Outline

- General comments on SC cavity design choices for accelerators
- Basics of SRF cavities
  - Structure Types
- Basic RF Cavity Design Principles
- Figures of Merit
  - Gradient, Losses, Q, Shunt Impedance, Peak Fields…
- Miracle of Superconductivity
- SC/NC comparison for CW application
- Design Aspects for Multicells
- Mechanical Aspects of Cavity Design
- Cavity Performance Aspects/Cavity Technology
  - Multipacting, Breakdown (Quench), Field Emission, Q-Slope
- Ultimate gradient possibilities
- Fundamental critical fields
- Wide Range of Applications

Overall Approach

- General introduction to many workshop topics
  - Focus on high velocity structures
  - Separate tutorials on high β and low β cavity design aspects
- Important Topics not covered
  - Input couplers
  - HOM couplers
  - Tuners, Vibrations, Microphonics
  - Cryomodules

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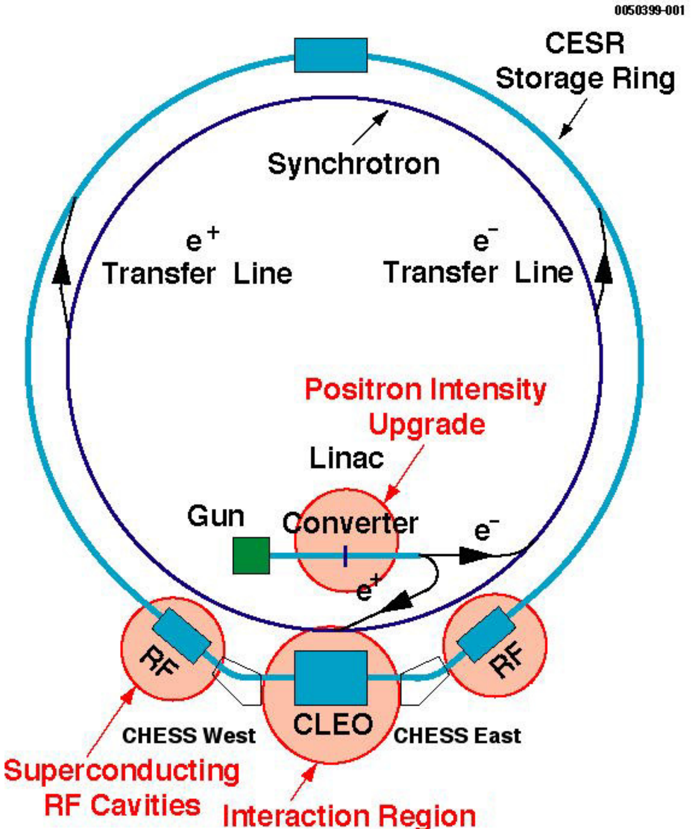
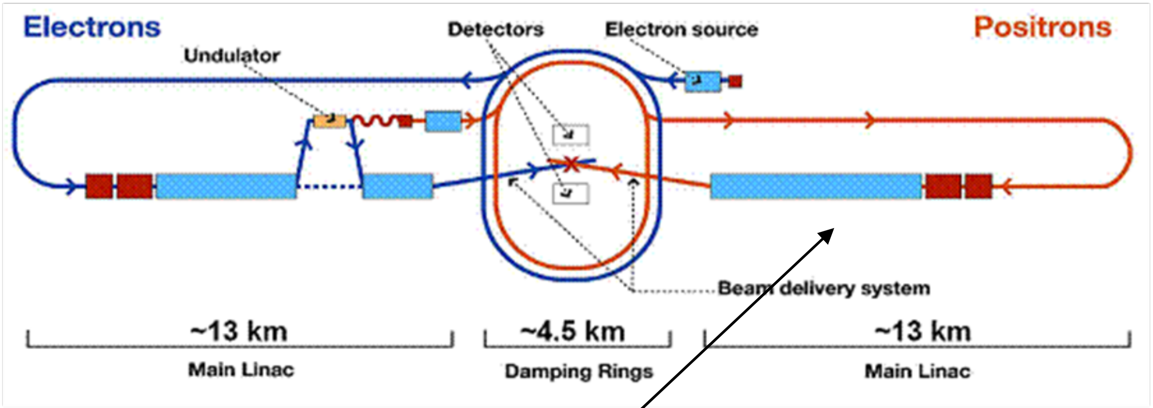
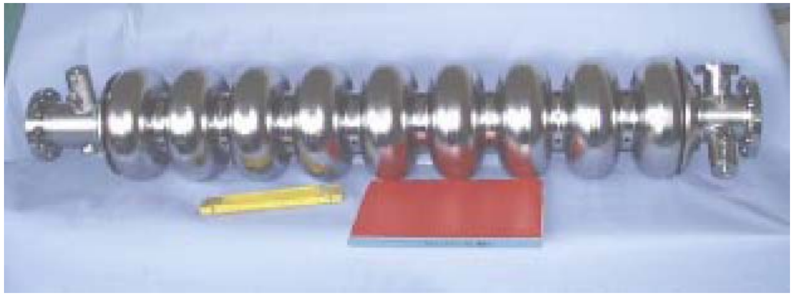
Apply concepts to two examples: Storage Ring, Linear Collider





ILC 16,000 cavities!



General Accelerator Requirements That Drive SC Cavity Design Choices

Voltage

Storage Rings

CESR-III: 7 MV, KEK-B HER: 14 MV, LEP-II: 3 GV

Proton Linac: 1 GV SNS, ESS

Linac-Based FEL or ERL : 500 MeV - 5 GeV

Linear Collider: 500 - 1000 GV

Duty Factor (RF on time x Repetition Rate)

Storage Rings: CW

Linac-Based FEL or ERL CW

Proton Linacs: < 10%

Linear Collider: 0.01 - 1%

Beam Current, Ave. Beam Power

Storage Rings: amp, MW

Linac-Based FEL or ERL 50 μA - 100 mA

Proton Linacs: 10 - 100 mA, 1- 10 MW

Linear Collider: few ma, 10 MW

Cavity Design Choices

- Main Choices
  - RF Frequency
  - Operating Gradient
  - Operating Temperature
  - Number of Cells
  - Cell Shapes
  - Beam Aperture
- Optimize for Capital + Operating Cost
- Best Cavity/Accelerator Performance for Least Risk
- Optimizations Involve Many Trade-offs
- Discuss parameters/dependencies
  - But not the trade-offs

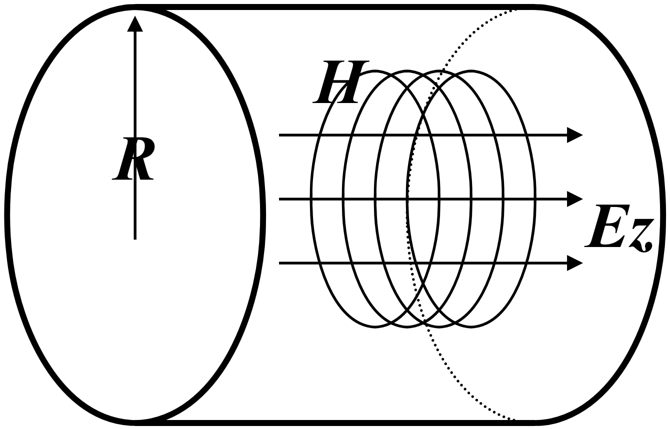
Basics for Radiofrequency Cavities

$$E_z = E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

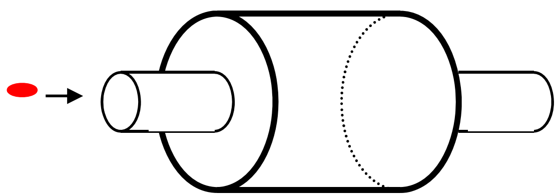
$$H_\phi = -i\frac{E_0}{\eta} J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega t},$$

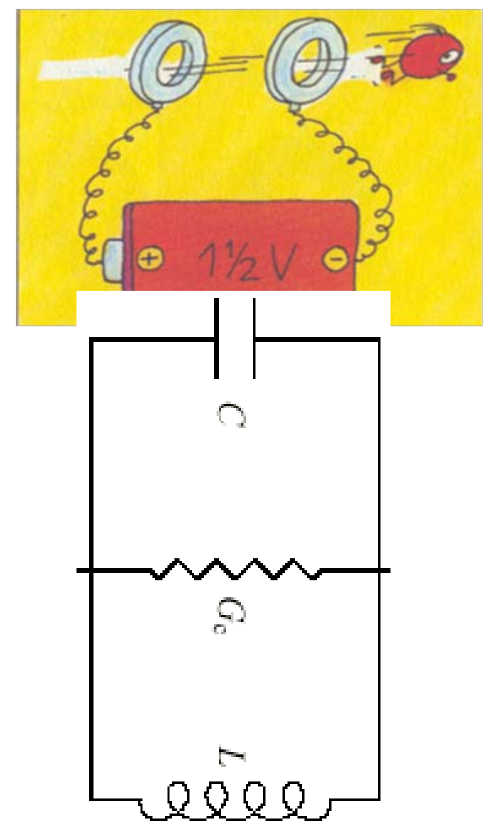
$$\omega_{010} = \frac{2.405c}{R},$$

TM$_{010}$ mode

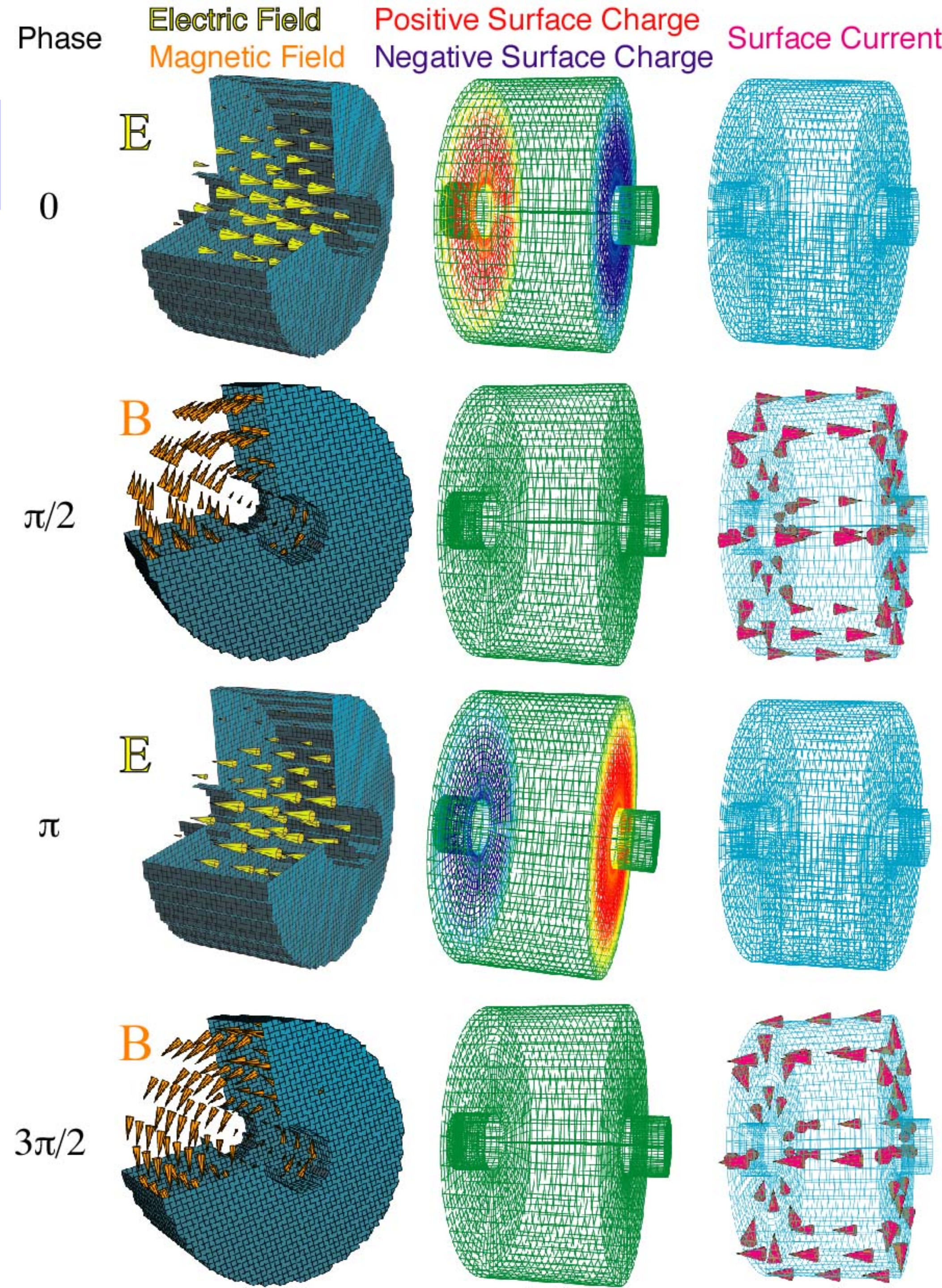


•Add beam tube for charge to enter and exit

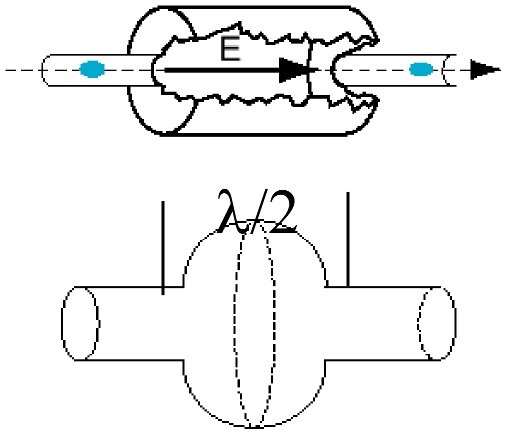




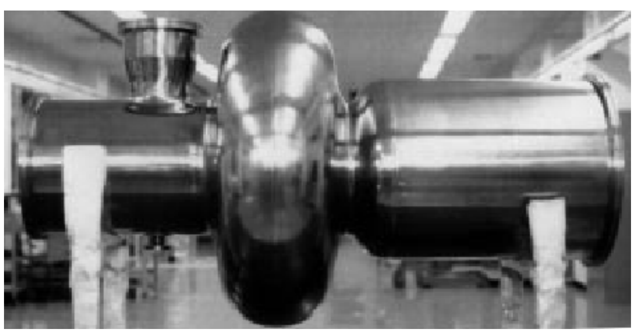
RF accelerator cavities
Fields and Currents



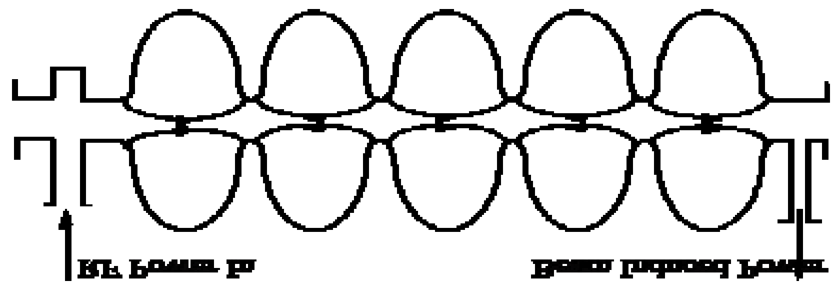
Medium and High Velocity Structures β = v/c = 0.5 -> 1

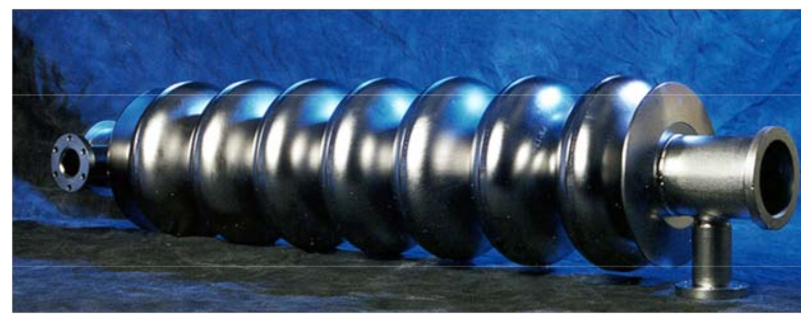


Basic Principle, v/c = 1



Single Cell





Multi-Cell Cavity

Squeezed Cells for v/c = 0.5

Structure Examples

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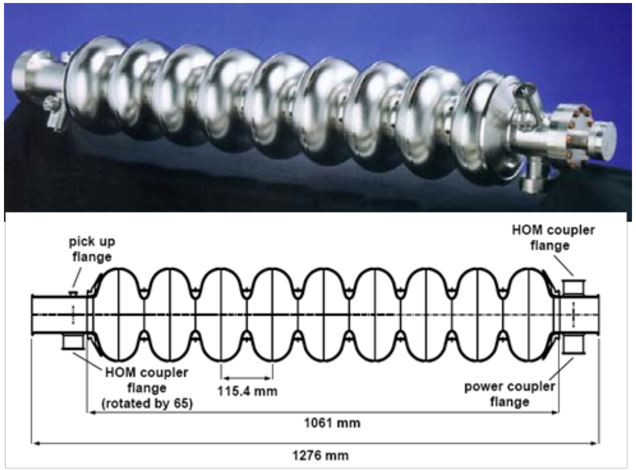
1300 MHz Structures for Accelerating Particles at v ~ c

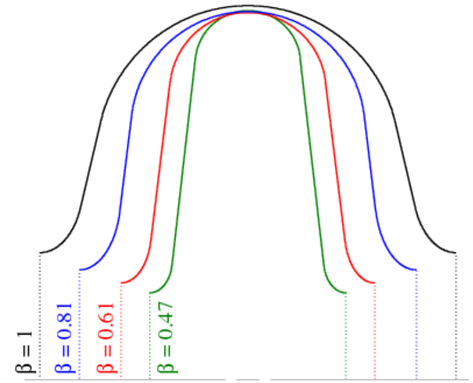


TESLA-shape

(DESY, TTF)

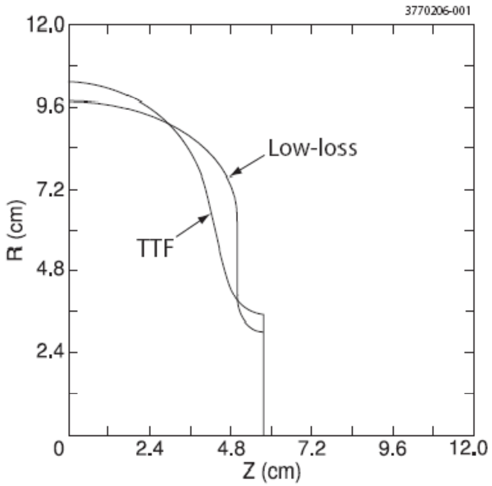
Structures for Particles at v < c (SNS)

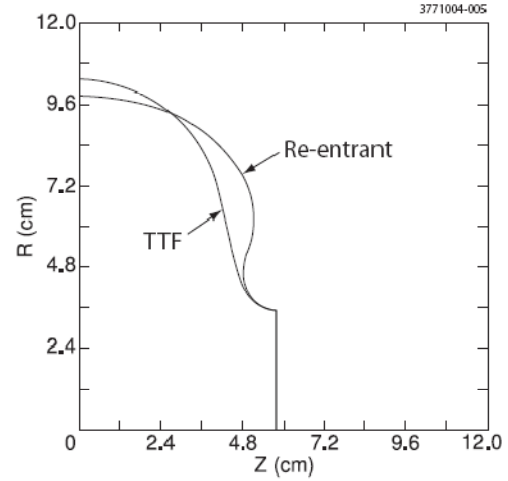
For protons at 1 ~ GeV



Low-Loss shape (Jlab, KEK…)

Re-entrant shape (Cornell)





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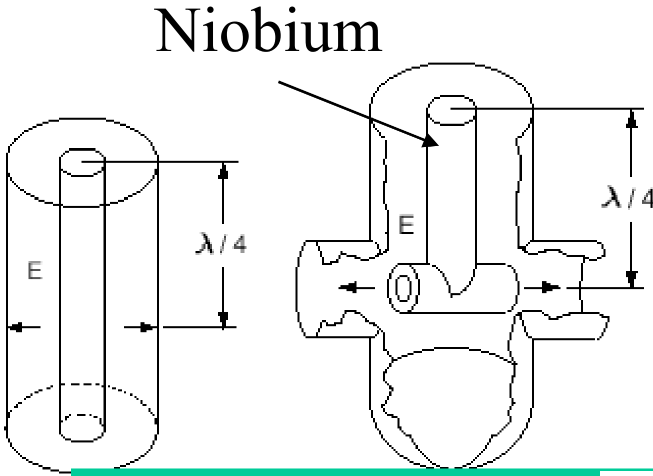
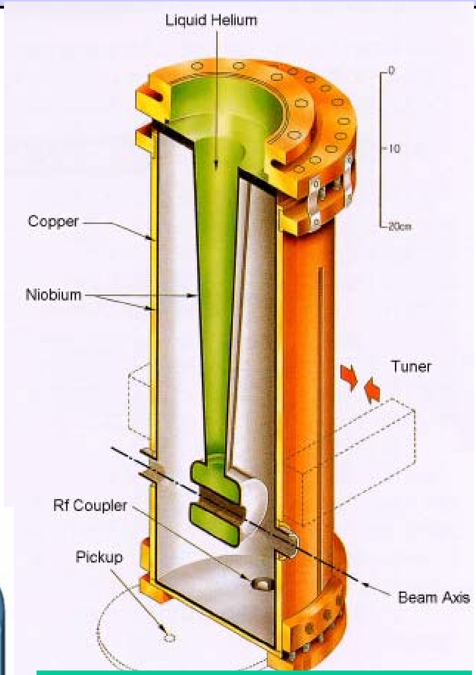
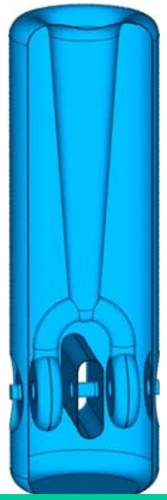
Low Velocity Structures, $\beta = v/c = 0.01 \rightarrow 0.2$



Basic Principle

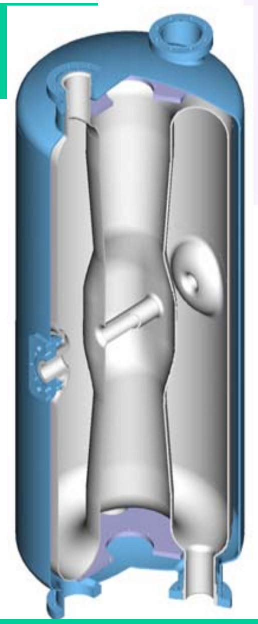


Quarter Wave



Inter-Digital

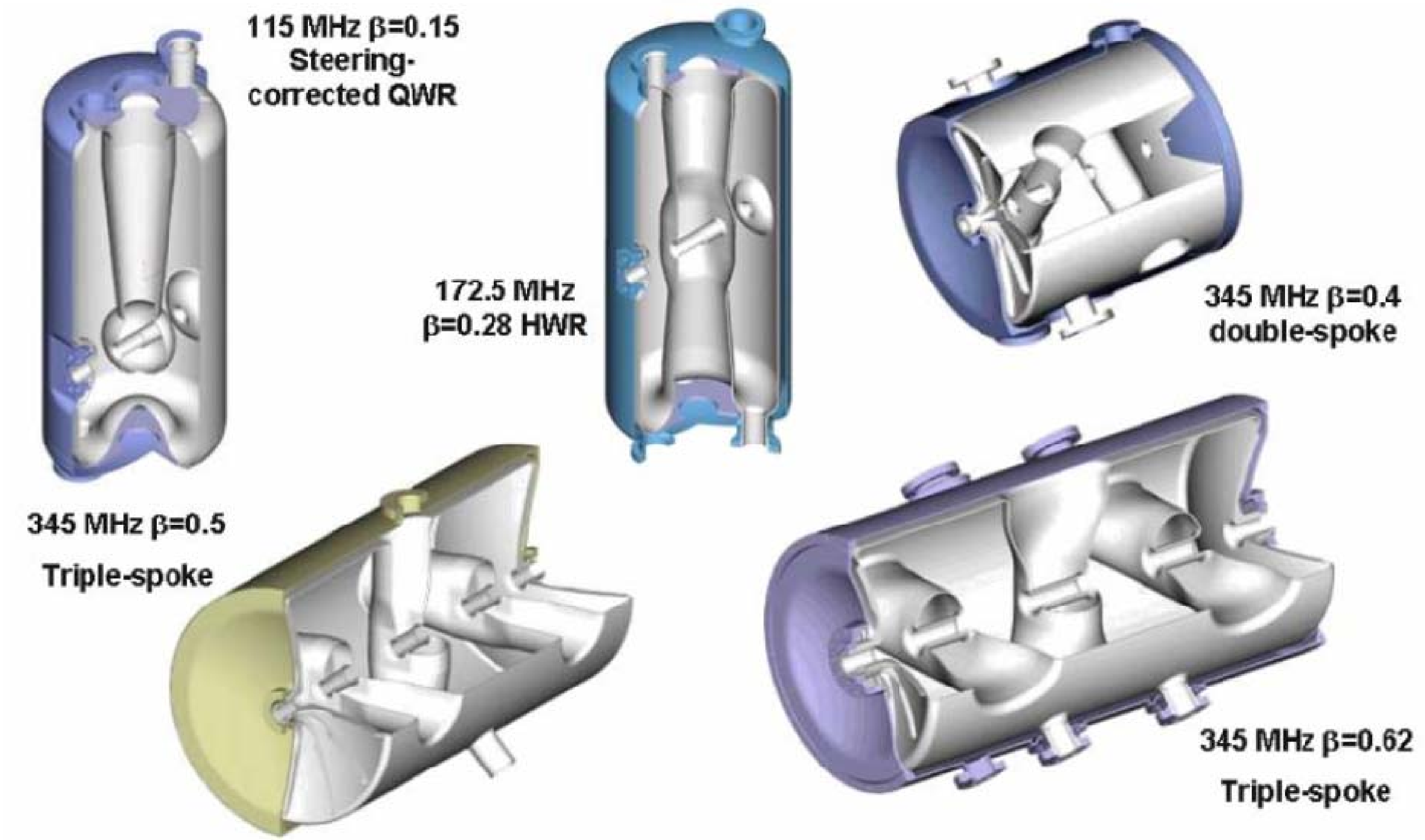
Split -Ring



Half-Wave

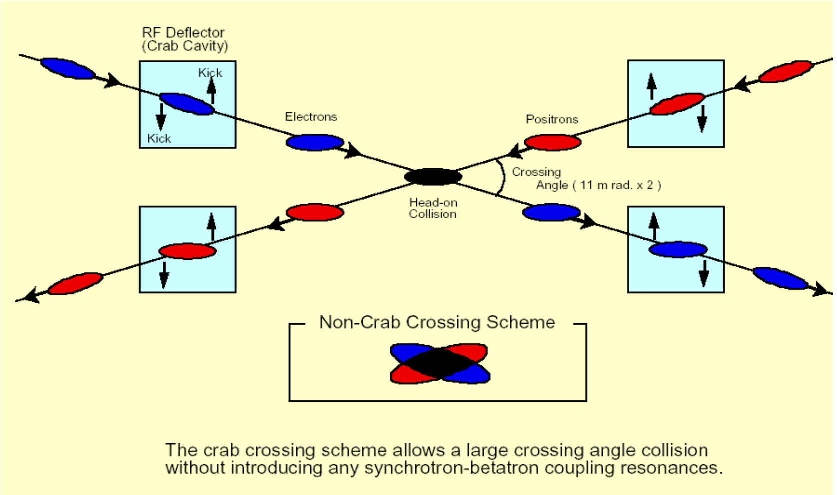
Spoke

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



Crab Cavities (Deflecting mode TM110)

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

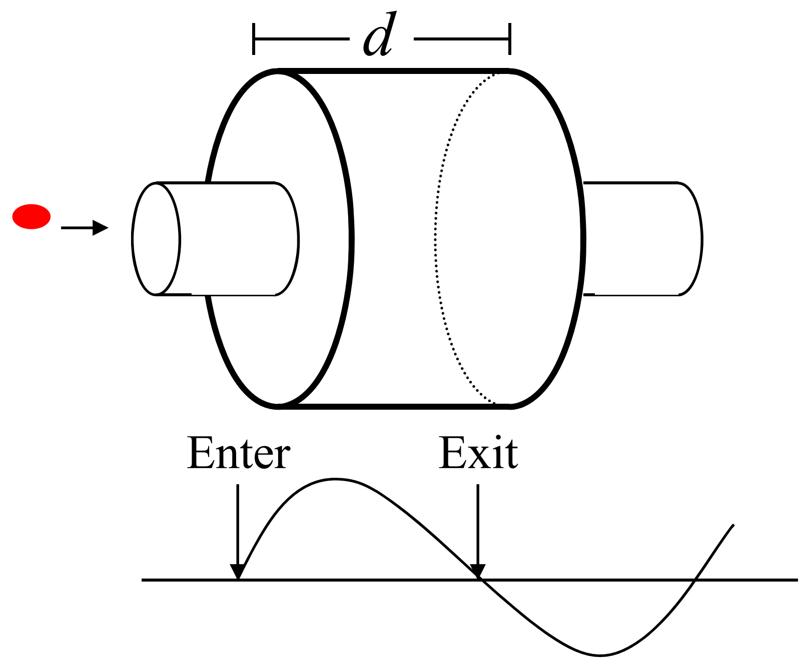


Figures of Merit
Accelerating Voltage/Field
($v = c$ Particles)

- For maximum acceleration need

$$T_{\mathrm{cav}} = \frac{d}{c} = \frac{T_{\mathrm{rf}}}{2}$$

so that the field always points in the same direction as the bunch traverses the cavity



- Accelerating voltage then is: $$V_c = \left| \int_0^d E_z(\rho = 0, z) e^{i\omega_0 z/c} dz \right|$$

$$V_c = E_0 \left| \int_0^d e^{i\omega_0 z/c} dz \right| = dE_0 \frac{\sin\left(\frac{\omega_0 d}{2c}\right)}{\frac{\omega_0 d}{2c}} = dE_0 T.$$

- Accelerating field is: $$E_{\mathrm{acc}} = \frac{V_c}{d} = 2E_0/\pi.$$

Figures of Merit for SC Cavity

- Accelerating Field and Q: E_{acc}, Q
- Stored Energy, Geometry Factor
- Peak Electric and Magnetic Field Ratios
  - E_{pk}/E_{acc}, H_{pk}/E_{acc}
- Shunt Impedance, Geometric Shunt Impedance: R_a, R_a/Q

Single Cell Cavities

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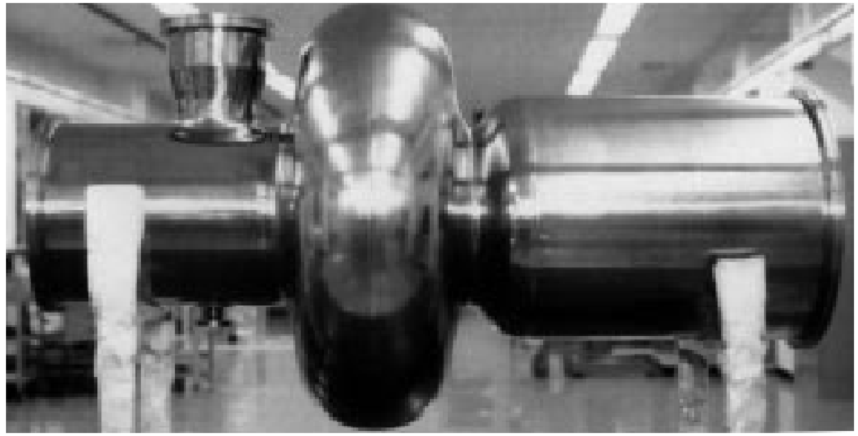
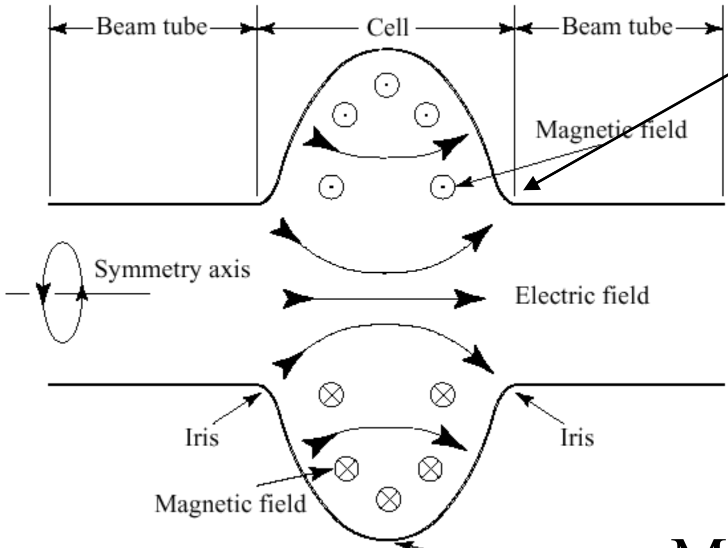
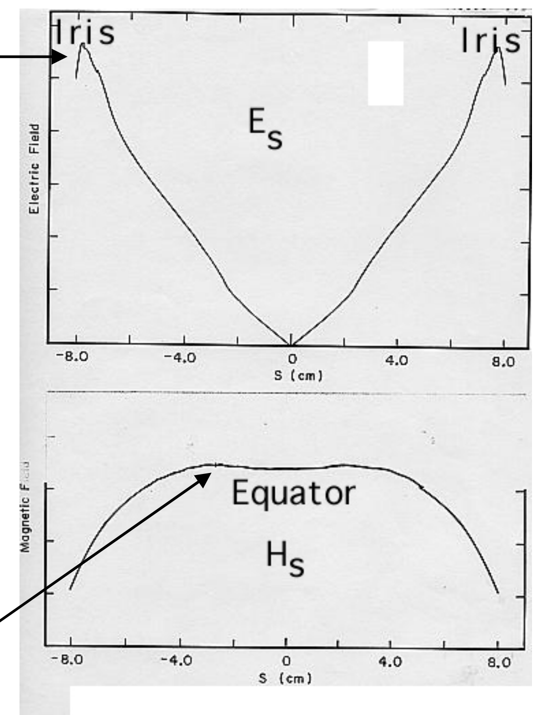
KEK-B Cavity



Electric field high at iris





Magnetic field high at equator

Figures of Merit
Peak Fields

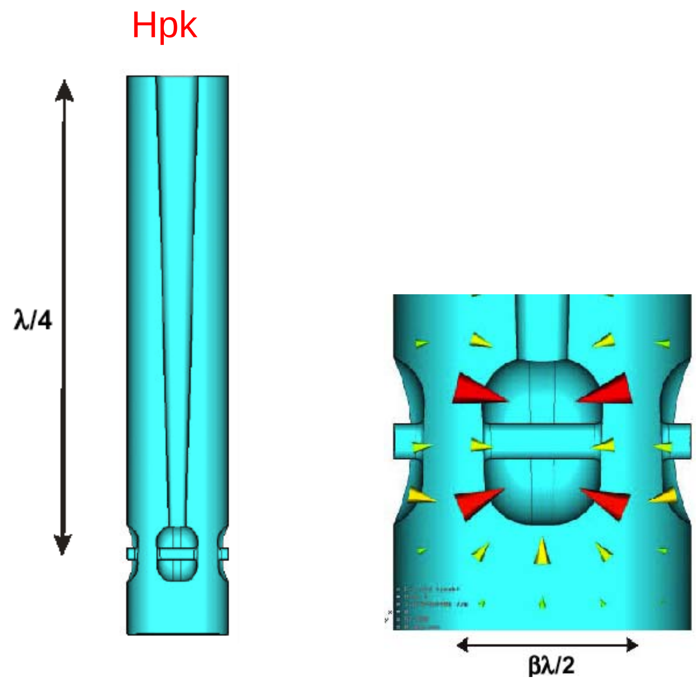
- *For* E_{acc} → important parameter is E_{pk}/E_{acc},
  - Typically 2 - 2.6
- Make as small as possible, to avoid problems with field emission - more later.
- Equally important is H_{pk}/E_{acc}, to maintain SC
  - Typically 40 - 50 Oe/MV/m
- H_{pk}/E_{acc} can lead to premature quench problems (thermal breakdown).
- Ratios increase significantly when beam tubes are added to the cavity or when aperture is made larger.

Peak fields for low beta cavities are higher

Typical

Epk/Eacc = 4 - 6

Hpk/Eacc = 60 - 200 Oe/MV/m



Figures of Merit

Dissipated Power, Stored Energy, Cavity Quality (*Q*)

- Surface currents ($\propto H$) result in dissipation proportional to the surface resistance (R_s):

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

- Dissipation in the cavity wall given by surface integral:

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, ds$$

- Stored energy is: →

$$U = \frac{1}{2} \mu_0 \int_V |\mathbf{H}|^2 \, dv$$

- Define Quality (*Q*) as $Q_0 = \dfrac{\omega_0 U}{P_c} = 2\pi \dfrac{U}{T_{rf} P_c}$

which is ~ 2 π number of cycles it takes to dissipate the energy stored in the cavity → Easy way to measure *Q*

- $Qnc \approx 10^4$, $Qsc \approx 10^{10}$

Galileo, 1600 AD

Geometry Factor

Since the time averaged energy in the electric field equals that in
netic field, the total energy in the cavity is given by

$$U = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2\, dv = \frac{1}{2}\epsilon_0 \int_V |\mathbf{E}|^2\, dv,$$

where the integral is taken over the volume of the cavity.

the dissipated power $$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2\, ds,$$

where the integration is taken over the interior cavity surface.

$$Q_0 = \frac{\omega_0 U}{P_c}, \qquad Q_0 = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2\, dv}{R_s \int_S |\mathbf{H}|^2\, ds}.$$

The Q_0 is frequently written as

$$Q_0 = \frac{G}{R_s},$$

where

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2\, dv}{\int_S |\mathbf{H}|^2\, ds}$$

Pill-Box Results

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For the pill-box TM$_{010}$ mode we find

$$U = E_0^2 \pi d \epsilon_0 \int_0^R \rho J_1^2 \left(\frac{2.405\rho}{R} \right) d\rho$$

$$P_c = \frac{R_s E_0^2}{\eta^2} \left\{ 2\pi \int_0^R \rho J_1^2 \left(\frac{2.405\rho}{R} \right) d\rho + \pi R d J_1^2 (2.405) \right\}$$

$$\int \rho J_\nu^2(\alpha\rho)\, d\rho = \frac{\rho^2}{2} \left[J_\nu^2(\alpha\rho) - J_{\nu-1}(\alpha\rho) J_{\nu+1}(\alpha\rho) \right]$$

$$U = \frac{\pi \epsilon_0 E_0^2}{2} J_1^2(2.405) d R^2$$

$$P_c = \frac{\pi R_s E_0^2}{\eta^2} J_1^2(2.405) R(R+d)$$

$$G = \frac{\omega_0 \mu_0 d R^2}{2(R^2 + Rd)} = \eta \frac{2.405 d}{2(R+d)} = \frac{453 \frac{d}{R}}{1 + \frac{d}{R}} \Omega.$$

G is indeed independent of the cavity's size.

$G = 257\ \Omega.$ $\qquad \dfrac{d}{R} = \dfrac{\pi}{2.405}$

If $R_s = 20$ nΩ $\qquad Q_0 = \dfrac{G}{R_s} = 1.3 \times 10^{10}.$

A typical length of $d = 10$ cm requires a cavity radius R of 7.65 cm or, equivalently, a resonant frequency of 1.5 GHz. For operation at $V_c = 1$ MV the following results are found to apply:

$$
\begin{aligned}
E_{\mathrm{acc}} &= \frac{V_c}{d} = 10\ \mathrm{MV/m} \\
E_{\mathrm{pk}} &= E_0 = \frac{\pi}{2} E_{\mathrm{acc}} = 15.7\ \mathrm{MV/m} \\
H_{\mathrm{pk}} &= 30.5\ \frac{\mathrm{Oe}}{\mathrm{MV/m}} E_{\mathrm{acc}} = 305\ \mathrm{Oe} \\
U &= E_0^2 \frac{\pi \epsilon_0}{2} J_1^2(2.405) d R^2 = 0.54\ \mathrm{J} \\
P_c &= \frac{\omega U}{Q_0} = 0.4\ \mathrm{W}.
\end{aligned}
$$

$$
\begin{aligned}
\frac{E_{\mathrm{pk}}}{E_{\mathrm{acc}}} &= \frac{\pi}{2} = 1.6 \\
\frac{H_{\mathrm{pk}}}{E_{\mathrm{acc}}} &= 2430\ \frac{\mathrm{A/m}}{\mathrm{MV/m}}
\end{aligned}
$$

Figures of Merit
Shunt Impedance (R_a)

- Shunt impedance (R_a) determines how much acceleration one gets for a given dissipation (analogous to Ohm's Law)

$$R_a = \frac{V_c^2}{P_c}$$

→ To maximize acceleration, must maximize shunt impedance.

Another important figure of merit is $\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U},$

•Ra/Q only depends on the cavity geometry → Cavity design impacts mode excitation

Evaluation - Analytic Expressions

1.5 GHz pillbox cavity, $R = 7.7$ cm, $d = 10$ cm

$$\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U},$$

$$\frac{R_a}{Q_0} = 150\ \Omega\ \frac{d}{R} = 196\ \Omega.$$

For Cu: $R_s = 10$ mohm → $Q = 25{,}700$, $R_a = 5$ Mohm

For Nb: $R_s = 10$ nohm → $Q = 25{,}700{,}000{,}000$, $R_a = 5$ Tohm!

Real Cavities
Codes

- Adding beam tubes reduces R_a/Q by about x2 => for Cu cavities use a small beam hole.
- Peak fields also increase.
  - Can be a problem for high gradient cavities
- Analytic calculations are no longer possible, especially if cavity shape is changed to optimize peak fields.
- → Use numerical codes.
- E.g., MAFIA, MicrowaveStudio, SuperLans, CLANS, Omega3P….

Accelerating Mode

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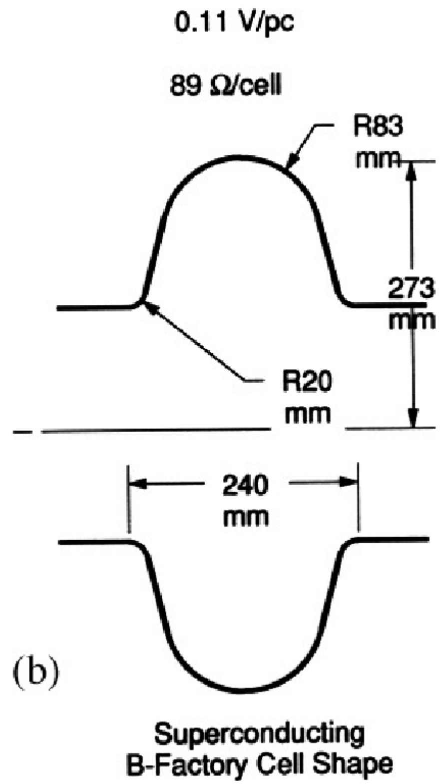
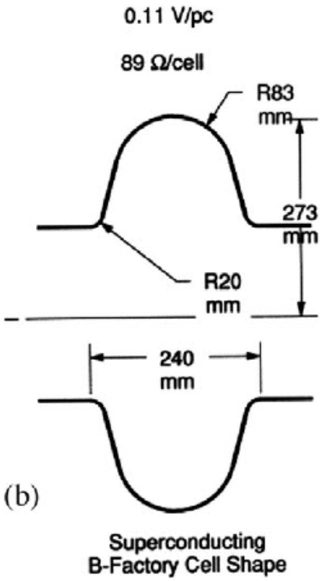


Quantity	Cornell SC 500 MHz	Pillbox
G	270 ohmΩ	257 Ω
R_a/Q_0	88 ohm/cell	196 Ω/cell
E_{pk}/E_{acc}	2.5	1.6
H_{pk}/E_{acc}	52 Oe/MV/m	30.5 Oe/(MV/m)

Copper Cavity Example CW and Low Gradient

$$R_s = \sqrt{(\pi f \mu_0 \rho)}$$

f = RF frequency
ρ = DC resistivity
μ_0 = permeability of free space



- Example: Assume we make this cavity out of copper
- Want to operate CW at 500 MHz and
- 1 MV (3 MV/m)

R/Q = 89 Ohm

- R_s = 6 mohm

→ Q = 45,000

→ R_a = 4 Mohm

→ P_{diss} = 250 kW

This would result in a overheating of copper cell. Water-cooled copper cavities at this frequency can dissipate about 40 kW.

(CW) copper cavity design is primarily driven by the requirement that losses must be kept small.

Minimizing Losses

Want high *Vacc*

If dissipation is too large, must reduce duty factor

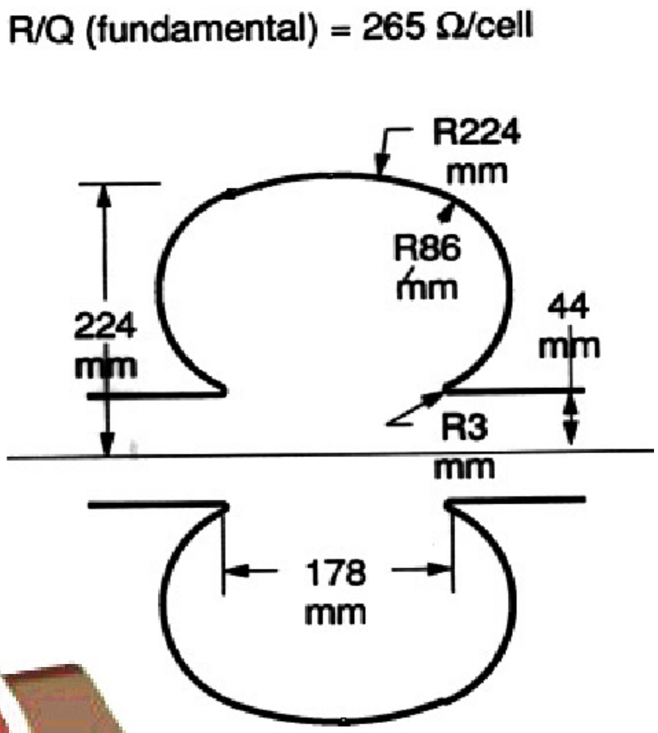
$$P_{\mathrm{diss}} = \frac{V_{\mathrm{acc}}^{2}}{R_{\mathrm{a}}} * \boldsymbol{DF} = \frac{V_{\mathrm{acc}}^{2}}{R_{\mathrm{a}}/Q * Q} * \boldsymbol{DF}$$

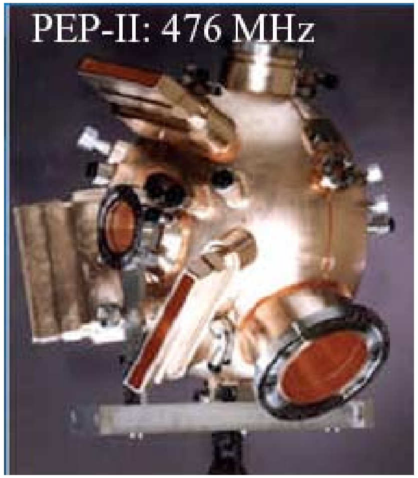
Depends only on geometry.
→ Maximize this for copper cavities

Determined by the material being used

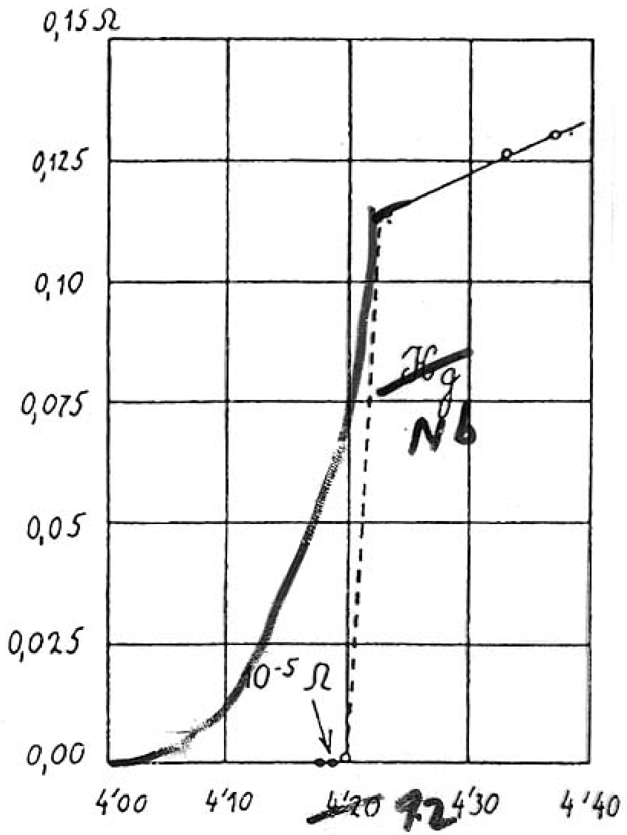
Optimizing CW Copper Cavities High Current Application

- Use small beam tubes
- Use reentrant design to reduce surface magnetic currents.
- → R_a/Q = 265 Ohm
- → P_{diss} = 80 kW @ 3 MV/m
- Still have to reduce voltage to 0.7 MV.
-





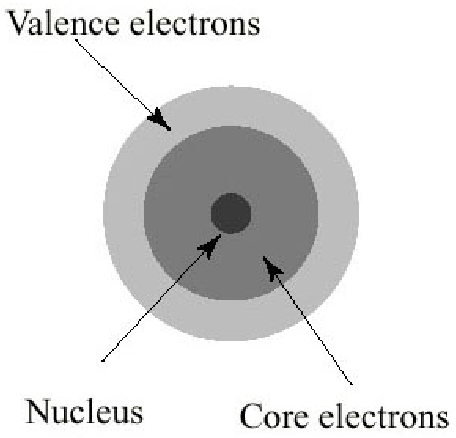
Superconductivity

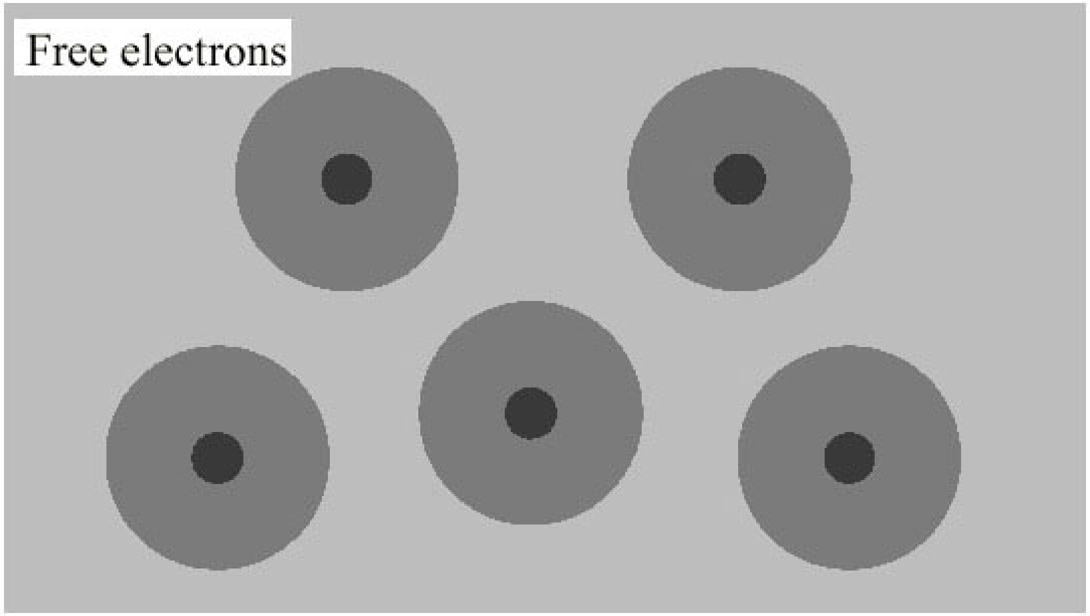


surement of superconductivity by Kamerlingh Onnes

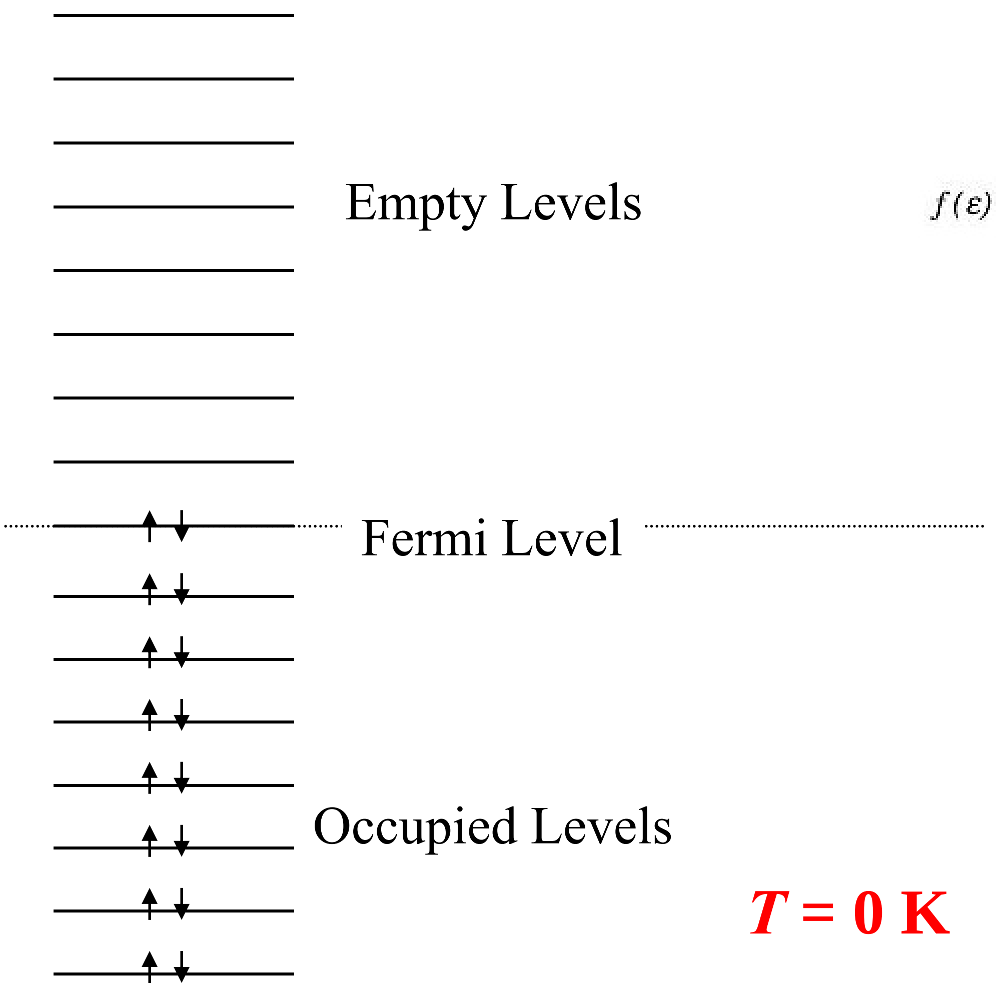
Figure 1-2. Heike Kamerlingh Onnes.

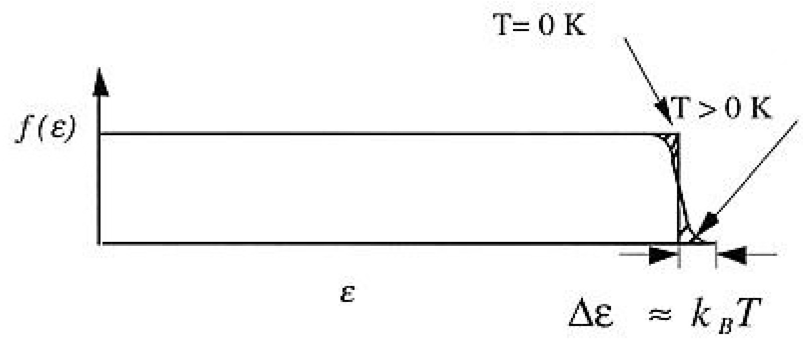
Elementary Solid State : Electrons in Solids





Electron Energy Levels

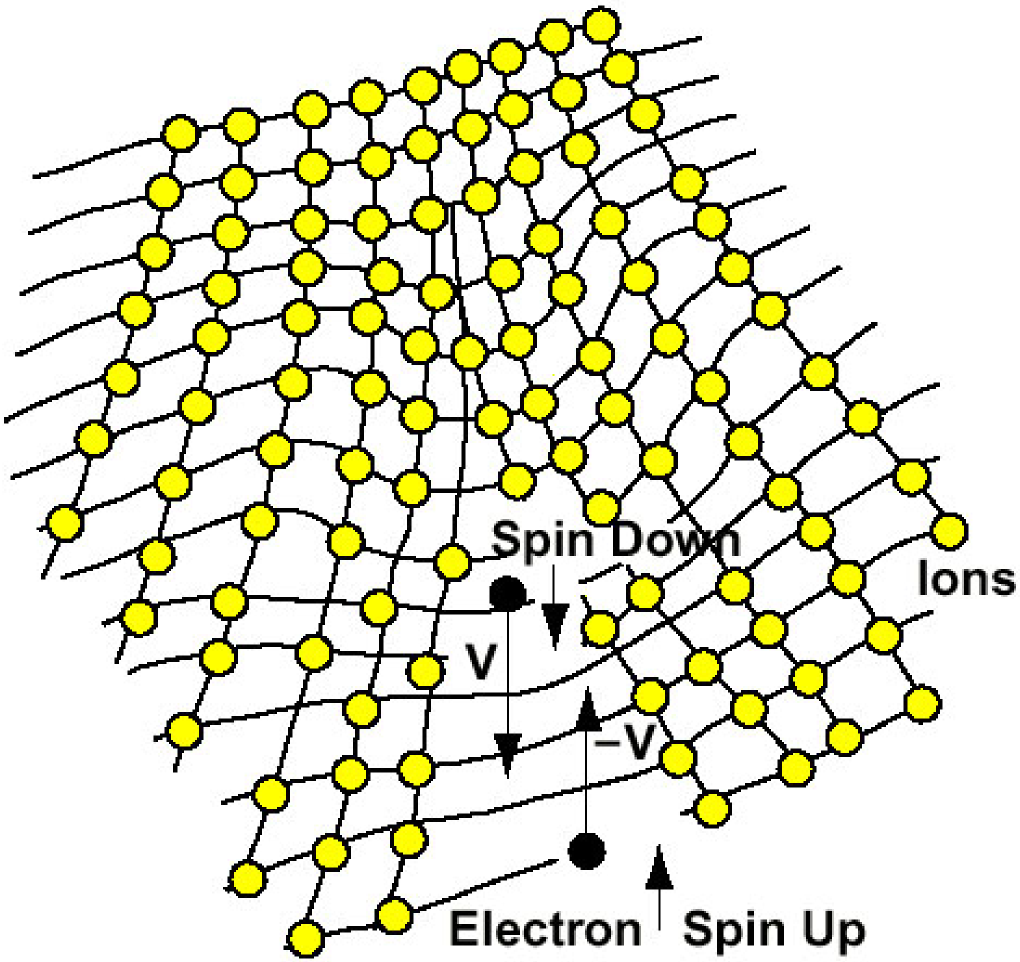




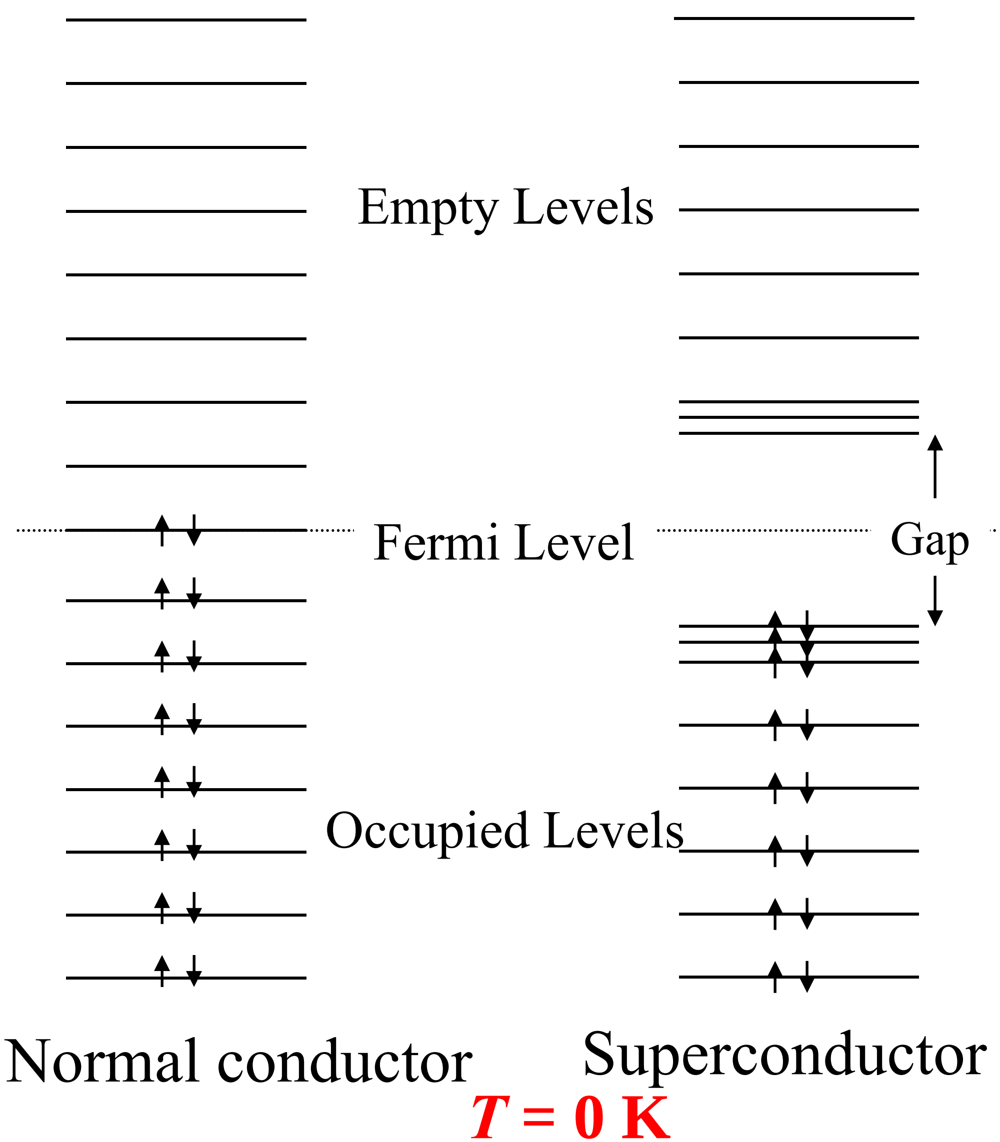
T = 0 K

Normal conductor

Electron-Phonon Interaction



Superconductivity



For $T > 0$K, have some excitation of "normal" electrons

$$n_{\mathrm{normal}} \propto \exp\left(-\frac{\Delta}{k_{\mathrm{B}}T}\right)$$

→ *Two Fluid Model*

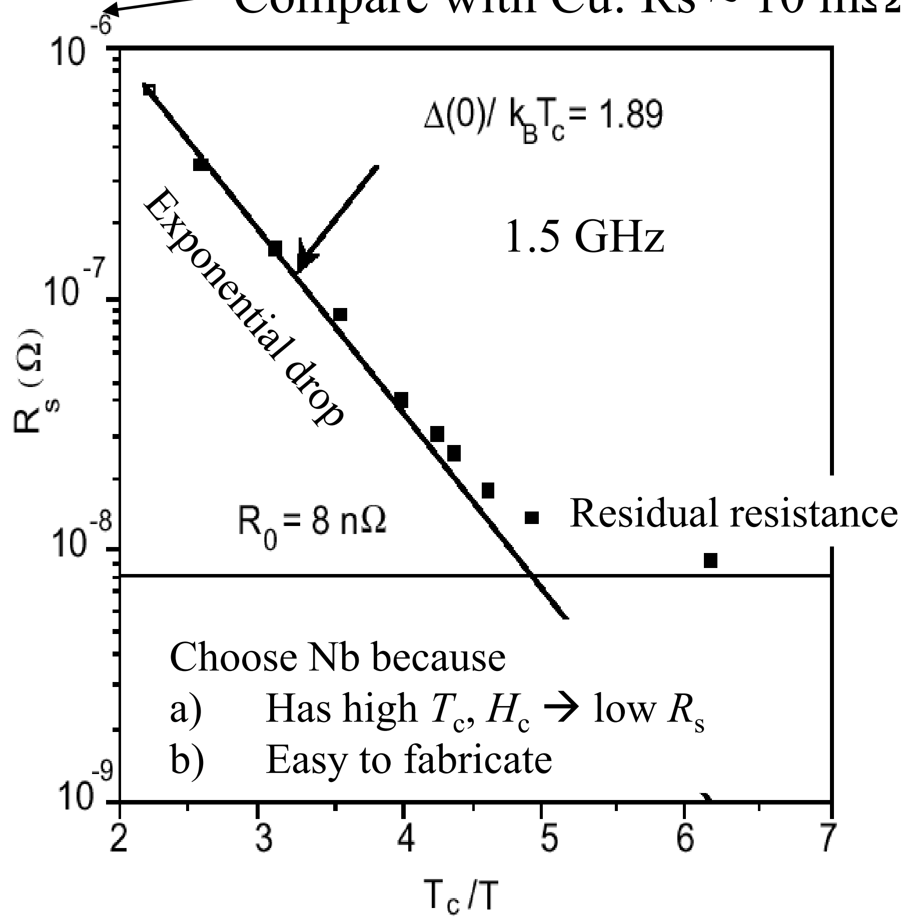
Simplified Explanation for Zero Resistance

- NC
  - Resistance to flow of electric current
  - Free electrons scatter off impurities, lattice vibrations (phonons)
- SC
  - Cooper pairs carry all the current
  - Cooper pairs do not scatter off impurities due to their coherent state
  - Some pairs are broken at T>0K due to phonon interaction
- But supercurrent component has zero resistance

Superconductors: RF Resistance

- DC resistance is zero because NC electrons are shorted out by SC ones.
- RF resistance small but finite because Cooper pairs have inertia → nc

Compare with Cu: Rs ~ 10 mΩ



$$R_s = A_s\omega^2 \exp\left(-\frac{\Delta(0)}{k_B T}\right)$$

More resistance the more the sc pairs are jiggled around

More resistance the more NC electrons are excited

Low Field Frequency and Temperature Dependence of Rs

$$R_s = A(\lambda_L, \xi_0, l)\ f^2\ e^{(-\Delta_0/kT)} \quad \text{for } T < 0.5\ Tc$$

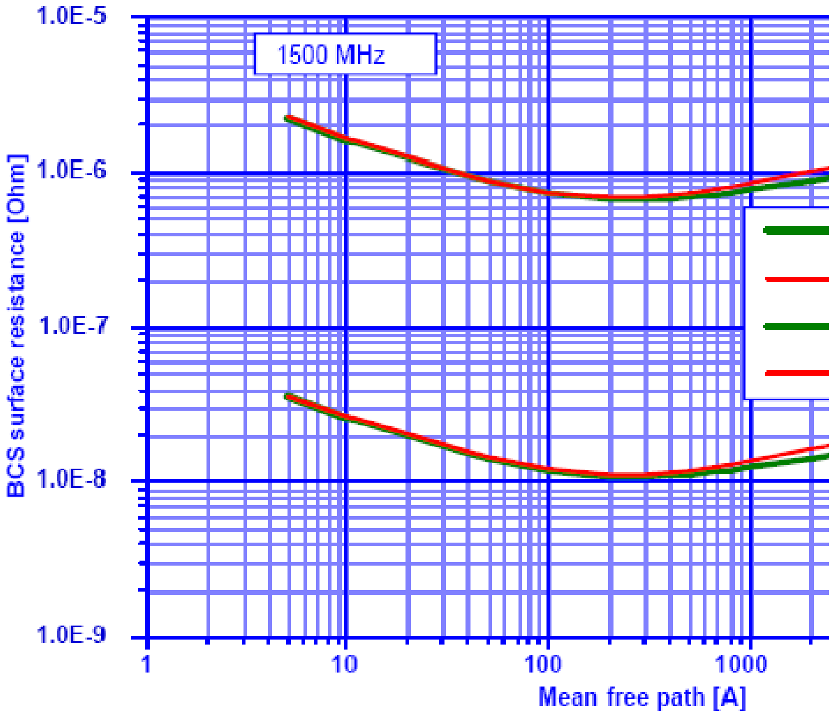
λ_L London penetration depth
ξ_0 Coherence length of Cooper pairs
v_F Fermi velocity
Δ_0 Energy gap
l electron mean free path
Tc = SC transition temperature

$$R_{bcs} = 3x\ 10^{-4} \left[\frac{f\,(\mathrm{GHz})}{1.5}\right]^2 \left(\frac{1}{T}\right) e^{-(17.67/T)}$$

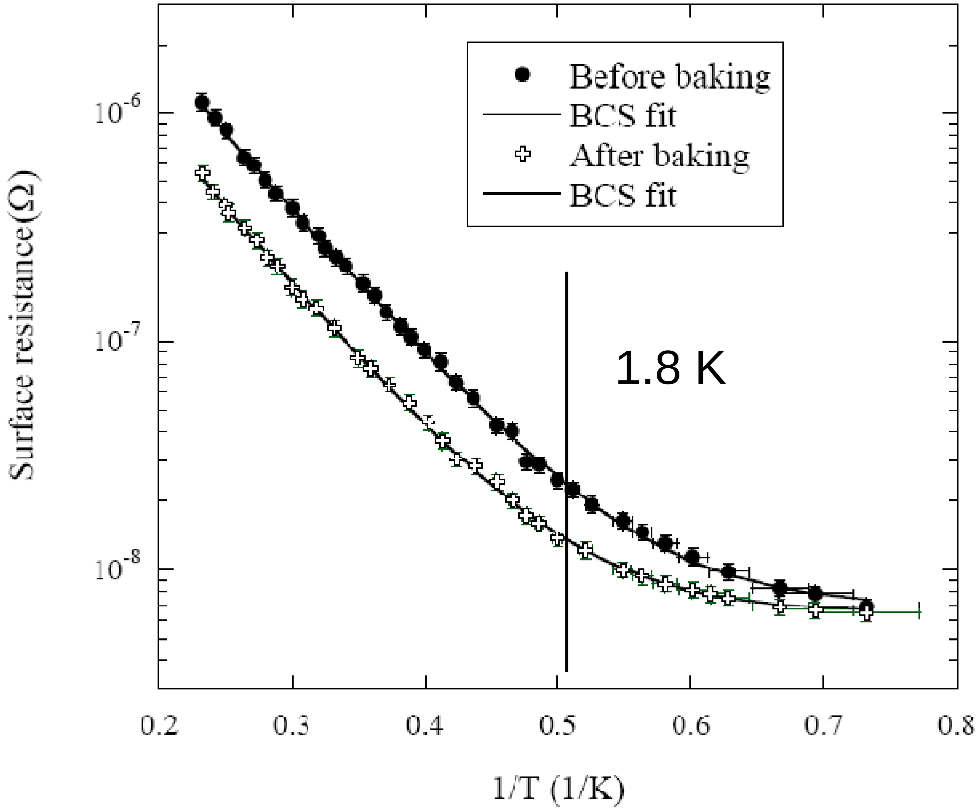
Good fitting function

Cavity Q_0

- 120 C bake
- Lowers electron mean free path and increases BCS Q



Kneisel et al



Ciovati et al

Superconducting Cavity

- Recalculate P_{diss} with SC Nb at 4.2 K, 1 MV, and 500 MHz.

$Q = 2 \times 10^9$ ($R_s \approx 15$ nΩ)

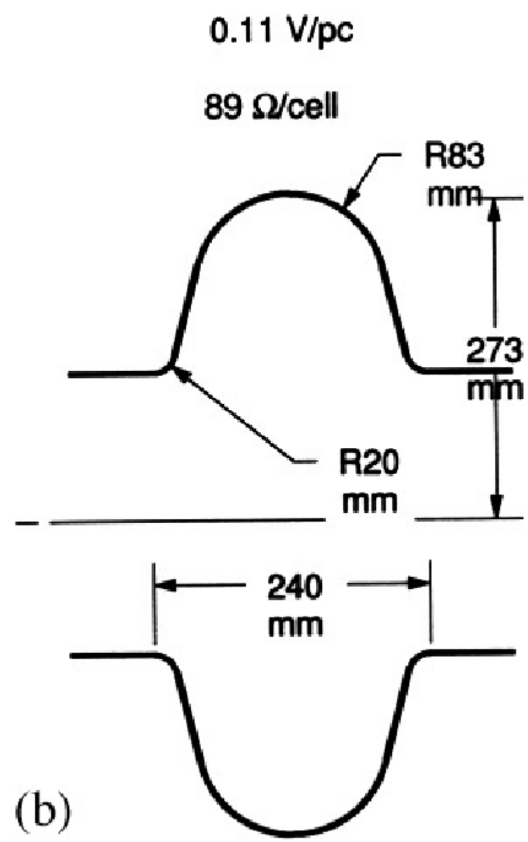
→ $R_a = 5.3 \times 10^{11}$

→ $P_{diss} = 1.9$ W!

→ $P_{ac} = 660$ W = AC power (Frig. efficiency = 1/350)

→ Include cryostat losses, transfer lines, etc.

→ P_{ac} increases, but is still 10-100 times less than that of Cu cavities.



Superconducting B-Factory Cell Shape

A challenge of the SC option is cryogenics

Refrigerator efficiencies are low

And one has to add other heat contributions from conduction, radiation, helium distribution.

Carnot efficiency of frig
and technical efficiency of frig machinery

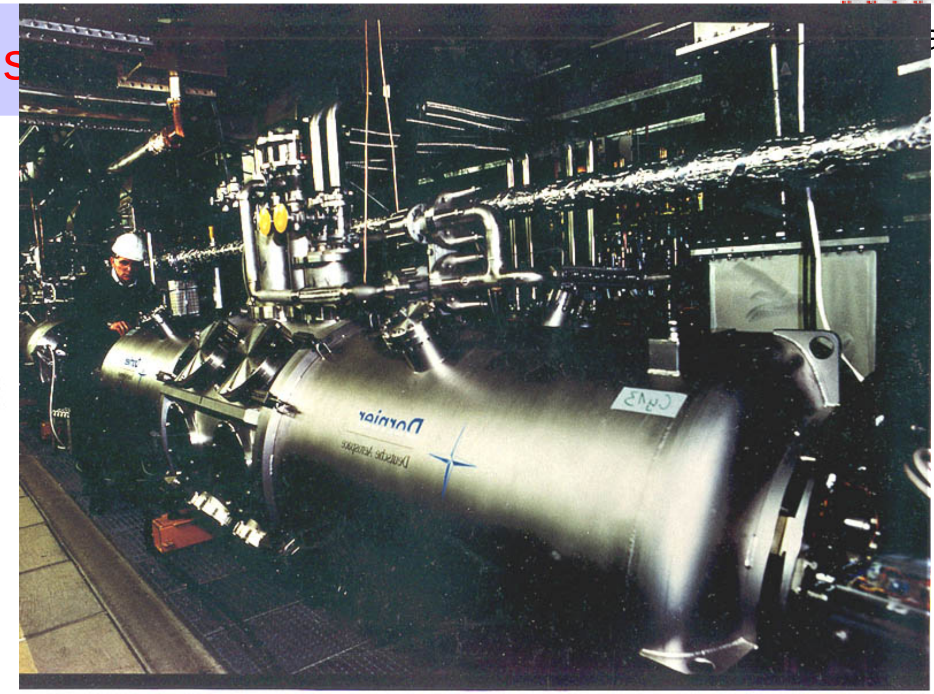
$$\eta_{Carnot} = \frac{4.5}{300 - 4.5} = 0.015$$

$$\eta_{technical} = 0.20$$

$$\eta_{total} = 0.003 = 1/333$$

SRF Requirements & Limitations

- Cryogenic system.



Real Estate Gradient lower than active gradient

(0.5 -> 0.7) Eactive
copper cavities 0.8 Eactive

Hi Tech:
Ultra-clean preparation and assembly required

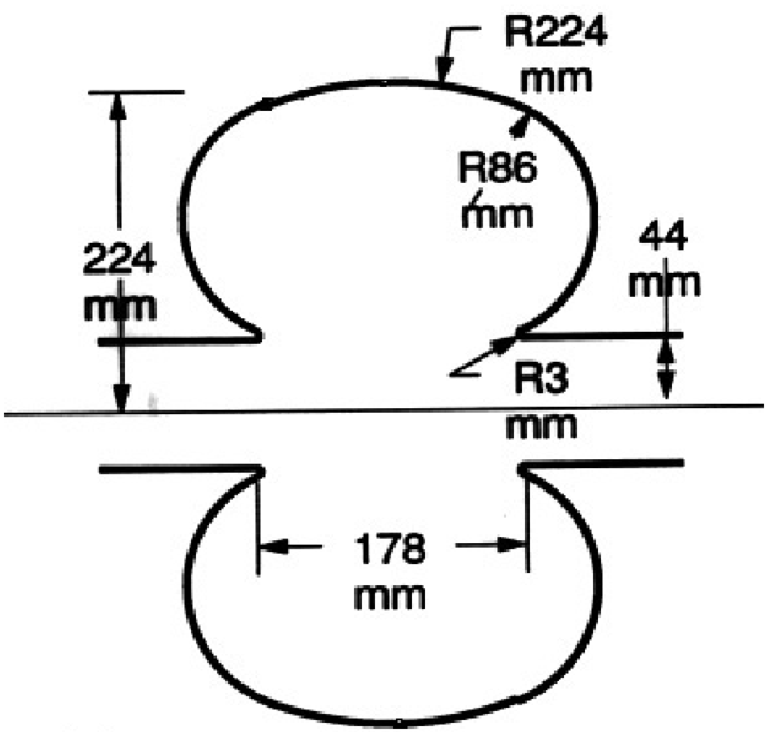
Max Eacc = 50 MV/m
More Later

SC Advantages

- Power consumption is much less → operating cost savings, better conversion of ac power to beam power.
- CW operation at higher gradient possible → Less klystron power required → capital cost saving
- Need fewer cavities for CW operation → Less beam disruption

Design Comparison

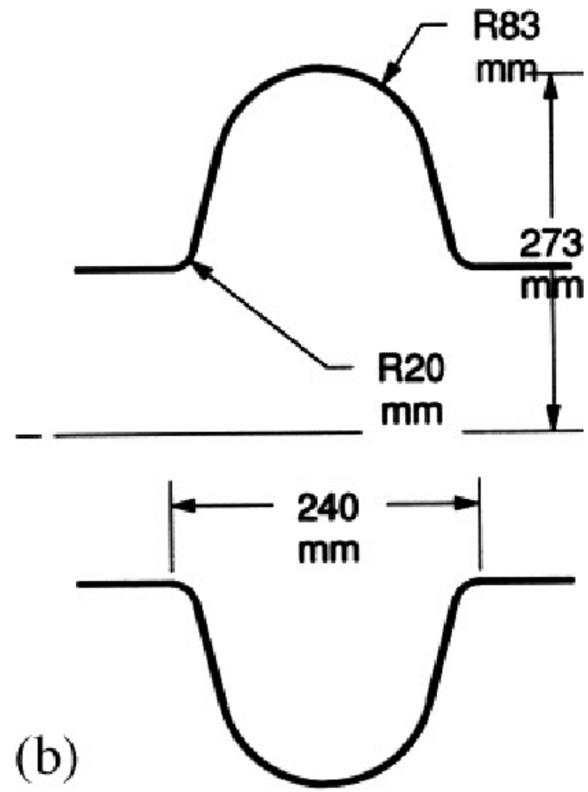
R/Q (fundamental) = 265 Ω/cell



Copper cavity shape

0.11 V/pc

89 Ω/cell



Superconducting
B-Factory Cell Shape

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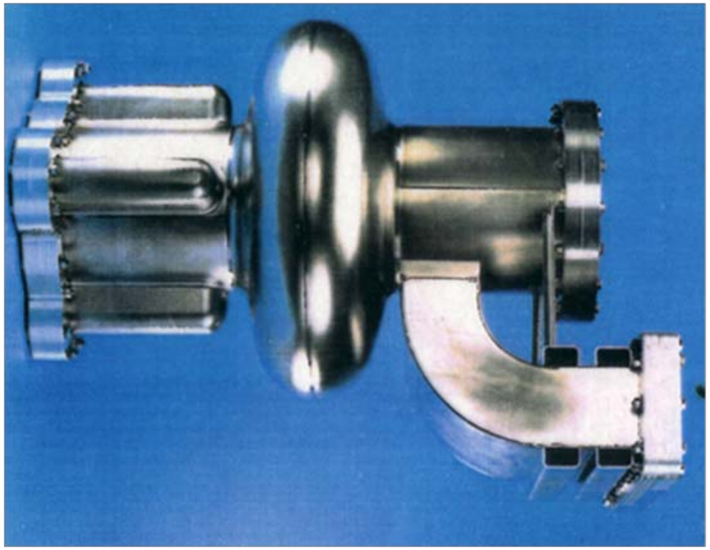
CW RF Cavities for Storage Rings


Copper Cavity: PEP-II

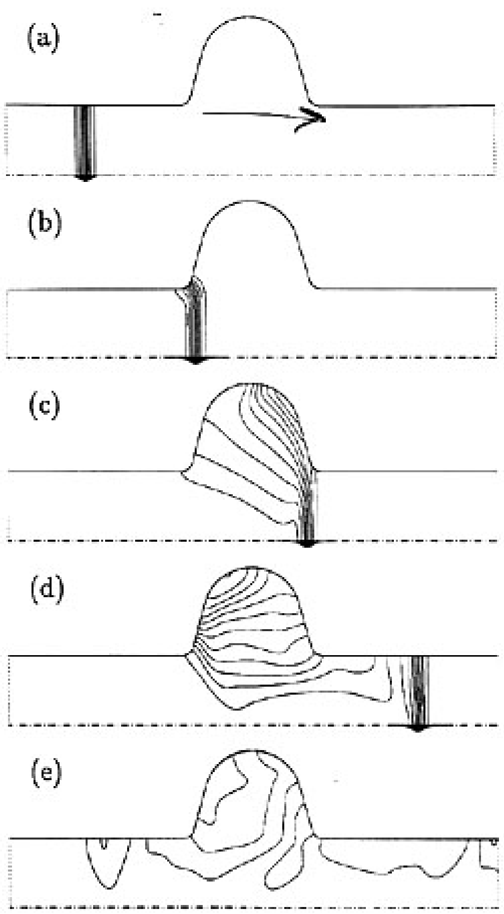


Superconducting Cavity:
CESR-III

Fundamental differences due to difference in wall losses

(Some) Further SC Advantages

- Freedom to adapt design better to the accelerator requirements allows, for example, the beam-tube size to be increased:
  - Reduces the interaction of the beam with the cavity (scales as size^3) → The beam quality is better preserved (important for, e.g., FELs).
  - HOMs are removed more easily → better beam stability → more current accelerated (important for, e.g., B-factories)
  - Reduce the amount of beam scraping → less activation in, e.g., proton machines (important for, e.g., SNS, Neutrino factory)



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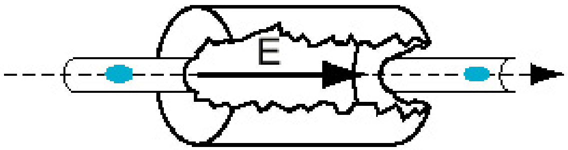
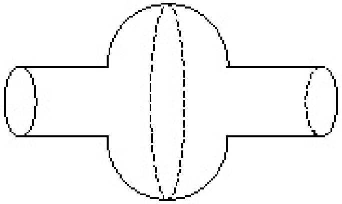
Additional Design Aspects for Multi-cell Cavities

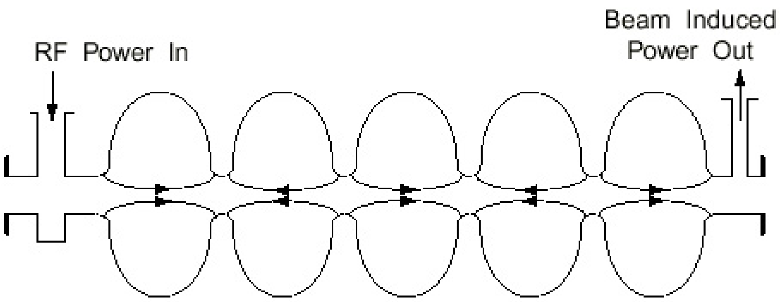


(a)

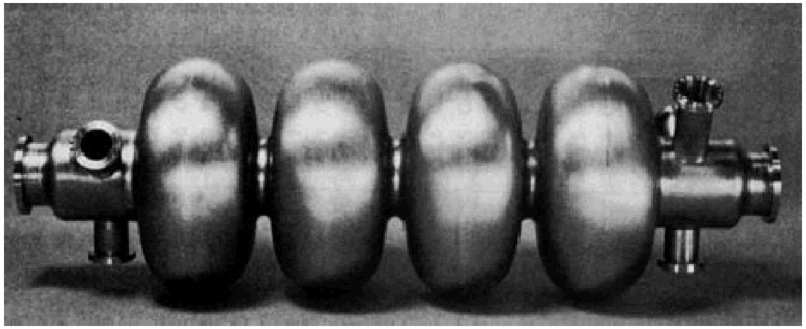


(b)

Standing Wave Mode

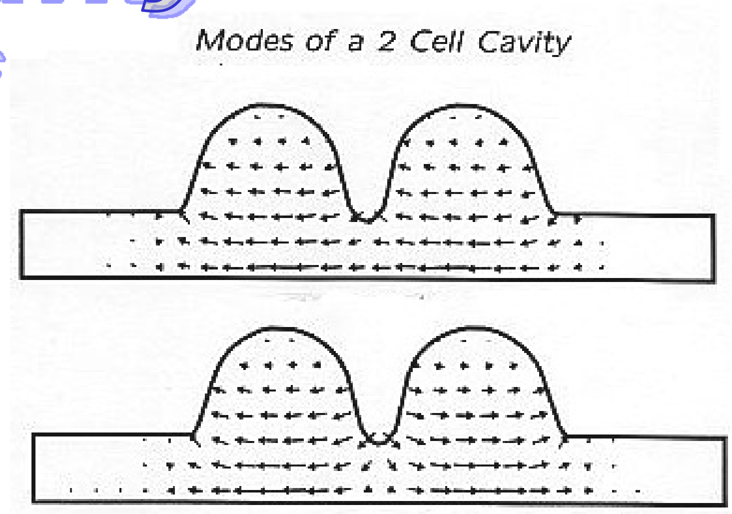


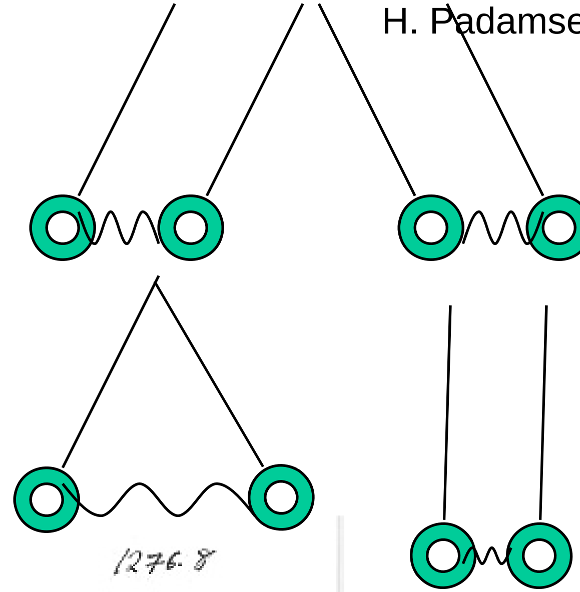
(c)



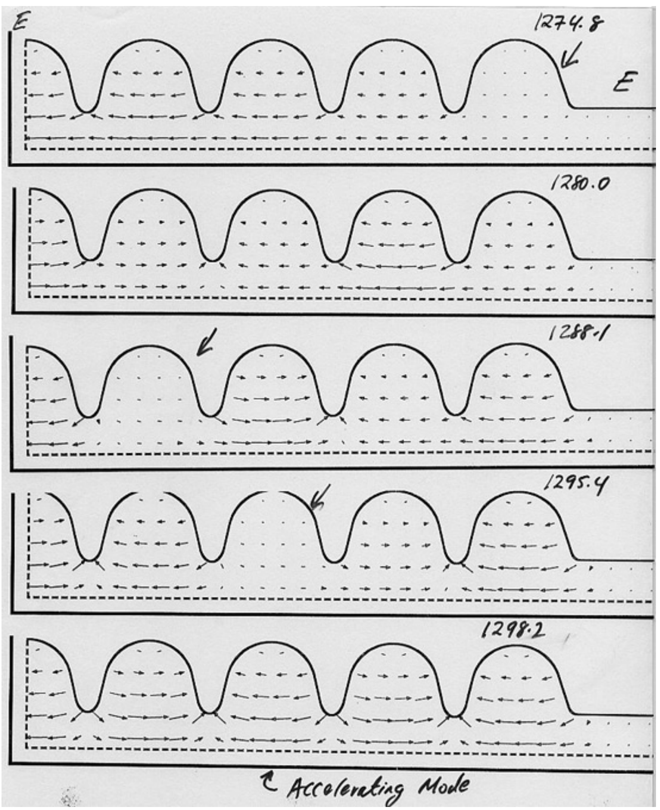
Multicell Cavity Modes

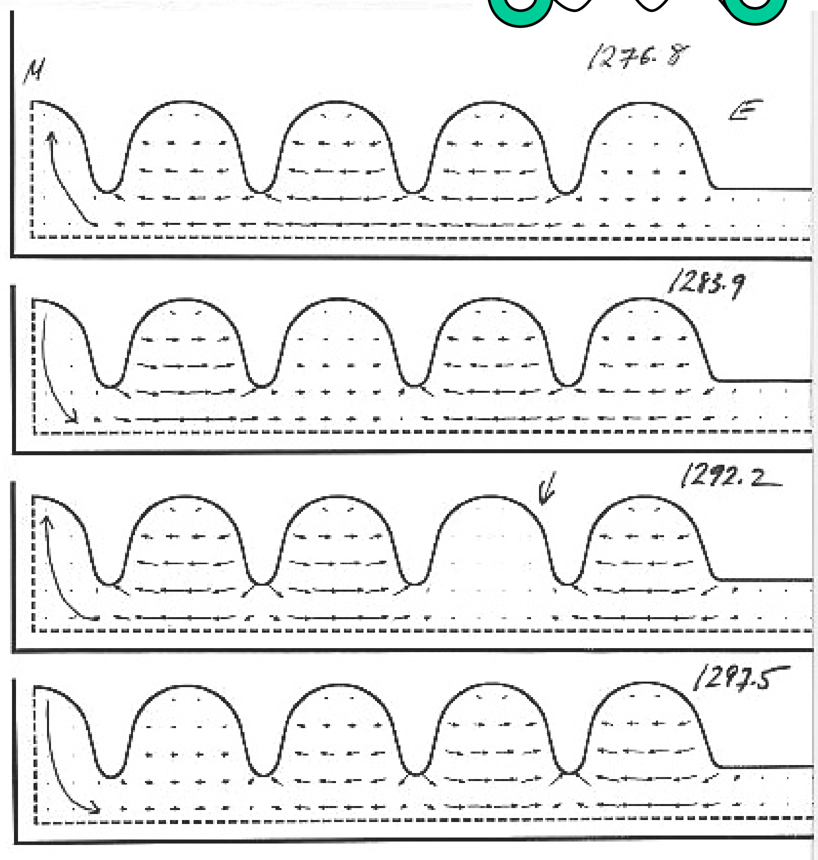
H. Padamsee



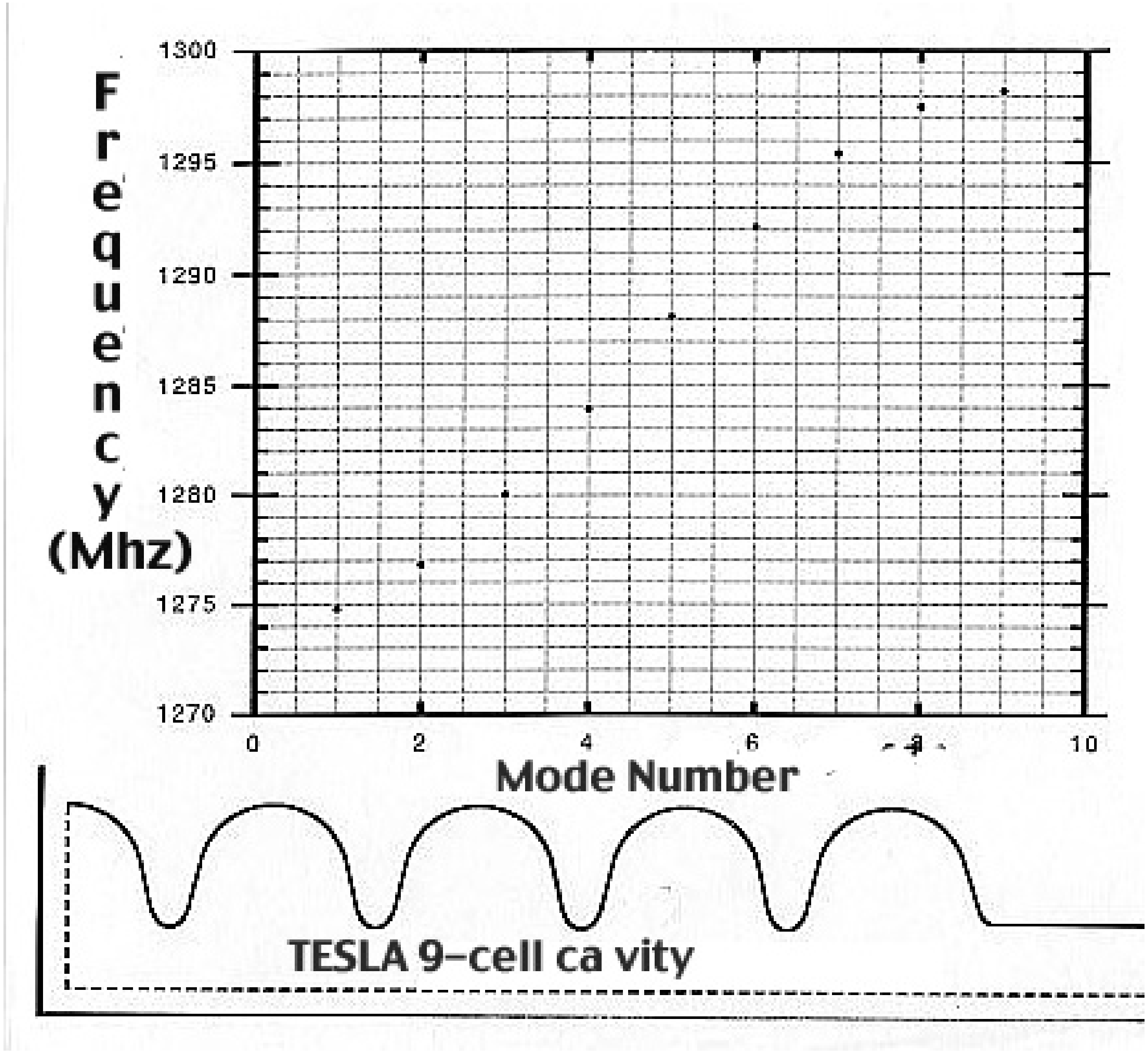


9-cell cavity

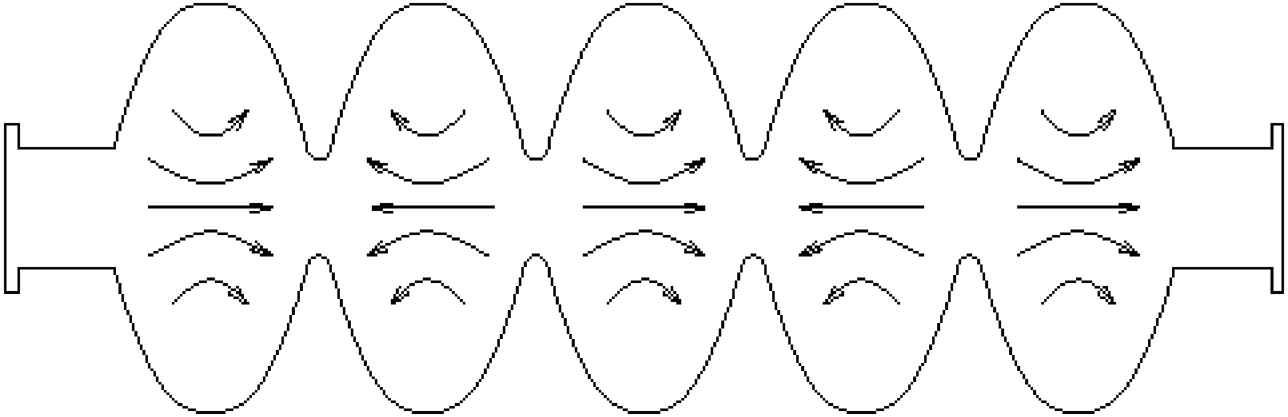




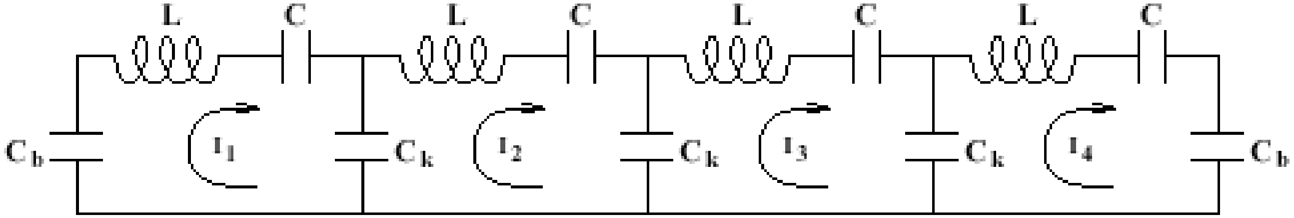
Dispersion Relation



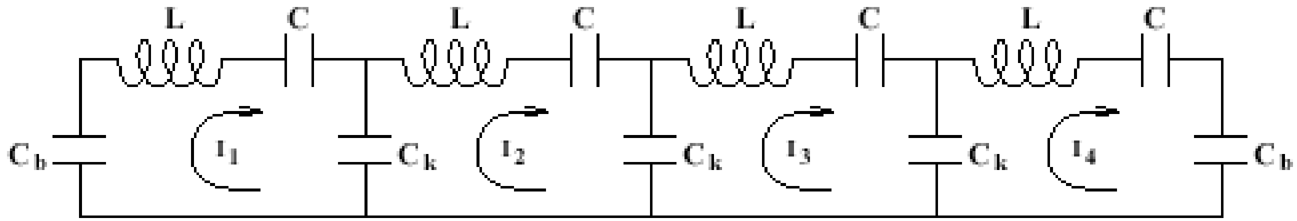
Circuit Model of MultiCells



: Sketch of the electric field lines of the π-mode of a 5-cell



Equivalent circuit for a 4-cell cavity with beam tubes.



define $\omega_0^2 = 1/LC$, $k = C/C_k$, $\gamma = C/C_b$,

Solve the circuit equations for mode frequencies

Dispersion Relation

$$\left(\frac{f_m}{f_0}\right)^2 = 1 + 2k\left[1 - \cos\left(\frac{m\pi}{N}\right)\right]$$

If we measure $f^{(N)}$ and $f^{(1)}$, this becomes

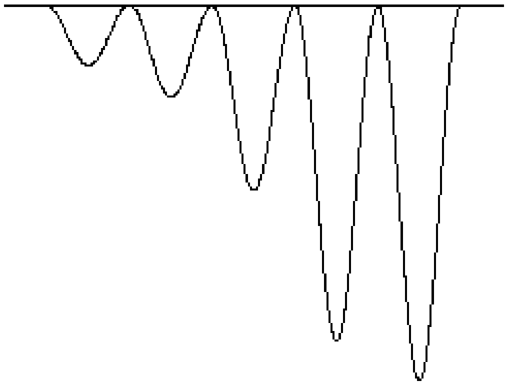
$$k = \frac{\frac{1}{2}\left[\left(f^{(N)}\right)^2 - \left(f^{(1)}\right)^2\right]}{2\left(f^{(1)}\right)^2 - \left(f^{(N)}\right)^2\left[1 - \cos\left(\pi/N\right)\right]}.$$

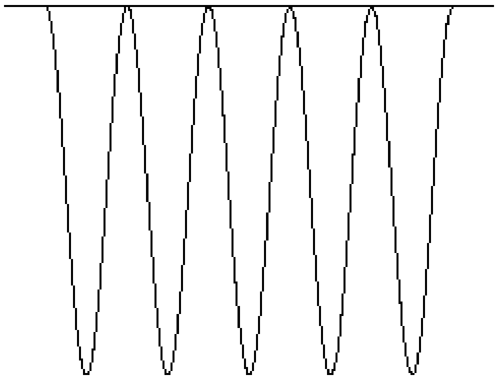
Mode spacing increases with stronger cell to cell coupling k

Mode spacing decreases with increasing number of cells N

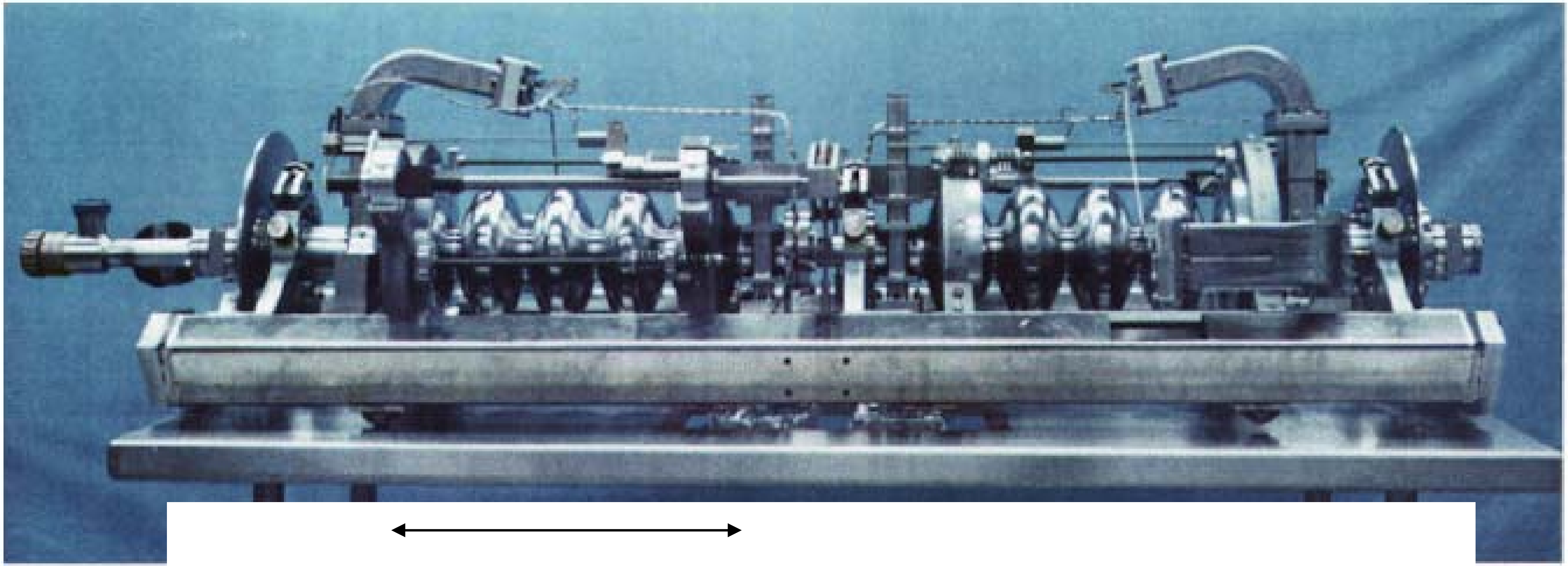
Field Flatness

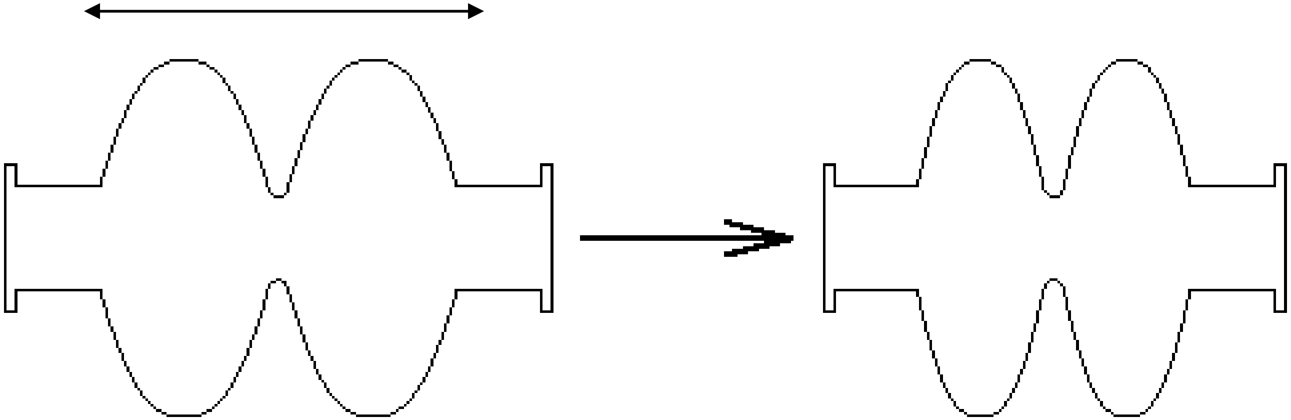
- Stronger cell-to-cell coupling (k) and smaller number of cells N means
  - Field flatness is less sensitive to mechanical differences between cells





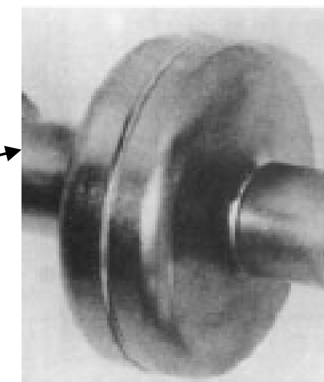
Tuning for Right Frequency and Field Profile

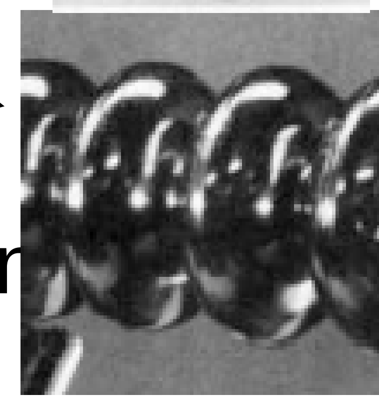


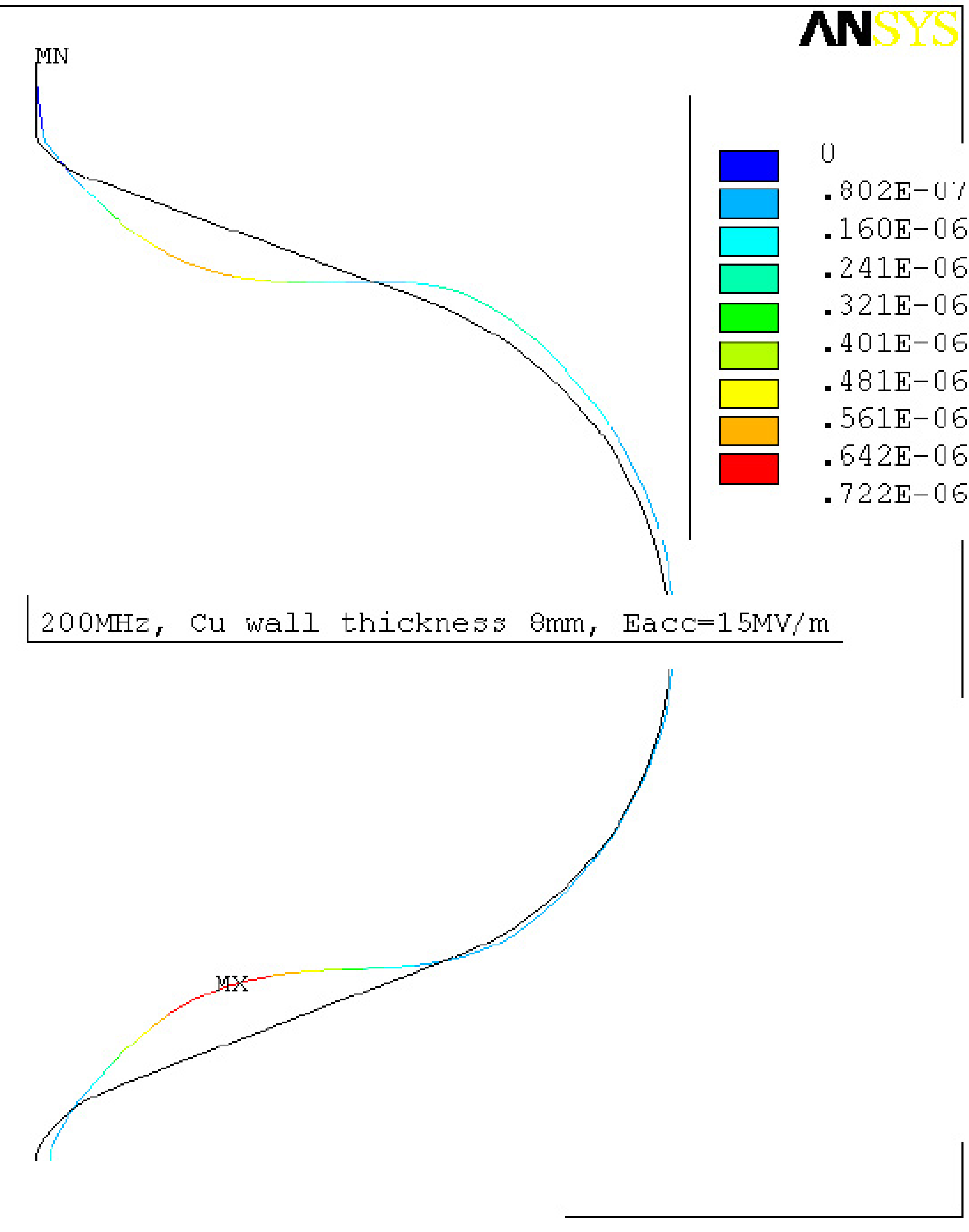


In Addition to EM Properties Mechanical Properties Are Also Important to Cavity Design

- Cavity should not collapse or deform too much under atmospheric load
- Shape
  - avoid flat regions
  - Elliptical profile is stronger
- Choose sufficient wall thickness
- Use tuner to bring to right frequen






ANSYS
MN
MX
0
.802E-07
.160E-06
.241E-06
.321E-06
.401E-06
.481E-06
.561E-06
.642E-06
.722E-06
200MHz, Cu wall thickness 8mm, Eacc=15MV/m

Detuning, Problem for pulsed operation as for TESLA

LORENTZ FORCE DETUNING

The rf magnetic field in a cavity interacts with the rf wall current resulting in a Lorentz force which can become important at high accelerating fields
The radiation pressure,

$$P_{\rm L} \propto \mu_0 H^2 - \epsilon_0 E^2,$$

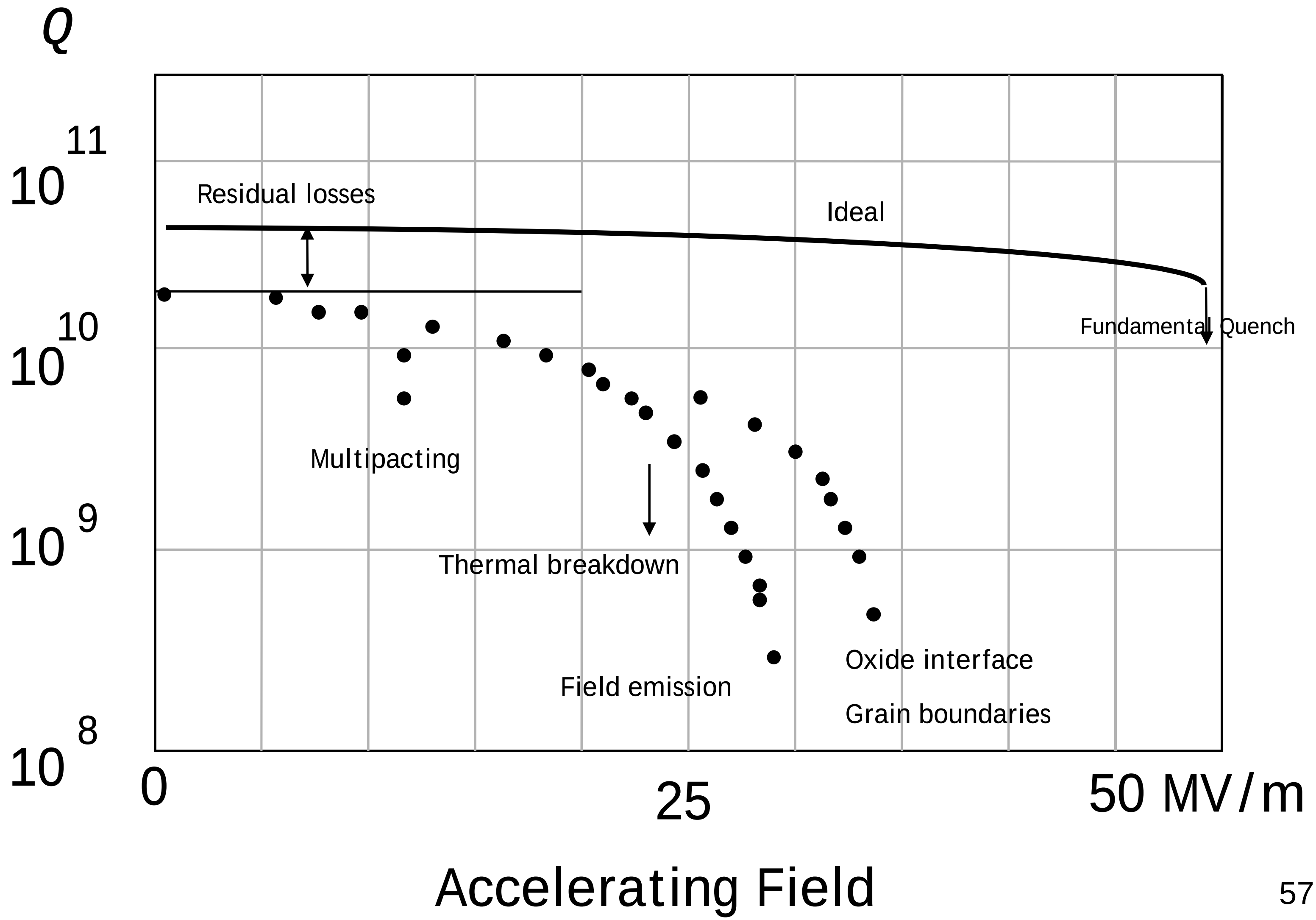
causes a small deformation of the cavity shape resulting in a shift of the cavity resonant frequency:

$$\Delta f \propto (\epsilon_0 E^2 - \mu_0 H^2)\Delta V.$$

Here ΔV is the change in the volume of the cavity region that is undergoing deformation. The typical coefficient is a few $\mathrm{Hz/(MV/m)^2}$.

Cavity Performance Characterization

Most Important : Q vs E curve

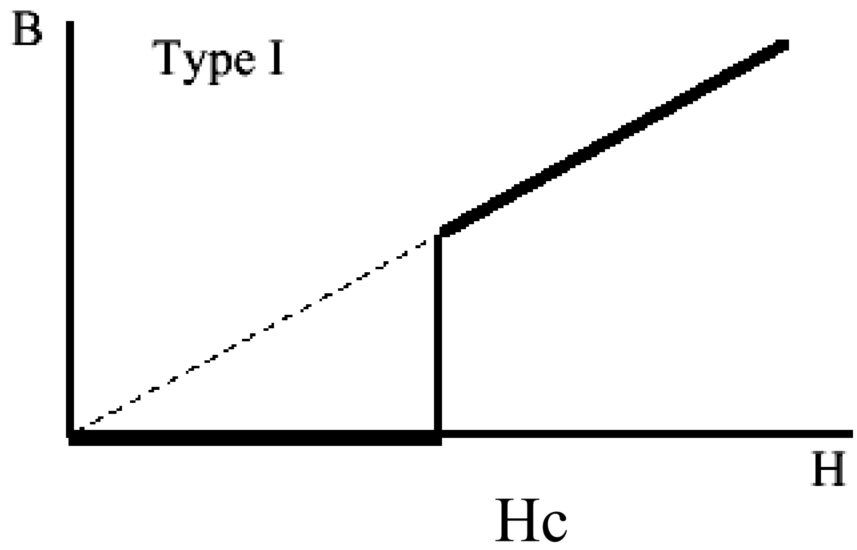


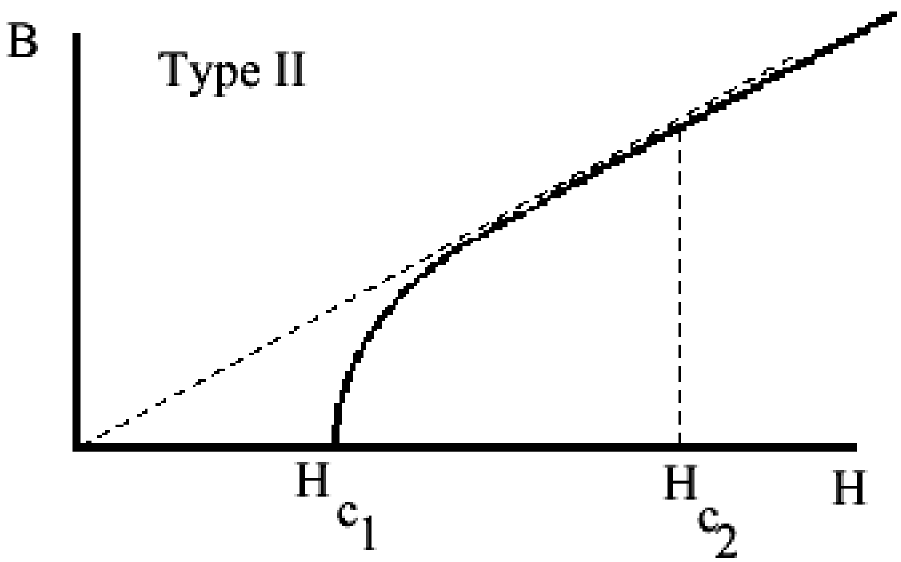
Critical Fields

- Superconductors only remain in the superconducting state if the applied field is less than the critical magnetic field H_c (2000 Oe for Nb for DC)
- But! Phase transition requires some time (1 μs?) to nucleate sc-nc transition.
- → For RF can exceed H_c up to the superheating field.

For typical $v = c$ cavities this is achieved at an accelerating field of $E_{acc} \approx 50$ MV/m.

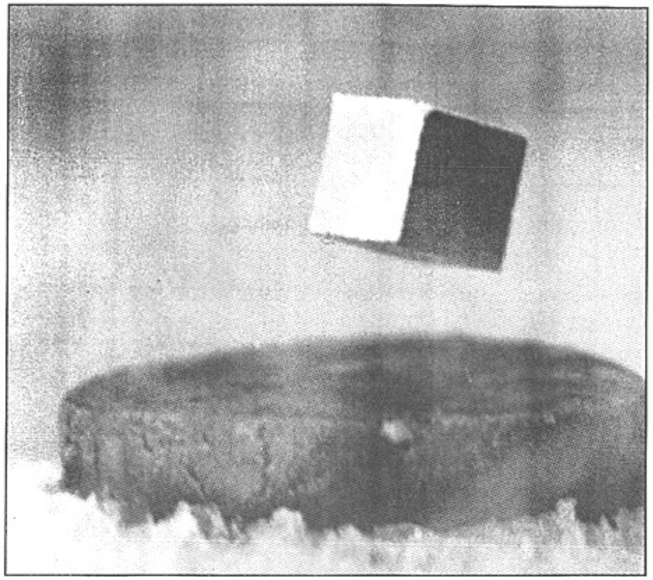
DC Critical Magnetic fields

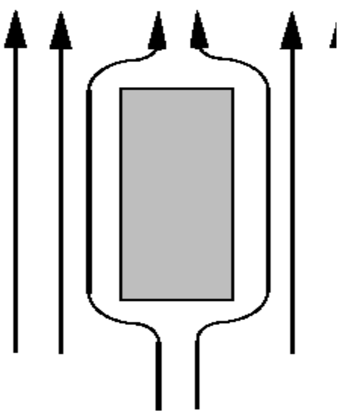


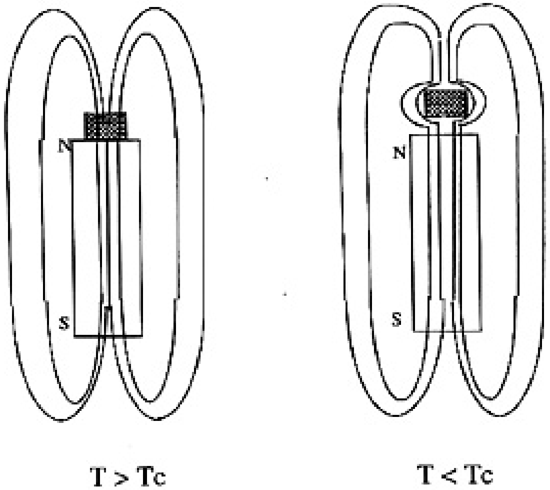


Meissner Effect

- Magnetic fields are screened by surface currents in the SC → perfect diamagnetism
- SC goes normal conducting when the energy needed for shielding exceeds that gained by being superconducting.





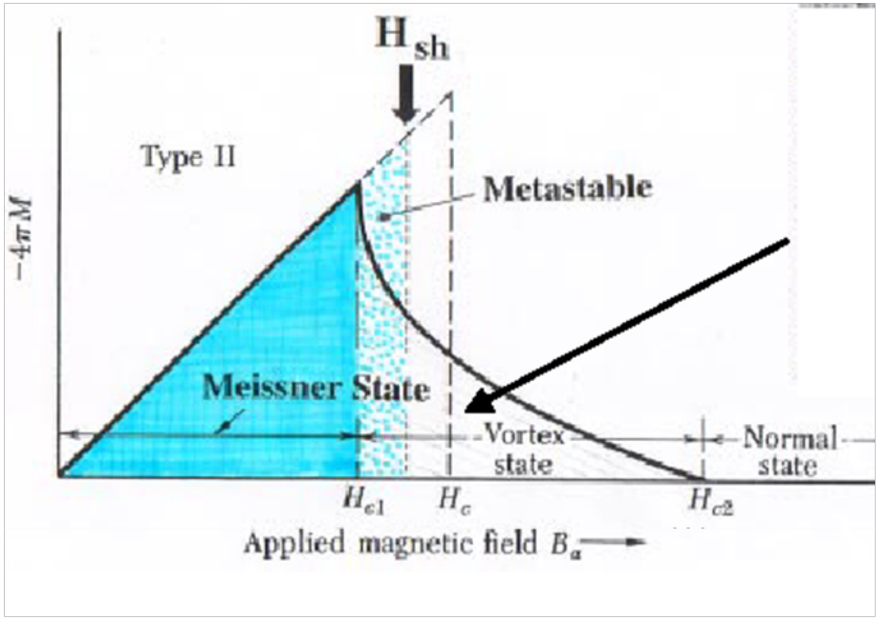


Levitation by Meissner Effect

Critical RF Magnetic Field

- What is the relationship between the RF critical magnetic field and the familiar DC critical magnetic fields?
- Is Hrf
  - H_{c1}, H_c, H_{sh}?
  - How does it depend on temperature?
  - How does it depend on
    - Ginzburg-Landau parameter $\kappa = \lambda/\xi$?
  - Nb: $\kappa \sim 1$, Nb3Sn: $\kappa \sim 20$..

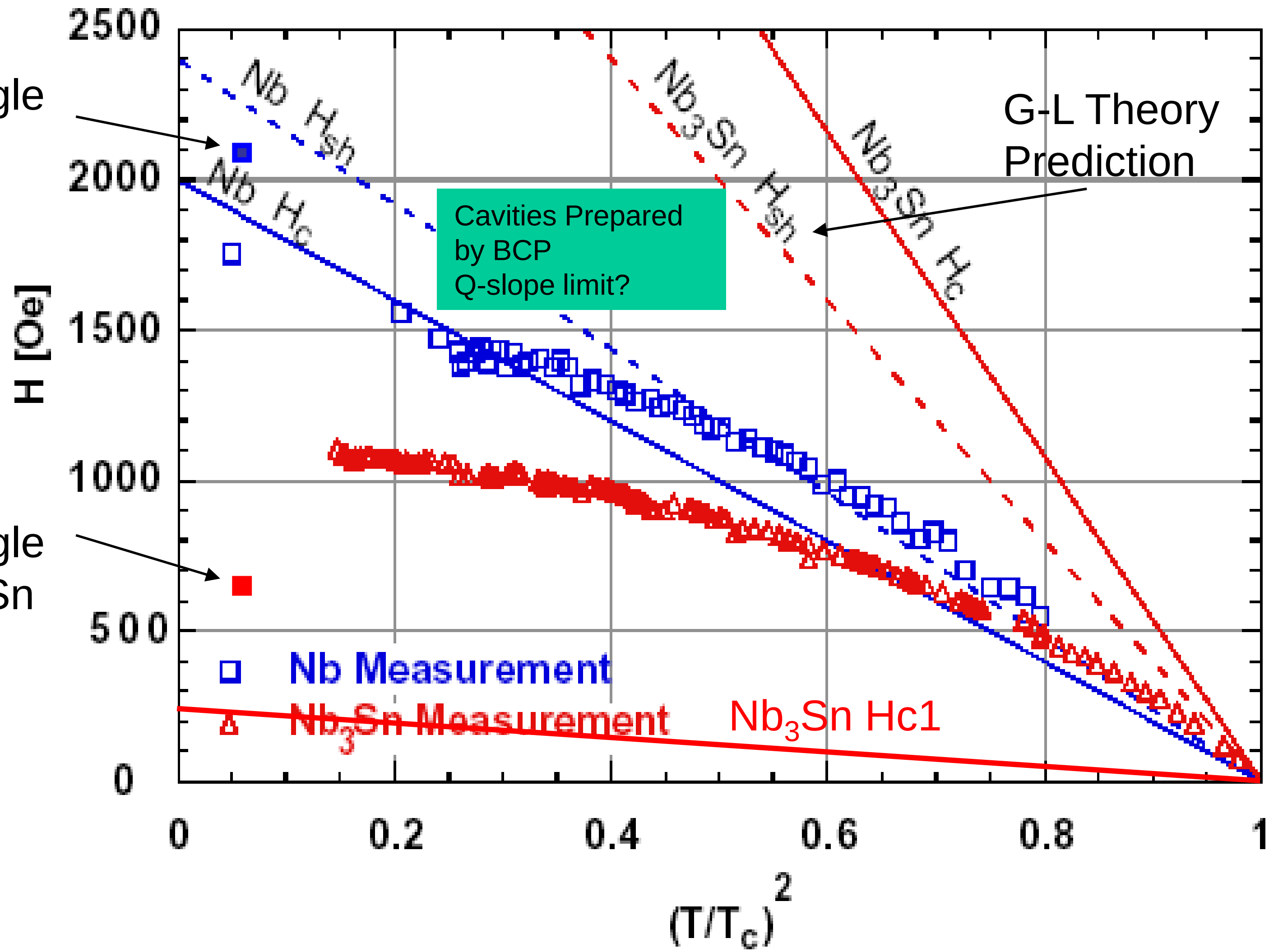
DC Critical Fields



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

Best single cell Nb cavity result

Best single cell Nb_3Sn cavity result



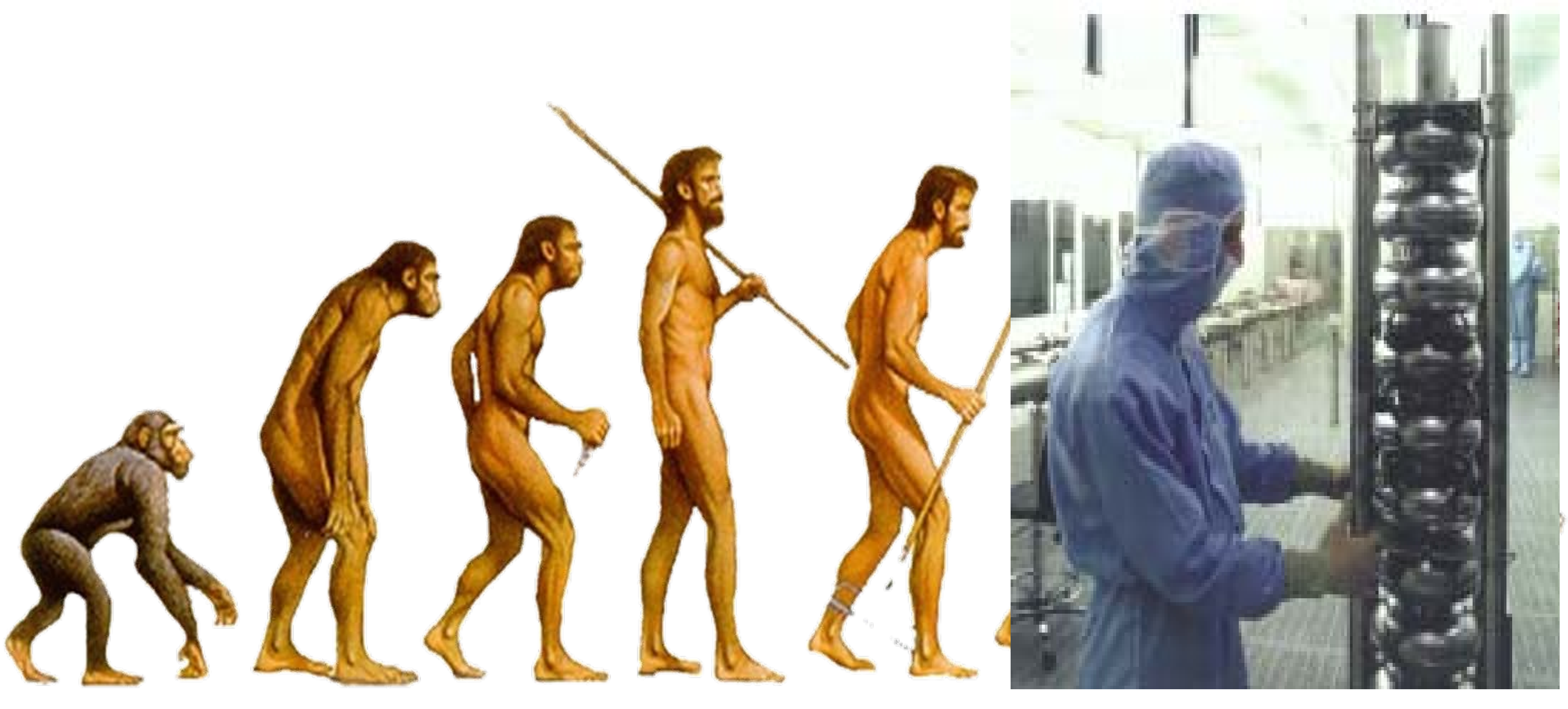
Theoretical RF Electric Field

- No known theoretical limit
- In SC test cavities, SC survives up to
  - Epk = Pulsed 220 MV/m
  - 145 MV/m CW over cm^2 area
- Single cell 1300 MHz accelerator cavity to Epk = 120 MV/m, CW (55 x 2.2)

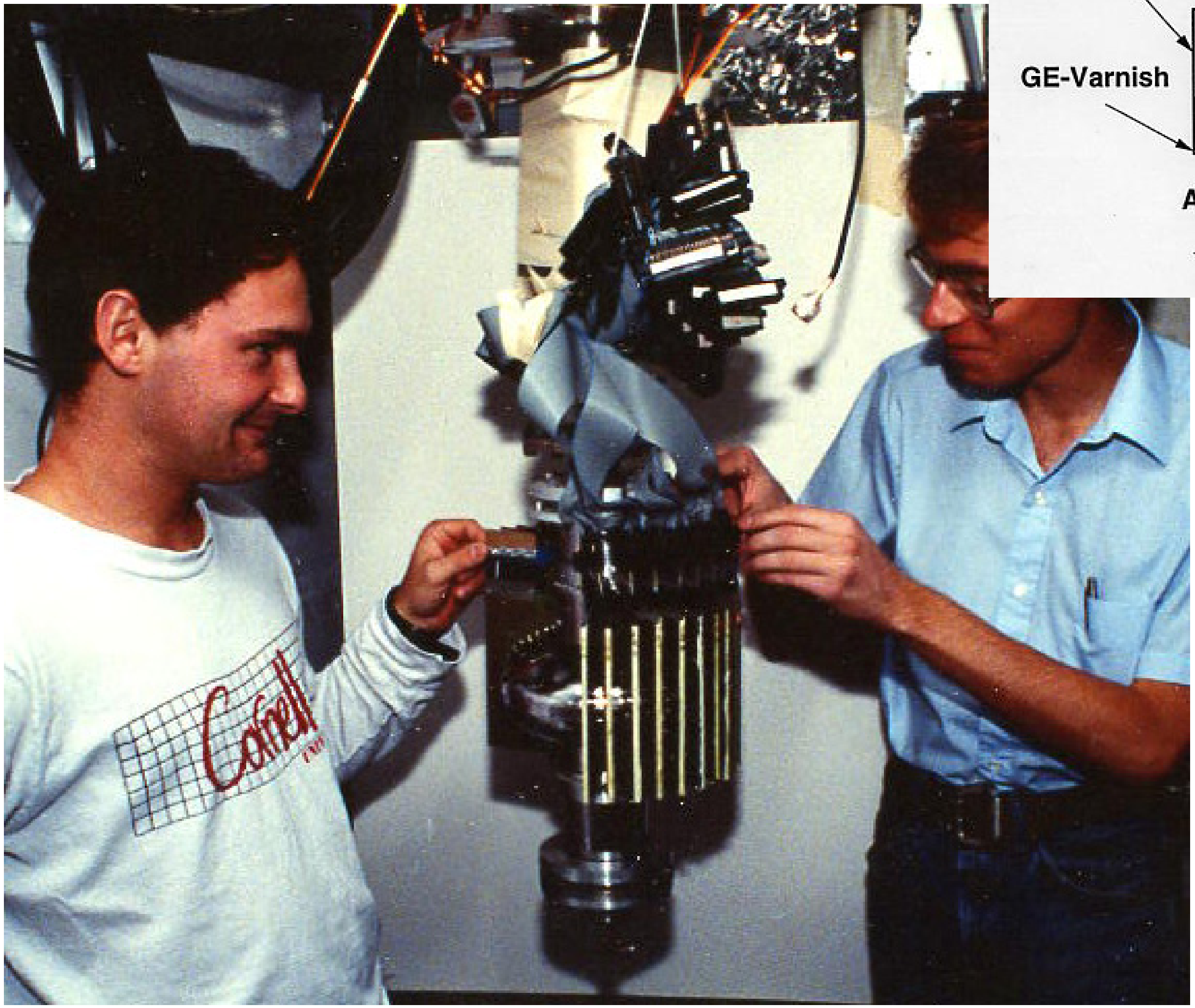
Evolution of Cavity Gradients (1970 – 2009)

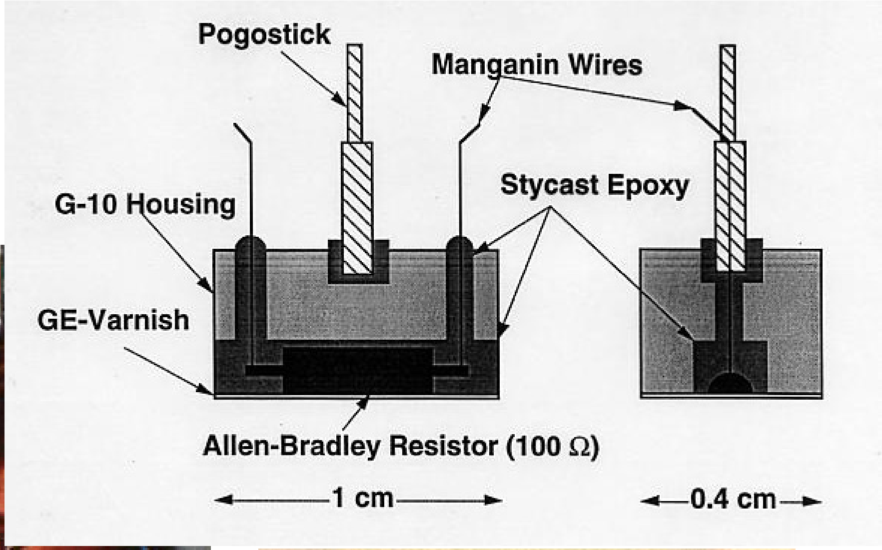
And SRF Technology Over 4 Decades

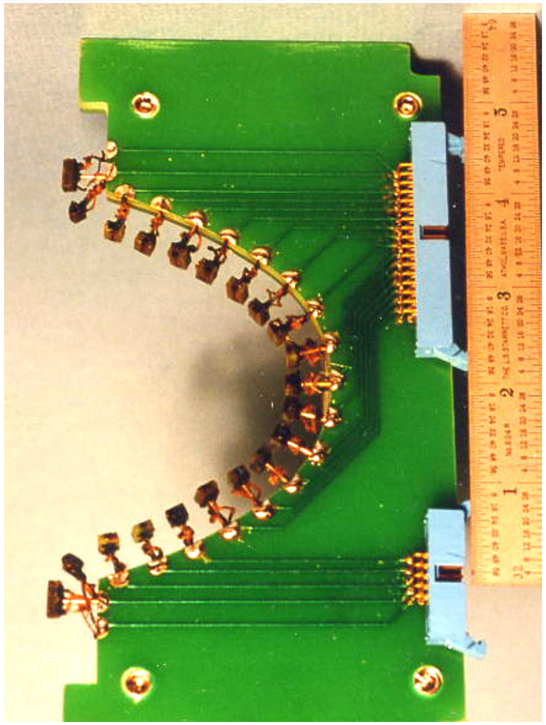
Steady progress in Gradients due to basic understanding of limiting phenomena and invention of effective cures



Thermometry Has Been the Key

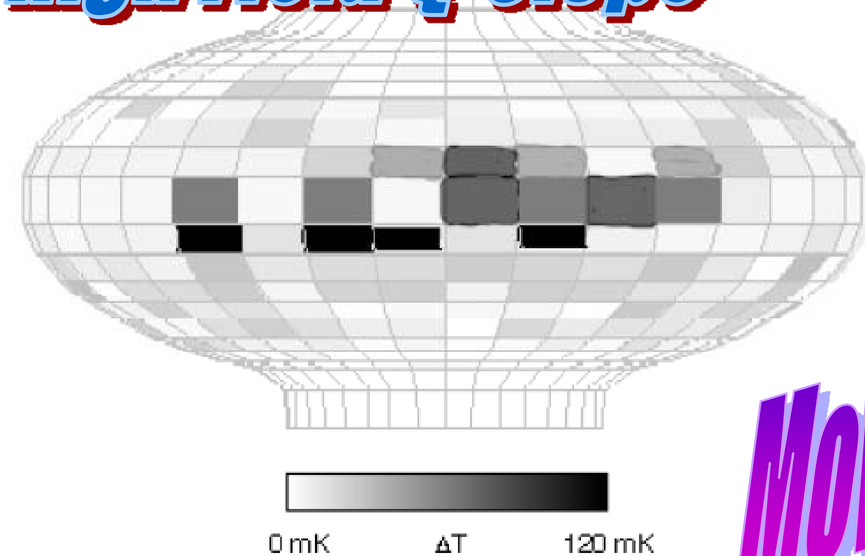




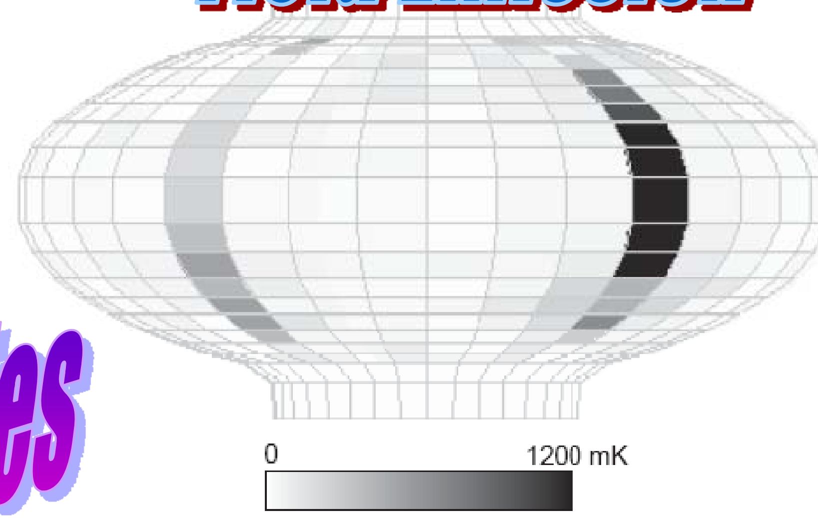


Temperature Maps Reveal Inner Life of Cavity

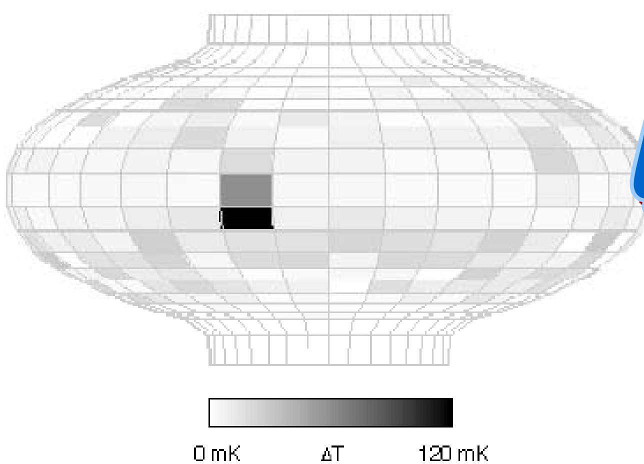
High Field Q-Slope



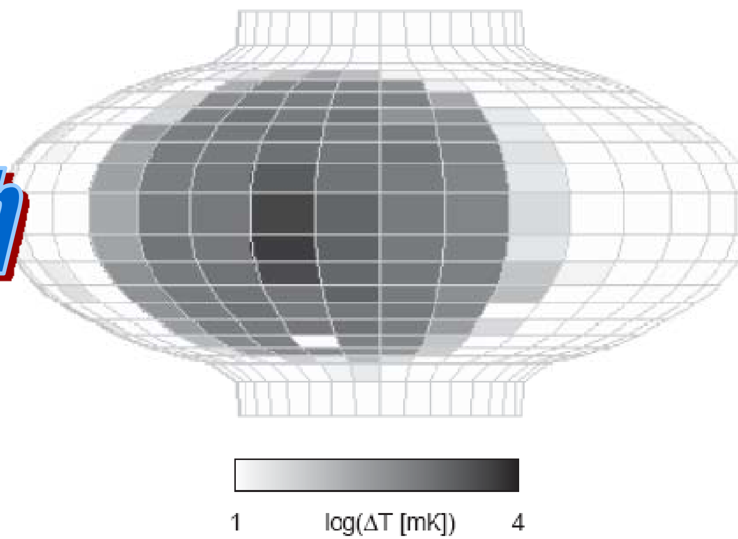
Field Emission



Movies

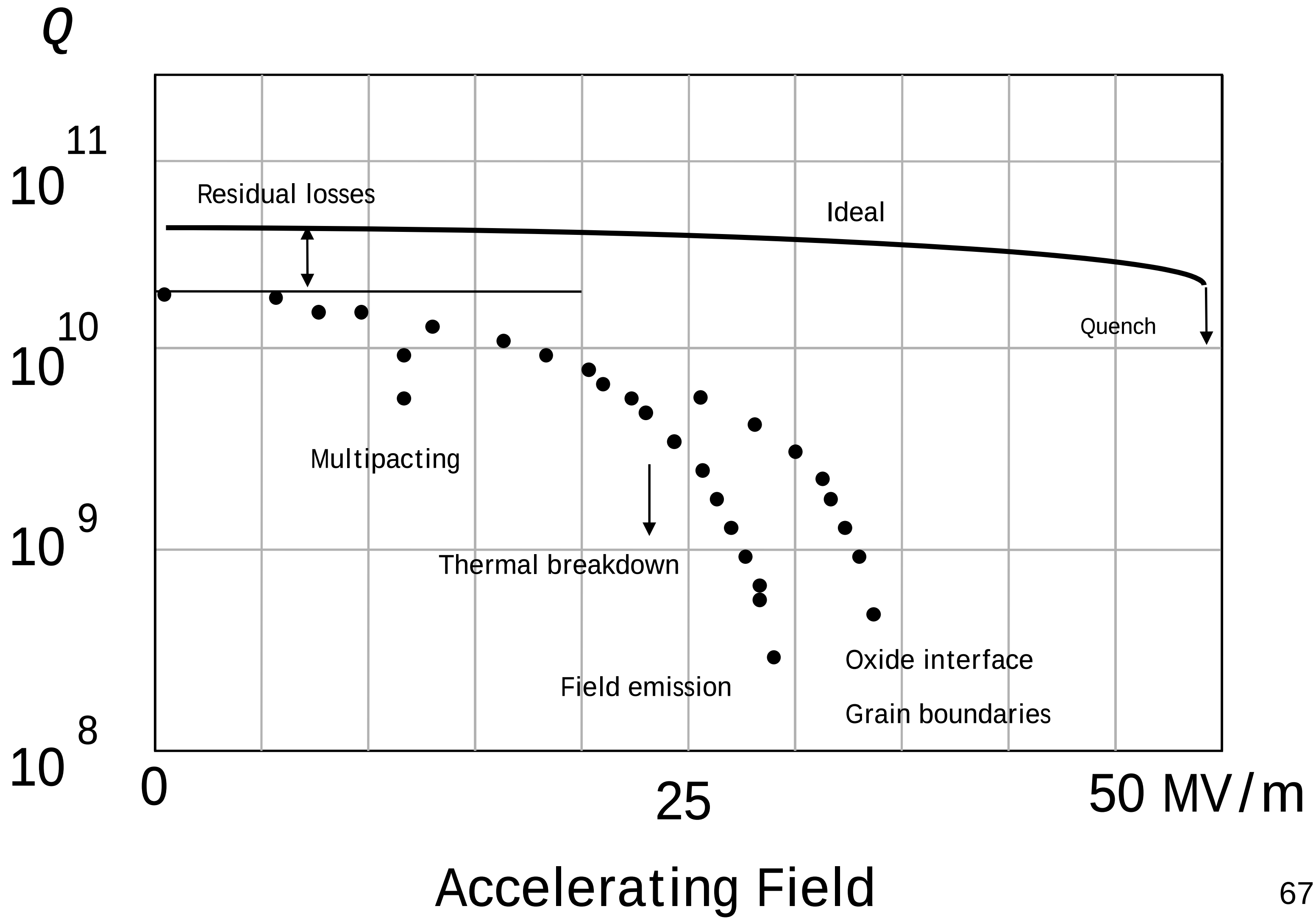


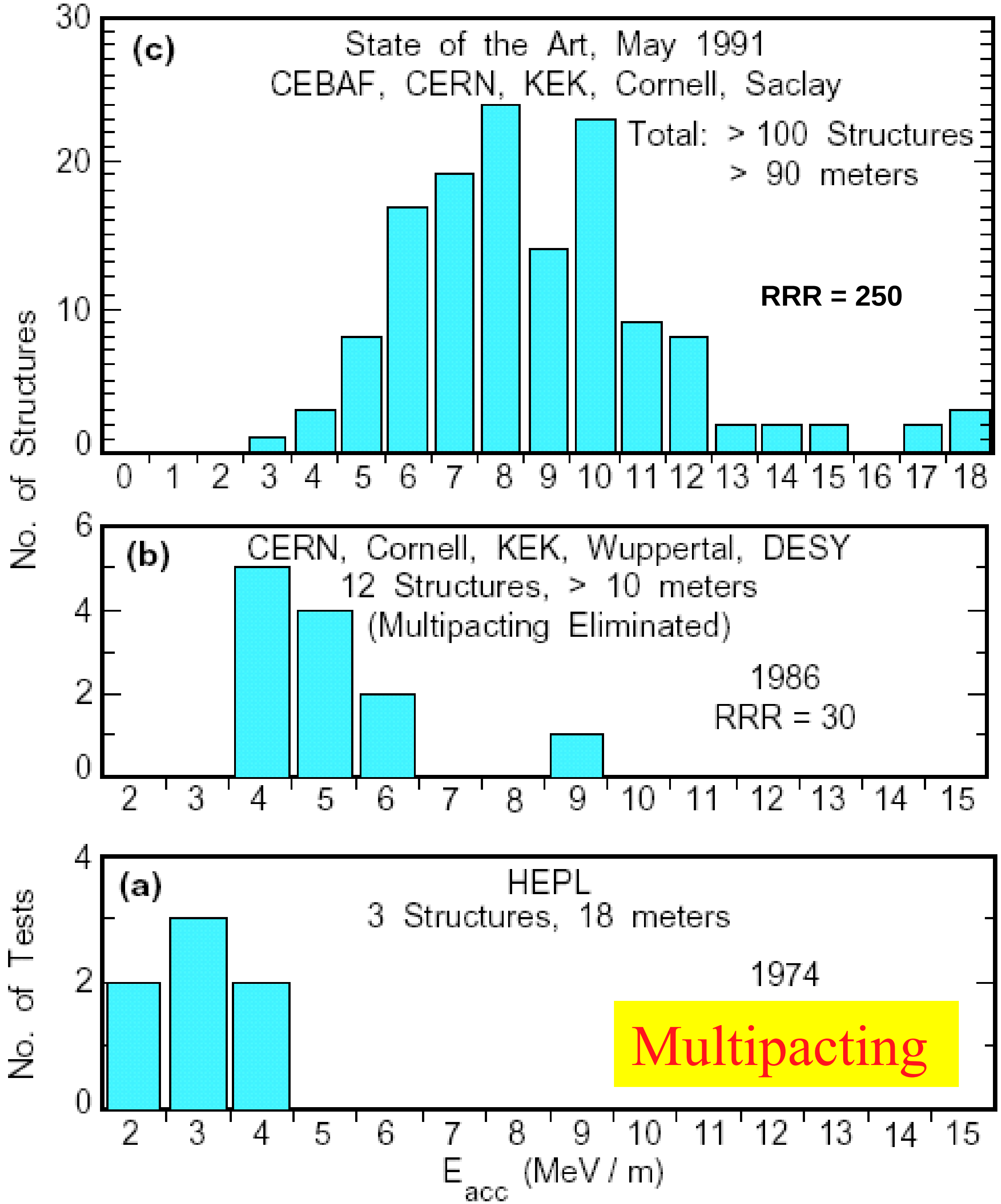
Quench



Cavity Performance Characterization

Most Important : Q vs E curve

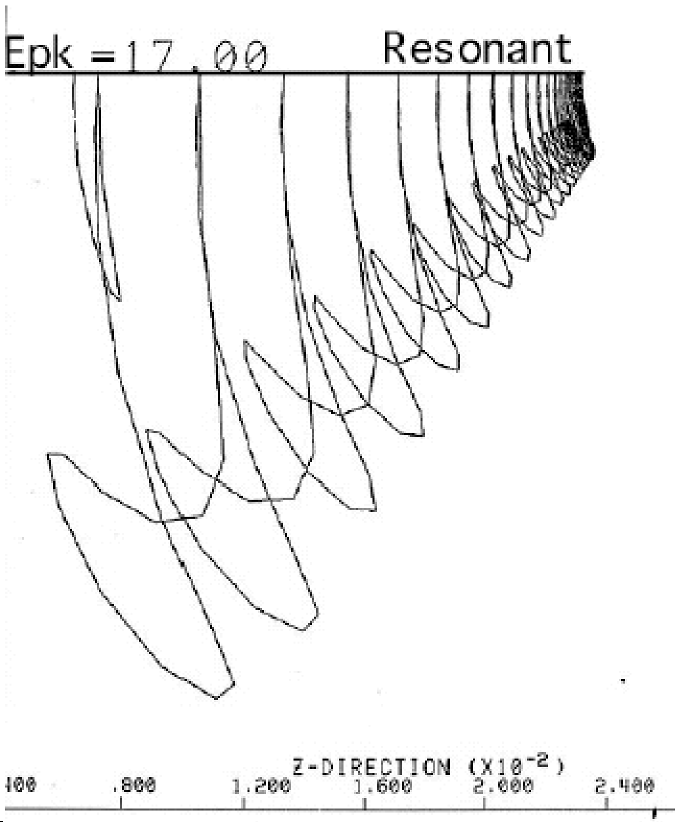


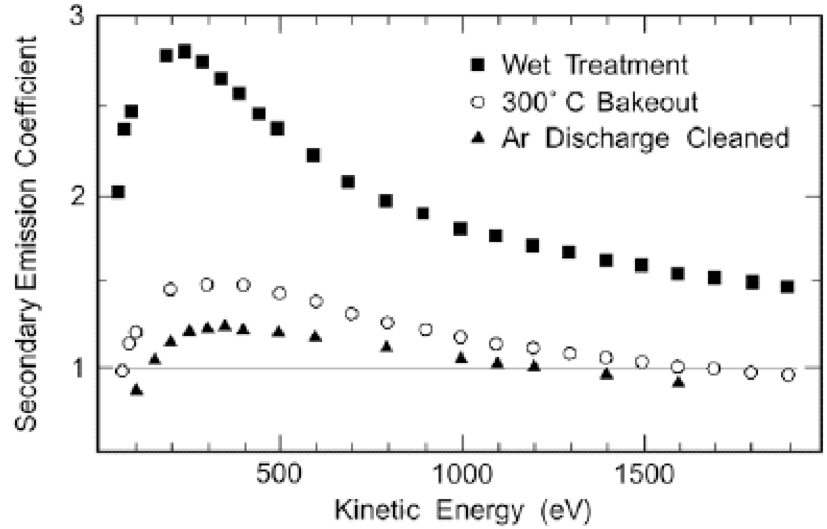


Field Emission

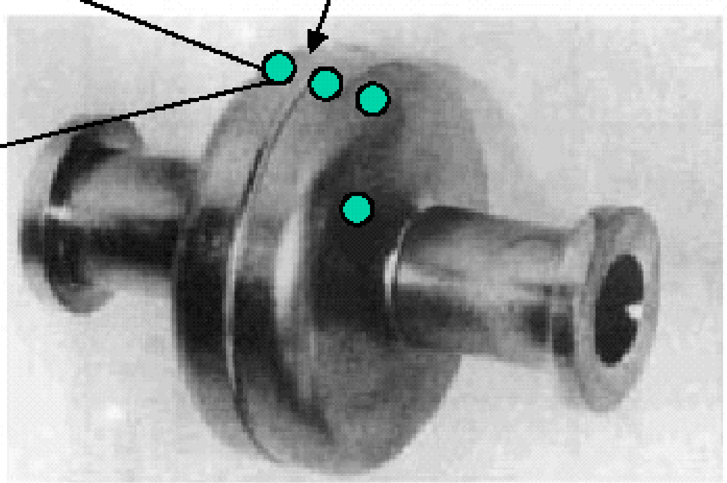
Thermal breakdown

Simulated Electron Trajectories

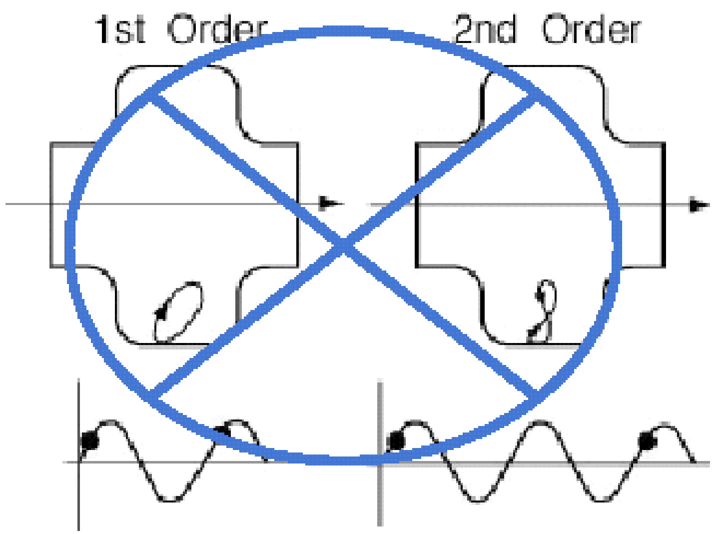


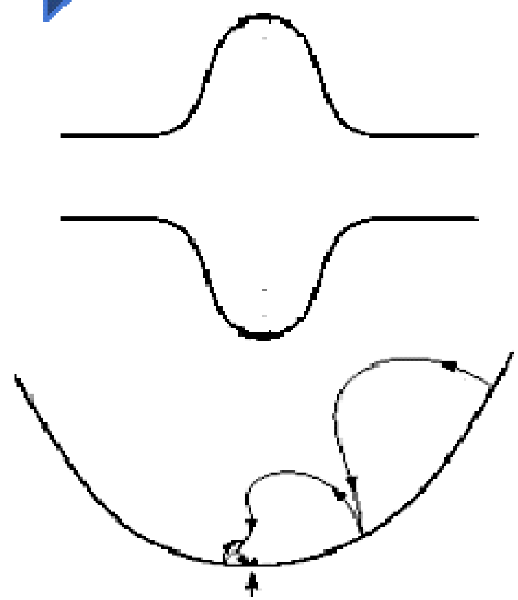


These thermometers show heating



Solution to Multipacting

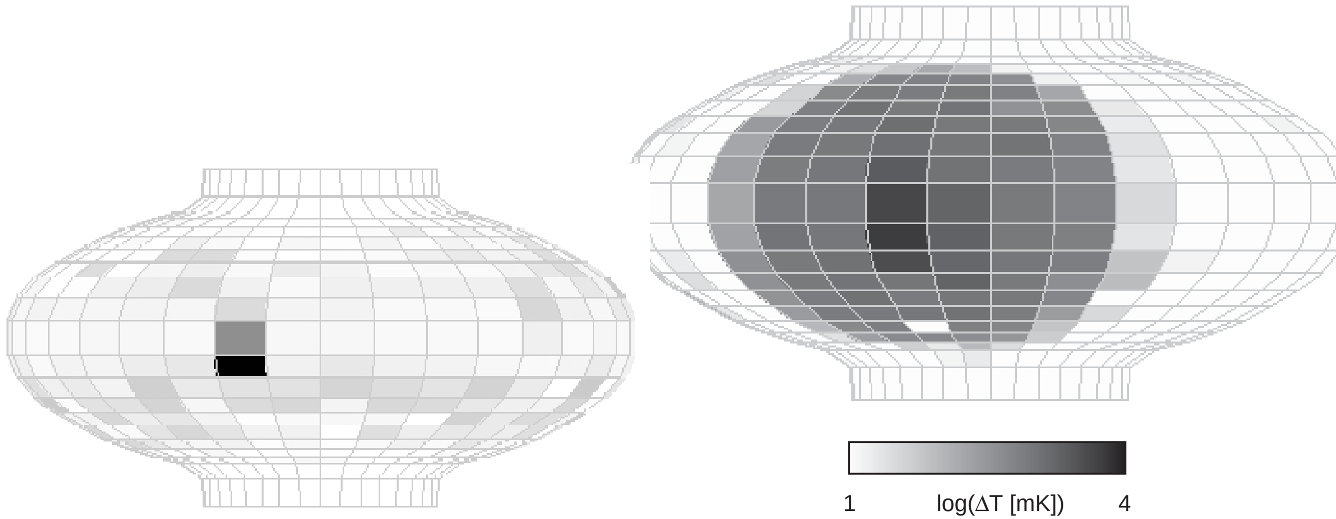


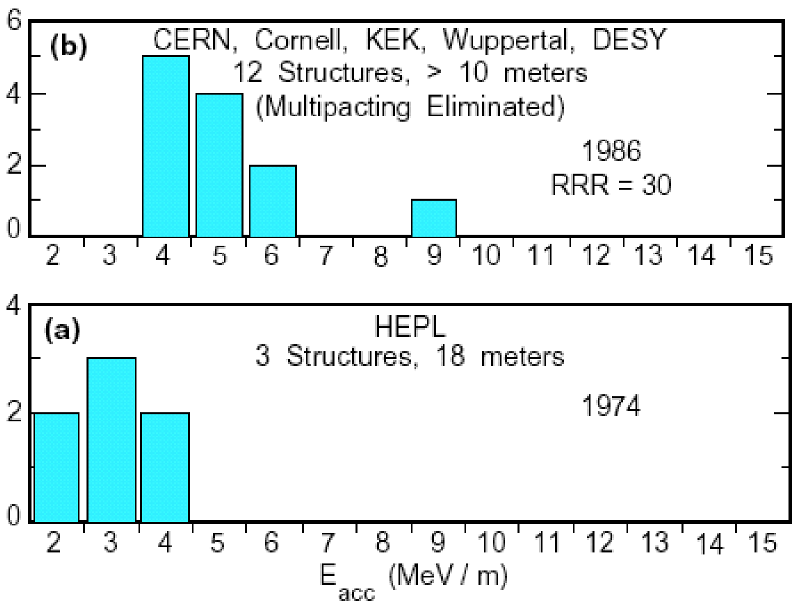


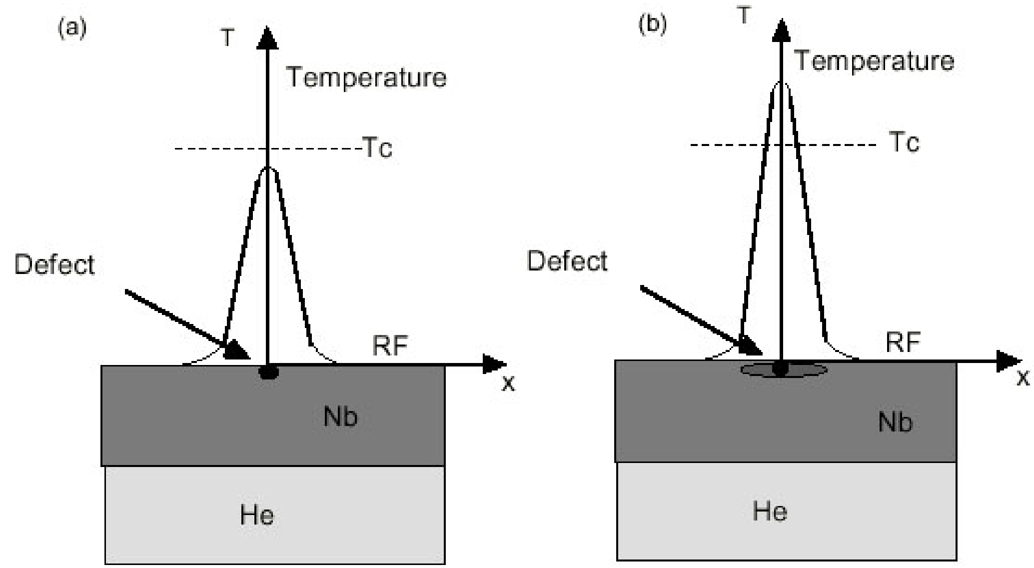
Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don't gain energy
→MP stops

H. Padamsee

Heating at sub-mm size defects leads to quench of superconductivity







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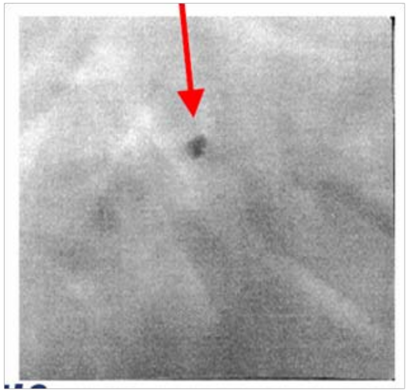
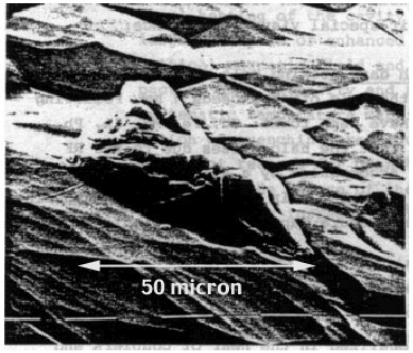
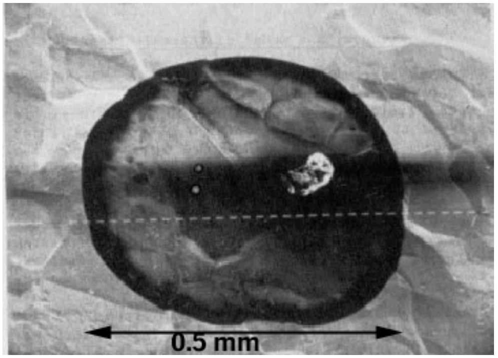
Museum of Defects Causing Quench



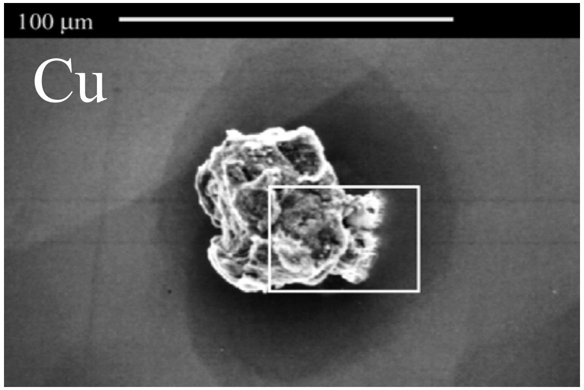
0.2 mm Ta defect, 15 MV/m



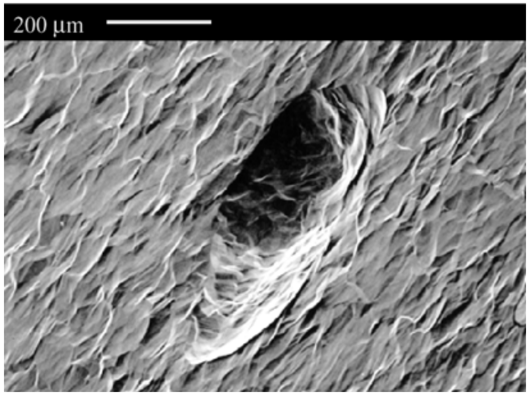
50 μm, with S, Ca, Cl, and K, 11 MV/m



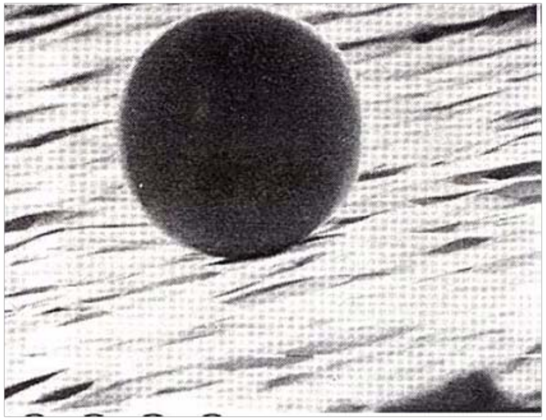
A chemical stain 440 μm in diameter. K, Cl, and P, 3. 4 MV/m



50 micron Cu particle fell into cavity

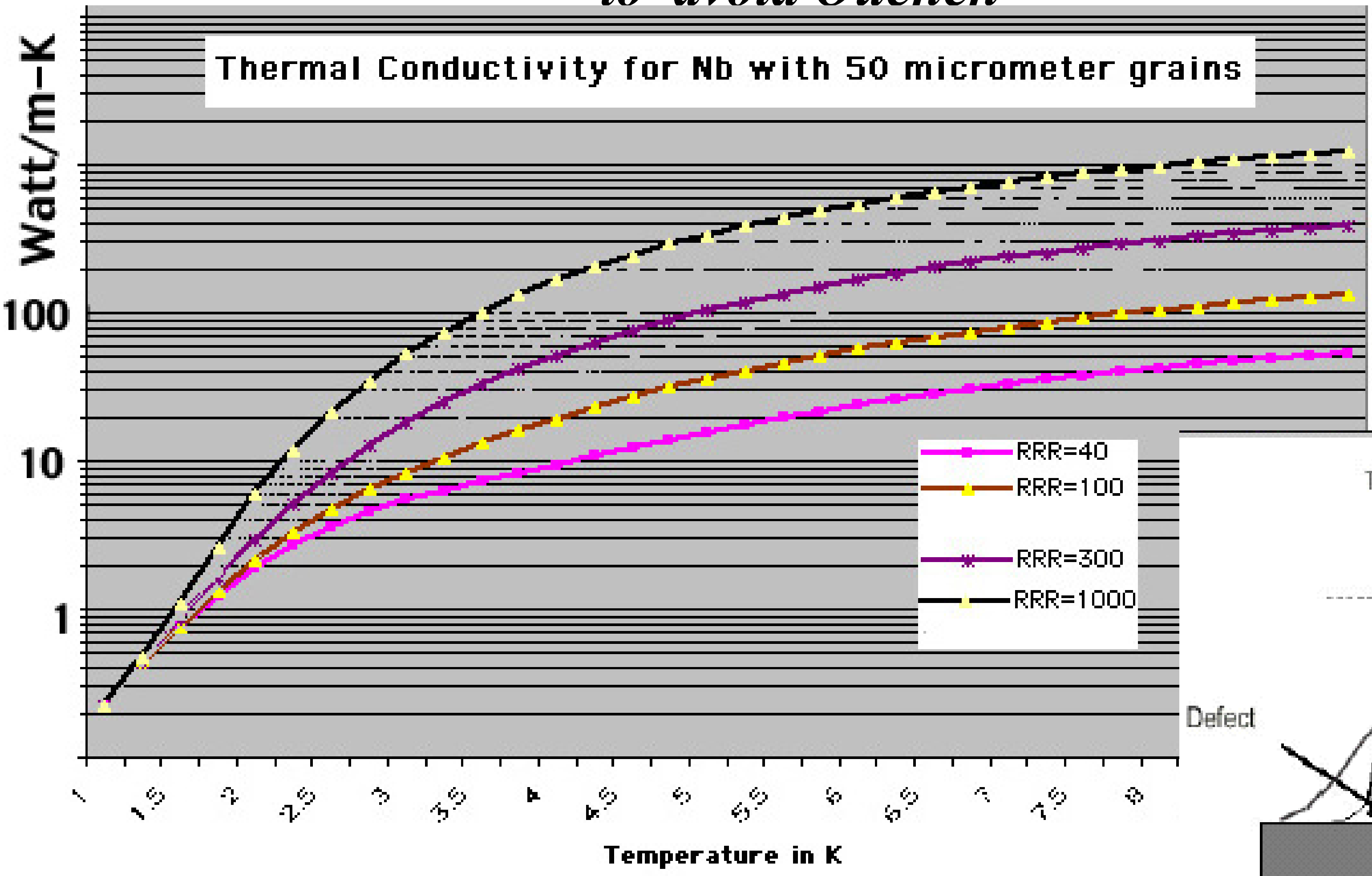


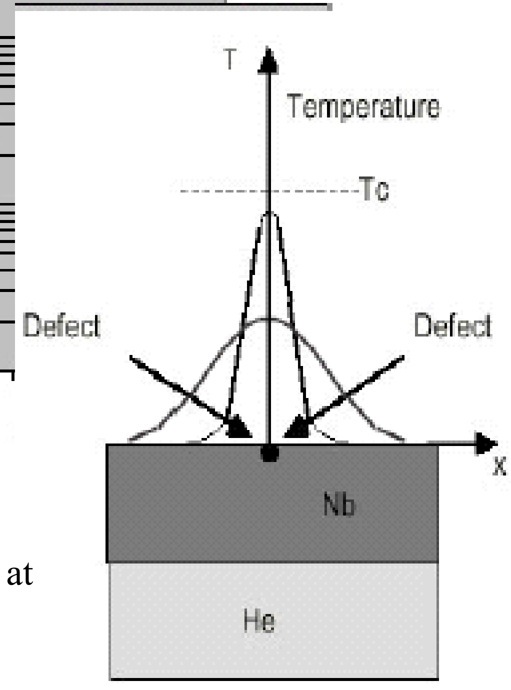
500 x 200 microns pit



Sub-mm Nb welding ball, avoidable

Improve Bulk Thermal Conductivity (and RRR) by raising purity to avoid Quench

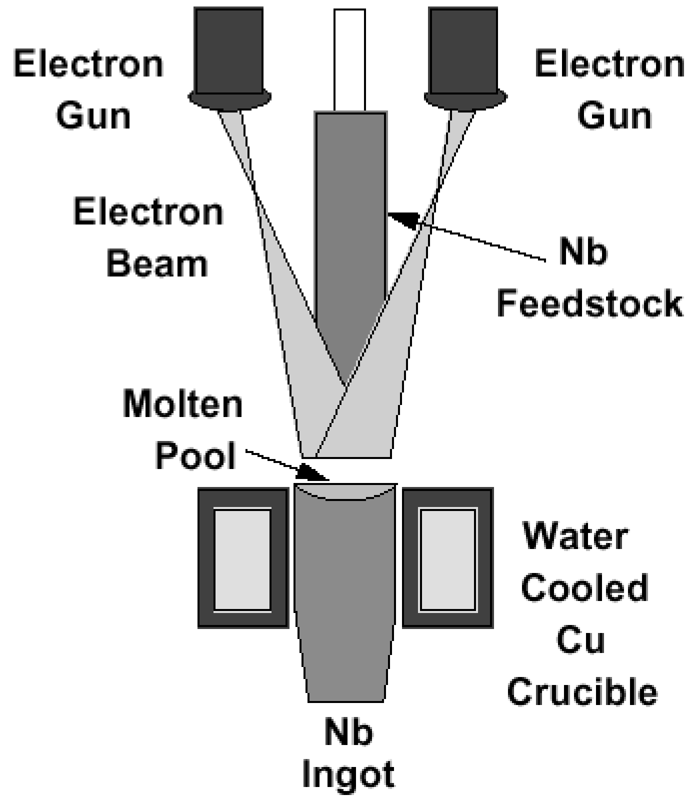




RRR: Residual resistance ratio = resistivity at room temperature divided by the resistivity at 4.2 K (in the normal conducting state!).

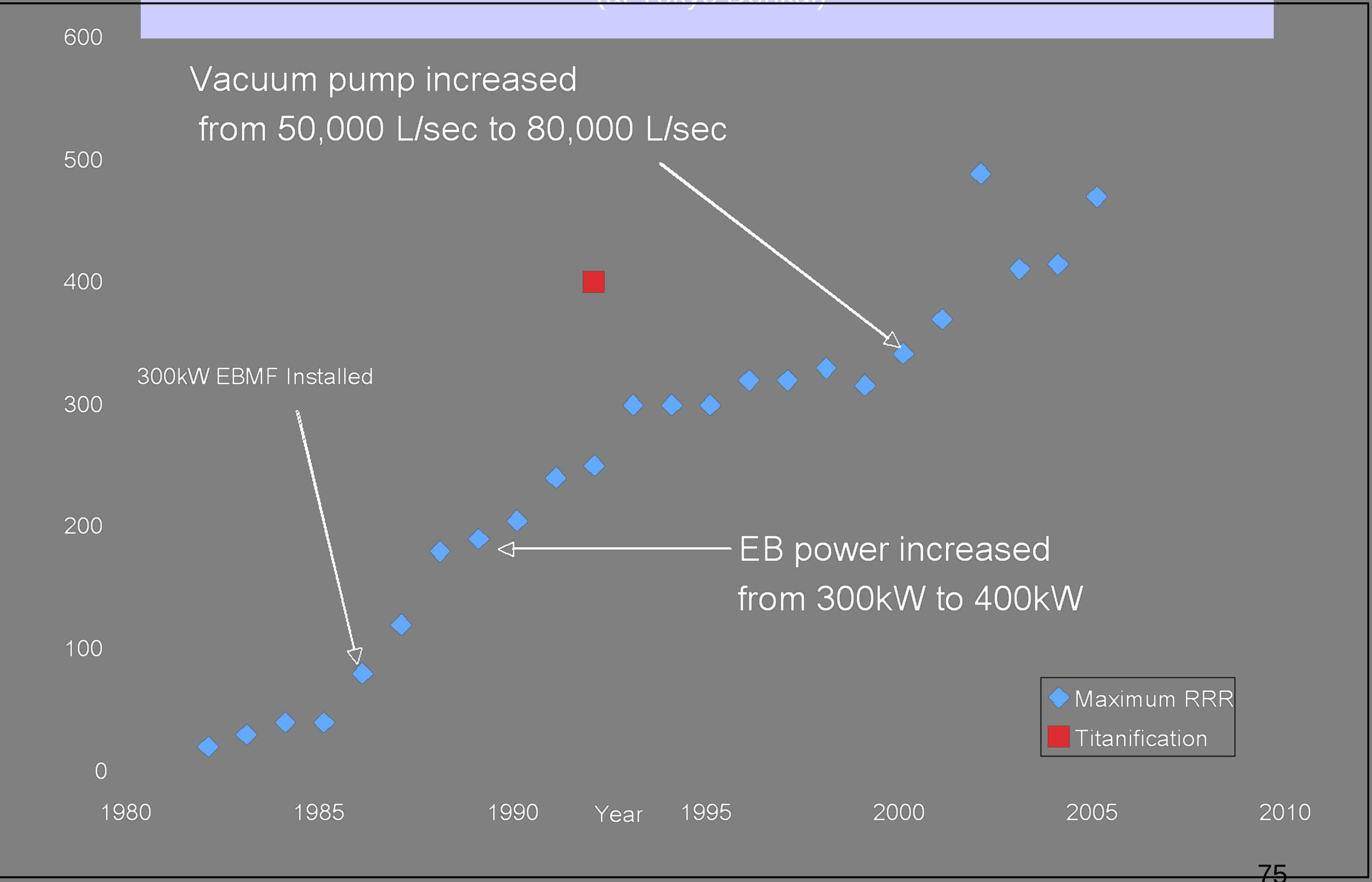
κ_T scales ≈ linearly with RRR.

Niobium Purification

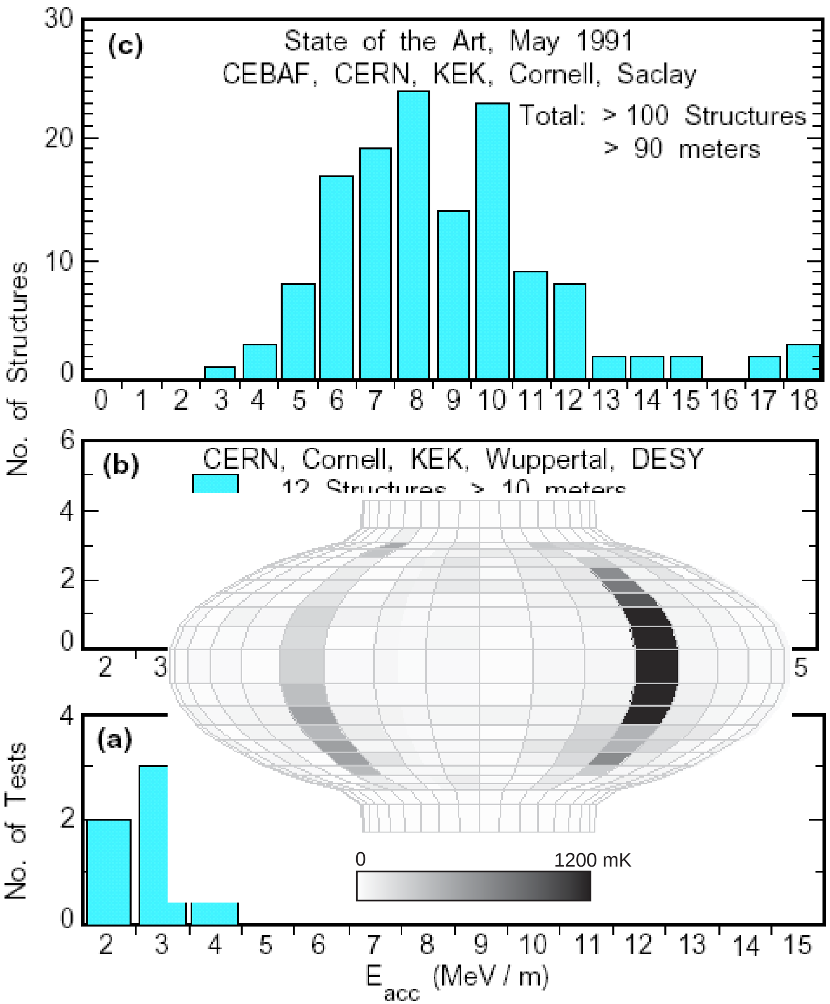


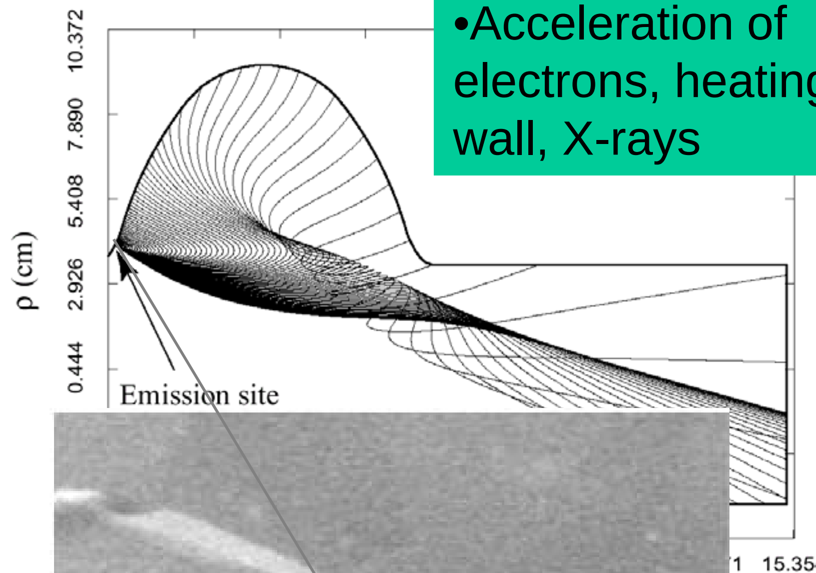
Interstitial O, N and C are the major impurities limiting Nb RRR

Typical Progress in RRR
(at Tokyo Denkai)



Field Emission

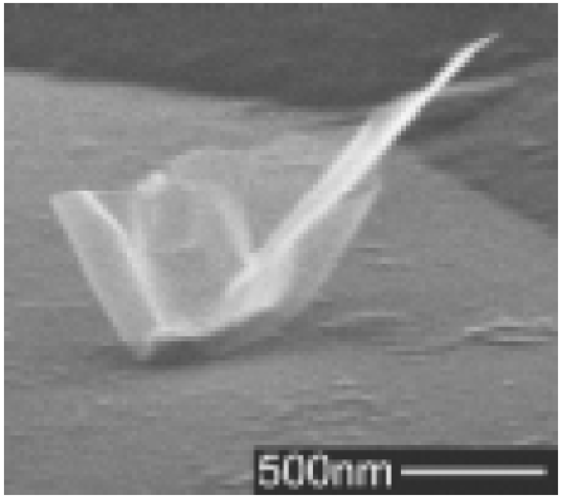


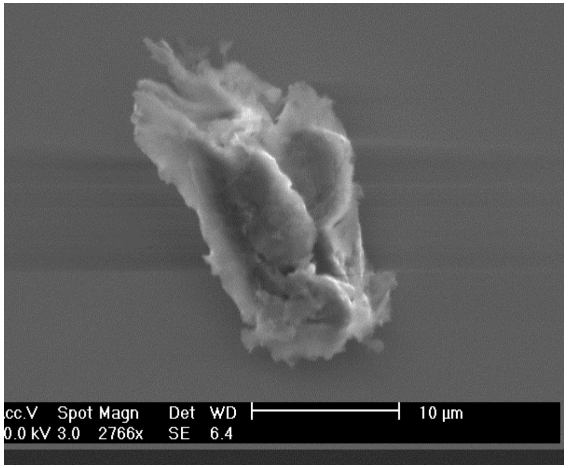


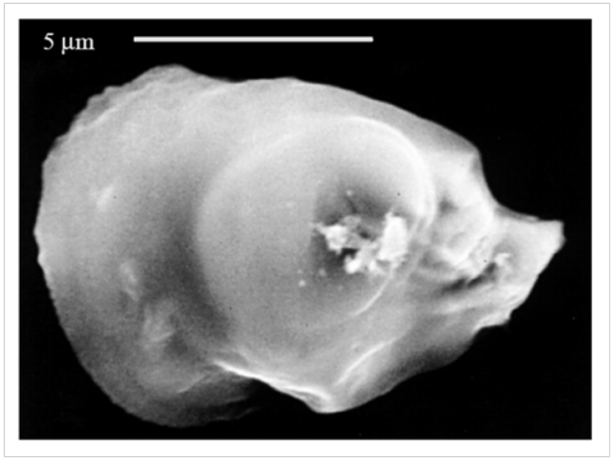
•Acceleration of electrons, heating wall, X-rays

•Impacting e
line heating detected by
thermometry.

Museum of Known Field Emitters 0.5 to 10 microns
Note the sharp features on the Particles.



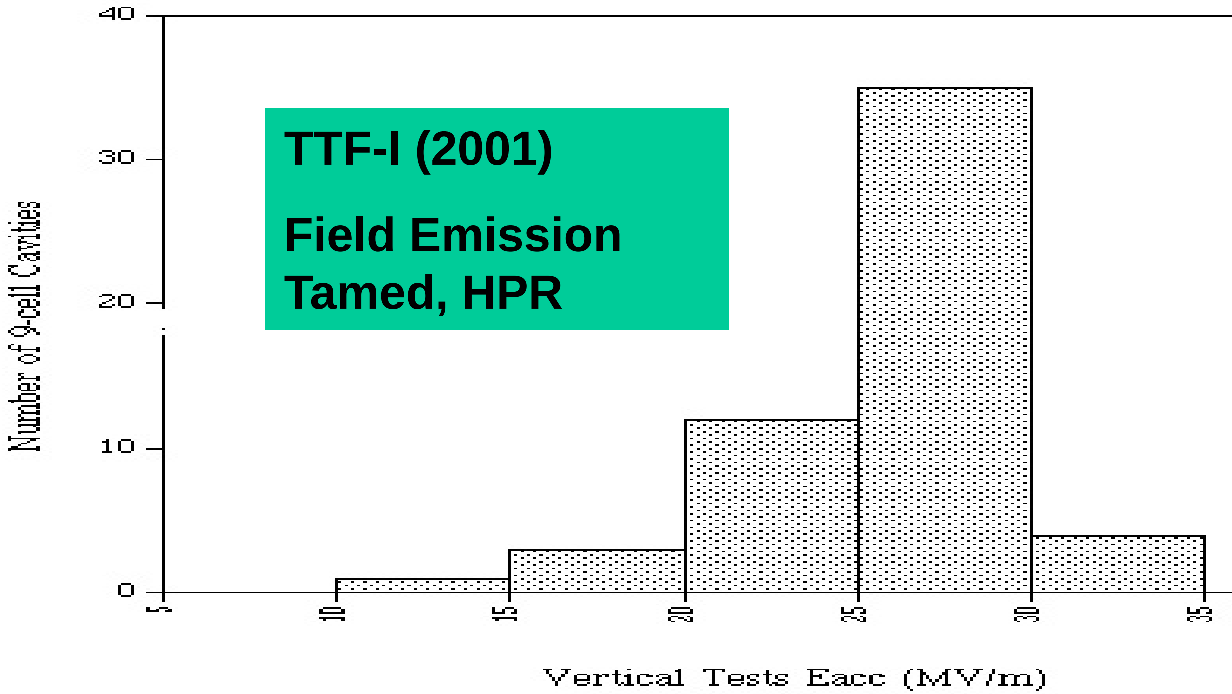


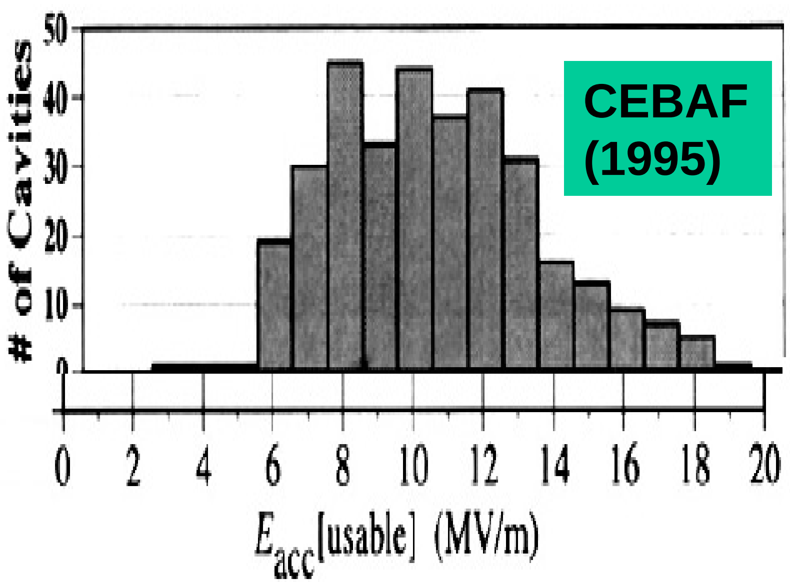


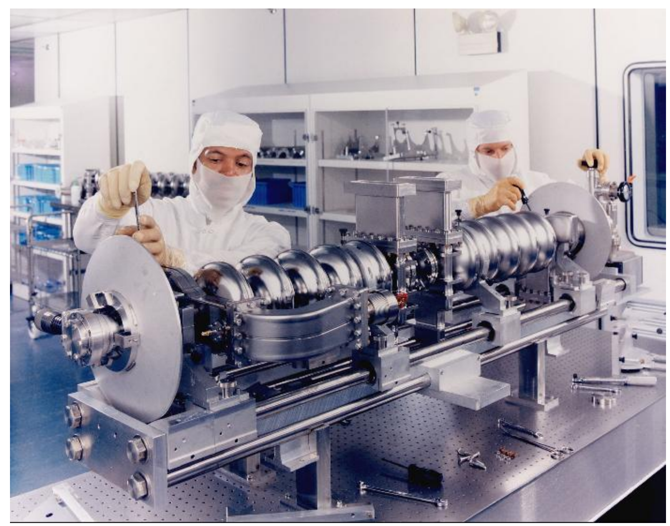
(a) Sub-micron field emitting particles found on sample prepared with 9-cell cavity

(b) Al particle found at a field emission site in the dc field emission scanning apparatus and subsequently analyzed with the SEM

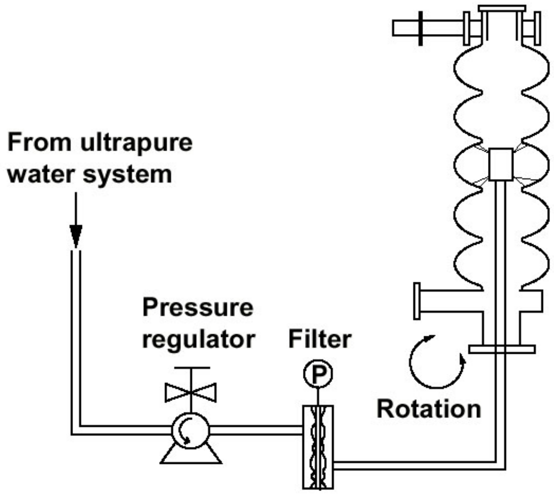
(c) Field emitting particle found with thermometry followed by dissection of a 1.5 GHz cavity. Carbon, oxygen, iron, chromium, and nickel were among the foreign elements detected

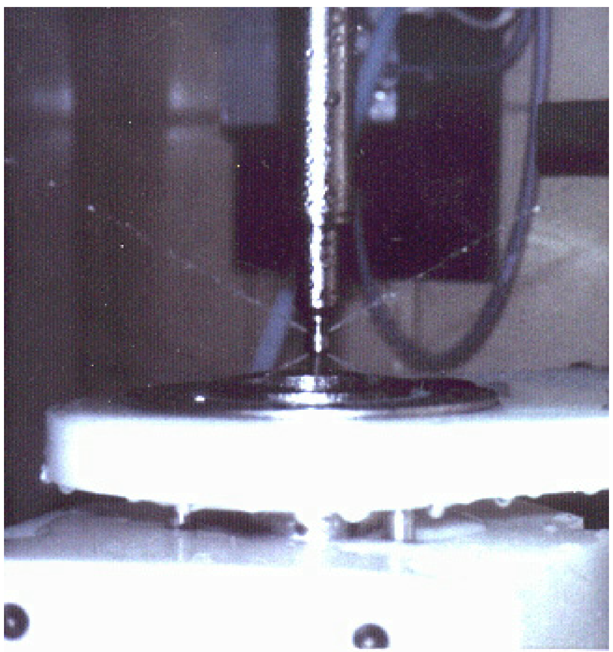

TTF-I (2001)
Field Emission Tamed, HPR
Number of 9-cell Cavities
Vertical Tests Eacc (MV/m)
0
10
20
30
40
5
10
15
20
25
30
35


CEBAF (1995)
# of Cavities
E_acc [usable] (MV/m)
0
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18
20



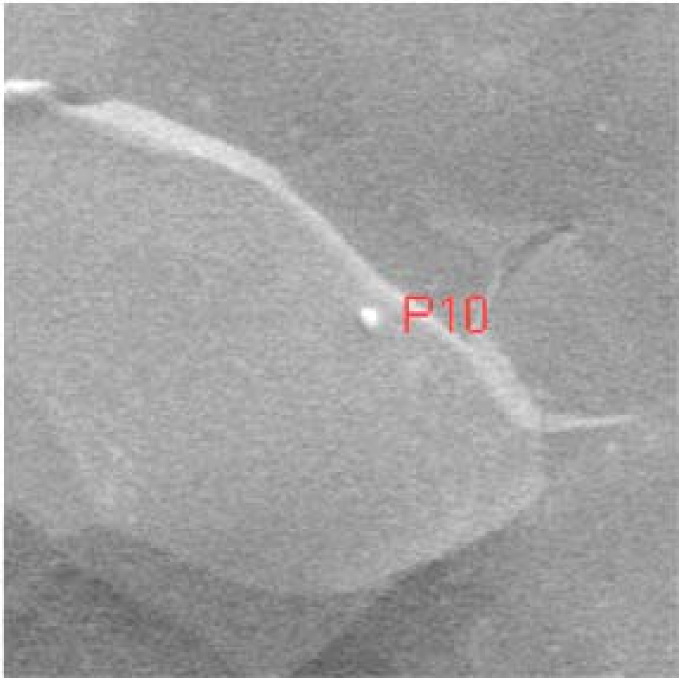
100 atm jet water rinsing

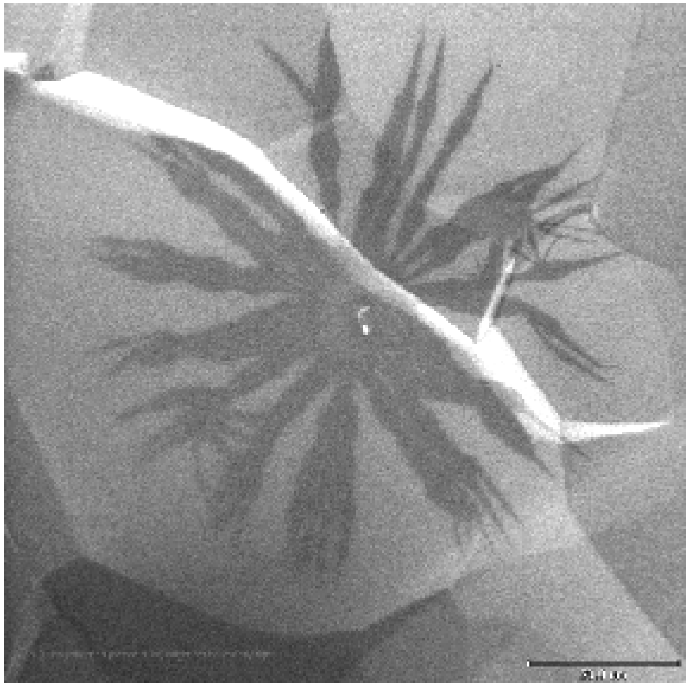




HPR and Assembly at Cornell in Class 100 Clean Room

< 100 particles/cu.ft > 1 μm

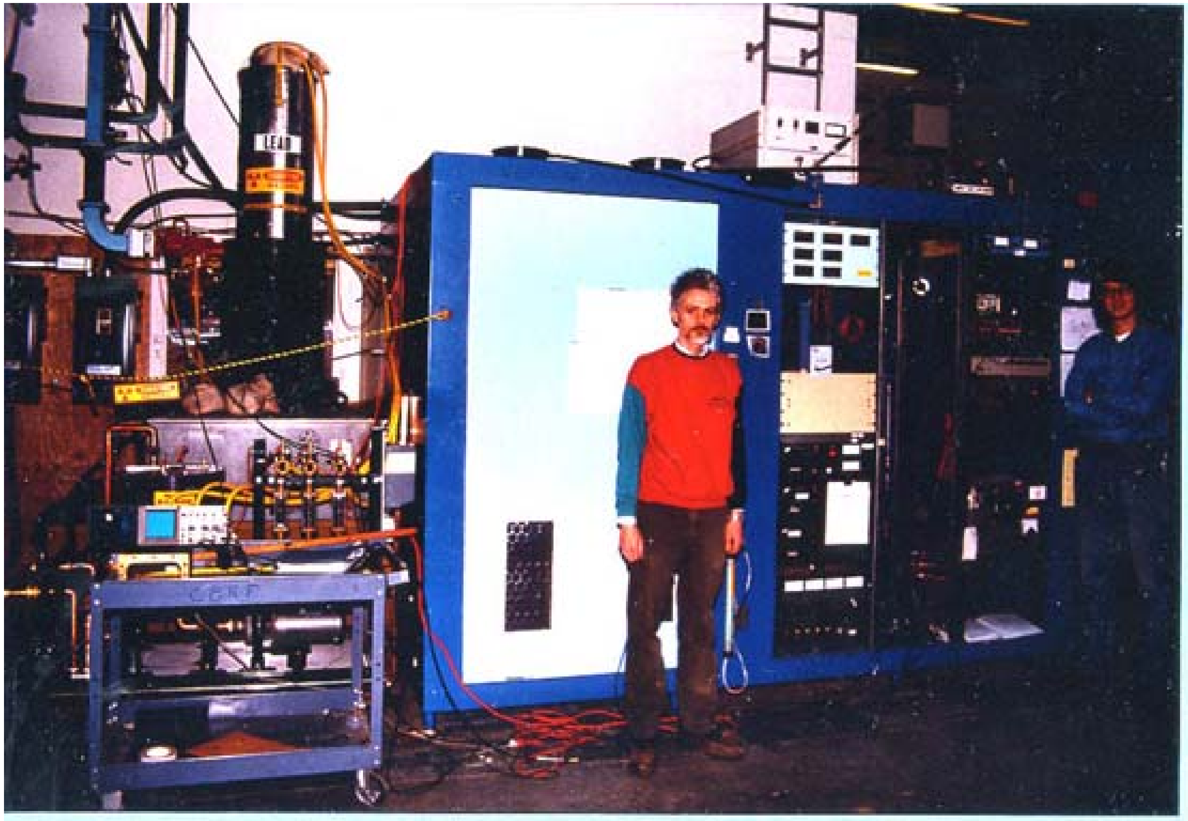




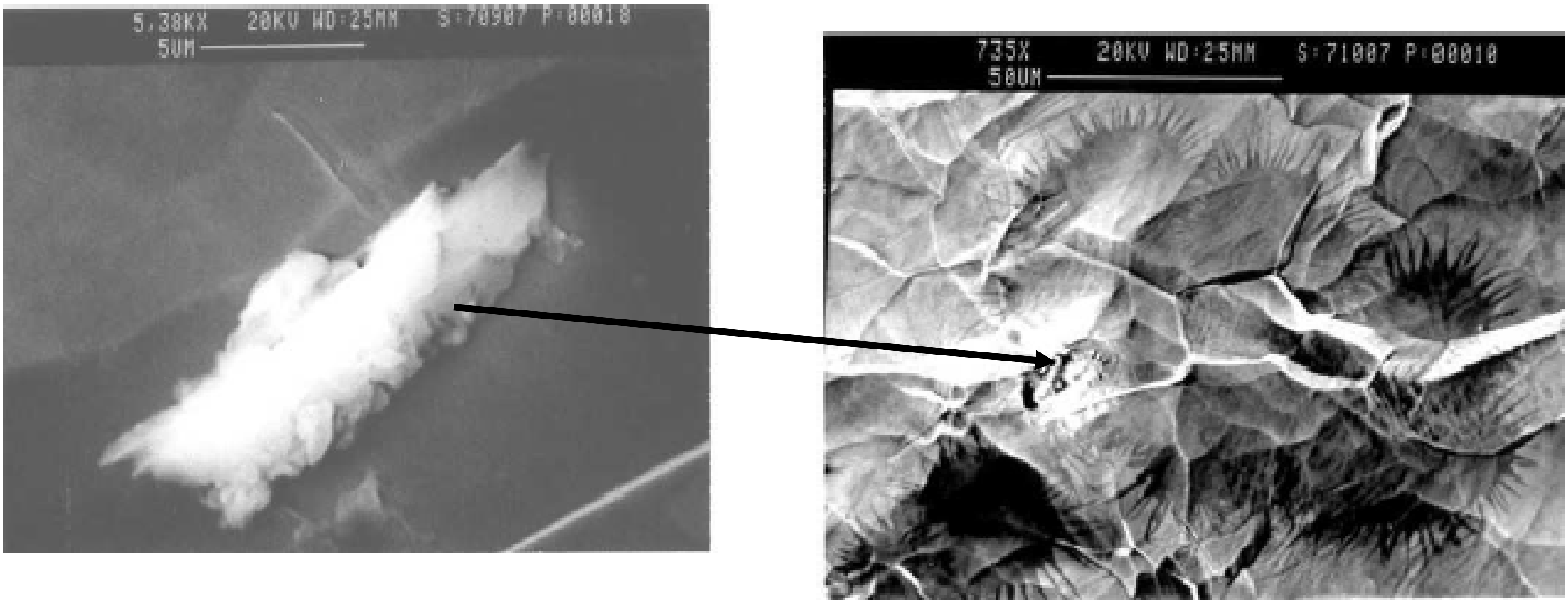
<u>All</u> RF Processing of Field Emission Means to Burn off Remaining Electron Emitters by Sparking

RF Processing Can be Enhanced With High Power RF

1 MW, 200 μsec pulses



CW Low Power RF Processing of Carbon Emitter Planted in 6 GHz Cavity



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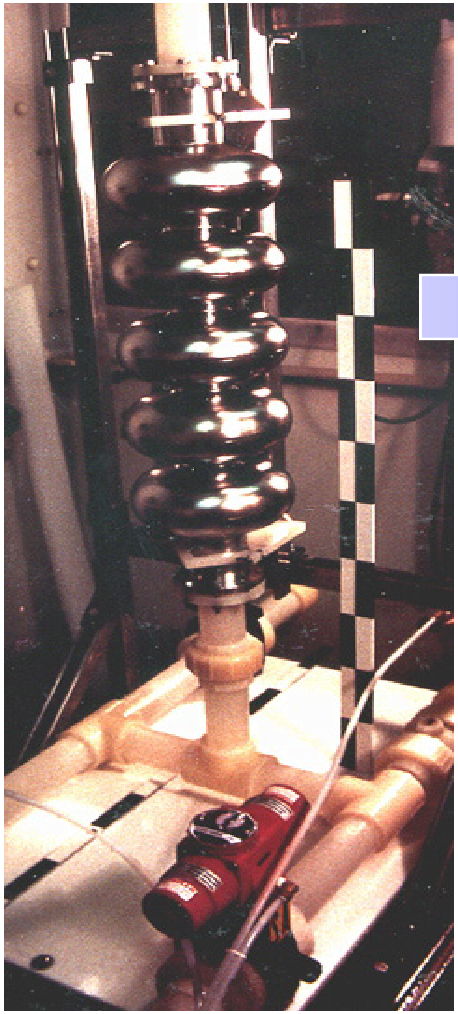
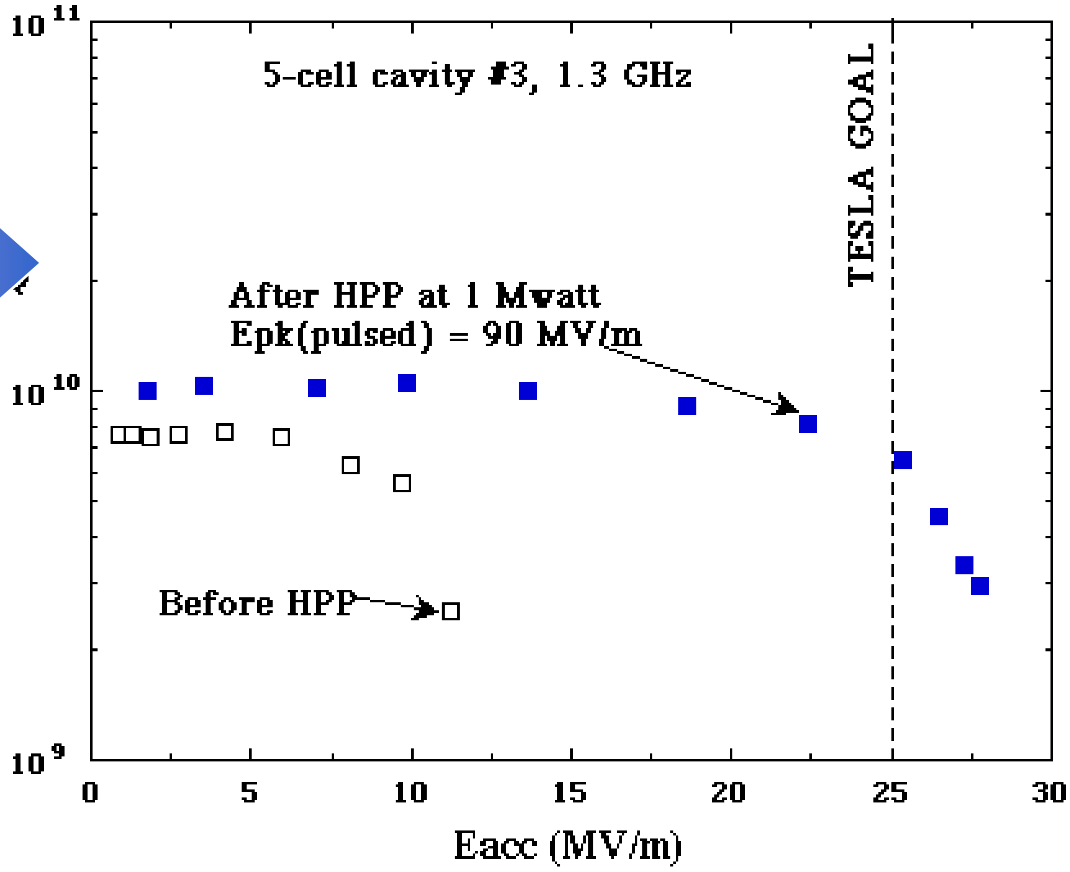
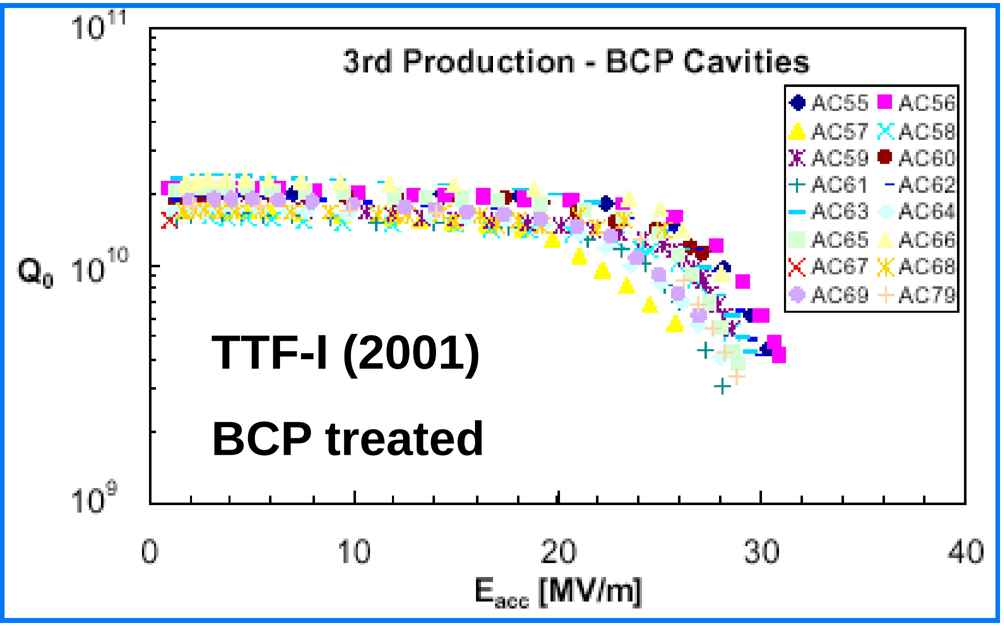
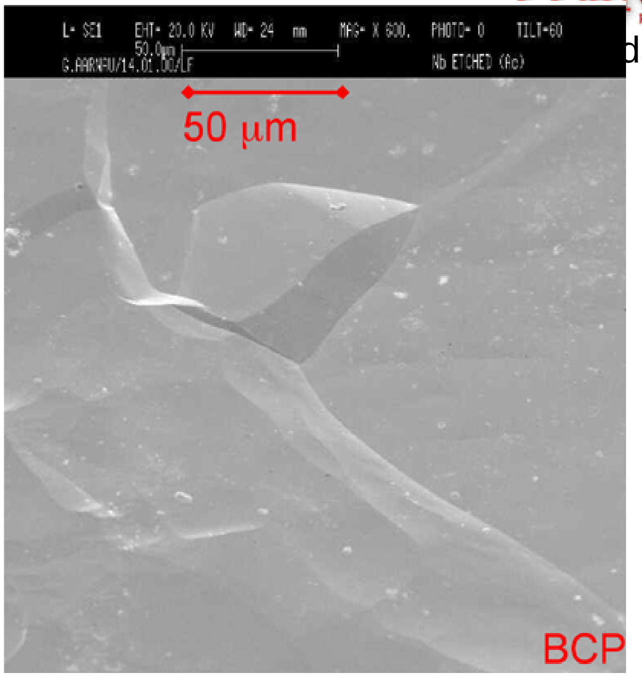
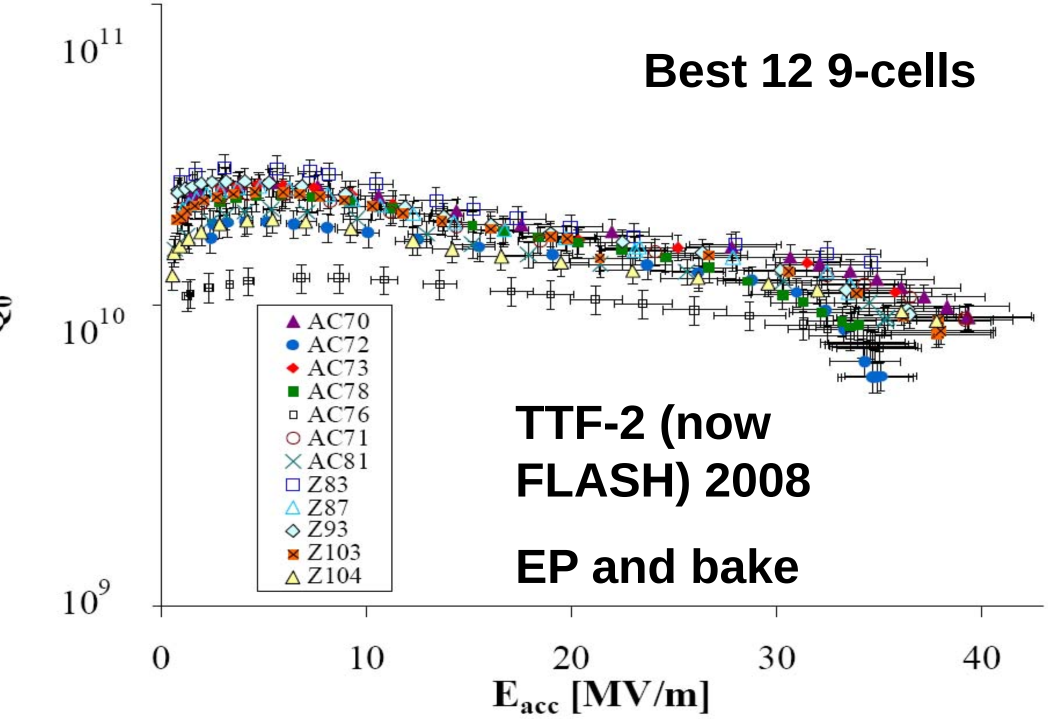
Push for High Gradients : Cornell, FNAL, DESY Collaboration Gradients > 25 MV/m in Three 5-cell 1300 MHz Cavities

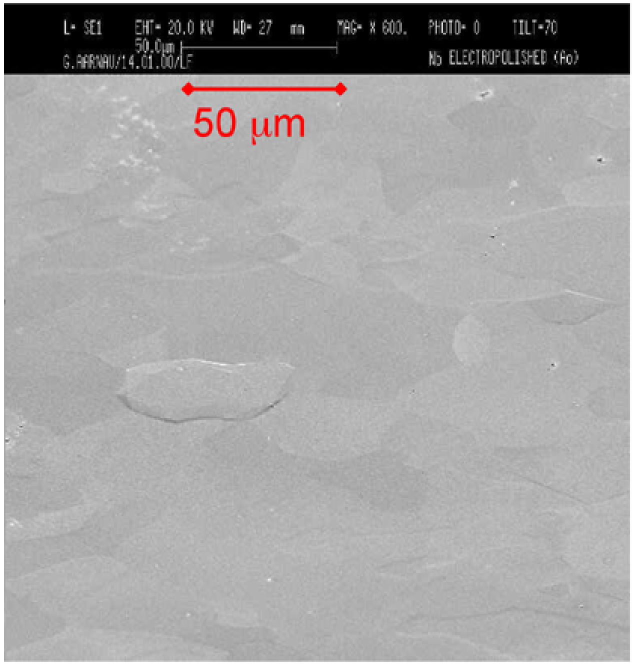




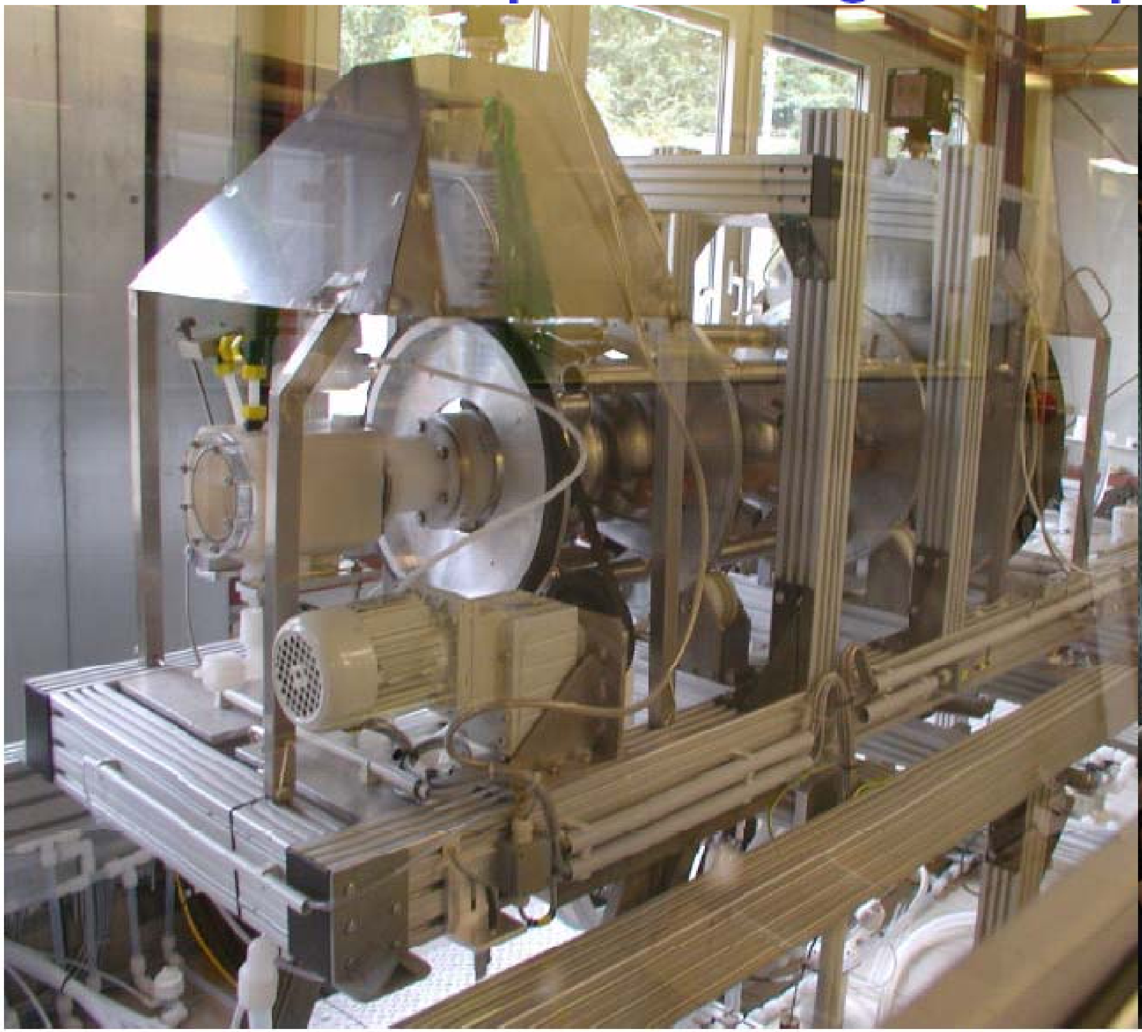

3rd Production - BCP Cavities
AC55 AC56
AC57 AC58
AC59 AC60
AC61 AC62
AC63 AC64
AC65 AC66
AC67 AC68
AC69 AC79
TTF-I (2001)
BCP treated
Q0
Eacc [MV/m]

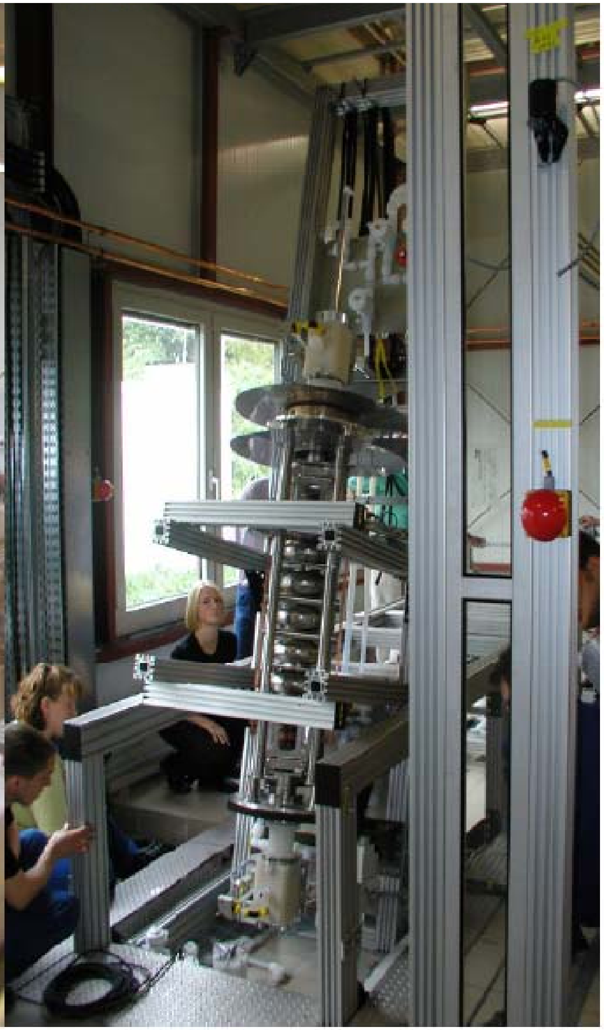

50 μm
BCP


Best 12 9-cells
AC70
AC72
AC73
AC78
AC76
AC71
AC81
Z83
Z87
Z93
Z103
Z104
TTF-2 (now FLASH) 2008
EP and bake
Eacc [MV/m]

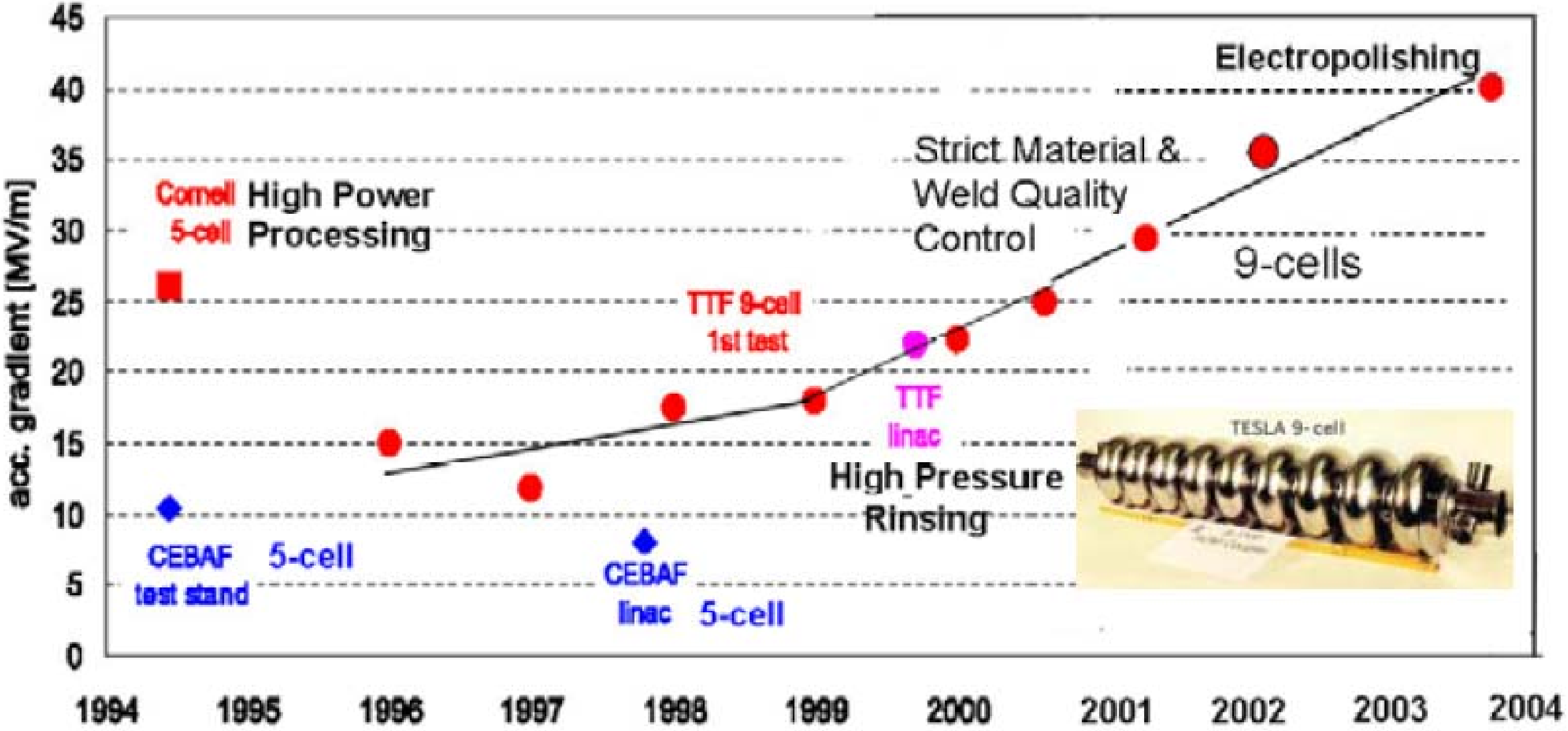

50 μm

Electropolishing Setup at DESY





Best Performance Results



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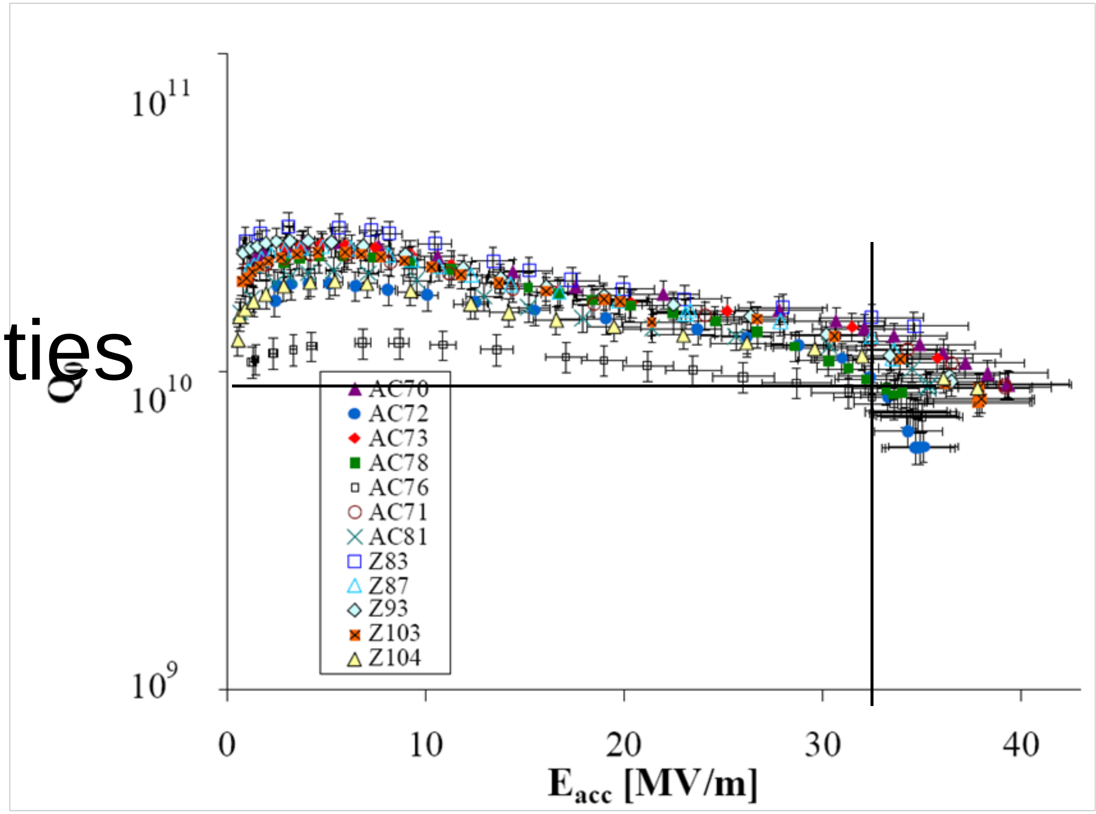
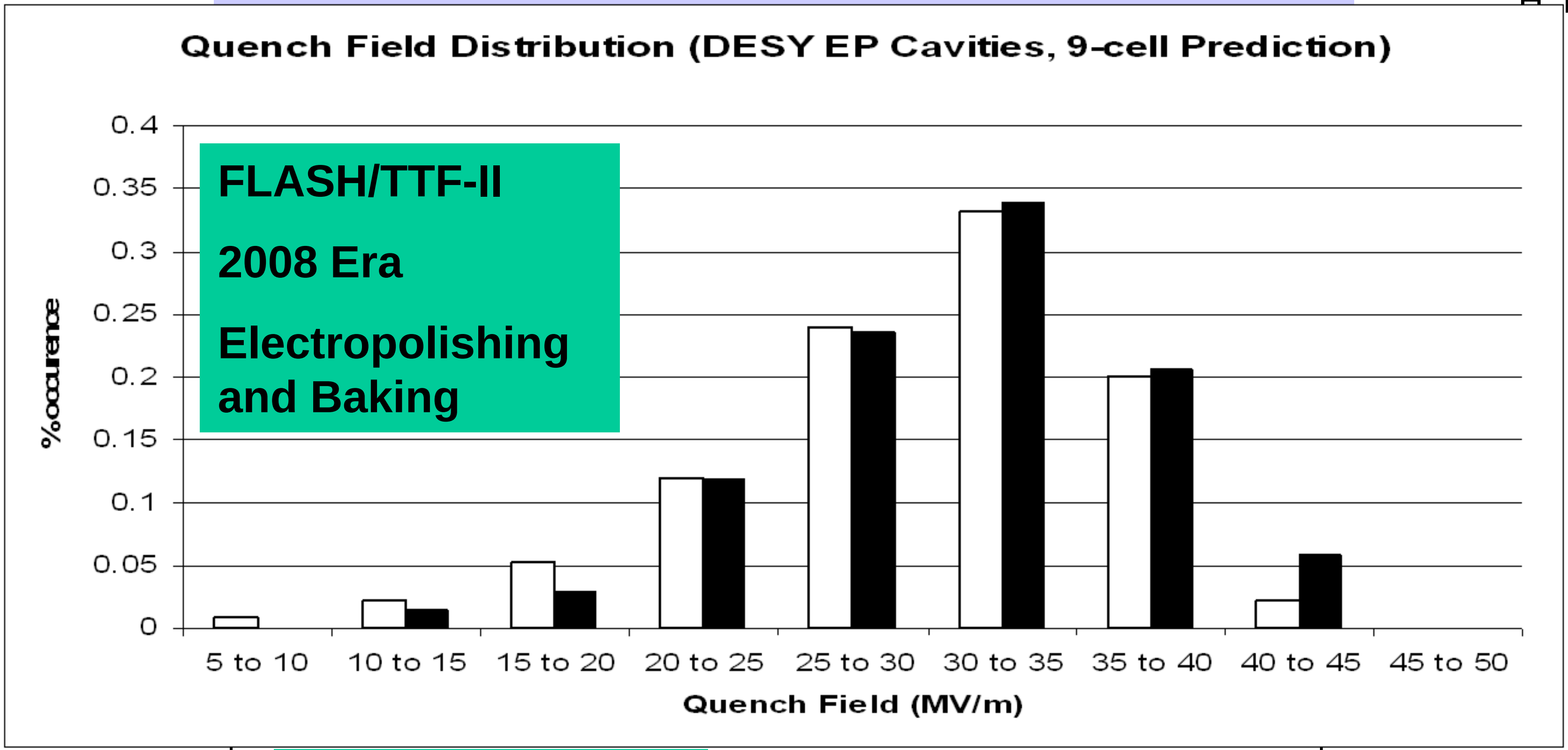
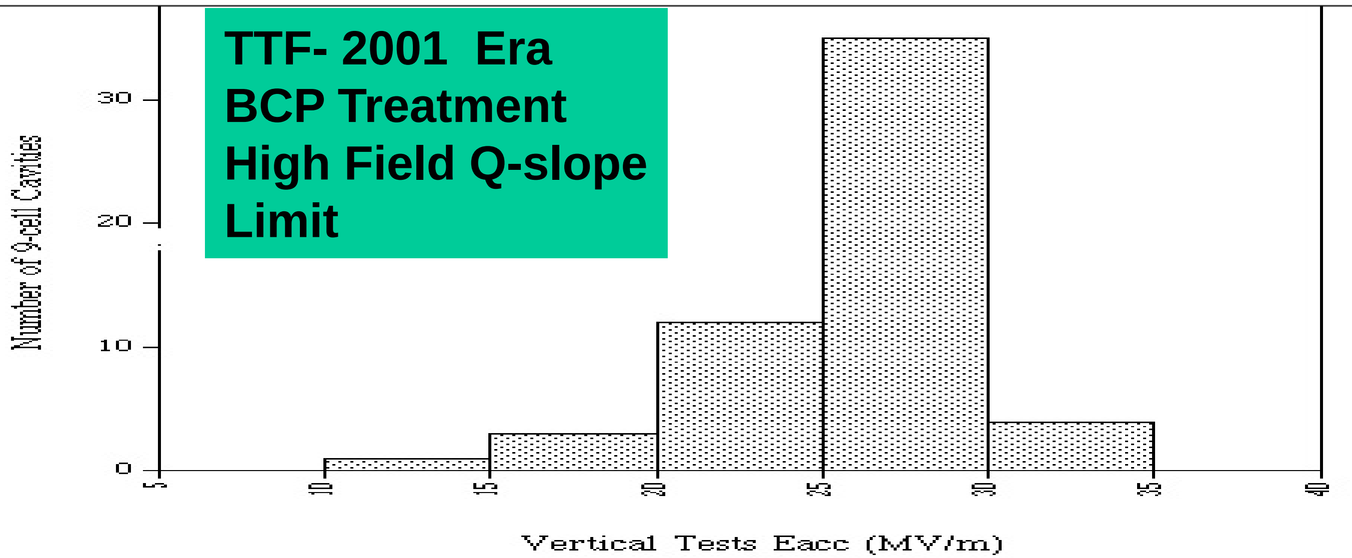
Outstanding Issues for Highest Gradient Applications: e.g. ILC

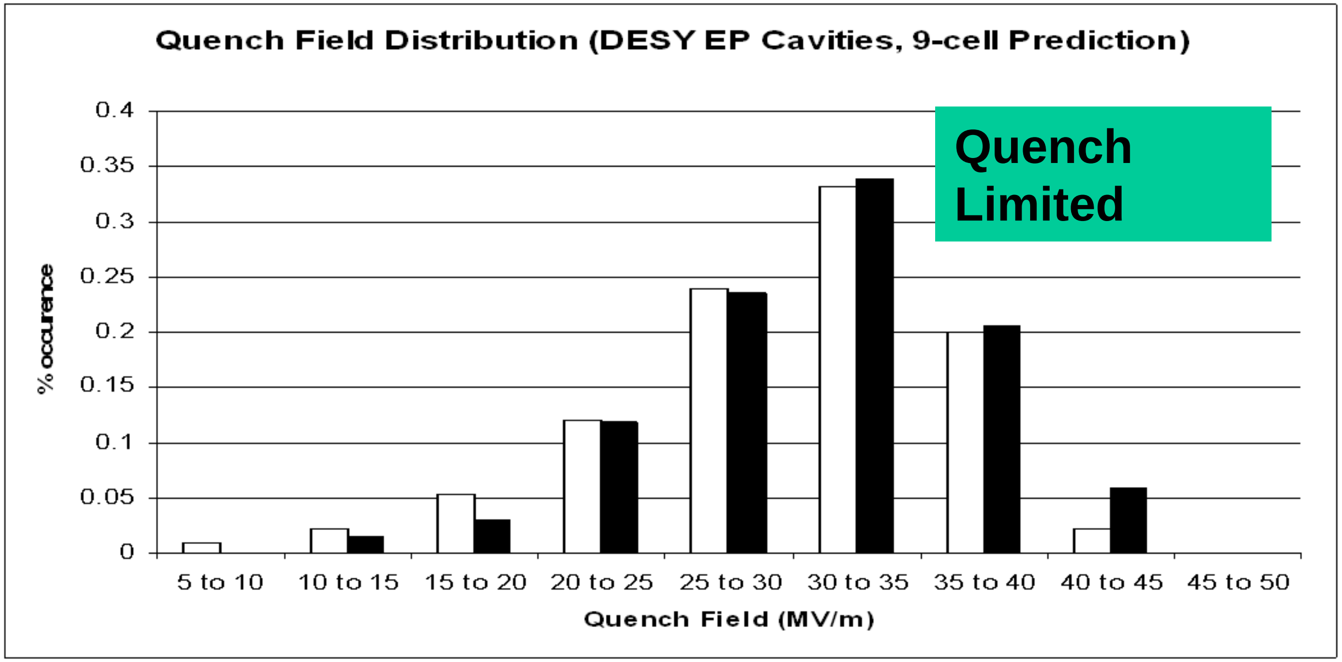
- Yield at 35 MV/m is low
- Spread is high:
  - – Quench
  - – Field emission
- Best 9-cell Cavities

  About one dozen

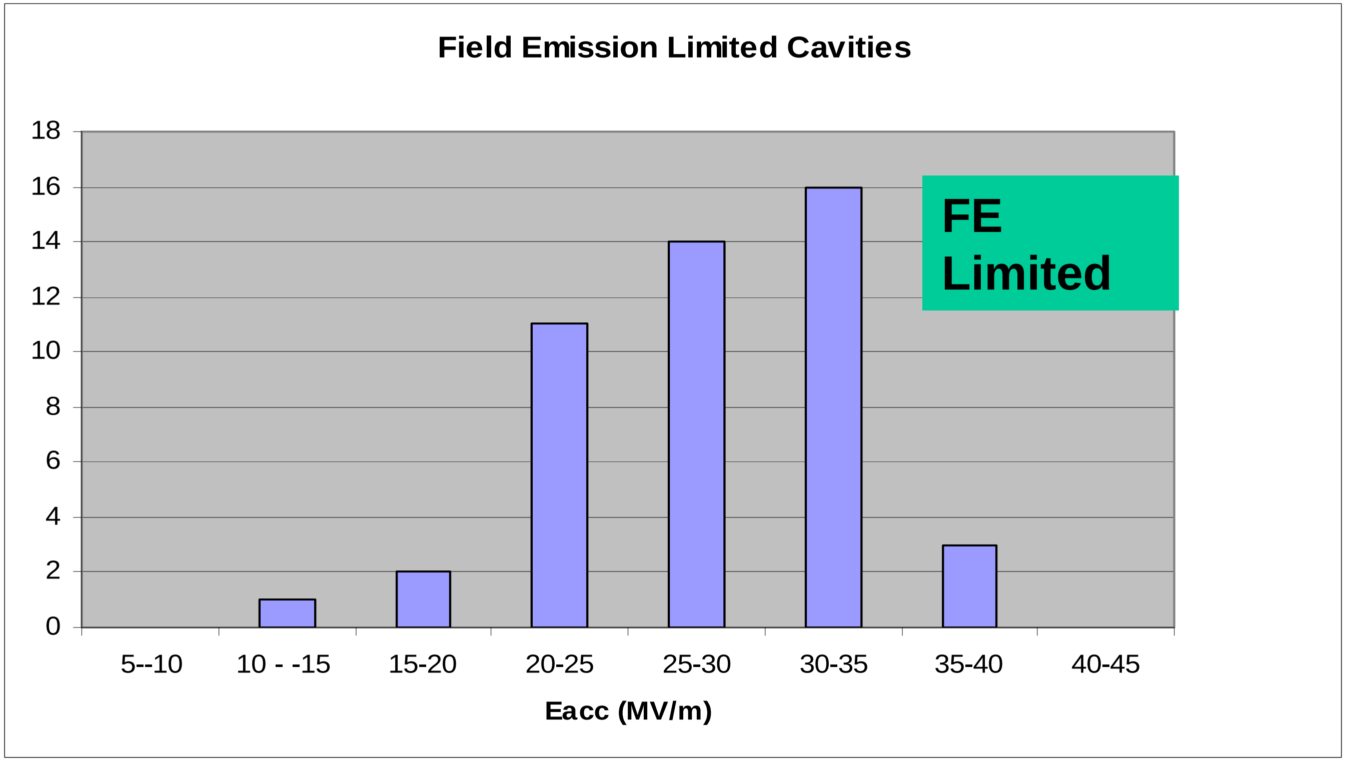



Quench Field Distribution (DESY EP Cavities, 9-cell Prediction)
FLASH/TTF-II
2008 Era
Electropolishing and Baking
%occurence
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
5 to 10
10 to 15
15 to 20
20 to 25
25 to 30
30 to 35
35 to 40
40 to 45
45 to 50
Quench Field (MV/m)


TTF- 2001 Era
BCP Treatment
High Field Q-slope Limit
Number of 9-cell Cavities
30
20
10
0
5
10
15
20
25
30
35
40
Vertical Tests Eacc (MV/m)



9-cell DESY Cavities Prepared by EP and Baking



Impact of SRF on Accelerators for Science

Existing and Future Applications

- Low energy nuclear physics, for nuclear shape, spin, vibration…
  - Heavy ion linacs
- Medium energy nuclear physics, structure of nucleus, quark-gluon physics
  - Recirculating linac
- Nuclear astrophysics, for understanding the creation of elements
  - Facility for rare isotope beams (FRIB)
- X-Ray Light Sources for life science, materials science & engineering
  - Storage rings, free electron lasers, energy recovery linacs
- Spallation neutron source for materials science and engineering, life science, biotechnology, condensed matter physics, chemistry
  - High intensity proton linac
- Future High Intensity Proton Sources for
  - Nuclear waste transmutation, energy amplifier, power generation from Thorium
- High energy physics for fundamental nature of matter, space-time
  - Electron-positron storage ring colliders, linear collider, proton linacs for neutrinos

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

Total > 7 GV installed (>3 GV still in operation: CEBAF, SNS, FLASH)

LEP-II was 3.5 GV, later de-commissioned for LHC

- HEP
  - Now: LHC, CESR-TA, KEK-B, Beijing Tau-charm Factory
  - Future: LHC-crab-crossing, ILC, Project X, CERN-SPL, Neutrino Factory, JPARC-Upgrade (neutrino beam line) Muon Collider
- NP
  - Low Energy
  - Now: ATLAS (Argonne), ALPI (INFN Legnaro Italy) , ISAC-II (TRIUMF), IUAC (Delhi)
  - Medium Energy Nuclear-Astrophysics
  - Now: CEBAF, 12GeV Upgrade,
  - Nuclear Astrophysics
  - Future: FRIB (MSU), ISAC-II (TRIUMF), Spiral-2, CERN ISOLDE Upgrade, Eurisol, RHIC-II, eRHIC, ELIC
- BES X-rays
  - Now: FLASH, X-FEL, CHESS, Canadian Light Source, DIAMOND, SOLEIL,Taiwan Light Source, Beijing Light Source (Tau-charm Factory), Shangai Light Source, Jlab-FEL/ERL, Rossendorf-FEL
  - Future: NSLS-II, Cornell-ERL, KEK-ERL, BESSY-ERL, WIFEL (Wisconsin), ARC-EN-CIEL, Pohang Light Source, Peking University,…
- BES: Neutron Sources
  - SNS, SNS upgrade,
  - Future: ESS (Sweden)
- Other High Intensity Proton Sources for
  - INFN, KAERI, Indian Laboratories at Indore, Mumbai and Kolkata