Superconductive Materials

Part 11

Basic Principle of SRF

Outline

In this lecture we will address these questions:

- Why is important the R&D on accelerating cavities?
- Superconductivity means no resistance. Why can't we reduce the losses to zero?
- Why is niobium the material choice which requires costly helium cooling?
- What are the fundamental and technical limitations of niobium SRF cavities?
- What are possible future materials and what are the challenges? *(next lesson)*

And now finally…

…RF Superconductivity

Surface Resistance of Superconductors

Superconducting currents are transported by Cooper pairs formed of two electrons

Flow without friction → DC supercurrents are lossless

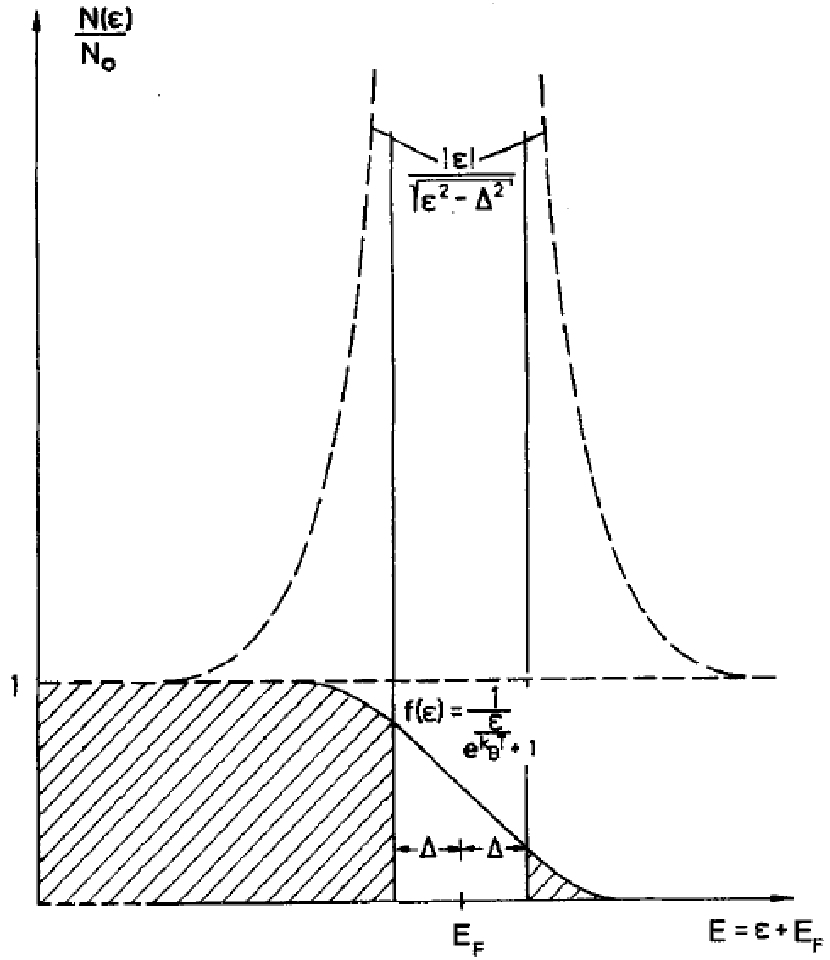
At **T > 0 K** there is a **small fraction of unpaired electrons**

$$n_n(T) \propto e^{-\Delta/k_B T}$$

Cooper pairs have a finite inertia. Under RF fields a time-varying E-field is induced in the material. **Normal electrons see this field, move and dissipate**

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

→ $R_s > 0$



Surface Resistance in the two fluid model

Basic ingredients for RF superconductivity

- Two fluid model (Gorter-Casimir)
- Maxwell electrodynamics
- London equations

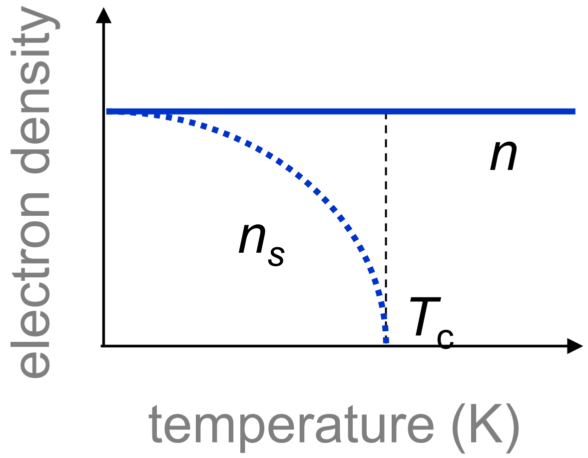
$$n_s / n_n = 1 - \left(T/T_c\right)^4$$

Close to 0 K:

$$n_n = \exp\left(-\frac{\Delta}{k_b T}\right)$$

Basic assumptions of two fluid model

- all free electrons of the superconductor are divided into two groups:
- superconducting electrons of density n_s
- normal electrons of density n_n
- The total density of the free electrons is $n = n_s + n_n$
- As the temperature increases from 0 to T_c, the density n_s decreases from n to 0



Electrodynamics of normal conductors

$$\boxed{\boldsymbol{E} = \boldsymbol{E}_0 \boldsymbol{e}^{i\omega t}}$$

We can derive the **skin depth** starting from the fundamental equation of electrodynamics:

Maxwell's equations **+** *Linear and isotropic Material's equation* **+** *Drude's model*

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

$$\boldsymbol{D} = \varepsilon_0 \varepsilon\, \boldsymbol{E}$$

$$\boldsymbol{B} = \mu_0 \mu\, \boldsymbol{H}$$

$$\boldsymbol{J} = \sigma\, \boldsymbol{E}$$

Skin depth

For a good conductor at RF frequencies: ωε << σ $\Rightarrow$ $\frac{\partial \boldsymbol{D}}{\partial t} \sim 0$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \cancel{\frac{\partial \boldsymbol{D}}{\partial t}} \Rightarrow \nabla \times \boldsymbol{H} = \boldsymbol{J} \xrightarrow[\boldsymbol{J} = \sigma\, \boldsymbol{E}]{\nabla \times} \nabla \times \nabla \times \boldsymbol{H} = \sigma\, \nabla \times \boldsymbol{E}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\boldsymbol{B} = \mu_0 \mu\, \boldsymbol{H}$$

$$\boldsymbol{H} = \boldsymbol{H_0 e^{i\omega t}}$$

$$\boldsymbol{\nabla^2 H = i\sigma\mu_0\mu\omega H}$$

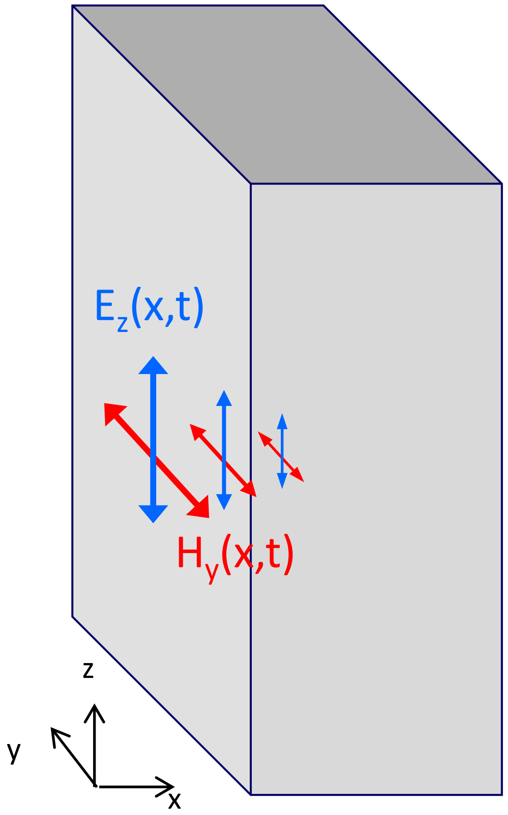
Skin depth (2)

$$\nabla^2 H = i\sigma\mu_0\mu\omega H$$

Solution (semi-infinite slab):

$$H_y = H_0 e^{-x/\delta} e^{-ix/\delta}$$

$$E_z = -\frac{(1+i)}{\sigma\delta} H_y$$



AC fields penetrate a thickness δ (the skin depth) $\delta = \sqrt{\frac{2}{\mu_0\mu\sigma\omega}}$

Surface impedence

Surface reactance

$$Z = \frac{E_{\parallel}}{H_{\parallel}} = R_s + iX_s$$

Surface resistance

For the semi-infinite plane conductor:

$$Z_n = \frac{|E_z|}{H_y}$$

$$E_z = -\frac{(1+i)}{\sigma\delta} H_y$$

$$Z_n = \frac{1+i}{\sigma\delta}$$

$$R_s = X_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0 \mu \omega}{2\sigma}}$$

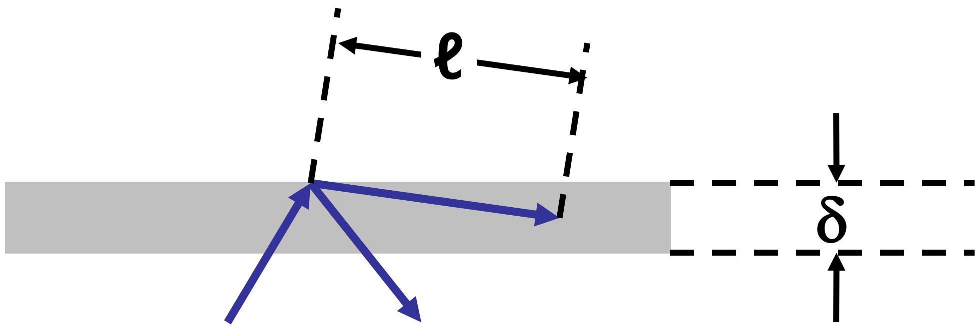
Anomalous skin effect

What happen at low T (and high frequency)?

$$R_s = \frac{1}{\sigma\delta}$$

σ(*T*) increases ⬆ δ decreases ⬇

The skin depth (the distance over which fields vary) **can become less than the mean free path of the electrons** (the distance they travel before being scattered) ⇒ $J(x) \neq \sigma\, E(x)$



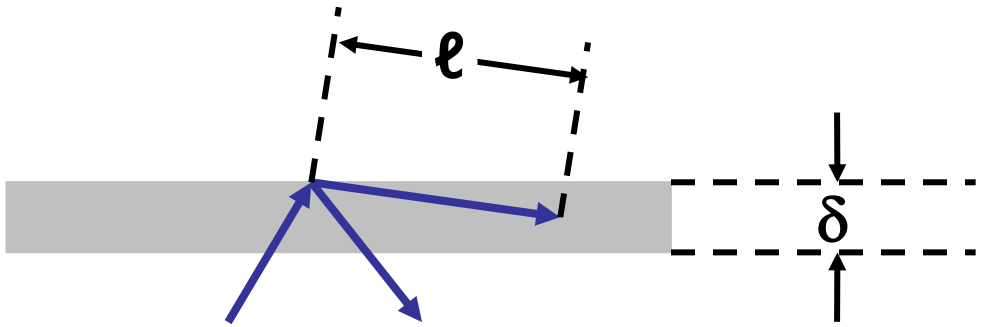
$$\delta = \sqrt{\frac{2}{\mu_0 \mu \sigma \omega}}$$

Anomalous skin effect (2)

Non local relationship introduced by Reuther and Sondheimer:

$$\boldsymbol{J} = \frac{3\sigma}{4\pi\ell}\int \frac{\boldsymbol{r}(\boldsymbol{r}\cdot\boldsymbol{E})e^{-r/\ell}}{r^4}d^3\boldsymbol{r}$$

Non-locality enters the problem when the response to a field can only be determined correctly by integrating over a volume of the size of ℓ^3 (3D case), where ℓ is comparable to or longer than the distance δ, the depth over which the ***E***-field varies



Surface resistance - some numbers

For Cu @ 300 K and 1.5 GHz:

σ (300 K) = 5.8 x 10^7 1/Ωm

$\mu_0 = 1.26 \times 10^{-6}$ Vs/Am

$\mu = 1$

$$\delta = \sqrt{\frac{2}{\mu_0 \mu \sigma \omega}} = 1.7\ \mu\mathrm{m}$$

$$R_s = \frac{1}{\sigma \delta} = 10\ \mathrm{m}\Omega$$

Surface resistance - some numbers (2)

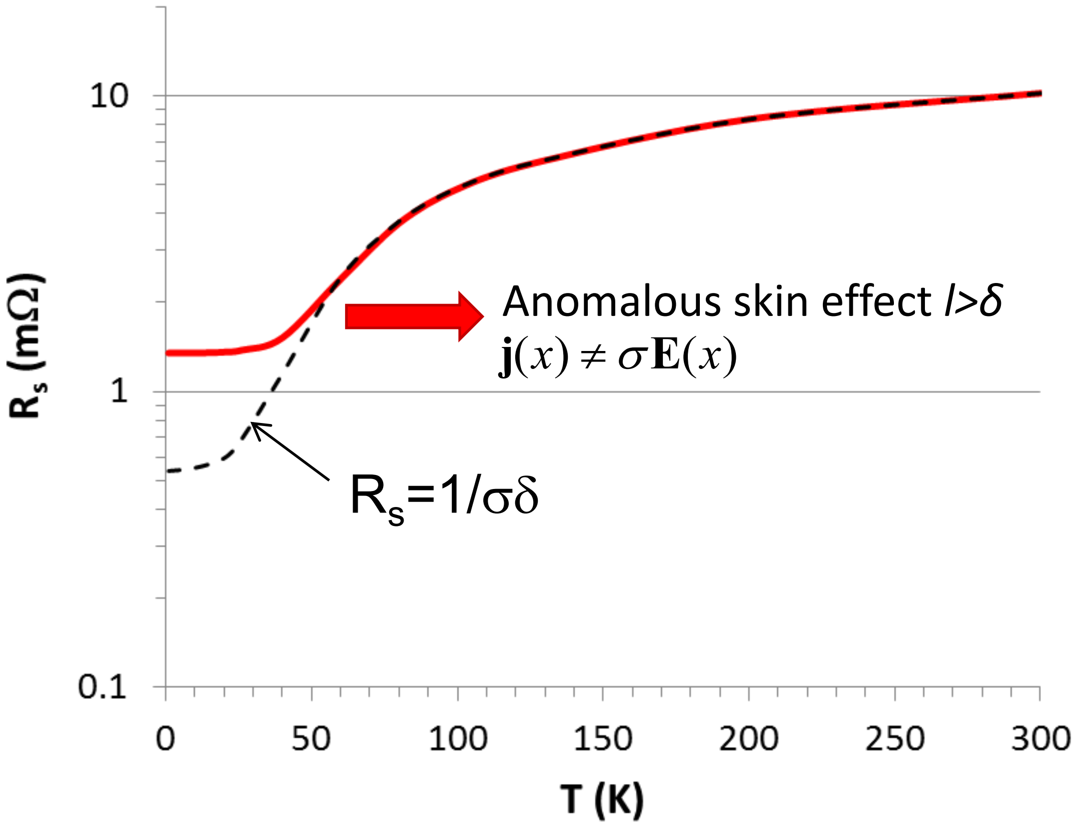
Surface resistance of Cu at 1.5 GHz as a function of temperature

R_s(300 K) ≅ 10 $\mathbf{m\Omega}$

R_s(4.2 K) ≅ 1.3 $\mathbf{m\Omega}$

RRR = σ(4.2K)/σ(300K) = 300

…in spite of the **resistivity decreasing by a factor 300** from 300 K to 4.2 K, **R_s only decreases by a factor of ~8**!



Surface Resistance in the two fluid model

London equation:

$$\frac{\partial}{\partial t}\vec{J}_s = \frac{\vec{E}}{\mu_0 \lambda_L^2} \Rightarrow J_s = -i \underbrace{\boxed{\frac{1}{\omega \mu_0 \lambda_L^2}}}_{\sigma_2} E$$

$$E = E_0 e^{i\omega t}$$

Two fluid model:

$$J = J_n + J_s = \underbrace{(\sigma_1 - i\sigma_2)}_{\sigma} E$$

$$\sigma_1 = \frac{n_n e^2 \tau}{m}, \quad \sigma_2 = \frac{n_s e^2}{m\omega}$$

$$\lambda_L^2 = \frac{1}{\mu_0} \frac{m}{n_s e^2}$$

Electrodynamics of SC is the same as NC, only that we have to change $\sigma \rightarrow \sigma_1 - i\,\sigma_2$

Penetration depth:

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} = \frac{1}{\sqrt{\mu_0 \omega \sigma_2}} \sqrt{\frac{2i}{1 + i\sigma_1/\sigma_2}} \cong (1+i)\lambda_L \left(1 - i\frac{\sigma_1}{2\sigma_2}\right)$$

$\sigma_1 << \sigma_2$ for SC at $T<<T_c$

$$H_y = H_0 e^{-\frac{(1+i)}{\delta}x} \Rightarrow \boxed{H_y = H_0 e^{-\frac{x}{\lambda_L}} e^{-i\frac{x}{\lambda_L}\frac{\sigma_1}{2\sigma_2}}}$$

For **Nb: λ_L = 36 nm**
compared to **δ = 1.7 µm** for **Cu** at 1.5 GHz

Surface Resistance in the two fluid model

Recall the definition of the surface impedance:

$$Z = \frac{|E_{\parallel}|}{\int_0^{\infty} J(x)dx} = \frac{E_{\parallel}}{H_{\parallel}} = R_s + i\,X_s = \sqrt{\frac{i\omega\mu_0}{\sigma}}$$

$$Z = R_s + i\,X_s = \sqrt{\frac{i\omega\mu_0}{\sigma}} = \sqrt{\frac{\omega\mu_0}{\sigma_1}}(\varphi_- + i\varphi_+)$$

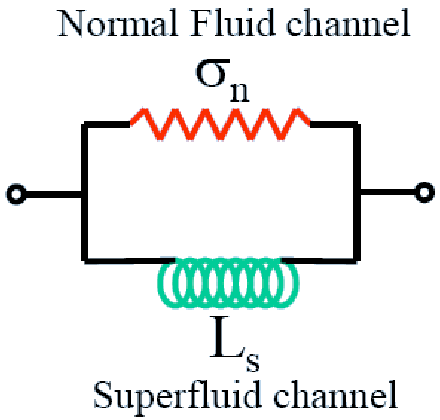
$$\varphi_{\pm}^2 = \frac{y}{1+y^2}\left(\sqrt{1+y^2} \pm 1\right) \qquad y = \frac{\sigma_1}{\sigma_2}$$

For a SC $\sigma_1 << \sigma_2 \rightarrow y << 1$

$$\varphi_- = \sqrt{\frac{y^3}{2}} \qquad \varphi_+ = \sqrt{2y}$$

$$R_s = \frac{1}{2}\mu_0^2\omega^2\sigma_1\lambda_L^3$$

$$Z_s = R_s + iX_s$$



$$X_s = \omega \underbrace{\mu_0 \lambda_L}_{L_s}$$

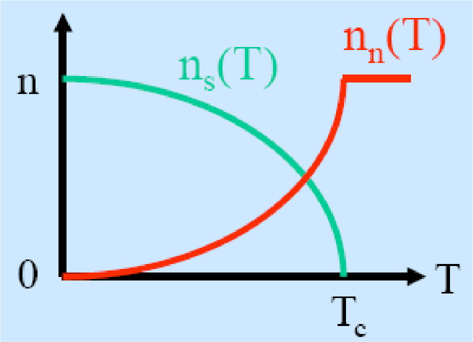
L_s: kinetic inductance

Surface Resistance in the two fluid model

$$R_s = \frac{1}{2}\mu_0 \omega^2 \sigma_1 \lambda_L^3$$

$R_s \propto \omega^2$ ➡ use low-frequency cavities to reduce power dissipation

R_s temperature dependence



$n_s(T) \propto 1-(T/T_c)^4$ near T_c

$\sigma_1(T) \propto n_n(T) \propto e^{-(\Delta/KBT)}$ at $T \ll T_c$

$$R_s \propto \omega^2 \lambda_L^3 \ell e^{-\Delta/k_B T}$$ $T<T_c/2$

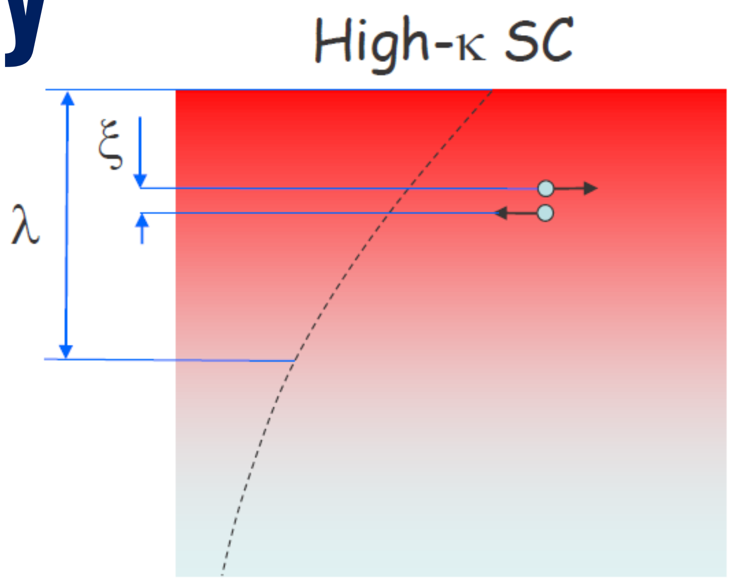
Rs within BCS theory

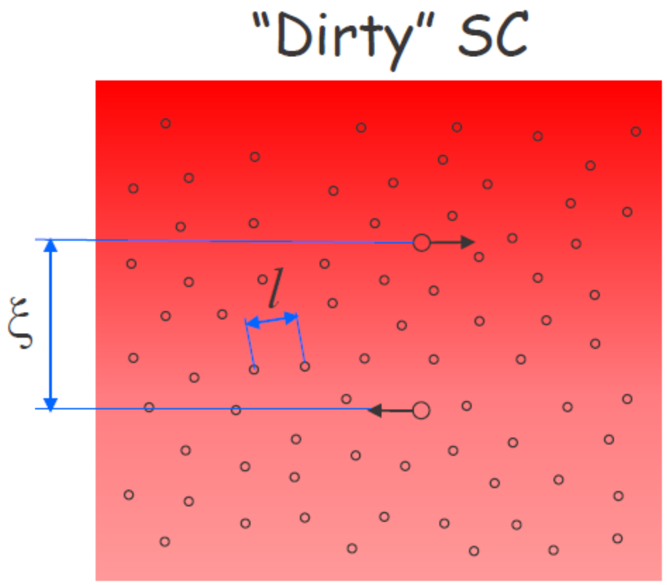
Mattias and Bardeen (1958) used time dependent perturbation theory to derive R_S for weak RF fields

Within this theory no simple formula can be derived. Several approximate formula can be found in the literature for some limits. A good approximation of R_{BCS} in the dirty limit for T<Tc/2 and ω<Δħ is:

$$R_{BCS} \cong \frac{\mu_0{}^2\omega^2\lambda_L{}^3\sigma_n\Delta}{k_B T}\ln\left[\frac{C_1 k_B T}{\hbar\omega}\right]\exp\left(-\frac{\Delta}{k_b T}\right)$$

$C_1 \sim 9/4$





Rs within BCS theory

There are numerical codes (Halbritter, 1970) to calculate R_{BCS} as a function of w, T and material parameters (x_0, l_L, T_c, D, l)

SRIMP

This webpage calculates BCS surface resistance under wide range of conditions, and is based on a program by Jurgen Halbritter. [J. Halbritter, Zeitschrift f�r Physik 238 (1970) 466]

Enter material parameters below, and click submit to calculate the BCS surface resistance. Results are given in a new window.
Please be aware that frequencies much lower than 1 MHz may cause substantial processing times (depending on the user's computer).

Submit

Frequency (MHz):	1300
Transition temperature (K):	9.2
DELTA/kTc:	1.86
London penetration depth (A):	330
Coherence length (A):	400
RRR:	300
Accuracy of computation:	.001
Temperature (of operation):	2

Results:

Diffuse Reflection:	Resistance (Ohm):	$\boxed{1.9031321344341478e-8}$
	Penetration Depth (um):	0.037746828693838295

Input Parameters:

Frequency (MHz):	1300
Transition temperature (K):	9.2
DELTA/kTc:	1.86
London penetration depth (A):	330
Coherence length (A):	400
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R_{BCS} Nb ≈ 20 nΩ

http://www.lepp.cornell.edu/~liepe/webpage/researchsrimp.html

BCS vs two fluid model

The treatment within BCS theory and two-fluid model give qualitatively similar results

Quantitatively they can **differ** by an order of magnitude

The BCS treatment gives qualitatively correct results for low field

To treat experimental data approximate formulae are useful, e.g.

$$R_S = \frac{\omega^2 \mathrm{A}}{T} \exp\left(-\frac{\Delta}{k_b T}\right) \qquad R_S = \frac{\omega^2 \mathrm{A}}{T} \exp\left(-\frac{1.76 T_c}{T}\right)$$

Here A accounts for all material parameters

The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

This equation implies *R_S*:

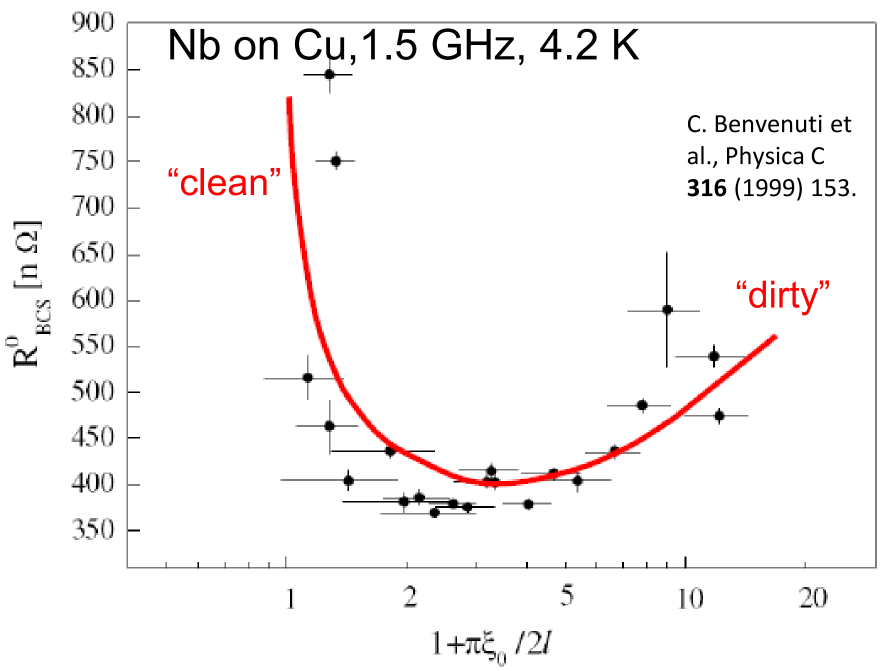
- Has a minimum for medium purity
- Is proportional to ω^2
- Decreases exponentially with temperature
- Vanishes as $T \rightarrow 0$ K
- Is independent of RF field strength

In the following we will compare these assumptions to experimental data and modify the formula if necessary

Material purity dependence of R_s

The dependence of the penetration depth on ℓ is approximated as $\lambda(\ell) \approx \lambda_L \sqrt{1 + \frac{\pi \xi_0}{2\ell}}$

$\sigma_1 \propto \ell$



$$R_s \propto \left(1 + \frac{\xi_0}{\ell}\right)^{3/2} \ell$$

$R_s \propto \ell$ if $\ell \gg \xi_0$ ("clean" limit)

$R_s \propto \ell^{-1/2}$ if $\ell \ll \xi_0$ ("dirty" limit)

R_s has a minimum for $\ell = \pi\xi_0/4$

Nb films sputtered on Cu

- By changing the sputtering species, the mean free path was varied
- RRR of niobium on copper cavities can be tuned for lowest R_S

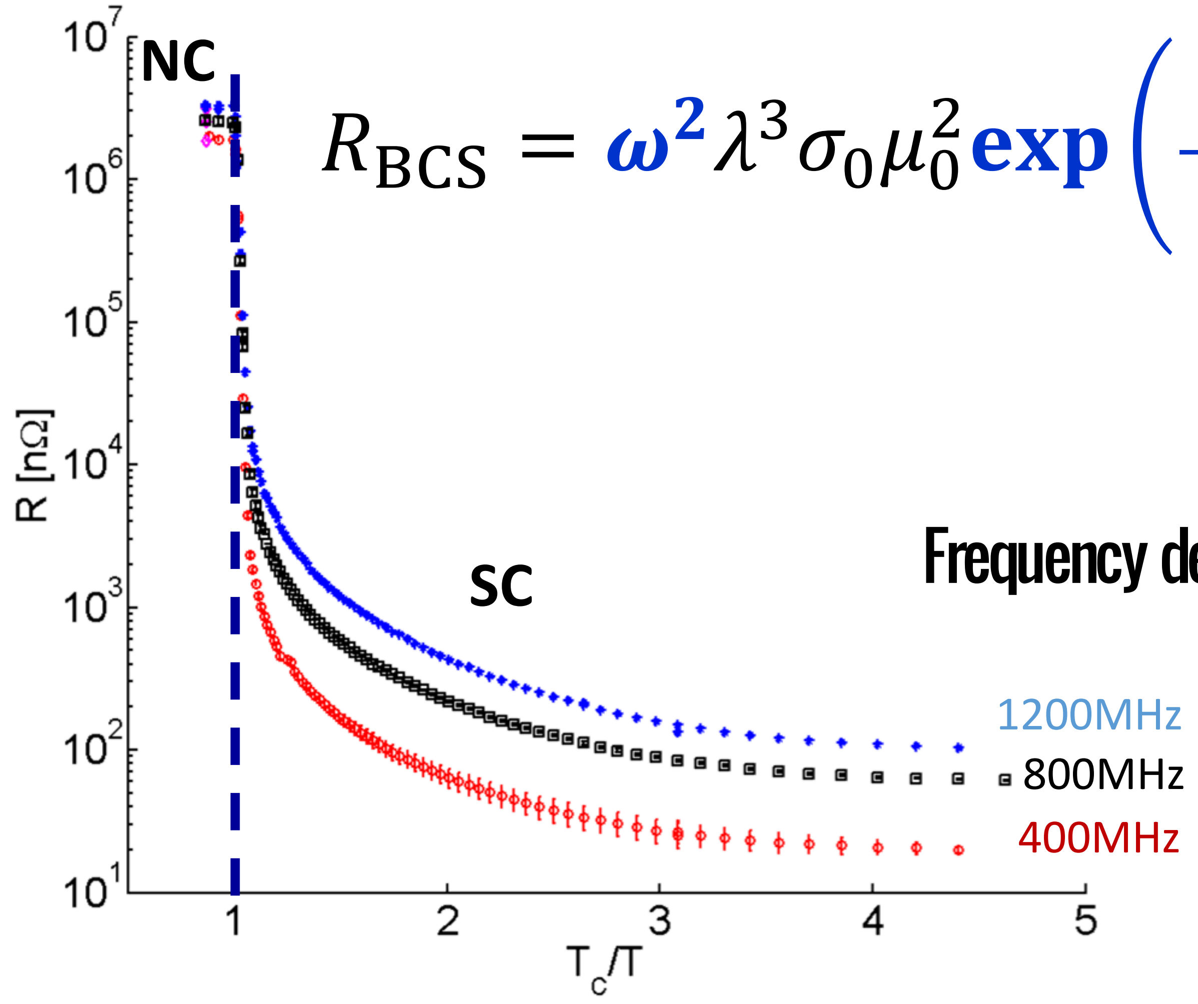
The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

This equation implies *R_s*:

- ✓ Has a minimum for medium purity
- Is proportional to ω^2
- Decreases exponentially with temperature
- Vanishes as T→0 K
- Is independent of RF field strength

The RF surface resistance



Measurement of the surface resistance at low field of niobium at three frequencies with the Quadrupole Resonator

$$R_{\mathrm{BCS}} = \boldsymbol{\omega^2} \lambda^3 \sigma_0 \mu_0^2 \, \mathbf{exp}\left(-\frac{\boldsymbol{\Delta}}{\boldsymbol{k_b T}}\right)$$

$$R_S(0\mathrm{K}) \neq 0$$

$$R_S = R_{\mathrm{BCS}}(T) + \mathrm{R}_{\mathrm{res}}$$

Frequency dependence for R_{BCS} and R_{res} are almost identical

Is there a common cause?

The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

This equation implies R_s:

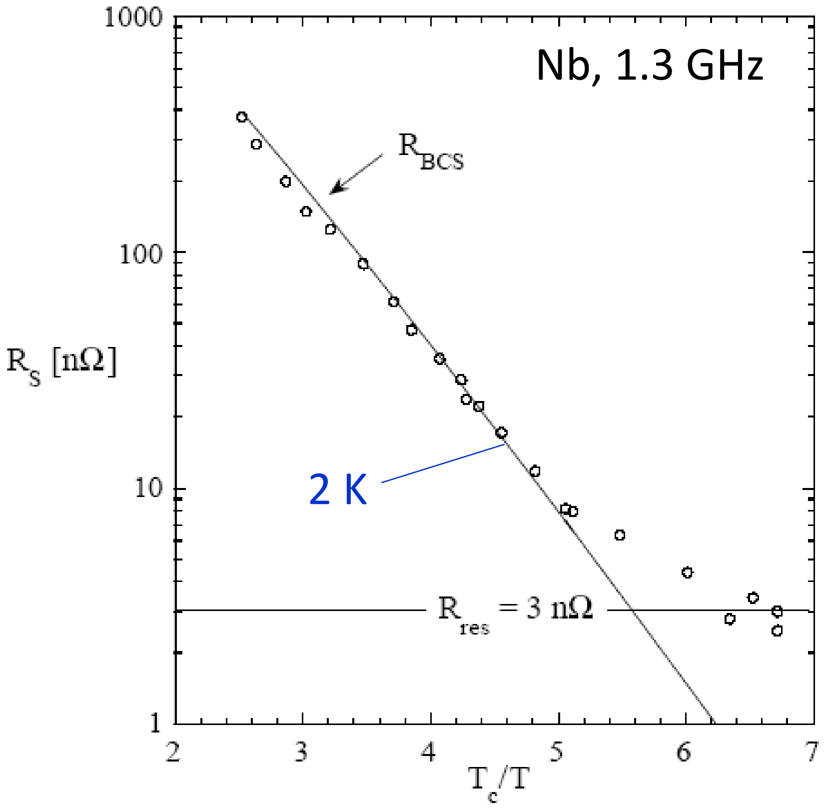
- ✓ Has a minimum for medium purity
- ✓ Is proportional to ω^2
- ✓ Decreases exponentially with temperature
- ✗ Vanishes as T→0 K
- Is independent of RF field strength

The residual resistance

For Nb R_{res} (~1-10 nΩ) dominates R_s at low frequency (f < ~750 MHz) and low temperature (T < ~2.1 K)

Possible contributions to R_{res}:

- Trapped magnetic flux and thermal currents
- Lossy oxides, metallic hydrides
- Normal conducting precipitates
- Grain Boundaries
- Interface Losses
- Magnetic Impurities



B. Aune et al., Phys. Rev. STAB ***3*** *(2000) 092001.*

Trapped Magnetic Flux

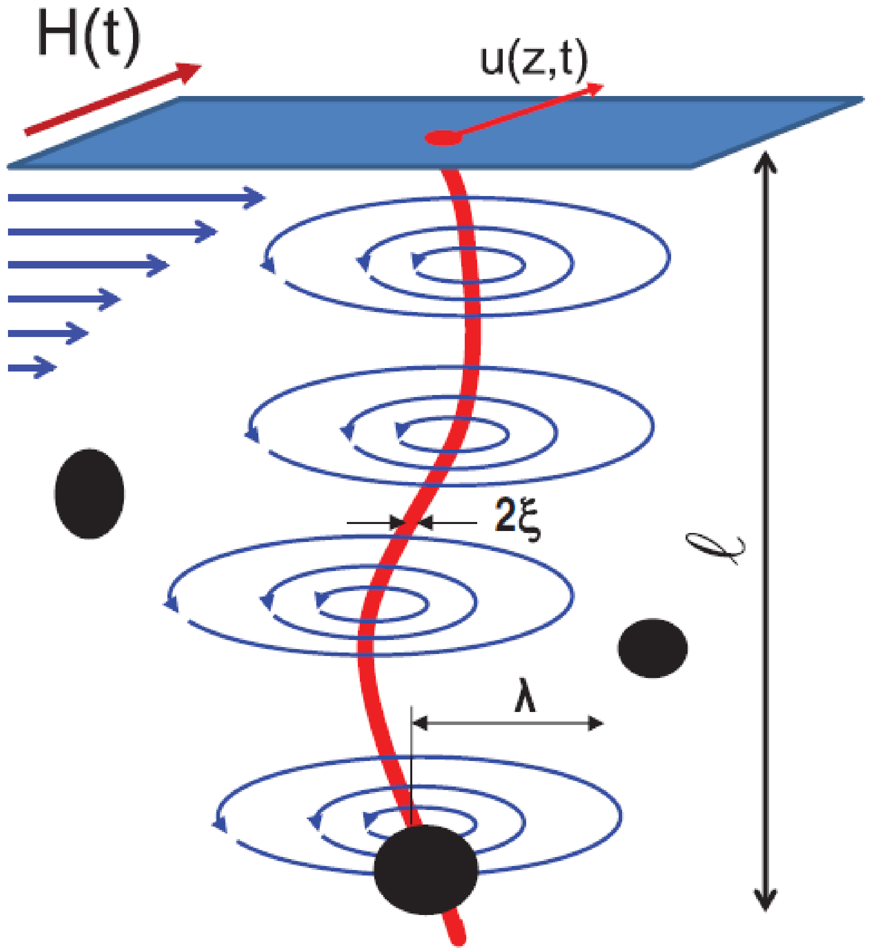
- Well understood contribution to R_{res}
- When a cavity is cooled down in an ambient DC magnetic field not all flux is expulsed – Incomplete Meissner effect
- In fact fields of a few μT (order earth magnetic field) can be completely trapped
- In cryomodules thermal currents can cause additional magnetic fields which can be trapped

Trapped magnetic flux

When a cavity is cooled down in an ambient DC magnetic field not all flux is expulsed - Incomplete Meissner effect

Trapped magnetic field can also result from thermoelectric currents

Dissipation due to oscillating vortex segments, driven by the RF field



Trapped Magnetic Flux Measurements

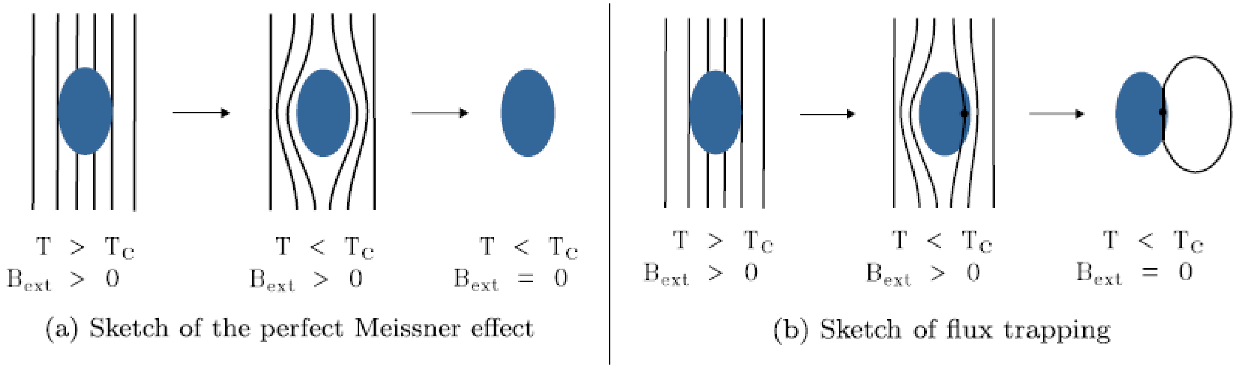
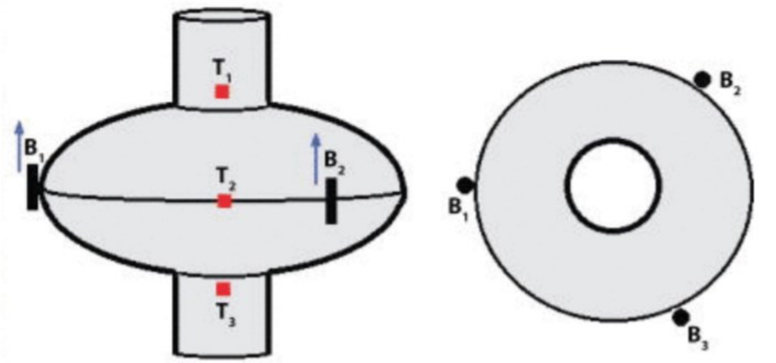
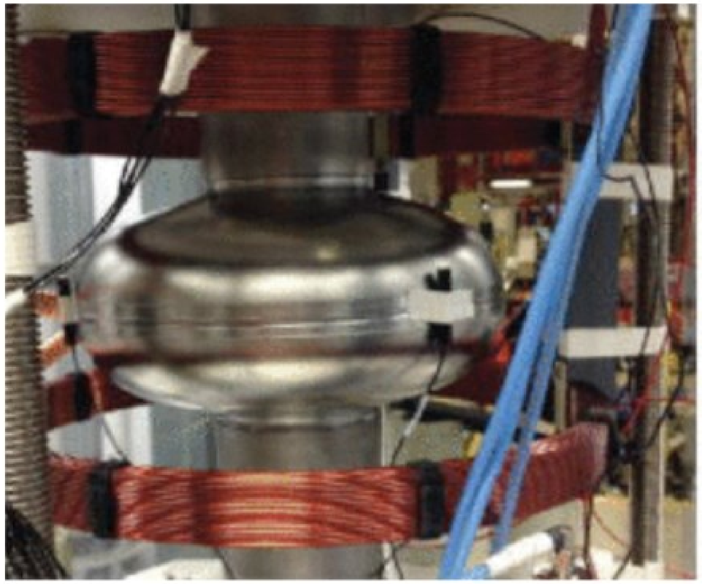


FIG. 1. Comparison between the perfect Meissner effect and the suppression of the flux expulsion due to flux pinning.





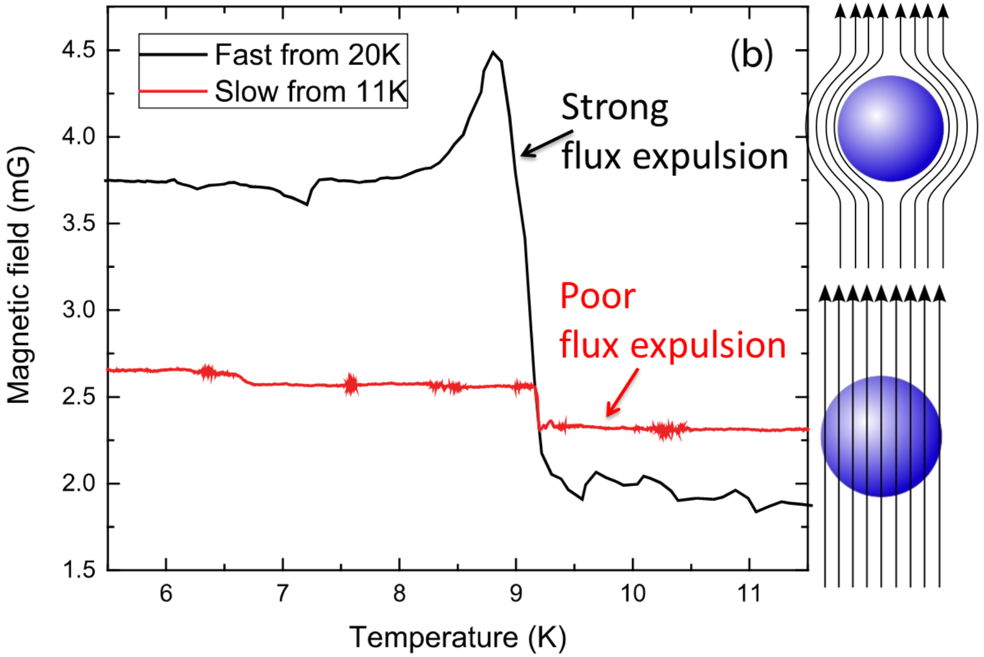
Experimental configuration used at Fermilab on Bulk cavities

Typical levels of trapped magnetic flux in cavities are between 100-1000 nT

Trapped Flux - Real Example

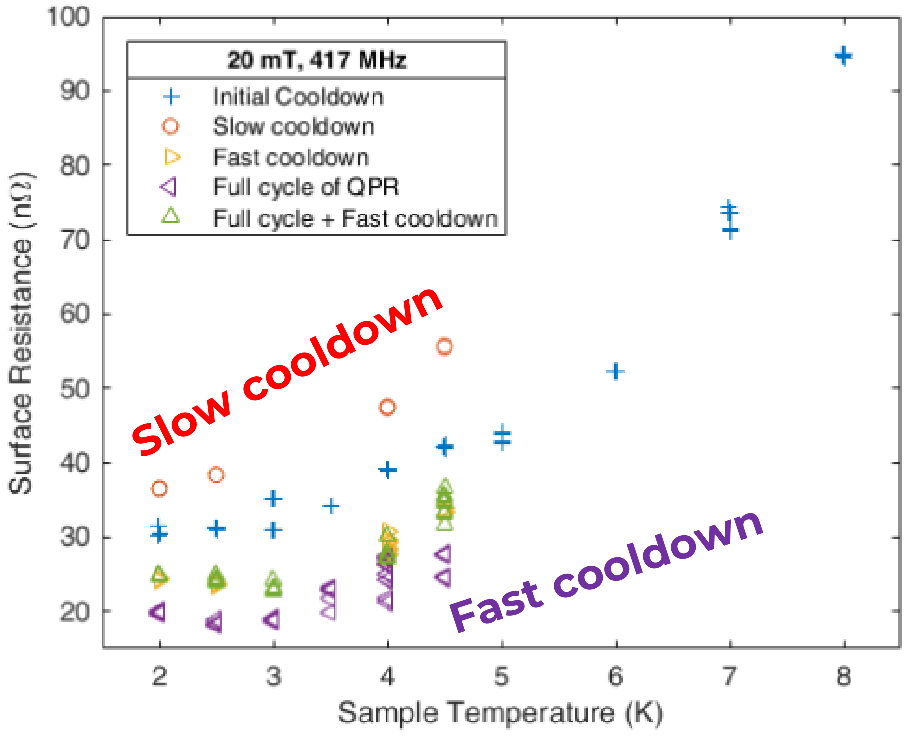
$$Q_0 \propto \frac{1}{R_{BCS} + R_{res} + \eta\, S\, B}$$

Fraction of Trapped Flux   Sensitivity



A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

OPR RF test



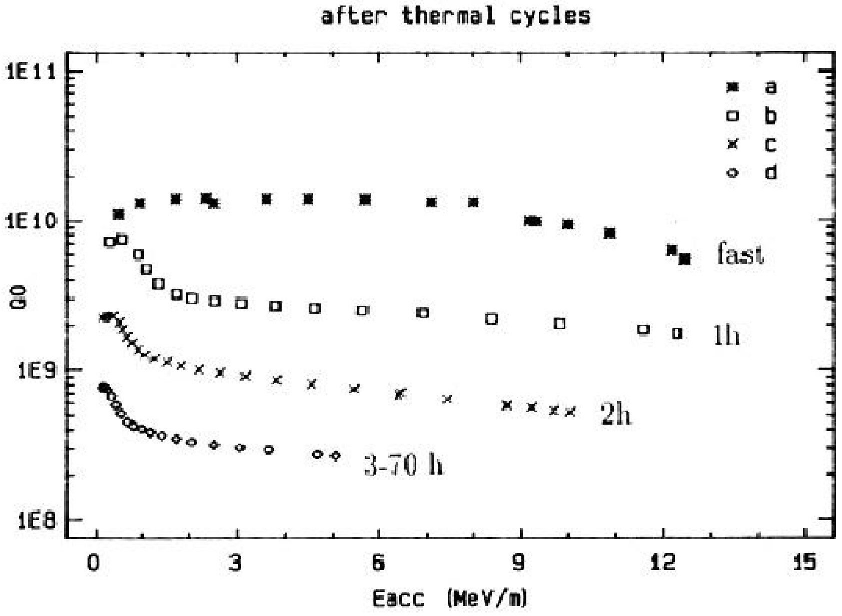
Courtesy of Oliver Kugeler and Sebastian Keckert

- **Cooldown procedure influence Rs**

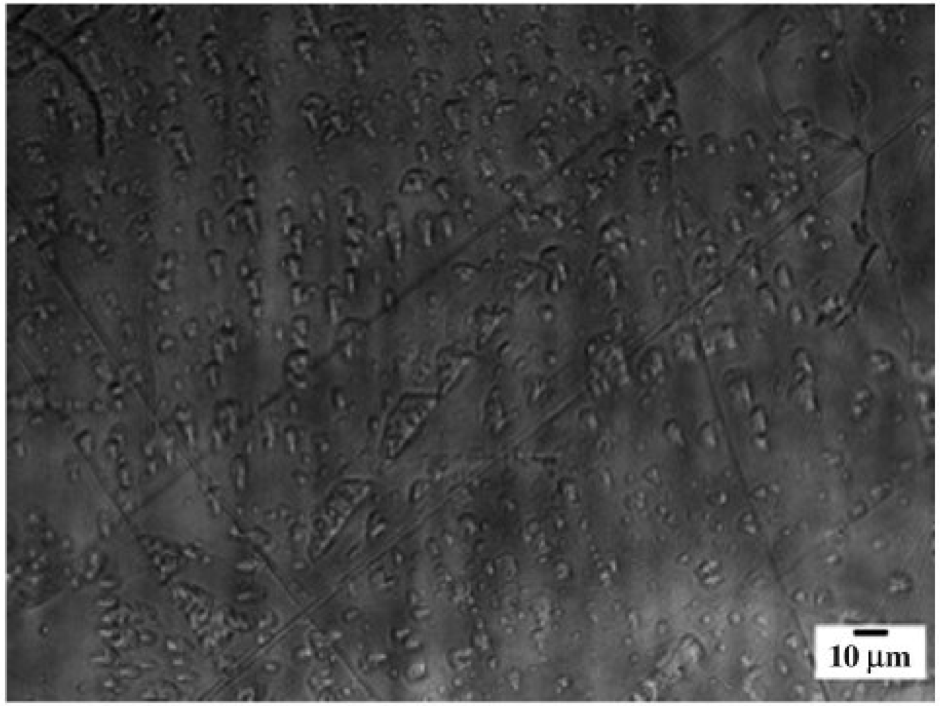
Normal conducting precipitates

Islands of **NbH precipitates** at the surface

- Bulk hydrogen conc. > 10 wt.ppm
- Cooling rate < ~1 K/min between 90 – 150 K

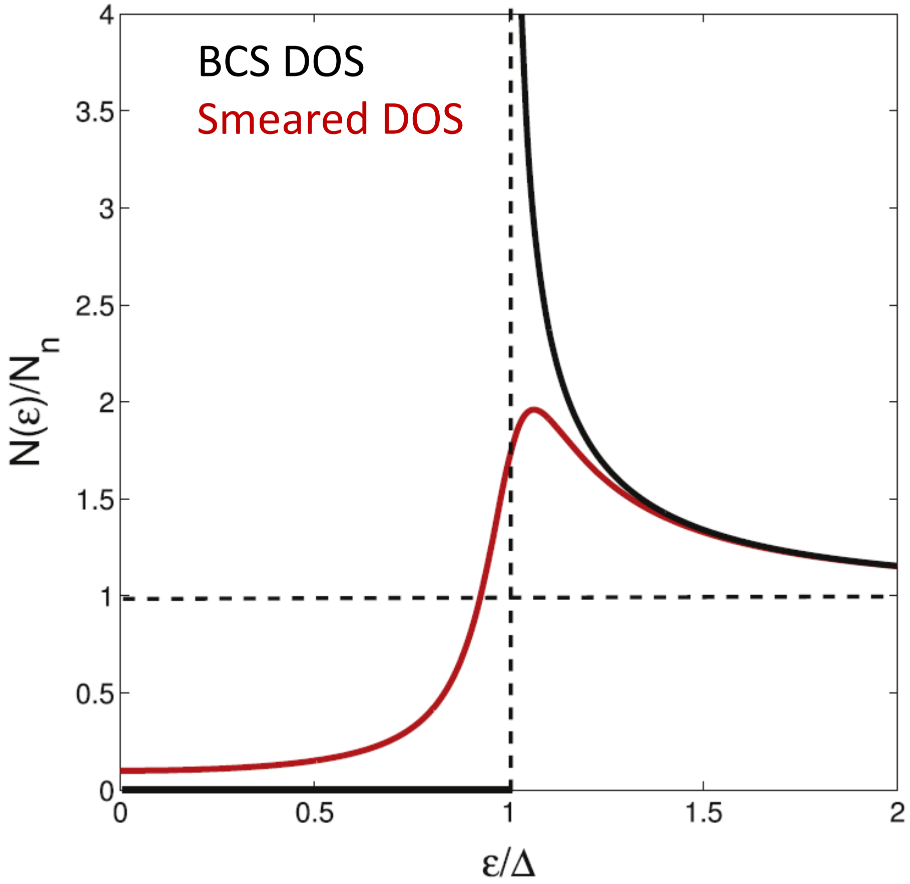


B. Bonin and R. W. Roth, *Proc. 5th SRF Workshop*, Hamburg, Germany, 199, p. 210.



F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams **15**, 122001 (2012)

The residual resistance



A. Gurevich Supercond. Sci. Technol. 30 (2017) 034004

Point contact tunneling experiments on Nb and Nb_3Sn have found finite density of states (DOS) inside the energy gap

The physics remains not fully understood, however subgap states will yield a finite R_S(0K) irrespective of physical mechanism

The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

This equation implies *R_s*:

- Has a minimum for medium purity
- Is proportional to ω^2
- Decreases exponentially with temperature
- Vanishes as T→0 K
- Is independent of RF field strength

The RF surface resistance

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This equation implies R_s:

- ✓ Has a minimum for medium purity
- ✓ Is proportional to ω^2
- ✓ Decreases exponentially with temperature
- ✗ Vanishes as $T \rightarrow 0$ K
- Is independent of RF field strength ?

The RF surface resistance

$$R_{\mathrm{BCS}} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 \exp\left(-\frac{\Delta}{k_b T}\right)$$

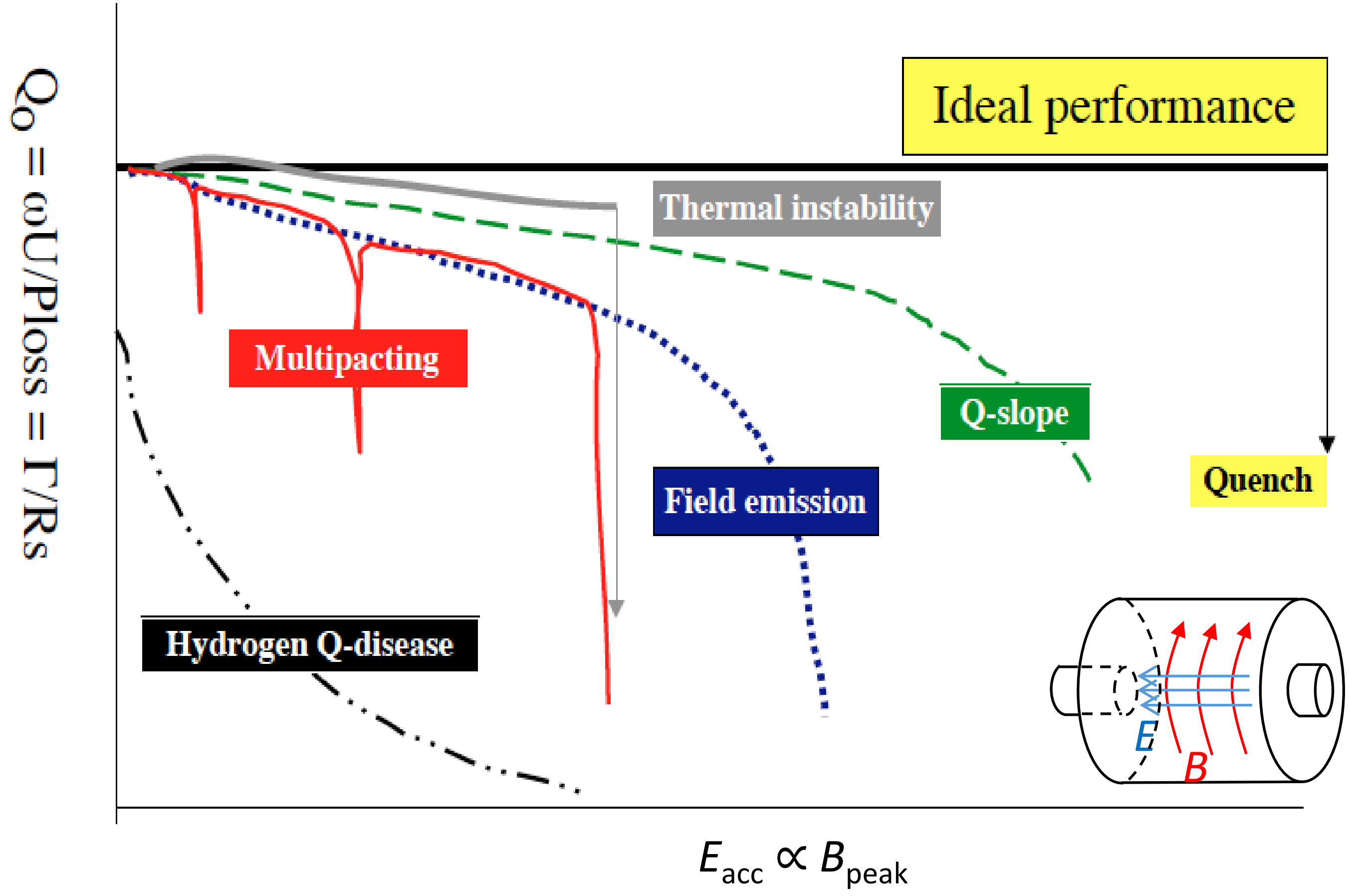
This equation implies *R_s*:

- ✔ Has a minimum for medium purity
- ✔ Is proportional to ω^2
- ✔ Decreases exponentially with temperature
- ✘ Vanishes as $T \rightarrow 0$ K
- ✘ Is independent of RF field strength

Not only do R_{BCS} and R_{res} depend on the RF field strength there can also be additional extrinsic losses limiting the cavity performance

Performance of SRF cavities

There are two parameters which define the performance of an SRF cavity: **quality factor** and the **accelerating gradient**



The quality factor:

$$Q = \frac{G}{R_s}$$

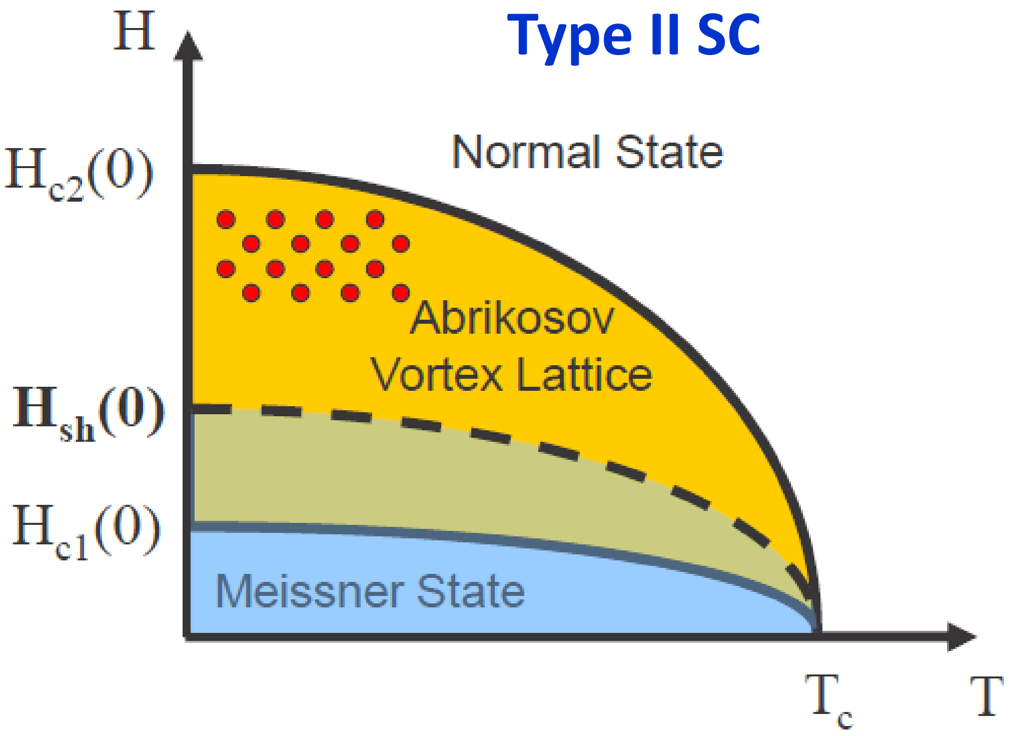
G = Geometrical Factor

$$Q = 2\pi f_0 \frac{U}{P_d} \qquad P_d = \frac{1}{2} R_s \int_s H^2 ds$$

The **accelerating gradient** can be limited by the peak surface electric field (field emission) or the peak surface magnetic field (quench)

There are two principal ways to increase performance: Shape and material optimization

RF critical field: superheating field (H_{sh})



Penetration and oscillation of vortices under the RF field gives rise to strong dissipation and the **surface resistance of the order of R_s** in the normal state

The **Meissner state can remain metastable at higher fields, $H > H_{c1}$** up to the superheating field H_{sh} at which the Bean- Livingston surface barrier for penetration of vortices disappears and the Meissner state becomes unstable

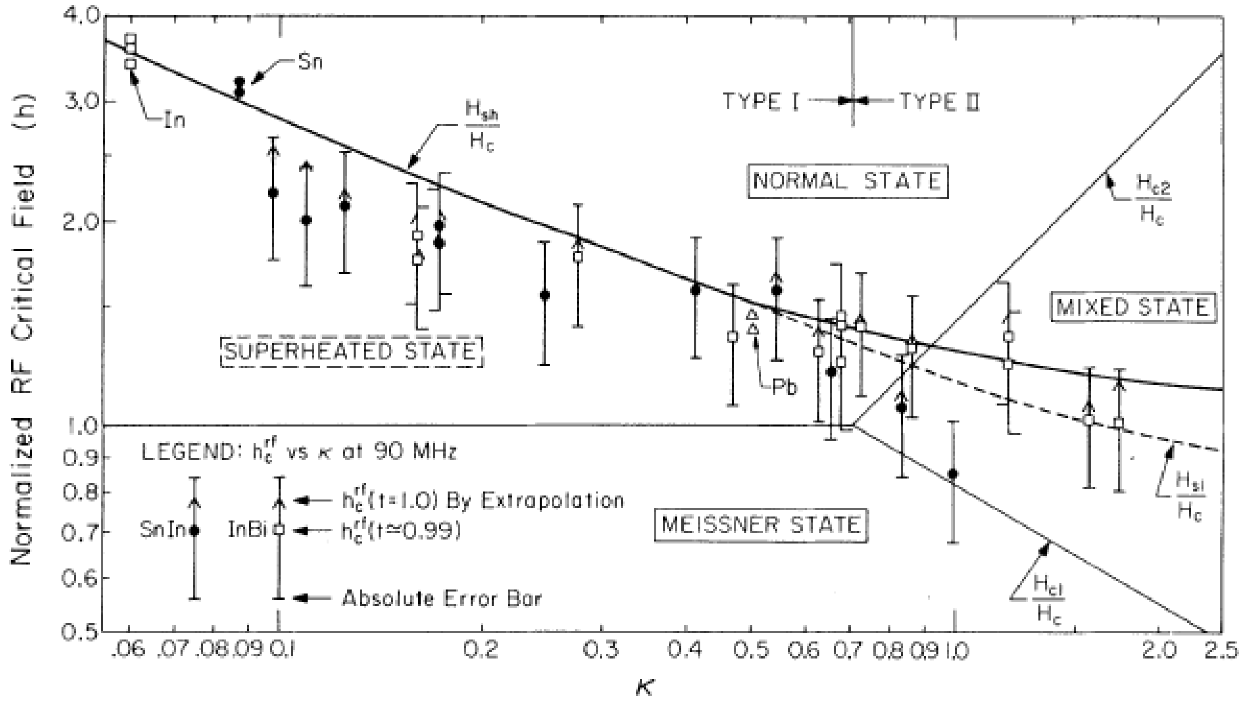
H_{sh} **is the maximum magnetic field** at which a type-II superconductor can **remain in a true non-dissipative state** not altered by dissipative motion of vortices

Superheating Field: theory

Weak dependence of H_{sh} on non-magnetic impurities

$$H_{sh}(T) \cong c(\kappa) H_c \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$c(\kappa)$ the ratio of the superheating field and the thermodynamic critical field

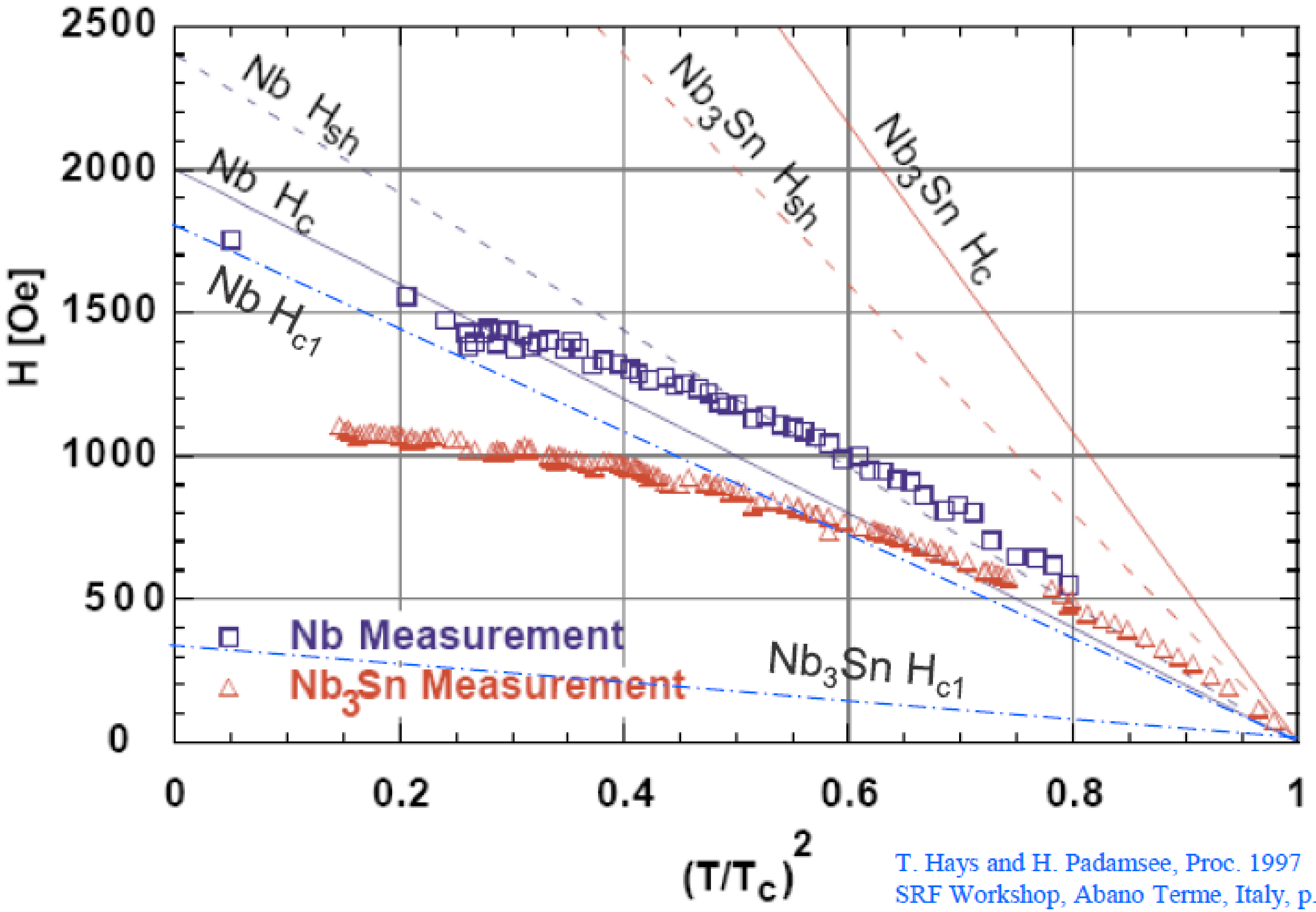


T. Yogi, G. J. Dick, and J. E. Mercereau. Critical rf magnetic fields for some type-i and type-ii superconductors. Phys. Rev. Lett., 39(13):826–829, Sep 1977.

Superheating Field: experimental results

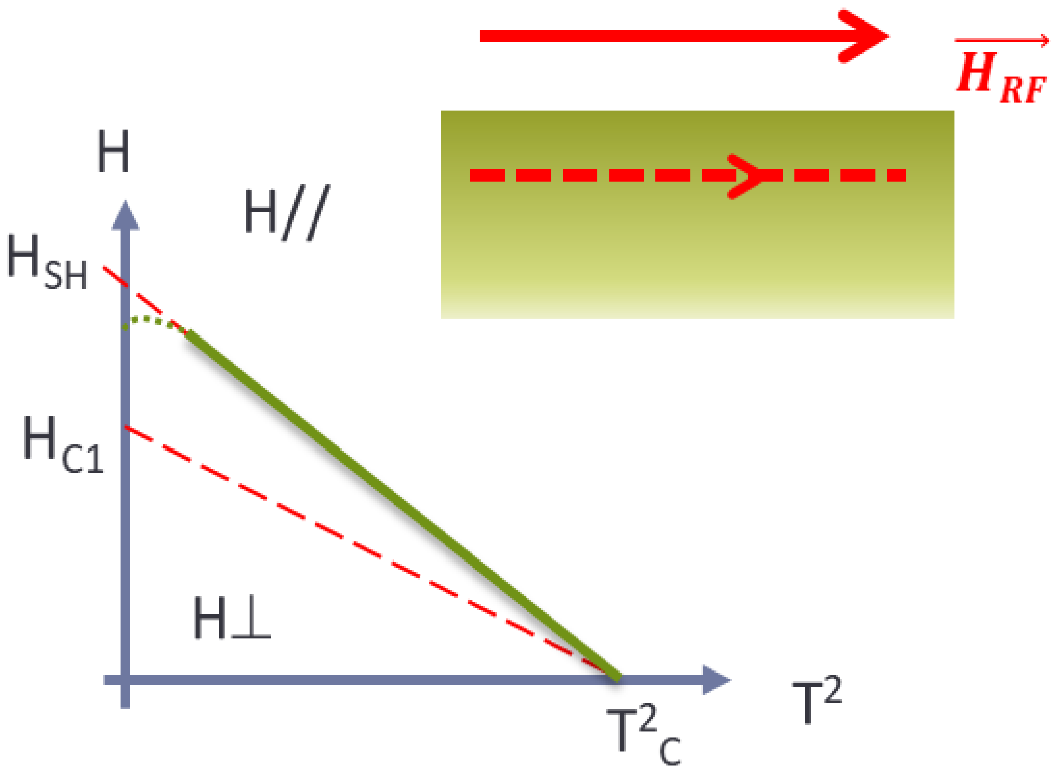
Use high-power (~1 MW) and short (~100 μs) RF pulses to achieve the metastable state before other loss mechanisms kick-in

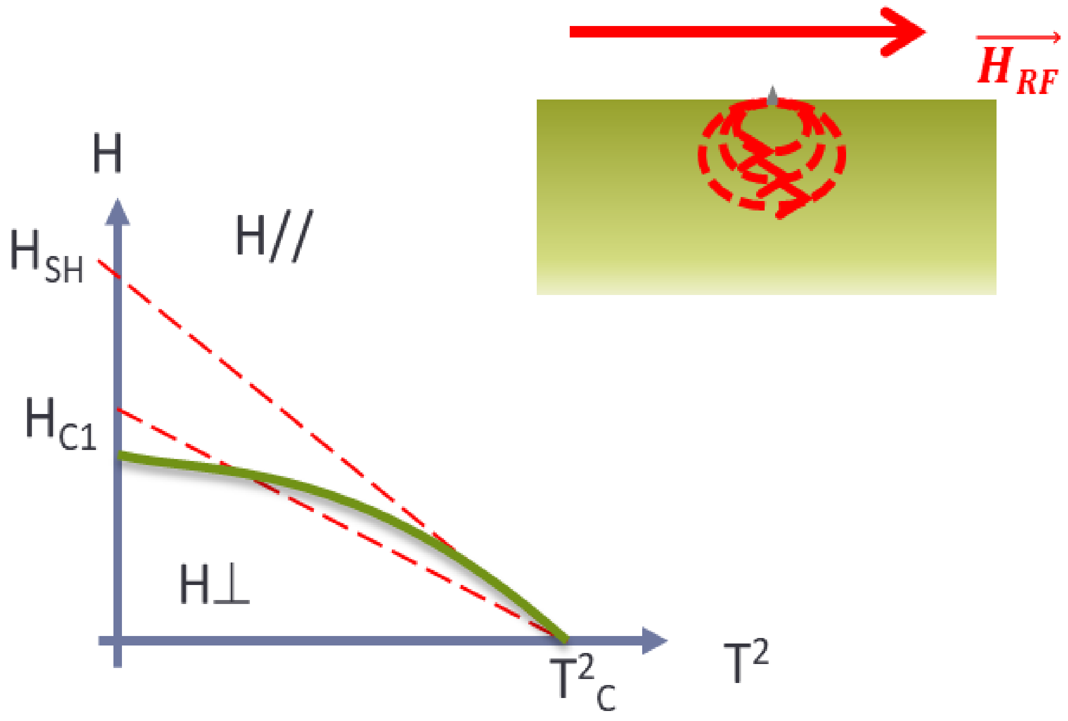
RF magnetic fields higher than *Hc_1* have been measured in both Nb and Nb_3Sn cavities. ***H_{RF}* in Nb_3Sn is << predicted *H_{sh}***



T. Hays and H. Padamsee, Proc. 1997 SRF Workshop, Abano Terme, Italy, p. 789 (1997) .

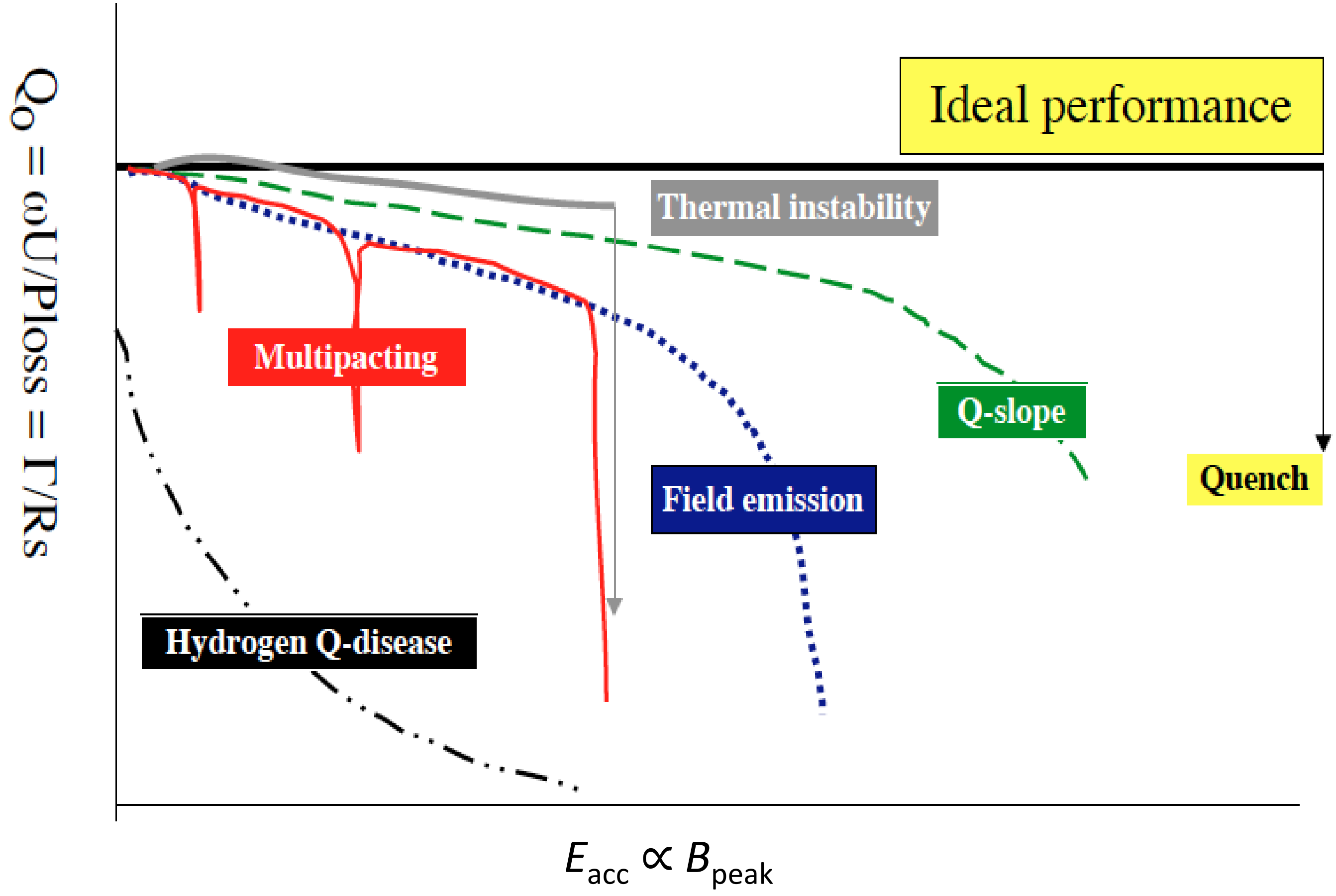
Superheating Field - real world





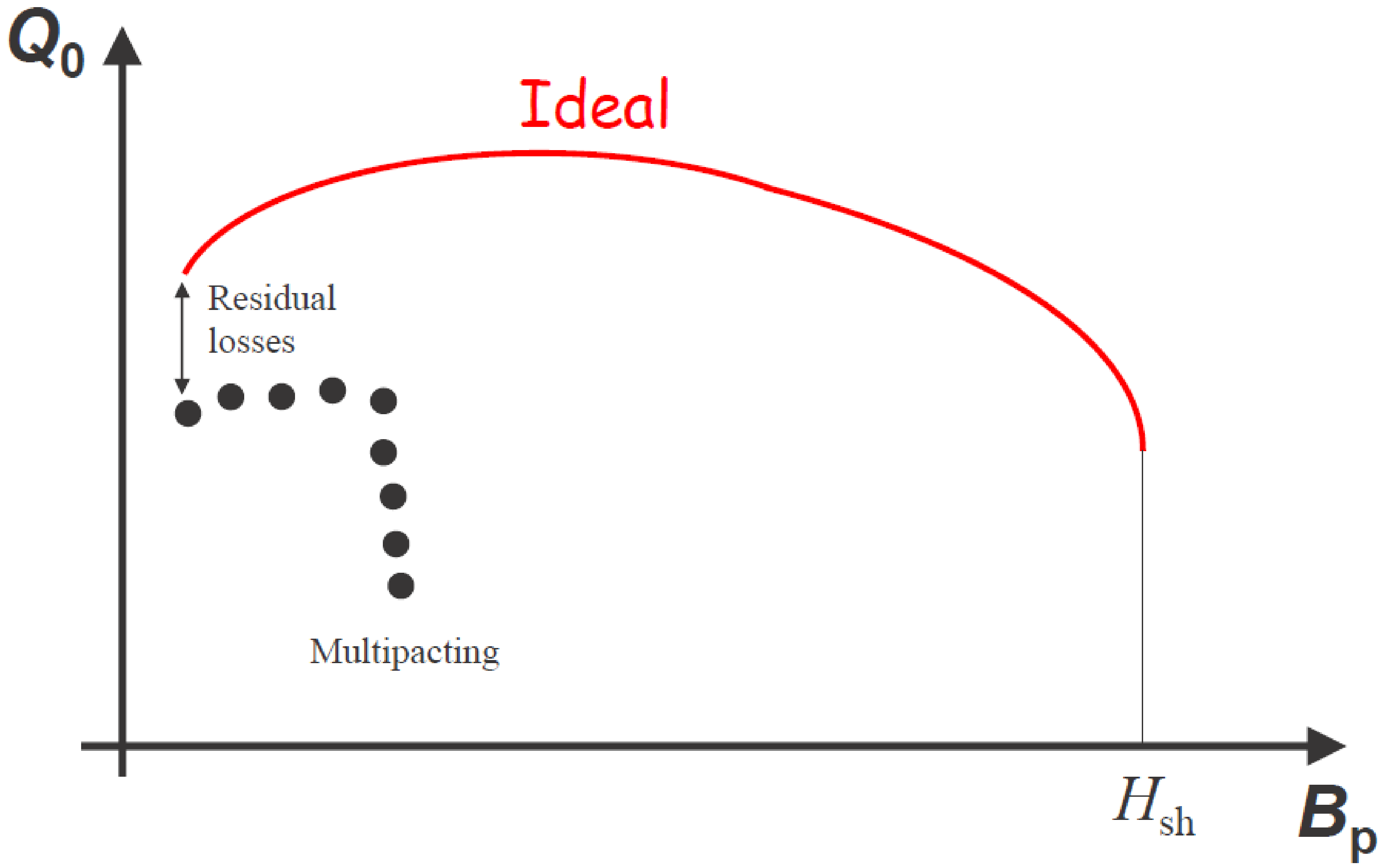
SRF Cavities Extrinsic Limitations

- Mechanical Vibrations
- Multipacting
- Thermal breakdown (Quench)
- Field Emission



$E_{acc} = 0.29\ B_p$ *for TESLA type cavities*

Performance limitations



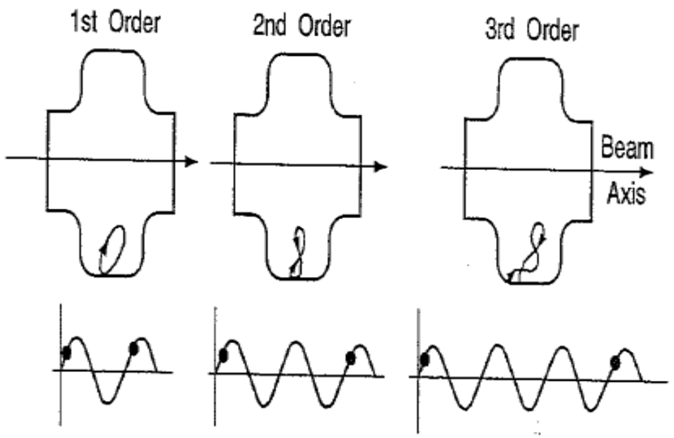
Multipacting

Resonant process with emission of electrons from the surface of the cavity

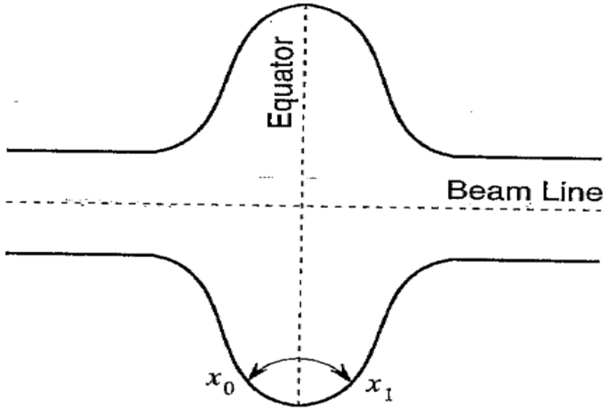
Multipacting is characterized by an exponential growth in the number of electrons in a cavity

Multipacting requires 2 conditions:

- Electron motion is periodic (resonance condition): cavity frequency = *n* x cyclotron frequency
- Impact energy is such that secondary emission coefficient is >1

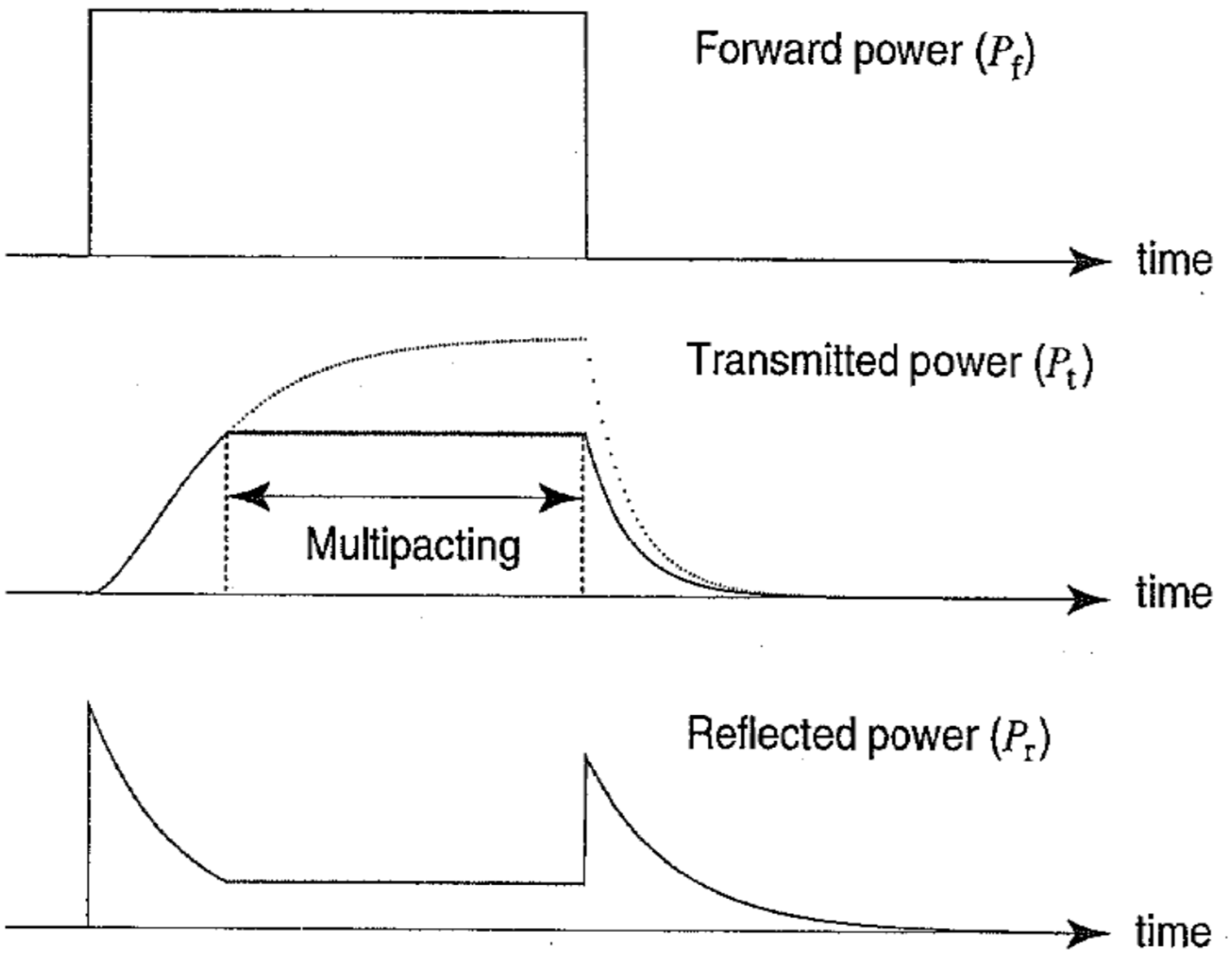


1 point Multipacting

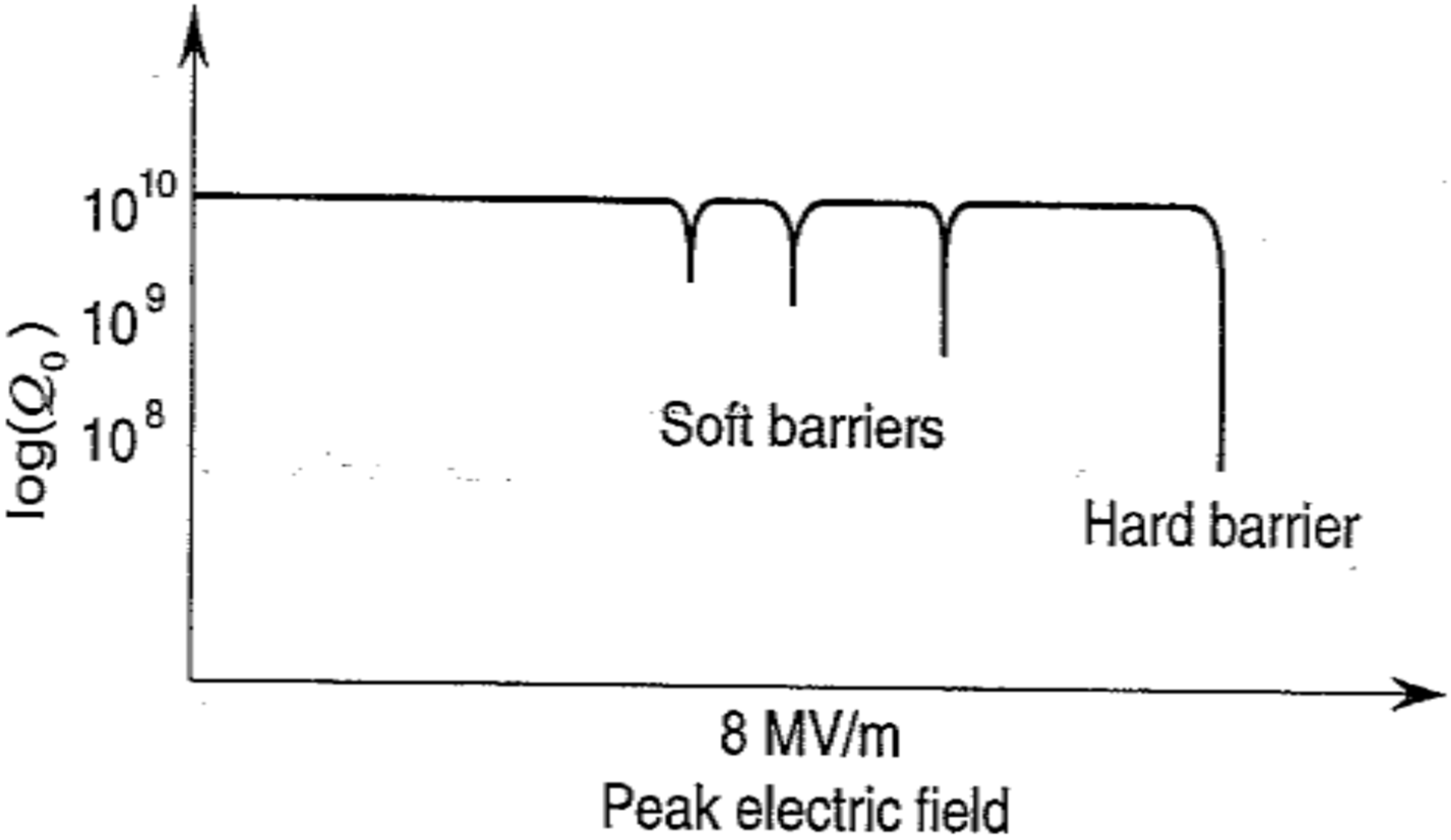


2 points Multipacting

Multipacting (power curves)

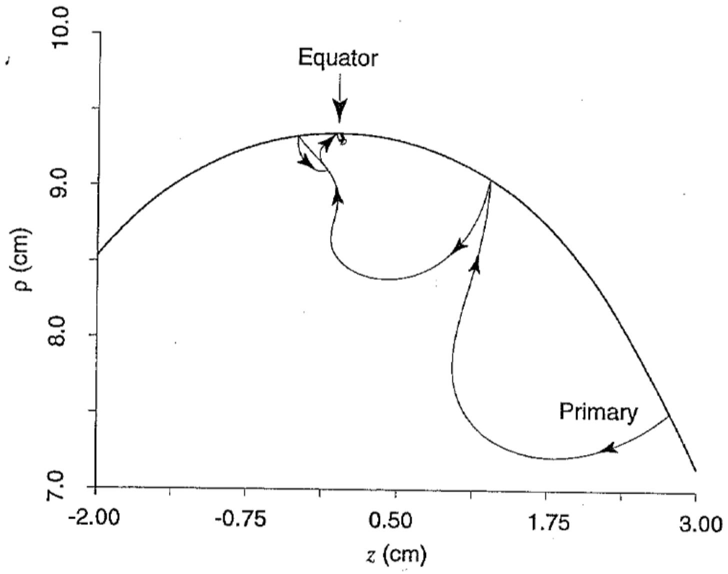


Multipacting (Q VS E_{acc})

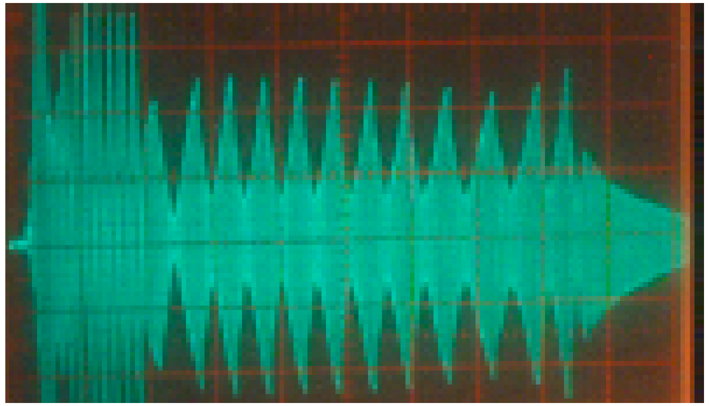


How to removes multipacting

1. Preventive strategy

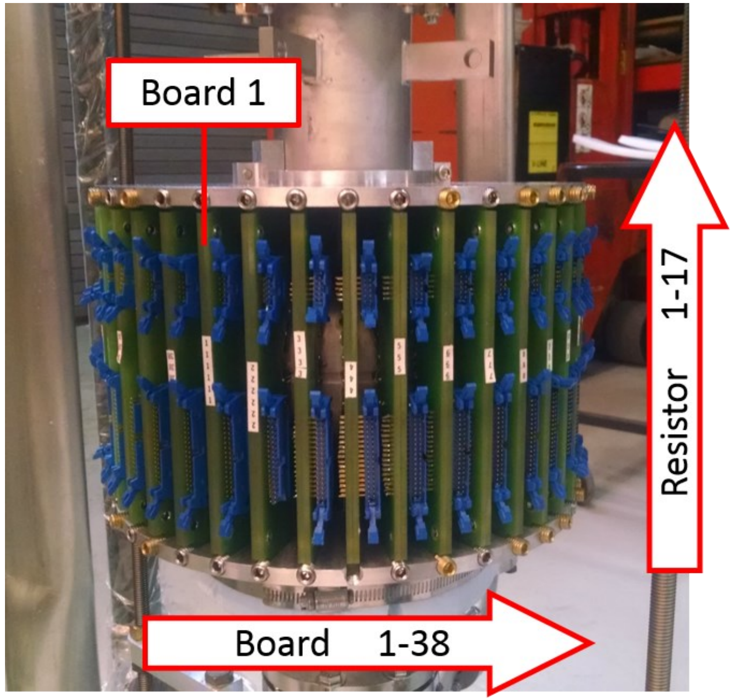


2. Healing strategy

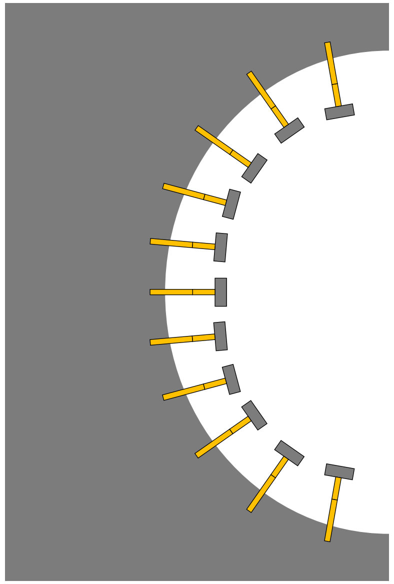


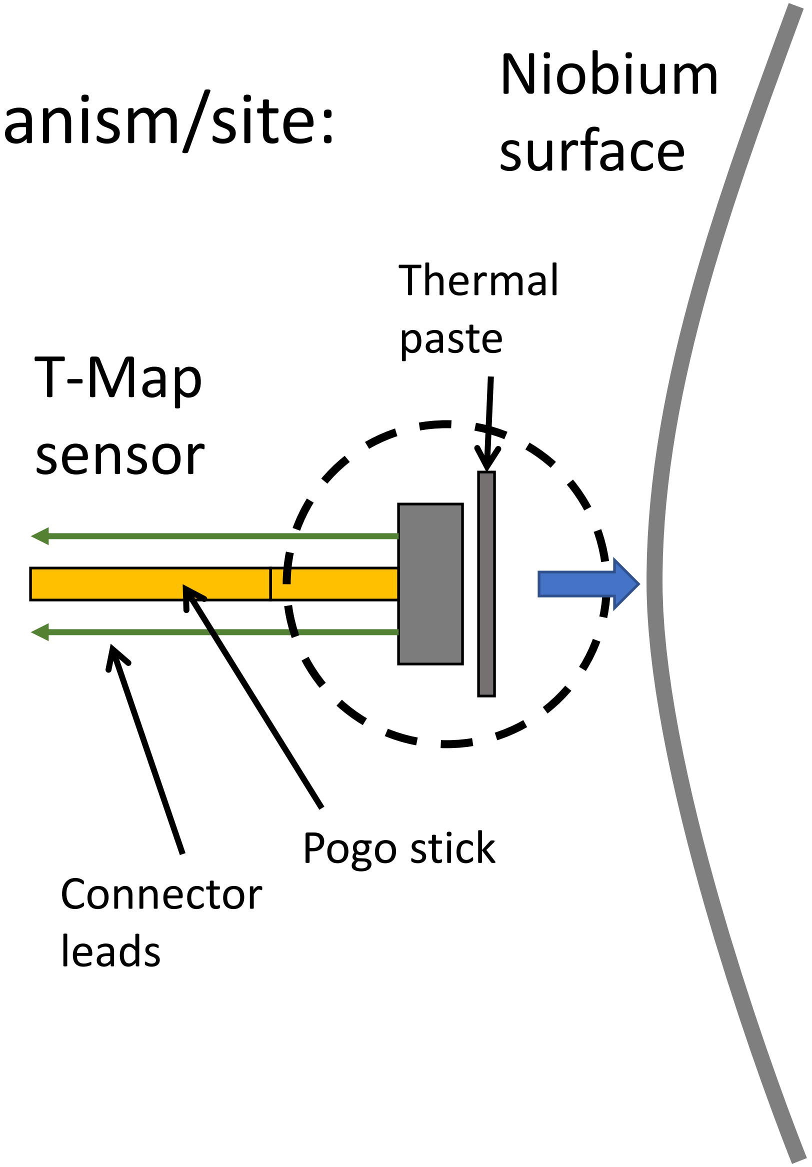
T-Map experiment

Use temperature map to look for quench mechanism/site:



T-Map board





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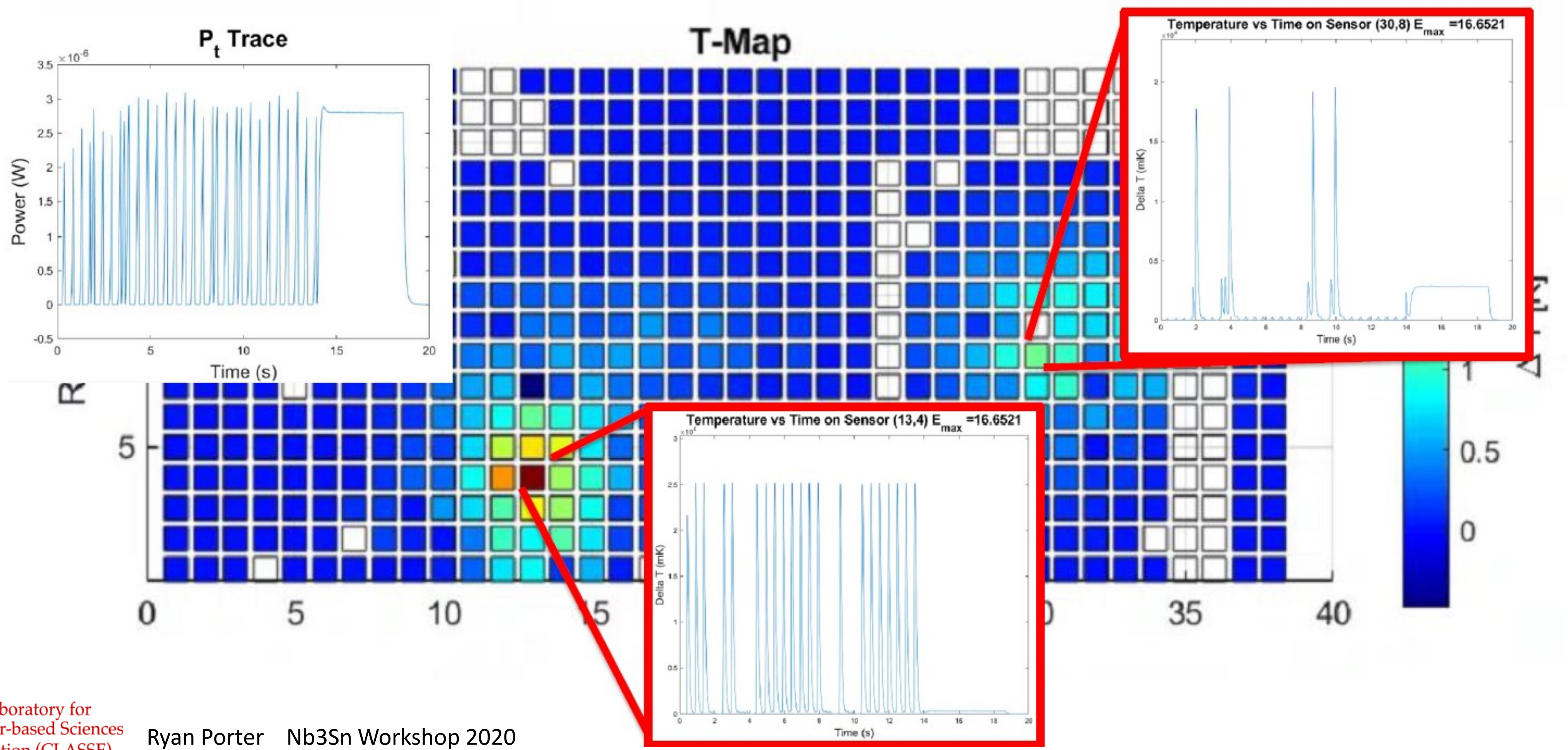
Ryan Porter Nb3Sn Workshop 2020

T-Map experiment

First quench site disappears after many quenches:



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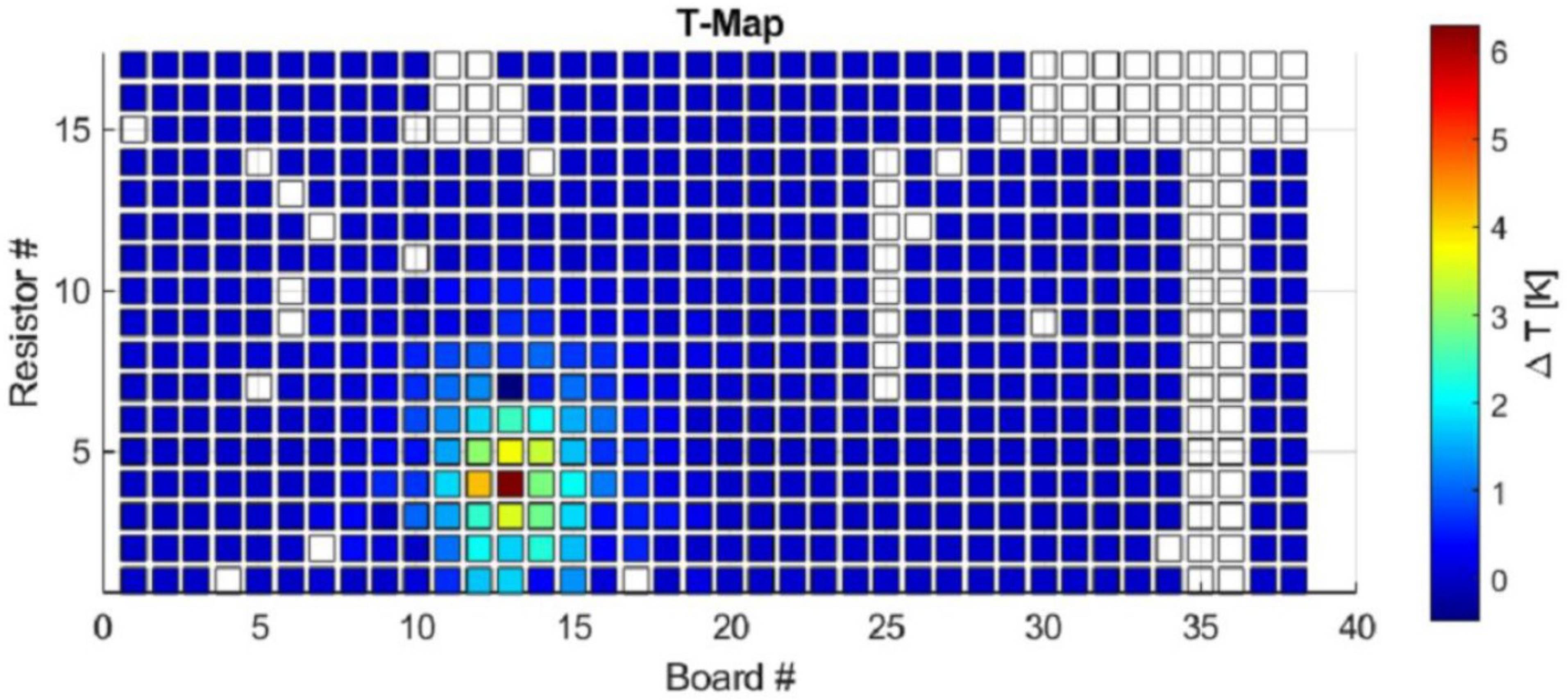
T-Map experiment

Observe quenches happening in two different spots:



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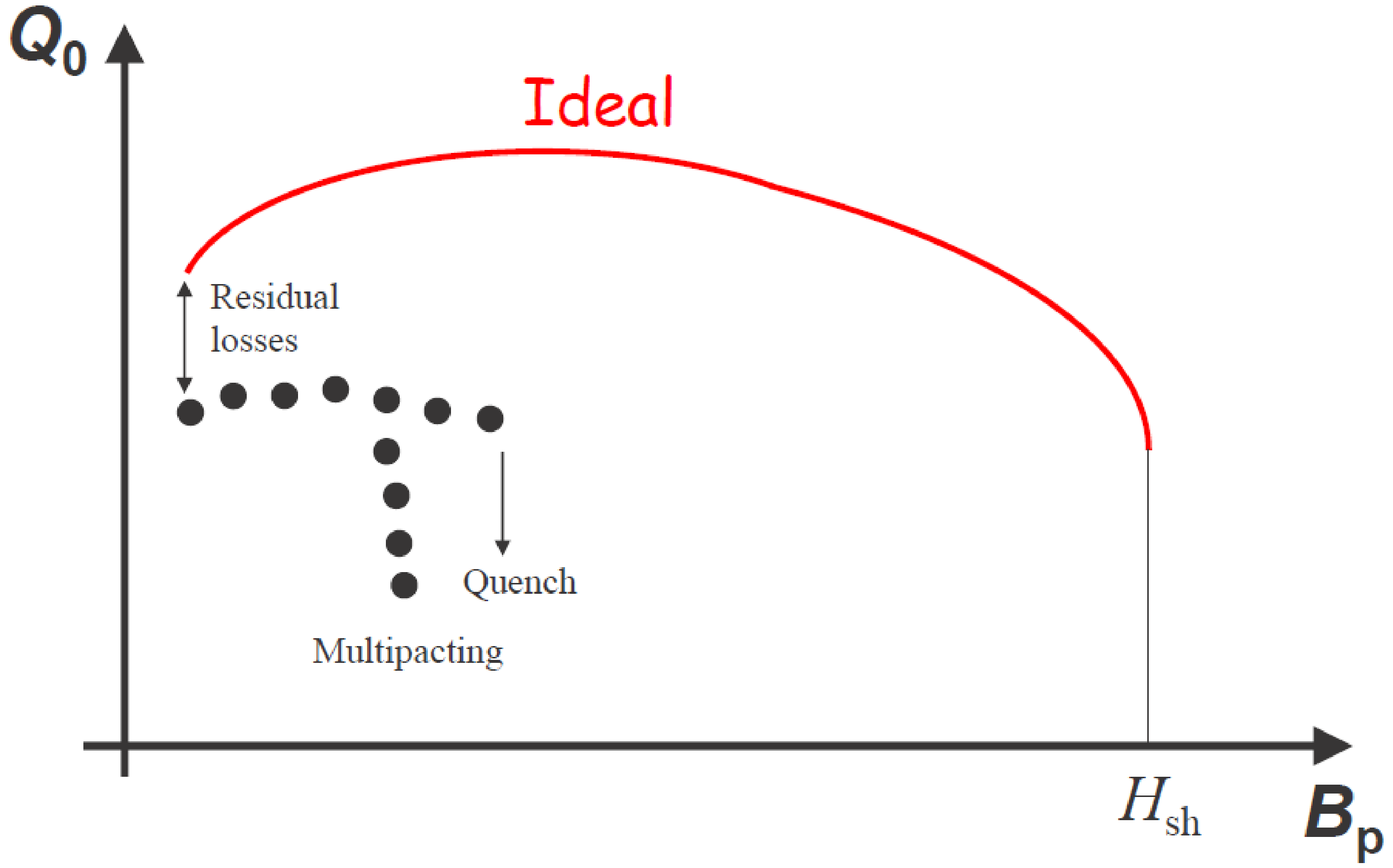
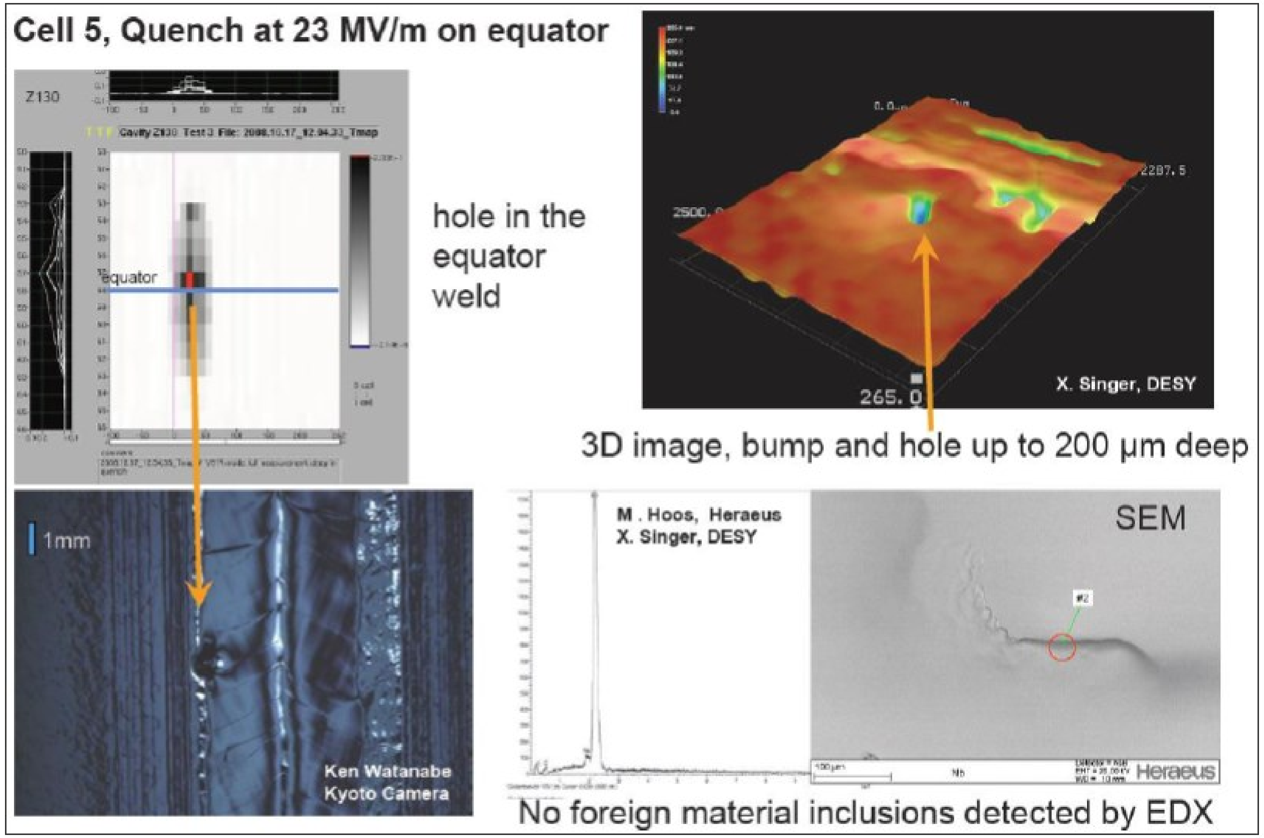
Performance limitations



Quench (Thermal Breakdown)

Localized heating at normal-conducting defects
Local magnetic field enhancement at sharp edges



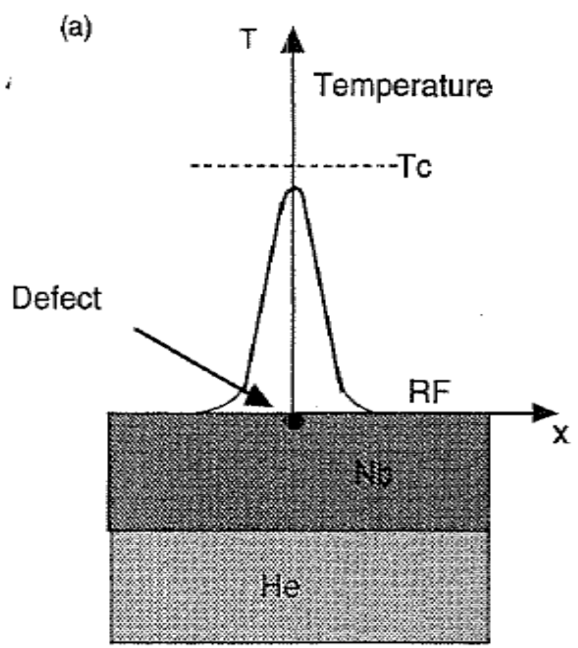
W. Singer, DESY

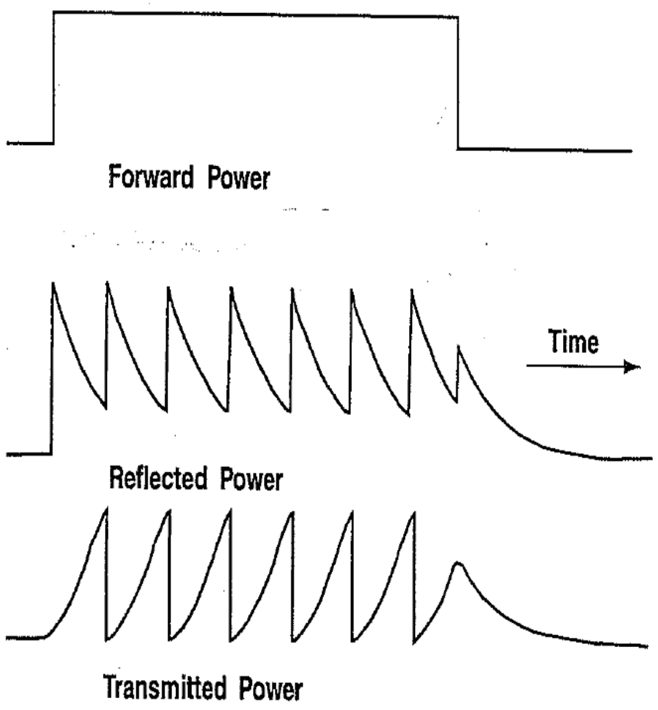
Thermal Breakdown

Quench is the final limitation set by the critical field of the material

A quench can however occur at much lower fields if the magnetic field locally exceeds the critical field or the temperature exceeds the critical temperature at sub mm size defects of high resistivity

At high fields these defects will heat up its surrounding area above T_c and a normal conducting area will spread causing a quench





Cures for Quench

Prevention: avoid the defects

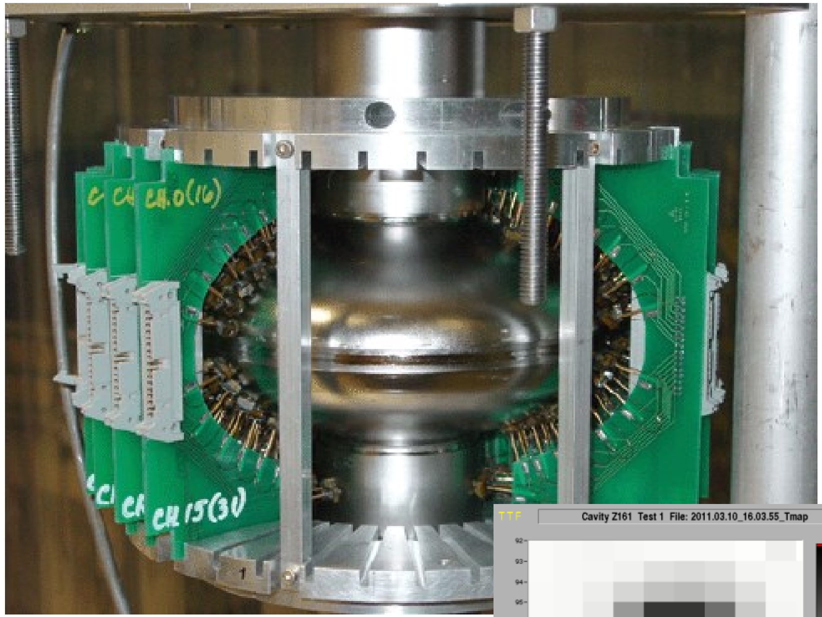
- Use material with high thermal conductivity: high purity niobium or niobium on copper cavities
- Careful electron beam welding or seamless cavities
- Eddy-current scanning of Nb sheets

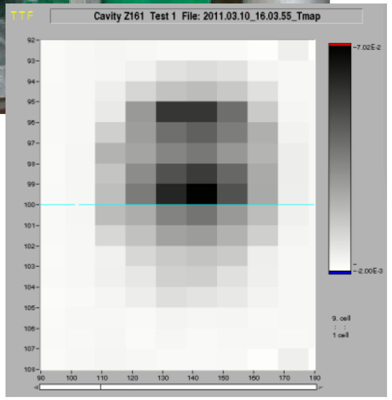
Post processing

- In production usually the cavity is chemically etched again
- Big defects with sizes of 1 mm can be mechanically grinded away. This requires knowledge of the quench position from online diagnostics during cold test and optical inspection afterwards

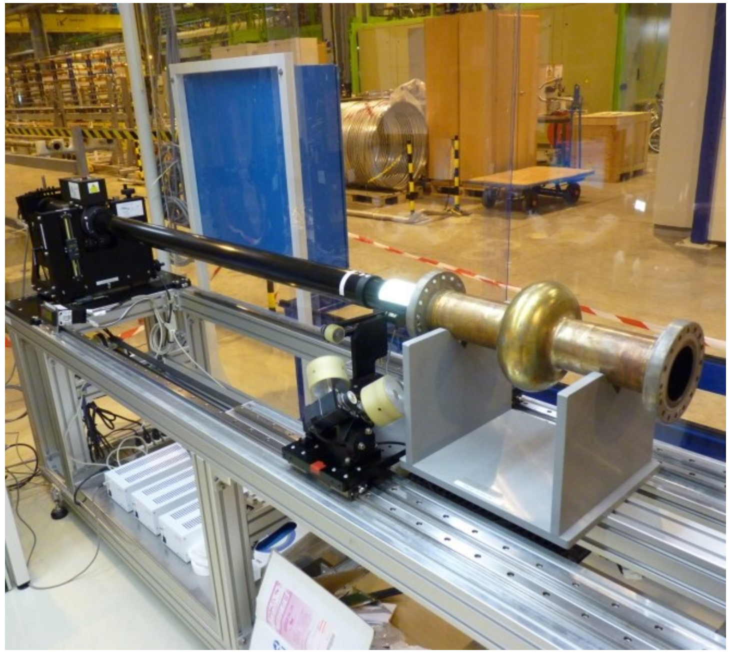
Quench localization and visualization

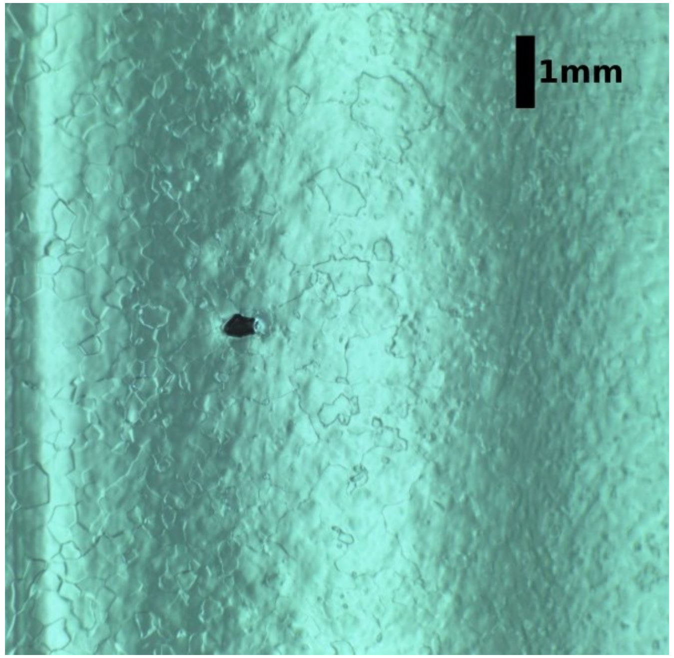
Quench sites can be located with temperature mapping



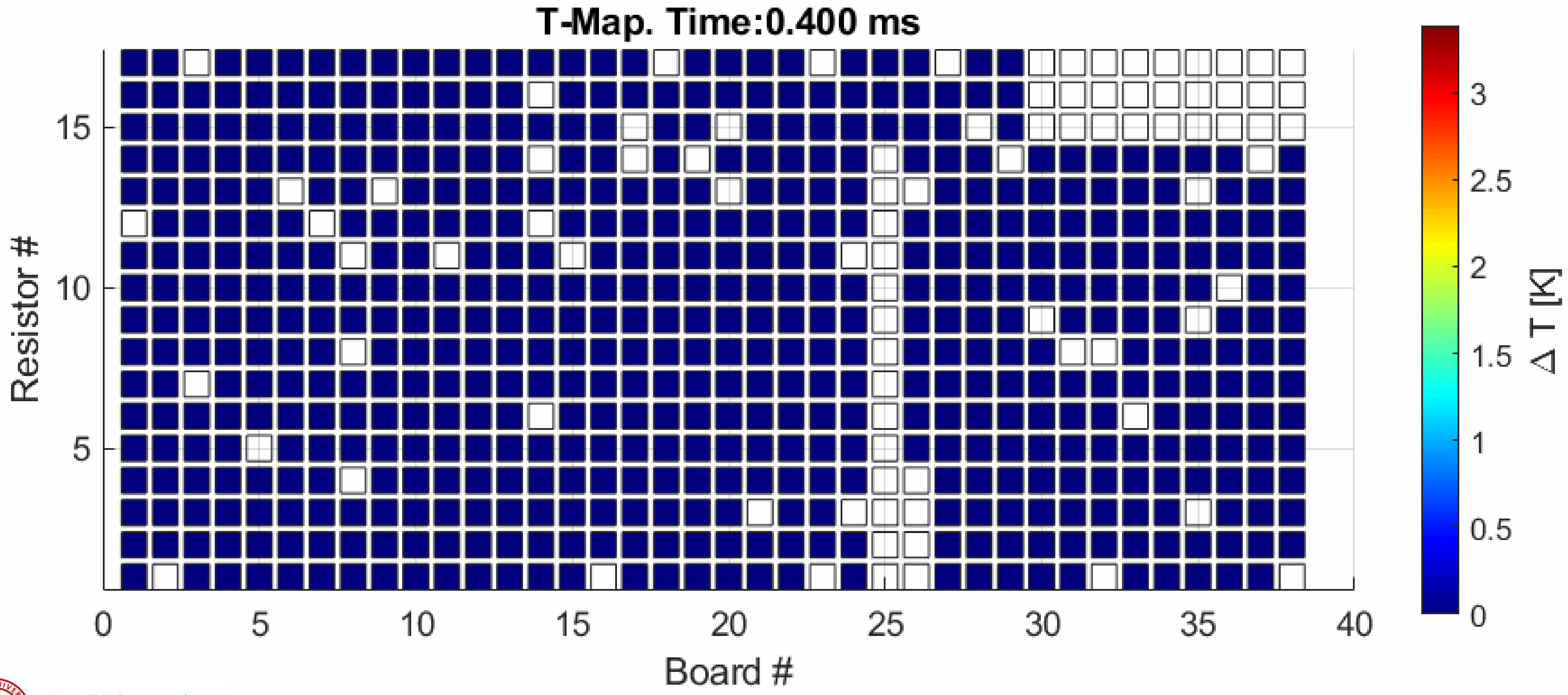


Afterwards the location can be visualized with an optical inspection system





Cavity Quench



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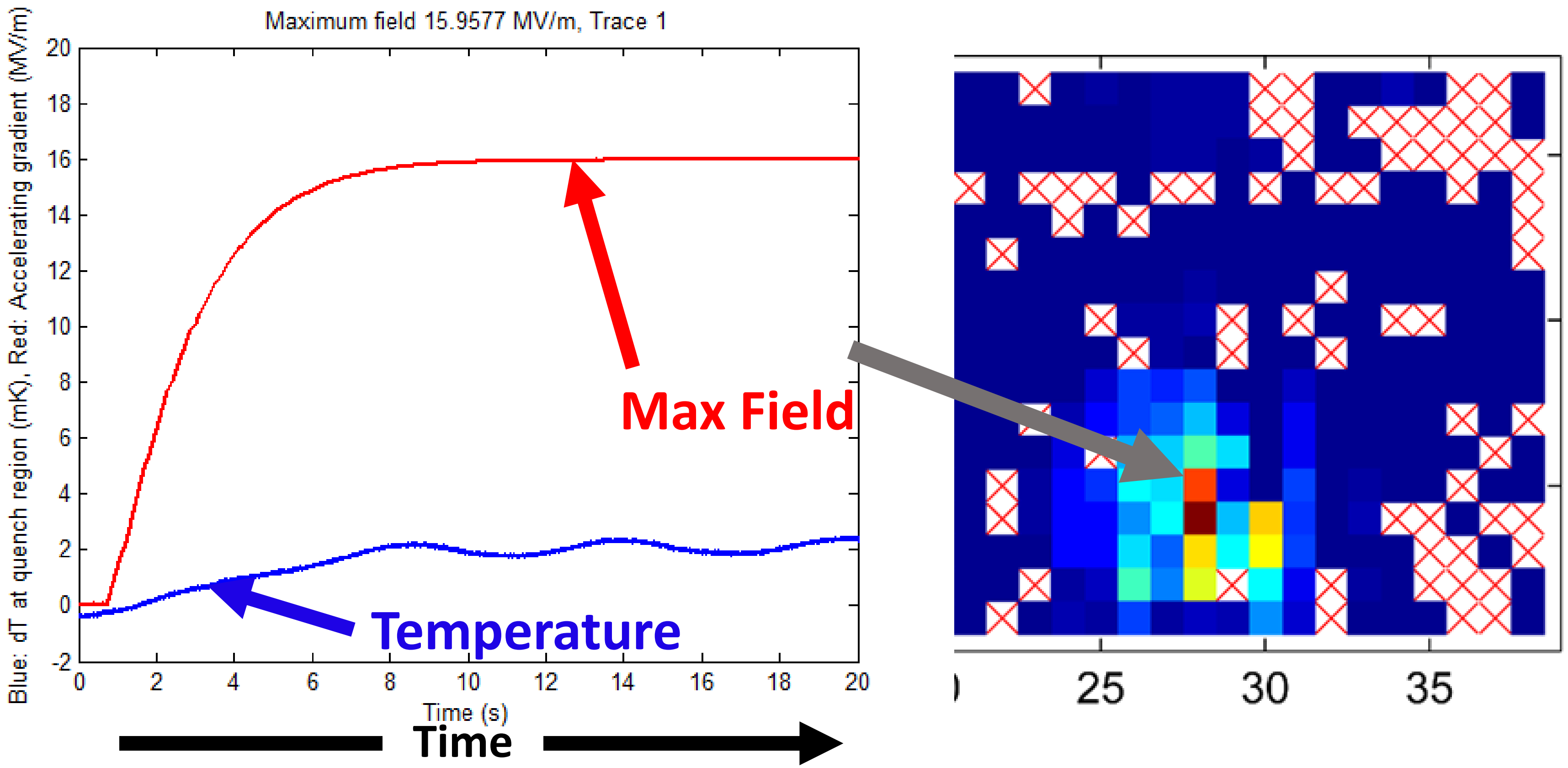
Near quench behavior

- Measure temperature of sensor near the quench point as field is increased



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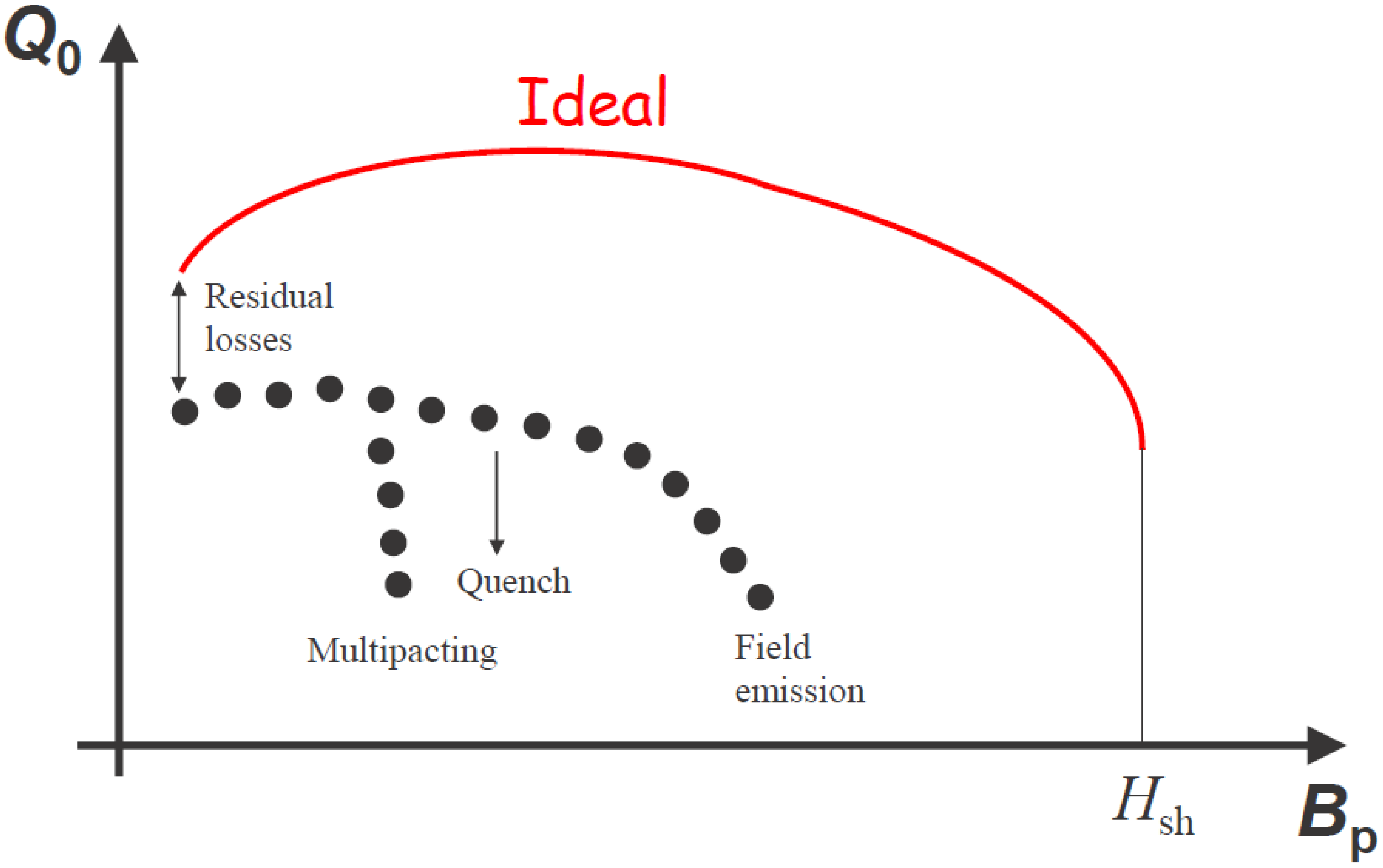
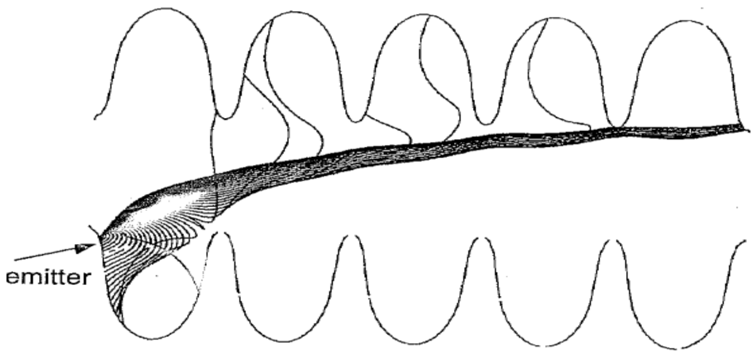
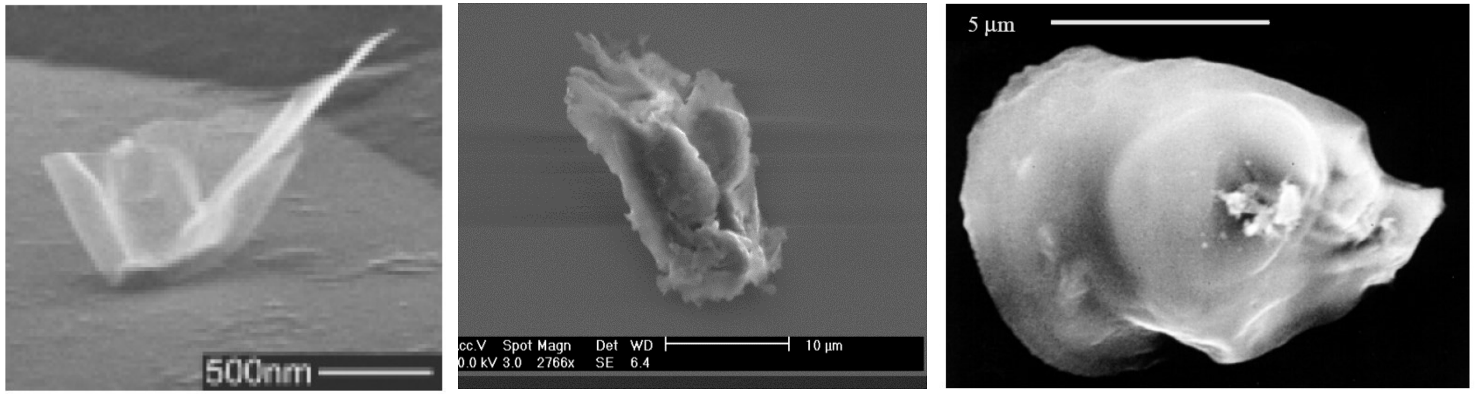
Performance limitations



Field emission

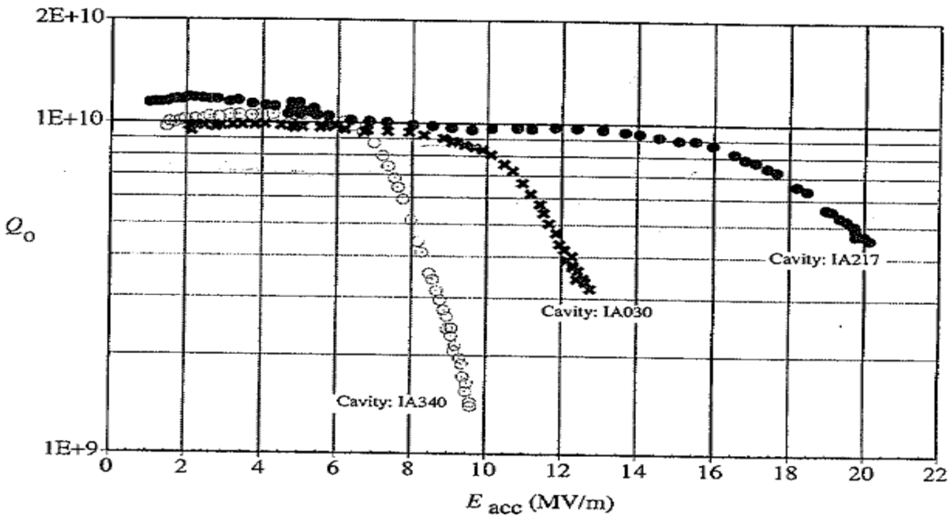
- Under high RF fields electrons can be released from the surface and accelerated





Field emitters found on dissected cavities (size 0.5-10µm with sharp edges)

- Released electrons will impact on the cavity wall creating x-rays and heating



→ Reduced Q-value

Cures for Field Emission

Prevention:

Semiconductor grade acids and solvents

High Pressure Rinsing with ultra-pure water

Clean-room assembly

Simplified procedures and components for assembly

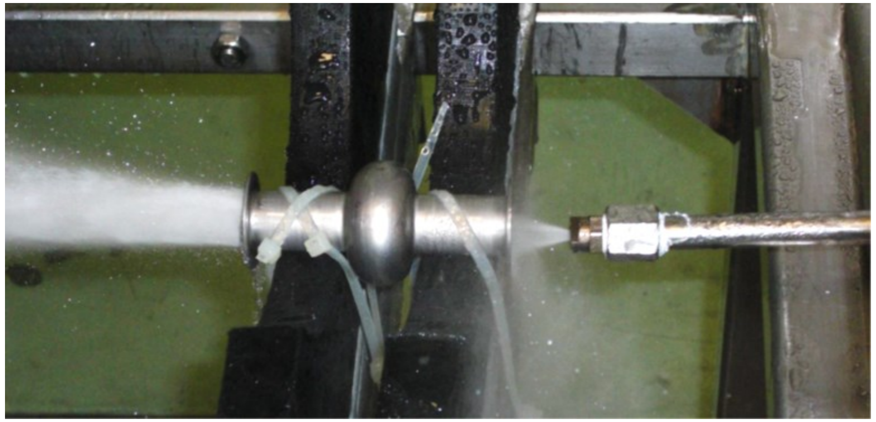
Clean vacuum systems (evacuation and venting without re-contamination)

Post-processing:

Helium processing

High Peak Power (HPP) processing

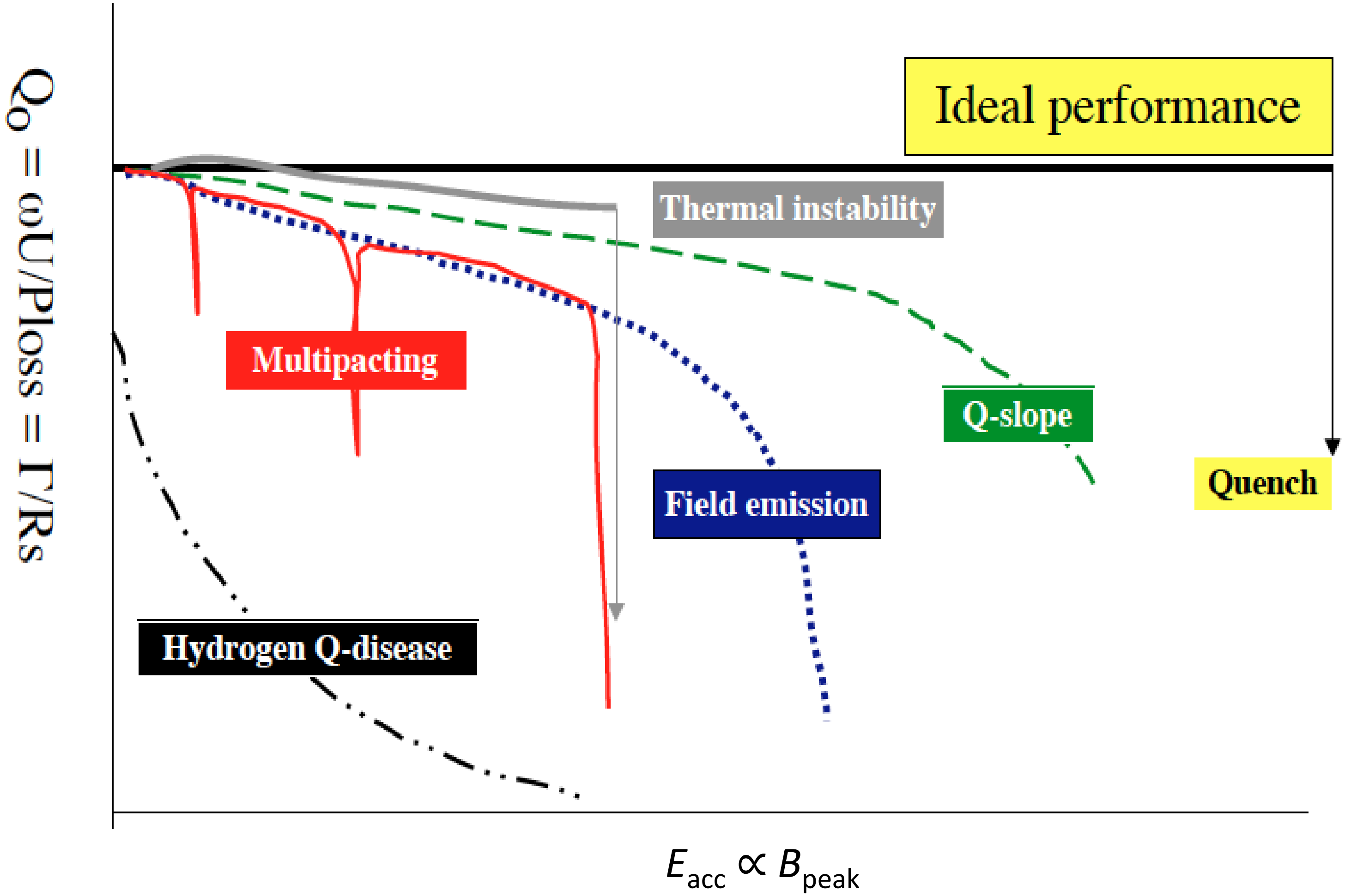
How to removes Field emission



Solution to field emission → **high pressure water rinsing** (100 atm)
and an **ultra-clean assembly** → remove field emitters and preserve cleanliness

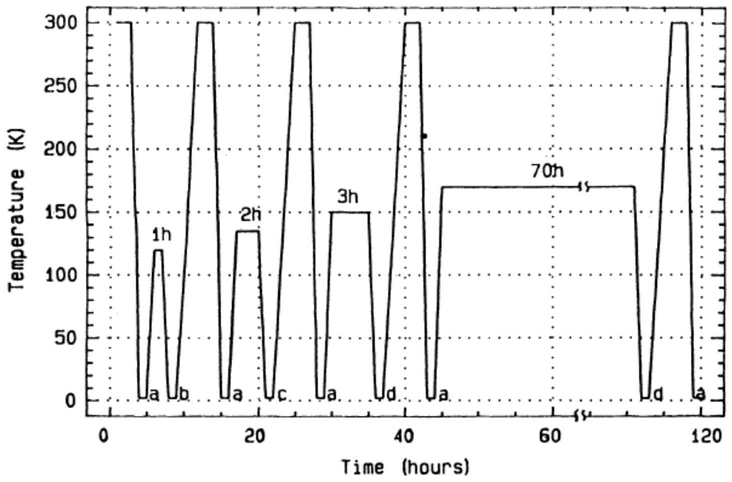
SRF Cavities Intrinsic Limitations

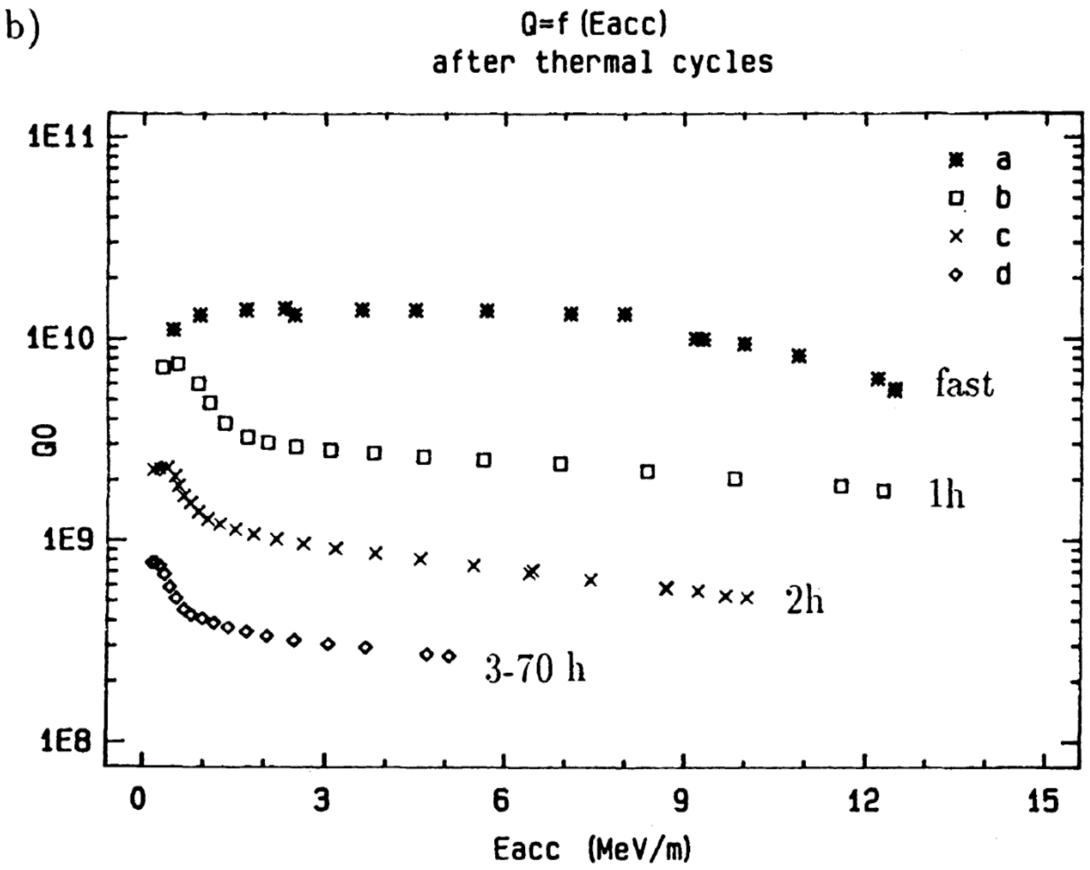
- Q-disease
- Q-slope



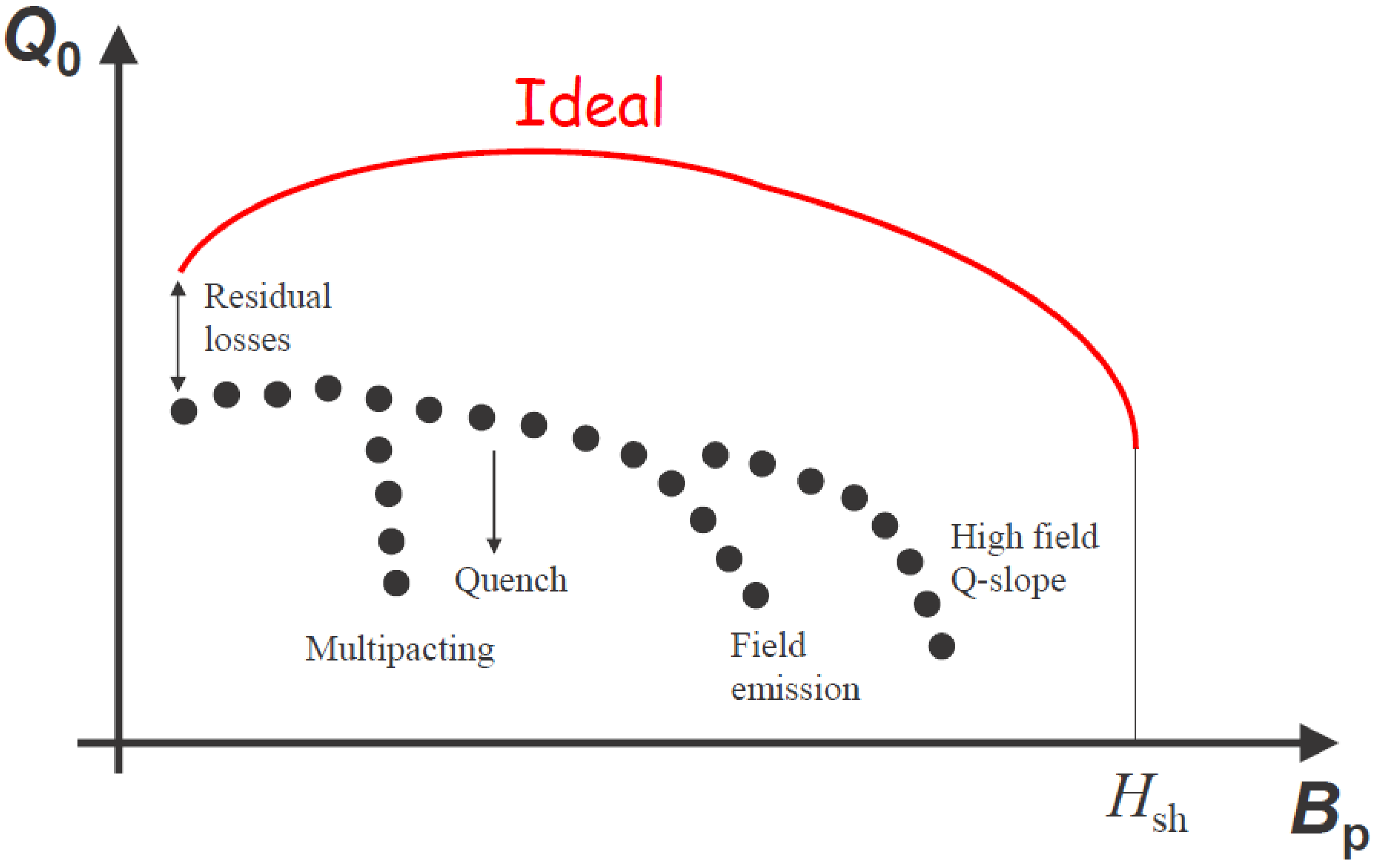
The hydrogen Q-disease

- If a cavity is cooled down slowly around 50-150K Q decreases
- Effect correlated to hydrides
- Some cavities recover after warm up to RT
- 800°C baking is always effective





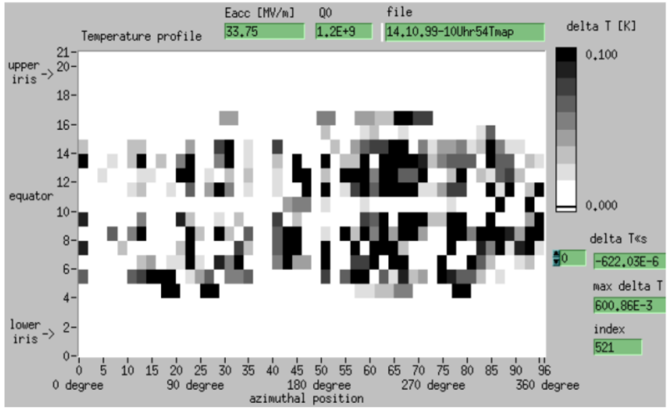
Performance limitations



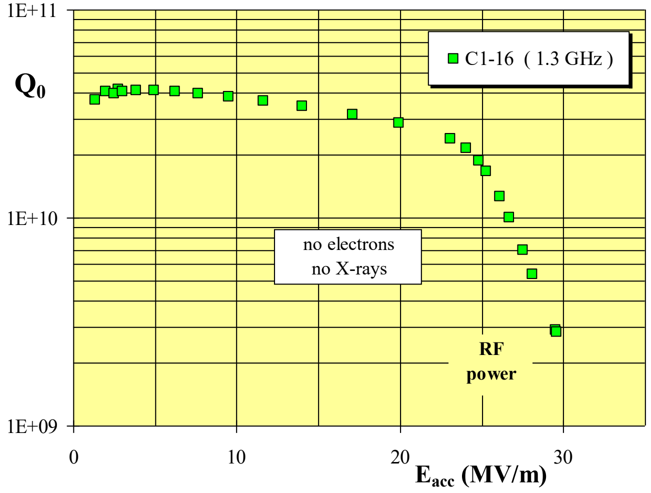
The high field Q-slope

Observations:

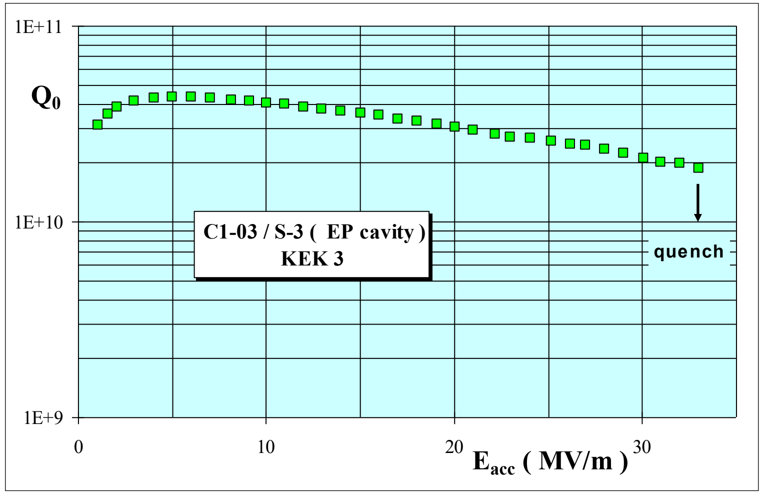
- Strong decrease of Q_0 above E_{acc} > 20 MV/m (in Tesla cavities B_p > 85 mT)
- Field emission not involved (no e $^-$, no X rays)
- T map: global heating in the area of max B-field
- Limitation by RF power supply or quench
- Seemingly a typical feature of BCP cavities
- Solved with EP instead of BCP and baking treatments



(L. Lilje *et al.* - SRF '99 - Santa Fe)



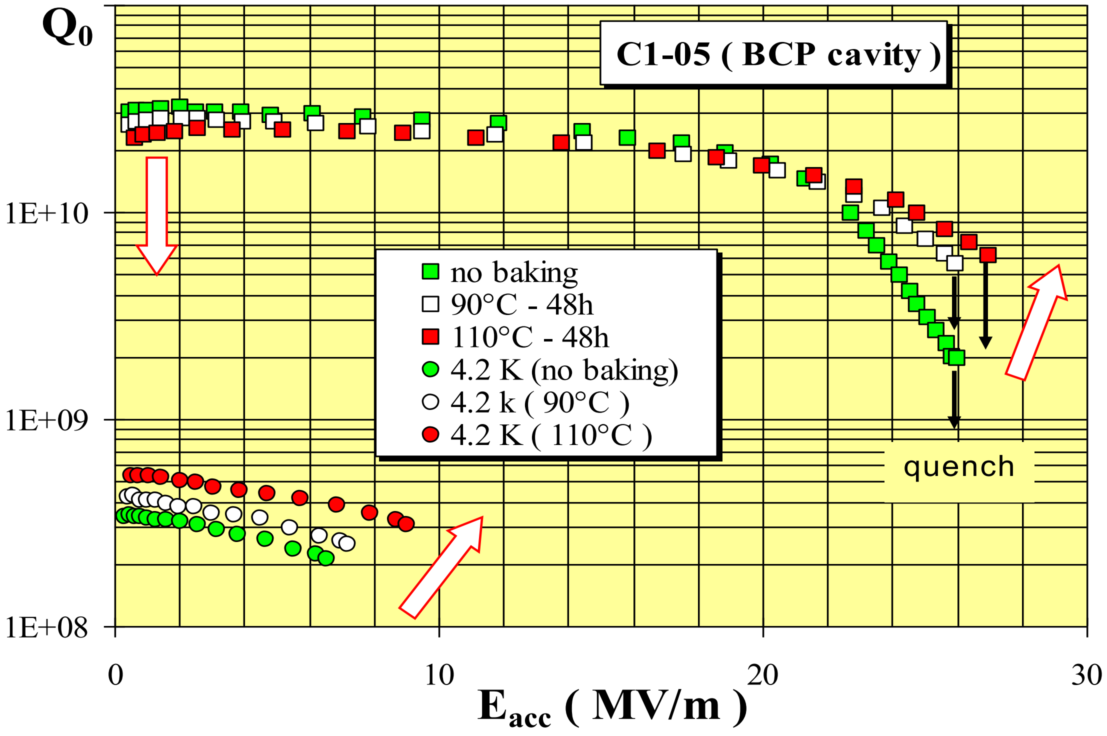
K. Saito *et al.* (SRF '97, Abano Terme)



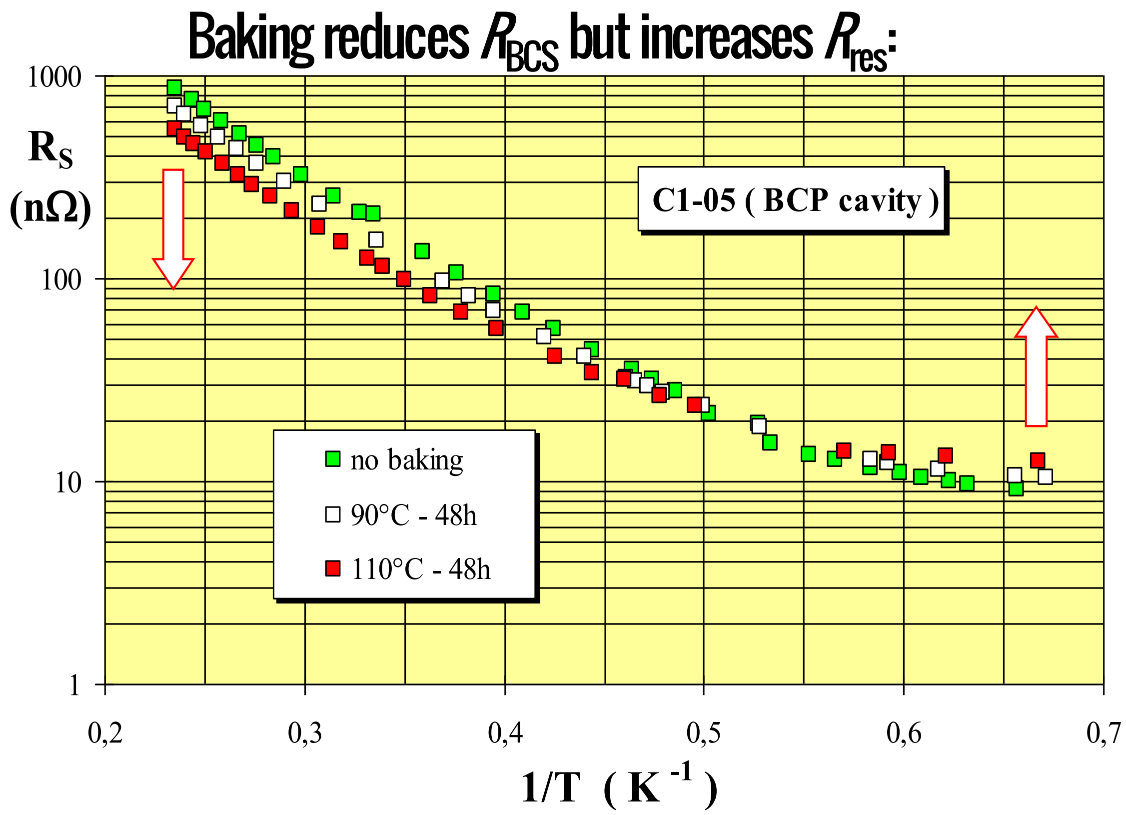
(E. Kako *et al.* - SRF '99 - Santa Fe)

Baking Effect on BCP Cavities

- “in-situ” baking discovered on BCP cavity
- slope improvement (90 < T < 120°C) - degradation (T > 150°C)

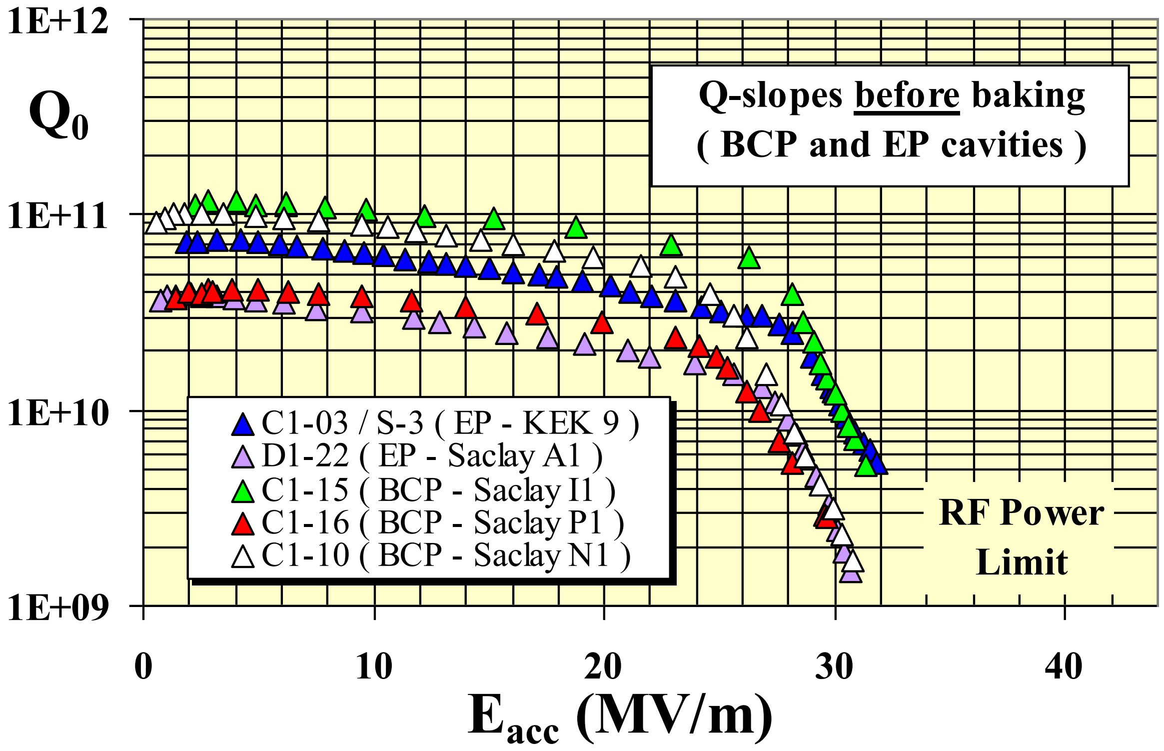


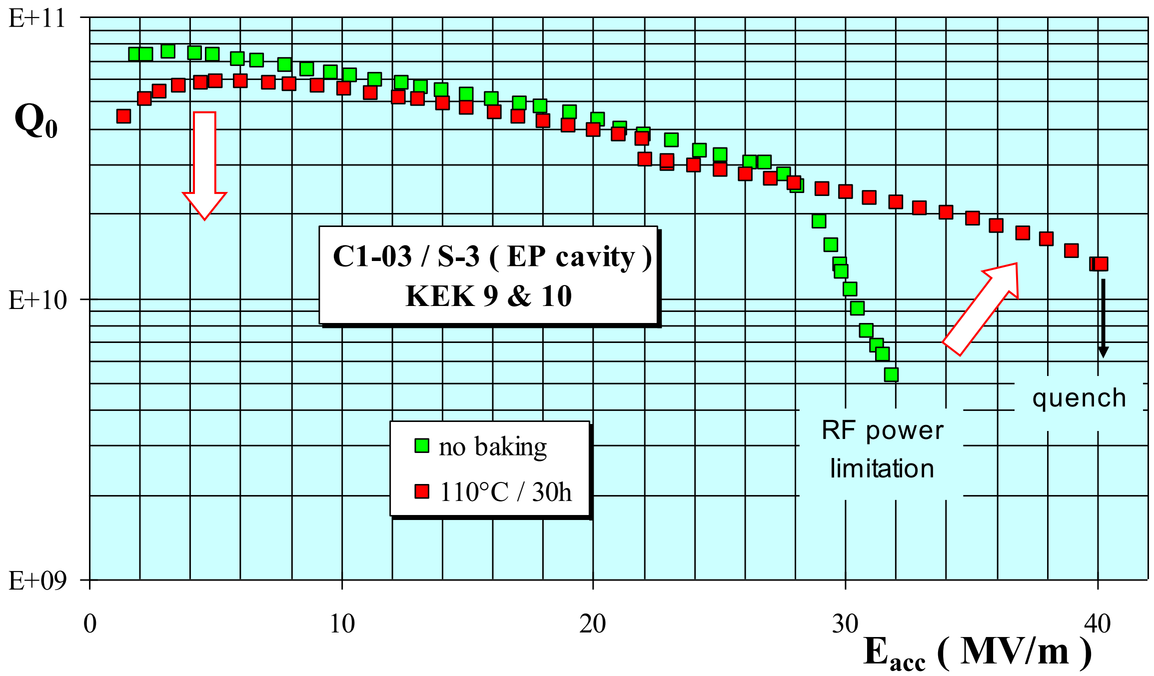
(B. Visentin *et al.* – EPAC ’1998 - Stockholm)



Baking Effect on EP Cavities

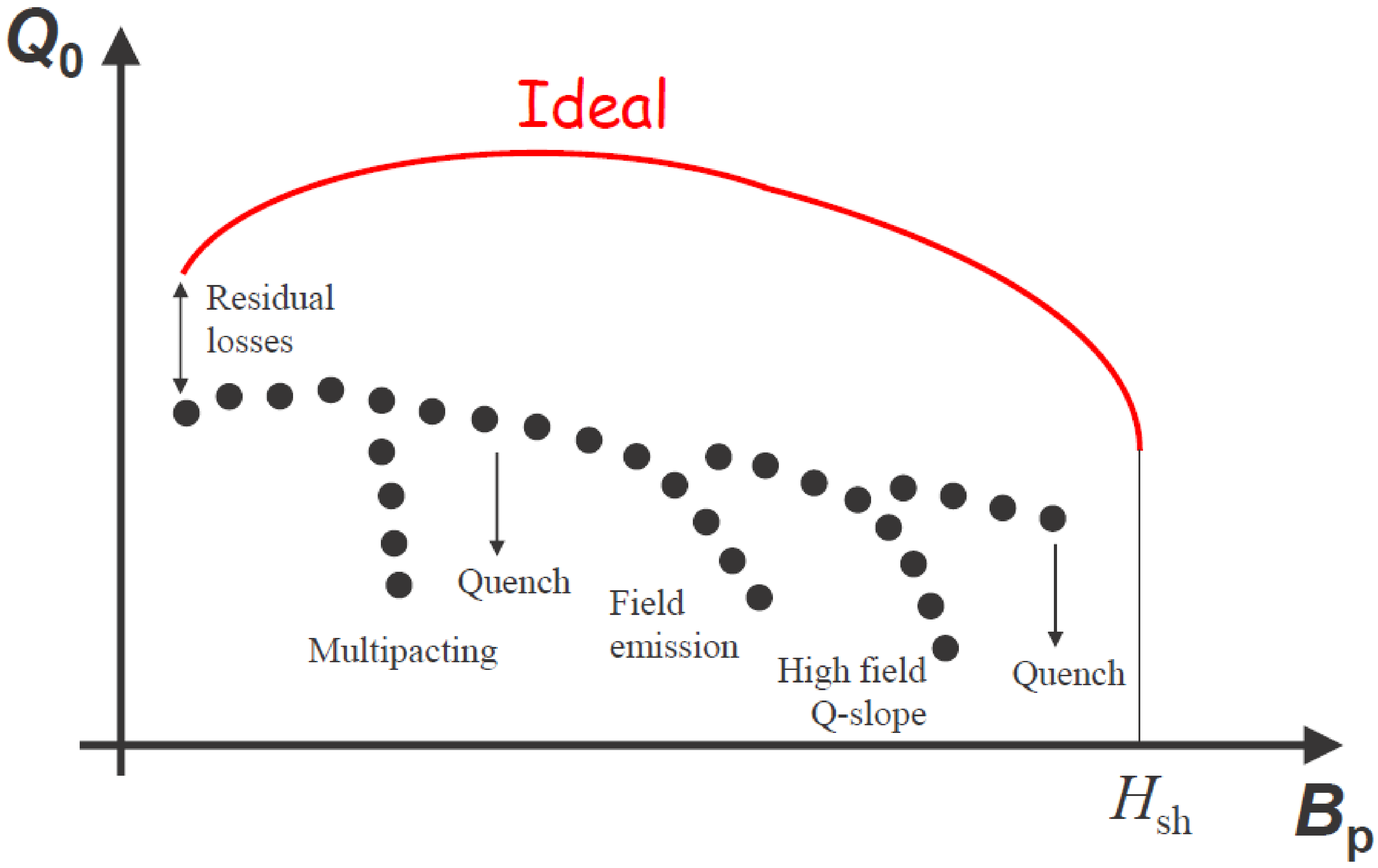
- Same phenomenon on E.P. cavities
- before baking: Q-slope identical to BCP
- after baking: **Q-slope improvement**



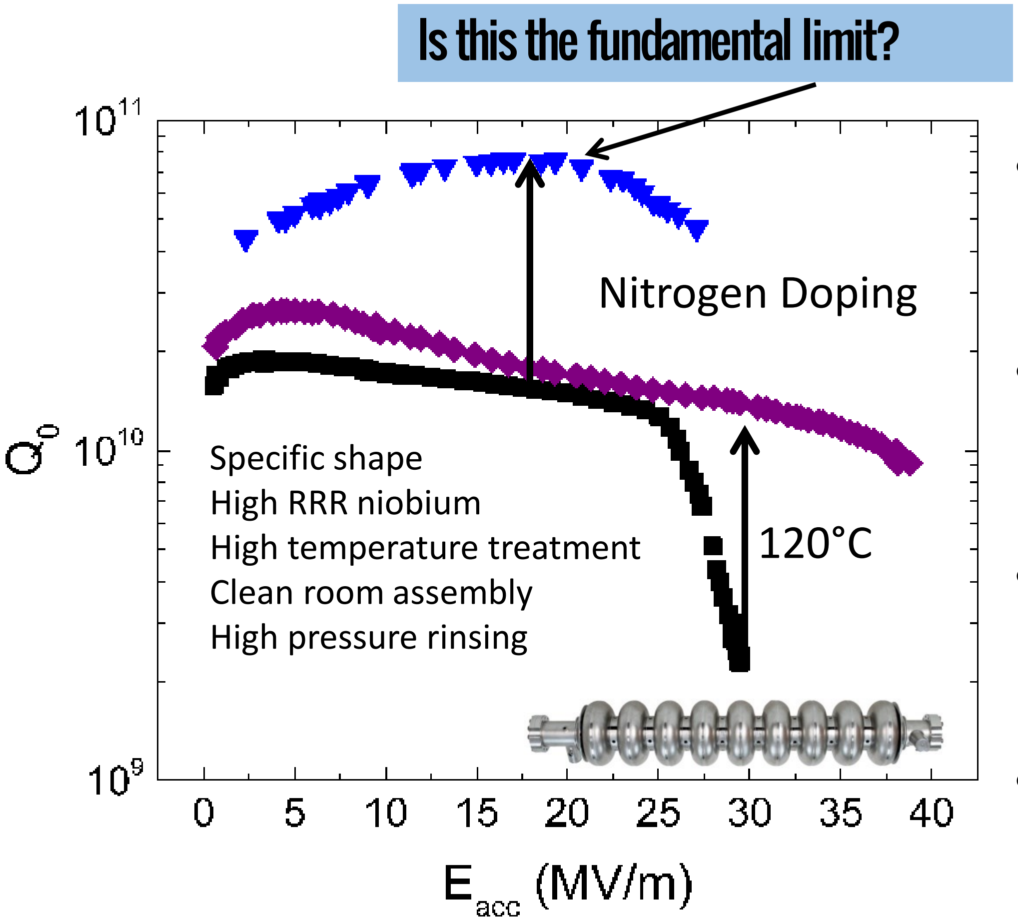


(*Saclay cavity – EP & tested @ KEK*)

Performance limitations



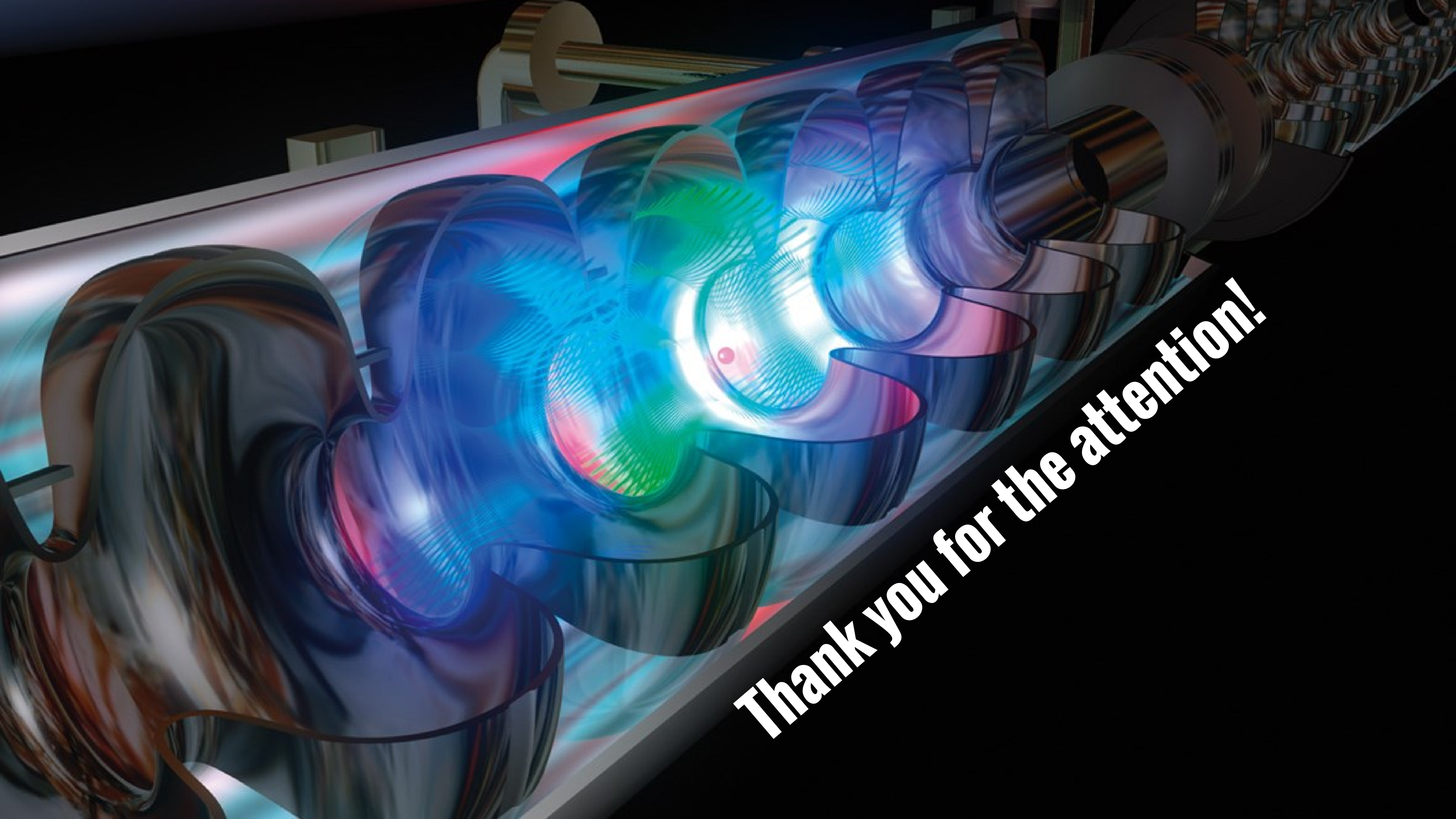
State of the art Nb cavities



- Nb is reaching fundamental limits in quality factor and accelerating gradient
- Unfortunately so far we can have only one or the other and only for elliptical niobium cavities.
- There is still margin for improvement of non-elliptical cavities.
- For performance far beyond the state of the art of elliptical cavities materials other than Nb need to considered

Recommanded Literature

- R. Padamsee, J. Knobloch and T. Hays – « RF Superconductivity for Accelerators », Wiley-VCH, 2008
- J. P. Turneaure, J. Halbritter, and H. A. Schwettman. « The surface impedance of superconductors and normal conductors: The Mattis-Bardeen theory. » Journal of Superconductivity 4.5 (1991): 341-355
- A. Gurevich « Theory of RF superconductivity for resonant cavities. » Superconductor Science and Technology, 30(3), 034004 (2017).
- SRF Tutorials


Thank you for the attention!