Raising the Bar on Superconducting Niobium Cavity Production, Processing, and Performance

Zachary A. Conway
Cornell University/ANL

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Contributors:

E. Kako (KEK)	G. Wu (FNAL)
D. Reschke (DESY)	W.D. Moeller (DESY)
C. Ginzburg (FNAL)	M.P. Kelly (ANL)
F. Eozenou (CEA-Saclay)	H. Hayano (KEK)
A. Yamamoto (KEK)	M. Ross (FNAL)

Purpose

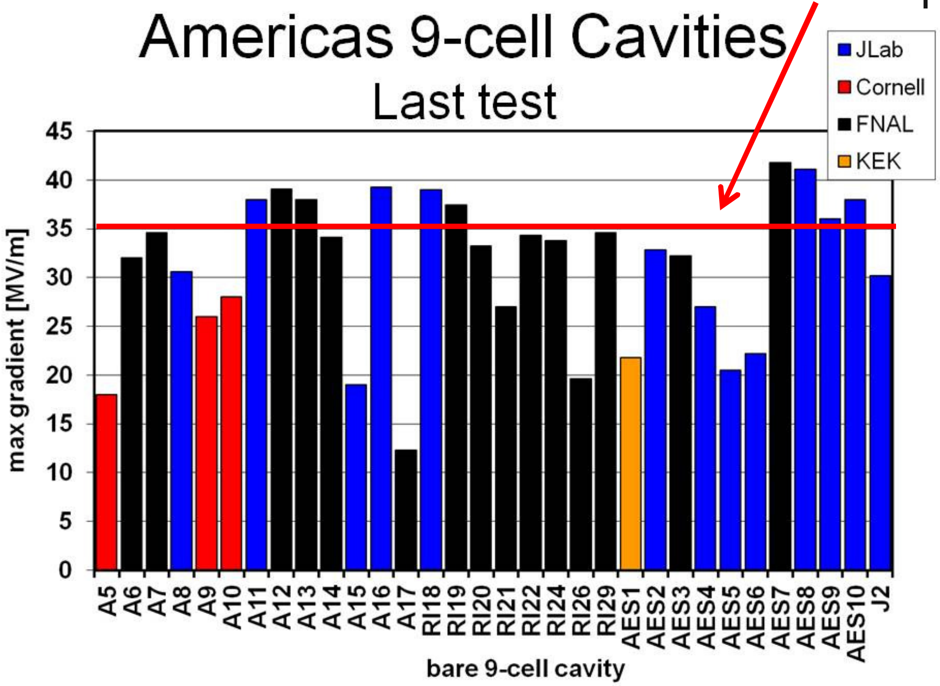
- High Accelerating Gradients Shorten Accelerators

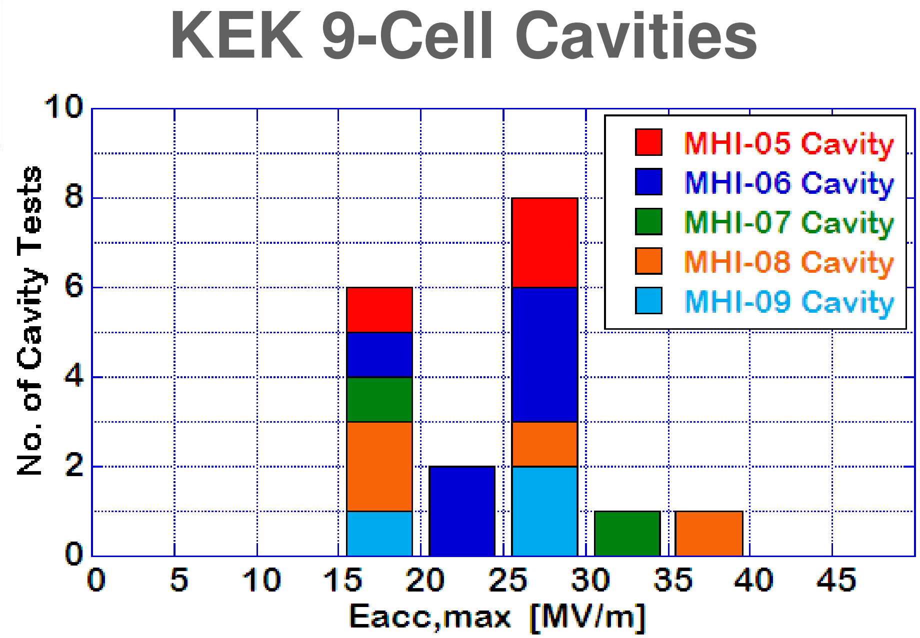
- High Accelerating Gradients Reduce the Accelerator Price
    - Fewer Cavities
    - Fewer Cryomodules
    - Shorter Accelerator
    - etc

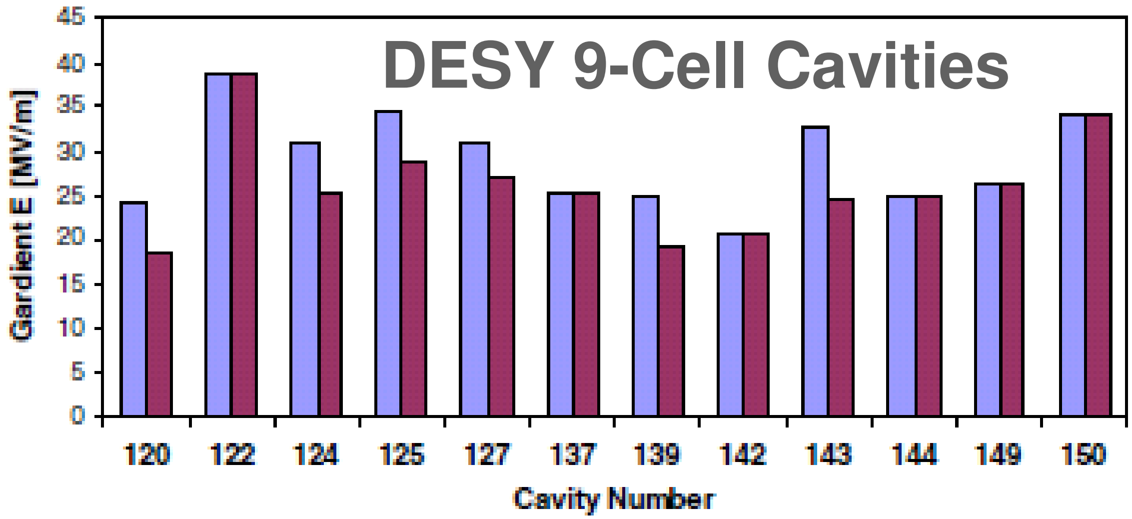
- This talk will focus on the on-going international effort to increase the maximum achievable gradient in accelerator cavities fabricated from niobium. To do this I will be focusing on the ILC S0 development work.

Where are we today?

Need to achieve > 35 MV/m in vertical ILC acceptance tests

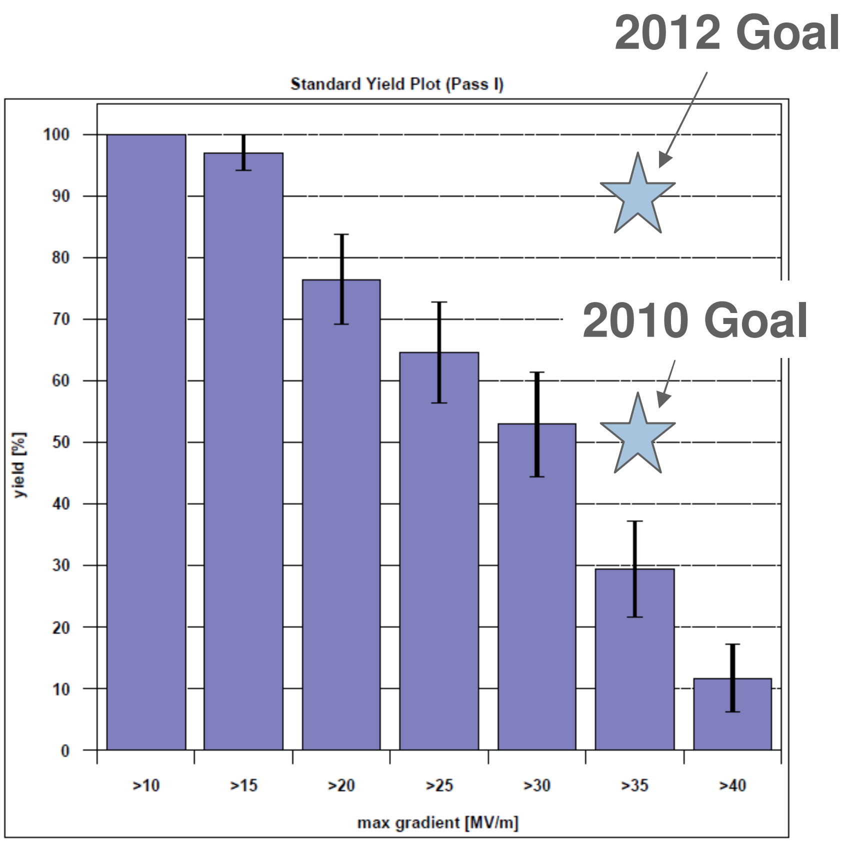


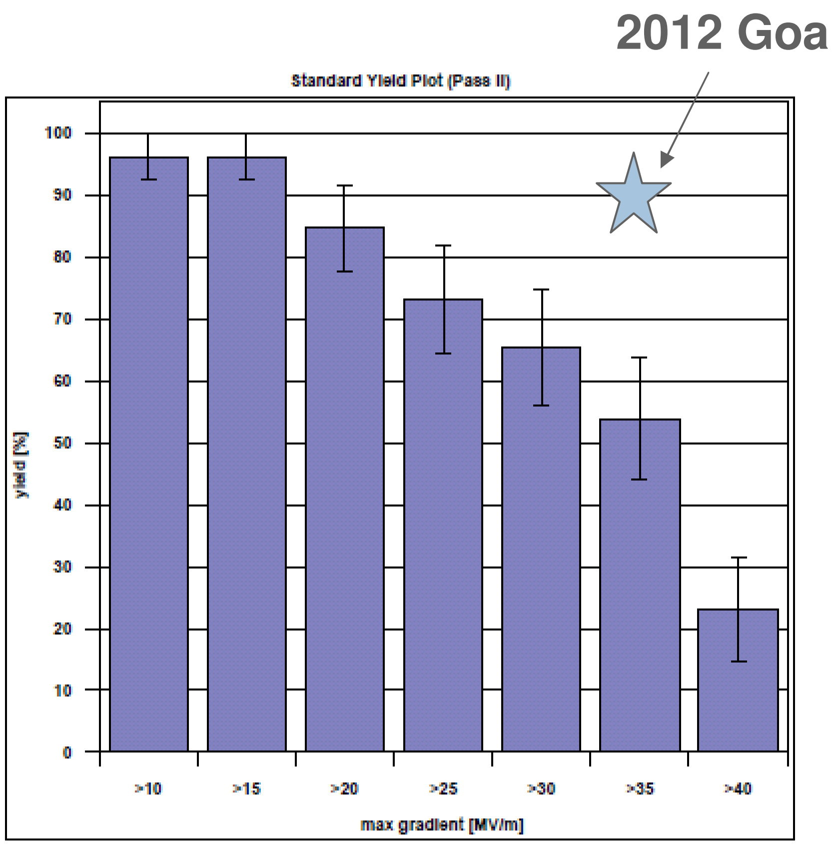




C. Ginsburg et al., THP026
E. Kako et al., TUP082
D. Reschke, PRST-AB, 071001

Where are we today?

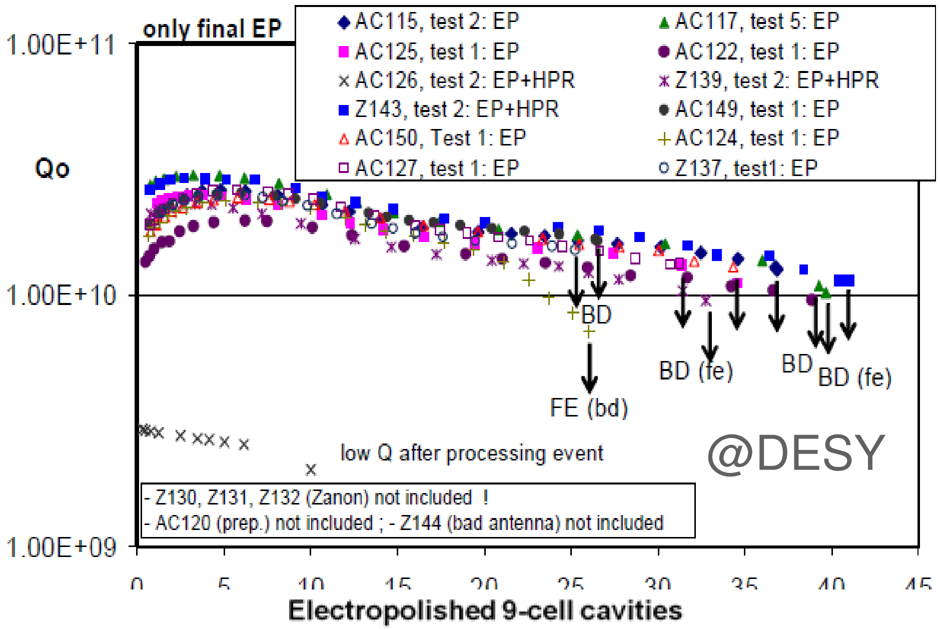


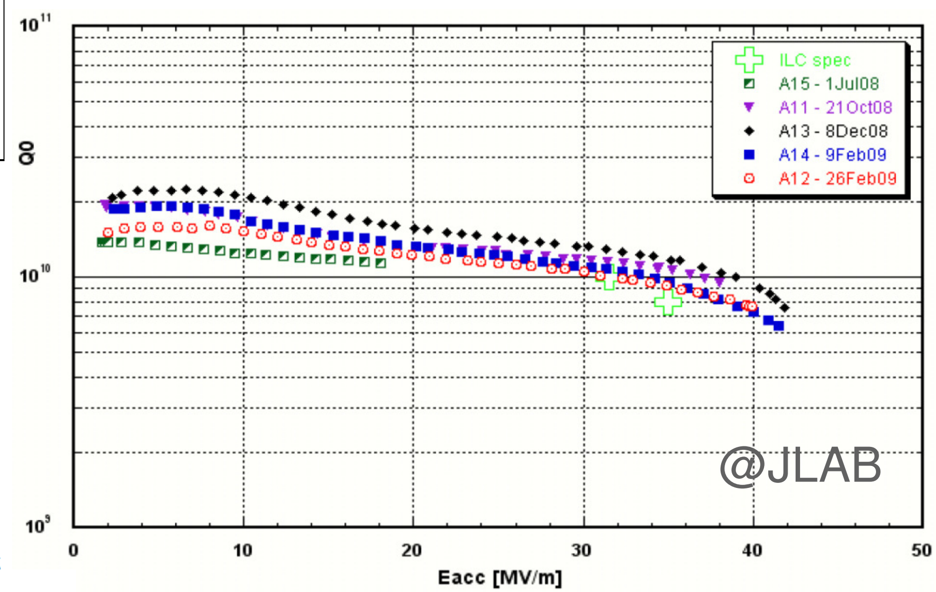


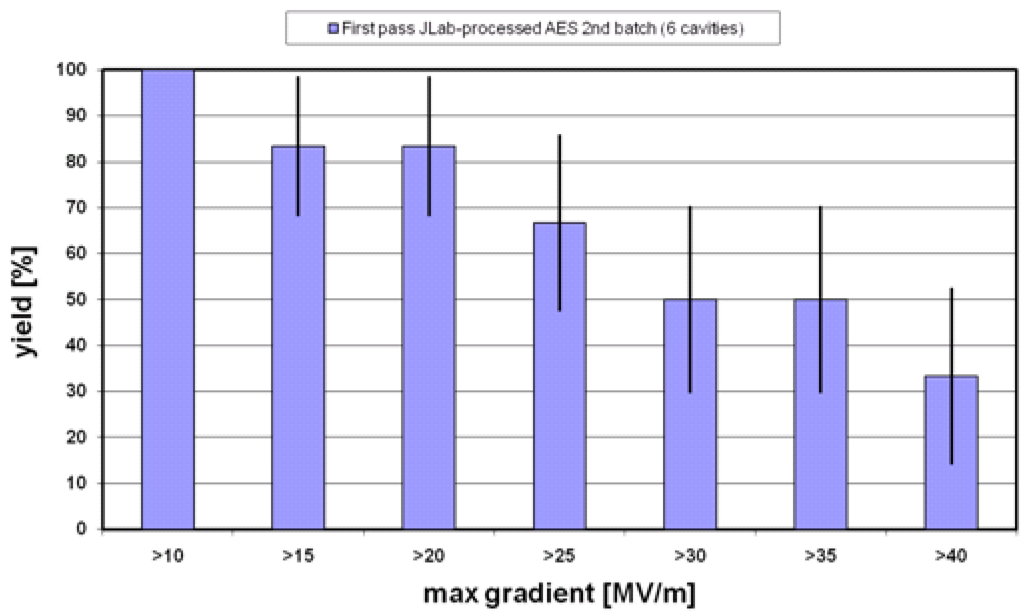
World Wide Yield Curves
Data Integrated Over The Past
~3 years

http://tesla-new.desy.de/cavity_database/ilc_data/

Where do we want to be?







- Several facilities have produced high-performance niobium cavities (E_{acc} > 35 MV/m during vertical testing).
  - DESY
  - JLAB
  - FNAL/ANL
  - KEK
- How do we produce a high performance cavity each and every time?

R. Geng, SRF2009, TUPPO015
D. Reschke et al., SRF2009, TUPPO051
C. Ginsburg et al., THP026

Outline

- Significant amounts of effort are being directed toward reliably producing cavities which perform at the theoretical limit of niobium
  - Improving and changing cavity polishing techniques
  - Locating and repairing performance limiting defects

- The rest of this presentation will focus on these two topics

Cavity Polishing

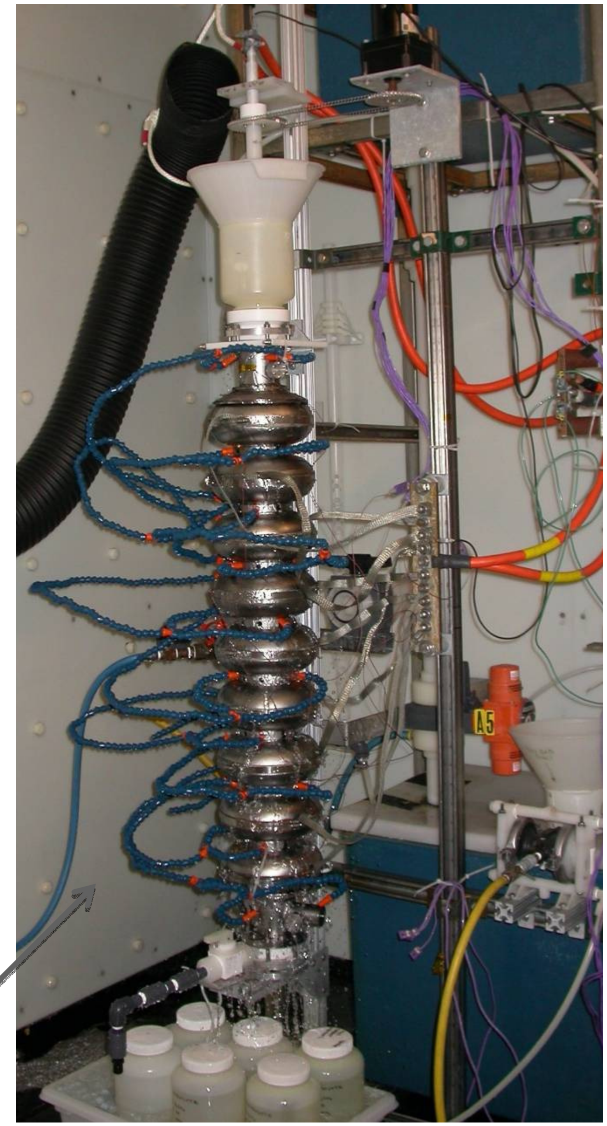
- All cavities must be polished (even after repairs) and the high-gradient standard is currently horizontal electropolishing (initially developed at KEK, Saito et al., SRF1989, Pg. 635).

- There has been a lot of recent work focused on improving the process and on developing alternative techniques which may simplify the process. This will be the focus of the next 5 slides
  - Alternative techniques (Cornell, JLAB, CEA-Saclay)
  - Basic R&D

Cavity Polishing

Horizontal Electropolish
ANL/FNAL Joint Processing Center

M.P. Kelly et al, LINAC08, Pg. 839, THP026



Cornell Vertical Electropolish
Also being developed at JLAB

Cavity Polishing

- There is interest in developing an alternative geometry to the KEK developed horizontal electropolishing technique (Saito et al., SRF1989, Pg. 635).
- Instead of polishing the cavity horizontally polish it vertically.
- Vertical has several advantages:
  - Eliminates rotary acid seals and acid flow valves
  - Eliminates sliding electrical contact
  - Eliminates the cavity vertical/horizontal position control fixtures
  - Simplifies the acid plumbing/containment, avoids circulation pumps
  - The outside of the cavity is actively cooled, providing better temperature control of the polishing reaction.
  - Soft cavities without stiffening rings do not sag
  - Acid is not reused but goes only once through the cavity
  - Lower cost, particularly for a large number of systems
  - Reduces the risk for sulphur and oxide contamination build-up in parts (These contaminants can eventually find their way to the cavity to cause field emission or rf losses.)
- But acid must be changed more frequently (after about 100 microns of material removal).
- For large amounts (e.g. 200 microns) of material removal the cavity orientation must be flipped after half the material removal to avoid up-down asymmetry.
- Vertical electropolishing has produced several high performance single cell cavities, a 5-cell cavity, and individual cells in 9-cell cavities.

Cavity Polishing

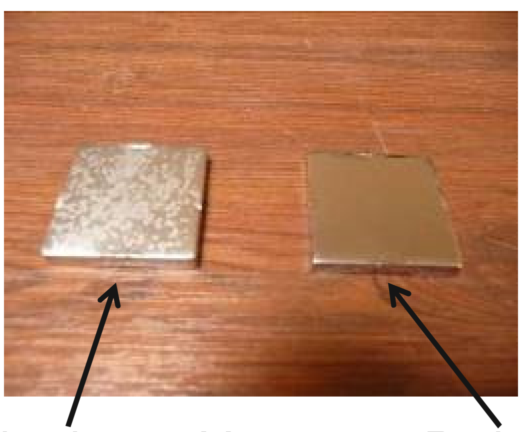
- The chemistry which takes place on the cavity surface during polishing is still not understood.

- A lot of work is going into understanding the process.

- Several important results have been obtained and will be the focus of the next 3 slides
  - Sulfur is thought to be a major contributor to field emission. It is hard to reduce sulfur contamination of cavity surfaces when there is so much of it in the electropolishing electrolyte.
  - The temperature of the electropolish procedure needs to be reduced
  - Electropolishing is not 100% effective at removing pit-like defects

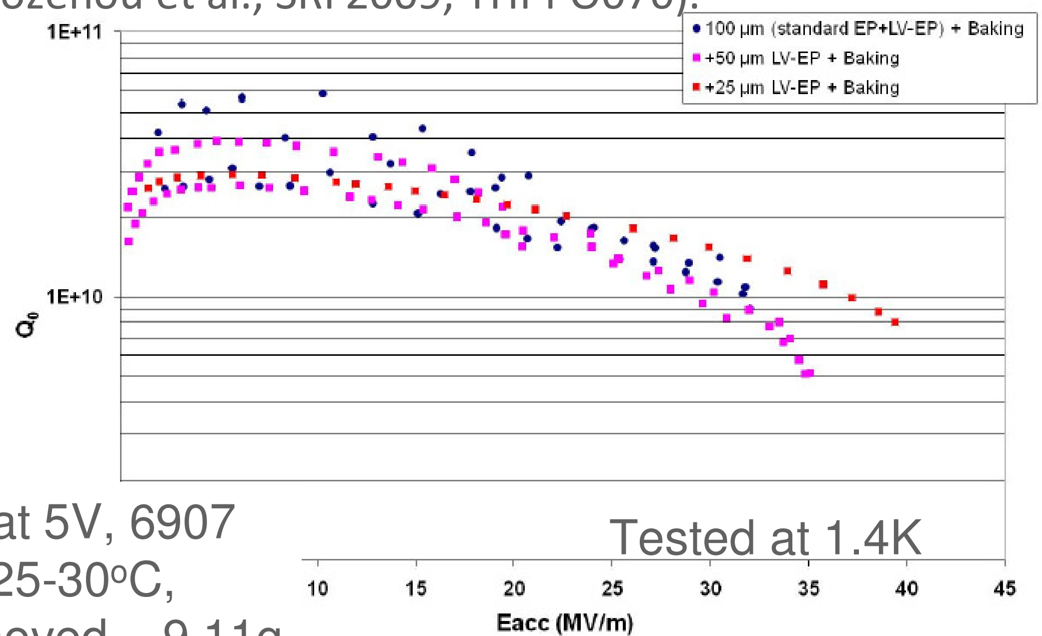
Cavity Polishing

- Sulfur comes from the electropolishing process which uses a high-concentration of sulfuric acid.
- Sulfur left on the cavity surface may cause field emission which increases the cavity RF losses and may limit the maximum achievable fields (Saito, SRF2007, TU202)
- To mitigate this effect ultrasonic degreasing and ethanol rinsing are employed (Geng et al., SRF2007, WEP28; Detlef Resche and Lutz Lilje, SRF2007, TUP77)
- Alternatively, less sulfur is generated during the polishing procedure if a lower process voltage is employed (Eozenou et al., SRF2009, THPPO070).



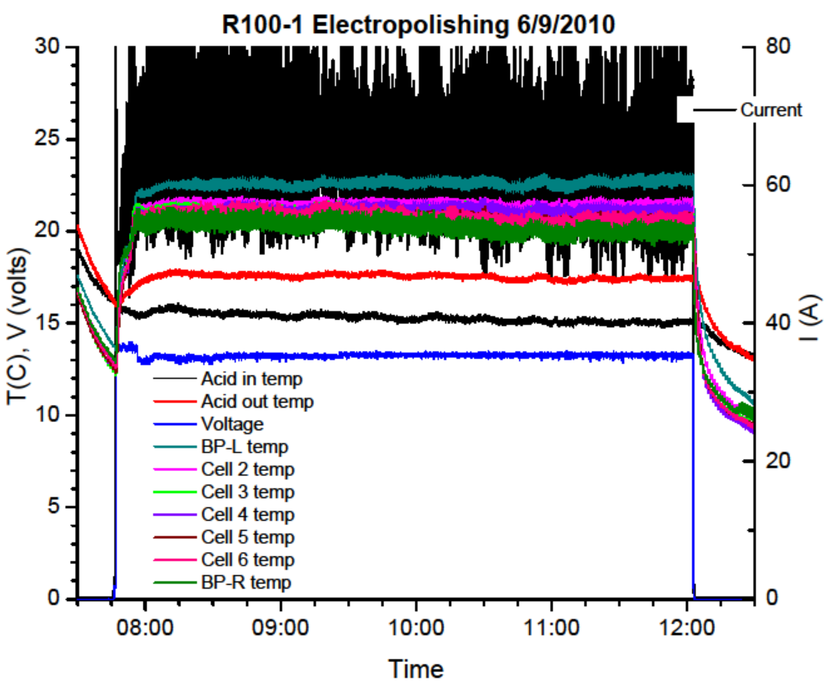
Polished at 20V, 4041 minutes, 25-30°C, mass removed = 9.18g

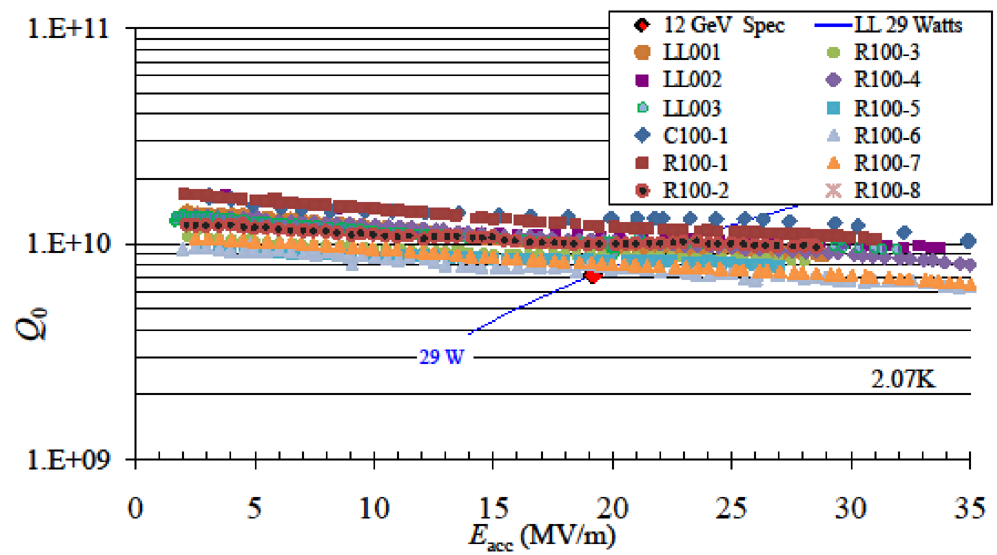
Polished at 5V, 6907 minutes, 25-30°C, mass removed = 9.11g



Cavity Polishing

- Reducing the polishing temperature reduces parasitic etching. (Reese et al., These Proceedings, THP010)
- By reducing the polishing temperature you may increase your chances of producing a high-performance cavity without defects.





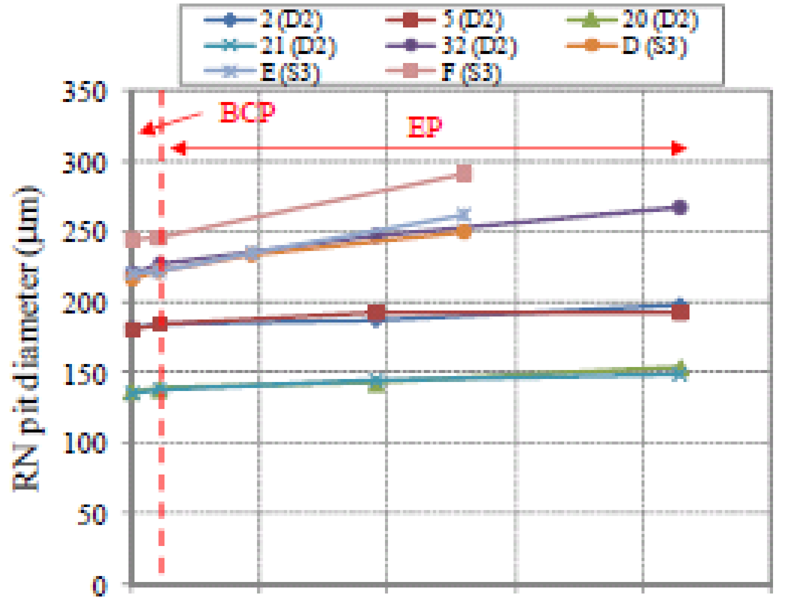
Defect Location and Repair

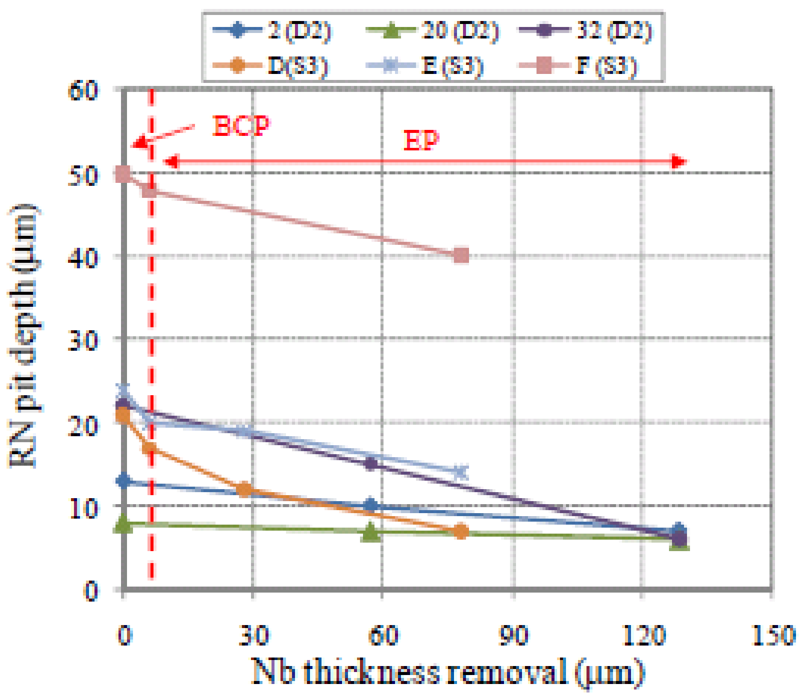
- Electropolishing is not 100% effective at removing pit-like defects because grain boundaries and defect locations are the preferential places for etching. (Delayen et al., SRF2001, PT014H.;Tian et al., SRF2009, TUPPO081; P. Michelato et al., SRF2009, THPPO091; T. Saeki, SRF2009, THPPO086, Genfa Wu of FNAL in private communication)
  - The next slide will give more details

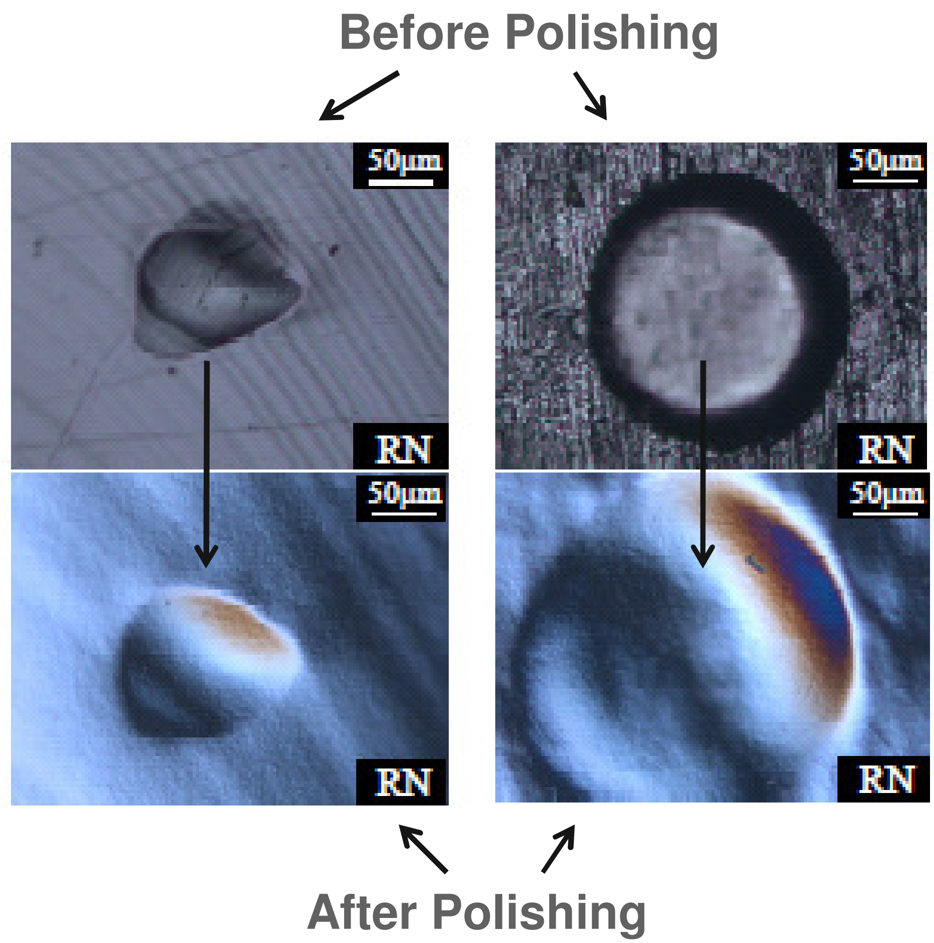
- Need alternative techniques to repair pit-like defects.
  - Enables us to repair cavities which do not meet performance specifications after initial processing/testing
  - Enables someone to determine if repairing/reprocessing a defective cavity is worthwhile.

- For example, the ILC needs this to reach the Technical Design Phase goal of 90% of produced cavities acheiving E_{acc} > 35 MV/m right now.

Not All Defects Can Be Polished/Etched Away…







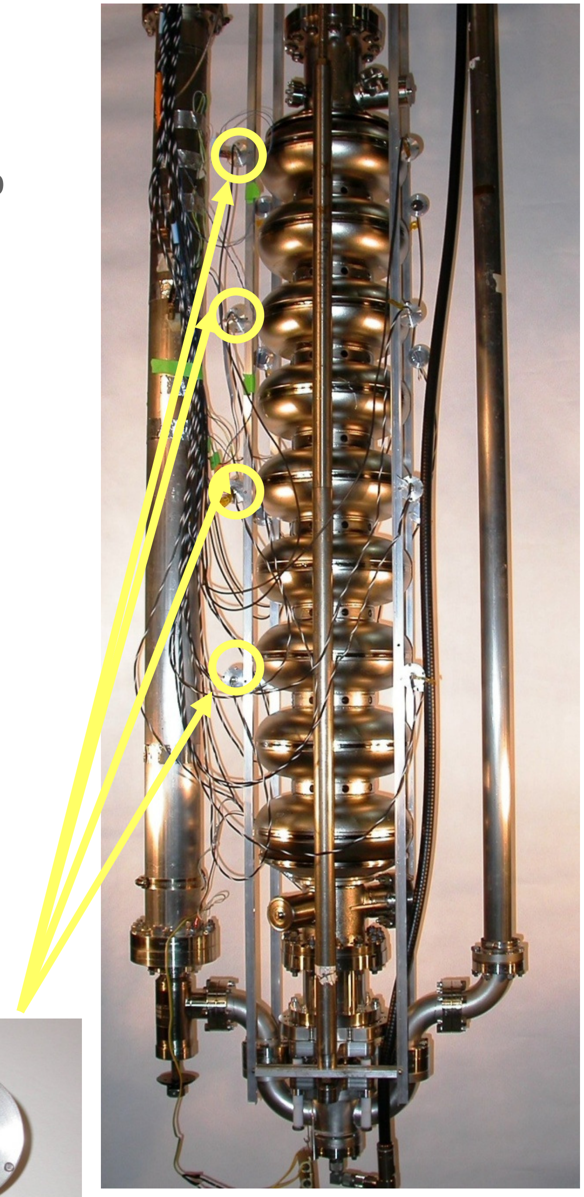
P. Michelato et al., INFN-Milano

Defect Location and Repair

- When a cavity does not perform with E_{acc} > 35 MV/m we ask why?
- Typically, this is due to either field emission or the cavity quenches at a defect.
  - FE has been suppressed by high pressure water rinsing, ultraasonic degreasing (Geng et al., SRF2007, WEP28) and by ethanol rinsing (Detlef Resche and Lutz Lilje, SRF2007, TUP77)
  - Defects need to be repaired
- To locate these defects we employ either thermometry or second sound wave detection
- Once we know where the defect is we can optically inspect and characterize the defect
- Once we know the character of the defect we can proceed with one of several repair techniques

Defect Location

- Thermometry (JLAB, Cornell, DESY, CERN, KEK)
  - Provides a full temperature map at varying field levels
  - Required for a detailed understanding of the cavity performance
  - Requires 100s-1000s of temperature transducers
- Second Sound (ANL, Cornell, DESY, FNAL, JLAB, CERN, KEK)
  - Only requires a few transducers (simple and fast)
  - Only locates the quench-spot
  - Convenient for the rapid testing/repair of cavities



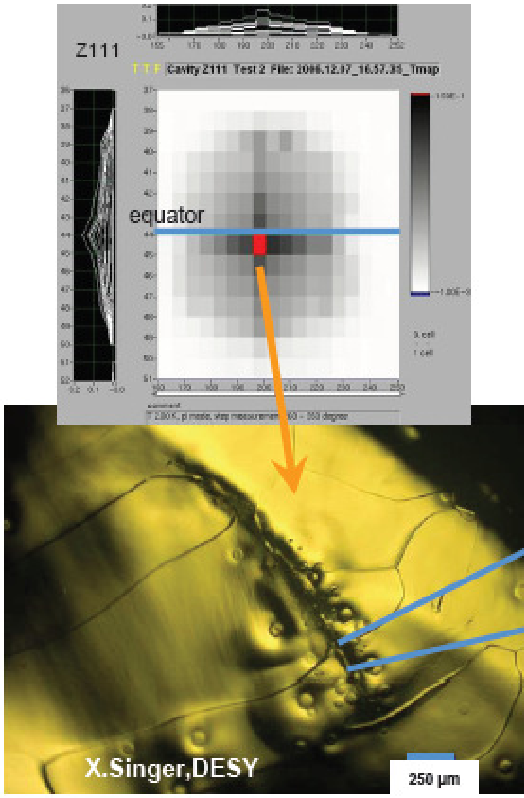
R. Geng, SRF2009, TUPPO015
Z.A. Conway et al., SRF 2009, TUOAAU05

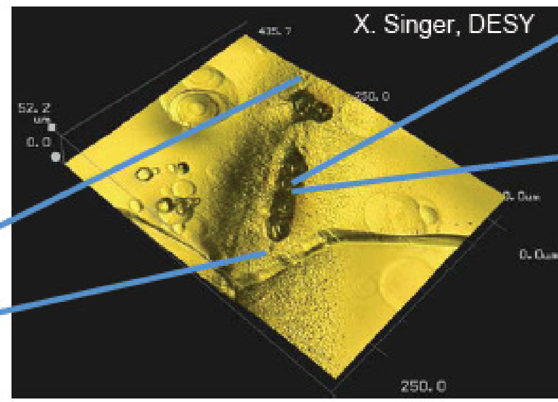
Defect Location

Cell 6, Quench at 16 MV/m on equator

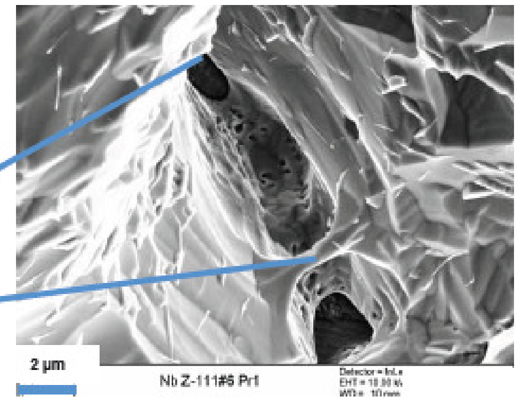
@DESY

- Holes with sharp edges along the grain boundaries in the equator weld
- Pits around the holes.

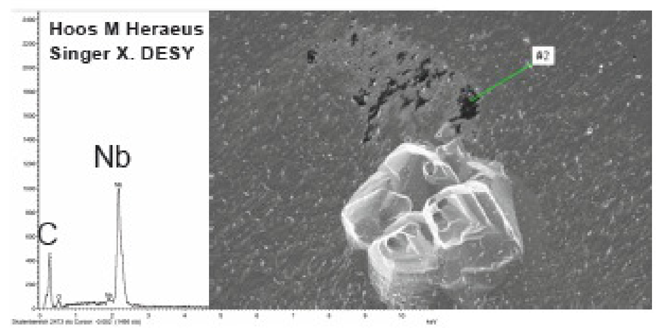




SEM



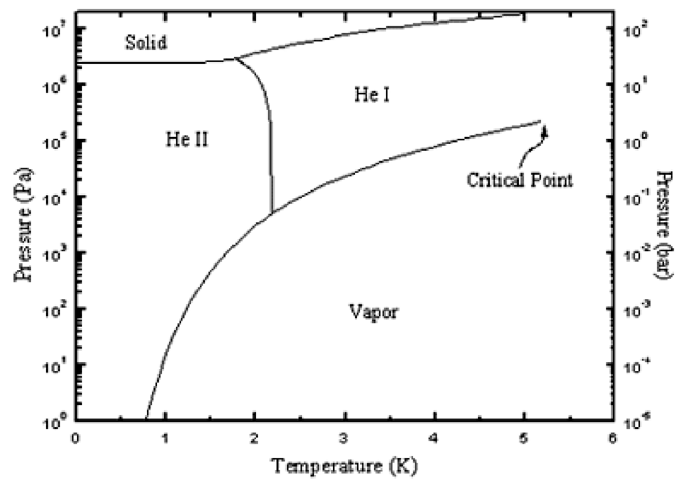
- Auger analysis: no foreign material
- EDX analysis: increased content of carbon in black spots

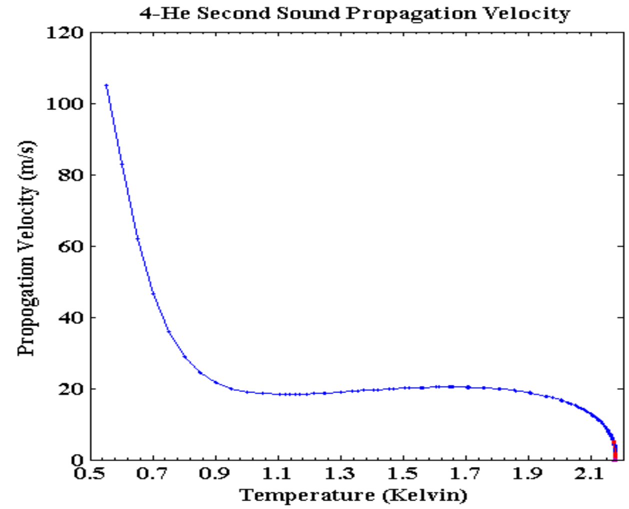


W.D. Moeller, SRF2009, tuoaau04

Defect Location

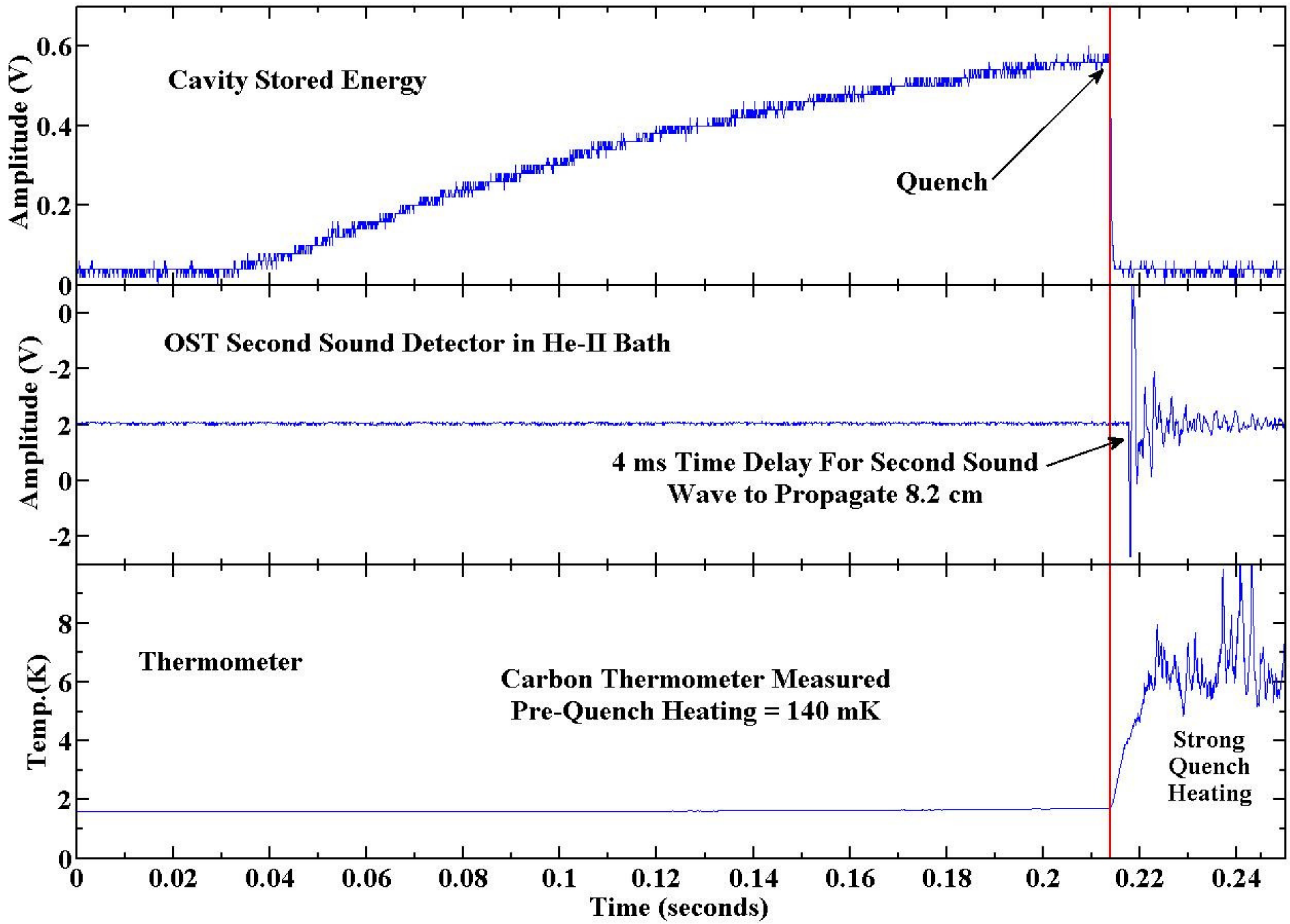
- Wave Propagation in LHe
  - Normal P-ρ wave = 1st Sound, with velocity = ~ 220 m/s
  - Below the lambda point a T-S wave can propagate = 2nd Sound, with velocity = ~ 20 m/s
  - Superfluid ρ-T wave = 4th Sound, with velocity = ~ 200 m/s
- The detector response time can be around 0.1 msec or less which implies a spatial uncertainty of 2 to 4 mm if the start time (initiation of cavity RF field collapse) can be determined to the same timing uncertainty
- Typically, one can localize the quench location to <2cm



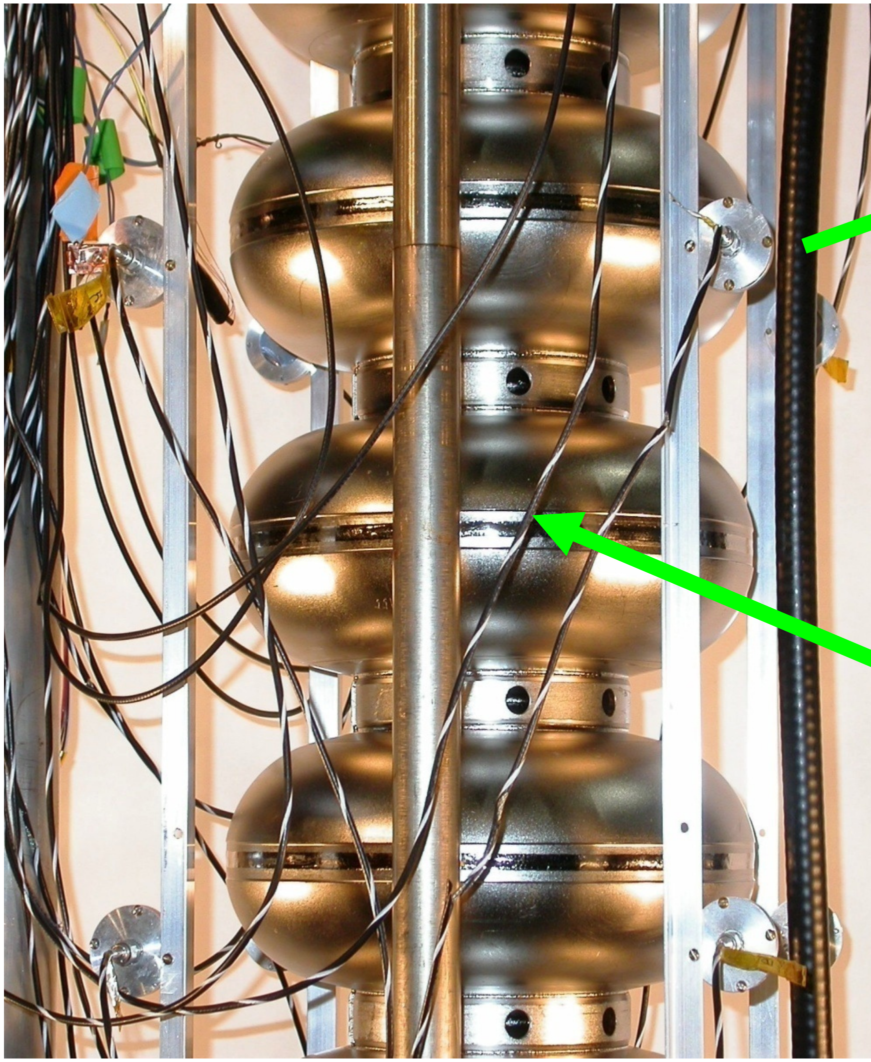


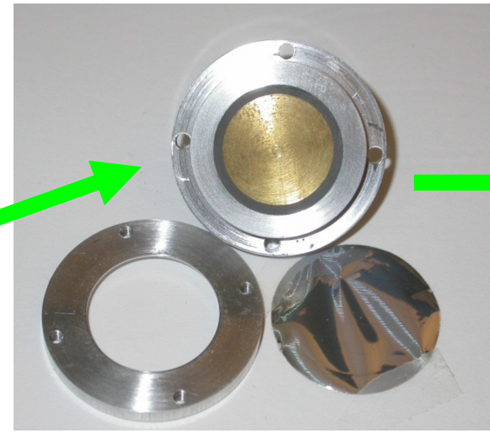
Russel J. Donnelly and Carlo F. Barenghi, "The Observed Properties of Liquid Helium at the Saturated Vapor Pressure." J. of Phys. Chem. Ref. Data, vol. 7, Issue 6, Pg. 1217 (1998).

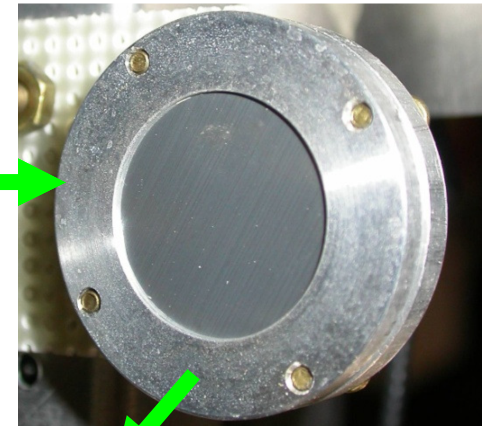
Defect Location

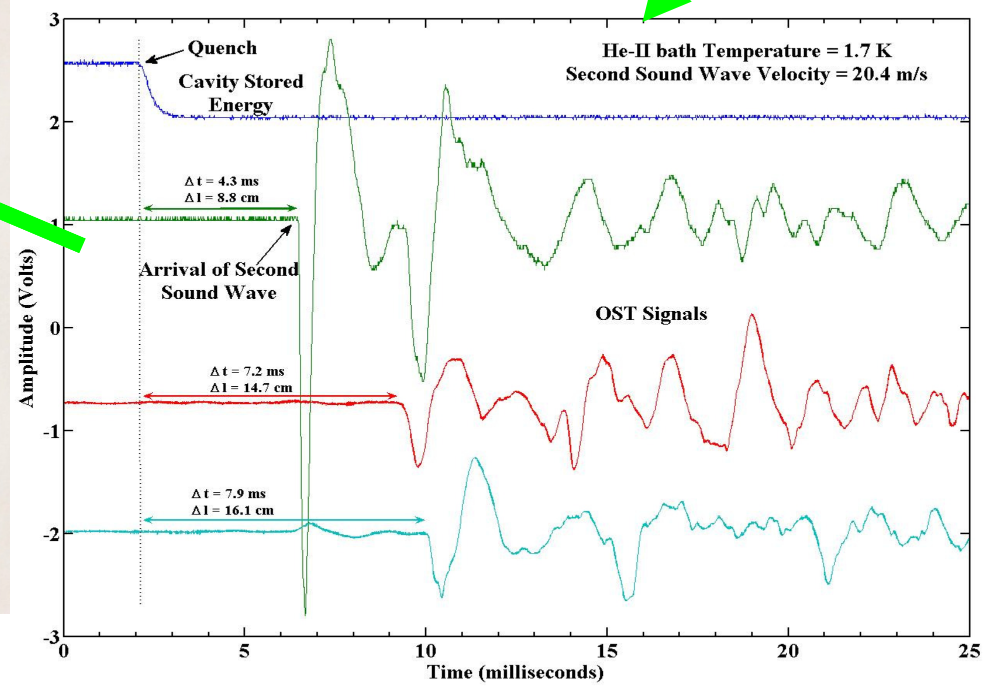


Defect Location





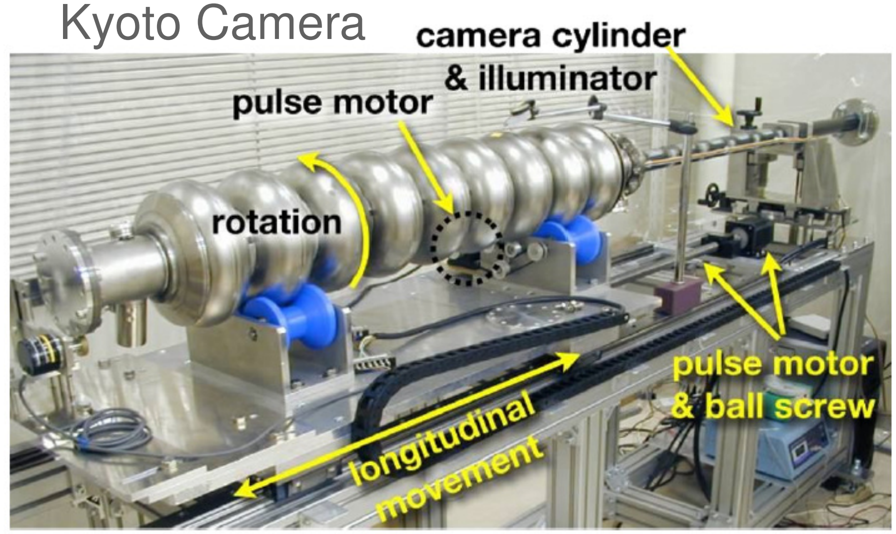


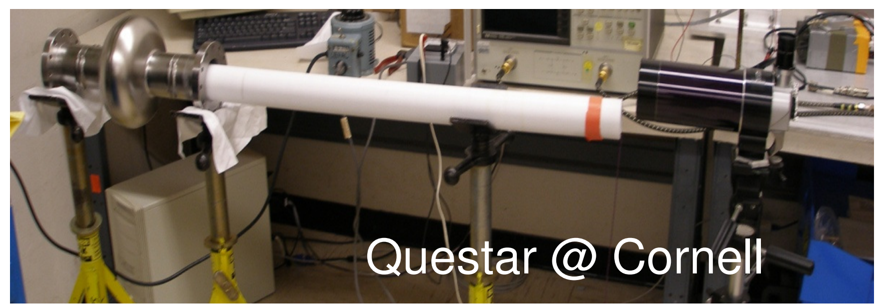


Optical Inspection

- Once you know where the defect is, go look at it and decide how best to proceed with fixing the defect
- There are several options available for rapid non-destructive optical inspection:
  - The KEK/Kyoto Camera (FNAL, DESY, JLAB, KEK) (Iwashita et al., PRST-AB 11, 093501 2008)
  - Questar Long-Distance Microscopes (Cornell, JLAB) (Conway et al., SRF 2009, TUOAAU05; Geng, SRF 2009, TUPPO015)
- In addition, high resolution imaging techniques provide more detailed information. e.g. defect molding, SEM, and profilometry

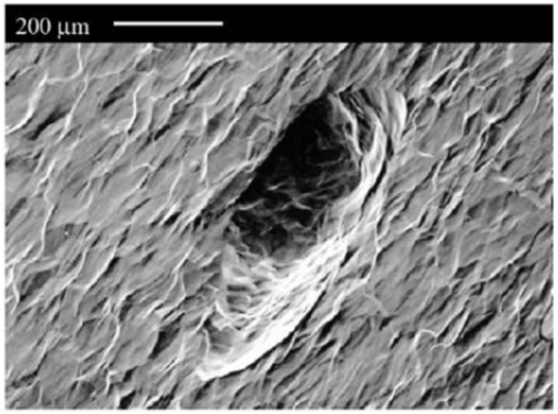
Kyoto Camera

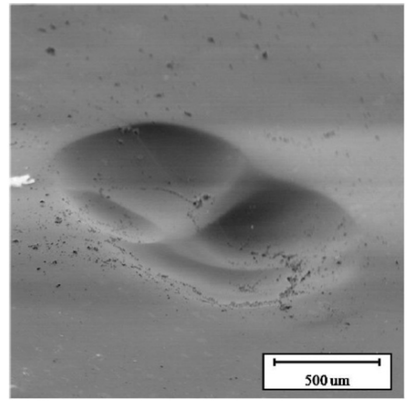


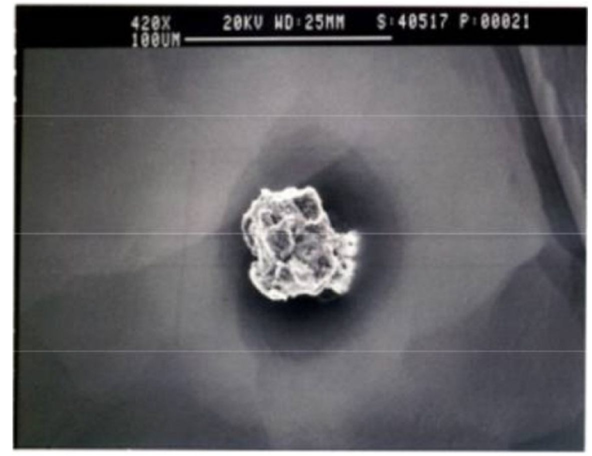


Optical Inspection

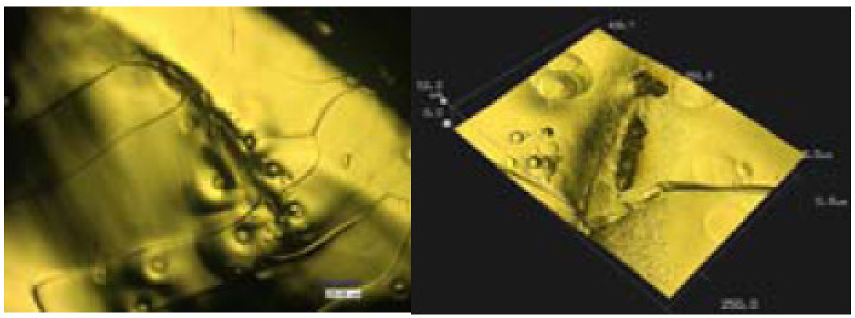
Cornell

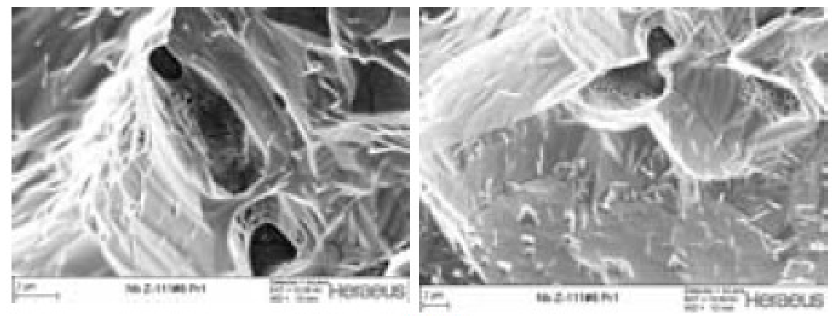






DESY

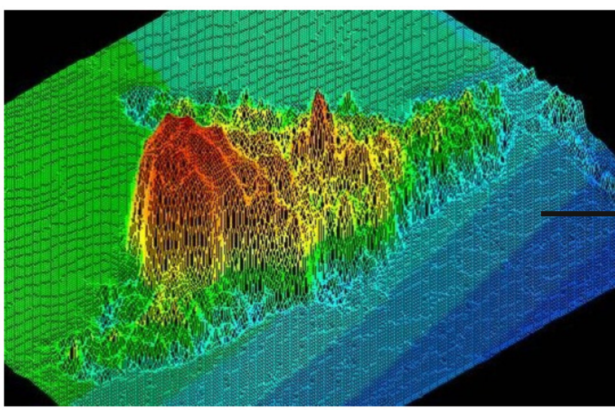


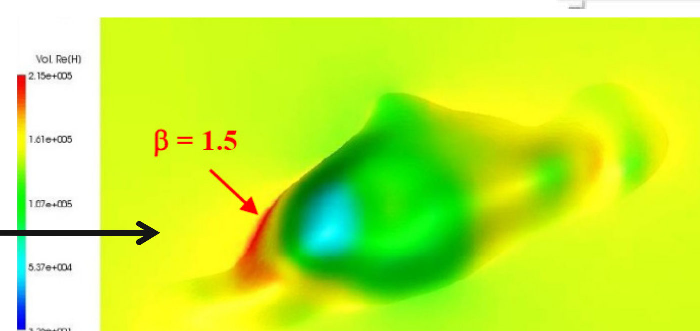


3D Microscopy

SEM

KEK





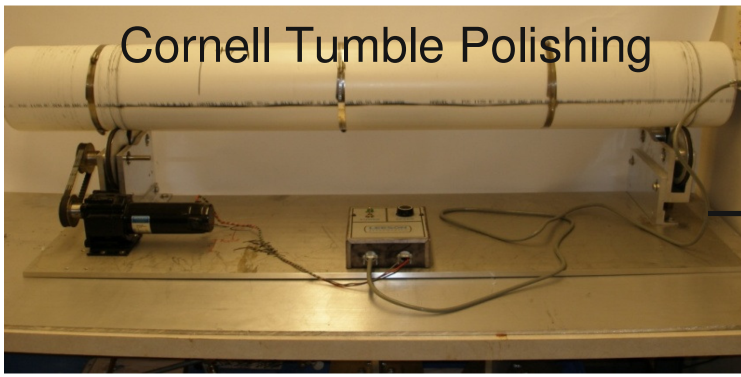
Y. Morozumi, IPAC10, WEPEC020
W. Singer et al., IPAC10, WEPEC007
Y. Xie et al., SRF2009, TUPPO049

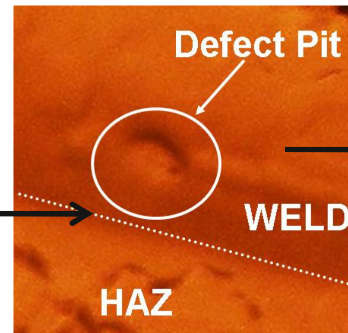
Cavity Repair Techniques

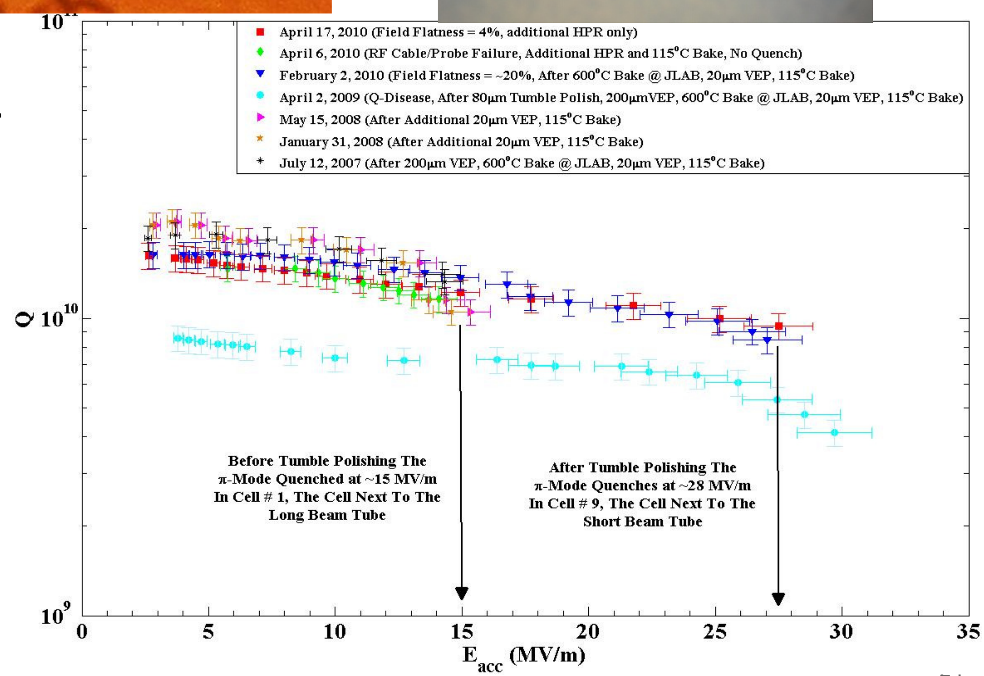
- Tumble Polishing or Centrifugal Barrel Polishing
- Electron Beam Melting (Geng, SRF 2009, TUPPO015)
- Laser Melting
- Local Grinding

Tumble/Centrifugal Polishing

- Centrifugal barrel polishing has been ongoing at KEK and DESY since the mid-1990's.
- Recently, it was demonstrated that tumble polishing can be employed to fix pit-like defects, E_{acc}(initial) = 15 MV/m and E_{acc}(after) = 28 MV/m
- Now Centrifugal-Barrel and tumble polishing devices are spreading.

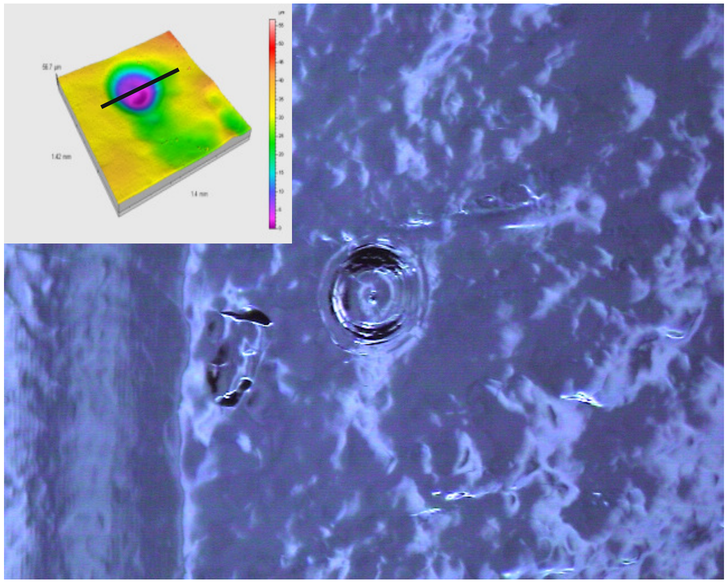


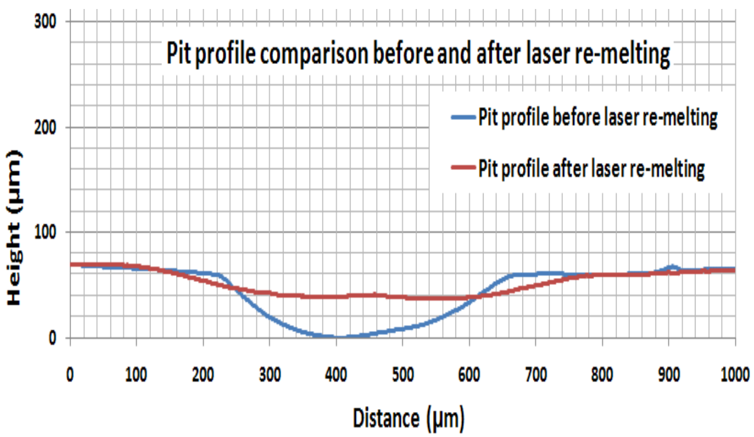


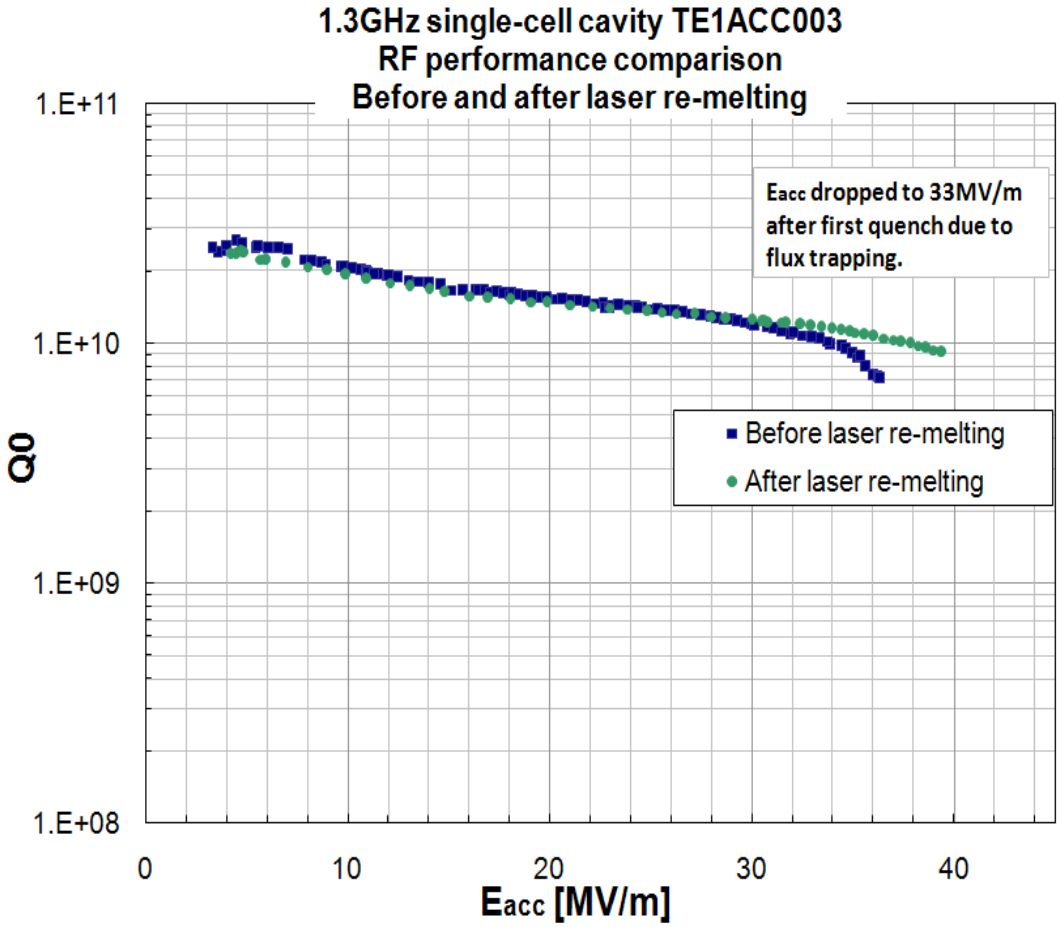


Laser Melting

@ FNAL



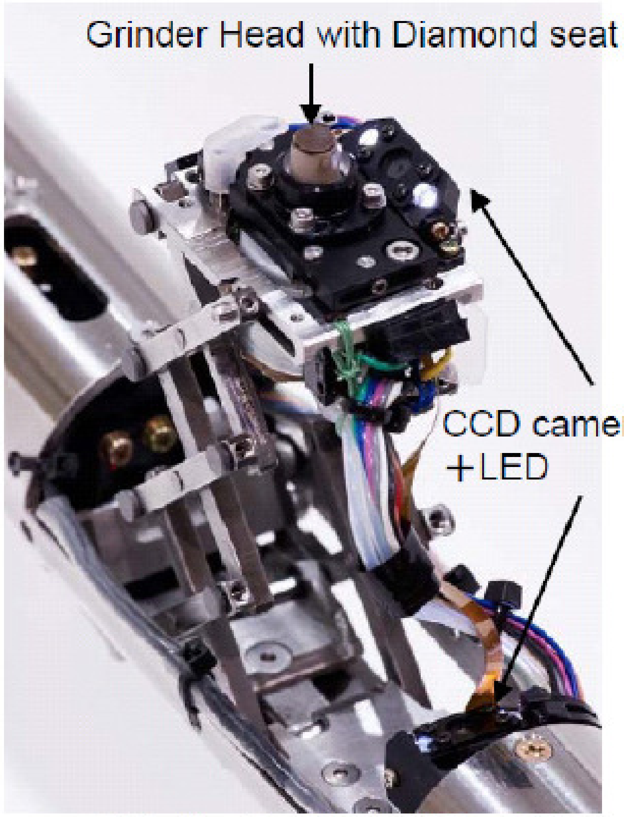




M. Ge, G. Wu, J. Ruan, J. Ozelis, T. Nicol, D. Sergatskov, D. Hicks, L. D. Cooley, "Restoration of accelerating gradient by Laser re-melting a pit in SRF cavity", manuscipt in preparation for Journal of Superconducting Science and Technology.

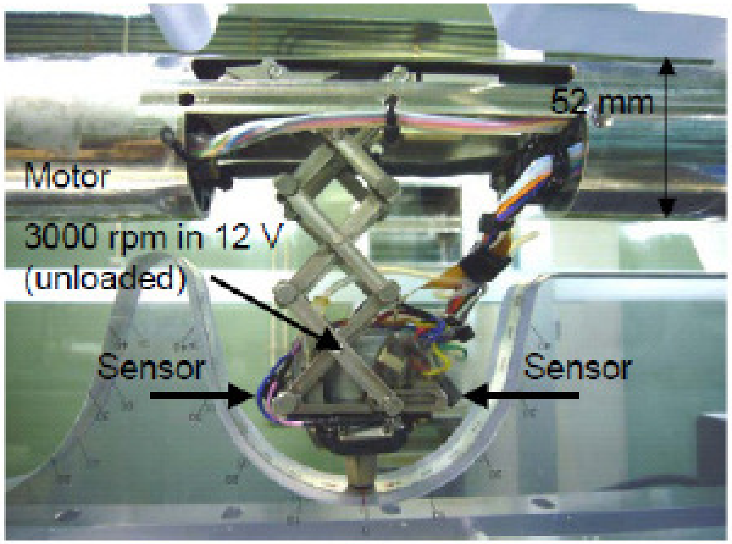
Local Grinding

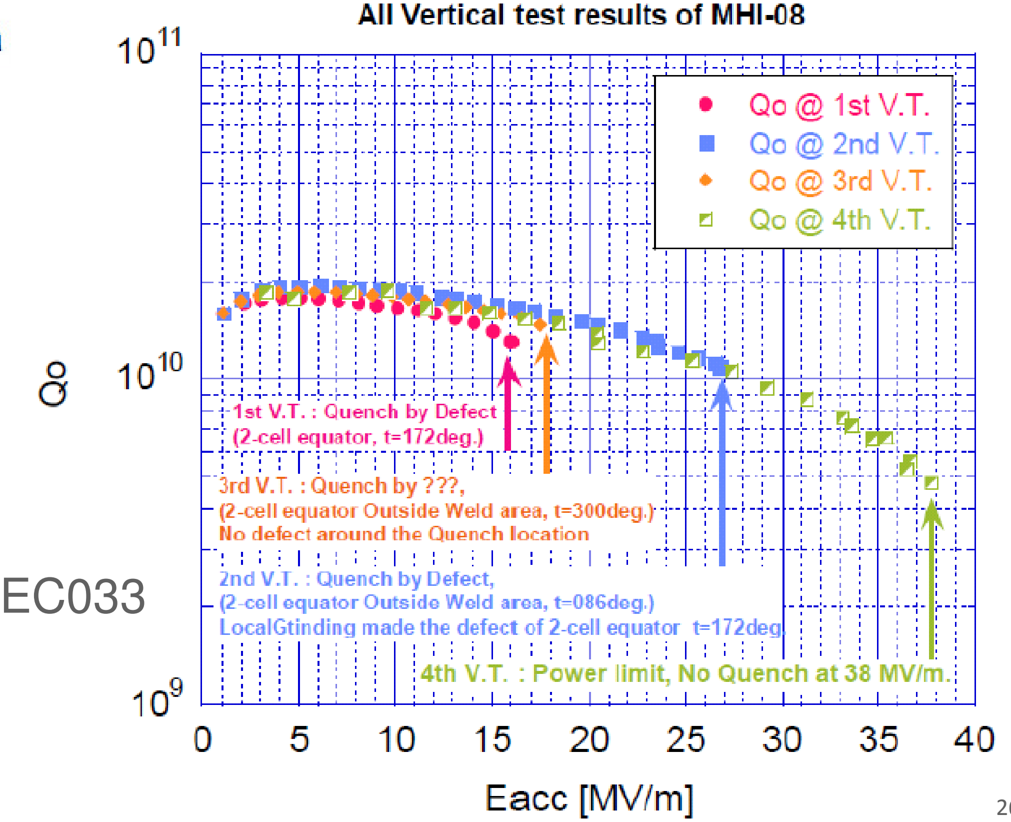
@KEK



Amount of Grinding: 5 um/10min, #400 , 10V
3 um/10min, #1000, 10V

Watanabe et al., IPAC2010, WEPEC033





Conclusions

- An international collaboration of people are working on improving cavity gradients and much improvement has been made.
- The ILC wants to have 90% of the produced cavities reach E_{acc} > 35 MV/m after one round of processing by 2012
  - Right now we are just about at 50%
  - If we produce 90% of the ~16,000 ILC cavities to the vertical acceptance standard we either
    - Have to repair ~1,600 cavities after the first test
    - Have to make ~17,780 cavities and have ~1,780 left over
- Still work needs to go into producing a high-performing cavity on the first processing pass.