Superconducting RF Cavity Preparation and Testing

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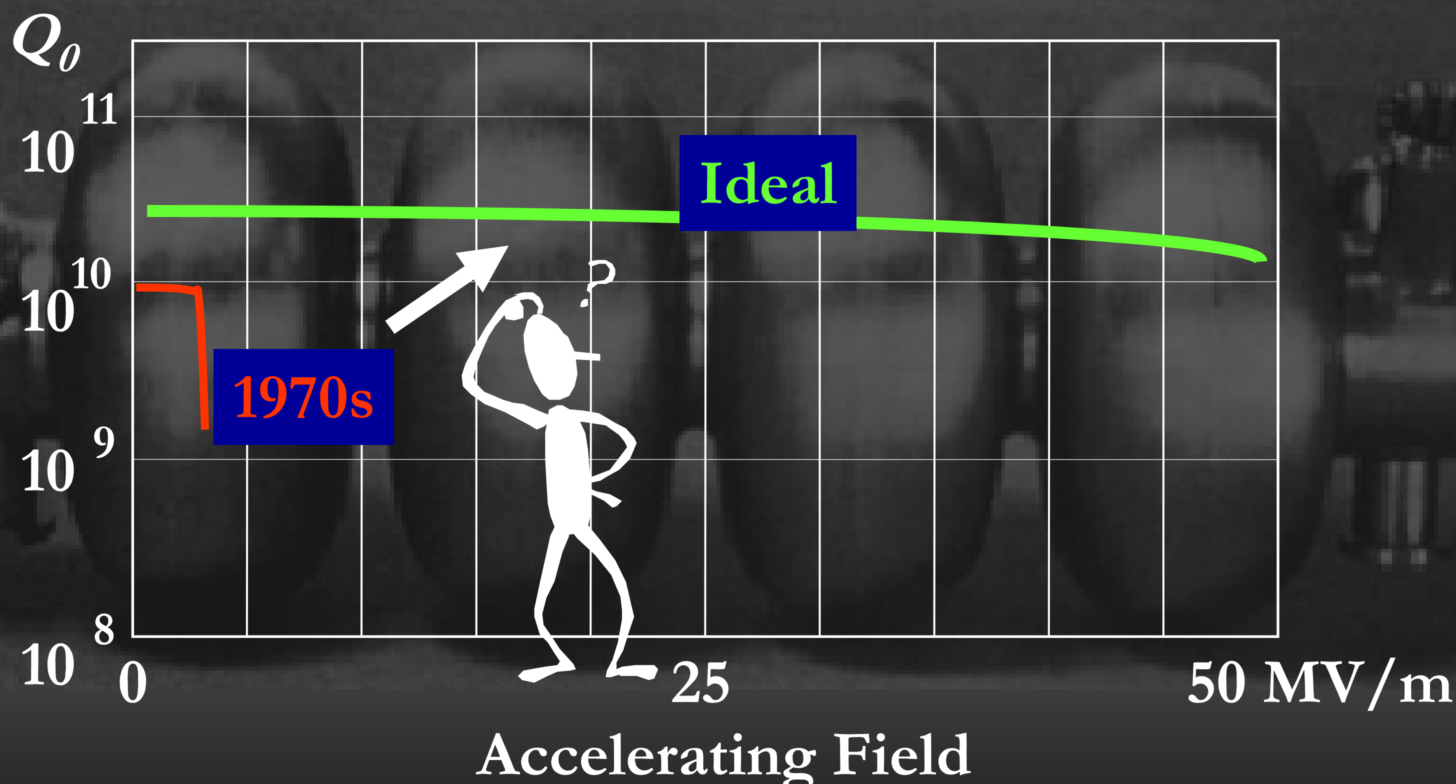
Outline

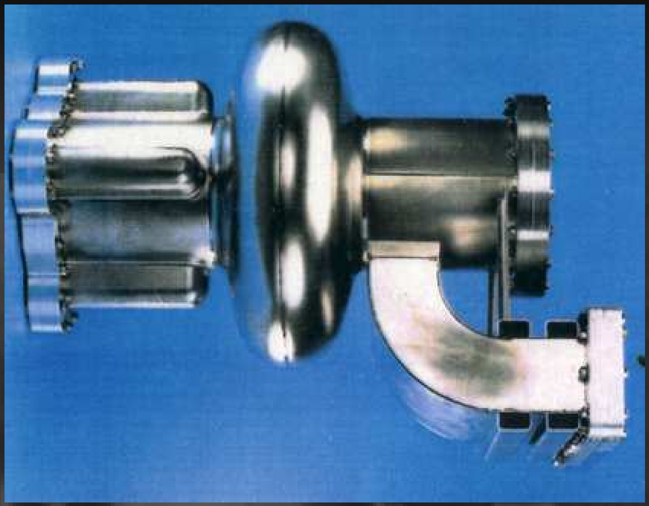
- Why do we test superconducting RF cavities?
- How do we test SRF cavities?
- How do we make and prepare SRF cavities?
- What do we find?

Why do we test superconducting RF cavities?



"Understanding" SRF Cavities

- Superconducting RF cavities look simple…
- … but making a good cavity is not simple at all
  - Took 30+ years to learn how to prepare the surface of Niobium cavities for highest RF fields
  - Fabrication and surface preparation involve a long list of critical steps = "recipe"

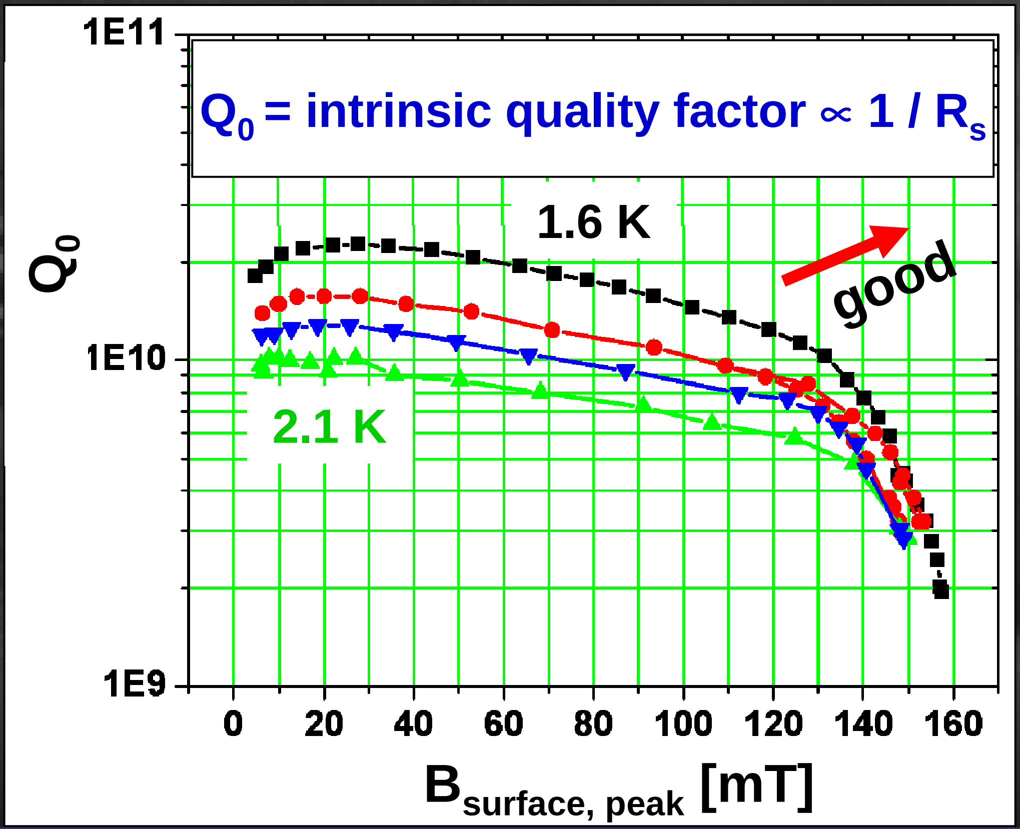


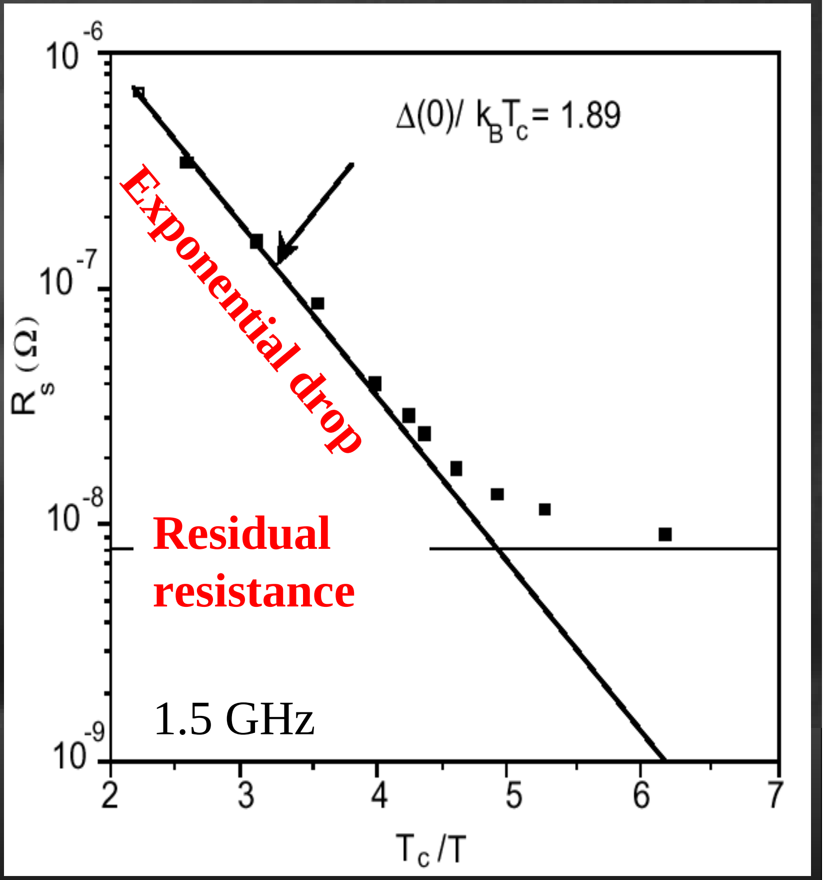
Science and Art

- How did we arrive at this "recipe"?
  - Science: Understanding superconductors in high fields at microwave frequencies (GHz)
  - Art: working in clean rooms…
  - Persistence: Performance tests of 100's of cavities to find out what we got…
  - Luck: found that drying cavities at 100 C not only helps to save time, but also reduces the RF surface resistance at high fields dramatically…

SRF Cavity Performance Tests

- Goal: Measure RF surface resistance of the cavity wall as function of RF field gradient and temperature
- Typical results:





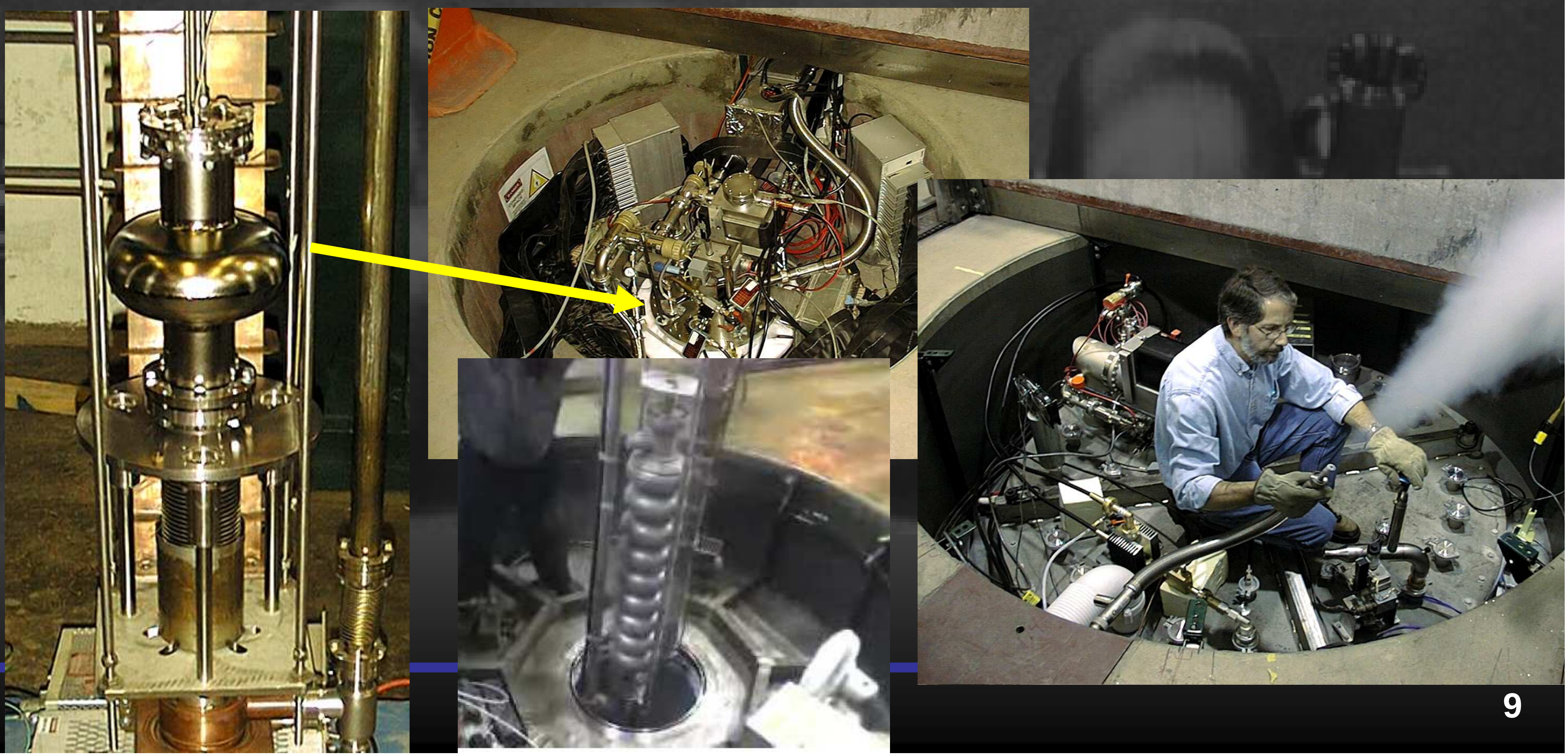
How do we test SRF cavities?

SRF Cavity Testing: The Challenge

1. Cool down SRF cavity below T_C to make it superconducting (usually ≤ 2K)
2. Couple RF power into the cavity to excite RF fields in the cavity at certain frequency ("mode")
3. Keep field amplitude constant to measure power dissipated in the cavity walls at this field level (this gives as the intrinsic Q_0)
4. Increase power to increase cavity field, measure dissipated power again…

Cavity Test Stand

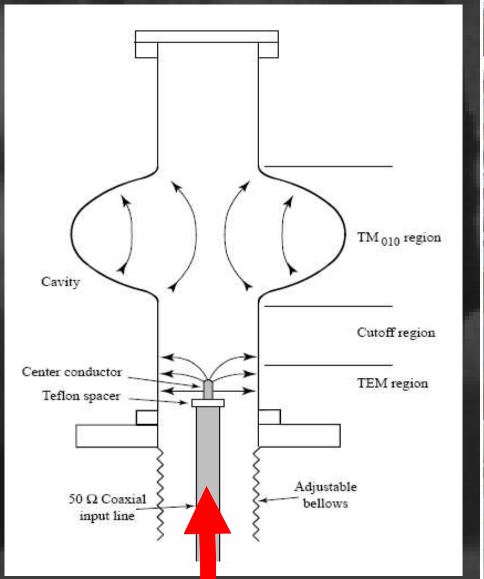
- **After fabrication and surface treatments, a SRF cavity is mounted on a test stand, evacuated and immerged into LHe.**



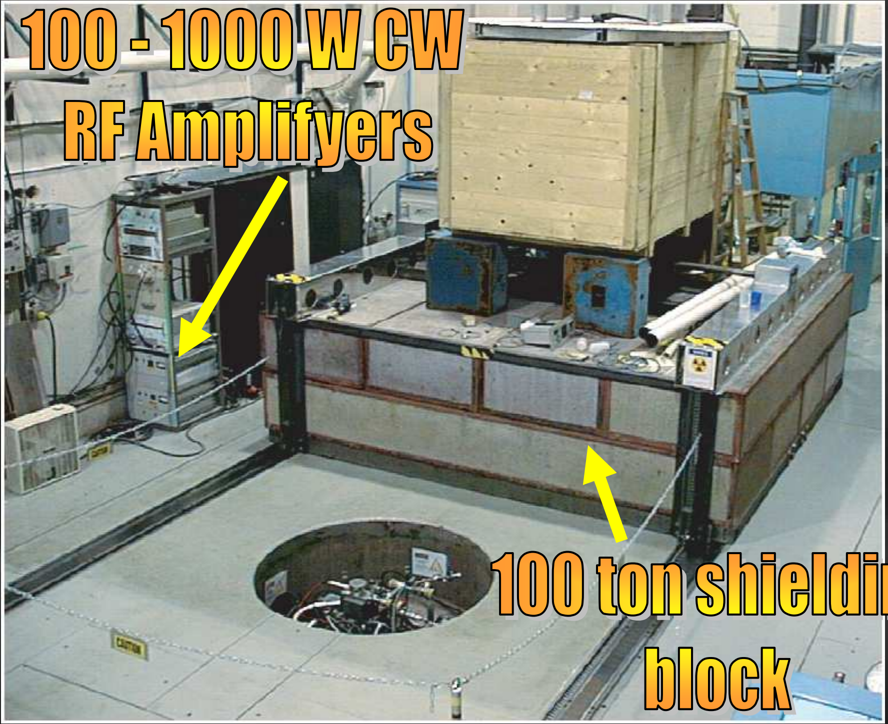
Field Excitation

- RF power from CW or pulsed power sources is coupled into the cavity to excite EM fields in the cavity (at GHz frequencies, 10's of MV/m).

1 MW klystron

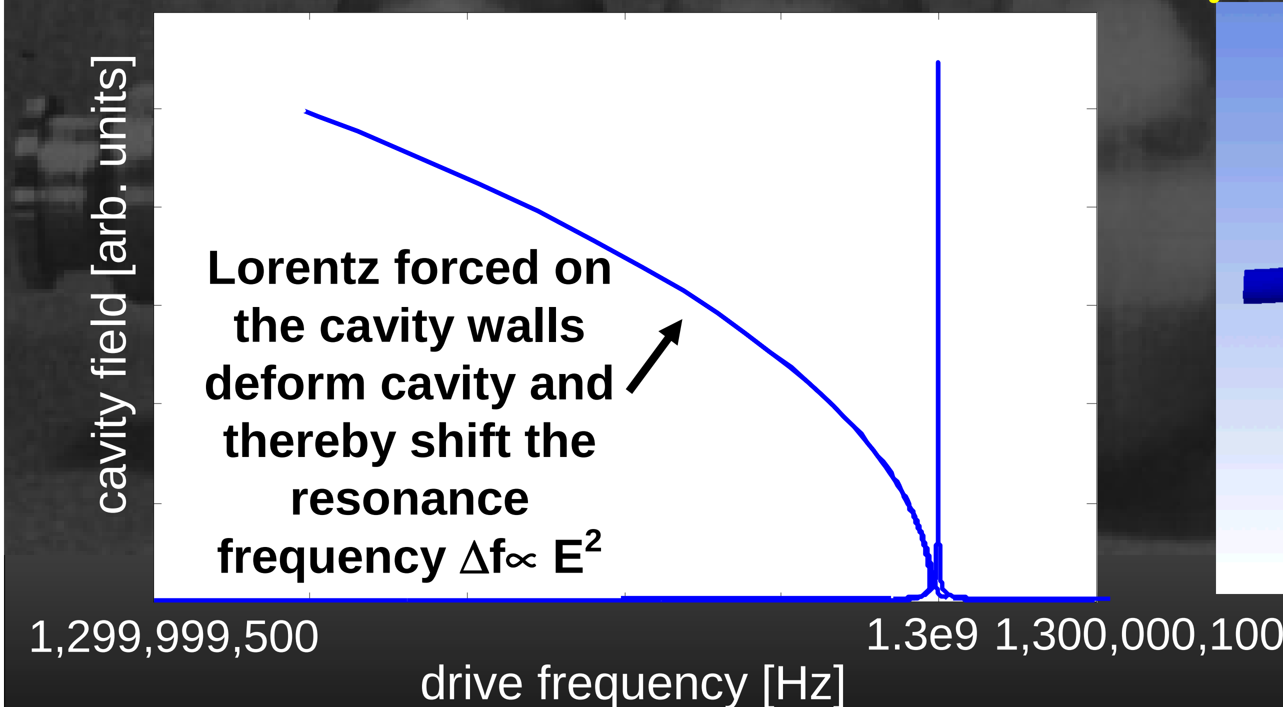


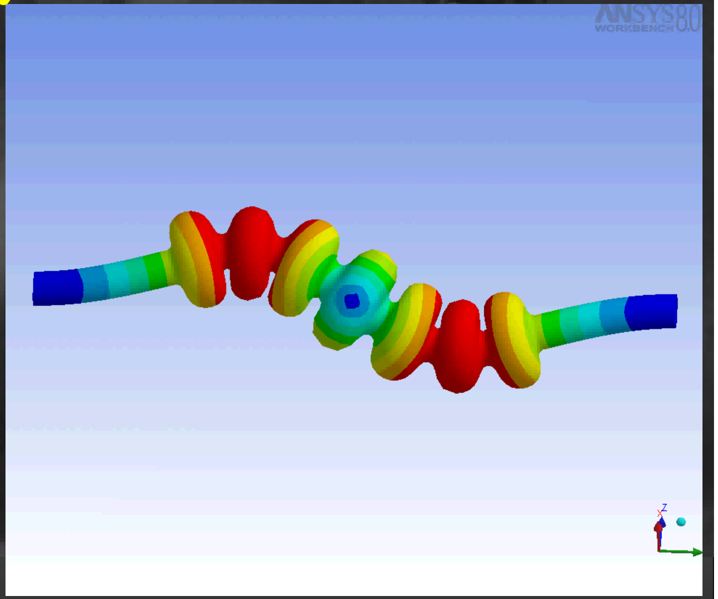
RF Power



Keeping the Field Stable…

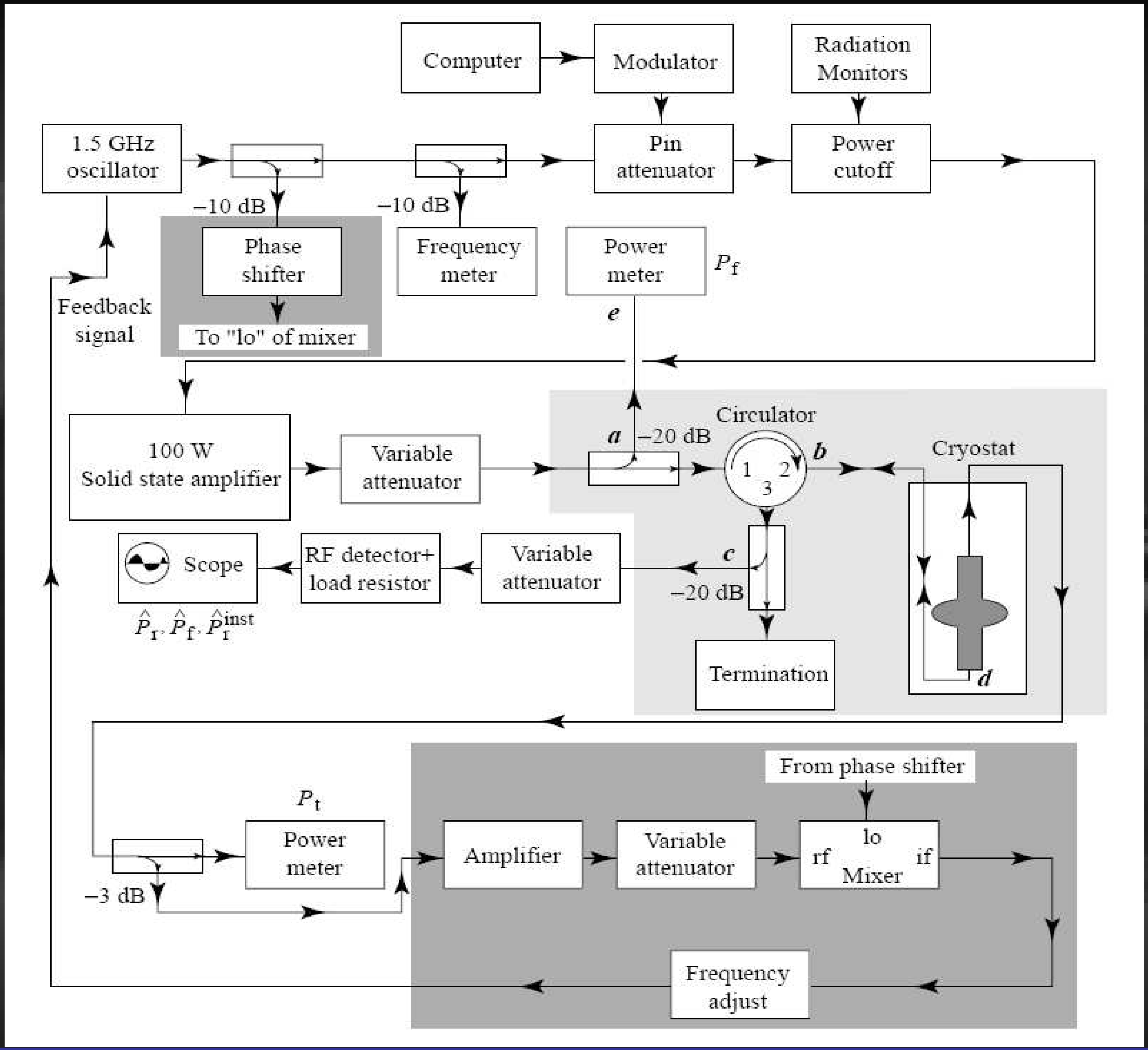
- SRF cavities are oscillators with extremely high quality factors of 10^{10} to 10^{11} !
- Width of resonance curve at GHz frequencies is 0.1 to 0.01 Hz!
- To keep field amplitude constant, need to drive oscillator on resonance ⇒ drive needs to follow cavity resonance!





…with a Feedback Loop

- The cavity is driven with constant amplitude (RF power)
- The drive frequency is adjusted to follow the natural cavity frequency
- This is done by a phase-looked-loop (PLL)



The Phase-Locked-Loop

Mixer as phase detector:

$V_1 \sin(\omega_1 t + \varphi_1)$ → X ← $V_2 \sin(\omega_2 t + \varphi_2)$

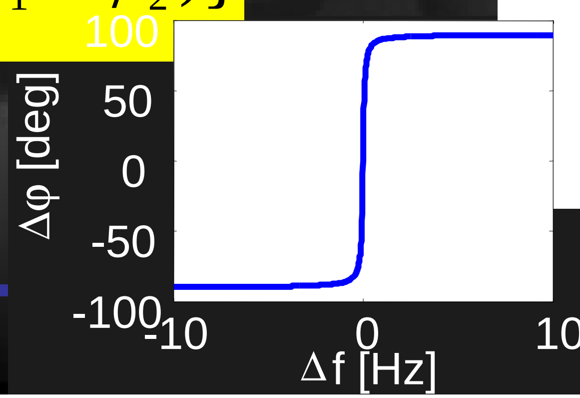
$$IF = \frac{1}{2} V_1 V_2 \left[\cos\{(\omega_1 - \omega_2)t + (\varphi_1 - \varphi_2)\} - \cos\{(\omega_1 + \omega_2)t + (\varphi_1 + \varphi_2)\} \right]$$

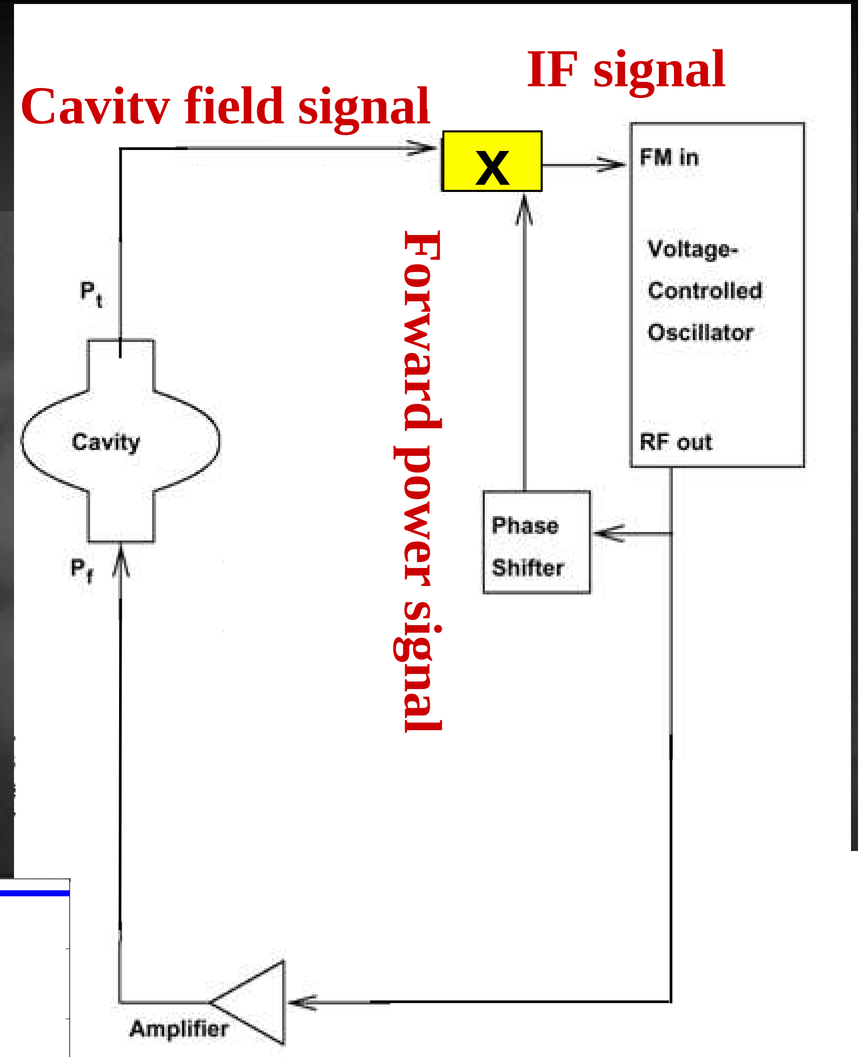
Filter high *f* component

$\omega_1 = \omega_2$ (driven oscil.)

$$IF = \frac{1}{2} V_1 V_2 \cos\{(\varphi_1 - \varphi_2)\}$$

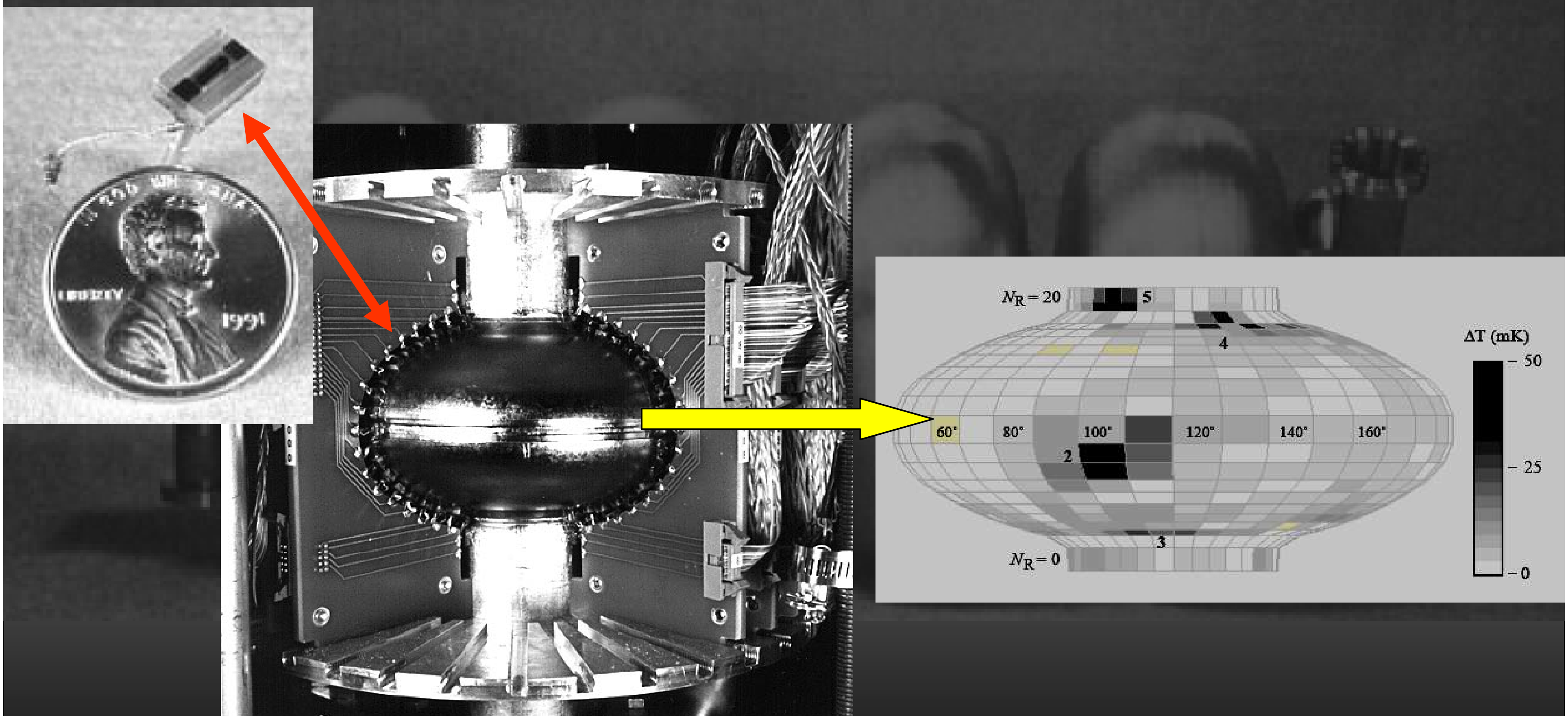
tan φ = 2Q Δf / f





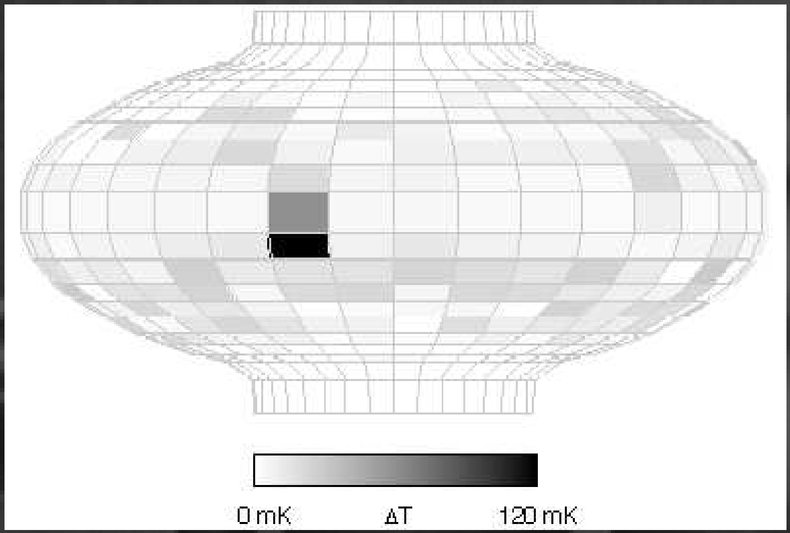
Temperature Mapping

- 100’s of temperature sensors are used to map the distribution of the losses in the cavity walls with mK resolution.

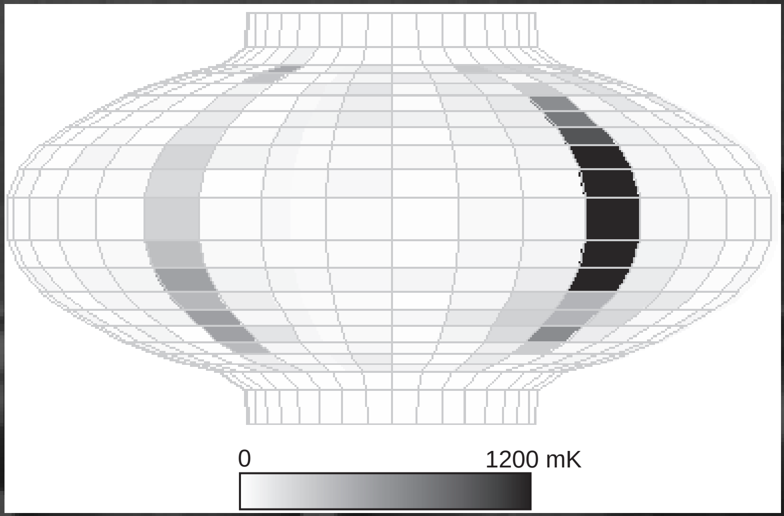


T-Mapping: A powerful Tool

Local defect $\Rightarrow$ quench



Electron field emission



- Allows to distinguish field limiting effects
- Gives "local" Q(E) curves

J. Knobloch et al.

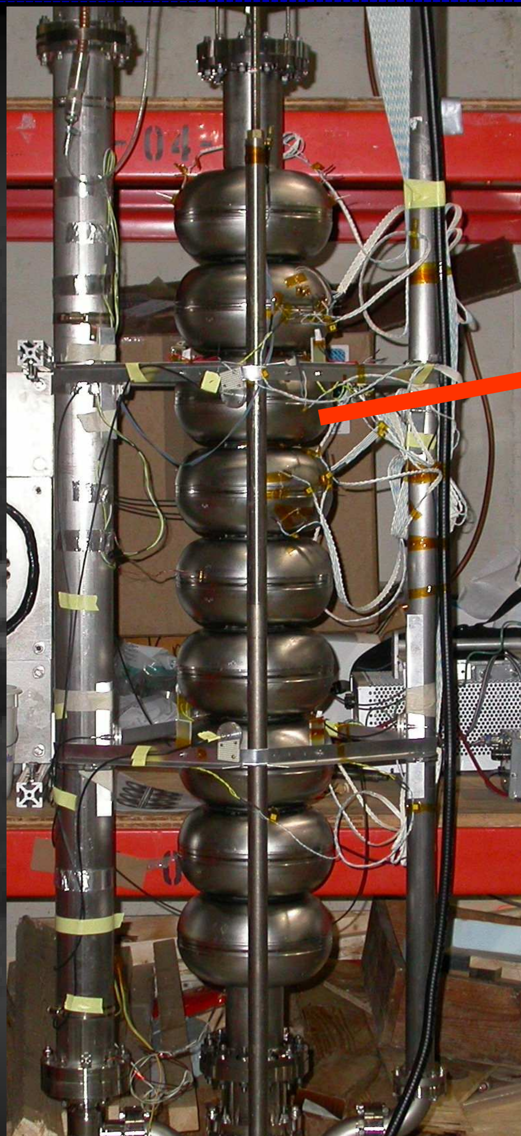
Quench Location Detection with Second Sound in superfluid Helium (I)

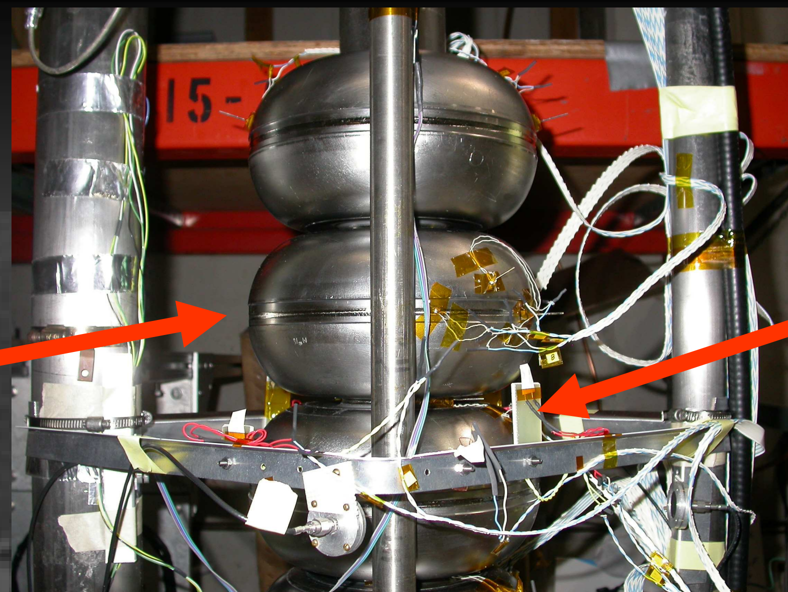
- Second sound waves in superfluid Helium: The normal and superfluid components oscillate in counter flow leaving stationary (to first order) the center of mass.

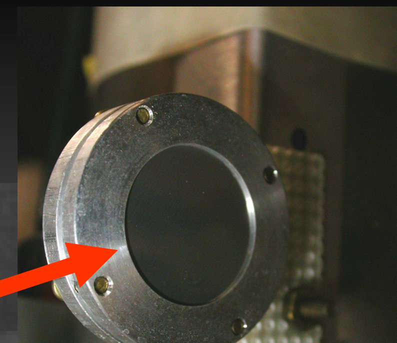
$$\rho_s \vec{v}_s + \rho_n \vec{v}_n = 0$$

- Measure second sound waves from heat at cavity quench location with oscillating superleak transducers (porous membrane is driven by the normal-fluid component of the wave)

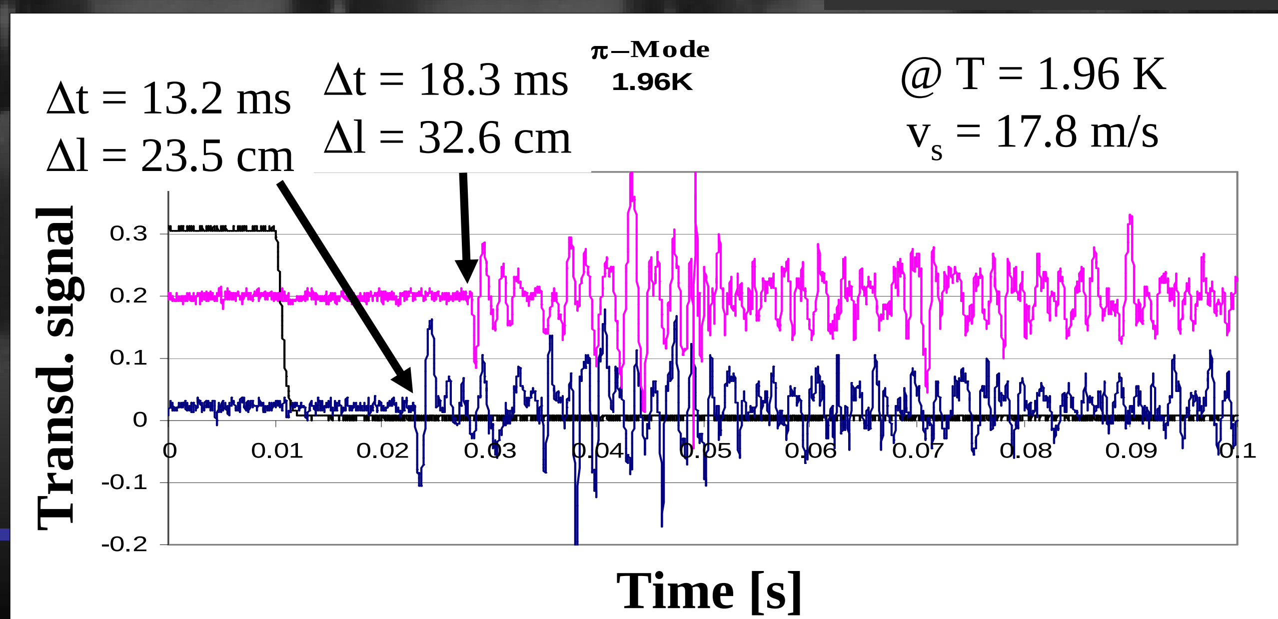
Quench Location Detection with Second Sound in superfluid Helium (II)







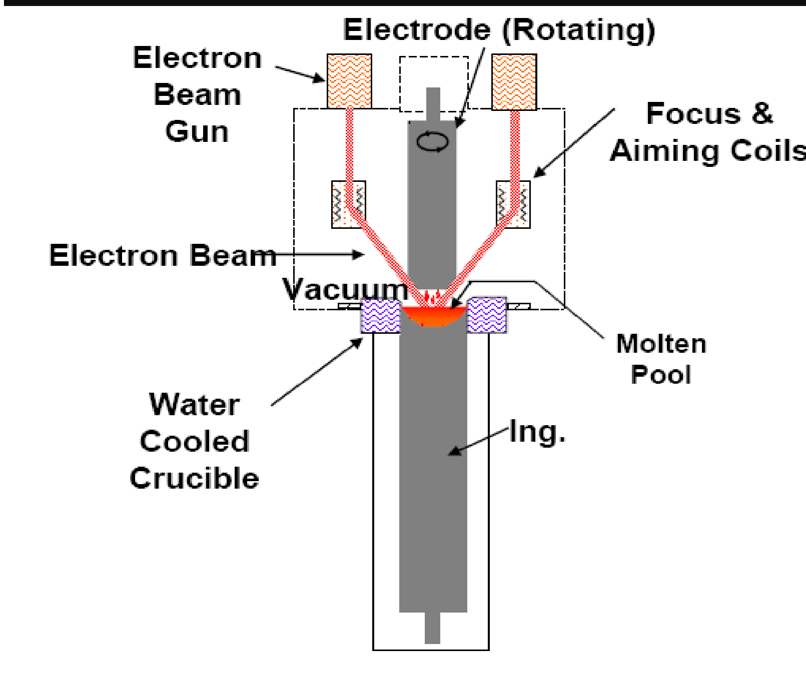
oscillating superleak transducers



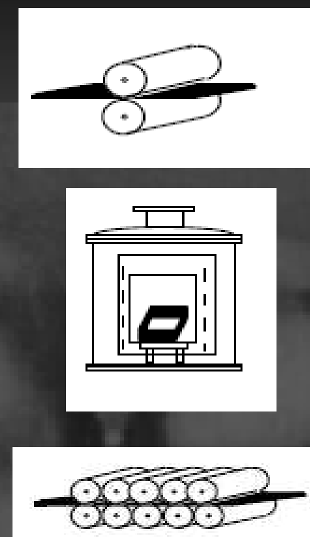
D. Hartill, Z. Conway et al.

How do we make and prepare SRF cavities?

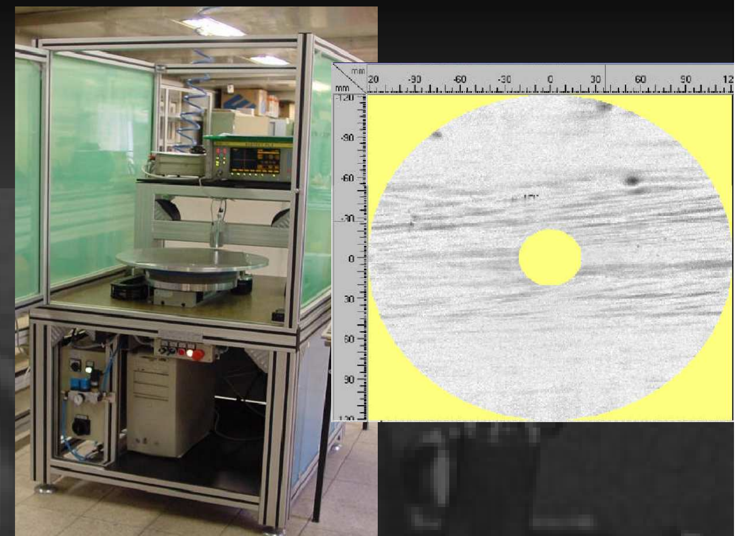
The Fabrication of an SRF Cavity (I)



Electron beam melting on Niobium (done several times to purify Niobium)

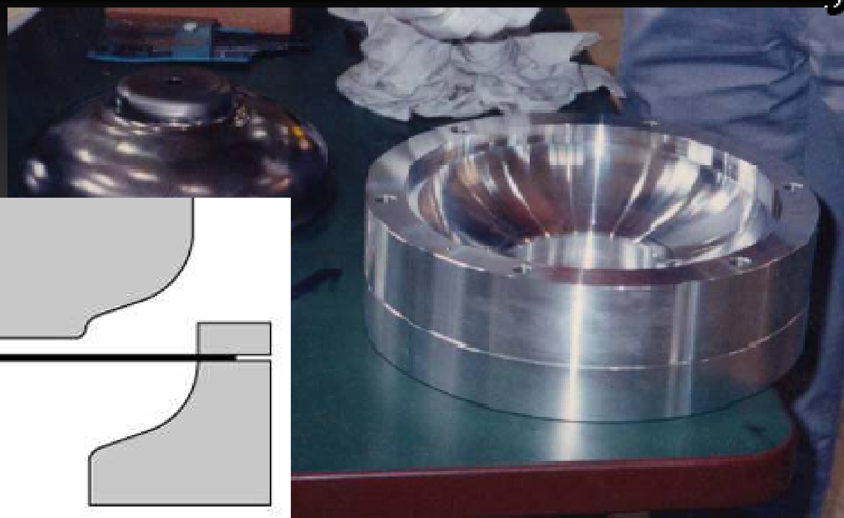


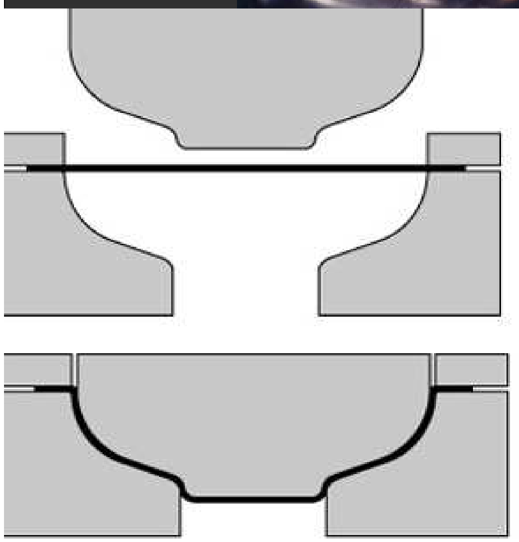
Rolling, annealing, levering, …gives Nb sheets

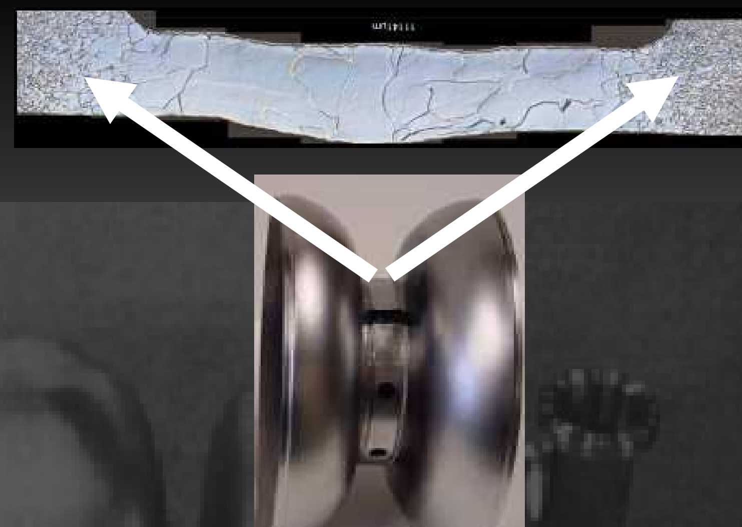


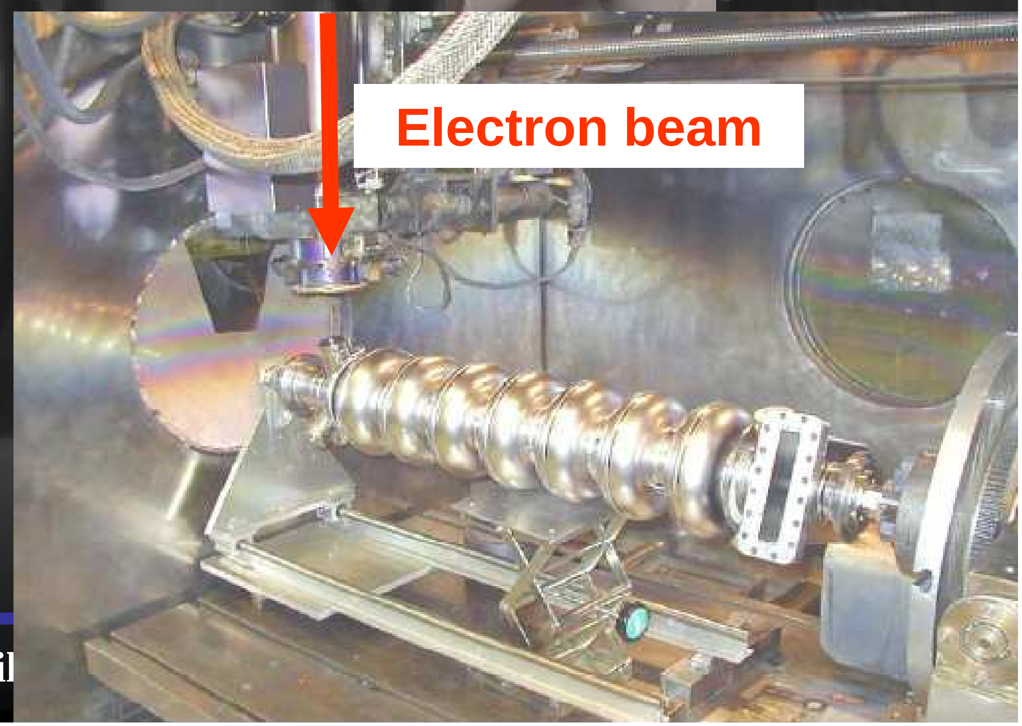
Sheets are scanned (eddy current; measures change of electric resistance) to check for foreign material inclusions (40 μm defect diameter sensitivity)

The Fabrication of an SRF Cavity (II)





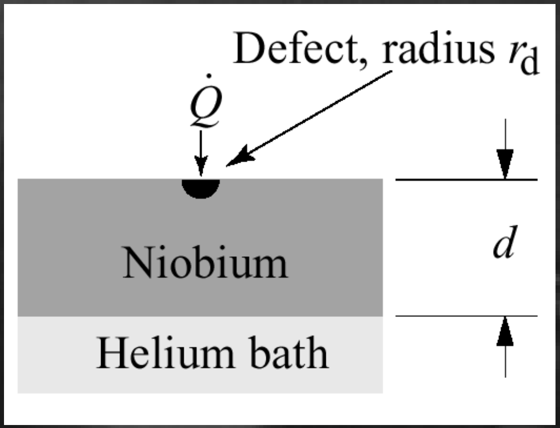




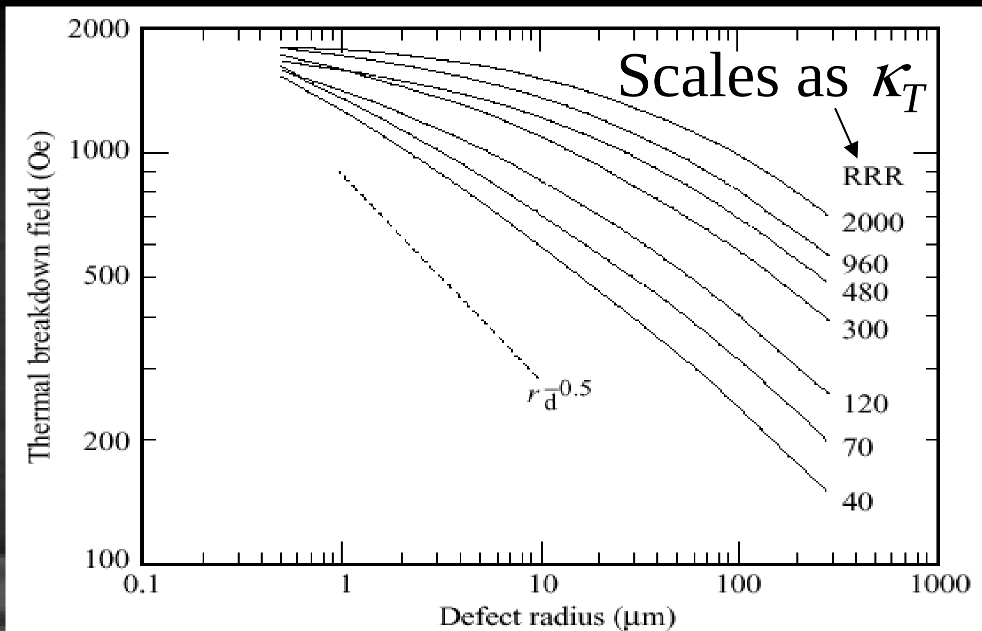
Half-cells are deep drawn and welded together in vacuum with an electron beam

1400 C Bake with Ti-Getter

- Thermal breakdown (quench) is usually triggered by a *small* normal conducting defect, when it heats the Nb above the critical temperature (100µm defect sufficient!)
- **Tolerate unavoidable defects but "neutralize" them by thermally stabilizing them.**
  - ⇨ Improve the thermal conductivity of niobium.
  - ⇨ Improve ***purity*** of the niobium.



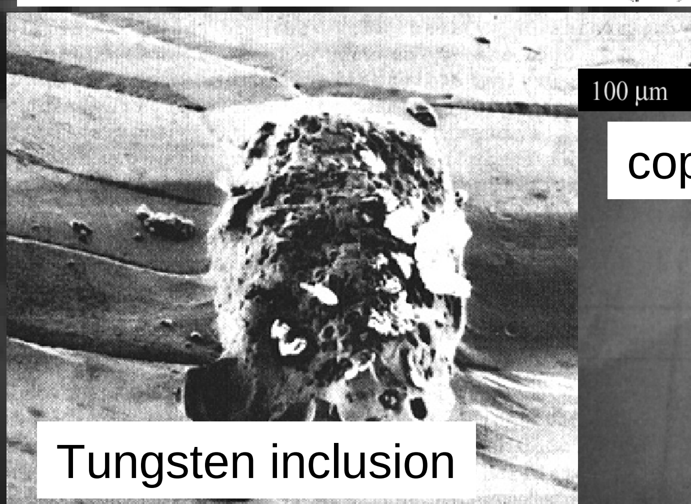
Thermal Breakdown

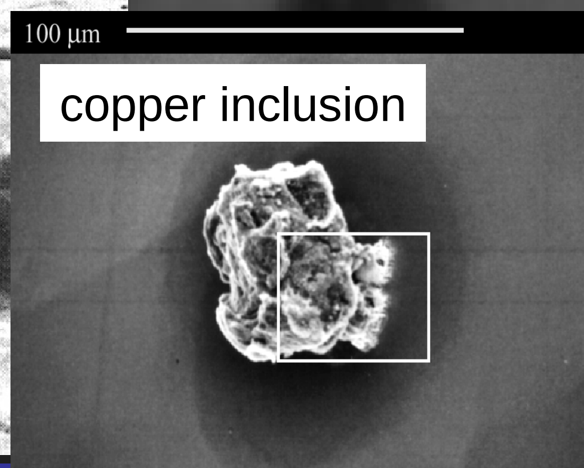


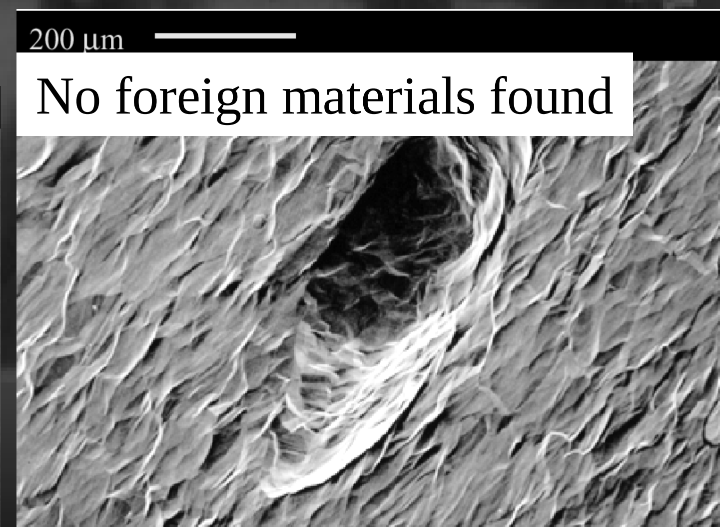
Breakdown field given by (very approximately):

$$H_{tb} = \sqrt{\frac{4\kappa_T (T_c - T_b)}{r_d R_d}}$$

κ_T: Thermal conductivity of Nb
R_d: Defect surface resistance
T_c: Critical temperature of Nb
T_b: Bath temperature

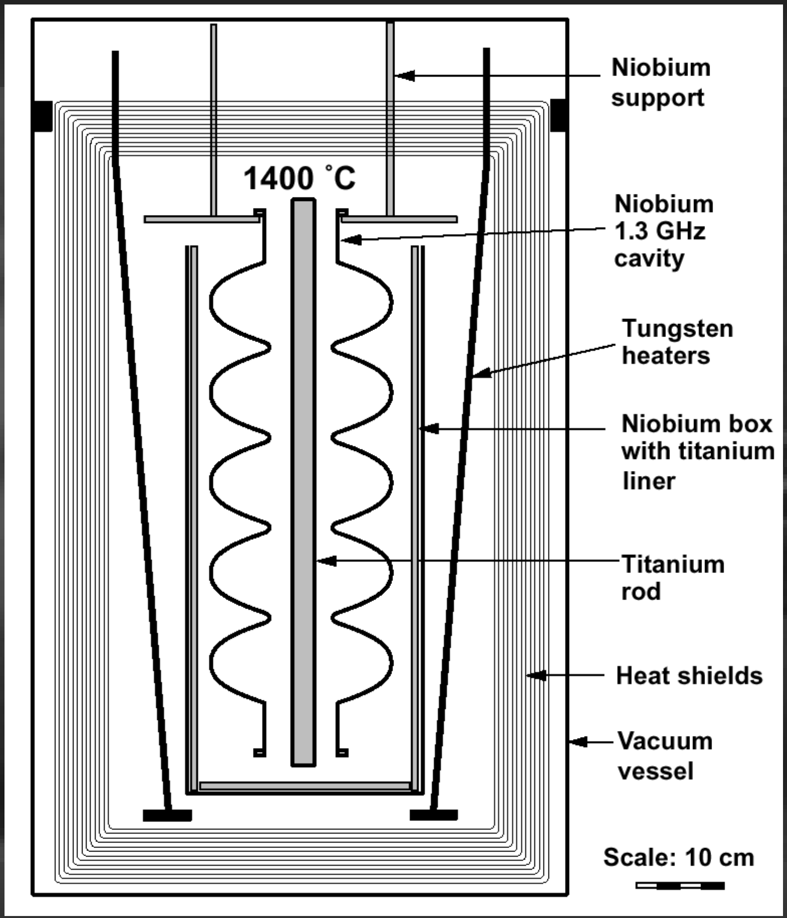




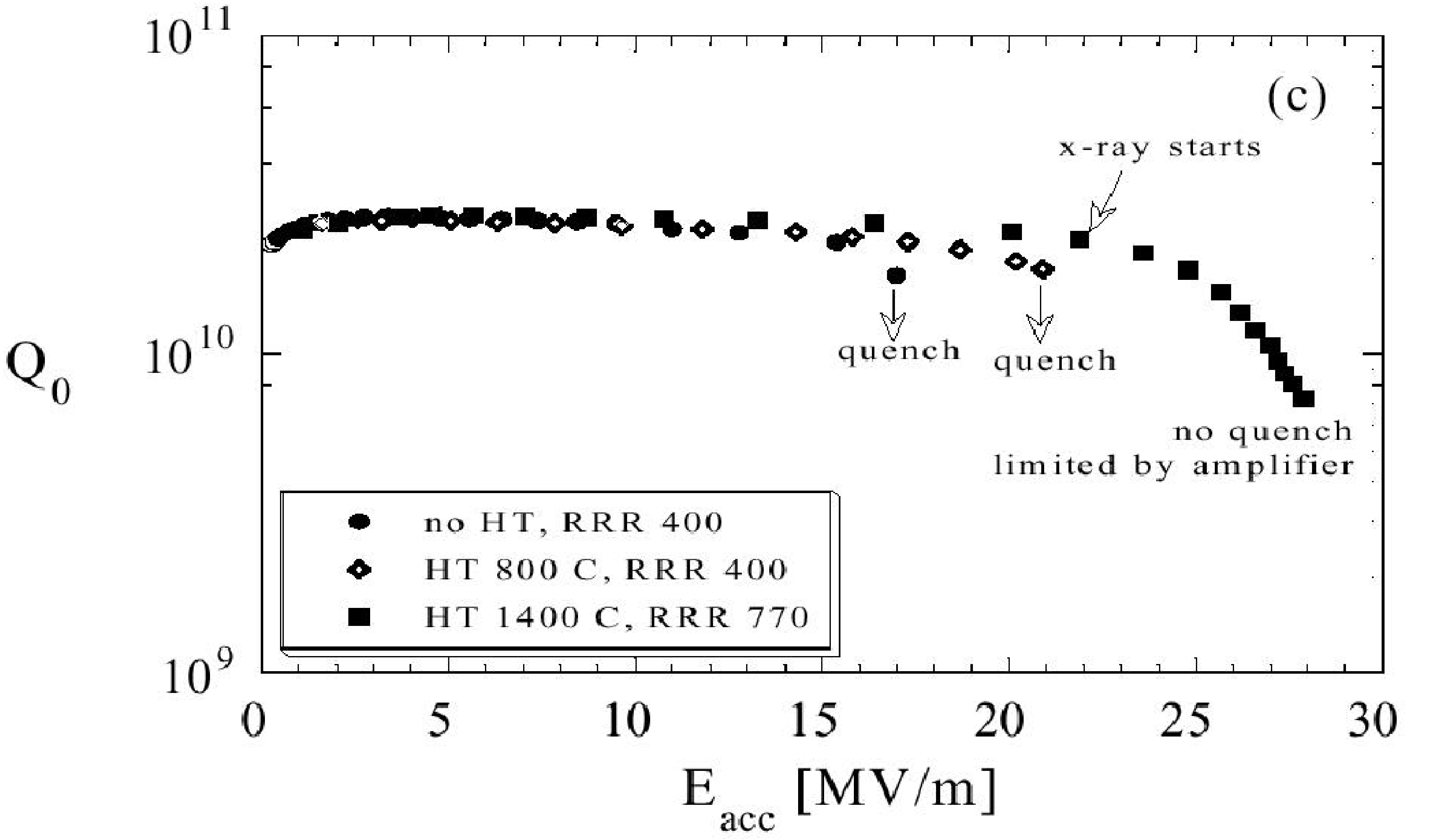


Thermal Breakdown

- **After cavity is produced**
  - Heat in vacuum furnace to ~ 1400 C
  - Evaporate Ti on cavity surface
  - Use titanium as getter to capture impurities that diffuse to the surface
  - Later etch away the titanium
  - Doubles the purity



Thermal Breakdown and Heat Treatments



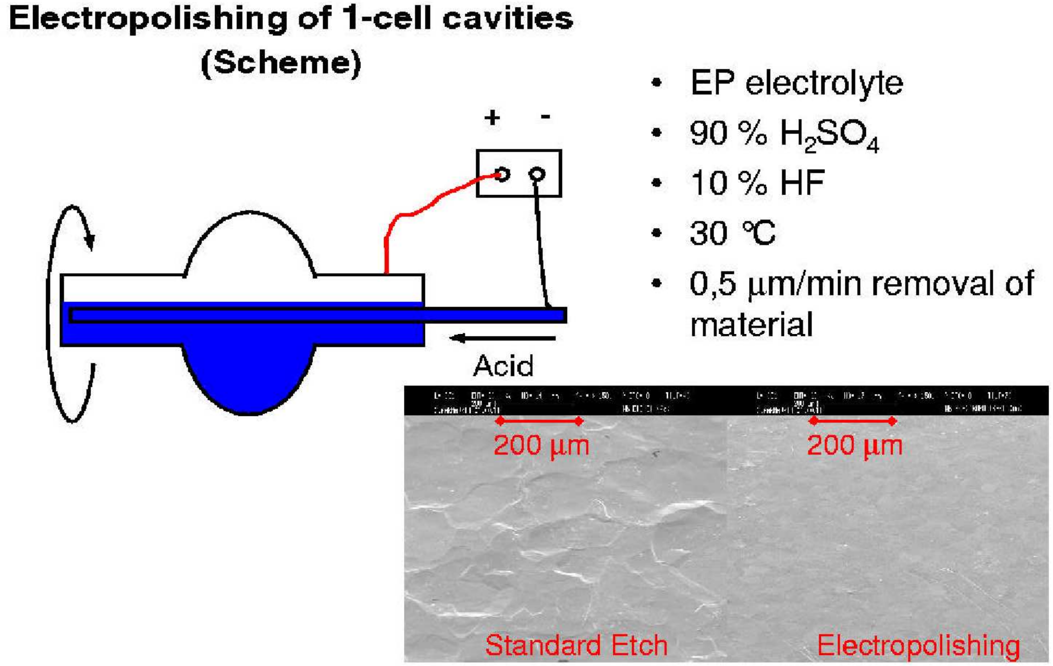
DESY results

Surface Preparation: Etching/Polishing

- Removes damaged surface layer (100 μm)

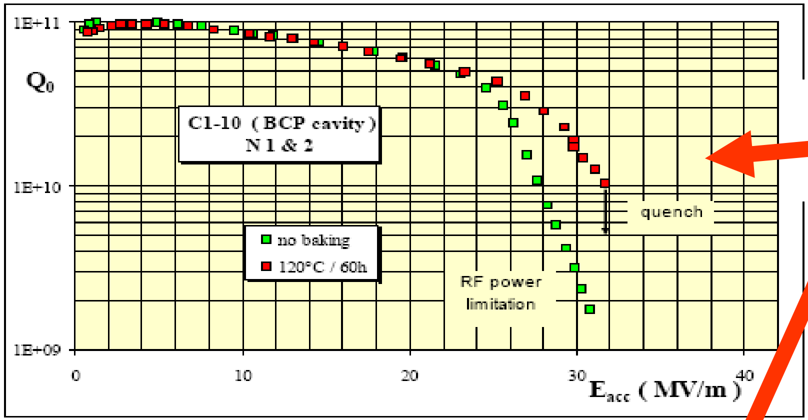
Chemically etching
BCP = HF + HNO_3 + H_3PO_4

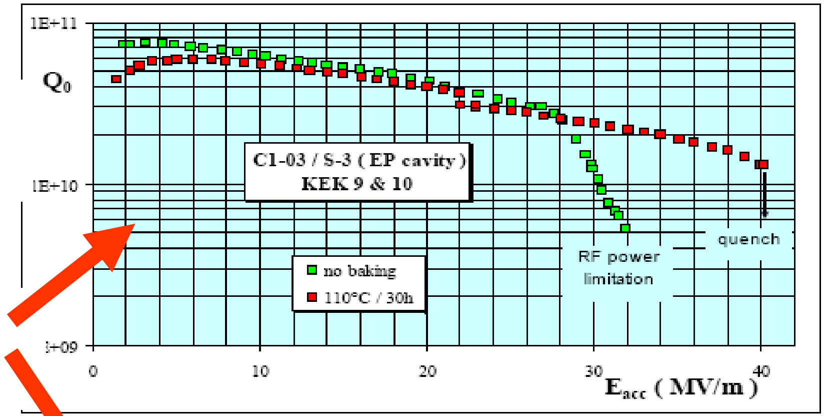
Electro-polishing
BCP = HF + HNO_3 + H_3PO_4



- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 μm/min removal of material

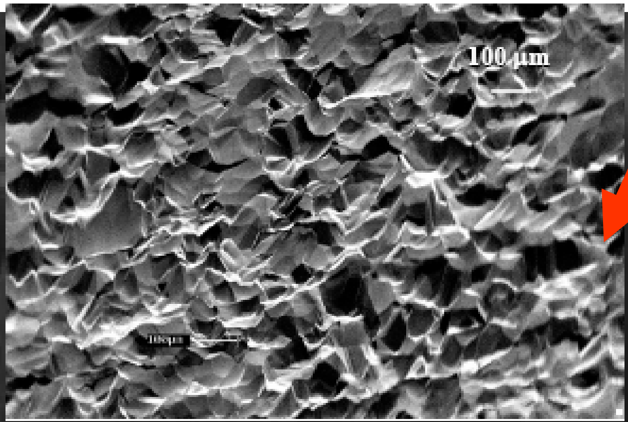
Chemically Etching vs. Electro-Polishing

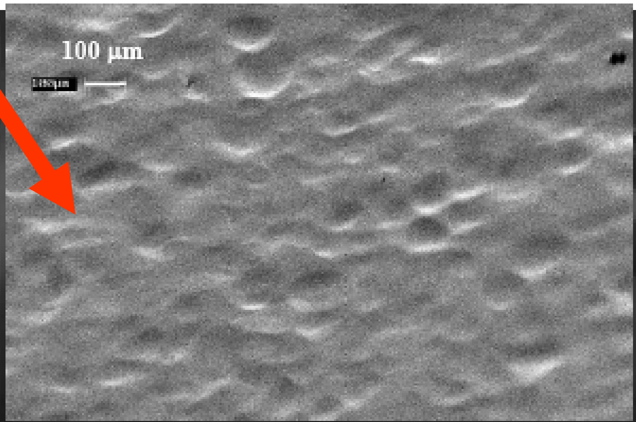




Chemically etched

Electro-polished



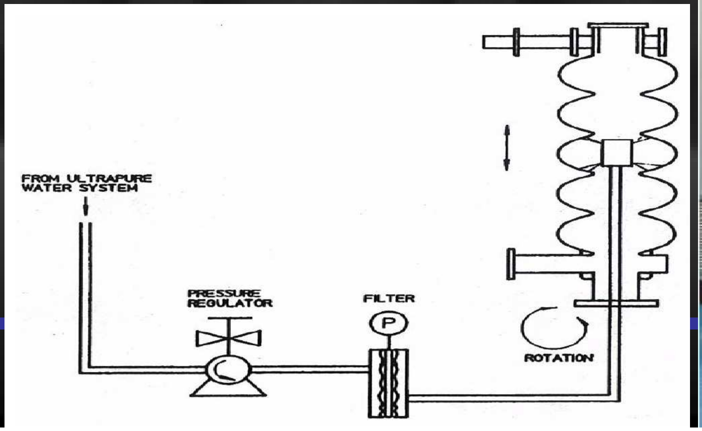


- Electro-polished cavities each (often) higher field gradients (but not always)
- Difference from surface roughness? Likely not…

High Pressure Rinsing and Clean Rooms

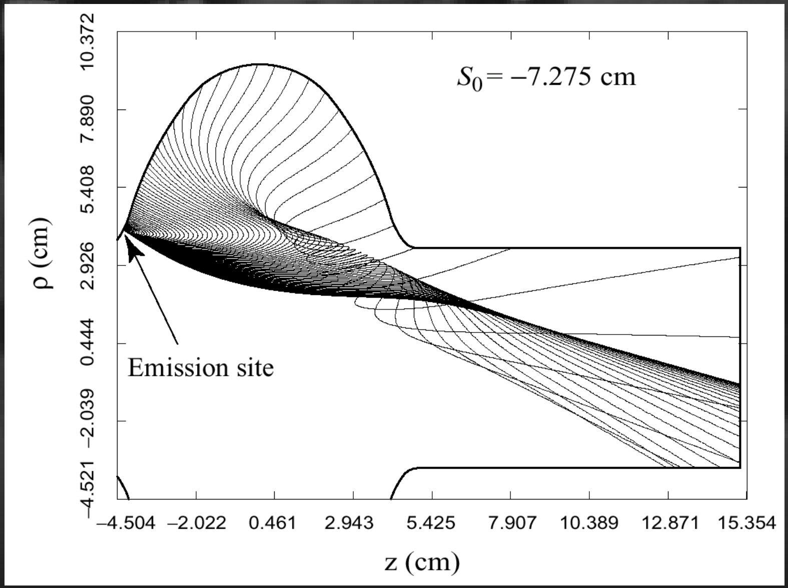
- All cavities and vacuum components are cleaned and assembled in clean rooms.

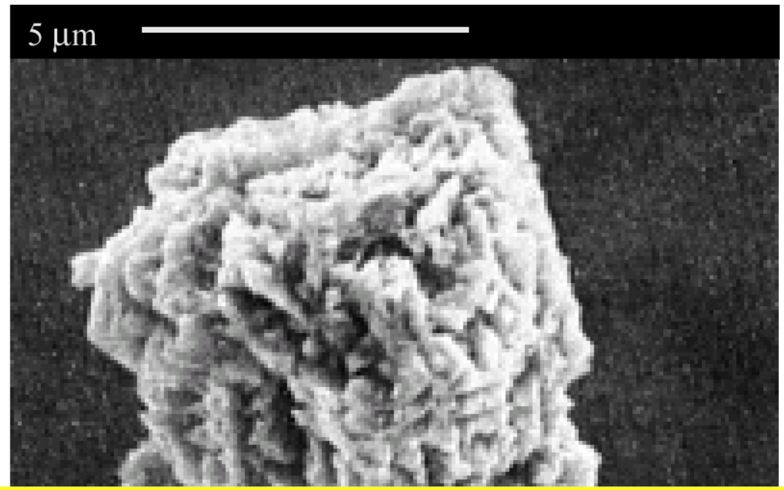
- ***Dust particles*** on the cavity surface are removed with up to 1000 psi ultra-pure water jets (High Pressure Rinsing)



Electron Field Emission (I)

- Emission of e⁻ (QM electron tunneling) from μm size defects in high E-fields.
- All emission is associated with (conducting) <u>microscopic</u> particles.
- Acceleration of electrons drains cavity energy.
- Impacting electrons produce heating of the surface.





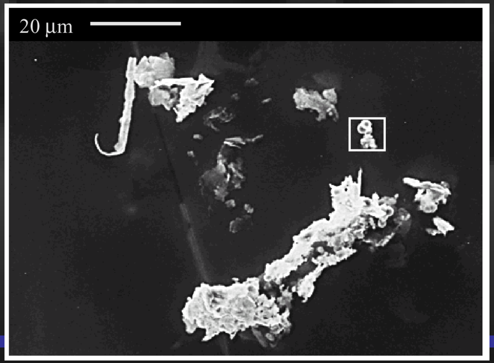
Micron size particles cause FE.

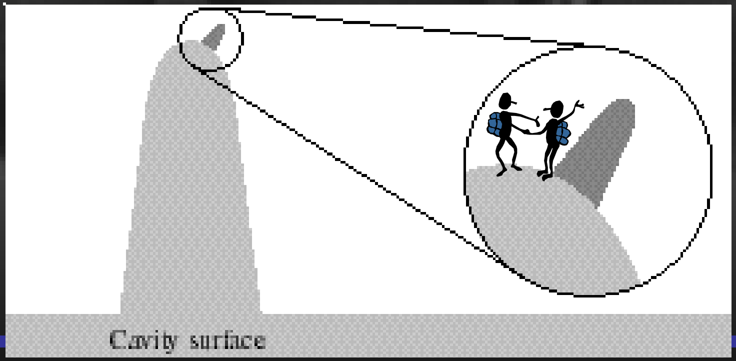
Electron Field Emission (II)

- **QM tunneling theory predicts exponential *Fowler–Nordheim* emission current density.**

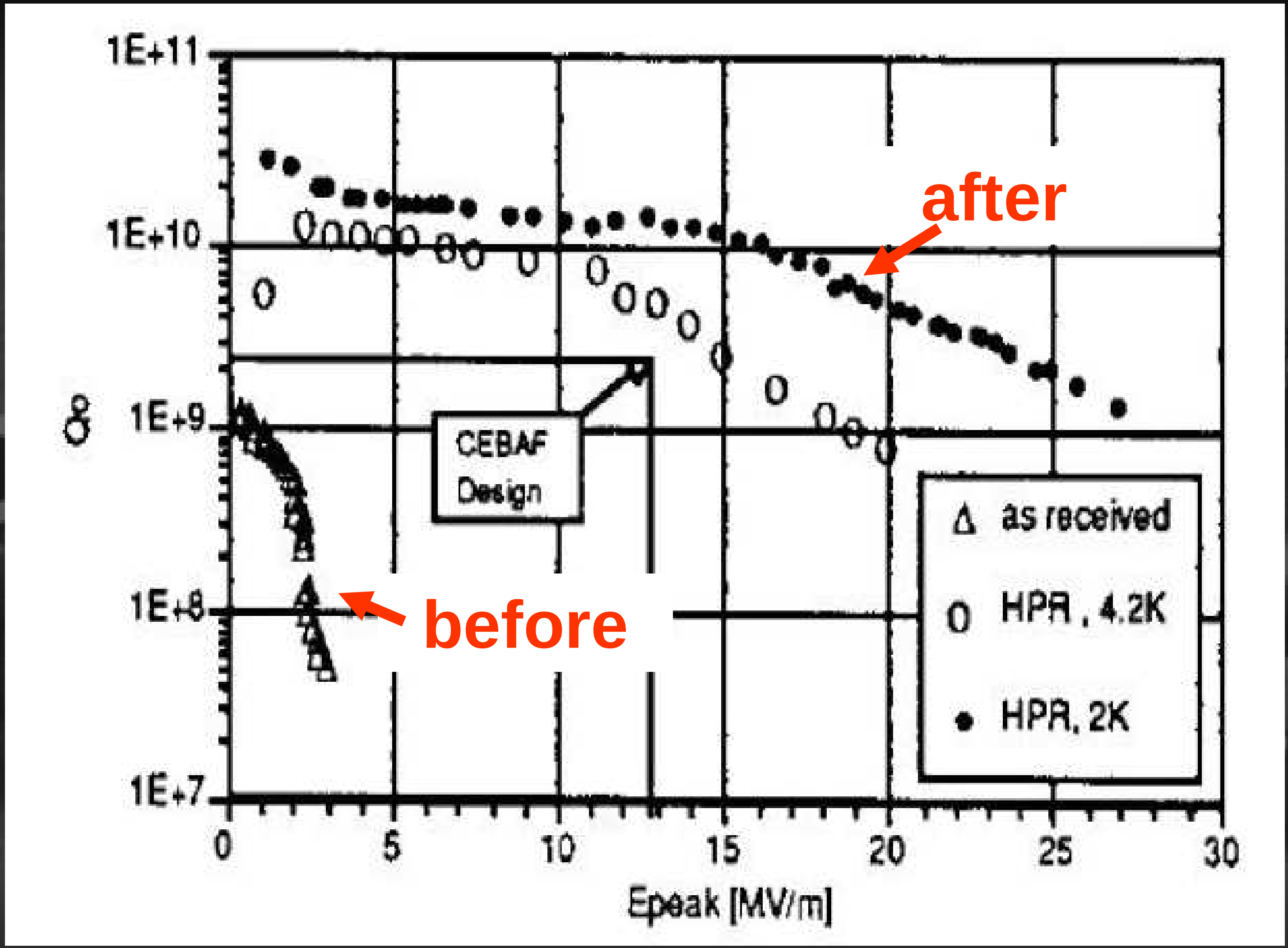
$$j_{FN} = C_1 E^2 \exp\left(-\frac{C_2}{E}\right)$$

- **Need GV/m fields!**
- **Fields in cavities are much lower than those theoretically required for field emission.**
- **Electric field enhancement model (tip-on-tip)?**



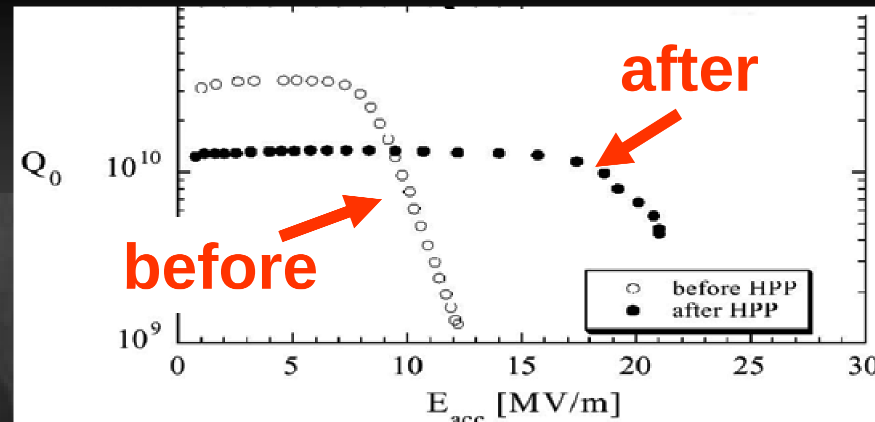


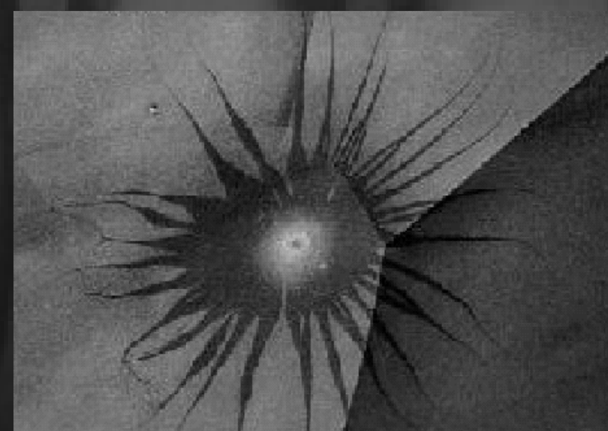
Before and After High Pressure Rinsing



High Power Processing

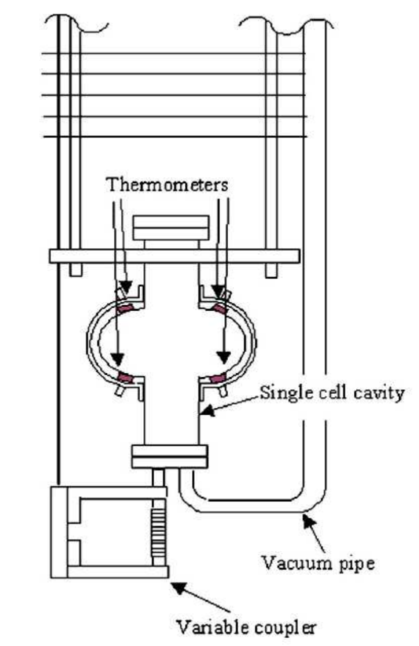
- In some cases applying of high power can cause the **destruction of field emitters** and improve the cavity performance.
- ⇨ Reduction of field emission **after** the cavity is installed in the accelerator

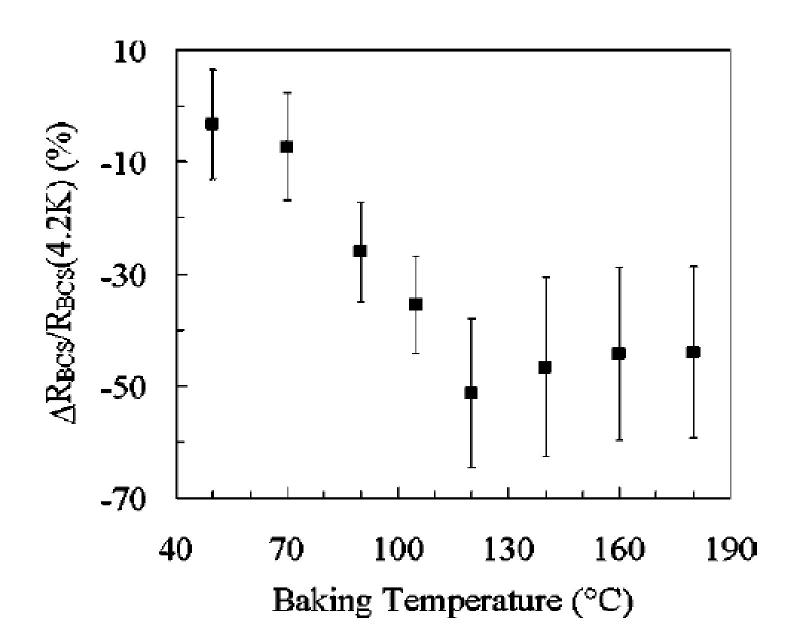




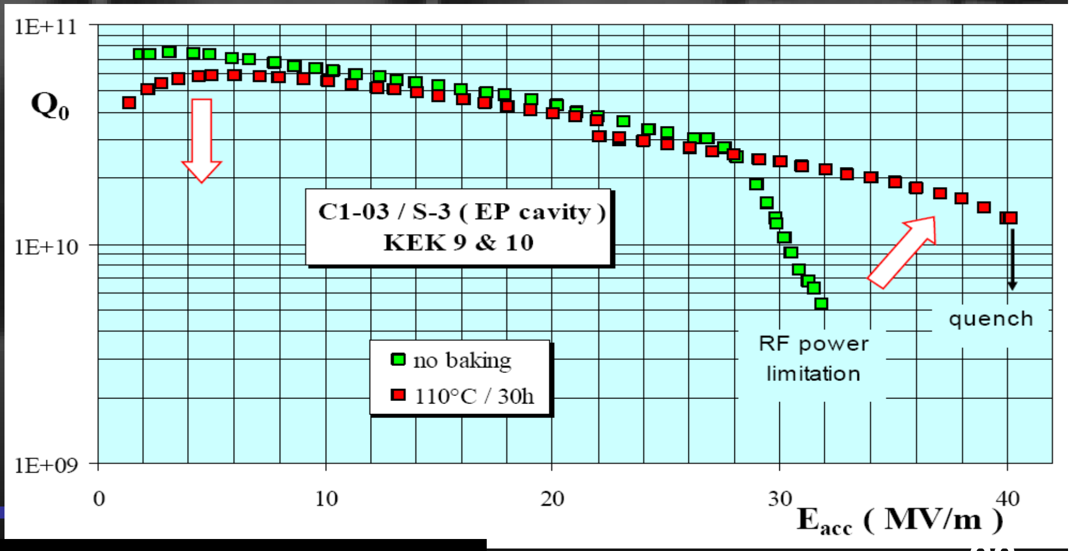
A final low Temperature Bake

- In-situ baking of the cavity at low temperatures (100 – 130 C) for 50 hours is good
  - Reduces the low field BSC surface resistance by 50%
  - Often allows to achieve higher maximum fields and lower surface resistance at high fields
- Why??? Many models…nothing conclusive





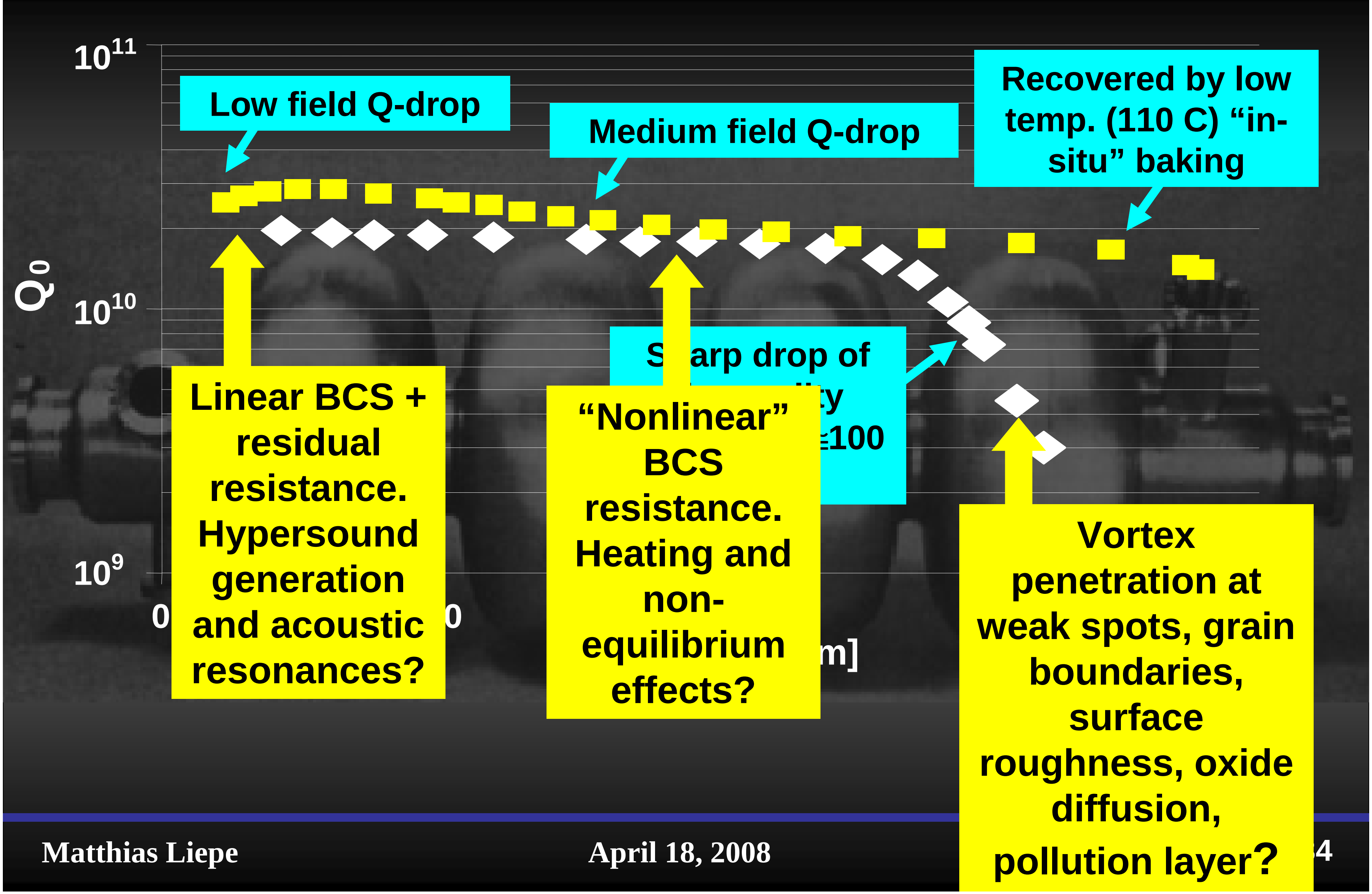
G. Ciovati et al.



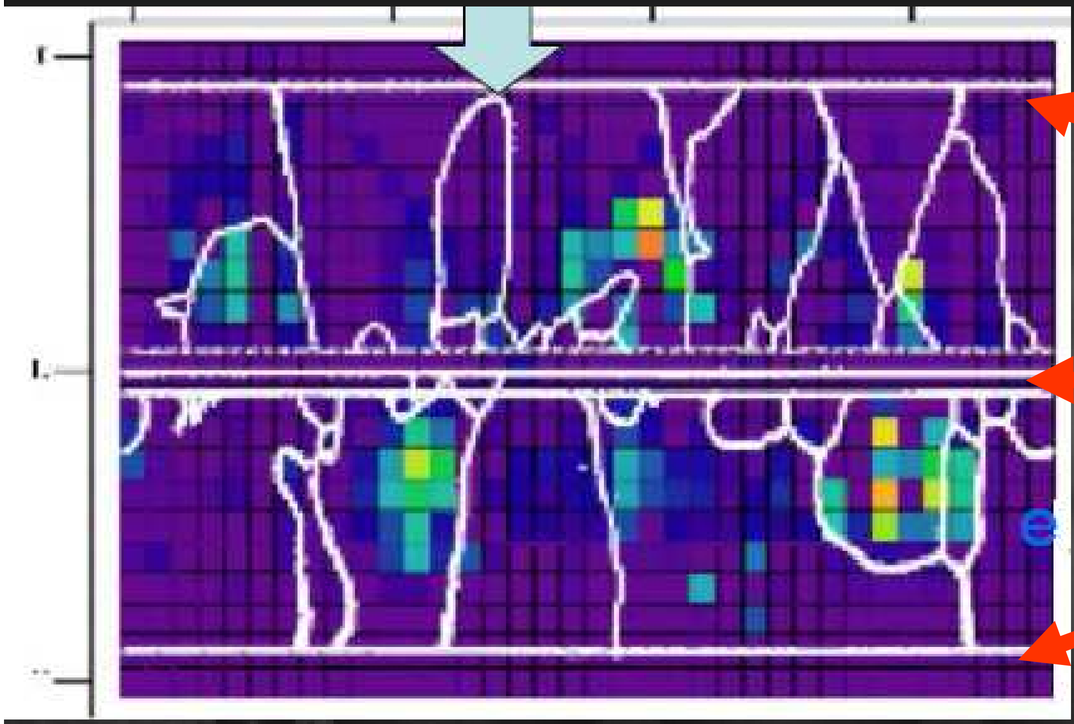
KEK results

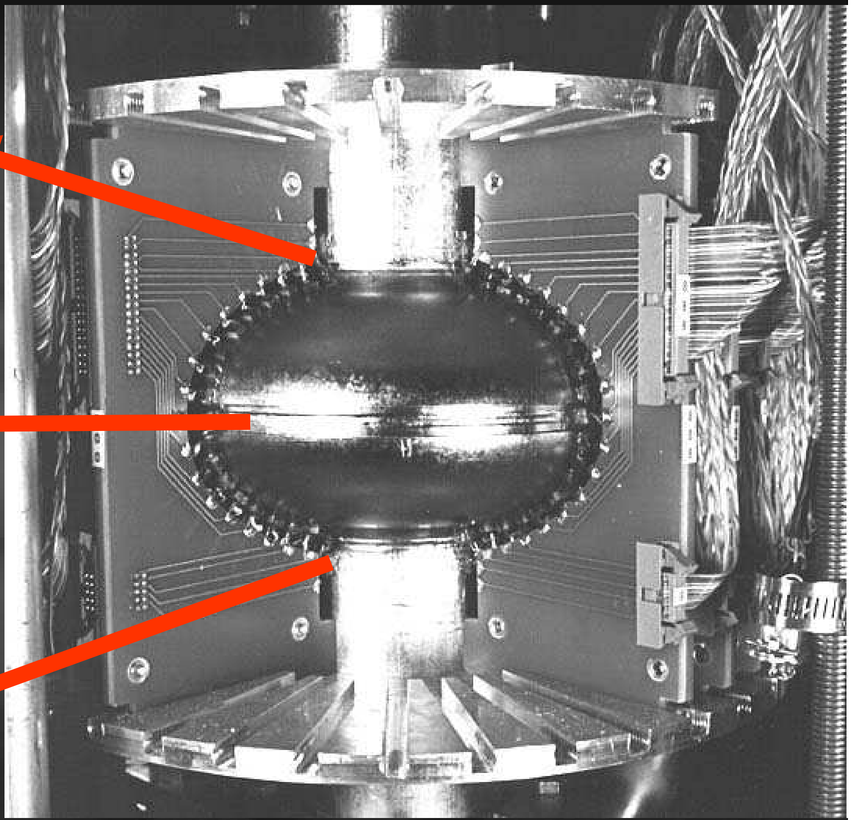
What do we find?

State of the Art Cavity Performance



Wall Heating Distribution at High Fields

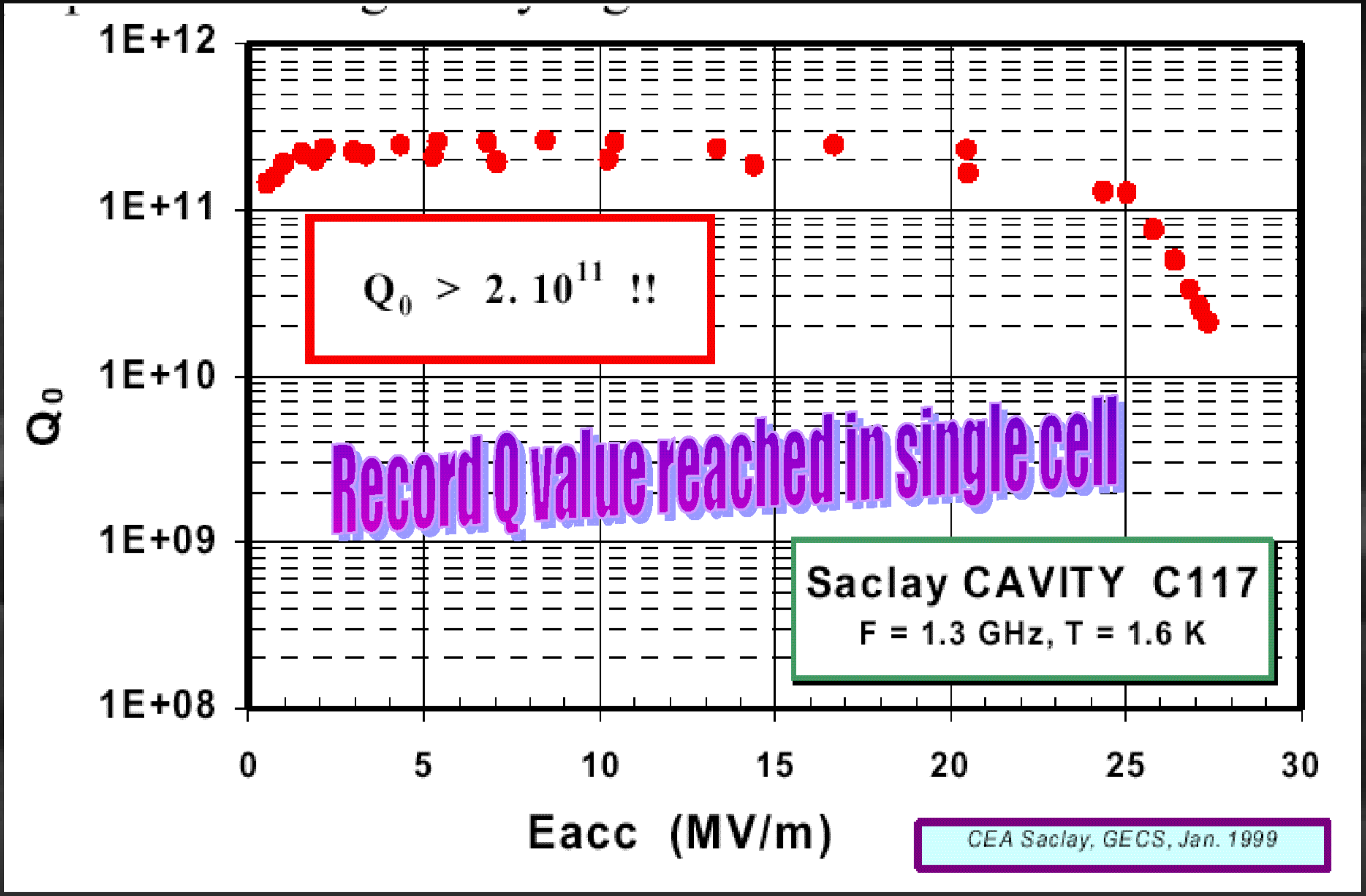




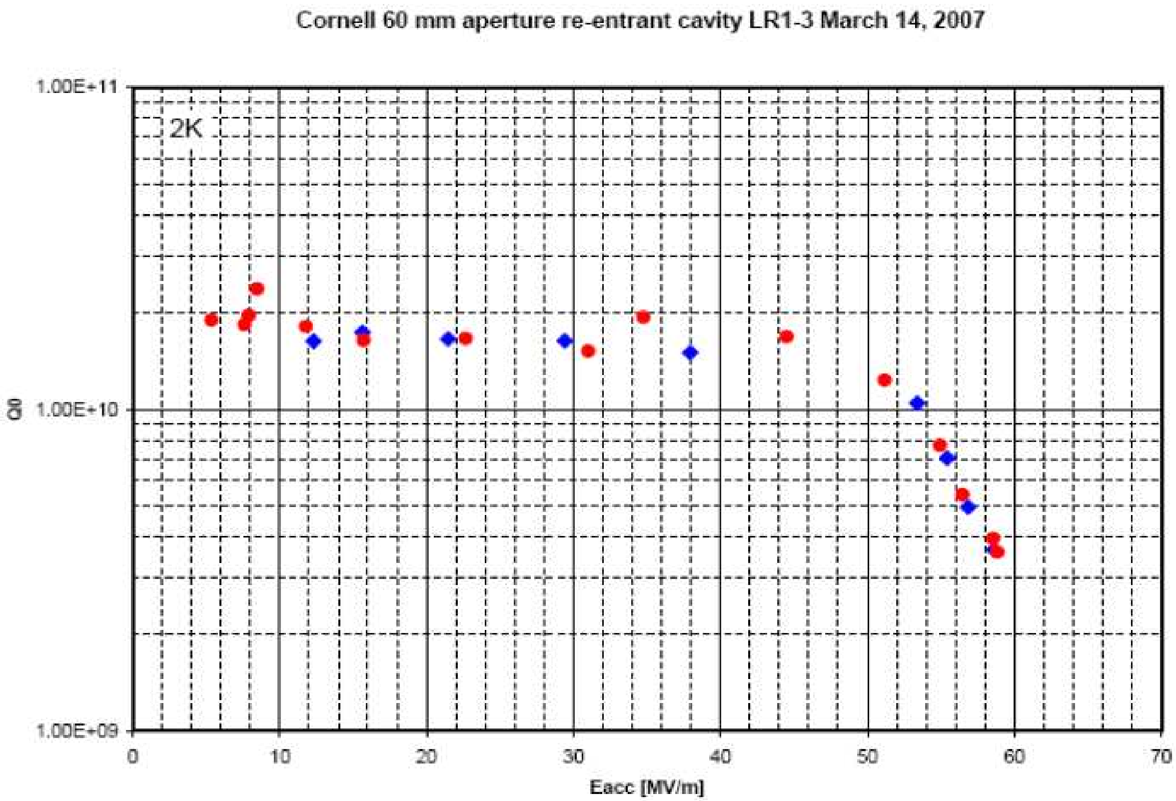
- See areas with increased heating / surface resistance at high magnetic RF fields (hot spots)
- ???

G. Eremeev et al.

Recorded Intrinsic Quality Factor



Record Field Gradient (2007 @ CU)



- **Accelerating gradient = 60 MV/m**

R.L. Geng et al.