual}(B)$$

- R_{BCS} is determined by Surface finish.
  - 120C bake / HF rinse
  - Nitrogen doping
- R_{res} is reduced by Flux control.
  - Magnetic shielding
  - cool down procedures
  - thermo currents effect

⇨ Depends on the surface finishing, the best way of flux control will be different.

Thermo currents effect

- Different Seebeck coefficients for Nb and Ti

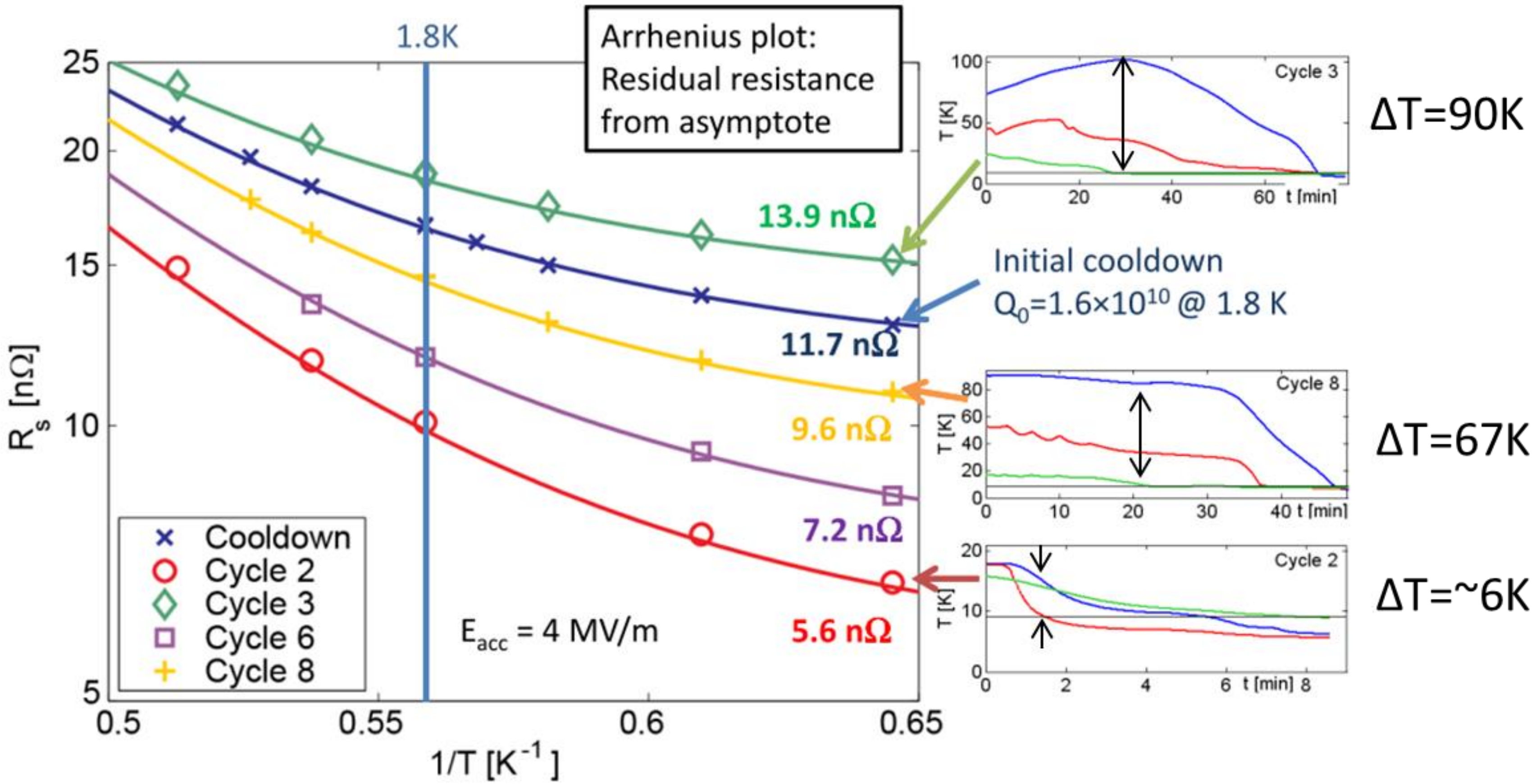


$$U_{thermo} = (S_{Niobium} - S_{Titanium}) \cdot \Delta T$$

Seebeck effect results in thermo currents. Once symmetry is broken, larger ΔT over cavity near T_C provides more thermo currents, more chance of flux trapping, and increase of R_{res}.

Images are modified from Oliver's slide in SRF2013

R_{res} vs. dT over cavity



Oliver Kugeler,
TTC high-Q working
group 17 Feb 2014

dT over cavity need to be minimized to avoid any increase of R_{res}.

High-Q cavities R&D

Lesson 1. Cornell ERL

Cornell ERL and Main Linac Cryomodule

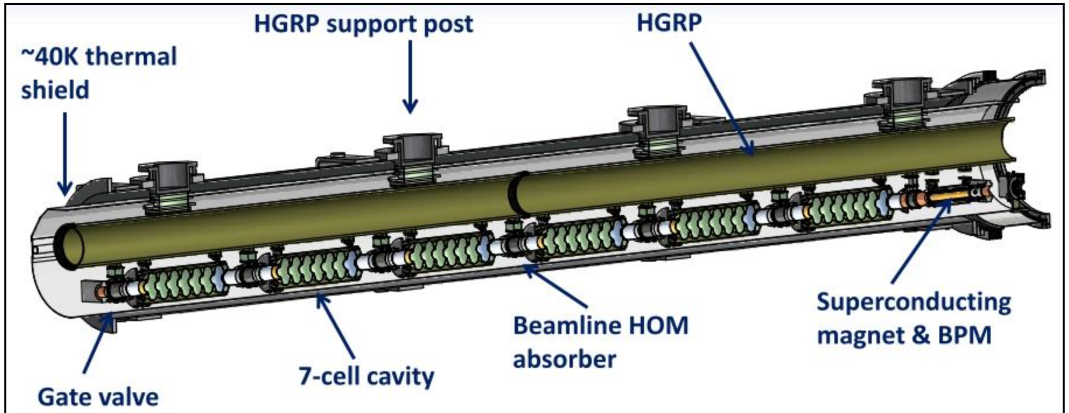
Cavity parameters

Qo=2.0e10 at Eacc=16.2MV/m, 1.8K.

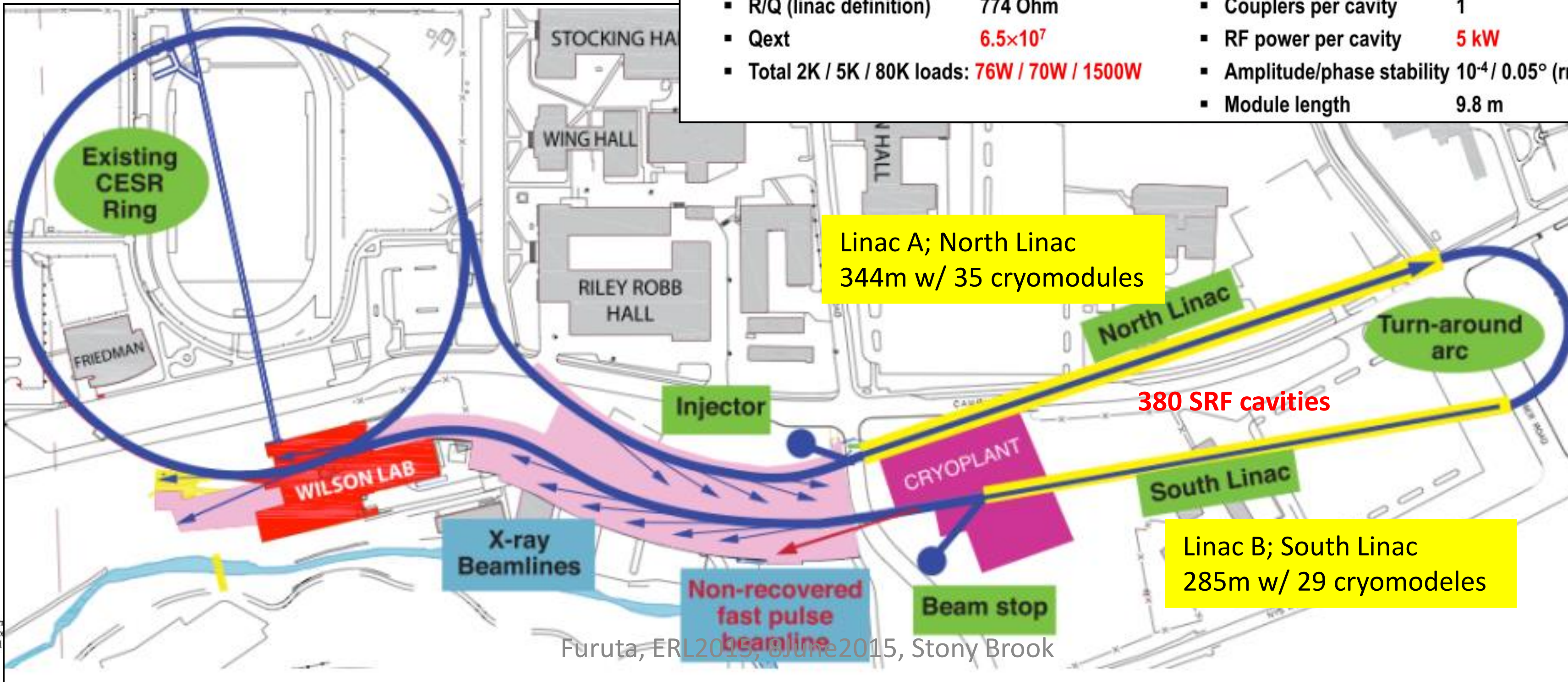
→ $P_{diss/cavity}$ ~ 11W.

Surface preparations

Bulk BCP + high temp. bake + light BCP + 120C bake + HF rinse.



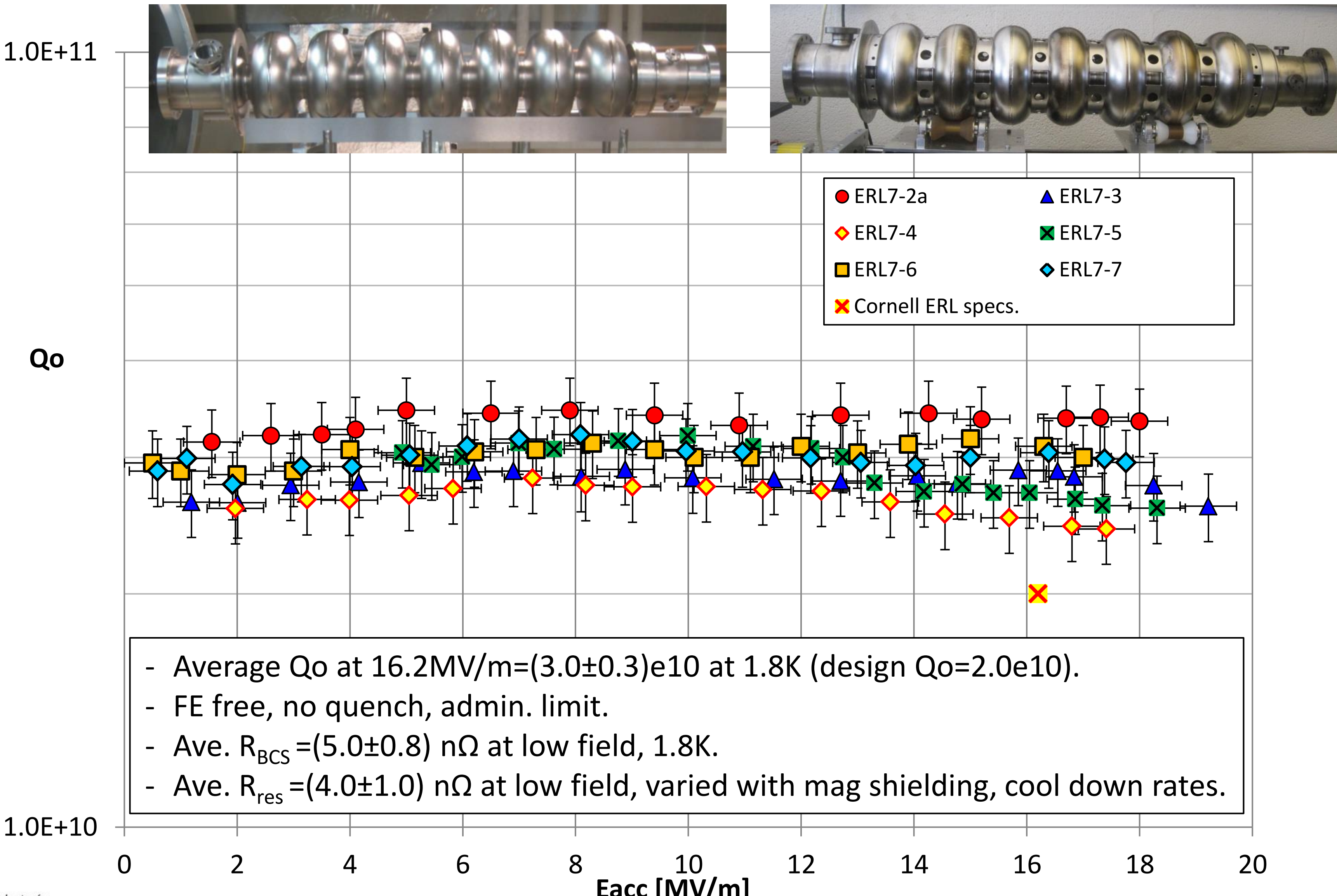
- Number of 7-cell cavities 6
- Acceleration gradient 16.2 MV/m
- R/Q (linac definition) 774 Ohm
- Qext 6.5×10^{7}
- Total 2K / 5K / 80K loads: 76W / 70W / 1500W
- Number of HOM loads 7
- HOM power per cavity 200 W
- Couplers per cavity 1
- RF power per cavity 5 kW
- Amplitude/phase stability 10^{-4} / 0.05° (rms)
- Module length 9.8 m



Linac A; North Linac
344m w/ 35 cryomodules

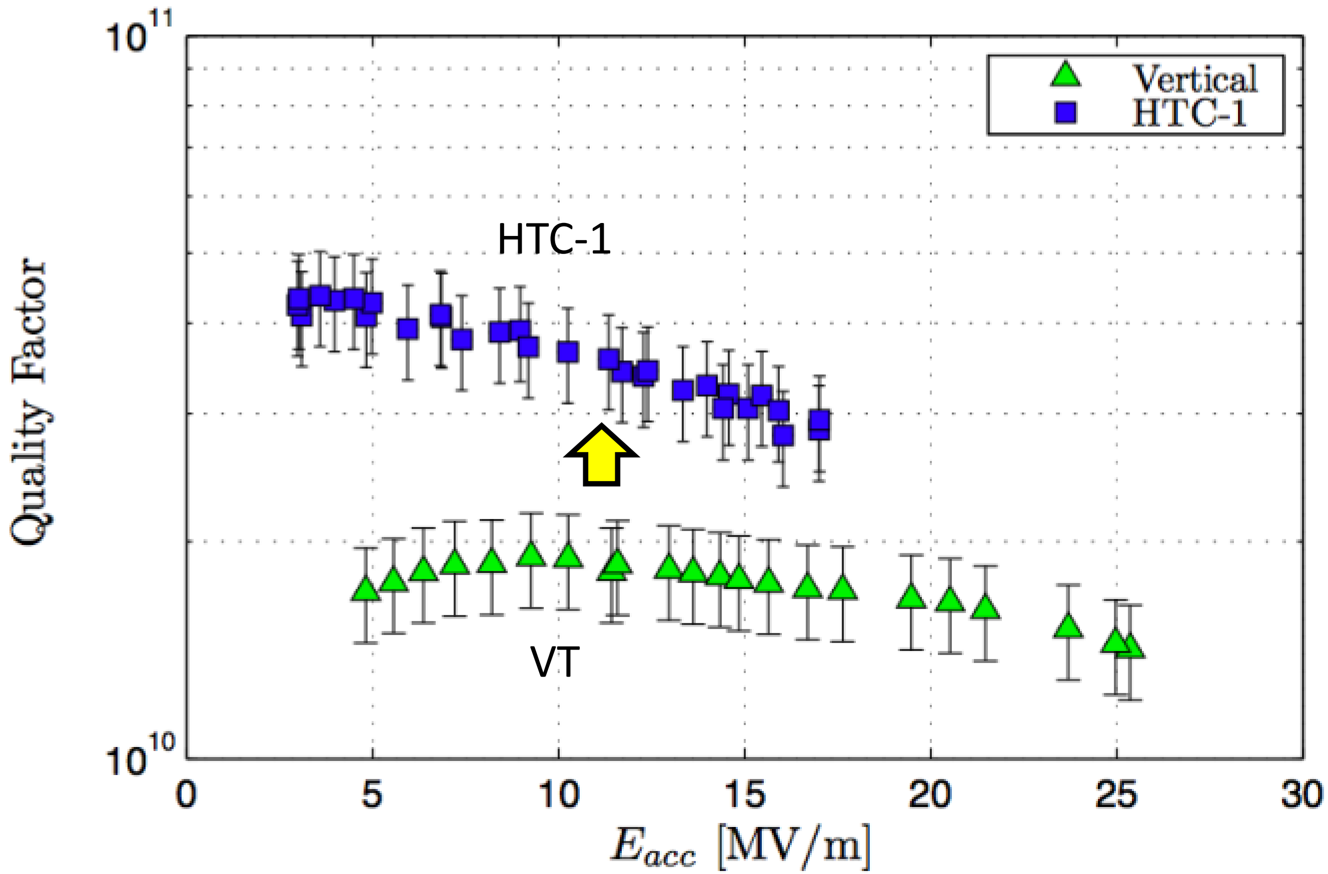
Linac B; South Linac
285m w/ 29 cryomodeles

ERL 7-cell VT achievements at 1.8K



- Average Qo at 16.2MV/m=(3.0±0.3)e10 at 1.8K (design Qo=2.0e10).
- FE free, no quench, admin. limit.
- Ave. R_{BCS} =(5.0±0.8) nΩ at low field, 1.8K.
- Ave. R_{res} =(4.0±1.0) nΩ at low field, varied with mag shielding, cool down rates.

Flux control w/ mag. shielding

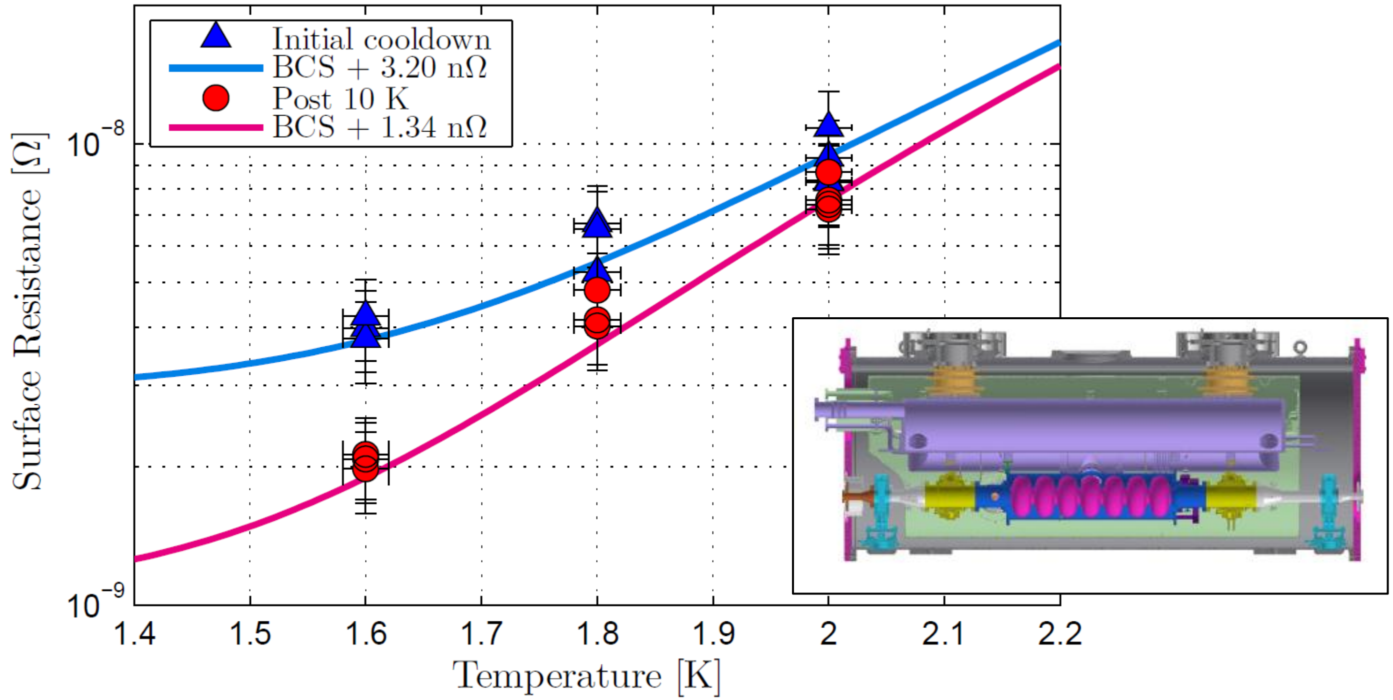


HTC has much better mag. shielding than VT dewar.
R_{res} was reduced from 11nOhm (VT) to 3.2nOhm (HTC-1)

Flux control w/ cool down

Initial cool down
R_{res}=3.2nOhm

Post thermal cycle
R_{res}=1.3nOhm



Initial Cooldown at 16.2 MV/m

Q_0(2.0 K) = 2.5 x 10^{10}
Q_0(1.8 K) = 3.5 x 10^{10}
Q_0(1.6 K) = 5.0 x 10^{10}

10 K thermal cycle at 16.2 MV/m

Q_0(2.0 K) = 3.5 x 10^{10}
Q_0(1.8 K) = 6.0 x 10^{10}
Q_0(1.6 K) = 10.0 x 10^{10}

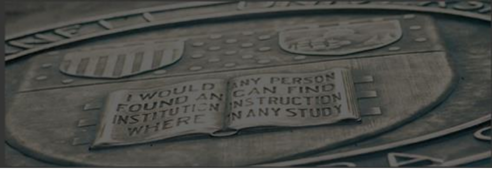
World record Qo in HT!!!

- Slow cool down rate through Tc; ~0.4K/h
- Small cavity temp. gradient; ~0.2K

N. Valles, TTC Topical Meeting on CW-SRF 2013

MLC status

MLC assembly was completed
Cool down will start July,
Measurement will be after
August.

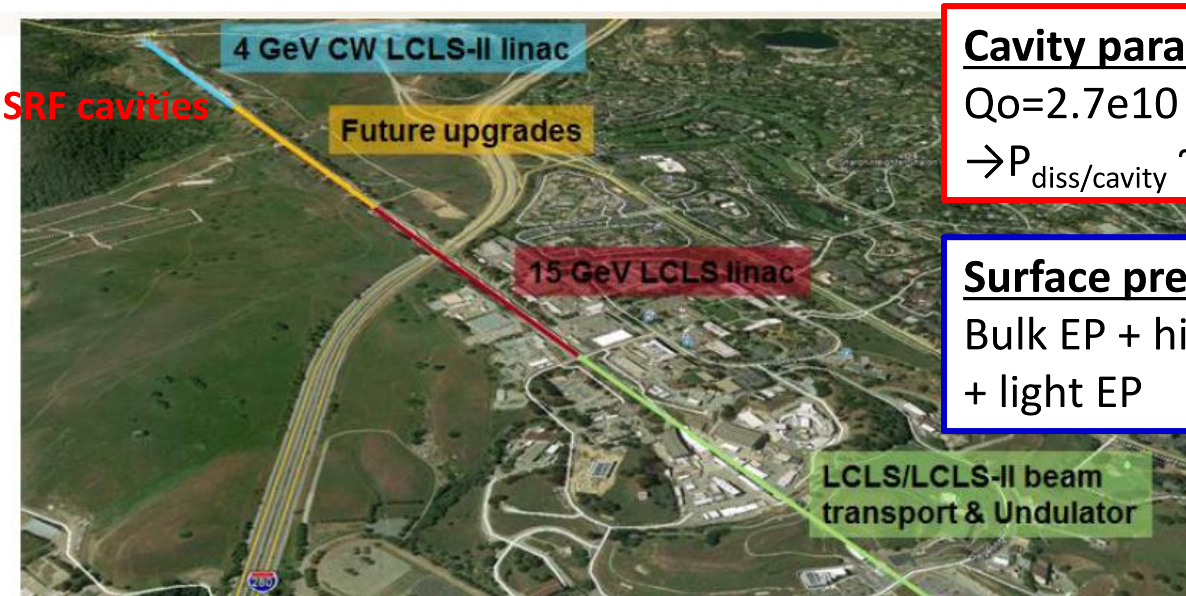


High-Q cavities R&D

Lesson 2. SLAC LCLS-II

SLAC LCLS-II

280 SRF cavities



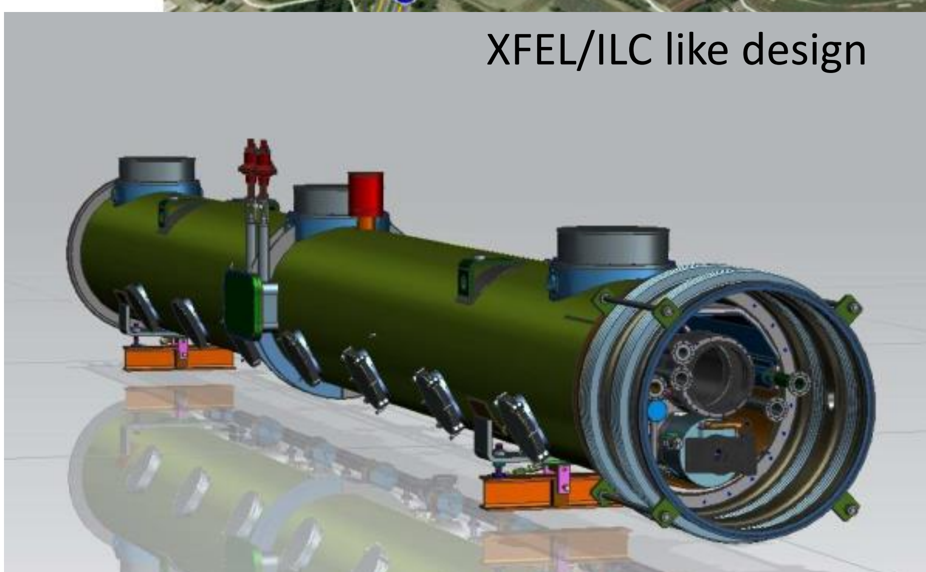
Cavity parameters

Qo=2.7e10 at Eacc=16MV/m, 2.0K

→$P_{diss/cavity}$ ~ 9W.

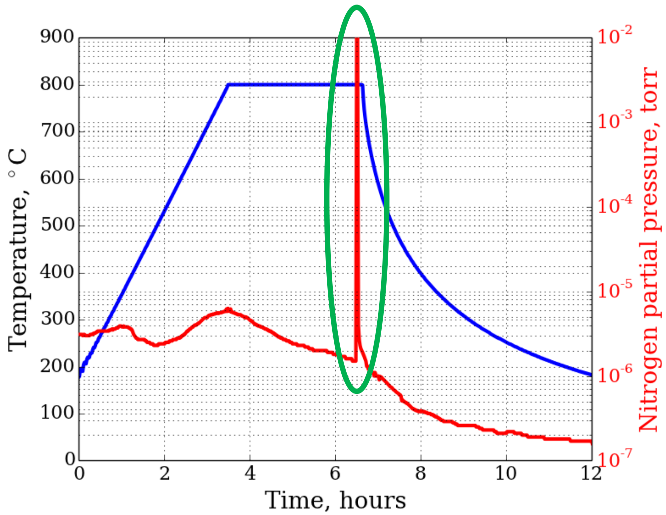
Surface preparations;

Bulk EP + high temp. bake w/ N2-dope + light EP

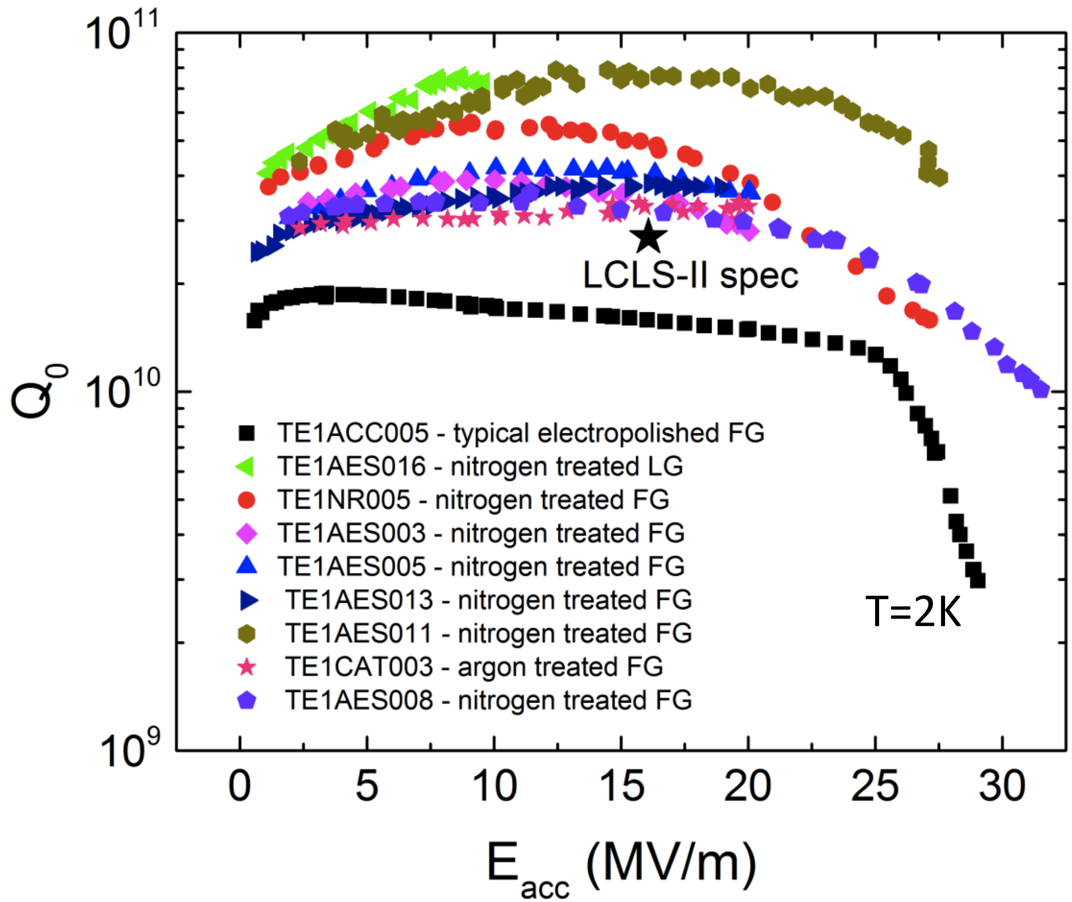


Fermilab	• 50% of cryomodules: 1.3 GHz • Cryomodules: 3.9 GHz • Cryomodule engineering/design • Helium distribution • Processing for high Q (FNAL-invented gas doping)
Jefferson Lab EXPLORING THE NATURE OF MATTER	• 50% of cryomodules: 1.3 GHz • Cryoplant selection/design • Processing for high Q
BERKELEY LAB	• Undulators • e- gun & associated injector systems
Argonne NATIONAL LABORATORY	• Undulator Vacuum Chamber • Also supports FNAL w/ SCRF cleaning facility • Undulator R&D: vertical polarization
Cornell University	• R&D planning, prototype support • processing for high-Q (high Q gas doping) • e- gun option

Nitrogen doping

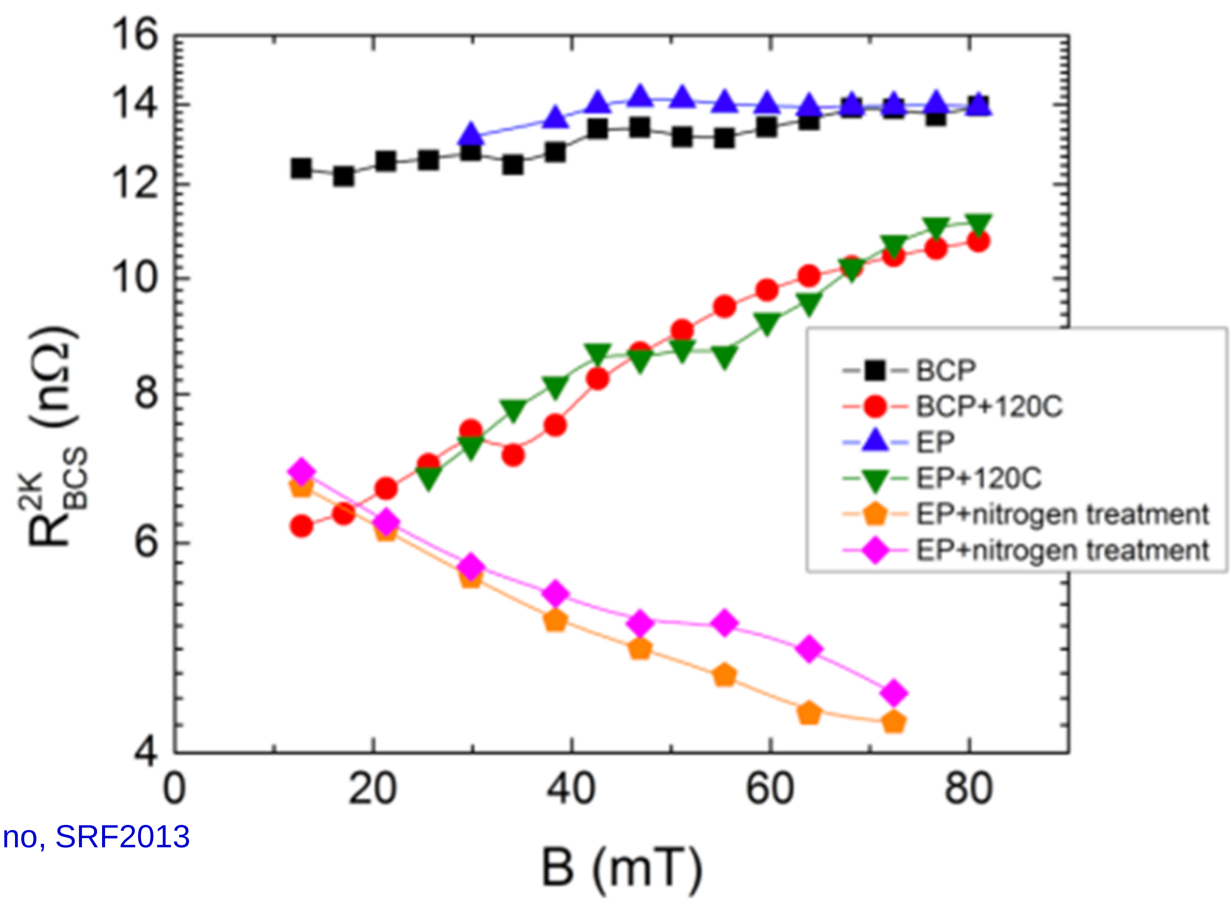


N2-dope parameter (FNAL)
N2 2min. ~20mTorr / 6min. Vac.



A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication) – selected for highlights of 2013

R_{BCS} vs. Surface finish



A. Grassellino, SRF2013

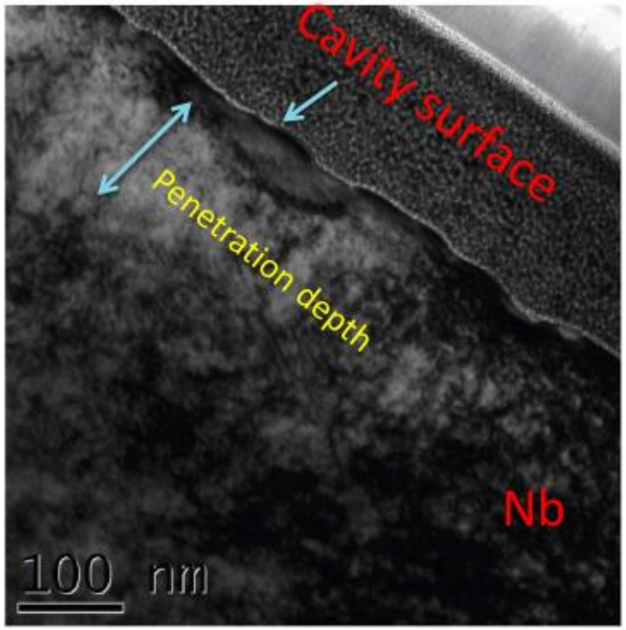
N2-dope provides much lower R_{BCS} than other surface finish in medium field.

Study on N-dope mechanism

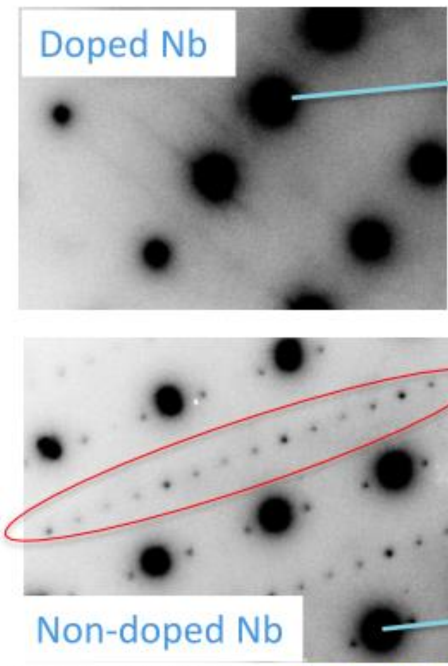
Nanostructural studies provide first clues

Y. Trenikhina (IIT/FNAL), A. Romanenko – to be published

TEM on FIB-prepared cutouts



Electron diffraction patterns from the penetration depth taken at 94K reveal the difference



Nb lattice

Secondary diffraction peaks appear signalling the formation of lossy niobium hydrides

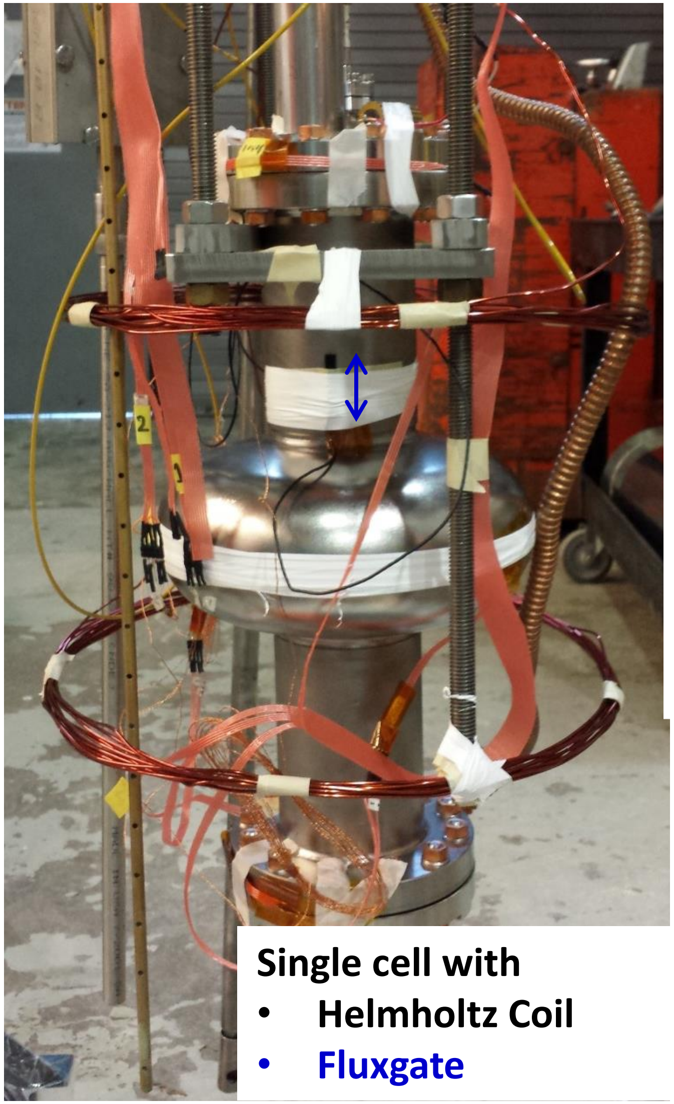
Nb lattice

- Hydrides may be the cause of the medium and high field Q slopes [see A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, 2013 Supercond. Sci. Technol. 26 035003]
- Nitrogen doping may fully trap hydrogen => only intrinsic Nb behavior is then manifested?

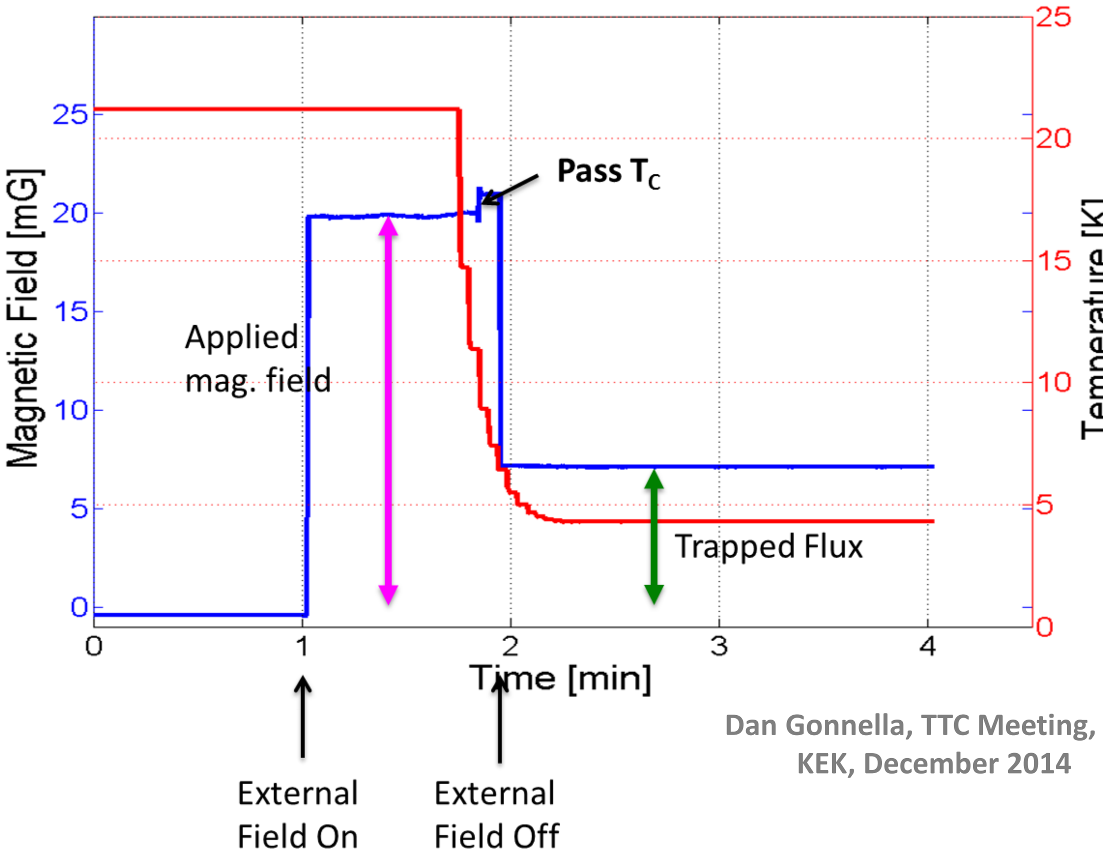
Fermilab

A. Romanenko, LINAC'2014

Flux control R&D for low R_{res}



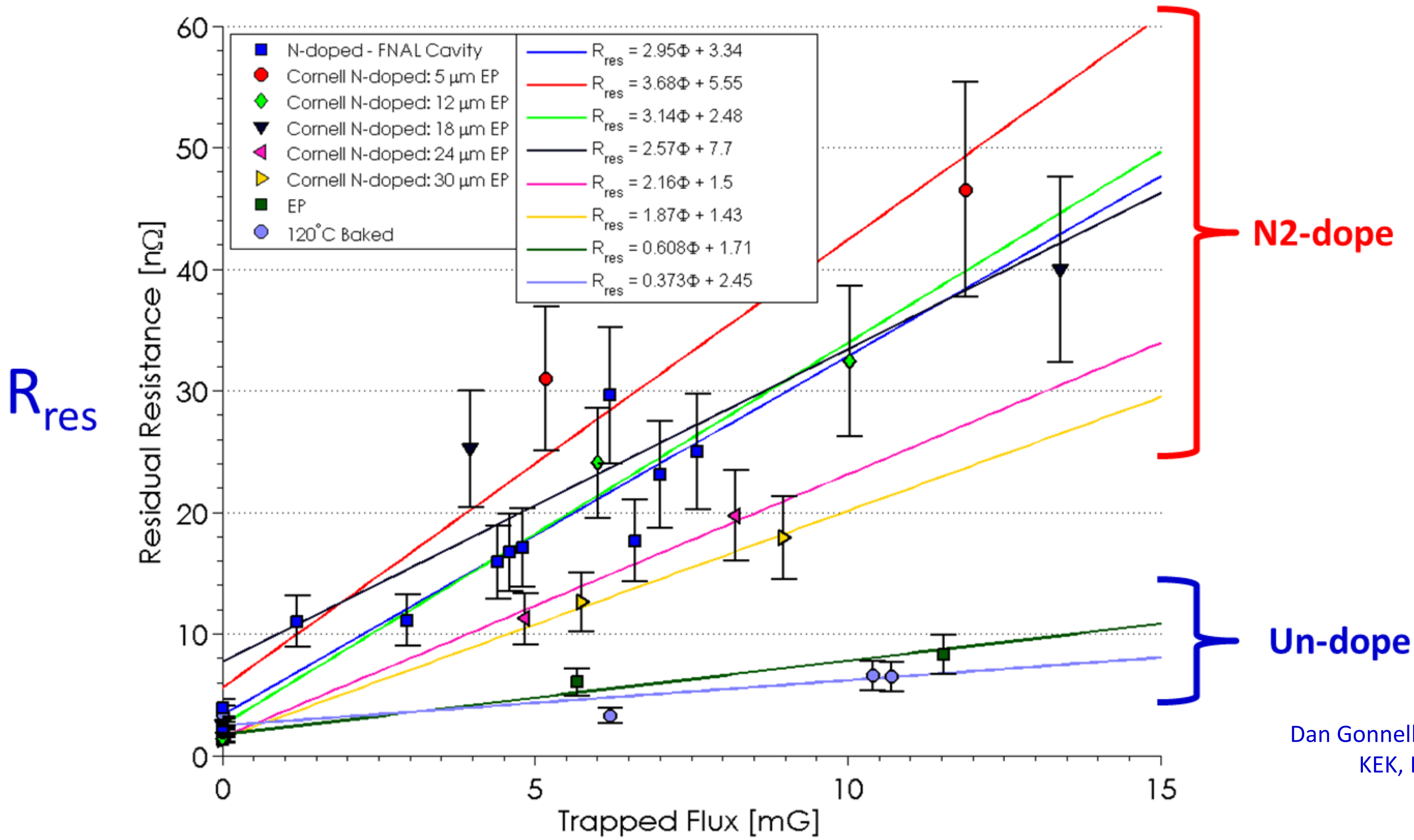
Single cell with
- Helmholtz Coil
- Fluxgate



Dan Gonnella, TTC Meeting, KEK, December 2014

Applied mag field vs. Trapped flux was measured under the different conditions cooling.

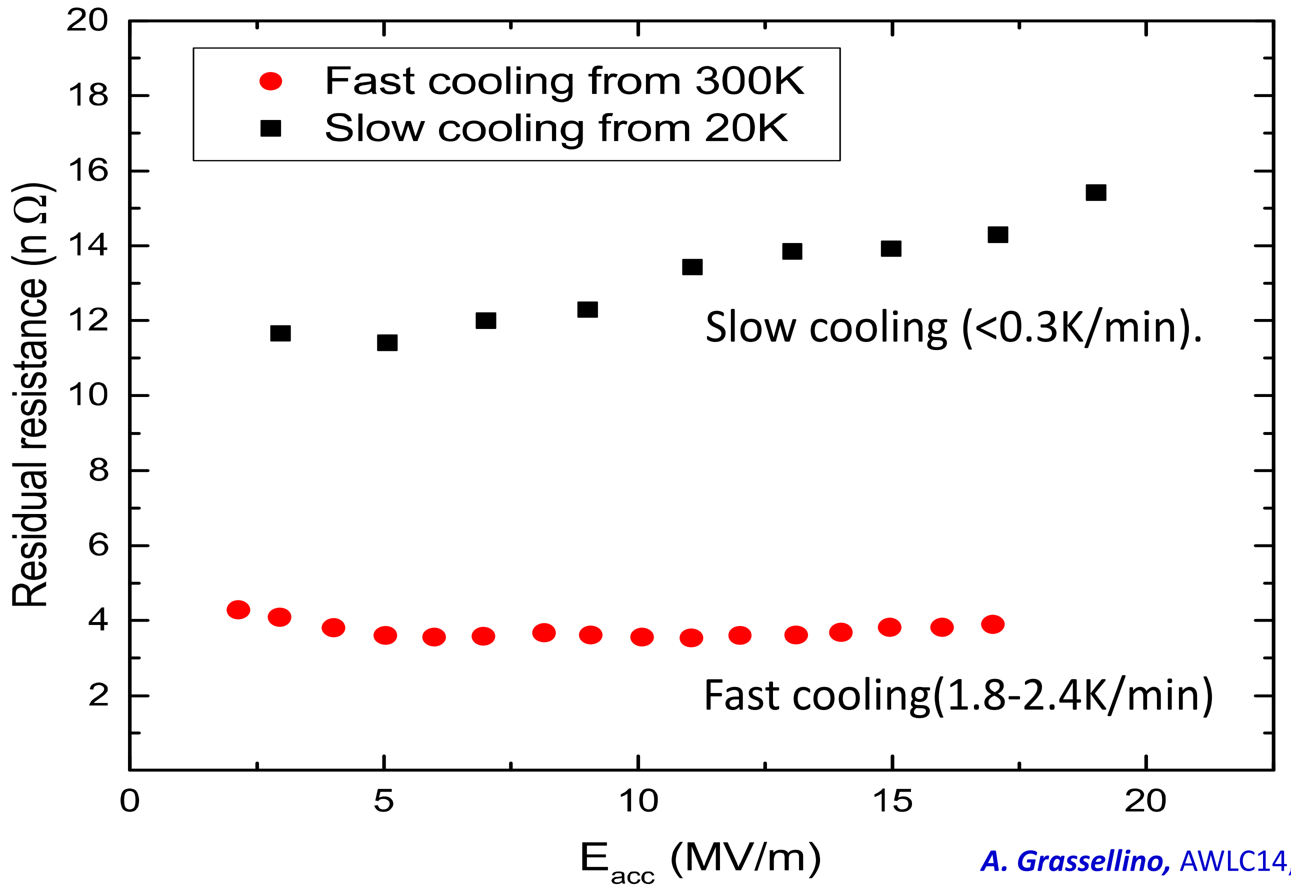
Sensitivities of flux trapping



Dan Gonnella , TTC Meeting, KEK, December 2014

Trapped flux contributes stronger to R_{res} in N2-doped cavities than un-doped cavities. R_{res} in N-doped is sensitive on flux trapping.

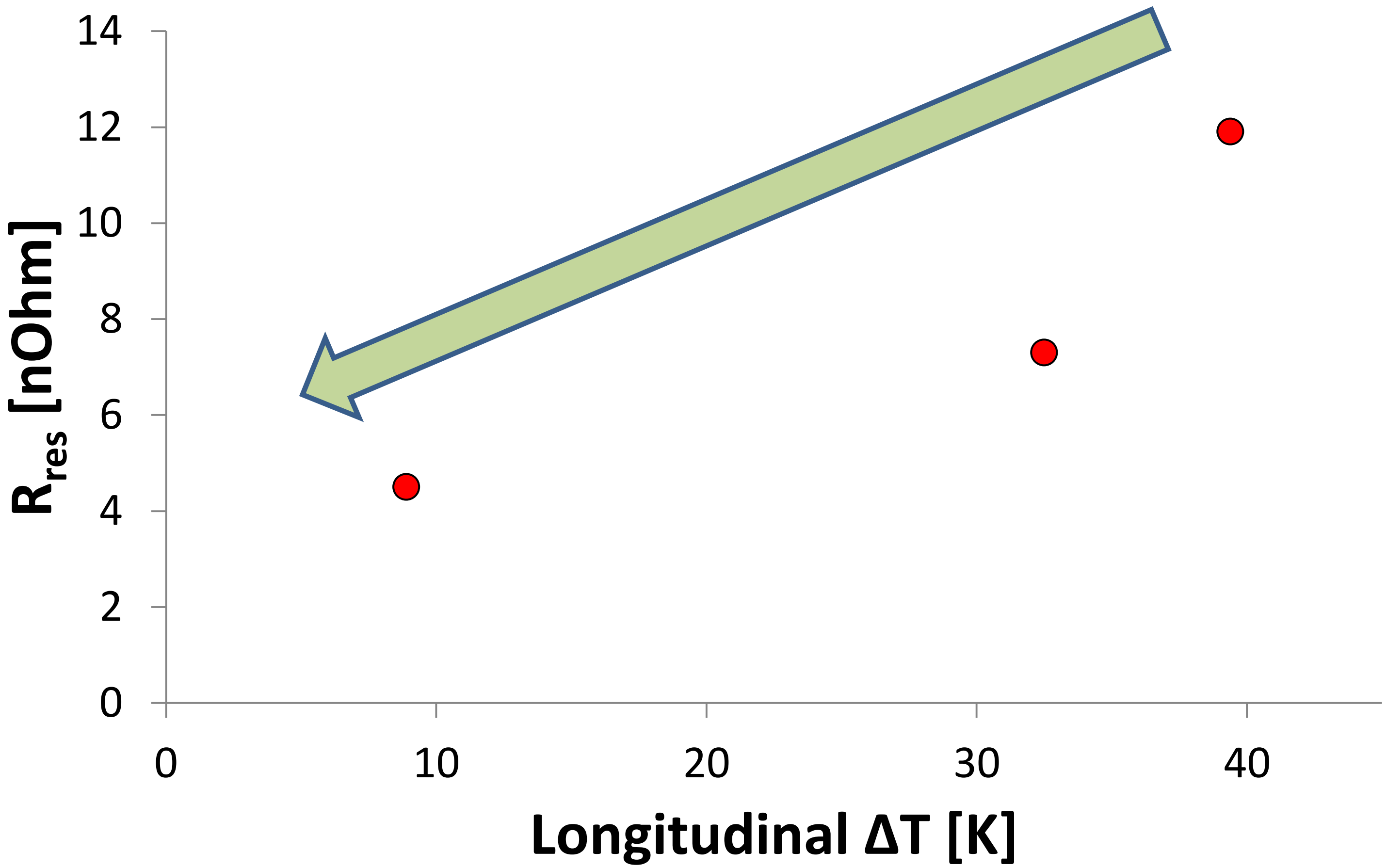
Flux control with cool down



A. Grassellino, AWLC14, Fermilab May 13th 2013

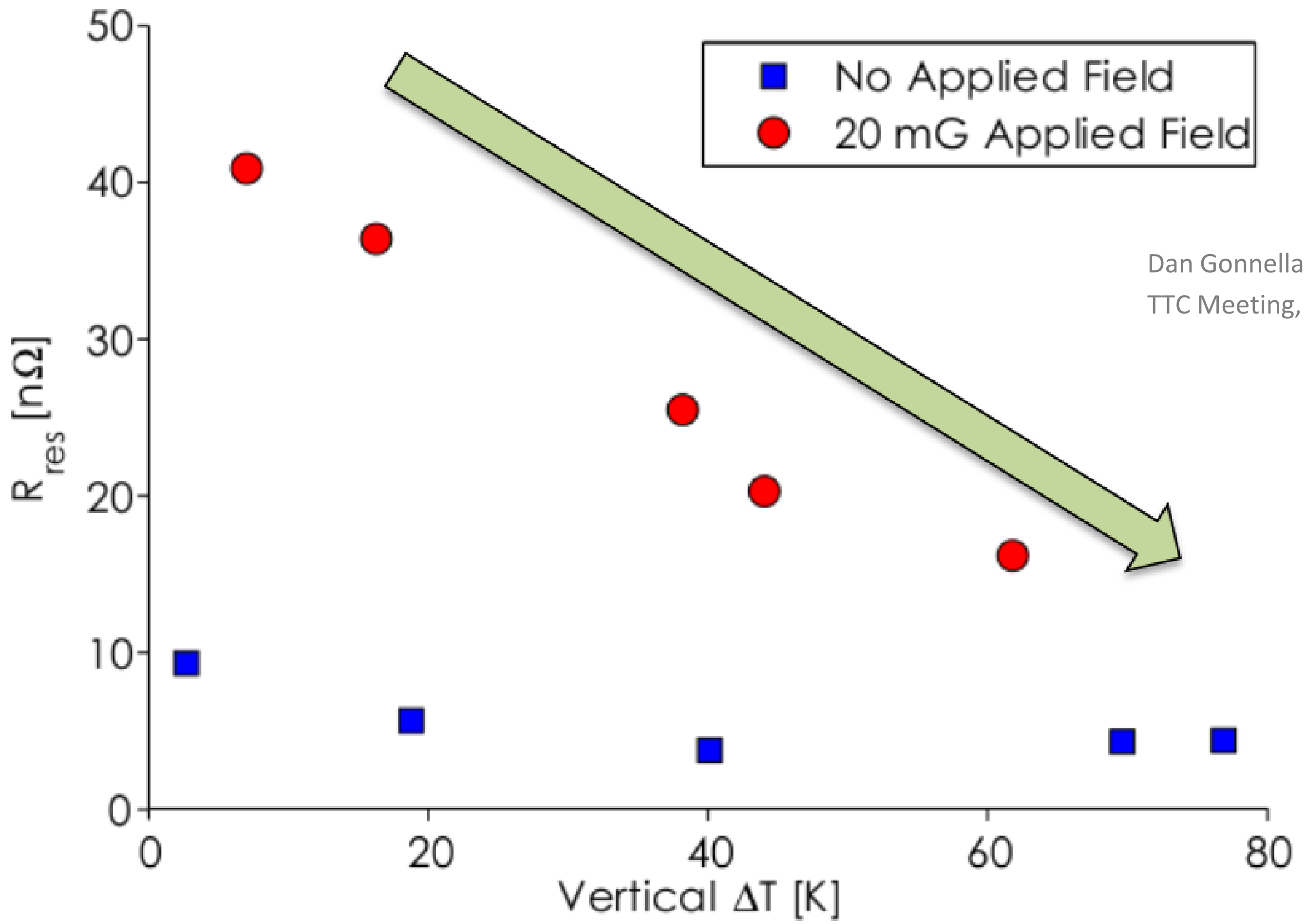
Fast cooling gives N2-doped cavities lower R_{res} (higher Qo) than Slow cooling.

Flux control with dT_{long} in HTC



Small longitudinal temperature gradients suppress thermo currents, and give **lower residual resistance**.

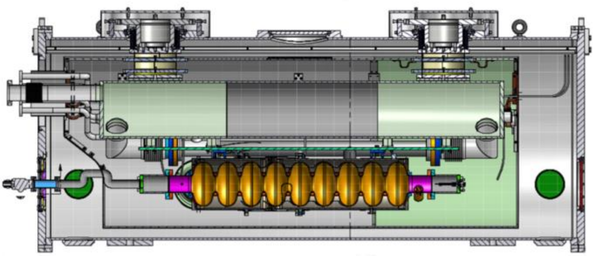
Flux control with dT_{vert} in HTC



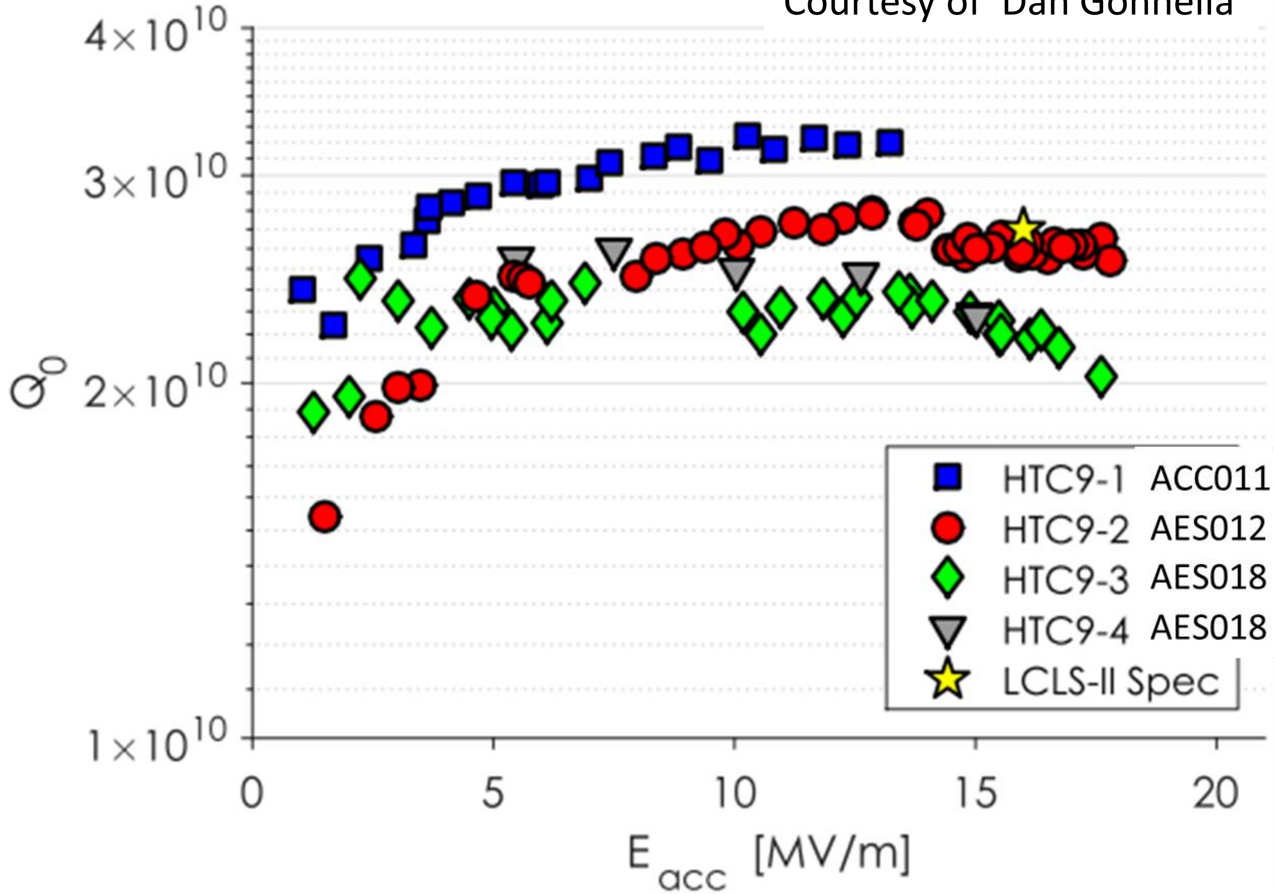
Dan Gonnella for the Cornell Team
TTC Meeting, KEK, December 2014

large vertical temperature gradients give more flux expulsion and **lower residual resistance**.

N_2-doped 9-cells in HTC at Cornell

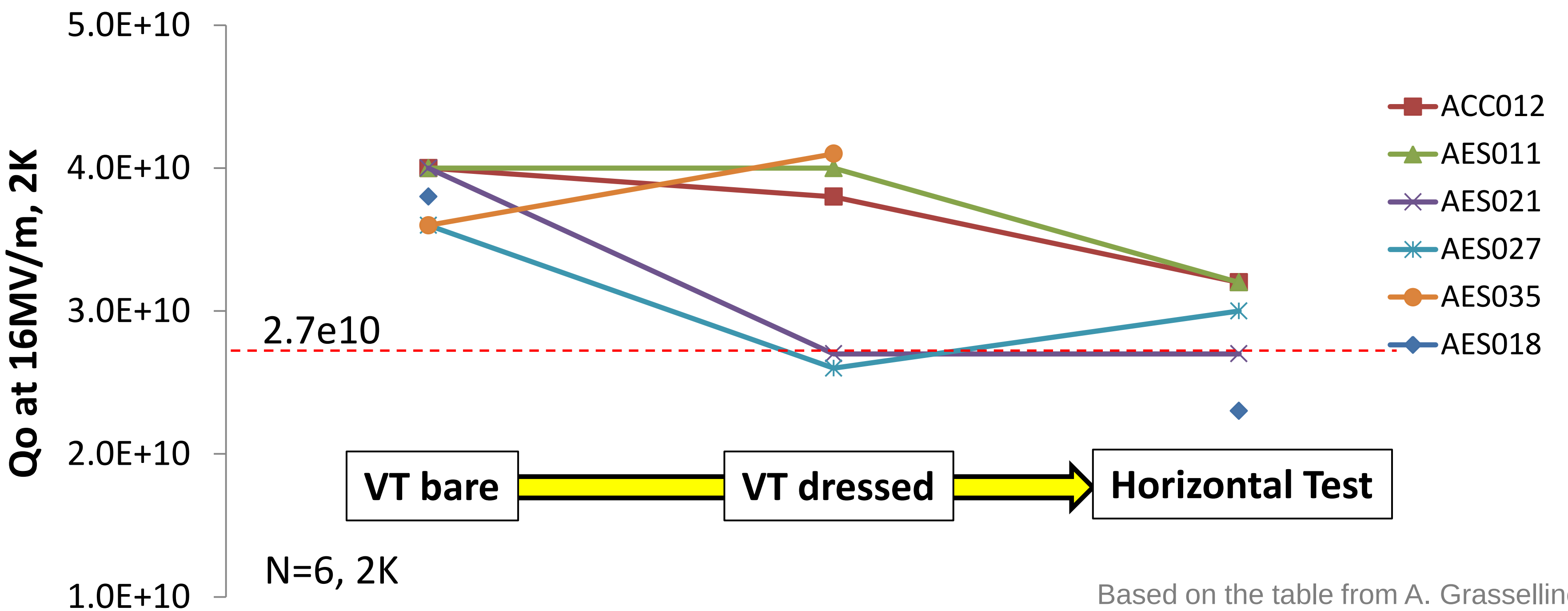


Courtesy of Dan Gonnella



- Cornell has completed four HTC tests with success so far.
- HTC9-5 assembly with high power coupler, tuner, and HOM antennas is ongoing, will be tested in July.

Qo preservation from VT to HT



Based on the table from A. Grassellino
TTC working group 23 Apr 2015

- LCLS-II specs have been achieved during horizontal tests.
- Q-degradation (~2nOhm increase in Rs) have been seen between initial VT and horizontal test. It seems to be caused by surface oxidation during the long duration of HPR.

Optimization for highest-Q

- Different surface finishes require different flux controls to minimize R_{res}, especially on cool down procedures.

	Cornell ERL	SLAC LCLS-II
1.3GHz SRF cavity	7-cell	9-cell
Highest Qo in HT at 16MV/m, 2K	3.5e10	3.2e10
Estimated $P_{diss/cell}$ at 16MV/m, 2K	0.9W	0.9W
Surface finish	120C bake + HF rinse	N2-dope
Cool down	Slow cool with minimized ΔT over cavity	Fast cool with minimized longitudinal ΔT large verica ΔT
Trapped flux effect	Not sensitive	High sensitive

Summary

- High-Q cavity challenges on Cornell ERL and SLAC LCLS-II have been done successfully by the optimized combinations of R_{BCS} and R_{res} control.
- R_{BCS} is determined by surface finishing, especially Nitrogen doping gives lower R_{BCS} than EP'ed or BCP'ed surface in medium field.
- Flux control is essential for lower R_{res} . Depends on the surface finish, optimized cool down procedures are required in horizontal cryomdules.
- Preserving high-Q performance from bare to dressed cavity, and vertical to horizontal test has been demonstrated successfully. Small Q-degradations were caused by surface oxidation during the long duration of HPR.
- High-Q of >3e10 at 2K in medium field is in hand now with high yield at horizontal test.

High-Q surprise!!

Thank you for your attentions.