Superconducting RF R&D
toward High Gradient

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Fermilab

LINAC08
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Outline

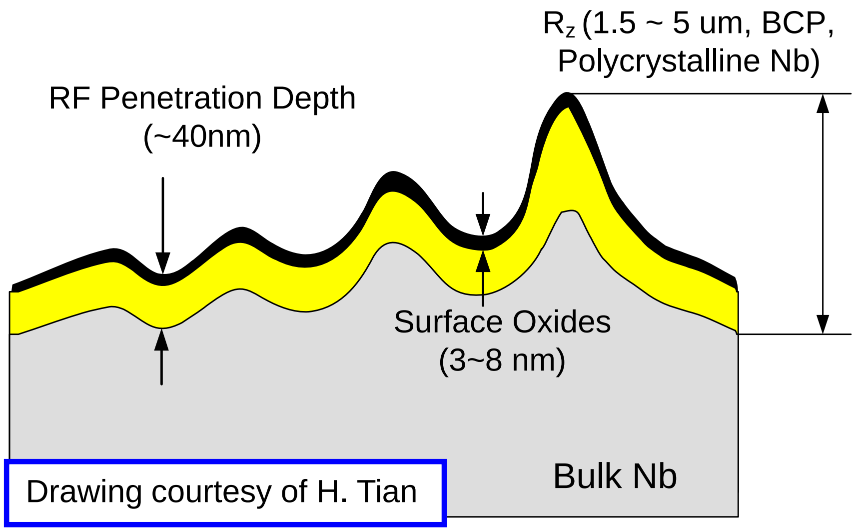
- State of the Art
- Cavity limitations
  - Studies to reduce field emission
    - Avoid localized electric field enhancement
  - Shape/manufacturing studies
  - Quench/Q-drop
    - Avoid localized magnetic field enhancement
- Investigations into cavity performance
- Outlook

High-gradient SRF cavity applications

Project	Gradient [MV/m]	# 9-cell cavities
STF at KEK	35 45	4 4
NML at Fermilab	35	24
FLASH at DESY	23.8 (XFEL)	48
XFEL at DESY	23.8	808
Project X at Fermilab	23.8 – 31.5	287
International Linear Collider	31.5	14,560

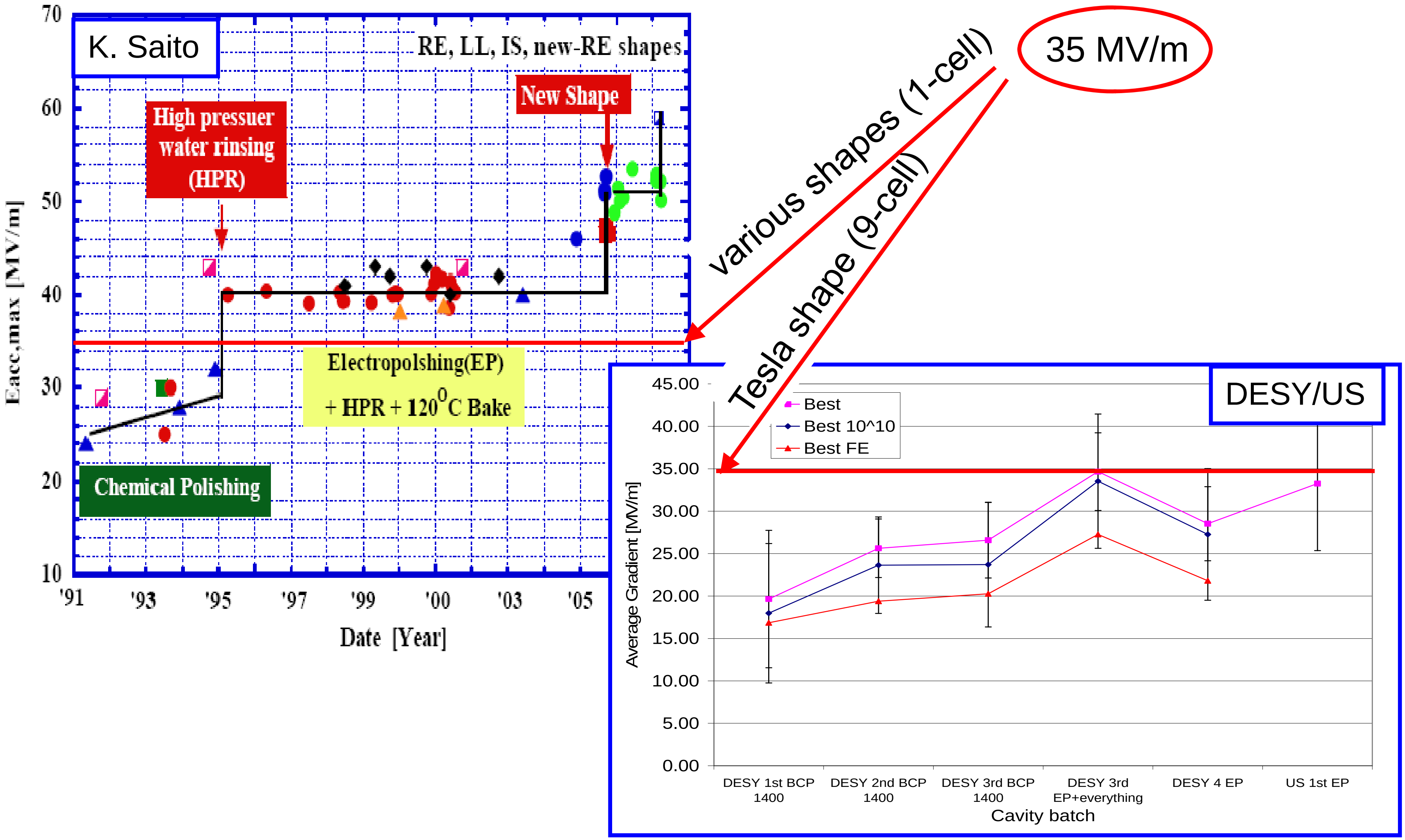
Today: >23 MV/m, beta=1 elliptical cavity shapes only

We know how to get 35 MV/m



- RF fields in ~40 nm of inner cavity surface
- Improve cavity performance
  - QC of material: pure (RRR≳300), eddy current scanning of Nb sheets
  - Smooth cavity inner surface
  - No inclusions of foreign particles or topological defects, e.g., bumps & pits or sharp grain boundaries
  - No dust or other microscopic contaminants introduced after surface preparation
- Good cavity shape with low Hpeak/Eacc and low Epeak/Eacc

35 MV/m in data



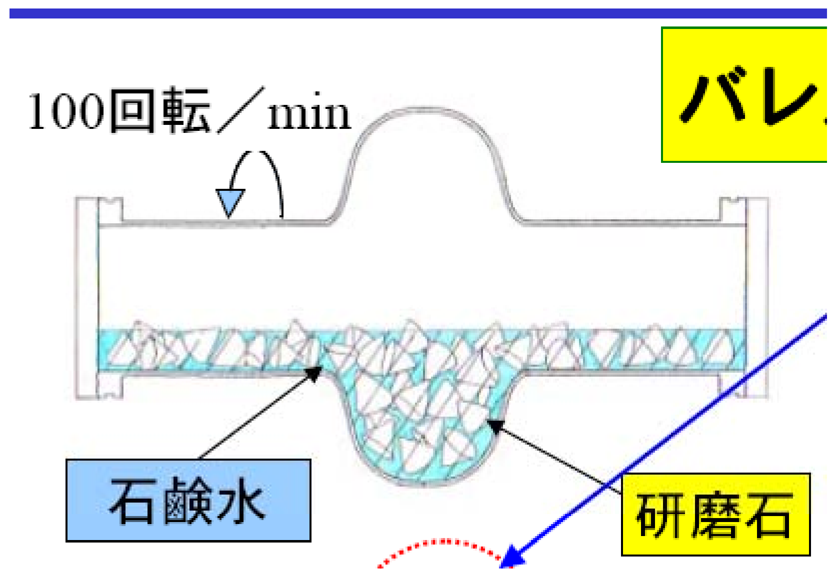
Surface Processing

- Initial preparation steps
  - Remove ~150 um
    - electropolishing (EP)
    - At KEK centrifugal barrel polishing (CBP)
    - [or buffered chemical polishing (BCP); may get you to 20 MV/m]
  - 800C anneal
- Final preparation steps
  - Degreasing with detergent
  - Light electropolishing (~20 um)
  - High pressure rinsing (HPR) with ultrapure water
  - Drying in class-10 cleanroom
  - Evacuation
  - Low-temperature baking (120C)

Centrifugal Barrel Polishing

- Abrasive small stones placed into cavity with water to form a slurry; cavity is rotated
- Standard technique at KEK
- Material preferentially removed from equator region
- Standard cavities have equator weld; CBP smooths the weld

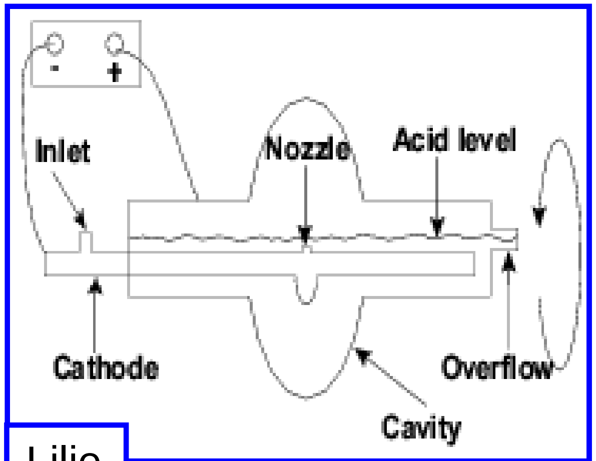
K. Saito



Electropolishing (EP)

Kelly et al., THP026

- Electrolytic current supported removal of metal
  - Niobium cavity is anode, aluminum cathode inserted on axis
  - Electrolyte is HF(40%):H_2SO_4 (1:9)
- Complementary to CBP; material removal preferentially on iris
- Results in mirror-smooth surface

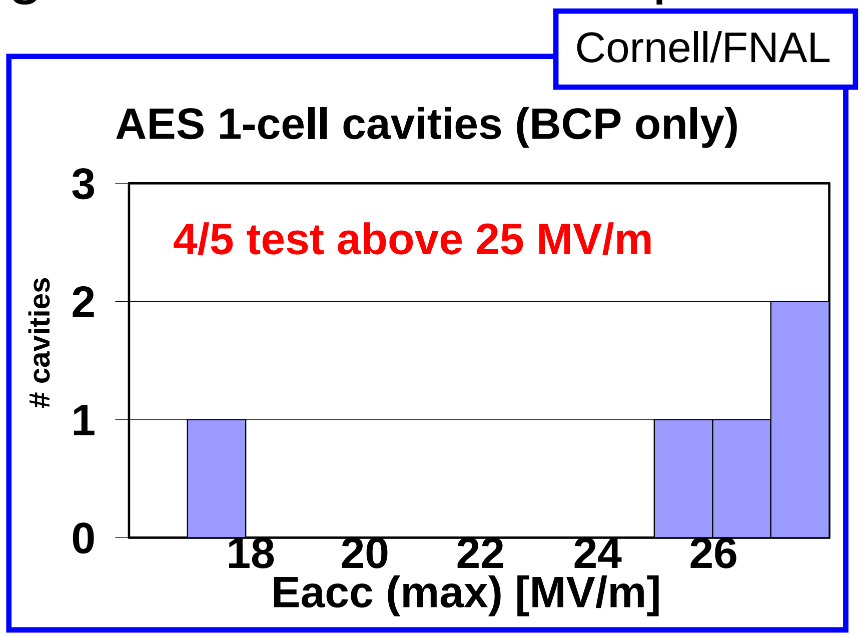


Lilje

ANL

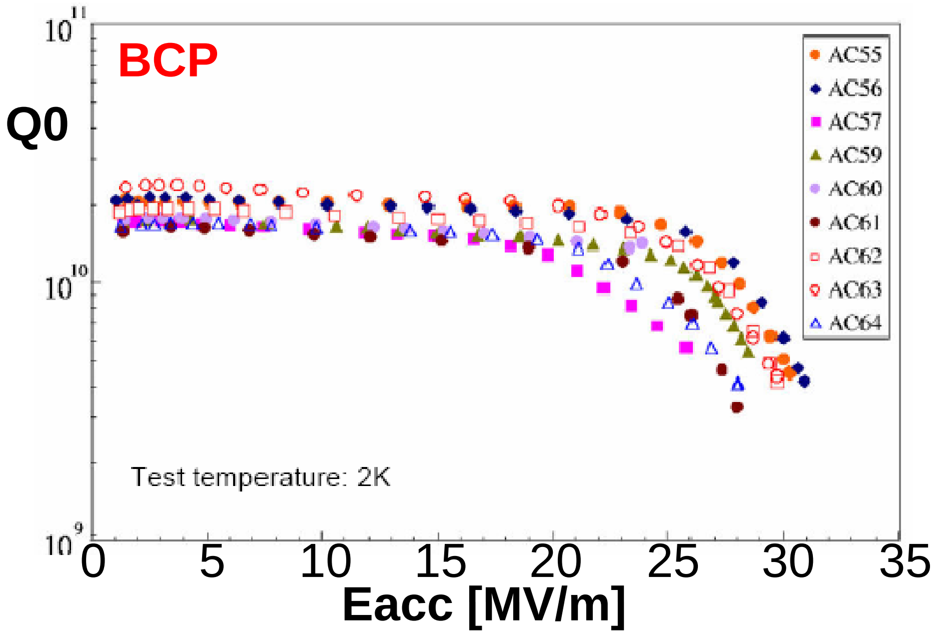
Buffered Chemical Polishing (BCP)

- HF(40%):HNO_3(65%):H_3PO_4(85%) (1:1:2)
- Tends to enhance grain boundaries
  - May be sufficient for large-grain cavities
- It is “easy” to get 25 MV/m using BCP alone, for example
  - 1-cell AES cavities
  - DESY 9-cell (p.10)

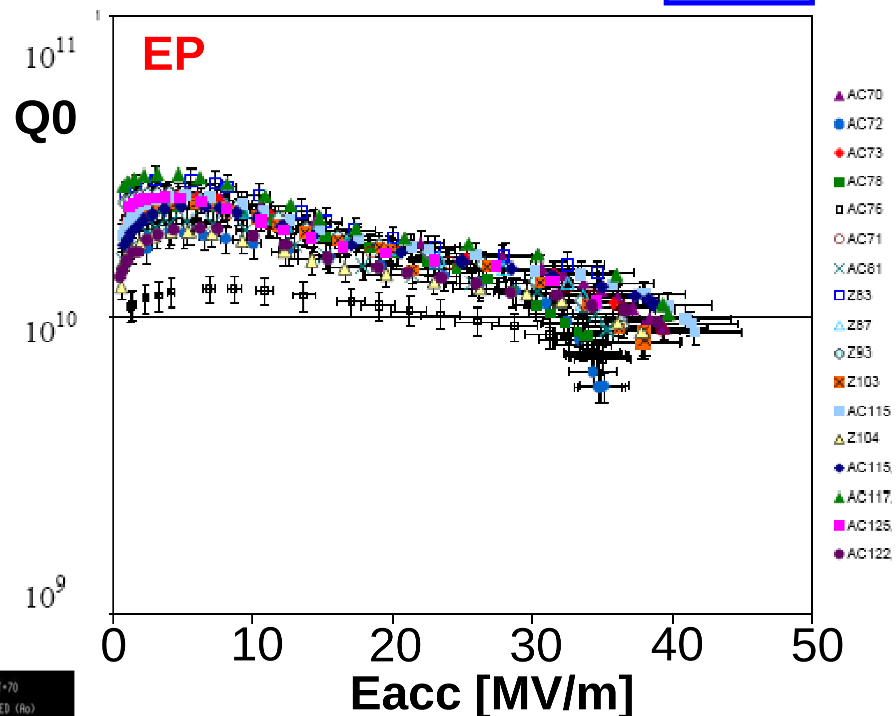


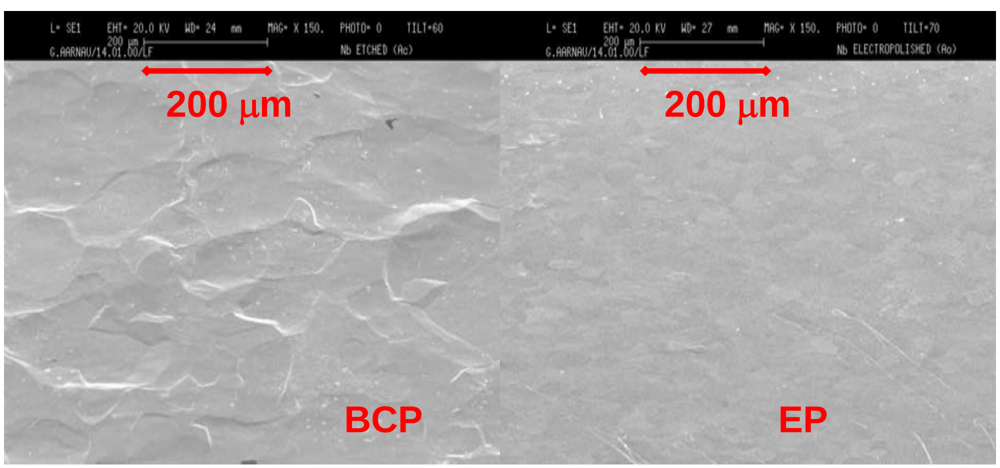
- Global gradient improvement after EP was introduced (p.5)

BCP vs. EP



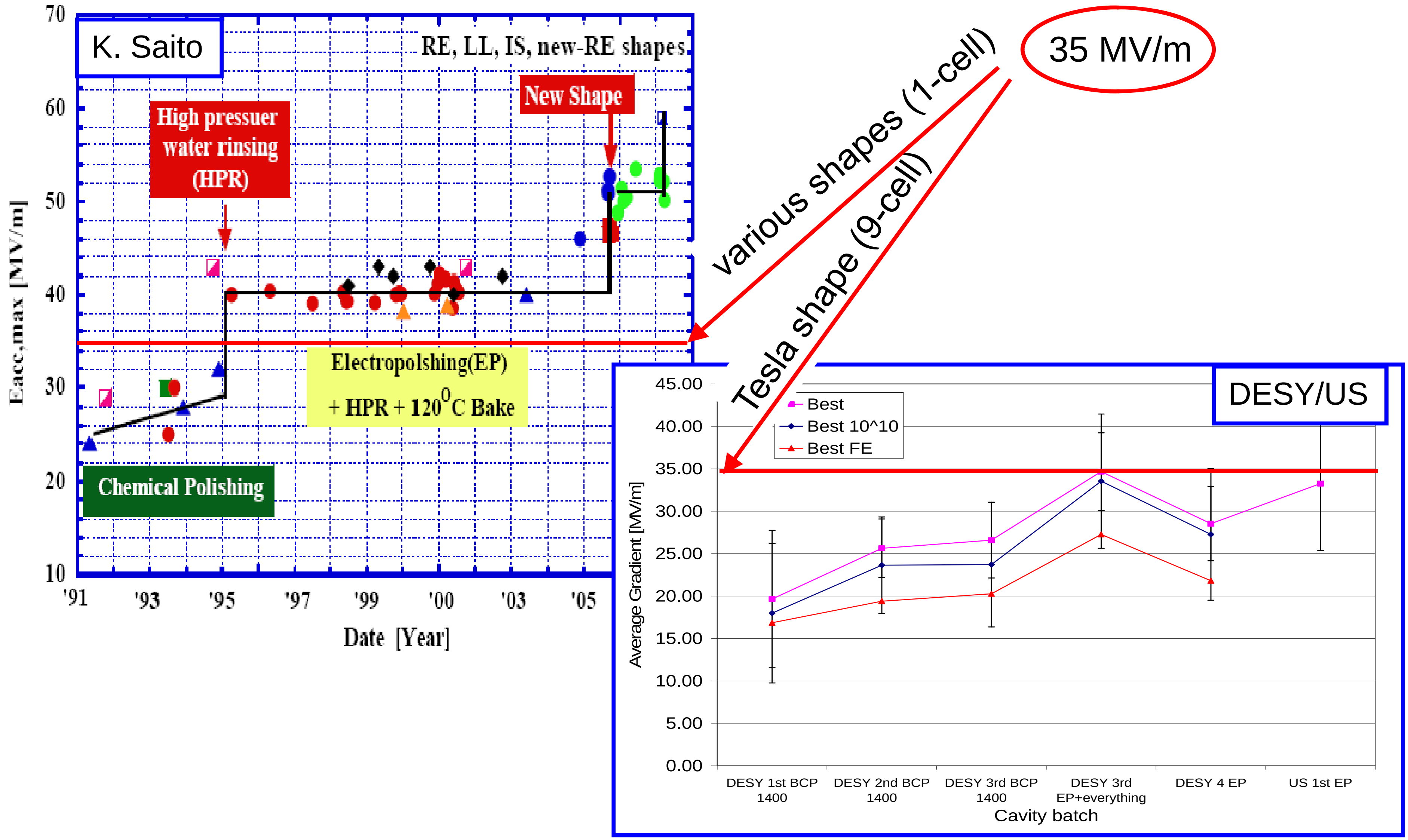
DESY





- DESY Production 3: Best tests with BCP (left) and EP (right)
  - Gradient max ~25-30 MV/m (BCP)
  - Gradient max ~35-40 MV/m (EP)
- BCP sufficient to get to 20 MV/m
- EP results in higher gradients

35 MV/m in data

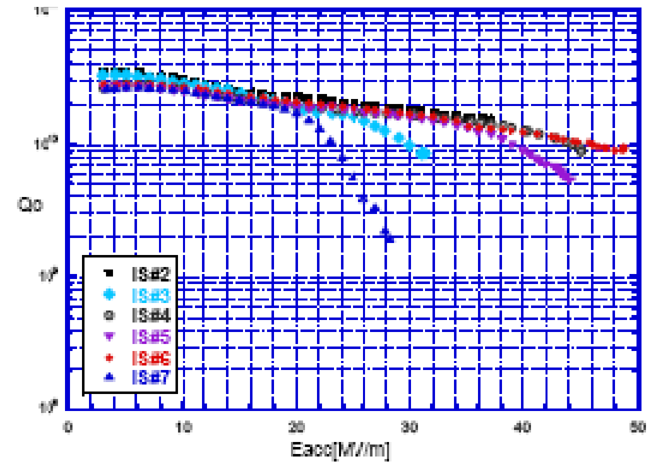


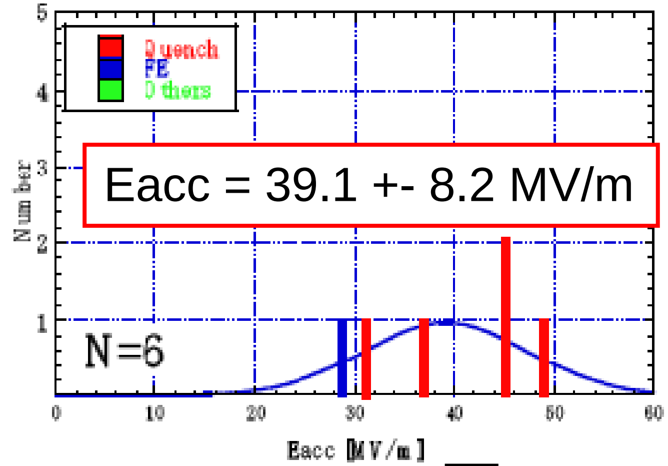
Studies to Reduce Field Emission

- Fresh EP
- Dry ice
- Degreasing
- Final rinse with ethanol

Fresh EP R&D

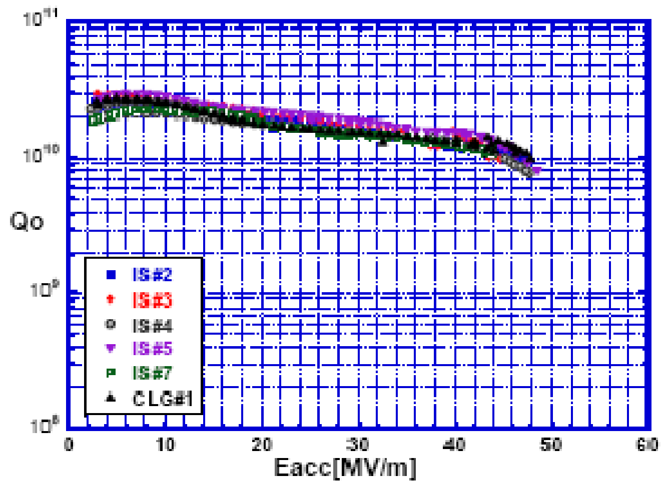
KEK Saito



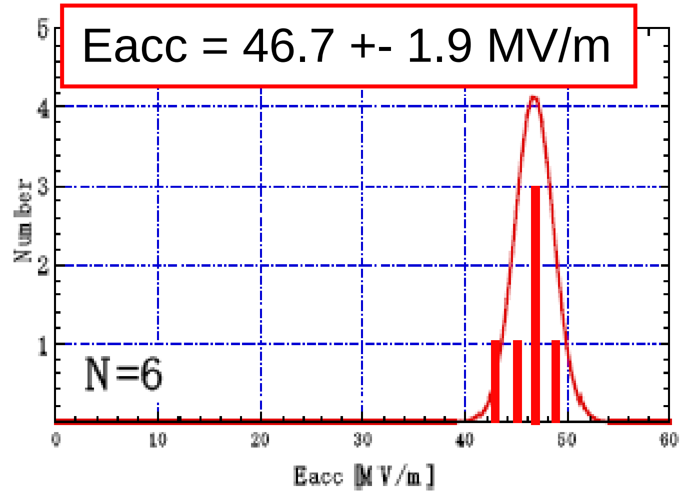


Eacc = 39.1 +- 8.2 MV/m

Add fresh/closed 3 μm EP



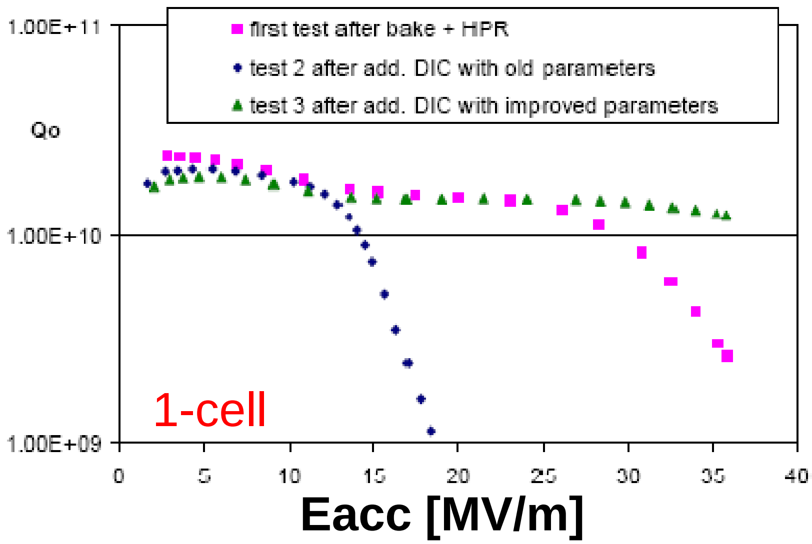
Eacc = 46.7 +- 1.9 MV/m

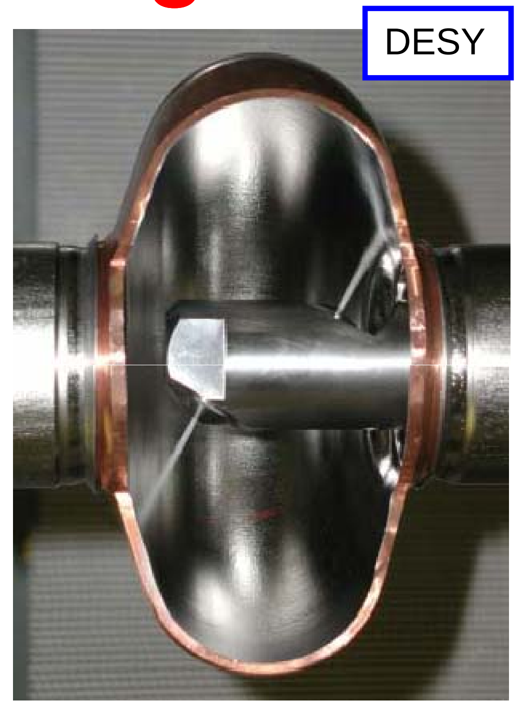


- 1-cell Ichiro shape
- Standard treatment CBP+BCP+anneal+ EP(80 μm) + HPR + bake (120C*48hrs)
- Improvement in gradient and *spread* by the addition of fresh/closed 3 μm etch
- Raises gradient for onset of field emission (FE)
- cannot be certain whether the final quench is caused by FE or by defect

Dry Ice Cleaning

Brinkmann et al., THP013

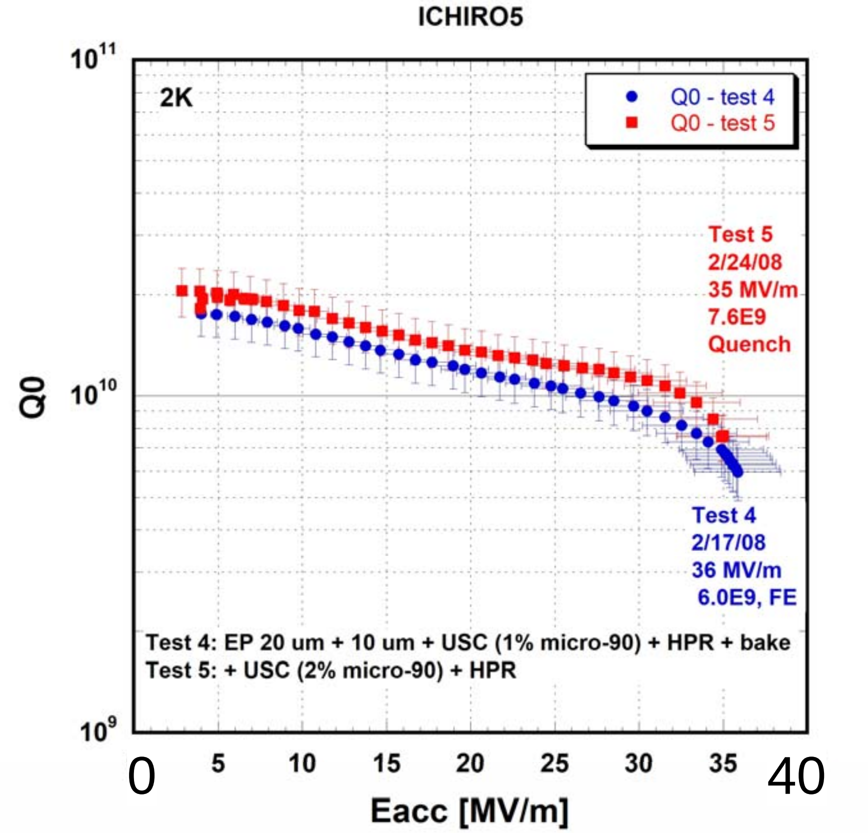


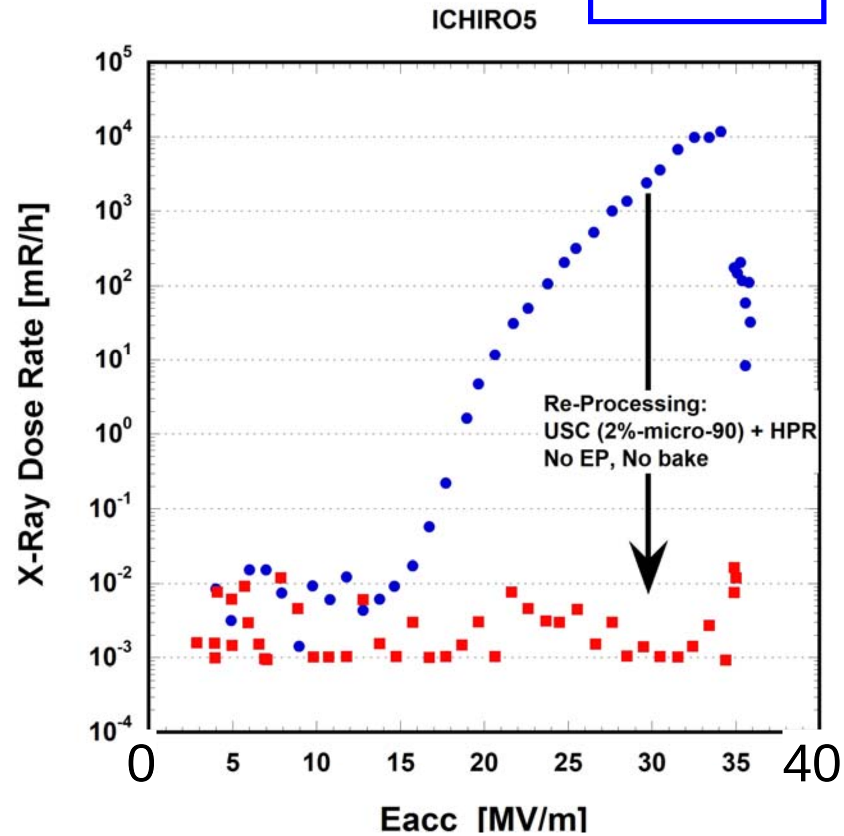


- Rapid cooling embrittles contaminating particles
- Pressure and shearing forces as CO_2 crystals hit surface
- Rinsing due to 500x increased volume after sublimation
- LCO_2 is a good solvent/detergent for hydrocarbons and silicones etc.
- Dry process; no residues; horizontal orientation
  - Could perform after coupler installation
- Good results on 1-cell cavity tests, plan extension to 9-cells

Degreasing R&D

KEK/JLab

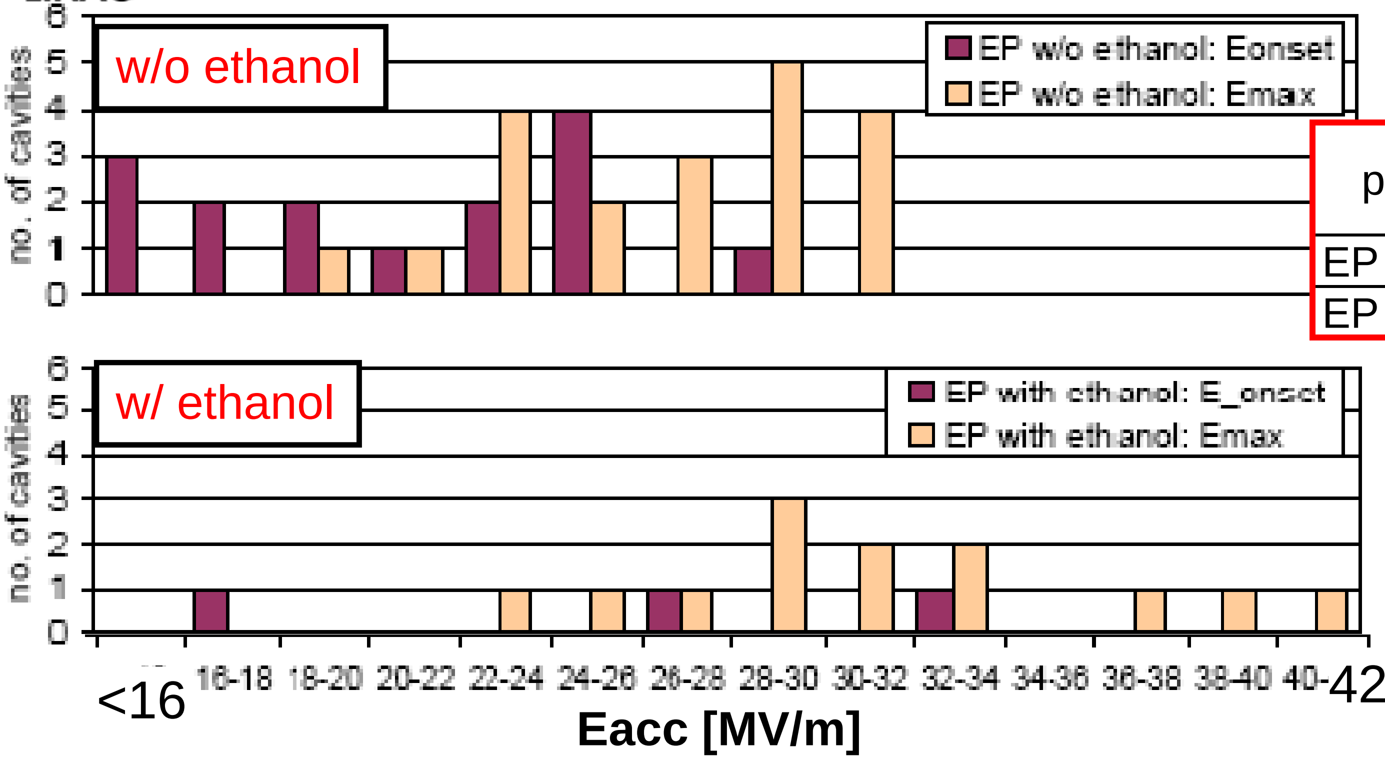




- One example: KEK 9-cell Ichiro-shape cavity tested at JLab
- Ultrasonic cleaning with degreaser effective in reducing field emission

Ethanol rinse R&D

DESY



preparation	$\langle E_{acc}^{max} \rangle$ [MV/m]
EP w/o ethanol	27 ± 4
EP w/ ethanol	31 ± 5

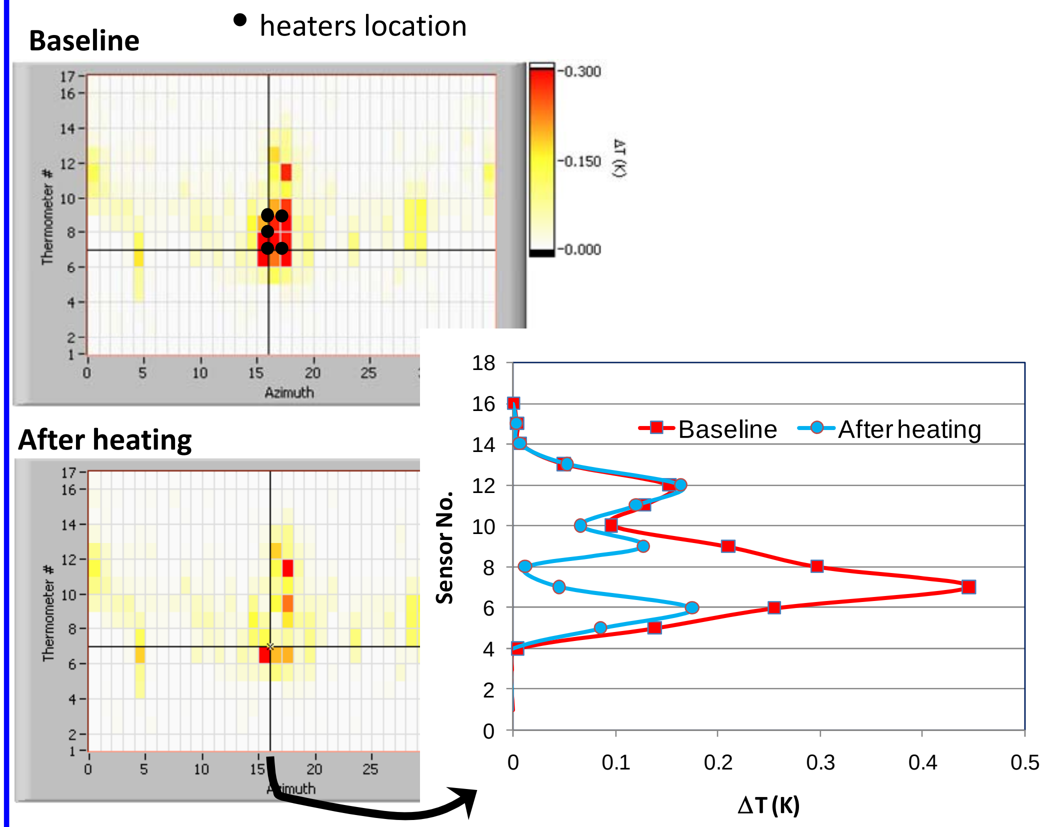
- Ethanol rinse immediately following final EP to remove sulfur particles
- DESY Production 4 cavities: 20 w/o ethanol and 13 w/ ethanol rinse
- #tests with FE greatly reduced by introduction of ethanol rinse
- Maximum gradient also improved (still large spread)
- Ethanol rinse effective to reduce or eliminate FE; now DESY standard

Fundamental SRF Studies: Trapped Vortices

Ciovati and Gurevich

Q-drop: Some cavities exhibit strong RF losses starting at Hpeak~90-100 mT [21-24 MV/m for Tesla-shape], without FE

- Trapped vortices are trapped magnetic flux which become trapped at surface defects
- Local thermal gradient applied to hot-spots caused hot spots to move and reduce intensity
- Movement of the hotspots after applying the gradient indicates that heating is due to trapped vortices rather than local variation in BCS resistance
- Works better on large-grain than fine-grain cavities – consistent with expectation of flux pinning strength



Shape/manufacturing studies

- Investigating fundamental changes to cavities
  - Shape
    - improve Eacc/Hpeak
  - Fabrication
    - hydroforming
  - Material
    - large-grain, single-grain
    - atomic layer deposition

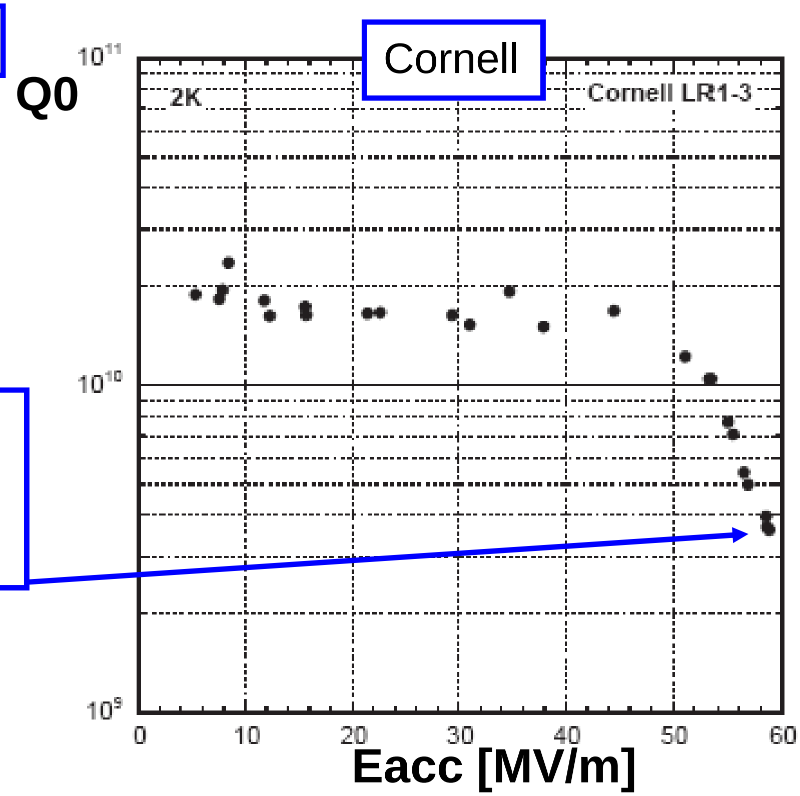
Alternative Shapes ≳50 MV/m

see Li et al., THP038, for whole new design

Tesla-shape cavity for comparison

World record:
59 MV/m Cornell 1-cell re-entrant shape

Ichiro shape



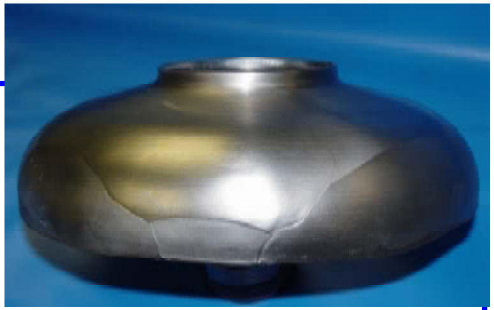
- Single-cell Ichiro-shape record is 53.5 MV/m [KEK Saito]
  - 46.7 +- 1.9 MV/m with optimized surface treatment parameters (p.13)
- 9-cell Ichiro-shape recently reached 32±4 MV/m in 5 process/test cycles (KEK/JLab)
- Low-loss shape reached 47.3 MV/m (DESY/KEK)

Large-grain/single-grain Nb cavities

Cornell, DESY, JLab, KEK, MSU/JLab, PKU/JLab

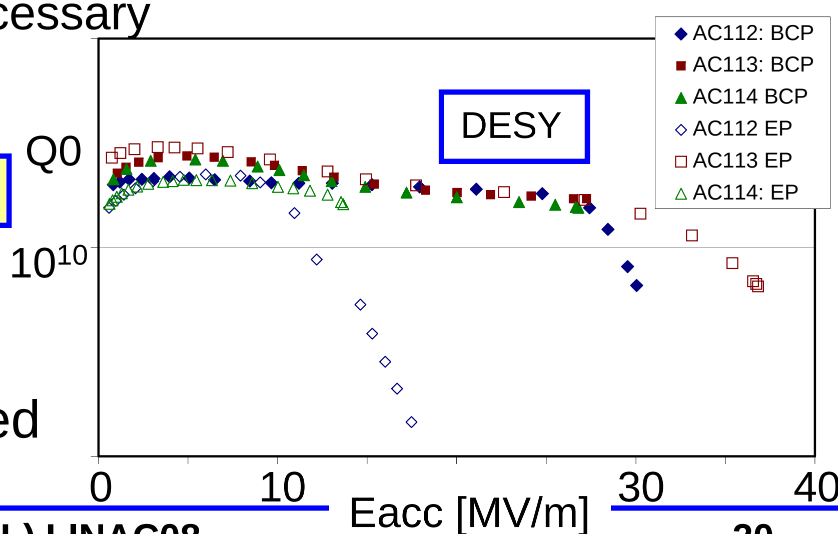
- Potential advantages
  - Reduced manufacturing & processing cost
  - Smooth surfaces with BCP only (no EP)

Large Grain half-cell



- Many large-grain 1-cell & 9-cell and few 1-grain 1-cell cavities fabricated & tested
- Recent LG fabrication experience – cost advantage not yet realized
  - Grains at equators: ragged equator edges, material may thin/rip at equator, springback deforms half-cells – companies consider problems surmountable
  - Effective cutting method being pursued by W.C. Heraeus and Tokyo Denkai
- Recent LG performance experience – comparable to fine-grain cavities
  - Unclear whether BCP sufficient or EP necessary
  - Many 1-cell tests: ~30-48 MV/m
  - New 9-cell test results →

Lilje&Reschke, THP014



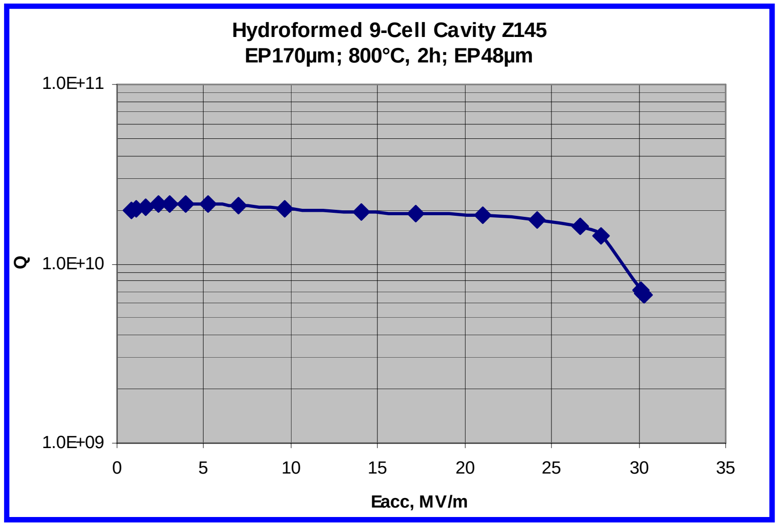
- Single-crystal cavities
  - Difficult to produce large-Ø 1-grain ingots
  - Several 1-cell tests: ~38-45 MV/m
- Study of crystal orientation effects needed

Hydroformed Cavities

Singer et al., THP043

DESY/JLab

- Remove equator weld as source of impurities or defects or inclusions
- 9-cell hydroformed cavity Z145
  - 3 3-cell units; 2 iris welds + beampipes
- Results: Eacc=30.3 MV/m, limited by quench, no FE
- High gradient Q-drop is pronounced, so the performance can be improved after 120C baking as next step



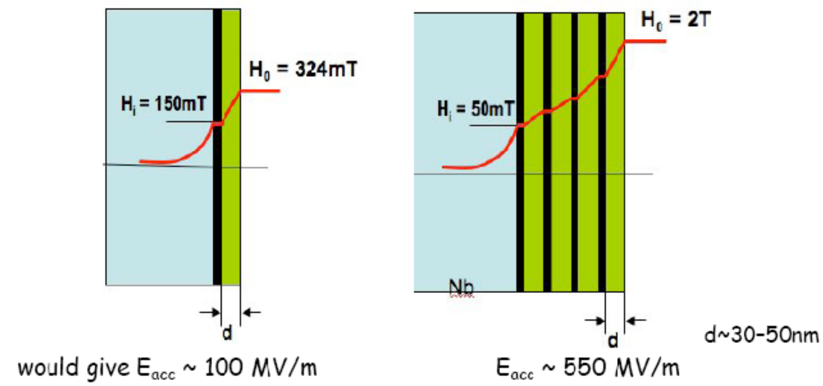
Z145 reached 30 MV/m, quench limitation

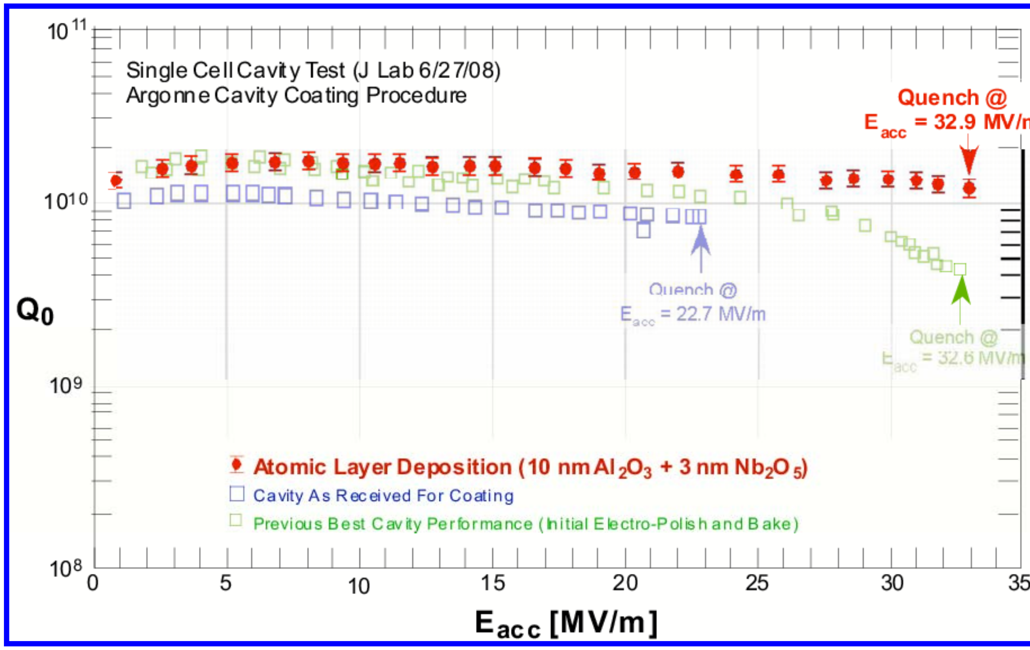
Atomic Layer Deposition

ANL/JLab

- Increase RF breakdown magnetic field of superconducting cavities by multilayer coating of alternating insulating layers and thin SC layers
  (Gurevich, APL88, 012511 (2006))
- Atomic layer deposition (ALD)
  - Flow gas through cavity forming chemical bond with Nb surface
  - Chemical bond cannot flake off
- 1-cell cavity ALD at ANL
- RF test at JLab: 33 MV/m without Q-drop
- Promising new possibility

The primary niobium layer is covered with an insulator and superconductor.
The top layer has high T_c, screens quench fields from the bulk niobium.
Multiple layers permit almost arbitrarily large accelerating fields.

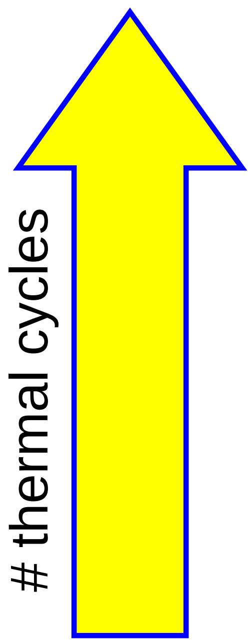




Understanding Cavity Behavior

- Quenches and field emission appear as hot spots on outer cavity surface.
  - Temperature mapping systems have been used for many years

- New hot spot detection systems include

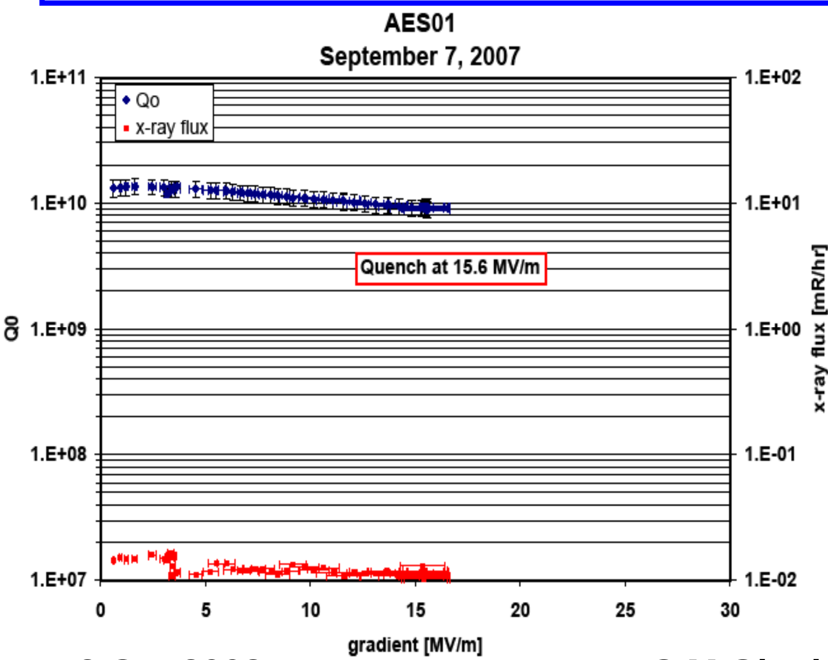


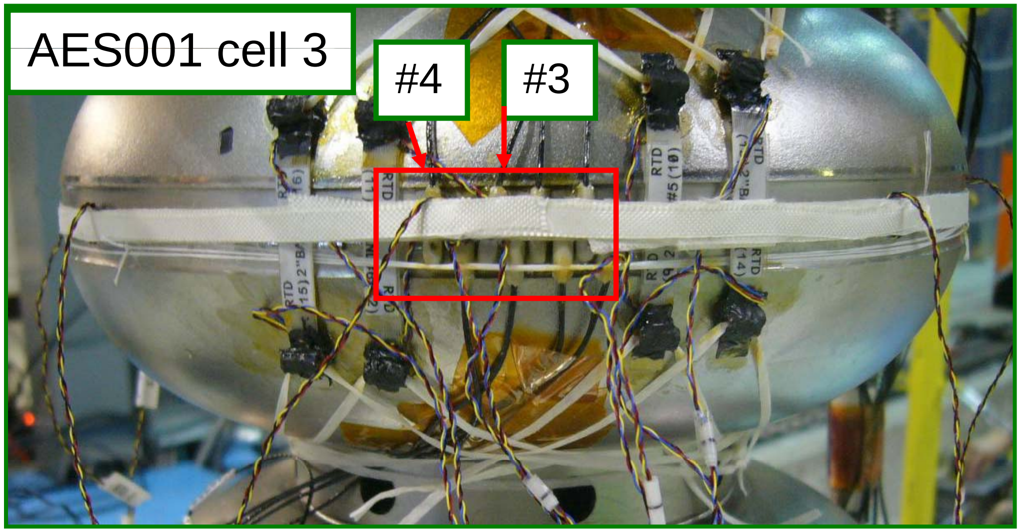
- Individual Cernox thermal sensors (FNAL)
- 2-cell Allen-Bradley temperature map (JLab)
- { 9-cell T-map under development (LANL, FNAL)
  Second sound sensors (Cornell) }

Quench Location with Fast Thermometry

FNAL

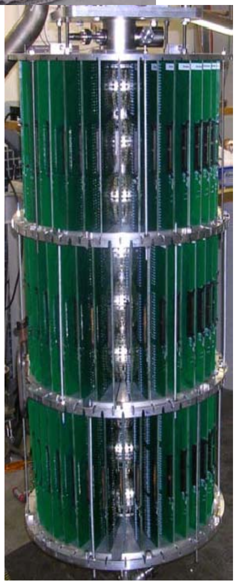
- Example of cavity which quenched at 16 MV/m without field emission
  - Temp rise ~0.1 K over ~2 sec in sensors #3 & #4 before quench seen on all sensors
- Cernox RTD sensors (precise calibration, expensive) with fast readout (10 kHz)
- Flexible placement of sensors, attached to cavity surface with grease and band; slow installation
- Suitable for any cavity shape and highly portable





2- and 9-cell T-mapping

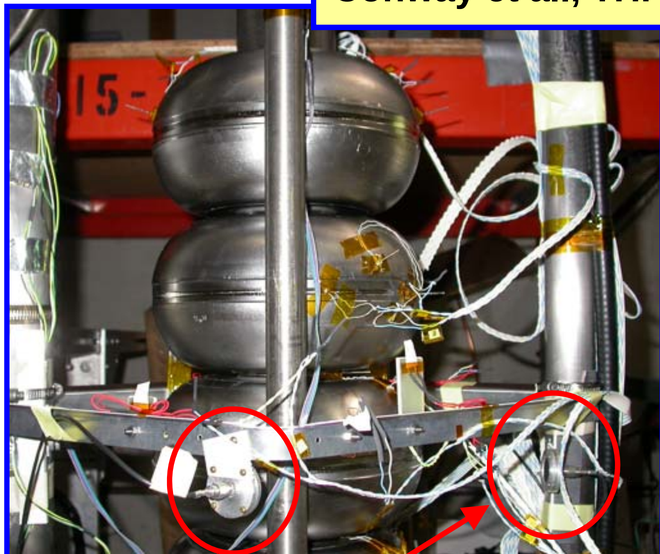
- 2-cell T-map
  - JLab using Allen-Bradley sensors
  - Requires two cooldowns, first with mode measurements
- 9-cell T-map
  - LANL using Allen-Bradley sensors and cold multiplexing
    - Promising preliminary results
  - FNAL using diodes
    - System under development
  - Could use on every test to find T-map on one cooldown
- Designed for specific cavity shape

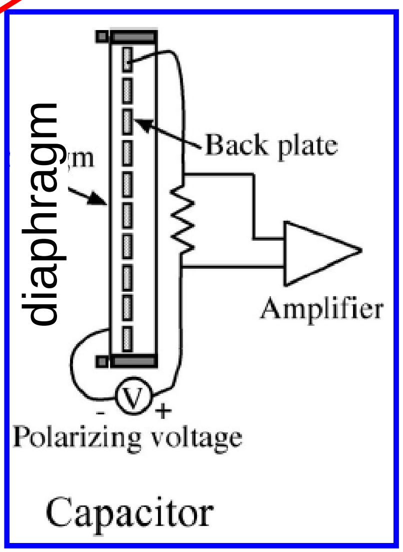


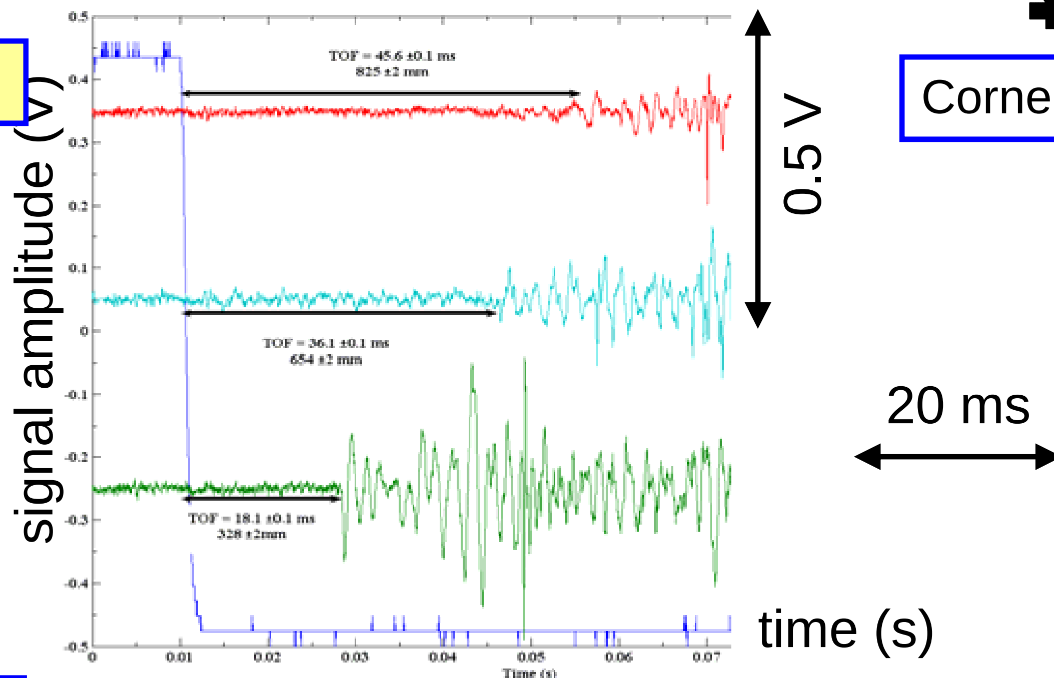
Quench location with 2nd Sound

Cornell

Conway et al., THP036



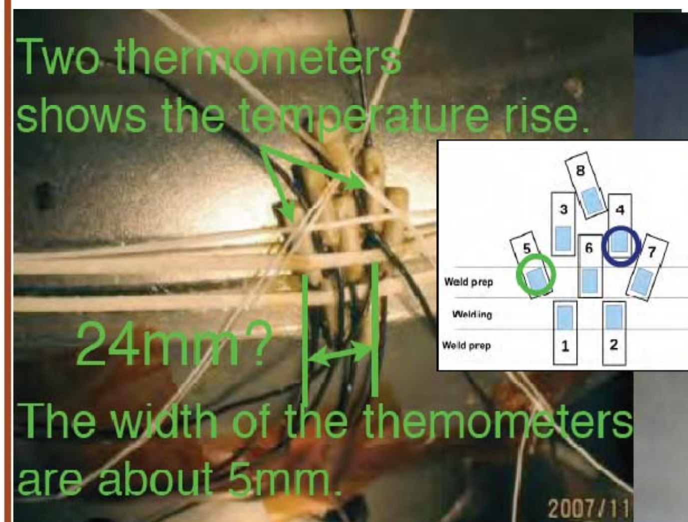




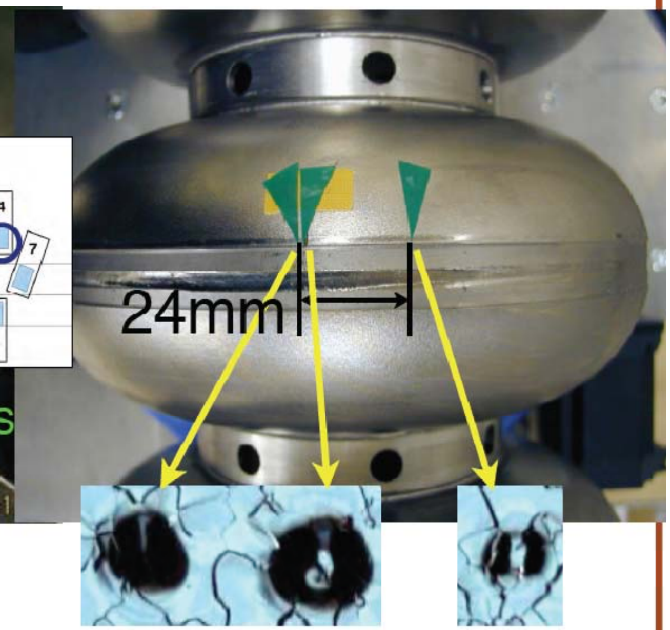
- Second sound is a thermal wave which can propagate only in superfluid helium; generated when heat pulse is transmitted from heat source through SF He
- Eight sensors detect arrival of wave
- Quench location from relative signal timing
- Suitable for any cavity shape

Exciting Optical Inspection

Correlation with Thermometry



Dmitri A. Sergatskov: Thermometry on AES01 cavity at Fermilab
@webex20071204



Two hot spots@FNAL/JLAB

Three spots found@Kyoto

Clever lighting technique and excellent spatial resolution 7 um/pixel

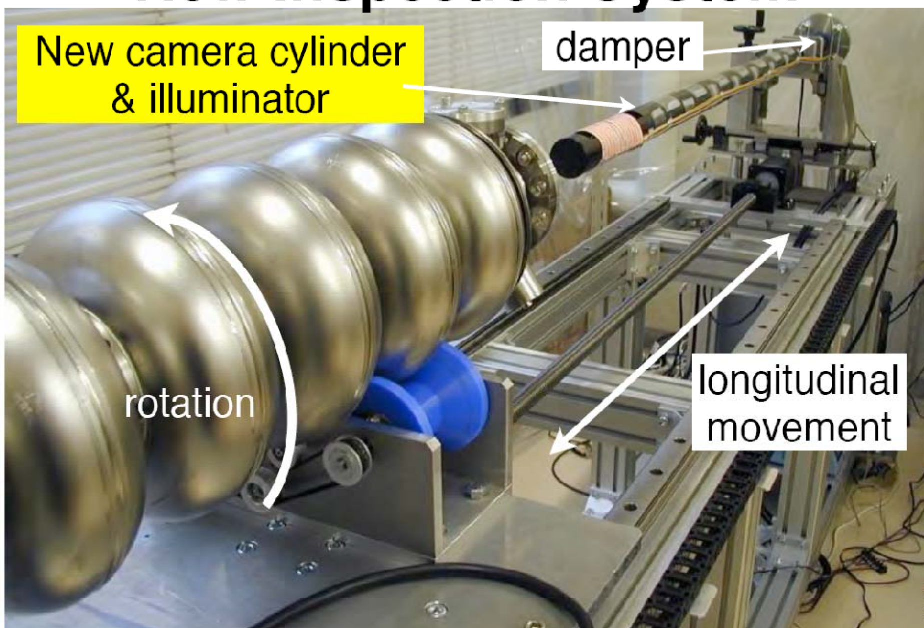
Kyoto U./KEK

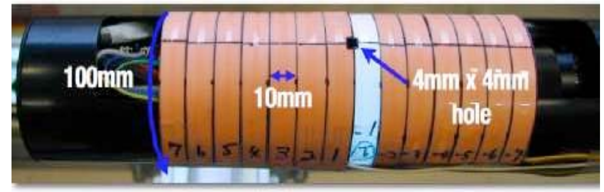
Optical Cavity Inspection

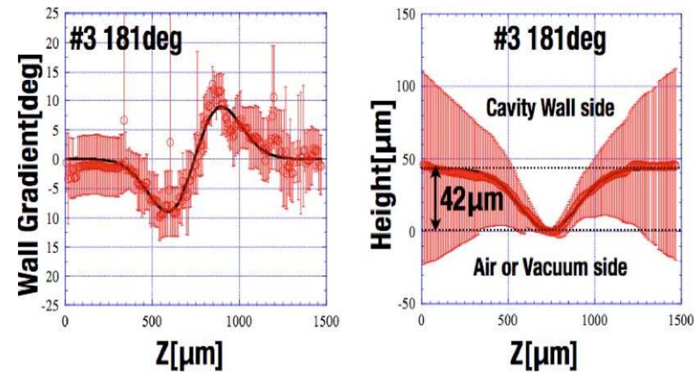
Iwashita et al., THP021

Kyoto U./KEK

New Inspection System

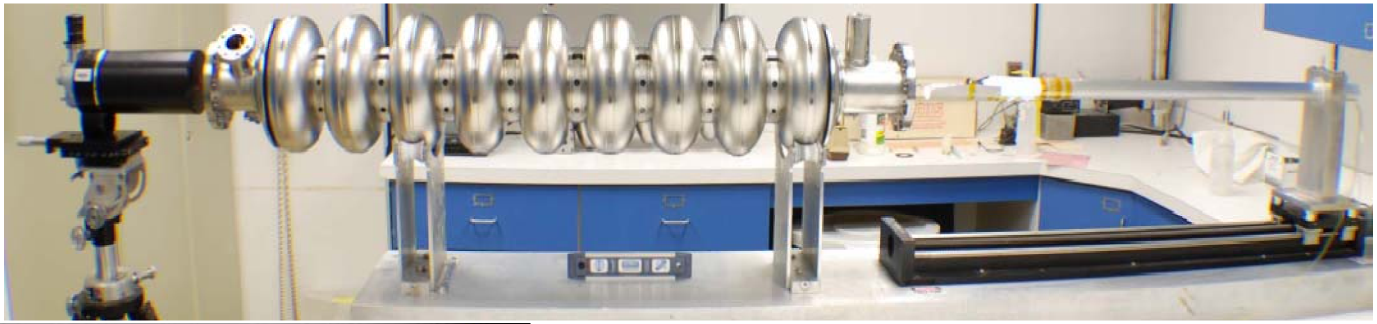




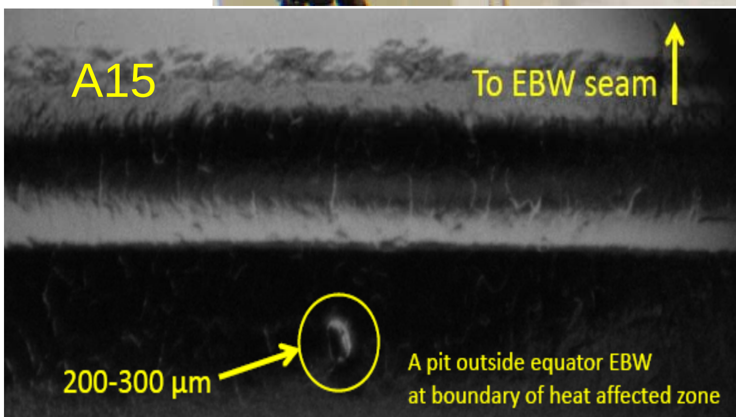


- Illumination by electroluminescent strips which can be turned off/on individually: shadows can be analyzed for 3D defect mapping (pit vs. bump) [bump is shown]
- Camera is inserted into cavity
- Digital images studied by a person – needs automation
- Many defects on several cavities now found, 50-600 um diameter

Optical Cavity Inspection



JLab



AES4 defect (~100 µm in dia.) near iris

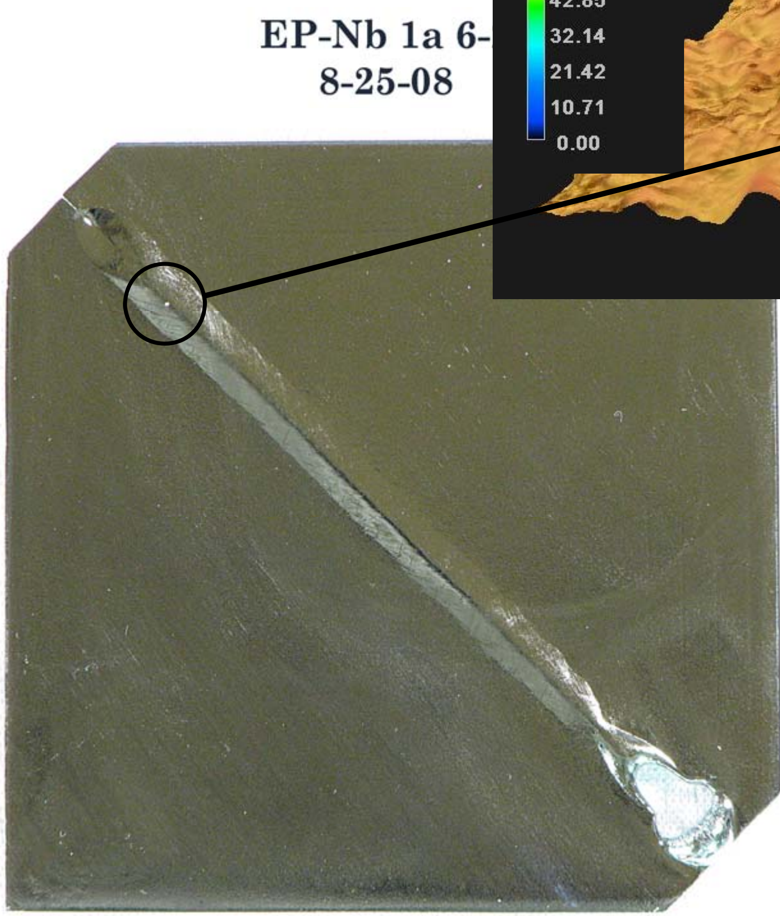
Geng et al., THP042

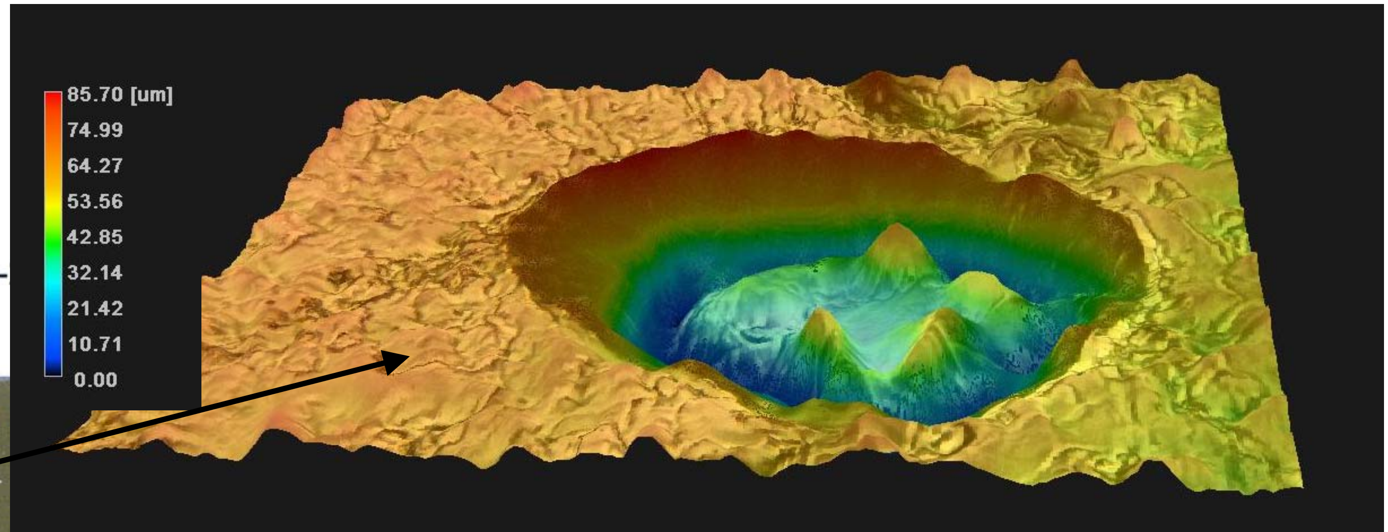
- Questar long-distance microscope for optical inspection
- Used for line-of-sight inspections, or combined with mirror
- Located defect on iris of AES4, suspected from mode meas. of inducing FE
- Located defect in heat-affected zone of equator weld on A15

Cornell also uses Questar technique
Additional optical inspection systems using borescopes under development at LANL and FNAL

Improving weld quality

FNAL/FSU





- 3 in by 3 in samples electron-beam welded together, then 210 µm removed by EP
- Rinsed with ultrapure water - no HPR or ultrasonic detergent rinse
- Inspected with 3D microscope
- Most spots are debris and not pits
- Remains to be seen how to link to cavity performance
- Feed back information to EB welders to improve weld

Outlook

- Very high gradients have been measured in niobium superconducting cavities
  - > 50 MV/m in single-cell Ichiro, re-entrant, low-loss shape cavities
  - > 35 MV/m has been measured in several 9-cell Tesla-shape cavities
- Rich R&D activity in the quest for highest gradients and reduced cost
- Fabrication and material
  - Promising new results from large-grain, single-grain and hydroformed cavities
  - Some cavities are quench limited to 15-20 MV/m associated with intriguing bumps/pits
    - High-resolution optical inspection and T-mapping are very important tools
    - Sample studies underway in effort to reproduce features and improve weld quality
    - Provide feedback to cavity manufacturers to eliminate this problem
- Surface treatment is crucial for optimum performance
  - Several promising studies on final preparation methods to reduce field emission
- Fundamental material investigations
  - Loss mechanisms related to high-field Q-drop
    - Reduce power dissipation at highest gradients
  - New superconductor-insulator composites with atomic layer deposition
    - Could potentially break the critical magnetic field limitation of niobium