Superconducting RF R&D for Future Accelerators

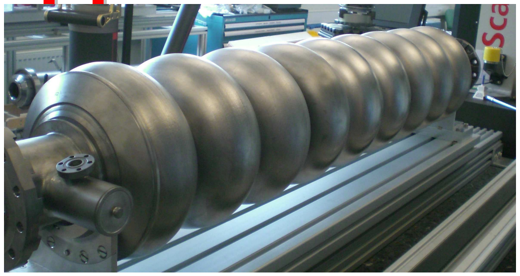
C.M. Ginsburg
Fermilab

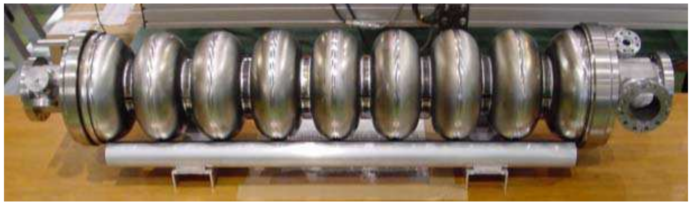
DPF2009 at Wayne State University in Detroit
July 28, 2009

Outline

- ❑Introduction and motivation
- ❑Cavity limitations and investigations into cavity performance
- ❑Fermilab infrastructure for SRF development
- ❑Outlook

High-gradient SRF cavity applications

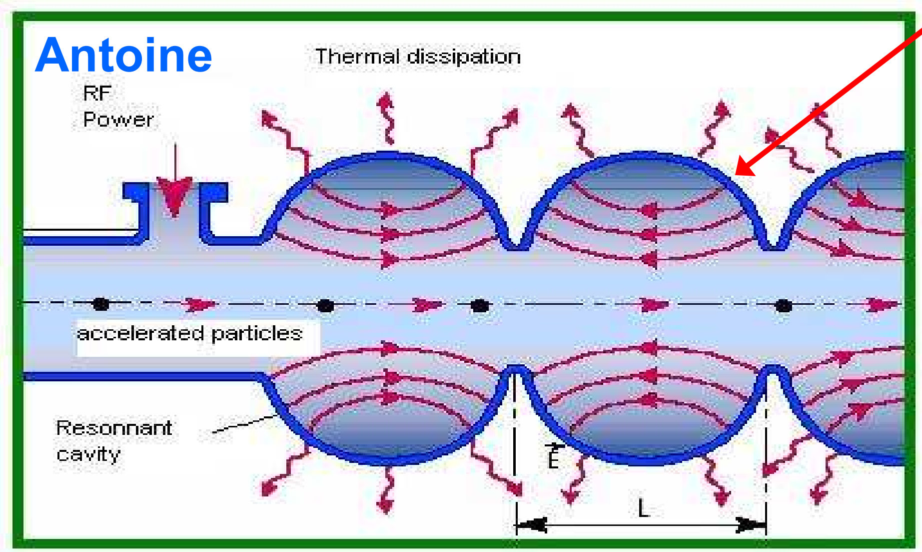




Project	**Gradient [MV/m]**	**# 9-cell cavities**
STF at KEK	35 45	4 4
NML at Fermilab	35	24
FLASH at DESY	23.8 (XFEL)	48
XFEL at DESY	23.8	808
Project X at Fermilab	23.8 – 31.5	287
International Linear Collider	31.5	14,560

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

Accelerating RF cavities, general



A cell

A cavity may consist of many cells

Red curves are electric field

- Electromagnetic cavity resonating at f = 1.3 GHz
- Electron is relativistic
- Electron enters cell at time t=0 and leaves at time t=L/c
- To receive maximum kick from cavity

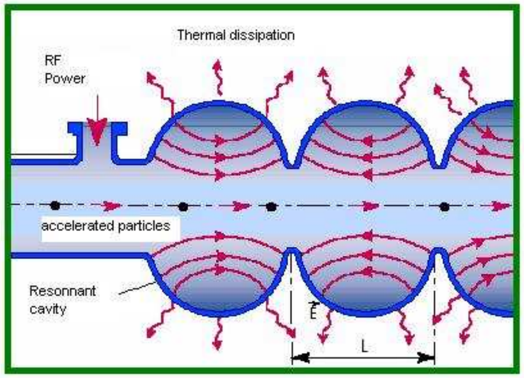
$$t = L/c = T_{RF}/2 = 1/(2f)$$

L=0.12 m   cell length

- Electron always sees a field pointing in the same direction

SRF Cavities: Surface Resistance

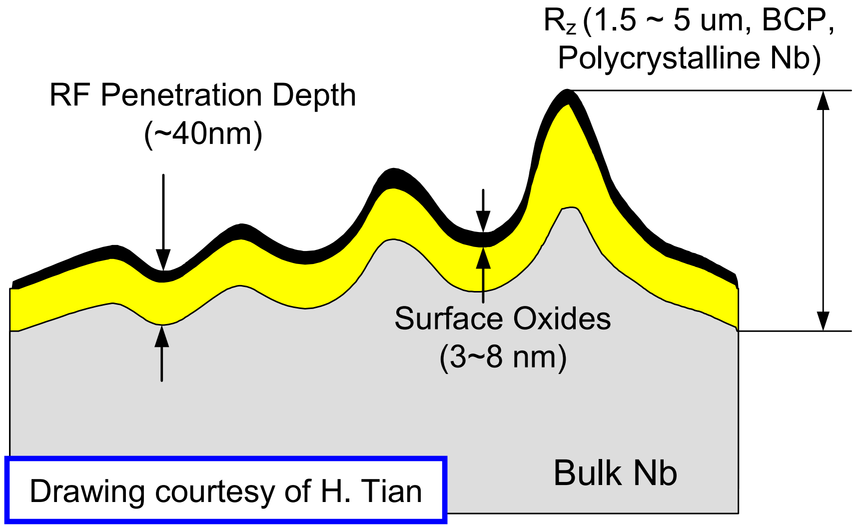
- ❑ To support RF fields in the cavity, currents flow within a thin (~40 nm) inner surface layer
- ❑ Superconductivity:
  - Above Tc, all electrons unpaired
  - At T=0, all electrons paired (Cooper pairs)
  - As T drops from T=Tc to T=0, number of unpaired electrons drops as exp(-Δ/kT)
- ❑ DC case: energetically favorable for pairs to carry entire current while unpaired electrons remain inert
  - ➢ Zero resistance
- ❑ RF case: pairs have inertia – forces must be applied to accelerate/decelerate
  - ➢ Finite but small resistance, which depends on RF frequency



SC: R_S(Nb) ~ 10's of nΩ (@ 2K)

NC: R_S(Cu) ~ few 100 μΩ

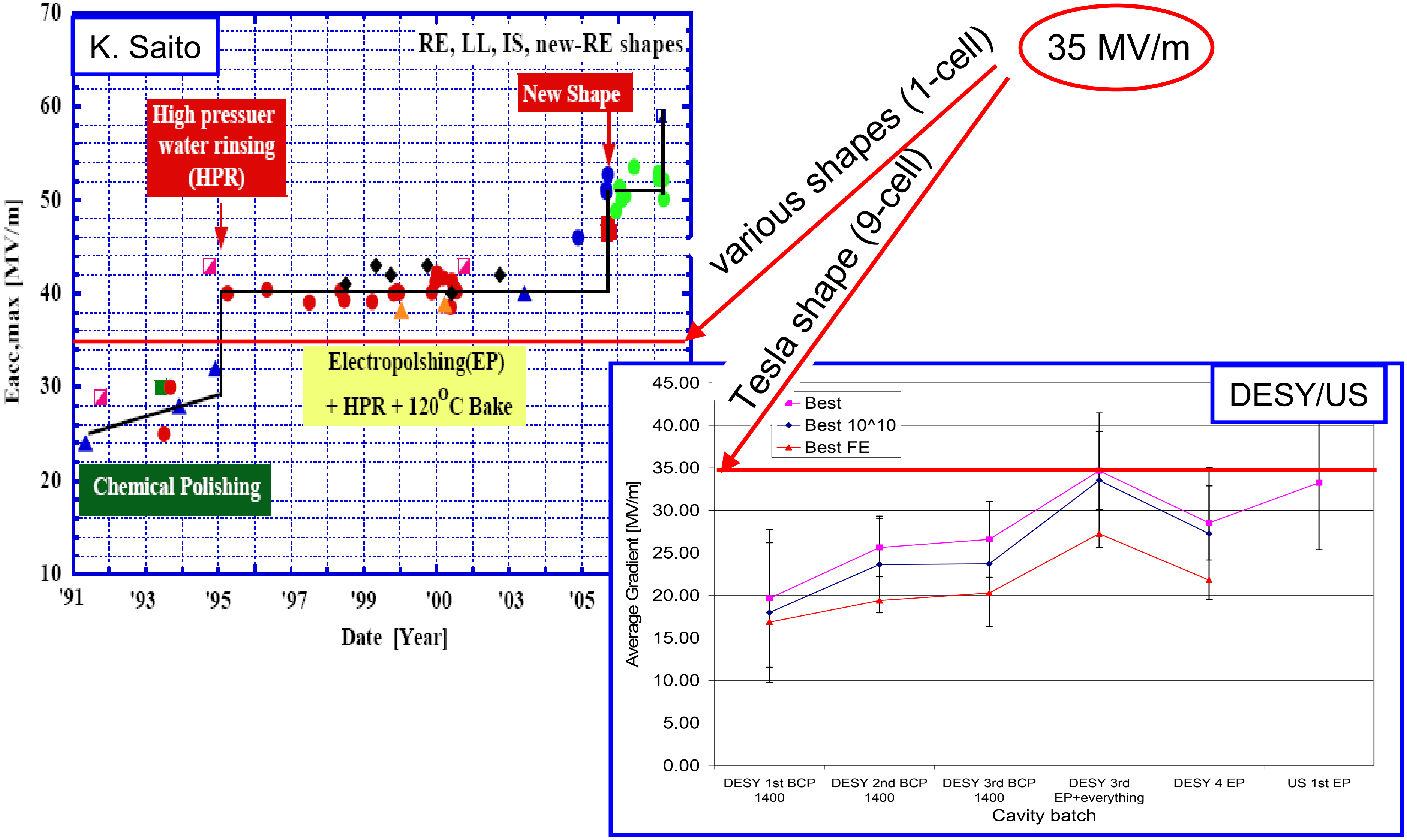
We know how to get 35 MV/m



Drawing courtesy of H. Tian

- 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



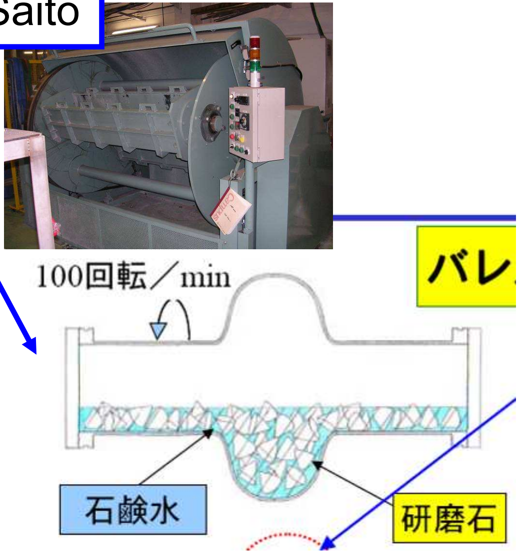
Surface Processing

- 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)

Surface removal and smoothing

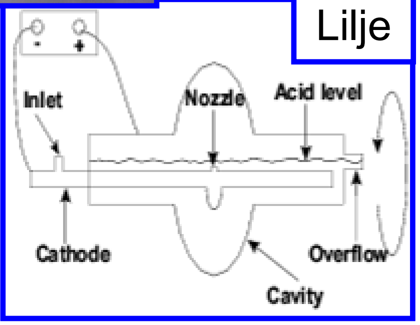
- Centrifugal Barrel Polishing (initial only)
    - Abrasive small stones placed into cavity with water to form a slurry; cavity is rotated
    - Standard technique at KEK
    - Material preferentially removed from equator region
    - Standard cavities have equator weld; CBP smooths the weld
- Electropolishing (EP): 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
- 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
    - “easy” to get 25 MV/m using BCP alone, e.g., p.10
- Global gradient improvement after EP introduced (p.7)

K. Saito



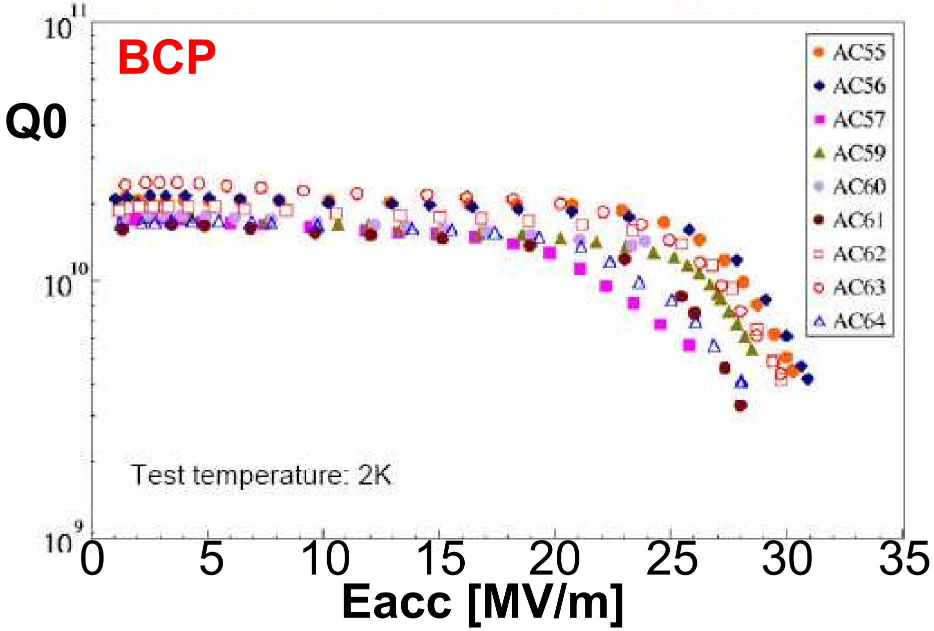
ANL

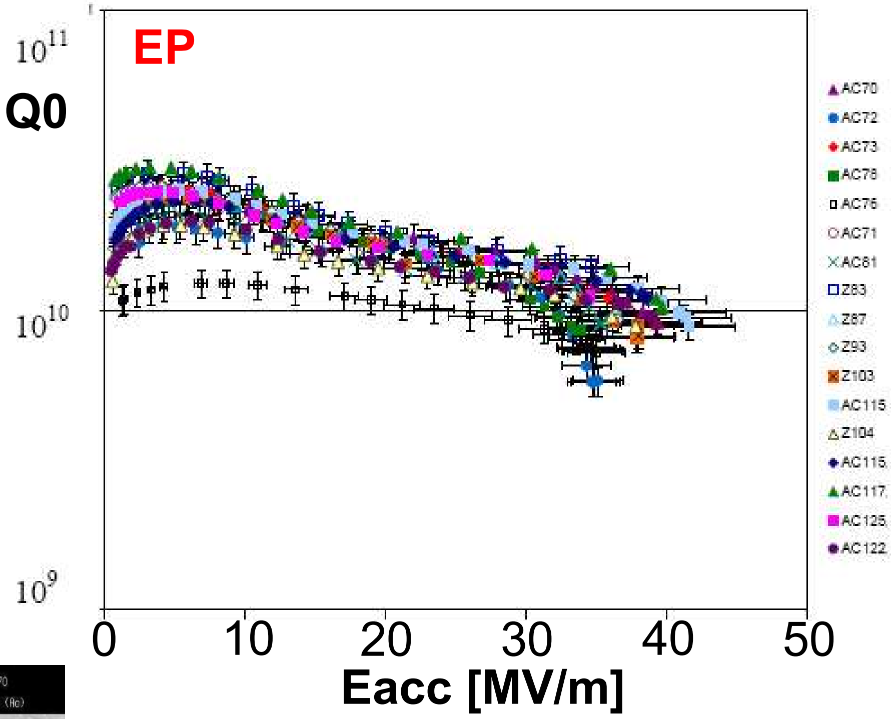
Lilje

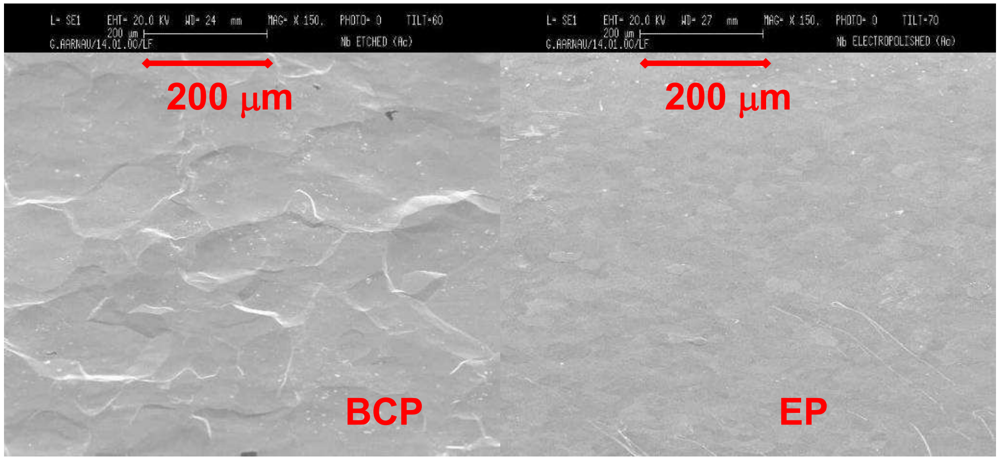


BCP vs. EP

DESY



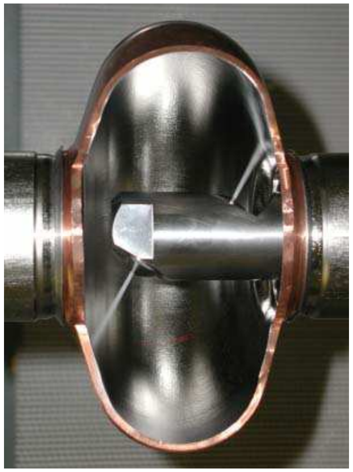




- ❑ DESY Production 3: Best tests with BCP (left) and EP (right)
  - ❑ Gradient max ~25-30 MV/m (BCP)
  - ❑ Gradient max ~35-40 MV/m (EP)
- ❑ BCP sufficient to get to 20 MV/m
- ❑ EP results in higher gradients

Reducing Field Emission

- Fresh EP (KEK - Saito)
  - 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)
- Dry ice (DESY)
  - 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 (JLab and elsewhere)
  - Ultrasonic cleaning with degreaser, e.g., micro-90, effective in reducing field emission
- Final rinse with ethanol (DESY)
  - Ethanol rinse immediately following final EP to remove sulfur particles
  - DESY Prod 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/eliminate FE
    - now DESY standard

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

Shape/manufacturing studies

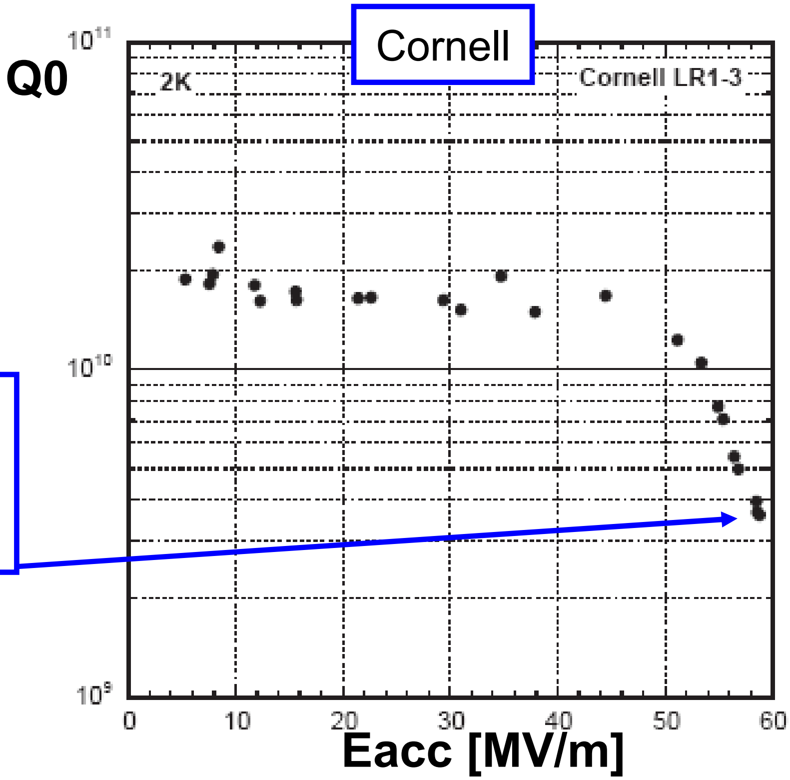
- Investigating fundamental changes to cavities
  - Fabrication, e.g., hydroforming
    - Remove equator weld as source of impurities or defects or inclusions
    - Intriguing results from one hydroformed cavity at DESY
      - 3 3-cell units; 2 iris welds + beampipes
      - Eacc=30.3 MV/m, limited by quench, no FE
  - Material
    - Large-grain, single-grain (DESY, JLab, KEK)
      - Anticipate reduced manufacturing & processing cost
      - Smooth surfaces with BCP only (no EP)
    - Atomic layer deposition (ANL, JLab, IIT, etc.)
      - Increase RF breakdown magnetic field of superconducting cavities by multilayer coating of alternating insulating layers and thin SC layers
      - Flow gas through cavity forming chemical bond with Nb surface
      - Chemical bond cannot flake off
  - Shape (continued next slide…)
    - improve Eacc/Hpeak

Alternative Shapes ≳50 MV/m

Tesla-shape cavity for comparison

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

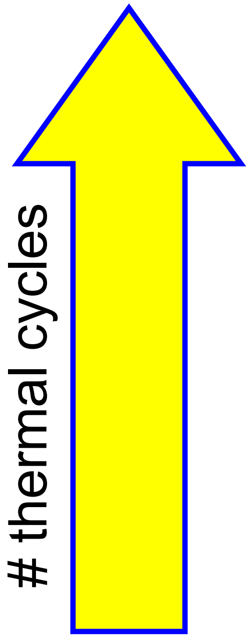
Ichiro shape



- ❑Single-cell Ichiro-shape record is 53.5 MV/m [KEK Saito]
  - ❑46.7 +- 1.9 MV/m with optimized surface treatment parameters
- ❑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)

Understanding Cavity Behavior

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

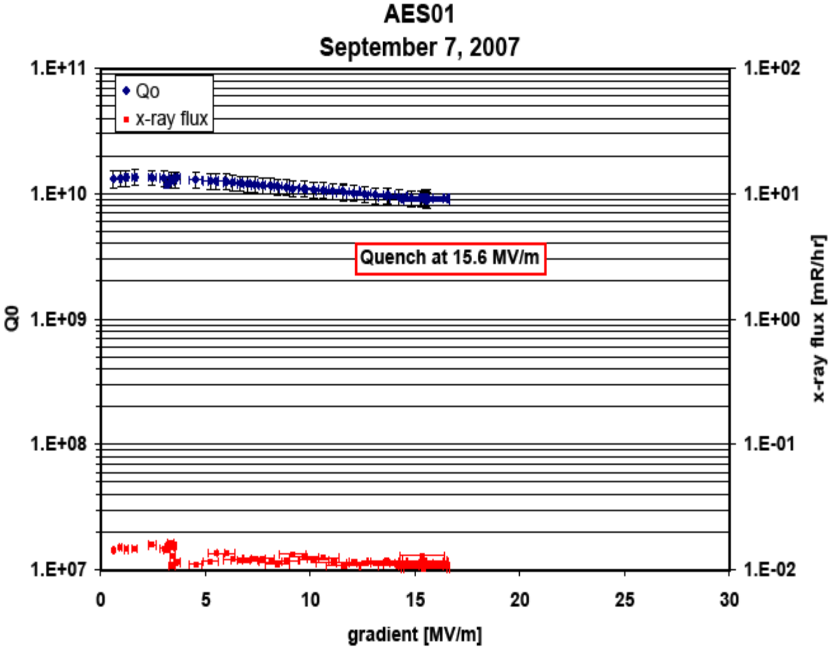


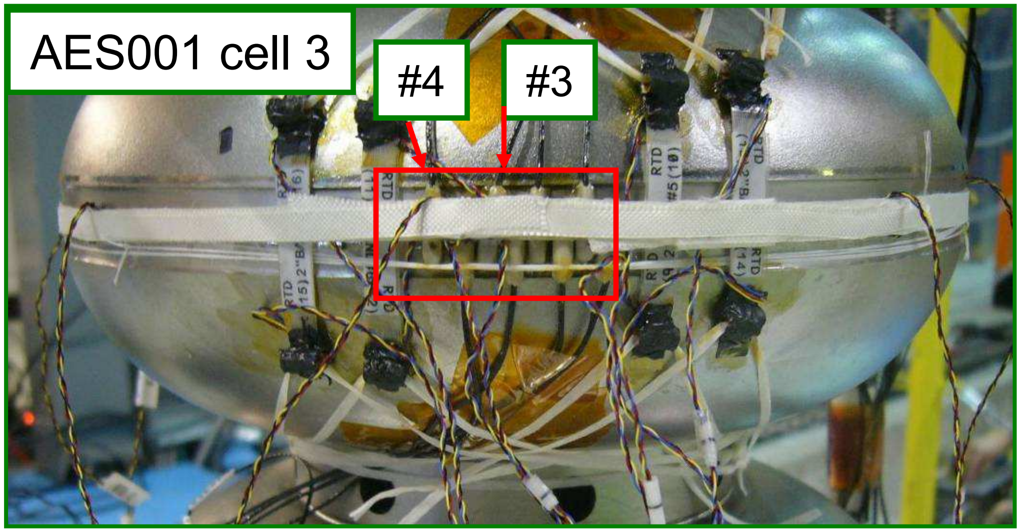
- Individual Cernox thermal sensors (FNAL)
- 2-cell Allen-Bradley temperature map (JLab)
- 9-cell T-map under development (LANL, FNAL)
  Second sound sensors (Cornell)

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

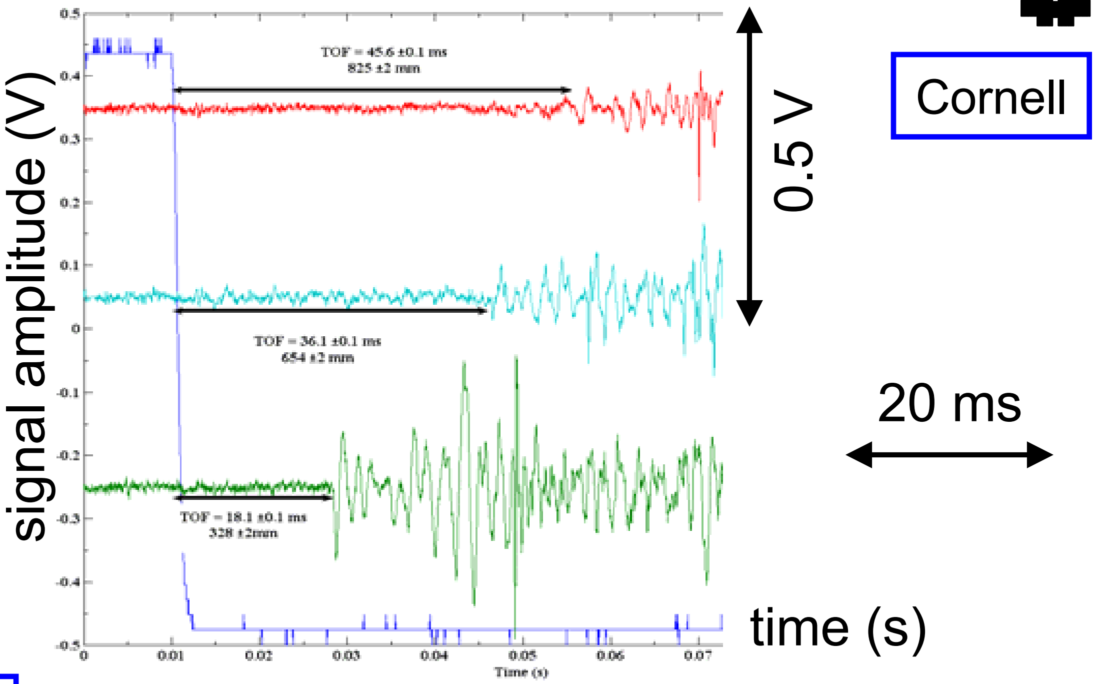




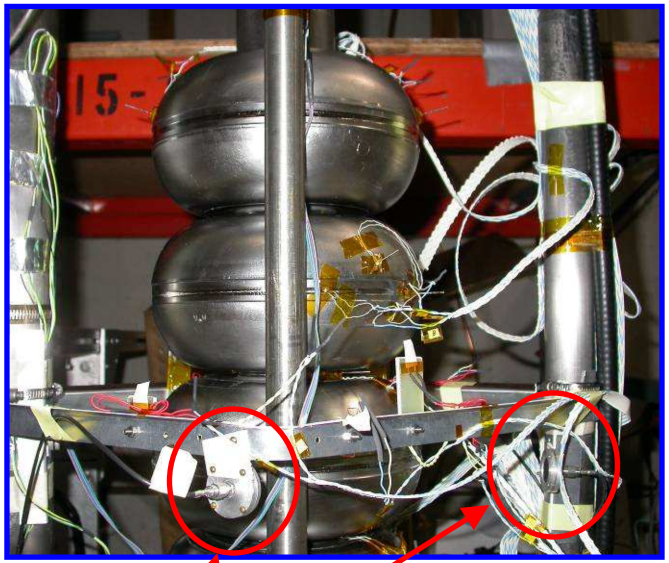
2- and 9-cell T-mapping

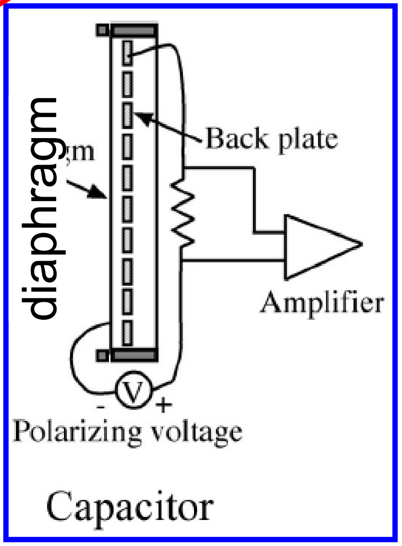
- 2-cell T-map
  - JLab using Allen-Bradley sensors
  - Requires two cooldowns, first with mode measurements
- 9-cell T-map
  - LANL using Allen-Bradley sensors and cold multiplexing
    - Promising preliminary results
  - FNAL using diodes
    - System under development
  - Could use on every test to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

Quench location with 2nd Sound



Cornell

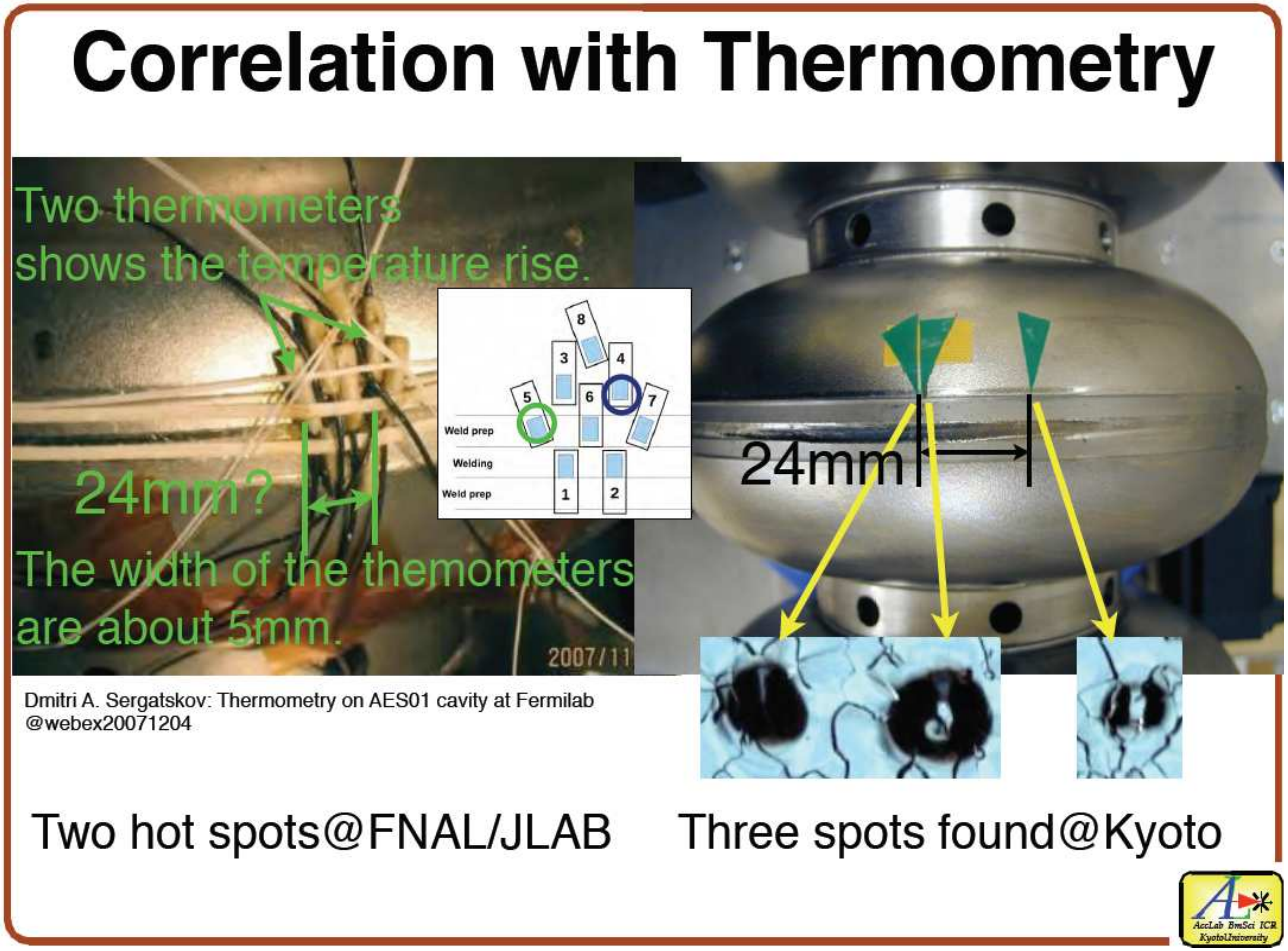




Capacitor

- ❑ 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

Two thermometers shows the temperature rise.

24mm?

The width of the themometers are about 5mm.

2007/11

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

24mm

Two hot spots@FNAL/JLAB

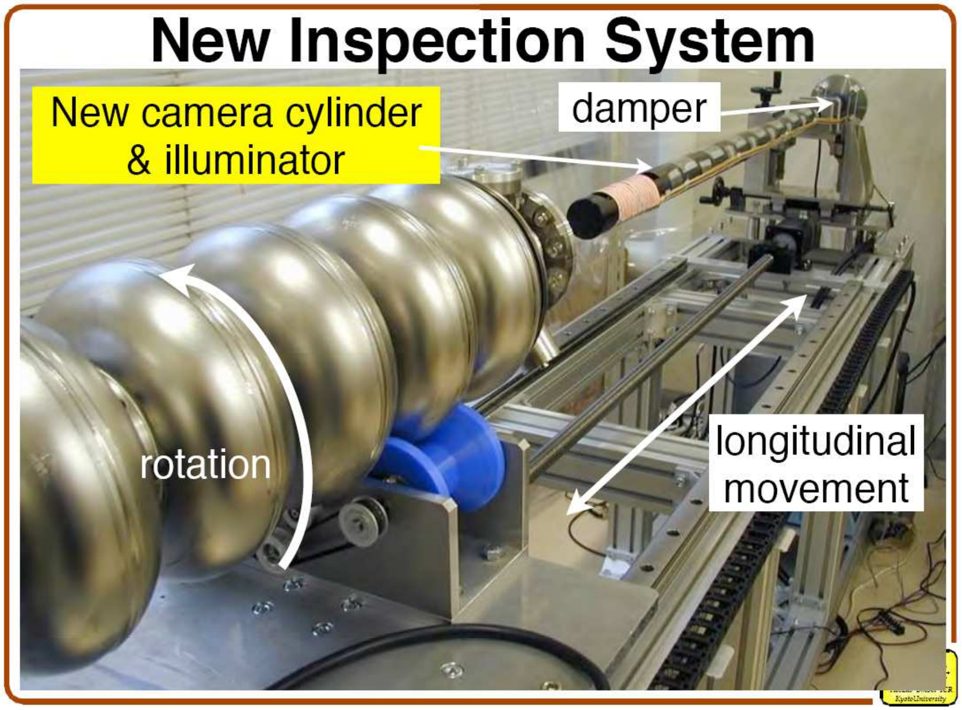
Three spots found@Kyoto

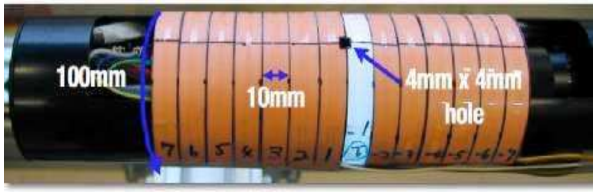
Clever lighting technique and excellent spatial resolution 7 um/pixel

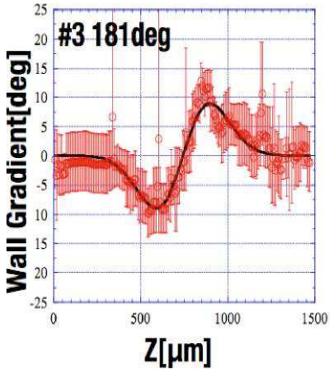
Kyoto U./KEK

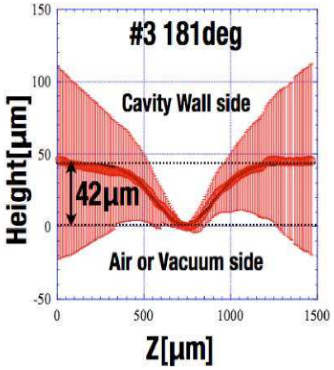
Optical Cavity Inspection

Kyoto U./KEK







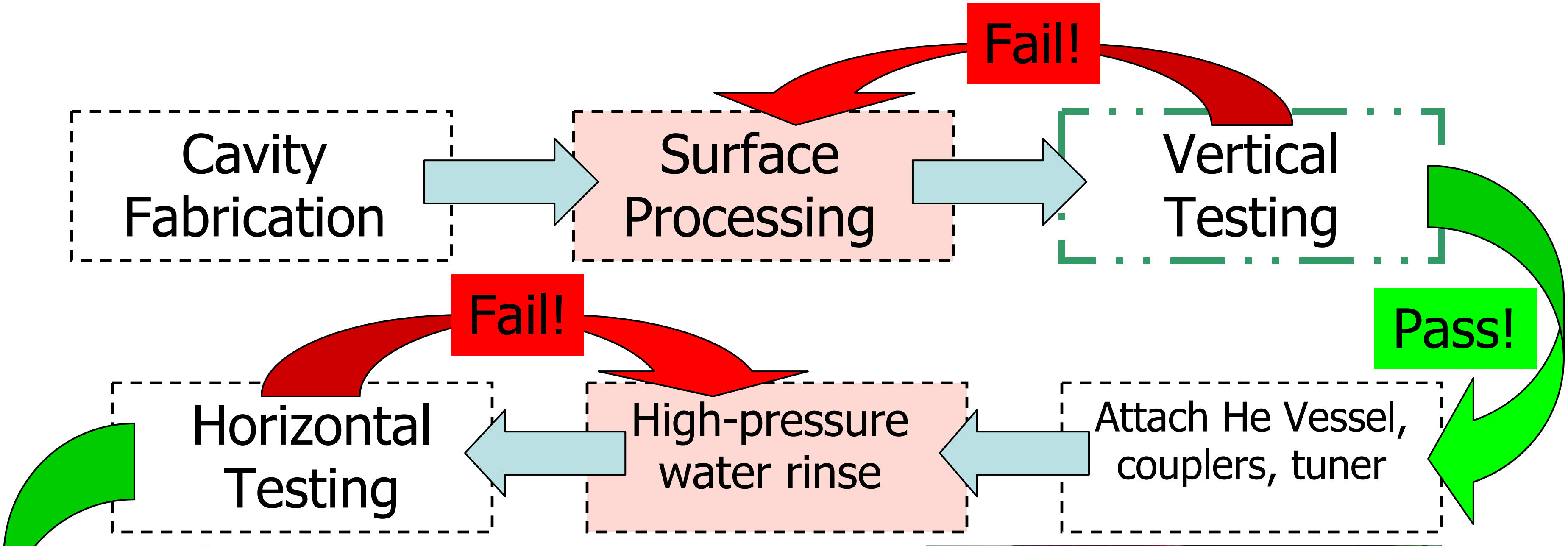


- ❑ Illumination by electroluminescent strips which can be turned off/on individually: shadows can be analyzed for 3D defect mapping (pit vs. bump) [bump is shown]
- ❑ Camera is inserted into cavity
- ❑ Digital images studied by a person – needs automation
- ❑ Many defects on several cavities now found,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

Key FNAL SCRF Program Goals

- Achievement of high gradients with high yields for future accelerators
  - Materials/fabrication/processing R&D
  - Testing, possibly with diagnostics
    - acceptance test and R&D tool
- Achievement of production rates needed to construct cryomodules for Project X and support ILC R&D

From Cavity to Accelerator



Cavity Fabrication

Surface Processing

Vertical Testing

Fail!

Pass!

Attach He Vessel, couplers, tuner

High-pressure water rinse

Horizontal Testing

Fail!

Pass!

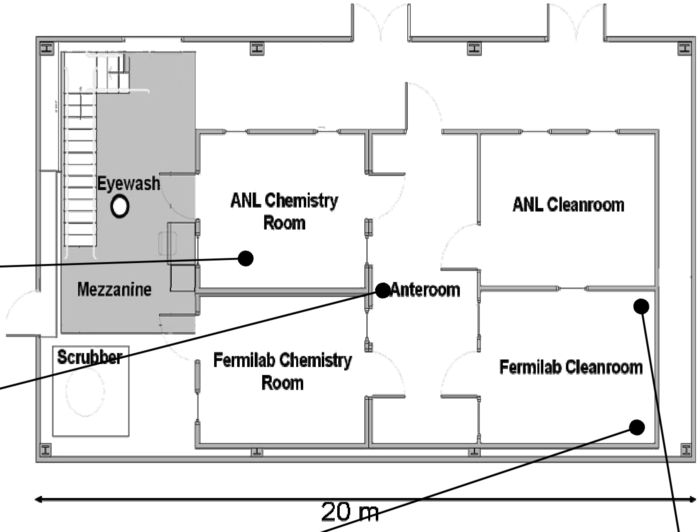
Cold String Assembly

cryomodule – an accelerator piece

Key FNAL SRF Infrastructure

- [Single-cell R&D]
- ANL/FNAL cavity processing facility
  - surface processing and assembly for vertical test
- Vertical test system
  - bare cavity CW low-power acceptance test
- Horizontal test system
  - dressed cavity pulsed high-power acceptance test
- Cryomodule assembly facility
  - put dressed cavities into a cryomodule
- Cryomodule test facility

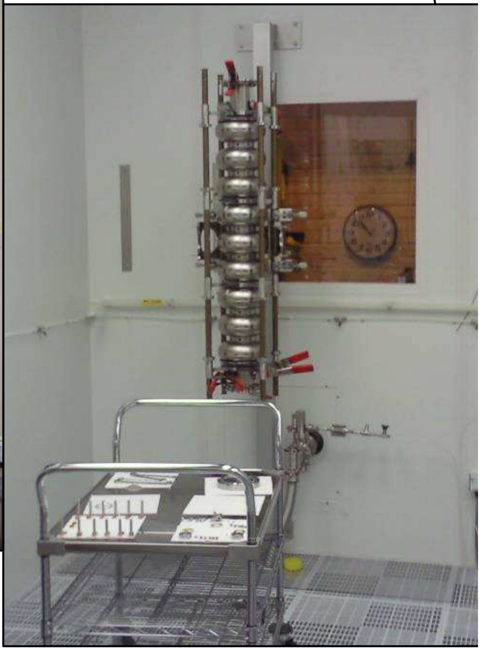
Argonne/Fermilab Cavity Processing Facility Operational



Electro-Polishing

Ultrasonic Degreasing

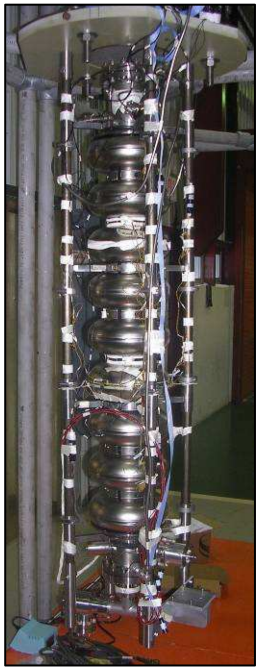
High-Pressure Rinsing

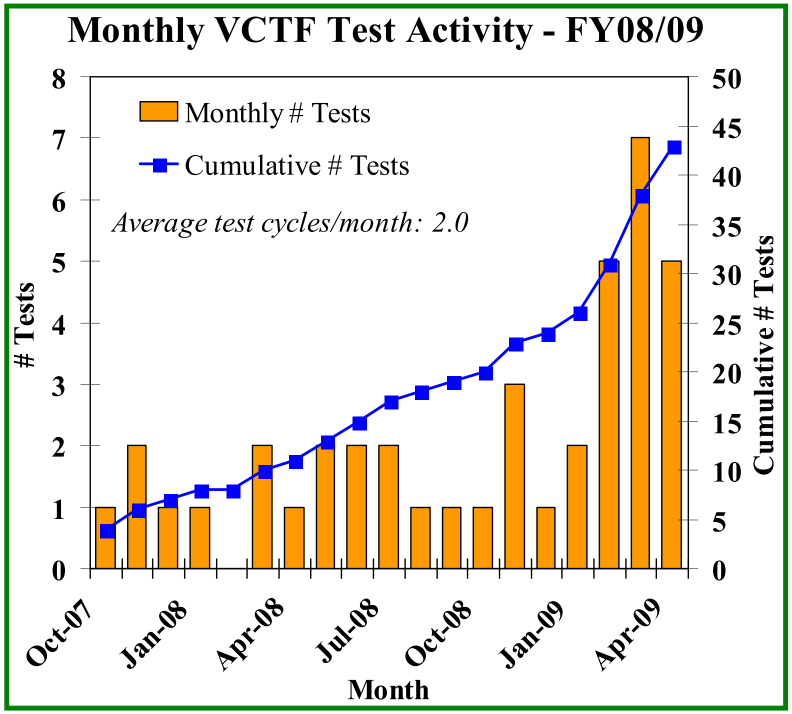


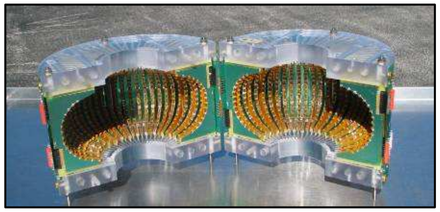
Assembly & Vacuum Leak Testing

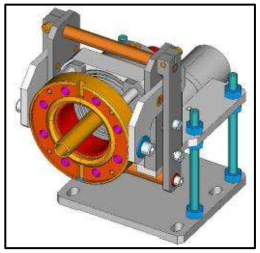
Fermilab Vertical Cavity Test Facility

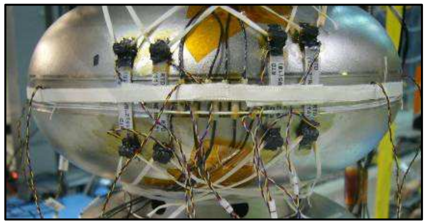
- >40 cavity tests in FY08/FY09, where “test” = cryogenic thermal cycle
  - 9-cell & single-cell 1.3 GHz elliptical cavities and 325 MHz HINS single-spoke resonators
  - instrumentation development, variable coupler, thermometry, cavity vacuum pump system, cavity vendor development
  - Many cavity tests dedicated to ANL/FNAL CPF commissioning
- Upgrades planned to increase cavity test throughput to >200 cavity tests/year by Oct 2011 to support projected PrX+ILC R&D



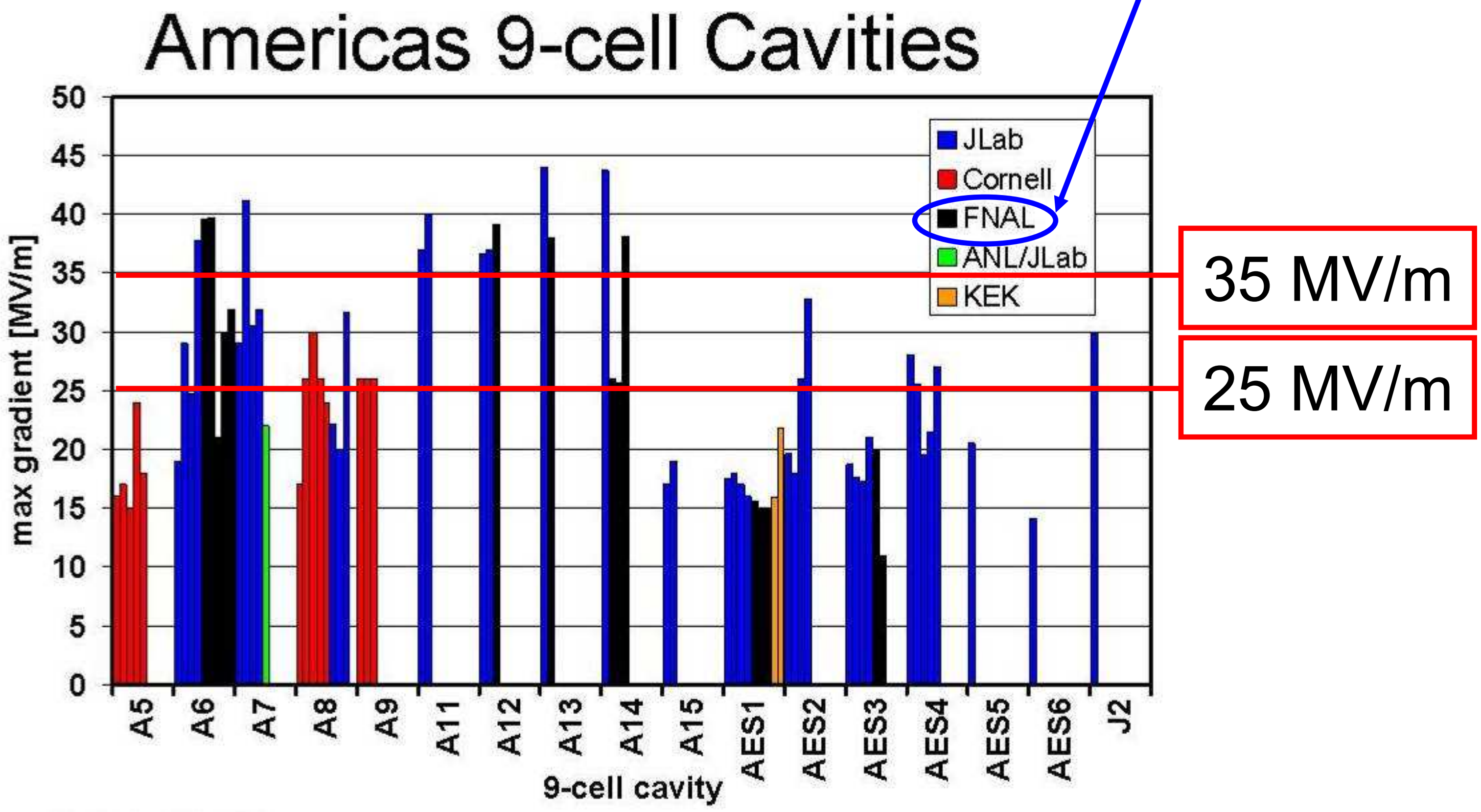








Fermilab 9-cell cavity tests



35 MV/m

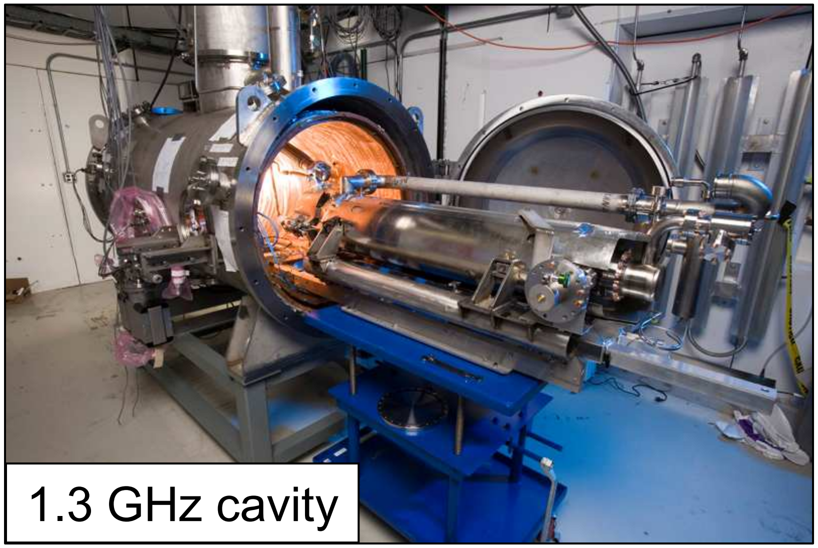
25 MV/m

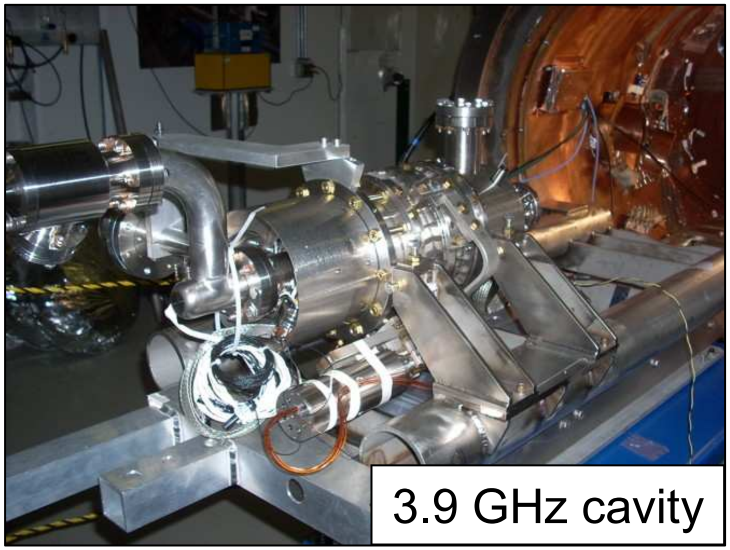
C.M. Ginsburg 2.June 2009

- VTS tests for: instrumentation development, cavity vendor development, ANL/FNAL cavity processing facility commissioning
- FNAL 9-cell tests done in strong collaboration with JLab/ANL
  - Most FNAL-tested cavities processed at JLab and tested without modification
  - Few FNAL tests of ANL processed/assembled cavities

Horizontal Test Stand operational

- Accomplishments
  - Commissioned for 1.3 and 3.9 GHz cavities
  - Four 3.9 GHz cavities tested in 2008 → installed in cryomodule for DESY
- Plan expanded capacity with addition of a second cryostat for PrX throughput requirements by 2012


1.3 GHz cavity


3.9 GHz cavity

Assembly Workflow @ CAF-MP9

Receive dressed Cavities

Receive peripheral parts

Assemble dressed Cavities to form a String in the **Cavity String Assembly Area** (Clean Room)

Install String Assembly to Cold Mass in the **Cold Mass Assembly Area**

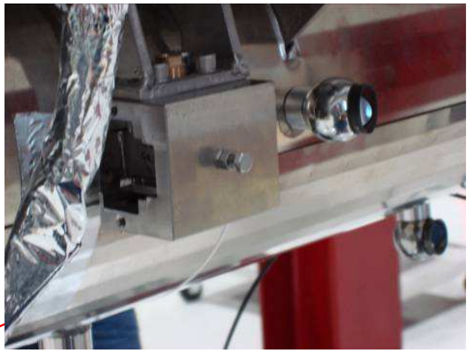
Transport the Cold Mass to **CAF-ICB**

Assembly Workflow @ CAF-ICB

Install the Cold Mass back to the Cold Mass Assembly Fixture in **Cold Mass Assembly Area**

⇩

Align Cavity String to the Cold Mass Support



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Install the String assembly with the cold mass into the Vacuum vessel in the **Vacuum Vessel Assembly** area

⇩

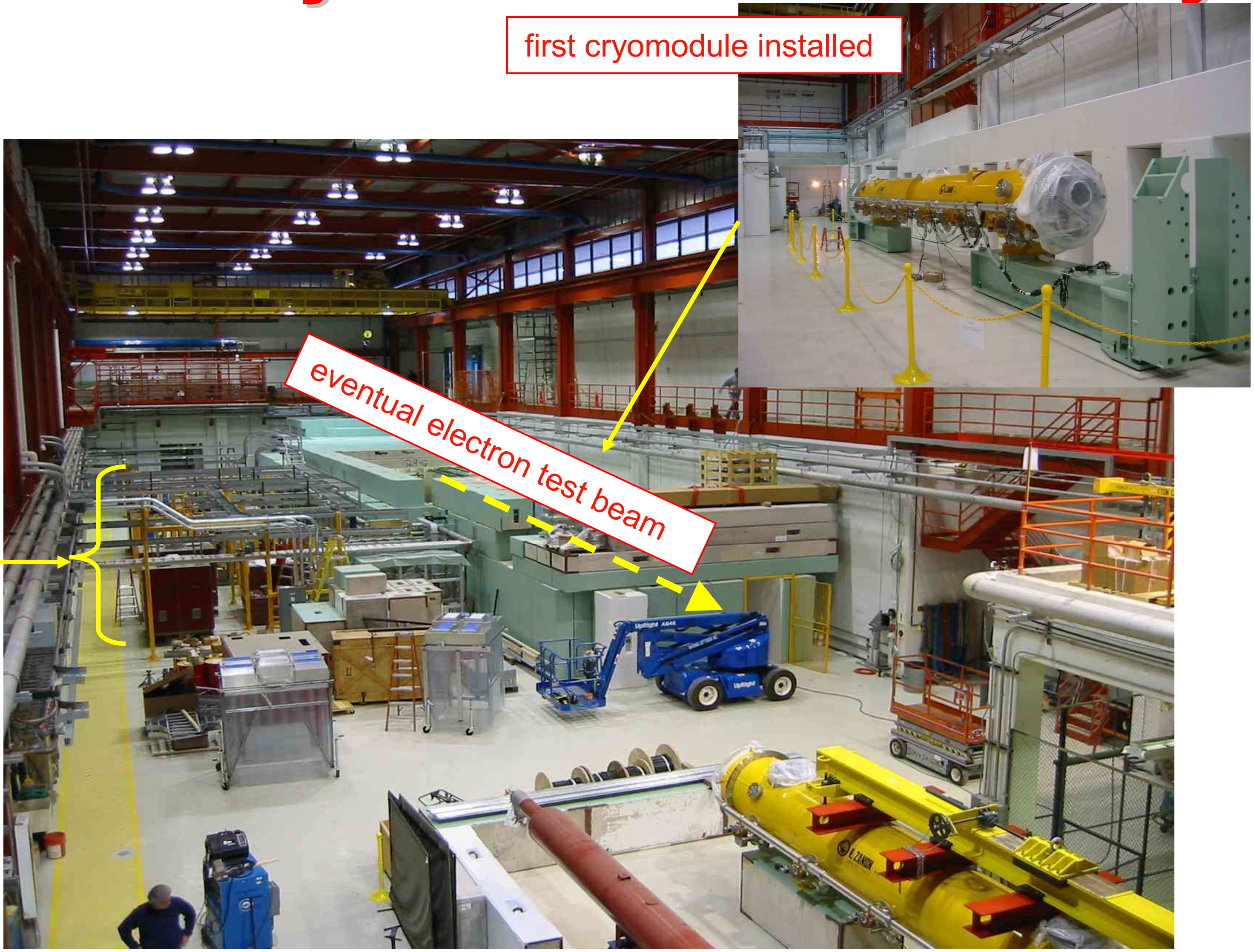
Ship Completed Cryomodule to **ILCTA-NML** for testing

NML Project Overview

- Overall Goal
  - Build an RF Unit Test Facility at the New Muon Lab building (NML)
    - RF unit = 3 cryomodules
    - 10-MW RF system
    - Electron beam with ILC parameters (3.2 nC/bunch @3 MHz, up to 3000 bunches @ 5Hz, 300-µm rms bunch length)
    - Various Project-X parameters will also be tested with beam
  - Provide a state-of-the-art facility for conducting advanced accelerator R&D for future accelerator components

- Current Phase (FY07 - FY09)
  - Prepare facility for testing first cryomodule *without* beam
    - Infrastructure, RF power, cryogenics
    - Install first cryomodule and Capture Cavity-2 (CC2), cooldown, and RF test

NML cryomodule test facility



first cryomodule installed

eventual electron test beam

RF Systems

Outlook

- Rich SRF cavity R&D activity in the quest for highest gradients, field-emission free performance, and reduced cost
  - Very high gradients have been measured in bare niobium superconducting RF 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
  - Achieving predictability at highest gradients on the large scale required for future accelerators is a challenge

- Fermilab SRF infrastructure substantially complete
  - One 1.3 GHz cryomodule using DESY dressed cavities already built, ready for testing
  - Most key infrastructure components are in place; final commissioning underway