Superconducting RF Cavities

ILC ART Review at Fermilab

Mark Champion

June 09, 2010

Outline

- Summary
- Organization
- Goals
- Accomplishments
  - Cavity processing and testing
  - Materials and single-cell R&D
  - Diagnostics development & repair techniques
  - Vendor development & cavity procurements
- Plan for FY2011
- Conclusion

Summary: Busy year with many accomplishments!

- Cavity yield increased to TDP-1 goal of 50%
- Outstanding nine-cell cavity performance results at Jefferson Lab
  - "Optimal" electro-polishing demonstrated repeatedly
- Increasing throughput and quality at the Argonne cavity processing facility
- Increasing throughput at the Fermilab vertical test stand and civil construction completed for VTS2-3
- Two dressed cavities provided to KEK for the S1-Global cryomodule
- Successful testing of dressed cavities in the Fermilab horizontal test system
- Propagation of second sound transducers and techniques from Cornell to Fermilab and Jefferson Lab
- North American cavity vendor development ongoing with new orders being placed now courtesy of ARRA funds
- Refrigerator with helium recovery commissioned at Cornell
- Cavity repair techniques demonstrated

Cavity Organization in the Americas Region

- GDE Project Manager: Akira Yamamoto – KEK
- GDE Cavity Leader: Rongli Geng – Jefferson Lab
- Americas Region Team Leaders
  - Mike Harrison – Brookhaven – ART Director
  - Mark Champion – Fermilab – ART Cavity Coordinator
  - Georg Hoffstaetter – Cornell
  - Rongli Geng – Jefferson Lab
  - Mike Kelly – Argonne

ILC GDE SRF Program Goals

TDP1: technical feasibility by 2010

- **Gradient (S0) to reach 35 MV/m with 50% yield**
- **One cryomodule (S1) to achieve average gradient of 31.5 MV/m**
- **Proof-of-Principle and System Engineering**
- **Cryomodule design with plug-compatible components**

TDP2: technical credibility by 2012

- **Gradient (S0) to reach 35 MV/m with 90 % yield**
- **One-RF unit (three cryomodules) operating with beam (S2)**

Goals of the Nine-Cell Cavity Program

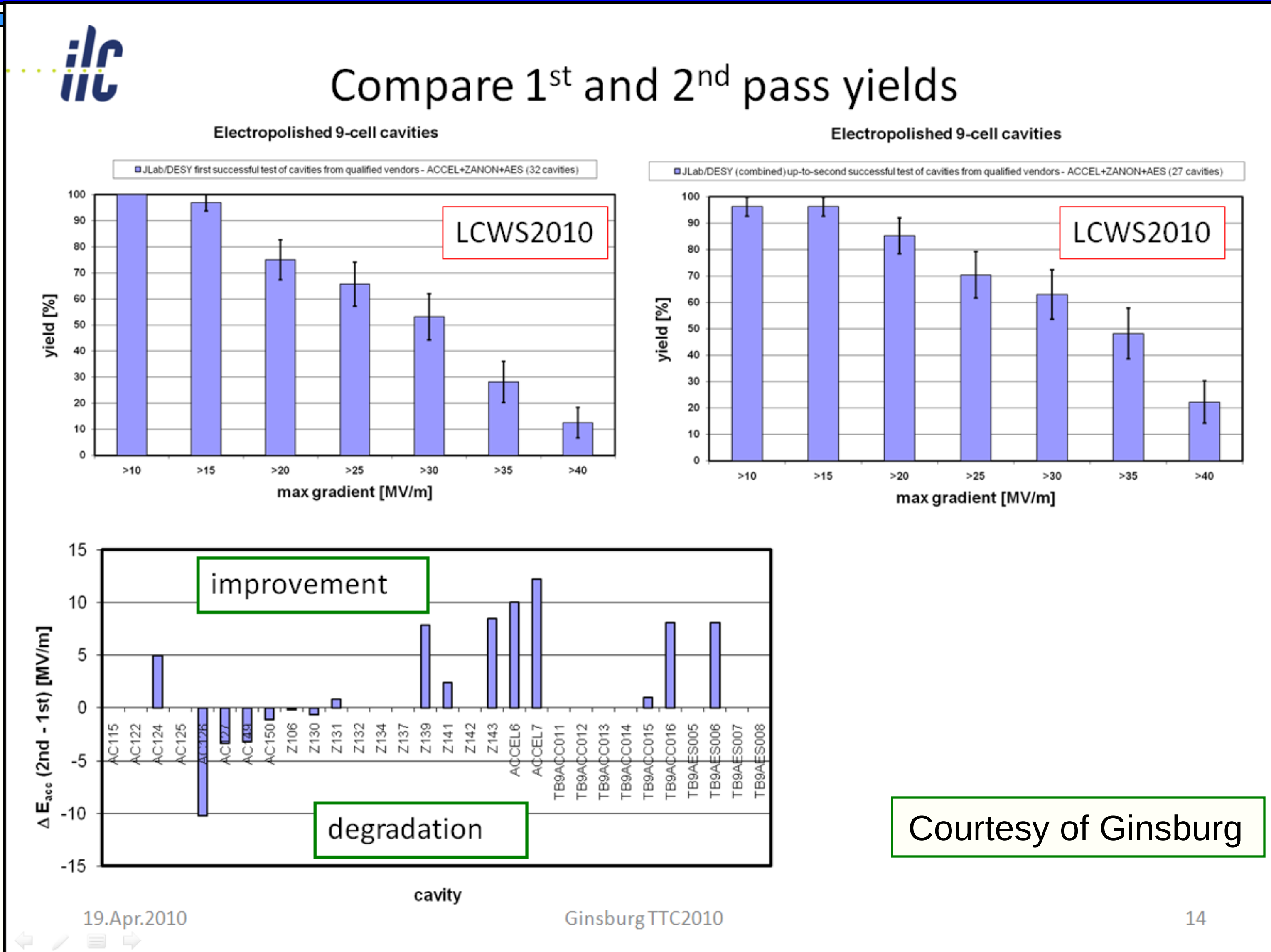
- Provide cavities for cryomodule assembly
  - Five additional cryomodules (40 cavities) planned for installation at the Fermilab New Muon Lab beam test facility
- Accumulate gradient and yield data
- Improve understanding of performance limits
  - Feed back into cavity fabrication
- Develop and apply cavity repair techniques
- Develop new cavity vendors
- Build expertise which will be applied to other programs, such as:
  - Project X at Fermilab
  - Jefferson Lab 12 GeV upgrade
  - Cornell ERL

Goals of the Single-Cell Cavity Program

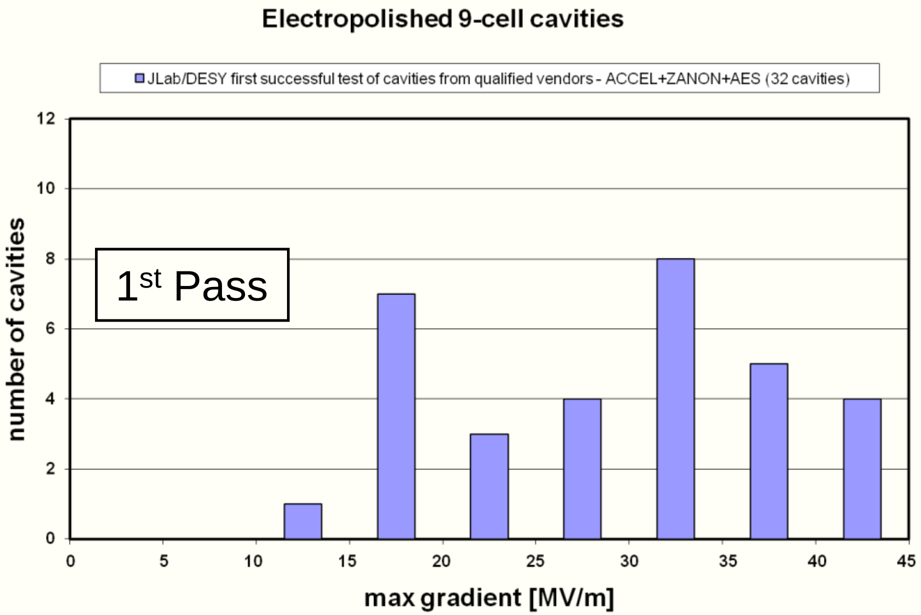
- Vendor development and qualification
- Facility and process qualification
- Diagnostics development
  - Second sound, optical inspection, replicas
- Process development
  - Electro-polishing
  - Tumbling
  - Laser and electron-beam re-melting, local grinding
- Fundamental studies
  - Gradient and quality factor limitations
  - Materials, impurities, geometric defects
  - Defect studies (cut outs)
  - Oxide layers

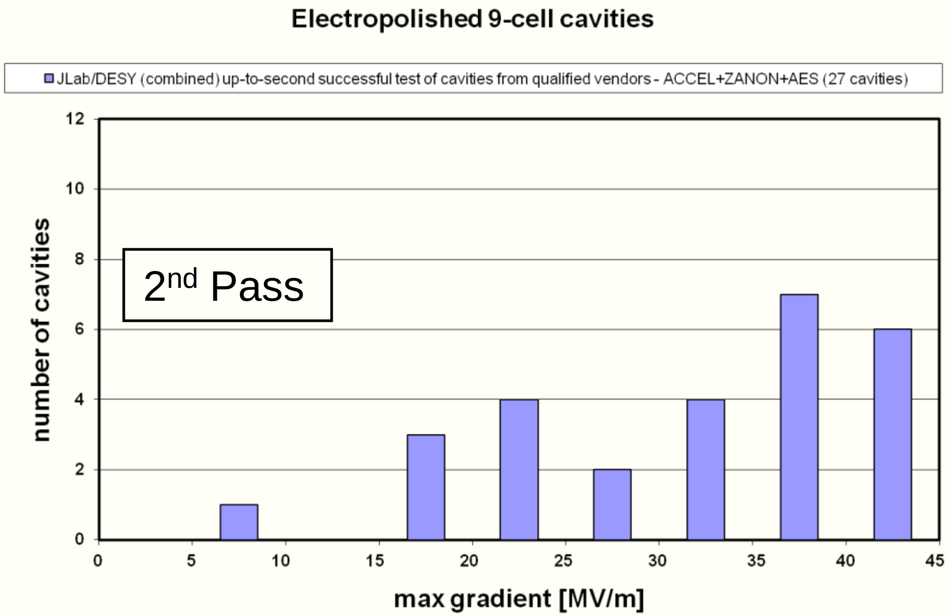
Americas

Yield Data from LCWS2010
50% yield achieved after 2nd-pass processing



Histogram view of LCWS2010 data



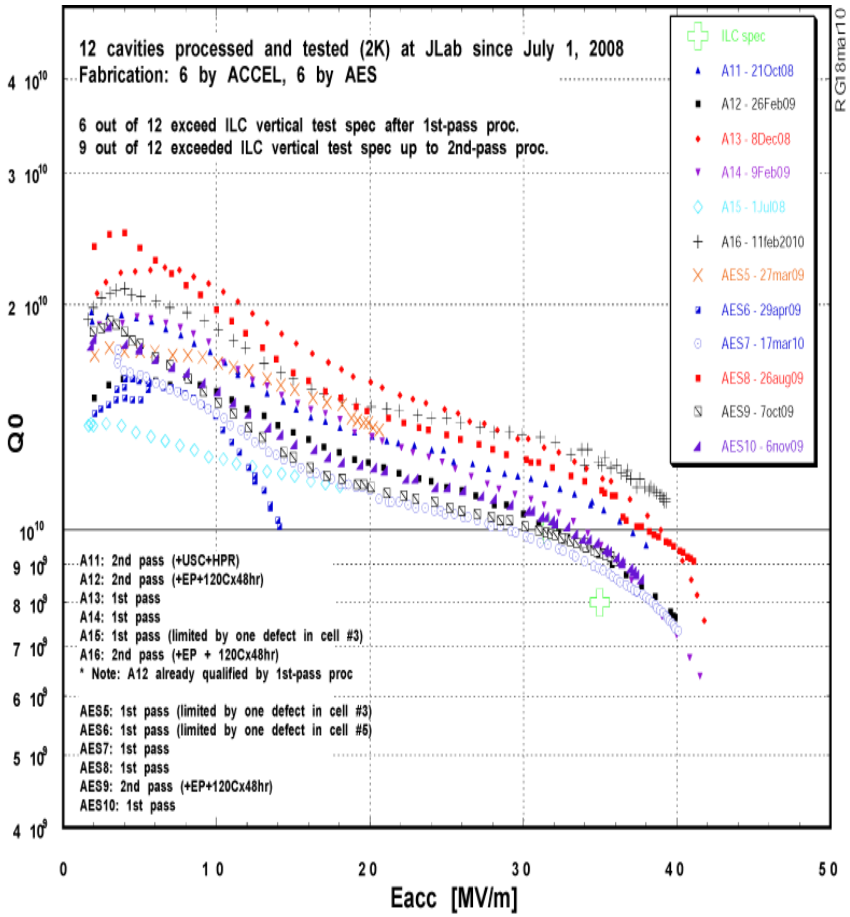


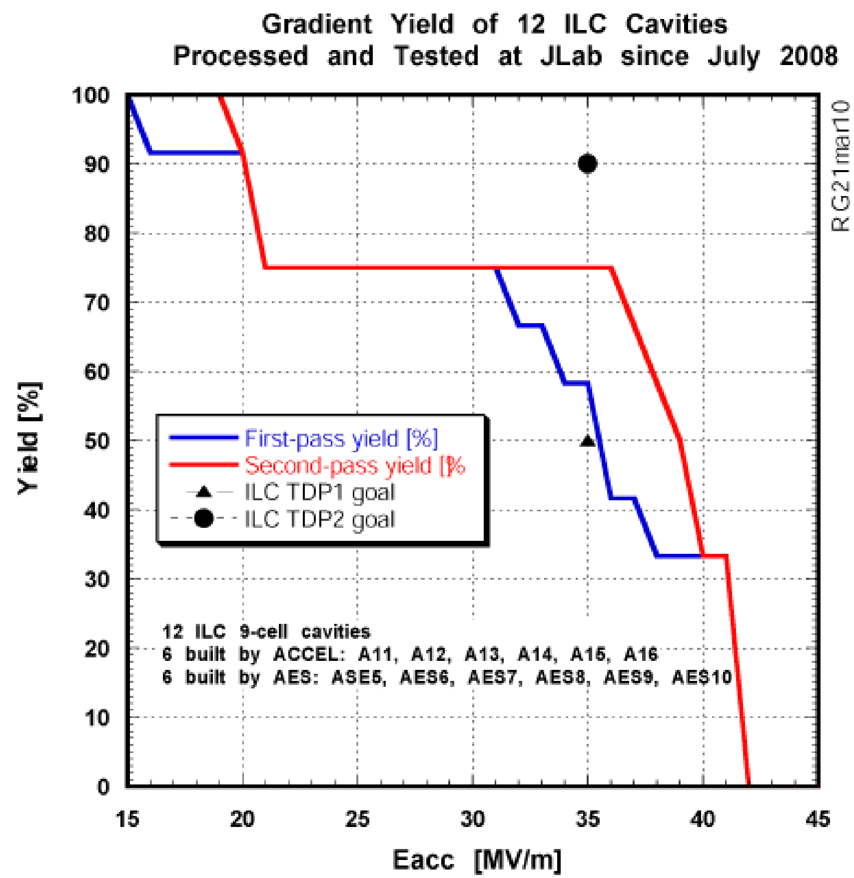
- **More cavities on the right after 2nd pass, as expected**
- **Also note that a significant number of cavities are in the 40-45 MV/m bin**

Courtesy of Ginsburg

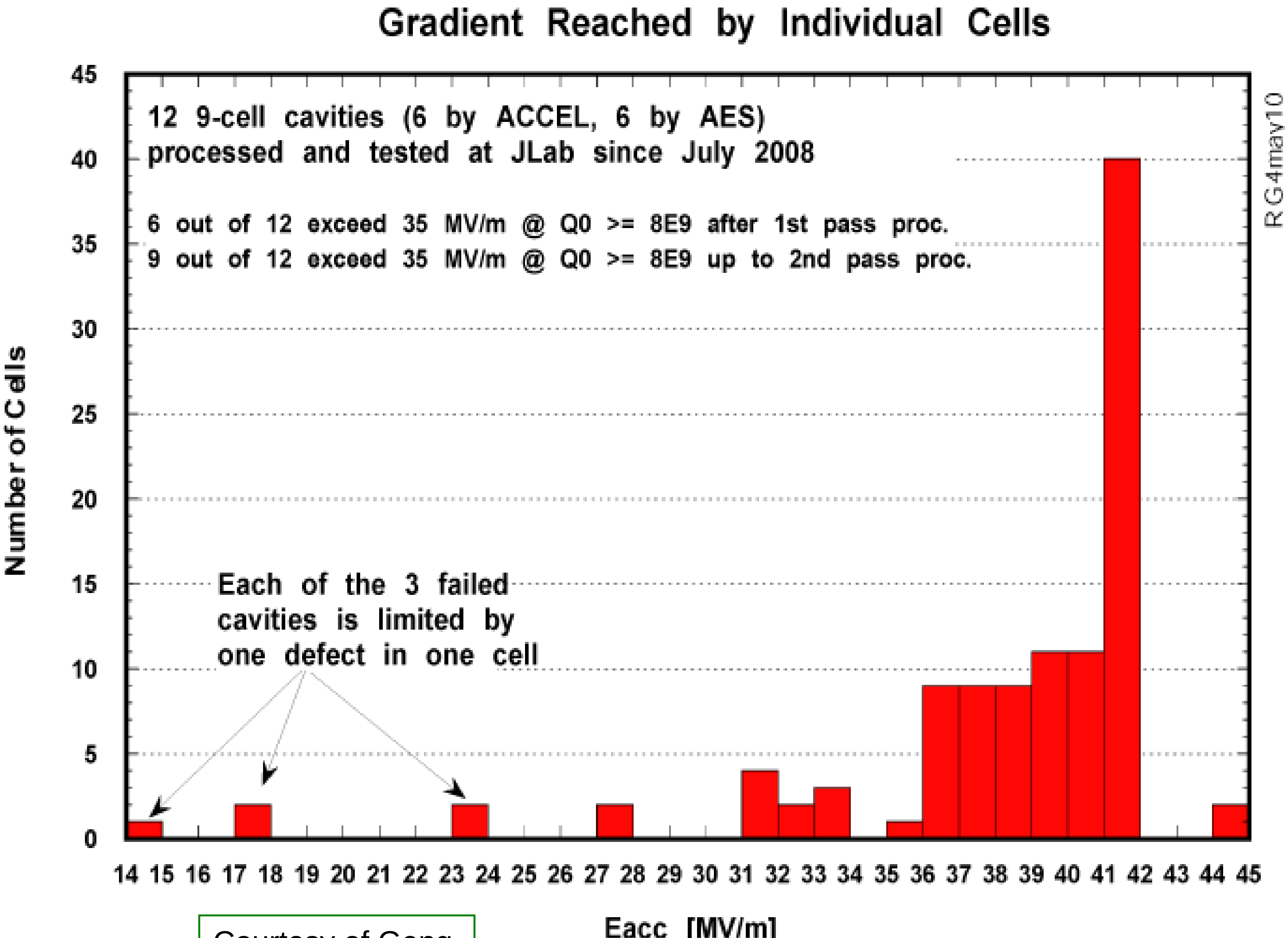
Most Recent 9-cell Results at JLab

6 cavities built by ACCEL and 6 by AES



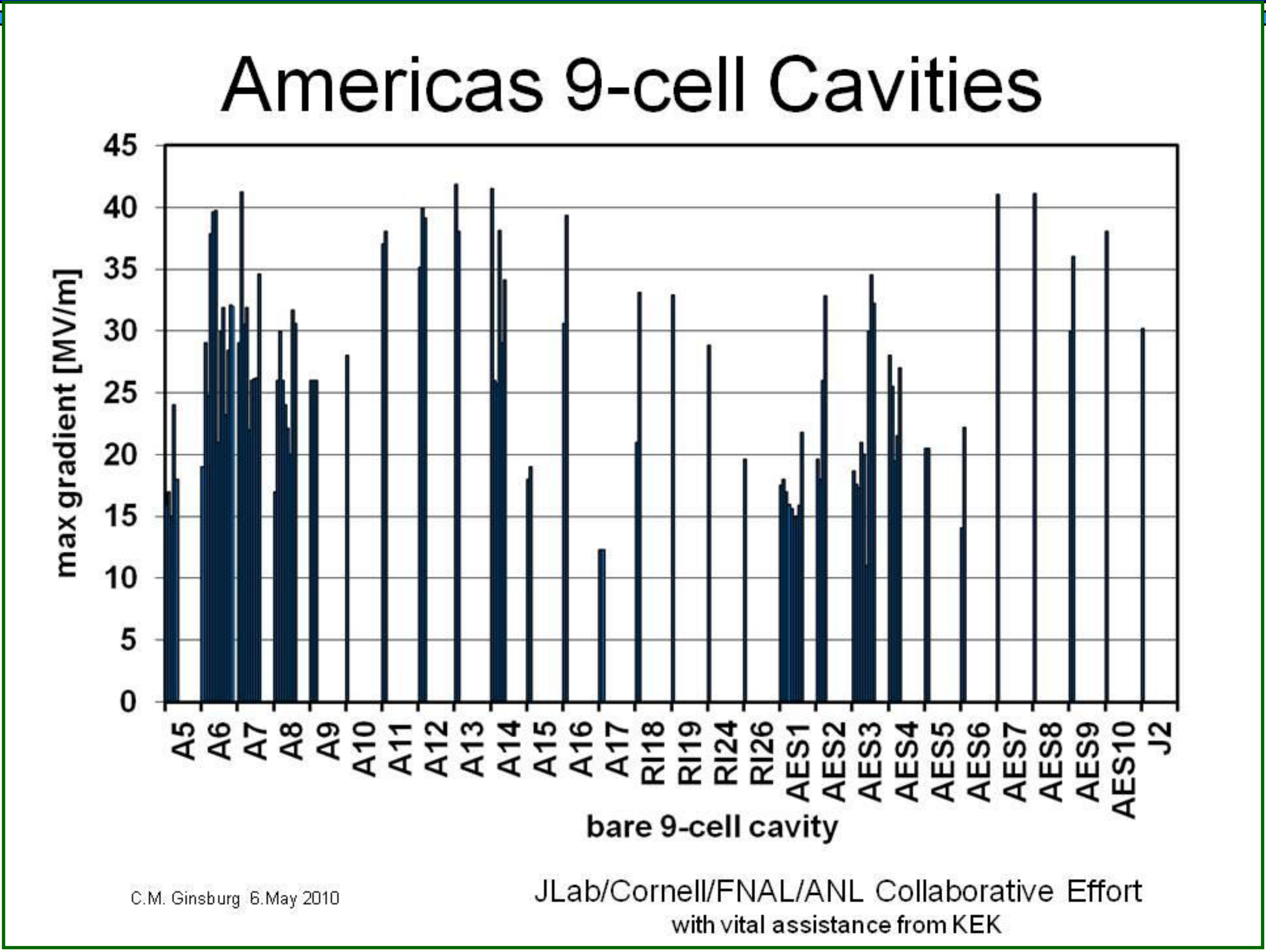


Courtesy of Geng



Courtesy of Geng

Overview of ART cavity performance

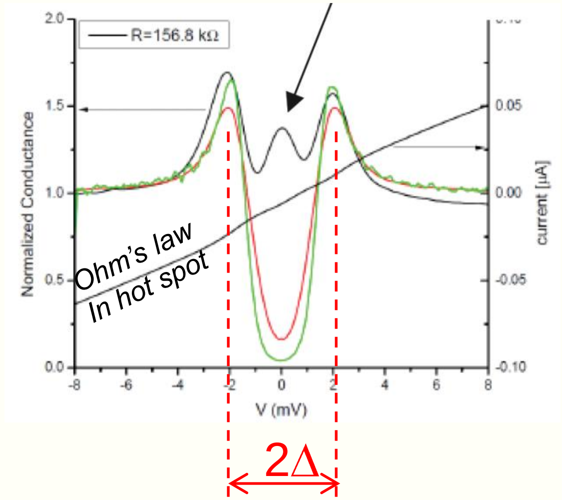


Materials achievements – past 12 months

Subtle effects of contaminants

- **Oxidation**
  - **Heavy oxidation (stuck HPR) initiates quench**
  - ***Defects* in the oxide structure may be sources of magnetic scattering**
- **Hydrogen**
  - **During EP, sulfate anodization (oxidation) of niobium may produce threading dislocations**
  - **EP also loads metal with hydrogen (unlike BCP)**
  - **Hydrogen binds to Nb vacancies, prevents removal of threading dislocations**
  - **Mild baking (120°C) releases vacancies and thereby restores dislocation climb, which improves surface resistance**
- **Implications**
  - **800 °C bake to remove surface hydrogen**
  - **Final EP must be cold**
  - **Avoid stress to the natural oxide**

Point-contact tunneling: Normal electrons at oxide hot spot



Typical superconductor response at cold areas (red, green)

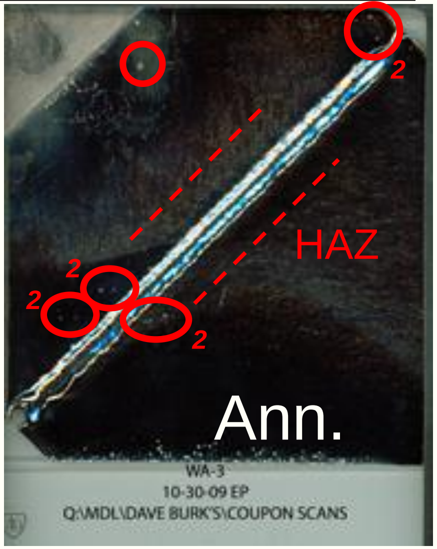
Ciovati – Jlab, Proslier – ANL, Zasadsinzki – IIT, Cooley, Romanenko – FNAL

Courtesy of Cooley

Materials achievements – past 12 months

Understanding origins of equator weld pits

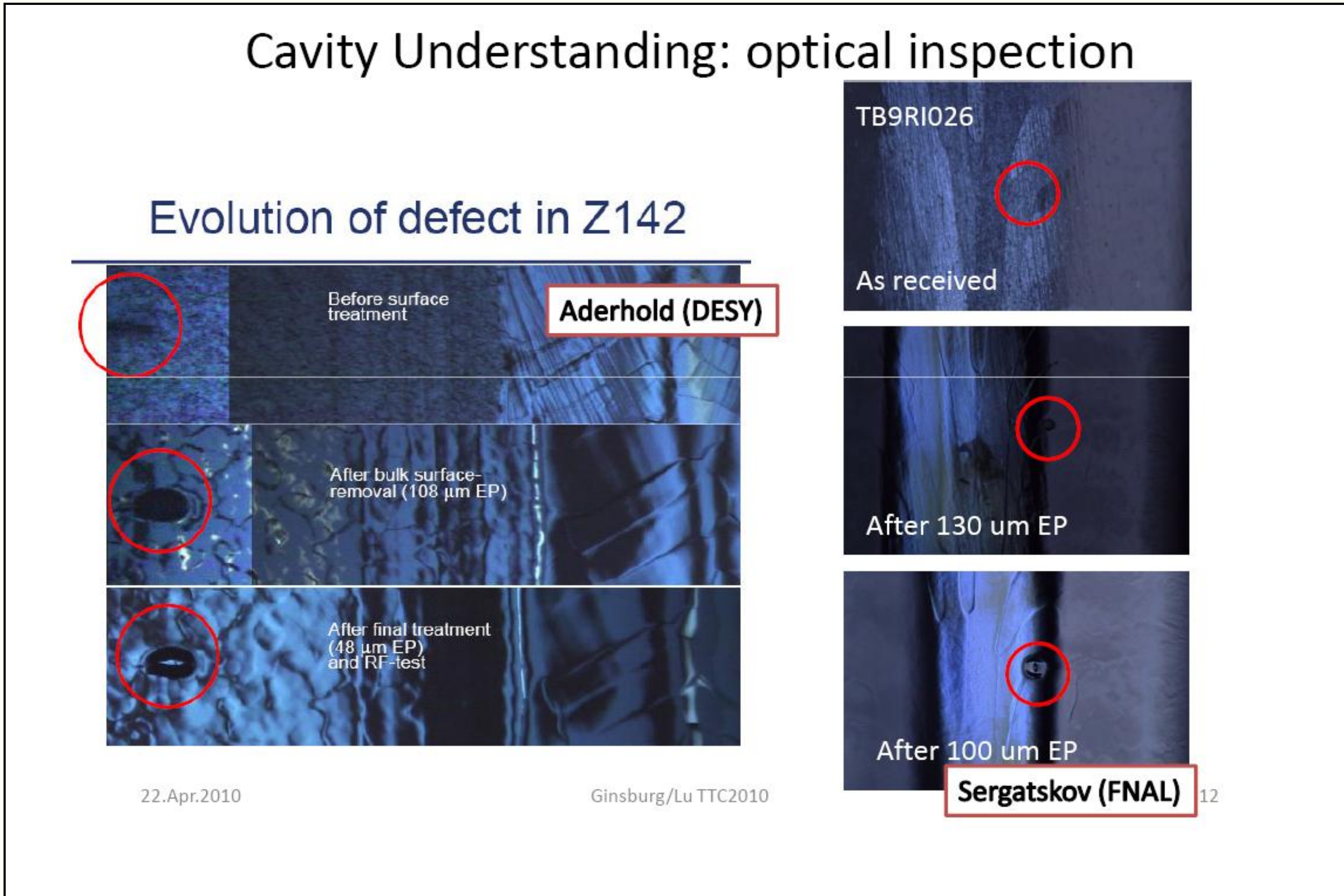
- Does the material state matter?
  - Cold-worked niobium has more pits after electropolishing than annealed niobium
  - Welding induces pits near the HAZ
  - Pits also occur in many places away from welds (but these places would experience lower fields in cavities)
- Implications
  - Anneal half-cells before welding
  - Anneal half-cells before chemical polishing
  - Do not weld at all – hydroform
    - See later slide



Dark color is artifact of brightness saturation

Courtesy of Cooley

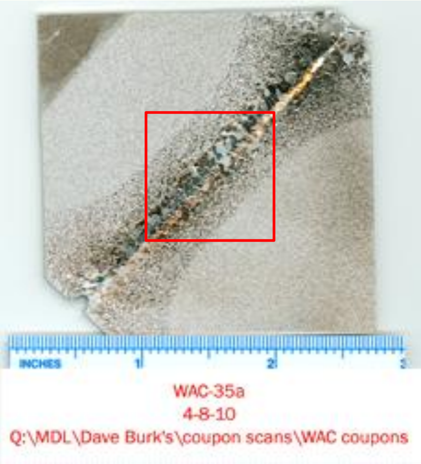
Optical inspection reveals evolution of defects



Materials achievements – past 12 months

Understanding electrochemistry

- **Do things go wrong?**
  - **Coupon EP is glossy, with no grain boundary contrast**
  - **Cavity EP is less glossy, with visible grain boundaries**
  - **Agitation and stirring circulate fluorine to coupon surface, producing grain-boundary contrast**
    - **High temperature reduces viscosity, promotes circulation (H. Tian Ph.D. thesis)**
    - **Some grains may etch quickly, leaving faceted pits**
- **Implications**
  - **Keep EP cold and don't agitate**
    - **Do not use acid flow as the coolant! Instead, apply external cold water spray to EP tool, and turn back flow.**
  - **Final EP will then be slow – use alternate process (tumbling) to make up processing time**
    - **Process MUST pre-condition surface to a roughness comparable with the thickness of fluorine diffusion layer (~40 µm at 20 °C – Reece et al.)**



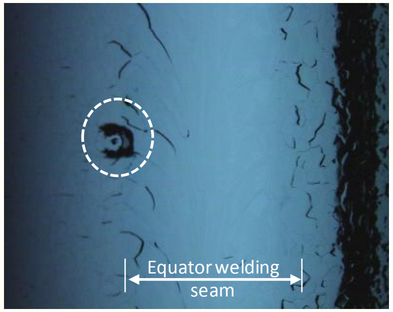
Non-typical EP coupon showing grains

Courtesy of Cooley

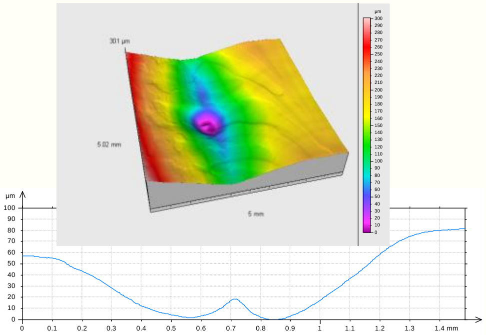
Cavity R&D achievements – past 12 months

Cavity diagnosis and repair

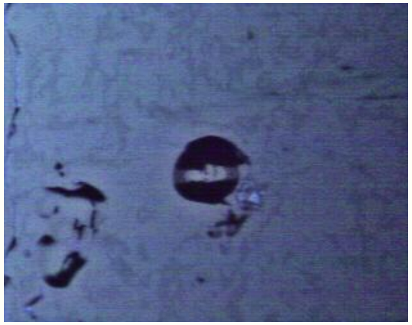
- Replicas
  - Access to valuable topographic information
    - JLab: E_{max} improves as roughness spectra decrease, but profiles are tedious to get
    - Laser confocal microscopy replaces profilometry, with 50x gain in data rate!
  - Replicas can be extracted from 9-cell cavities too, with risks
- Laser melting
  - Melting is a viable repair, no degradation seen
    - *Improvement* from ~20 to >35 MV/m has yet to be shown
  - 9-cell repair apparatus is in development



TE1AES004



Diameter: 1300μm, Depth: 60μm
A 15μm tiny bump in the center.



The Pit before re-melting

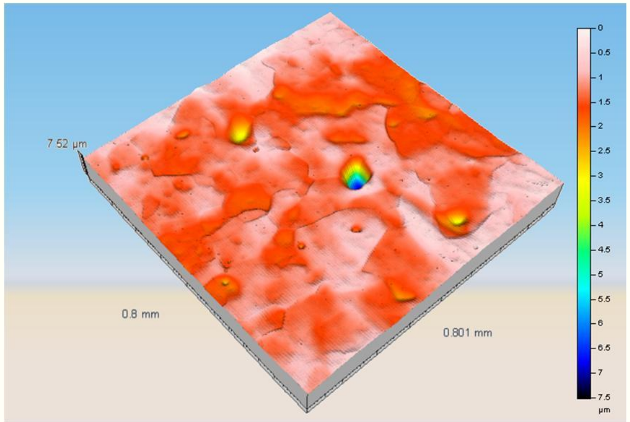
After re-melting

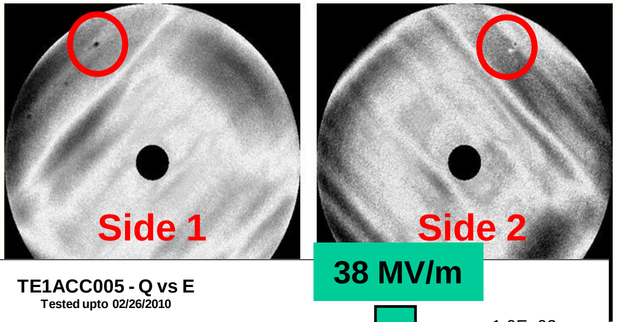
Courtesy of Cooley

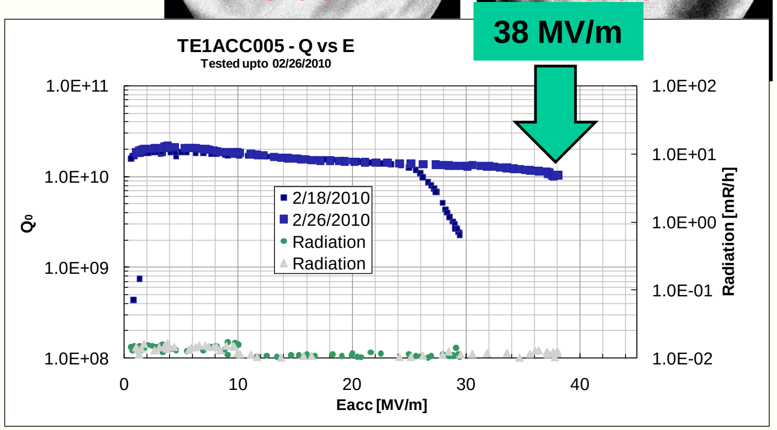
Single-cell cavity achievements – past 12 months

<u>**Risks found to be benign**</u>

- **Tumbling: 40 MV/m despite numerous pits and dings**
  - **Equator bead is completely removed, however. Is this more important than we realize?**
  - **Implication: contamination matters more than micro-roughness**
- **Eddy-current scanning: defects do not initiate quench!**
  - **Defect at equator penetrates entire thickness, yet cavity attains >35 MV/m**
  - **Implication: spot check with ECS, but do not scan all sheets**







Courtesy of Cooley

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Implications of materials and cavity R&D

- Going forward, yield improvement should result if:
  - Annealing is integrated into the welding task
  - Bulk material removal attains a target roughness comparable to the fluorine ion diffusion length during final removal, ~40 µm
  - 800 °C baking is used to remove bulk AND surface hydrogen
  - Final EP is cool and free from agitation, with external water cooling
  - Excess oxidation, and strain of the oxide, is avoided
- Opportunities to simplify the cavity process are available
  - Tumbling / CBP to remove equator bead
  - Spot-check via ECS
- Rate of information gain is accelerating
- Open questions not effectively attacked by materials R&D yet:
  - Big weld bubbles, blisters: Should we avoid welding altogether?
  - Spectroscopy from "real" cavity surfaces
  - Niobium spec: Every Nb batch is different, but to what extent do the differences propagate through the process?

Courtesy of Cooley

FY10 Highlights at JLAB

- Completed processing and testing of all six 9-cell cavities of AES second production.
  - 4 out of 6 passed ILC vertical test spec
  - AES has become the first US vendor qualified for ILC cavity
- Demonstrated 75% gradient yield at Eacc >= 35 MV/m with Q0 >= 8E9 up to second-pass processing
  - Latest data based on 12 9-cell cavities
  - 6 built by ACCEL and 6 by AES
    - These results major ART contribution to global S0 milestone for TDP-1
    - These high performance cavities allow S1 goal demonstration at S1-G & FNAL CM2
- Completed 9-cell EP optimization of JLab horizontal EP facility
  - JLab optimal EP shown to be simple and repeatable
  - JLab optimal EP expertise transferred to 3 technicians
    - Two JLab technicians (one is now working at AES)
    - One FNAL technician
  - JLab optimal EP parameters being transferred to other facilities

FY10 Highlights at JLAB (cont.)

- Commissioned Cornell OST's and performed comparative studies with JLab fixed thermometry system for 9-cell cavity
  - Received OST's from Cornell
- Commissioned Kyoto camera and performed comparative studies with JLab long-distance-microscope based 9-cell optical inspection machine
  - Kyoto camera on loan from KEK
- Collaborated with KEK on several gradient R&D subjects
  - EP sample exchanges for contaminant studies
  - KEK ICHIRO7 processing and RF testing at JLab
  - JLab LG#1 9-cell cavity local grinding at KEK

Delivered EP and Vertical Test Cycles of 9-cell Cavities by JLab in collaboration with FNAL

	FY07	FY08	FY09	FY10 (till May 10)	Total
# of 9-cell cavities proc. and tested	7	11	11	11	28 distinct 9-cell cavities
# of EP cycles	28	17	25	15	85 (250 h voltage on time)
# of cryogenic cavity RF tests	31	27	29	21	108
# of vacuum furnace cavity heat treatment for FNAL/Cornell				5	>5

FY10 throughput limited by manpower and cavity availability

Summary for past year

- ✧ Demonstrated that tumbling can fix pit and bump defects, a major limit to high-voltage operation: 15MV/m repaired to 28MV/m with good Q.
- ✧ Demonstrated the effectiveness of vertical electro-polishing (VEP): 37MV/m in cells of a 5-cell and 9-cell cavity.
- ✧ Optimized parameters for VEP by single and multi-cell tests: reduced temperature and acid agitation.
- ✧ Developed time resolved second-sound detection by oscillating super-leak transducers (OSTs) to locate quench spots.
- ✧ Dissemination of the Cornell-OST technique by providing OSTs and evaluation techniques to many international laboratories.
- ✧ Demonstrate that OSTs can be used to localize quenches inside a helium jacket, potentially during regular cavity operation in an accelerator.
- ✧ Developed a 5-cell test stand for temperature mapping: qualified for high voltage performance.
- ✧ Started to construct a 9-cell test stand based on the 5-cell approach.
- ✧ Developed temperature mapping boards with 1320 thermometers for the 5-cell system and 2376 thermometers for the 9-cell system: completed.

Vertical Electropolish

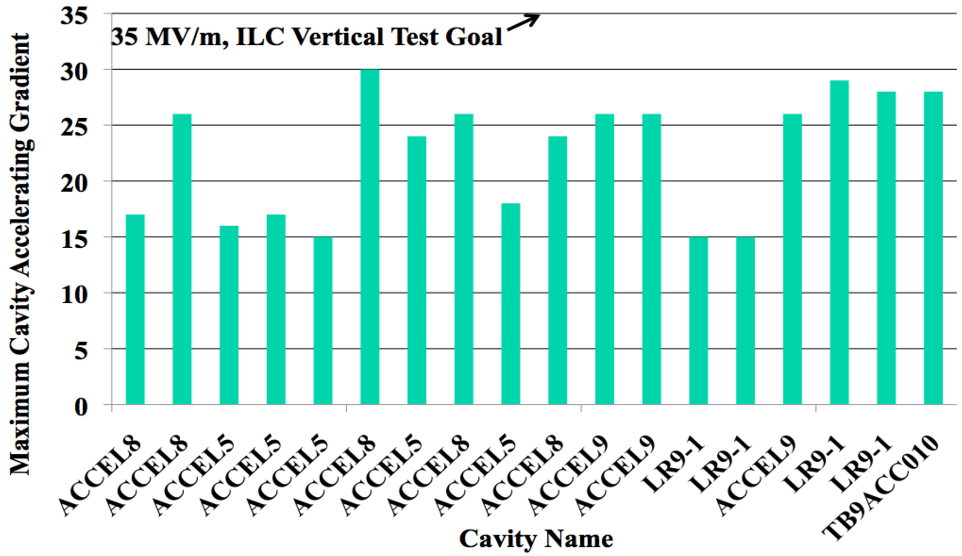
CLASSE

Vertical Electropolish (VEP) has many advantages over the standard EP procedure:

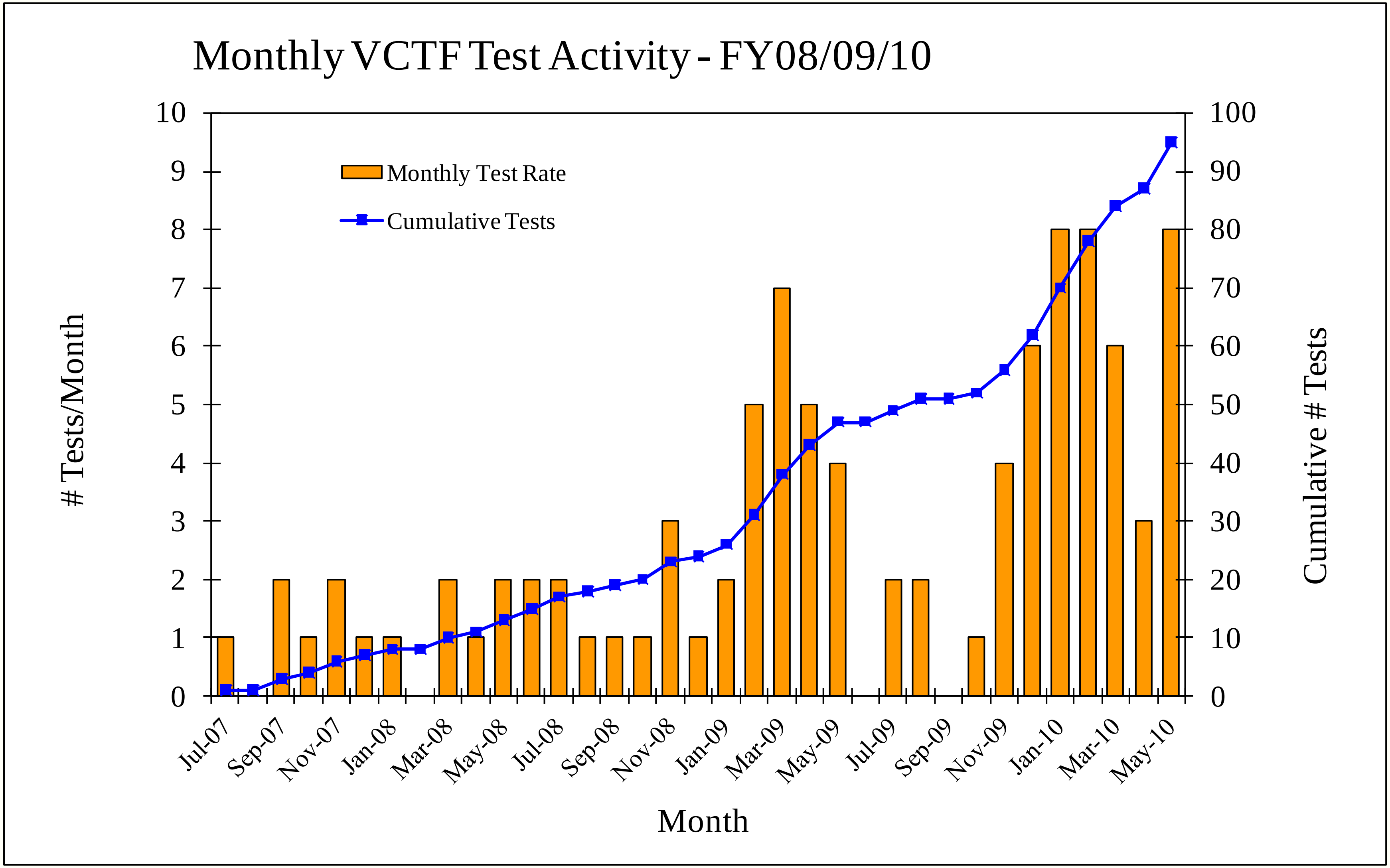
1) Eliminates rotary acid seals
2) Eliminates sliding electrical contacts
3) Eliminates the cavity vertical/horizontal position control fixturing
4) Simplifies the acid plumbing, containment, and cooling
5) Potential for better temperature control than in a partially filled cavity
6) One time use of acid, no pumping back into the cavity of used acid
7) Better cavity stability, usable for cavities without stiffening rings
8) Higher etch rates compared to partially filled cavities in horizontal EP.
9) Lower capital equipment costs
10) Fewer parts reduces the risk of contaminants building-up

We VEP-ed several 9-cell cavities during recent years:

Potential for cheaper Installations at the many cavity vendors needed for ILC Cavity production.



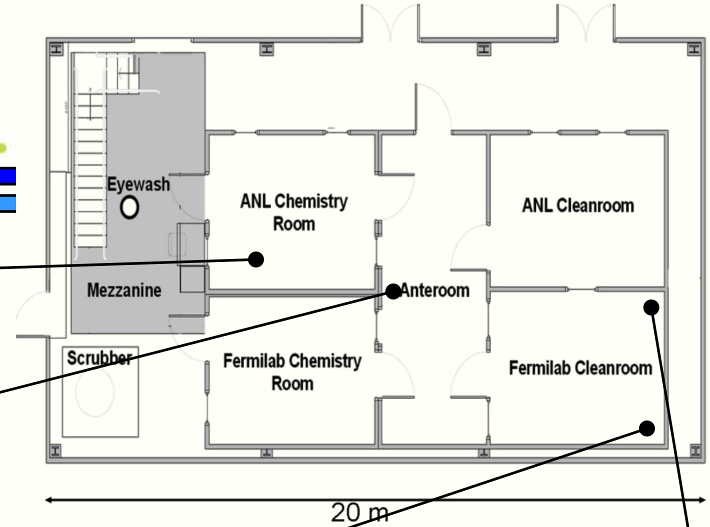
Increasing throughput at Fermilab vertical test facility



Courtesy of Ozelis

Americas

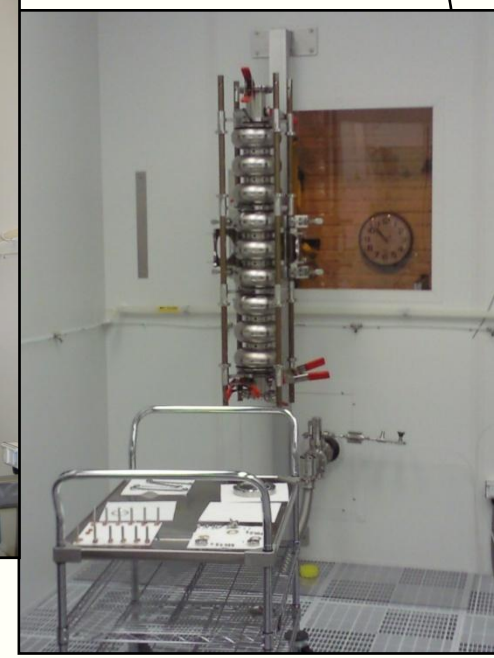
ANL/FNAL SCSPF Overview



Electro-Polishing

Ultrasonic Degreasing

High-Pressure Rinsing



Assembly & Vacuum Leak Testing

Progress at the Argonne/Fermilab Superconducting Cavity Surface Processing Facility (SCSPF)

2010 Summary Data

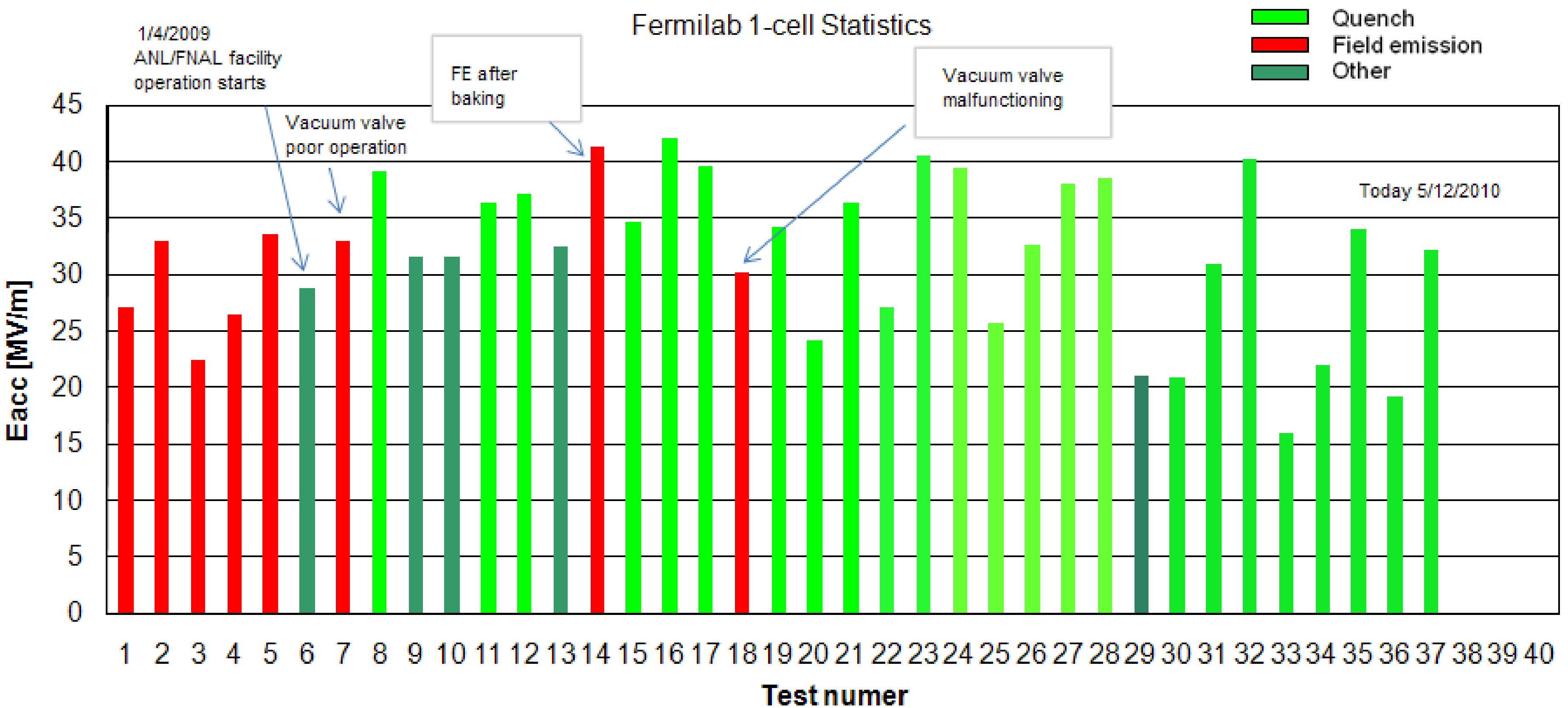
- 24 cavity test preparations completed January-May 2010
  - 10 one-cell preps
  - 9 nine-cell vertical preps
  - 5 horizontal test preps
- 6 bulk EP
- 11 light EP
- 68 HPR cycles

Resultant Test Highlights

- Highest Gradient 9-cell (rinsed and assembled only): TB9AES007 41.8 MV/m (processed/tested at JLab – test results in agreement)
- Highest Gradient w-ANL EP and w/o FE: TB9RI029 34.6 MV/m
- Latest Horizontal test TB9AES009 was FE-free at 35 MV/m
- 20+ single-cell processes FE-free in a row—up to 42 MV/m
- Multiple 30+MV/m 9-cell processed through SCSPF

Courtesy of Rowe

Single-cell processing highly optimized at ANL/FNAL



- **No field emission for majority of process and test cycles**

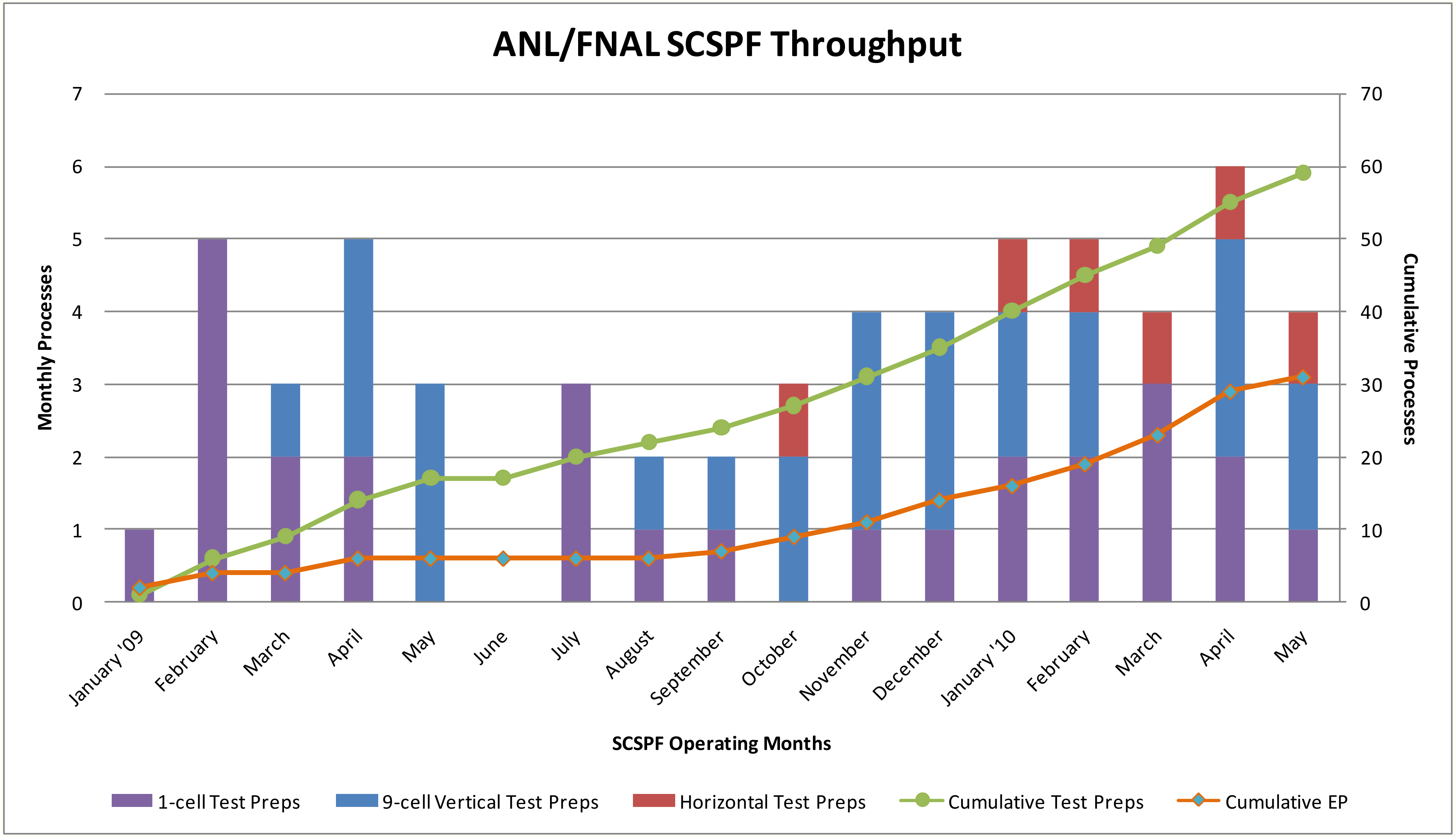
Courtesy of Wu

Additional News from the ANL/FNAL SCSPF

- **Latest two light EP cycles performed using lower voltage and temperature per-JLab success. Results promising on TB9RI024 and TB9RI029.**
  - **Experience at JLab being transferred to SCSPF**
- **Minor upgrade plans underway for HPR tool**
  - **New turntable dive mechanism**
  - **Splash shielding to prevent belt slippage**
- **Four fully trained Fermilab cavity processing technicians**
  - **Two full time (both trained on extended assignments to JLab)**
  - **Two contract (added in last year)**
- **Two new Argonne engineering associates**
  - **Trained to perform electro-polishing + maintenance/upgrades**
- **New EP tool in development for quarter-wave and 650 MHz resonators.**
- **Flash BCP capability in current EP room a short-term objective**

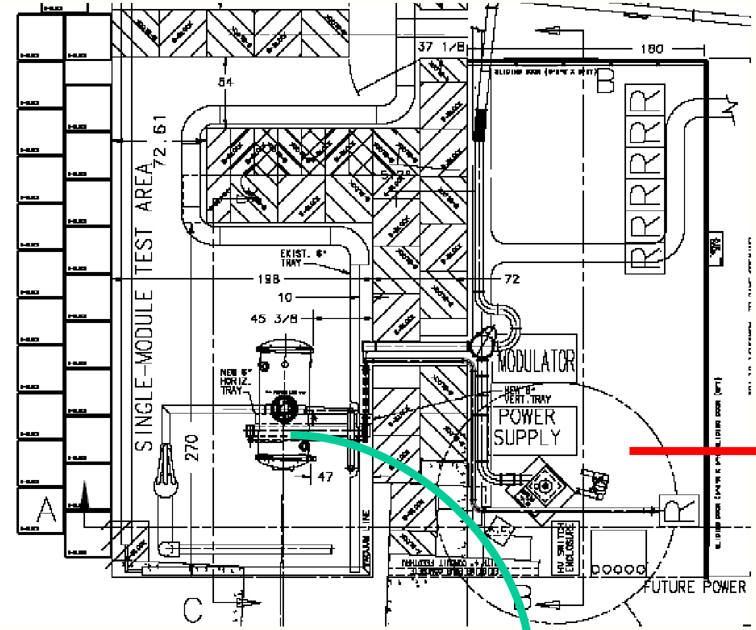
Courtesy of Rowe

Throughput at the Argonne/Fermilab Superconducting Cavity Surface Processing Facility (SCSPF)



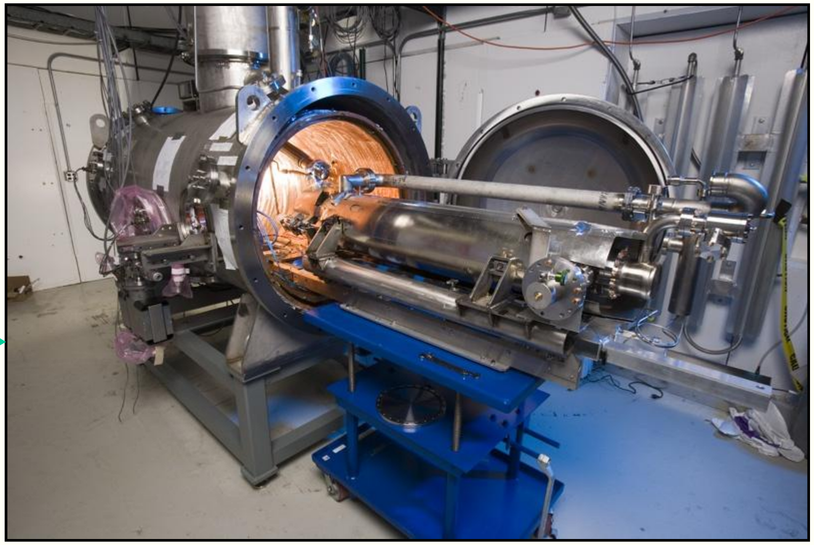
Courtesy of Rowe

The Fermilab Horizontal Test System (HTS)



Meson Detector Building

300 kW klystron + modulator and charging supply (1.3 ms pulses at 5 Hz)



Test cryostat and dressed 1.3 GHz cavity

Courtesy of Hocker

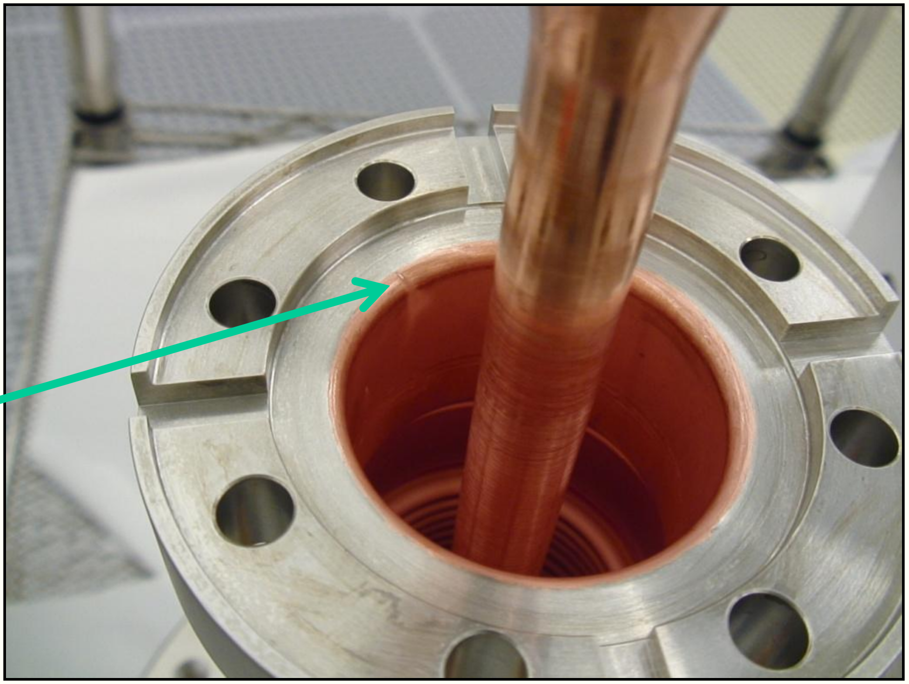
Recent HTS test results

Cavity	Max gradient	Q_0	Field Emission	Destination
TB9AES004	31 MV/m	1.1×10^{10}	Very little	S1-Global CM
TB9ACC013	>35 MV/m	1.2×10^{10}	Heavy*	CM2
TB9AES009	35 MV/m	0.7×10^{10}	None	CM2

time

*FE brought about by breakdown in the input coupler at ~37 MV/m --- prior to this event TB9ACC013 was FE-free

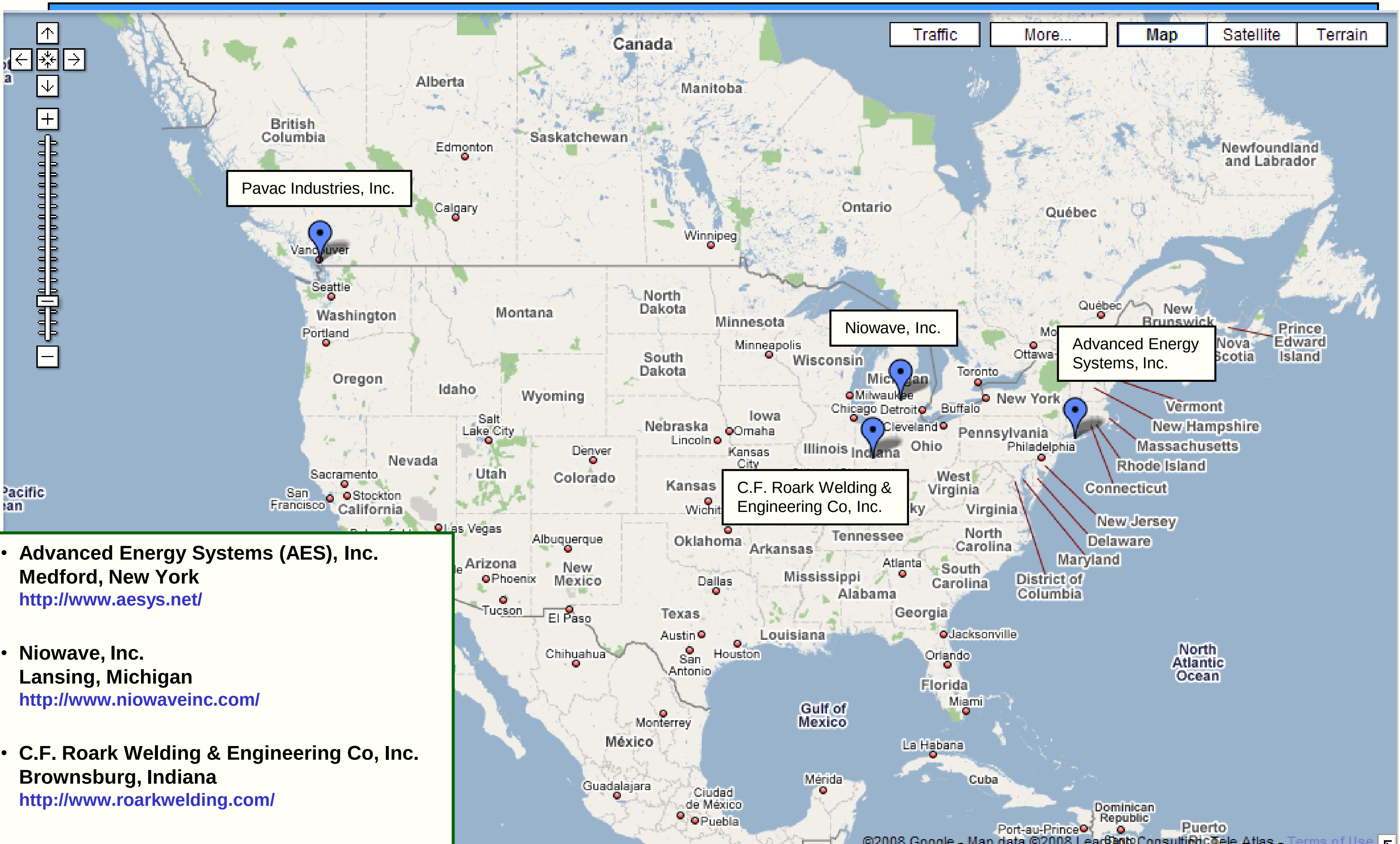
Void in Cu plating + "vapor trail"



Courtesy of Hocker

Americas

Americas Region Cavity Vendors

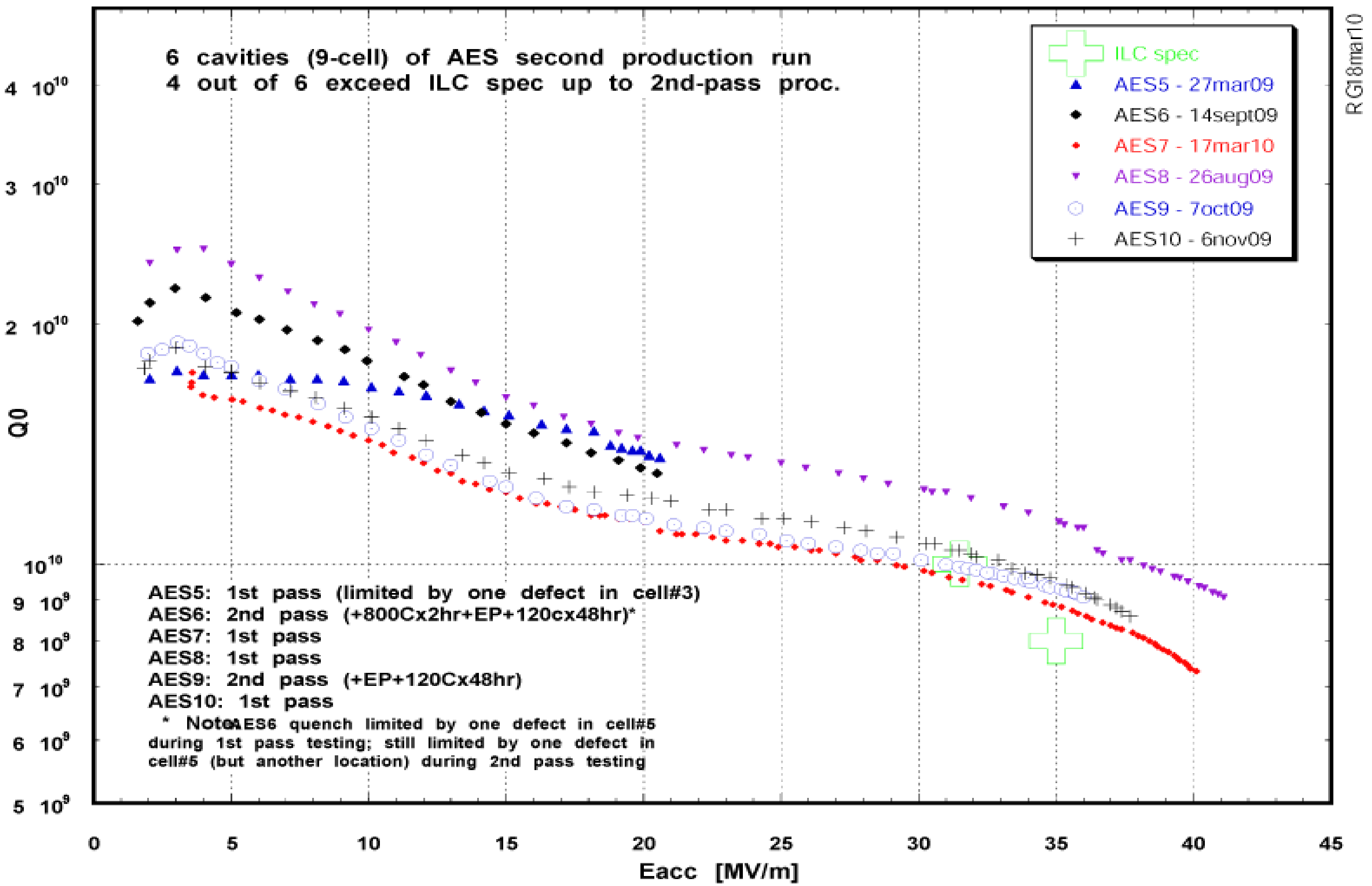


- **Advanced Energy Systems (AES), Inc.**
  Medford, New York
  http://www.aesys.net/
- **Niowave, Inc.**
  Lansing, Michigan
  http://www.niowaveinc.com/
- **C.F. Roark Welding & Engineering Co, Inc.**
  Brownsburg, Indiana
  http://www.roarkwelding.com/
- **Pavac Industries, Inc.**
  Richmond, British Columbia
  http://www.pavac.com

ART nine-cell cavity inventory

Tesla-shape nine-cell cavities		
Description	**No. Cavities**	**Status**
AES 1-4	4	tested
AES 5-10	6	tested
AES 11-16	6	due June 2010
AES 17-36	20	Planned deliveries: 10 in Apr-Jun 2011, 10 in Mar-May 2012
Accel 6-9	4	tested
Accel 10-17	8	tested
Accel 18-29	12	testing in progress
Jlab fine-grain 1-2	2	fabrication complete; testing in progress
Niowave-Roark 1-6	6	First two received; balance due summer 2010
Niowave-Roark 7-16	10	Planned deliveries: 3 in Jun 2011, 3 in Mar 2012; 4 in Dec 2012
Pavac 1-10	10	Planned deliveries: 3 in Jun 2011, 3 in Mar 2012; 4 in Dec 2012
Total	**88**	
Already Received	38	
Tesla-shape single-cell cavities		
Description	**No. Cavities**	**Status**
AES 1-6	6	tested for vendor qualification; currently used for R&D
Accel 1-6	6	tested for vendor qualification; currently used for R&D
Niowave-Roark 1-6	6	tested for vendor qualification; currently used for R&D
Pavac 1-6	6	First three received; balance due summer 2010
Total	**24**	
Already Received	21	

Performance of AES 2nd Production Cavities Processed and Tested at JLab



Much progress and many good results, but challenges remain!

- GDE TDP-2 goal is to achieve gradient of 35 MV/m with 90% yield by end of 2012
  - Currently at 50% (JLab 12-cavity data set has 75% yield)
- The primary impediment to higher yield is defects on or near an equator weld
  - The reason for the defects, and therefore the prevention, is uncertain at this time (material properties or cavity fabrication processes?)
  - Often a nine-cell cavity is limited by a single defect
  - Single-cell cavities often have no defects
- What to do?

How will we achieve the TDP-II yield goal?

- **The goal of 35 MV/m with a yield of 90% will be achieved via the following actions:**
  - **Repair of performance-limiting defects: tumbling, laser and electron beam re-melting, and local grinding**
  - **Development of hydro-forming as an alternative technique for the fabrication of nine-cell cavities**
  - **Utilization of nine-cell R&D cavities to improve understanding of defect formation and prevention**
  - **Ongoing single-cell and sample R&D programs**

Cavity repair by tumbling

1) AES fabricated 9-Cell Cavity originally quenched at E_{acc} = 15 MV/m, after tumbling and reprocessing E_{acc} > 30MV/m in the repaired cell.

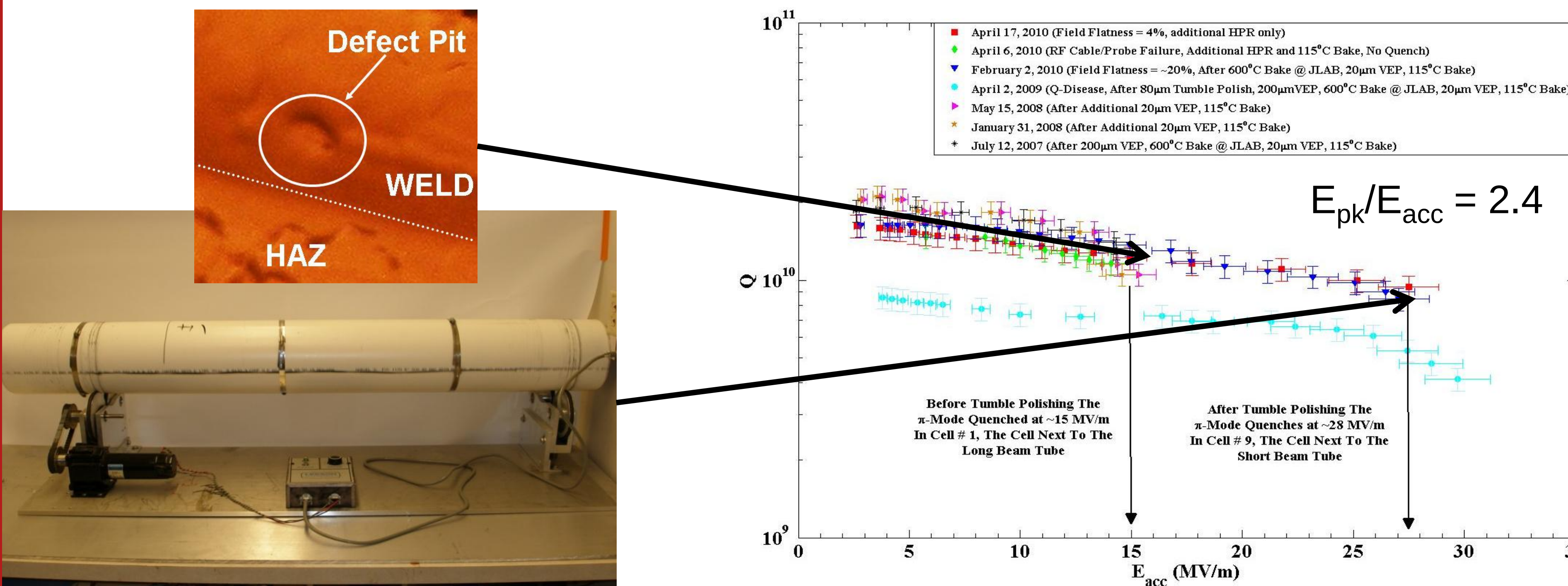
2) When excited in the 5p/9-mode, E_{acc} = 37 MV/m in the center cell.

3) Initially reduced Q was repaired by 2h, 800C baking.

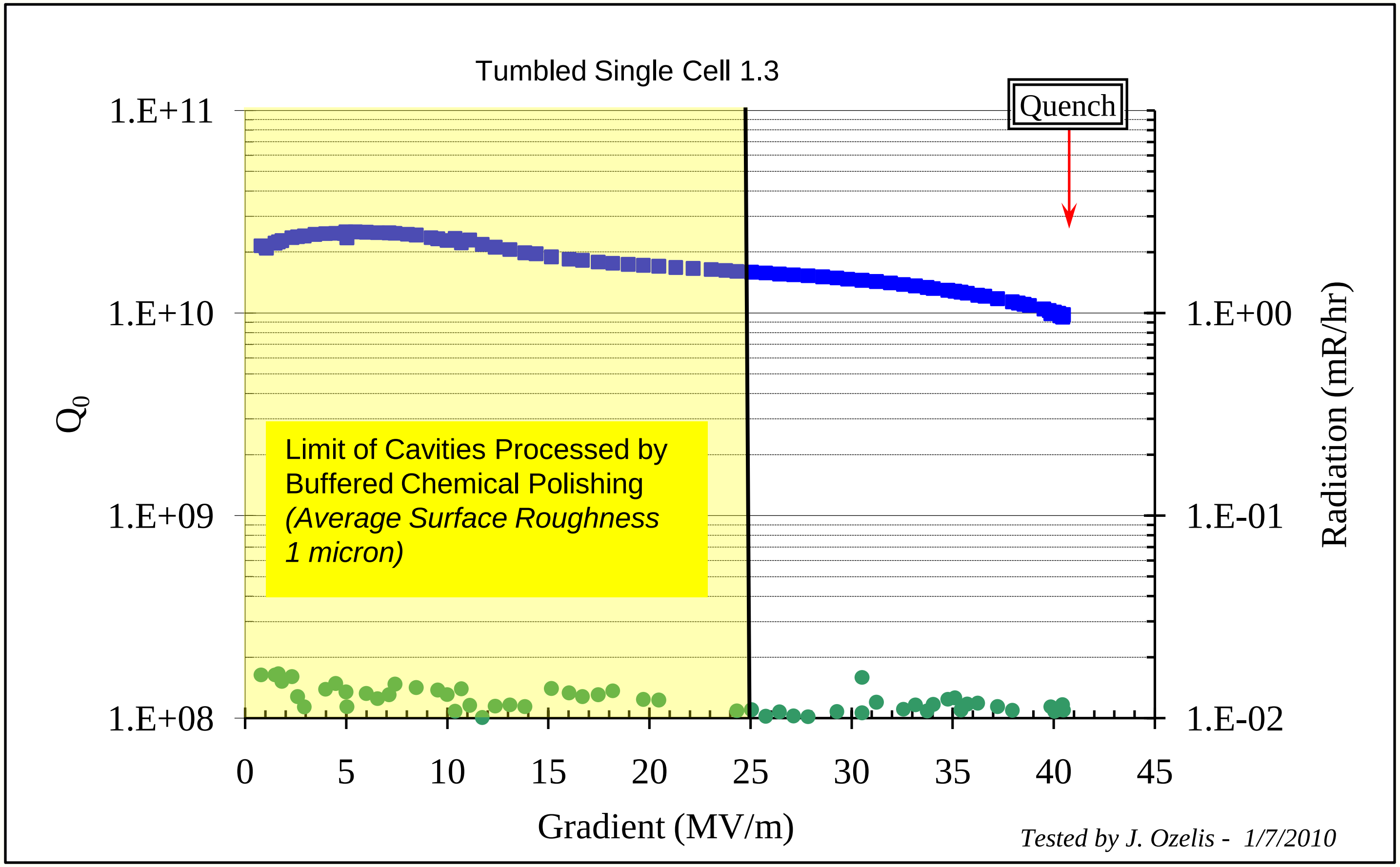
Conclusion:

1) Tumbling is an effective option to repair weld defects, e.g. pits.

2) Individual cells in cavities processed with VEP can reach fields exceeding 35 MV/m for satisfactory Q values.



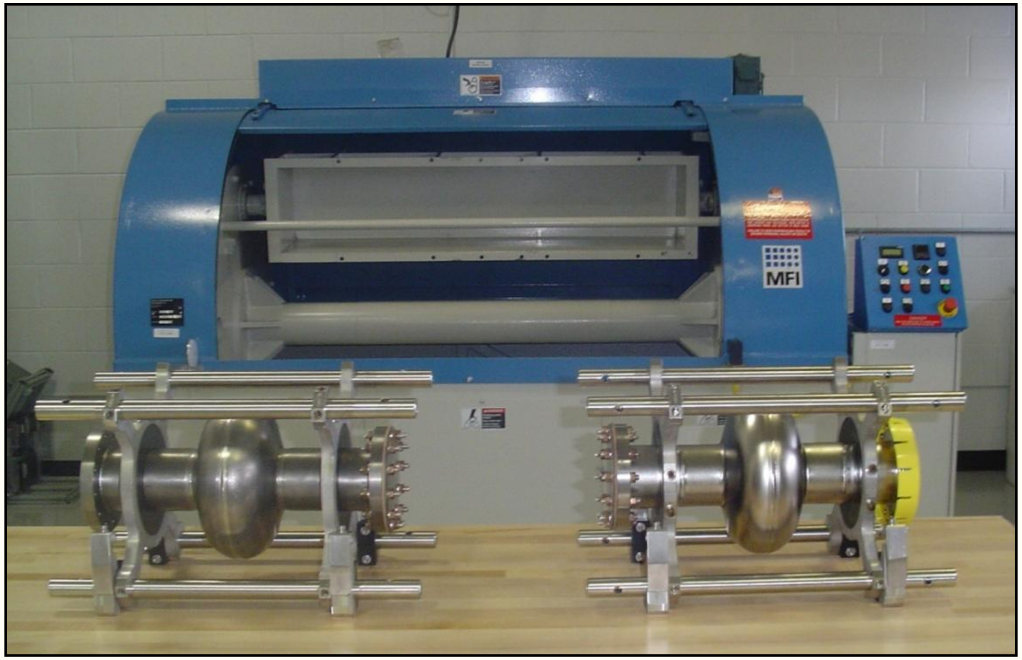
TE1ACC004 (single-cell) achieved >40 MV/m after tumbling at Fermilab



Hard Quench, No Field Emission,
Residual Resistance of 4.5 nΩ

Courtesy of Cooper

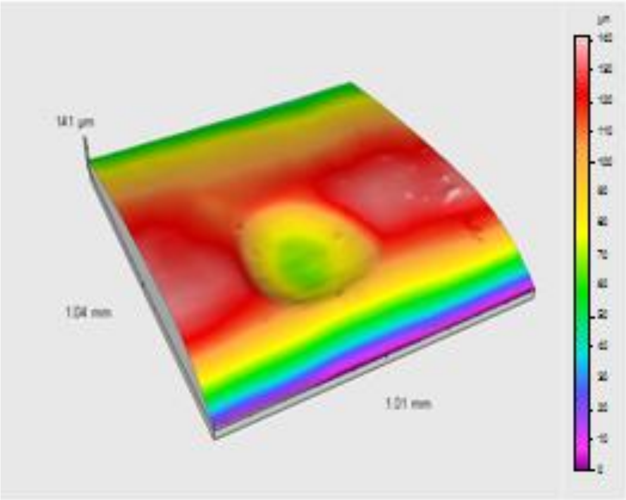
Tumbling machines are becoming ubiquitous in the Americas

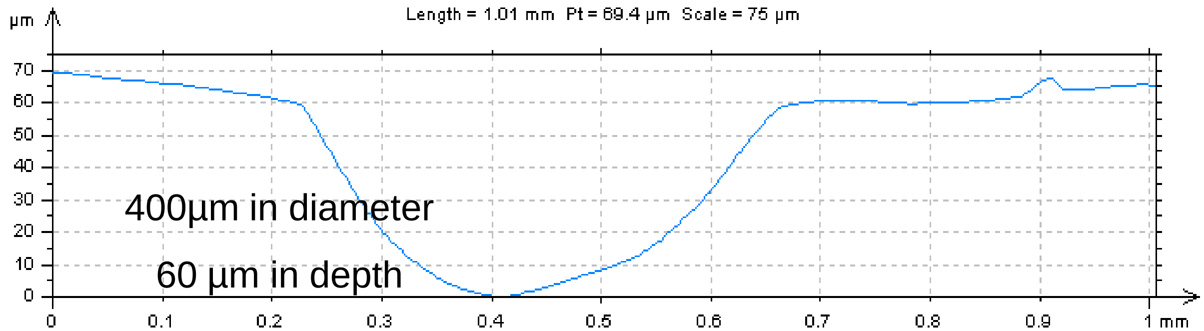


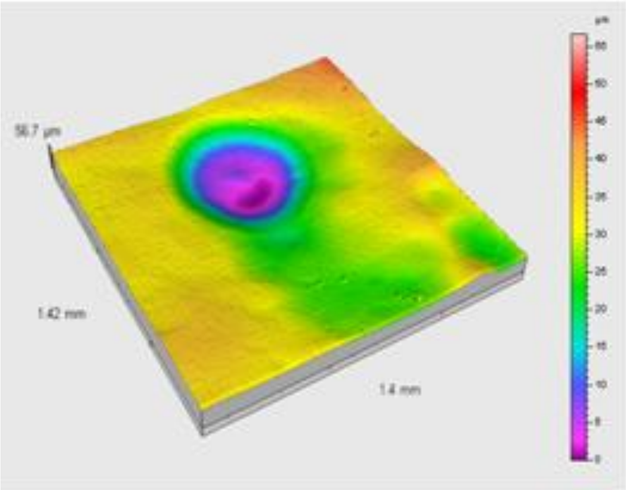
Fermilab Tumbling Machine

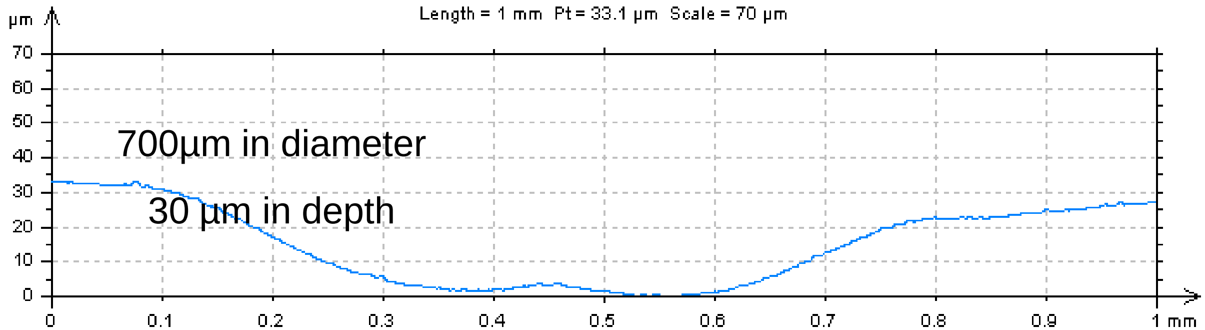
- **Fermilab and Jefferson Lab have nearly identical machines**
  - **Same company, different gearing**
- **Cornell has the same machine on order for delivery later this year**
- **If tumbling becomes part of the "standard process," we will be well-positioned for implementation**

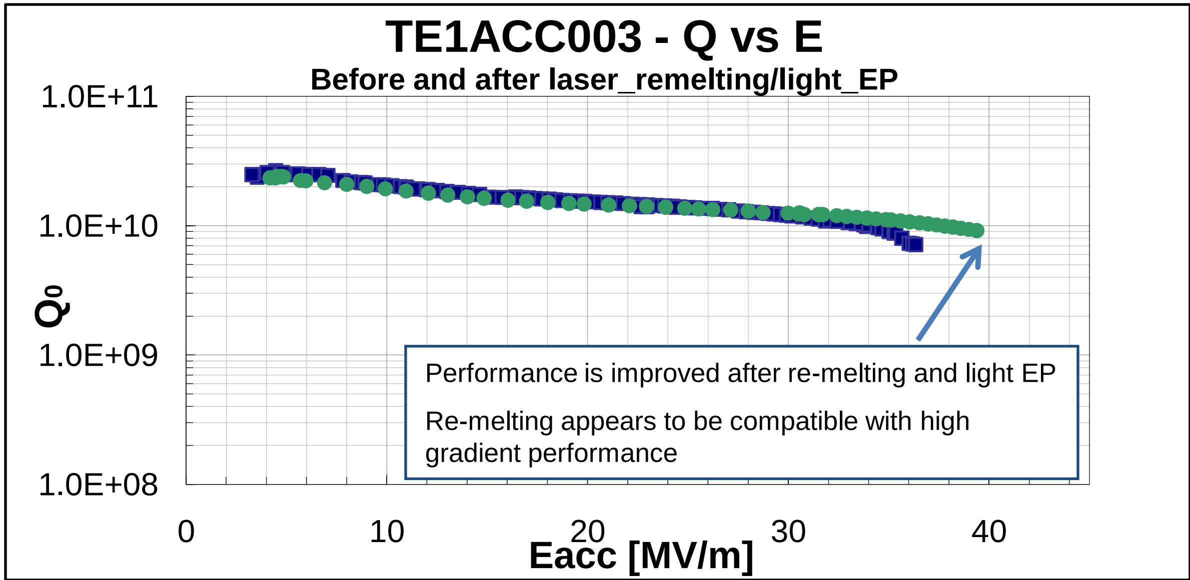
Cavity pit profile comparison before and after Laser processing





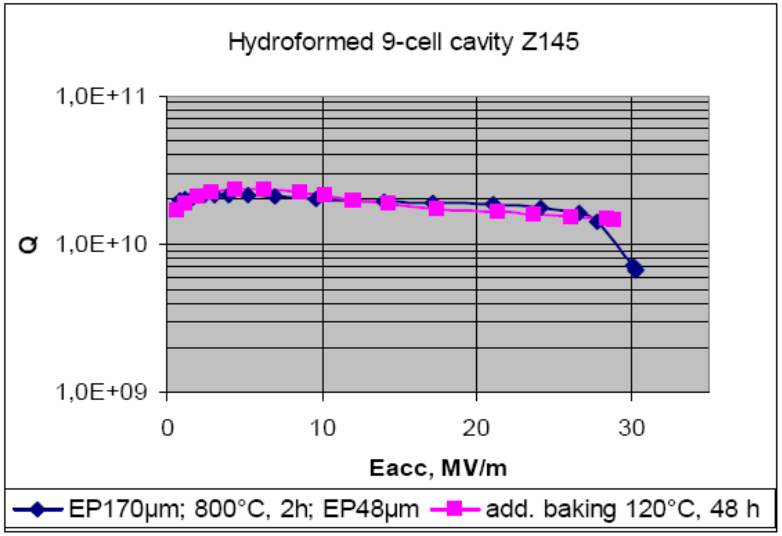


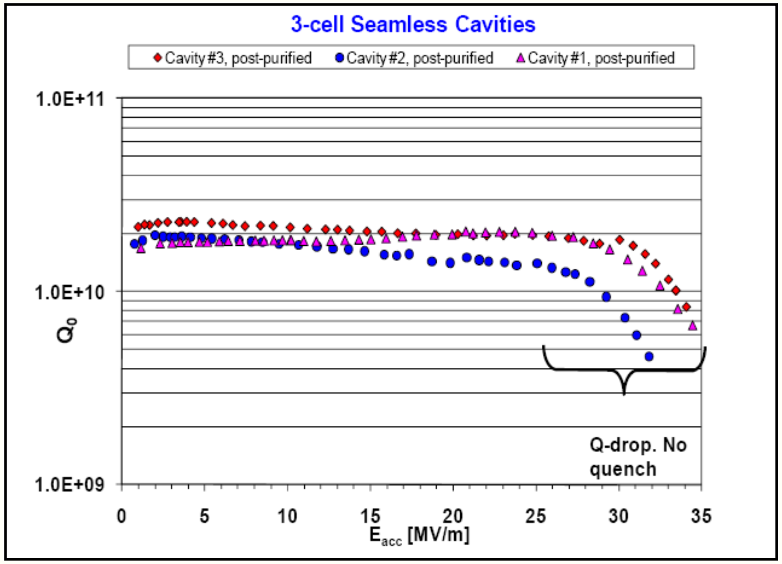




Courtesy of Wu

Performance of Hydroformed Cavities





- Currently DESY is the only facility to successfully hydroform multicell cavities
- Very first 9-cell hydroformed cavity (3x3-cell iris-welded together) achieved 30 MV/m
- Subsequent trio of 3-cell cavities tested individually performed from 32-35 MV/m --- NO quench, limited by Q-drop (not EP'd or baked)

Courtesy of Hocker

Americas

Recent Hydroforming Activities

- Recrystallized fine-grain Nb tube developed by Black Labs LLC and ATI-Wah Chang
  - Uniform microstructure, good for forming
  - Long enough for a complete 9-cell
- Two tubes were formed into 2- and 3-cell units at the DESY facility with assistance from FNAL (winter 2009-2010)
- Plan to assemble, process and test a nine-cell cavity from these components

Courtesy of Hocker

Americas

Planning for FY11

- **Assumptions**
  - **Funding flat overall**
  - **However, allocation for *Cavity Gradient R&D* and *Cavity R&D Value Engineering* will increase by ~$1M**
    - **Provides initial support for hydroforming and nine-cell R&D cavities initiatives**
  - **New nine-cell cavities (26 additional cavities by end of FY11)**
    - **Niowave/Roark : four in summer 2010; three in June 2011**
    - **AES : six in June 2010; 10 in June 2011**
    - **Pavac : three by July 2011**
  - **Human resources approximately constant**
- **Plans**
  - **Process and test nine-cell cavities → deliver to cryomodule assembly**
  - **Initiate hydroforming work with goal of building nine-cell units in North America**
  - **Fabricate nine-cell R&D cavities and begin processing/testing**
  - **Continue single-cell and sample R&D**

New vacuum ovens planned for Fermilab and Cornell

Jefferson Lab oven presently used for hydrogen degassing of all Americas Region cavities

- Fermilab oven in fabrication at vendor
- Plan to install & commission in summer 2010
- Cornell has ordered same oven

Americas

Conclusion

- Much progress over the last year
  - Cavity yield is increasing
  - Argonne/Fermilab processing and testing rate and quality increasing
  - New infrastructure
    - Tumbling machines everywhere
    - Helium refrigerator with recovery at Cornell
- Need to keep pushing on yield improvement
  - Hydroforming
  - Nine-cell R&D cavities
  - Single-cell and sample studies
- Budget appears to be adequate
- Human resources
  - Always need more, but we have made significant additions over the last year (not all supported by ART)