HEPAP

SRF R&D

Hasan Padamsee

Cornell University

Outline

- Quick Survey of On-Going and Future Applications
- A Selection of Technology Highlights
- Outstanding issues:
  - Common to all applications
  - High gradient applications
  - CW operation (medium gradient)
  - Weak beam loading
- Is there a higher gradient future beyond Niobium Cavities?

SRF Has Become a Core Technology Worldwide for a Variety of Accelerators

- HEP
  - Now: LHC, CESR-TA, KEK-B, Beijing Tau-charm Factory
  - Future: ILC, ProjectX, CERN-SPL, Neutrino Factory, JPARC-Upgrade (neutrino beam line) Muon Collider
- NP, Nuclear-Astrophysics
  - Now: CEBAF, 12GeV Upgrade,
  - Future: FRIB (Argonne/MSU), ISAC-II (TRIUMF), Spiral-2, CERN ISOLDE Upgrade, Eurisol, RHIC-II, eRHIC, ELIC
- BES X-rays
  - Now: FLASH, X-FEL, CHESS (NSF), Canadian Light Source, DIAMOND, SOLEIL,Taiwan Light Source, Beijing Light Source (Tau-charm Factory), Shangai Light Source, Jlab-FEL/ERL, Rossendorf-FEL
  - Future: NSLS-II, Cornell-ERL (NSF), KEK-ERL, BESSY-ERL, WIFEL (NSF), ARC-EN-CIEL, Pohang Light Source, Peking University,…
- BES: Neutron Sources
  - SNS, SNS upgrade,
  - Future: ESS (Bilbao?)
- Other High Intensity Proton Sources for
  - Nuclear waste transmutation, Energy amplifier, Power generation from Thorium
  - INFN, KAERI, Indian Laboratories at Indore, Mumbai and Kolkata

Strong World-Wide Collaboration Forums for SRF Technology and Applications

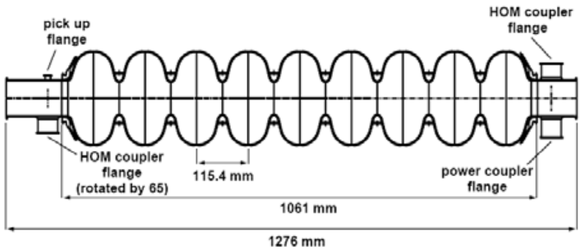
- SRF Workshops every 2 years
  - Beijing, Cornell, Travemunde, Santa Fe…
  - Next Workshop : Berlin in September 2009
- Tesla-Technology Collaboration (TTC) meetings every 6 months
  - Delhi, Hamburg, KEK, Frascati…
- Focused on major technical issues
  - E.g. Gradient yield R&D, Industrialization, couplers, tuners…
- ILC Collaboration Meetings
  - Monthly

SRF Capabilities in the US
Associated Projects

- Argonne National Lab
  - Heavy Ion (ATLAS), FRIB
- Brookhaven National Lab
  - ERL for eRHIC and RHIC-II
- Cornell University, LEPP
  - CESR/CHESS, ERL, ILC
- Fermilab
  - ILC, Project X
- Jefferson Lab
  - CEBAF, ILC, ELIC
- Michigan State University
  - ReAccelerator, FRIB
- Oak Ridge National Lab
  - SNS

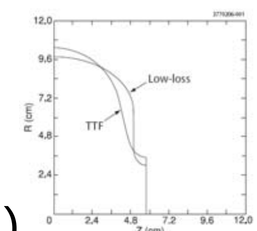
Structure Examples

1300 MHz Structures for Accelerating Particles at v ~ c

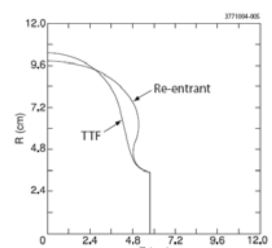


TESLA-shape

(DESY, TTF)



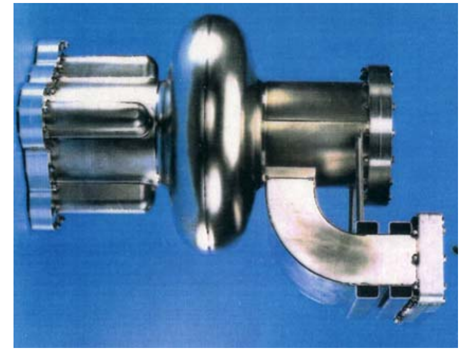
Low-Loss shape (Jlab, KEK…)



Re-entrant shape (Cornell)

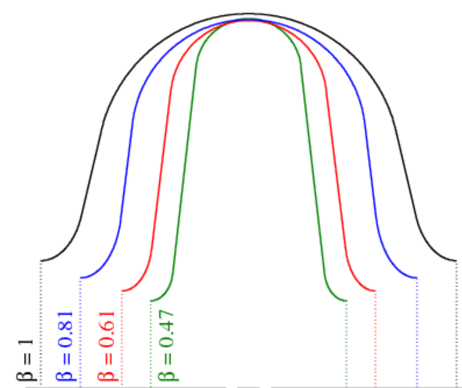
1-cell 500 MHz for high current storage rings

CESR, DIAMOND, CLS, TLS, SLS…



Structures for Accelerating Particles at v < c

For protons at 1 ~ GeV



Low-Velocity Structures for Heavy Ions
$\beta = v/c$: 0.28 -0.62

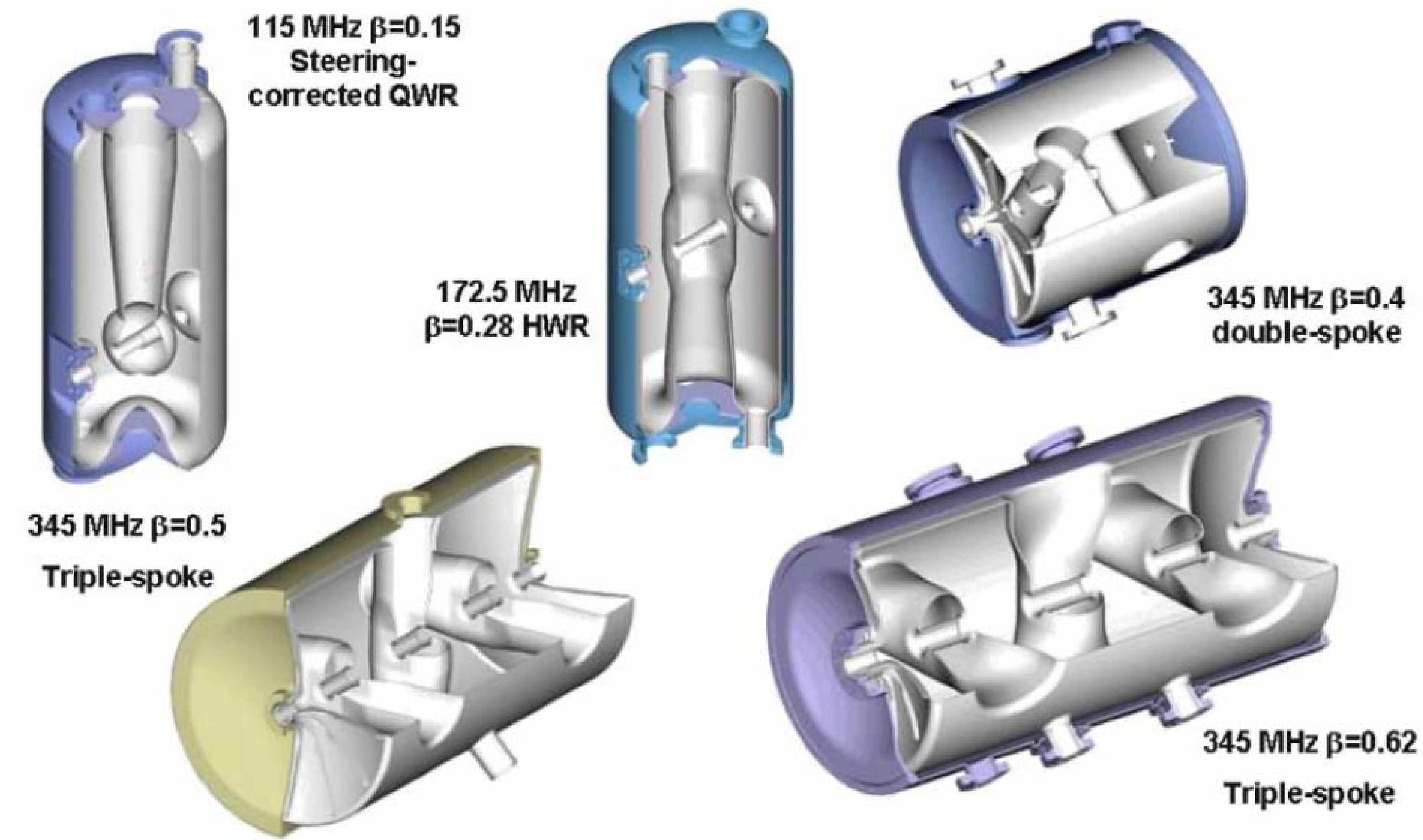
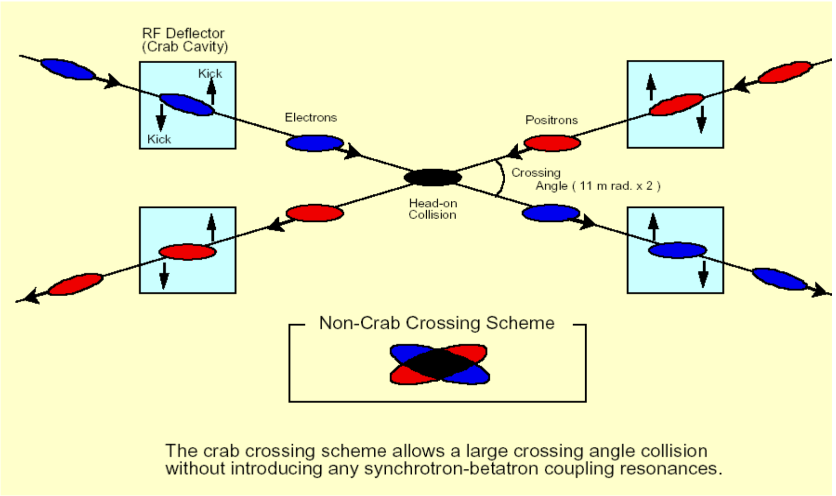


Figure 2: Five types of SC cavities developed for the AEBL driver linac.

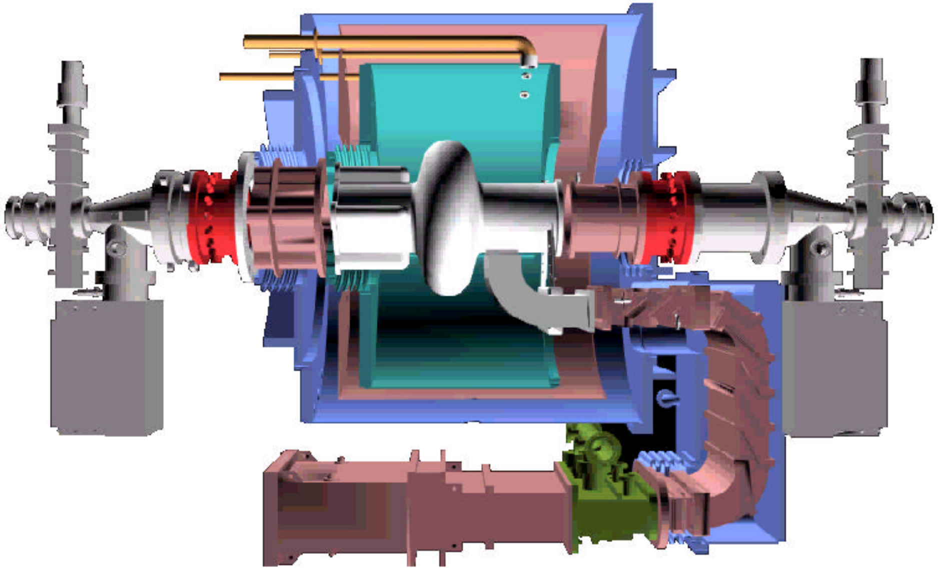
Crab Cavities (Deflecting mode)

- KEK-B
- Possibly LHC-upgrade
- Possibly Ultra-fast X-ray source

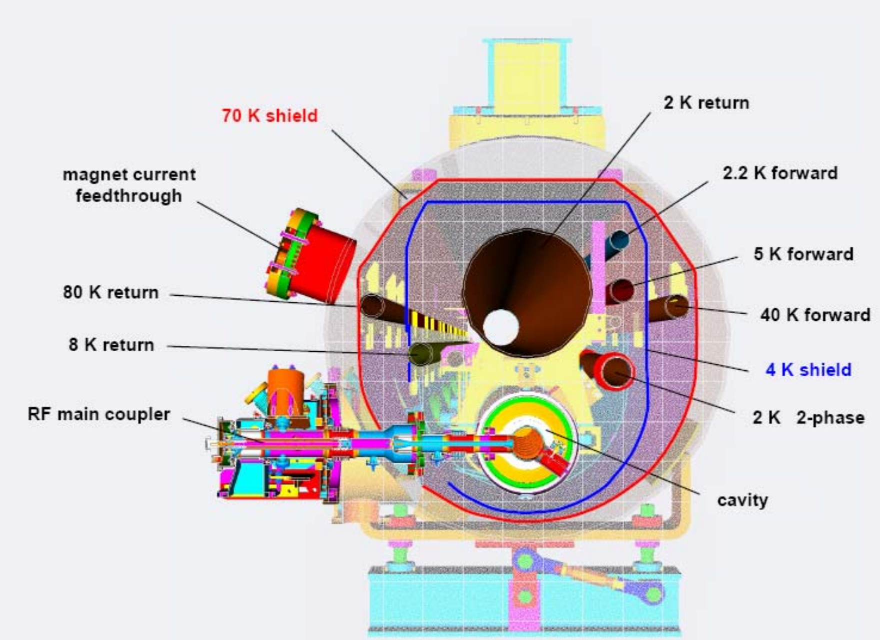


Cryomodule Examples

For Tesla-Test Facility (now FLASH)



CESR Module for High Current Storage Rings



Low β Module (TRIUMF)

Common Issues for All SRF Applications

- Niobium material control (more on this later)
- Good fabrication procedures
  - Key element is electron beam welding
- Good surface preparation procedures
  - chemical treatment
  - furnace treatment
  - high pressure rinsing
  - clean room assembly
- Operation
  - Accommodate gradient distribution for maximum energy gain
    - Provide flexibility in rf distribuition
  - Reliability of operation, low trip rate,
    - low x-ray production level during operation…
- Production and testing capacity/rate of cavities, cryomodules

Likely US Upcoming Projects : Cavity/CM Demands

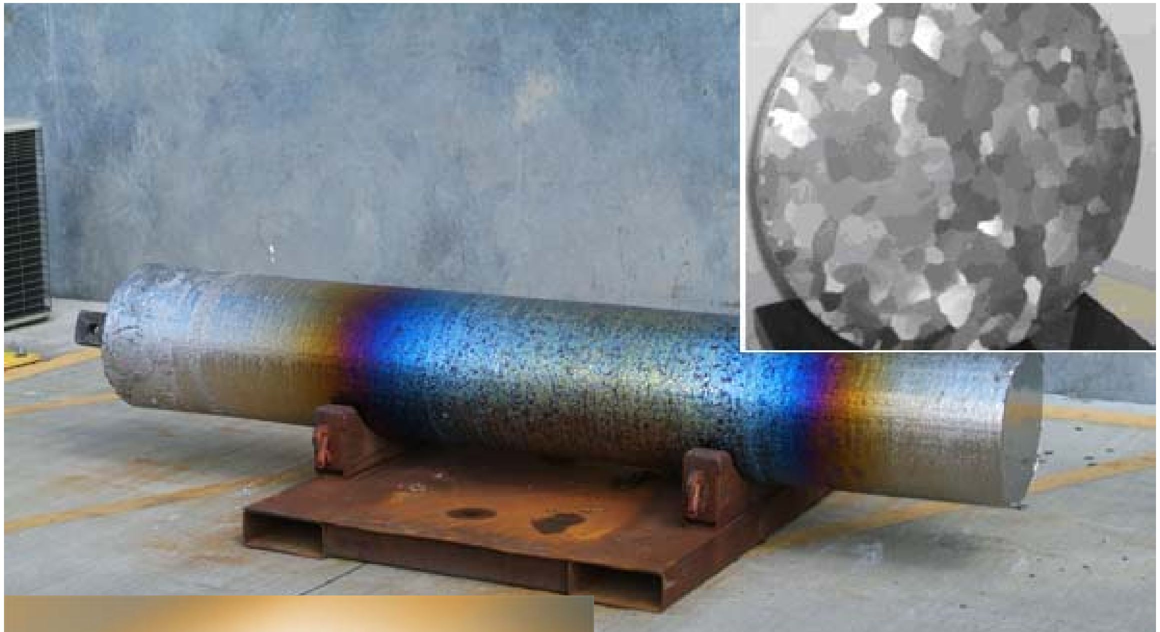
- > 1000 cavities, 150 CM
  - Jlab upgrade: 80 cavities, 10 CM
  - ProjectX: 320 cavities, 40 CM
  - ERL Cornell: 450 cavities, 75 CM
  - FRIB: 200 low beta cavities 35 CM
    - QWR, HWR, Spoke
- On top of XFEL: 1000 cavities, 125 CM
- ILC…Some fraction of 16,000 cavities, 2000 CM
- => Need to broaden industrial base for cavities and CM

Status of World-Wide Industrial Capability

- Strong European industrial base:
  - growing due to XFEL
  - ACCEL, Zanon, Thales…
- American industrial base:
  - Developing slowly
  - AES, Niowave/Roark, PAVAC, CPI, Meyer Tool
- Asian industrial base:
  - Growing
  - Mitsubishi Heavy Industries, Mitsubishi Electrical, Nomura Plating, Toshiba

Nb Material Is Common to All Projects

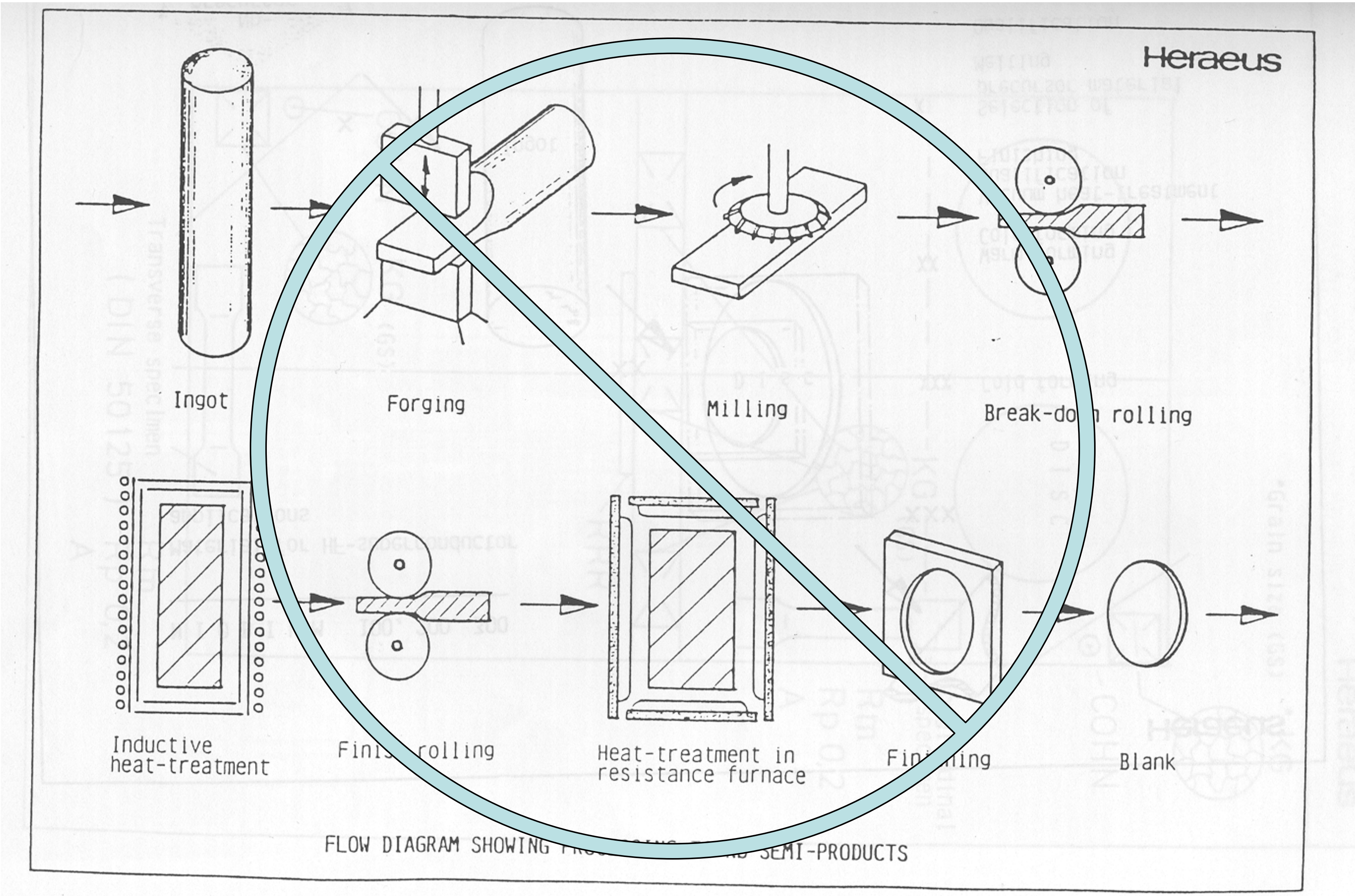
- Basic material specs for “good” cavities have been defined
- Starting material quality control procedures developed
  - RRR, grain size, yield strength, eddy-current scanning to screen out defects…
- A new development is large grain material
- Possible advantages are
  - Cost reduction (slice directly from ingot)
  - BCP only (skip more intricate EP)
    - Not valid for highest gradients
- Some fabrication issues still need to be worked out
- Overall performance is same as small grain
- Single crystal: too hard for mass production
  - But Useful for basic studies
  - E.g. Grain boundaries are <u>not</u> the main cause for high field Q-slope



Standard Ingot and slice

Large grain ingot and slice

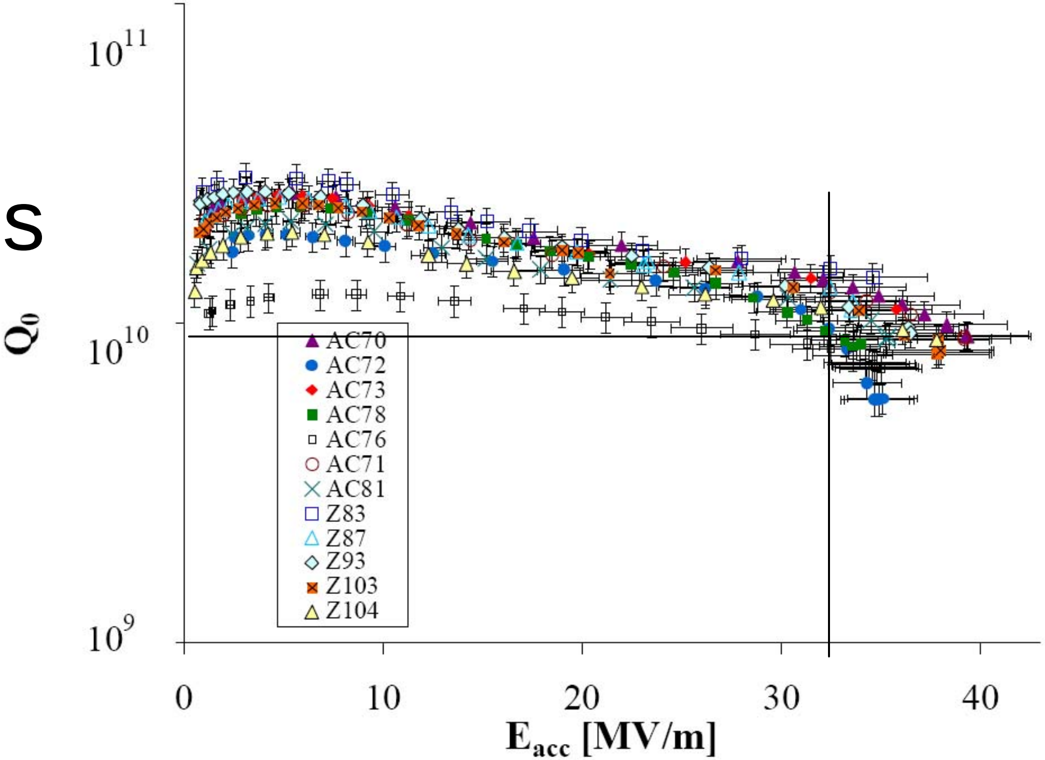
Go Directly from Ingot to Sheet?



Outstanding Issues for Highest Gradient Applications: e.g. ILC

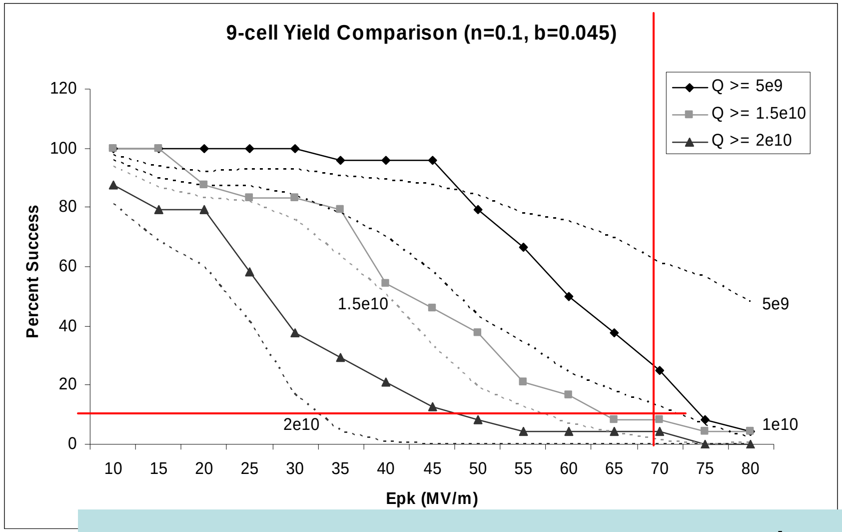
- Gradient Yield at 35 MV/m is low
- Gradient spread is high
  - Quench
  - Field emission
- Best 9-cell Cavities

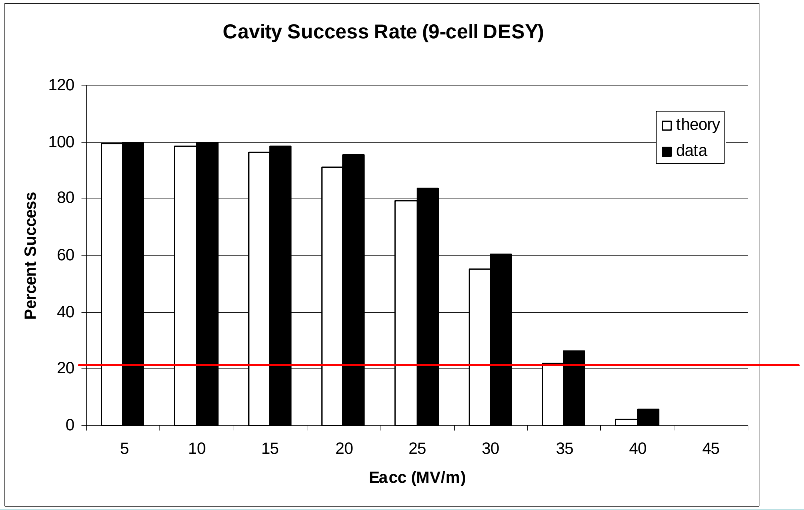
  About one dozen



Gradient Yield (Before 2008)

- Field emission Quench





5 15 25 35 MV/m 5 15 25 35 MV/m

DESY Yield Curves from Q vs E,

24 tests on ten 9-cells

Dashed curves are yields due to field emission modeling (theory)

TESLA Note 2008-2

66 DESY Tests on 51

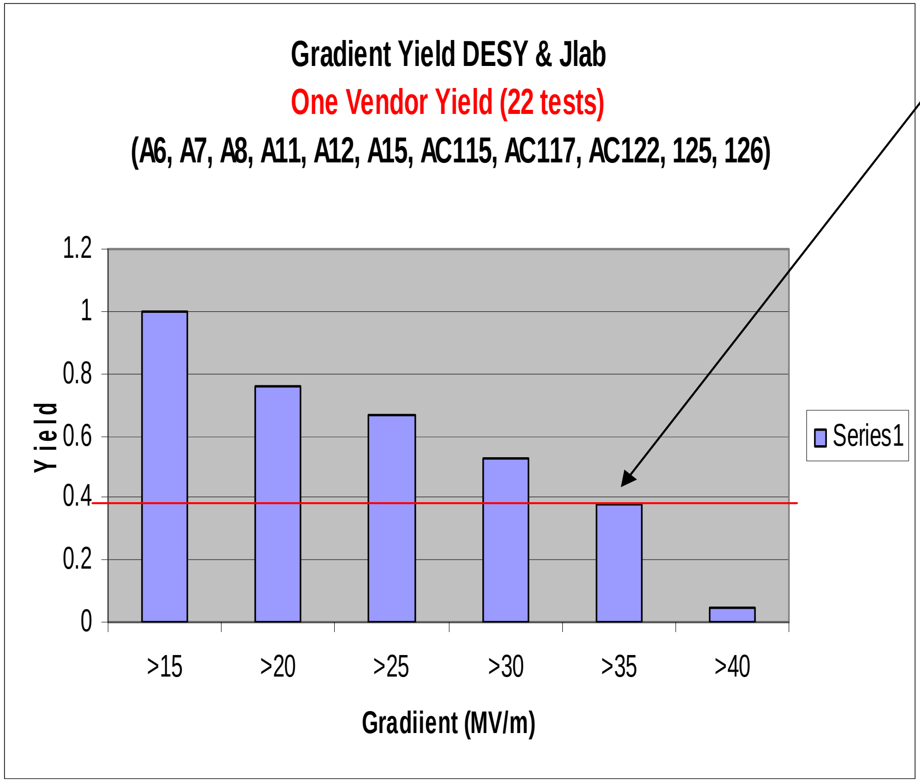
9-cell cavities, TESLA Note 2008-8

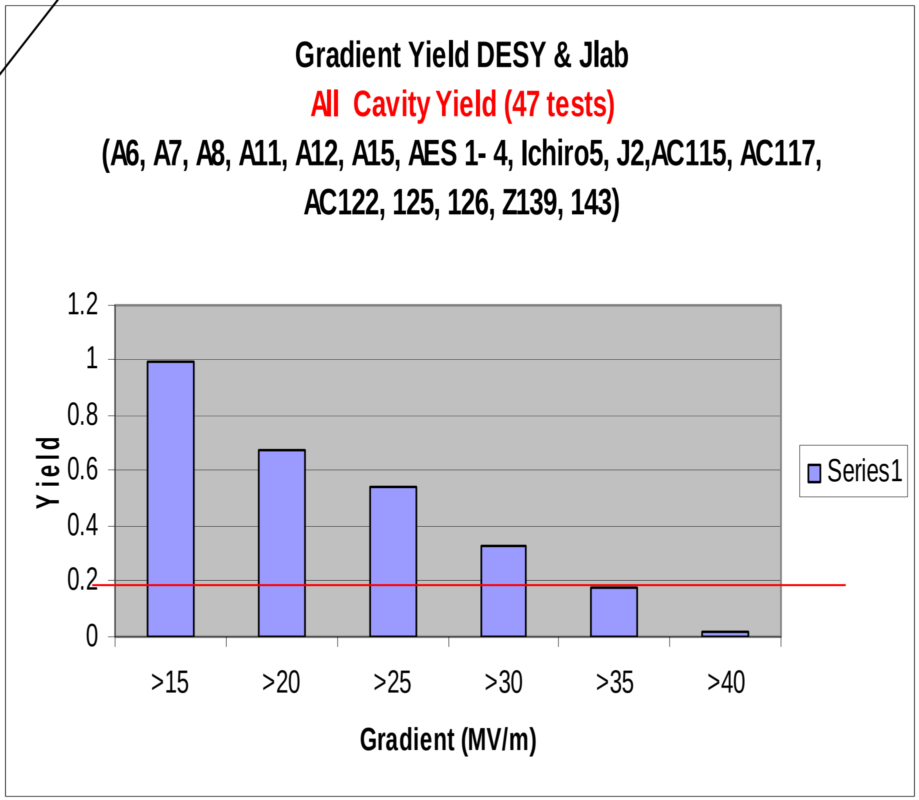
Two vendors

Cavities prepared by EP/HPR/800C/EP/HPR/Bake

Open bars are yields due to quench modeling

Progress in Gradient Yield Over Last One Year





Latest 1-vendor Gradient Distribution

(quench and field emission)

Latest many vendor Gradient Distribution

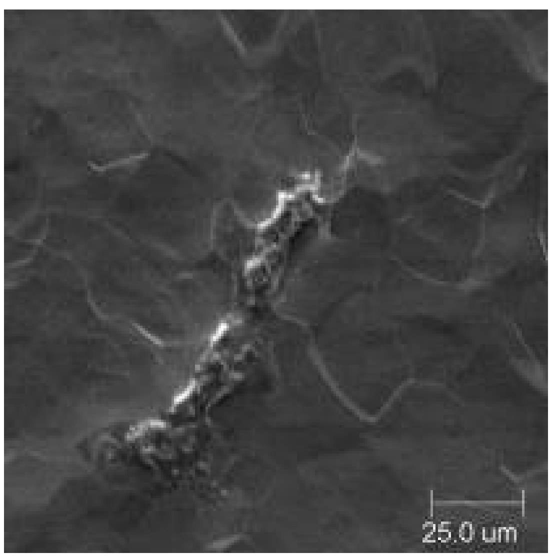
(quench and field emission)

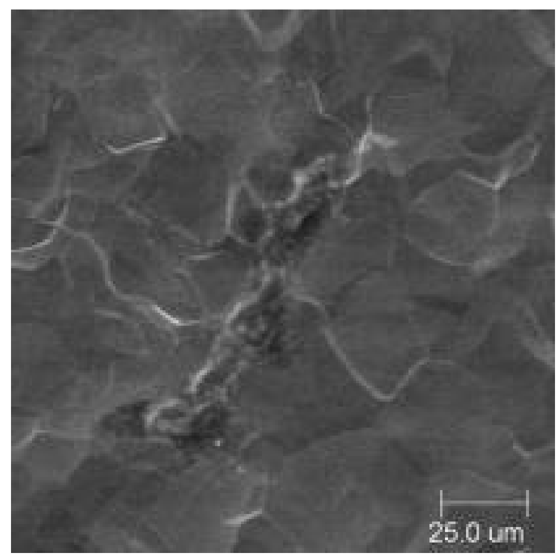
Field Emission Reduction

- Improvement mostly due to reduction in field emission with better cleaning after electropolishing
  - Jlab: Ultrasonic degreasing
  - DESY: Ethanol rinsing

S particle deposited on sample during EP

(Cornell Basic R&D)





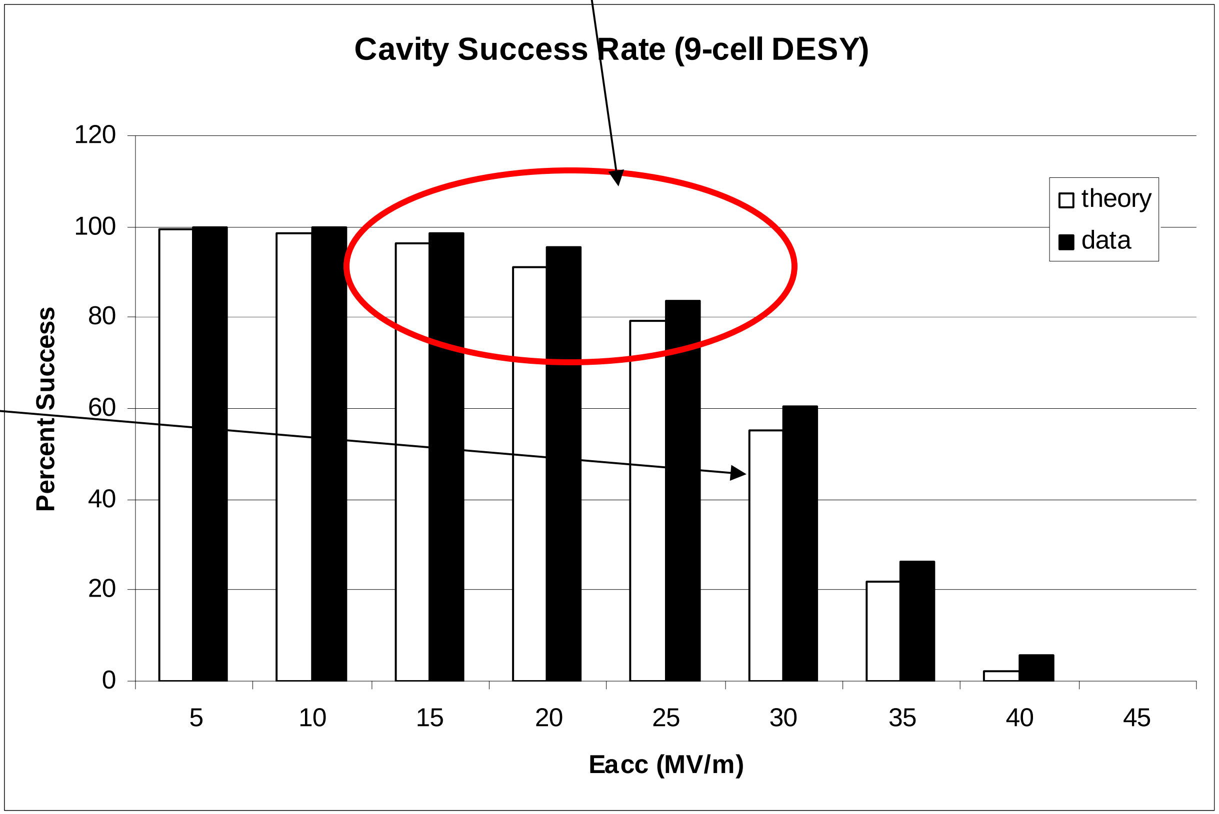
Dissolved particle,

but leaves an imprint, Possible quench site?

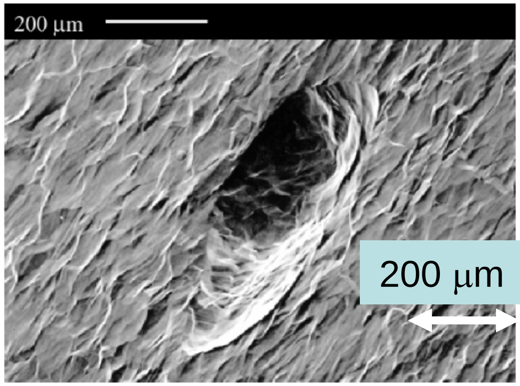
unknown

Success in Identifying Sources of Quench Below 25 MV/m (Limiting 20% of Cavities)

- More R&D needed to identify quench sources for gradients > 25 MV/m !
- Limiting 40% of cavities
- Remaining cavities make it over 35 MV/m



Museum of Identified Sources of Quench Below 25 MV/m (Pits and Bumps)

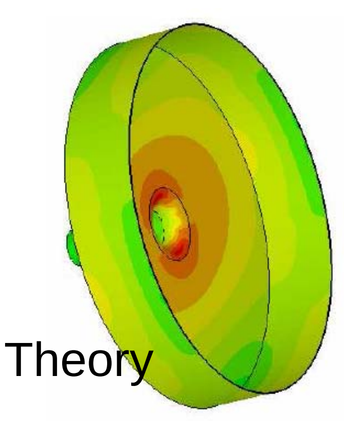


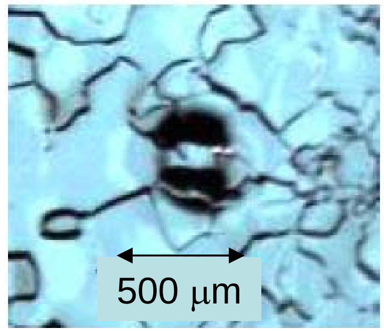
Pit with sharp edges

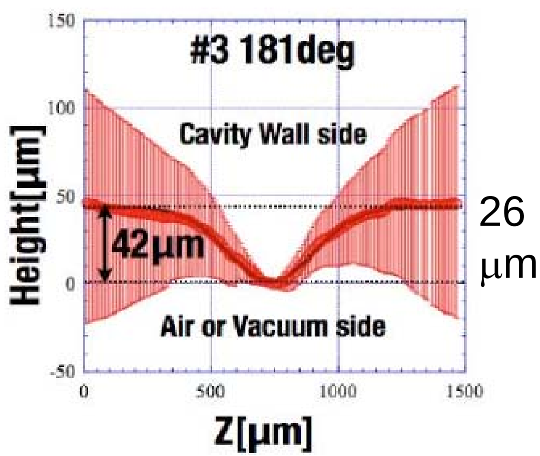
Reported in Thesis of J. Knobloch (1997)

Quenched at 93 mT

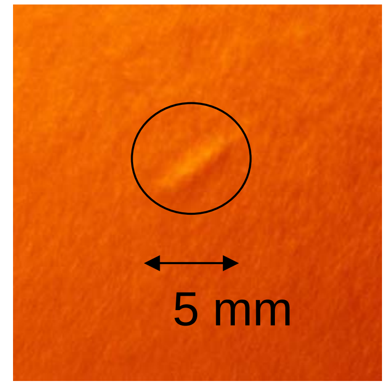
Eacc =21 MV/m





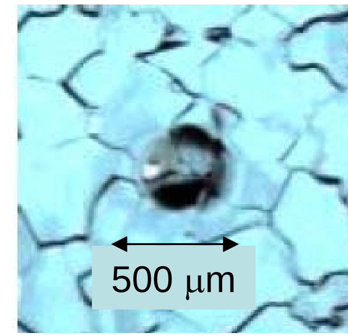


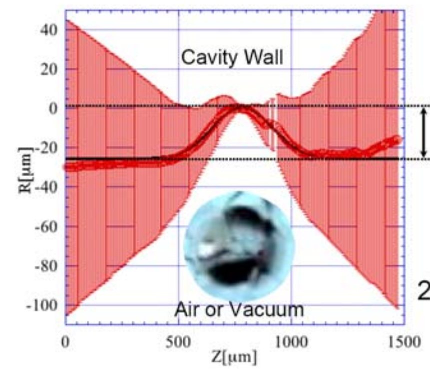
Bump found by KEK Optical Inspection with CCD camera in AES 9-cell cavity with thermometry (Jlab and FNAL) Quench at 18 MV/m



Bump found at Quench location on Niowave/Roark 1-cell cavity (Cornell)

Deep scratch subsequently found on Cavity Forming Die



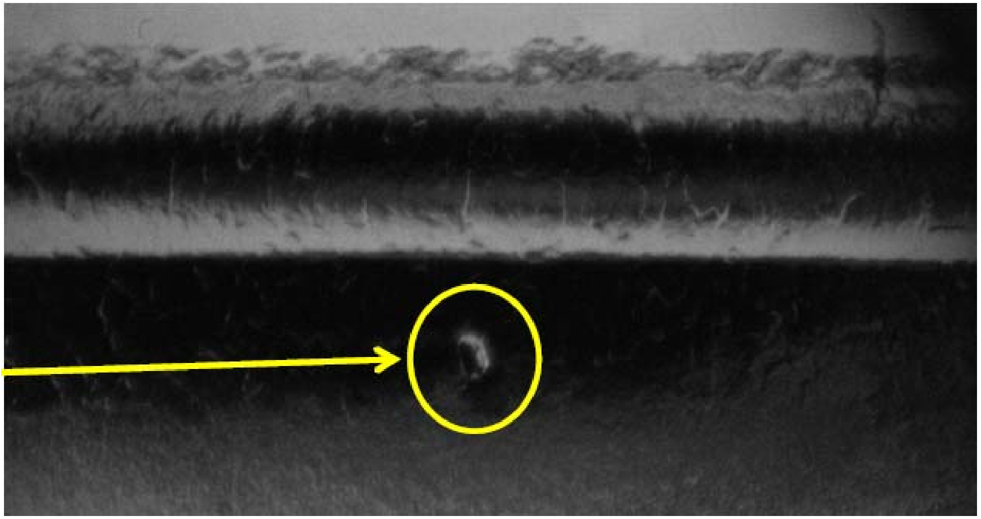


Pit found by KEK optical inspection with CCD camera in AES #1cavity

Quench at ~ 18 MV/m

Museum of Quench Sources (con't) for Eacc < 25 MV/m

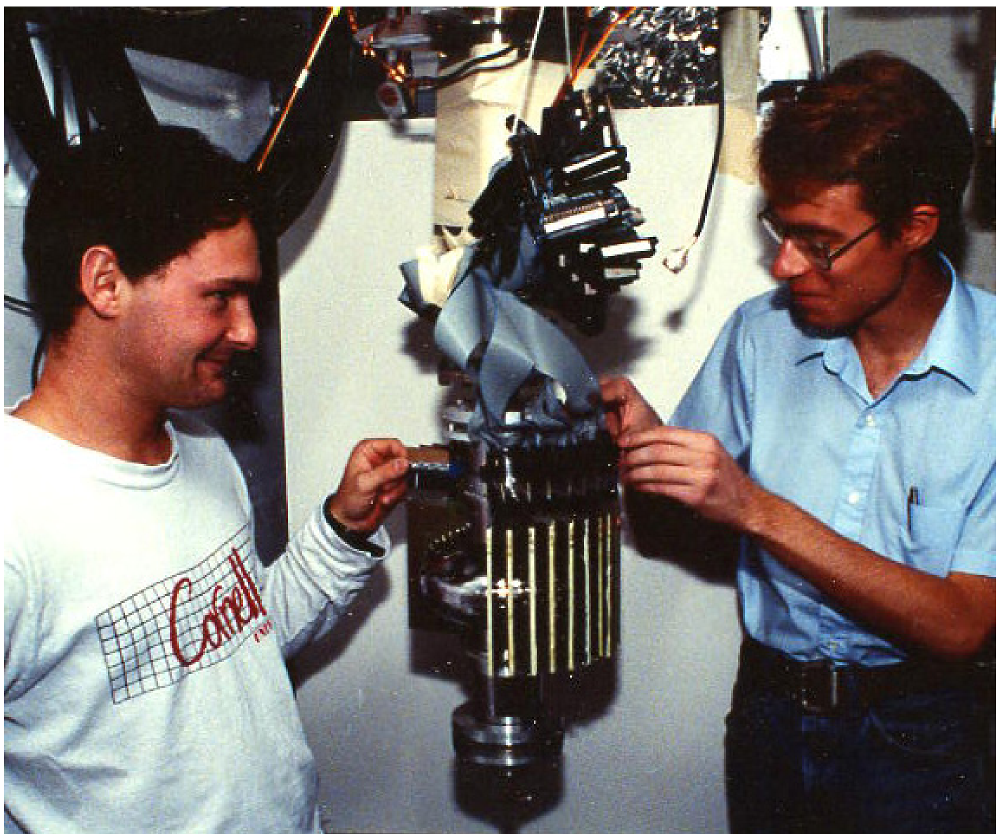
- Rough spot near weld seam, correlated with quench signal from thermometry
  - (DESY Cavity and quench location, KEK Optical inspection

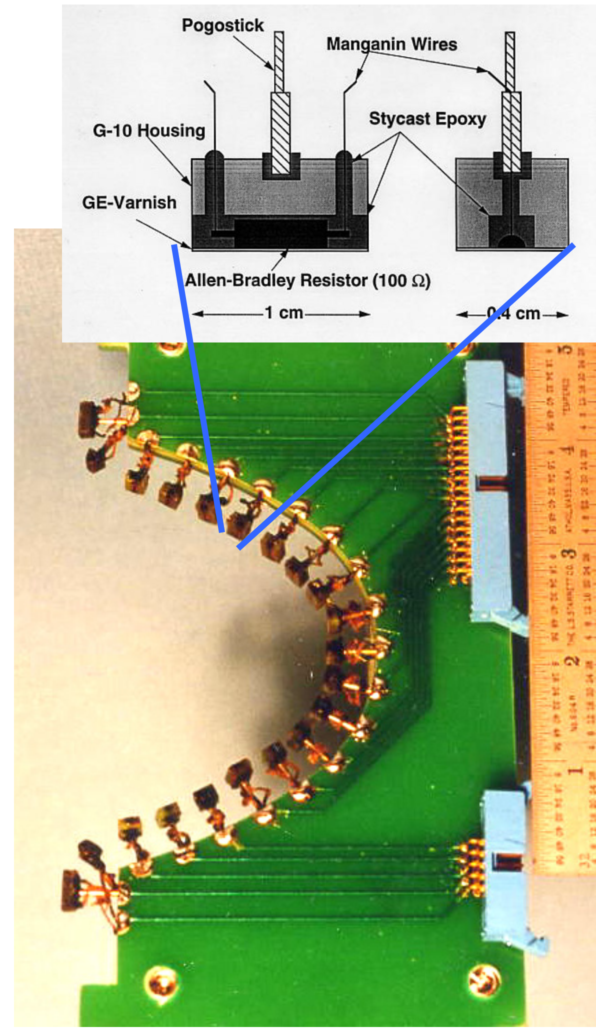


- 100 μm pit near weld
- Quench at 18 MV/m
  - Jlab quench location and optical inspection
  - With remote Questar

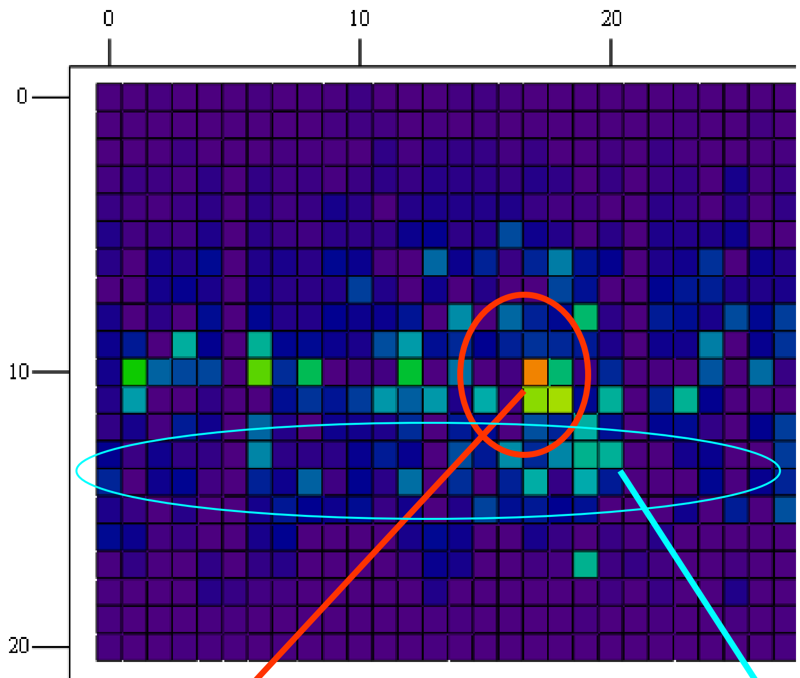
Recent Result on **Pre-Heating** at Large Pit (lots of EP)

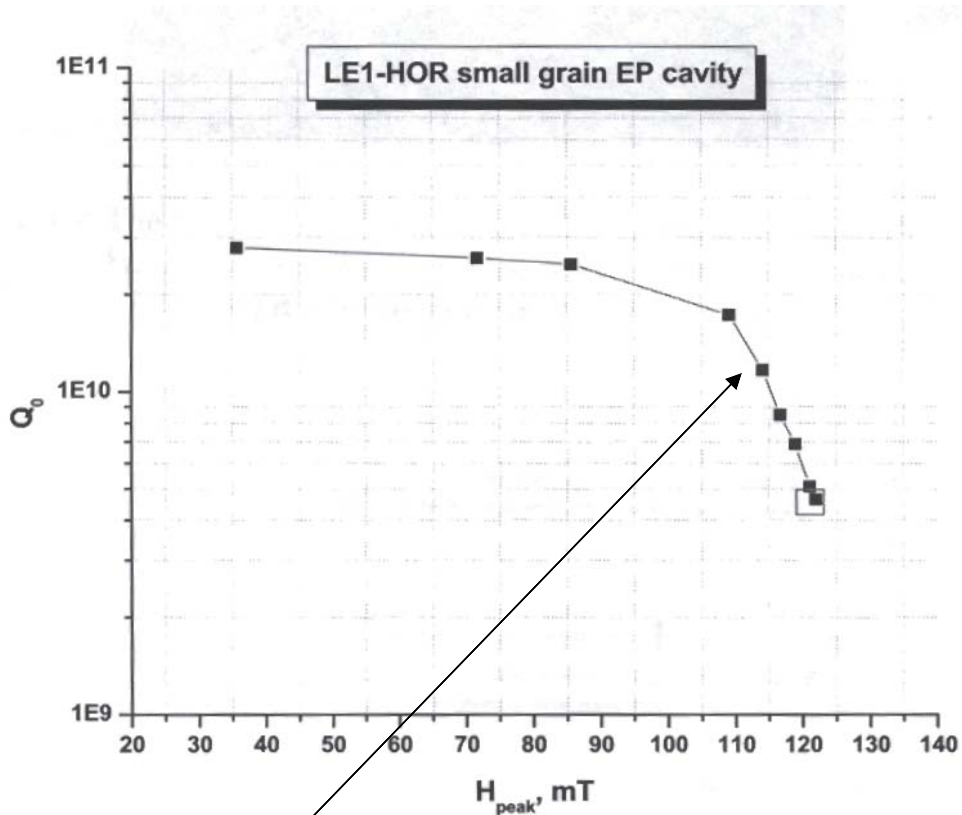
- Cornell 1-cell massive thermometry system works in superfluid to detect heating BELOW quench
- 760 thermometers for 1-cell, 1500 MHz cavity
- Grain size 1 mm, preparation:
  - EP, 800 C, EP, HPR (no bake)





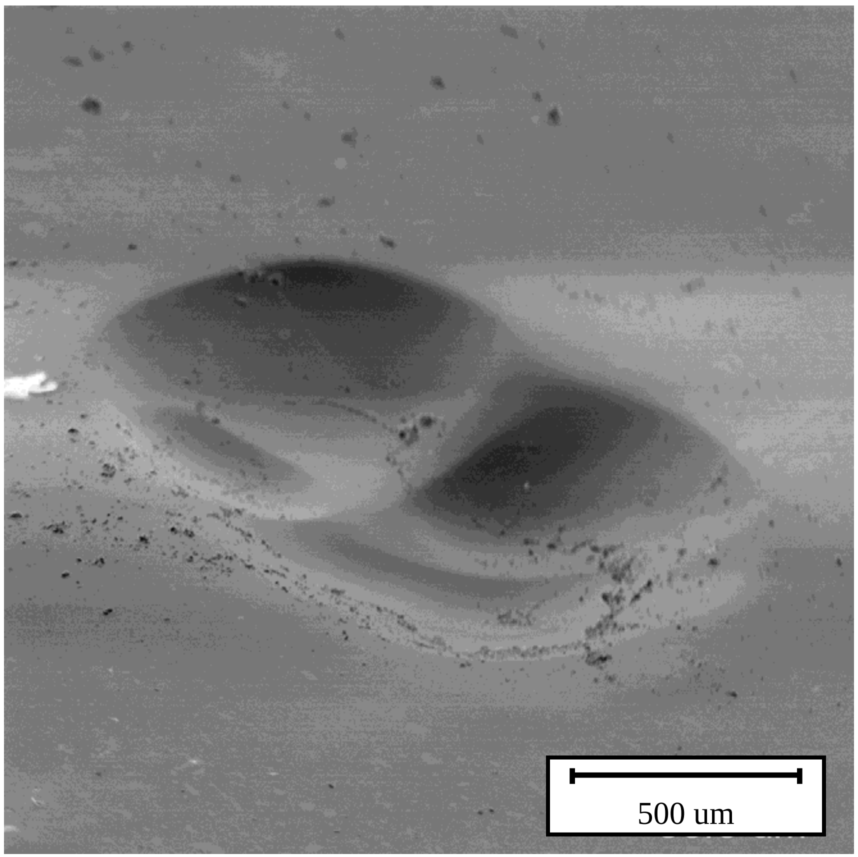
Temperature Map & Q vs E



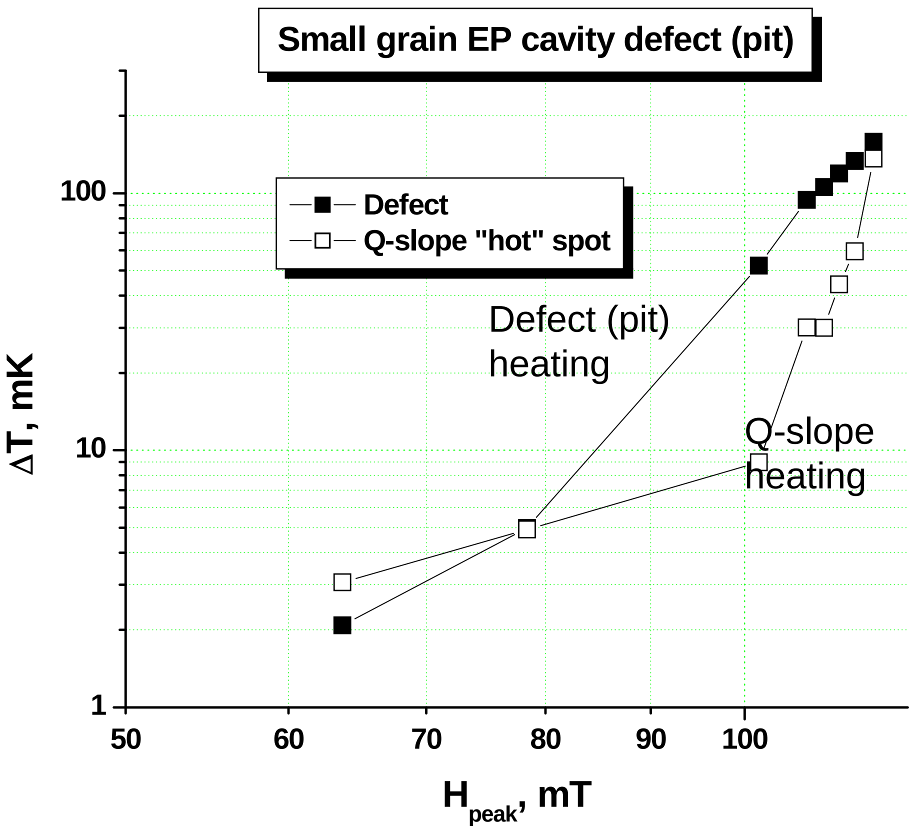


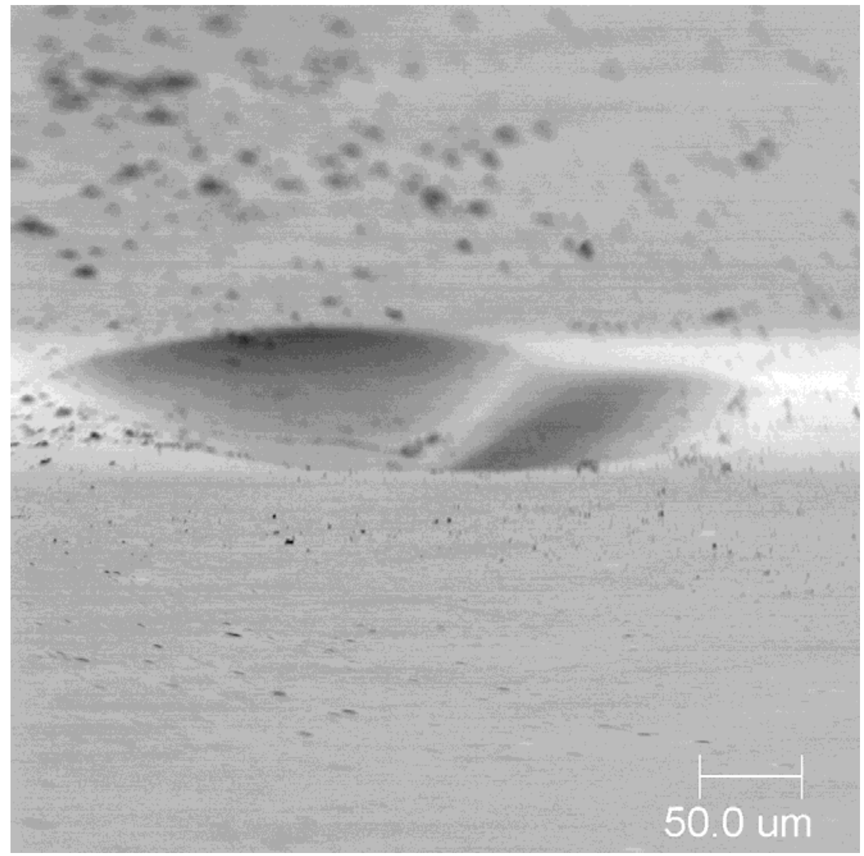
- General heating due to high field Q-slope
- Defect heating at pit before quench

SEM back-scattered image



Individual thermometer responses




50.0 um

Outstanding Issues for CW Applications, Medium Gradient, e.g. ERL, FEL

- High Q_0 and High Q_{ext} (related to input coupler strength)
- If $Q = 10^{10}$ at 2 K, 450 cavities (5 GeV ERL)
  - 2 K heat load = 14 kW (AC power = 13 MW)
- Reduce by factor of 10 if $Q_0 = 10^{11}$ at 1.6 K
- Does higher Q outweigh increased refrigeration cost from 2 K to 1.6 K?
- Need excellent shielding for earth's magnetic field in cryomodule
  - 5 mGauss
- If beam loading is negligible, only need RF power to reach operating field (15 MV/m)
- Operate at highest Qext allowed by microphonics to reduce RF power demand to < 5 kW per cavity.

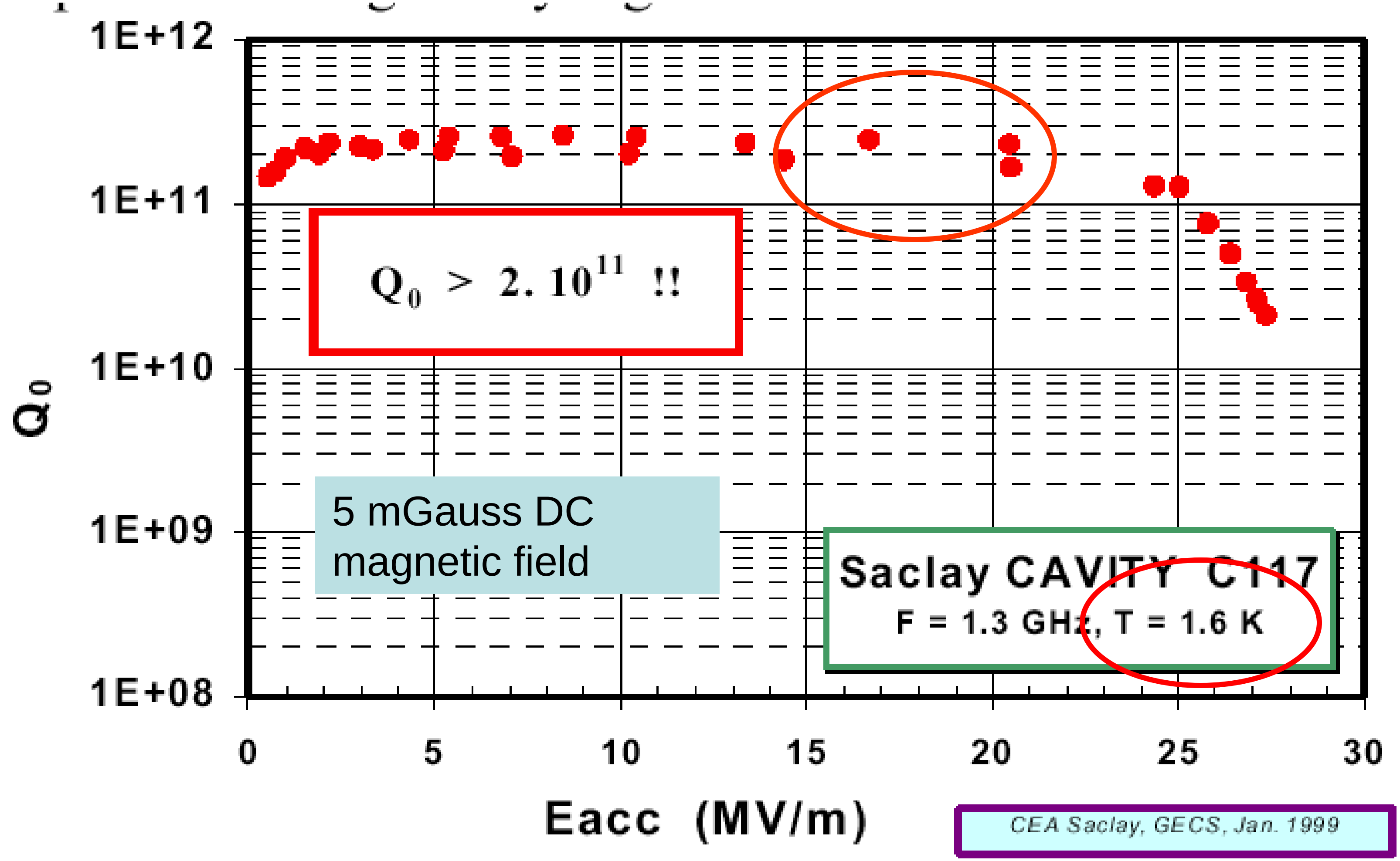
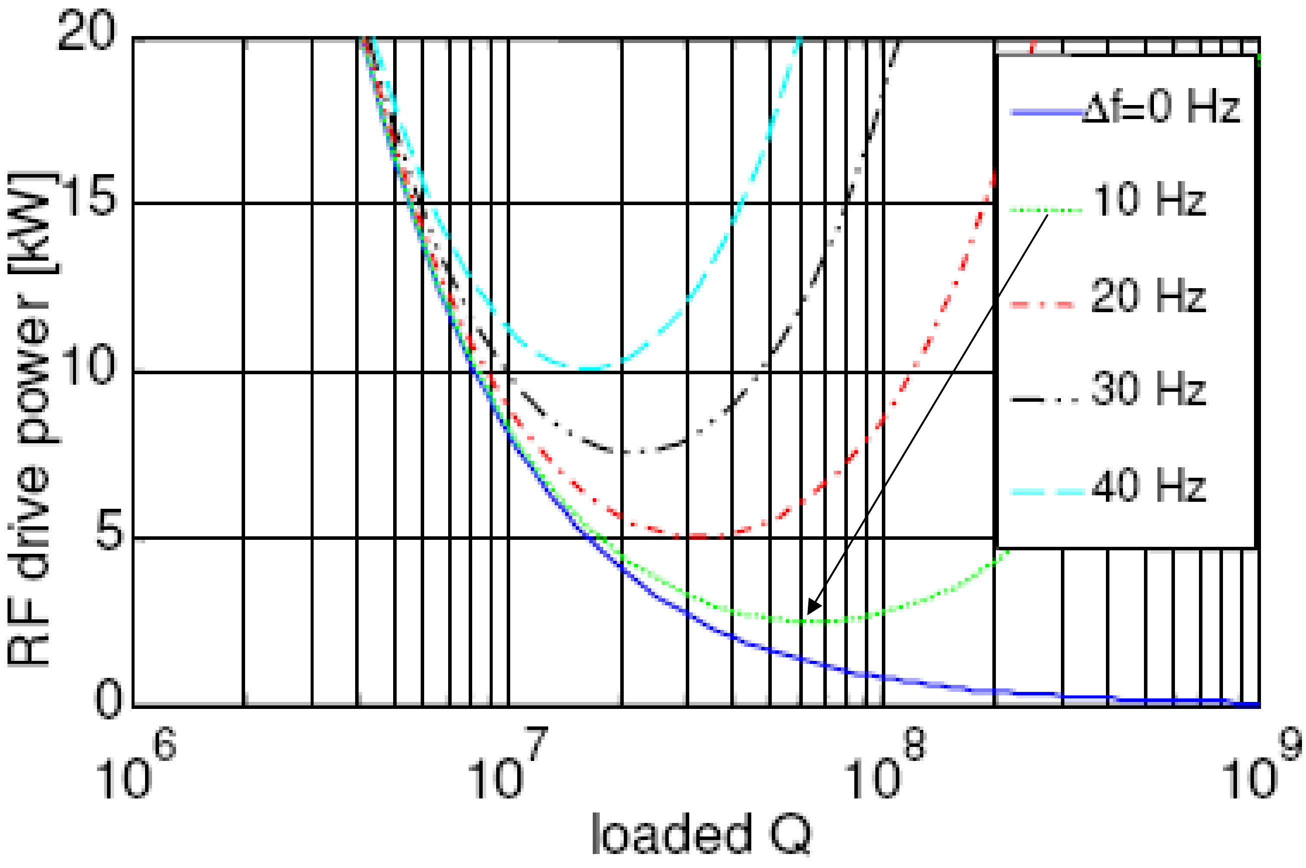


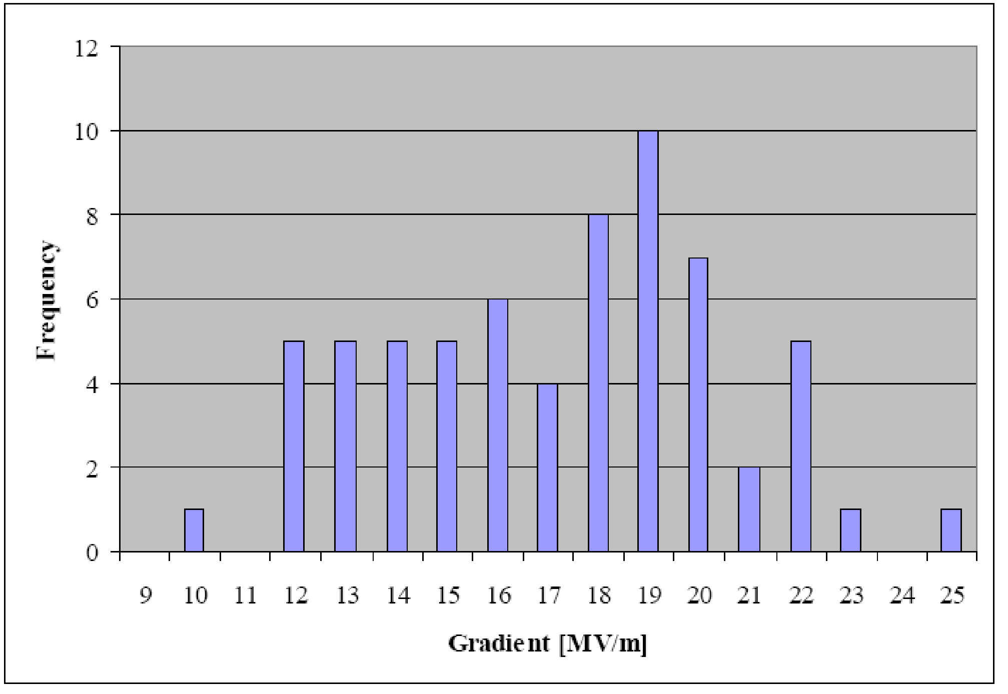
Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}.



- Peak rf drive power as function of *QL* for a 1.3GHz, 7-cell cavity at 20 MV/m accelerating gradient. The power is determined by the peak microphonics cavity detuning during cavity operation

Outstanding Issues for High Intensity Proton Applications, Medium Gradient

- Flexibility to make optimal use of gradient spread
  - e.g. one klystron/cavity
- Gradient distribution on-line without beam for 65 out of 81 cavities.
  - The average is 17.8 MV/m
- Beam loss
  - Good matching
- Reliability



Beam Loss (SNS)

- As of EPAC 08

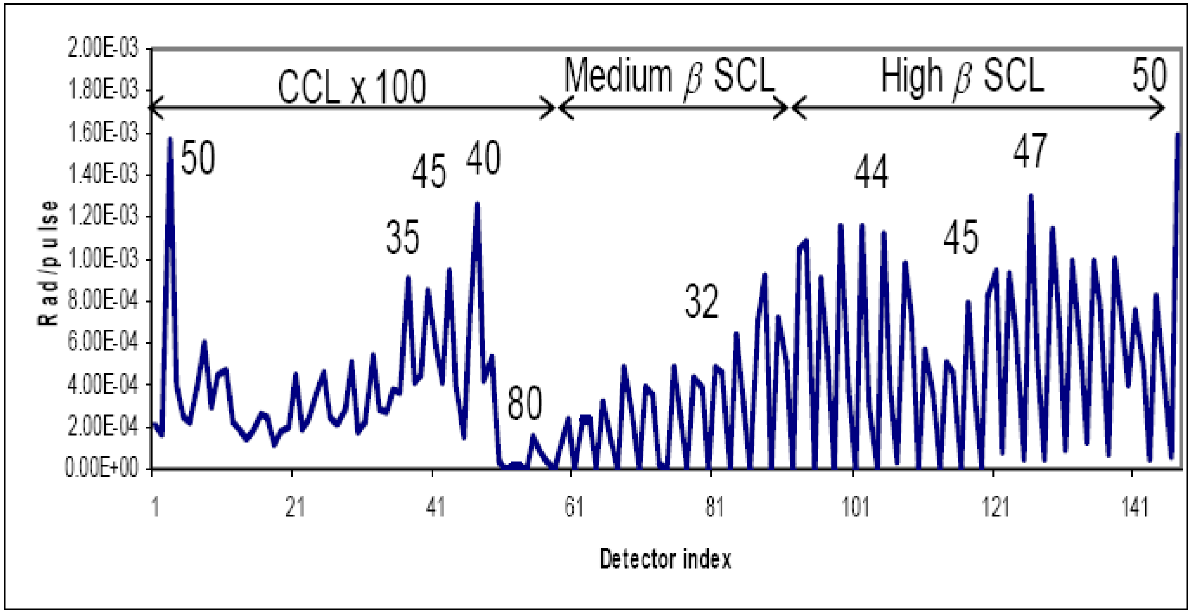


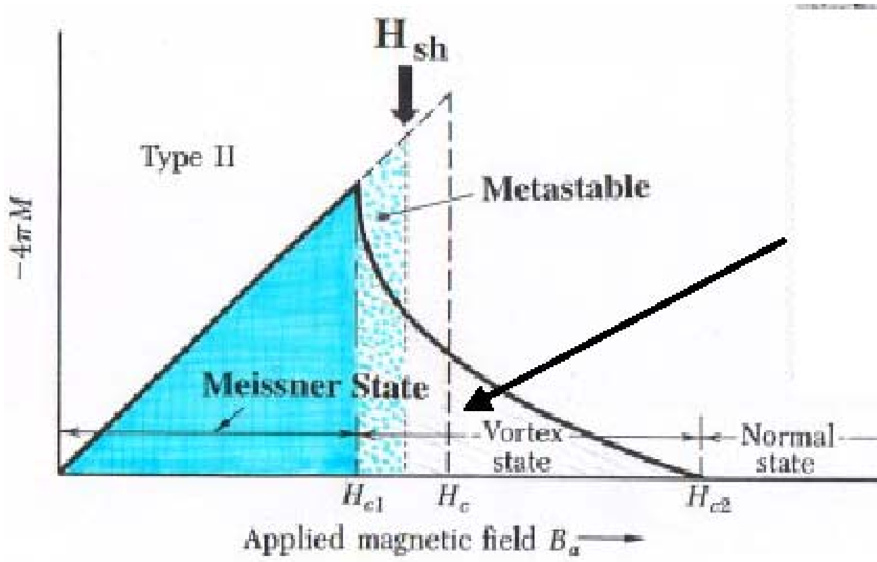
Figure 4: Linac beam loss monitor signals (rads/pulse) recorded during 475 kW operation. Numbers overlayed show residual dose rates (mrem/hr) at 30 cm measured ~24 hours after beam operation.

Beyond Niobium Cavities

For TeV Upgrade Linear Collider?

- Is Nb (50 - 60 MV/m) the end of the road for superconducting cavity gradients?
- Outstanding question:
- What is the relationship between the RF critical magnetic field and the famililar DC critical magnetic fields?
- Is Hrf
  - H_{c1}, H_c, H_{sh}?
  - How does it depend on temperature?
  - How does it depend on
    - Ginzburg-Landau parameter $\kappa = \lambda/\xi$?
  - Nb: $\kappa \sim 1$, Nb3Sn: $\kappa \sim 20$..

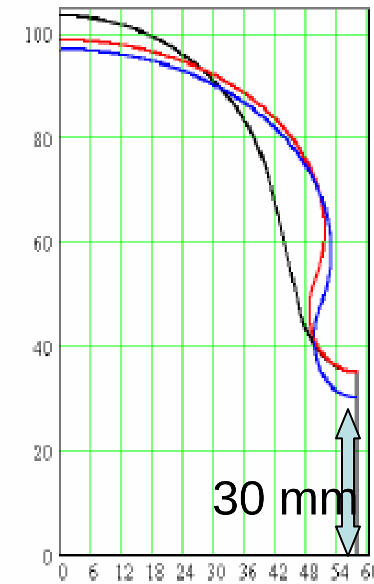
DC Critical Fields

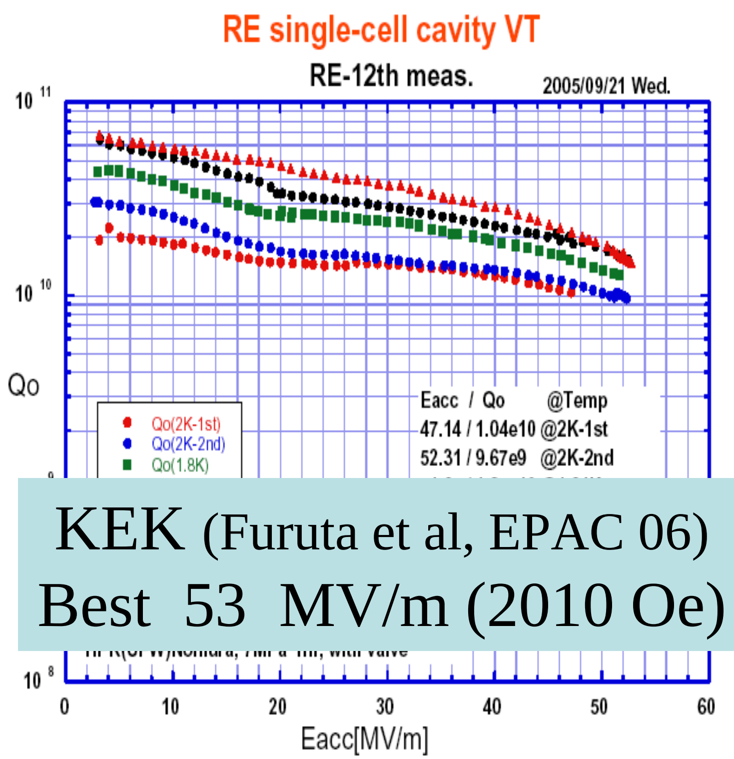


Best Nb Cavities:

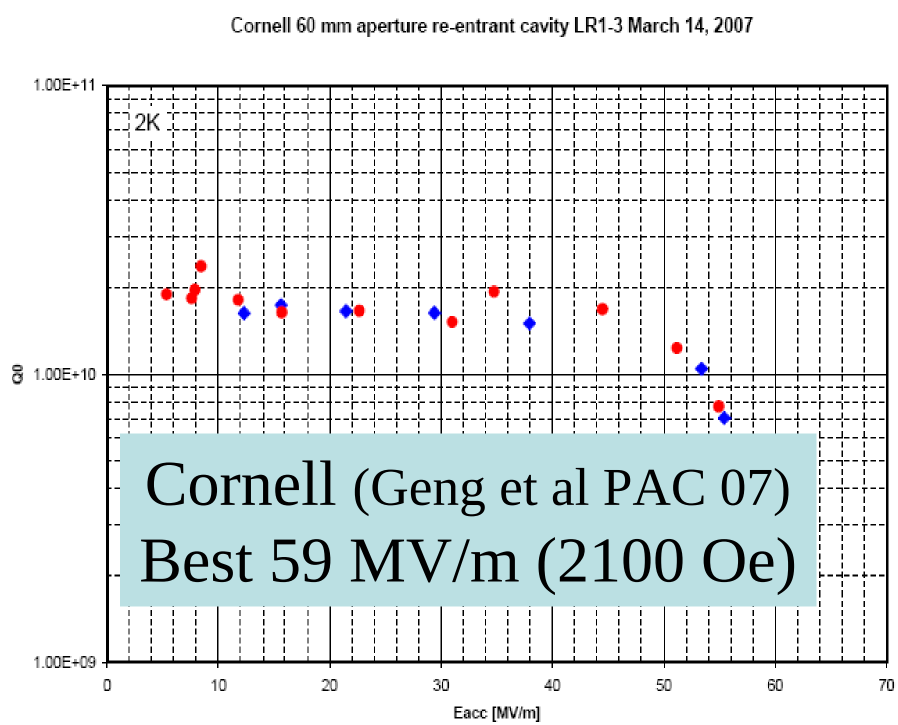
Cornell Collaboration with KEK

- Two Re-entrant Shape Single Cell Cavities
  - H_{pk} = 38, 36 Oe/MV/m
- Cavities built at Cornell, treated and tested at KEK
- # 1 Best 53 MV/m (2010 Oe) at KEK,
- #2 Best 59 MV/m (2100) Oe at Cornell





KEK (Furuta et al, EPAC 06)
Best 53 MV/m (2010 Oe)

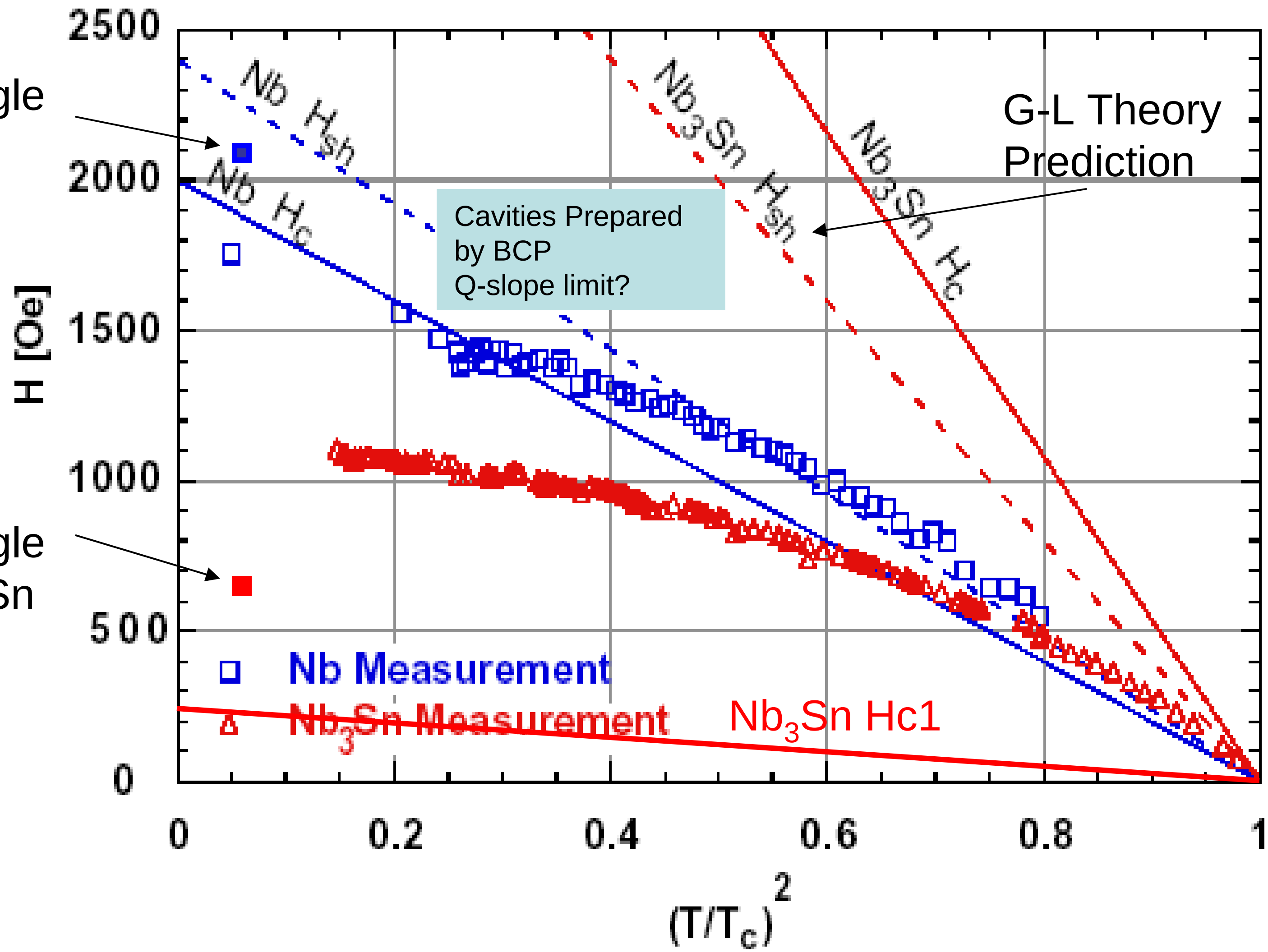


Cornell (Geng et al PAC 07)
Best 59 MV/m (2100 Oe)

Cornell Experimental Status (1996)
Measured RF Critical Field for : Nb_3Sn Using High Pulse Power
(Calibrated results with Nb)

Best single cell Nb cavity result

Best single cell Nb_3Sn cavity result



New from Theoretical Condensed Matter Physics

(Cornell: Jim Sethna)

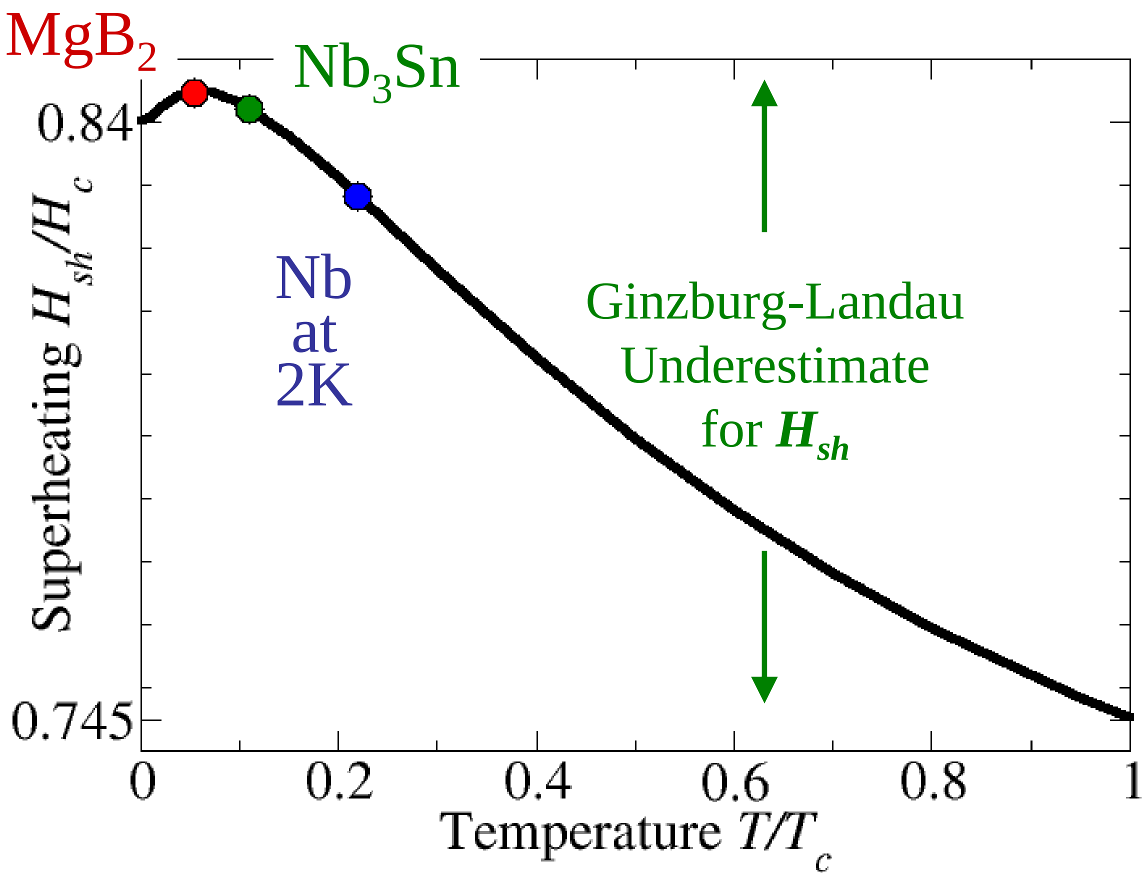
- Are the phenomenological Ginzburg-Landau Predictions correct?
- New approach goes beyond Ginzburg-Landau
- Theoretically calculates the maximum possible H_{sh} from advanced formulations of BCS theory
  - Eilenberger theory
- For perfect samples of practical materials
- Nb_3Sn, MgB_2 at realistic operating temperatures (2K)?
- Only valid for High kappa materials

Eilenberger (BCS) Results !

Superheating field $H_{sh}(T)$ from the Eilenberger Equations

And large κ (so not applicable for Nb)

13% larger ***Hsh*** at low ***T*** than Ginzburg-Landau estimate !



Hrf-critical = Hsh ~ 0.9 Hc

Which means

Theory gives hope for 100 – 200 MV/m !

- Eilenberger (BCS) Theory predicts
- $\boldsymbol{E_{acc}}$ ~ 120 MV/m for perfect Nb_3Sn
- and 200 MV/m for perfect MgB_2 !!
- Strong motivation for materials and cavity push
- But be prepared for a long road to realization
- Can we do it?
- At least 5 years of well supported R&D !