Superconductivity in Particle Accelerators

SRF Cavities for Acceleration

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The next 45 minutes of your life

1. Acceleration of charged particles
2. Some basics of RF cavities
3. Superconductivity
4. Implications for cavity design
5. Current state-of-the-art and active research

Acceleration of charged particles

Some examples of accelerators

Accelerator	Status	“Mission”	Particle species	Particle energy
ESS	In construction	Materials research	p+	2 GeV
MAX-IV	Beginning operations	Materials research	e-	3.4 GeV
ILC	Design	Fundamental physics	e- & e+	500 GeV
ISIS	Active operations	Materials research	H- & p+	800 MeV
LCLS	Active operations	Materials research	e-	13 GeV
LHC	Active operations	Fundamental physics	p+ (+ a lot more!)	5 TeV

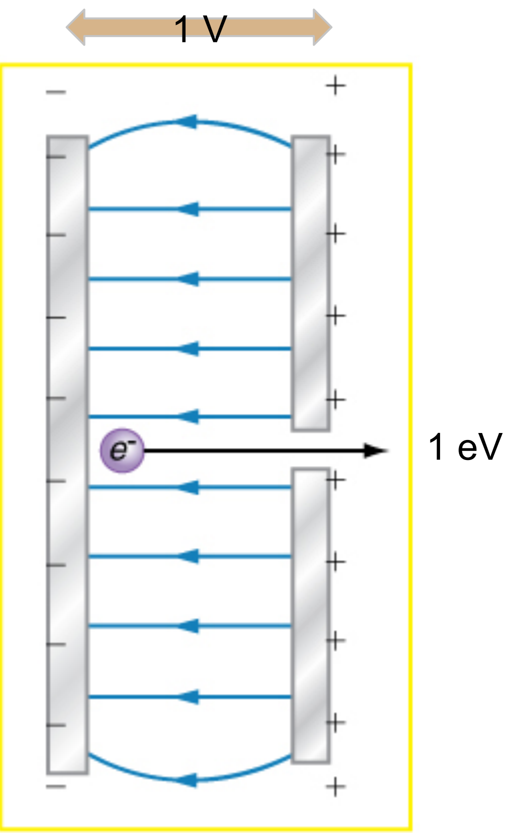
Electromagnetic action on charged particles

The Lorentz Force

$$\vec{F} = q\vec{E} + \vec{v} \times \vec{B}$$

Depends only on the magnitude & direction of the field -- perfect for acceleration

Always perpendicular to particle's motion -- use for steering, not for acceleration



Static Acceleration
Considering the huge particle energy required, this is impractical for all but the most simple accelerators.
For more than 100's of keV, bad things happen...

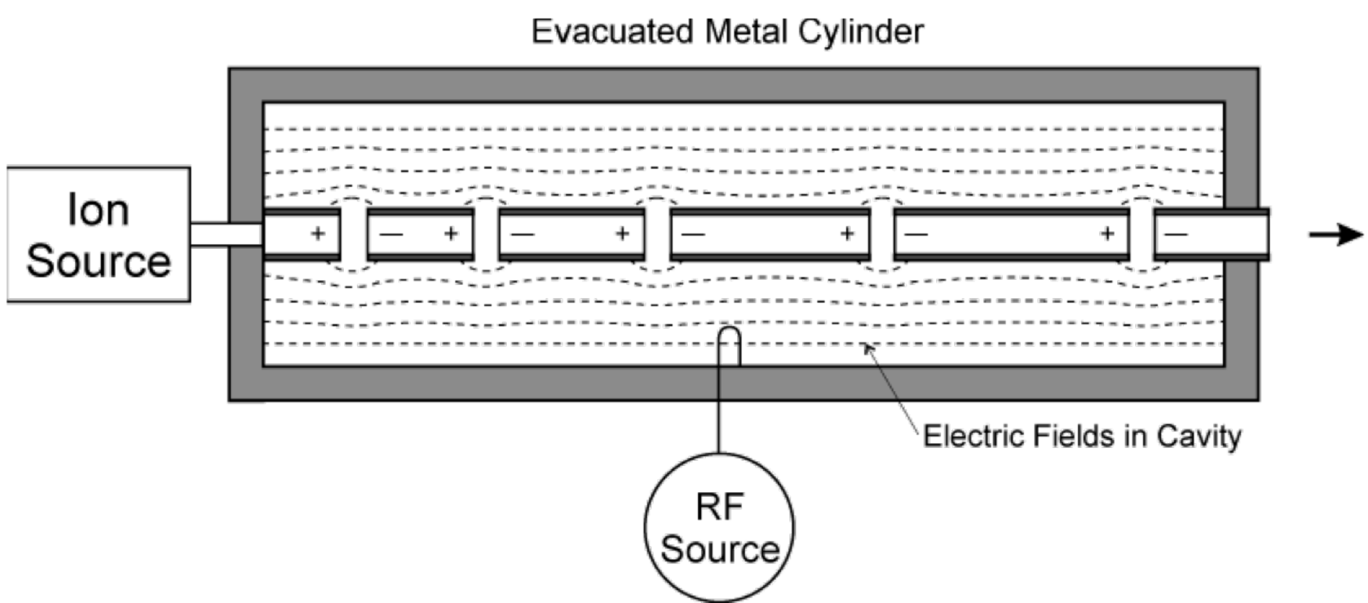
Bad things...

Solution -- sinusoidal fields

$$\vec{E} = \vec{E}_0\,(r, \theta, z) \cdot e^{i\omega t}$$

$$\omega = 2\pi f$$

- Vary the field rapidly
  - 10's of MHz or more
- The electrical breakdown doesn't have time to fully develop before the field reverses
- Time the beam to arrive when the field has the correct phase



Basics of RF Cavities

Some physics

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

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

$$\vec{\nabla} \cdot \vec{D} = q$$

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

Vacuum conditions

$$\vec{J} = 0$$

$$q = 0$$

$$\vec{E}(z, r, \phi, t) = \vec{E}_0(z, r, \phi) \cdot e^{i\omega t}$$

$$\vec{H}(z, r, \phi, t) = \vec{H}_0(z, r, \phi) \cdot e^{i\omega t}$$

$$E_z(r = R) = 0$$

$$E_\phi(r = R) = 0$$

$$H_r(r = R) = 0$$

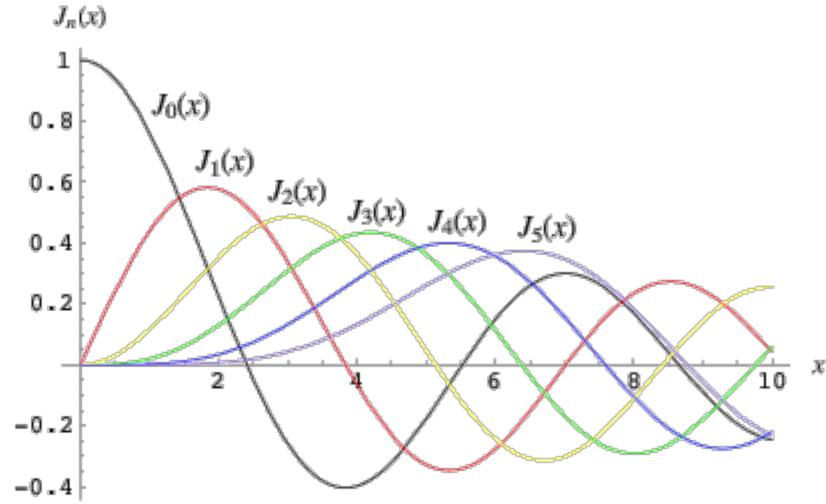
Cylindrical metallic boundary

Oscillatory solution

A full derivation is well worth doing, but not today :)

Look at Jackson's book, "Classical Electrodynamics", page 356

Simplest Solution



The zero'th Bessel function

$$E_z = E_0 \; J_0(k_c r)\, e^{-ik_z z} \; e^{i\omega t}$$

z component of the electrical field. Since the cavity is aligned such that the beam moves in the z direction, it is this component that accelerates the beam

The amplitude of the field. For example, 10 MV/m

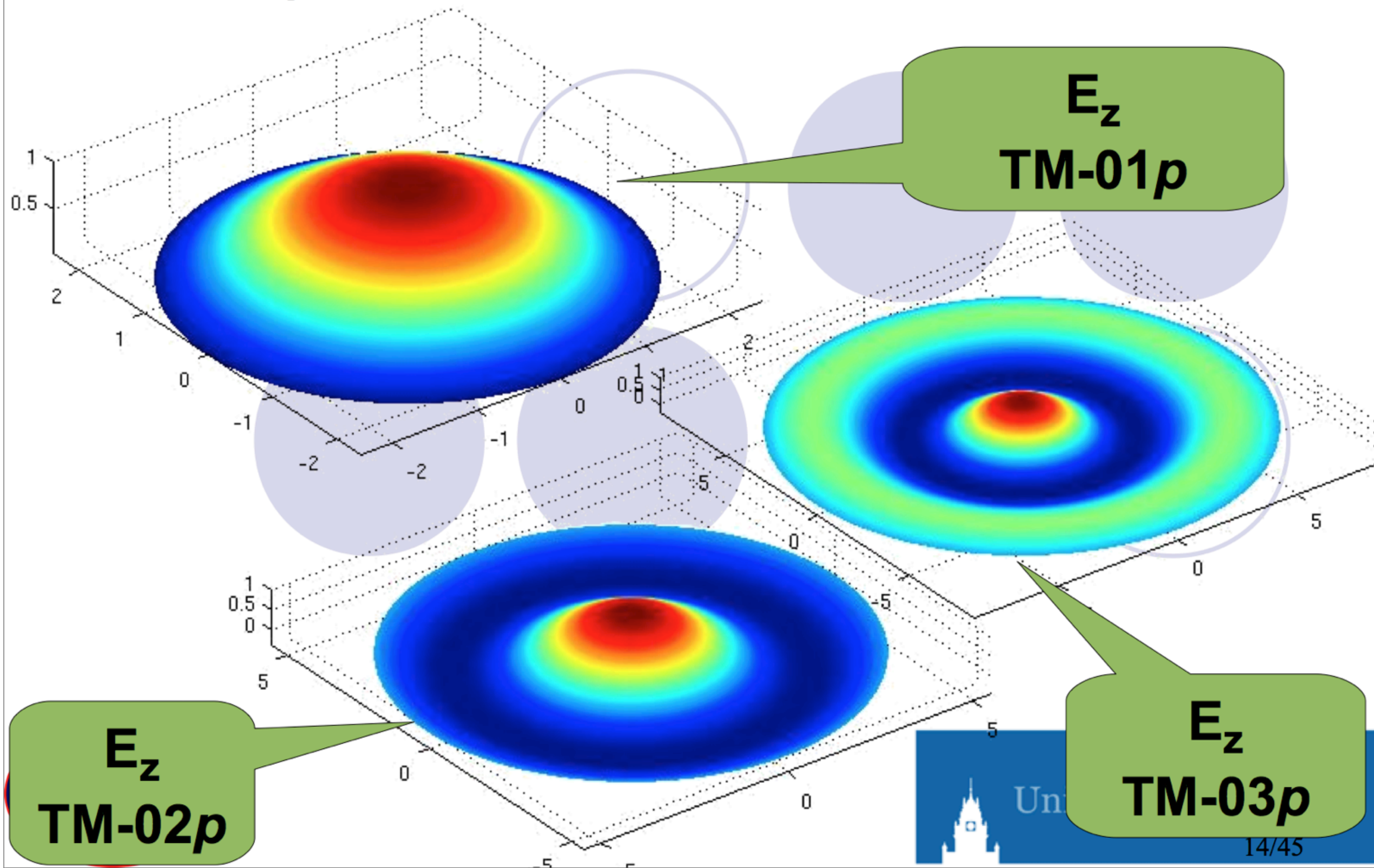
Oscillatory in *z* (as long as *kz* is real…)

Oscillatory in *t*

Note that for simplicity only *Ez* is shown here. There are other non-zero EM components, and you can see these in Jackson's book.

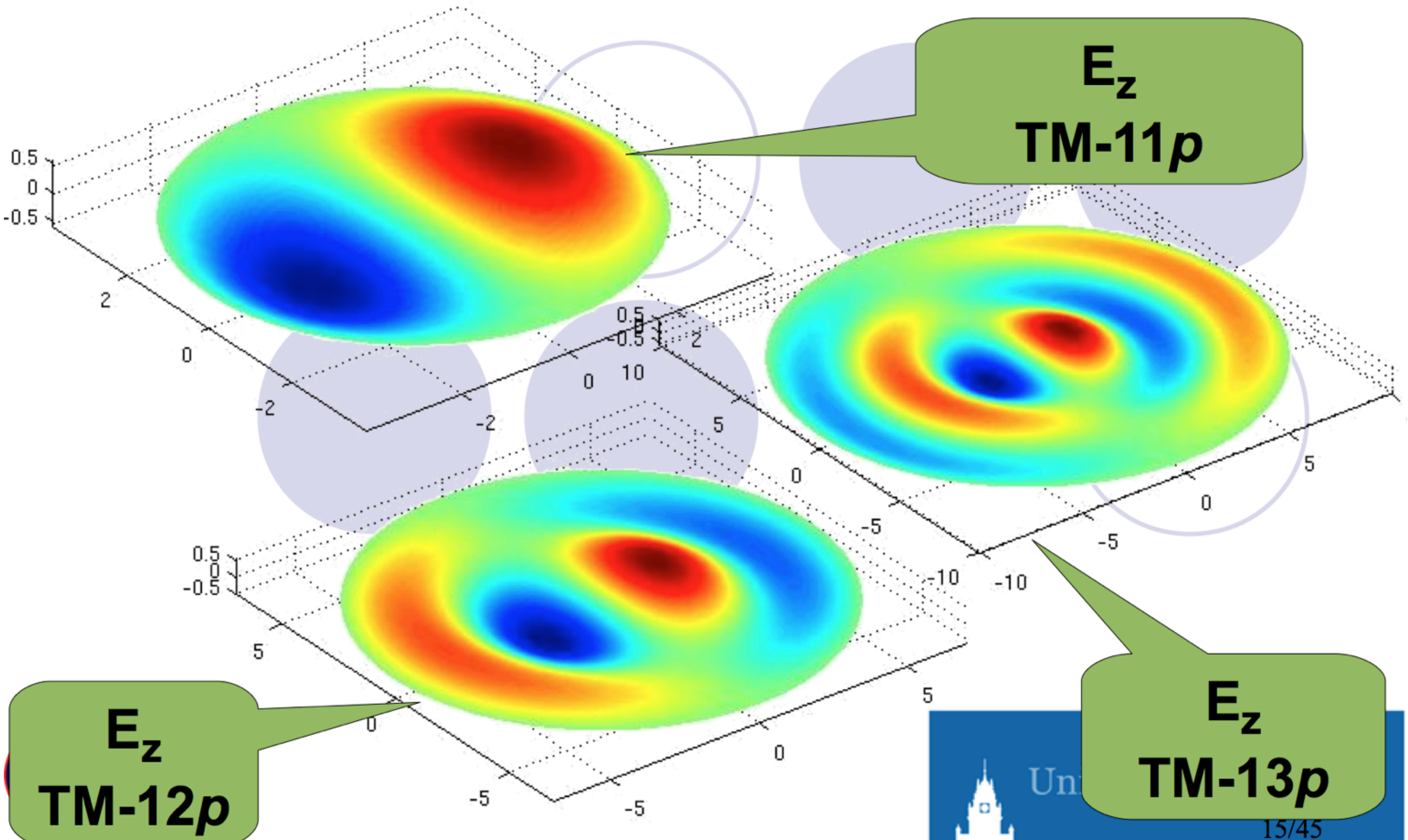
Visualising the fields

Monopole solutions



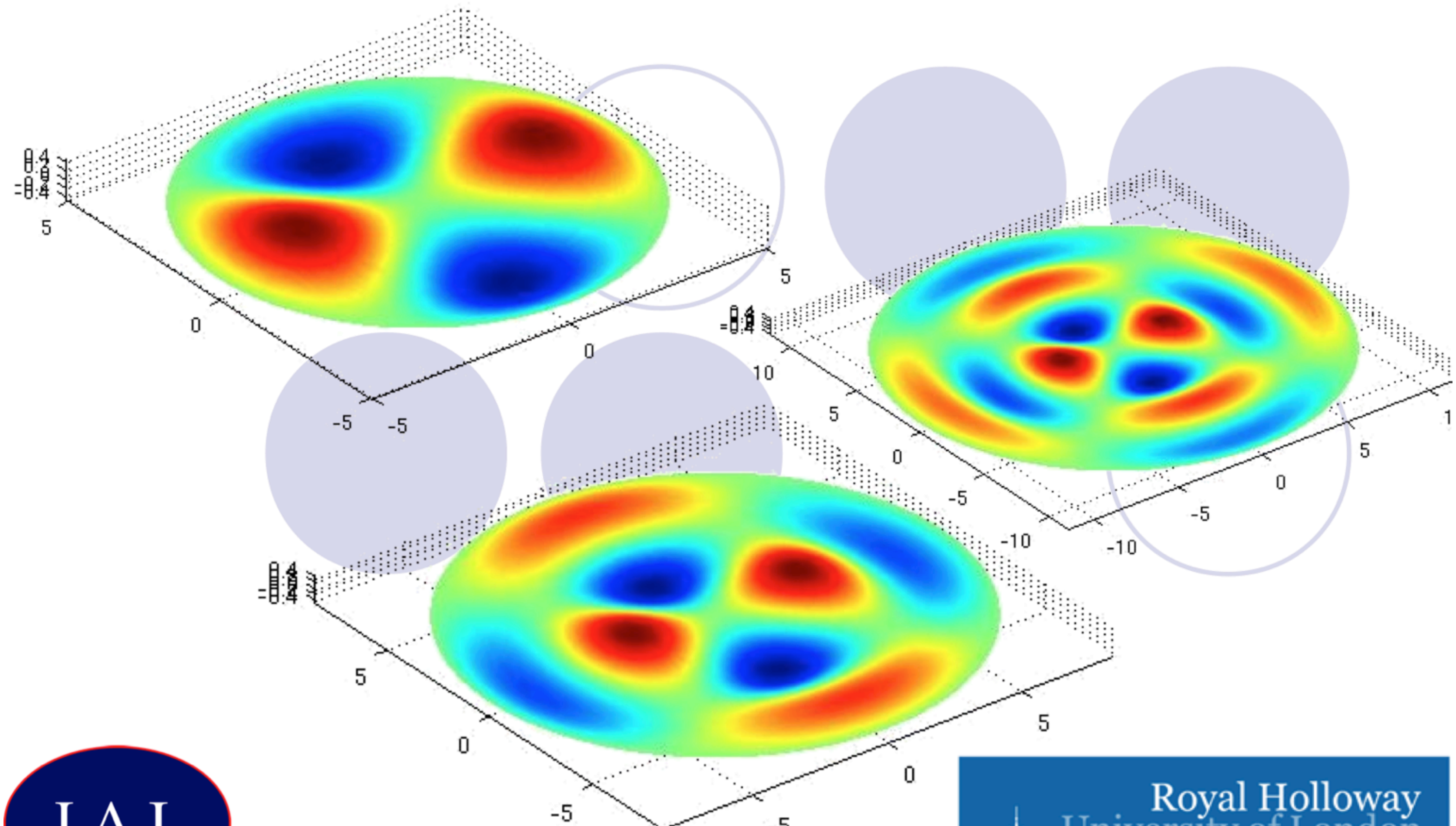
Visualising the fields

Dipole solutions



Visualising the fields

Quadrupole solutions

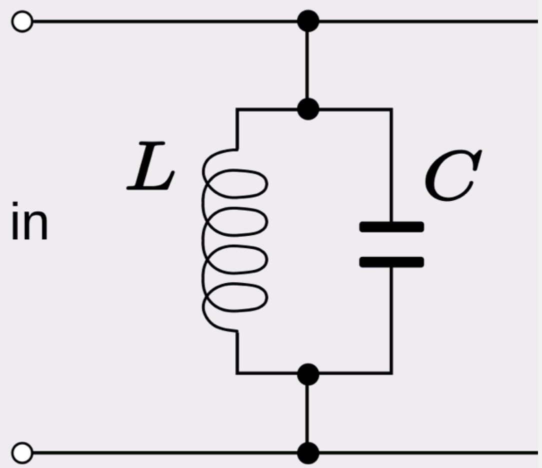


Superconductivity

A mathematical cavity model

Cavity as LC resonator

Input power



Output power?

Power is not just carried away by the beam, but also by resistive losses in the cavity walls

$$Q_0 = \frac{\omega W}{P_{diss}} = R\sqrt{\frac{1}{LC}}$$

$$\omega = \sqrt{\frac{1}{LC}}$$

Quality Factor, *Q0*, is proportional to the ratio of the energy stored in the field to the rate of power loss. So low losses requires a high shunt resistance.

Ohmic resistance

Perfect crystalline lattices should have zero resistivity

- Quantum-mechanical wave functions can extend infinitely without disruption

But…

- Lattice imperfections, thermal jitter, etc., disrupt the wave function

So, non-zero resistivity is a quantum mechanical phenomenon

Cooper pairs

Electrons (neg. charge) attract the lattice ions (pos. charge) as they move through the material.

Induces an apparent pos. charge excess, attracting other electrons

So -- electrons can be coupled

Cooper pairs

Pairing is due to an interaction between lattice vibrations and electron motion

- Pairs electrons of equal **but opposite** momentum
- That is, electrons moving in opposite directions

Imagine a sea of electrons constantly making and breaking Cooper bonds

- Not so much a waltz -- more like a barn-dance

Cooper pairs

The Cooper bonds are very low energy

Easily disrupted by thermal energy

So superconductivity only appears at very low temperatures

Two-Fluid Model

View the SC material as consisting of a mix of two fluids: NC & SC

Fraction of SC fluid goes to zero above the critical temperature, *Tc*

Below *Tc*, the fraction of SC fluid rises to 100% at T=0K

Important to note that this is just a mathematical model, and does not represent the actual physics inside the material

$$n_{normal} \propto e^{-\frac{\Delta}{k_B T}}$$

Predictions of the Two-Fluid Model

Below *Tc*, we have a mixture of superconducting Cooper pairs & normal-conducting electrons

Apply a DC voltage

- The SC pairs will conduct current without resistance, shorting out the finite-resistivity of the normal electrons
- Thus, the entire mixture appears to be superconducting

Now apply a sinusoidally varying voltage

- Inertia of the Cooper pairs causes them to slightly lag behind the voltage
- So they don't instantly follow the field, and therefore don't perfectly short-out the field from the normal electrons
- Therefore, normal current will also flow, dissipating power as usual

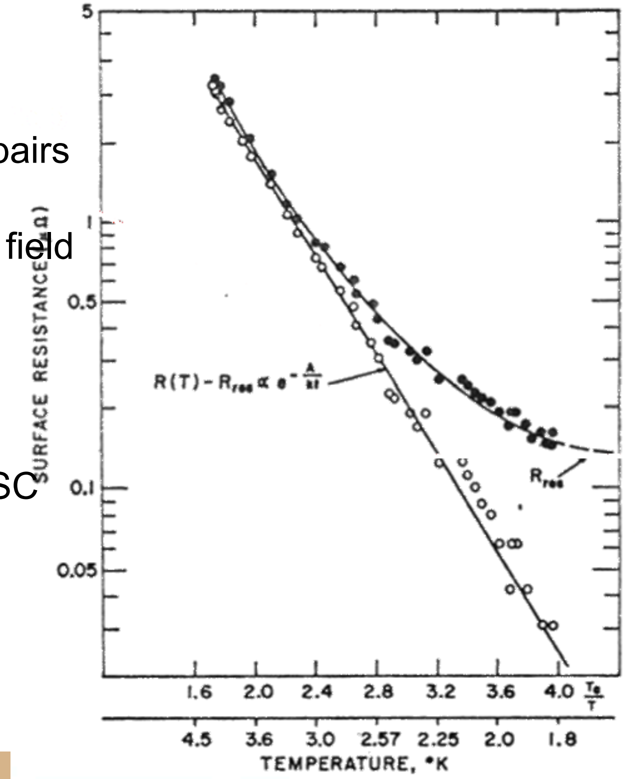
Predictions of the Two-Fluid Model

SC materials will have zero DC-resistivity below *Tc*

They will have very low, but non-zero, RF-resistivity

The RF resistivity will scale as follows:

- Quadratic with frequency
  - Increasing frequency means increased lag of the Cooper pairs
  - Increasing frequency means decreased penetration of the field into the material
- Proportional to the conductivity of the normal fluid
  - It is the normal fluid that provides the resistivity when the SC fluid lags the field
- Exponential drop with temperature
  - Following the fraction of the normal fluid



Material purity

Super-pure material is better, isn't it?

As usual in physics, the answer is "*Yes. And no*"

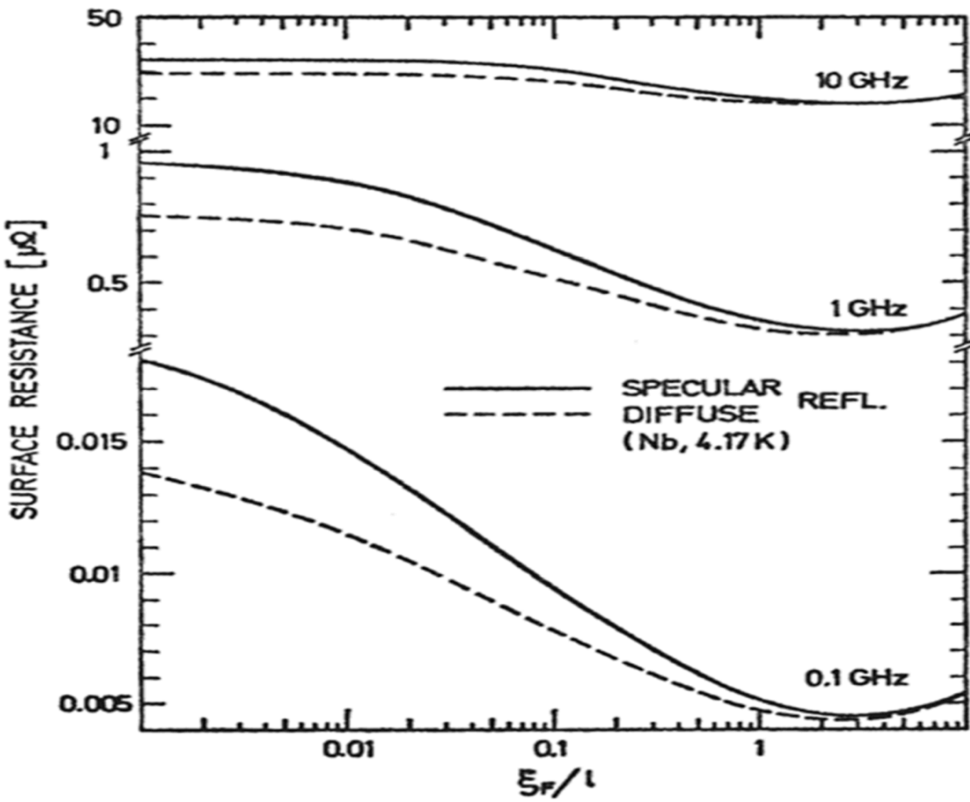
Impurities decrease the mean-free path of the normal electrons

- Gives them less time to "cause trouble"
- Decreases the resistivity

But!

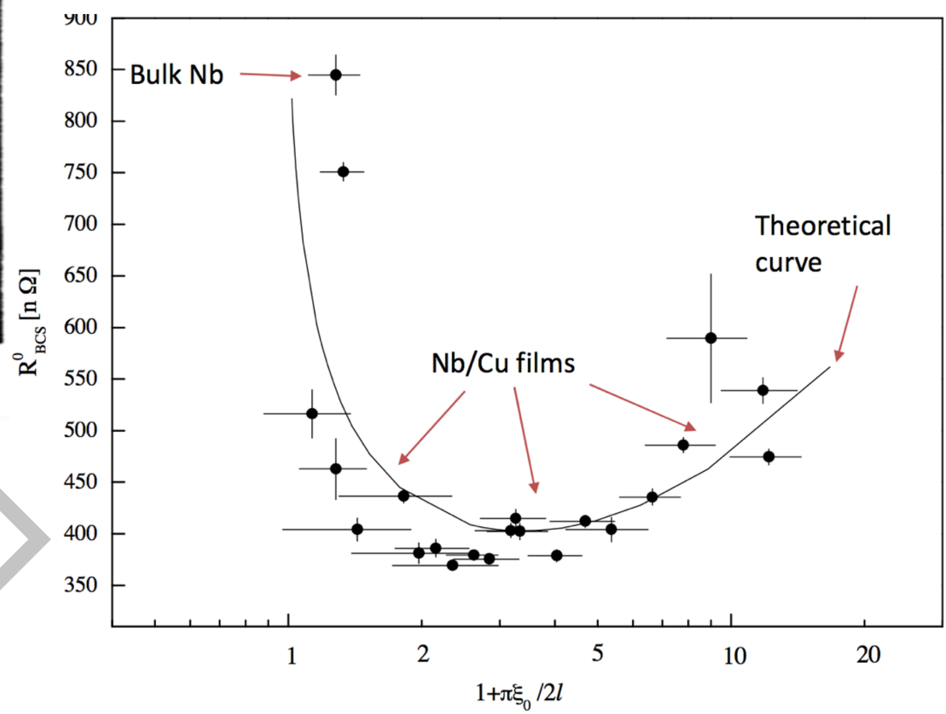
- Eventually the mean free path will become comparable to the London penetration depth
  - The depth the field extends into the material
- The equations then predict a turn-over in the resistivity

Material Purity



Theory

Measurement



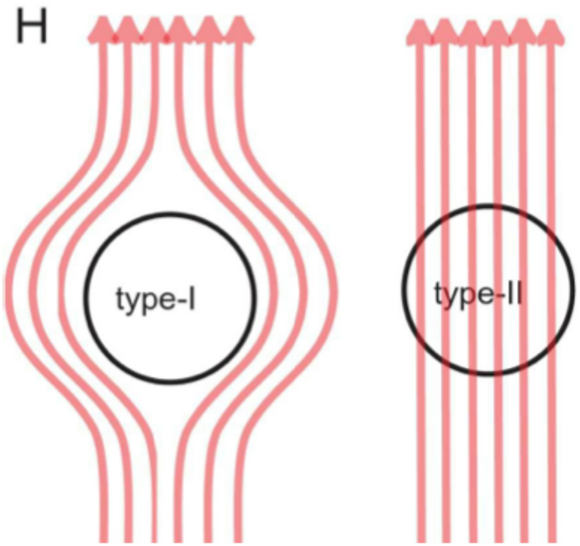
Type-I & Type-II SC materials

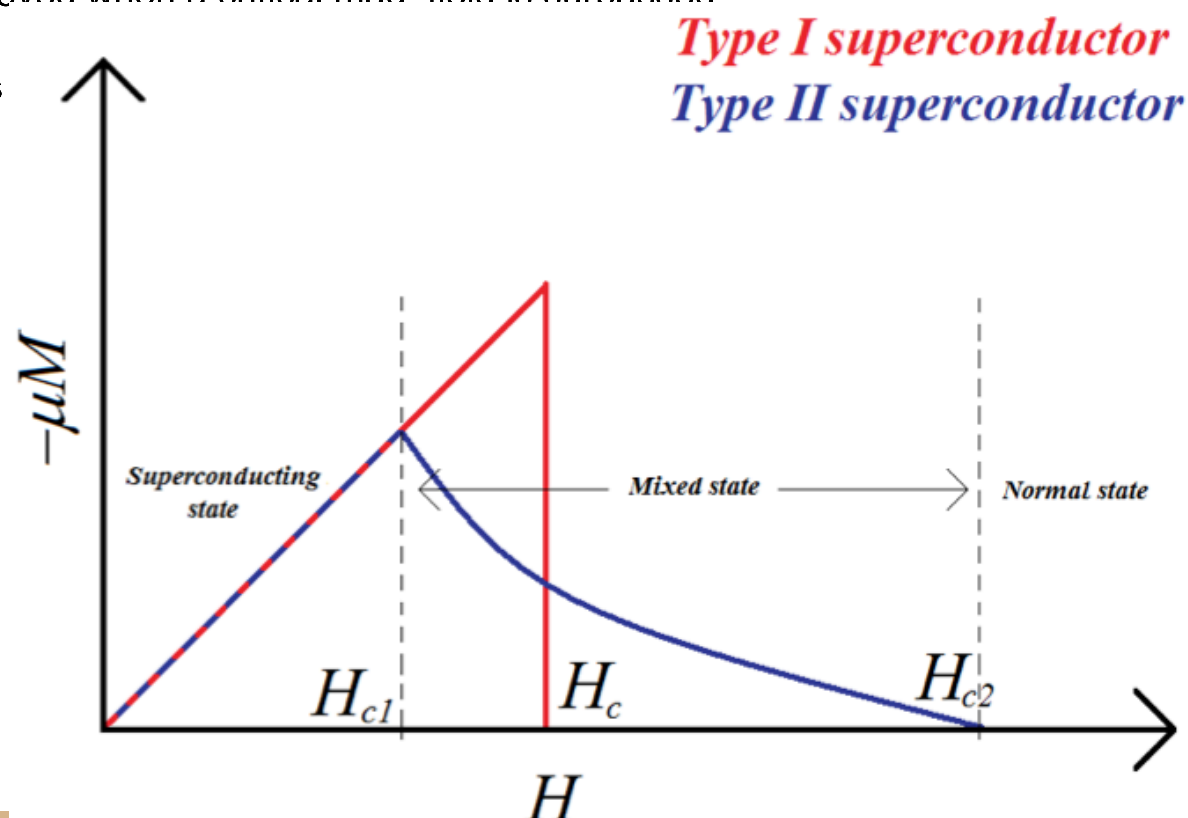
Theory predicts two types of SC material

Type-I: Expels magnetic fields from the body of the material when crossing *Tc*

Superconductivity destroyed when a critical mag. field is surpassed

Type-II: Traps magnetic fields





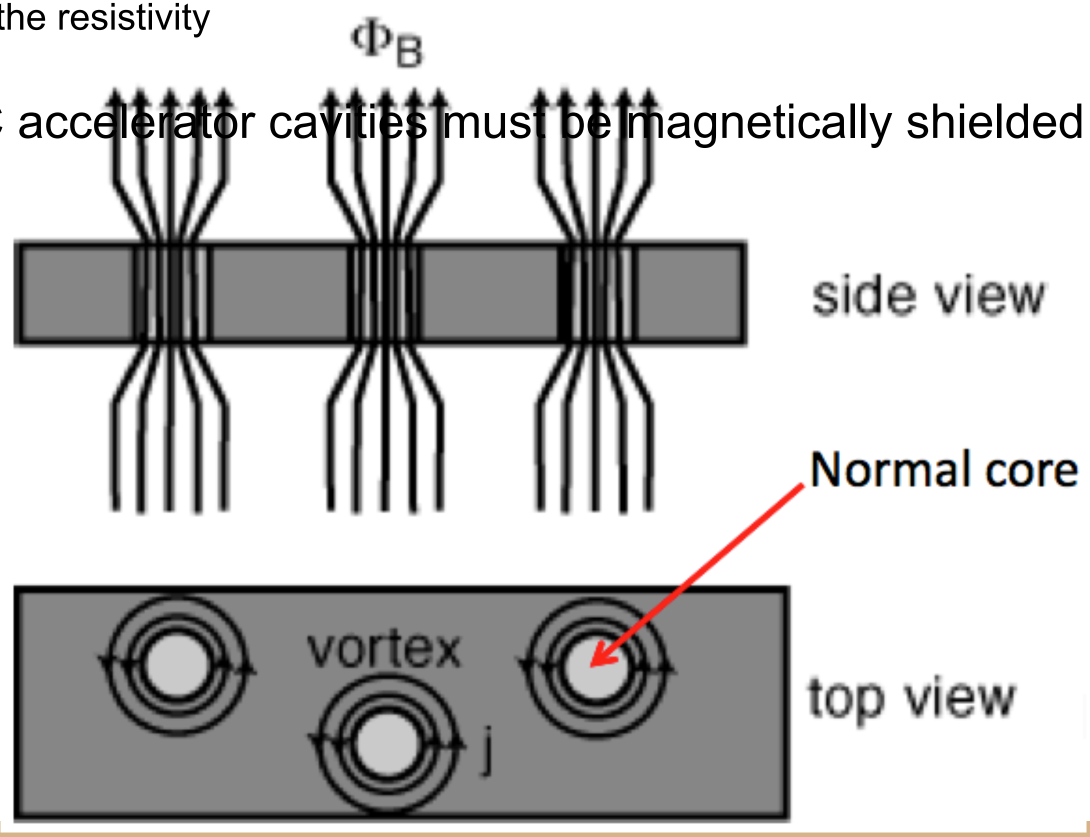
Niobium (type-II) is used in accelerators

Any mag. flux present during cool-down will be trapped

Forms vortices that can scatter SC current

Increasing the resistivity

Therefore SC accelerator cavities must be magnetically shielded during cool-down



SC implications on cavity design

Machine parameters

- SC helps accelerators due to the almost-zero power loss
  - Almost all power goes to the beam
- Very high-Q0 of SC cavities may result in a long-filling time
  - The filling time "wasted power"
    - The RF source is on, but there is no beam
  - Reduce this in two ways:
    - Increased beam-pulse length -- reduces the fraction that the filling time accounts for
    - Increased beam current -- "loads" the cavity heavily, resulting in a reduced fill-time

In general it is advisable to adapt the machine parameters to the users' needs, and then choose the technology appropriately.

- Low frequencies

State-of-the-art & active research

Electrical breakdown

- High frequencies chosen to limit breakdown effects
- But breakdowns still occur, in two forms:
    - Field emission
        - Electrons pulled from the cavity surface, and accelerated
        - Absorb the energy of the RF field
            - Decreasing the Q0
            - Destroying the efficiency of the acceleration
        - Damages downstream components
    - Multipactor
        - Emission & absorption of electrons in a self-amplifying avalanche
        - Absorbs the energy of the RF field

Field emission

Field emission in a single cavity

Field emission

Field emission in multiple cavities

Multipactor

Coupler multipactor

Multipactor

- Closely related to the problem of field emission
- Difference is the re-emission of particles from impact points
  - A re-emission ratio greater than 1 results in an avalanche
  - Re-emission depends on the RF phase at the time of impact
    - So the particles must arrive at the right time
    - This results in a resonance condition
- So multipactor only happens for specific RF amplitudes
  - Leads to “multipactor bands”

Some typical real-world problems