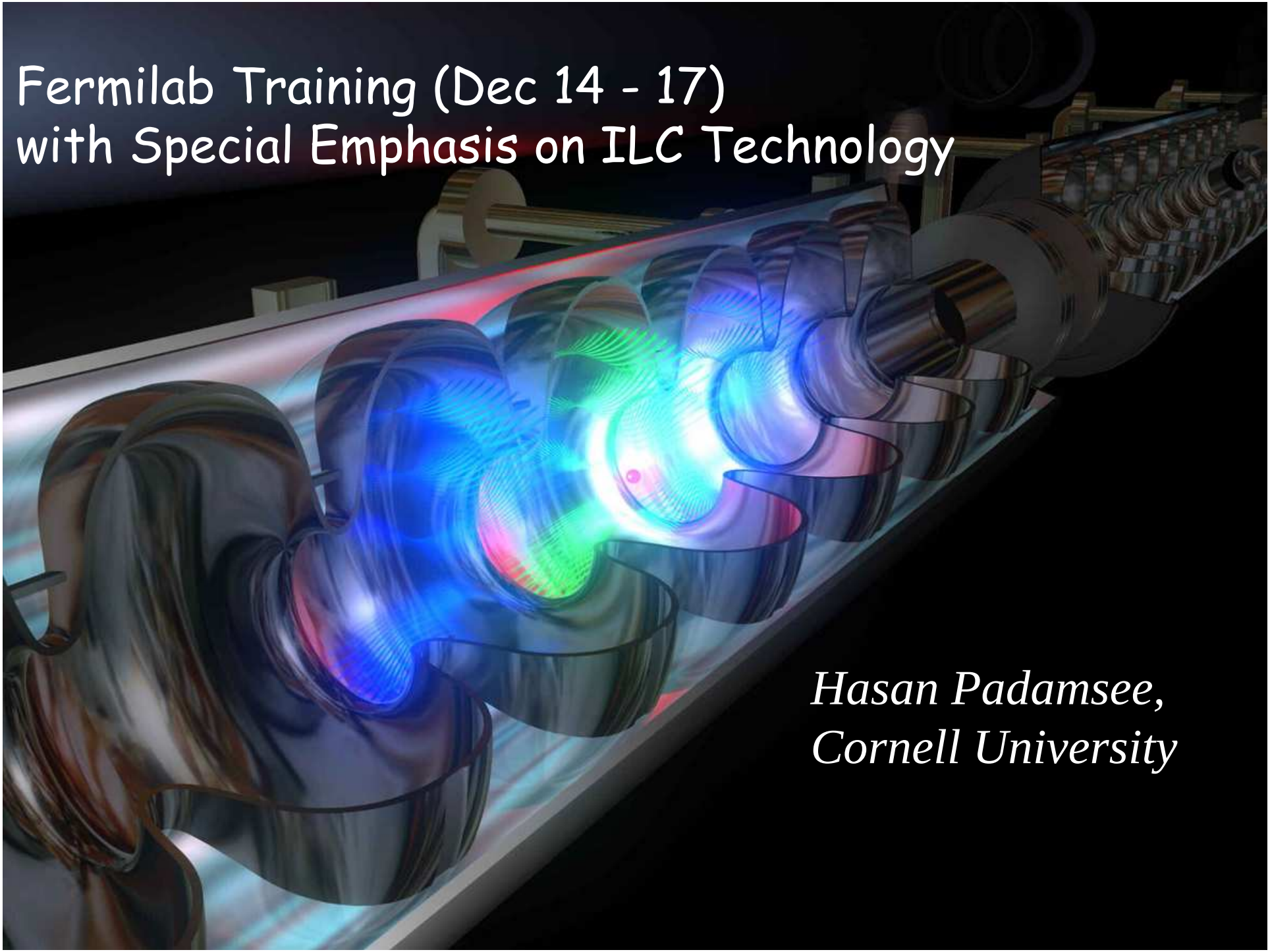
Fermilab Training (Dec 14 - 17) with Special Emphasis on ILC Technology



Hasan Padamsee,
Cornell University

Superconducting RF Training

- Cavities
- RF Superconductivity
- World Wide Applications - Past and Present
- Cavity Performance - Theoretical
- Future Applications (afternoon)
- Cavity Performance - Real
- Surface Resistance
- High Field Behavior
  - Multipacting, Thermal breakdown, Field Emission, Q-slope
- Alternate Materials Efforts (afternoon)
- Cavity Fabrication
- Cavity Preparation
- Cavity Testing
- Accessories
  - Input Couplers, HOM Couplers, Tuners
- Fabrication Movies, Alternate Fabrication Methods (afternoon)
- TESLA Cryomodule Assembly and Movies (Anyone speak German?)

Overall Approach: Mostly Conceptual with Pictures Movies

Stress here on Technical Aspects, less on math, handwaving instead

(More physics and math at USPAS)

References: Extensive Literature +
Text Book (1998)
Lots of Review Papers, some pdf files on CD
SRF Workshop Proceedings (1980, 83, 85….2003)
12th Worskhop, Cornell, July 10 - 14, 2005
http://www.lns.cornell.edu/public/SRF2005/

CD of lectures

12th International Workshop on RF Superconductivity
SRF 2005
Cornell University, Ithaca, New York, USA
July 10-15, 2005
Program Committee
H. Padamsee - Wolfgang Chapman - Cornell University
C. Antoine - SACLAY
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http://www.lepp.cornell.edu/public/SRF2005

Superconducting RF Cavities Fundamentals

Outline

1. RF Cavities
   - Basic Concept
   - Figures of Merit
   - NC and SC conducting cavity examples and comparison

2. Superconductivitiy
   - Impact on cavities design
   - Advantages of SC cavities

RF Cavities: Energy for Accelerators: Examples

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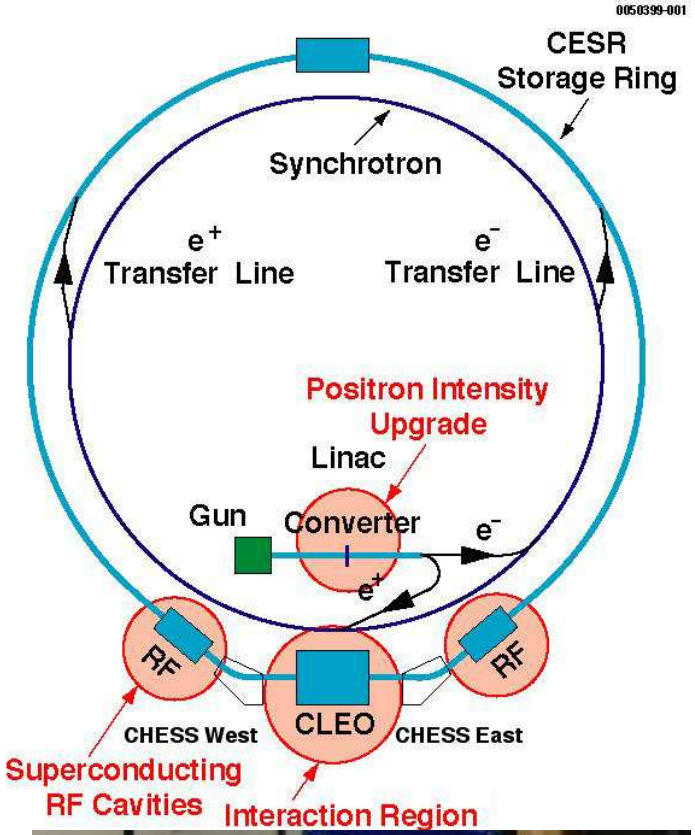
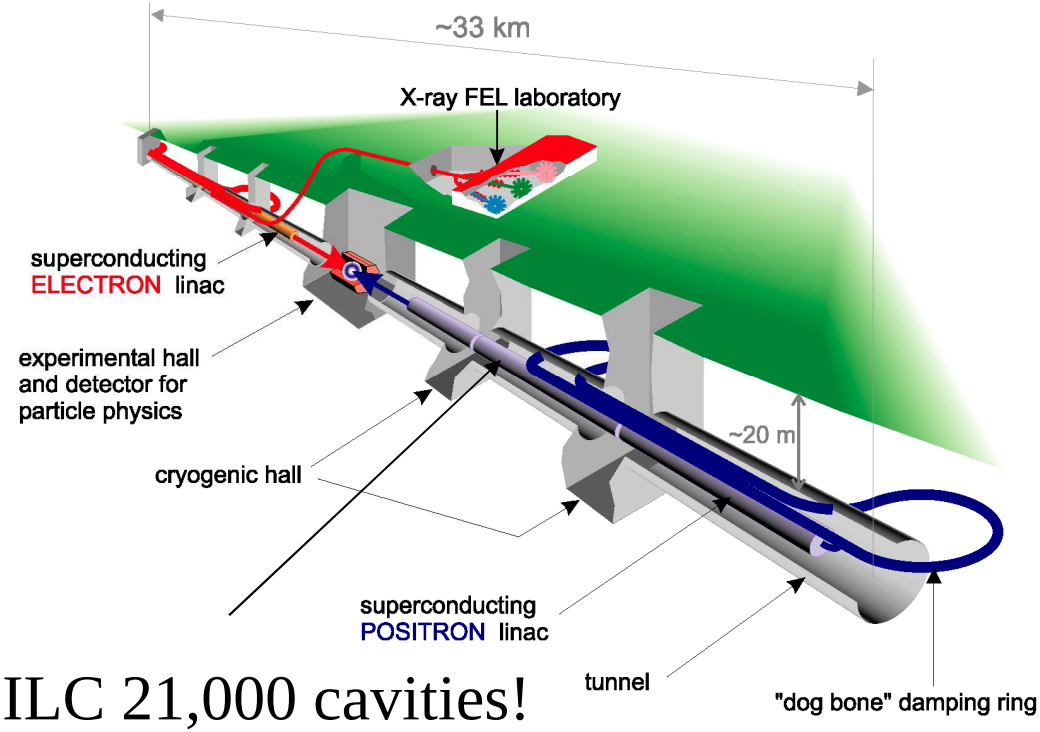
Storage Rings



Linear Colliders



ILC 21,000 cavities!

General Accelerator Requirements

Voltage

Storage Rings

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

Proton Linac: 1 GV

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

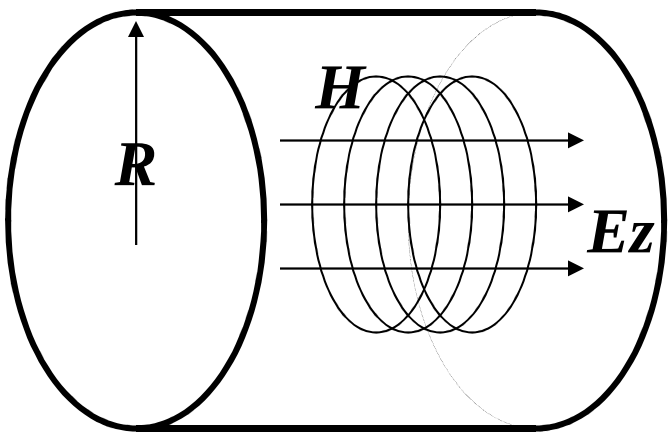
Linac-Based FEL or ERL 50 μA - 100 mA

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

Linear Collider: few ma, 10 MW

Radiofrequency Cavities

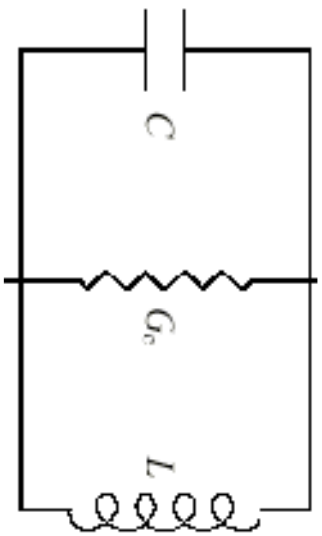
TM_{010} mode



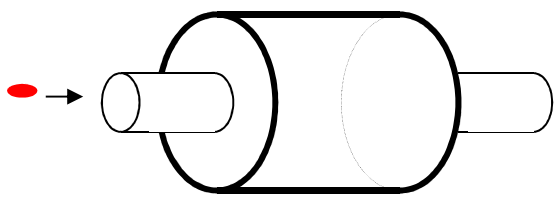
$$E_z = E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

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

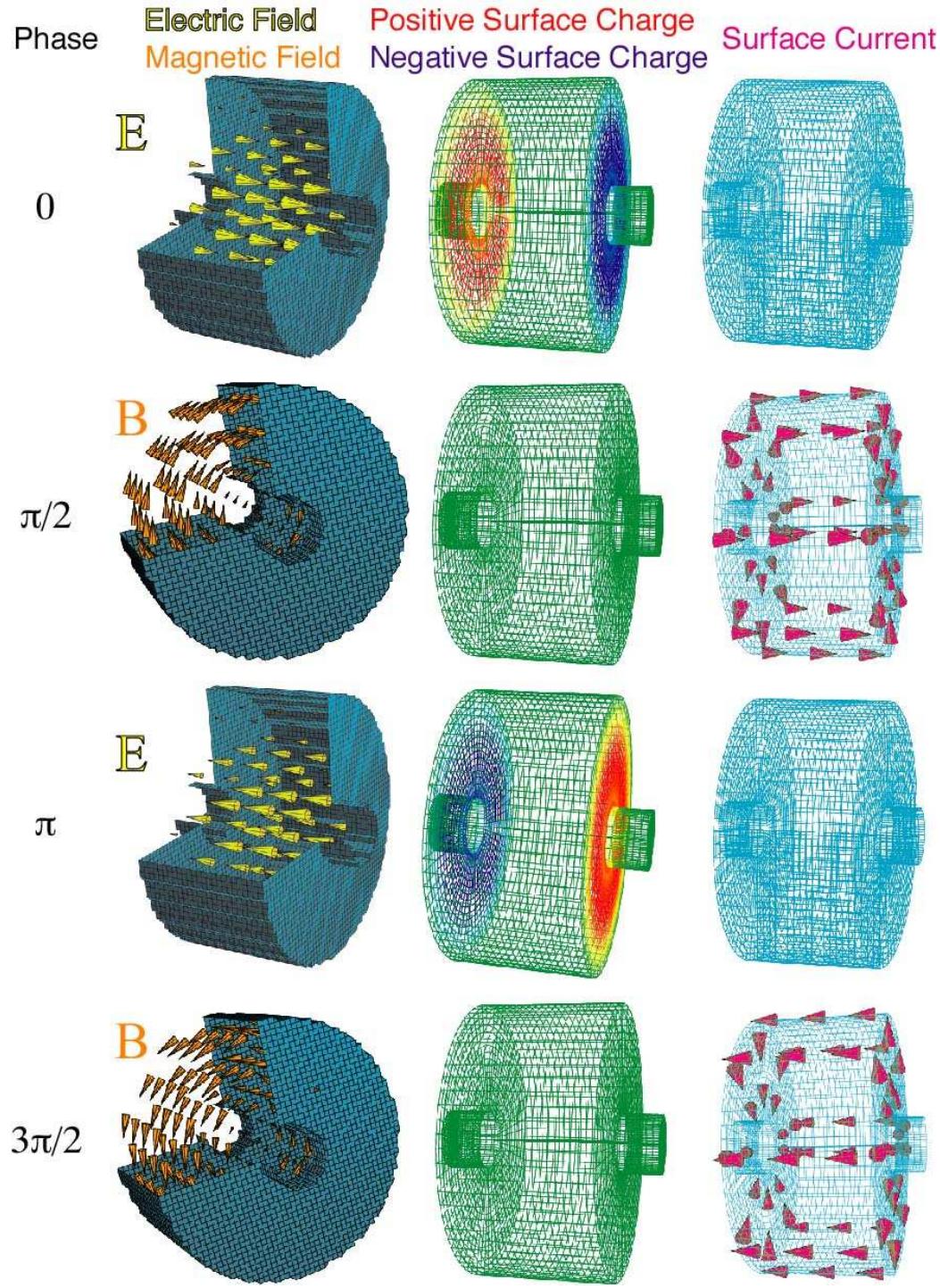
$$\omega_{010} = \frac{2.405c}{R},$$



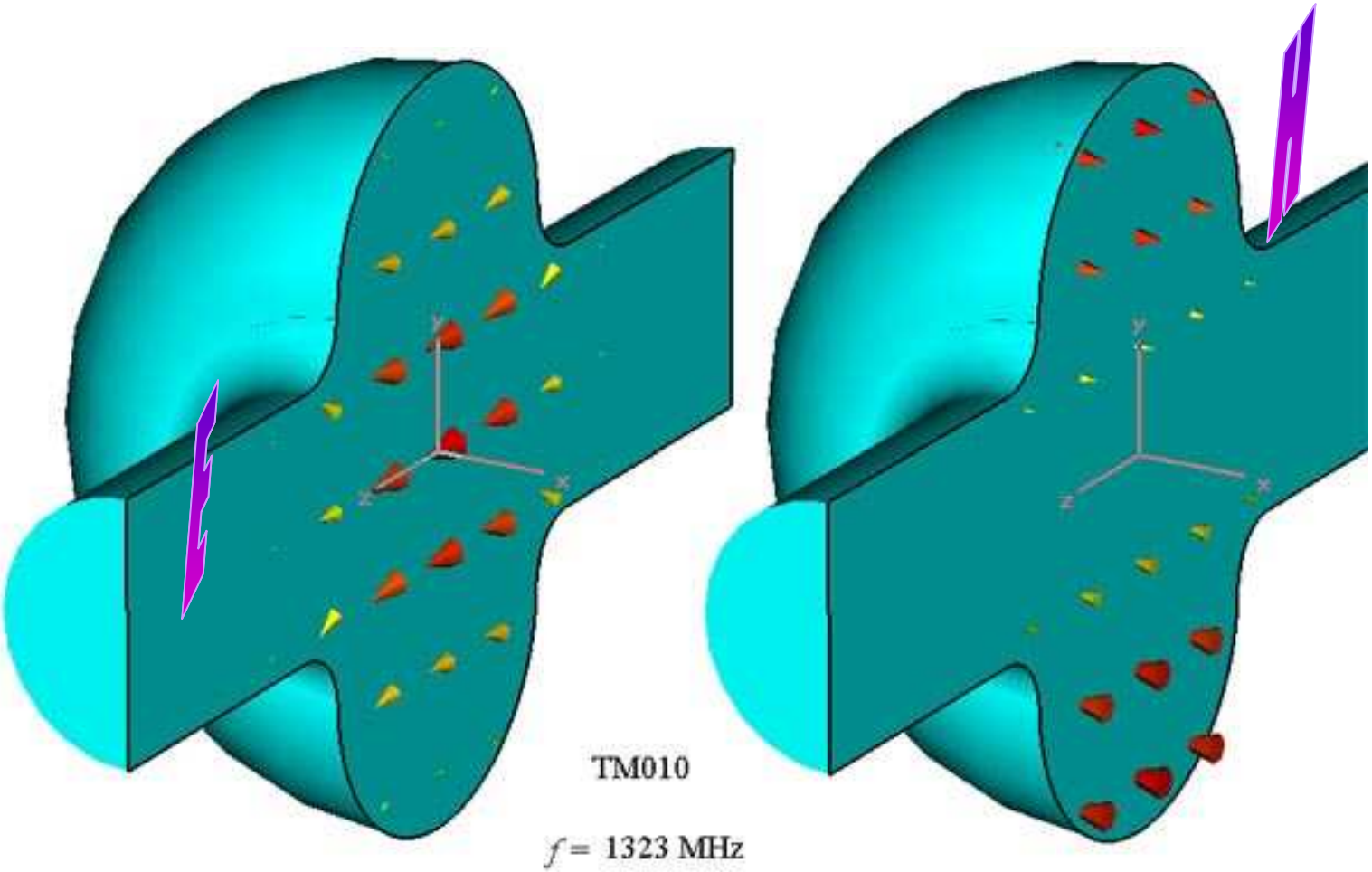
•Add beam tube for charge to enter and exit



RF accelerator cavities



Real shape



Single Cell Cavities

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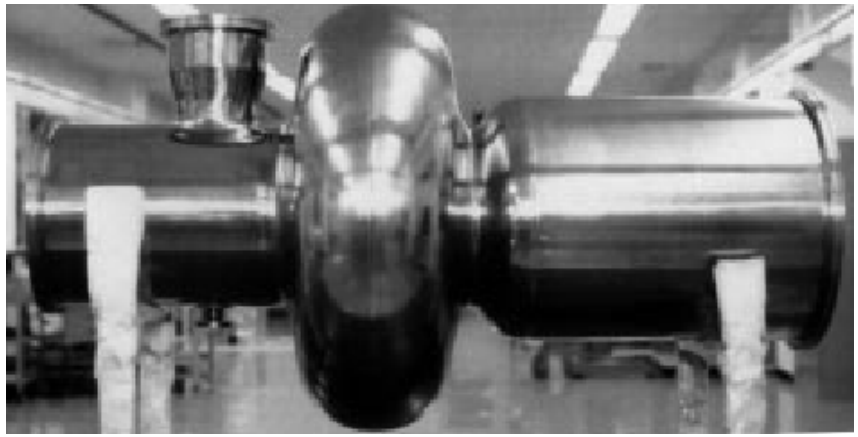
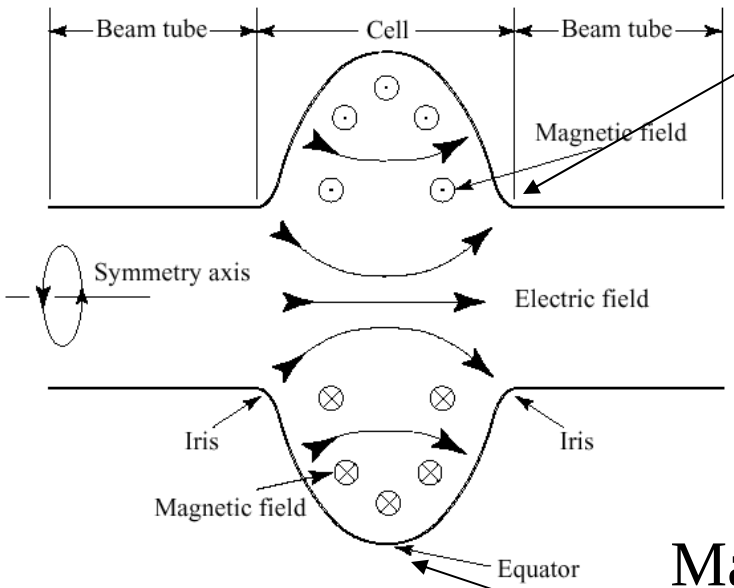
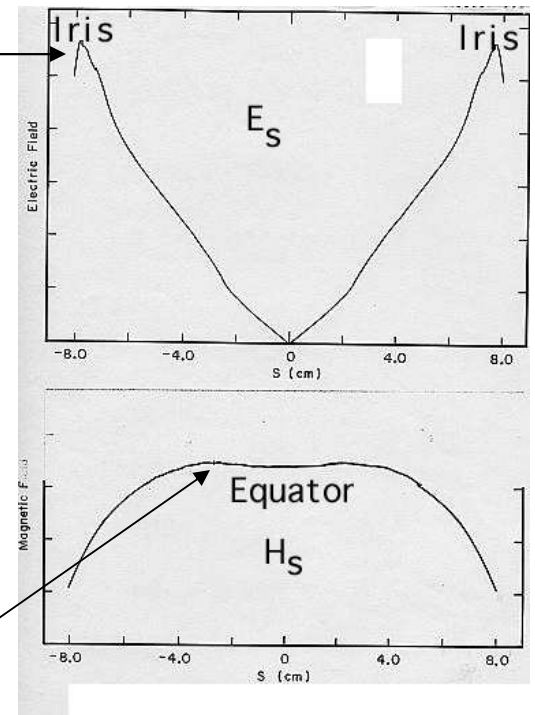
KEK-B Cavity



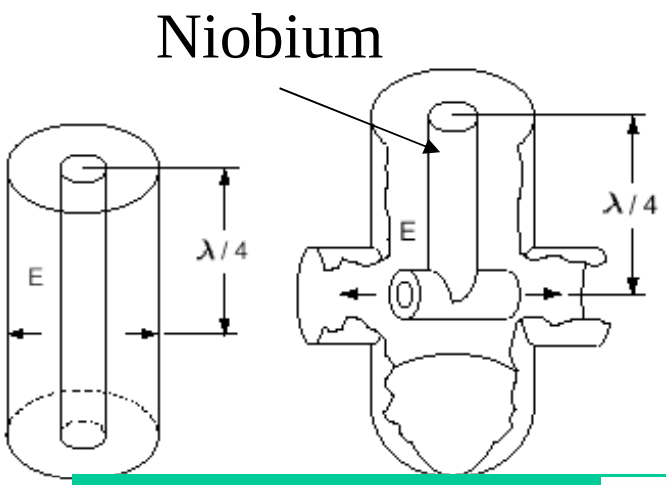
Electric field high at iris



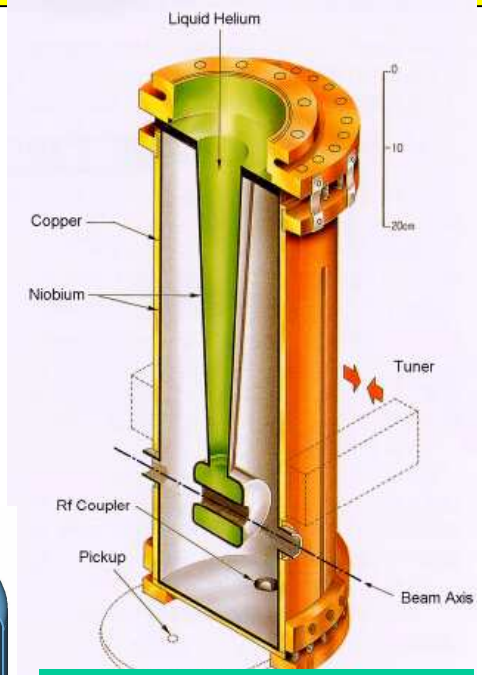


Magnetic field high at equator

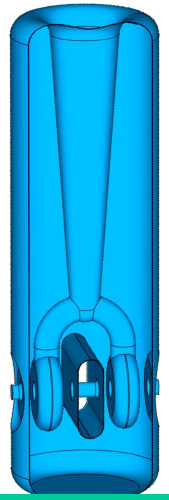
Low Velocity Structures, $\beta = v/c = 0.01 \rightarrow 0.2$



Basic Principle

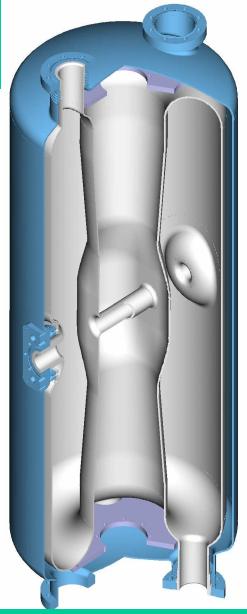


Quarter Wave



Inter-Digital

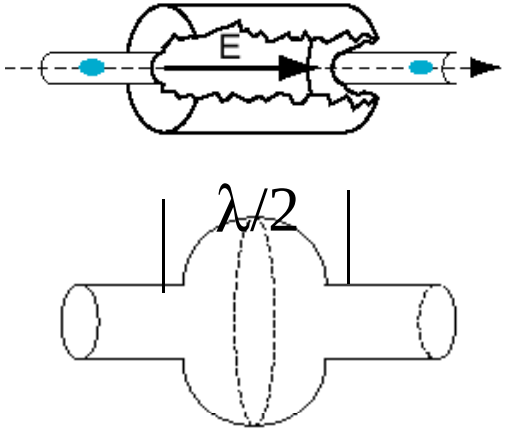
Split -Ring



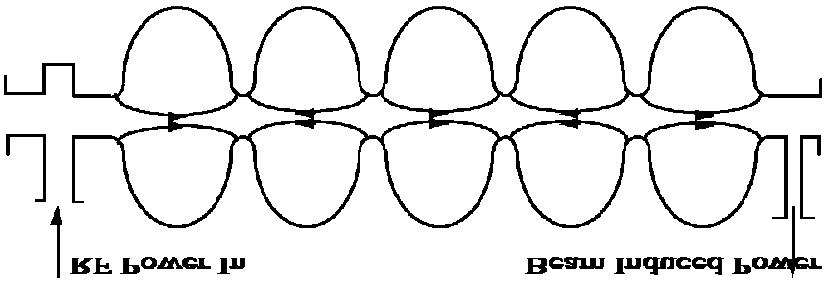
Half-Wave

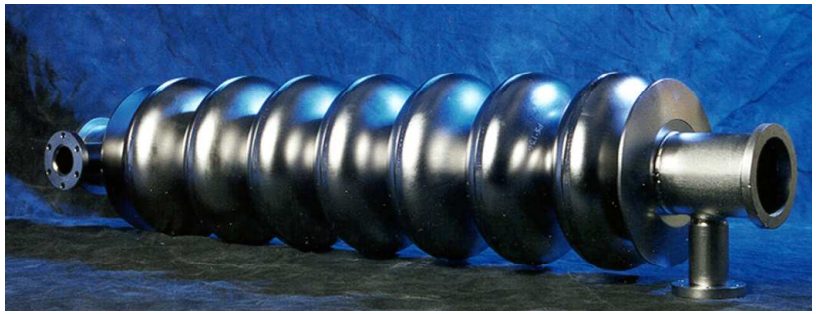
Spoke

Medium and High Velocity Structures $\beta = v/c = 0.5 \rightarrow 1$

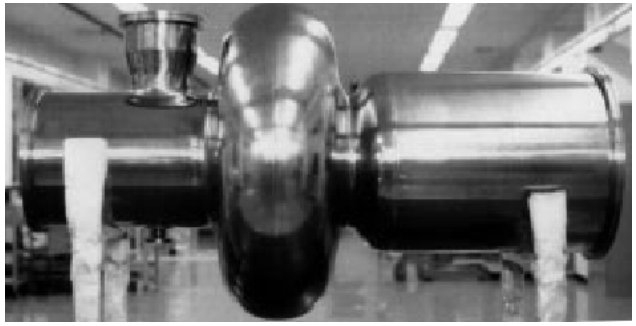


Basic Principle, v/c = 1

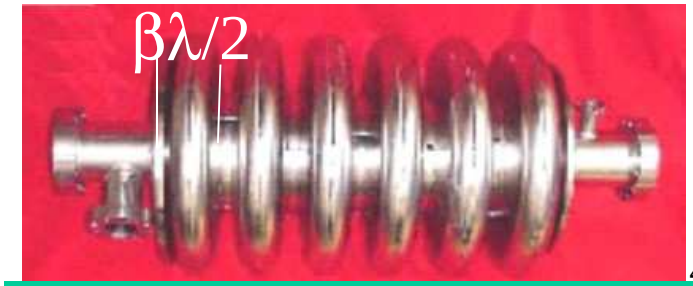




Multi-Cell Cavity



Single Cell



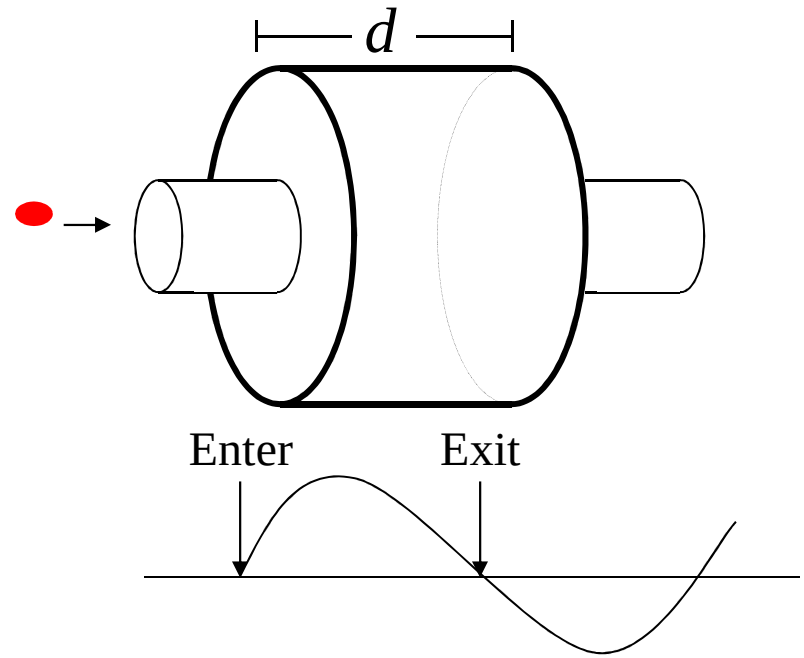
Squeezed Cells for v/c = 0.5

Figures of Merit
Accelerating Voltage/Field, Eacc
(*v* = *c* Particles)

- For maximum acceleration need

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

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



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

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

- Accelerating field is: $E_{\text{acc}} = \frac{V_{\text{c}}}{d} = 2E_0/\pi.$

Figures of Merit
Peak Fields

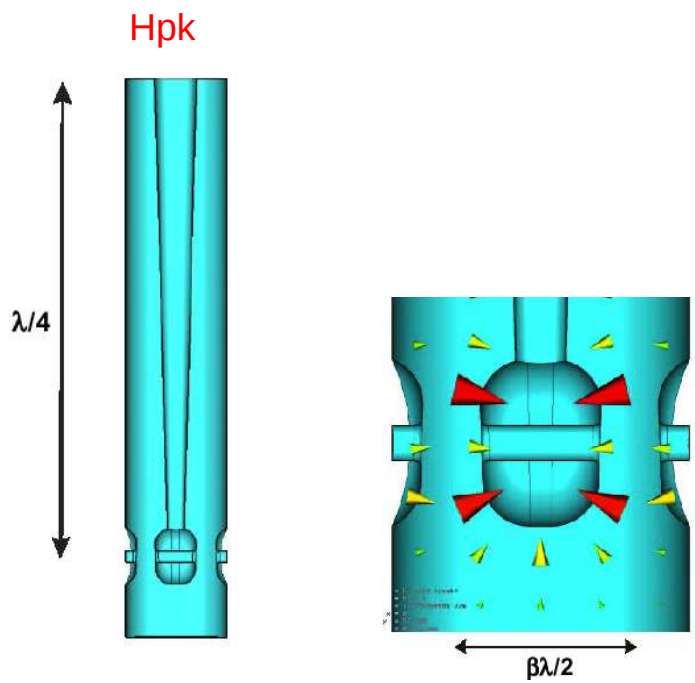
- *For* E_{acc} → important parameter is $\boldsymbol{E_{pk}/E_{acc}}$,
  - Typically 2 - 2.6
- Make as small as possible, to avoid problems with field emission - more later.
- Equally important is $\boldsymbol{H_{pk}/E_{acc}}$, to maintain SC
  - Typically 40 - 50 Oe/MV/m
- $\boldsymbol{H_{pk}/E_{acc}}$ 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

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

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

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.

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

If $R_s = 20\ \mathrm{n}\Omega$ $\qquad Q_0 = \frac{G}{R_s} = 1.3 \times 10^{10}.$

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:

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

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

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.
- → Use numerical codes.
- E.g., Superfish, MAFIA, SuperLans (finite difference and finite element)

Accelerating Mode

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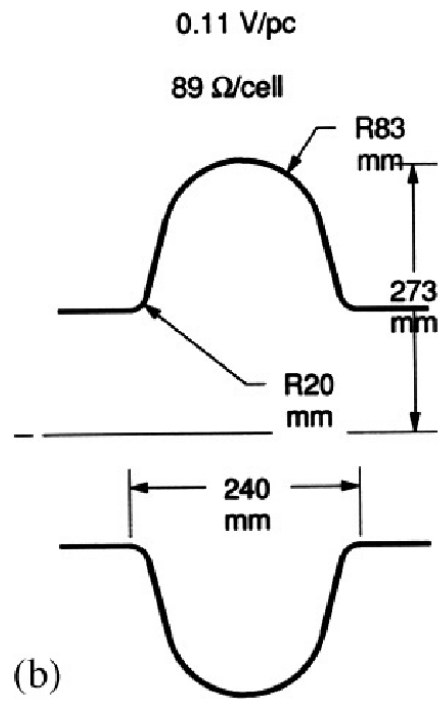
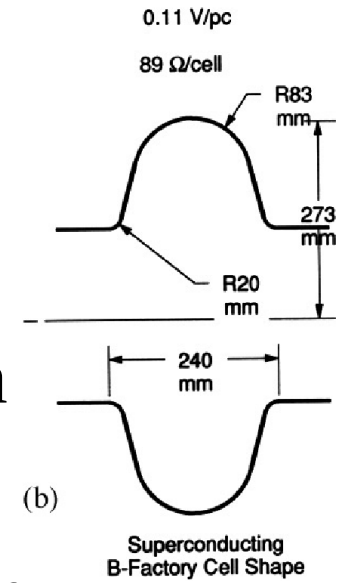


Superconducting
B-Factory Cell Shape

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



- 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

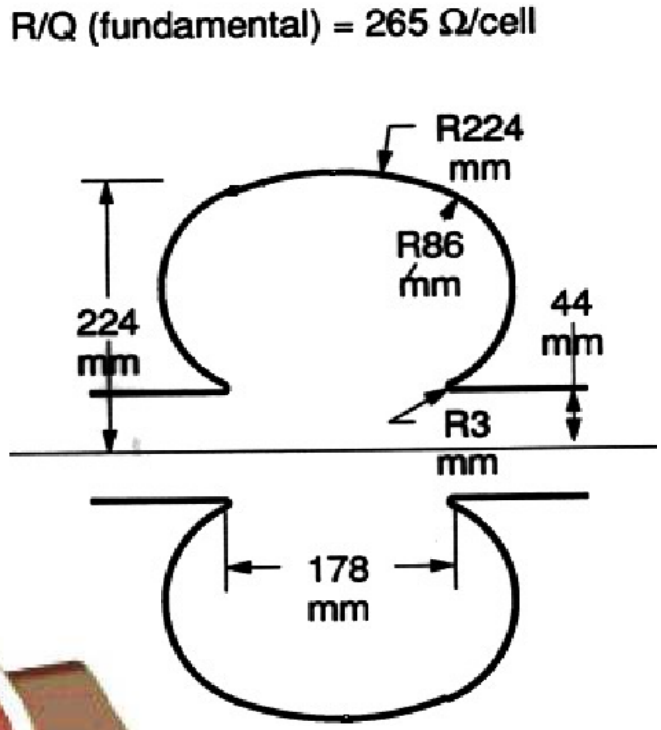
$$P_{\text{diss}} = \frac{V_{\text{acc}}^{2}}{R_{\text{a}}} * \boldsymbol{DF} = \frac{V_{\text{acc}}^{2}}{R_{\text{a}}/Q * Q} * \boldsymbol{DF}$$

Depends only on geometry.
→ Maximize this for copper cavities

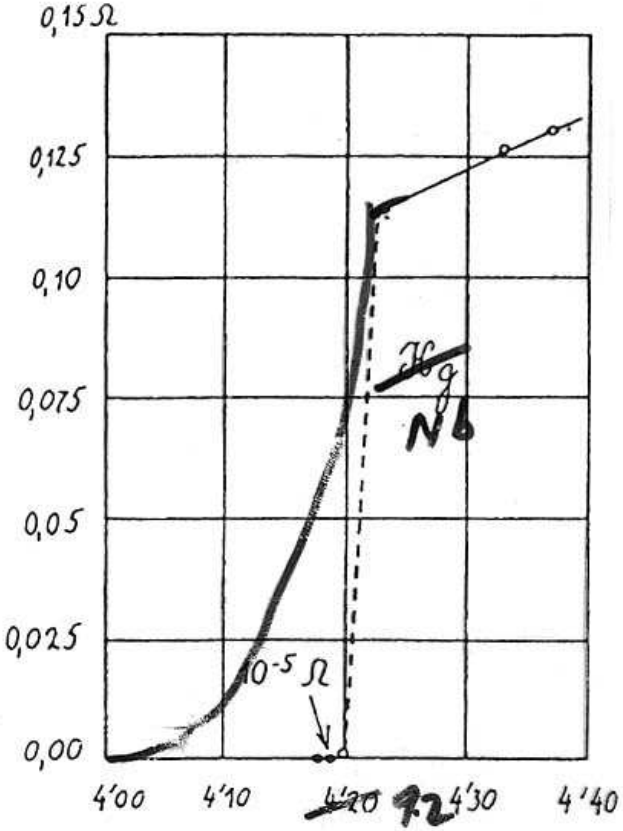
Determined by the material being used

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.
-



Enter Superconductivity



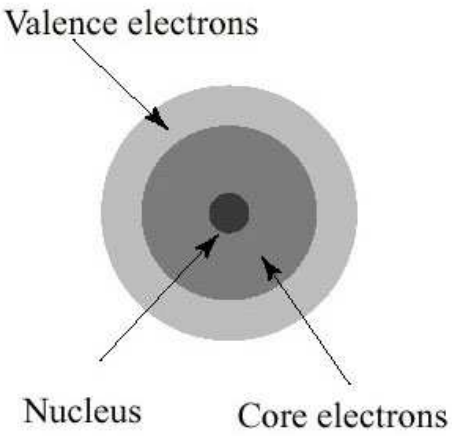
surement of superconductivity by Kamerlingh Onnes

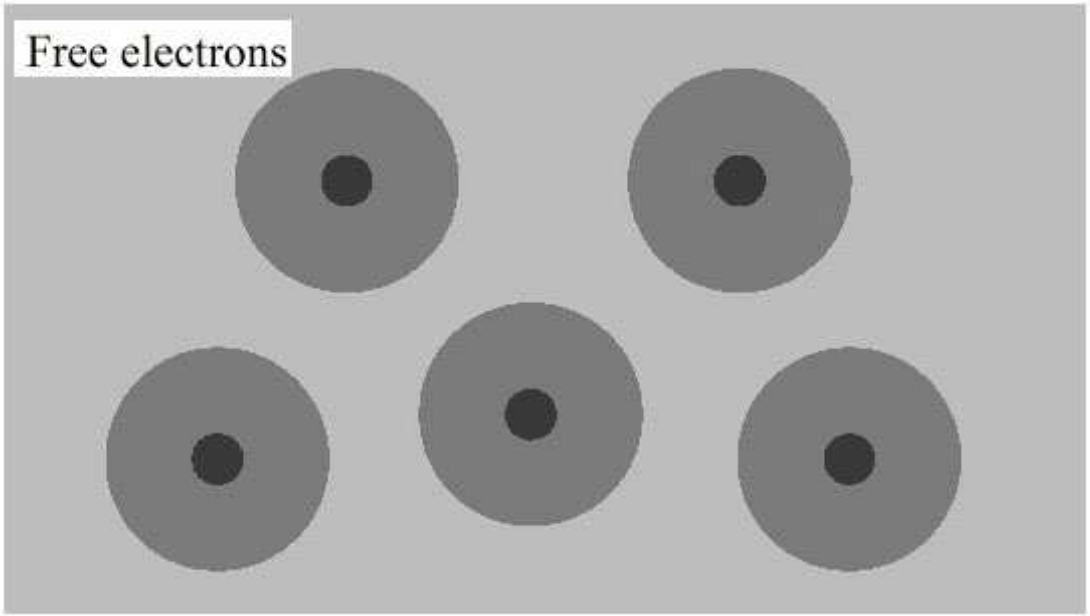
4 The Convergence of Classical Concepts

Figure 1-2. Heike Kamerlingh Onnes. Courtesy AIP Niels Bohr Library and

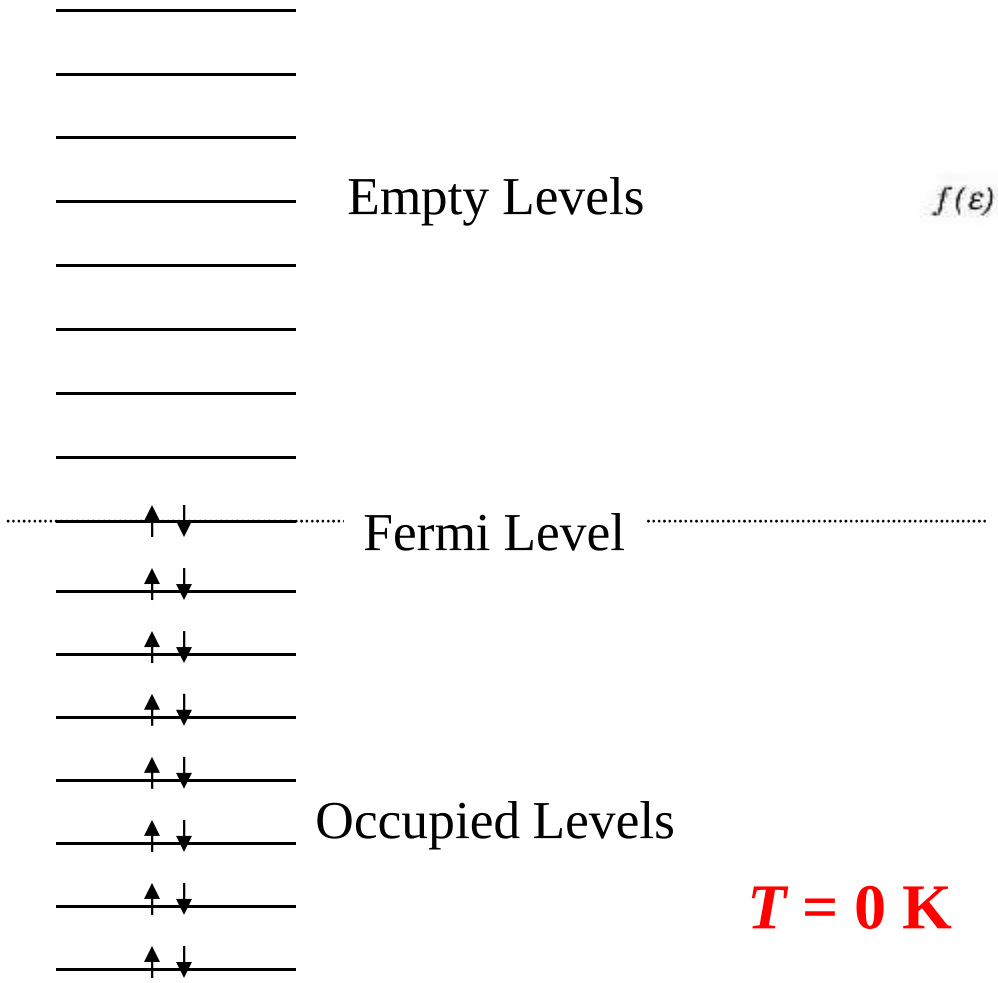
1911

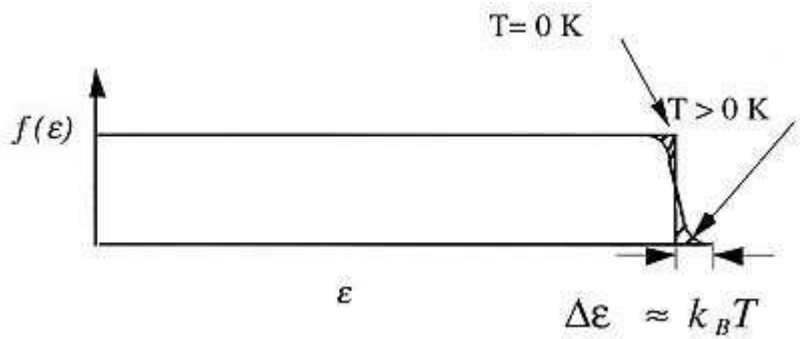
Electrons in Solids





Electron Energy Levels

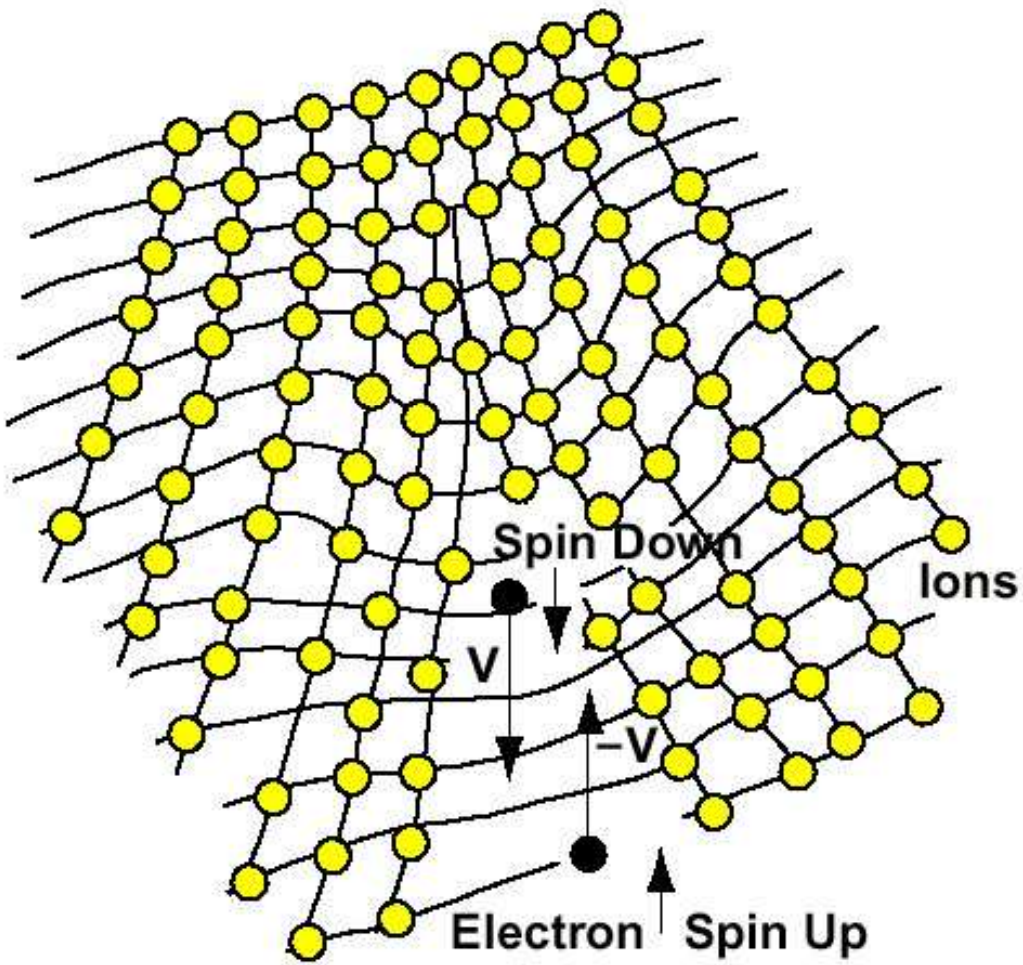




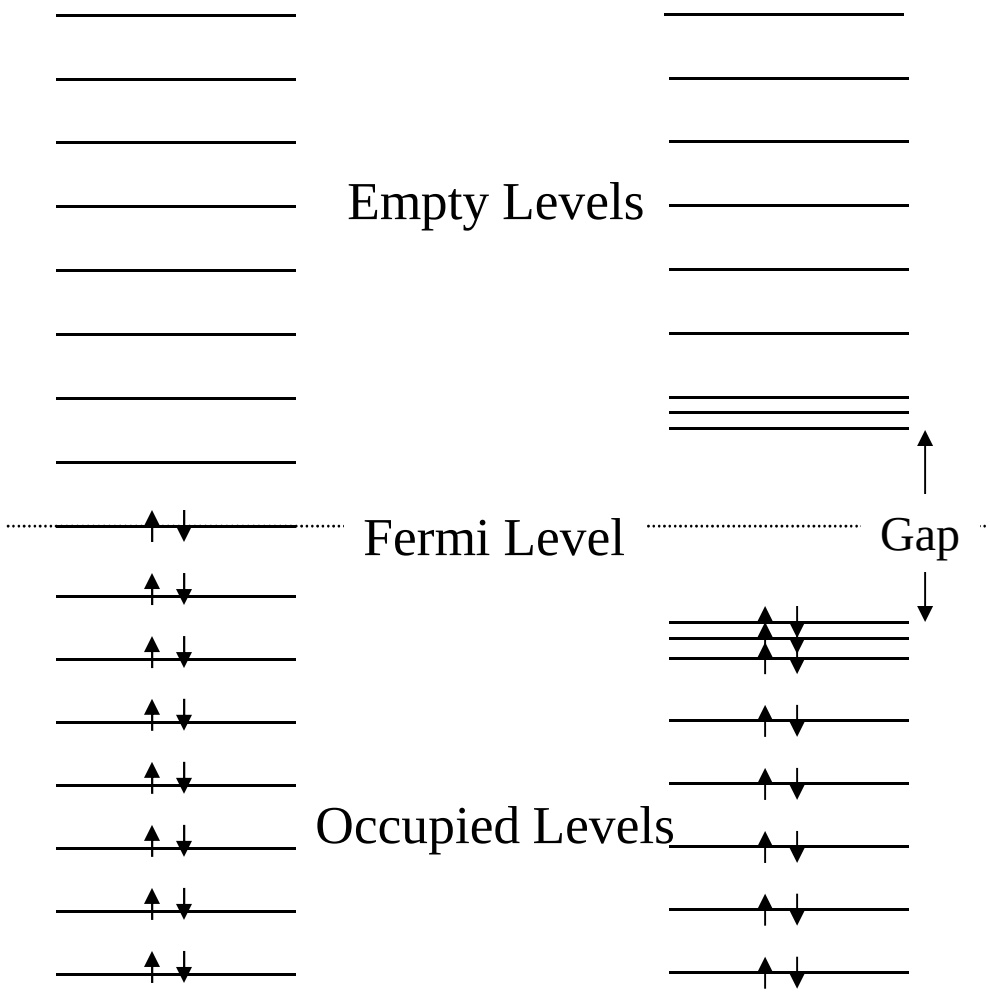
***T* = 0 K**

Normal conductor

Electron-Phonon Interaction



Superconductivity



Normal conductor

Superconductor (electrons form Cooper pairs)

***T* = 0 K**

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

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

→ *Two Fluid Model*

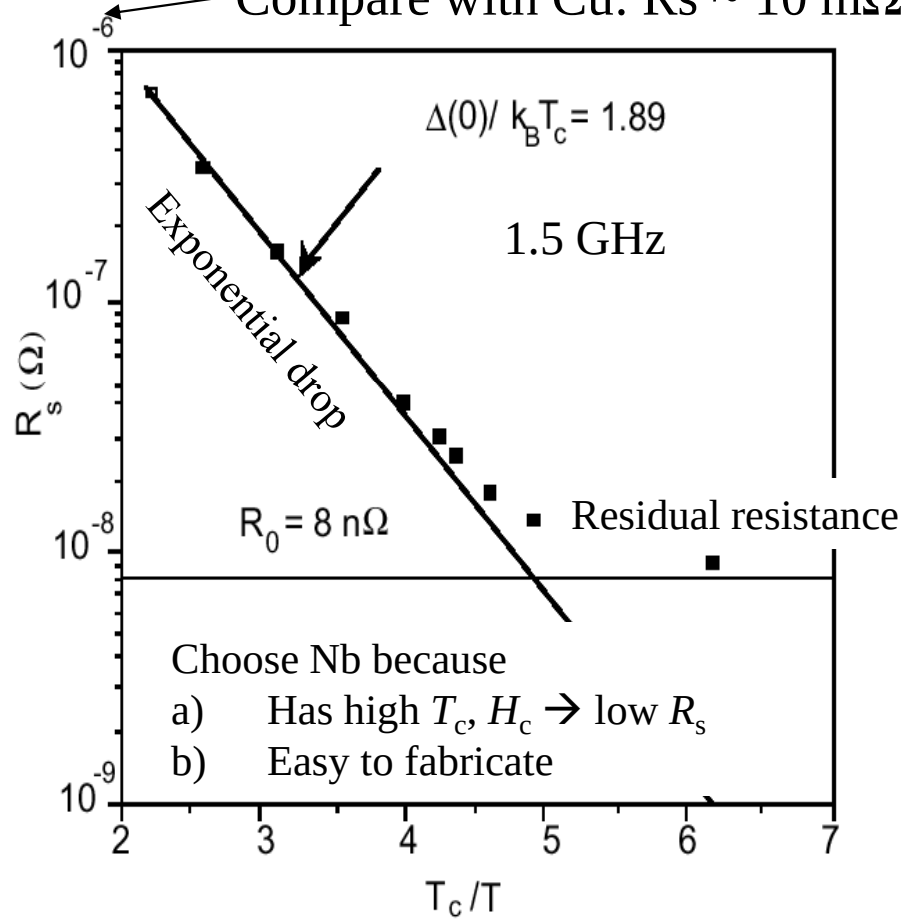
Superconductors: RF Resistance

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

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

More resistance the more the sc pairs are jiggled around

Compare with Cu: Rs ~ 10 mΩ



Choose Nb because
a) Has high T_c, H_c → low R_s
b) Easy to fabricate

More resistance the more NC electrons are excited

Low Field Frequency and Temperature Dependence of Rs

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

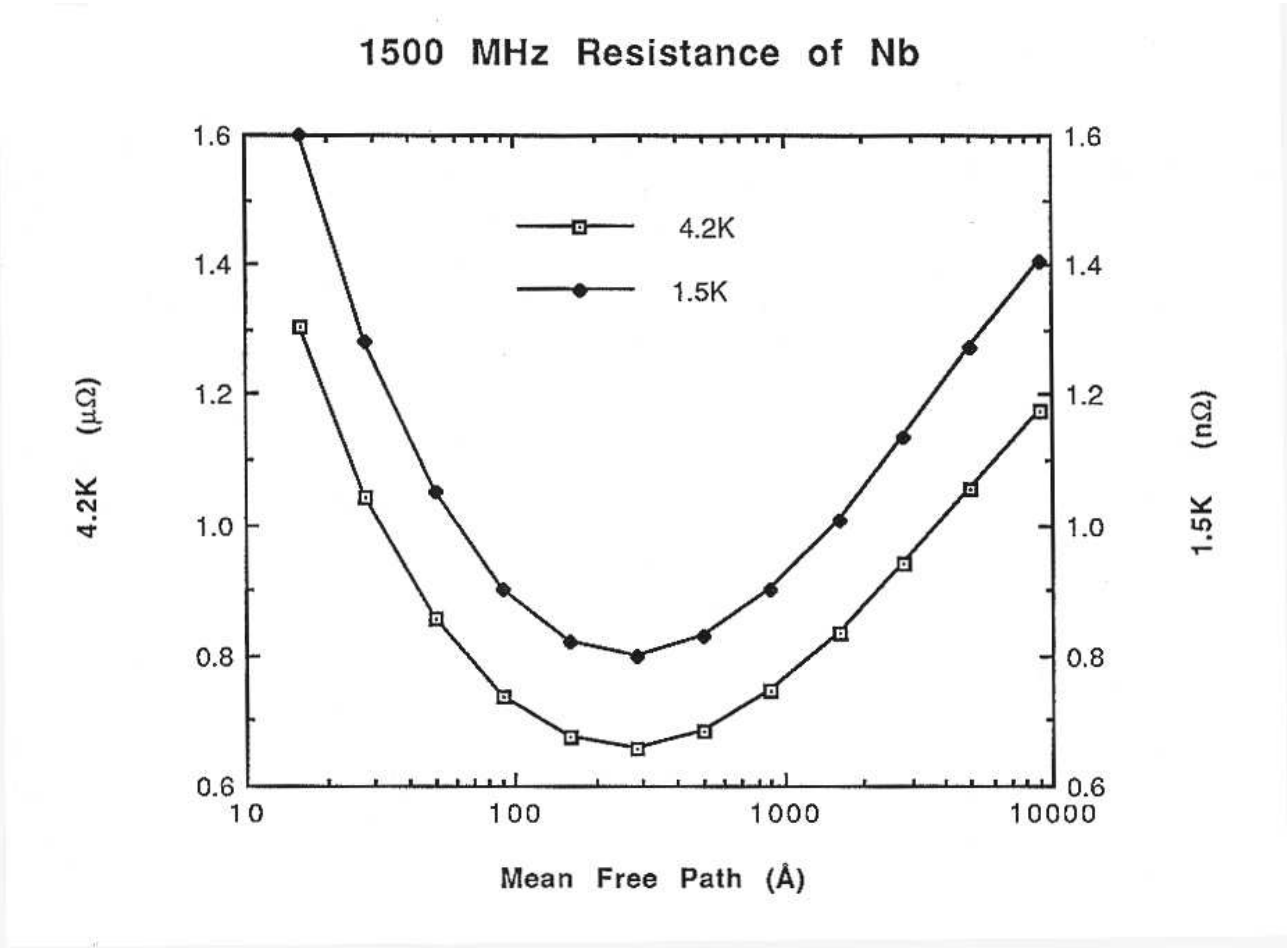
λ_L London penetration depth
ξ_0 Coherence length of Cooper pairs
v_F Fermi velocity
Δ_0 Energy gap
l electron mean free path
Tc = SC transition temperature

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

Good fitting function

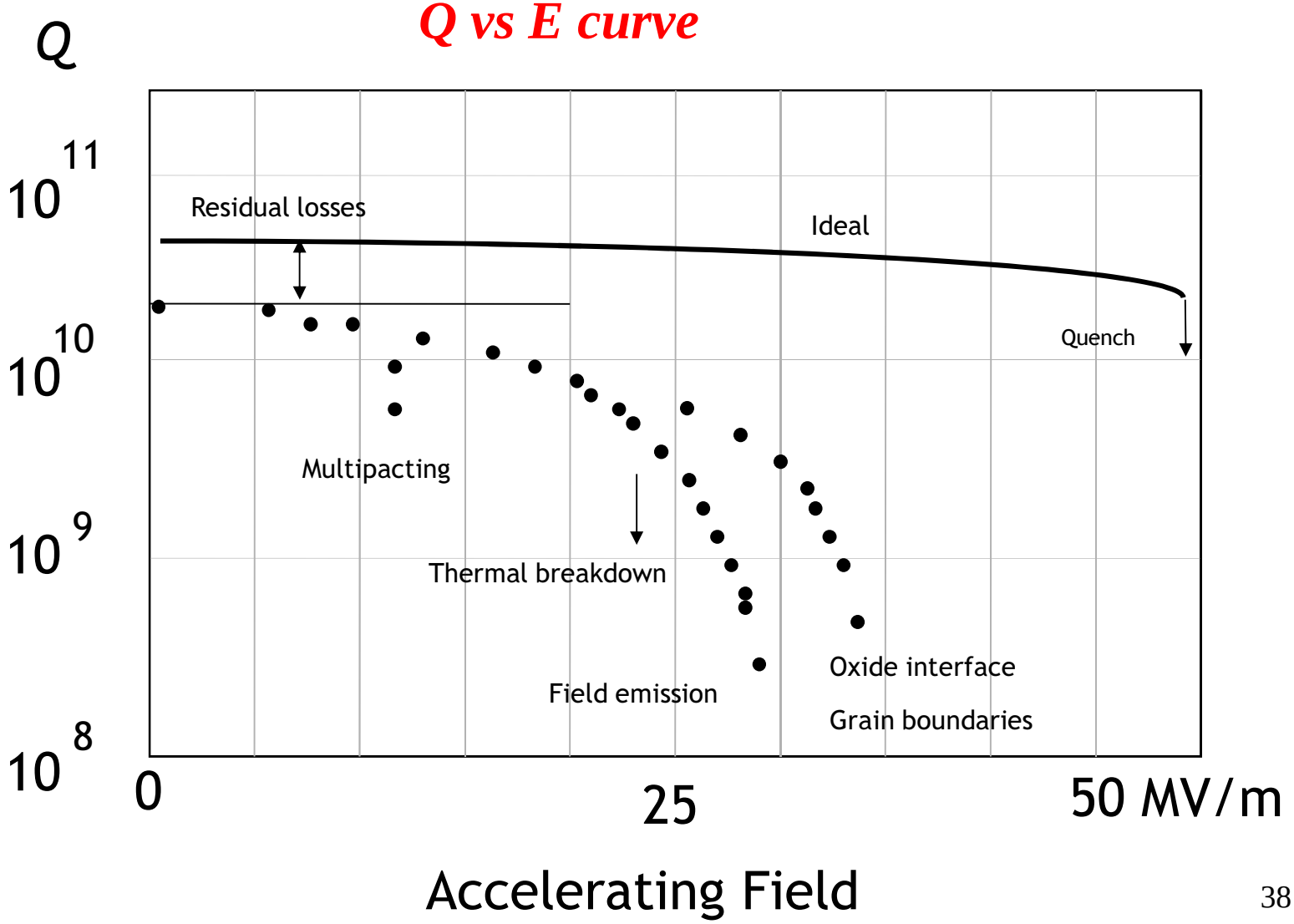
Surface Resistance

Influence of electron mean free path



Most Important Cavity Performance Characterization

Q vs E curve



Compare SC and NC FOR CW Application 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)

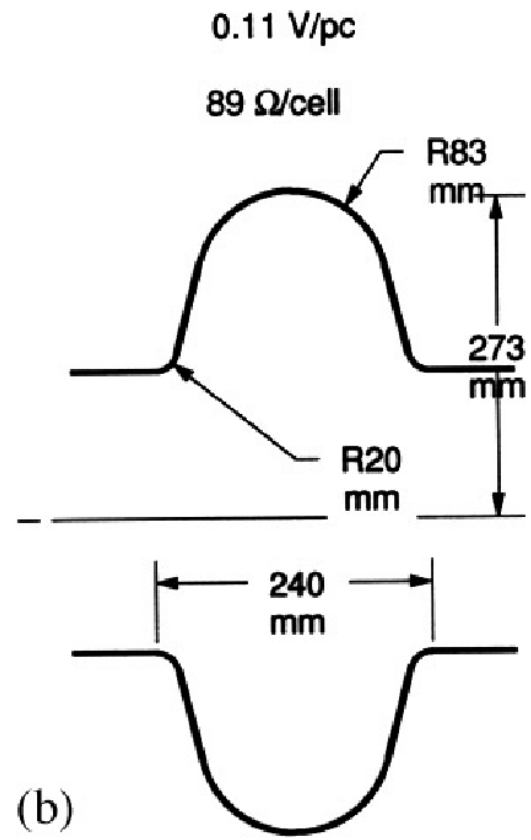
→ $R_a = 5.3 \times 10^{11}$

→ $P_{diss} = 1.9$ 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

Challenges of the SC option

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

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

$$\eta_{technical} = 0.20$$

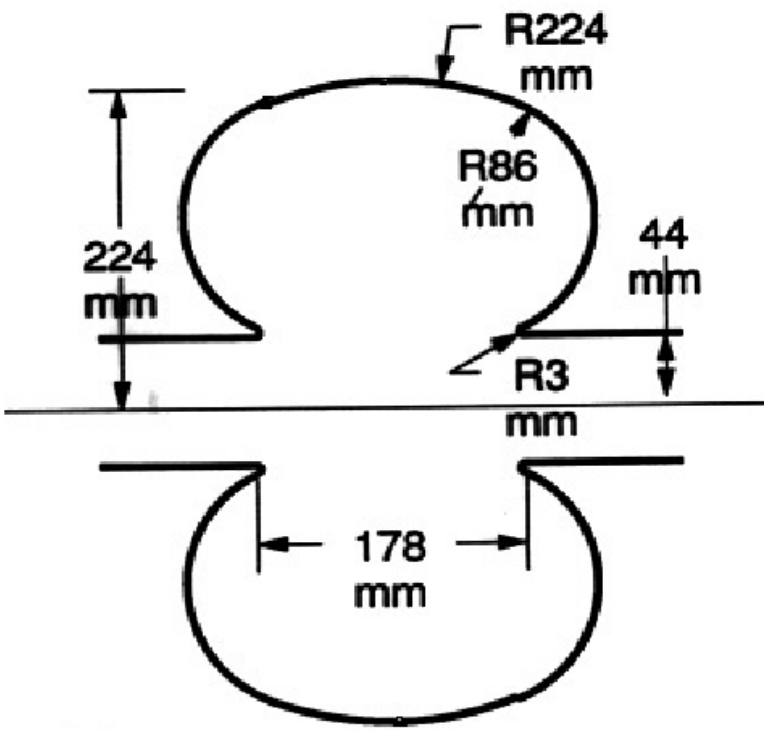
$$\eta_{total} = 0.003 = 1/333$$

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

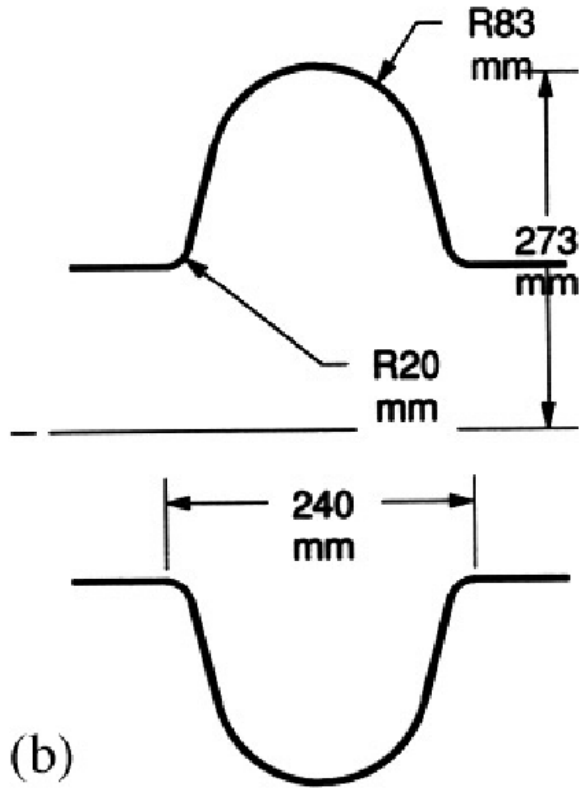
R/Q (fundamental) = 265 Ω/cell



Copper cavity shape

0.11 V/pc

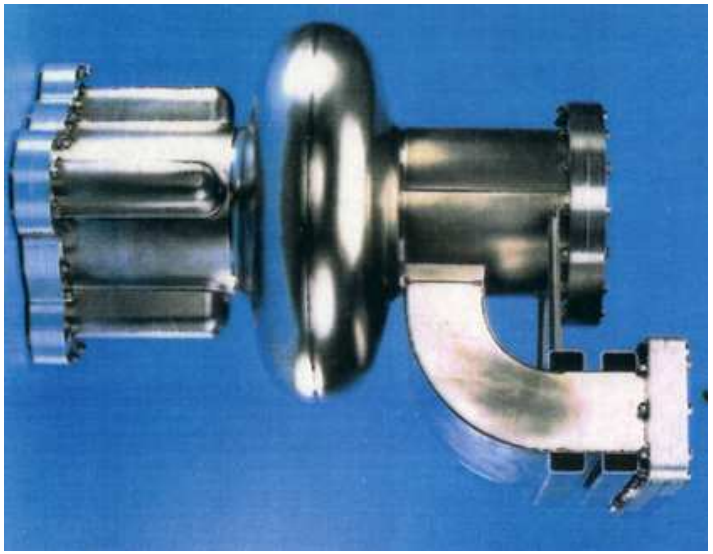
89 Ω/cell



Superconducting
B-Factory Cell Shape

CW RF Cavities for Storage Rings

Copper Cavity: PEP-II

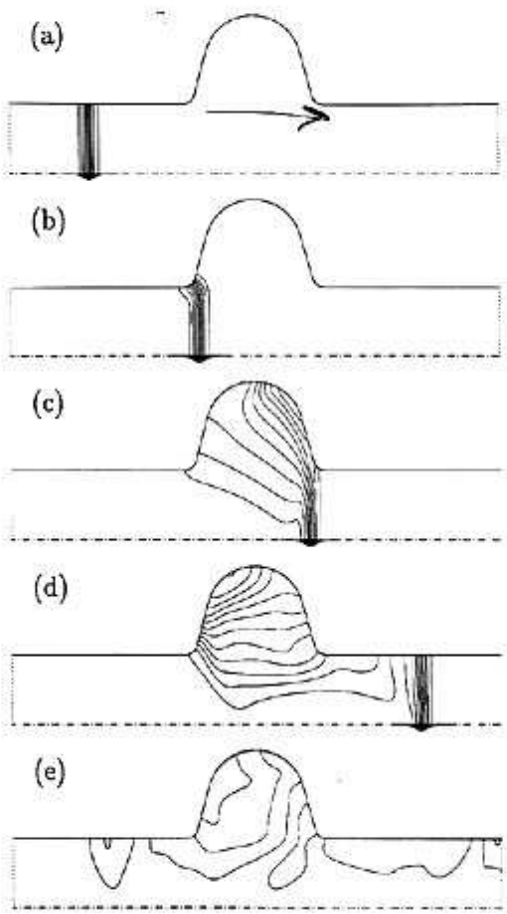


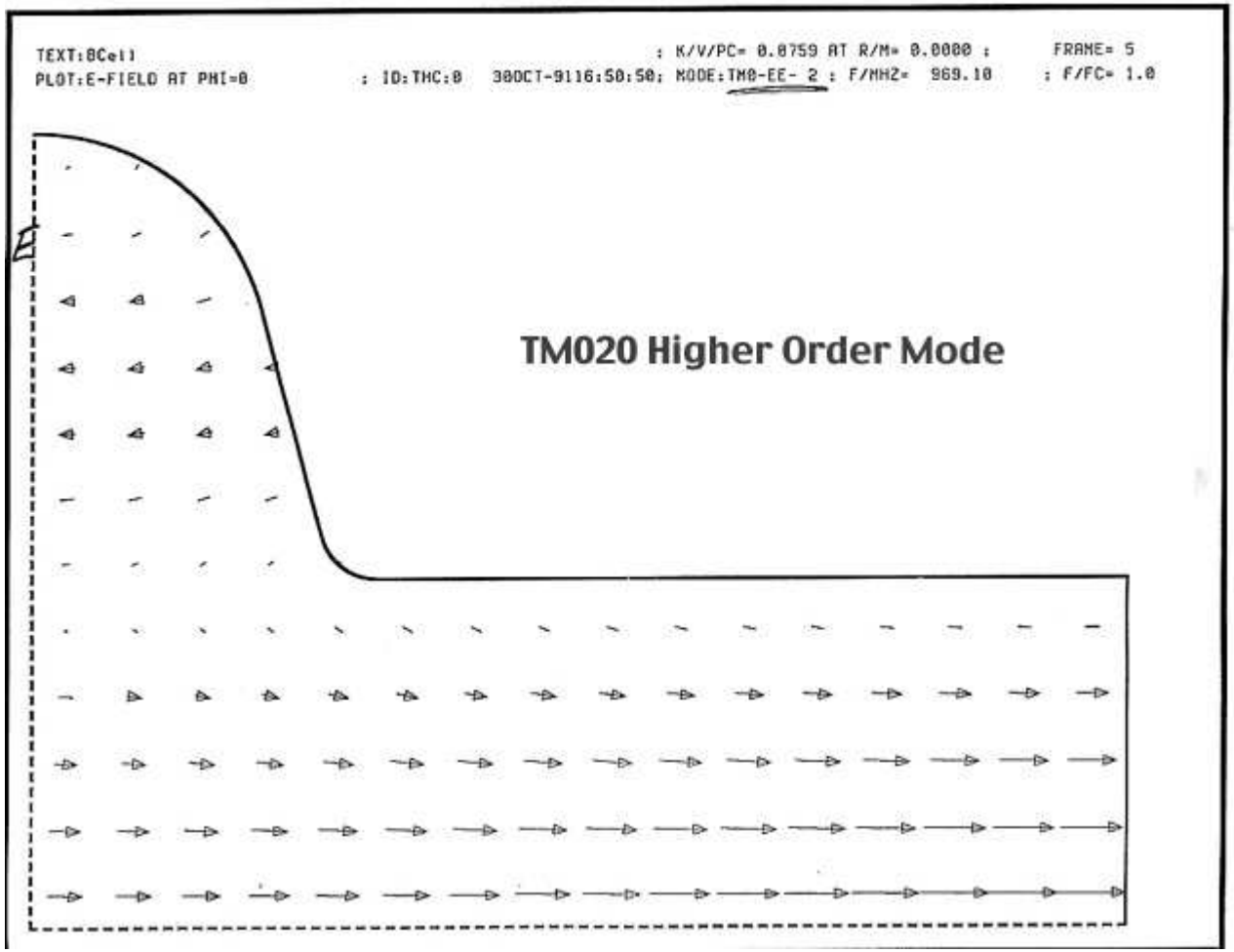
Superconducting Cavity:
CESR-III

Fundamental differences due to difference in wall losses

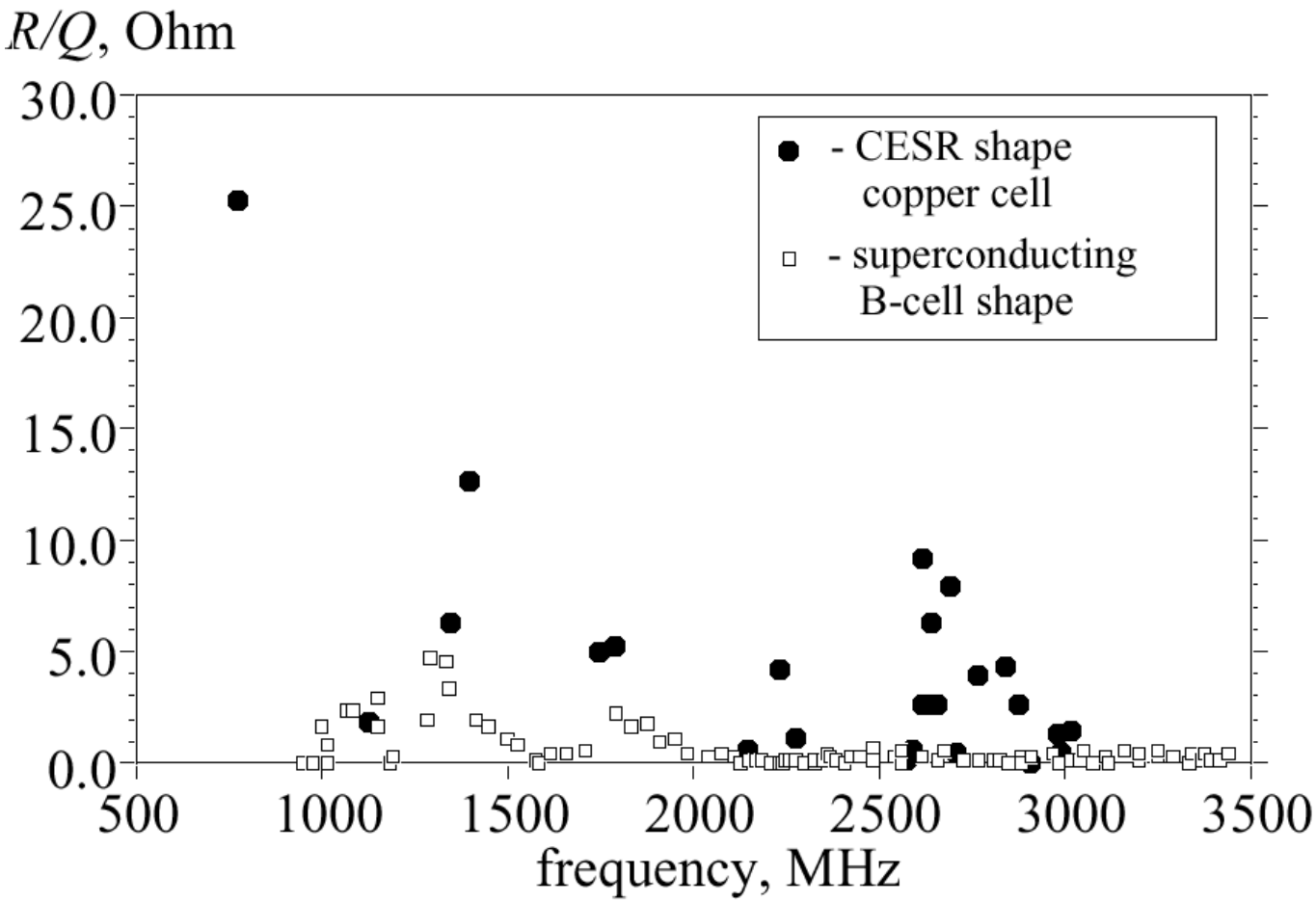
(Some) Further SC Advantages

- 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)

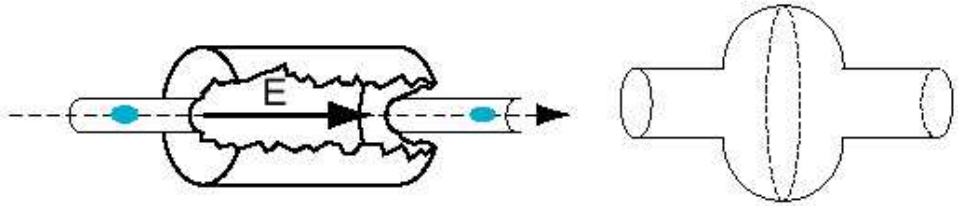



TEXT:8Cell
PLOT:E-FIELD AT PHI=0
: ID:THC:0 30OCT-9116:50:50; MODE:TM0-EE- 2 : F/MHZ= 969.10
: K/V/PC= 0.8759 AT R/M= 0.0000 :
FRAME= 5
: F/FC= 1.0
E
TM020 Higher Order Mode

Higher-Order Modes Impedance

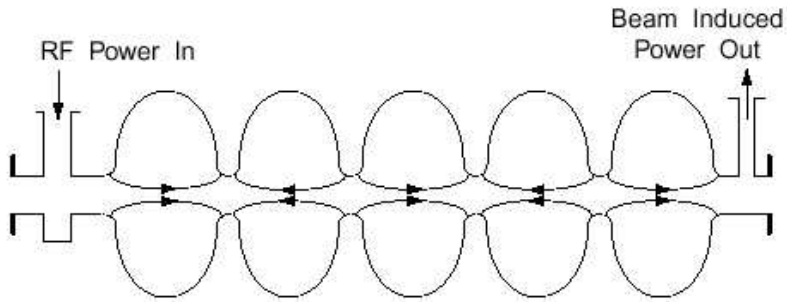


Multi-cell Cavities

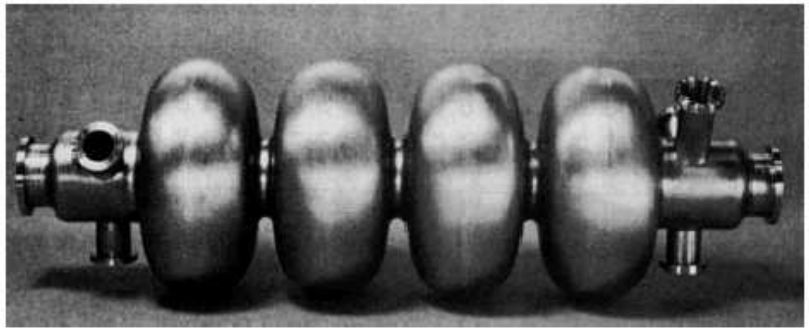


(a) (b)

Standing Wave Mode

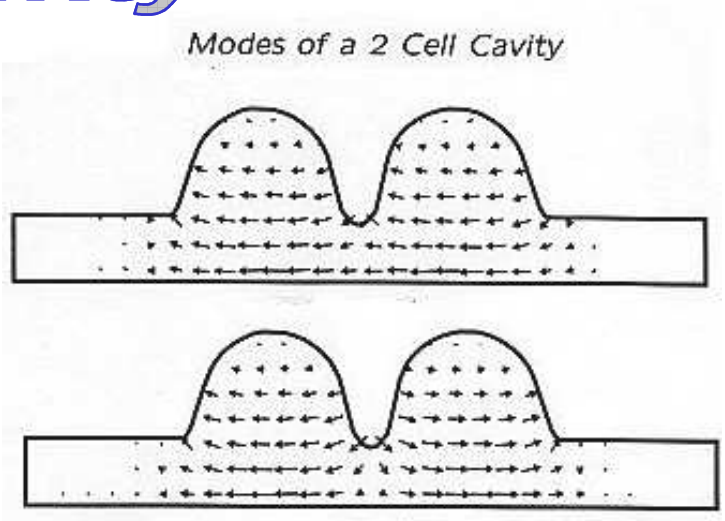


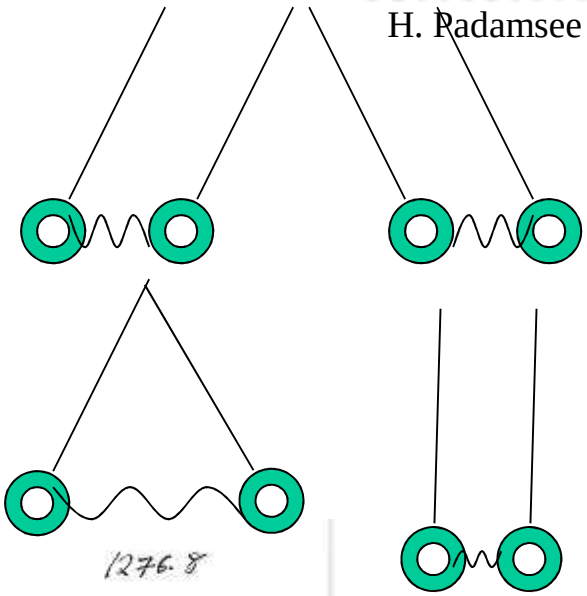
(c)



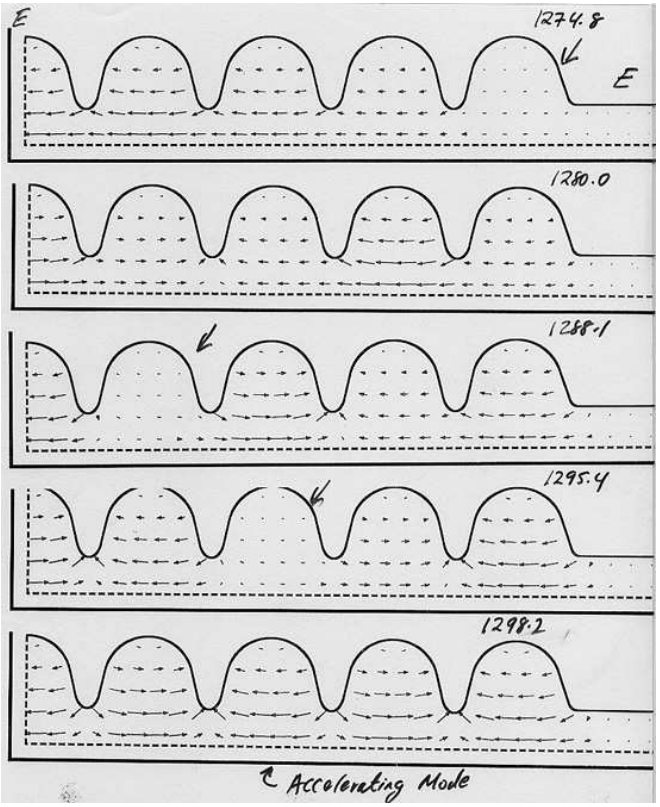
Multicell Cavity Modes

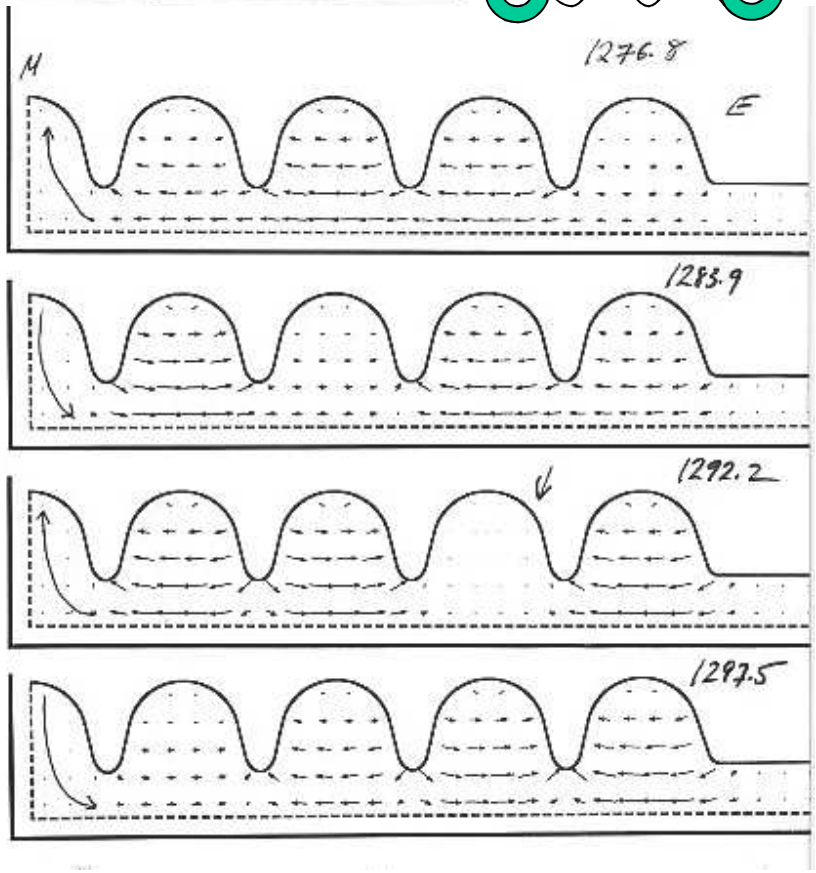
CORNELL UNIVERSITY
H. Padamsee



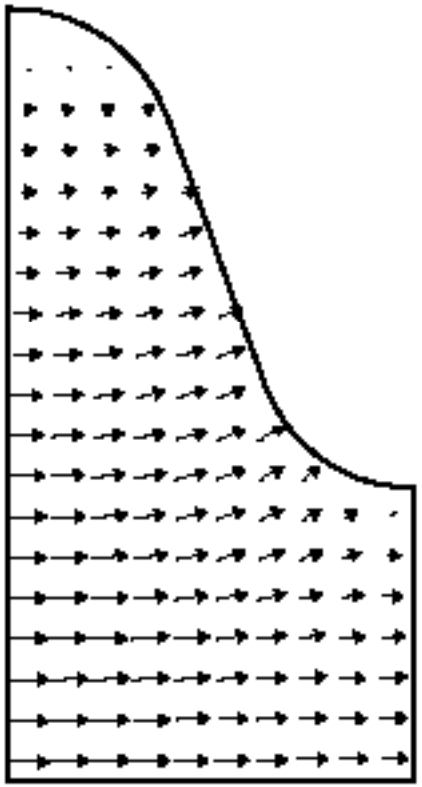


9-cell cavity

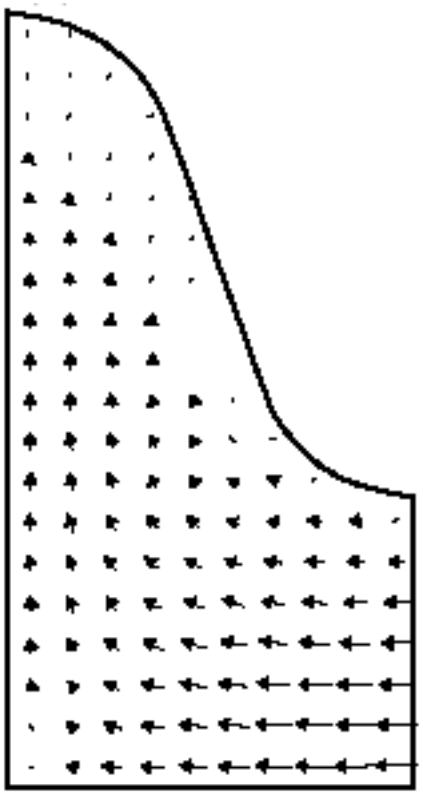




Boundary Conditions

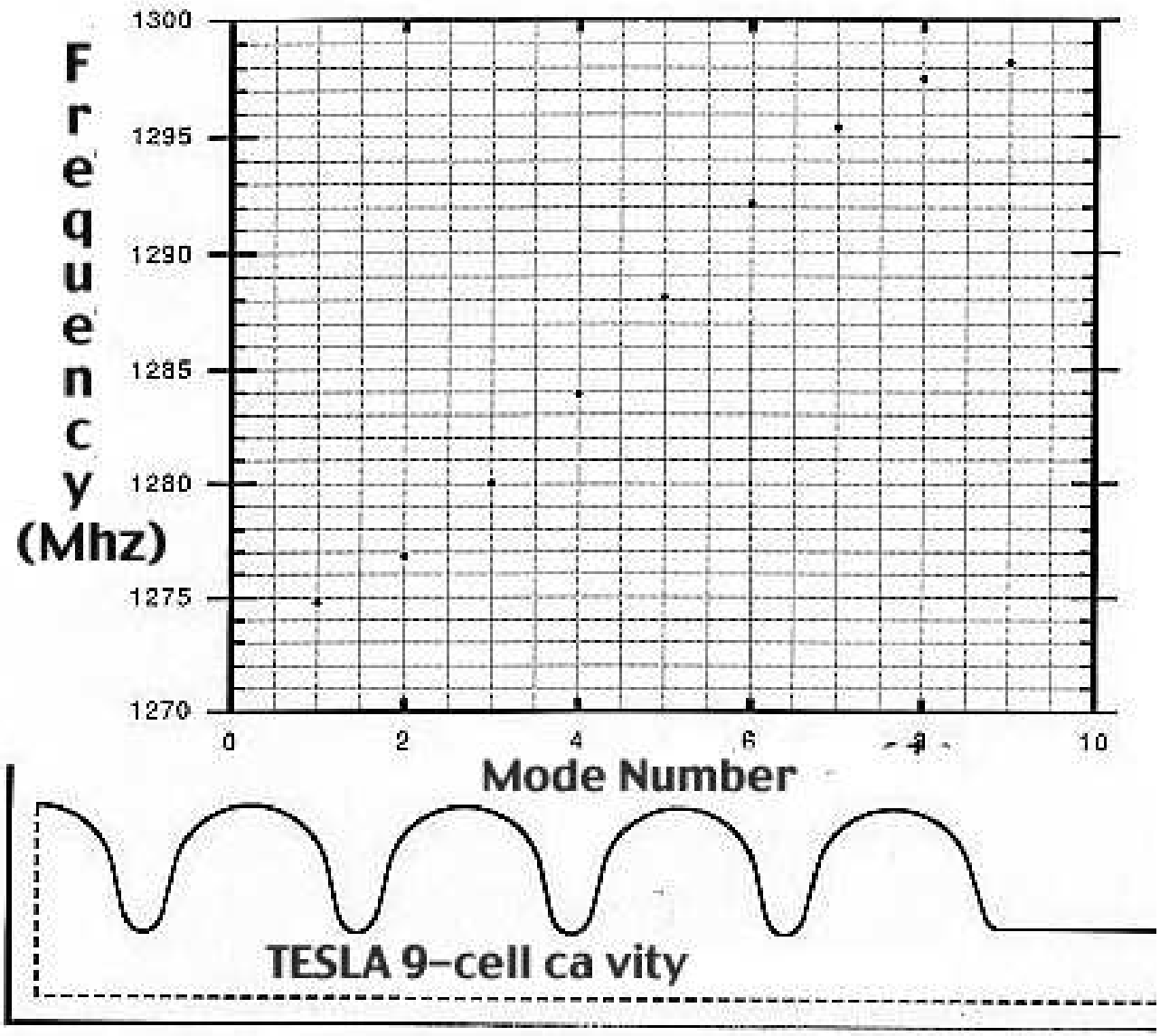


(a) Electric - Electric

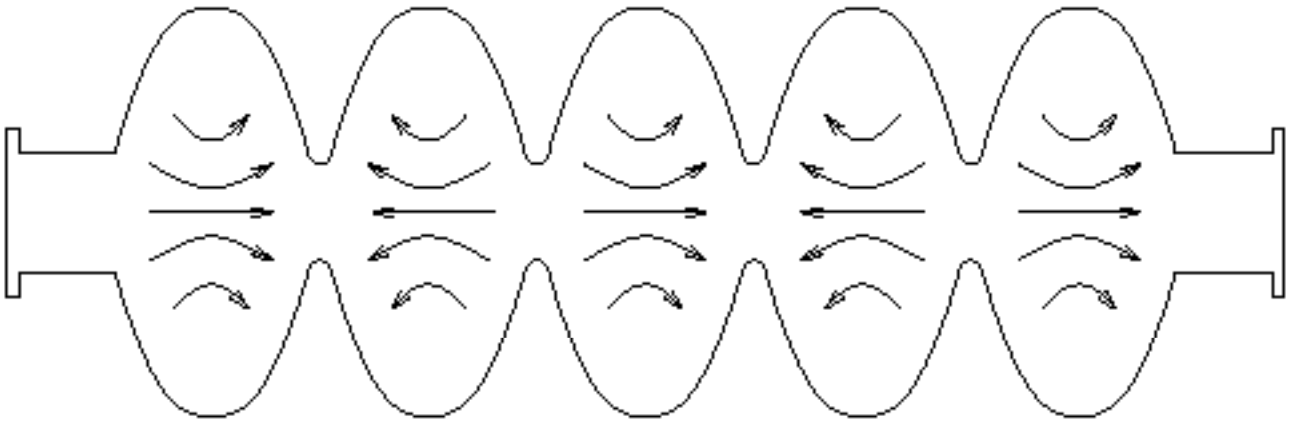


(c) Magnetic - Electric

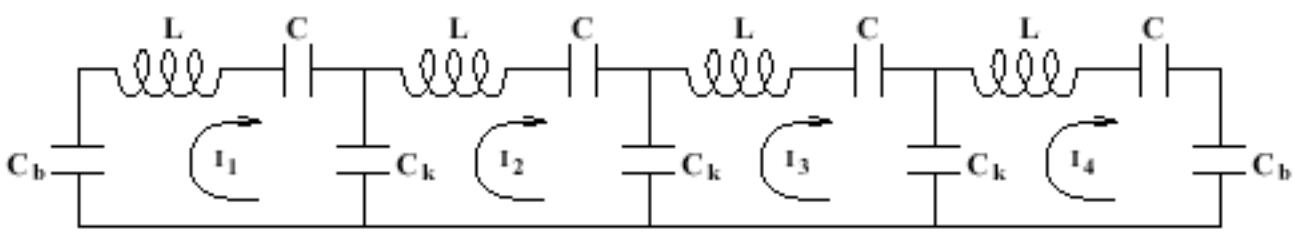
Dispersion Relation



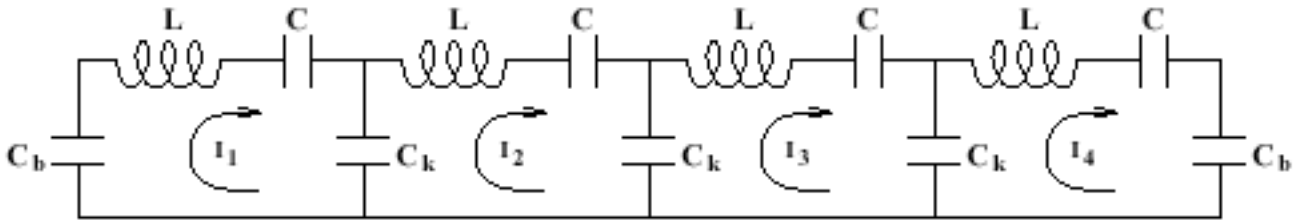
Circuit Model of MultiCells



: 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

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

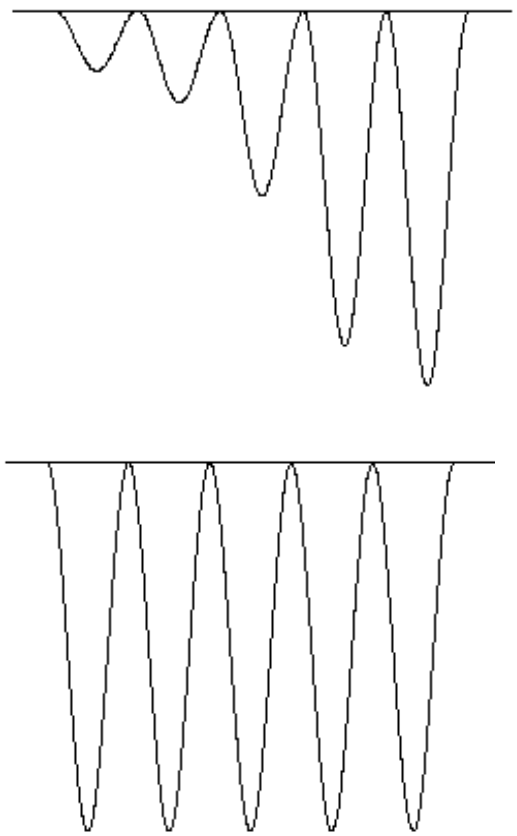
If we measure $f^{(N)}$ and $f^{(1)}$, this becomes

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

Mode spacing increases with stronger cell to cell coupling k
Mode spacing decreases with increasing number of cells N

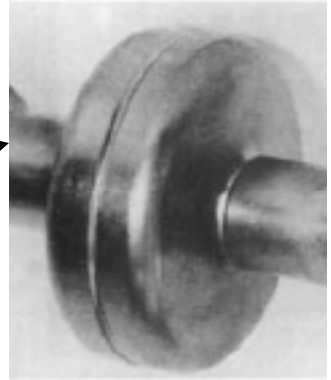
Field Flatness

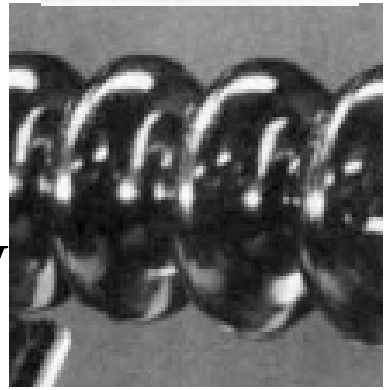
- Stronger cell-to-cell coupling (k) and smaller number of cells N means
  - Field flatness is less sensitive to mechanical differences between cells



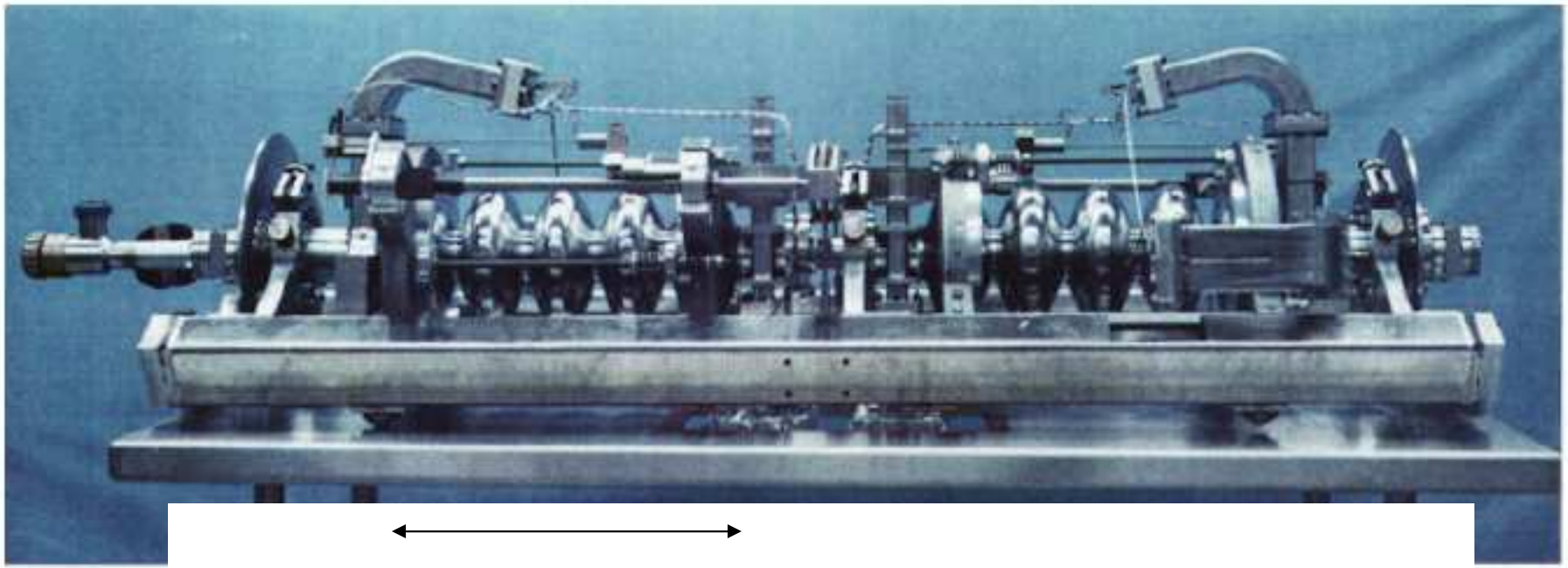
Apart from EM Properties Mechanical Properties Are Also Important to Cavity Design

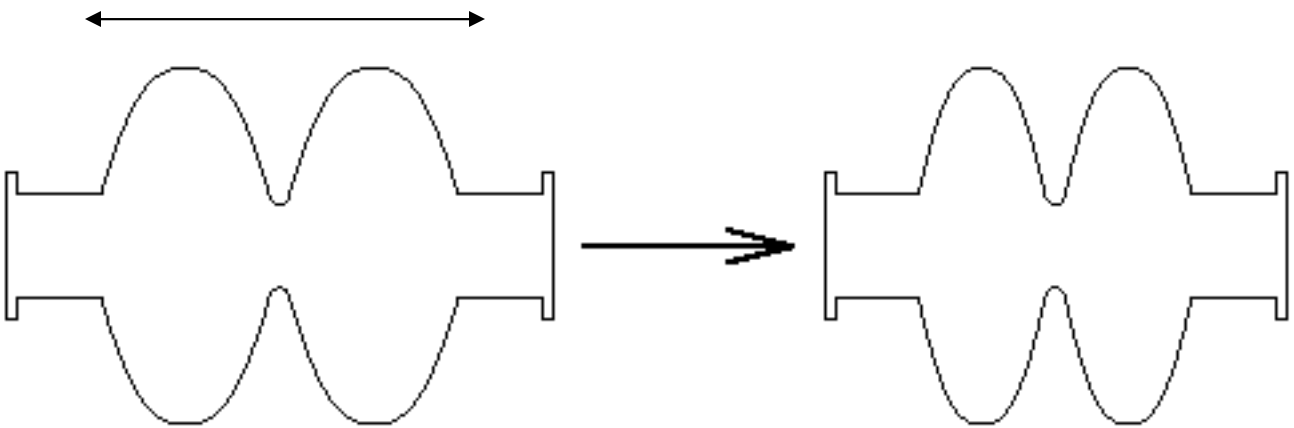
- Cavity should not collapse or deform too much under atmospheric load
- Shape
  - avoid flat regions
  - Elliptical profile is stronger
- Choose sufficient wall thickness
- Use tuner to bring to right frequency





Tuning for Right Frequency





Detuning, Problem for pulsed operation as for TESLA

LORENTZ FORCE DETUNING

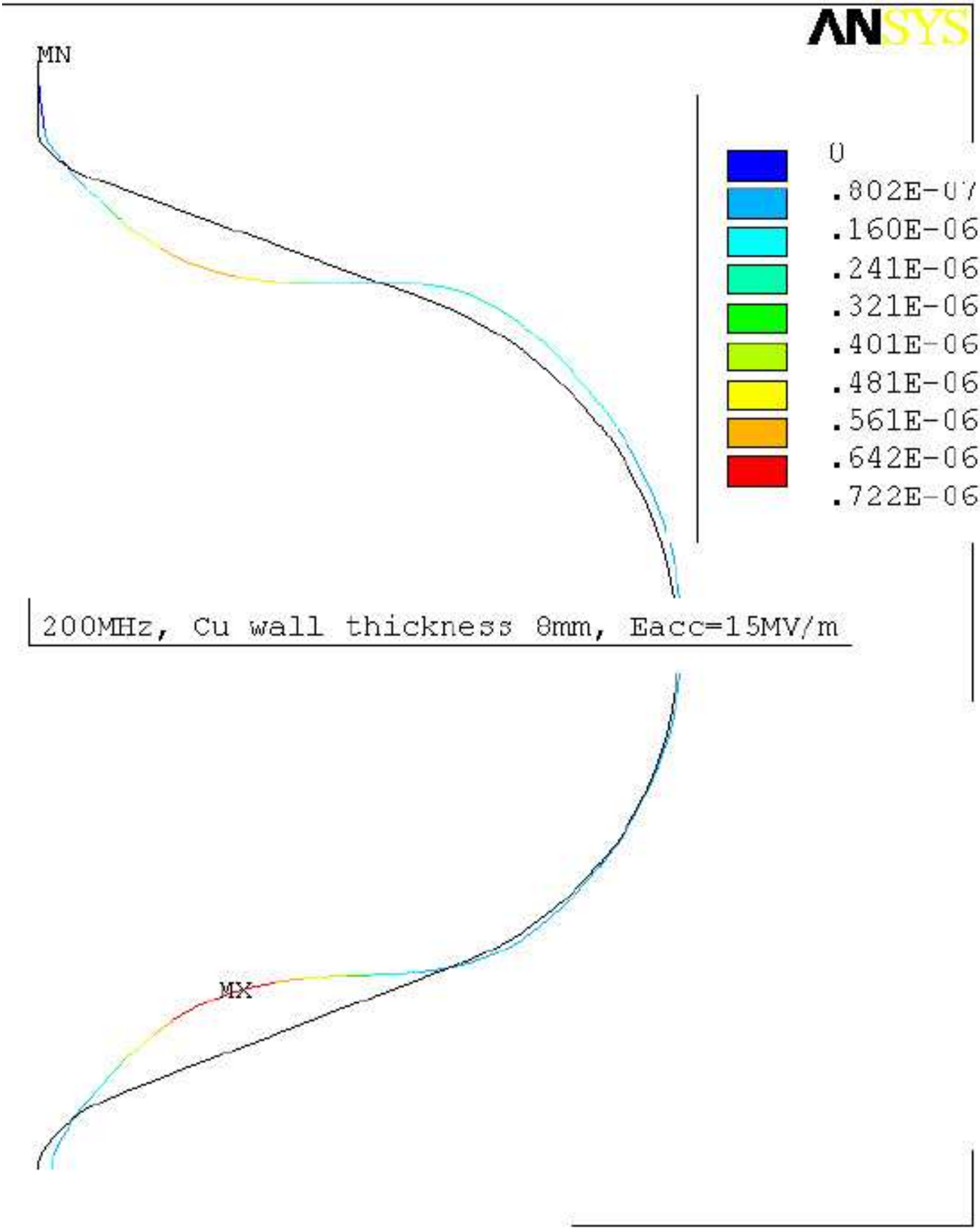
The rf magnetic field in a cavity interacts with the rf wall current resulting in a Lorentz force which can become important at high accelerating fields
The radiation pressure,

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

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 $\mathrm{Hz/(MV/m)^2}$.


ANSYS
MN
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
MX

see

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Mechanical Vibrations

Choose wall thickness, shape
And bracing to raise resonant
Frequency