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

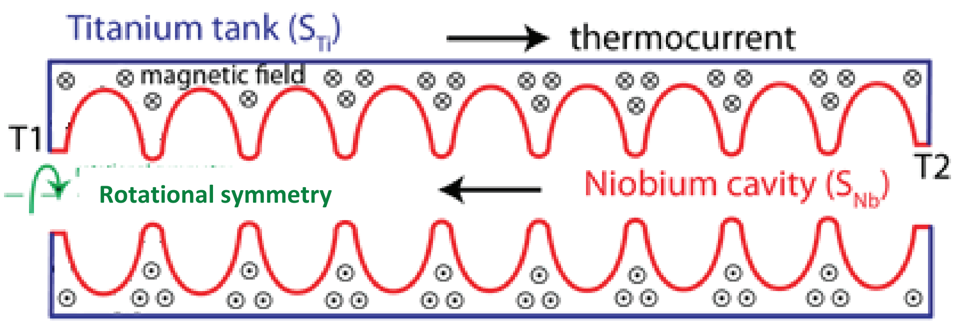
$$R_S(T,B) = R_{BCS}(T,B) + R_{residual}(B)$$

- 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

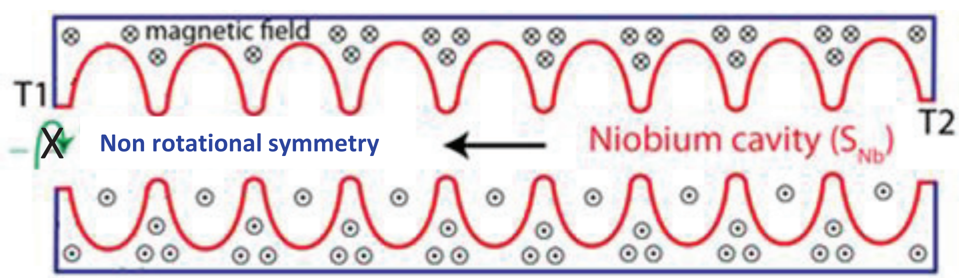
⇨ Depends on the surface finishing,
the best way of flux control will be different.

Thermo currents effect

- Different Seebeck coefficients for Nb and Ti



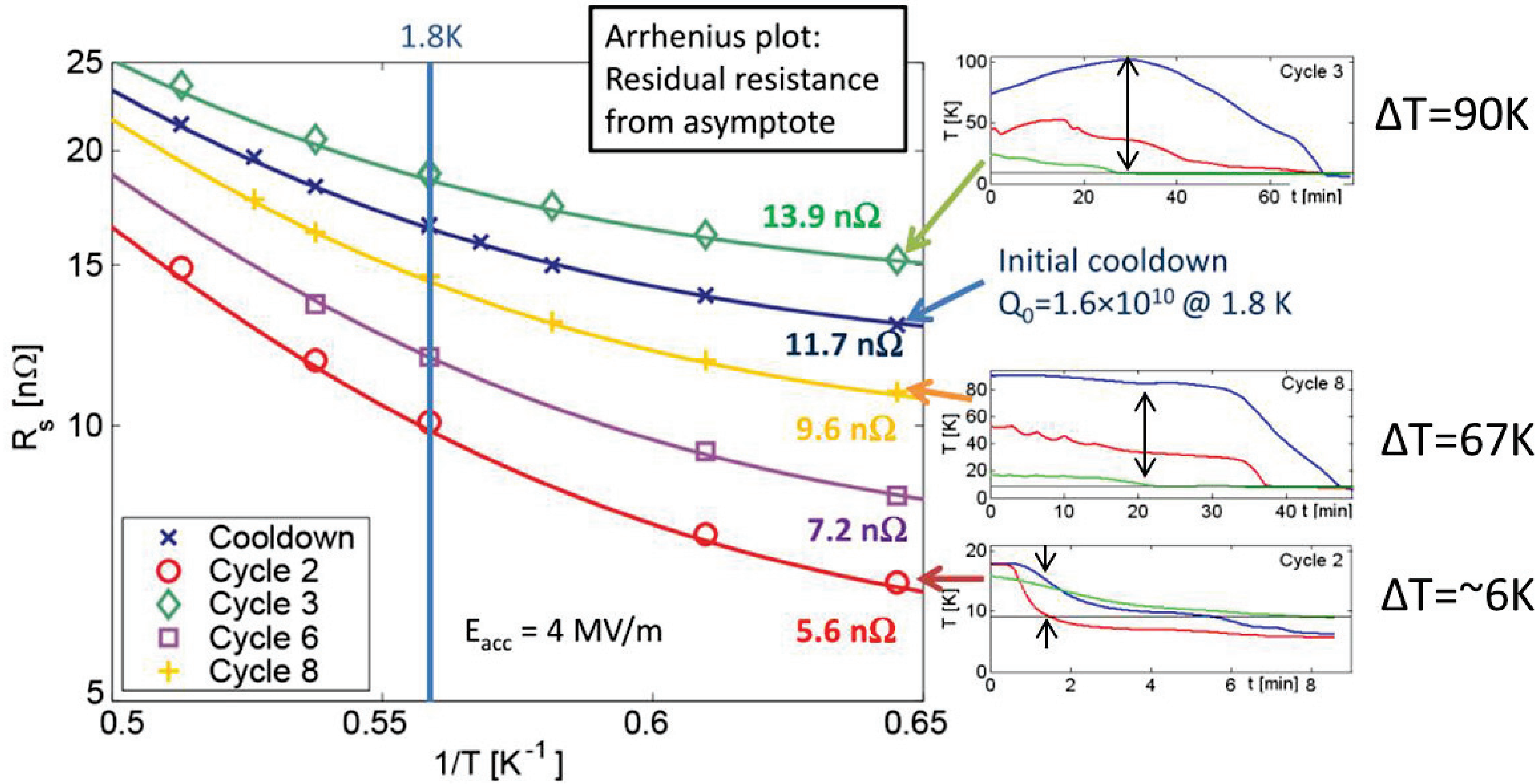
$$U_{thermo} = (S_{Niobium} - S_{Titanium}) \cdot \Delta T$$



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

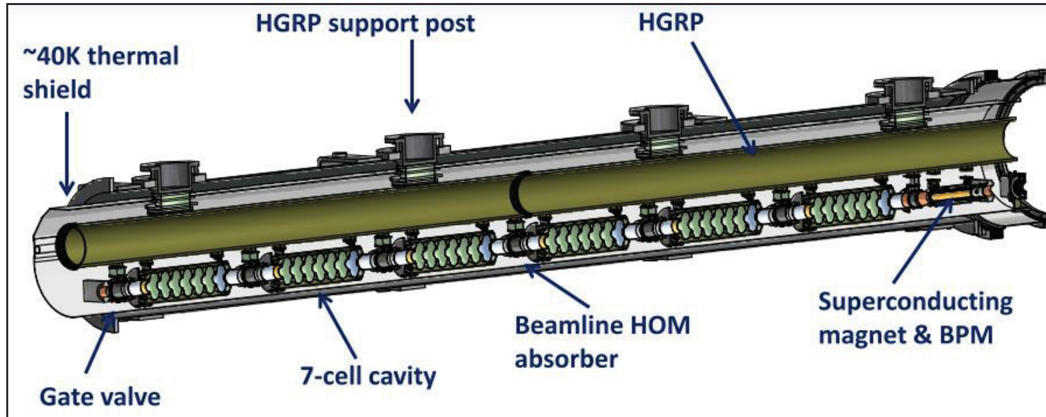
Cavity parameters

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

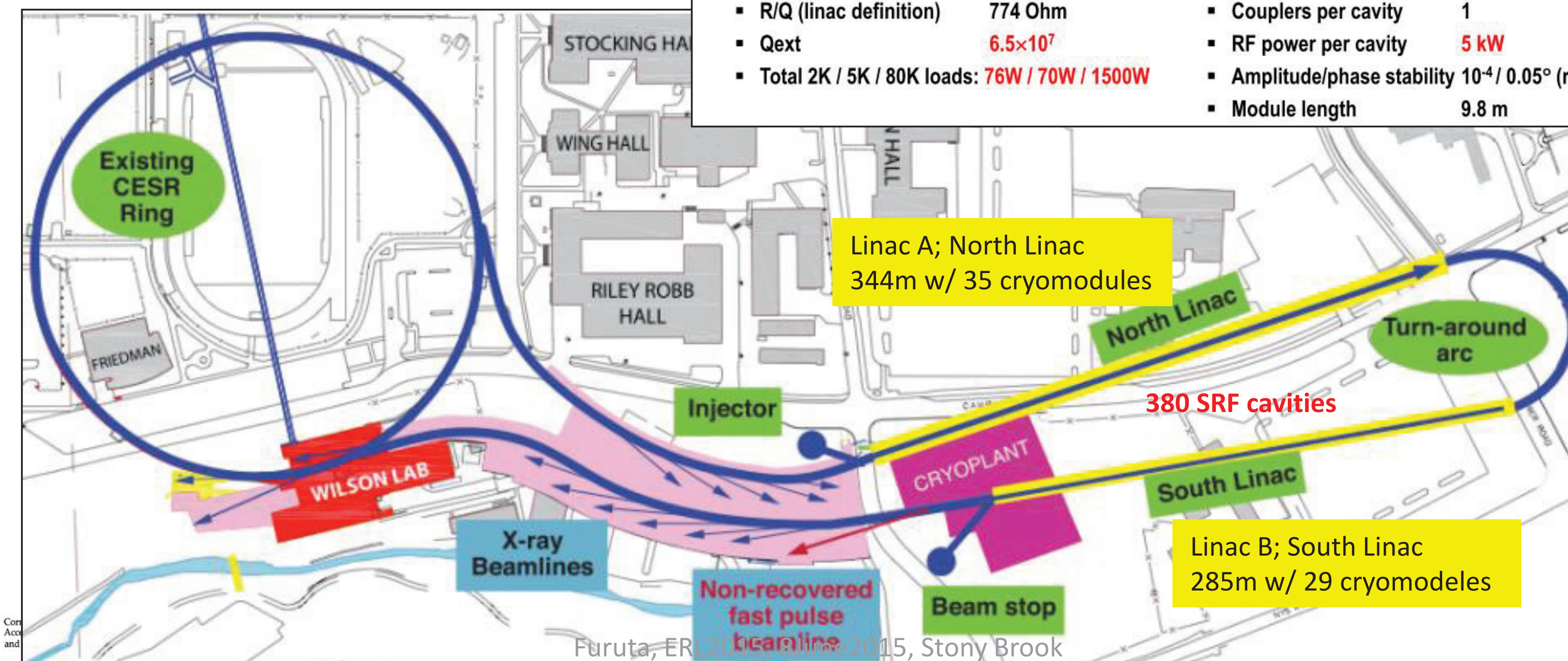
→ $P_{diss/cavity}$ ~ 11W.

Surface preparations

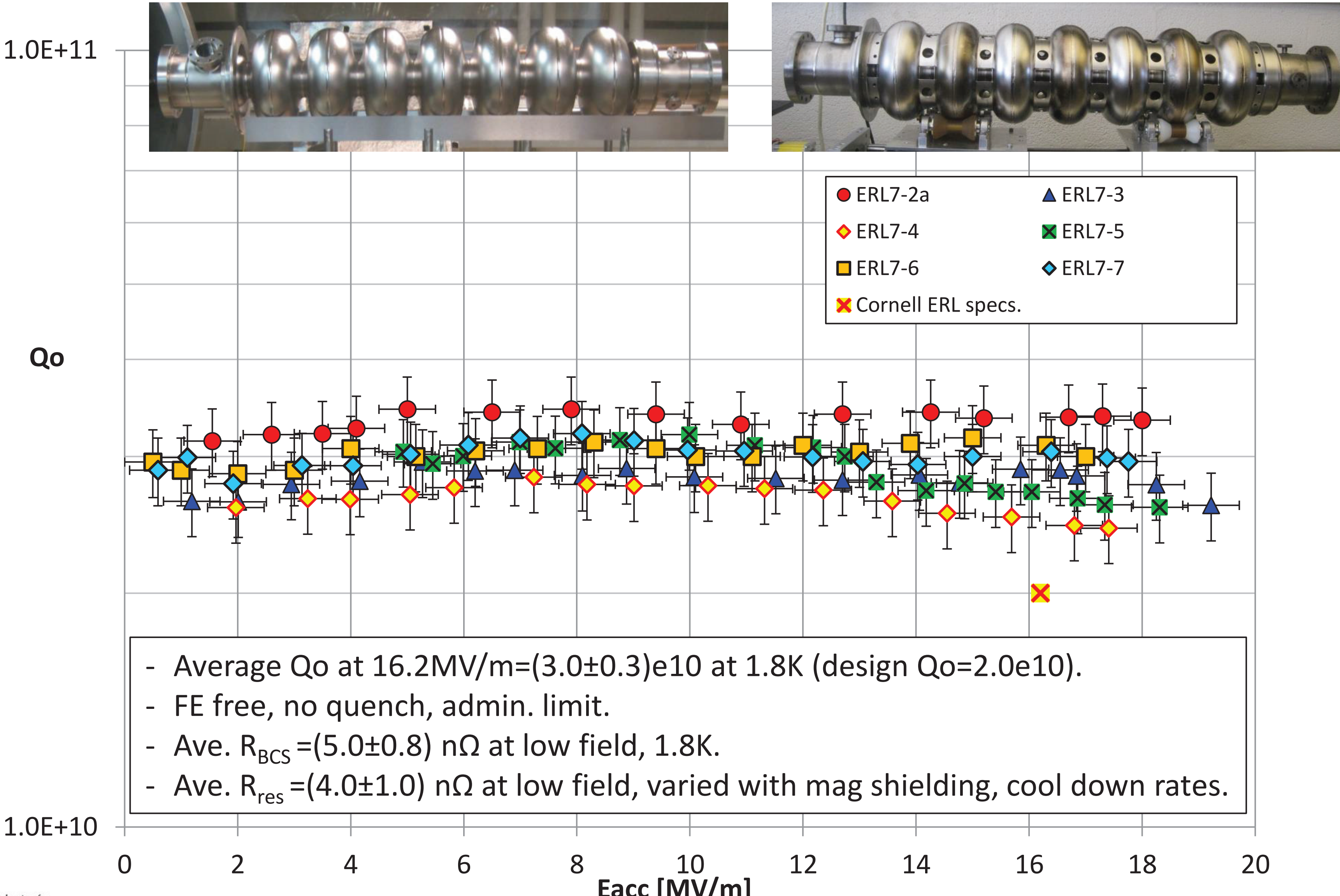
Bulk BCP + high temp. bake + light BCP + 120C bake + HF rinse.



- 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

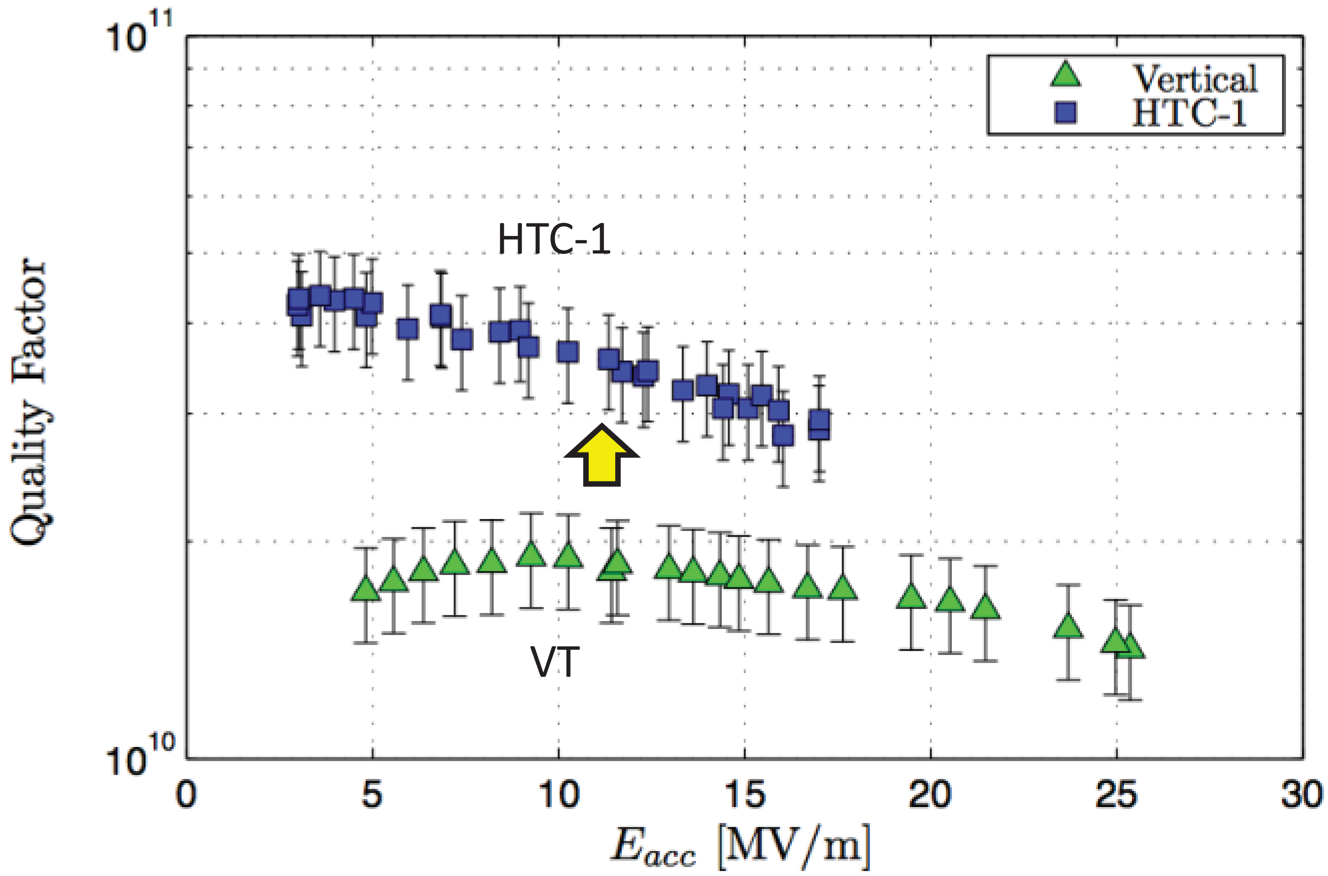


ERL 7-cell VT achievements at 1.8K



- 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



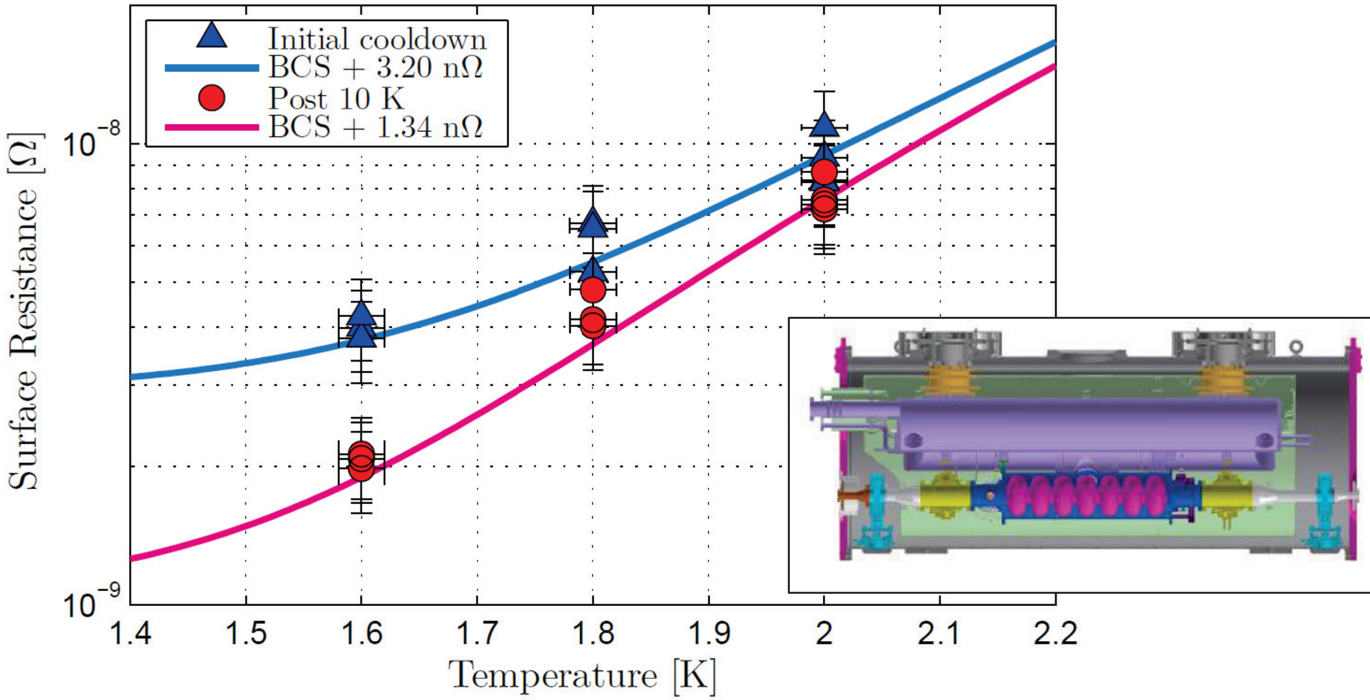
HTC has much better mag. shielding than VT dewar.

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

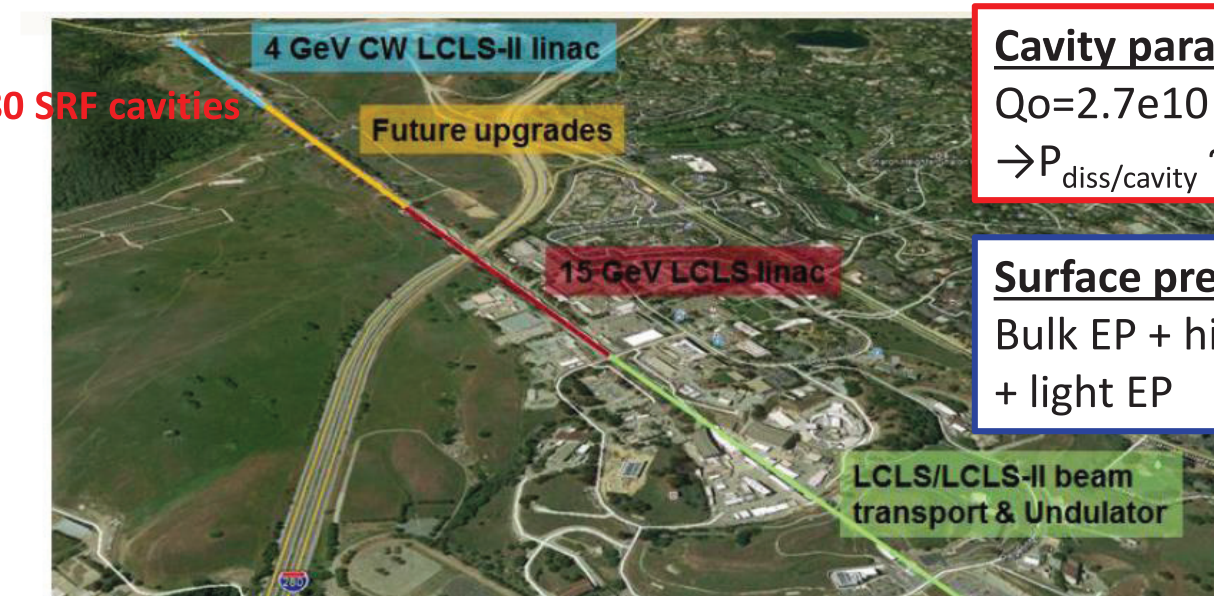
MLC assembly was completed
Cool down will start July,
Measurement will be after August.

High-Q cavities R&D

Lesson 2. SLAC LCLS-II

SLAC LCLS-II

280 SRF cavities



Cavity parameters

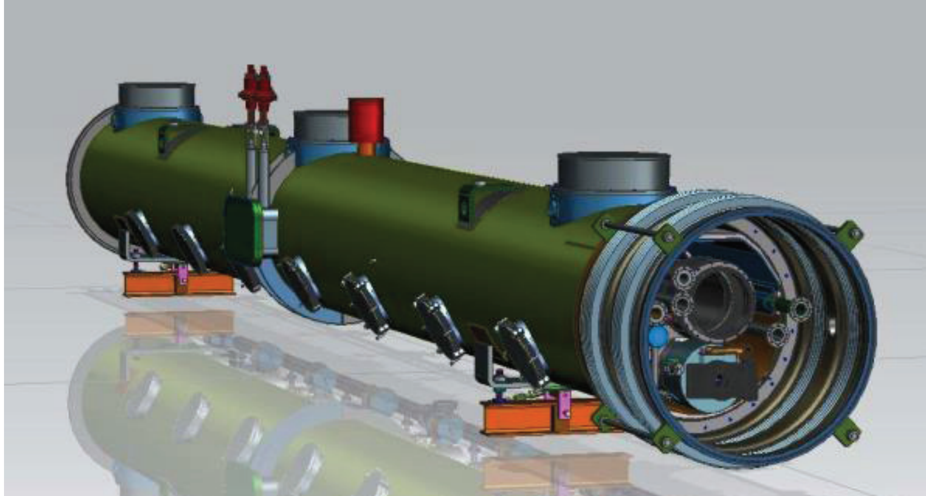
Qo=2.7e10 at Eacc=16MV/m, 2.0K

→$P_{diss/cavity}$ ~ 9W.

Surface preparations;

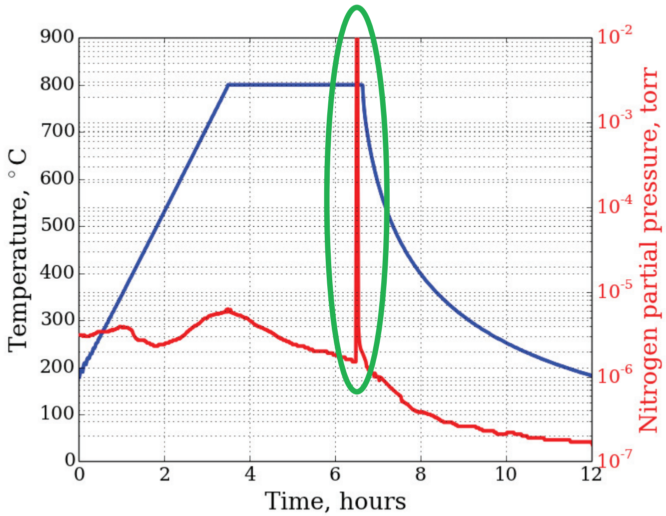
Bulk EP + high temp. bake w/ N2-dope + light EP

XFEL/ILC like design

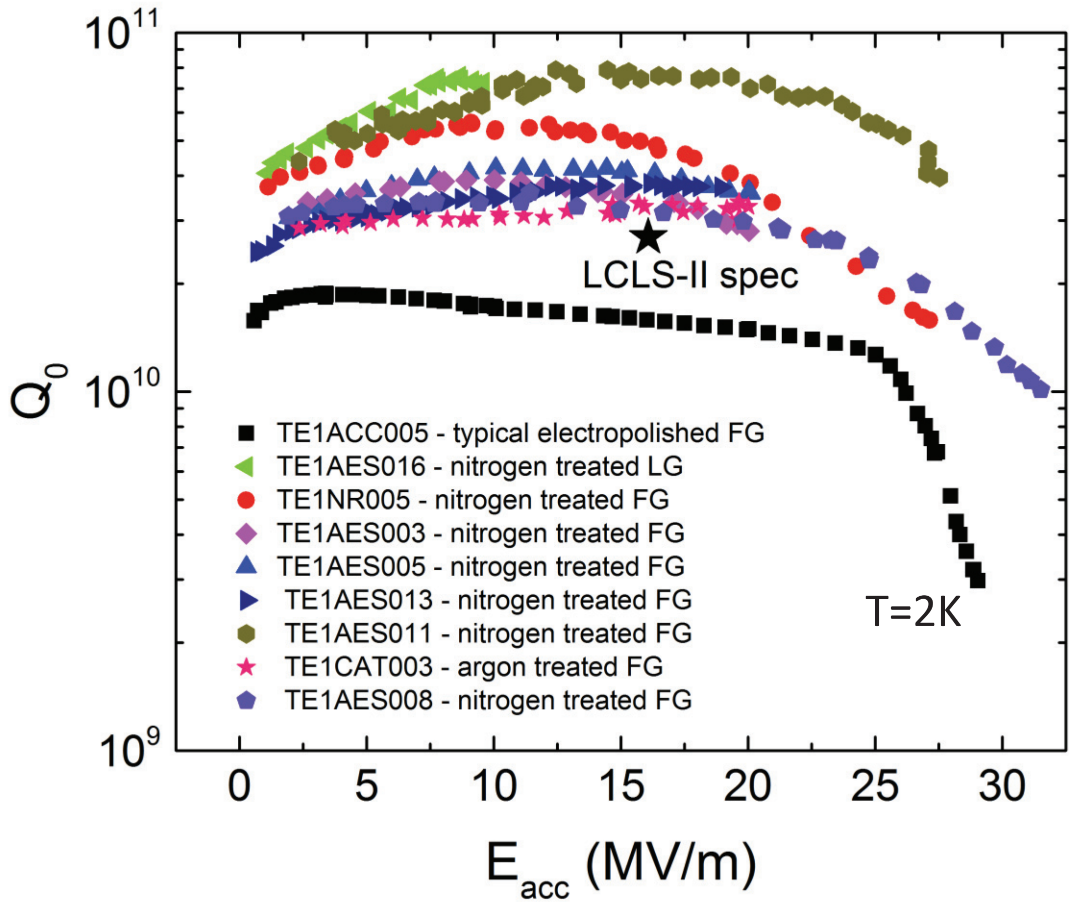


Fermilab	• 50% of cryomodules: 1.3 GHz • Cryomodules: 3.9 GHz • Cryomodule engineering/design • Helium distribution • Processing for high Q (FNAL-invented gas doping)
Jefferson Lab EXPLORING THE NATURE OF MATTER	• 50% of cryomodules: 1.3 GHz • Cryoplant selection/design • Processing for high Q
BERKELEY 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

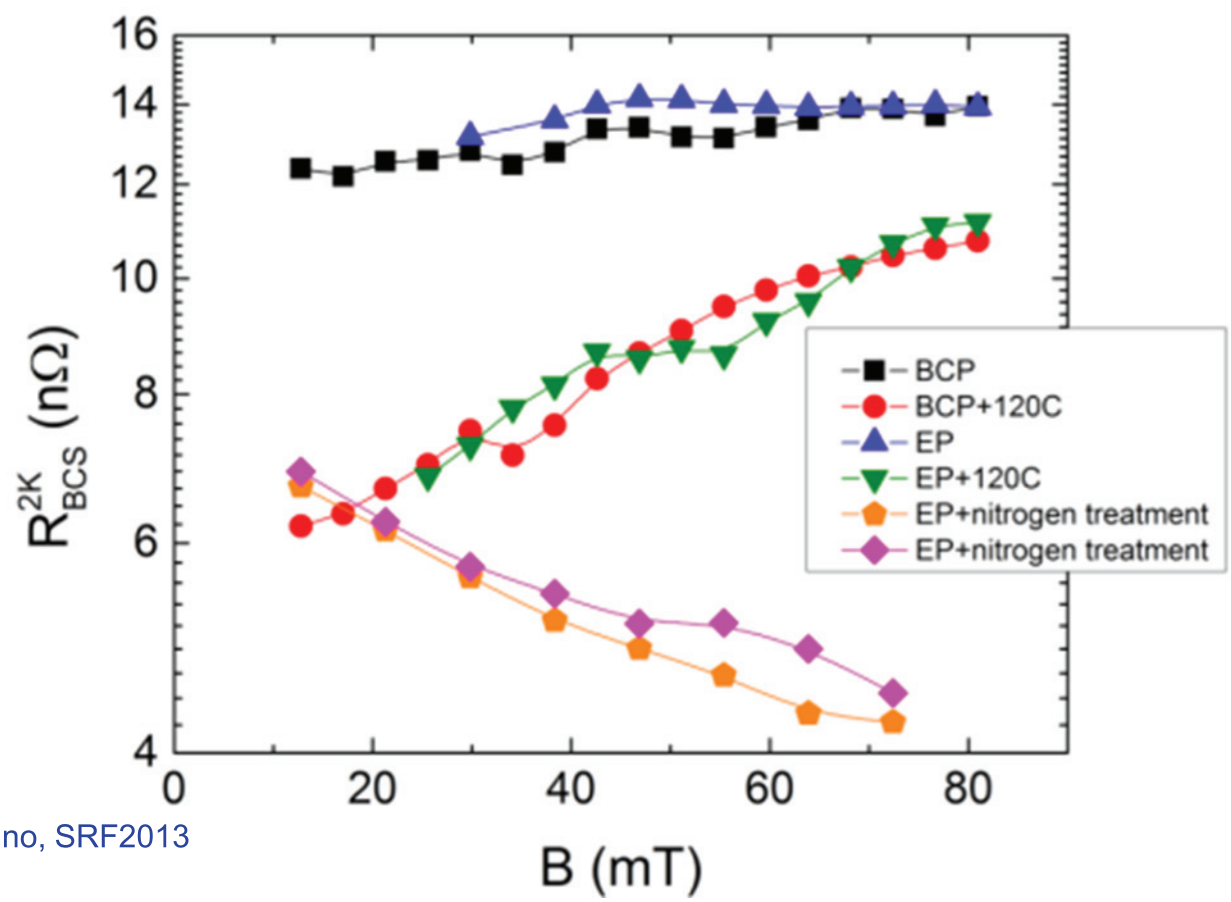


N2-dope parameter (FNAL)
N2 2min. ~20mTorr / 6min. Vac.



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

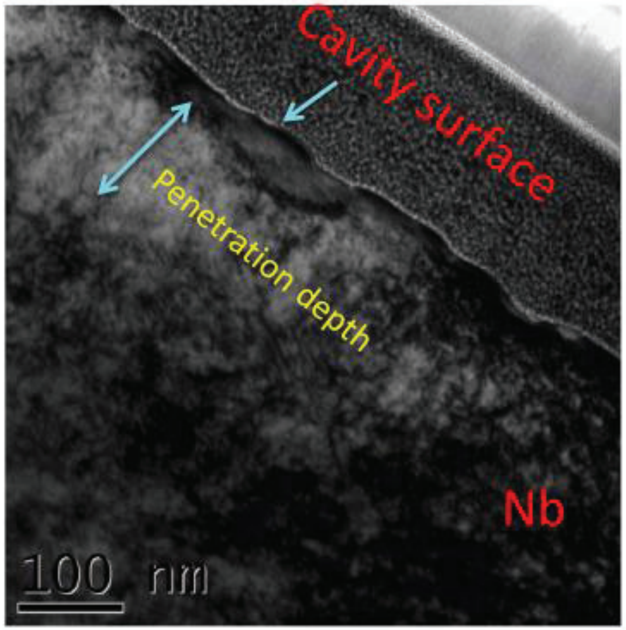
N2-dope provides much lower R_{BCS} than other surface finish in medium field.

Study on N-dope mechanism

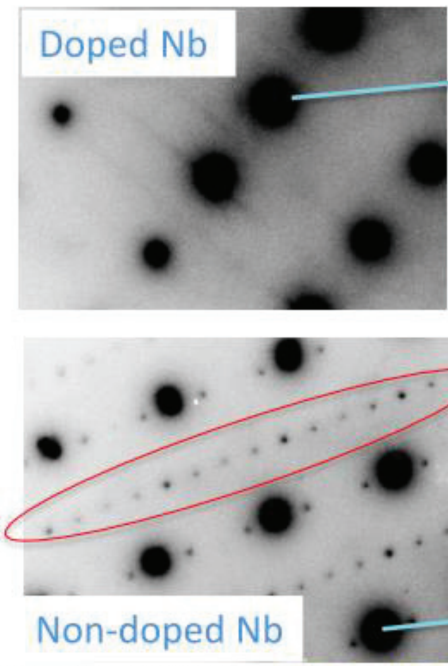
Nanostructural studies provide first clues

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

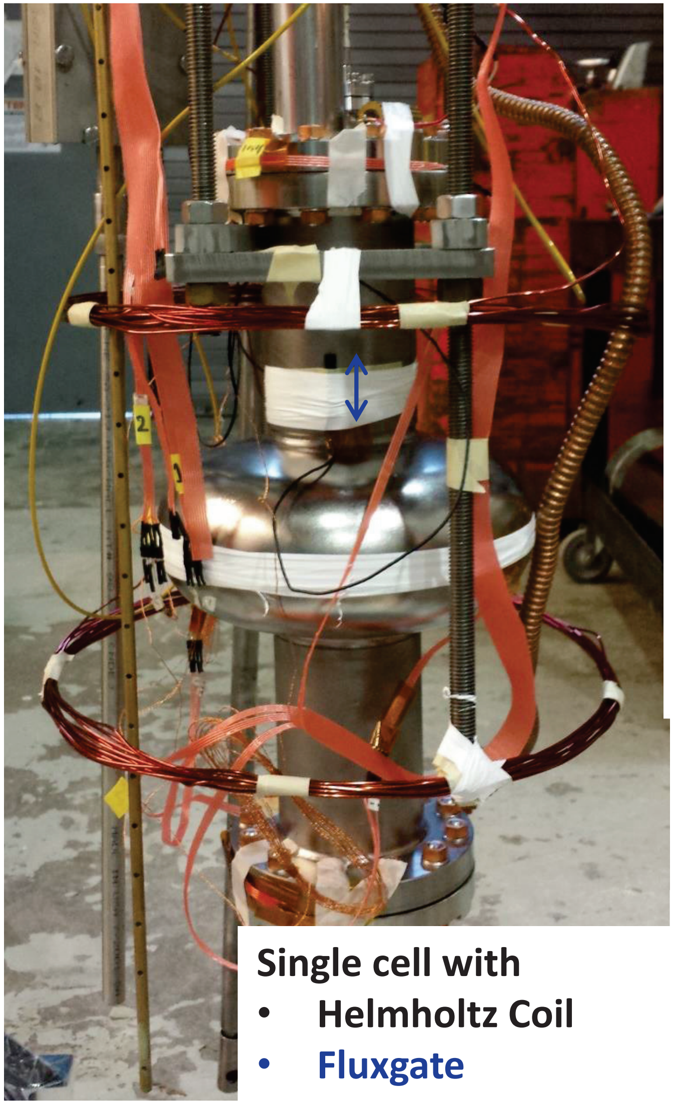
Nb lattice

- 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?

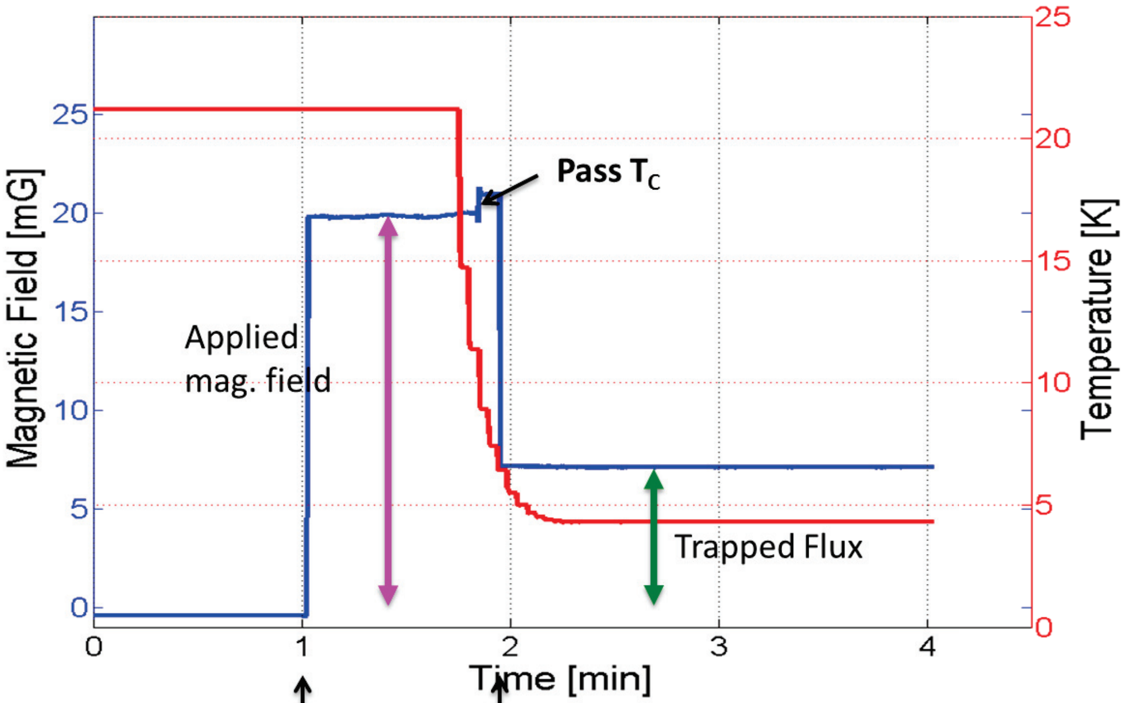
Fermilab

A. Romanenko, LINAC'2014

Flux control R&D for low R_{res}



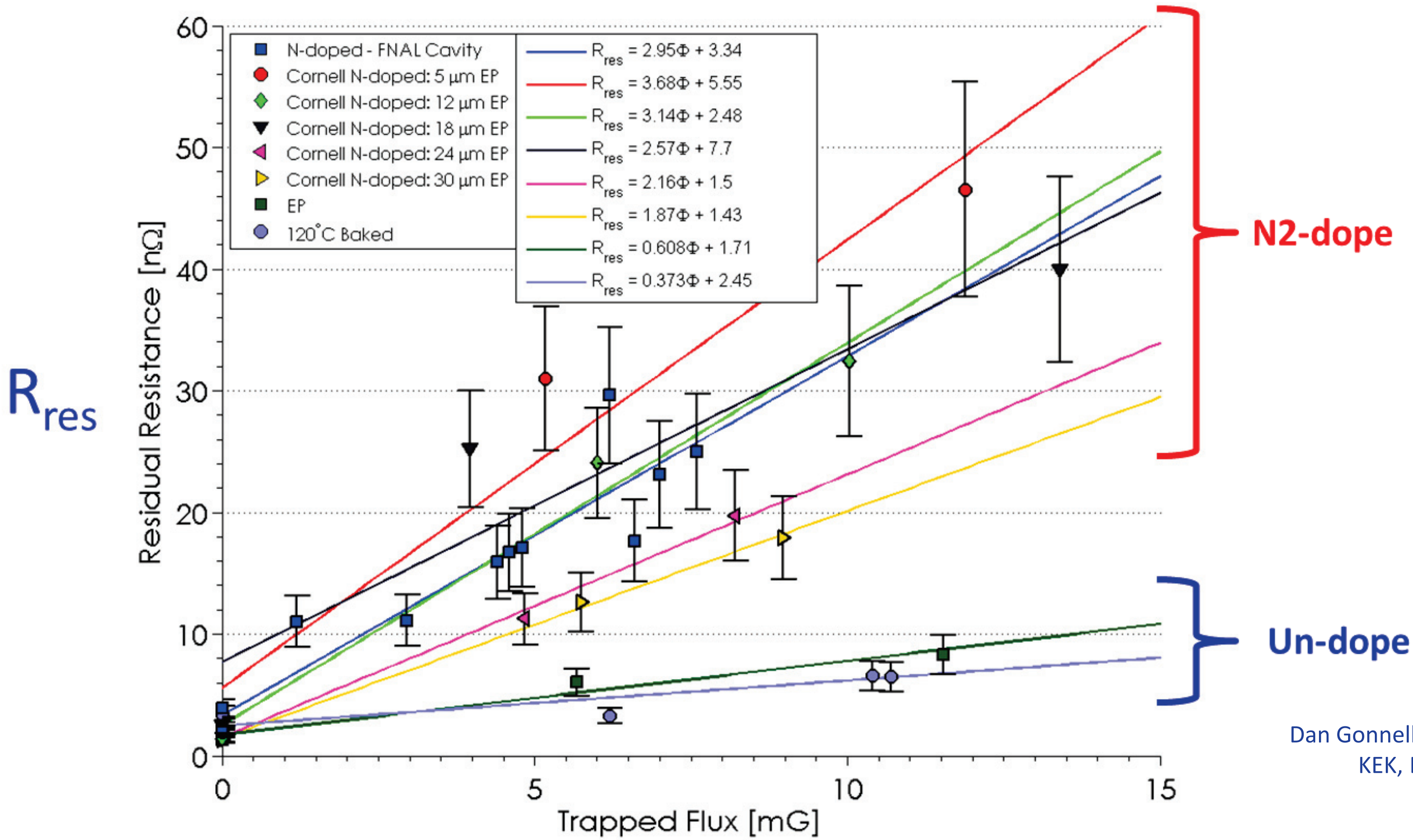
Single cell with
- Helmholtz Coil
- Fluxgate



Dan Gonnella, TTC Meeting,
KEK, December 2014

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

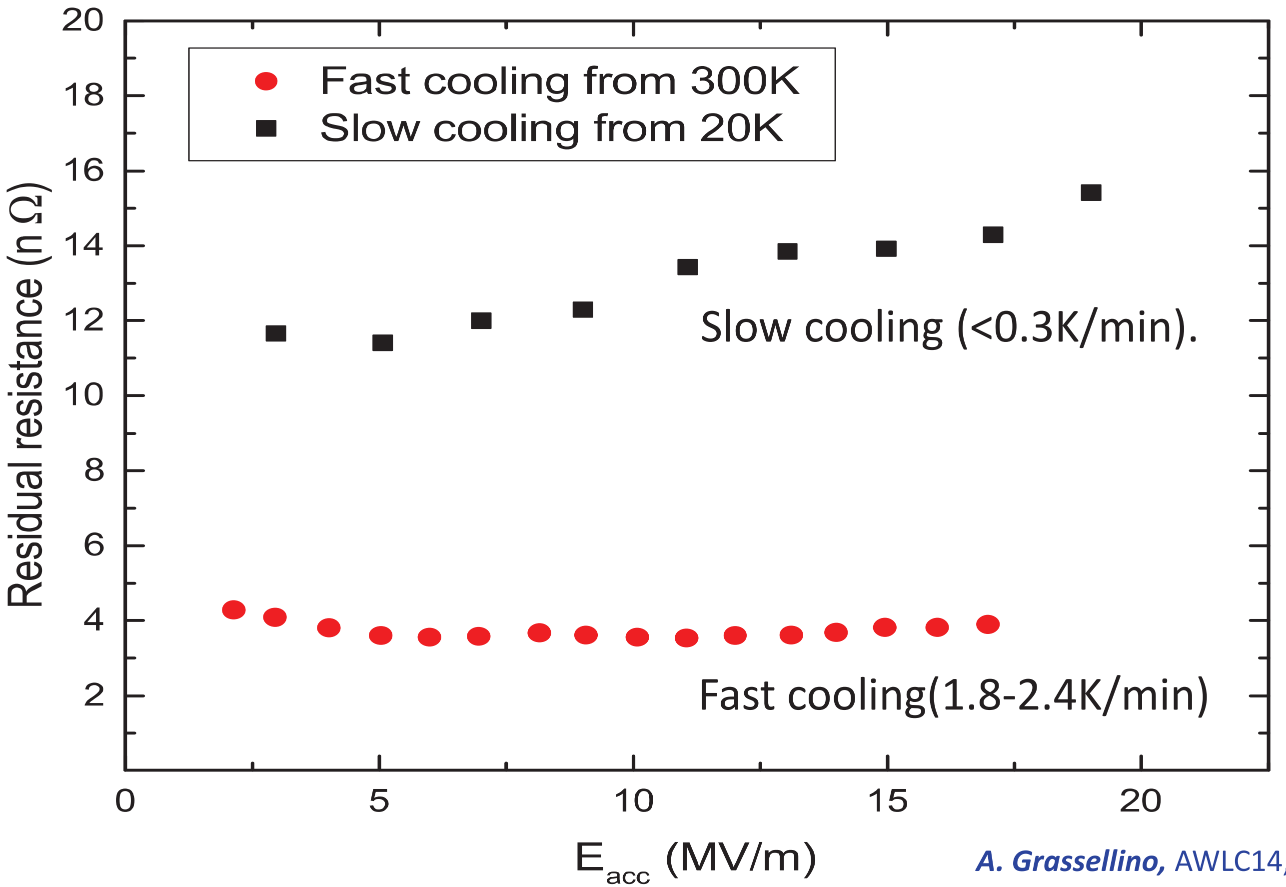
Sensitivities of flux trapping



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.

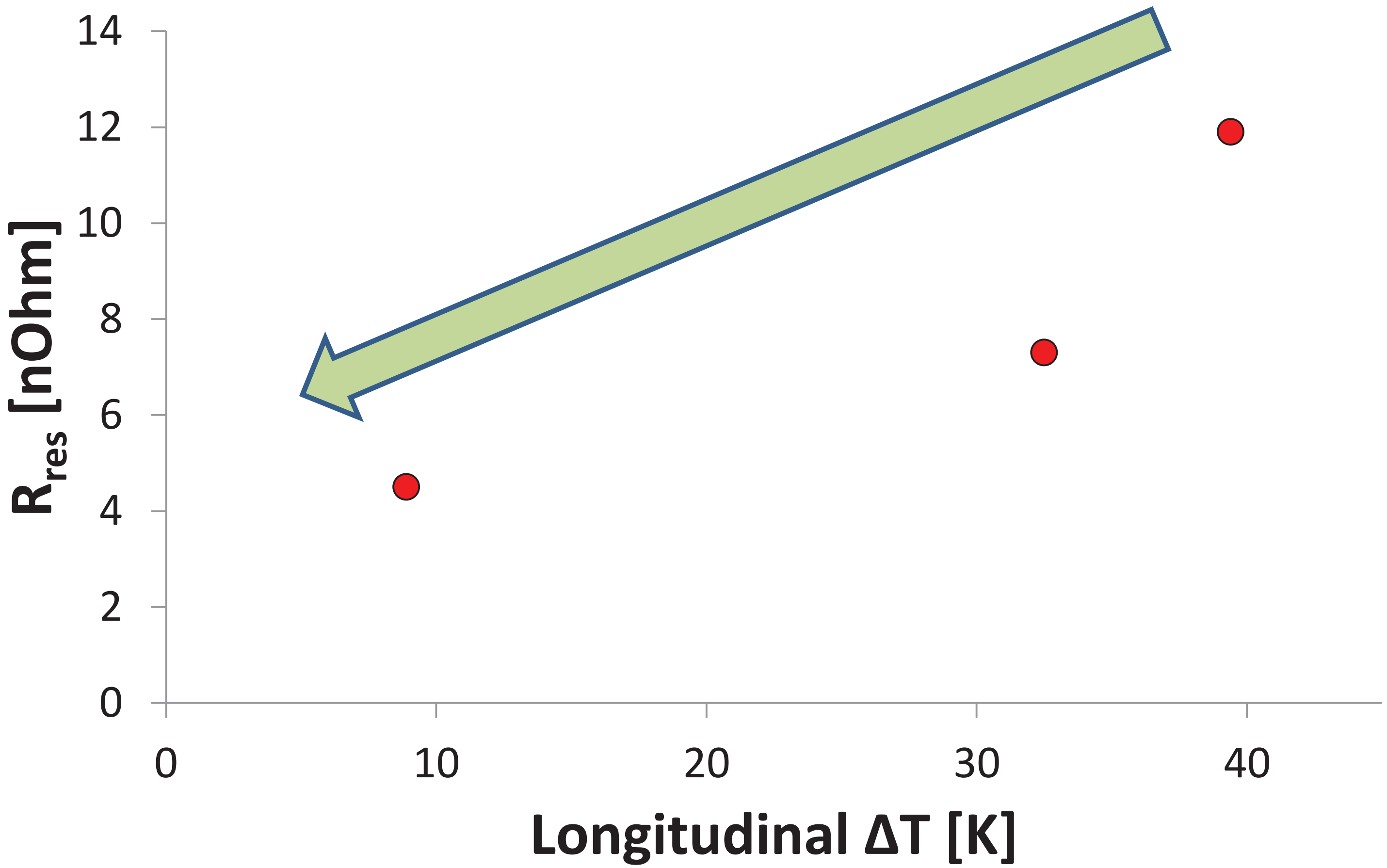
Flux control with cool down



A. Grassellino, AWLC14, Fermilab May 13th 2013

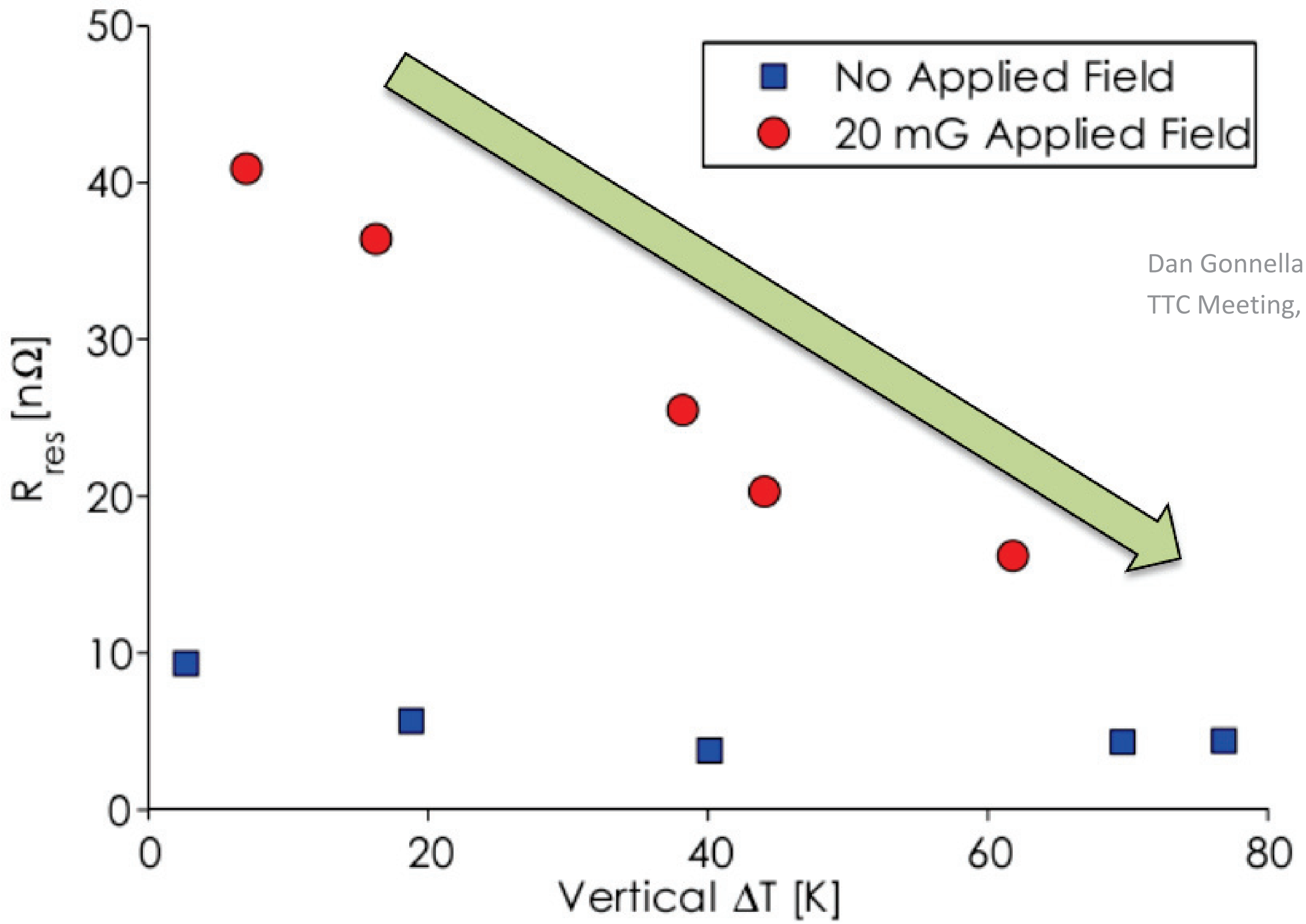
Fast cooling gives N2-doped cavities lower R_{res} (higher Qo) than Slow cooling.

Flux control with dT_{long} in HTC



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

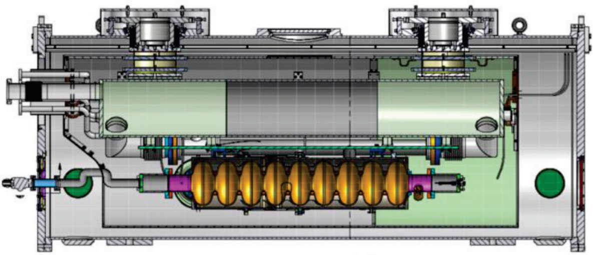
Flux control with dT_{vert} in HTC

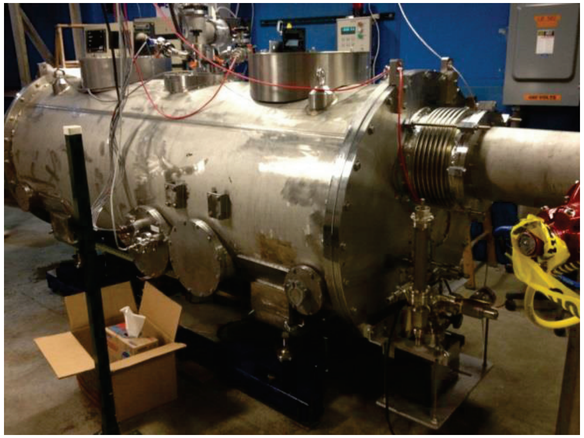


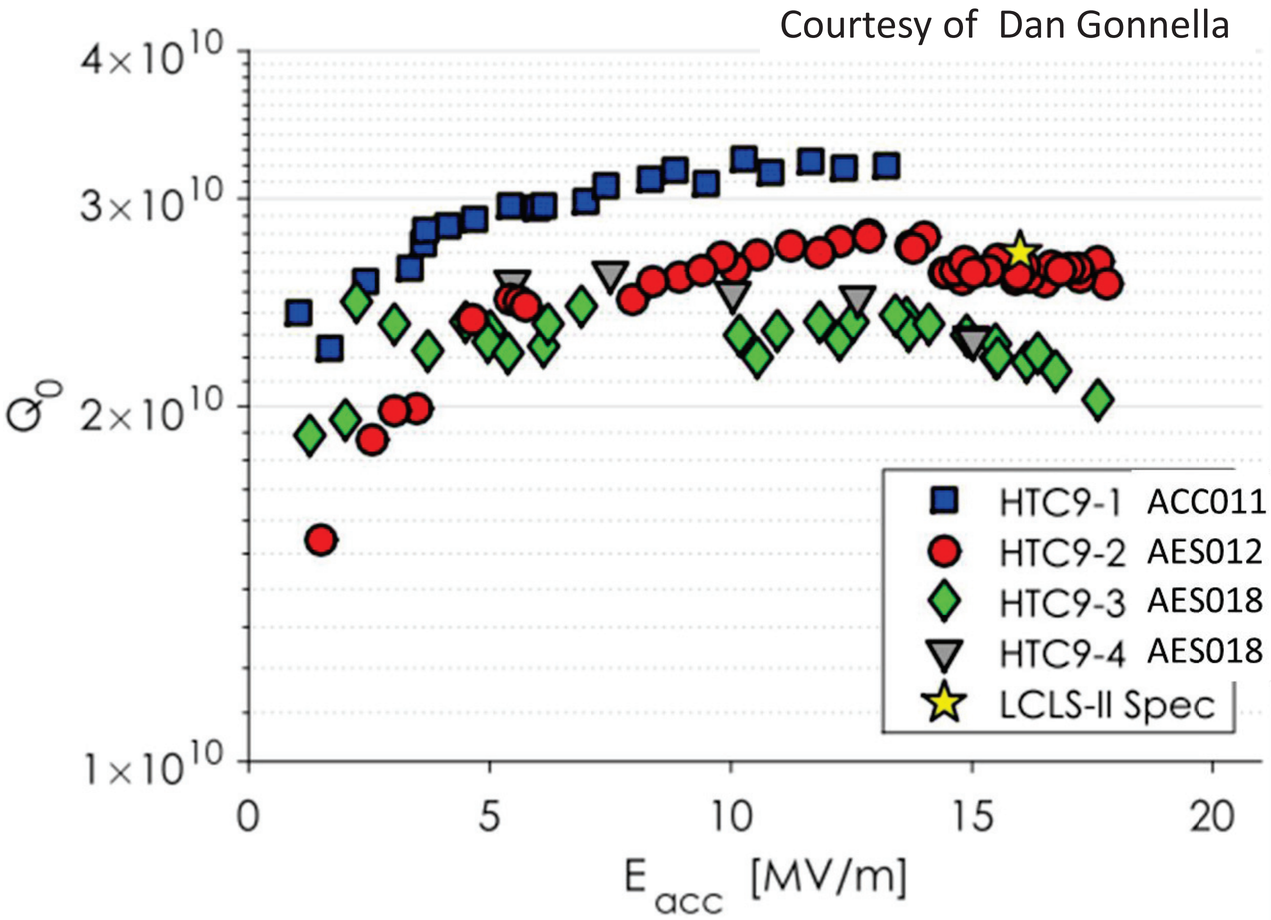
Dan Gonnella for the Cornell Team
TTC Meeting, KEK, December 2014

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

N2-doped 9-cells in HTC at Cornell

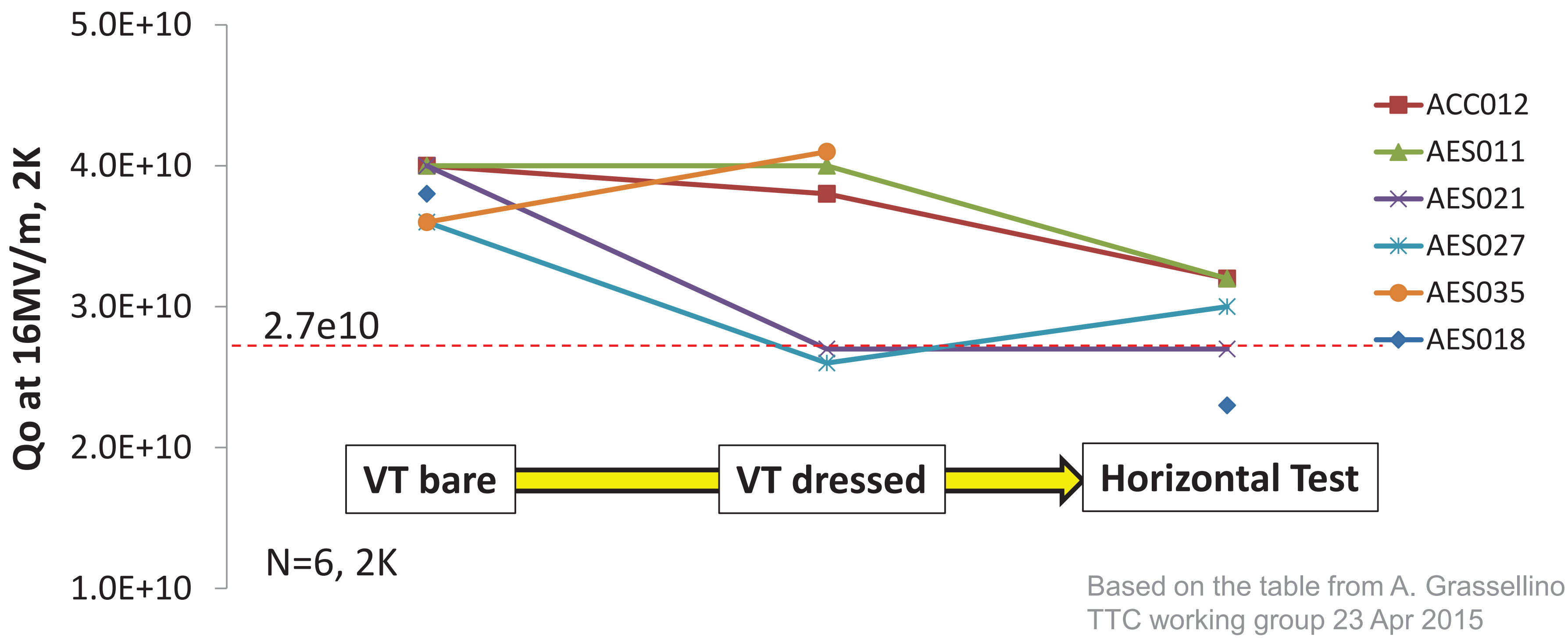






- Cornell has completed four HTC tests with success so far.
- HTC9-5 assembly with high power coupler, tuner, and HOM antennas is ongoing, will be tested in July.

Qo preservation from VT to HT



- 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

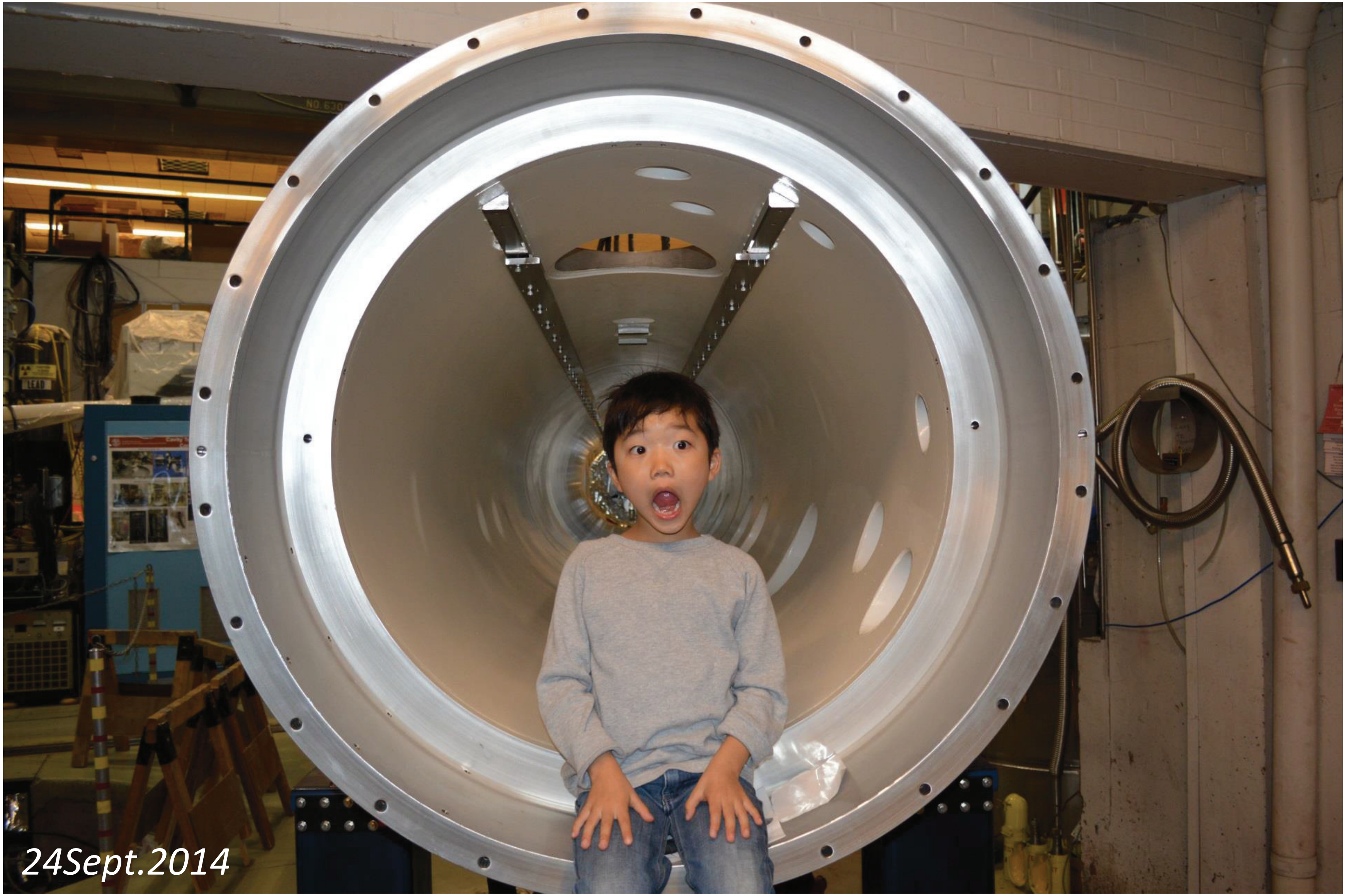
- Different surface finishes require different flux controls to minimize R_{res}, especially on cool down procedures.

	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.