Limits in SRF Cavity Performance

Material/surface aspects

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2013 Tutor

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Acknowledgements

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Limits in SRF Cavity Performance

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Phenomenon/Integrated Properties

Intrinsic **Extrinsic**

Limits

- Fields

+ Heat

Actual Exposed Material

"Where all the atoms are"

"Less than 0.15 mm^3 matters"

- Mechanical
- Chemical
- Thermal

"Therapies"

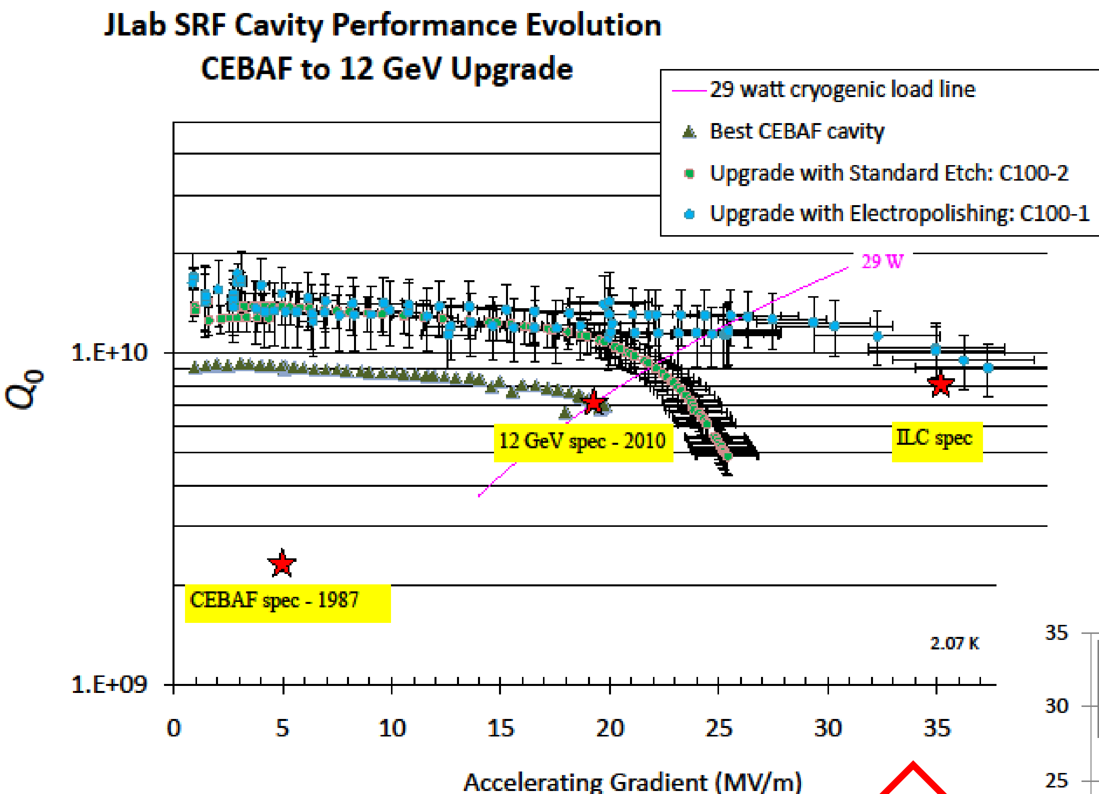
Actual Applied Processes

"What we can buy or make"

Real Materials

"Is our detailed understanding here adequate?"

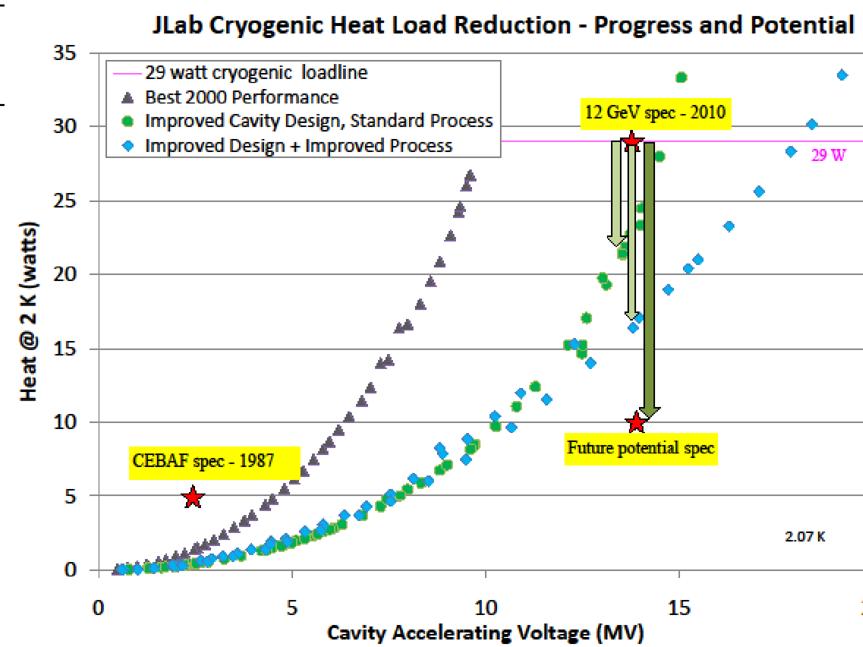
No



The key figures of merit are ***Q*** and **Accelerating Gradient.**
Together with structure geometry, these determine the **heat produced.**

same data

higher cryo costs



more compact accelerator

Phenomenon/Integrated Properties

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Extrinsic

- Multipacting
- Field emission
- *Geometrically enhanced fields*

Intrinsic

- BCS R_s
- thermal conductivity
- ρ_n
- flux penetration
- H_c
- T_c
- "residual R_s" = "other not controlled/understood losses"
  - Dominated by the material structure within λ of the surface.

Cavities' fabrication scheme

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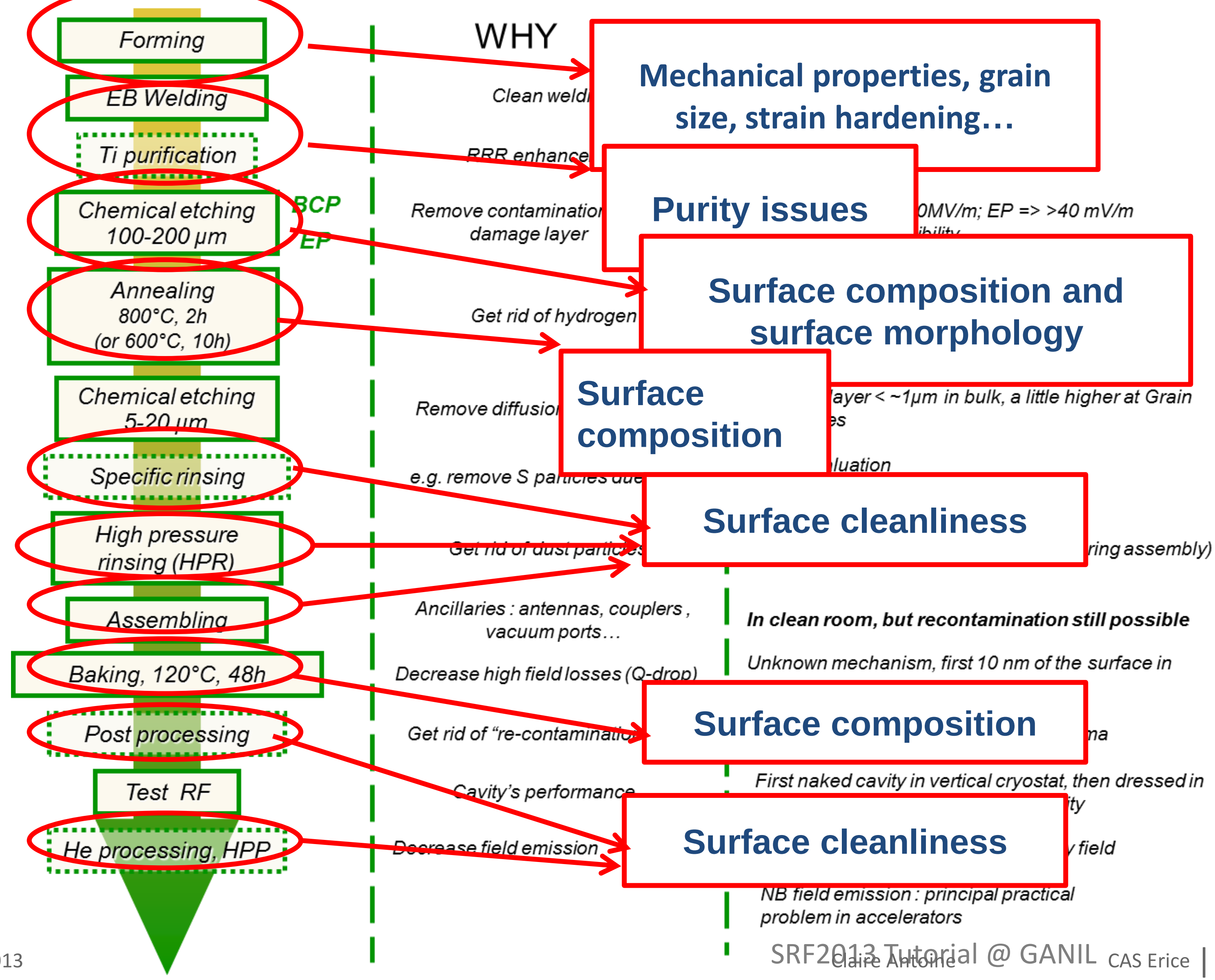
Step	WHY	COMMENTS
Forming		
EB Welding	*Clean welding*	*Nb = getter material.* *If RRR/ 10 @ welding => Q_0/10*
Ti purification	*RRR enhancement*	*RRR 300-400 now commercially available*
~~Chemical~~ etching 100-200 µm (**BCP**, **EP**, *CBP*)	*Remove contamination and damage layer*	*Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility*
Annealing 800°C, 2h (or 600°C, 10h)	*Get rid of hydrogen*	*Source of H: wet processes* *H segregates near surface in form of hydrides (= bad SC)*
Chemical polish 5-20 µm	*Remove diffusion layer (O, C, N)*	*Diffusion layer < ~1µm in bulk, a little higher at Grain Boundaries*
Specific rinsing	*e.g. remove S particles due to EP*	*Under evaluation* *HF, H_2O_2, ethanol, degreasing,…*
High pressure rinsing (HPR)	*Get rid of dust particles*	*Not always enough (recontamination during assembly)*
Assembling	*Ancillaries : antennas, couplers , vacuum ports…*	***In clean room, but recontamination still possible***
Baking, 120°C,12-48hr	*Decrease high field losses (Q-drop)*	*Unknown mechanism, first 10 nm of the surface in concern.*
Post processing	*Get rid of "re-contamination" ?*	*Under evaluation: dry ice cleaning, plasma*
Test RF	*Cavity's performance*	*First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility*
He processing, HPP	*Decrease field emission*	*RF power with/ without He to destroy field emitters (dust particles)* *NB field emission : principal practical problem in accelerators*

Cavities' fabrication scheme vs. surface and material properties



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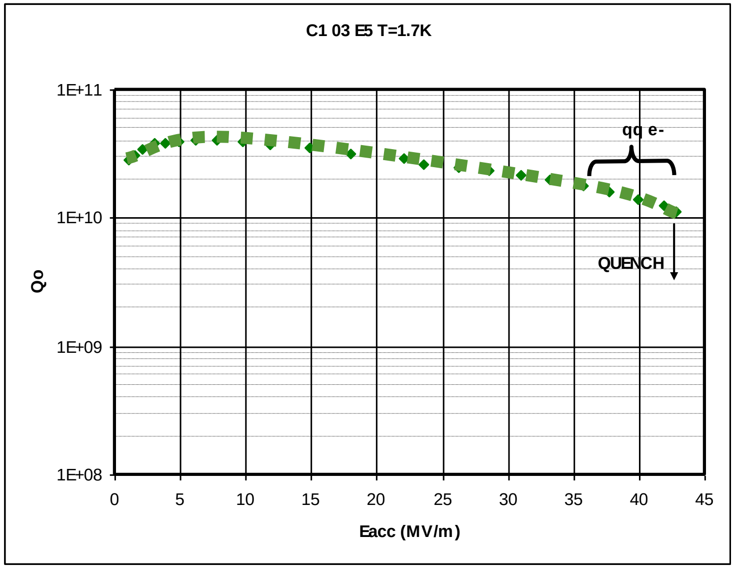
Niobium cavities



Typical performance

(CEA/Saclay- CARE-SRF project Cavity):

40-45 MV/m !

Niobium: **bulk, electropolished** and **baked**

…and **cleanroom** assembled

Practical issues

- we do not know the exact origin of the limitations:

classical theory (BCS) is not enough to fully predict RF observations,

- reproducibility not good

RF superconductivity: a surface phenomenon

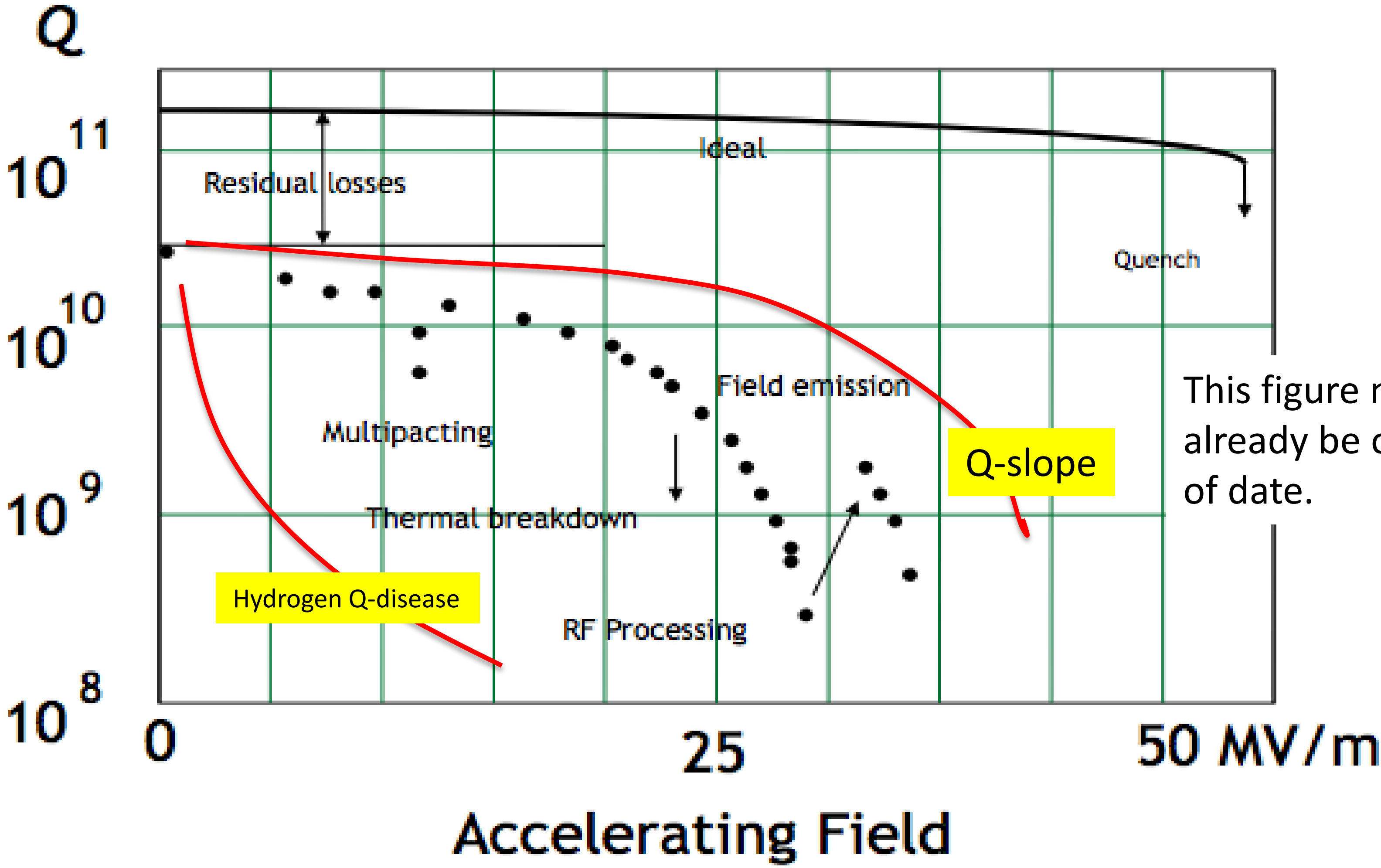
λ_L = field penetration depth
= where **thermal dissipation** occurs

Nb : **~ 50 nm**

R&D activities :

- surface , solid state physics; connection with cavities' behavior

Ideal vs Real Performance

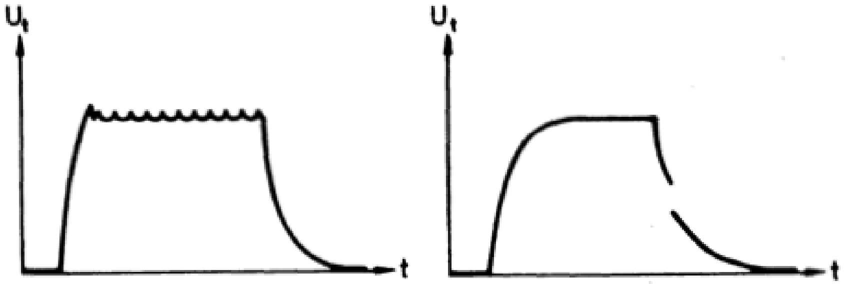


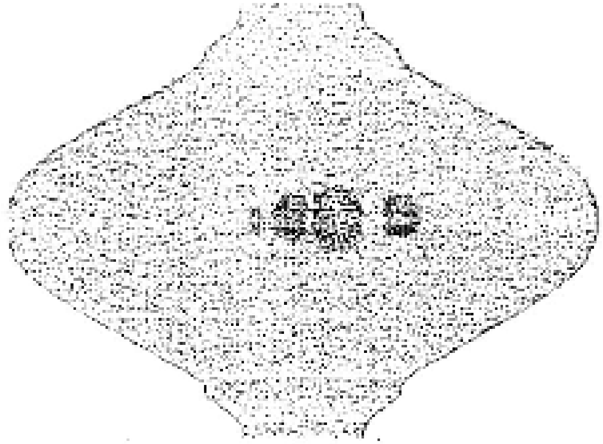
This figure may already be out of date.

Multipacting (MP)

Symptom of Multipacting

- Gradient stops rising despite more RF power is provided to cavity
  - “Barrier”
- Detection of X-rays
- Detection of electrons by biased probes at right place
- “wavy” transmitted and reflected power signal
- Detection of temperature rise
  - “hot spot” may move



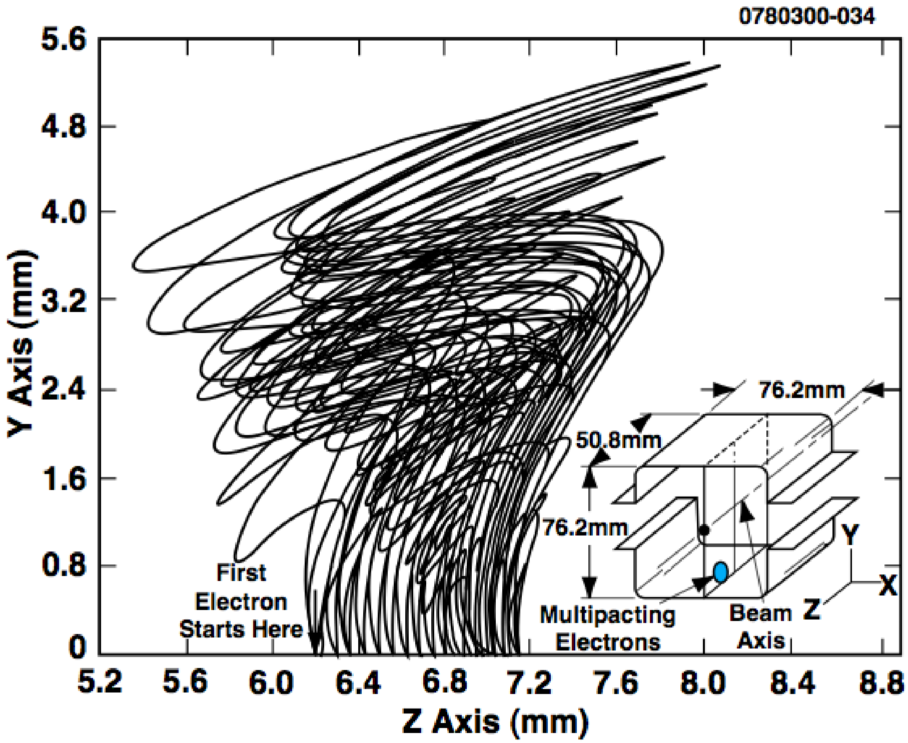


Symptom of Multipacting

- Barrier can be overcome if RF field is sustained (RF conditioning)
  - "Soft barrier" can be processed through in a few minutes
  - "Hard barrier" may take much longer time
- "Memory effect"
  - Some processed barrier may re-appear – "lost memory"
  - Some will not re-appear once processed – "memorized"
- Barrier usually has specific field range
  - Multipacting band width
- One cavity may have multiple barriers

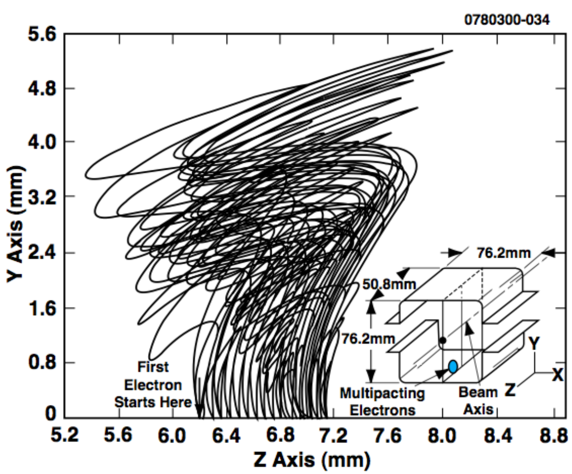
Physics of Multipacting

- Rapid growth of number of electrons from noise due to existence of conditions for resonant electron movement in cavity space
- Electron trajectories may occupy only a small volume near cavity surface due to “confinement effect” by RF magnetic field
- Confined electrons return to cavity surface
- Electrons gain energy due to acceleration by RF electric field
- Energetic electrons bombard surface, causing secondary electron emission
- Process becomes self sustaining when secondary electron emission coefficient of surface is larger than 1

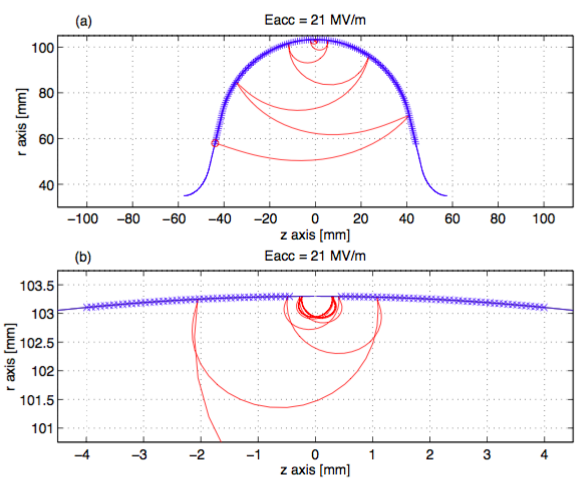


Understanding of Multipacting

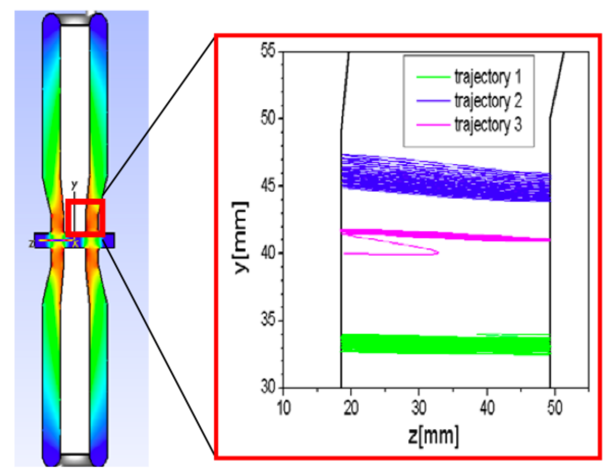
- One or more local areas might be involved in MP
  - 1-point MP (1-side MP)
  - 2-point MP (2-side MP)
  - …



1-point MP
Muffin-tin cavity



2-point MP
Elliptical β=1 cavity



2-point MP
Half-wave β<1 cavity

Understanding of Multipacting

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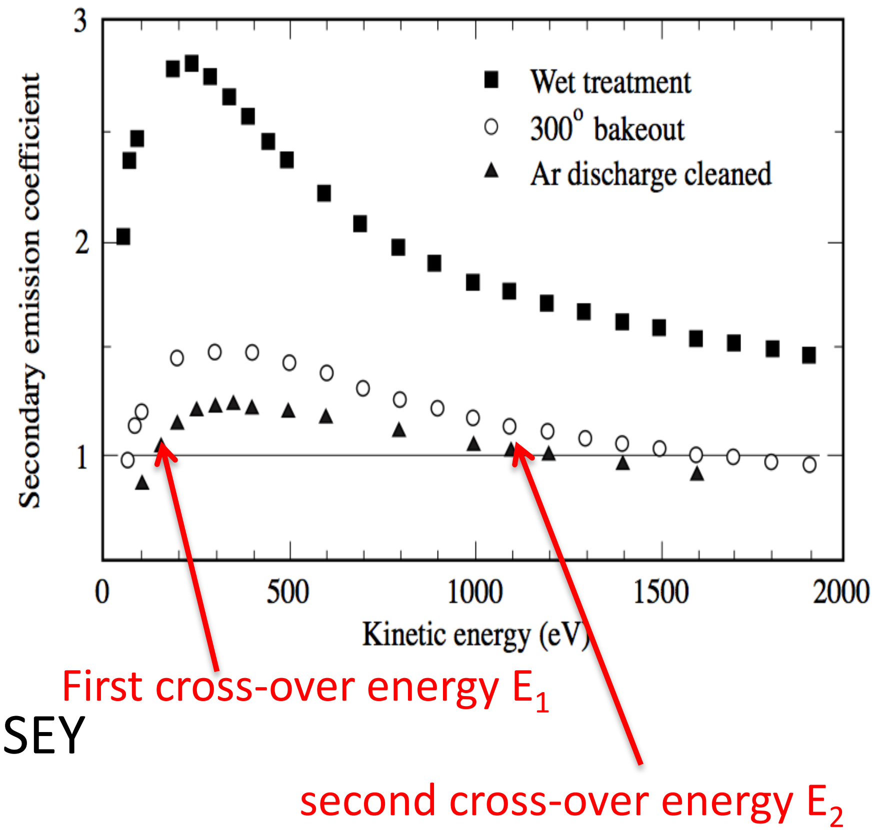
- Secondary electron emission
  - Secondary electrons are low energy 2-5 eV
  - Secondary electron yield (SEY) depends on impact energy of primary electrons
    - First cross-over energy E_1
    - Second cross-over energy E_2
  - SEY is a material property and sensitive to surface condition
    - Electron bombardment reduces SEY
      - Conditioning effect



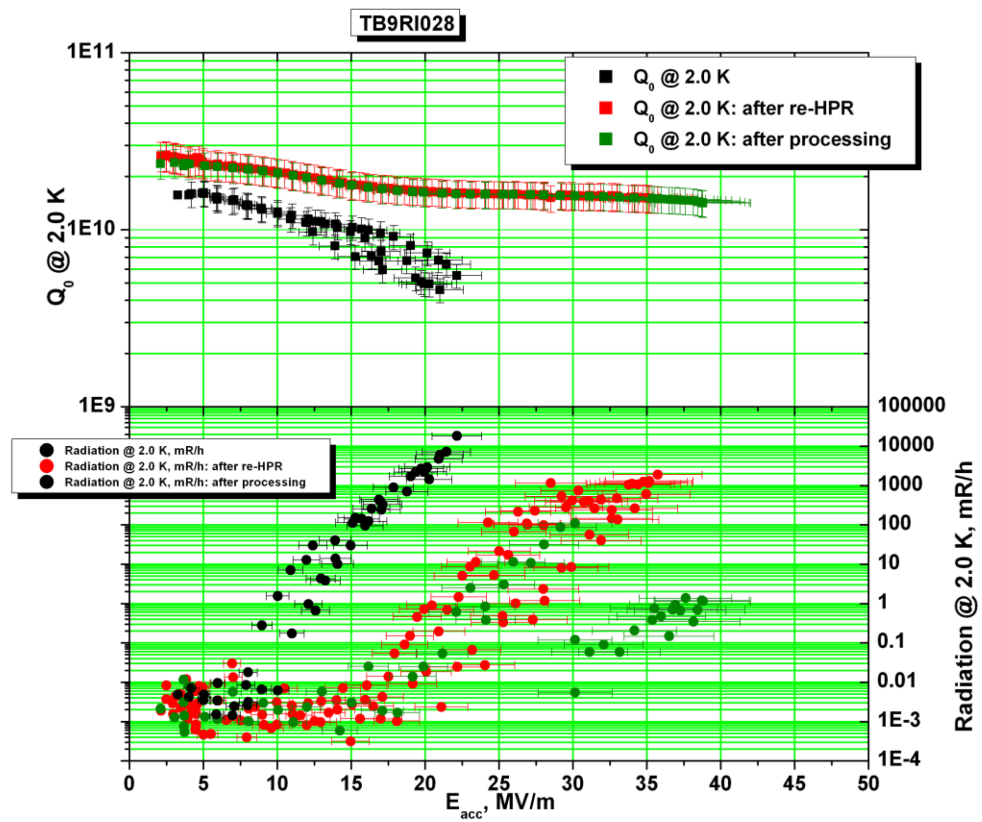
Last Word on Multipacting

- Elliptical β=1 cavities are reaching very high gradients at 1300 MHz with no known limit due to hard MP
  – Soft MP barriers appear to ubiquitous
- MP issue needs close attention in these cavities:
  – Elliptical β<1 cavities at 500-900 MHz
  – All TEM class cavities
- Experimental measurements are still essential in assessing MP characteristics of new cavity designs

Field Emission

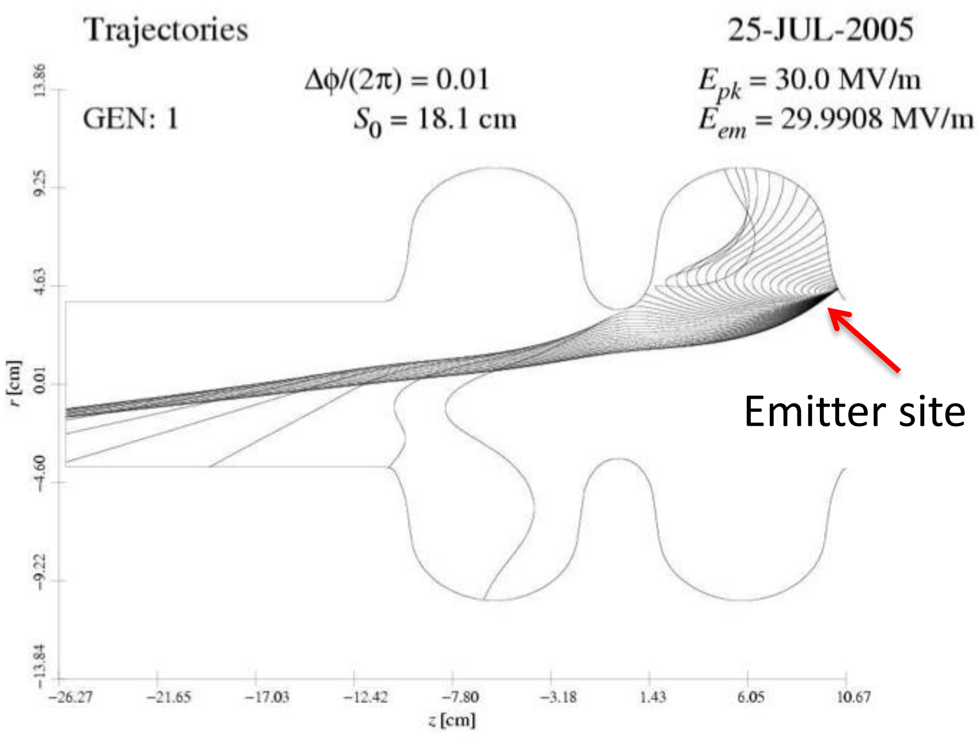
Symptom of Field Emission

- Detection of ionization radiation at cavity or remote to cavity, such as above top plate of test stand
  - Mostly X-rays
  - Sometimes neutron also for high gradient cavities
- Detection of free electrons intercepted by biased probes or Faraday cup placed inside cavity
- May be
  - Be stable
  - "Process" away
  - Become unpredictably worse



Physics of Field Emission

- Electron emission from site of "field emitter"
- Emitted electrons captured and accelerated by RF field
- Energetic electrons strike cavity wall



Physics of Field Emission

- Electron emission from site of "field emitter"
  - Quantum mechanical process – tunneling effect
  - Fowler-Nordheim Law: note exponential field dependence of tunneling current

$$I_{\mathrm{FN}} = j_{\mathrm{FN}} A_{\mathrm{FN}} = A_{\mathrm{FN}} \frac{e^3 E^2}{8\pi h \Phi t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_e\Phi^3}v(y)}{3heE}\right)$$

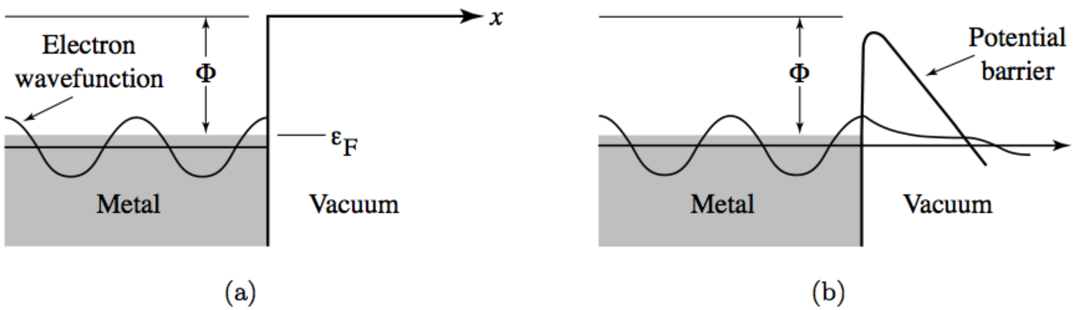


Figure 3.2: Electrostatic potential of the metal–vacuum interface. (a) No electric field applied, (b) with an electric field applied.

Physics of Field Emission

- Modified Fowler-Nordheim
  - Electric field enhancement factor β_{FN}
    - Typical value 50-500 for SRF cavity
  - Effective emitter area A_{FN}
    - Typical value $10^{-18} - 10^{-9}$ m^2

$$I_{\rm FN} \;=\; j_{\rm FN} A_{\rm FN} = A_{\rm FN} \frac{e^3 (\beta_{\rm FN} E)^2}{8\pi h \Phi t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_{\rm e}\Phi^3}v(y)}{3he\beta_{\rm FN} E}\right)$$

Physics of Field Emission

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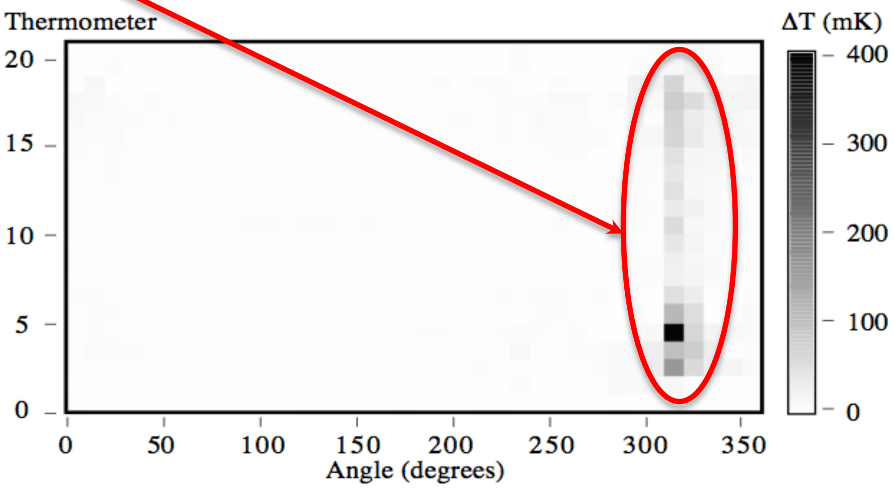
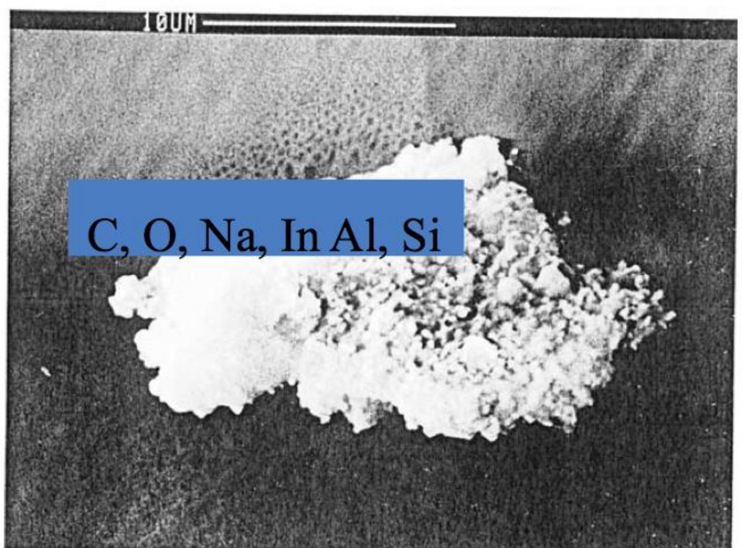
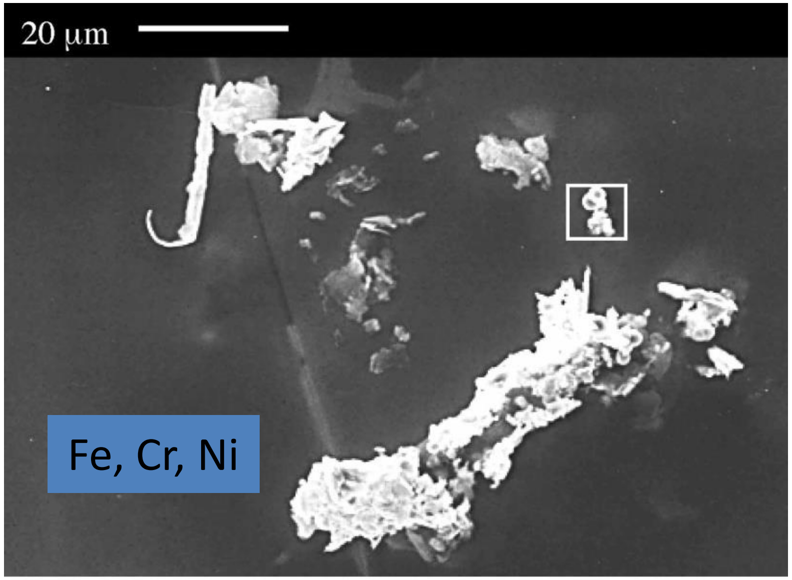
- Emitted electrons captured and accelerated by RF field
  - This consumes RF energy stored in cavity and hence cause rapid Q_0 decline (recall exponential increase in current as field is raised)
- Energetic electrons strike cavity wall
  - Deposit heat and cause local rise of wall temperature
    - Cause line heating at cavity wall because electrons emitted at different RF phase angle follow different trajectory in the plane defined by cavity axis and emitter location
    - Also contribute to Q decline
  - Produce X-rays due to Bremsstrahlung Effect
  - May produce neutron through (γ,n) reaction
    - Will cause activation



Field Emitters

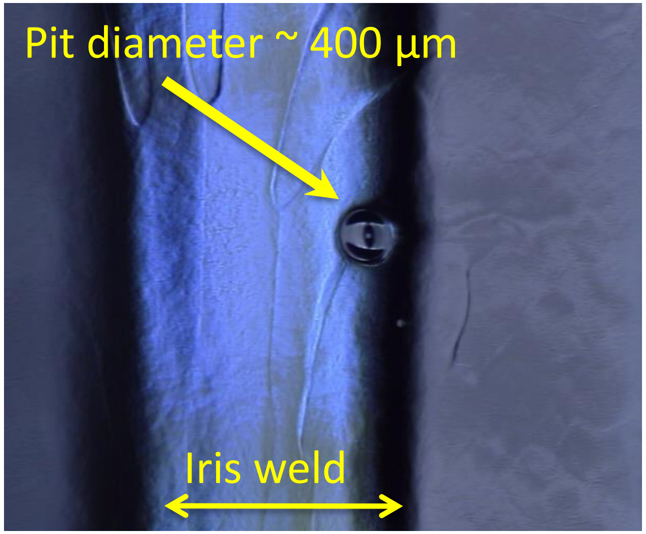
- Microscopic particles
  - from external source, consist foreign material
  - Airborne
  - From cavity assembly hardware and tool

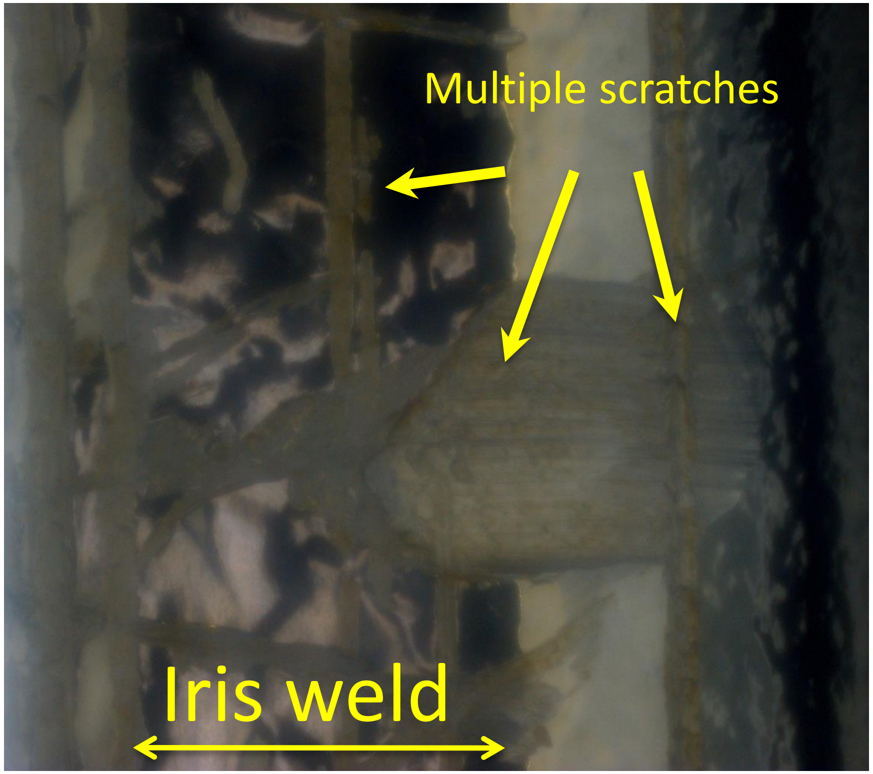




Field Emitters

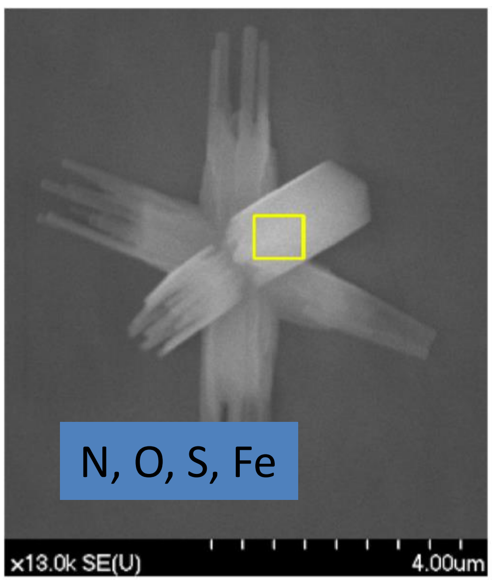
- Geometrical defects
  - Is permanent feature, is part of cavity
  - Pits (from fabrication)
  - Scratches
    - HPR wand damage

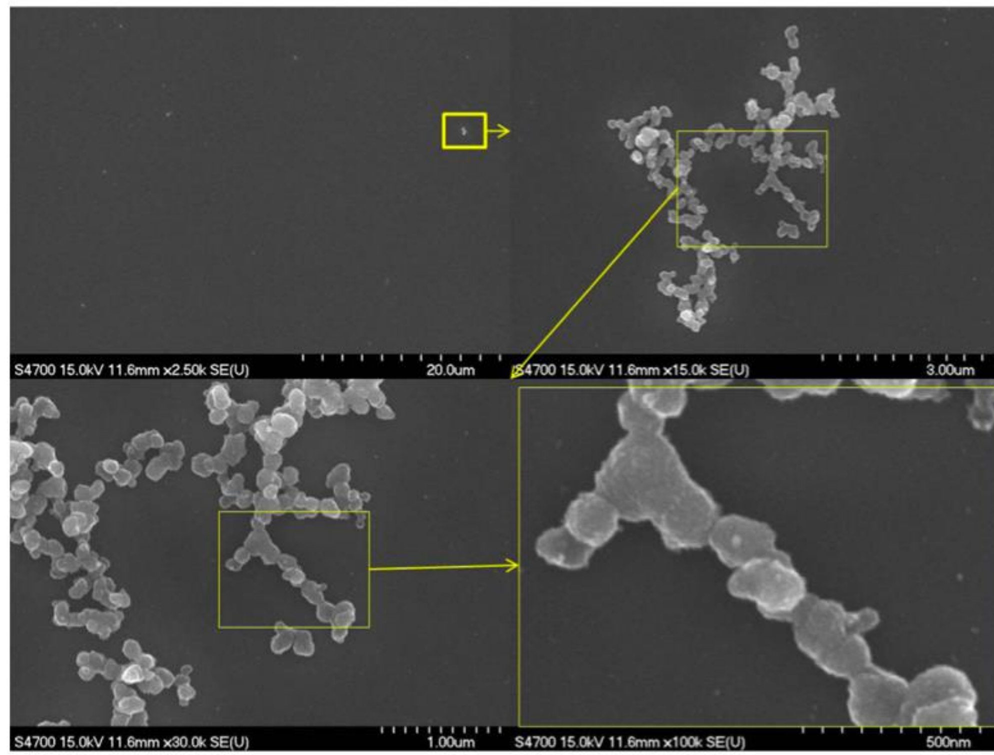




Field Emitters

- Contaminants from surface processing
  - Niobium oxide granules (electropolished surface)
  - Sulfur
    - And other elements

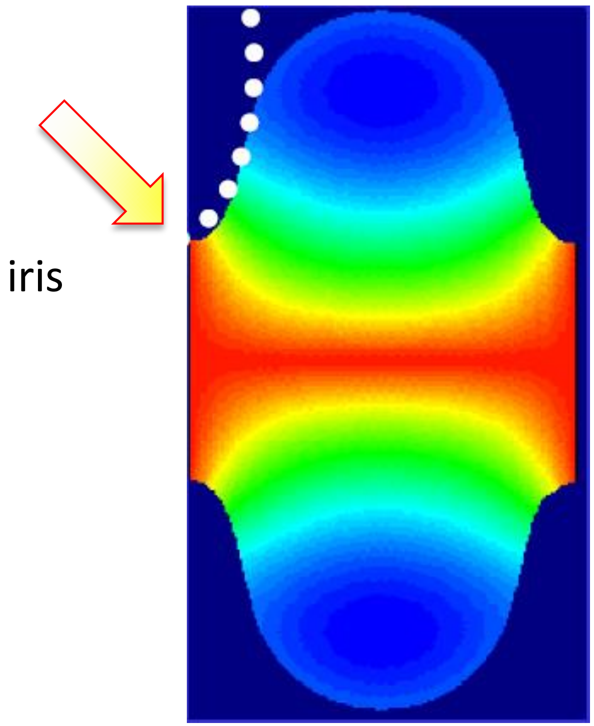




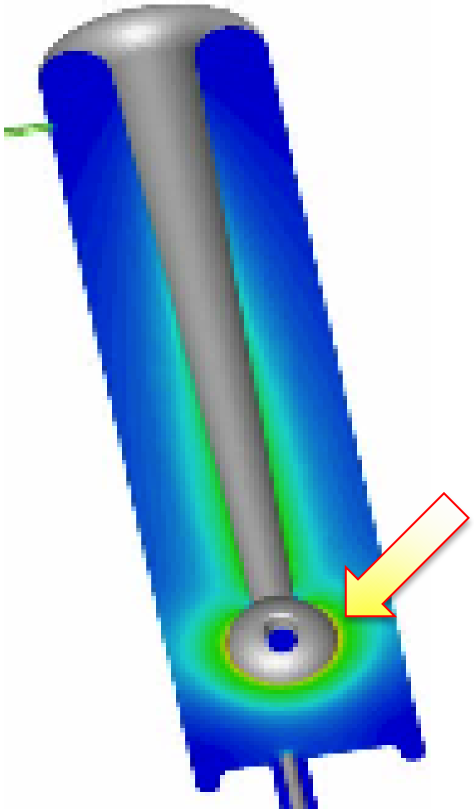
Courtesy X. Zhao

Understanding of Field Emission

- Field emission is primarily an electric field effect
  - High electric field region (arrow) in cavity is critical



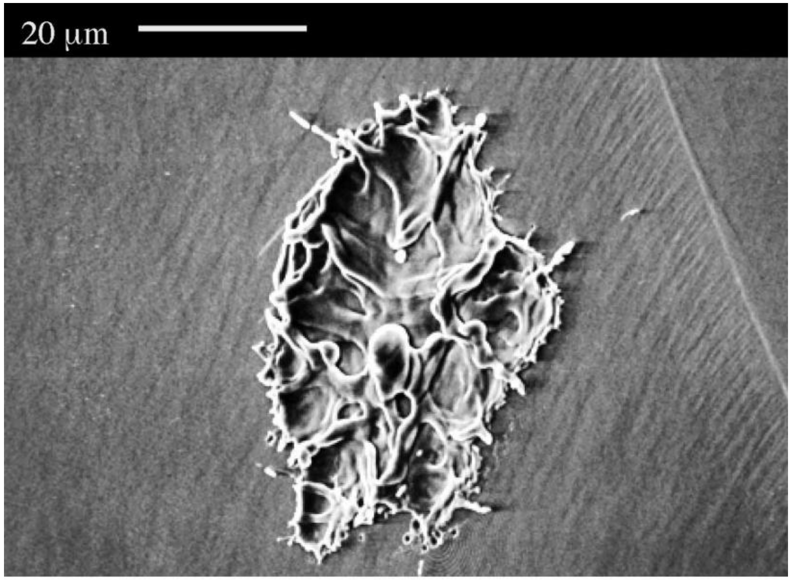
Elliptical cavity (TM-class)



Half-wave cavity (TEM-class)

Understanding of Field Emission

- Processing events – extinction of field emitter
  - Micro-tip melting, gas release
  - Discharge/plasma
  - Breakdown/emitter destruction



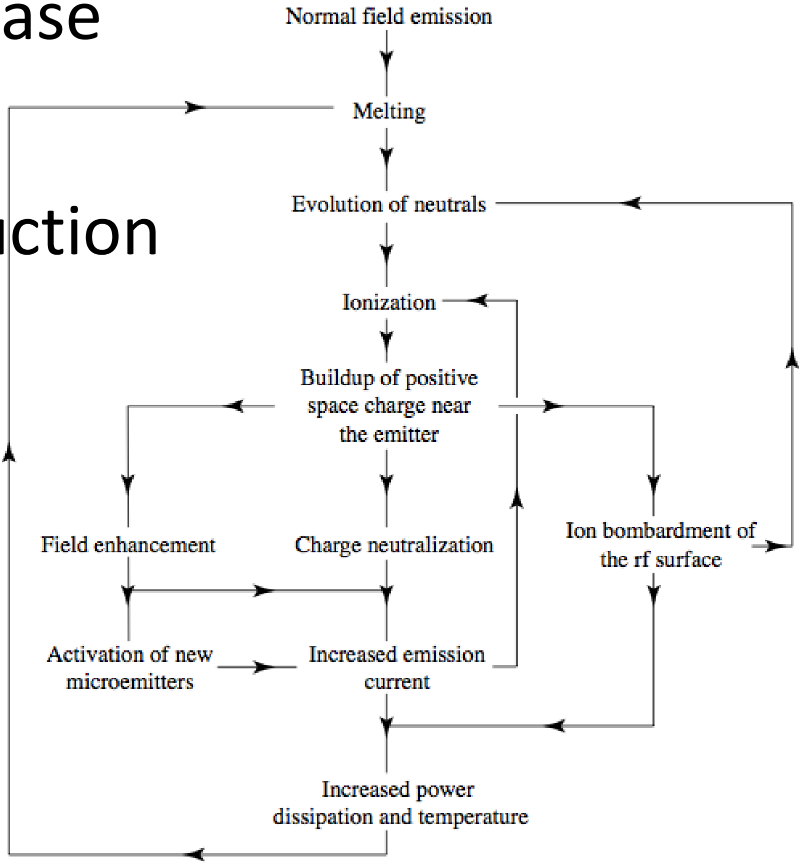
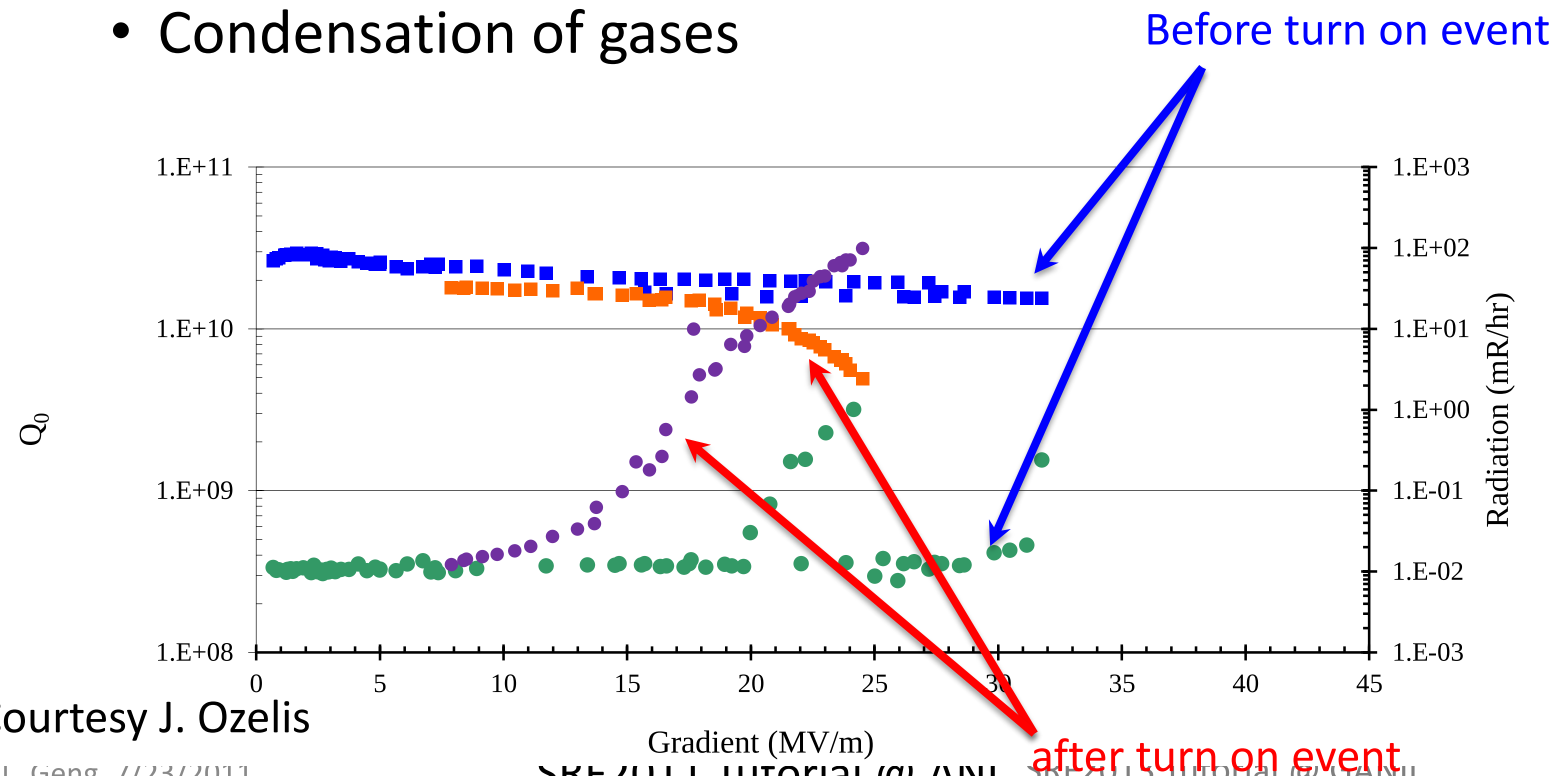


Figure 5.36: Flow chart of the feedback loop leading up to rf processing.

Understanding of Field Emission

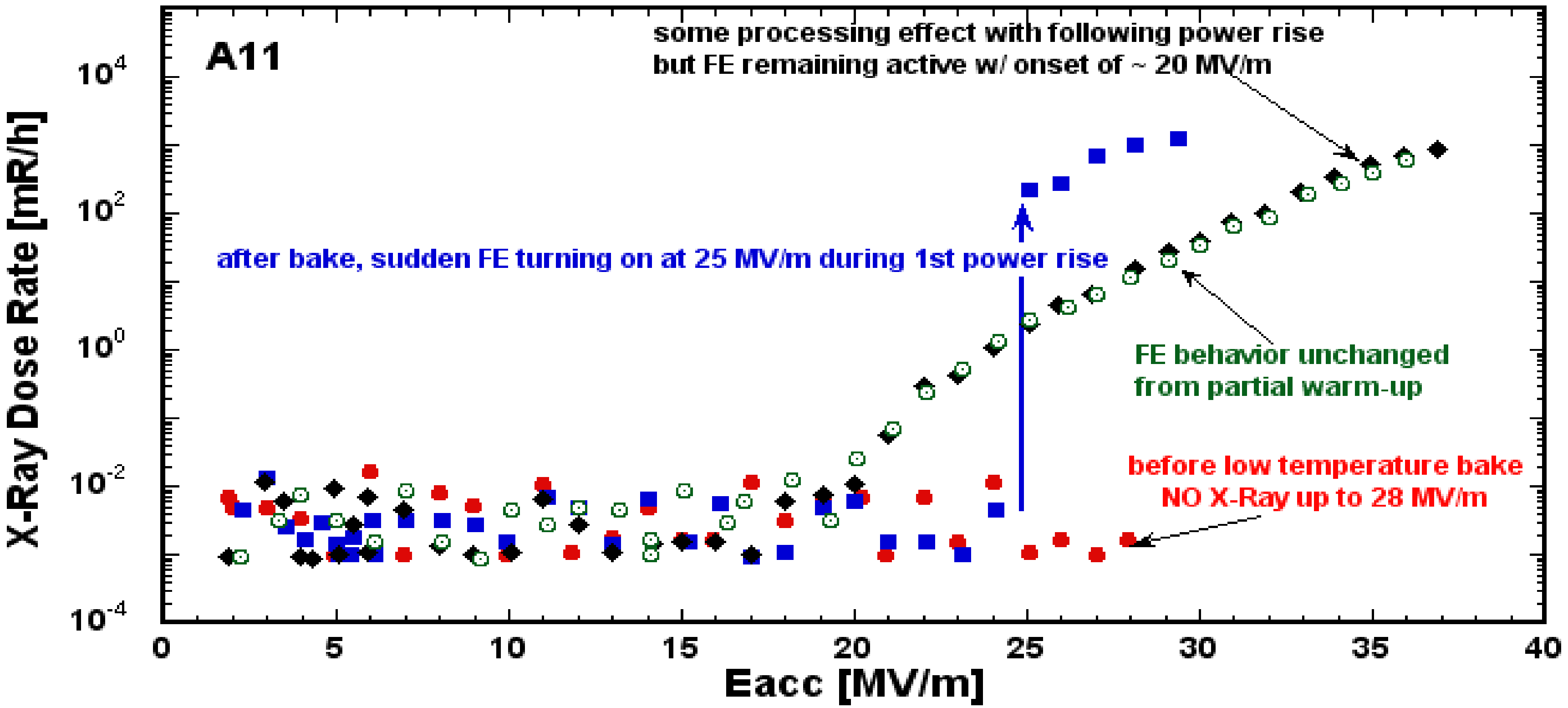
- Field emission turn on events
  - Activation of field emitter
    - Arrival of particles
    - Condensation of gases



Courtesy J. Ozelis

Understanding of Field Emission

- Field emission turn on events
  - Activation of field emitter
    - Baking (120 °C) induced (for electropolished cavity)



Avoiding Field Emission

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- Post-Chemistry Cleaning
  - Ethanol rinsing
  - Ultrasonic cleaning (De-ionized water + detergent)

B. van der Horst, SRF2007

Avoiding Field Emission

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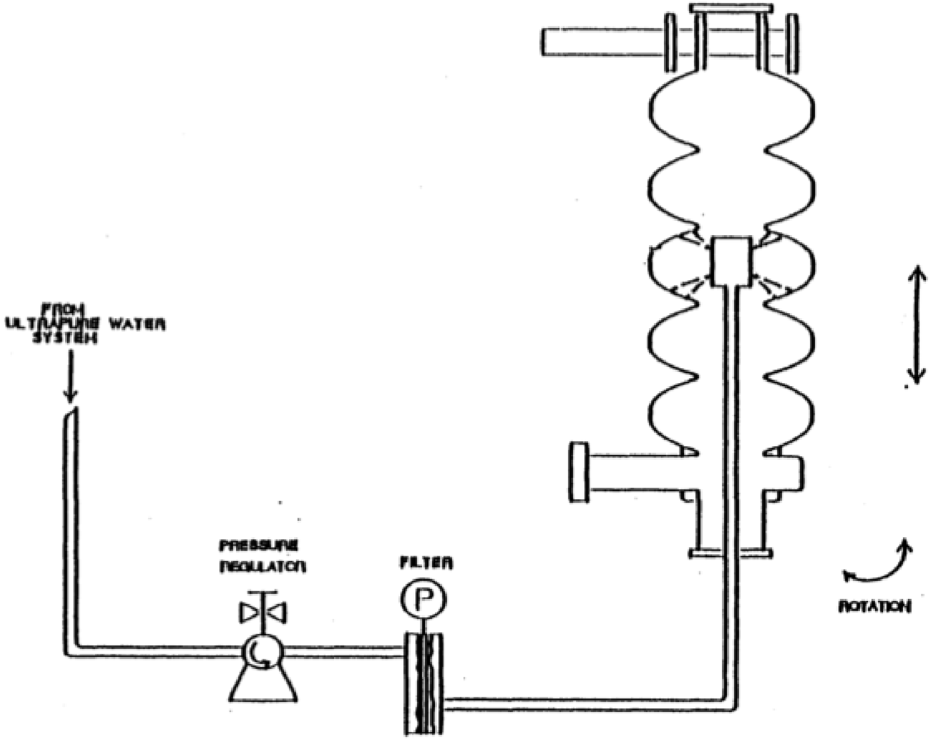
- High Pressure Water Rinsing (HPR)
  - De-ionized water, 18 MΩ-cm resistivity
  - 1300 PSI pressure

(click photo for video)



Courtesy P. Kneisel

Avoiding Field Emission

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- Clean room assembly
  - Class-10

Avoiding Field Emission

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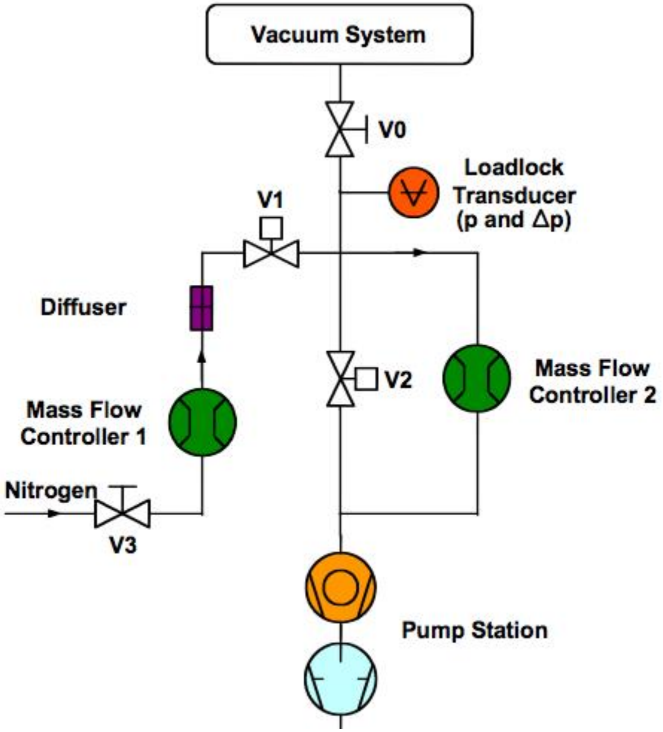
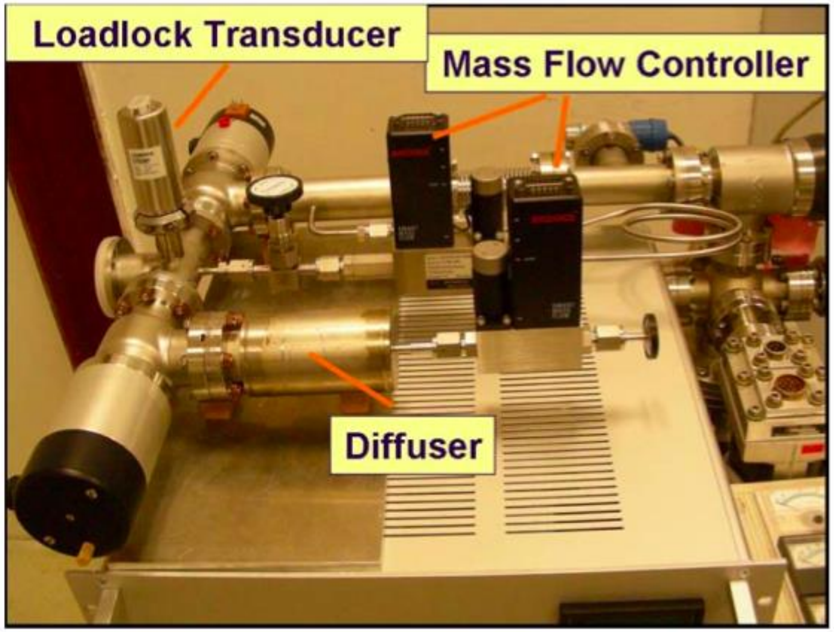
- Slow pump down
  - Prevent re-contamination
- Oil-free pumping system





K. Zapfe and J. Wojtkiewicz, SRF2007

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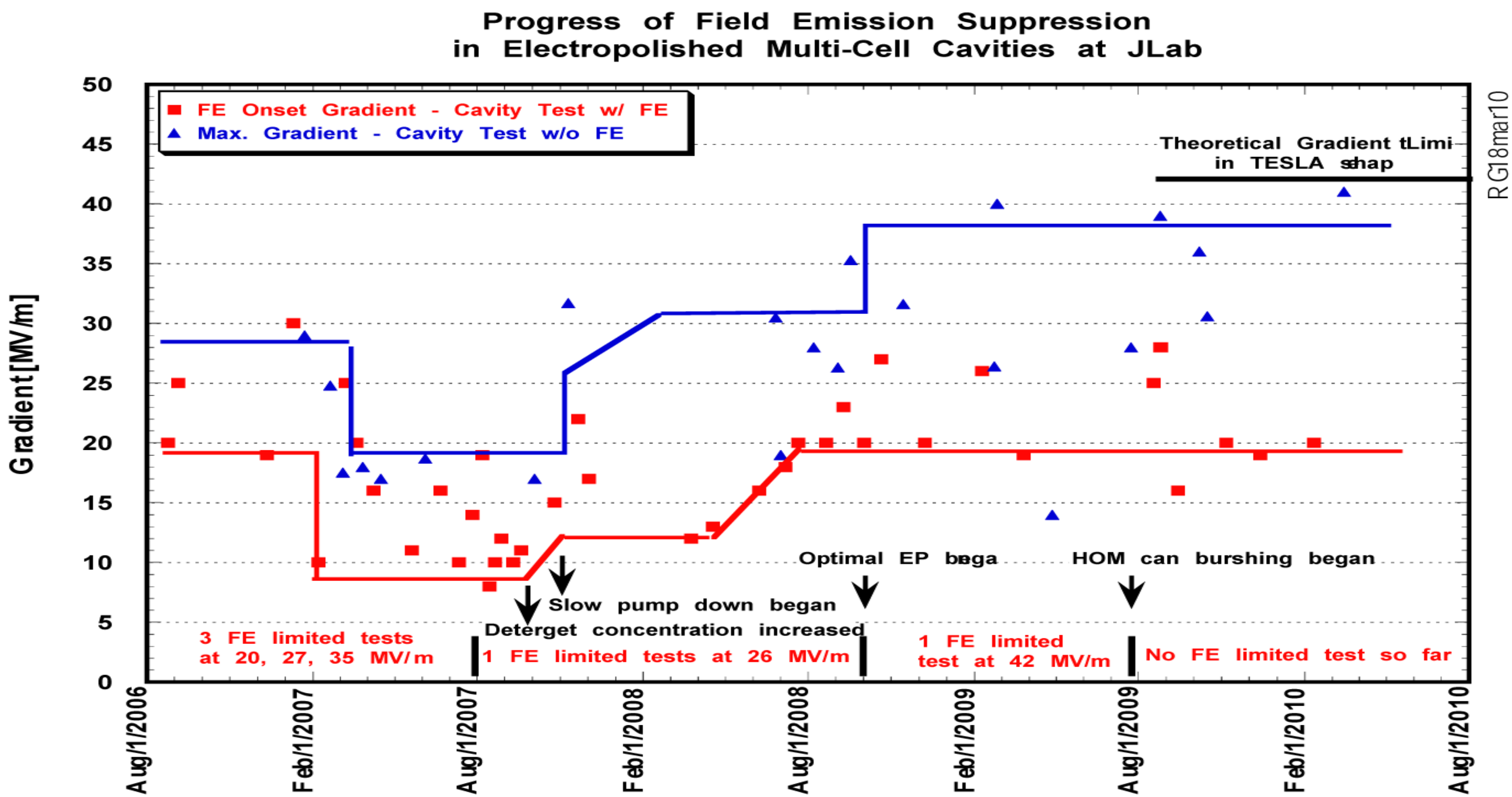
Last Word on Field Emission

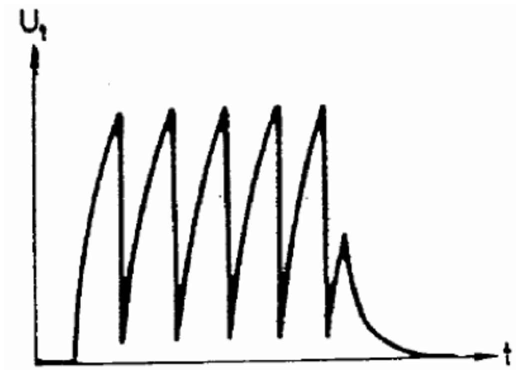


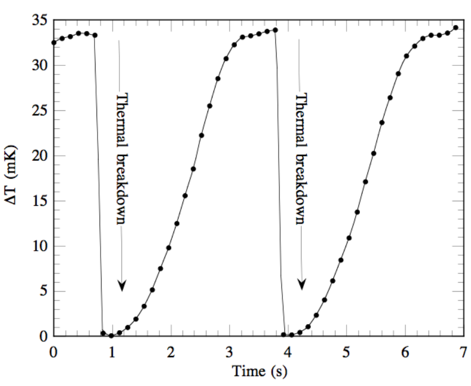
Progress has been made in recent years in reducing field emission. “Field emission free” cavity vertical testing of 1 meter long 9-cell 1300 MHz cavities has been reported at DESY, FNAL, JLab, KEK in gradient range of 35-45 MV/m. Much less cavities are limited by field emission. But challenges remain toward reliable control of field emission. Such as “sudden field emitter turn on” at high gradient, degradation from vertical test to cryomodule test. Plenty room for innovation and creativity.

Quench

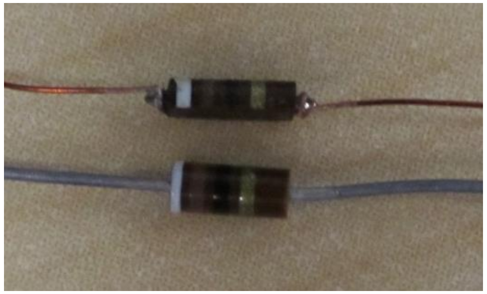
Symptom of Quench

- Sudden collapse (<ms time scale) of field in SRF cavity
  - Field may self recover
  - Or may not
- Detection of temperature rise at cavity wall near quench source
  - Can be as high as a few K



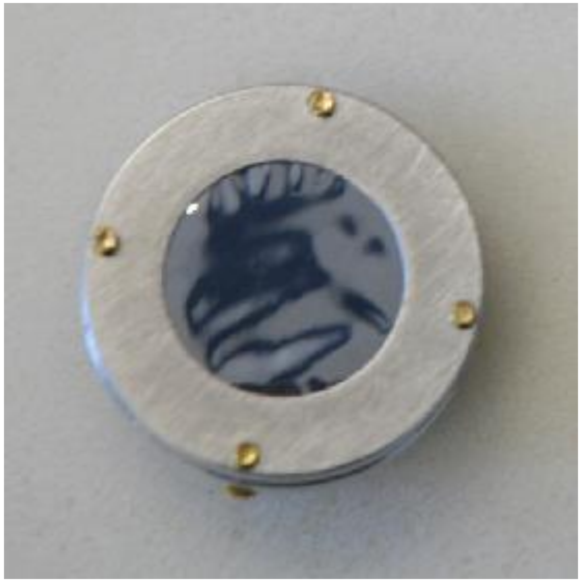


Quench Diagnostic
Commonly Used Heat Pulse Detectors



Allen-Bradley
carbon resistor
100 Ω, 1/8 W

Cernox



Cornell OST

Used at 1.8 K for defect localization

Physics of Quench

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- Quench caused by field emission
  - Heat deposition at electron bombardment site (earlier slides)
- Quench caused by multipacting
  - Heat deposition at electron bombardment site(s)
- Quench caused by resistive heating of local normal conducting defect
  - Thermal breakdown
- Quench caused by growing normal conducting region driven by magnetic field
  - “magneto-thermal” breakdown
- Quench caused by uniform heating (Global Thermal Instability)
- Ultimate limit: quench due to RF critical field

Physics of Thermal Quench

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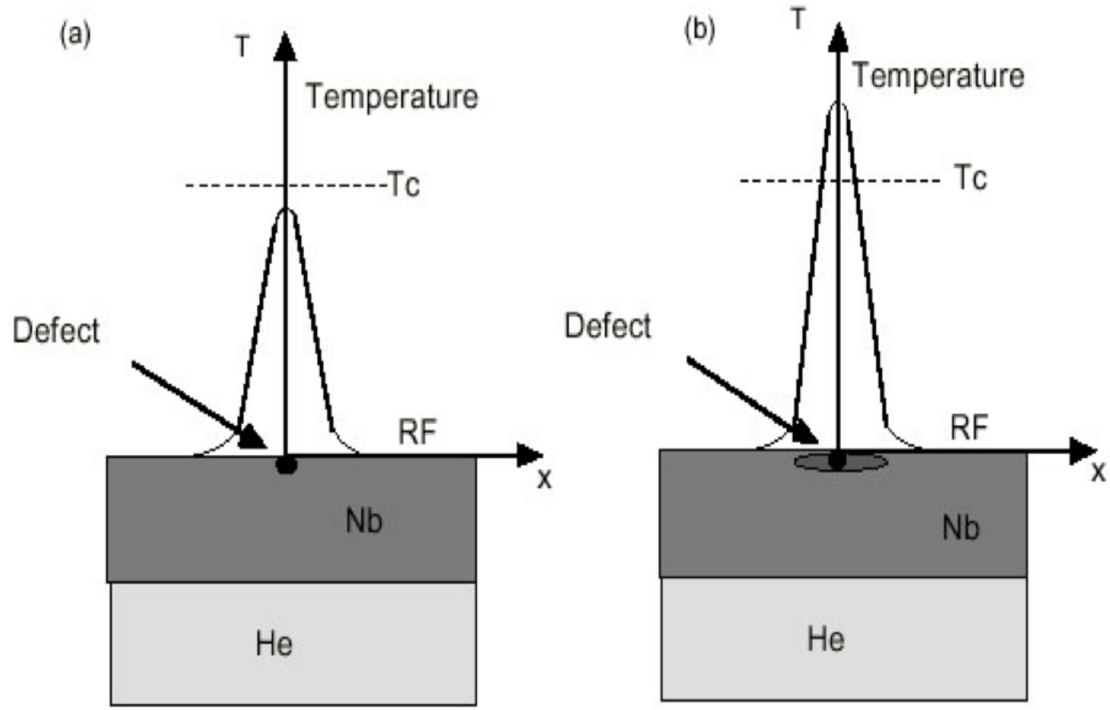
- Power dissipation in normal conducting defect generates heat
- Poor thermal conductivity of superconducting wall limits heat conduction
- This causes temperature rise to exceed T_c (9.25 K) in surrounding superconducting region
- This causes additional resistive heating
- The normal conducting region grows rapidly, leading to quench

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |\mathbf{H}|^2$$

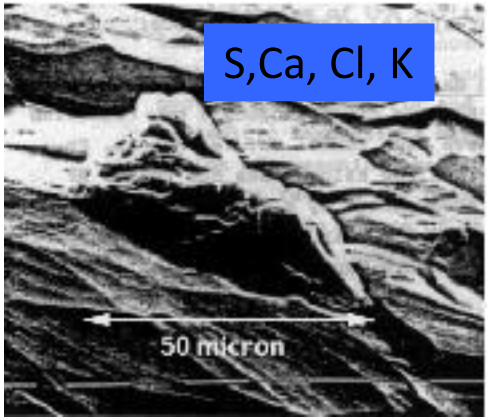
Rs: nΩ, s.c.; mΩ, n.c.

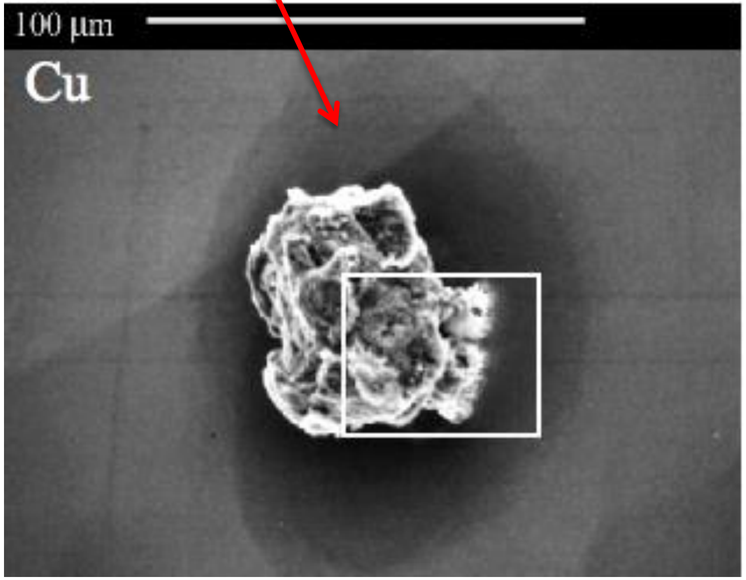


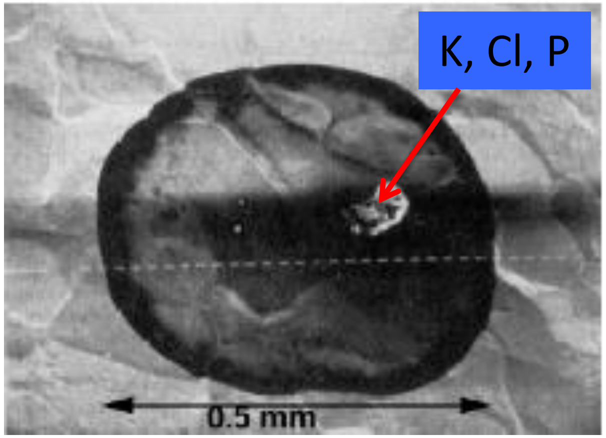
Courtesy H. Padamsee

Defects

- N.C. defect with foreign material
  - inclusion
  - Stain
  - Copper particle







50-500 µm

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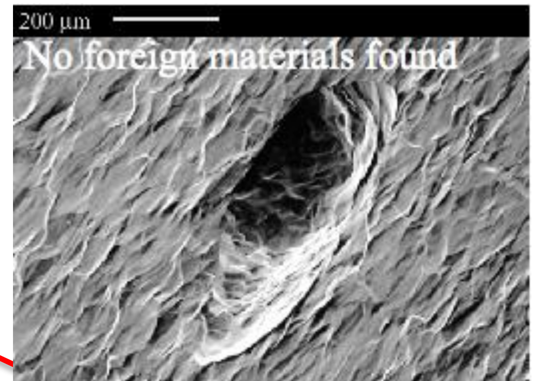
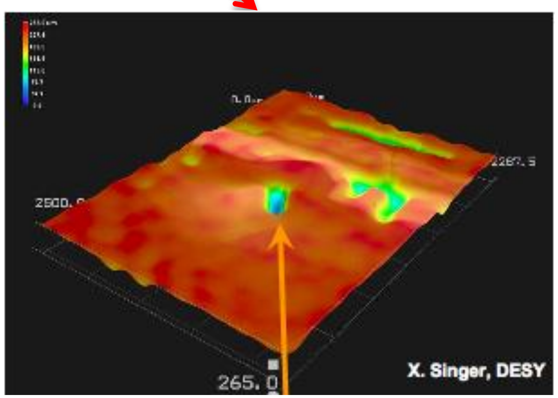
Defects

- Geometrical defect (no foreign material)
  - pit
  - Bump
  - hole





200-800 µm

Courtesy W. Singer

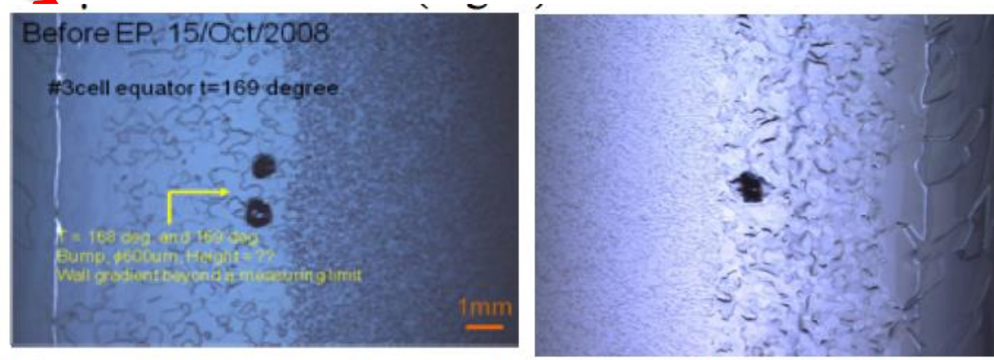


Figure 2: Defects observed near quench site of AES1(L) & AES3(R), limited at 16 & 21 MV/m, respectively. These circular defects have a diameter of ~ 600 µm and are outside the equator EBW (5-10 mm from weld seam).

Courtesy H. Hayano, K. Watanabe

Understanding of Thermal Quench

- Thermal breakdown field is determined by
  - Defect size (r_d)
  - Defect surface resistance (R_d)
  - Thermal conductivity of wall material (~ Tc)
  - Heat transfer across Nb/LHe interface (Kapitza)

$$H_{\mathrm{tb}} = \sqrt{\frac{4\kappa_T(T_{\mathrm{c}} - T_{\mathrm{b}})}{r_{\mathrm{d}} R_{\mathrm{d}}}}.$$

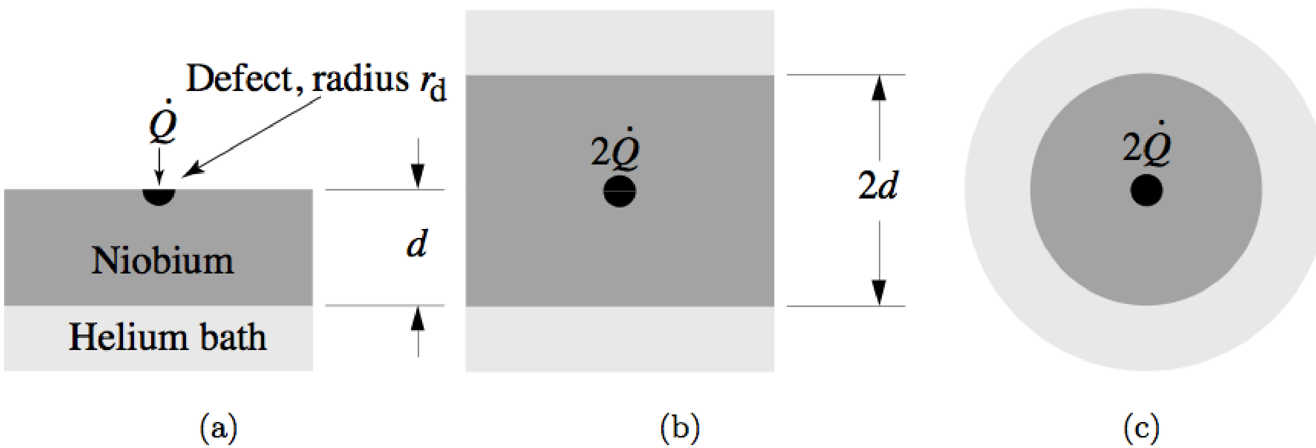
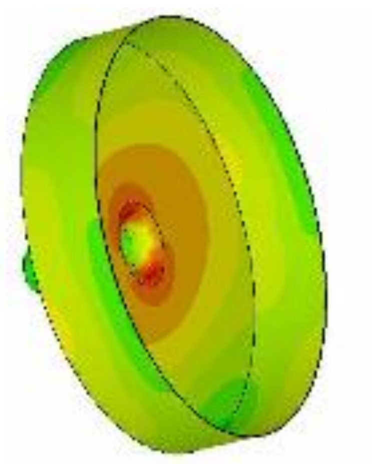


Figure 3.10: Geometry used to determine the thermal breakdown field due to a defect.

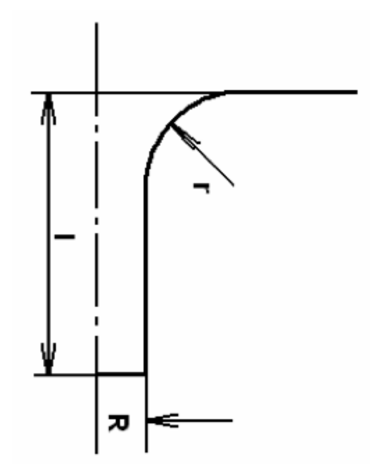
Understanding of Magneto-Thermal Quench

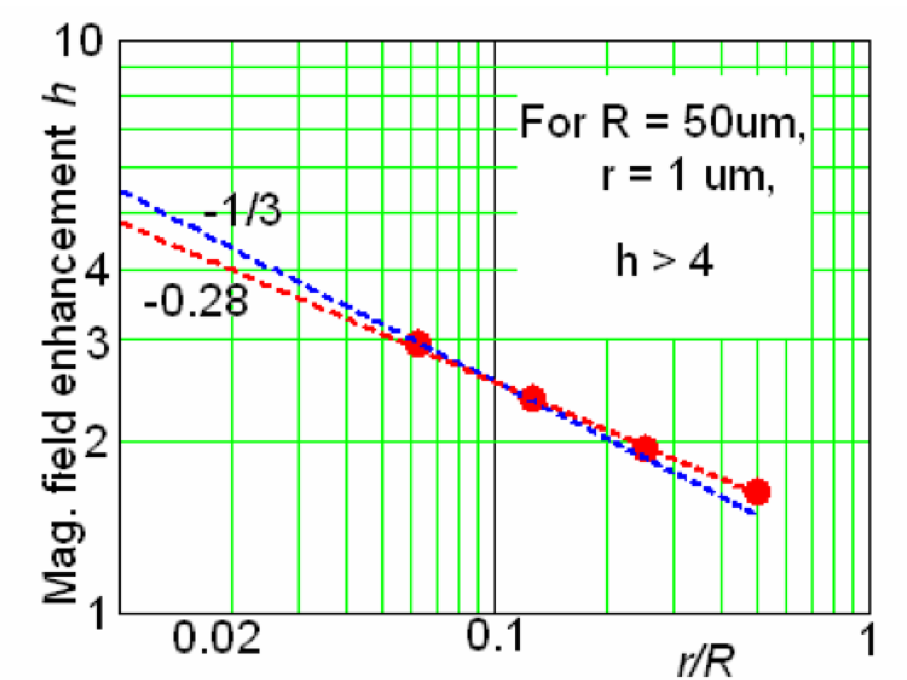
Jefferson Lab

- Magneto-thermal breakdown is determined by
  - Local magnetic field enhancement factor $h \propto (r/R)^n$
  - Thermal conductivity of wall material ($< T_c$)

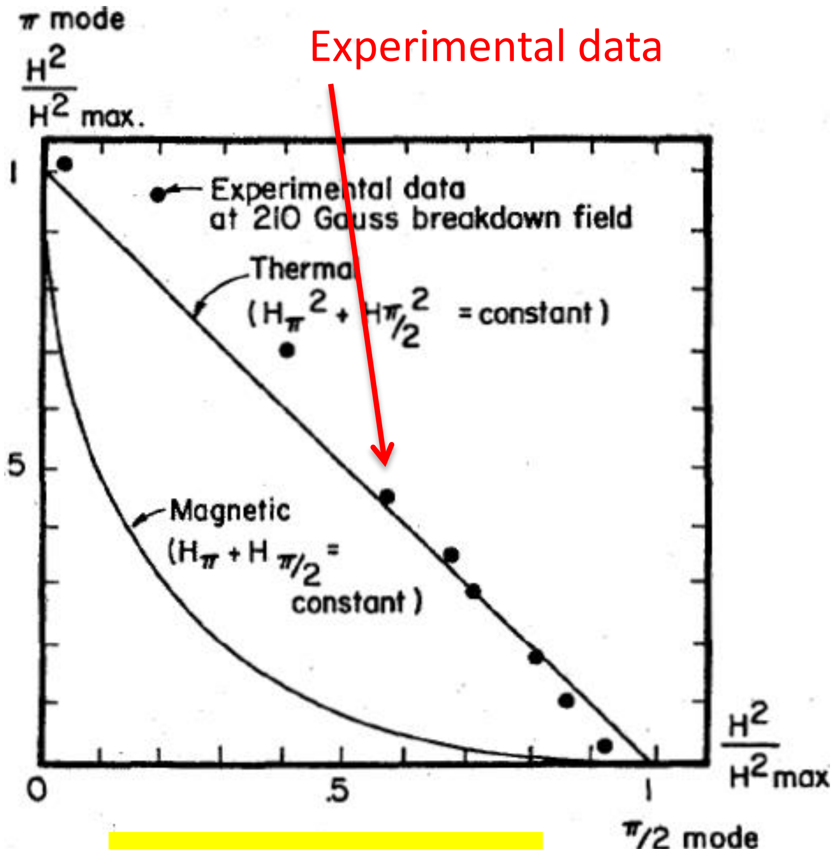


Courtesy V. Shemelin



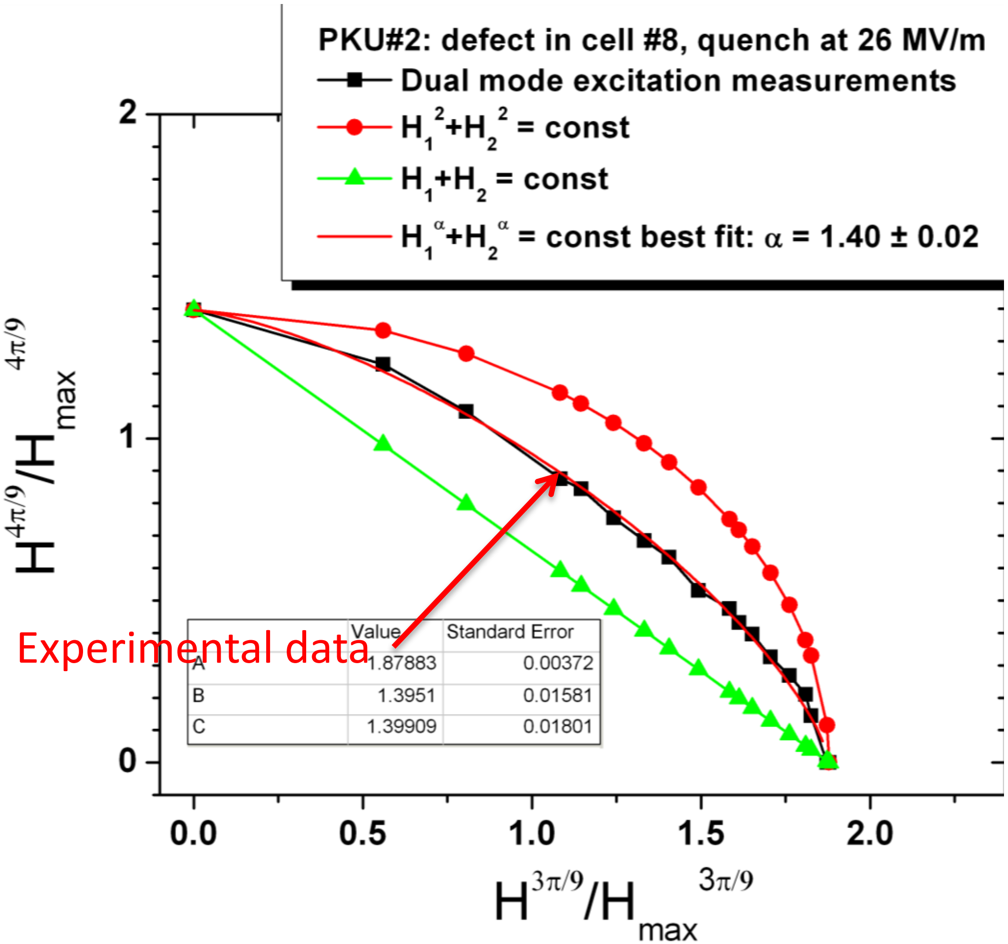


Understanding of Thermal and Magneto-Thermal Quench



Thermal breakdown

Courtesy H. Padamsee

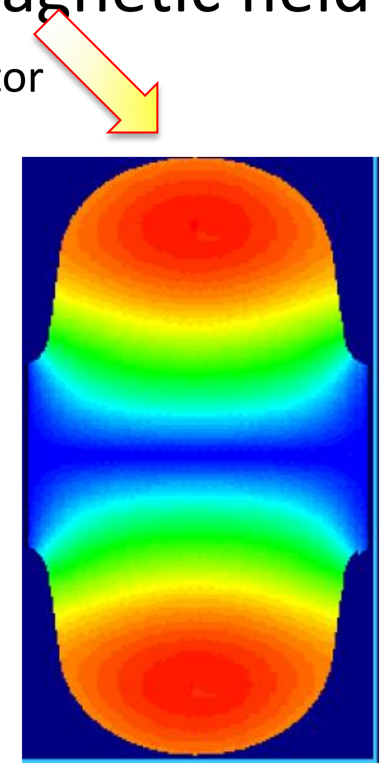


Magneto-Thermal breakdown

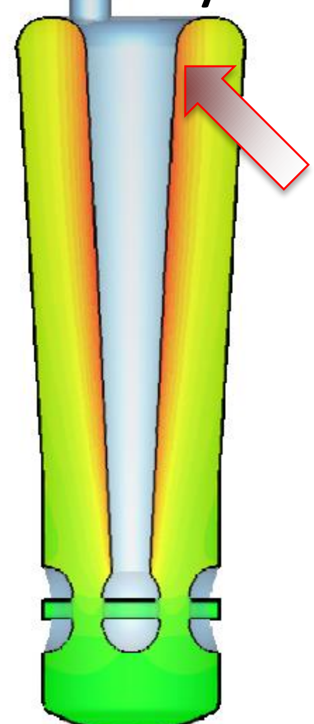
Courtesy G. Eremeev

Understanding of Quench

- Quench is primarily a magnetic field effect at surface defects
  - High magnetic field region (arrow) in cavity is critical



Elliptical cavity (TM-class)



Half-wave cavity (TEM-class)

Overcoming Magneto-Thermal Breakdown

Jefferson Lab

- Produce smooth surface = avoid having defects
  - Global mechanical polish

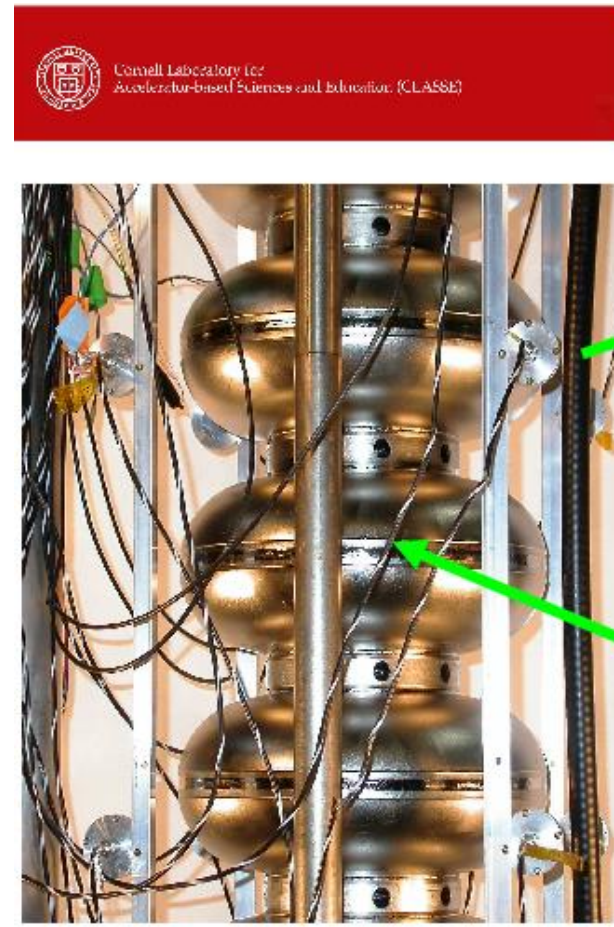
Courtesy C. Cooper

Overcoming Magneto-Thermal Breakdown

Jefferson Lab

- Removal quench-causing geometric defects
  - First localize defect
    - OST for rapid quench location
  - Then assess quench region
    - high-resolution optical inspection

Courtesy H. Hayano



Courtesy Z. Conway

SRF2011 Tutorial @ ANL

Overcoming Quench

Jefferson Lab

"Knobs" for improved reproducibility in overcoming local quench at very high gradient of 40-50 MV/m

Material
Nb: > 2000 Oe (exp.)
2400 Oe (the.)
Nb_3Sn: > 4000 Oe (the.)

Achievable gradient

Cavity surface chemistry

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Cavity wall thermal conductance

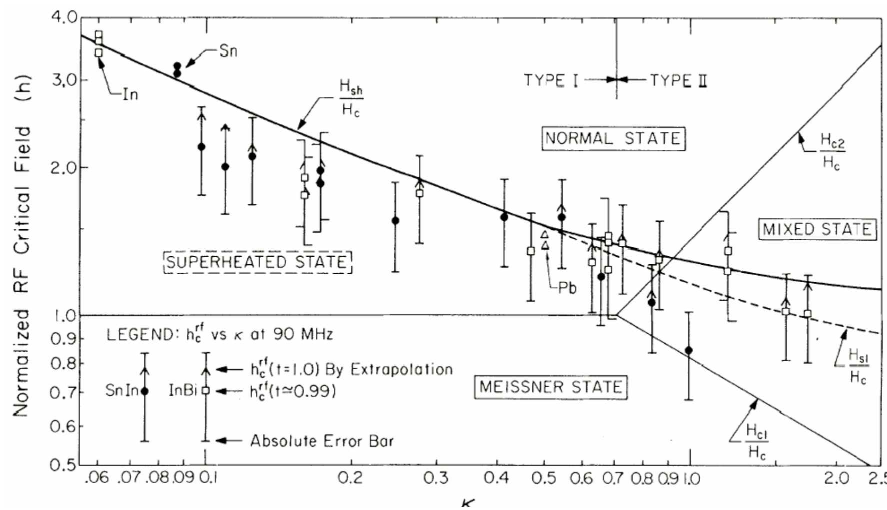
Cavity surface smoothness

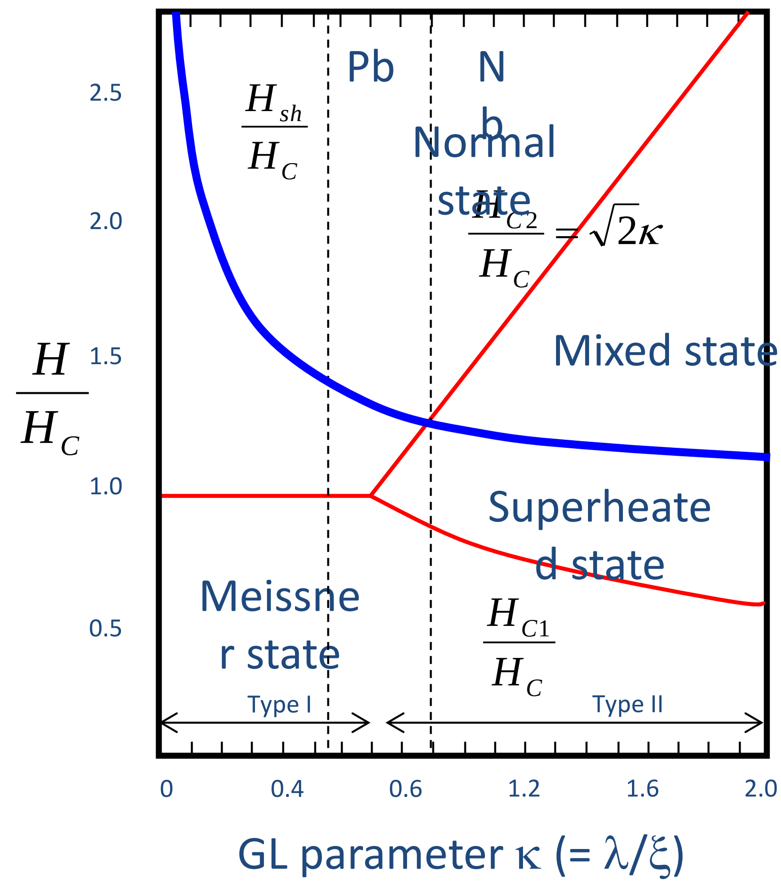
Cavity shape

(1) Alternate cavity shape for reduced Hpk/Eacc ratio. In hand (LL, RE, LSF).
(2) Uniform cavity processing for reduced local "bad" spots. In hand (EP).
(3) Smooth surface for reduced local magnetic field enhancement. In hand(CBP & derivative + EP).
(4) Improved wall thermal conductance for increased local heating tolerance.
- Cavity heat treatment optimization for "phonon peak engineering"
- Use Nb/Cu composite material (such as explosion bonded material)

SRF limits

- **What is the critical field in RF ?:**





- **Superheating field ?**
  - normal zone nucleation ~10^{-6} s
  - RF ~10^{-9} s *

BUT

  - 1! vortex penetration ~10^{-13} s **

H_{SH} ~1,2.H_C pour κ ~1

H_{SH} ~0,75.H_C pour κ>>1

** H. Padamsee, J. Knobloch, and T. Hays, "RF superconductivity for accelerators". 1998: J. Willey & son.*

*** Gurevich, Brandt, Smethna…*

Last Word on Quench

- RF critical field sets ultimate limit in achievable gradient
  - Still not settled theoretically
    - See Enzo Palmieri's "Basic principles of RF superconductivity"
  - Experimentally observed quench seems to be **always caused by local defect**
  - Experimental record peak surface magnetic field
    - Cornell 1-cell 1300 MHz re-entrant shape cavity: 2065 Oe
    - DESY 9-cell 1300 MHz large-grain TESLA-shape cavity: 1950 Oe
- Niobium is still the dominant material for known SRF based projects
  - Plenty of intricate issues remain further understanding
  - Still room for improvement
- Niobium replacement materials are being actively explored
  - Beating Nb's quench performance has not yet been demonstrated
  - See Anne-Marie Valente-Feliciano's "Beyond Bulk Niobium"

Understanding and Minimizing RF Losses – Pushing the limit

Heat = $, €, ¥

What is "ideal" SC Surface Resistance?

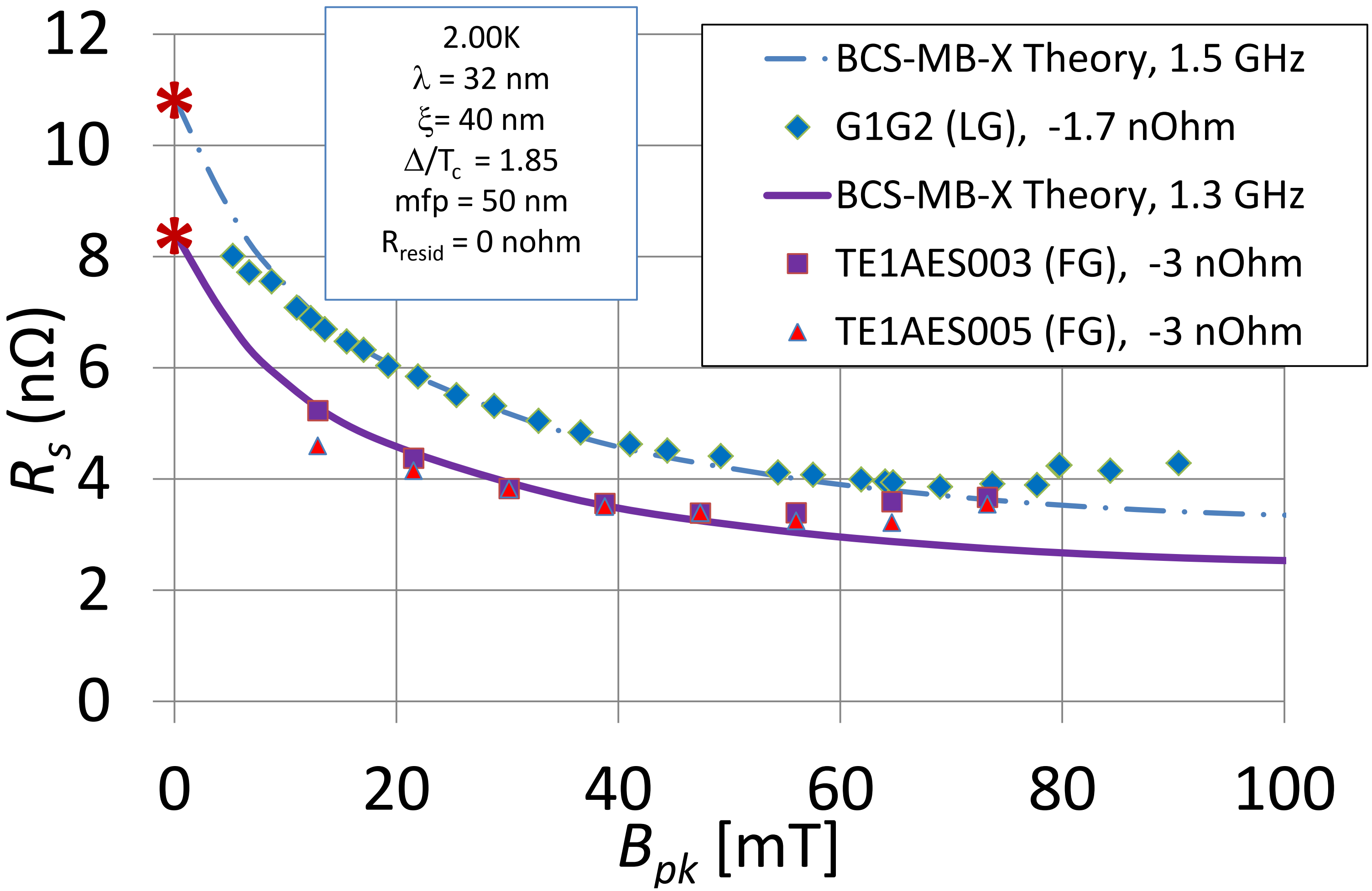
Jefferson Lab

- So far, Mattis-Bardeen SC surface resistance theory, built on BCS has addressed **only the *B*=0 limit**.
- How would "perfect" Nb behave ? $\boldsymbol{R_s(B,T)}$
- Recent theory and unusual experimental results now suggest that we have not been expecting enough. (more later)
- Even "perfect" Nb can yield non-linear RF losses with fine-scale surface roughness.
  - E.g. cf. etched vs EP'd fine grain Nb. (See Chen Xu's poster next week)

What is “ideal” SC Surface Resistance?

Jefferson Lab

- Previously, Mattis-Bardeen SC surface resistance theory, built on BCS has addressed **only the *B*=0 limit**.



B.P. Xiao, *et al*., Physica C: Superconductivity, 2013. 490(0): p. 26-31.

Symptoms of Parasitic Losses

- Q_0 is lower than what is expected from theory
  - BCS theory predicts exponential temperature dependence of surface resistance $R_s \propto_n \omega^2 \lambda_L^3 \ell \exp\left(-1.86 T_c / T\right)$
    - Recall $Q_0 = \frac{G}{R_s}$
  - Temperature independent term is called residual resistance
  - Residual resistance limits achievable Q_0

Symptoms of Parasitic Losses

Jefferson Lab

- **Q-disease**
  - Q_0 at low field degrades when cavity parked at a temperature 70-150 K for extended period of time
  - Similar effect when cavity cool down rate is slower than 1K/min in passing 70-150 K

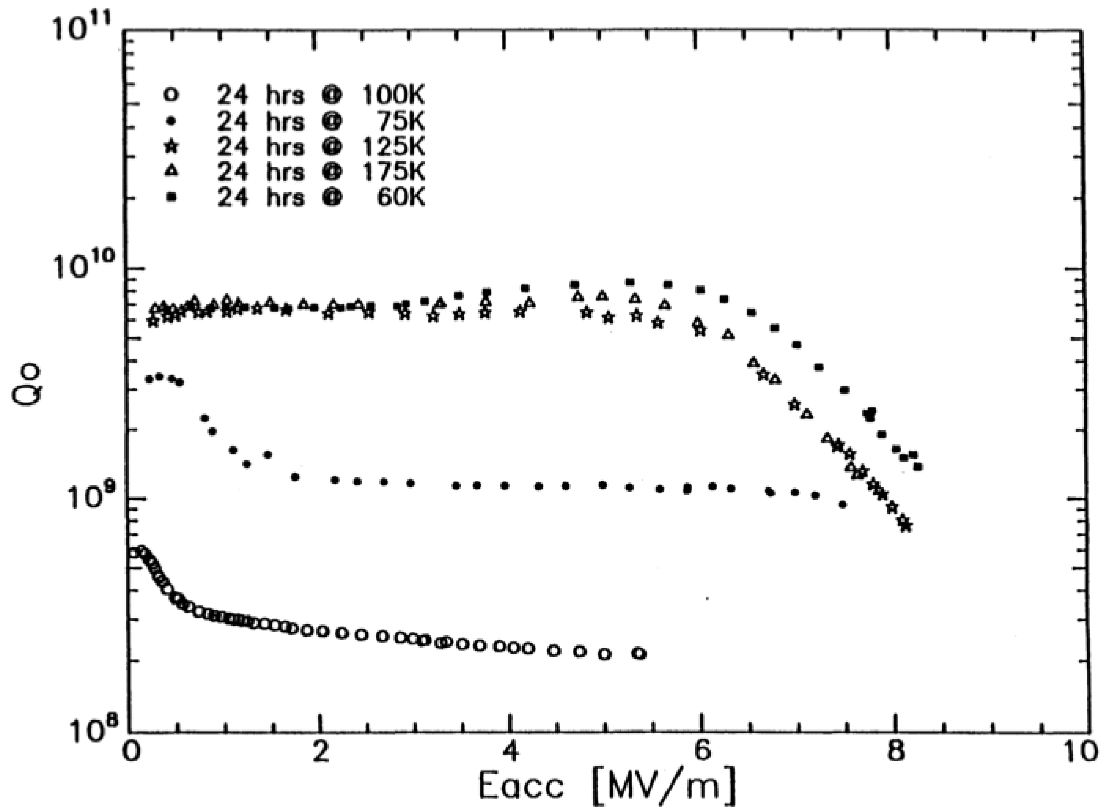


Figure 1 : Eacc – Dependence of Q – Degradation on "Holding" Temperature

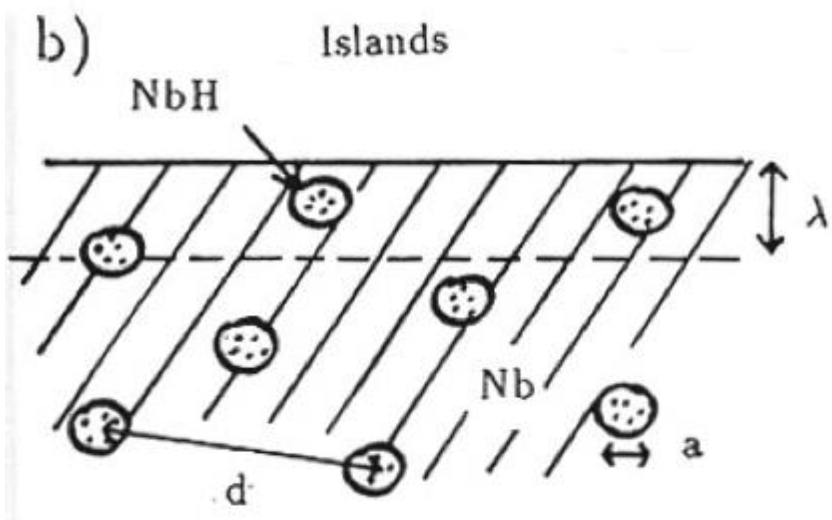
J. Halbritter, P. Kneisel, K, Saito, SRF1993

Understanding Parasitic Losses

Jefferson Lab

Q-disease

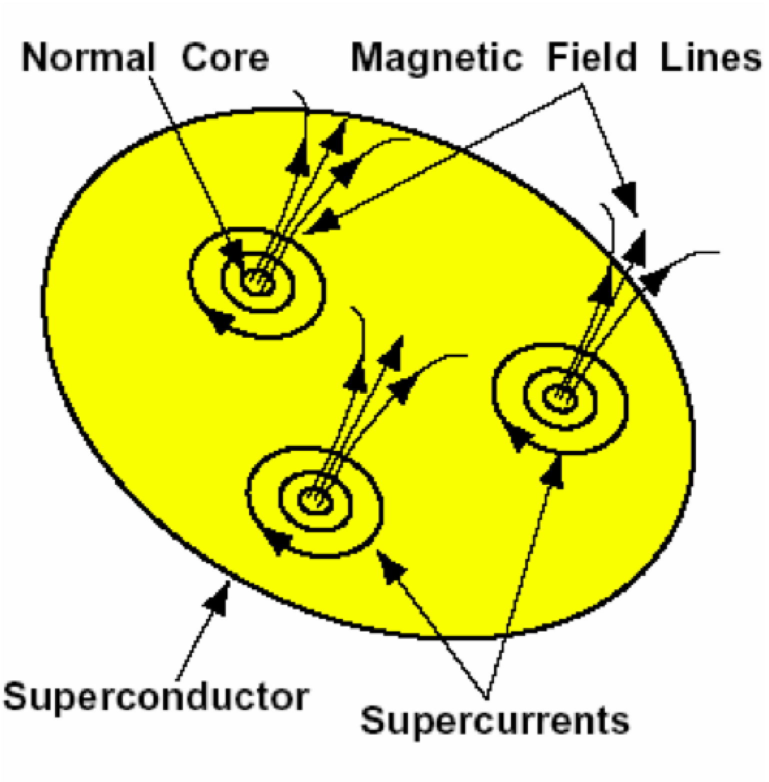
- Hydride phase
  - Nb-H system undergoes phase transition at low temperatures
  - H mobility still high at 100 K
    - H in bulk Nb precipitates
    - Forms islands of weak superconductor
  - Danger arises when bulk H concentration in Nb > 2 wt ppm
  - Higher danger for high purity Nb
    - H is bound by impurities



Understanding Parasitic Losses

Jefferson Lab

- **Frozen flux effect**
  - DC magnetic field is “trapped”
    - Fluxon
    - Normal conducting core
  - Sources of DC magnetic field
    - Earth magnetic field
    - Thermal-electric current due to temperature gradient during cavity cool down or local quench during test
  - Mechanisms of losses
    - RF dissipation at n.c. core
    - Fluxon dynamical flow



Understanding Parasitic Losses

Jefferson Lab

- Scaling of residual resistance due to frozen flux effect
  - Linear dependence on external field H_{ext}
  - Inverse linear dependence on second critical field H_{c2}
  - Linear dependence on superconductor's normal state surface resistance R_n
- Frequency scaling: $\sqrt{f}$
  - Recall $R_n \sim \sqrt{f}$

$$R_{\Phi} \approx \frac{H_{\mathrm{ext}}}{2H_{\mathrm{c2}}} R_{\mathrm{n}}$$

For Nb, residual resistance contribution due to frozen flux:

$$R_{res} = \alpha H_{dc} \sqrt{f / GHz}$$

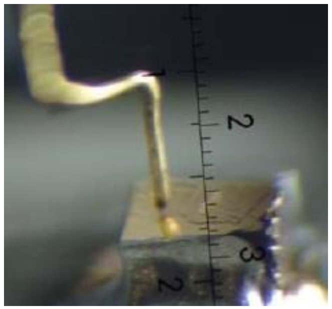
α = 0.2-0.3 nΩ/mG

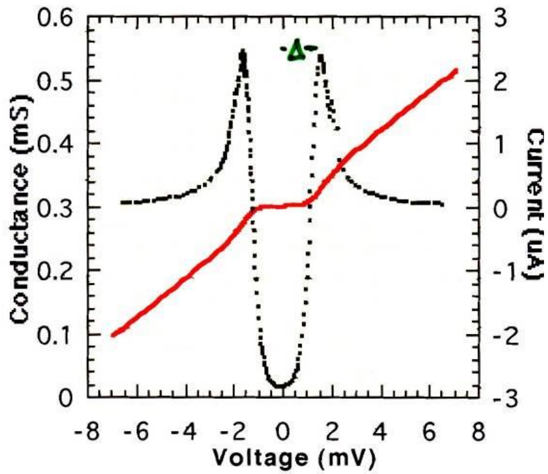
10 mG -> ~ 3 nΩ

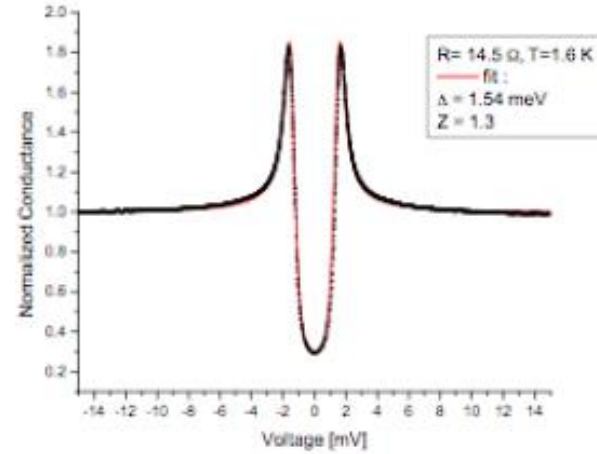
120 C BAKING AND SC GAP

Jefferson Lab

bulk Nb (UH Vann. >2200°C)
= reference →

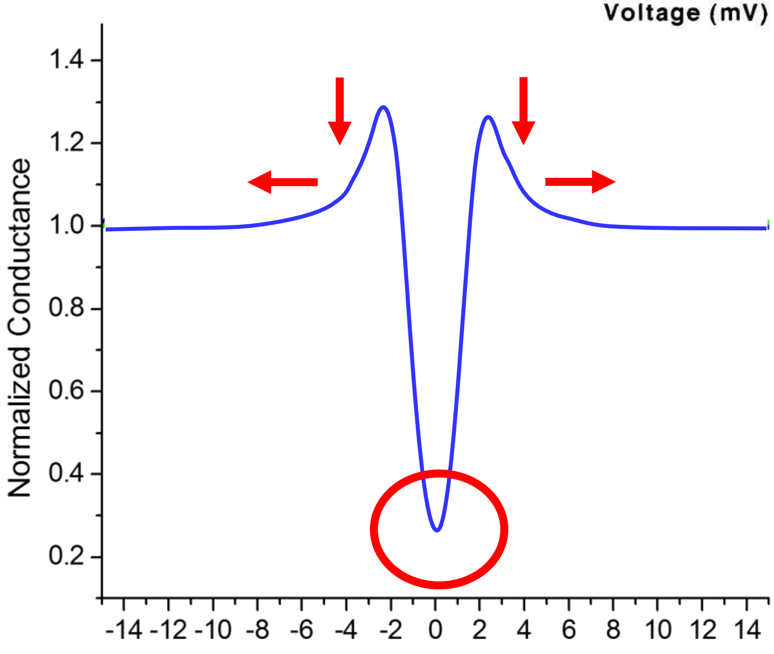






↑. Nb low Z conductance
(measurement deep, past the oxide layer)

Nb high Z conductance
(oxide-SC interface included in the measurement)
→



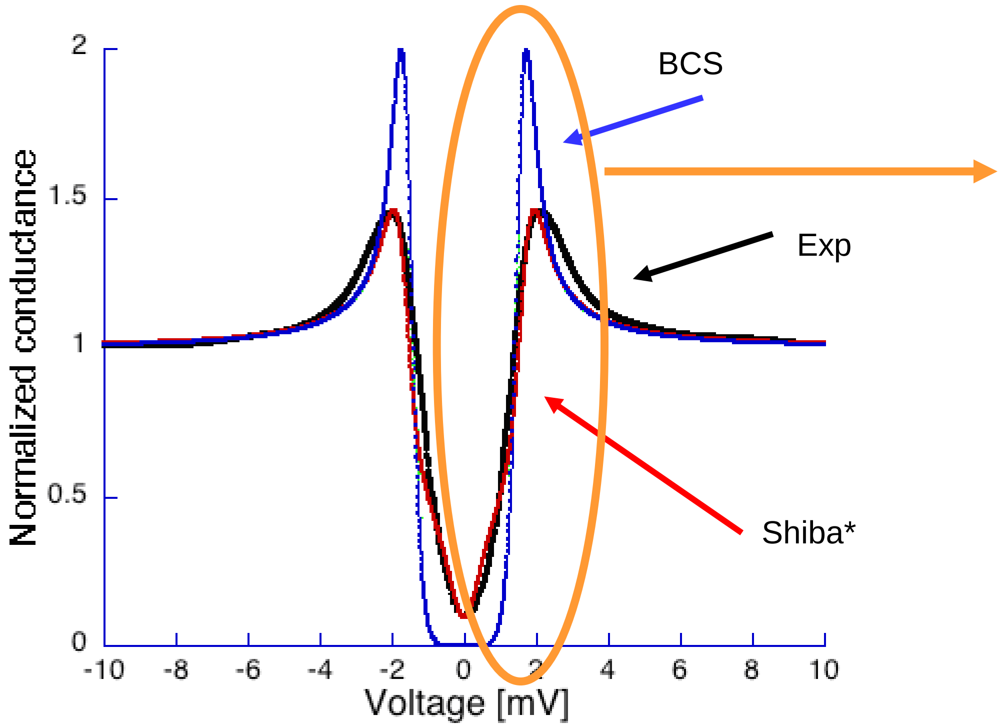
- Bulk : BCS behavior
- Δ ~ Nb bulk : 1.55 meV
- Behavior ≠ BCS @ interface

High field dissipations:

PCT Results 2

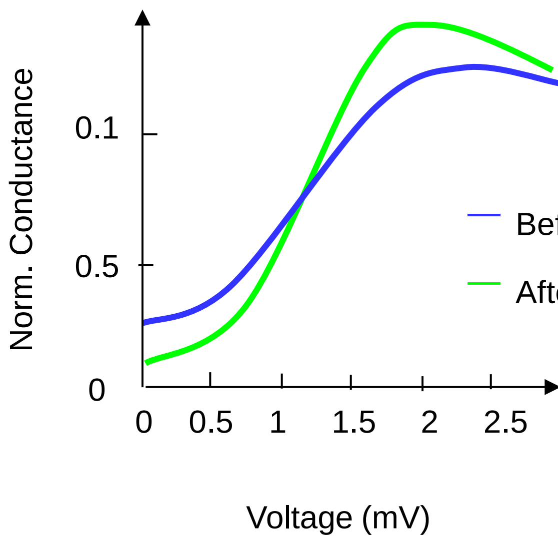
@ interface :

- Broadened conductance => Mechanism = Cooper pair breaking
- Fit = Shiba => quasiparticles inelastic scattering / impurities
- Baking : ↓ inelastic scattering part of the signal
- Same results air/vacuum => interface !



high Z (w. oxide)

[T. Proslier et al,IIT, ANL, 2007]



NB baking in air !

** H.Shiba Prog.Theo.Phys. 50, 50 (1973);*

Reducing Parasitic Losses

Jefferson Lab

- Minimize H uptake from processing
  - BCP etching at < 15 °C
  - “H free” EP
- Hydrogen out-gassing in vacuum furnace
  - 800 °C x 2hr
  - Or at lower temperature for longer time
- Minimum or no chemistry after out-gassing
- Engineer a diffusion block underneath or within the surface oxide?

Overcoming Residual Losses

Jefferson Lab

- Use ingot (LG) Niobium material

BCP-etched large grain cavity
9-cell 1300 MHz
Consistent lower surface resistance with more than 10 cavities

Heraeus large-grain Nb

$\langle Q_0 \rangle$ = 2E10 @ 20 MV/m, 2K
Q_0 3-4E10 @ 20 MV/m, 1.8K

W. Singer et al., STTIN2010

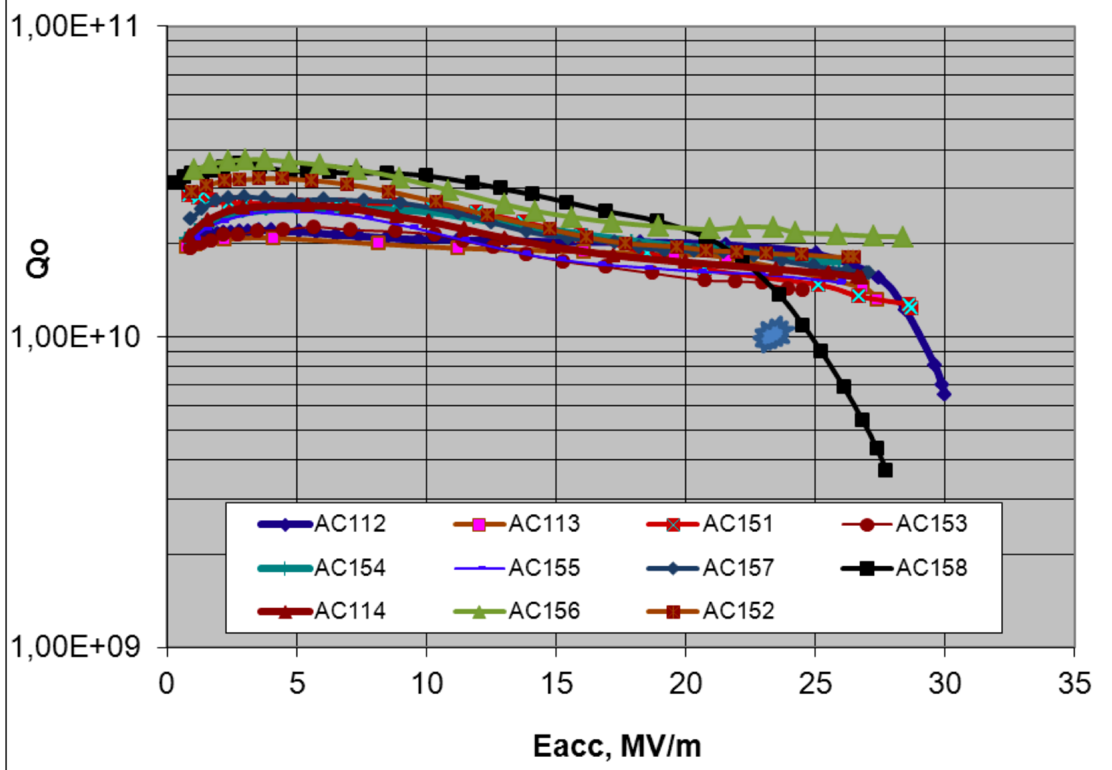


Figure 7: Q(Eacc) of the cavities AC112- AC114 and AC151-AC158 at 2K. Test after 100 µm rough BCP, annealing at 800°C for 2h followed by a fine BCP 20 µm and baking at 120°C for 48h (AC112 was not baked). Star shows the XFE requirements

Non-linear Parasitic Losses

Jefferson Lab

- Q_0 declines as field is raised
  - Without any X-ray present
  - Decline starts at gradient 3-4 MV/m
    - "Medium field Q-slope"
  - Rapid decline above 20 MV/m
    - "High field Q-slope"
  - Observable in bulk Nb cavities, Nb thin film coated Cu cavities and Nb_3Sn coated cavities

Non-linear Parasitic Losses

Jefferson Lab

dapnia cea saclay

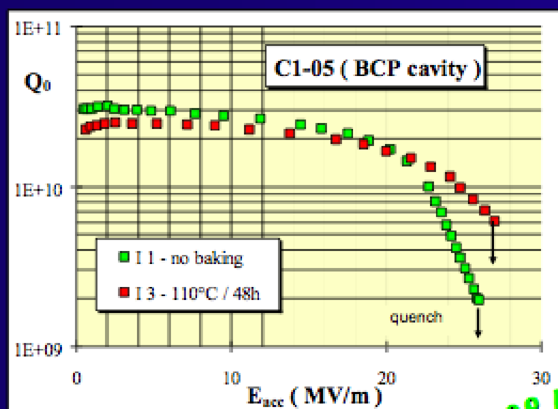
BAKING AND Q-SLOPES

Pushing the Limits of RF Superconductivity

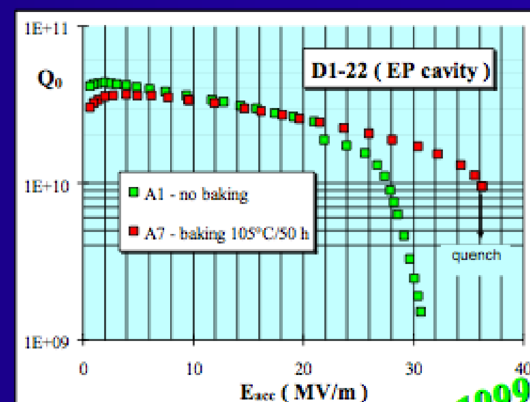
Workshop ~ Argonne Nat. Lab. ~ 22-24 Sept. 2004

Baking has an effect on the three Q-slopes (BCP and EP cavities):

- *enhancement at low field*
- *slight flattening at medium field*
- *strong improvement at high field*



EPAC 1998 [1]



SRF Workshop 1999 [2]

Without Baking : Electropolished Cavity Can Not Reach 40 MV/m

Bernard VISENTIN

6

Non-linear Parasitic Losses

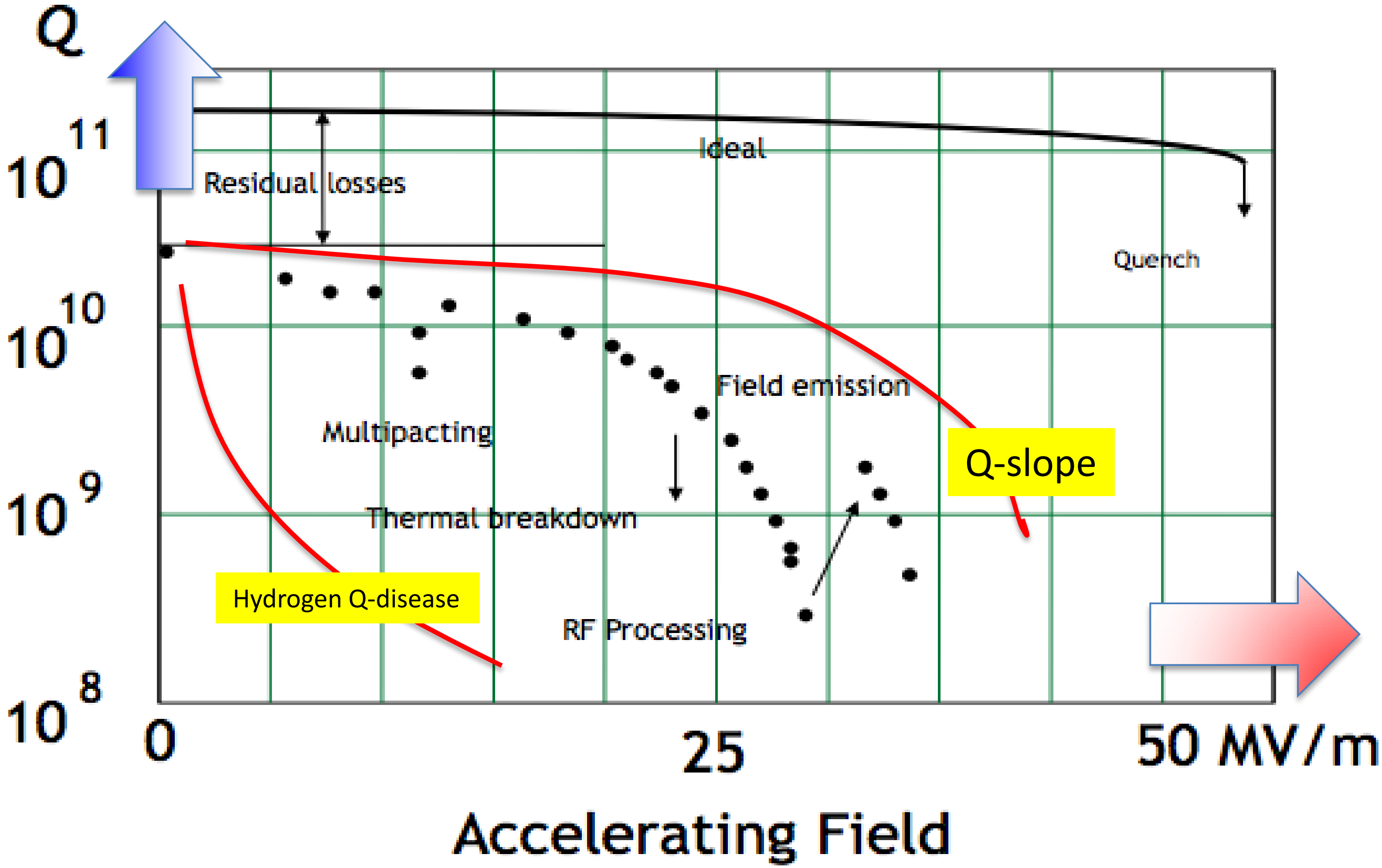
Jefferson Lab

- This is an active area of research presently in SRF community
  - Theoretical
    - Non-linear BCS
    - Vertex
    - Weak SC inclusions
    - …
  - Experimental
    - Oxygen
    - Dislocation
    - Hydrogen
    - …

Jefferson Lab

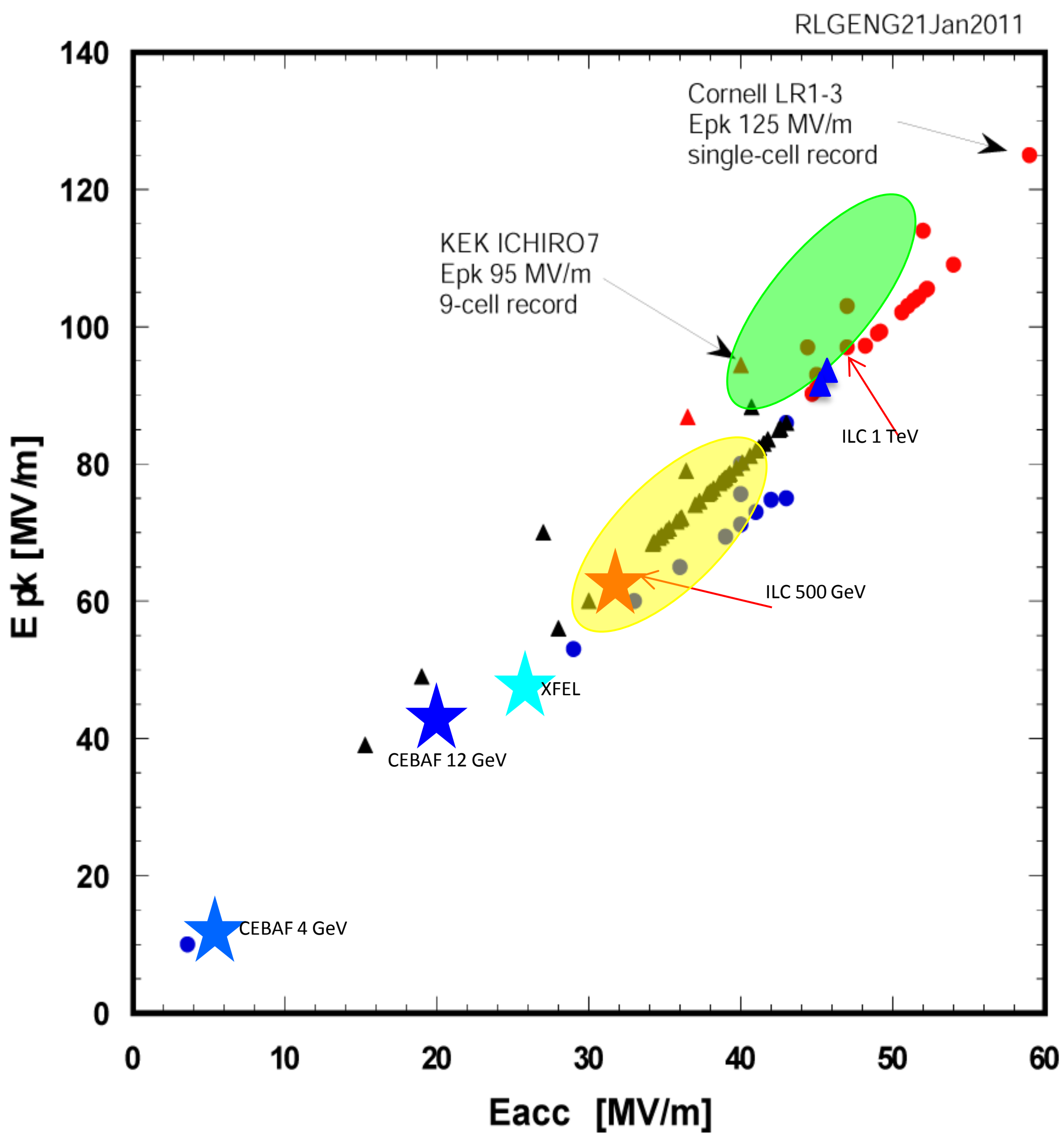
Cavity Performance Limits
and
SRF Based Accelerators

Performance Pushing Directions



Achieved Peak Surface Electric Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity)

Jefferson Lab



Achieved Peak Surface Magnetic Field in L-band SRF Niobium Cavities
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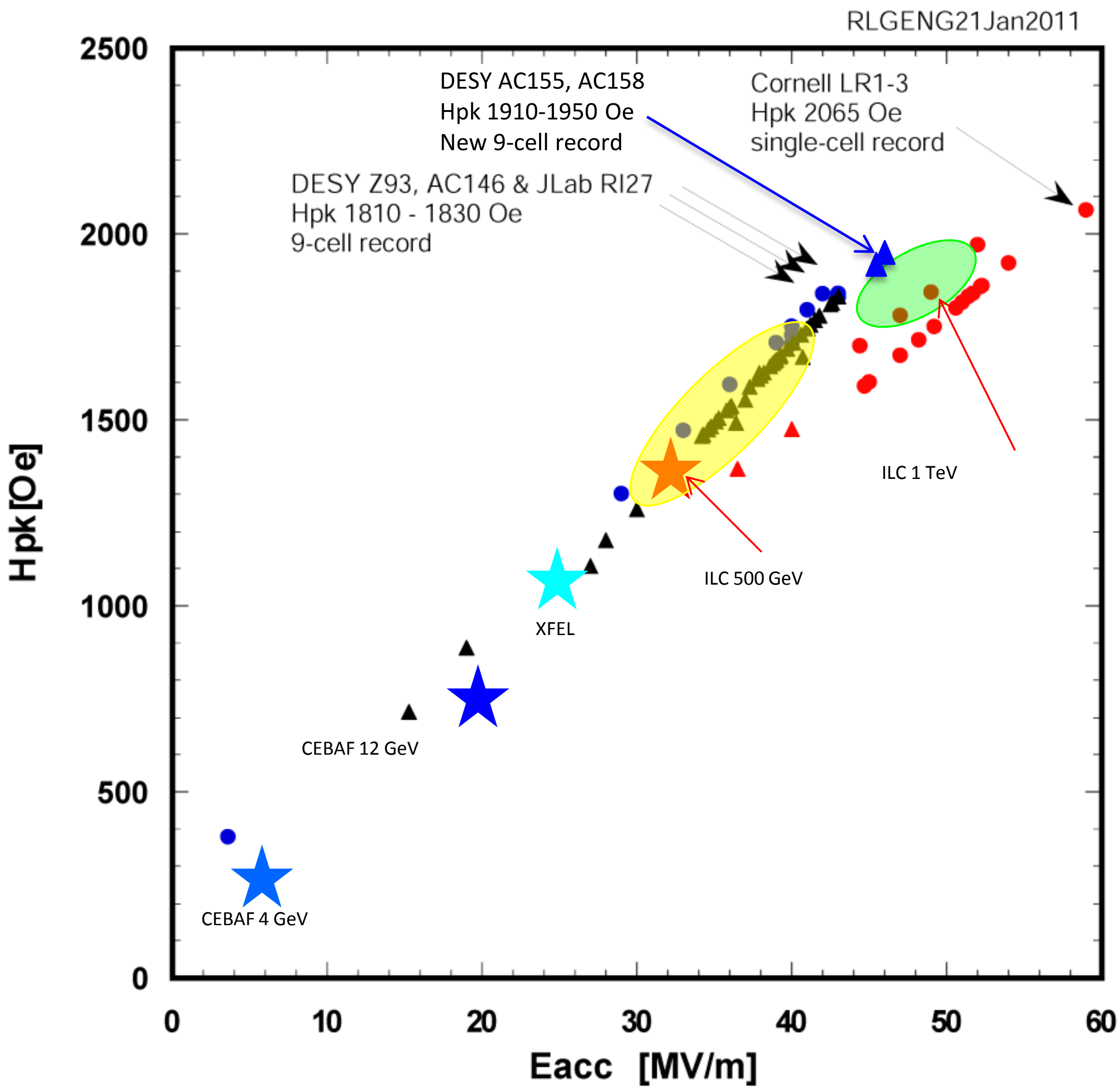
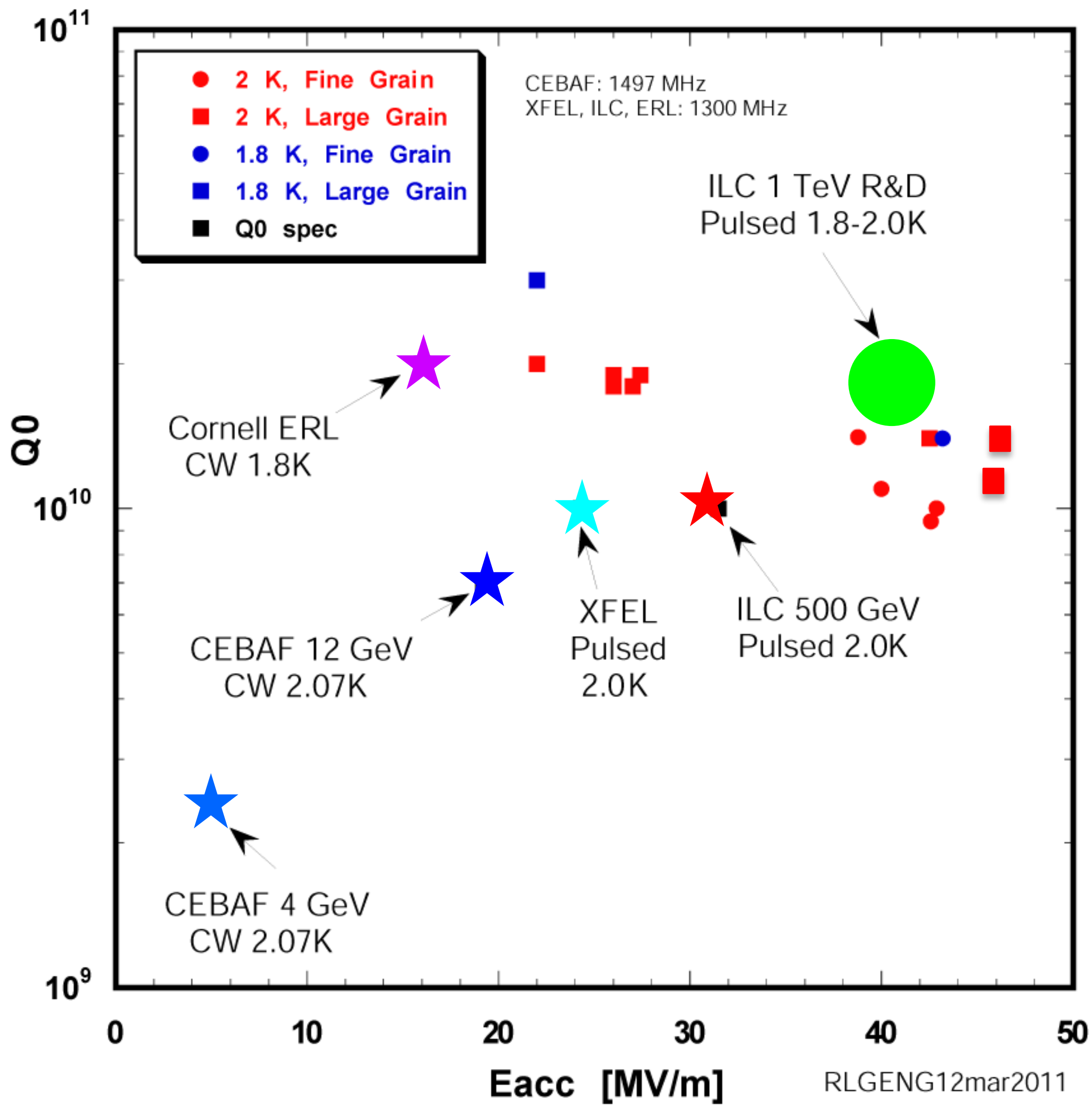


Achieved Q0 at Maximum Eacc by 9-Cell 1300 MHz TTF-style Nb Cavities

Jefferson Lab



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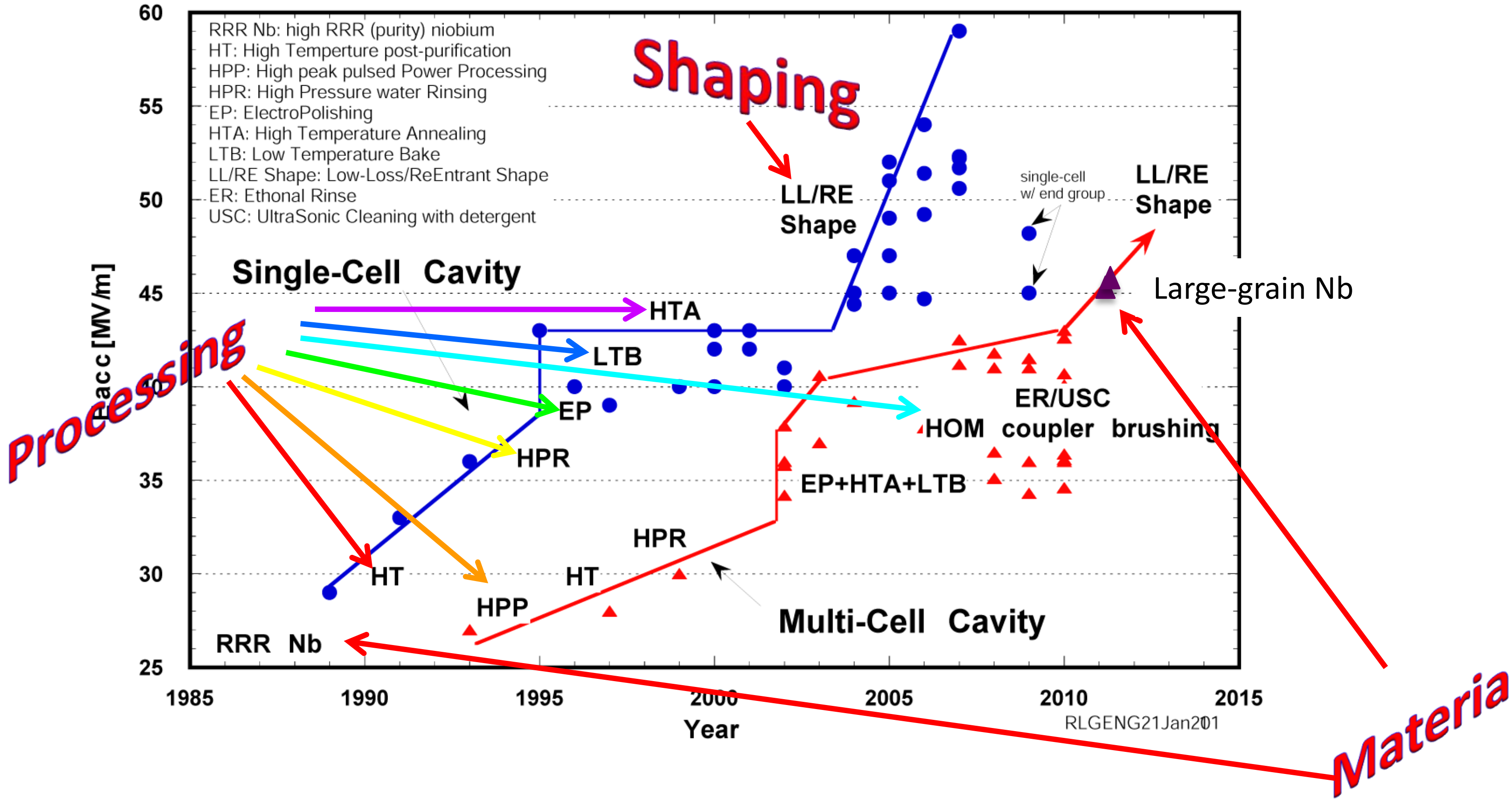
L-Band SRF Niobium Cavity Gradient Envelope Evolution



Understanding in gradient limits and inventing breakthrough solutions are responsible for gradient progresses. This has been a tradition in SRF community and rapid gradient progress continues. Up to 60 MV/m gradient has been demonstrated in 1-cell 1300 MHz Nb cavity. 45-50 MV/m gradient demonstration in 9-cell cavity is foreseen in next 5 years.

Limits in SRF Cavity Performance

Jefferson Lab

Phenomenon/Integrated Properties

Intrinsic **Extrinsic**

Limits

- **- Fields**
- **+ Heat**

Actual Exposed Material

"Where all the atoms are"

"Less than 0.15 mm^3 matters"

- Mechanical
- Chemical
- Thermal

"Therapies"

Actual Applied Processes

"What we can buy or make"

Real Materials

"Is our detailed understanding here adequate?"

No