# Lecture 13
# Superconductivity

J. G. Weisend II

# Goals

- Describe the basic physics behind superconductivity (mainly low $T_C$ )
- Describe the requirements of practical superconducting materials
- Describe how superconducting materials are turned into practical conductors for applications
- Touch briefly on superconducting radiofrequency systems (SCRF)
- Touch briefly on Hi$T_C$ superconductivity

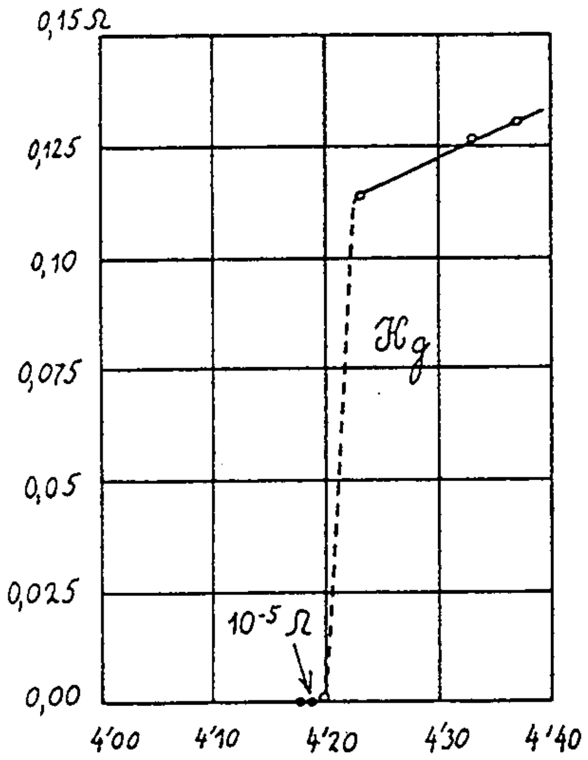
- Note that the next 2 lectures will really only give an overview on the subject and there are many, many other details. A good thorough introduction to superconductivity is a full semester class and even that will not cover everything

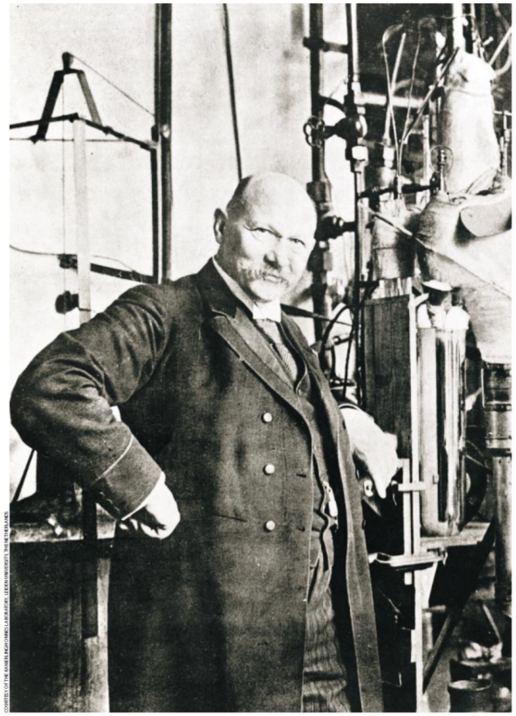
# Introduction

- As we’ve seen, superconductivity is a major motivating factor for the use of cryogenics – particularly in scientific applications but also in commercial systems such as MRI
- Cryogenic engineers will frequently be called upon to design systems to cool and keep cold superconducting equipment
- Thus, understanding the requirements of superconductors is an important part of the training of a cryogenic engineer.
- What is a superconductor?
  - A superconductor is a material that conducts DC electrical current with zero resistive losses under certain specific conditions
    - When in the superconducting state the resistive loss is identically zero not just vanishingly small but zero

# Discovery of Superconductivity

- H. Kamerlingh-Onnes  June 9, 1911 – University of Leiden
  - Kamerlingh-Onnes had previously been the first to liquefy helium in 1908
  - Having liquid helium available enabled this discovery



# Conditions for Superconductivity

- Critical Temperature
  - All superconductors have a temperature above which they no longer become superconducting
- This is an obvious condition but by no means the only condition
- To understand the other conditions we need to understand the magnetic properties of superconductors
- Not all materials are superconductors – most in fact aren't

**Table 2.9. Critical Temperature and Critical Field of Type I Superconductors**

| Material | $T_c$ (K) | $\mu_0 H_0$ (mT) |
|---|---|---|
| Aluminum | 1.2 | 9.9 |
| Cadmium | 0.52 | 3.0 |
| Gallium | 1.1 | 5.1 |
| Indium | 3.4 | 27.6 |
| Iridium | 0.11 | 1.6 |
| Lanthanum α | 4.8 | |
| β | 4.9 | |
| Lead | 7.2 | 80.3 |
| Lutecium | 0.1 | 35.0 |
| Mercury α | 4.2 | 41.3 |
| β | 4.0 | 34.0 |
| Molybdenum | 0.9 | |
| Osmium | 0.7 | ~6.3 |
| Rhenium | 1.7 | 20.1 |
| Rhodium | 0.0003 | 4.9 |
| Ruthenium | 0.5 | 6.6 |
| Tantalum | 4.5 | 83.0 |
| Thalium | 2.4 | 17.1 |
| Thorium | 1.4 | 16.2 |
| Tin | 3.7 | 30.6 |
| Titanium | 0.4 | |
| Tungsten | 0.016 | 0.12 |
| Uranium α | 0.6 | |
| β | 1.8 | |
| Zinc | 0.9 | 5.3 |
| Zirconium | 0.8 | 4.7 |

From: Helium Cryogenics
Van Sciver

# Superconductors & Magnetism

- Superconductors are also perfect diamagnets i.e. they expel all magnetic field (the Meissner effect)
  - This is a different result than if we considered the material as a pure conductor
    - » This is demonstrated by the "floating magnet" trick
- If  the applied magnetic field exceeds a certain level, the superconductor reverts back to a normal conductor.
- Critical Field
  - All superconductors have a field above which they become normally conducting

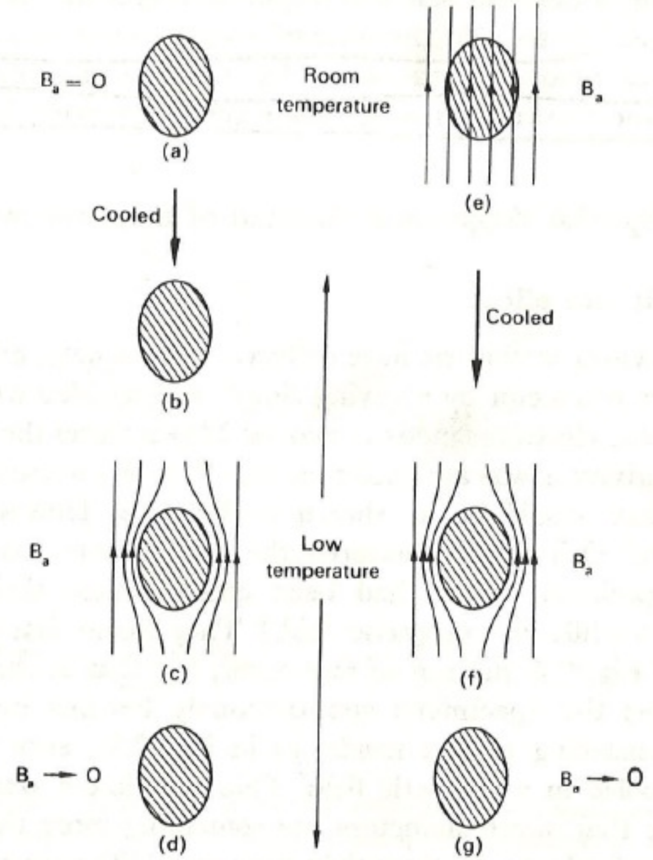



FIG. 2.3. Magnetic behaviour of a superconductor. (a)–(b) Specimen becomes resistanceless in absence of magnetic field. (c) Magnetic field applied to superconducting specimen. (d) Magnetic field removed.

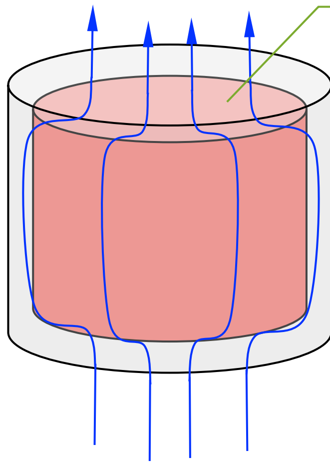
(e)–(f) Specimen becomes superconducting in applied magnetic field. (g) Applied magnetic field removed.

# Type II Superconductors

- Some superconductors have 2 critical fields: below the first ($H_{c1}$) all magnetic flux is expelled from the material. Above the first but below the second ($H_{c2}$) the flux penetrates in the form of quantized magnetic fields or fluxons. In this "mixed state" the bulk of the material remains superconducting
- Such material are called Type II superconductors
- Type II materials tend to be alloys though Nb is an important Type II superconductor
- Type II superconductors have much (orders of magnitude) higher upper critical fields and thus are more useful in technology

# Type II Superconductors

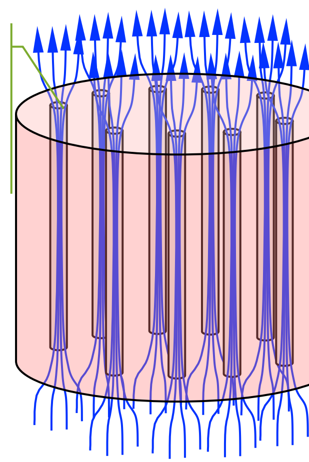
Type I ($\kappa < 1/\sqrt{2}$)



*Complete field exclusion*

Pure metals
$B_C \approx 10^{-3} \ldots 10^{-2}$ T

Type II ($\kappa > 1/\sqrt{2}$)



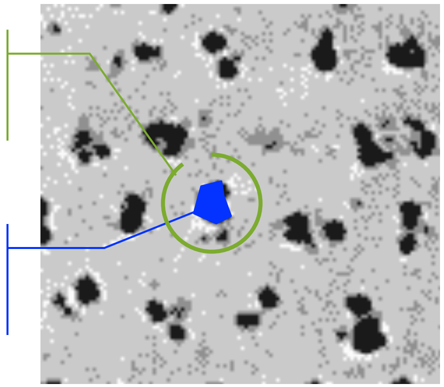
*Partial field exclusion*
*Lattice of fluxons*

Dirty materials: alloys
intermetallic, ceramic
$B_C \approx 10 \ldots 10^2$ T

Ginzburg, Landau, Abrikosov, Gor'kov, 1950…1957

# Fluxons can be directly seen (note similarity to quantized vortices in He II)

- Courtesy L. Boturra of CERN




$$\Phi_0 = h/2e = 2.07 \times 10^{-15} \text{ Wb}$$

Observation on Pb-4at% In magnetised by a field of 3000 Oe and decorated by Co particles

Essmann & Träuble, 1967

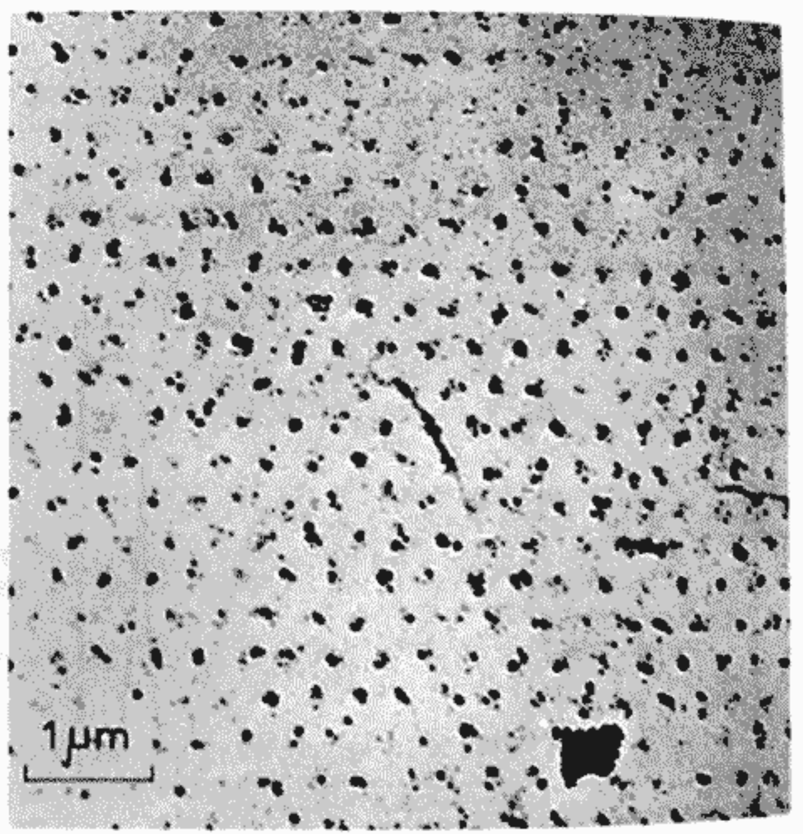



Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

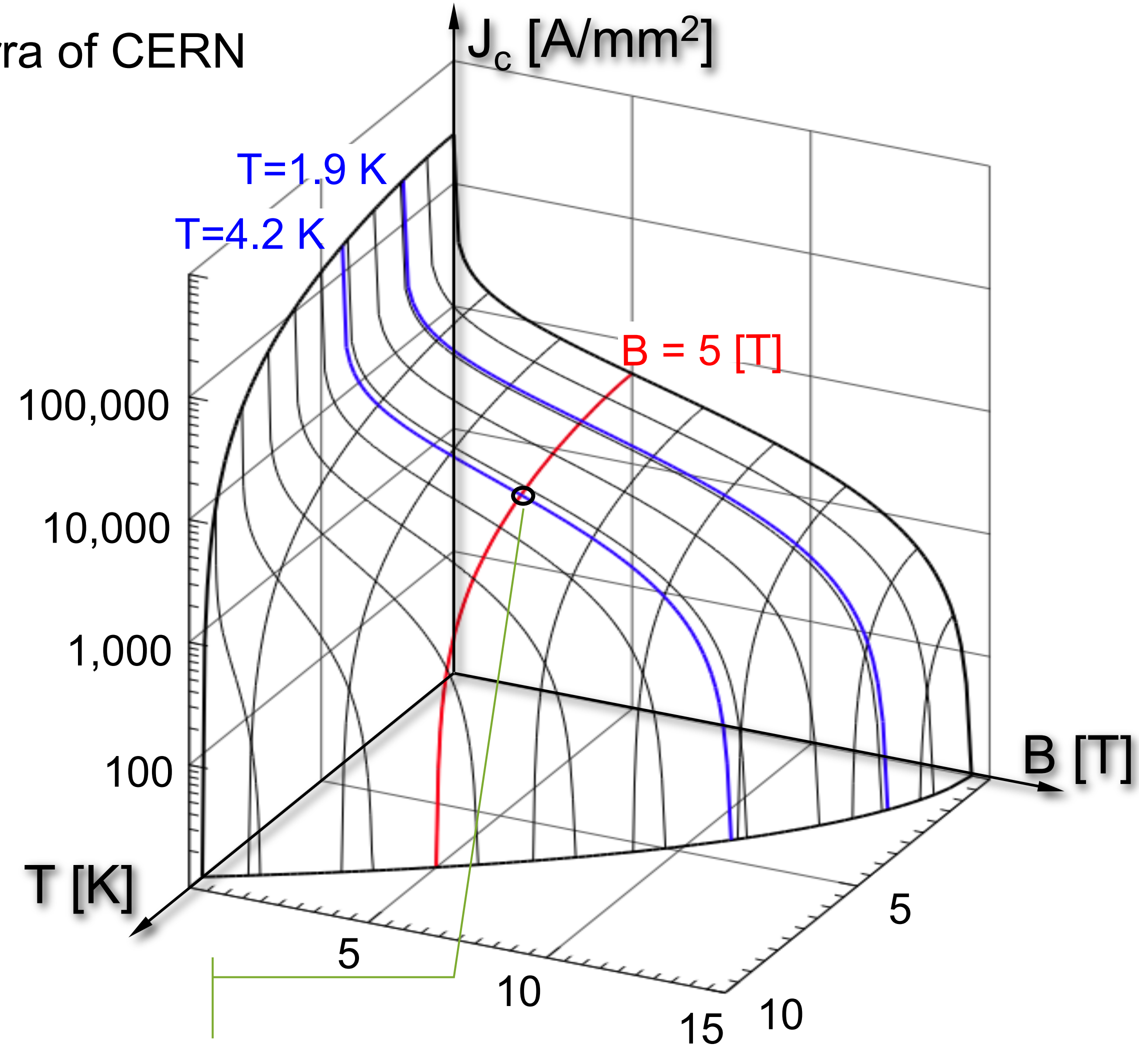
# Critical Current

- A third parameter in superconductivity is critical current. If the critical current is exceed superconductivity breaks down
- The current in a superconductor stems from 2 causes. The transport current and the shielding currents required for the Meisser or mixed states. Thus, the critical current and critical fields are related.
- If we exceed the critical current ( frequently expressed as critical current density $J_c$ ) critical temperature or critical field the material stops being a superconductor
- We call this "going normal" or <u>Quenching</u>
- Thus the point at which a material is superconducting becomes a 3D space

# LHC NbTi Wire

Courtesy L. Boturra of CERN

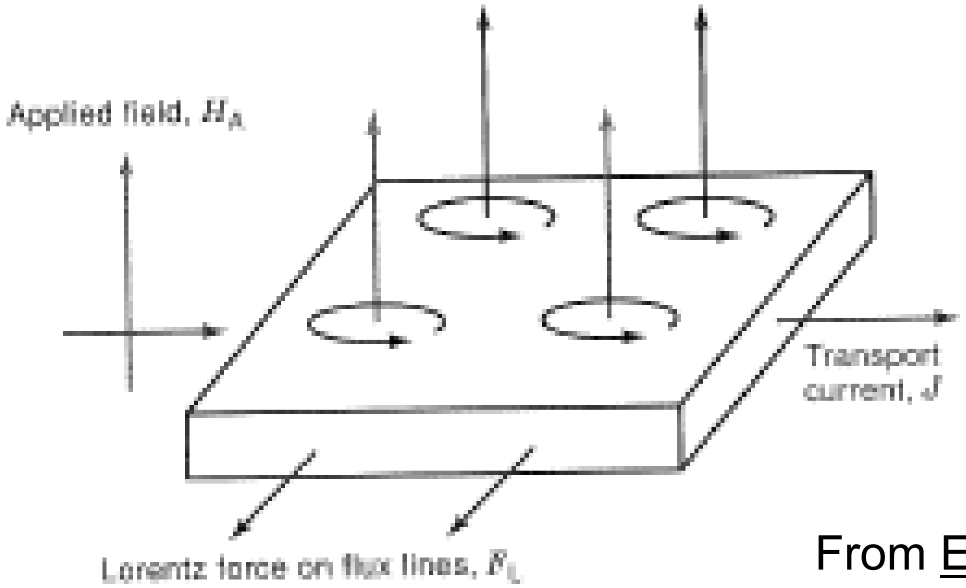
Note
Improvement in B
and Jc
@ T = 1.9 K




Jc (5 T, 4.2 K) ≈ 3000 A/mm$^2$

# Flux Pining

- In Type II superconductors the Lorentz force caused by the interaction between the current and the magnetic field will cause the fluxons to move.
- Movement of the fluxons will cause heating and thus quenching of the superconductor




From Engineering Superconductivity
P. Lee

# Flux Pining

- In practical superconductors the fluxons are pined to prevent movement – this allows higher current densities.
- Pinning sites are created by complicated metallurgical processes (heat treatments, cold work and alloying)
- This development over the last 30 years has been a major victory in developing practical superconductors for applications

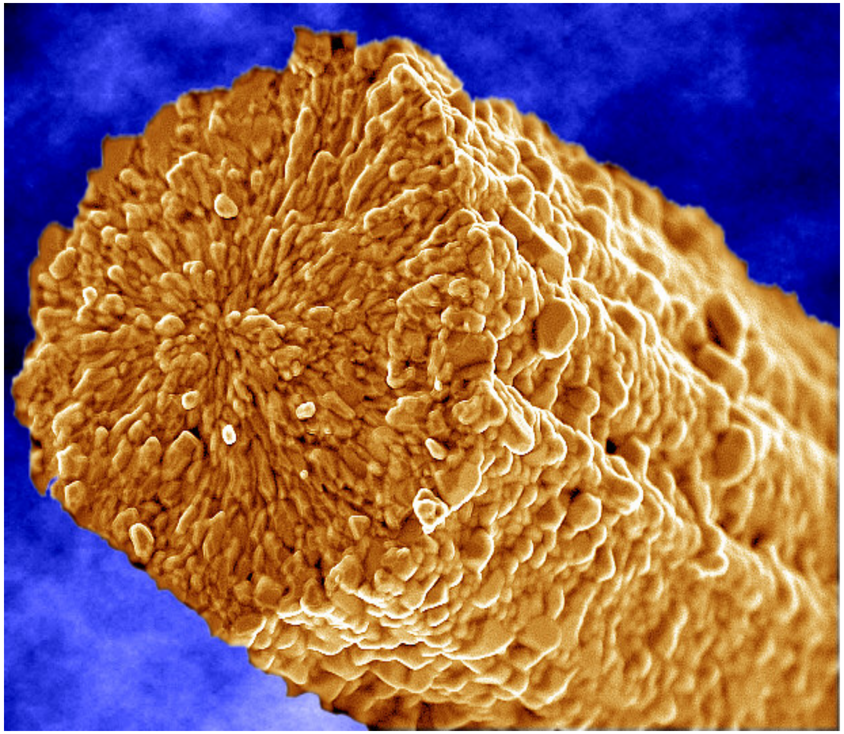
# Flux Pinning Sites

Courtesy L. Boturra of CERN

Precipitates in alloys

Grain boundaries in inter-metallic compounds


Microstructure of Nb-Ti



Microstructure of $Nb_3Sn$

# But Wait!
# What Causes Superconductivity?

- The following is a very hand waving explanation of the origin of low temperature superconductivity
- There is a very elegant, accurate and complicated description of low temperature superconductivity:
  - This is the Bardeen-Cooper- Schrieffer theory or BCS theory
- Simply put
  - Electrons in the material are linked together into Cooper pairs via an attractive force that comes from the oscillations of the (positively charged) lattice
  - These Cooper pairs now act more like bosons and in a sense undergo a Bose-Einstein condensation similar to that seen in He II
  - This "condensate" in effect acts as one "unit" you can not scatter or change the energy of a single electron without changing the energy of all of them
    - » There is thus an energy gap and unless the energy of interactions exceeds this value there is no scattering and thus no resistance
- BCS theory explains and predicts observable behavior in low Tc superconductors

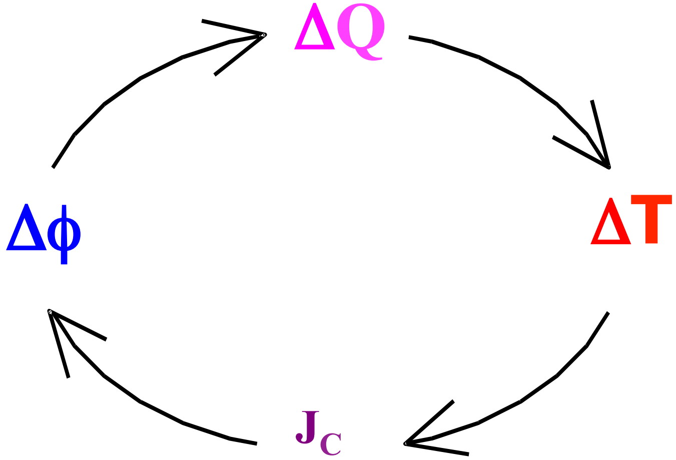
# Impact of Changing Currents

- Even superconductors have losses when exposed to alternating currents or fields. The detailed explanation of these losses is beyond the scope of this course but a brief overview will be given since it drives the design of practical superconductors.
- The first thing they understand is that AC losses exist in superconductors and while they can be reduced they can not be eliminated.
- They are broadly speaking 2 major sources AC losses in superconductors: hysteresis (caused by flux jumping) and losses caused by AC coupling between adjacent filaments.

# Flux Jumps

slide courtesy of L. Boturra - CERN

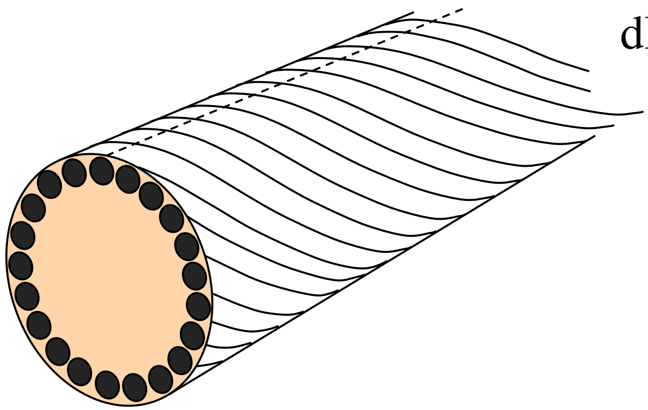
- Unstable behavior is shown by all superconductors when subjected to a magnetic field:
  - B induces screening currents, flowing at critical density $J_C$
  - A change in screening currents allows flux to move into the superconductor
  - The flux motion dissipates energy
  - The energy dissipation causes local temperature rise
  - $J_C$ density falls with increasing temperature



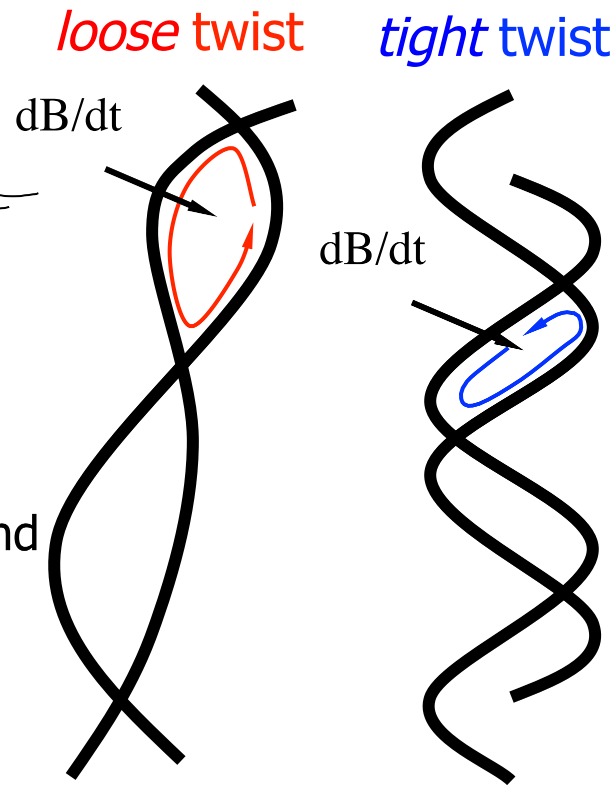

Flux jumping is cured by making superconductor in the form of fine filaments. This weakens the effect of $\Delta\phi$ on $\Delta Q$

slide courtesy of L. Boturra - CERN

# Filaments coupling



All superconducting wires and are twisted to decouple the filaments and reduce the magnitude of eddy currents and associated loss



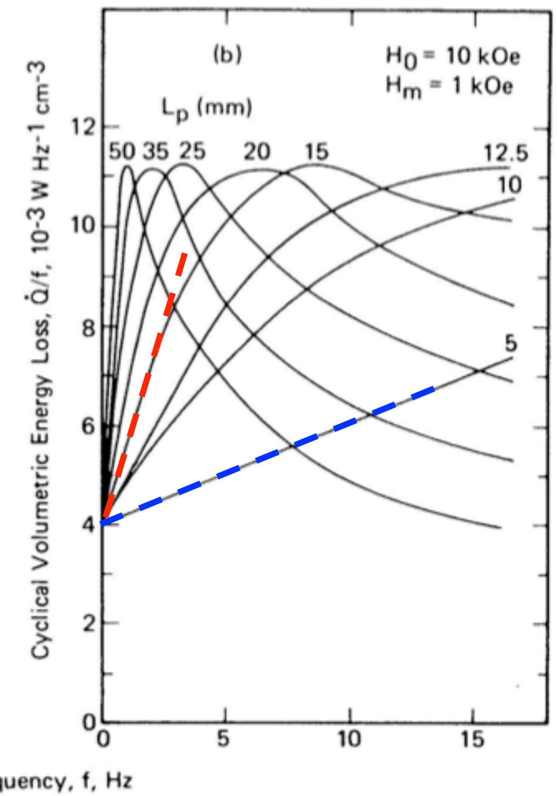
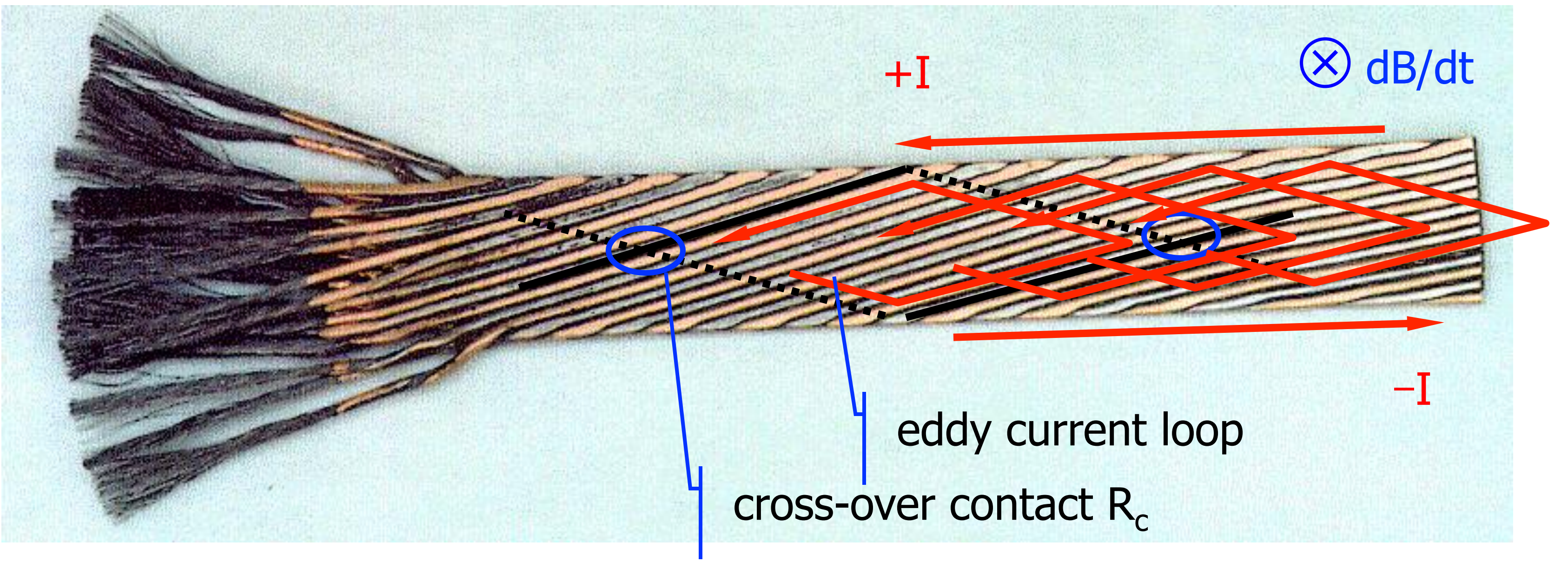




Figure 26-8. Energy loss per cycle ($\equiv \dot{Q}/f$) plotted *versus* frequency of the alternating component of an applied field $H_a(\omega) = H_0 + H_m \sin \omega t$. (a) The per-cycle *coil* loss is plotted for six values of $H_m$ between 0.25 and 1.25 kOe at $H_0 = 10$ kOe; (b) the per-cycle *volumetric* loss of the composite is plotted for eight values of the twist pitch, $L_p$, at $H_0 = 10$ kOe, $H_m = 1$ kOe—after KWASNITZA and HORVATH [KWA74, KWA76].

slide courtesy of L. Boturra - CERN

# Coupling in cables




The strands in a cable are coupled (as the filaments in a strand). To decouple them we require to twist (transpose) the cable and to control the contact resistances

# Practical Superconductors

- Superconductors are relatively poor conductors when normal
- Superconductors do have resistive losses when the current is varied
- Superconductors can't generally be used as a bulk material. They are divided into filaments (tens of $\mu$m in DIA) housed in a good conductor (known as a stabilizer) matrix. This:
  - Prevents flux jumping and resultant heating
  - Increases stability
- Groups of filaments themselves are also twisted into a cable to reduce coupling and resulting AC losses in the cables
- AC fields also induce eddy current losses in the good conductor within which the superconducting filaments are housed
- The two workhorse practical low Tc superconductors are:
  - Nb Ti (ductile)
  - $Nb_3Sn$ ( higher Jc and Hc but a brittle inter metallic compound)

# Practical Superconductors

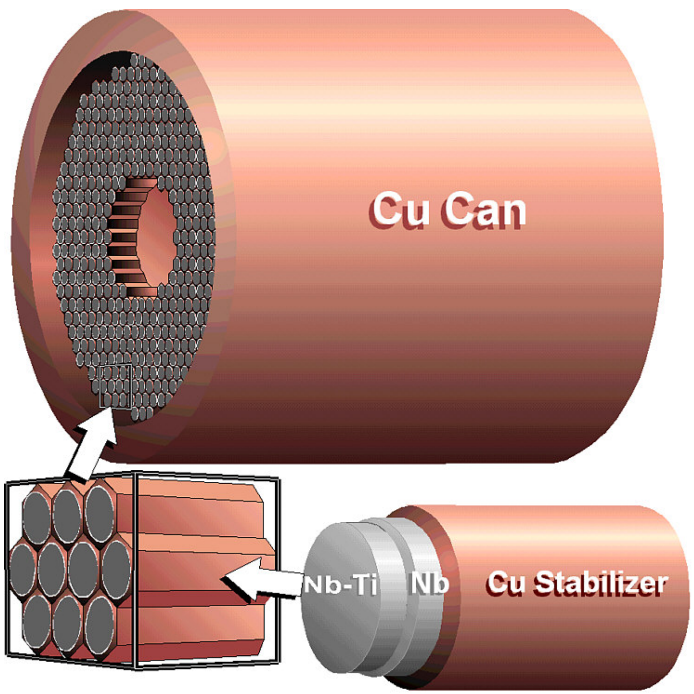
- It's important to note that while superconductivity was discovered in 1911, practical high current density superconducting materials were developed until the 1960s and weren't suitable for wide spread technological applications (understanding flux pining, manufacturing techniques ) until the 1980's
- This has implications for applications using the much more complicated HiTc superconductors
- How doe we create superconducting wire?

*Graphics by courtesy of Applied Superconductivity Center at NHMFL*

slide courtesy of L. Boturra - CERN

# Nb-Ti manufacturing route

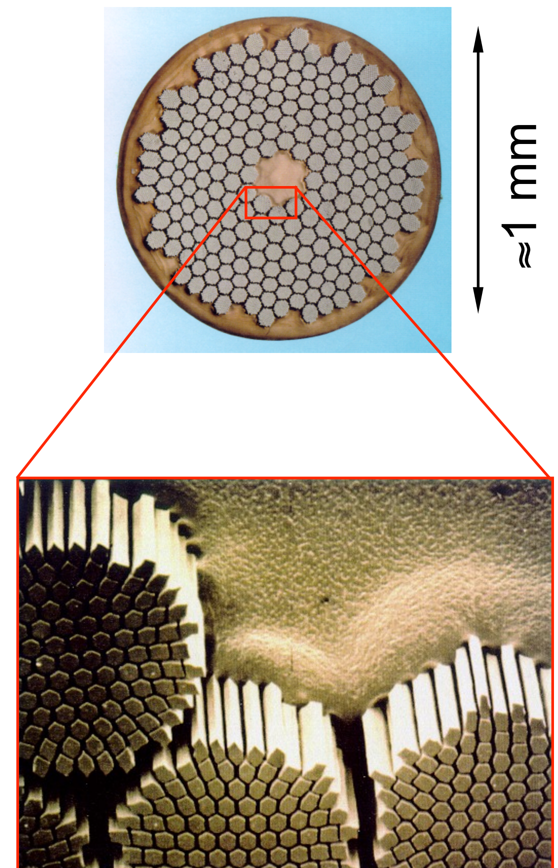
NbTi billet




$I_C$(5 T, 4.2 K) ≈ 1 kA

extrusion
cold drawing

heat
treatments

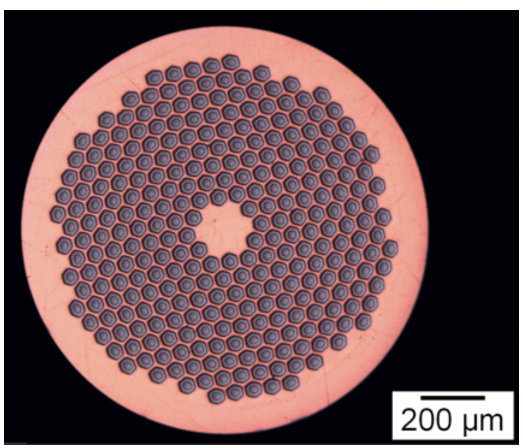



NbTi is a ductile alloy that can sustain large deformations

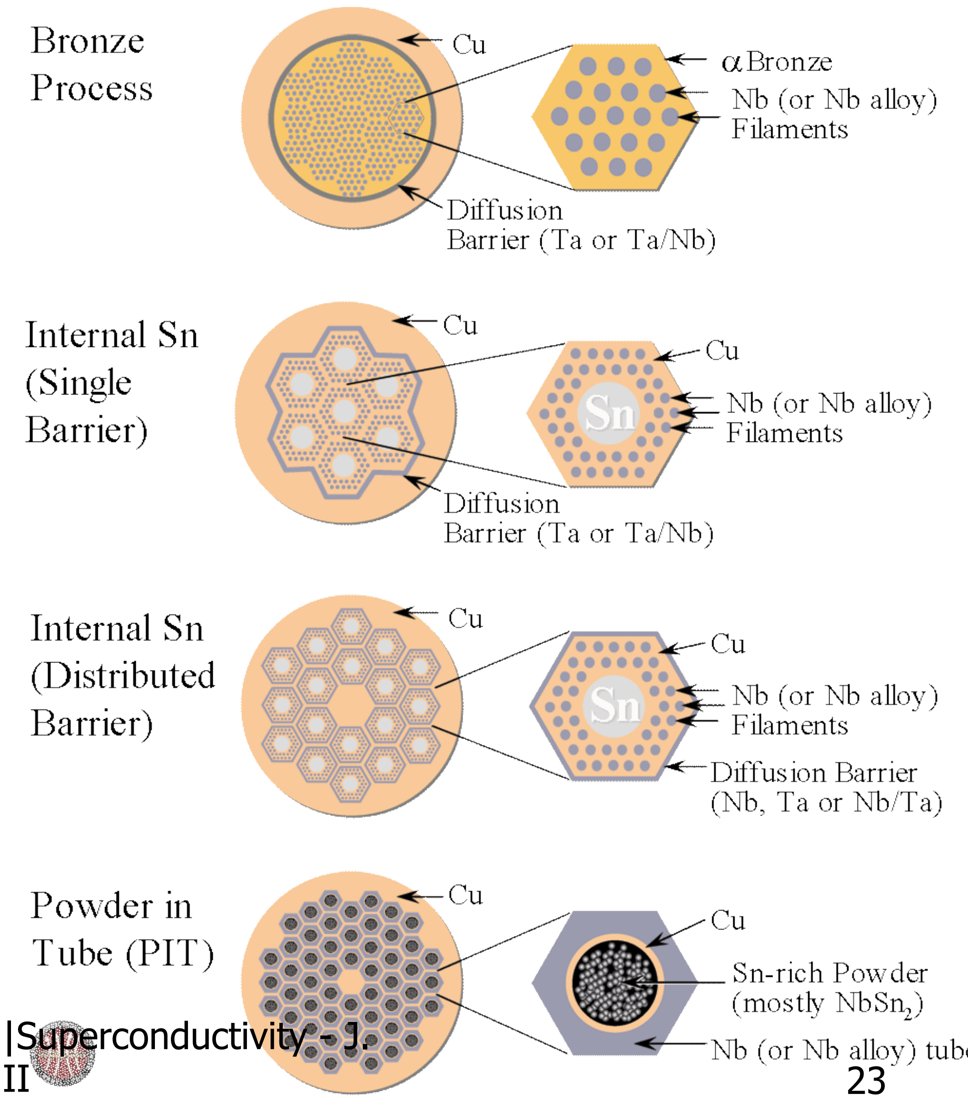
LHC wire

# $Nb_3Sn$ manufacturing routes

$Nb_3Sn$ is brittle and cannot be drawn in final form. The precursors are drawn and only later the wire is heat-treated to ≈650 C, to form the $Nb_3Sn$ phase



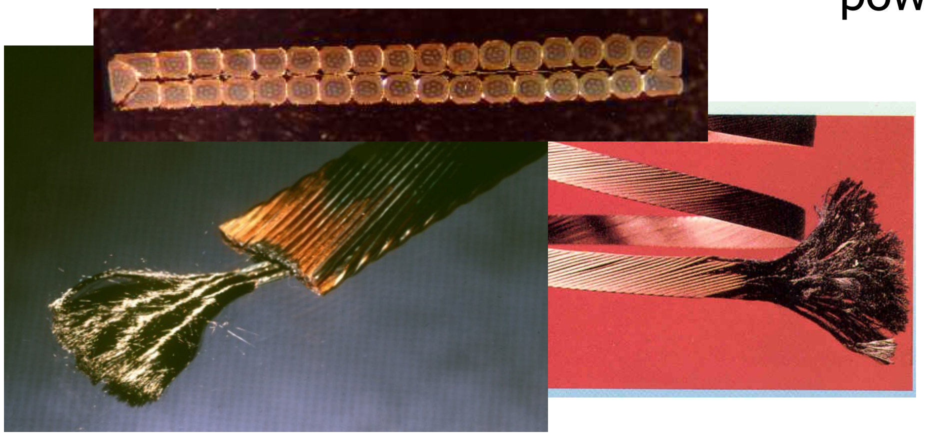

$I_C$(12 T, 4.2 K) ≈ 1.5 kA



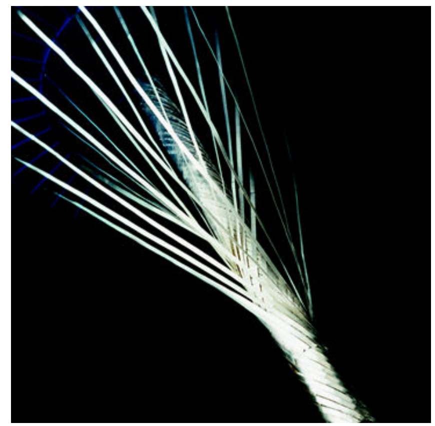
slide courtesy of L. Boturra - CERN

# Superconducting cables

Rutherford

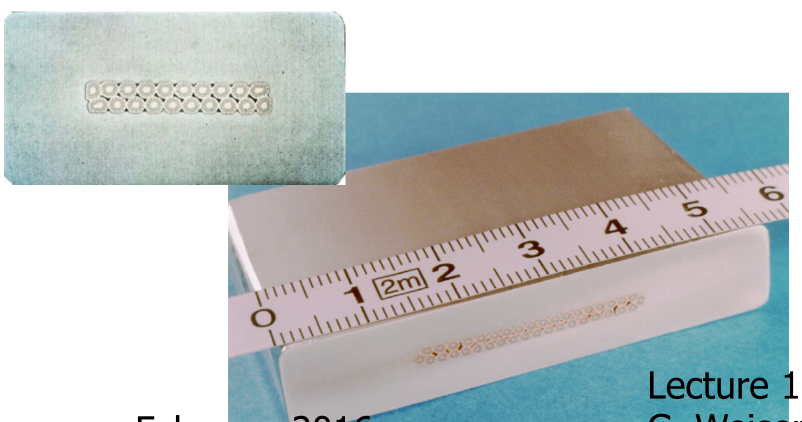


Braids for
power transmission



CICC

Super-stabilized



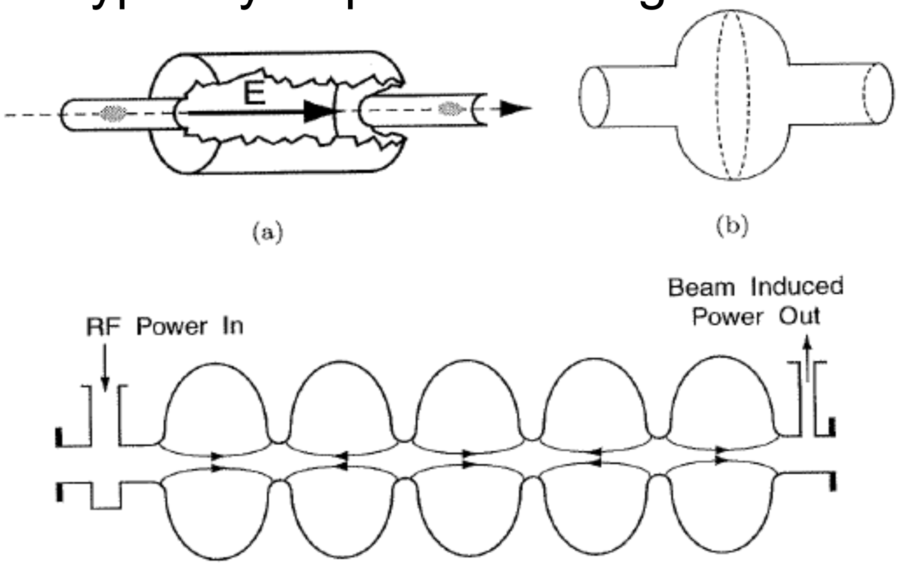
Internally cooled

# Superconducting RF
# Another Important Application

- In this application, resonant cavities are created to set up oscillating, standing waves (radio frequency) that create an accelerating electric field in the direction of the moving charged particle.
- The superconductor in this case is solid (though thin) niobium operating at LHe temperatures (most frequently at He II temperatures)
- There are always AC losses in this application
- There is a lot of subtle detail regarding cavity design and surface treatment in this application
- Two major types of cavities exist: Low Beta and High Beta applications
- Beta is speed of particle/speed of light
  - Single particles such as electrons and protons can reach almost Beta = 1
  - Ions such as those used in FRIB or RHIC reach much lower speeds ~ beta = 0.5

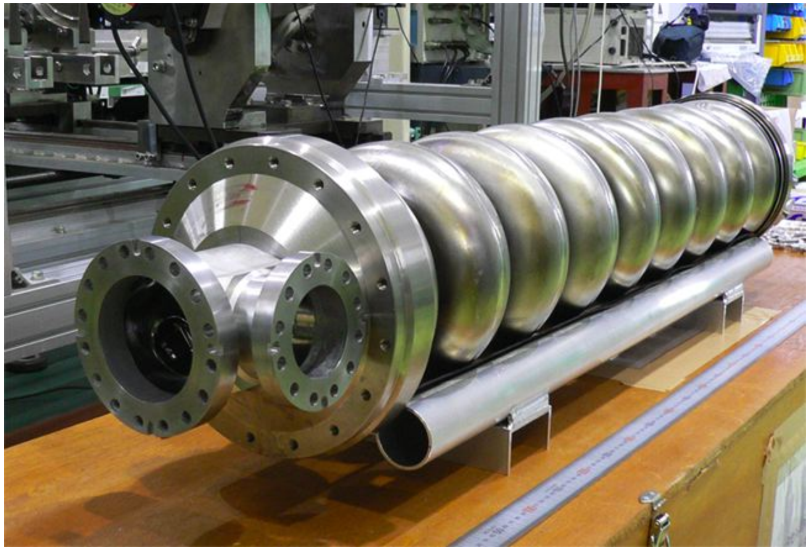
# Examples of SRF Cavities

- High Beta
  - Typically elliptical in design



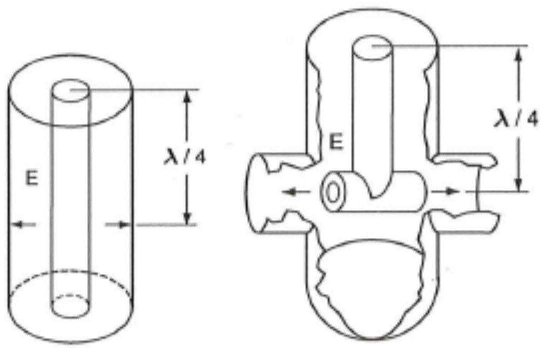

From H. Padamsee et al.
Superconducting RF for Accelerators

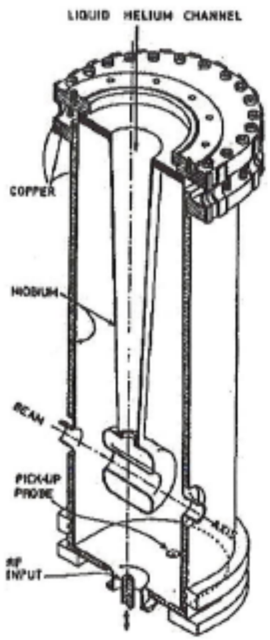
ILC cavity 1.3 GHz
1 m long



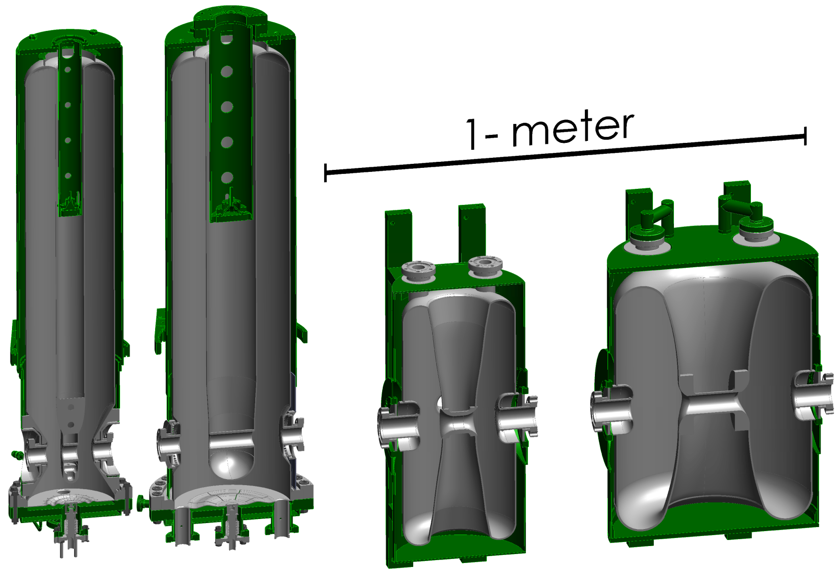
# Examples of SRF Cavities

Low Beta
¼ wave & ½ wave cavities




From H. Padamsee et al.
Superconducting RF for Accelerators




FRIB Cavities

# High Temperature Superconductivity

- First Discovered in 1986 in Yttrium Barium Copper Oxide

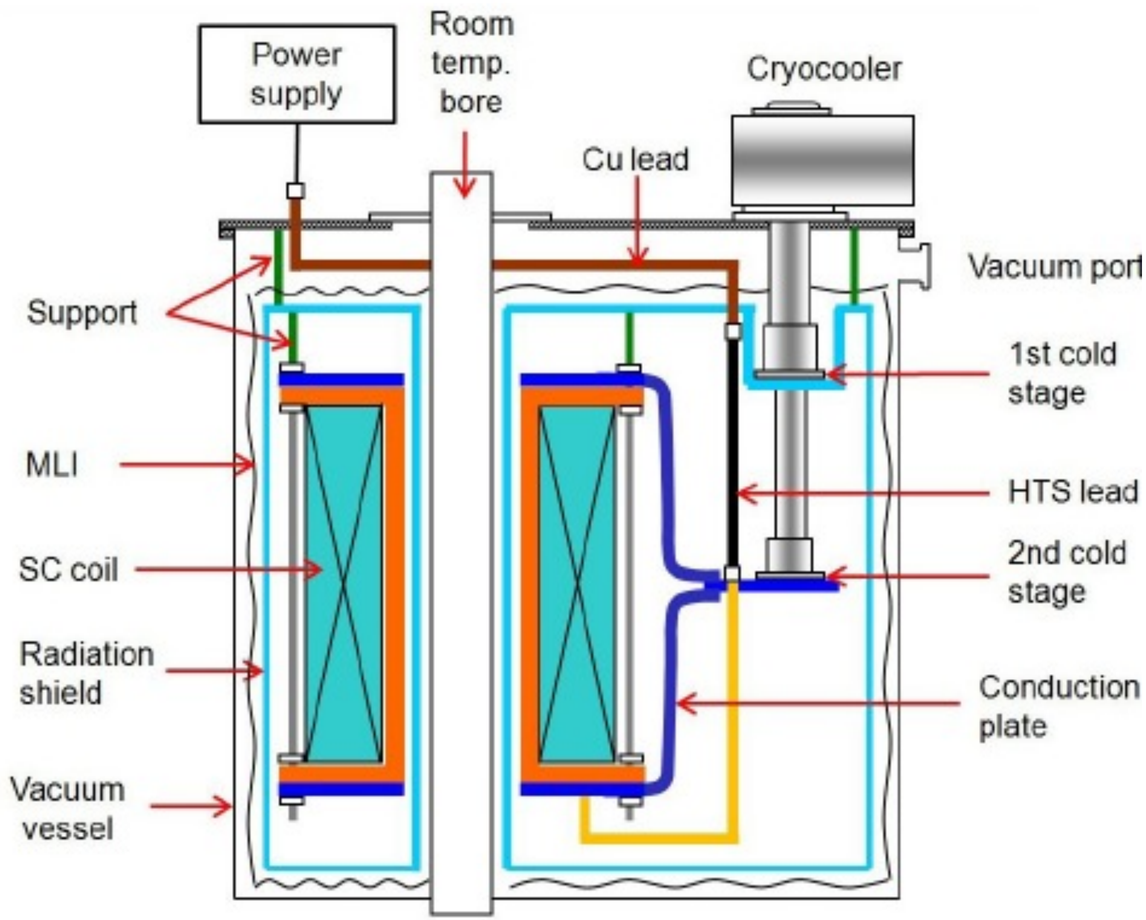
($YBa_2Cu_3O_{7-x}$), referred to commonly as YBCO - Tc ~92 K

- Many other similar ceramic materials soon followed such as $Bi_2Sr_2Ca_2Cu_3O_6$ (Bi-2223) – Tc ~ 110 K and $HgBa_2Ca_2Cu_3O_8$ (Hg-1223) – Tc ~ 134 K
- This lead to the so-called "Woodstock of Physics" at the 1987 APS March Meeting in NYC
- Despite the initial excitement technical progress has been slow and HiTc superconductors have a number of issues:
  - While the Tc is high the critical current was (at least initially) is quite low
  - These materials are anisotropic (performance depends on their orientation)
  - These materials are brittle ceramics and thus very hard to turn into wires
  - BCS theory doesn't explain the presence of superconductivity in these materials – no good theory exists though some type of coherent phenomena must be behind it.

# High Temperature Superconductivity

- But don't despair !
  - Remember superconductivity was discovered in 1911 but practical low Tc superconductors really didn't arrive until the 80's
- There are commercial niche applications of HiTc superconductors even today
- HiTc current leads for providing current to low Tc s/c magnets
  - These leads allow superconductivity up to about 50 – 80 K and serve to reduce the overall heat leak into the LHe space since HiTc materials are poor thermal conductors
- Superconducting electronics in the form of low noise microwave filters for use in cell phone towers operating at about 50 K
- Note also the temperature range for HiTc superconductors ( ~ 50 – 200 K ) ties in nicely with the performance range for small cryocoolers
  - The development of small cryocoolers and rise of HTS applications have gone hand in hand

# High Temperature Superconductivity Binary Current Leads




From Choi et al.
Adv. Cryo. Engr. Vol 55 (2010)

# Use of HTS Microwave Filters in Cell Phone Base Stations

Courtesy R. Radebaugh