Superconducting RF Accelerators: Why all the interest?

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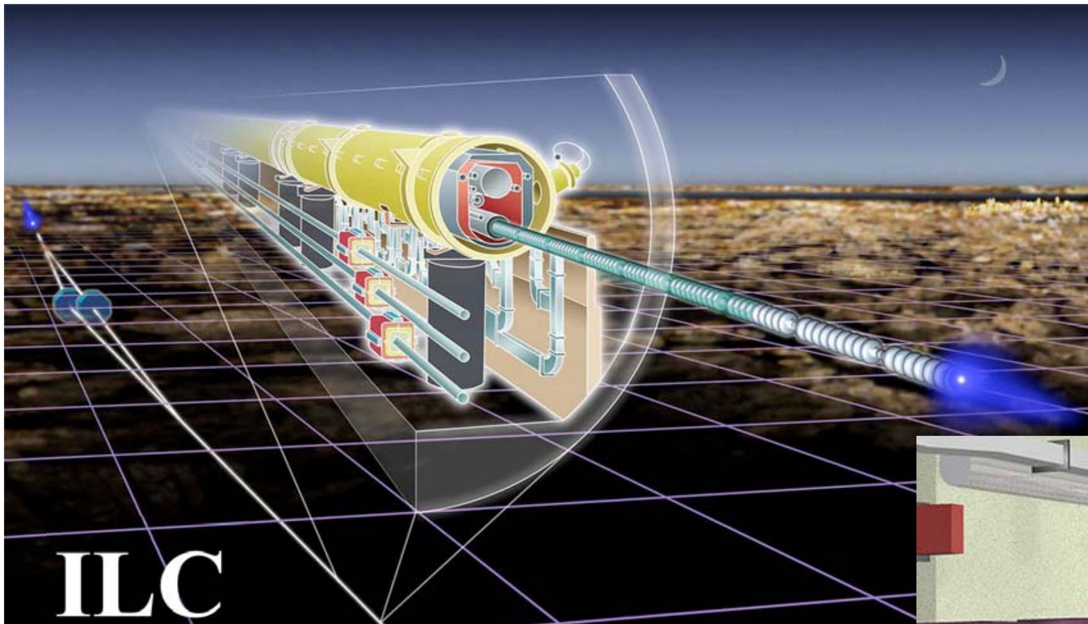
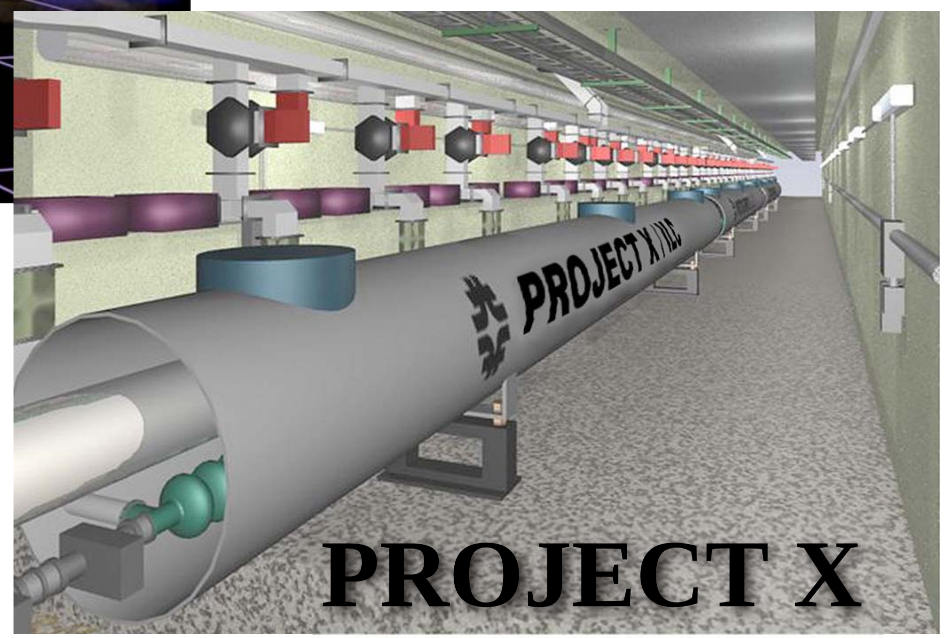
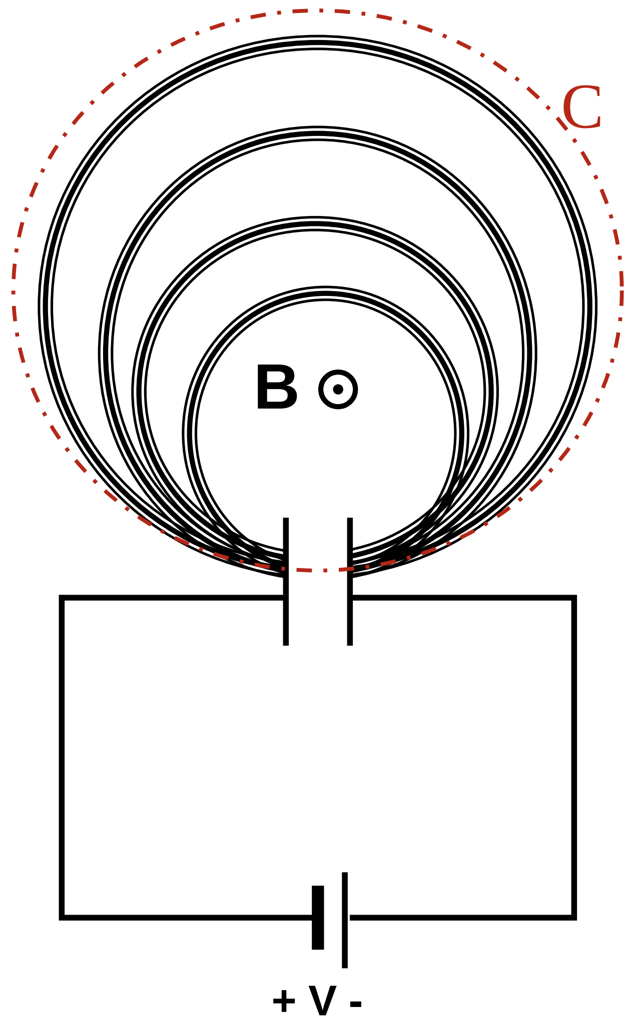
The HEP prespective



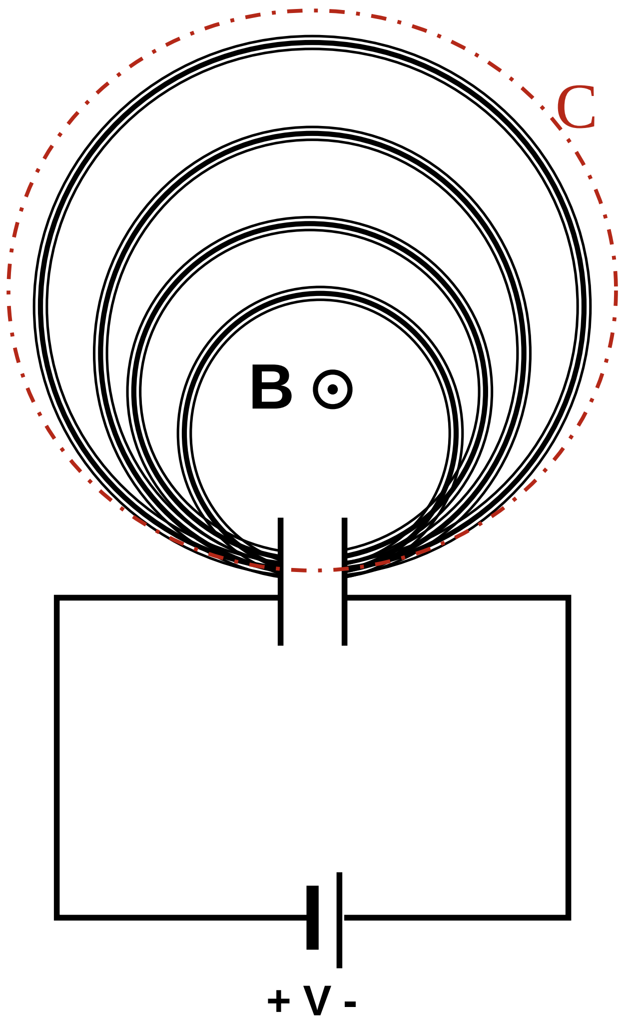


Why do we need RF structures & fields?

Possible DC accelerator?



Maxwell forbids this!



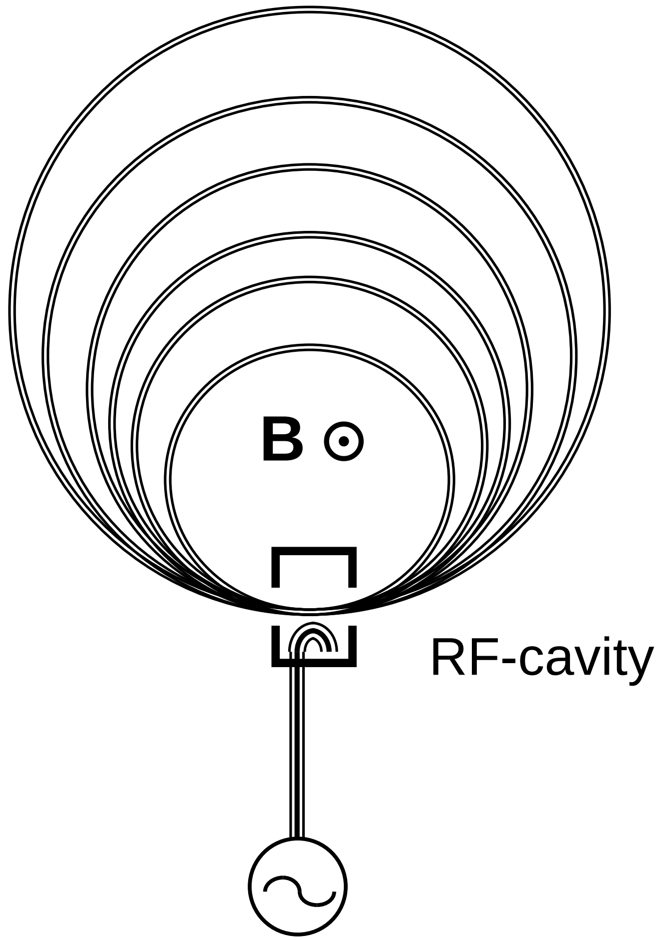
$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

or in integral form

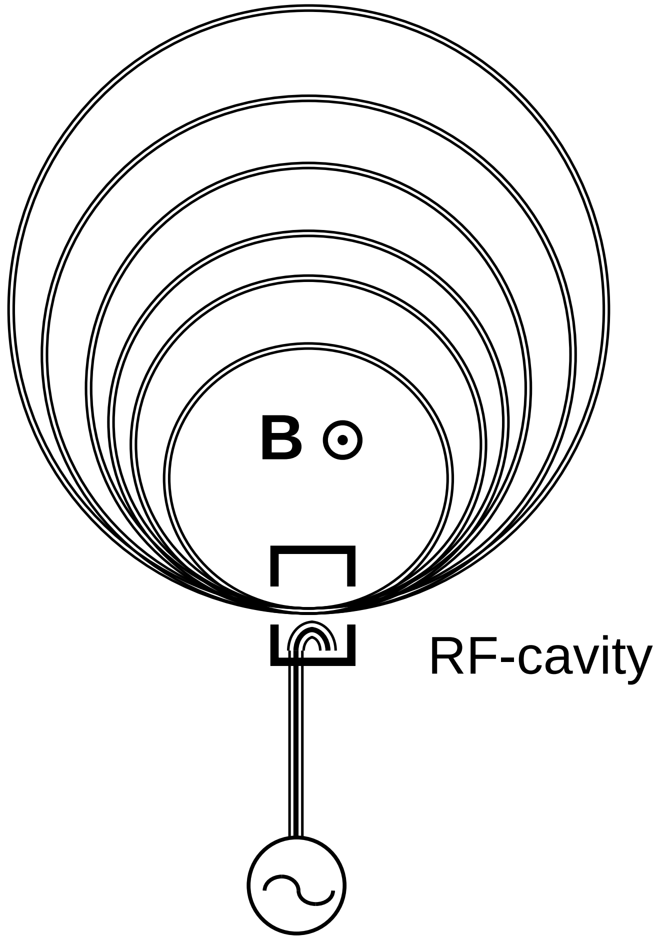
$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot \mathbf{n} \, da$$

∴ There is no acceleration without time-varying magnetic flux

Will this work?



We can vary B in an RF cavity



Note that inside the cavity

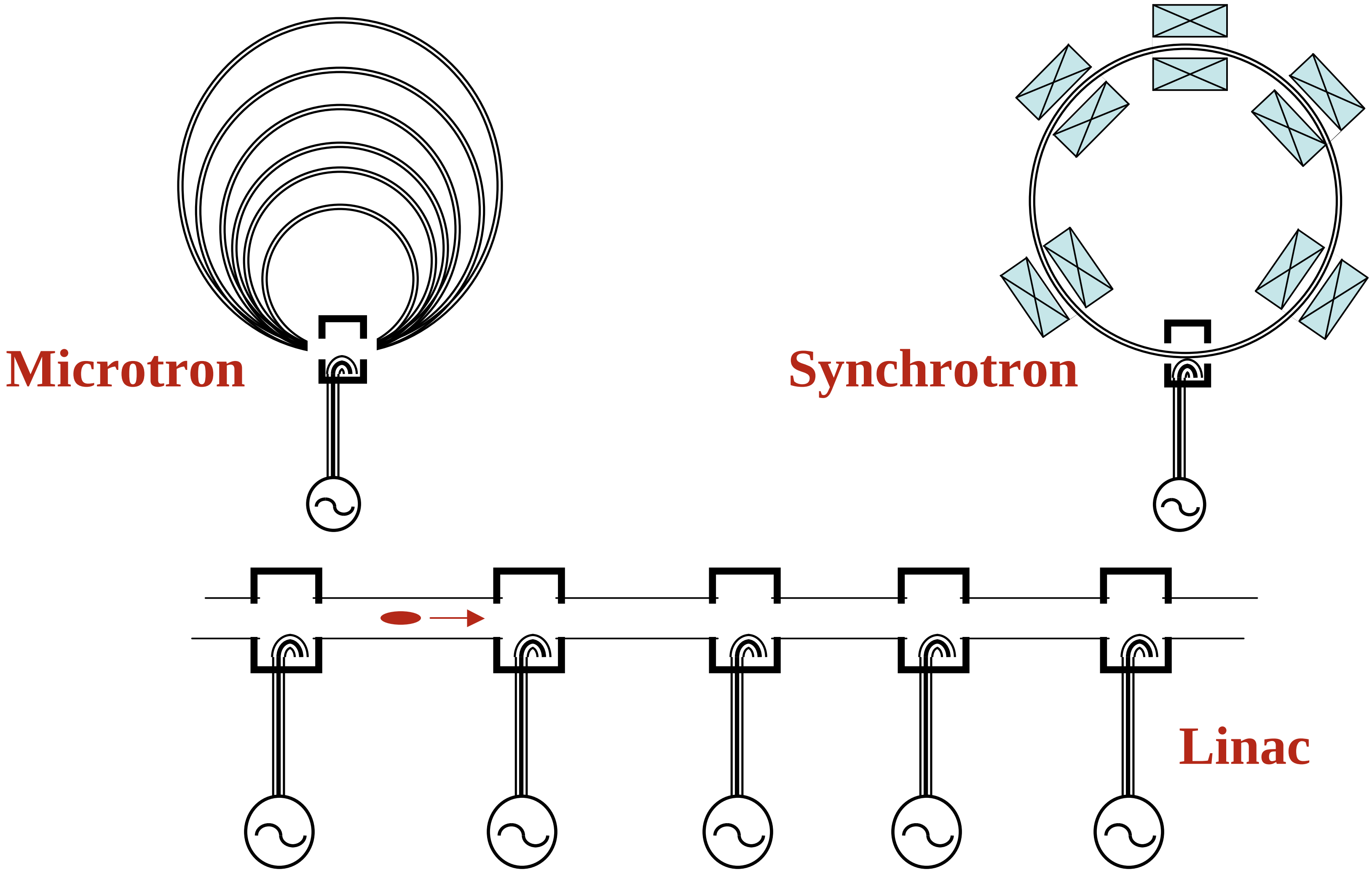
$dB/dt \neq 0$

However,

Synchronism condition:

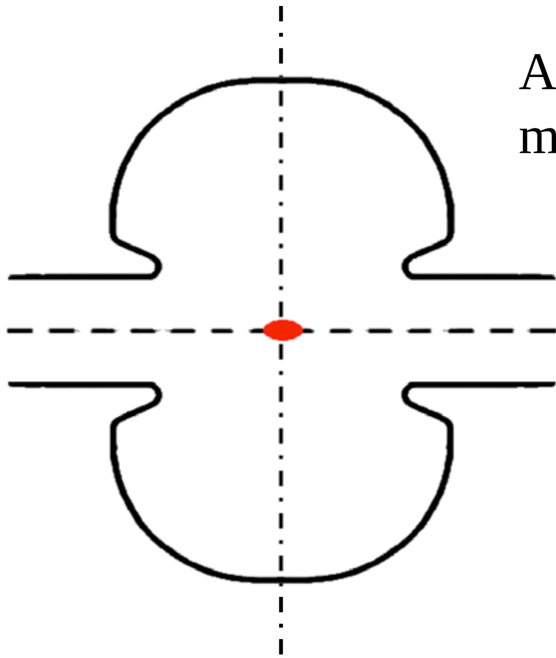
$\Delta\tau_{rev} = N/f_{rf}$

We can arrange rf-cavities in many ways



- Fields and voltages are complex quantities

$$\tilde{V} = Ve^{i\omega t + \vartheta_o}$$



At t = 0 particle receives maximum voltage gain

Z_o is the reference plane

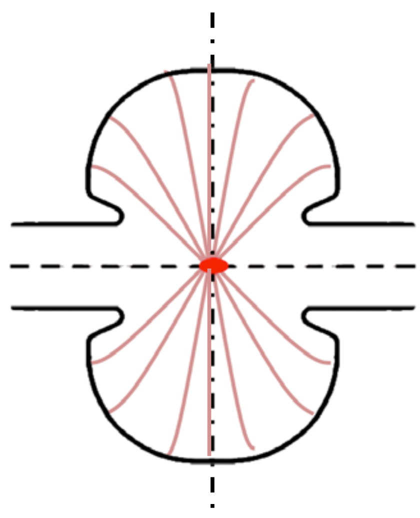
Basic principles: Reciprocity & superposition

- If you can kick the beam, the beam can kick you

==>

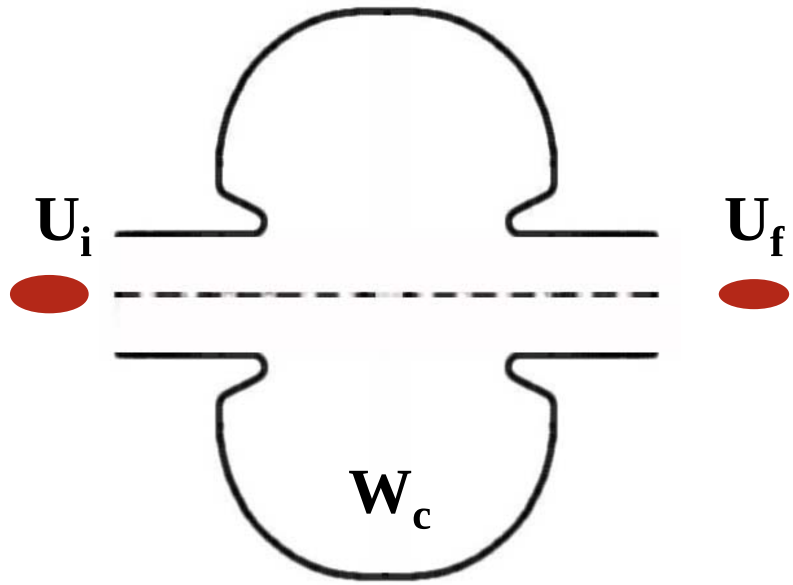
$$\text{Total cavity voltage} = V_{generator} + V_{beam\text{-}induced}$$

$$\text{Fields in cavity} = \mathbf{E}_{generator} + \mathbf{E}_{beam\text{-}induced}$$



Basic principles: Energy conservation

- Total energy in the particles and the cavity is conserved
  - Beam loading



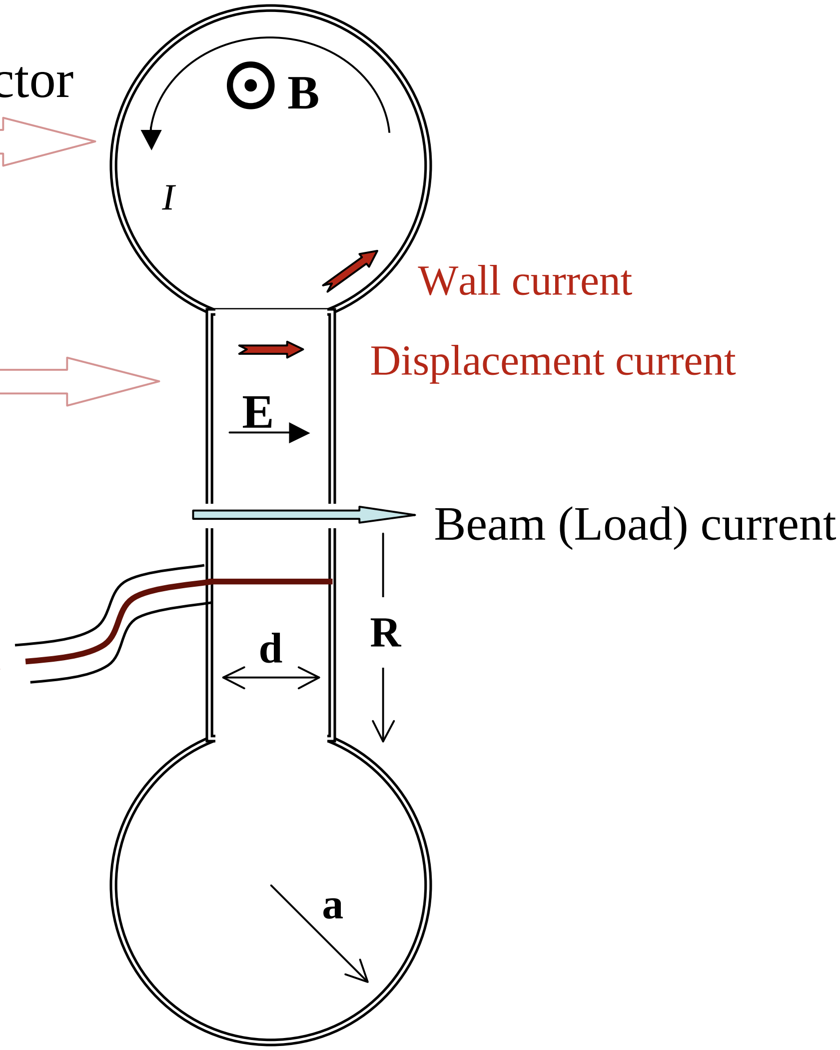
$$\Delta W_c = U_i - U_f$$

Basic components of an RF cavity

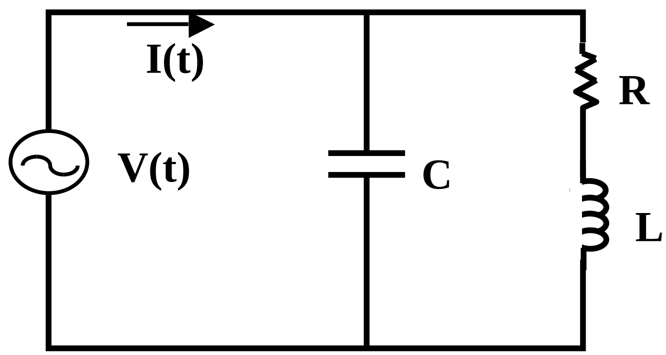
Outer region: Large, single turn Inductor

Central region: Large plate Capacitor

Power feed from rf - generator



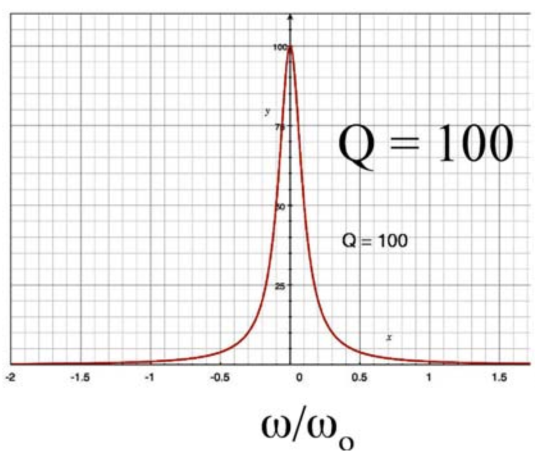
Lumped circuit analogy of resonant cavity

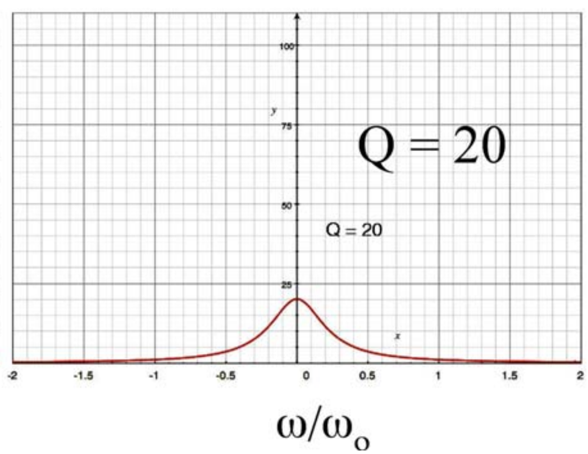


$$Z(\omega) = \left[j\omega C + (j\omega L + R)^{-1} \right]^{-1}$$

$$| Z(\omega) | \sim \left[\left(1 + \frac{\omega^2}{\omega_o^2} \right) + (\omega RC)^2 \right]^{-1}$$

The resonant frequency is $\omega_o = 1 / \sqrt{LC}$





Width to reduce

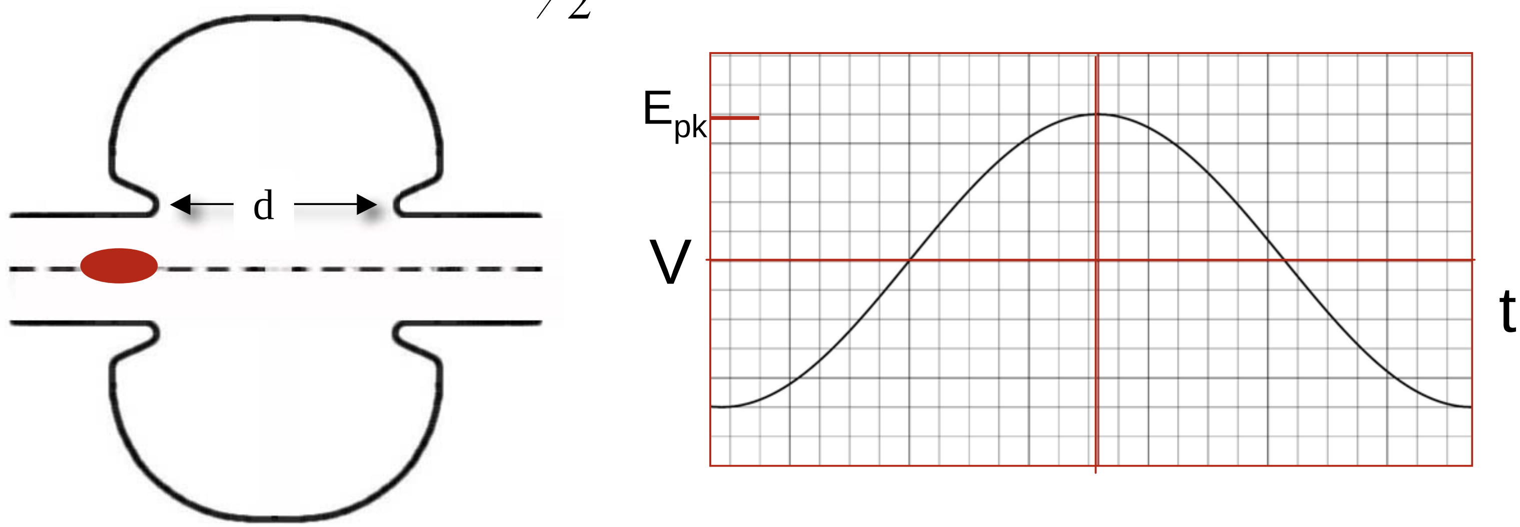
Z by e^2

$$\frac{\Delta\omega}{\omega_0} = \frac{R}{\sqrt{LC}} = \frac{1}{Q}$$

Figure of Merit: Accelerating voltage

- The voltage varies during the time that bunch takes to cross the gap
  - → reduction of the peak voltage by Γ

$$\Gamma = \frac{\sin\left(\vartheta/2\right)}{\vartheta/2} \quad \text{where} \quad \vartheta = \omega d/\beta c$$



For maximum acceleration $T_{cav} = \frac{d}{c} = \frac{T_{rf}}{2}$ ==> $\Gamma = 2/\pi$

Figure of merit from circuits - Q

$$Q = \frac{\omega_o \circ \text{ Energy stored}}{\text{Time average power loss}} = \frac{2\pi \circ \text{Energy stored}}{\text{Energy lost per cycle}}$$

$$\mathscr{E} = \frac{\mu_o}{2} \int_v |H|^2 dv = \frac{1}{2} L\, I_o I_o^*$$

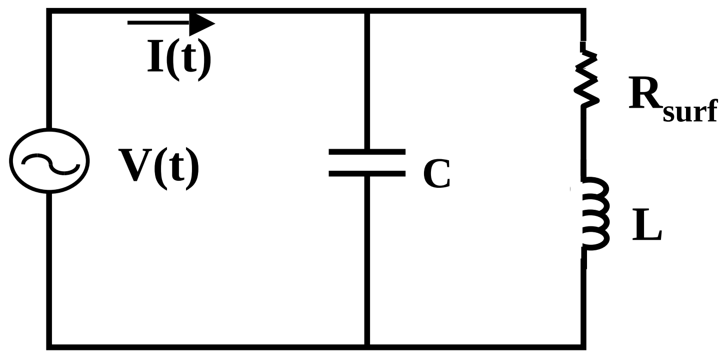
$$\langle \mathscr{P} \rangle = \frac{R_{surf}}{2} \int_s |H|^2 ds = \frac{1}{2} I_o I_o^* R_{surf}$$

$$R_{surf} = \frac{1}{\text{Conductivity} \circ \text{Skin depth}} \sim \omega^{1/2}$$

$$\therefore \; Q = \frac{\sqrt{L/C}}{R_{surf}} = \left(\frac{\Delta\omega}{\omega_o}\right)^{-1}$$

What makes SC RF attractive?

Recall the circuit analog



As R_{surf} ==> 0, the Q ==> ∞.

In practice,

$Q_{nc} \sim 10^4$ $Q_{sc} \sim 10^{11}$

Figure of merit for accelerating cavity: power to produce the accelerating field

Resistive input (shunt) impedance at ω_o relates power dissipated in walls to accelerating voltage

$$R_{in} = \frac{\langle V^2(t) \rangle}{\mathscr{P}} = \frac{V_o^2}{2\mathscr{P}} = Q\sqrt{L/C}$$

Linac literature more commonly defines "shunt impedance" without the "2"

$$\mathscr{R}_{in} = \frac{V_o^2}{\mathscr{P}} \sim \frac{1}{R_{surf}}$$

For SC-rf $\mathscr{P}$ is reduced by orders of magnitude

BUT, it is deposited @ 2K

Translate circuit model back to directly driven, re-entrant RF cavity model

Outer region: Large, single turn Inductor

$$L = \frac{\mu_o \pi a^2}{2\pi(R+a)}$$

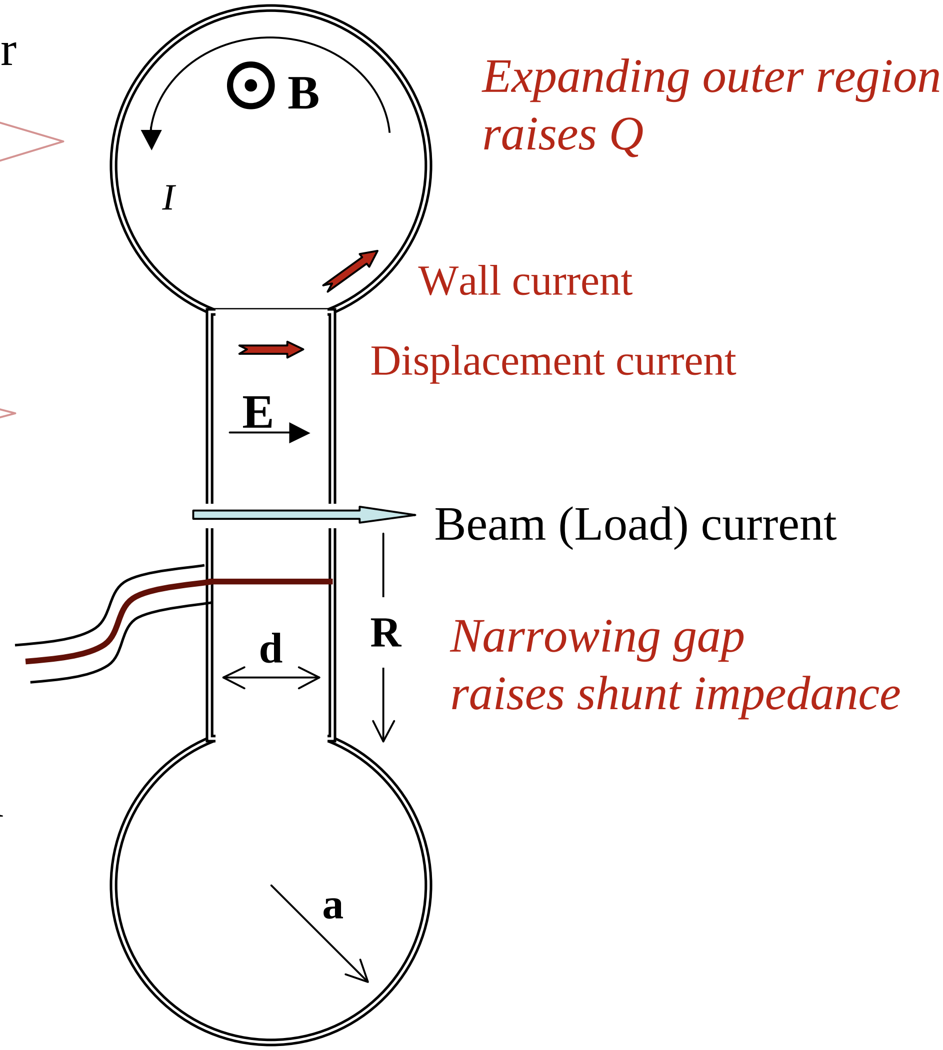
Central region: Large plate Capacitor

$$C = \varepsilon_o \frac{\pi R^2}{d}$$

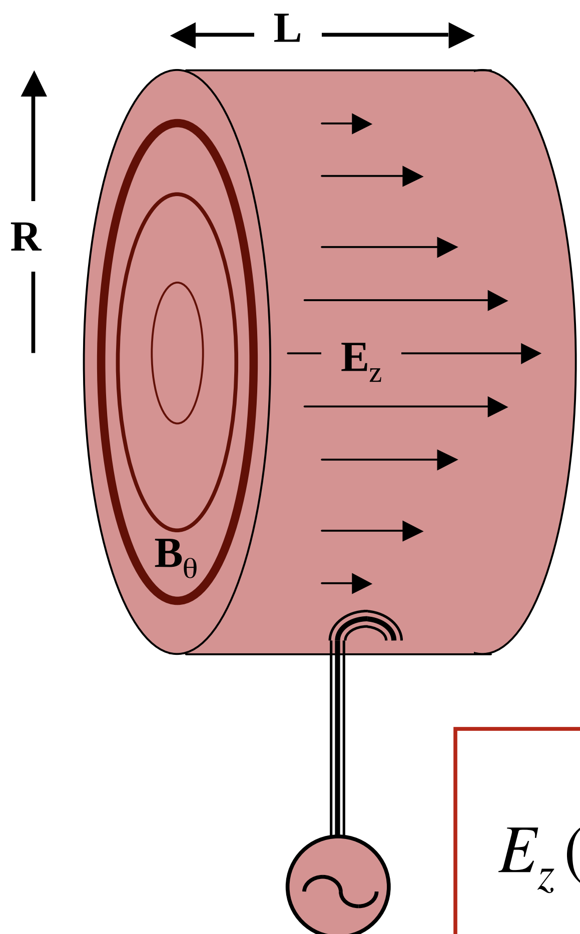
$$\omega_o = 1/\sqrt{LC} = c\left[\frac{2((R+a)d}{\pi R^2 a^2}\right]^{1/2}$$

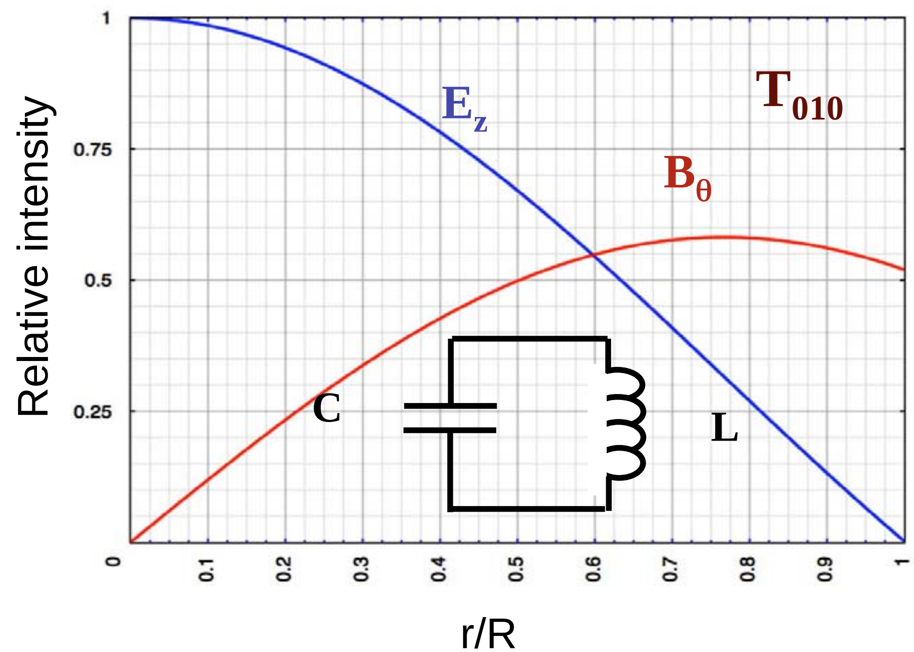
Q – set by resistance in outer region

$$Q = \sqrt{L/C} / \mathcal{R}_{surface} = \omega L / \mathcal{R}_{surface}$$



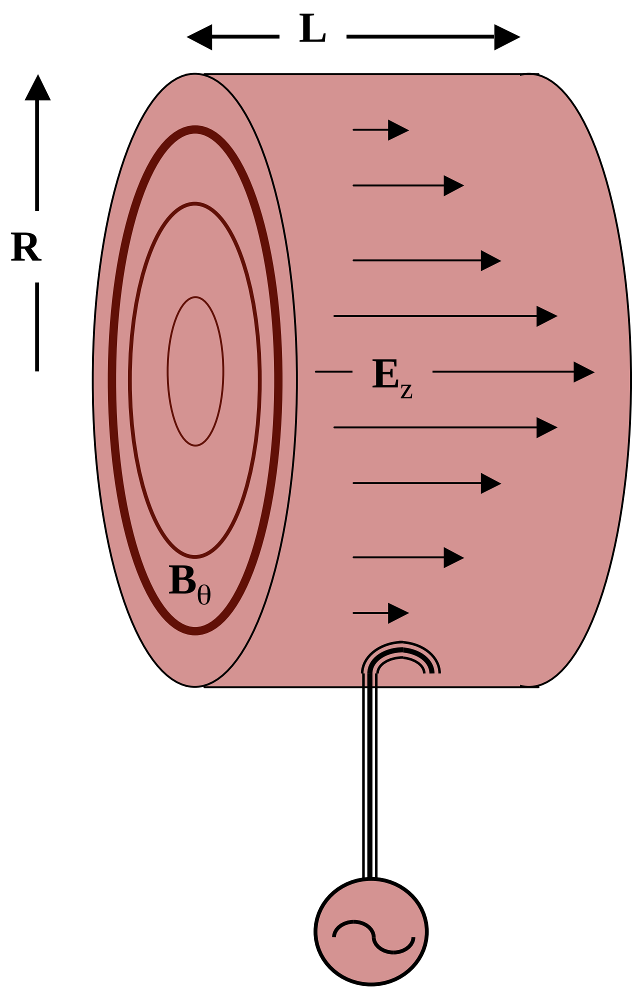
In an ideal pillbox, ω_o is independent of L





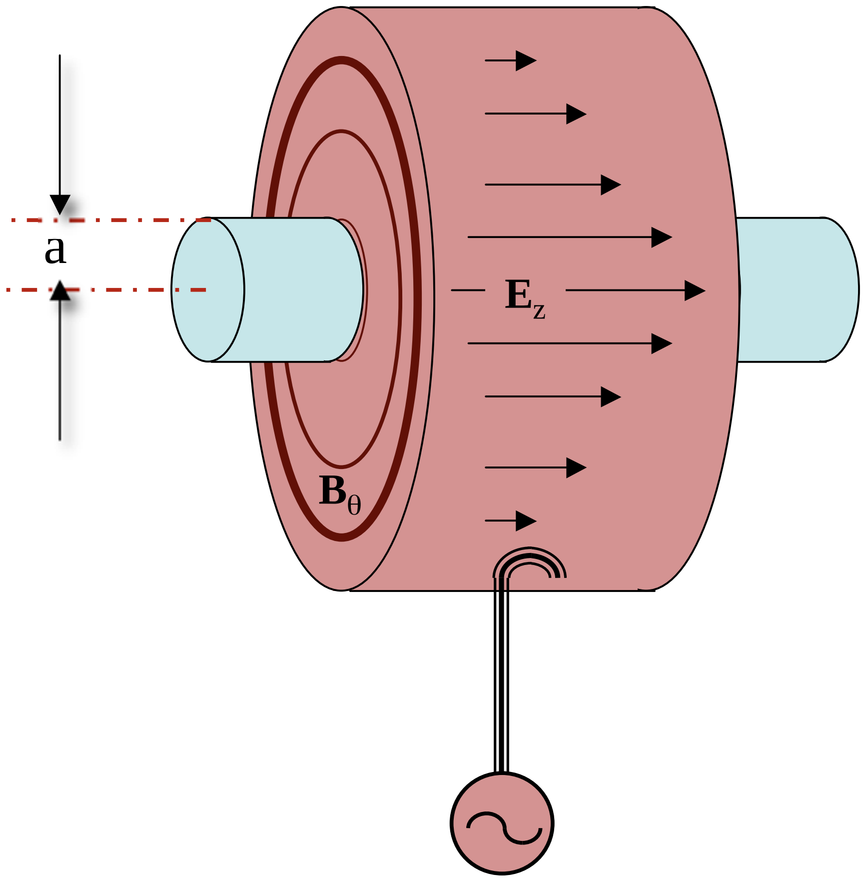
$$E_z(r) = E_o \, J_o\left(\frac{\omega}{c} r\right) \quad \Longrightarrow \quad \omega = 2.405 \frac{c}{R}$$

Simple consequences of pillbox model



- Increasing R lowers frequency
  ==> Stored Energy, $\mathcal{E} \sim \omega^{-2}$
- $\mathcal{E} \sim E_z^{\,2}$
- Beam loading lowers E_z for the next bunch
- Lowering ω lowers the fractional beam loading
- Raising ω lowers $Q \sim \omega^{-1/2}$
- If time between beam pulses,
  $T_s \sim Q/\omega$
  almost all $\mathcal{E}$ is lost in the walls

The beam tube makes the field modes (& cell design) more complicated



- Peak E no longer on axis
  - ➙ $E_{pk} \sim 2 - 3 \times E_{acc}$
  - ➙ $FOM = E_{pk}/E_{acc}$
- ω_o sensitive to cavity length
  - ➙ Mechanical tuning & detuning
- Beam tubes add length & $'s w/o acceleration
- Beam induced voltages ~ a^{-3}
  - ➙ Instabilities

Comparison of SC and NC RF

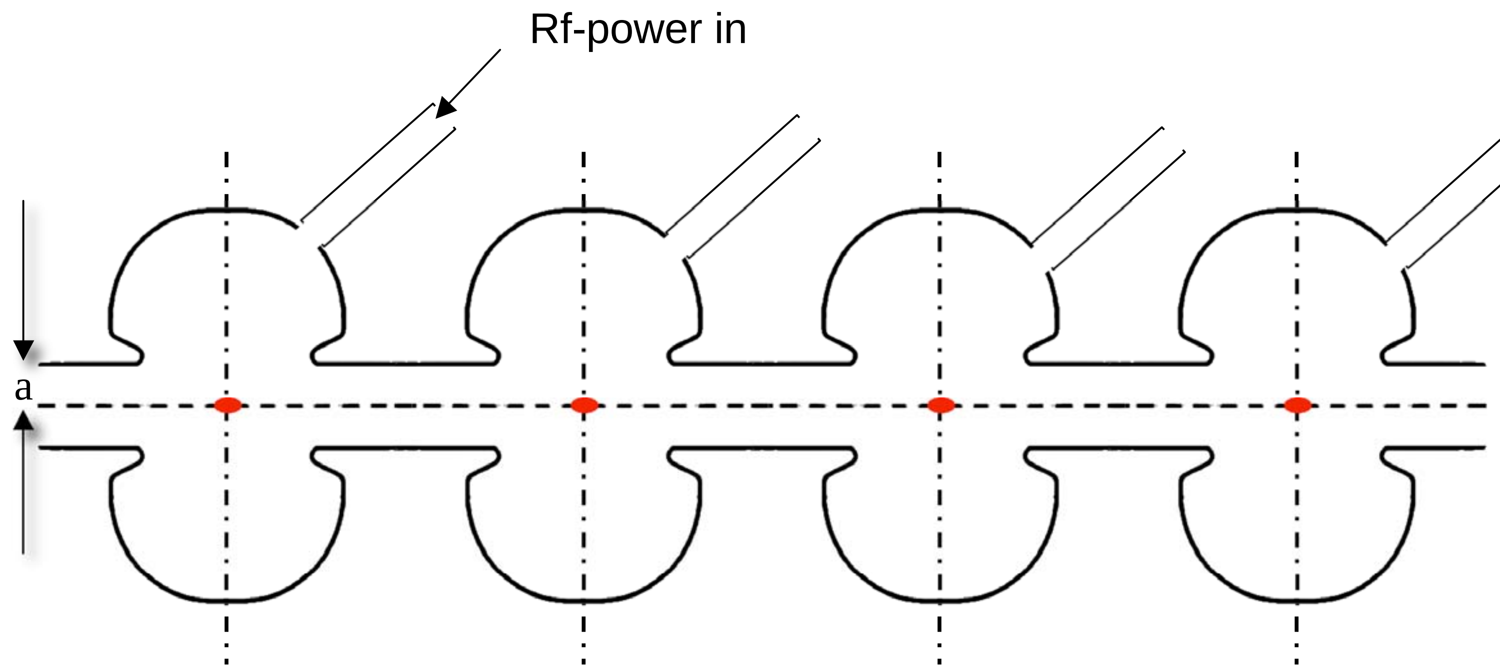
Superconducting RF

- High gradient
  ==> 1 GHz, meticulous care
- Mid-frequencies
  ==> Large stored energy, $\mathcal{E}_s$
- Large $\mathcal{E}_s$
  ==> very small ΔE/E
- Large Q
  ==> high efficiency

Normal Conductivity RF

- High gradient
  ==> high frequency (5 - 17 GHz)
- High frequency
  ==> low stored energy
- Low $\mathcal{E}_s$
  ==> ~10x larger ΔE/E
- Low Q
  ==> reduced efficiency

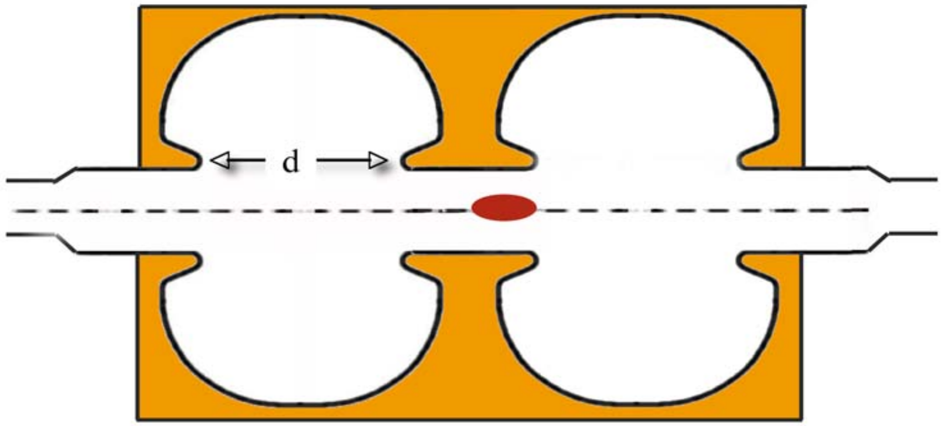
Linacs can be considered as a series of distorted pillbox cavities…



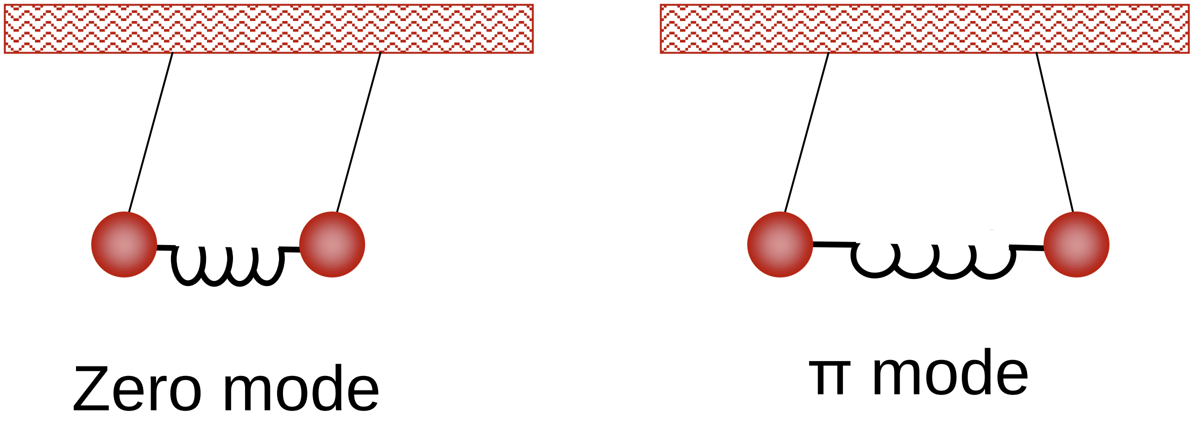
In warm linacs "nose cones" optimize the voltage per cell with respect to resistive dissipation

$$Q = \frac{\sqrt{L/C}}{\mathscr{R}_{surface}}$$

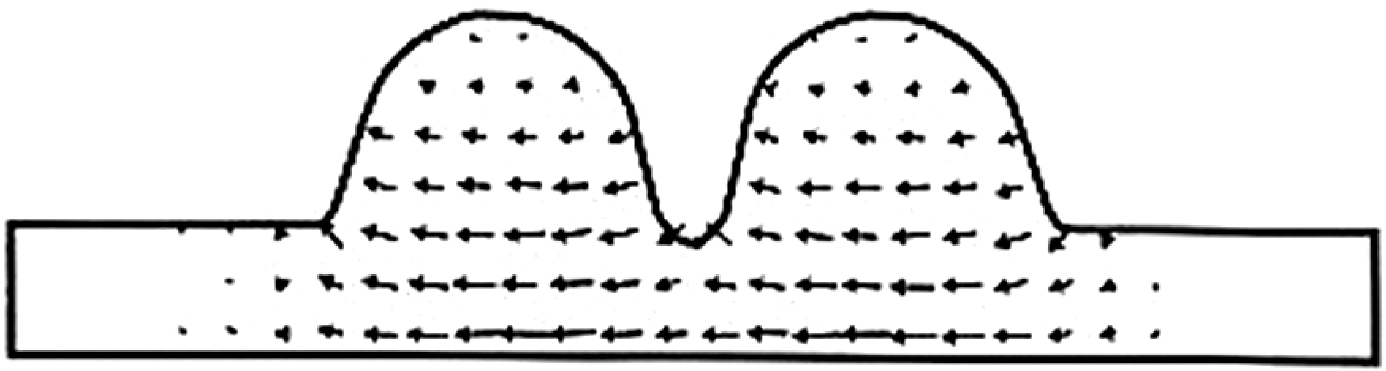
Linacs cells are linked to minimize cost

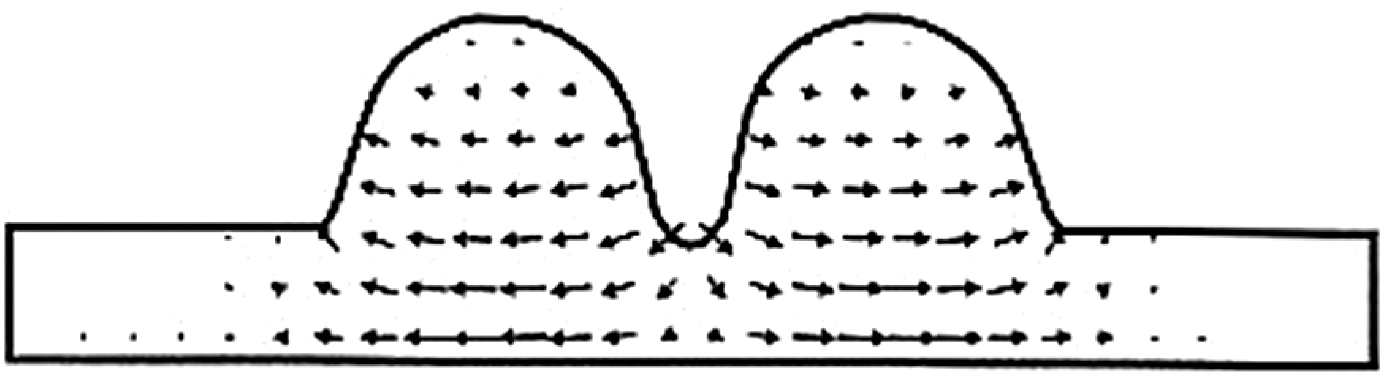


==> coupled oscillators ==>multiple modes

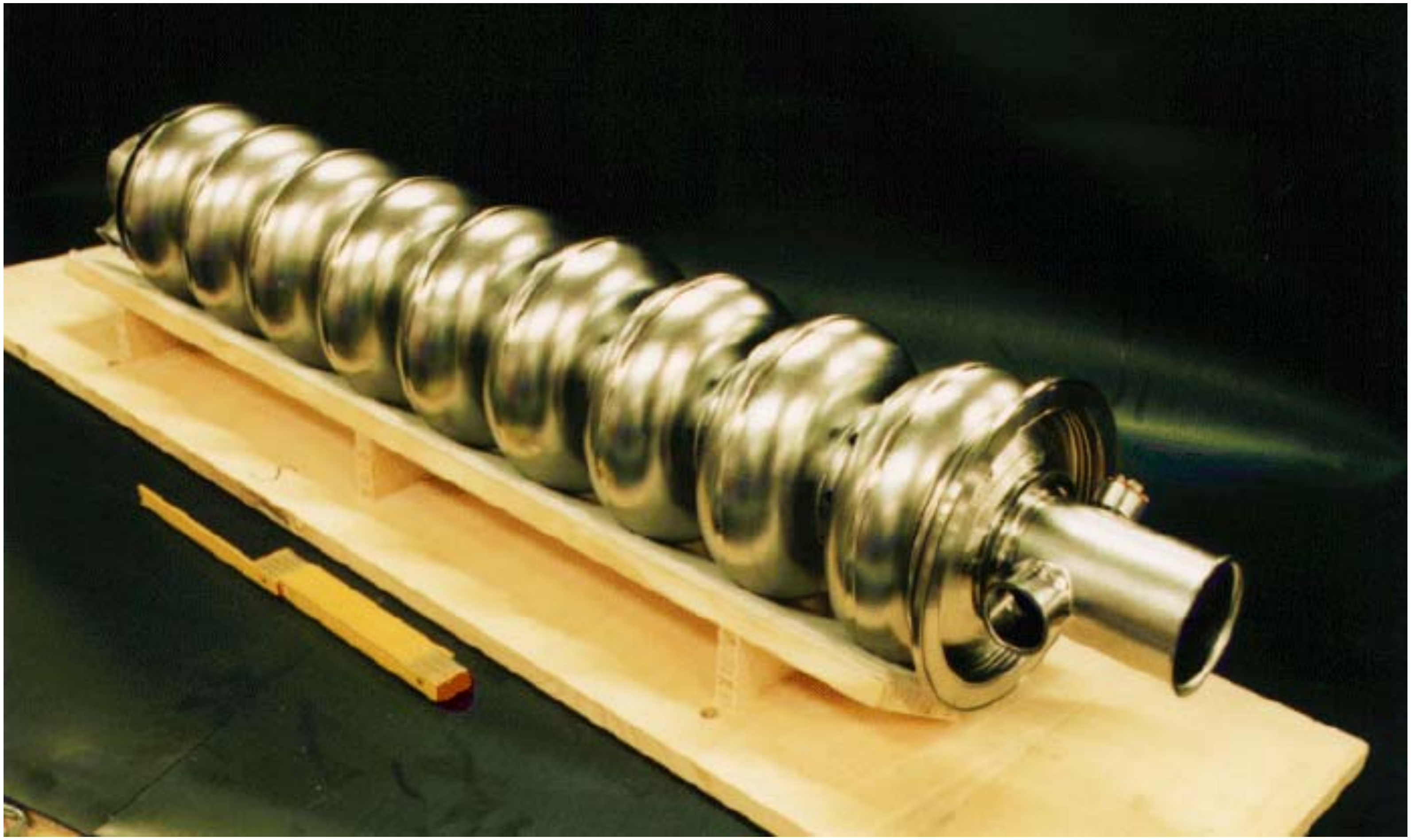


Modes of a two-cell cavity

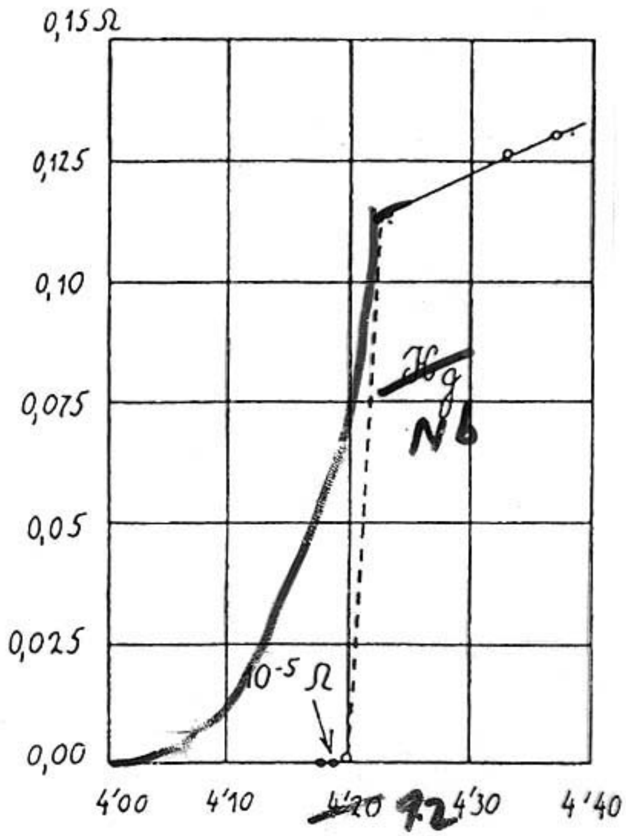




9-cavity TESLA cell



Enter Superconductivity



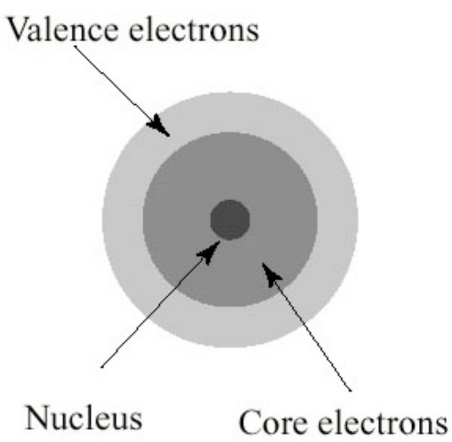
surement of superconductivity by Kamerlingh Onnes

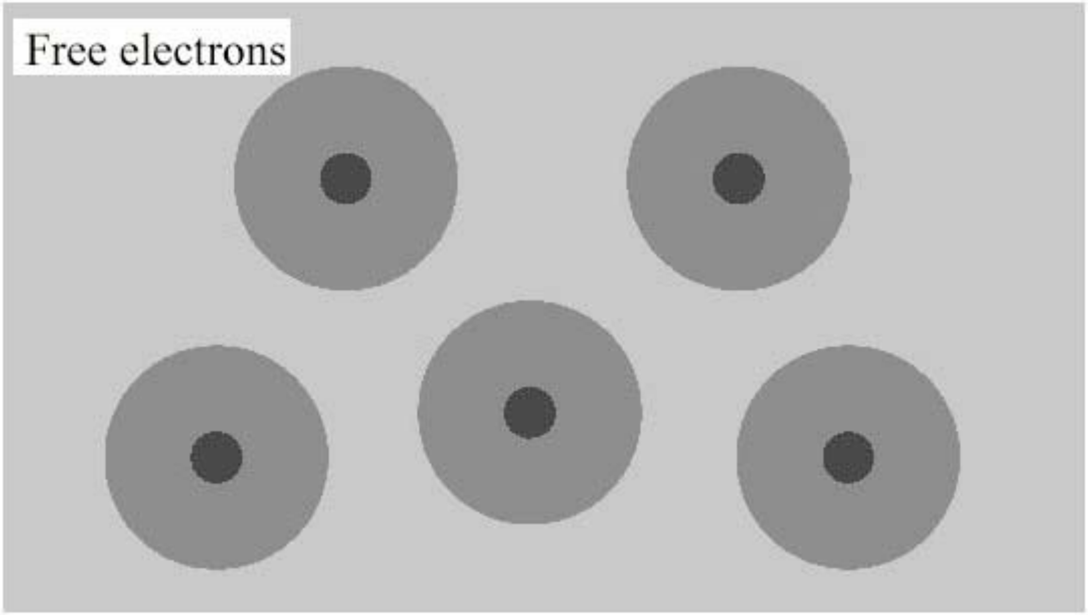
4 *The Convergence of Classical Concepts circa 1900*

Figure 1-2. Heike Kamerlingh Onnes.

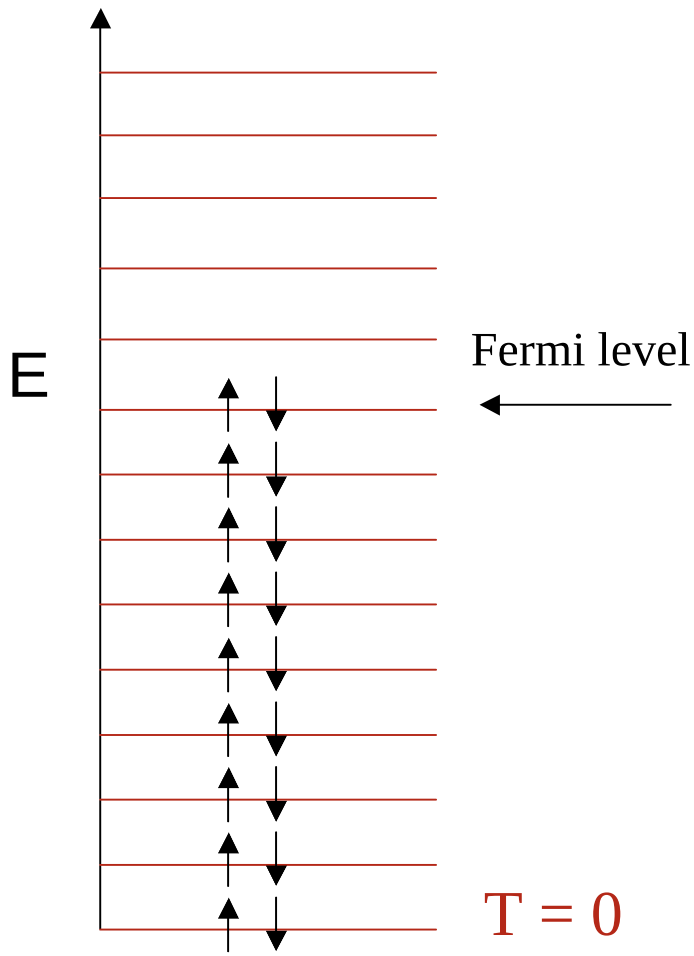
1911

Electrons in Solids - naïve picture

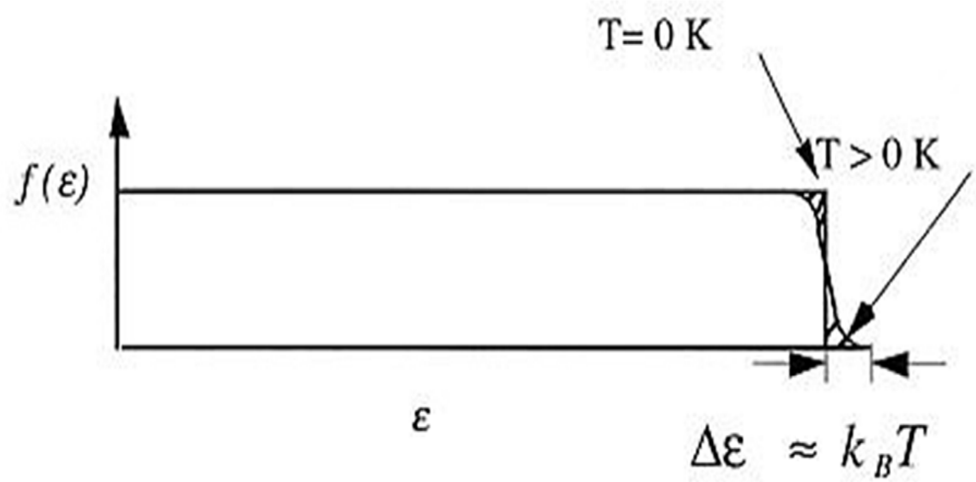




Energy distribution of electrons in normal conductors

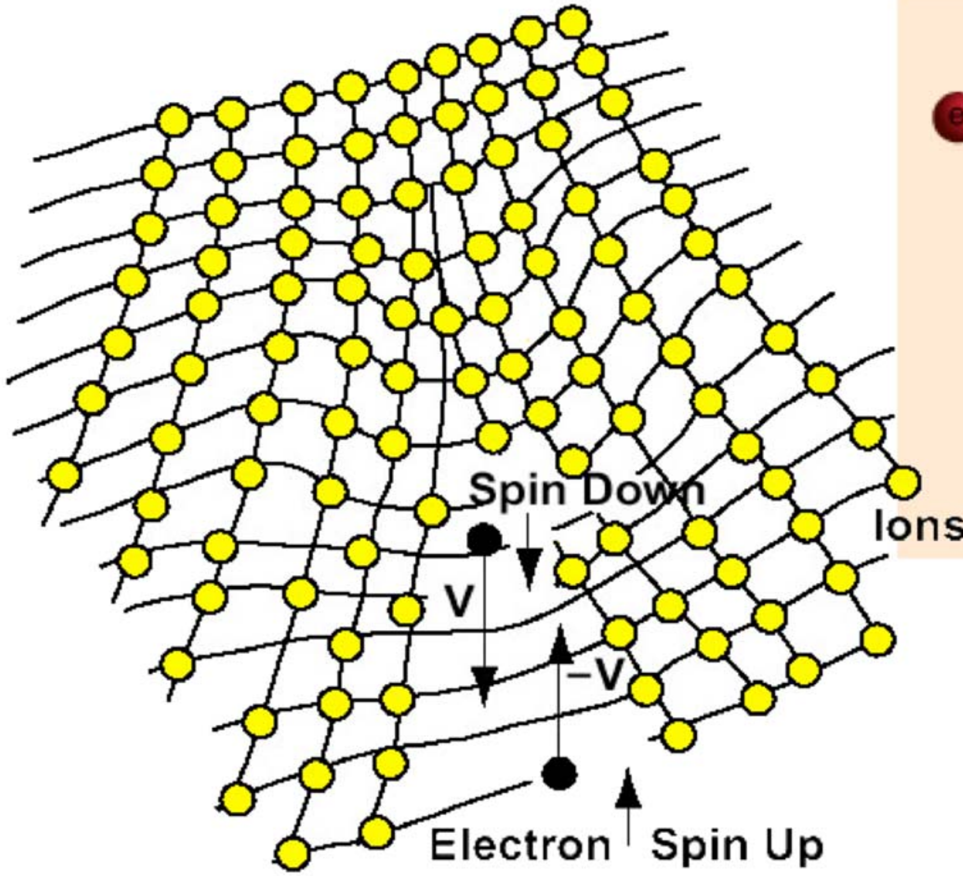


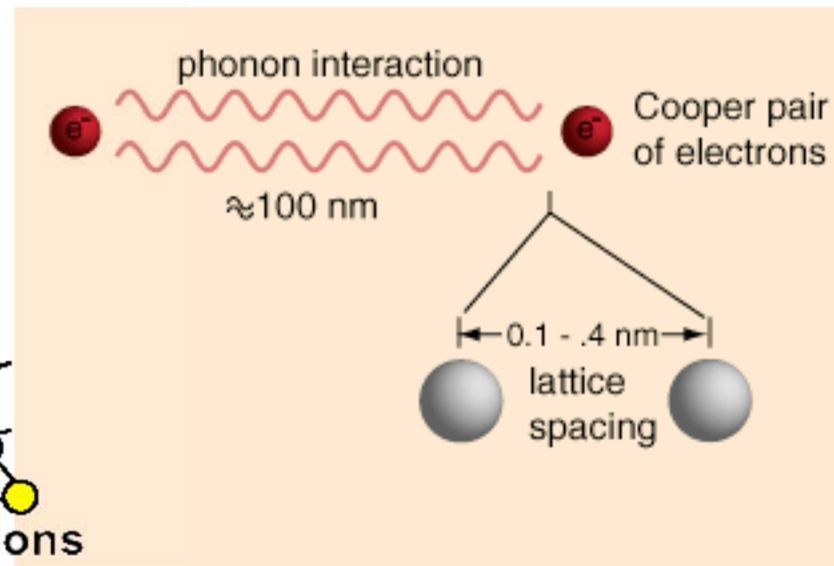
T = 0



T > 0

Electron-Phonon interaction ==> electron pairs - BCS theory



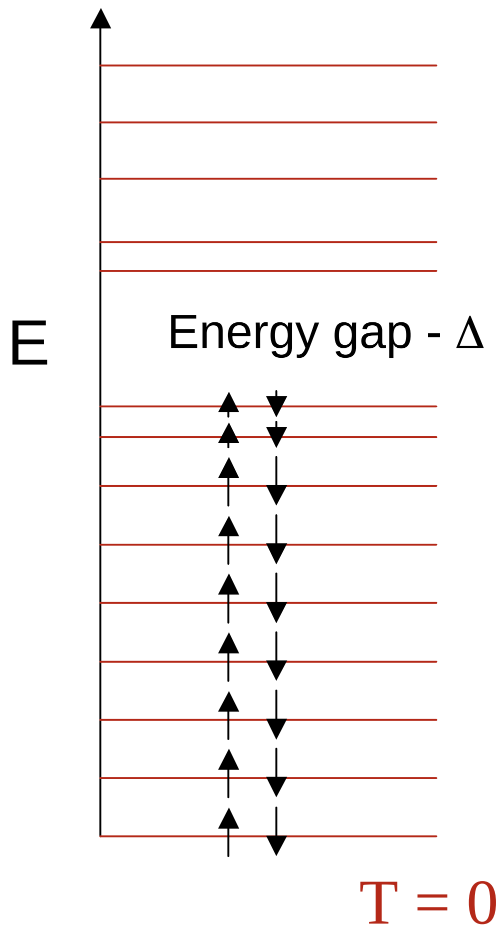


An e^- moving thru a conductor attracts nearby ions. The lattice deformation causes another e^-, with opposite "spin", to move into region of higher + charge density.

The two e^- are held together with a binding energy, 2Δ

In superconductors interaction of electrons with lattice phonons ==> pairs (bosons)

- Possibility of Bose condensate at $T_{critical}$



Two fluid model:

For $T_c > T > 0$, excitation of unpaired electrons

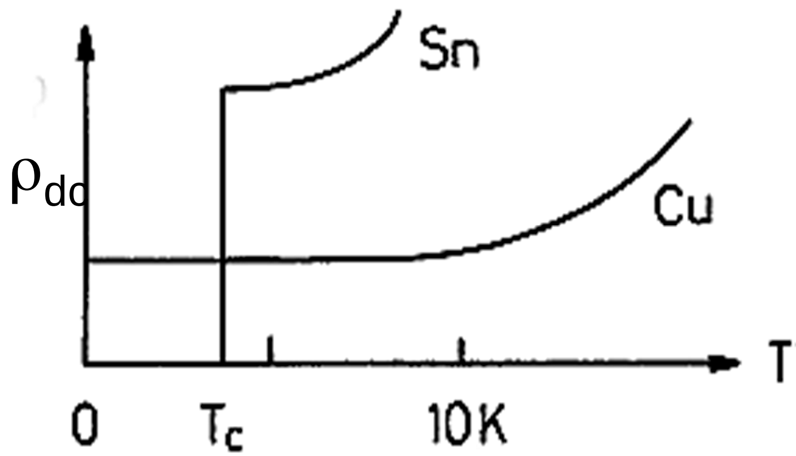
$$n_{\mathrm{normal}} \propto \exp\left(-\frac{\Delta}{k_{\mathrm{B}}T}\right)$$

where 2Δ is the energy to break apart the Cooper pairs, until no electrons are paired above T_c

DC conductivity in superconductors

- DC resistance = 0

  because unpaired electrons are shorted out by Cooper pairs.



RF Resistance in Superconductors

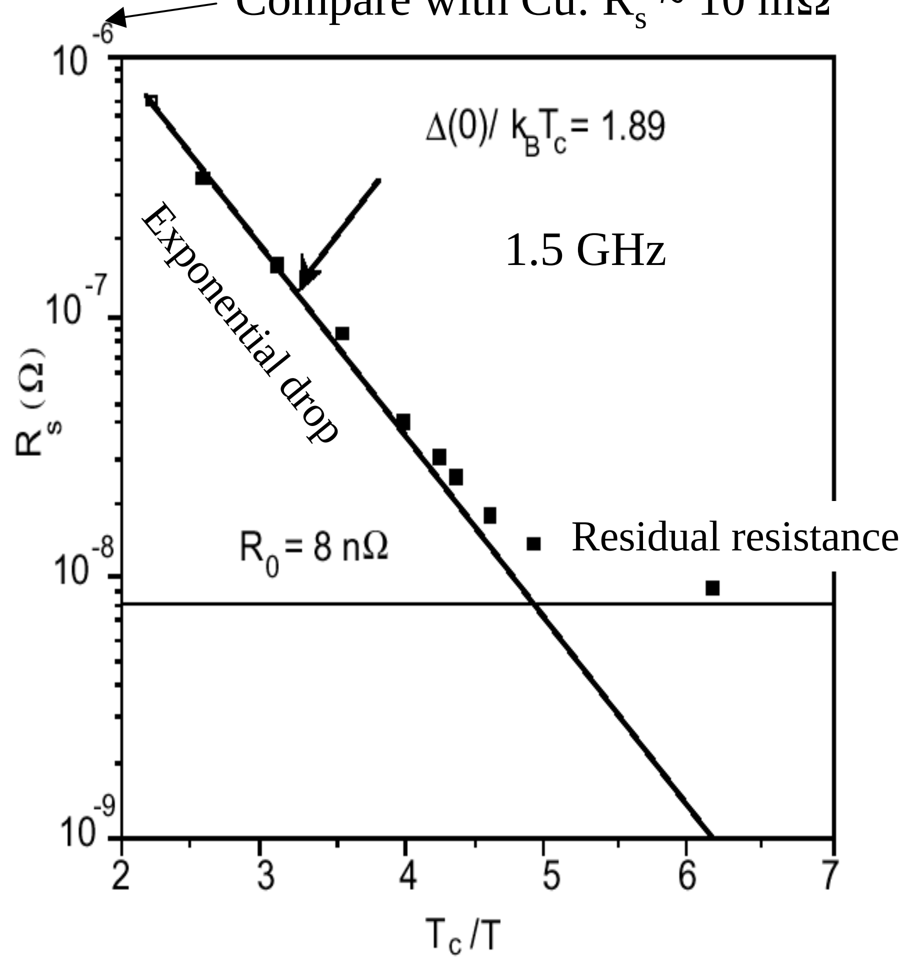
- RF resistance is finite because Cooper pairs have inertia → unpaied electrons "see" an electric field.

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

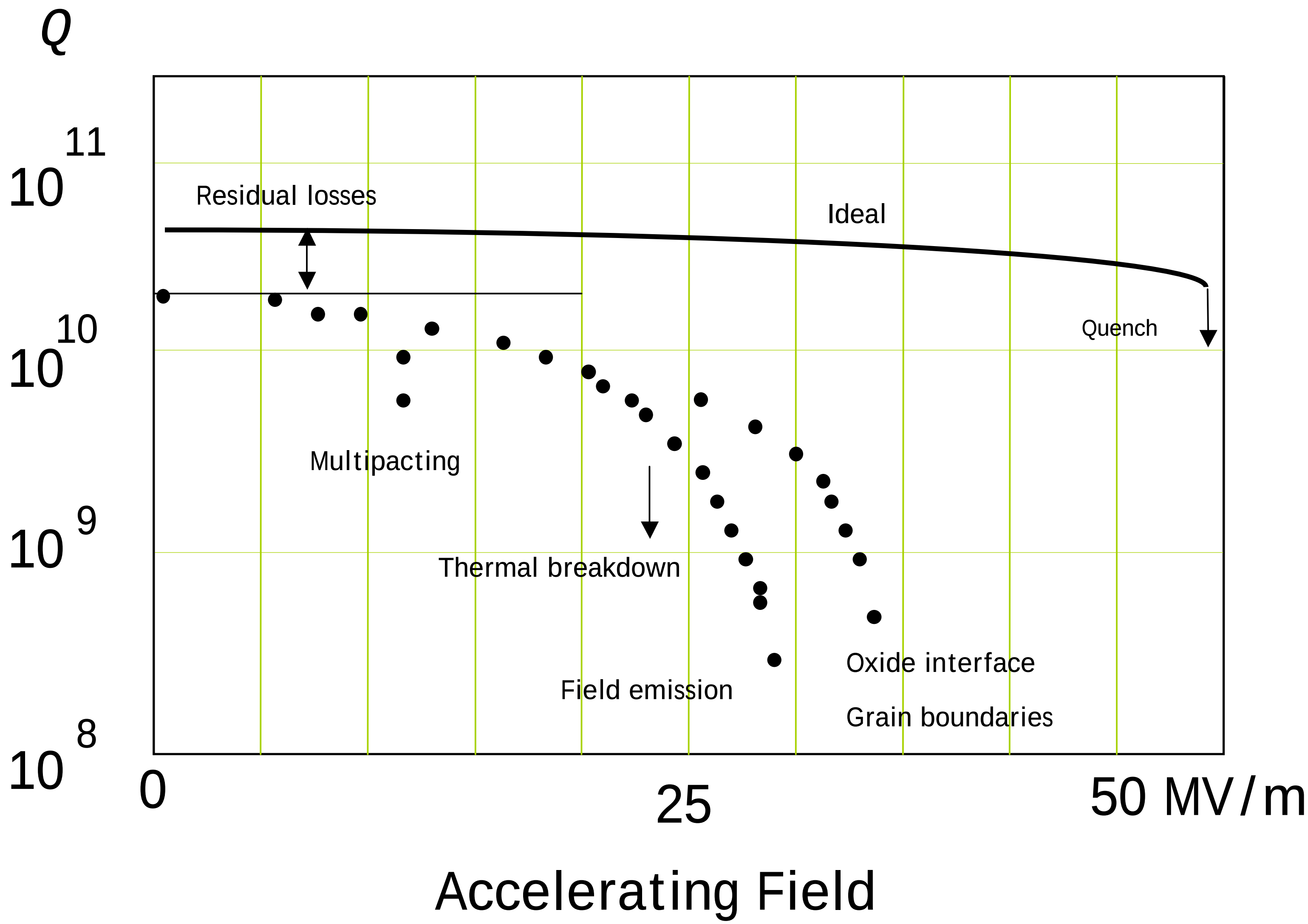
More resistance the more the sc pairs are jiggled around

More resistance the more unpaired electrons are excited

Compare with Cu: R_s ~ 10 mΩ

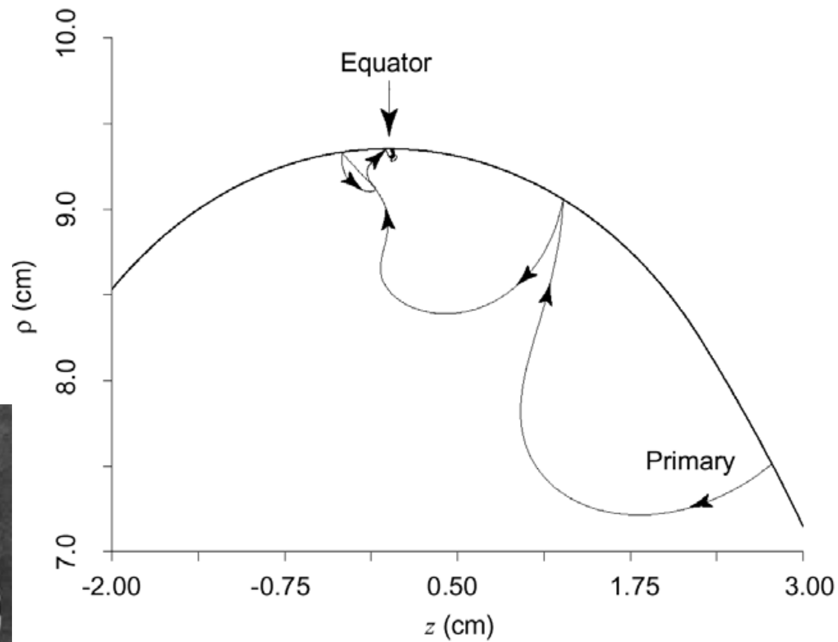


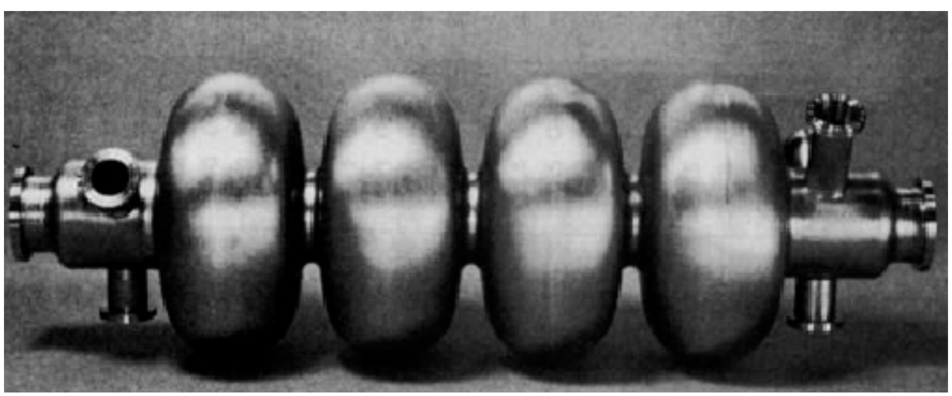
In practice several effects limit the most important measure of cell performance



Multipacting Solution

- First spherical, later elliptical shape cells.

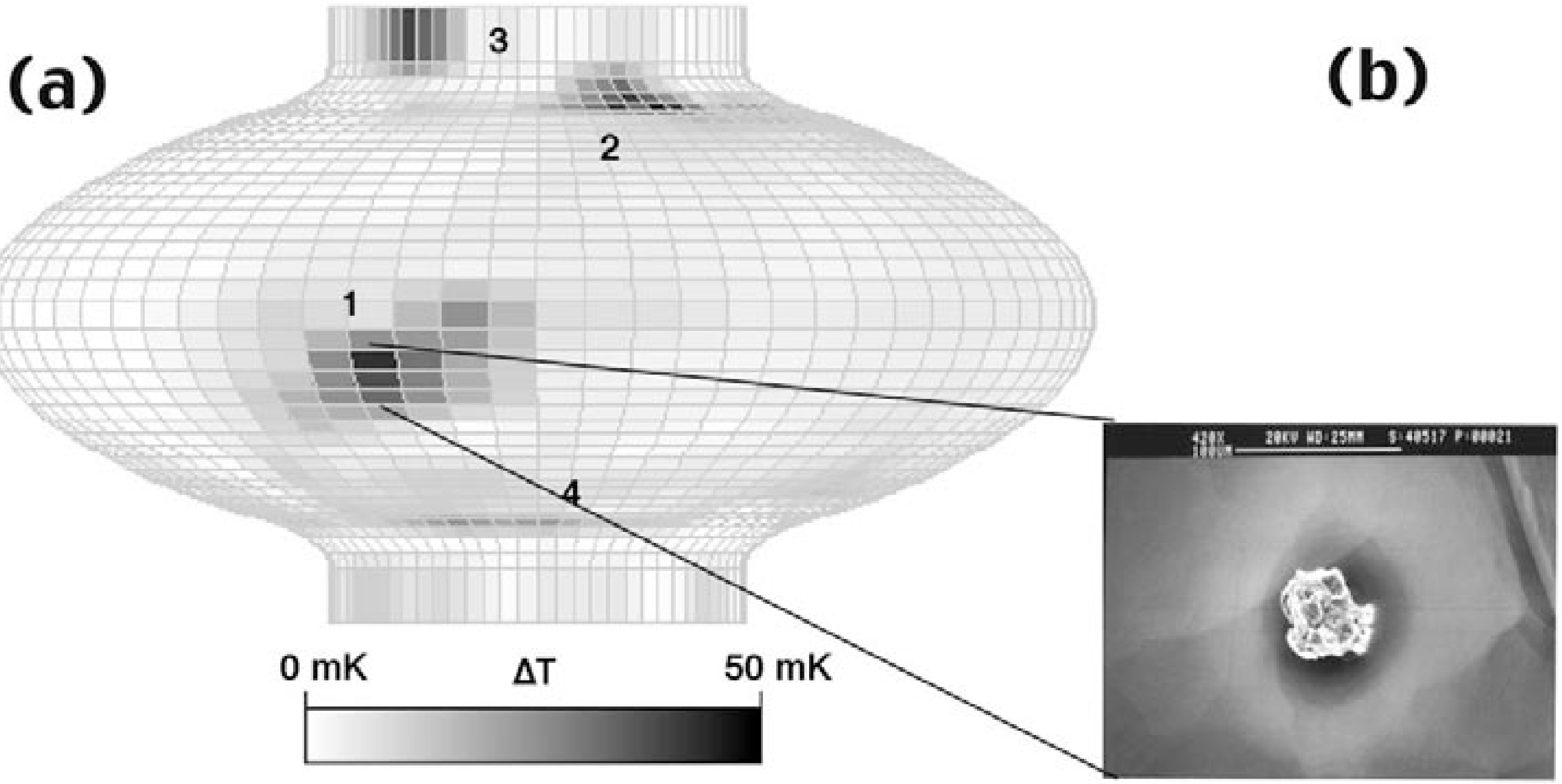




350-MHz LEP-II cavity (CERN)

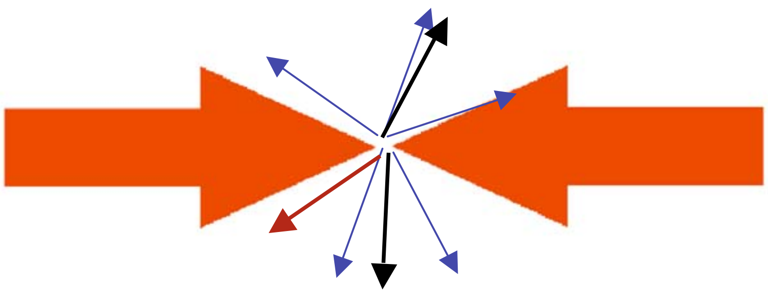
Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don't gain energy
→MP stops

Thermometry at a quench point



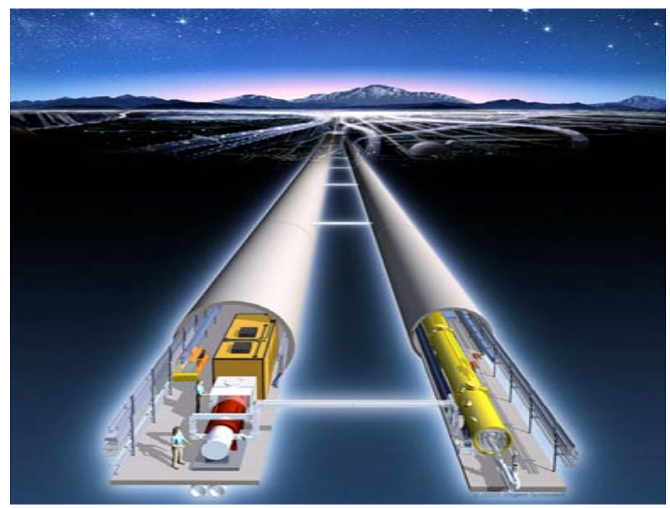
Why do we need beams?

Collide beams



FOMs: Collision rate, energy stability, Accelerating field

Examples: LHC, ILC, RHIC

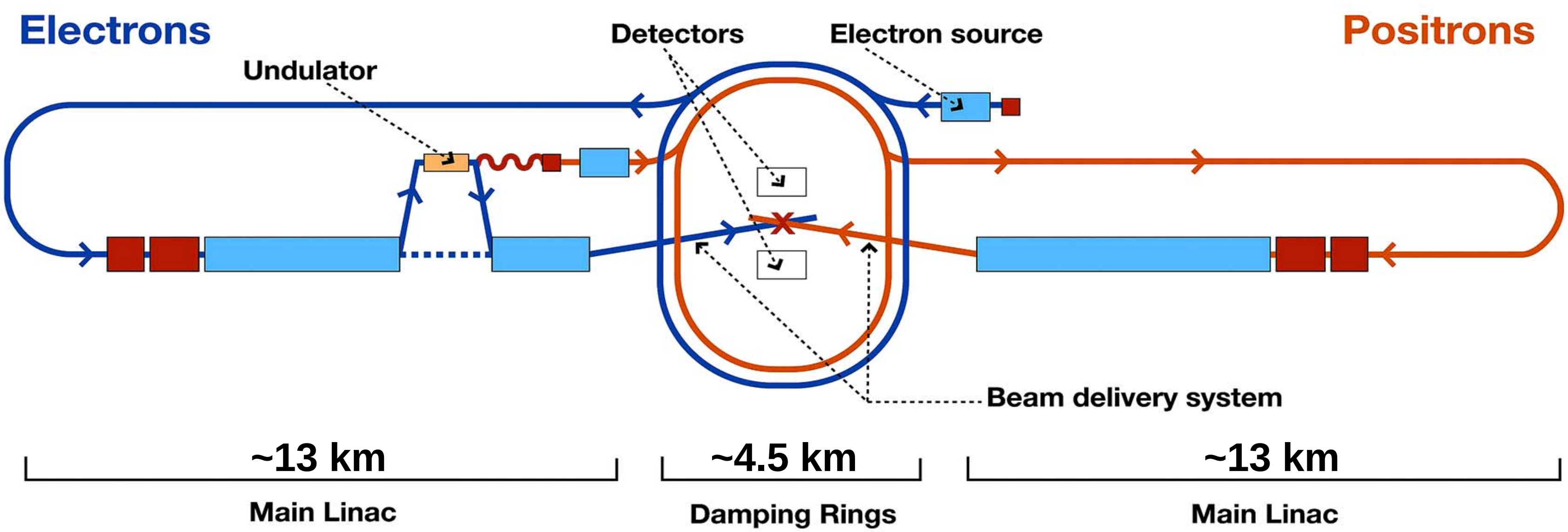


In LHC storage rings…

- Limited space & Large rf trapping of particles
  - ➙V/cavity must be high
- Bunch length must be large ($\leq$ 1 event/cm in luminous region)
  - ➙RF frequency must be low
- Energy lost in walls must be small
  - ➙R_{surf} must be small

SC cavities were the only practical choice

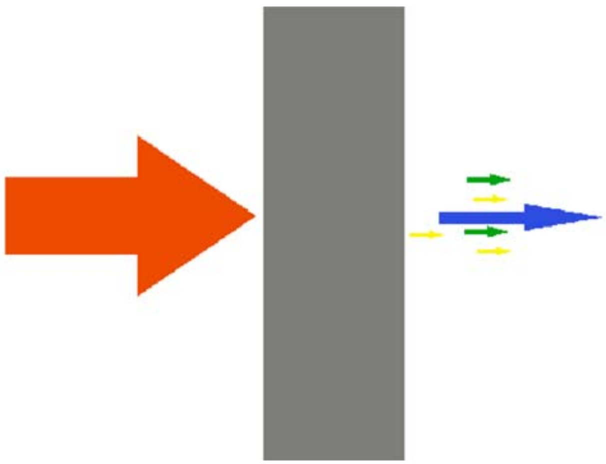
For ILC SC rf provides high power, high quality beams at high efficiency

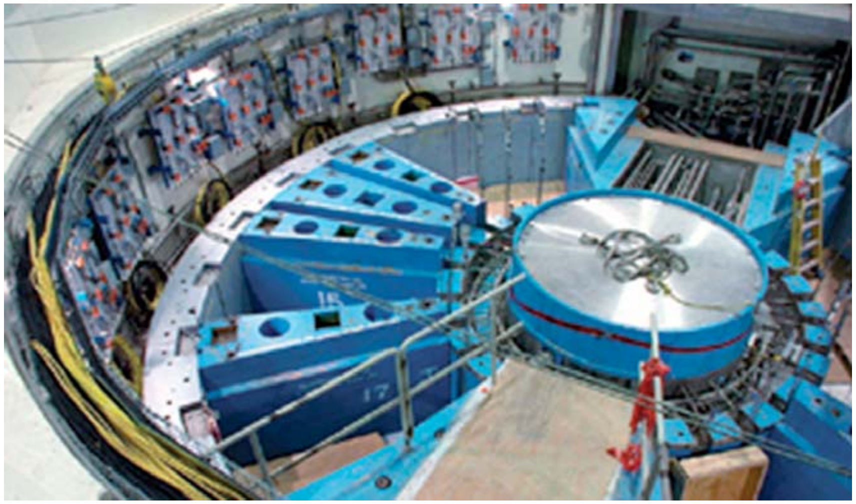


- **To deliver required luminosity (500 fb^{-1} in 4 years) ==>**
  - powerful polarized electron & positron beams (11 MW /beam)
  - tiny beams at collision point ==> minimizing beam-structure interaction
- **To limit power consumption** ==> high "wall plug" to beam power efficiency
  - Even with SC rf, the site power is still 230 MW !

Why do we need beams?

Intense secondary beams





1 MW target at SNS

FOM: Secondaries/primary
Examples: spallation neutrons,
neutrino beams

The Spallation Neutron Source

- 1 MW @ 1GeV (compare with ILC 11 MW at 500 GeV (upgradeable to 4 MW)

==> miniscule beam loss into accelerator

==> large aperture in cavities ==> large cavities

==> low frequency

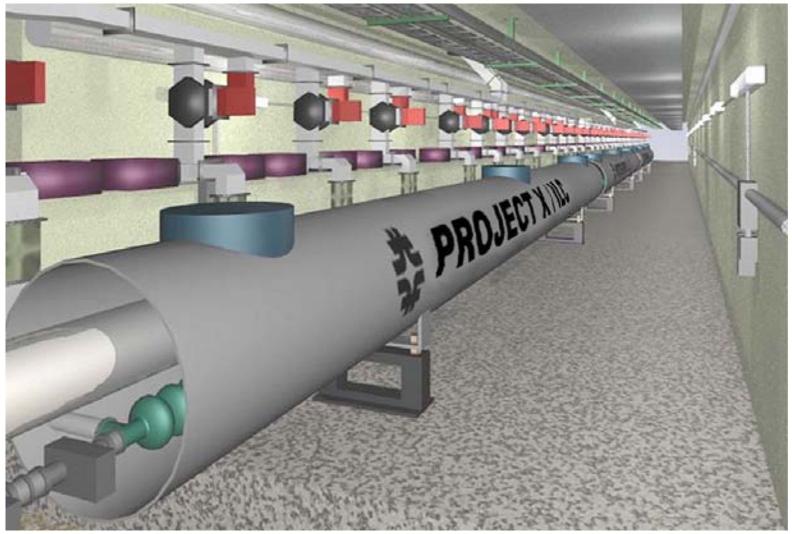
==> high energy stability

==>large stored energy

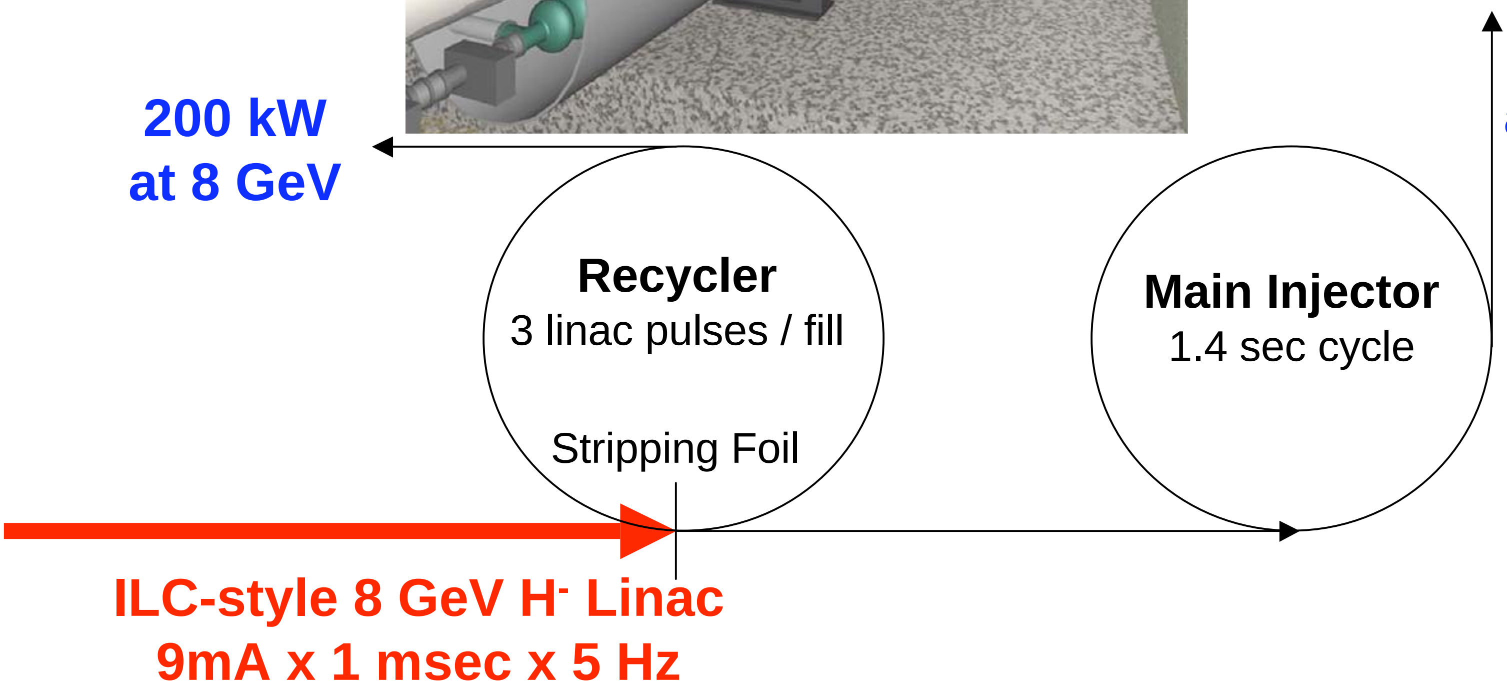
==> high efficiency at E_z

==> SC RF

Proton Intensity Frontier Option: Project X



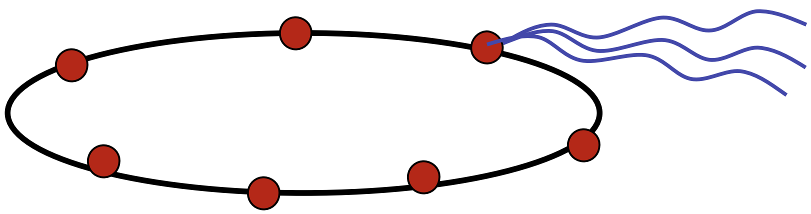
Initially NOvA
Possibly DUSEL later



Matter to energy: Synchrotron radiation science

Synchrotron light source

(pulsed incoherent X-ray emission)



FOM: Brilliance v. λ

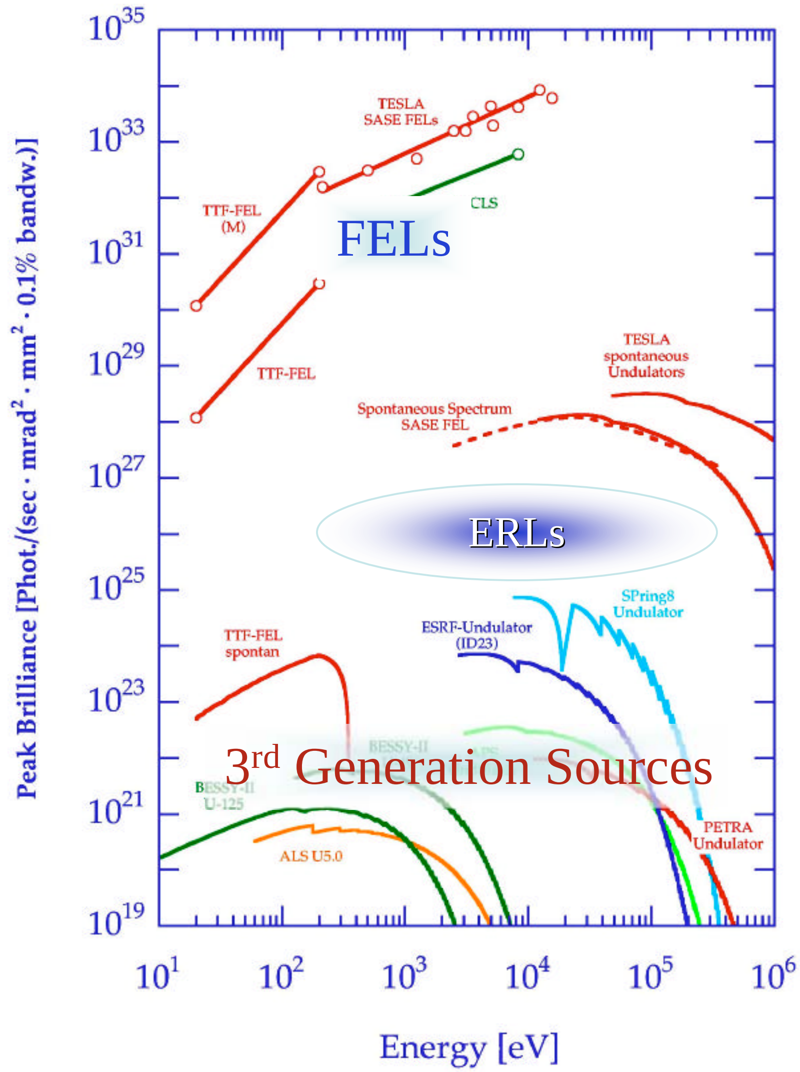
B = ph/s/mm²/mrad²/0.1%BW

Pulse duration

Science with X-rays

Imaging

Spectroscopy



Matter to energy: Energy Recovery Linacs

Hard X-rays ==> ~5 GeV

Synchrotron light source

(pulsed incoherent X-ray emission)

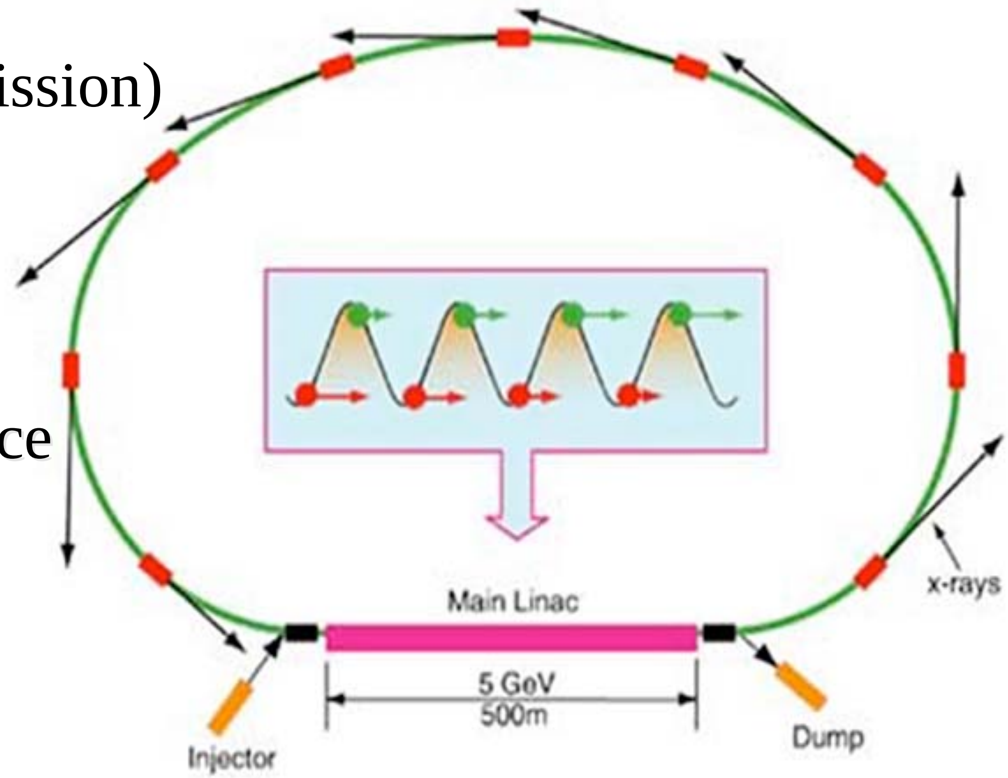
Pulse rates – kHz => MHz

X-ray pulse duration ≤ 1 ps

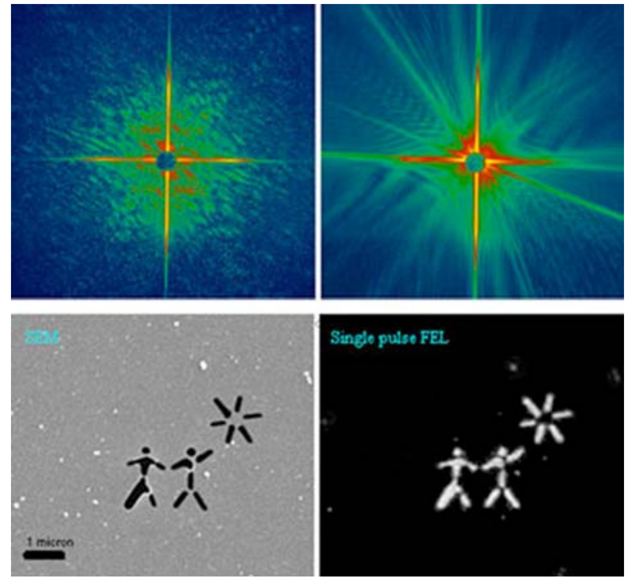
High average e-beam brilliance & e-beam duration ≤ 1 ps

⇒ One pass through ring
⇒ Recover beam energy
⇒ High efficiency

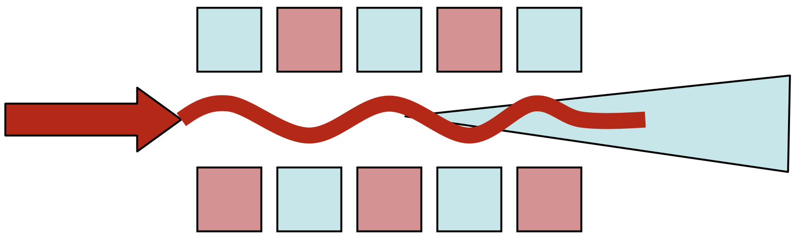
⇒ SC RF



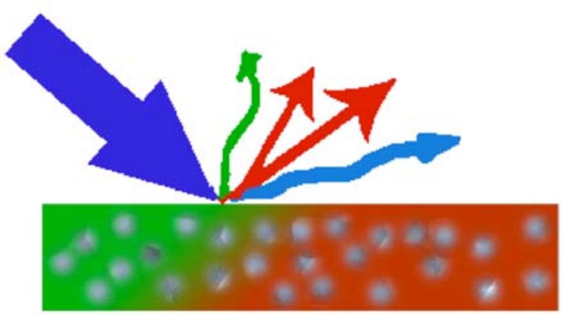
Even higher brightness requires coherent emission ==> FEL



Free electron laser



FOM: Brightness v. λ
Time structure



Full range of FEL-based science requires…

- Pulses rates 10 Hz to 10 MHz (NC limited to ~ 100 Hz)
  - ➙ High efficiency
- Pulse duration 10 fs - 1 ps
- High gain
  - ➙ Excellent beam emittance
    - ==> Minimize wakefield effect
    - ==> large aperture
    - ==> low frequency
  - ➙ Stable beam energy & intensity
    - ==> large stored energy in cavities
    - ==> high Q

===> SC RF

8 GeV Superconducting Linac

With X-Ray FEL, 8 GeV ν & Spallation Sources, ILC & ν-factory