# EXPLORATION OF VERY HIGH GRADIENT CAVITIES *

G. Eremeev†
TJNAF, Newport News, VA 23606, U.S.A.

*Abstract*

Several of the 9-cell ILC cavities processed at Jefferson Lab within ongoing ILC R&D program have shown interesting behavior at high fields, such as mode mixing and sudden field emission turn-on during quench. Equipped with thermometry and oscillating superleak transducers (OSTs) system for quench detection, we couple our RF measurements with local dissipation measurements. In this contribution we report on our findings with high gradient SRF cavities.

## INTRODUCTION

Within ILC R&D yield study five 9-cell cavities produced by Research Instruments have been processed and tested at Jefferson Lab. All cavities passed ILC specification for vertical acceptance test after the second pass. In Fig. 1 we plot $Q_0$ vs $E_{\rm acc}$ for all five cavities at $T_{\rm LHe\ bath}$ = 2.0 K. The highest gradient was reached in TB9RI027, which was limited at $E_{\rm acc}$ = 43 MV/m at 1.8 K with quality factor above $10^{10}$(not shown in the figure).

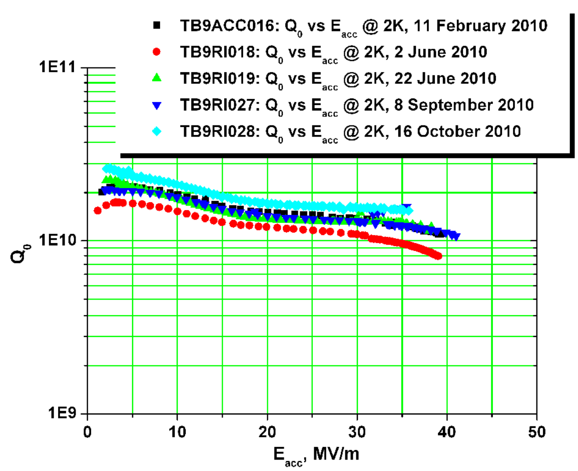


Figure 1: $Q_0$ vs $E_{\rm acc}$ for five RI cavities tested at Jefferson Lab in 2010 are plotted in this picture. All cavities met ILC vertical acceptance test specification.

All cavities have shown field emission, which rose above background noise of $1{\cdot}10^{-2}$ mR/h at $E_{\rm acc} \cong 25$ MV/m. In Fig. 2 we plotted radiation vs accelerating gradient measurement results.

Several interesting phenomena were recorded during these acceptance tests. In TB9RI019 and TB9RI027 we observed spontaneous pass-band mode excitation during $\pi$-mode measurements at high fields.

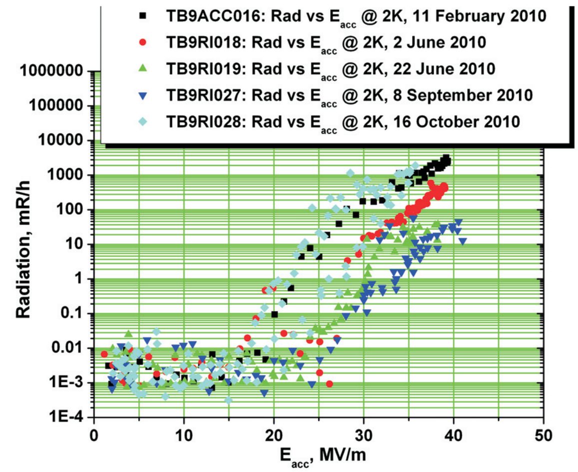


Figure 2: Radiation as function of field for five RI cavities tested at Jefferson Lab in 2010 is plotted in this figure. All cavities have shown field emission above $1{\cdot}10^{-2}$ mR/h noise floor at accelerating gradients above 25 MV/m.

We also observed a sudden field emission turn-on in TB9RI027 at high fields, which degraded performance of the cavity. This event was recorded with our 2-cell thermometry cell. In this contribution we summarize our observations of these high field phenomena in SRF cavities.

## SPONTANEOUS MODE-MIXING

Sponteneous mode excitation has been observed in 9-cell ILC cavities in many labs [1], [2], [3]. We observed mode mixing during RF tests of TB9RI019 and TB9RI027. Both cavities had field emission above 1 mR/h, when mode-mixing was observed.

During TB9RI019 $\pi$ mode measurement we observed appearance of the $7\pi/9$ mode on the spectrum analyzer screen above $E_{\rm acc}$ = 31 MV/m. Below $E_{\rm acc}$ = 31.5 MV/m an equilibrium with both modes present could be achieved and the cavity was not quenching with both modes present. Above $E_{\rm acc}$ = 31.5 MV/m the growing $7\pi/9$ pass-band mode will eventually cause cavity to quench. We recorded the time it took for the second mode to appear on spectrum analyzer screen above noise floor of -80 dBm. In Fig. 3 we plotted this time as well as the time it took the cavity to quench due to mode-mixing above 31 MV/m.

During TB9RI019 testing, mode mixing was also observed for $4\pi/9$ and $2\pi/9$ modes measurements. During $4\pi/9$ mode measurement, spontaneous excitation of $3\pi/9$, $5\pi/9$, and $\pi$ was observed. During $2\pi/9$ mode measure-

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
† grigory@jlab.org

ment, excitation of $3\pi/9$ and $\pi/9$ was recorded. During this mode measurement 'beating' of $3\pi/9$ and $\pi/9$ was observed in CW: with $2\pi/9$ mode stable on the spectrum analyzer, the $\pi/9$ peak value steadily increases, the $3\pi/9$ mode decreases until the $\pi/9$ value suddenly drops, while the $3\pi/9$ mode peak value jumps up, and the process repeats itself.

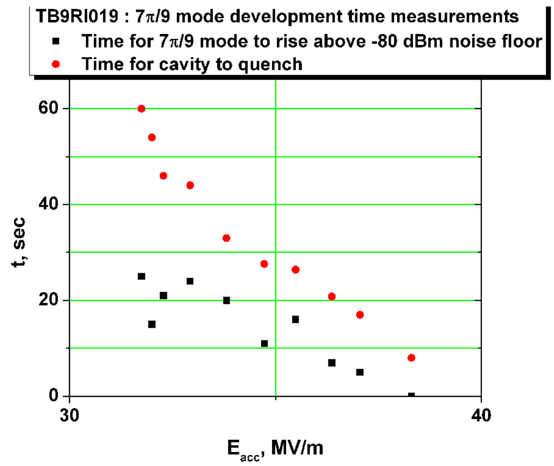


Figure 3: Mode-mixing measurements in TB9RI0019. Black dots show the time it took for the second mode to appear on the spectrum analyzer screen above the noise floor of -80 dBm. Red dots show the time it took for the cavity to quench during mode-mixing.

In TB9RI027 appearance of the $7\pi/9$ mode was observed on the spectrum analyzer above -80 dBm noise floor during $\pi$-mode measurements. Mode mixing started at $E_{\mathrm{acc}}$ = 31 MV/m. The cavity could be parked at a constant gradient up to 36 MV/m with both modes present on spectrum analyzer screen. Above $E_{\mathrm{acc}}$ = 36 MV/m mode-mixing caused the cavity to quench in CW; however, in pulsed mode the cavity reached $E_{\mathrm{acc}}$ = 41 MV/m in $\pi$ mode at $T_{\mathrm{LHe\ bath}}$ = 2.0 K limited by the available power.

## HIGH-FIELD FIELD EMISSION EVENT

TB9RI027 has reached $E_{\mathrm{acc}}$= 41 MV/m in the acceptance test after the first pass processing at Jefferson Lab. The limitation in the test was available power at $T_{\mathrm{LHe\ bath}}$ = 2.0 K. To find the limit of the cavity we decided to measure to a lower temperature of $T_{\mathrm{LHe\ bath}}$ = 1.8 K. The cavity quenched during $T_{\mathrm{LHe\ bath}}$ = 1.8 K test at $E_{\mathrm{acc}}$ = 43 MV/m. The measurements indicated that the cavity was limited by quench in cell #5. To better understand quench limitation and the preheating pattern of the quench location, 2-cell JLab thermometry system [4] was attached to the cavity and the test was repeated at $T_{\mathrm{LHe\ bath}}$ = 1.8 K. During repetitive quenching we observed a sudden field emission event, which degraded the achievable gradient to below 35 MV/m. Following the field emission event field emission onset decreased from $E_{\mathrm{acc}} \cong 25$ MV/m down to $E_{\mathrm{acc}} \cong 12$ MV/m. In Fig. 4 we plotted the quality factors and radiation levels before and after the field emission event.

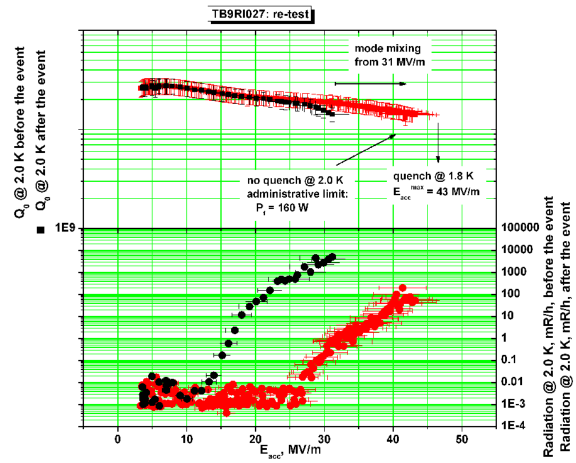


Figure 4: TB9RI027 $Q_0$ and radiation vs $E_{\mathrm{acc}}$ results before and after field emission event at $T_{\mathrm{LHe\ bath}}$ = 1.8 K. The red squares in the upper plot are $Q_0$ vs $E_{\mathrm{acc}}$ measurements and the red circles in the lower plot show radiation vs $E_{\mathrm{acc}}$ before the field emission event. The black squares in the upper plot are $Q_0$ vs $E_{\mathrm{acc}}$ measurements and the black circles in the lower plot show radiation vs $E_{\mathrm{acc}}$ after the field emission event.

Before the field emission event, analysis of the preheating data captured at $E_{\mathrm{acc}}$ = 41 MV/m shows that there is no outstanding heating at the quench location, which we identified to be close to the thermometer at (5,7), Fig. 5.

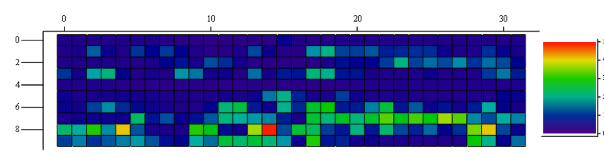

Figure 5: Temperature map of TB9RI027 at $E_{acc}$ = 41 MV/m before the field emission event. No indications of outstanding heating is present on the temperature map.

After preheating data was recorded, the cavity was put into repetitive quench. On the temperature map we observed a reproducible quench at the same location, see the upper image in Fig. 6. After several minutes of repetitive quenching, the quench location suddenly moved to a different place on the temperature map and quench gradient degraded; see the lower image in Fig. 6.

After the field emission event a clear field emission heating pattern can be see on the temperature map. In Fig. 7 we present a temperature map at $E_{\mathrm{acc}}$ = 34 MV/m after the field emission event. One can see the line of heating along index 15 induced by field emission.

We compared the preheating data for thermometers at the original quench location and quench location after field emission event. In Fig. 8 we plotted temperature rise as a function of field for the thermometry closest to new quench location. Before the event there is not precursor to field

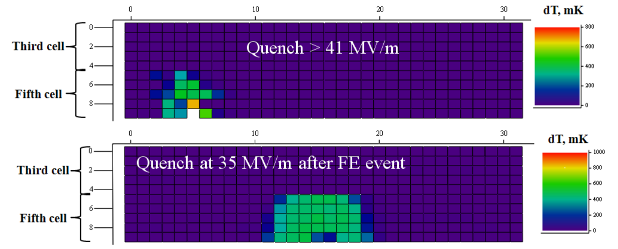


Figure 6: Temperature maps captured during repetitive quench of TB9RI027 before and after the field emission event. In the upper picture temperature maps of quench before field emission event is presented. In the lower picture temperature maps of quench after field emission event is presented.

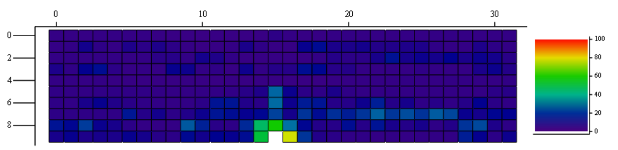

Figure 7: Temperature map of TB9RI027 after the field emission event at $E_{\mathrm{acc}}$ = 41 MV/m. A clear field emission preheating pattern can be seen on this temperature map.

emission behavior up to the highest field. After field emission event the thermometer shows a clear exponential field dependence above $E_{\mathrm{acc}}$ = 25 MV/m. Higher temperature rise at low fields indicates that the low field surface resistance at this location increased as well.

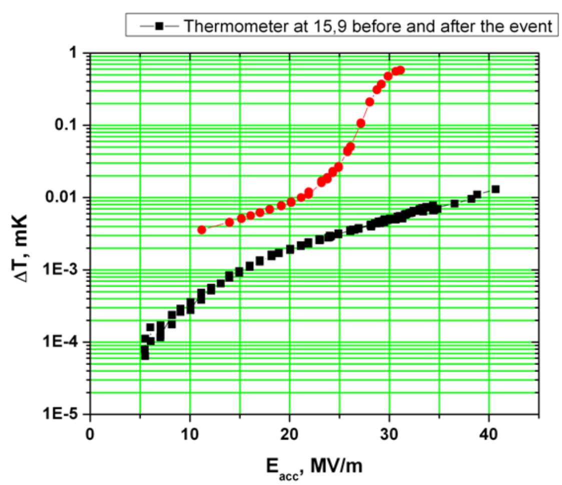


Figure 8: Preheating data from a thermometer close to new quench location. After field emission event thermometer field dependence changes from quadratic to a clear exponential behavior above $E_{\mathrm{acc}}$ = 25 MV/m. Low field temperature rise is also different before and after field emission event, indicating an increase in low field surface resistance.

The thermometer close to original quench location also had a different field dependence after the field emission event, Fig. 9. After the field emission event the surface

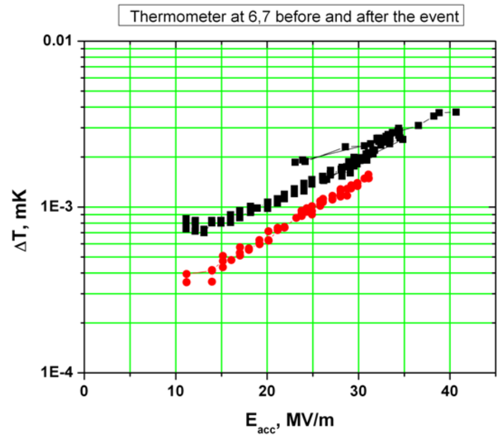


Figure 9: Preheating data from a thermometer close to original quench location. After field emission event thermometer still shows quadratic behavior at low field. The shift to a high temperature rise at low field indicates modification in surface resistance at the original quench location after field emission event.

resistance in the region was reduced.

Modification in the low field surface resistance at the original quench location and new quench location indicated by thermometers in these regions point to modification of niobium surface during high field quench in TB9RI027.

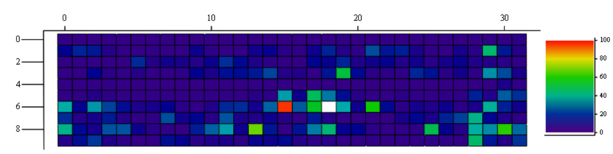

Figure 10: Temperature map of TB9RI027 after re-HPR at $E_{\mathrm{acc}}$ = 44 MV/m in the center cell. Neither original nor new quench location shows any outstanding heating.

After these tests the cavity was removed from the test stand, re-HPR, and tested again. The field emission was still present, but temperature maps showed no field emission pattern up to the highest field in $\pi$ mode. We also measured this cavity in other pass-band modes. In the $5\pi/9$ mode the maximum end cell gradient was 34.5 MV/m. The amplitude ratio of end cell field to center cell field is 1.28 for this mode, therefore, the center cell reached $E_{\mathrm{acc}}$ = 44 MV/m [5]. In Fig. 10 we show the temperature map during $5\pi/9$ mode at $E_{\mathrm{acc}}$ = 44 MV/m. The temperature map does not have any traces of field emission that was limiting the cavity after the high-field field emission turn-on in the previous test: high pressure rinsing removed field emission induced by the high field event.

## CONCLUSION

Several of the 9-cell ILC cavities processed at Jefferson Lab within ongoing ILC R&D program have shown interesting behavior at high fields, such as mode mixing and sudden field emission turn-on during quench. TB9RI019 and TB9RI027 showed spontaneous pass-band mode generation above $E_{\mathrm{acc}}$ = 31 MV/m during $\pi$ mode measurements. The time it took for the pass-band mode to increase above the noise floor and to cause quench decreases approximately linearly with the $\pi$ mode gradient. During TB9RI027 testing we observed sudden field emission turn on in 5th cell. The thermometers indicated modification of the low field surface resistance at both the original and the new quench location, which leads us to the conclusion that the high field quench caused modification of the niobium surface.

## ACKNOWLEDGEMENT

We appreciate support from Andrew Burrill, Joyner Carlton, Steve Castignola, Isiah Daniels, Chris Dreyfuss, James Davenport, Stephen Dutton, Jim Follkie, Danny Forehand, Tom Goodman, Teena Harris, Chad Johnson, Pete Kushnick, Kurt Macha, Michael Morrone, Roland Overton, Sarah Tipton of JLab, and also would like to thank for suggestions and useful discussions Rongli Geng, Ari Palczewski, Charlie Reece, Bob Rimmer, and Hui Tian.

## REFERENCES

[1] Geng R L 2009 *Proc. of 14th International Conference on RF Superconductivity (Berlin)* p. 213

[2] Kreps G, Goessel A, Proch D, Moeller W-D, Kostin D, Twarowski K 2009 *Proc. of 14th International Conference on RF Superconductivity (Berlin)* p. 289

[3] Yamamoto Y, private communications

[4] Ciovati G, Flood R, Kneisel P, Machie D, Morrone M 2008 *JLAB-TN-08-012*

[5] Wang H 2007 *JLAB-TN-07-052*