Nb-on-Cu Cavities for 700 – 1500 MHz SRF Accelerators

Katherine Velas & Mahadevan Krishnan*

Alameda Applied Sciences Corporation (AASC) , San Leandro, CA, 94577

at

DOE Nuclear Physics SBIR/STTR Exchange Meeting, August, 2017

* presenter

Acknowledgements

S. Chapman, I. Irfan
Alameda Applied Sciences Corporation (AASC), San Leandro, California

C. Reece, L. Phillips, A-M Valente Feliciano, A. Palczewski J. Spradlin
Thomas Jefferson National Accelerator Facility (JLab), Newport News, Virginia

S. Aull
European Organization for Nuclear Research (CERN), Geneva, Switzerland

C. Zhou
Analytical Instrumentation Facility, North Carolina State University, Raleigh, NC

Research is supported at AASC by DOE office of Nuclear Physics via SBIR Grant DE-SC0011371

The JLab effort was provided through a Cooperative Research and Development Agreement, CRADA 2015S007

Outline

- Alameda Applied Sciences Corporation
- Phase II Project Goals
- Relevance to NP Programs
- Current Status of Project
- Plans to Advance Project Goals

Alameda Applied Sciences Corporation

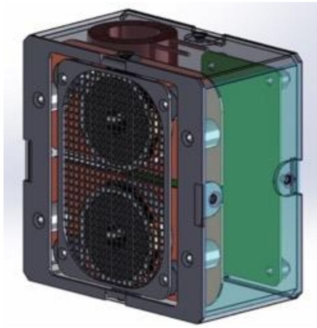
Superconducting Thin Films

1.3GHz Cu cavity

Nb coated cavity

CED creates well adhered, crystalline coatings

Electric Propulsion for Small Satellites



10μN/W, 1700s I_{SP}

Fast Gas Valve

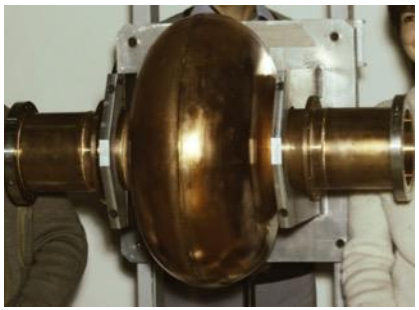
100Bar / 50μs opening/ <500μs closing

Diamond Radiation Detectors

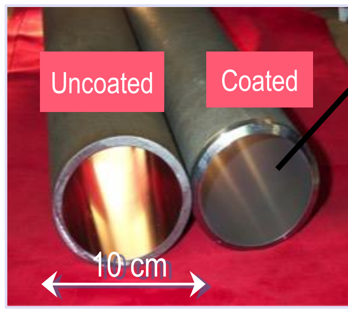
UV and soft x-ray ≤ 15 keV

- Founded in 1994, privately held CA Corporation
- 6 employees, ~$1.3 million 2016 revenue
- Develop/license IP via contract R&D
- Four Pre-commercial/Product areas:
  - Cathodic arc coatings CED
  - Electric Micro-Propulsion Thrusters
  - Fast Supersonic Gas Valves
  - Diamond Radiation Detectors

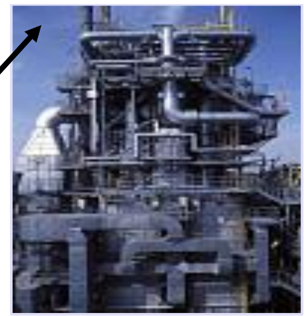
Cathodic Arc Coatings (CED^{TM})



CED coating of Cu cavities for SRF



Anti-coking coating on furnace tube



Benefit: extended interval between de-cokings

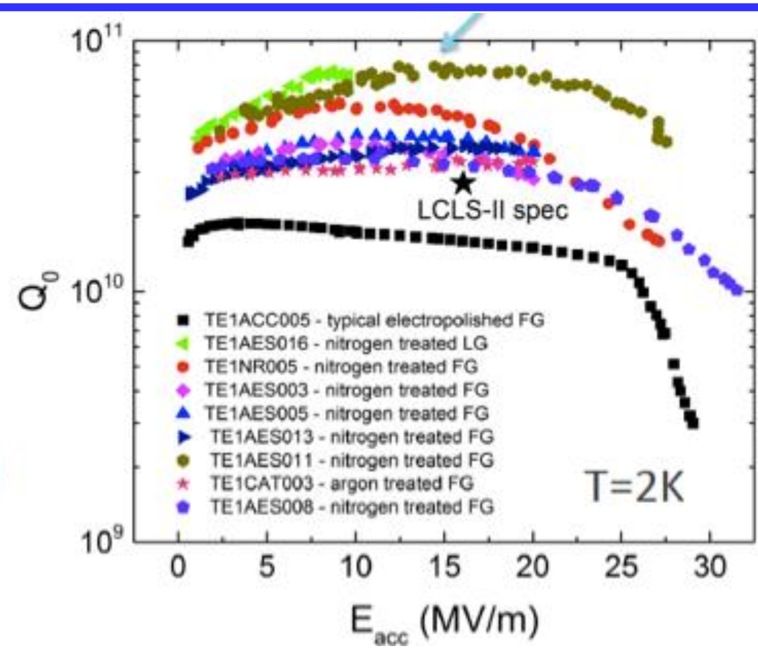
Motivation for SRF advancement

- More than 10000 particle accelerators worldwide; most use *normal* cavities
- Construction of ILC, FCC, and ADS reactors would benefit from cheaper superconducting cavities
- Facility for Rare Isotope Beams (FRIB), ILC and other large facilities:
  - *NSAC report states that as a result of technical advances, a world-class rare isotope facility can be built at ≈ half the cost of the originally planned Rare Isotope Accelerator (RIA), employing a superconducting linac*
- SRF at 2K is good, but operating at ~10K would further reduce SRF costs as the cryogenic cooling moves towards off the shelf cryo-coolers
- Replacing bulk Nb with Nb coated Cu cavities would also reduce costs
- The ultimate payoff would be from Cu or cast Al SRF cavities coated with higher temperature superconductors (NbN, Mo_3Re, Nb_3Sn, MgB_2, oxypnictides)

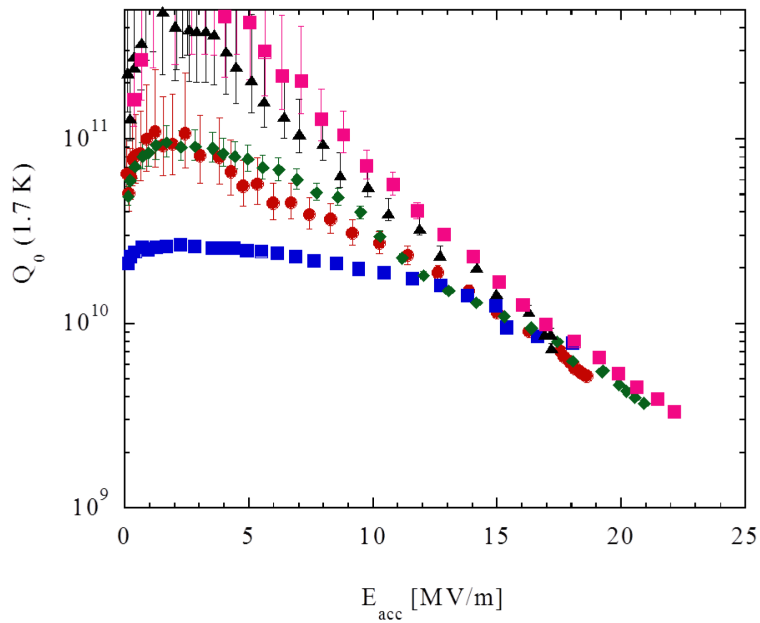
AASCs thin film superconductor development is aimed at these goals

Current State of SRF Cavities

- Performance of 1.3 GHz cavities enhanced by nitrogen doping
- Magnetron sputtered Nb on Cu cavities (CERN) showed large Q-slope
- Proven alternative technologies will reduce costs, spur private investment, and encourage scientific advancement & discovery

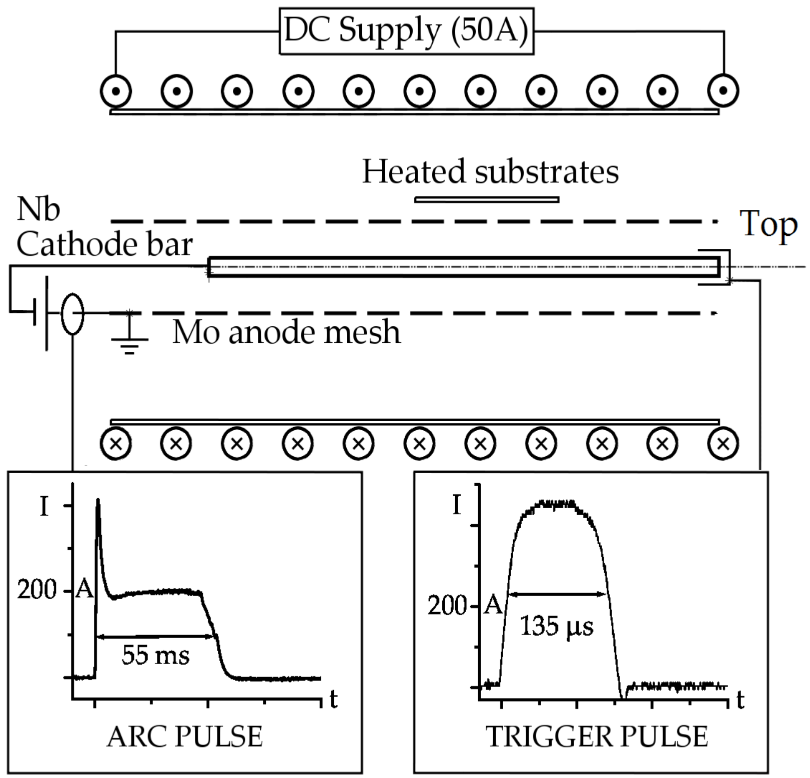


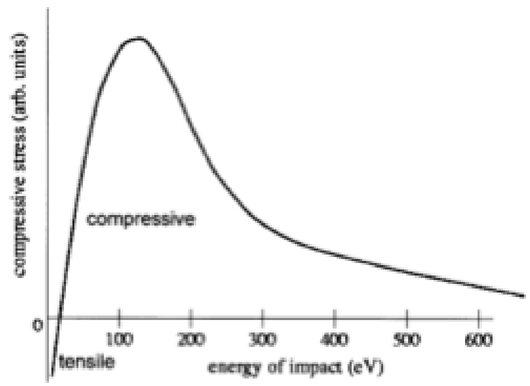
Above: Nitrogen doped bulk Nb
Below: CERN magnetron sputtered Nb on Cu



Coaxial Energetic Deposition (CED™)

- Energetic Condensation Method
- CED uses 100V/200A power supply to drive cathodic arcs
- CED implants 60-120 eV Nb ions (avg. charge +3) a few monolayers below the surface
  - *Sub-plantation, not implantation*
- Ions shake up lattice promoting good adhesion and crystal growth
- Heat substrate to promote defect free crystal growth
- Adding -60 V bias gives 240 – 300 eV ions, reduces compressive stress, and increases film density





Internal stress as a function of incident ion energy*

*M. M. M. Bilek, D.R. McKenzie, R.N. Tarrant, S.H.M. Lim, D.G. McCulloch, Surface and Coatings Technology 156 (2002)

Challenges for thin film SRF: Path to success

- Research on Nb coated coupons showed us that CED has promise for SRF applications

- How do we grow low-defect Nb films on 3D cavity structures?

- Study RF performance of Nb coating on Cu cavities

- Correlate RF performance of cavities with coating parameters using data from Cu coupons

- Measure $Q_o \sim 10^{10}$ at up to 20 MV/m
  - Bulk Nb cavities have raised the bar ($Q_o \sim 10^{11}$) with nitrogen doping

- Proceed to multi-cell Nb coated Cu cavities to fully validate thin film solution

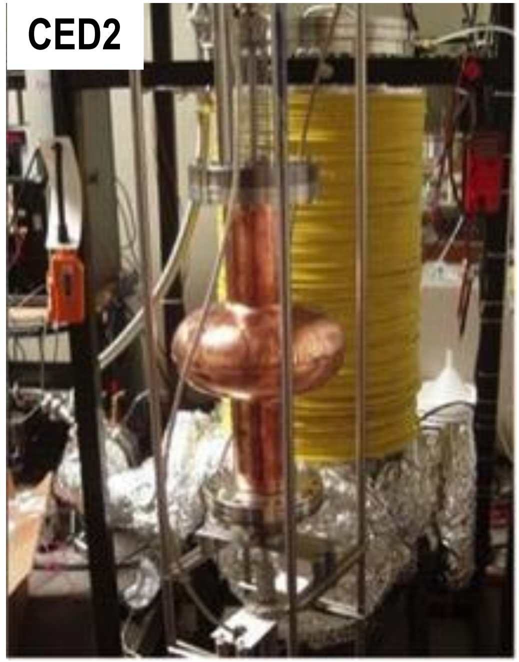
Phase II Tasks

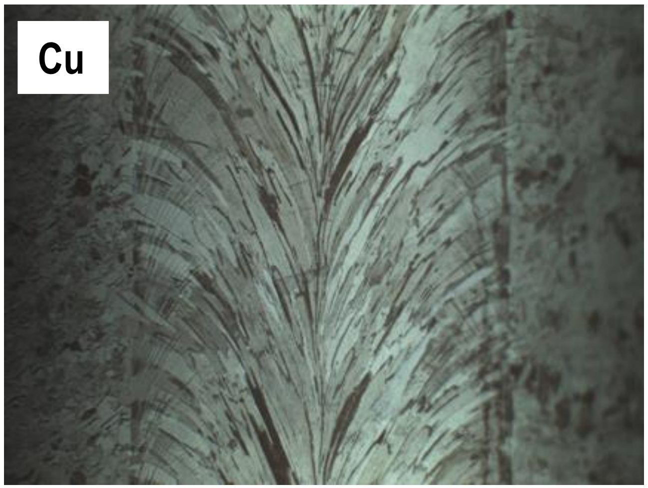
- ✓ Improve CED trigger (year 1)
- ✓ Upgrade CED2 for cavity coating (year 1)
- ✓ Optimize thickness control (year 1)
- ✓ Coat and test first batch of Cu cells (year 1)
- ✓ Make improvements to coating procedure (year 2)
- ✓ Coat and test second batch of Cu cells (year 2) - ongoing

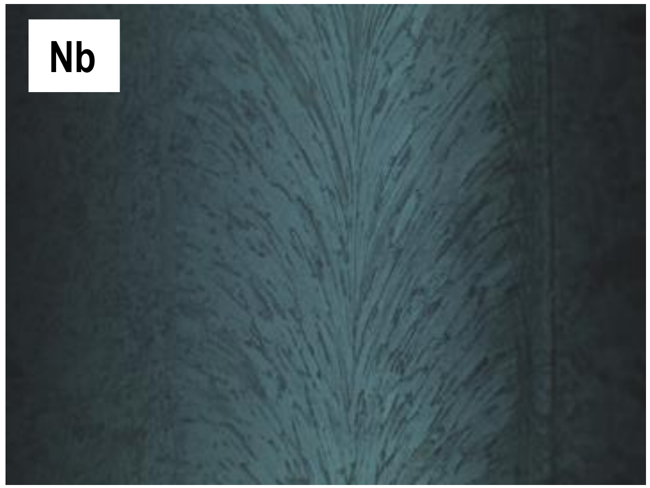
Cu cavity coating inside CED-2 establishes baseline

LSFC-B

- Base vacuum pressure 7×10^{-7} Torr
- Cavity heated to 275 °C
- No bias voltage
- 2 µm film deposited
- Optical inspection shows Nb inherits crystal structure of Cu substrate

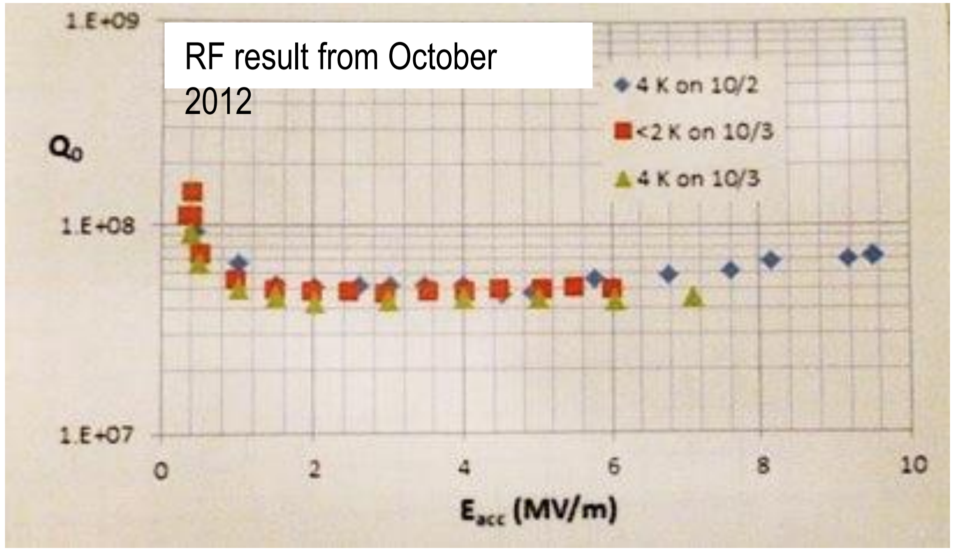


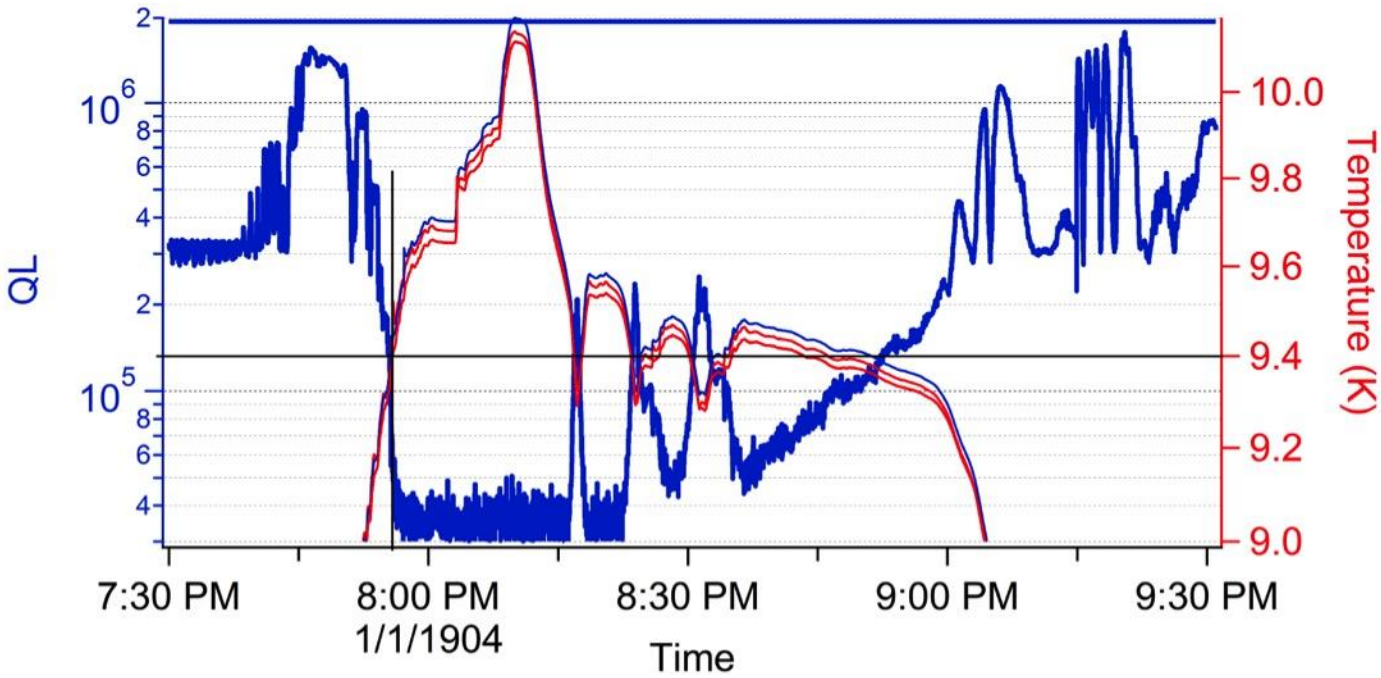




RF Test shows improvement but more needed

- Clear T_c at 9.4 K
- Q_o limited to $1.5x10^8$
- Results independent of temperature*
  (2 or 4 K) or cooling speed



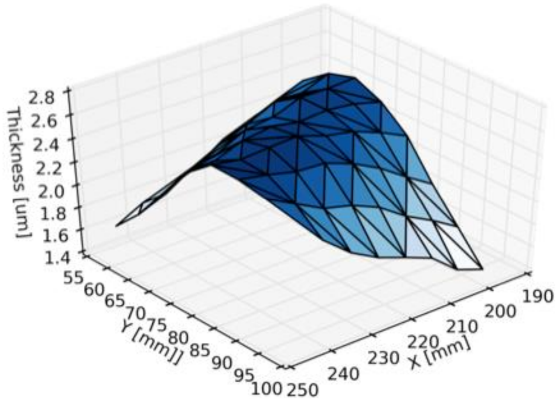


* Early indication that impurities might be playing a role in the film

CERN Resonator provided extensive data

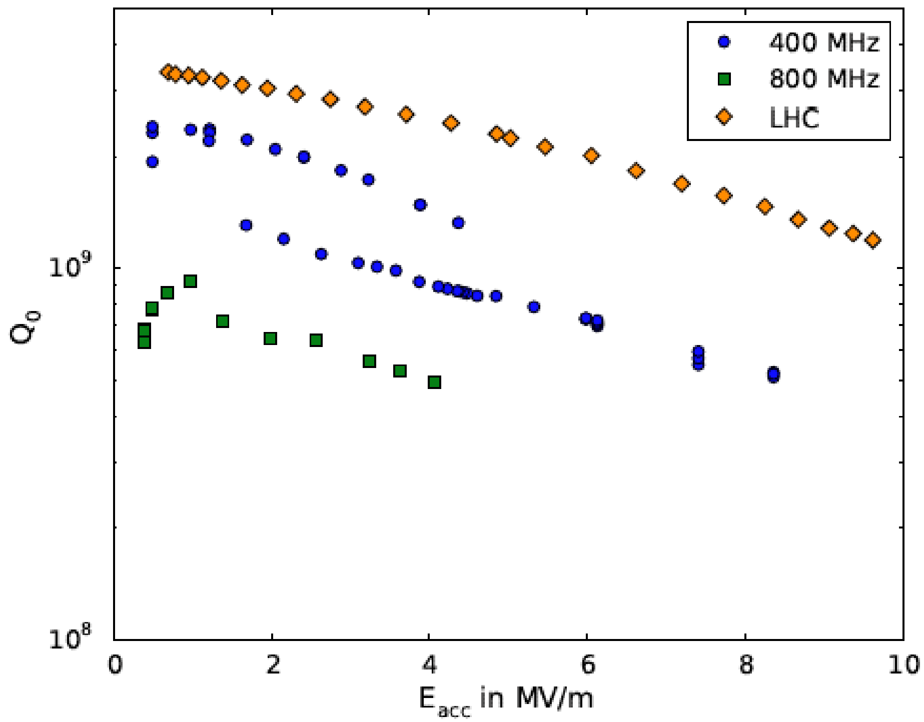
- T_c at 9.27 K suggests low film stress
- Low-field Q close to LHC specs
- Reduced energy gap suggests contamination
  - Energy gap in bulk Nb ≈ 17 K
- Mean free path near BCS optimum

Property	Value
Critical temperature (T_c)	(9.27 ± 0.1) nm
Effective penetration depth λ (0,ℓ)	(53 ± 1) nm
Mean free path	(35 ± 4) nm
Residual resistance ratio RRR	(13 ± 4)
Low field residual resistance R_{res} at 400 MHz	(47.6 ± 1.8) nΩ
BCS factor A_{BCS} for 400 MHz	(7126 ± 1071) nΩK
Energy gap Δ / k_B	(11.1 ± 0.4) K



Thickness profile of coating on CERN resonator

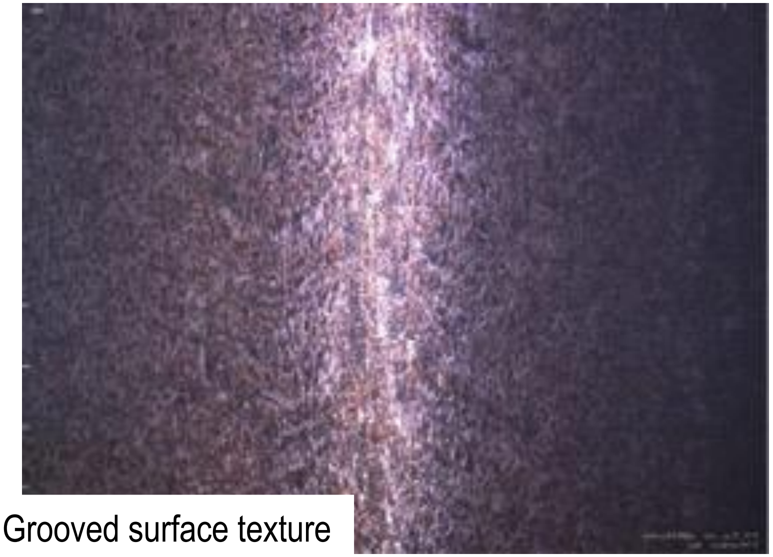
Left: QR mounted for coating. Right: after coating



Surface resistance data at 4K for both frequencies translated into $Q(E_{acc})$ for the LHC geometry. The typical LHC performance is shown for comparison.

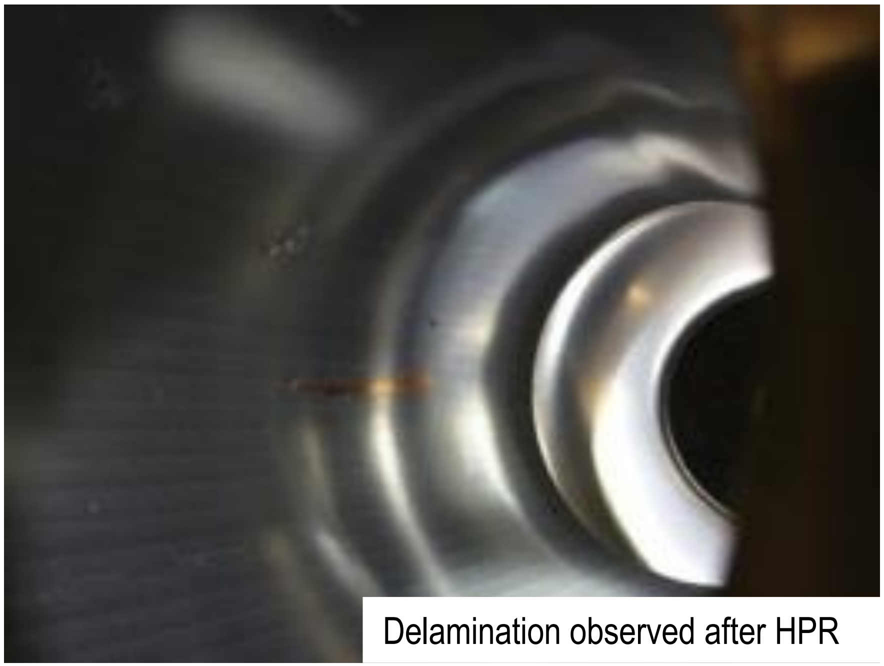
Fermilab cavity failure emphasizes surface prep

- Coating on Fermilab cavity was stripped using centrifugal barrel polishing (CBP)
- CBP left cavity with grooved surface
- Electropolish could not smooth the surface
- Coating delaminated during high pressure rinse



Grooved surface texture

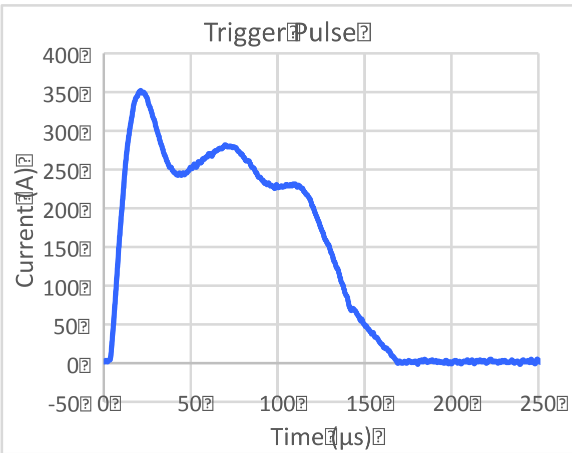
Cavity after coating



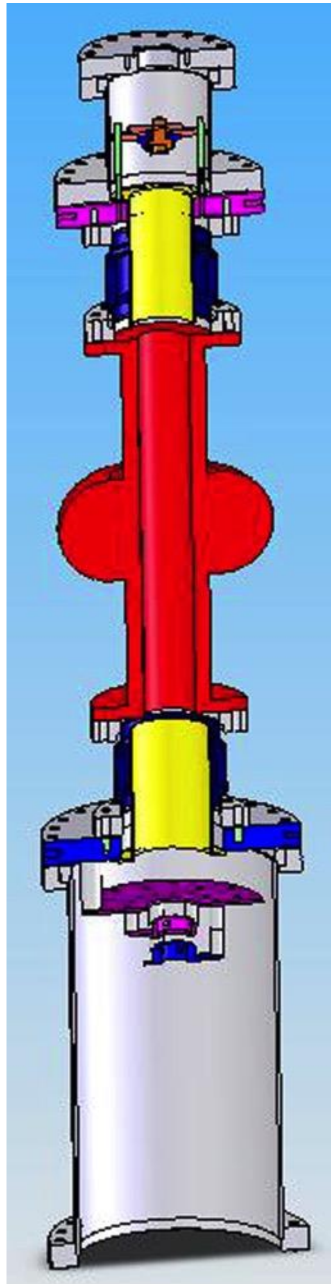
Delamination observed after HPR

RF Test results motivated coater upgrades

- Film quality will benefit from improved vacuum and cleanliness
- Trigger system could be introducing impurities
- Heaters used in vacuum could be emitting impurities
- Design new coating system – CED-U
- Improve trigger hardware to eliminate impurities

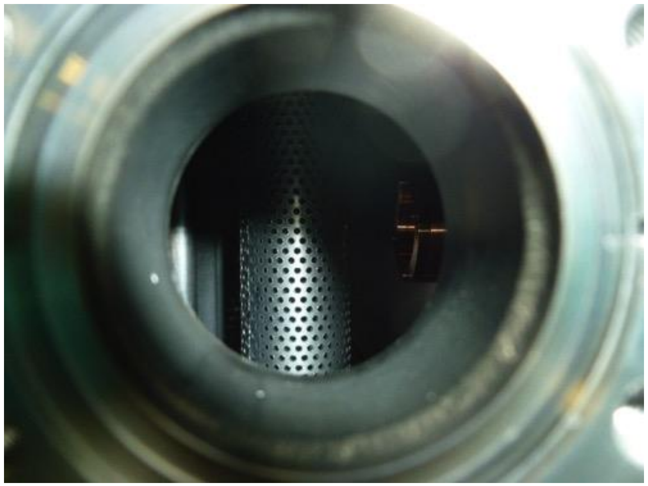


- New trigger system increases reliability
- Simplified trigger hardware has over 50,000 pulses without failure



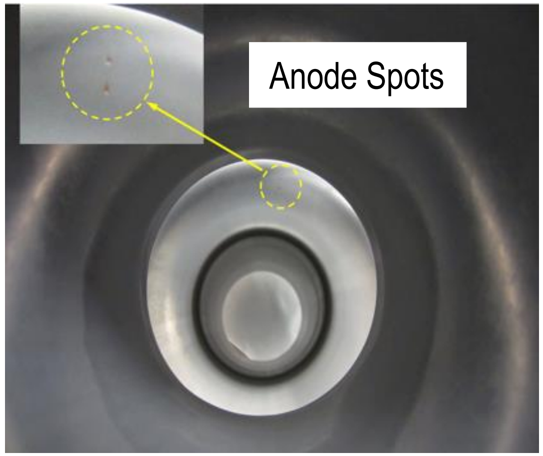
CED-U chamber pumps on cavity

- Use sub-chamber to coat coupons
- Base vacuum of $1x10^{-8}$ Torr
- Upgrades added N_2 purge and feed-throughs to heat coupons from outside



Optimize thickness uniformity with modified anode

- Ensure thickness uniformity with variable transmission anode
- First test used 33% in beam pipe, >90% in ellipse and resulted in anode spots that damaged the film

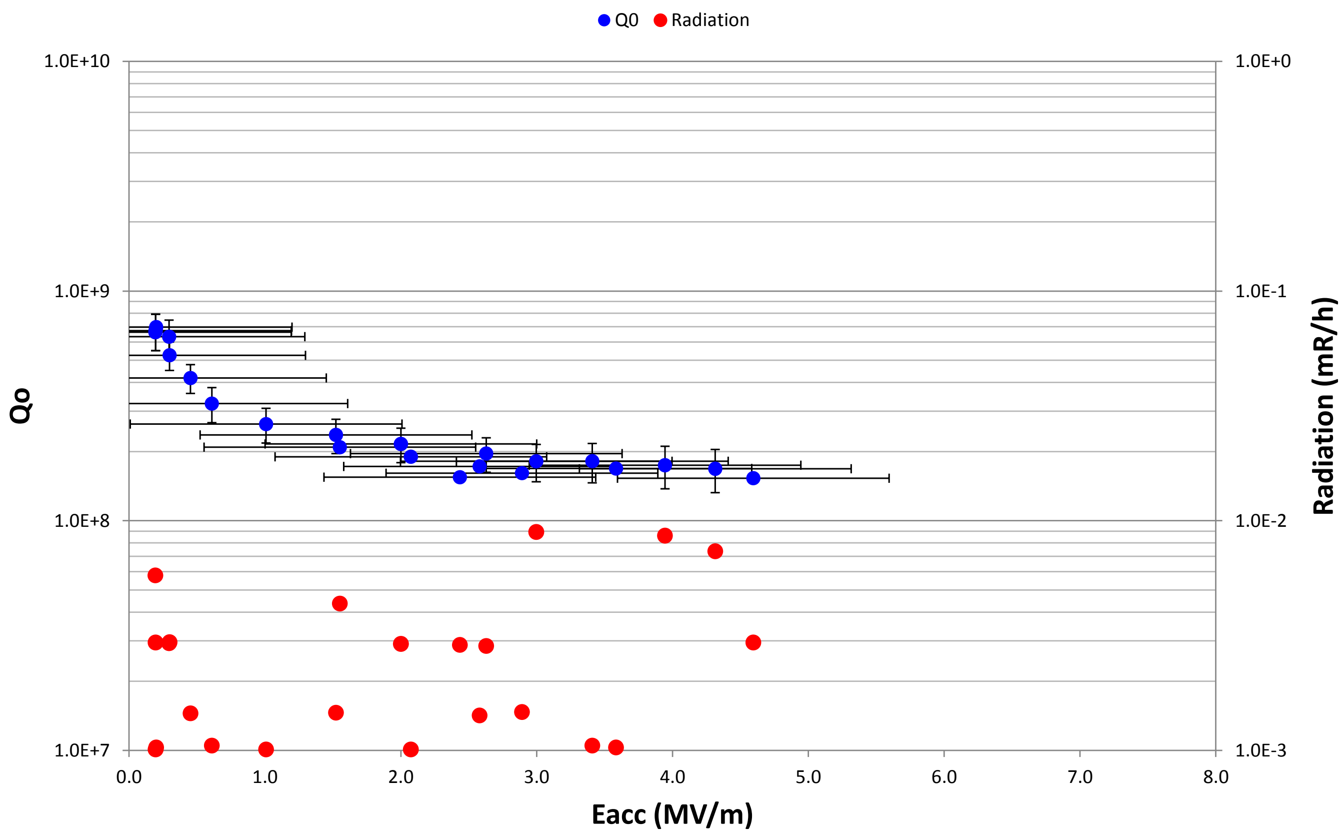


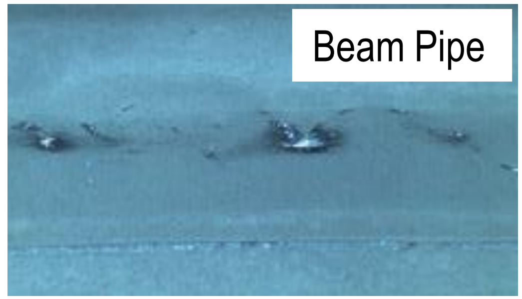
- Now using anode with 23% in beam pipe, 63% in ellipse

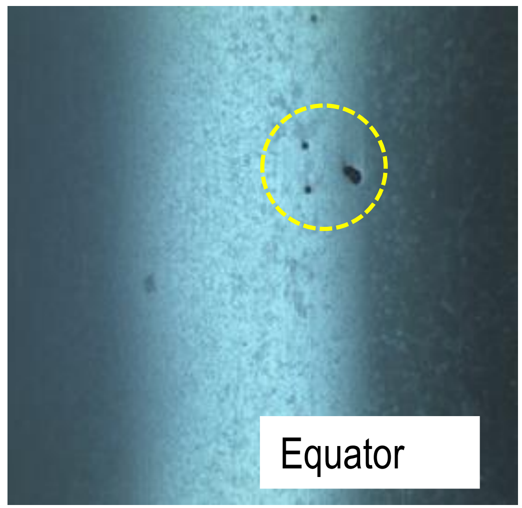
Measure	Value		Unit
Coating pulse width	0.285		s
Arc velocity	4		m/s
coated length	114		cm
Arc current	135		A
Charge per pulse	38.5		C
Erosion rate	25		µg/C
Eroded mass per pulse	9.60E-04		g
Substrate radius	3.9	10	cm
Anode Transparancy	23%	63%	
Fluence at substrate	7.9E-08	8.4E-08	g/cm^2
Nb density	8.57		g/cc
Thickness per pulse	9.2E-09	9.8E-09	cm
# of pulses	25000		
Film Thickness	2.30	2.46	µm
Average Film Thickness	2.38±0.08		µm

First cavity coated in CED-U set record

- Cavity LSFC-3 coated with 1.8 µm Nb at 200 °C with -40 V bias at 5×10^{-8} Torr
- Zero field $Q_o \approx 1 \times 10^9$
- Exhibits Q-switch and Q_o falls to 2×10^8
- Defects in Cu substrate cause local quench and degrade performance

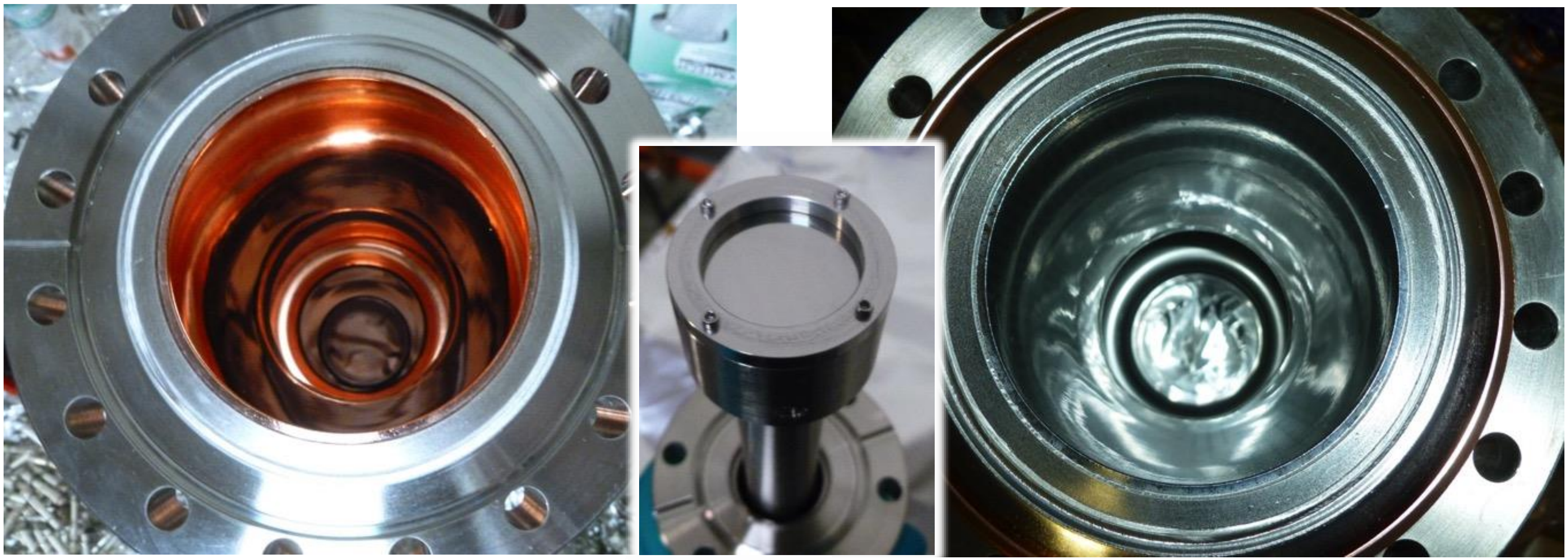




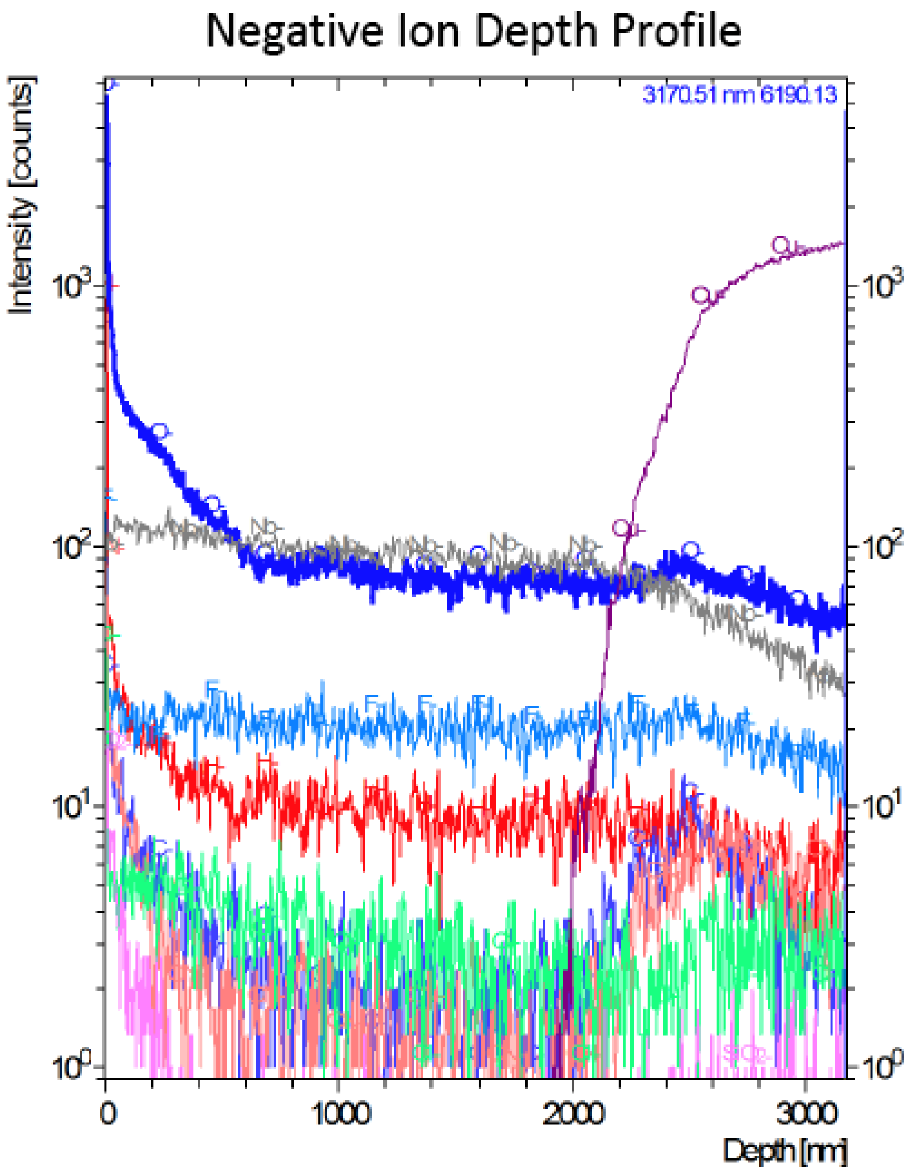


Cavity at JLab awaiting RF test

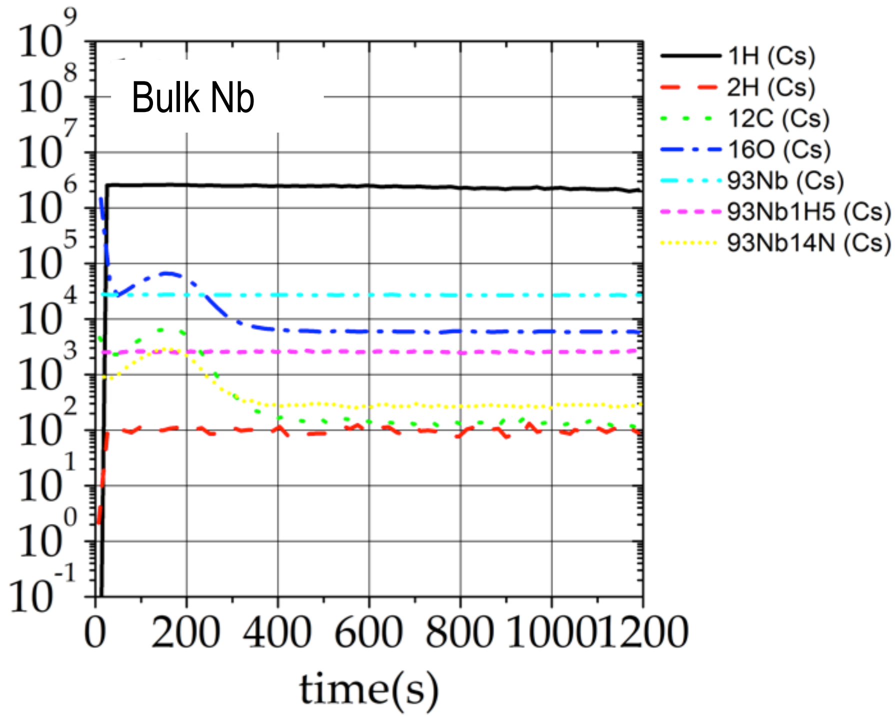
- LSFC-2 coated at 170 °C and -60 V bias with 2 μm and base vacuum of 1×10^{-8} Torr
- Flushed chamber with 50 psi of purified N_2 for 10 minutes before final vacuum seal
- Sharp superconducting transition at 9.37 K



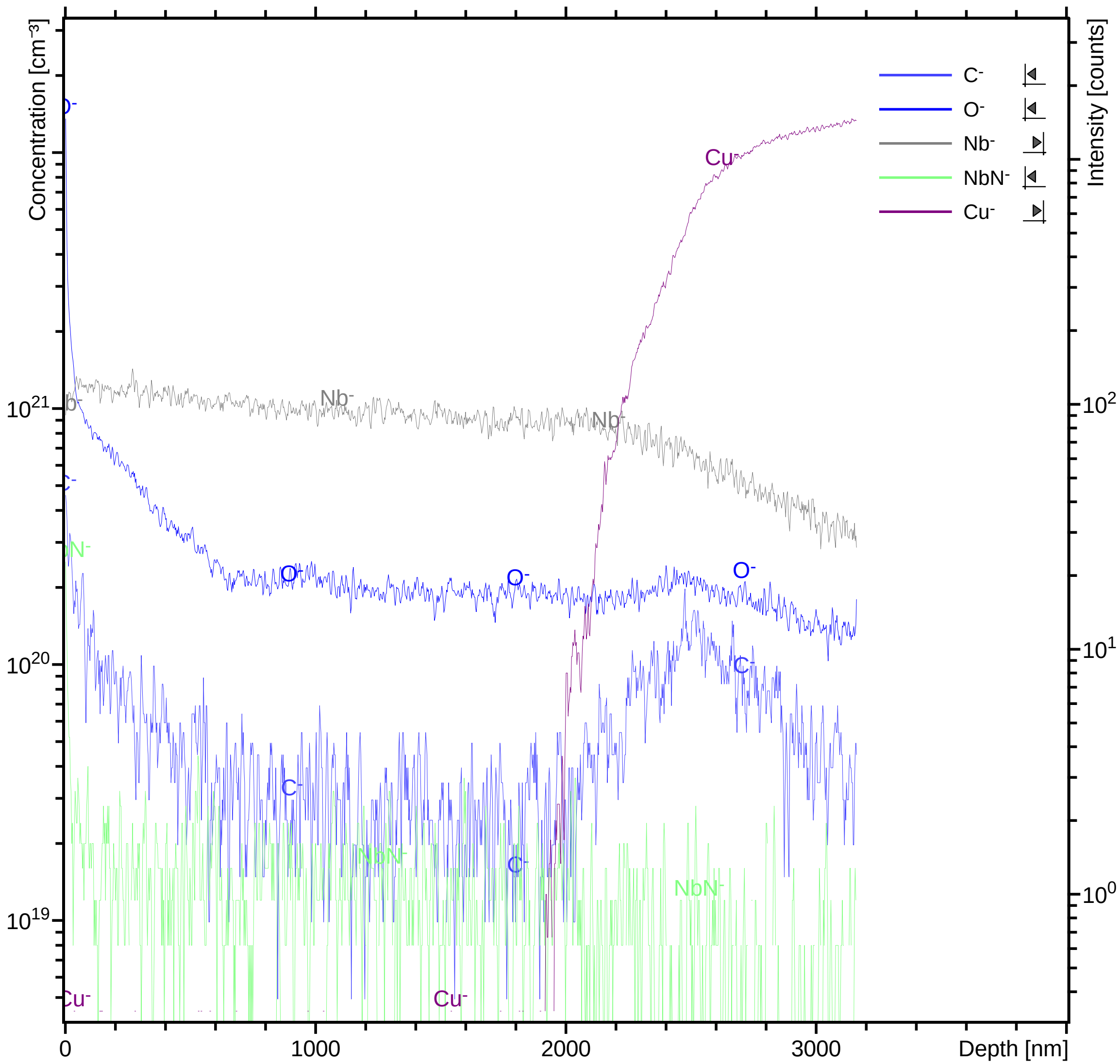
SIMS Data shows low impurity content



- Copper coupons polished with similar procedure as elliptical cavity
- Coupons coated with same bias and temperature as cavity
- Tests on coupons coated at the same time and under the same conditions are crucial in understanding Nb film on cavity



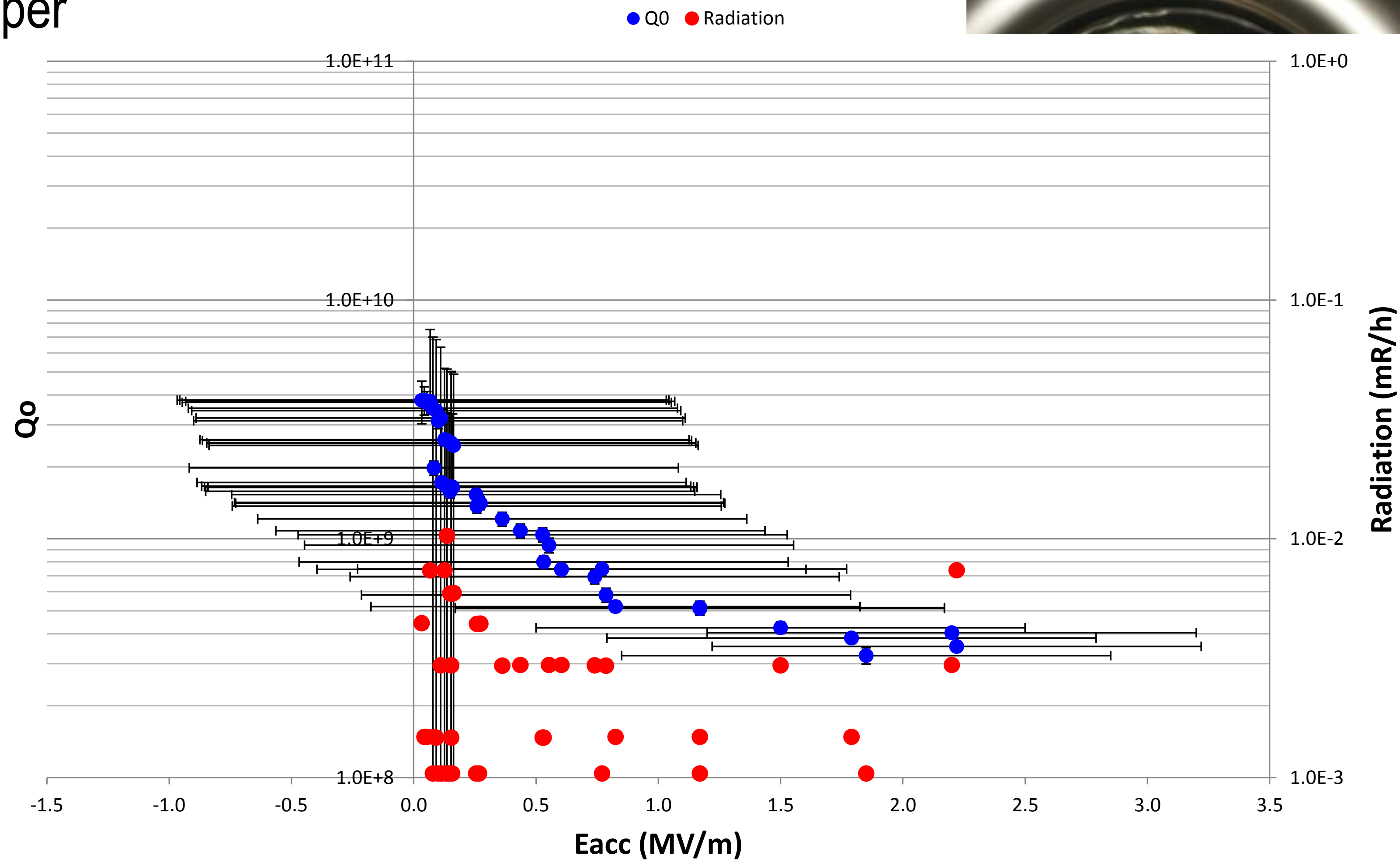
Absolute Concentrations of O, C, and N



- C, O and N are on conc. scale (left y-axis).
- Nb and Cu are on intensity scale (right y-axis)
- N almost reaches the detection limit of the ToF SIMS
- First 600 nm shows higher O and C contamination.

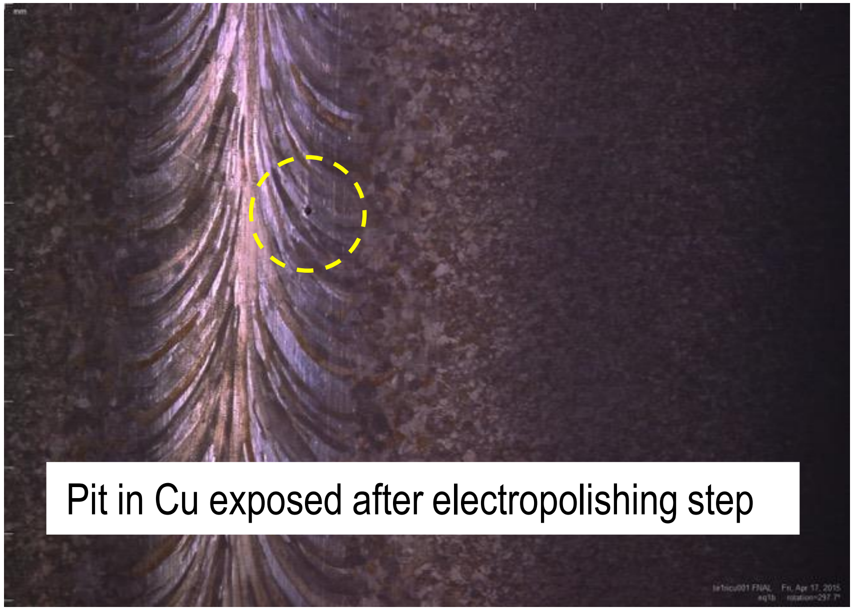
LSFC-2 Sets Another Record for High Q

- Zero field $Q_o \approx 4x10^9$. *Highest ever in CED cavity*
- Exhibits Q-switch and Q_o falls to $4x10^8$
- Bubble in ellipse that caused Q-switch was likely due to poor surface preparation and/or defects in copper

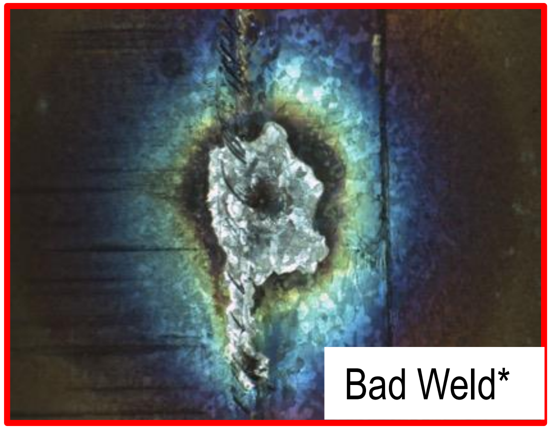


Next cavities have improved Cu surface

- Defects in Cu substrate can cause local quench and degrade SRF performance
- E-beam weld (JLab) requires precision and careful preparation
- Next set of cavities (JLab) have improved welding procedure with careful QC



Pit in Cu exposed after electropolishing step



Bad Weld*

Good Weld*

* J. Spradlin et. al., 7th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity,, Jefferson Lab, Newport News, VA, July 2016

Next coatings will be prepared in JLab Cleanroom

- Cannot eliminate sources of contamination in AASC environment
- Therefore, cavities henceforth to be prepared in cleanroom at JLab
- CED-U hardware being shipped to JLab for cleaning and assembly
- All parts will be cleaned and assembled in JLab cleanroom
- Next cavity coating (at JLab) should see best performance yet

Summary and Plans

- CED-U is an upgraded CED coating system that directly pumps on a cavity to allow heating from outside and removes potential sources of impurities
- Each cavity coated in CED-U set new record for highest Q_o measured in cavity coated using Coaxial Energetic Deposition
- Improvements have been made in cavity manufacture and EP procedure
- Q-switch likely a result of Cu surface particulates or impurities in the film from "dirty" vacuum at AASC
- Coating at JLab is best hope at breakthrough
- AASC continues to get closer to validating Nb coated Cu for SRF accelerators