High-Q and high-gradient research updates from Cornell University

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On behalf of the SRF group of Cornell University

ALCW2018

May 31, 2018

Outline

- Vertical electropolishing (VEP) updates
- Bipolar electropolishing (BEP) updates
- Low-temperature doping updates

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Motivation of Vertical Electropolishing

- VEP has lower cost compared to horizontal EP;
- VEP requires smaller space for the system set-up;
- VEP'd SRF cavities have similar performance compared with HEP'd cavities.

Cornell VEP system for the ILC R&D project
(high-gradient research)

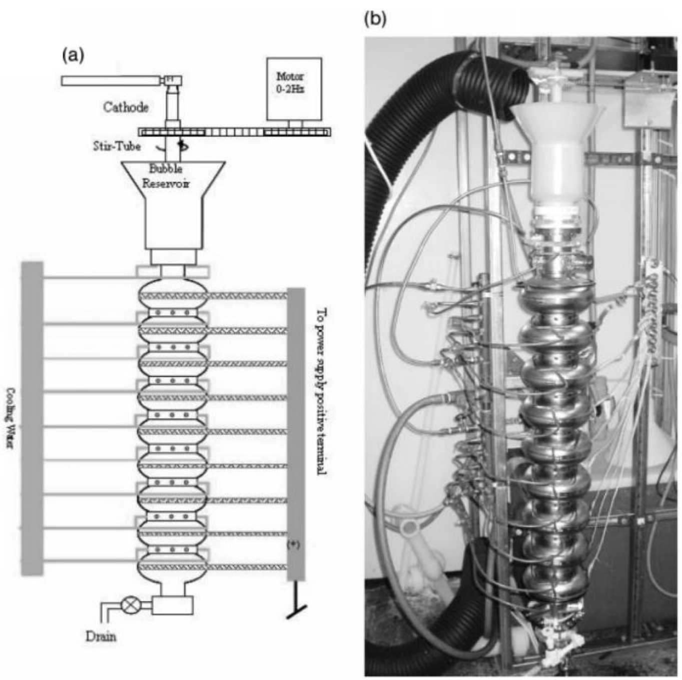
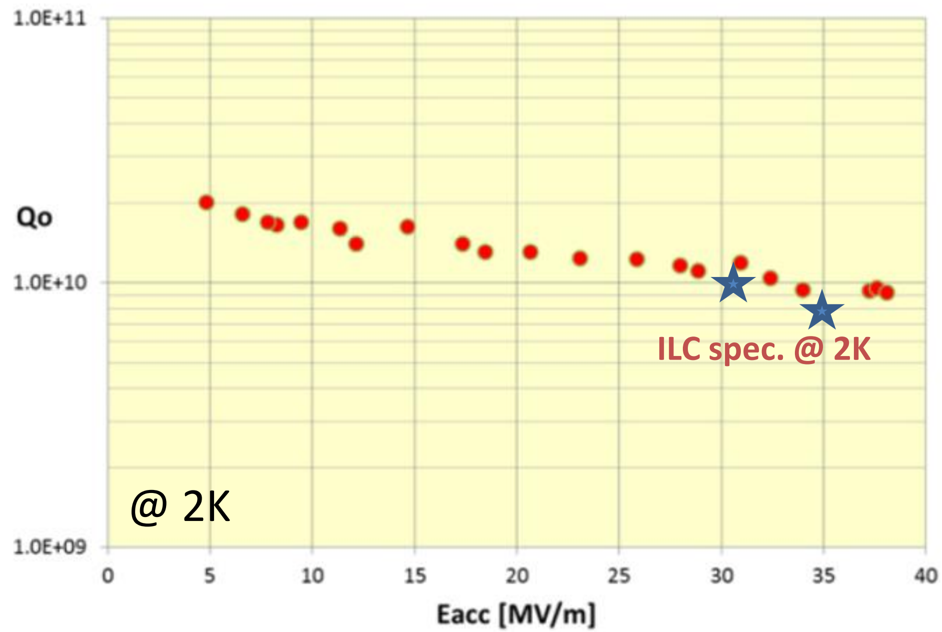


Fig. 7.12 Vertical electropolishing: (a) schematic layout; (b) photograph of the setup [434].

Cornell VEP for 9-cell set-up



High gradient achievement of Cornell's VEP with 1.3GHz TESLA shape 9-cell.

Cornell Vertical electropolished 9-cell and single-cell SRF cavities achieved the ILC specification at 2K (E_{acc} >35MV/m with Q_0>0.8e10)

Cornell VEP system for the LCLS-II R&D project

(high-Q_0 research)

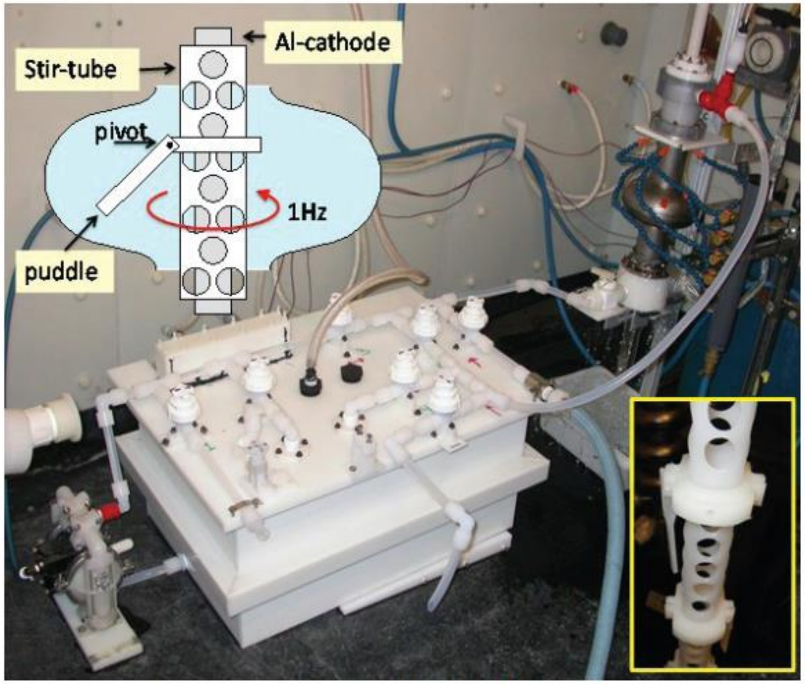
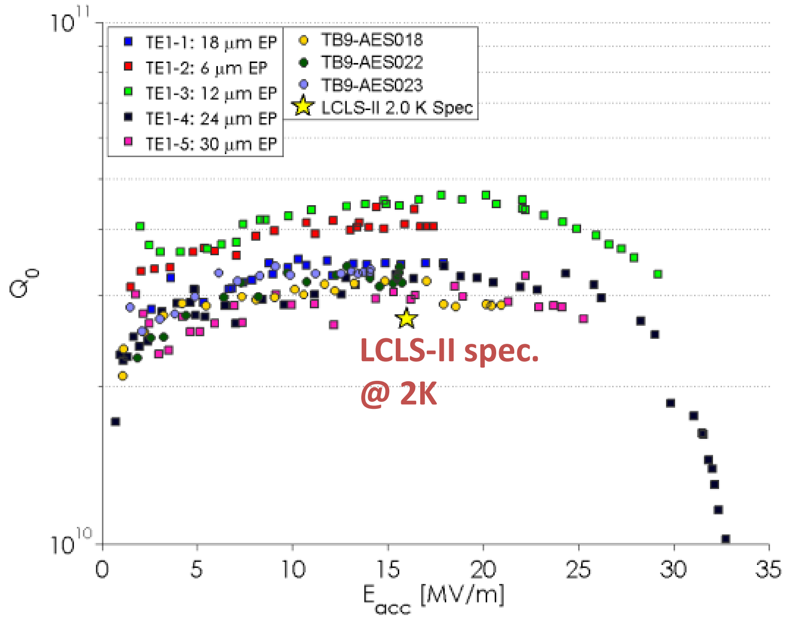


Figure 1: Cornell's VEP system.



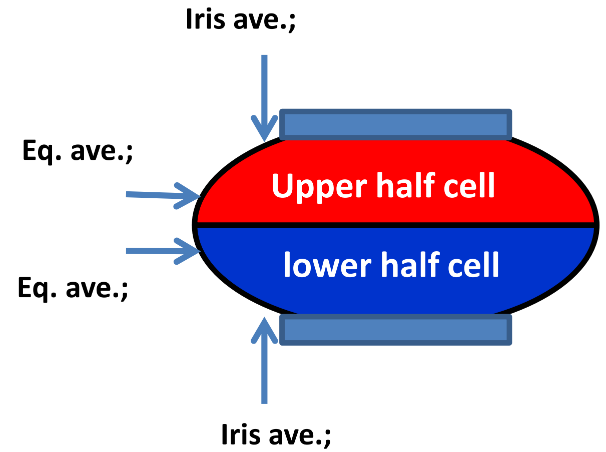
Q_0 vs E_{acc} performance and 2.0 K for all eight cavities. Errors are 20% on Q_0 and 10% on E_{acc}

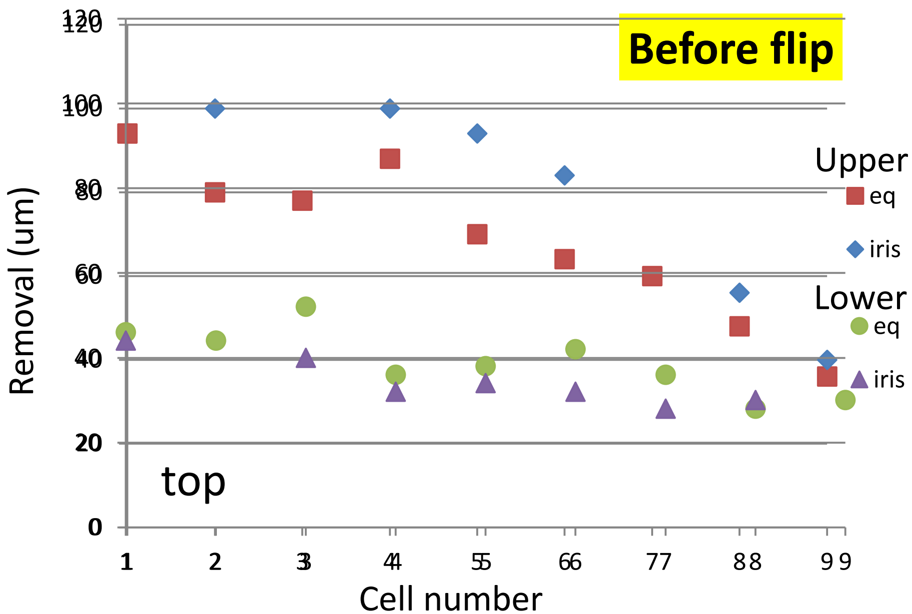
The nitrogen-doped 9-cell and single-cell SRF cavities after VEP all achieved the LCLS-II specification (E_{acc}>16MV/m , Q_0>2.7e10 at 2K)

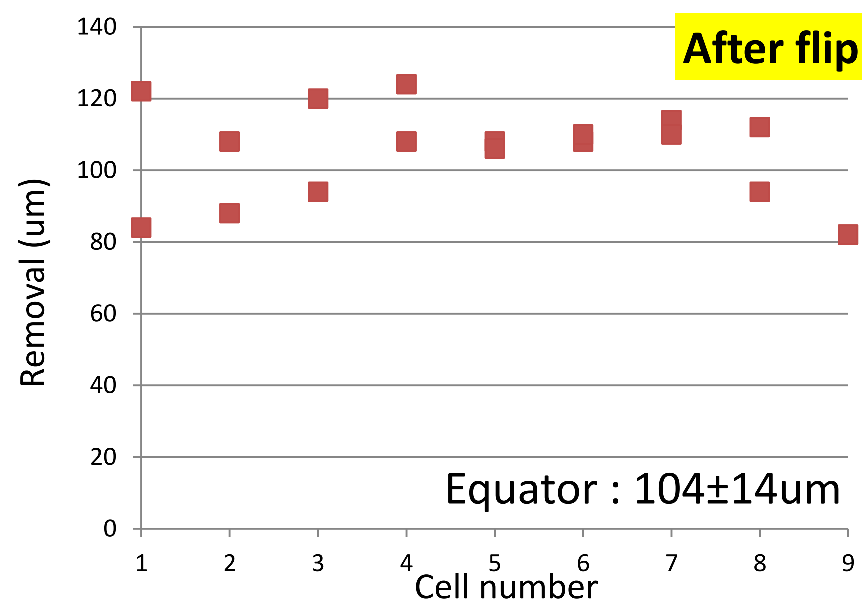
Motivation of Ninja cathode development

(collaborated with KEK and Marui)

- Gravity effect causes VEP removal un-uniform;
- Cavity has to be flipped in a VEP;
- Ninja Cathode has been designed to compensate the removal un-uniform;







Ninja cathode development in collaboration with KEK and Marui

Cornell's and Marui's VEP Cathode

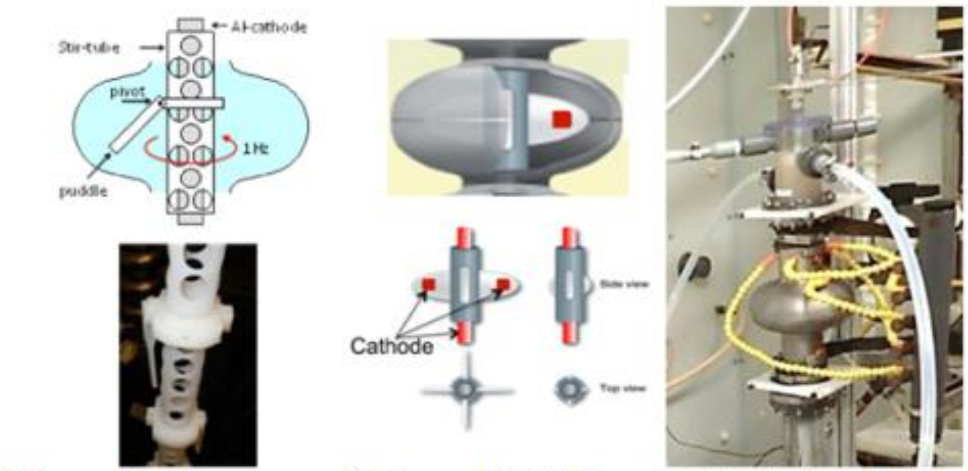


Figure 1: Images of Cornell VEP cathode (left); Marui's i-cathode Ninja type-I (middle), and single cell on the VEP stand at Cornell.

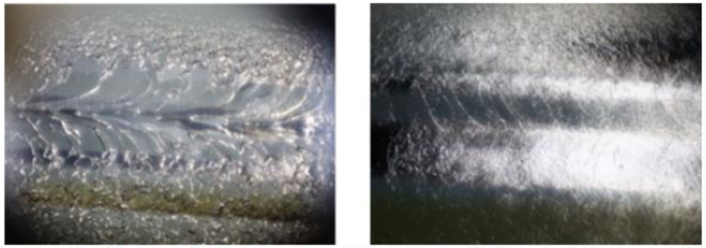
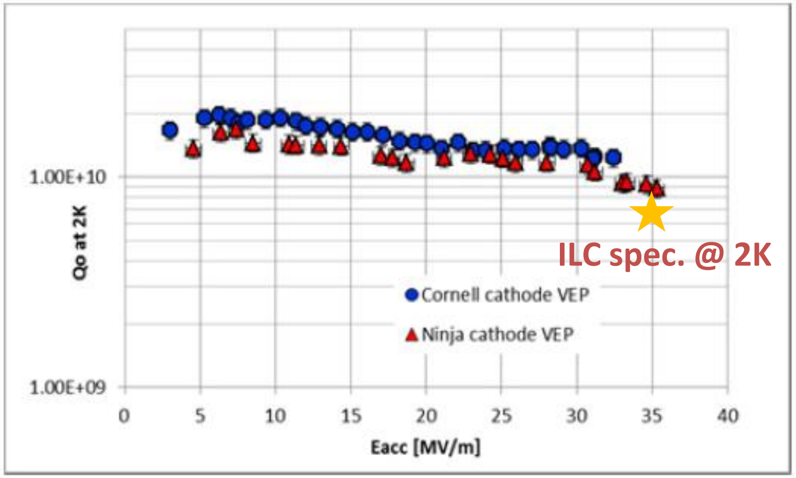


Figure 2: Optical inspection images of the equator weld seam on the RF surface; Cornell VEP (left), Ninja cathode type-I (right).



RF test results of NR1-2 at 2K.

Surface preparation of NR1-2:

- **NR1-2: CBP (30µm)+BCP (60µm)+800C baking (2hrs),**
- **Two VEPs (20µm each) using the Ninja cathodes of type-I & II,**
- **120C baking (48hrs) and RF test,**
- **NR1-2 treated by the Ninja cathode achieved the ILC spec.**

		Cornell cathode	Ninja type-I	Ninja type-II
Removal [um] (preliminary)	Target	20	20	20
	Top half cell	24	36	29
	Bottom half cell	14	20	18

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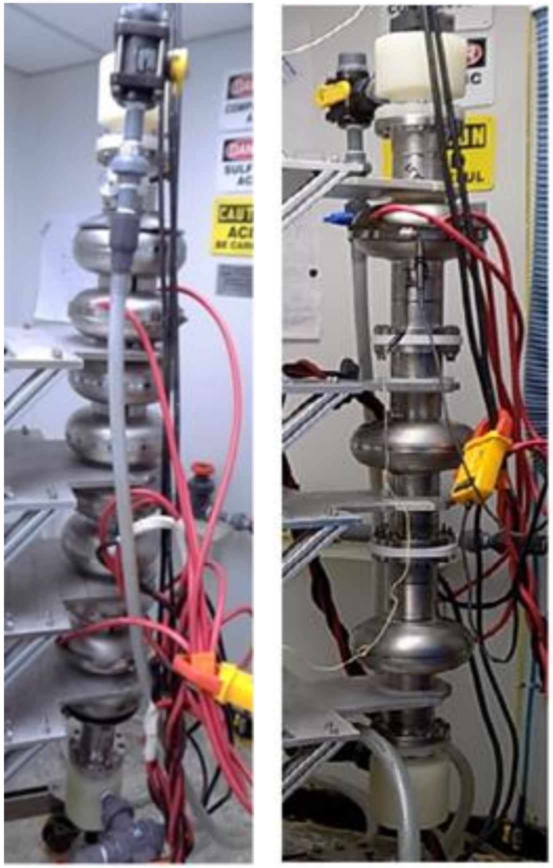
Motivation of Bipolar-EP

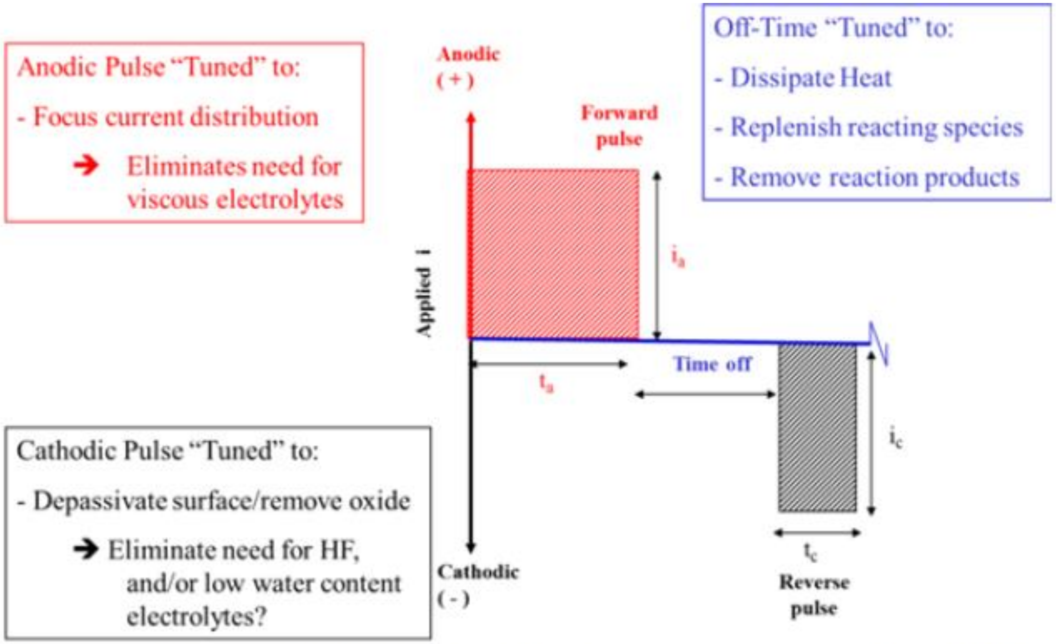
- Regular EP contains HF.
- HF is toxic !
- Regular EP will require >10,000 liters HF acid for ILC project (~8000 1.3GHz 9-cell SRF cavities).

Bipolar-EP development collaborated with Faraday Inc.

(HF-free EP technique using H_2SO_4 acid)

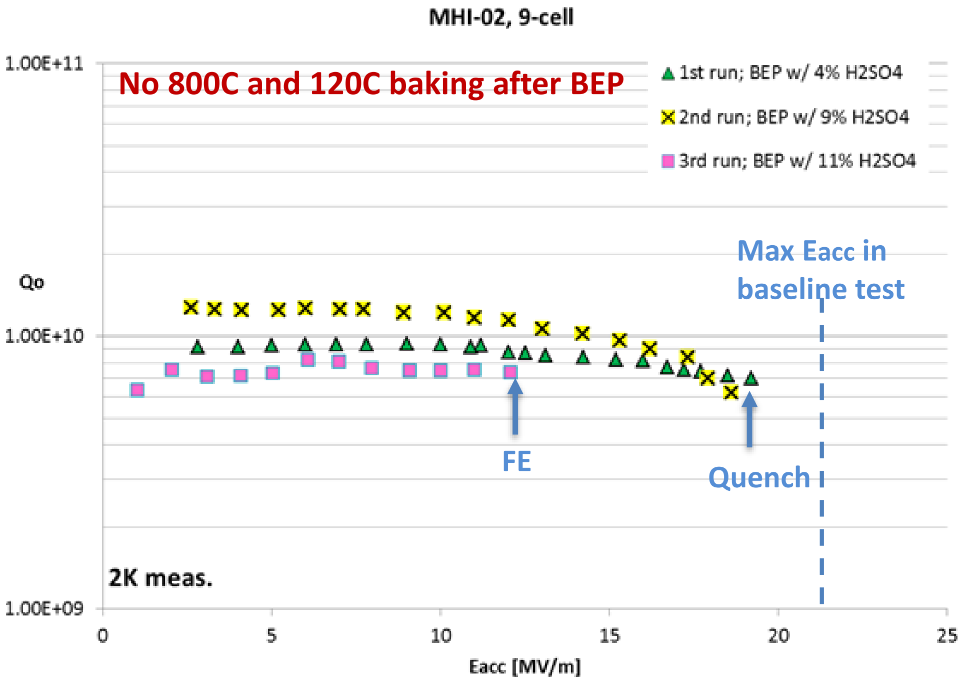


BEP setup of 9-cell and single-cell SRF cavities



1. an anodic forward pulse to grow an oxide layer on niobium surface,
2. voltage time off to dissipate the heat, remove reaction products, and replenishes reacting species;
3. a cathodic pulse with reversed voltage to remove the oxide layer on the niobium surface, thus eliminating the need for HF.

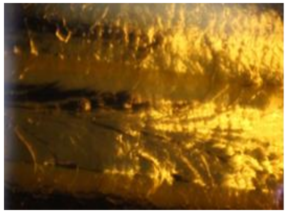
9-cell cavity BEP results

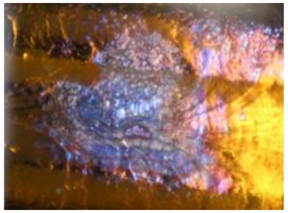


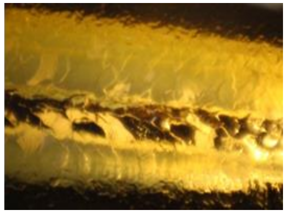
- Baseline test: cavity quenched at 22MV/m,
- BEP degraded gradient ~ 4MV/m,
- Gradient was limited by quench and FE,
- Low Q0 due to the oxide layer on surface.

Optical inspection images:

- **1st Run:**

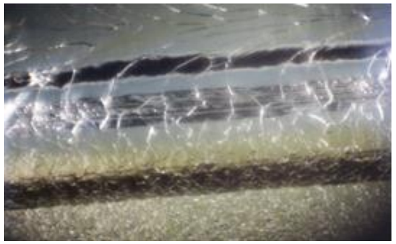






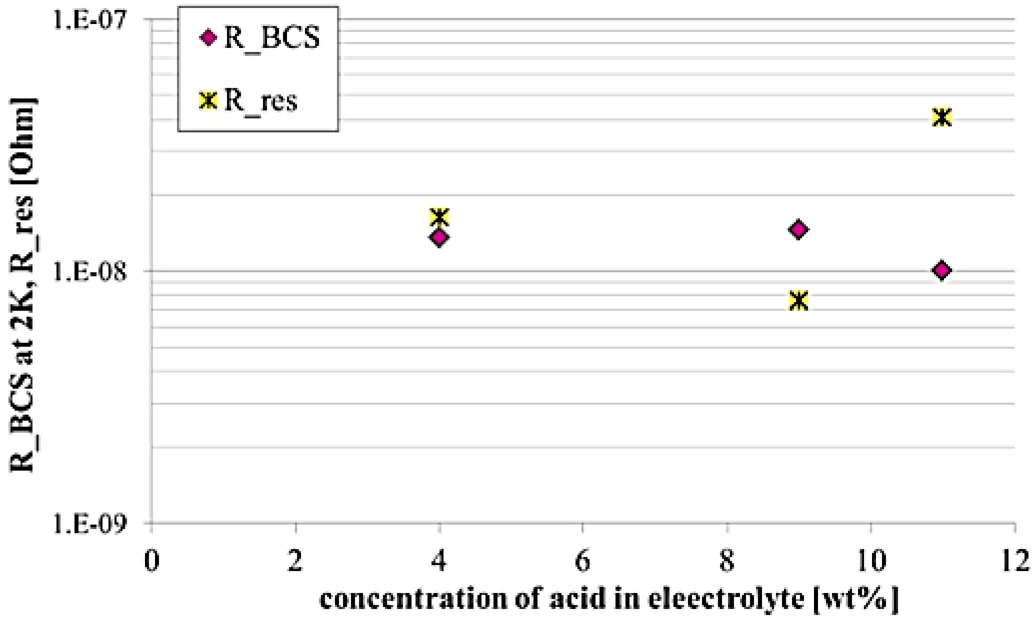
Surface coated with thick and golden oxide layer after 63um BEP of the 9-cell cavity.

- **2nd Run: BEP 8.5um, surface looks similar to the conventional EP surface;**
- **3rd Run: BEP 7um, surface has light yellow layer.**



	wt% H_2SO_4	Anodic pulse	Time off	Cathodic pulse	Remov-al
1st run	4%	4V, 200ms	800ms	10V, 200ms	63μm
2nd run	9%	4V, 100ms	600ms	10V, 200ms	8.5μm
3rd run	11%	4V, 100ms	600ms	10V, 200ms	6.9μm

Surface resistance analysis of the 9-cell cavity results



BEP on 9-cell	*w/w% H2SO4*	*Q at 2K, 5MV/m*	*R_{bcs} at 2K*	*R_{res}*
1st run	*4%*	*0.93e10*	*14 nΩ*	*16 nΩ*
2nd run	*9%*	*1.26e10*	*15 nΩ*	*8 nΩ*
3rd run	*11%*	*0.53e10*	*10 nΩ*	*41 nΩ*

- **BCS resistance (R_{BCS}) is ~10-15 $n\Omega$, which is regular to a normal VEP**
- **Residual resistance (R_0) has large scattering from 8 to 41 $n\Omega$.**

Single-cell cavity-string BEP results

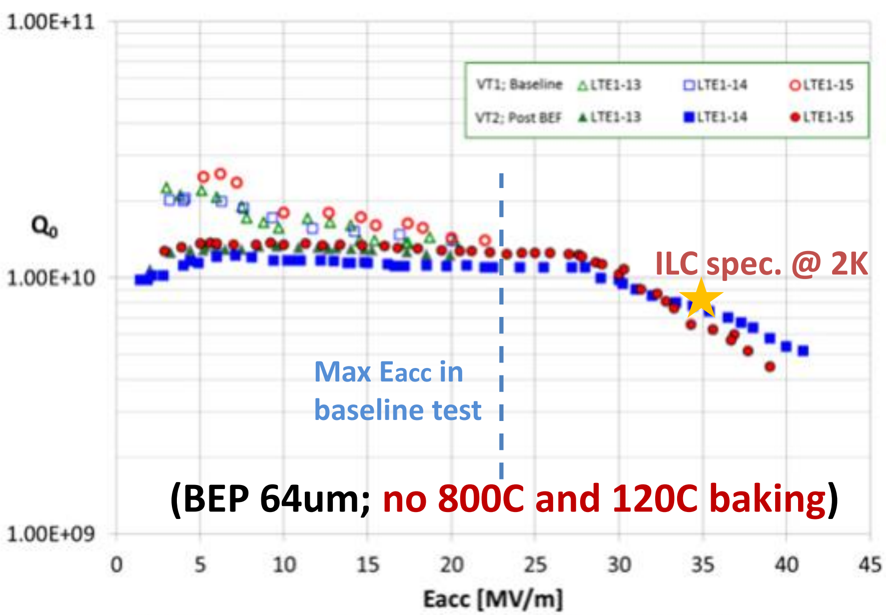


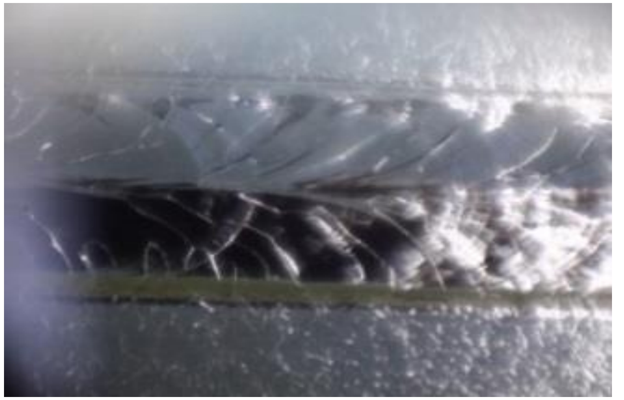
Table 1: Summary of the $E_{acc,\ max}$ and Q_0 at 2K

	1st run; Baseline RF test		2nd run; RF test post BEP	
	E_{acc} max, Q_0 at 2K		E_{acc} max, Q_0 at 2K	
LTE1-13	20MV/m	1.4E+10	20MV/m	1.22E+10
LTE1-14	20MV/m	1.4E+10	41MV/m	5.2E+09
LTE1-15	22MV/m	1.4E+10	39MV/m	4.5E+09

- Baseline test: Eacc ~20MV/m limited by quench,
- BEP improved two single-cell Eacc up to ~40MV/m,
- Q_0 is flat when Eacc is between 5-30MV/m,
- high-field Q-slope started after 30MV/m.

Optical Inspection comparison

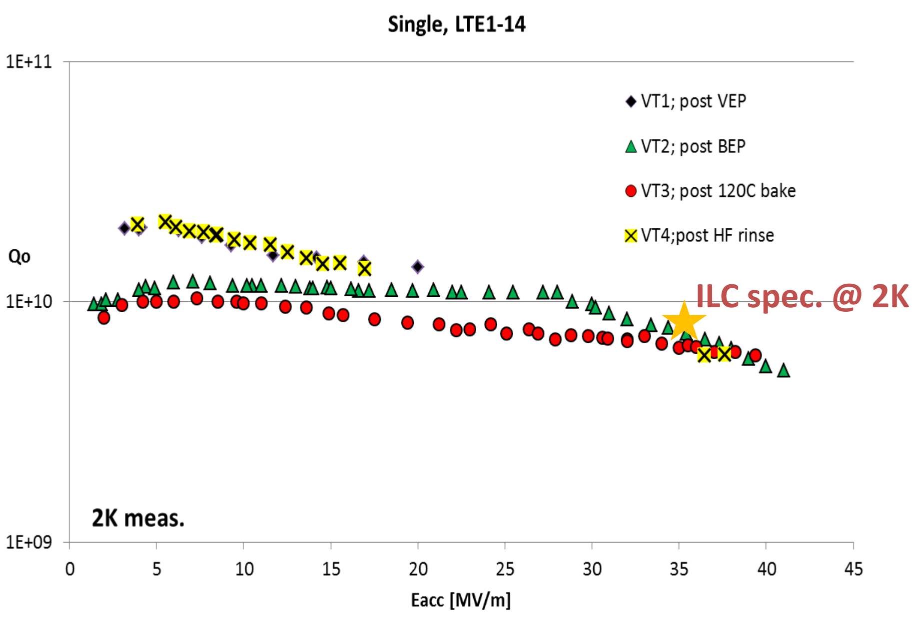
Cornell VEP

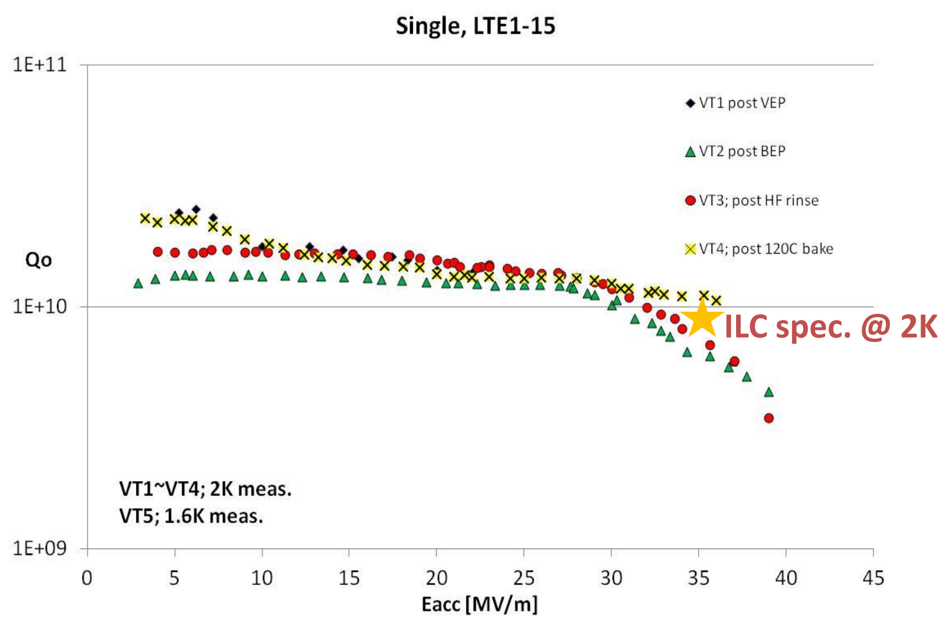


BEP

Post treatment study after BEP

- HF rinsing to remove bad oxide layer;
- 120C baking to improve Q





LET1-14:

1) **120C baking:** Q_0 degraded at low, medium fields; no change at high fields. E_{acc}~ 40MV/m.
2) **HF rinsing:** Q_0 was improve at low fields; no change at high fields. E_{acc}~ 40MV/m.

LET1-15:

1) **HF rinsing:** Q_0 was improved at low, medium fields; no change at high fields. E_{acc}~ 40MV/m.
2) **120C baking :** Q_0 was improve at low fields; no high-field Q-slope. E_{acc} quenched at 38MV/m.

Conclusions of BEP study

- Gradient of the BEP'd cavities can achieve ~40MV/m,
- Q0 varies from ~8e9 to 1.2e10 based on BEP parameters,
- The post treatments can reduce surface resistance of BEP'd cavity down to conventional VEP level.

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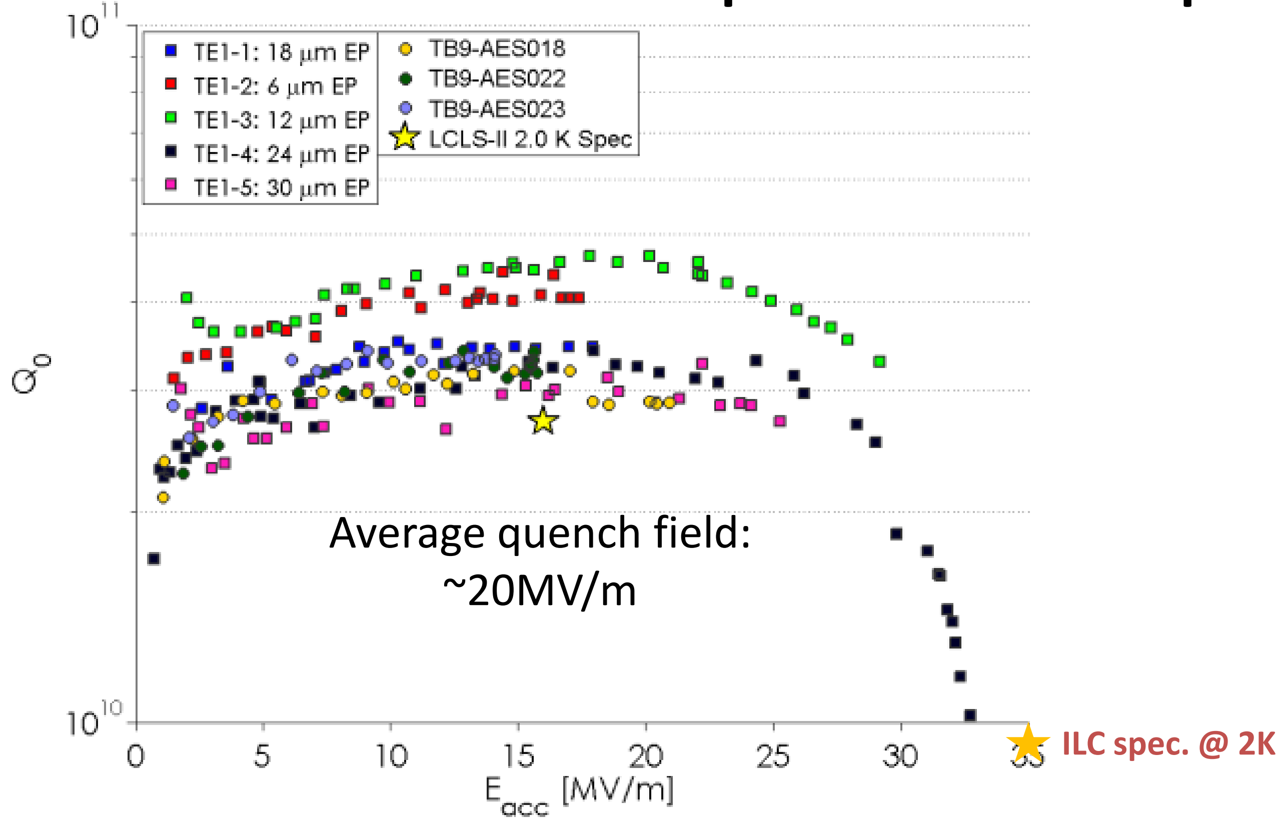
Motivation of Low-temperature doping



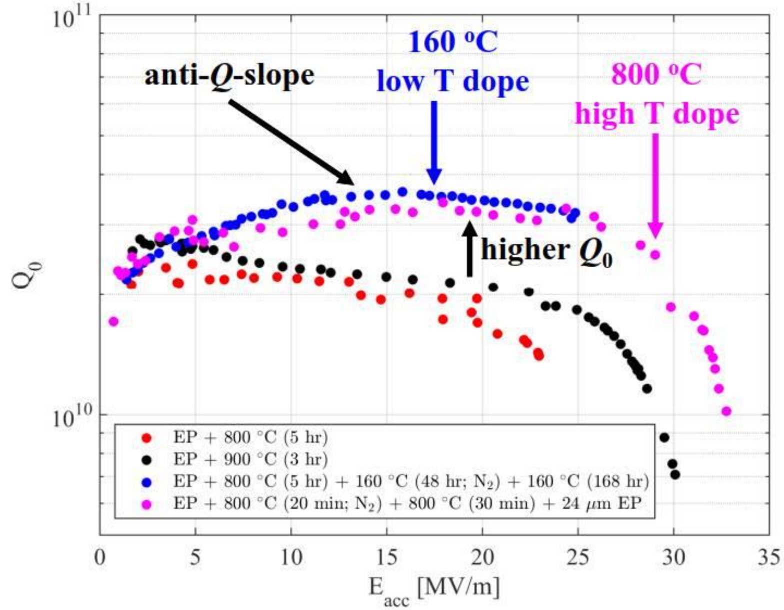
- **High-temperature (800C) doping cavity has high-Q, but gradient of most cavities does not achieve the ILC specification;**
- **Low-temperature (120-160C) doping might be a solution for producing high-Q and high-gradient cavities.**

Low-temperature doping at Cornell

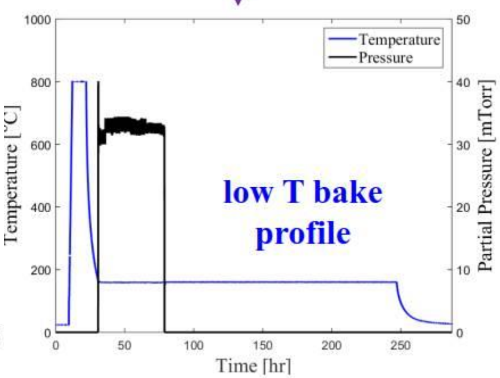
- Low temperature baking (**120 – 160 °C**) in a low pressure **nitrogen** atmosphere results in '***Q*-rise**' and **higher low-field Q_0 values**

A . Grassellino *et al.*, *Unprecedented Quality Factors at Accelerating Gradients up to 45 MV/m in Niobium Superconducting Resonators via Low Temperature Nitrogen Infusion.* arXiv:1701.06077.

P. N. Koufalis, D. L. Hall, M. Liepe, J. T. Maniscalco. *Effects of Interstitial Oxygen and Carbon on Niobium Superconducting Cavities.* arXiv:161208291.



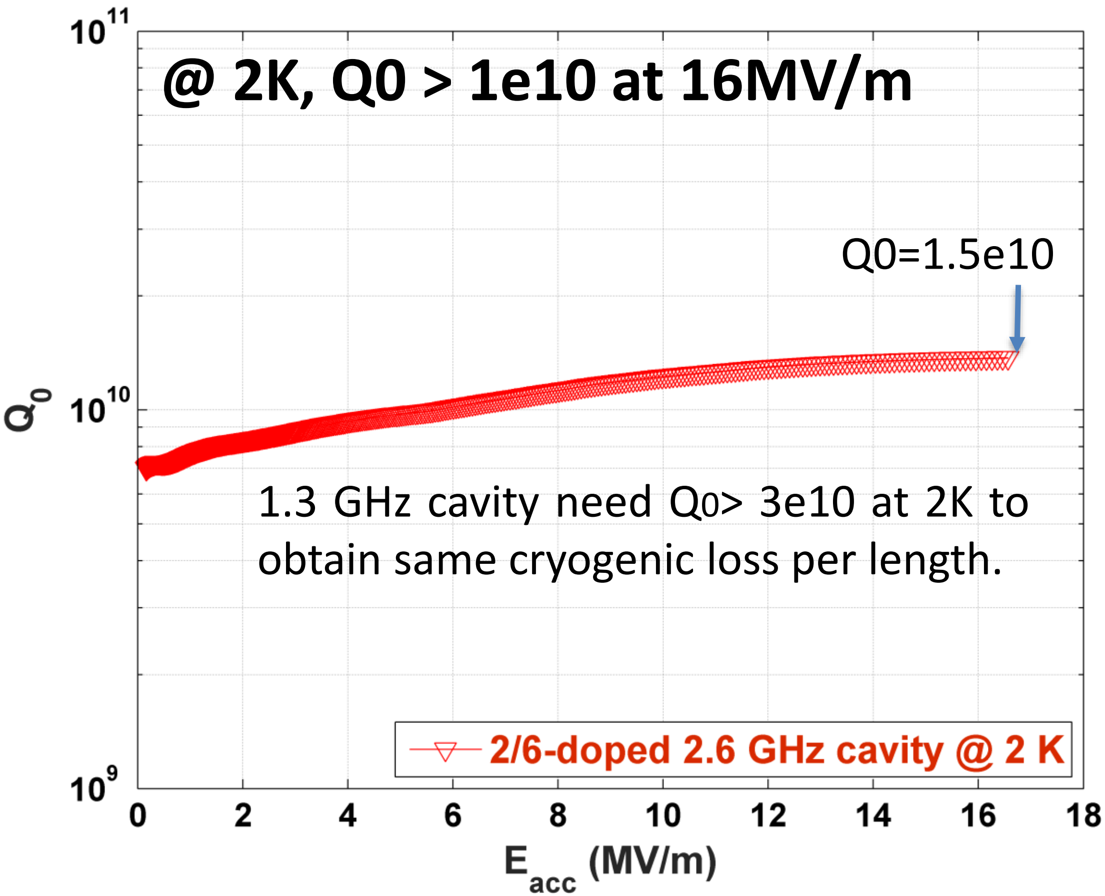
Continuously flowing N_2 atmosphere!



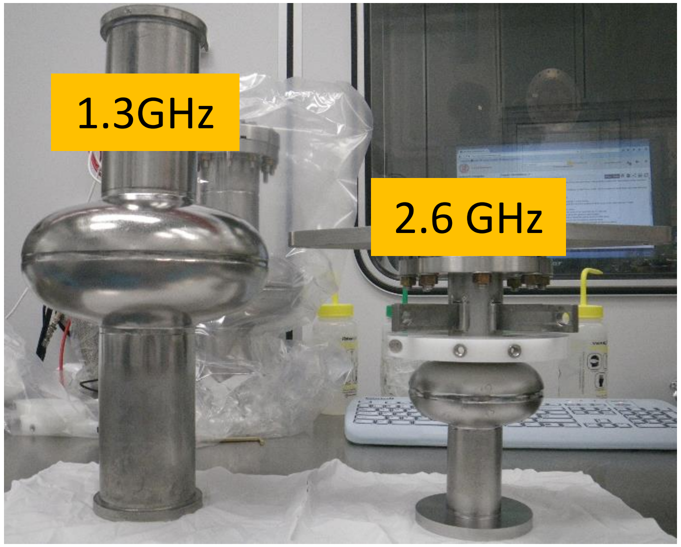
- Nitrogen diffuses **only 2 – 5 nm** into niobium at these temperatures
- Observed that **carbon** and **oxygen diffuse significantly** into niobium at **160 °C**

One more thing…

Latest results of **2.6GHz** Nitrogen-doped single-cell SRF cavity



M. Martinello et al., SRF2017, Lanzhou, China, 2017.



- **2/6 Doping recipe;**
- **Q-value is comparable with a 1.3GHz EP'd cavity (non-doped);**
- **R_{BCS} ~11 nΩ at 16MV/m;**
- **R_0 ~ 8 nΩ**
- **E_{pk}/E_{acc} = 1.86**
- **B_{pk}/E_{acc} = 4.25 mT/ (MV/m)**

Acknowledgement

Cornell SRF group:

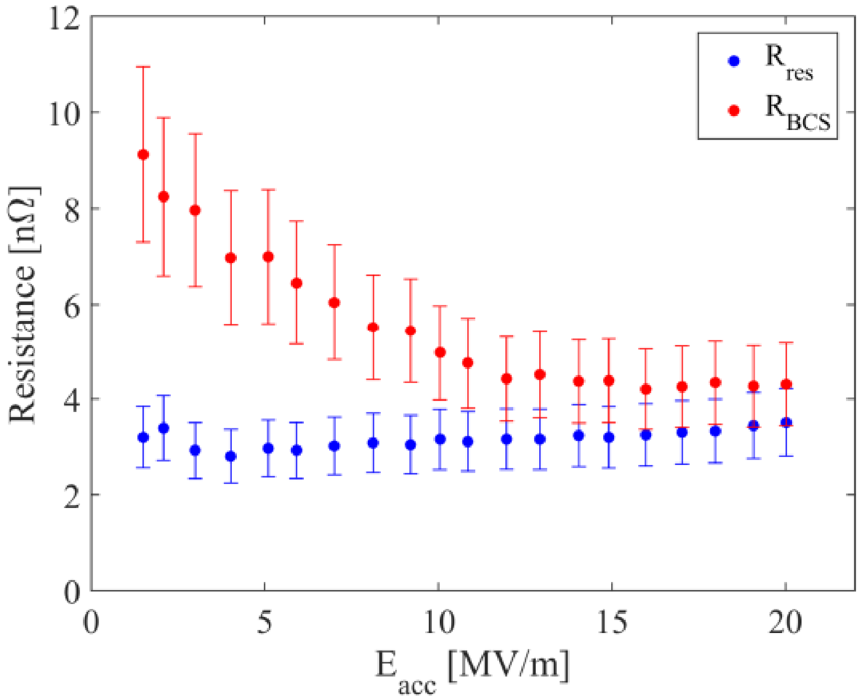
P. Bishop, H. Conklin, F. Furuta, T. Gruber, A. Holic, J. Kaufman, P. Koufalis, G. Kulina, M. Liepe, J. Maniscalco, T. Oseroff, R. Porter, J. Sears, S. Zeryck.

Thanks for your attention!

Surface resistance analysis of low T doping results

- R_{BCS} **decreases** with increasing E_{acc}; **same effect** seen in **high-*T* nitrogen-doped** cavities (**caused by reduction of mean free path!**)

Low T Dope



High T Dope