Fundamental Studies of Impurity Doping in 1.3 GHz and Higher Frequency SRF Cavities

J. T. Maniscalco, P. N. Koufalis, M. Liepe

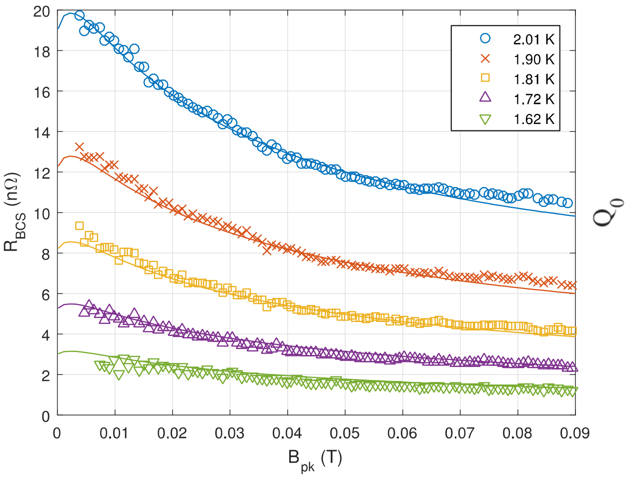
CLASSE, Cornell University

TUPO054

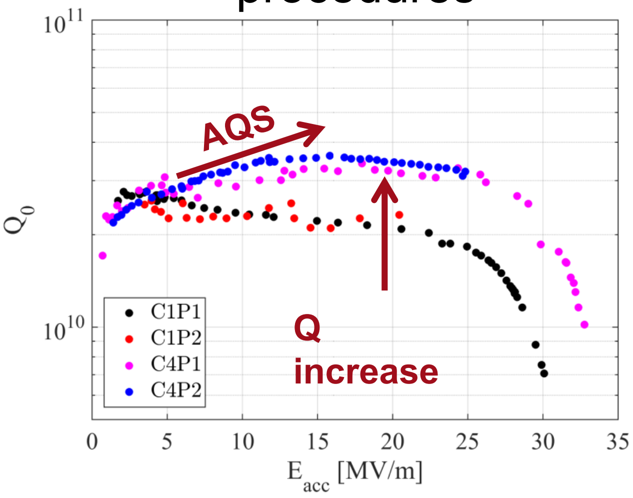
Overview

- Hot topic in SRF accelerators:
  The “anti-Q-slope”, triggered/revealed by impurity doping

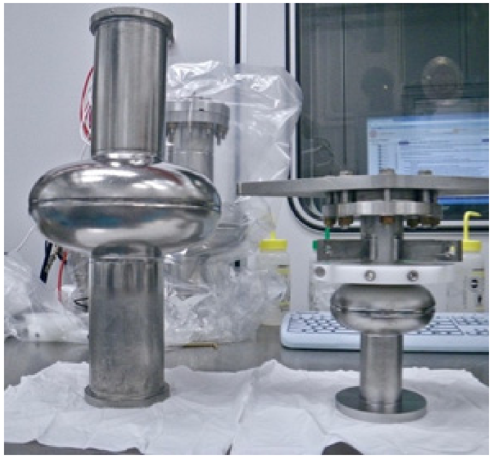
Improving theoretical understanding



Exploring alternative doping agents and procedures

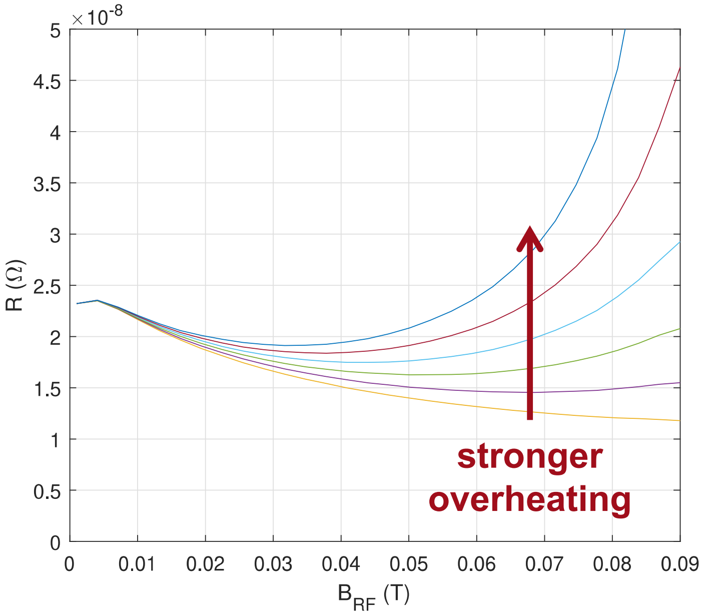


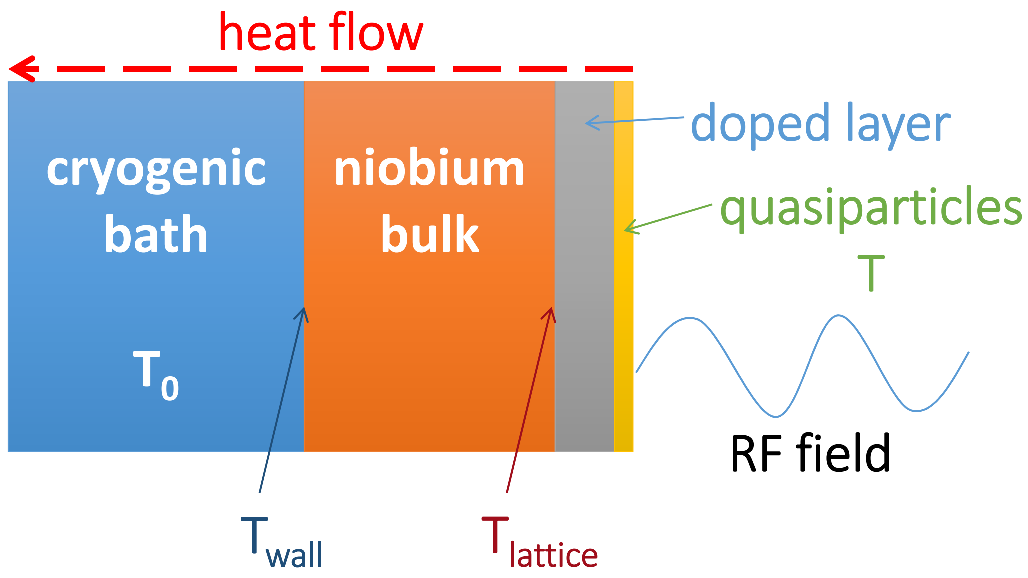
Moving to higher frequencies



Improving theory

- Model: thermal overheating of quasiparticles controls the strength of the anti-Q-slope and the behavior at high field
- Developing a theoretical understanding of thermal effects




heat flow

cryogenic bath

T_0

niobium bulk

doped layer

quasiparticles

T

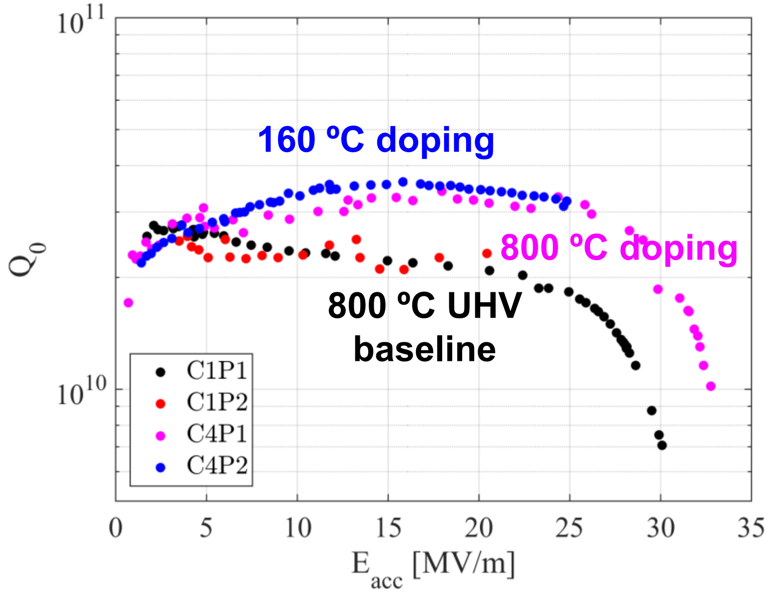
RF field

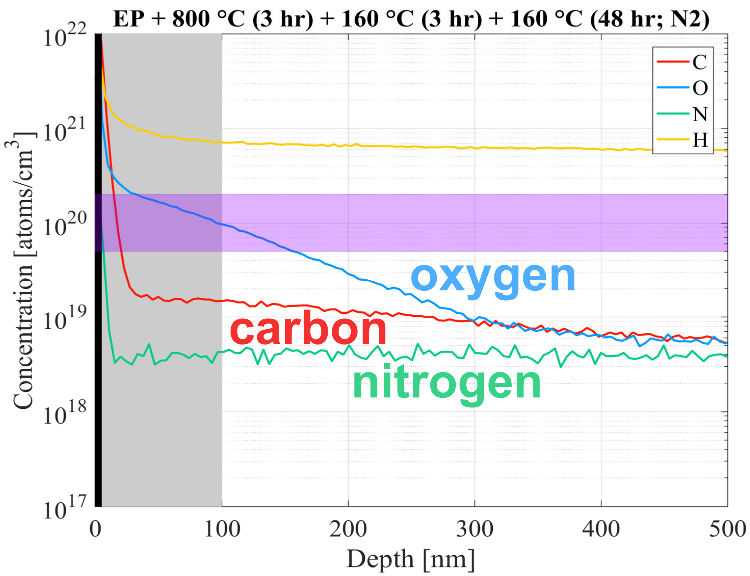
T_{wall}

$T_{lattice}$

Exploring alternative doping

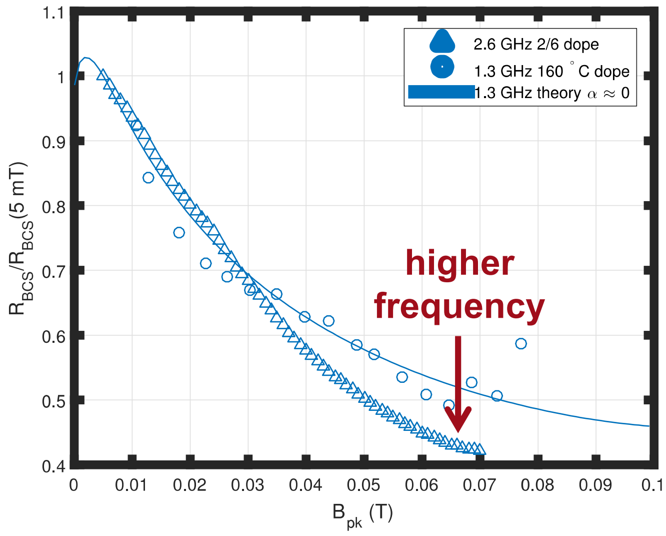
- Low-T doping: 800 ºC UHV degas, 48 hr 40 mTorr N_2 gas (with impurities) little or no post treatment
- AQS similar to high-T doping, but with different impurities!

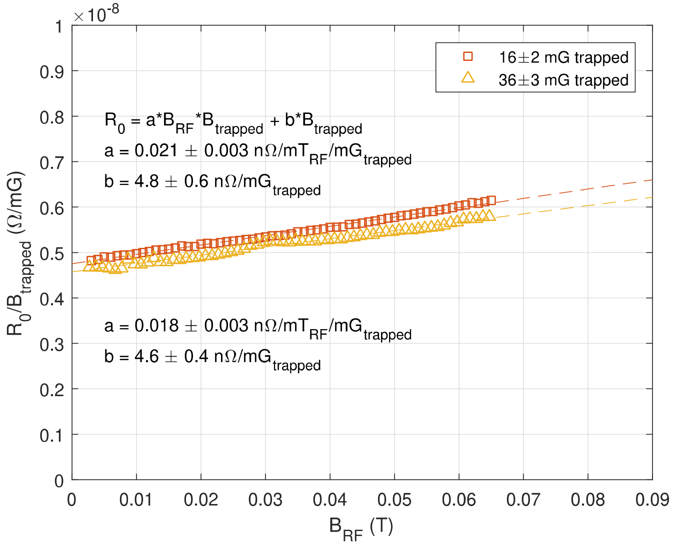




Moving to higher f_0

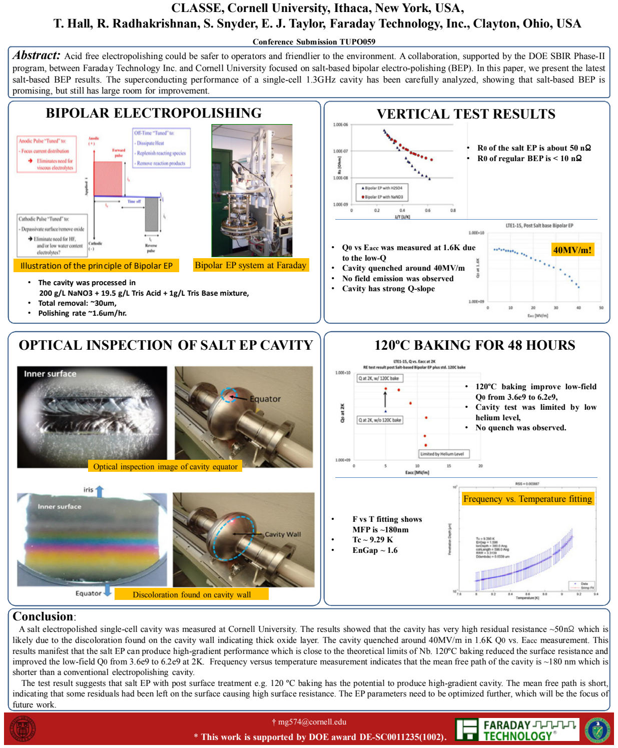
- High frequency cavities: steeper Q rise, compact cavities and cryomodules
- Working with theory partners in CBB to develop understanding of frequency dependence





Come see our posters!

TUPO057-59



CLASSE, Cornell University, Ithaca, New York, USA,
T. Hall, R. Radhakrishnan, S. Snyder, E. J. Taylor, Faraday Technology, Inc., Clayton, Ohio, USA

Conference Submission TUPO059

Abstract: Acid free electropolishing could be safer to operators and friendlier to the environment. A collaboration, supported by the DOE SBIR Phase-II program, between Faraday Technology Inc. and Cornell University focused on salt-based bipolar electro-polishing (BEP). In this paper, we present the latest salt-based BEP results. The superconducting performance of a single-cell 1.3GHz cavity has been carefully analyzed, showing that salt-based BEP is promising, but still has large room for improvement.

BIPOLAR ELECTROPOLISHING

Illustration of the principle of Bipolar EP

Bipolar EP system at Faraday

- The cavity was processed in 200 g/L NaNO3 + 19.5 g/L Tris Acid + 1g/L Tris Base mixture,
- Total removal: ~30um,
- Polishing rate ~1.6um/hr.

VERTICAL TEST RESULTS

- R0 of the salt EP is about 50 nΩ
- R0 of regular BEP is < 10 nΩ

- Q0 vs Eacc was measured at 1.6K due to the low-Q
- Cavity quenched around 40MV/m
- No field emission was observed
- Cavity has strong Q-slope

OPTICAL INSPECTION OF SALT EP CAVITY

Optical inspection image of cavity equator

Discoloration found on cavity wall

120°C BAKING FOR 48 HOURS

- 120°C baking improve low-field Q0 from 3.6e9 to 6.2e9,
- Cavity test was limited by low helium level,
- No quench was observed.

Frequency vs. Temperature fitting

- F vs T fitting shows MFP is ~180nm
- Tc ~ 9.29 K
- EnGap ~ 1.6

Conclusion:

A salt electropolished single-cell cavity was measured at Cornell University. The results showed that the cavity has very high residual resistance ~50nΩ which is likely due to the discoloration found on the cavity wall indicating thick oxide layer. The cavity quenched around 40MV/m in 1.6K Q0 vs. Eacc measurement. This results manifest that the salt EP can produce high-gradient performance which is close to the theoretical limits of Nb. 120°C baking reduced the surface resistance and improved the low-field Q0 from 3.6e9 to 6.2e9 at 2K. Frequency versus temperature measurement indicates that the mean free path of the cavity is ~180 nm which is shorter than a conventional electropolishing cavity.

The test result suggests that salt EP with post surface treatment e.g. 120 °C baking has the potential to produce high-gradient cavity. The mean free path is short, indicating that some residuals had been left on the surface causing high surface resistance. The EP parameters need to be optimized further, which will be the focus of future work.

† mg574@cornell.edu

* This work is supported by DOE award DE-SC0011235(1002).

TUPO054

Conference Submission TUPO054

Abstract

As the demand for more powerful, more efficient, and smaller superconducting RF accelerators continues to increase, both impurity doping and high-frequency cavities (> 1.3 GHz) have become hot topics for fundamental research because of their potential to significantly decrease surface losses and cost respectively. In this report, we present recent experimental and theoretical results on undoped and nitrogen-doped high-frequency cavities and on alternative doping agents in traditional 1.3 GHz cavities, with a focus on understanding the fundamental science of impurity doping.

2/6 Doping at 2.6 GHz

At IPAC 2018, we reported on a 2.6 GHz ILC-shape single-cell cavity that was doped with the "2/ 6" recipe*, the standard treatment for LCLS-II cavities. We present here measurements of the sensitivity of the residual resistance R_0 to trapped magnetic flux. This sensitivity is shown below with two-parameter linear fits for two cooldowns, one with 16±2 mG and one with 36±3 mG trapped. The mean linear intercept coefficient, 4.7±0.5 nΩ/ mG, is twice the coefficient for 1.3 GHz cavities doped with the same method to the same mean free path 46 nm, which indicates a linear scaling of sensitivity with frequency.

160 °C doping at 2.6 GHz

We prepared a 2.6 GHz ILC-shape cavity with the 160 ºC "N-infusion" doping treatment†. This cavity showed a strong anti-Q-slope (AQS). The magnitude of the drop in BCS resistance is consistent with strong doping and 160 ºC doping at 1.3 GHz, but the slope is steeper than in those cavities and steeper than can be predicted by the Gurevich theory which has been successful for strongly doped/ infused 1.3 GHz cavities.

We also used SIMS to look at the atomic impurity content in the surface. We found that there was a minimal amount of N present in the sample, but high levels of C and O, indicating that these atoms may be responsible for the anti-Q-slope in 160 ºC-doped cavities.

160 °C Doping at 1.3 GHz

In our research efforts for the LCLS-II HE upgrade R&D project, we have also treated several 1.3 GHz ILC-shape single-cells with variations of the 160 ºC treatment: one with a 48-hour dope, one with a 96-hour dope, and a retest of the 96-hour cavity after ~5 nm surface removal by HF rinse. Both the 48-hour cavity and the first test of the 96-hour cavity yielded an unusual field-dependent BCS resistance, generally increasing but with a region of decreasing R_{BCS} from ~20 to ~40 mT.

After the HF rinse, the 96-hour cavity showed a strong anti-Q-slope (AQS) consistent with previous 160 ºC N-doped and C/ O-doped cavities, as well as 800 ºC N-doped cavities with mean free path < 10 nm. We performed theoretical fits using our model based on the Gurevich theory of the AQS, modified to account for depth-dependent material parameters and with an improved thermal transport model. The fits were also consistent with the model for strongly-doped cavities.

Above: experimental results of the BCS surface resistance and theoretical fits for the 96-hr 160 ºC-doped cavity with HF rinse.

Below, left: experimental results of the BCS resistance for the 96-hr 160 ºC-doped cavity prior to HF rinsing.

Below, right: same for the 48-hr 160 ºC-doped cavity.

---

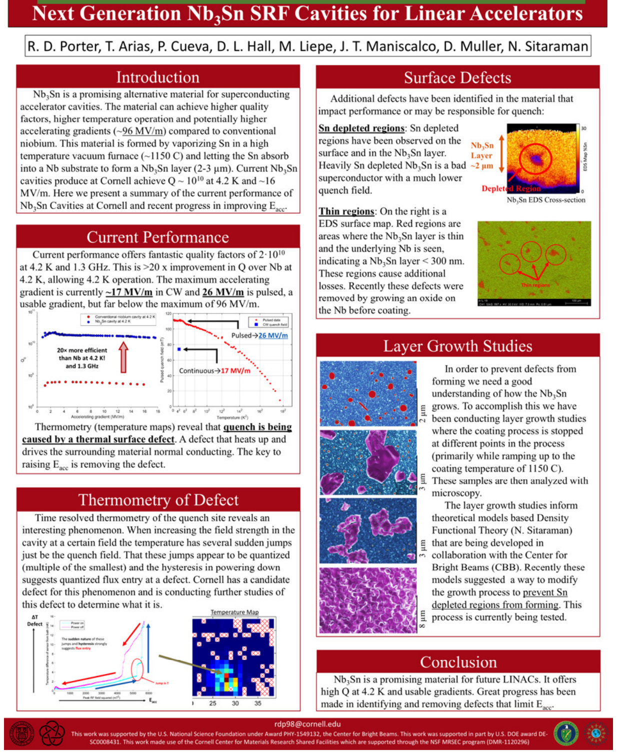
* 2/ 6 doping: UHV degas for 3 hr, 40 mTorr N_2 for 2 min, UHV anneal for 6 min (all steps at 800 ºC). Doping is followed by several µm removal by vertical electropolish.

† 160 ºC doping: 800 ºC UHV degas for 3 hr, 160 ºC UHV for 3 hr, 40 mTorr N_2 for 3 hr.

* jtm288@cornell.edu

This work was supported in part by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams, and under Award PHY-1734189.
This work was also supported by the U.S. Department of Energy and the LCLS-II HE Project.

TUPO055



Next Generation Nb_3Sn SRF Cavities for Linear Accelerators

R. D. Porter, T. Arias, P. Cueva, D. L. Hall, M. Liepe, J. T. Maniscalco, D. Muller, N. Sitaraman

Introduction

Nb_3Sn is a promising alternative material for superconducting accelerator cavities. The material can achieve higher quality factors, higher temperature operation and potentially higher accelerating gradients (~96 MV/m) compared to conventional niobium. This material is formed by vaporizing Sn in a high temperature vacuum furnace (~1150 C) and letting the Sn absorb into a Nb substrate to form a Nb_3Sn layer (2-3 µm). Current Nb_3Sn cavities produce at Cornell achieve Q ~ 10^{10} at 4.2 K and ~16 MV/m. Here we present a summary of the current performance of Nb_3Sn Cavities at Cornell and recent progress in improving E_{acc}.

Current Performance

Current performance offers fantastic quality factors of $2\cdot10^{10}$ at 4.2 K and 1.3 GHz. This is >20 x improvement in Q over Nb at 4.2 K, allowing 4.2 K operation. The maximum accelerating gradient is currently **~17 MV/m** in CW and **26 MV/m** is pulsed, a usable gradient, but far below the maximum of 96 MV/m.

Thermometry (temperature maps) reveal that **quench is being caused by a thermal surface defect**. A defect that heats up and drives the surrounding material normal conducting. The key to raising E_{acc} is removing the defect.

Thermometry of Defect

Time resolved thermometry of the quench site reveals an interesting phenomenon. When increasing the field strength in the cavity at a certain field the temperature has several sudden jumps just be the quench field. That these jumps appear to be quantized (multiple of the smallest) and the hysteresis in powering down suggests quantized flux entry at a defect. Cornell has a candidate defect for this phenomenon and is conducting further studies of this defect to determine what it is.

Surface Defects

Additional defects have been identified in the material that impact performance or may be responsible for quench:

Sn depleted regions: Sn depleted regions have been observed on the surface and in the Nb_3Sn layer. Heavily Sn depleted Nb_3Sn is a bad superconductor with a much lower quench field.

Nb_3Sn EDS Cross-section

Thin regions: On the right is a EDS surface map. Red regions are areas where the Nb_3Sn layer is thin and the underlying Nb is seen, indicating a Nb_3Sn layer < 300 nm. These regions cause additional losses. Recently these defects were removed by growing an oxide on the Nb before coating.

Layer Growth Studies

In order to prevent defects from forming we need a good understanding of how the Nb_3Sn grows. To accomplish this we have been conducting layer growth studies where the coating process is stopped at different points in the process (primarily while ramping up to the coating temperature of 1150 C). These samples are then analyzed with microscopy.

The layer growth studies inform theoretical models based Density Functional Theory (N. Sitaraman) that are being developed in collaboration with the Center for Bright Beams (CBB). Recently these models suggested a way to modify the growth process to prevent Sn depleted regions from forming. This process is currently being tested.

Conclusion

Nb_3Sn is a promising material for future LINACs. It offers high Q at 4.2 K and usable gradients. Great progress has been made in identifying and removing defects that limit E_{acc}.

rdp98@cornell.edu

This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. This work was supported in part by U.S. DOE award DE-SC0008431. This work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1120296)