Lecture 10
Superconductivity, Superconducting RF & Superconducting Magnets

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Goals

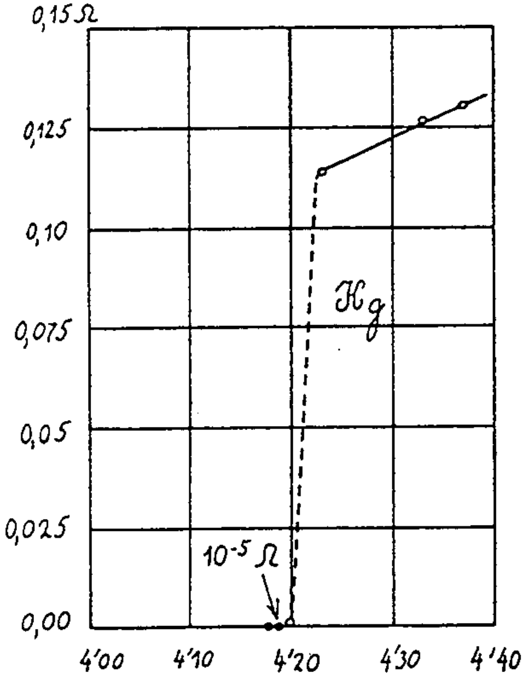
- Describe the basic physics behind superconductivity (mainly low T_C)
- Describe the requirements of practical superconducting materials
- Describe how superconducting materials are turned into practical conductors for applications
- Discuss superconducting magnets including stability, protection and show an example
- Discuss superconducting radiofrequency systems (SCRF)
- Touch briefly on HiT_C superconductivity

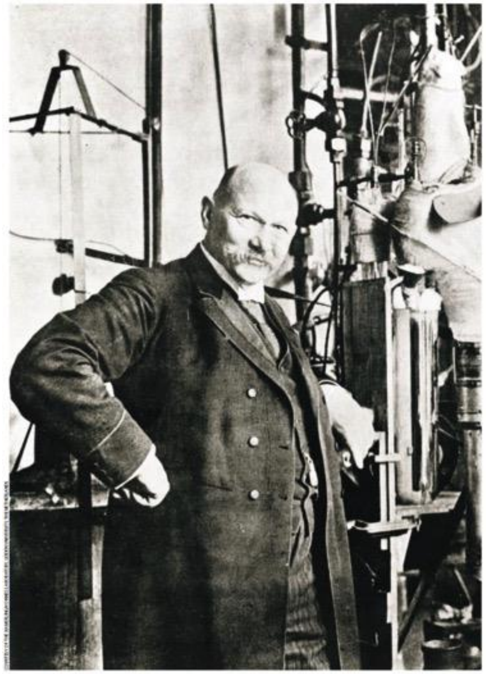
Introduction

- As we' ve seen, superconductivity is a major motivating factor for the use of cryogenics – particularly in accelerators 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

Superconductors & Magnetism

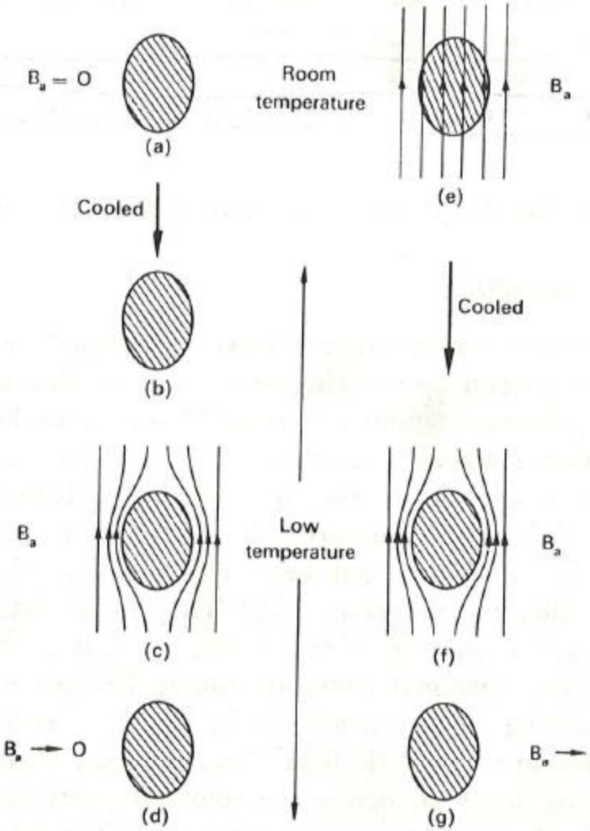


FIG. 2.3. Magnetic behaviour of a superconductor. (a)–(b) Specimen becomes resistanceless in absence of magnetic field. (c) Magnetic field applied to superconducting specimen. (d) Magnetic field removed.

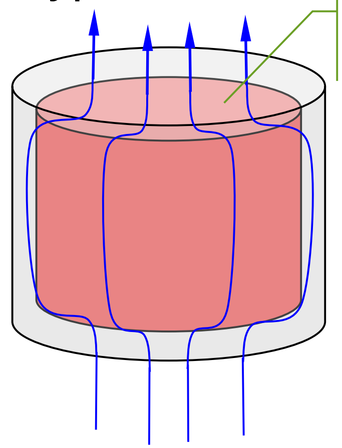
(e)–(f) Specimen becomes superconducting in applied magnetic field. (g) Applied magnetic field removed.

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

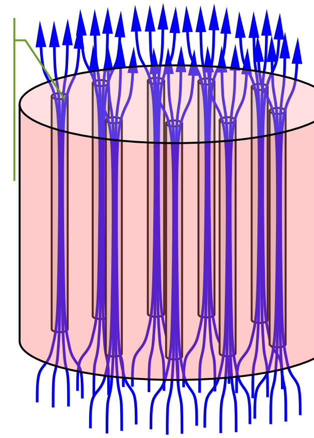
Pure metals

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

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

Partial field exclusion

Lattice of fluxons



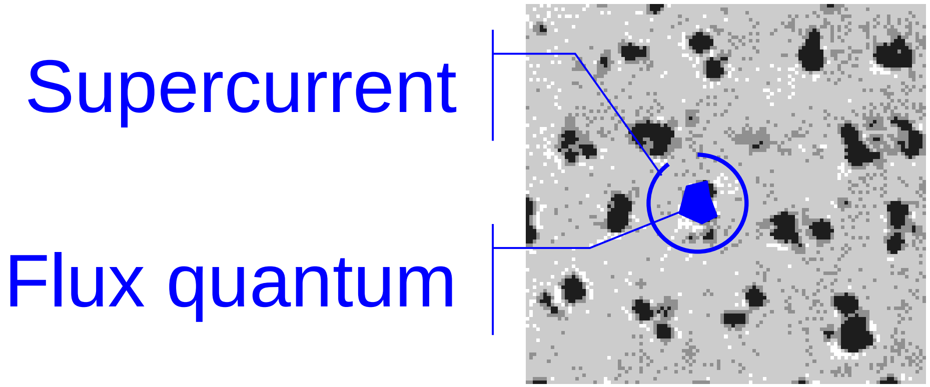
Dirty materials: alloys intermetallic, ceramic

$B_C \approx 10 \ldots 10^2$ 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

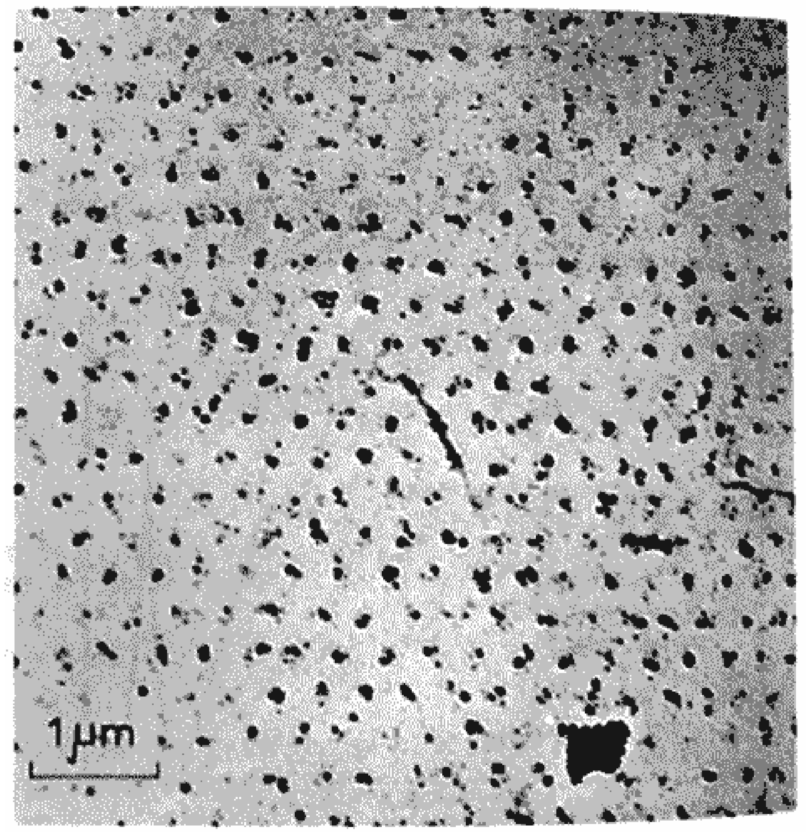


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

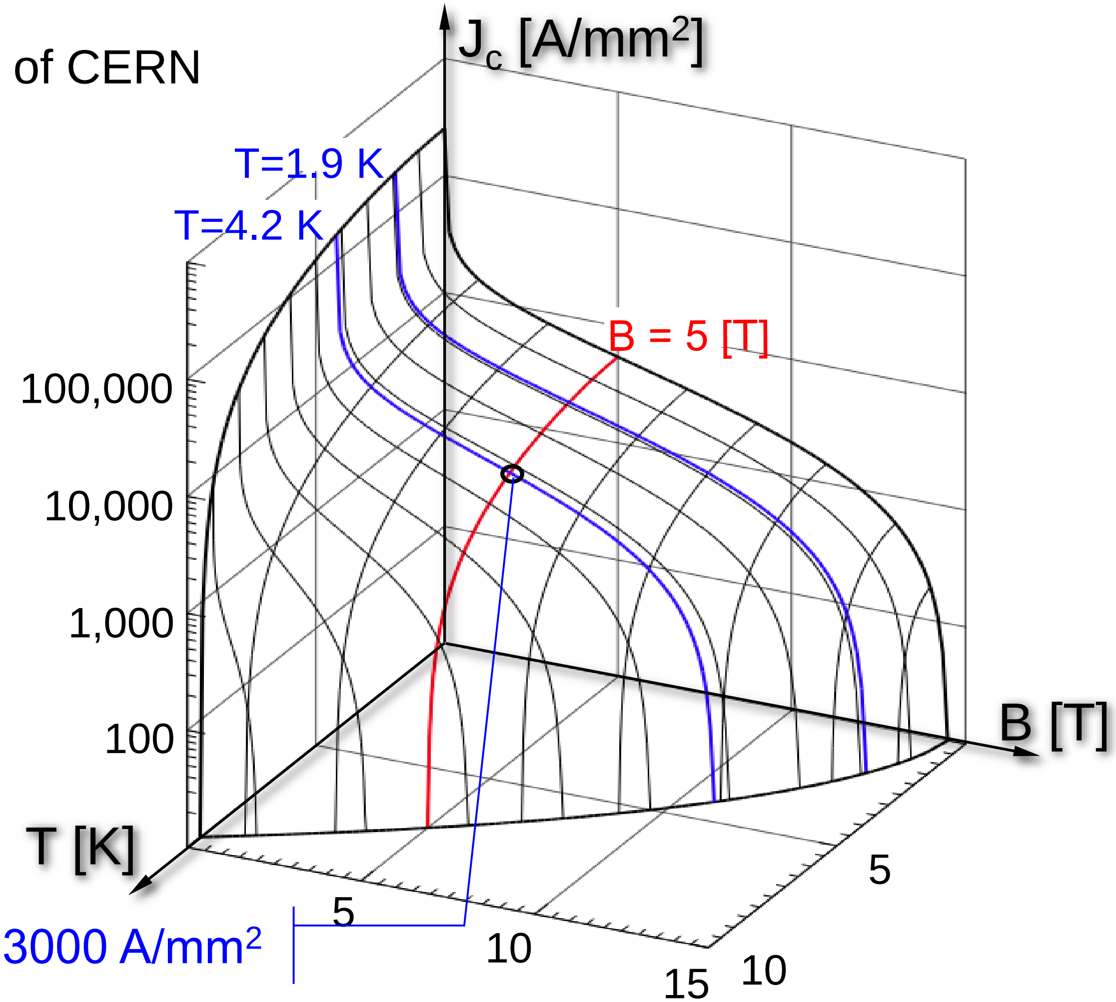
Critical Current

- 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

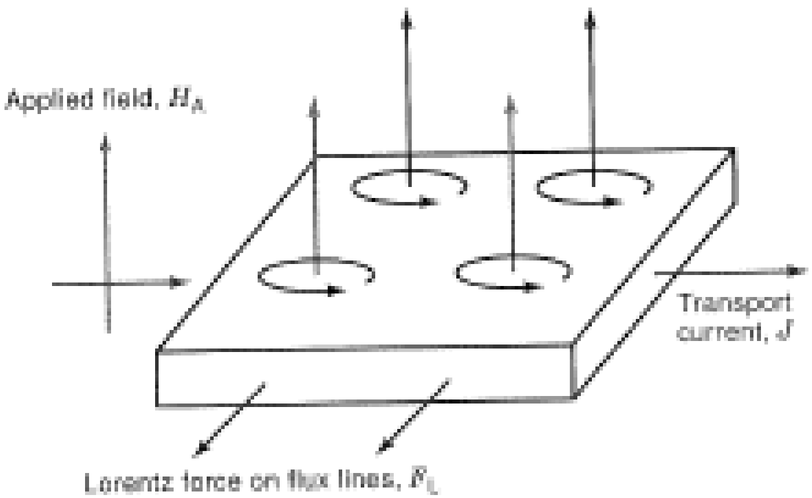
Note
Improvement in B
and Jc
@ T = 1.9 K



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 <u>Engineering Superconductivity</u>
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

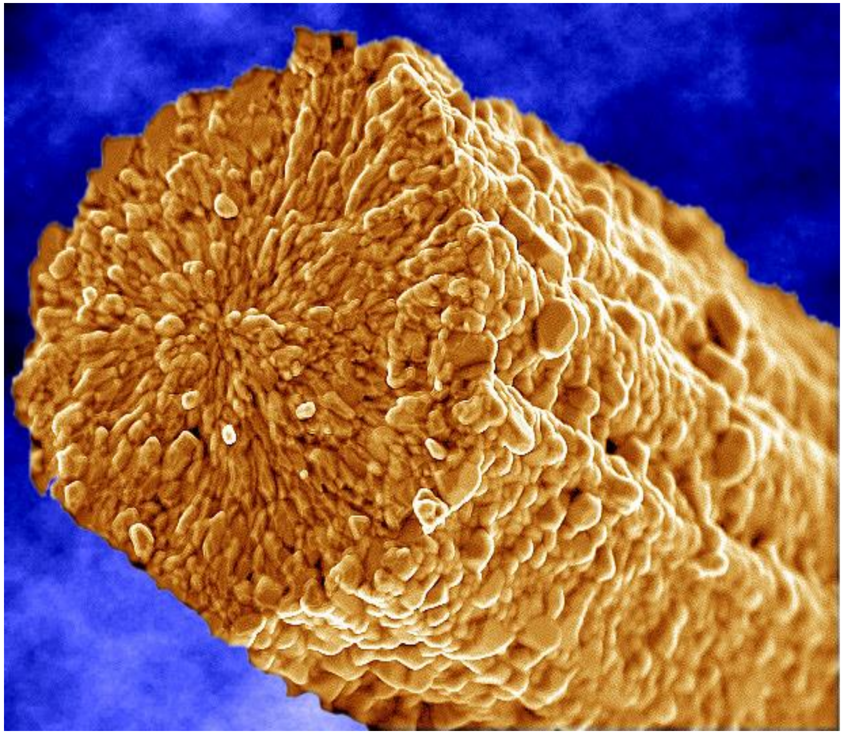
Flux Pining Sites

Courtesy L. Boturra of CERN

Grain boundaries in inter-metallic compounds

Precipitates in alloys

Microstructure of Nb-Ti



Microstructure of Nb_3Sn

But Wait! What Causes Superconductivity?

- The following is a <u>very</u> 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

Another Way to Model Superconductivity is via the "Two Fluid Model"

- This imagines superconducting materials as being composed of two kinds of electrons : Those in Cooper pairs and those not in Cooper pairs
  - Above T_C there are no Cooper pairs
  - At absolute zero all electrons are in Cooper pairs
- In DC applications the Cooper pairs carry all the electric current and thus there is zero resistance
- But in AC (i.e. RF) applications the oscillating electric field affects both the Cooper pairs & the non paired electrons & the movement of the non paired electrons result in resistance.
  - Thus there is always electrical loss in AC superconductivity
- A similar model is also used to describe He II

Impact of Changing Currents

- In addition to the intrinsic losses caused by AC currents in superconductors. There are additional AC losses that can be reduced via superconductor design
- They are broadly speaking 2 major sources of additional AC losses in superconductors: hysteresis (caused by flux jumping) and losses caused by AC coupling between adjacent filaments.
- See Backup slides for additional details

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 μm 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 do we create superconducting wire?

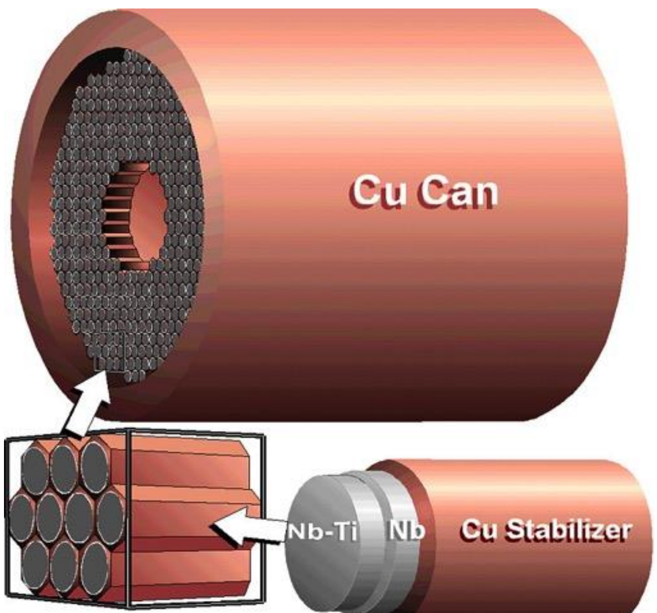
Nb-Ti manufacturing route

Graphics by courtesy of Applied Superconductivity Center at NHMFL

slide courtesy of L. Boturra - CERN

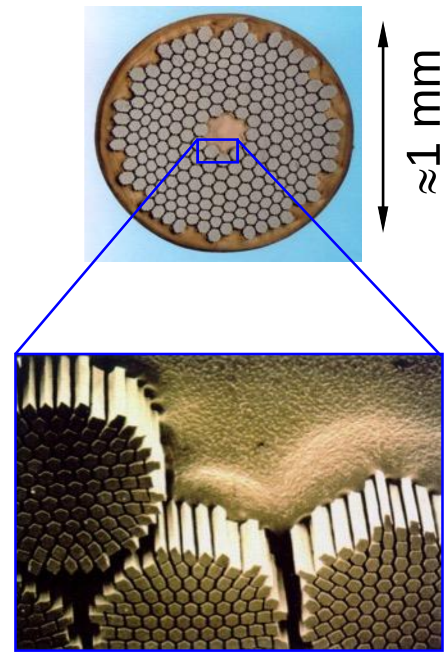
NbTi billet

I_C(5 T, 4.2 K) ≈ 1 kA



extrusion
cold drawing

heat
treatments



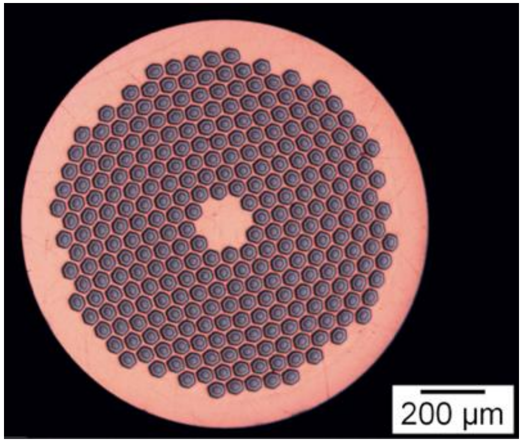
LHC wire

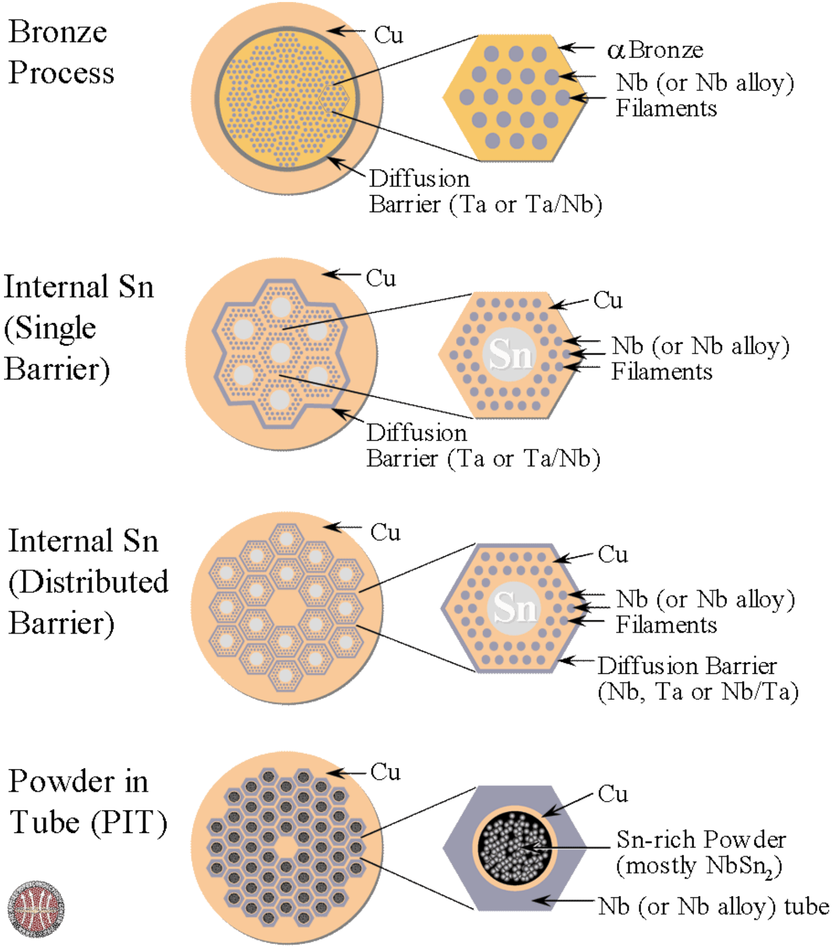
NbTi is a ductile alloy that can sustain large deformations

Nb_3Sn manufacturing routes

Graphics by courtesy of Applied Superconductivity Center at NHMFL

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



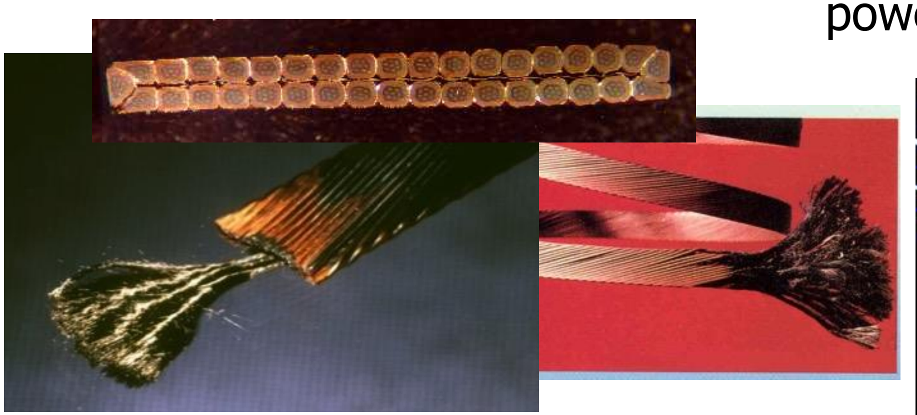


I_C(12 T, 4.2 K) ≈ 1.5 kA

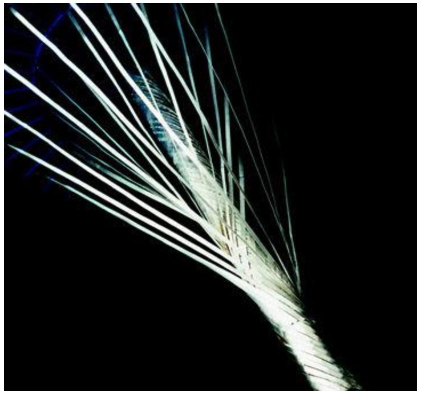
slide courtesy of L. Boturra - CERN

Superconducting cables

Rutherford

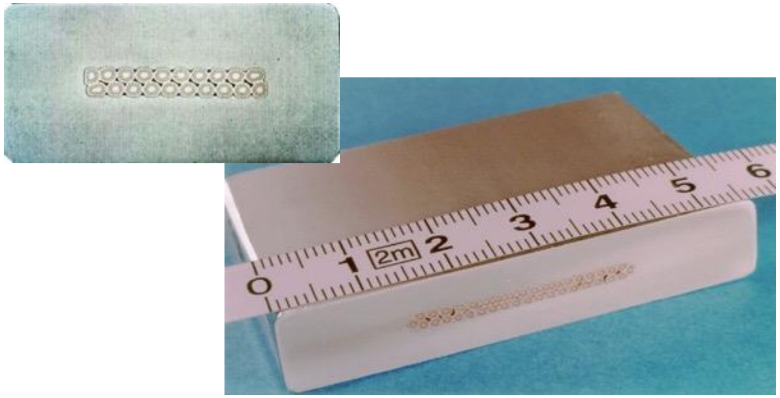


Braids for
power transmission



CICC

Super-stabilized



Internally cooled

slide courtesy of L. Boturra - CERN

Superconducting Radio Frequency Cavities

- From the 70’s to the 90’s the principle application of superconductivity in particle accelerators was in the area of s/c magnets (Tevatron, HERA, LHC)
- Since then, for a variety of reasons (e.g. technical advances in SRF and the growth of linac applications) the use of SRF cavities for particle acceleration has become increasingly important and in many cases is the primary application of superconductivity & cryogenics in accelerator designs

Superconducting RF is Very Popular

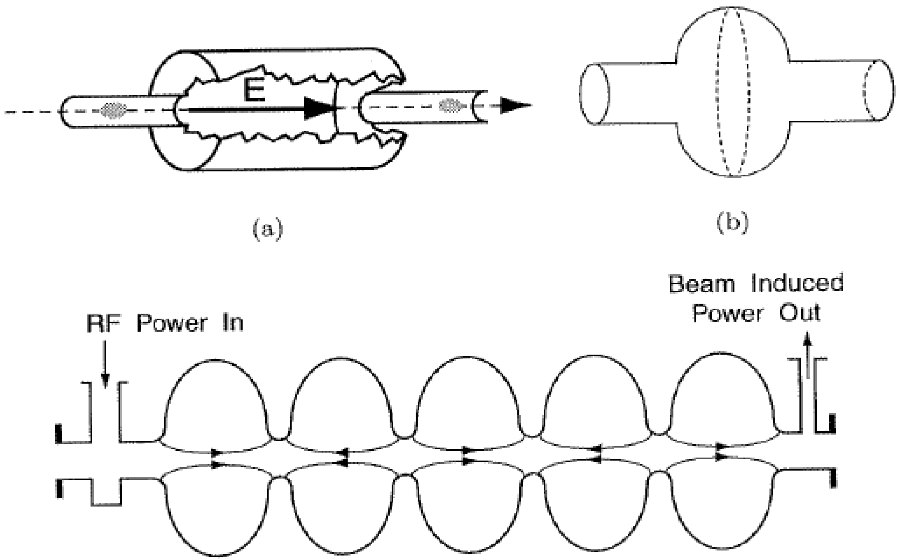
Name	Accelerator Type	Lab	T (K)	Refrigeration Capacity	Status
CEBAF	Electron Linac	JLab	2.1	4.2 kW @ 2.1 K	Operating
12 GeV Upgrade	Electron Linac	Jlab	2.1	4.2 kW @ 2.1 K	Operating
ESS	Proton Linac	ESS	2.0	3 kW @ 2 K	Under Construction
SNS	H^- Linac	ORNL	2.1	2.4 kW @ 2.1 K	Operating
E Linac	Electron Linac	TRIUMF	2.0	288 L/Hr	Operating
S-DALINAC	Electron Linac	TU Darmstadt	2.0	120 W @ 2.0 K	Operating
ERL	Electron Linac	Cornell	1.8	7.5 kW @ 1.8 K	Proposed
XFEL	Electron Linac	DESY	2.0 5 -8 40-80	2.5 kW @ 2 K 4 kW@ 5 -8 K 26 kW @ 40-80 K	Operating
ATLAS	Heavy Ion Linac	ANL	4.7	1.2 kW @4.7	Operating
LCLS II	Accelerator	SLAC	2.0 K	8 kW @ 2 K 30.6 kW @ 35 -55 K 2.6 kW @ 4.5 -6 K	Under Construction
ISAC - II	Heavy Ion Linac	TRIUMF	4		Operating
FRIB	Heavy Ion Linac	MSU	2.1 4.5 33/55	3.6 k W @ 2.1 K 4.5 kW @ 4.5 K 20 kW @ 35/55 K	Under Construction

Basics of SRF Cavities

- SRF cavities deserve their own course. (see suggested reading list)
- This will be a brief overview of the basics of SRF cavities.
- Practical cavity material is pure Niobium
- Cavities have beam vacuum on the inside (usually separate from insulation vacuum) and are surrounded and cooled by a bath of saturated Lhe
- Cavities come in all shapes and frequencies (~ 80 MHz – 3.9 GHz) depending on the accelerator design)

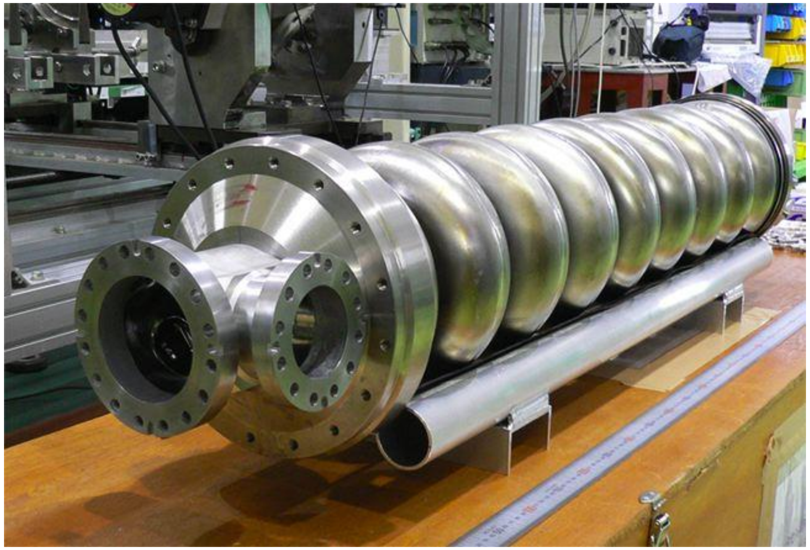
Examples of SRF Cavities

- High Beta
  - Typically elliptical in design



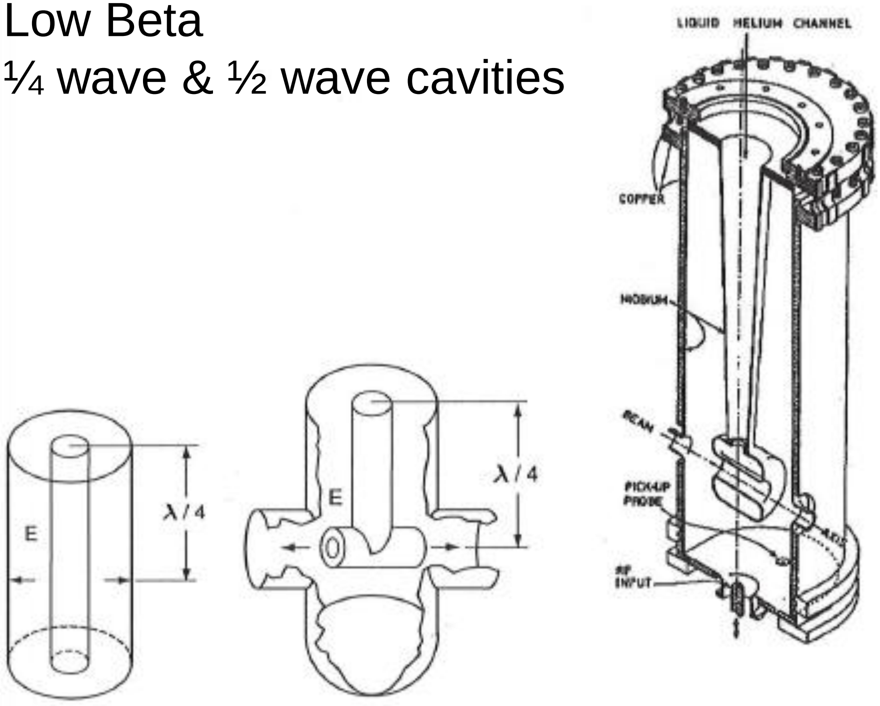
From H. Padamsee et al.
Superconducting RF for Accelerators

ILC cavity 1.3 GHz
1 m long – also LCLS II

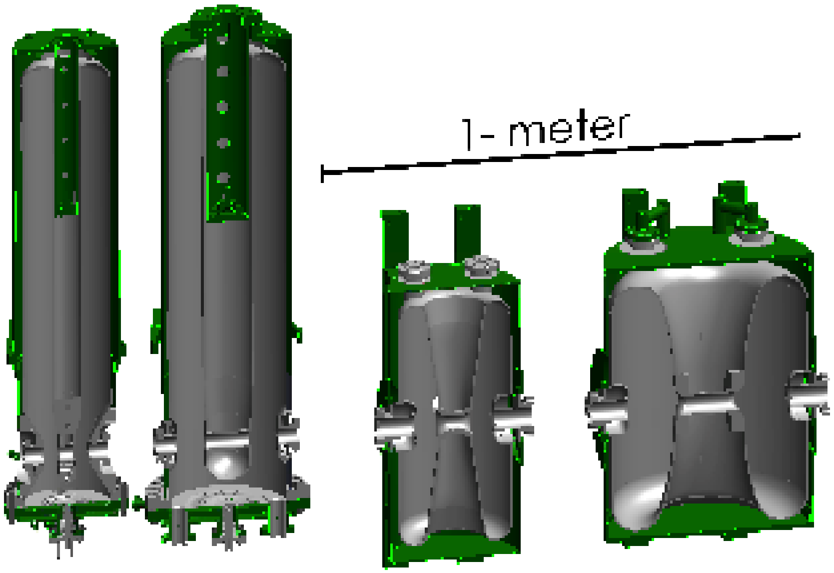


Examples of SRF Cavities

Low Beta
¼ wave & ½ wave cavities



From H. Padamsee et al.
Superconducting RF for Accelerators



FRIB Cavities

Surface Resistance, Frequency and Temperature

- The RF surface resistance (which we want to minimize) of a SRF cavity is given by:

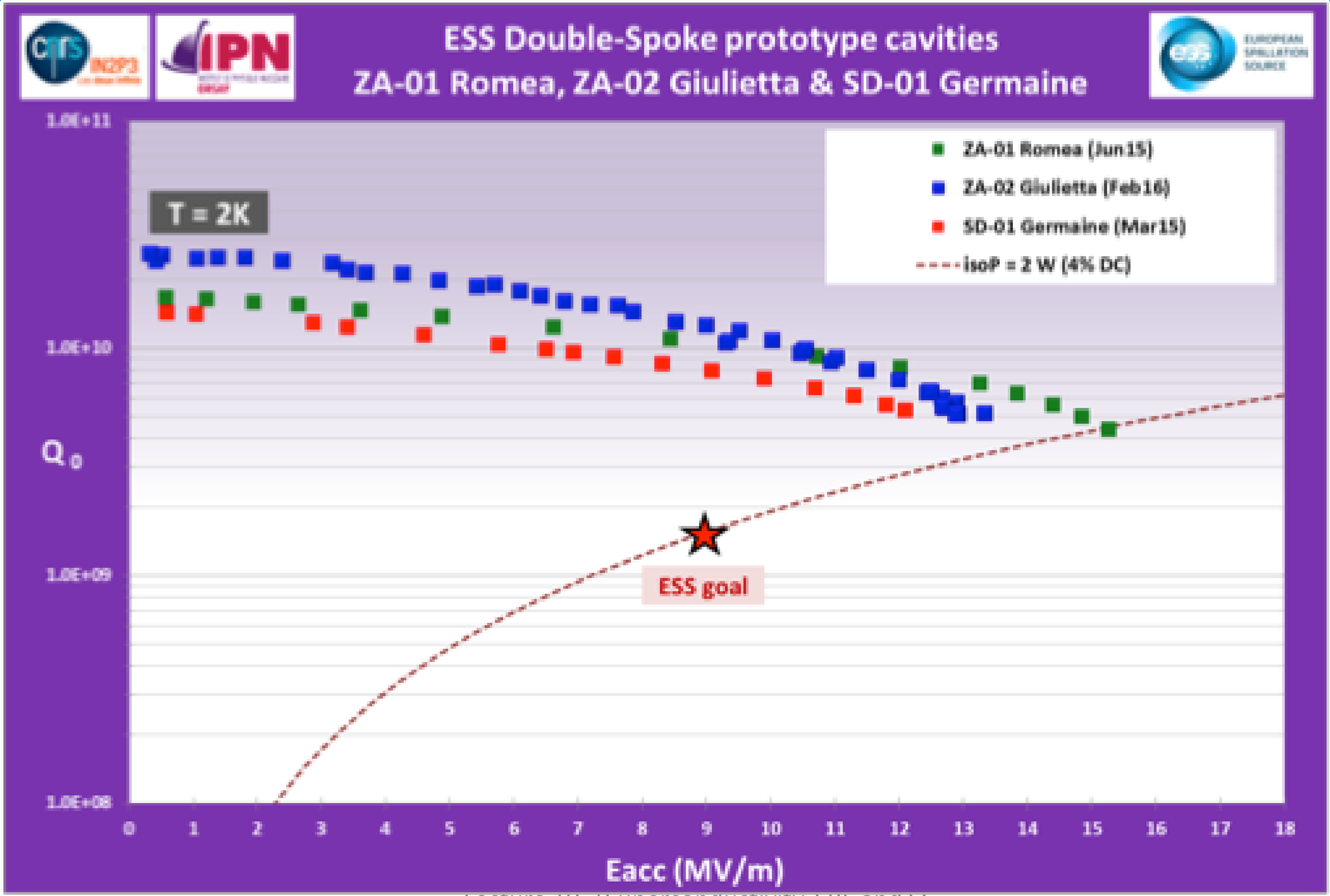
$$R_s = A\left(\frac{1}{T}\right) f^2 e^{(-\Delta(T)/kT)} + R_0$$

- The surface resistance goes up with frequency and down with temperature: lower temperature equals less resistance, particularly at higher frequencies
- As will be seen, removing heat at lower temperatures is less thermodynamically efficient, thus there is also an energy cost to be paid for operating at lower temperatures.
- What is the optimal temperature?
  - Above about 500 – 700 MHz you win by operating below 4.2 K (typically 1.8 – 2 K)
  - At lower frequencies (e,g. 80 MHz) you are better at 4.2 K thermodynamically but there may be other considerations (FRIB)
  - Between these limits it's a fairly broad minimum. Most systems operate ~ 2 K – He II

Cavity Performance

- Two of the main parameters for describing Cavity performance are the accelerating gradient E_{acc} (MV/m) and the cavity quality factor Q_0
- Q_0 is defined as the energy stored in the cavity divided by the energy lost in one RF period
  - Q_0 is related to the surface resistance. The lower the surface resistance the higher the Q_0 and the lower the energy deposited into the cavity wall and cryogenic system Thus the higher the Q_o the better

Example of SRF Cavity Performance ESS Double Spoke Cavities



Cavity Performance Can Be Degraded By a Number of Phenomena

- Quenching or thermal break down – normal (non superconducting) zones develop in the cavity
- Field Emission – electrons are pulled off the surface of the cavity and accelerated by the RF field (degrades Q_0)
- Local Magnetic Fields

Cavity Processing

- Research has shown that both Field Emission and Thermal Breakdown can be significantly reduced by proper processing of the cavities. This processing consists of an intricate set of steps involving:
  - Cavity surface cleaning by chemicals (buffered chemical processing) or by electropolishing
  - Cavity surface cleaning by High Pressure Rising with ultrapure water
  - Various heat treatments
- Major progress in this area has made SRF cavities much more useful
  - CEBAF (1980's) designed for 5 MV/m (actual performance was better) CEBAF 12 GeV upgrade (2000's) specified & met 19.2 MV/m
  - ILC cavity specification is 35 MV/m

Cavity Cleanliness

- Once processed, the RF surface i.e. the beam vacuum surface of the cavities must be kept extremely clean to maintain performance. This results in:
  - Assembly of cavity strings in cleanrooms
  - Connection of beam tube vacuums within local cleanrooms during cryomodule installation
  - Very strict vacuum and particle free requirements for cavity systems
  - Presence of fast acting valves to subdivide beam vacuum in the case of accidents

Other Aspects of SRF Cavities

- Q Disease – related to interstitial hydrogen in the niobium.
  - Can be treated via heat treatments or may set limits on cavity cool down and warm up rates
- Local magnetic fields (including the Earth's) degrade cavity performance
  - Result is that cavities are designed with passive and sometimes active magnetic shields. Use of magnetic materials near cavities must be carefully examined
- Cavities are resonant structures that require tuning frequently at cryogenic temperatures

Other Aspects of SRF Cavities

- Vibrations (microphonics) can detune cavities depending on cavity stiffness and design
  - This may put strict limits on vibrations near cavities
  - Use of He II (see later lecture) prevents bulk boiling in the helium bath that may affect the cavity tune

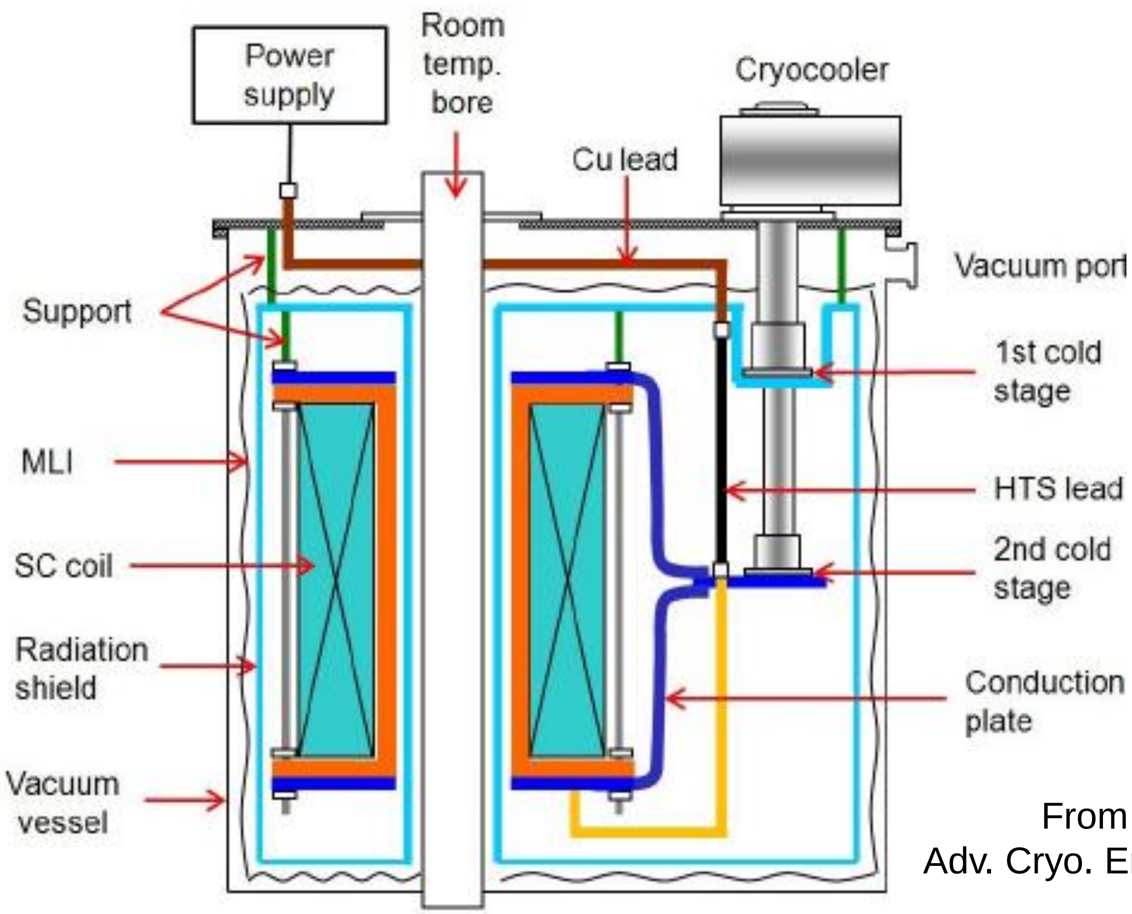
High Temperature Superconductivity

- 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

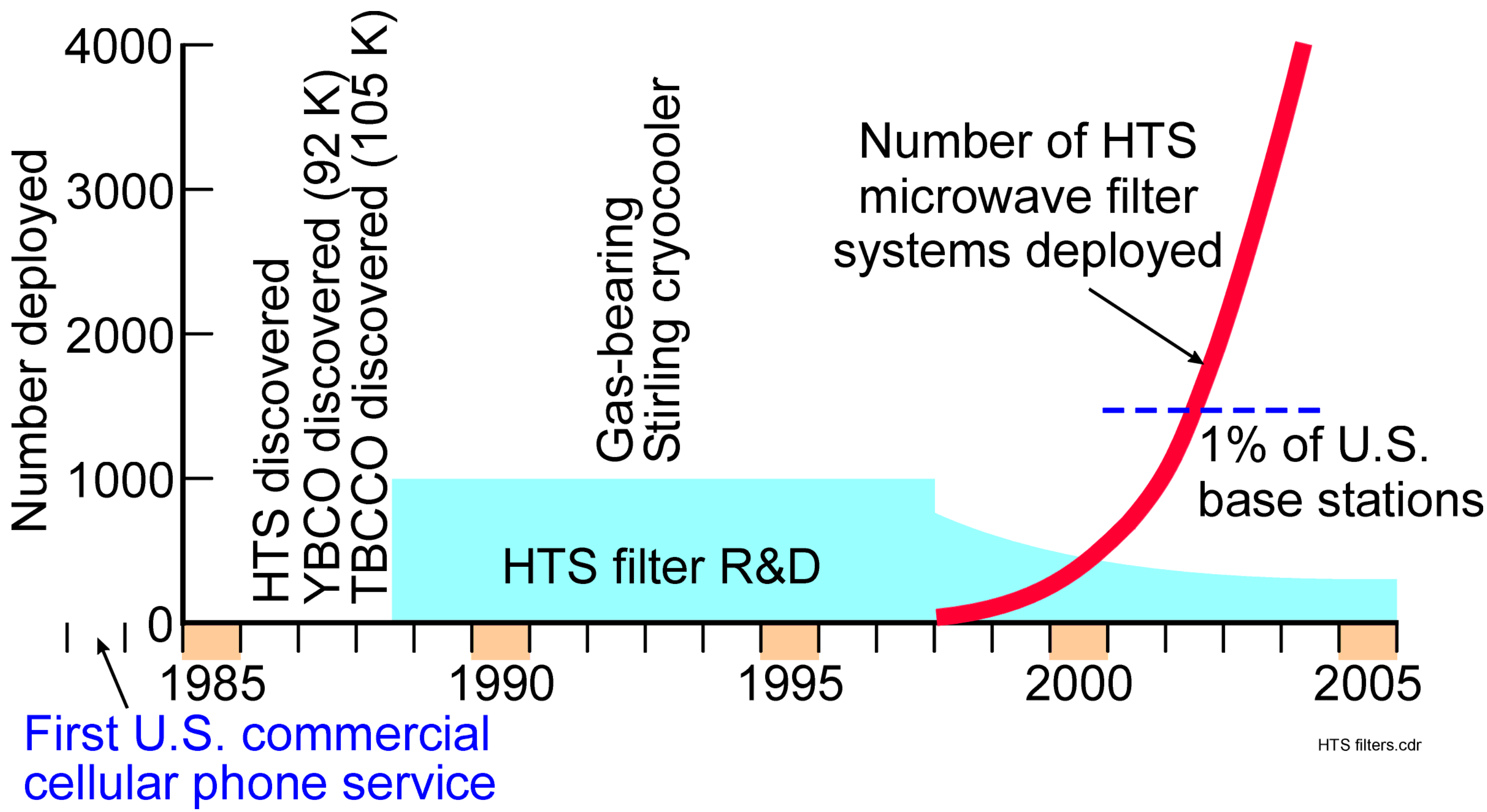
High Temperature Superconductivity Binary Current Leads



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

Use of HTS Microwave Filters in Cell Phone Base Stations

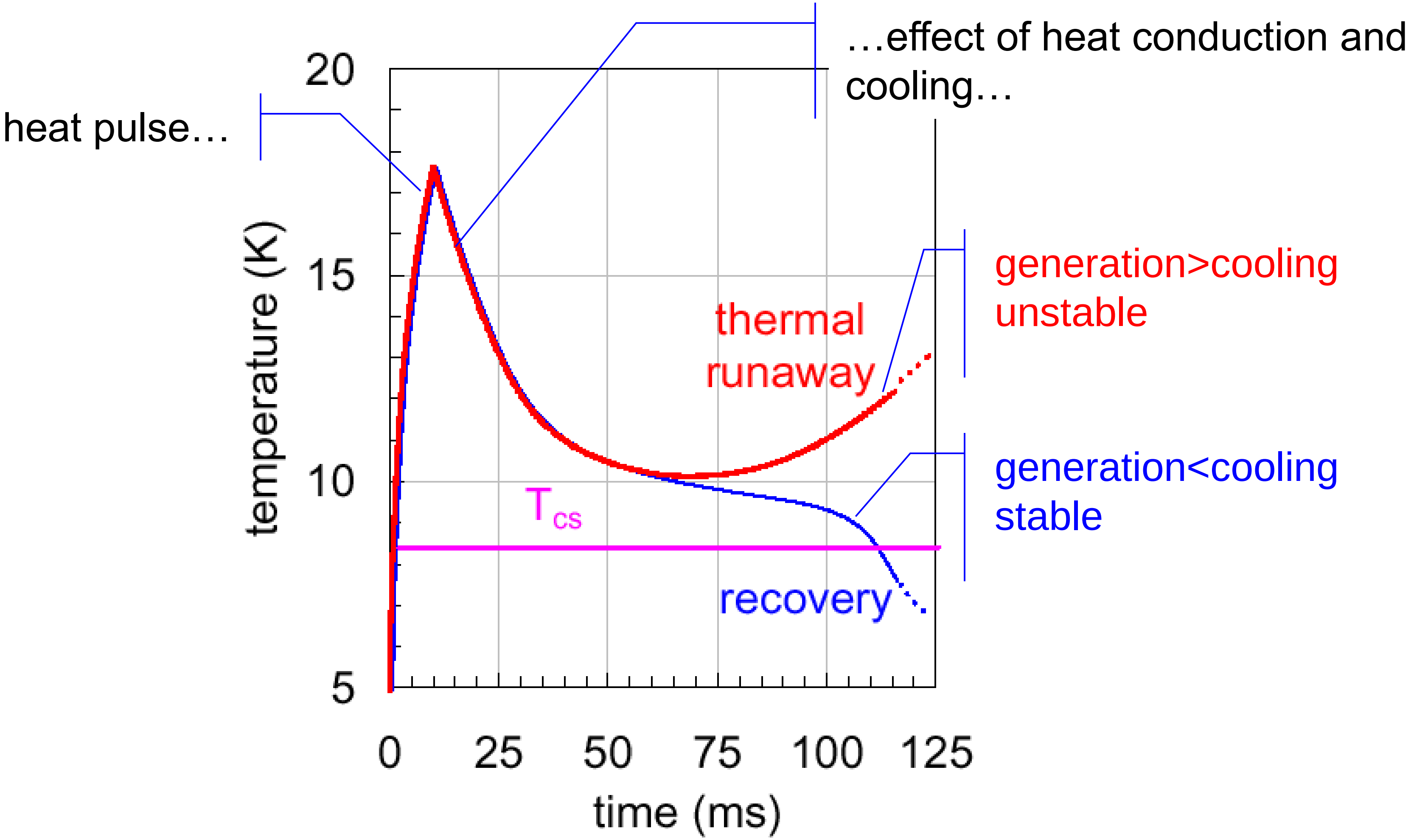
Courtesy R. Radebaugh



Stability of Superconducting Magnets

- When a wire in a s/c magnet undergoes a temperature rise, there are 2 possibilities:
  - It can cool back down and remain superconducting
  - It can warm up above Tc and "quench" (become normally conducting in all or most of the magnet)
- Which one occurs depends on the amount of heat generation and cooling

A Genaric Temperature Transient

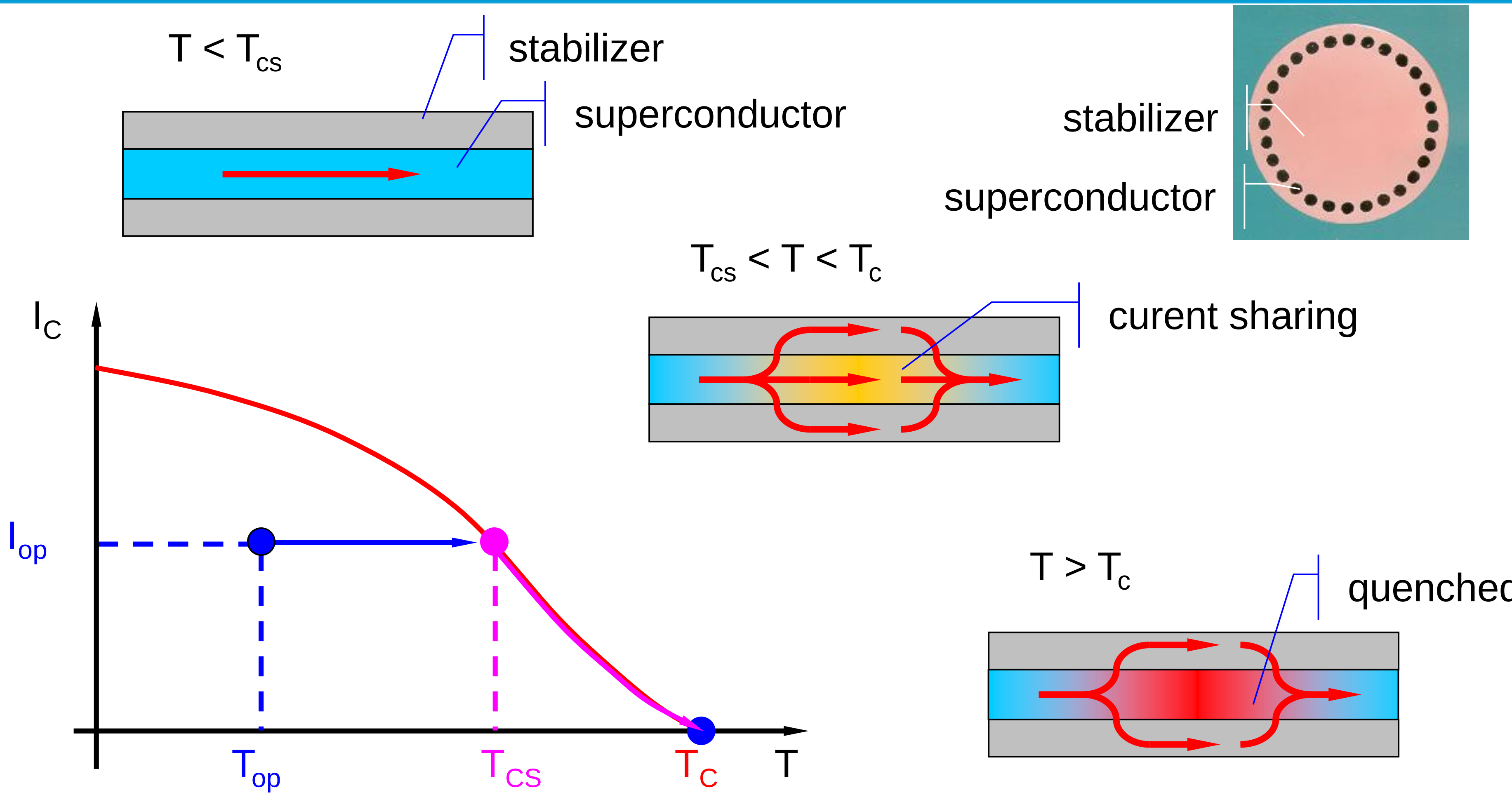


Perturbation spectrum

- mechanical *events*
  - wire motion under Lorentz force, micro-slips
  - winding deformations
  - failures (at insulation bonding, material yeld)
- electromagnetic *events*
  - flux-jumps (important for large filaments, old story !)
  - AC loss (most magnet types)
  - current sharing in cables through distribution/redistribution
- thermal *events*
  - current leads, instrumentation wires
  - heat leaks through thermal insulation, degraded cooling
- nuclear *events*
  - particle showers in particle accelerator magnets
  - neutron flux in fusion experiments, separator magnets

slide courtesy of L. Boturra - CERN

Current Sharing



Stability of Superconducting Magnets

- Fully cryostable: magnet will recover regardless of size of normal zone (disturbance) May be true of large detector magnets e.g BaBar detector or MRI magnets, but generally magnets are conditionally stable up to some heat input level.
- Adiabatic stability: magnet will recover if heat input is not too big – more typical of accelerator magnets or potted-coil magnets

Stability of Superconducting Magnets(2)

Why not make all magnets fully cryostable?

← **S800 dipole coil**

A1900 dipole coil →

S800 dipole coil took 6 weeks to wind
A1900 dipole coil took 2 days

Criteria for Fully Cryostable Magnets

- Stekley Criteria – most conservative, doesn't account for end cooling

$$\alpha = \frac{\rho I^2}{hPA(T_c - T_b)}$$

α < 1 magnet is stable

- Equal area theorem
  - Takes into account the cooling of the conductor via conduction at the ends
  - Can be expressed as a graphical solution comparing the areas under the cooling and heating curves (see references)
- There are many cooling options for S/C magnets and SRF cavities – see lecture 15

Quench Detection & Protection

- Superconducting magnets store large amounts of energy either individually (20 MJ for the Babar detector magnet) or connected in series (10's of GJ)
- If all the energy is deposited in a small volume, bad things happen!

Quench Detection & Protection

- The goal is to rapidly and accurately detect the quench and safely dispose of the energy
  - Spread throughout the magnet
  - In an external dump resistor
  - In a coupled secondary
  - In magnet strings, bypass the energy of the other s/c magnets away from the quenching one
- Remember it's the stored energy in the magnet(s) not the power supply that's problem (S/C magnet power supplies are low voltage, high current, so increased resistance in a quenched magnet prevent further power input)

Detecting Quenches

- Can't just measure voltage directly as magnet ramping causes voltage and give a false signal
- The general approach is to subdivide the magnet with voltage taps and build a bridge circuit that cancels out voltage due to ramping
- Redundant QD systems are necessary
- Other measurements such as temperature, helium level or vacuum level might be used to look for precursors to trouble but take care not to "over interlock the magnet"
- HTS magnets are of special concern due to slow quench propagation, so sensitive QD required

Strategy: energy dump

B.J. Maddock, G.B. James, Proc. Inst. Electr. Eng., **115**, 543, 1968

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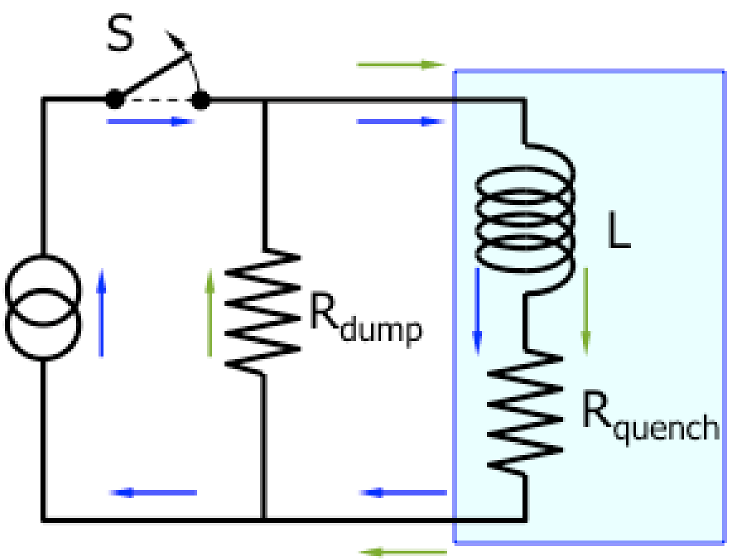


$$R_{dump} >> R_{quench}$$

normal operation

quench

- the magnetic energy is extracted from the magnet and dissipated in an external resistor:

$$I = I_{op} e^{-\frac{(t-\tau_{detection})}{\tau_{dump}}} \qquad \tau_{dump} = \frac{L}{R_{dump}}$$

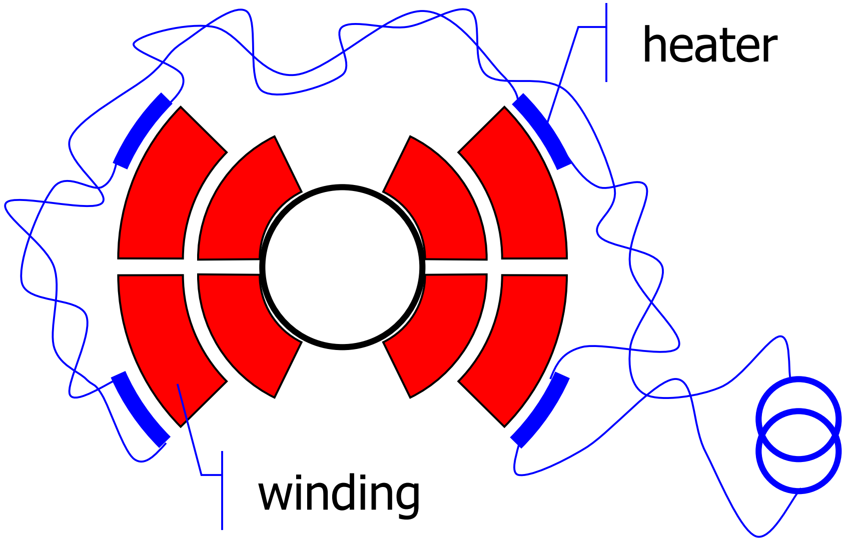
- the integral of the current:

$$\int_0^\infty J^2 dt \approx J_{op}^2 \left(\tau_{detection} + \frac{\tau_{dump}}{2} \right)$$

- can be made small by:
  - fast detection
  - fast dump (large R_{dump})

Strategy: heaters

- the quench is spread actively by firing heaters embedded in the winding pack, or in close vicinity to the conductor
- heaters are mandatory in:
  - high performance, aggressive, cost-effective and highly optimized magnet designs (high current density)…
  - …when you are really desperate
- advantages:
  - homogeneous spread of the magnetic energy withn the winding pack
- disadvantages:
  - active
  - high voltages at the heater
  - Doesn't work well with highly stable magnets



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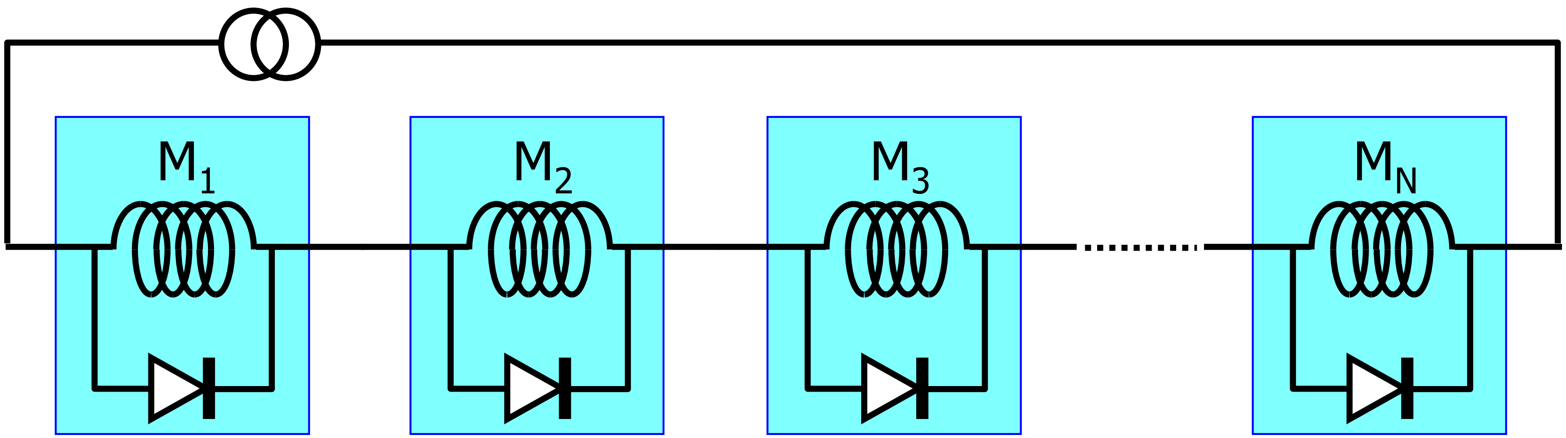
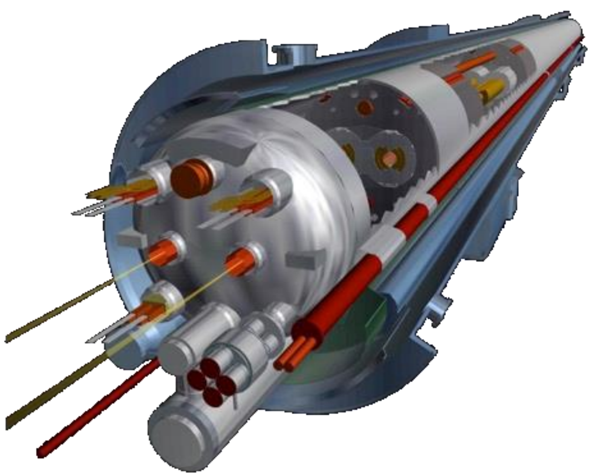
Magnet strings

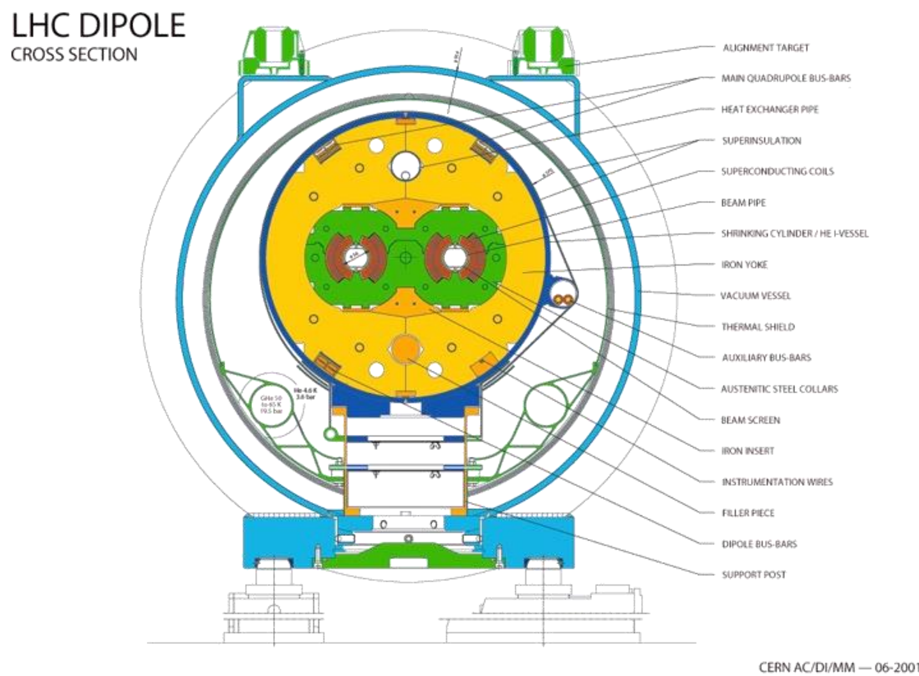
- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the discharge



Example #1 LHC Dipole

$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 8	(MJ)
cold mass	≈ 35	(tonnes)





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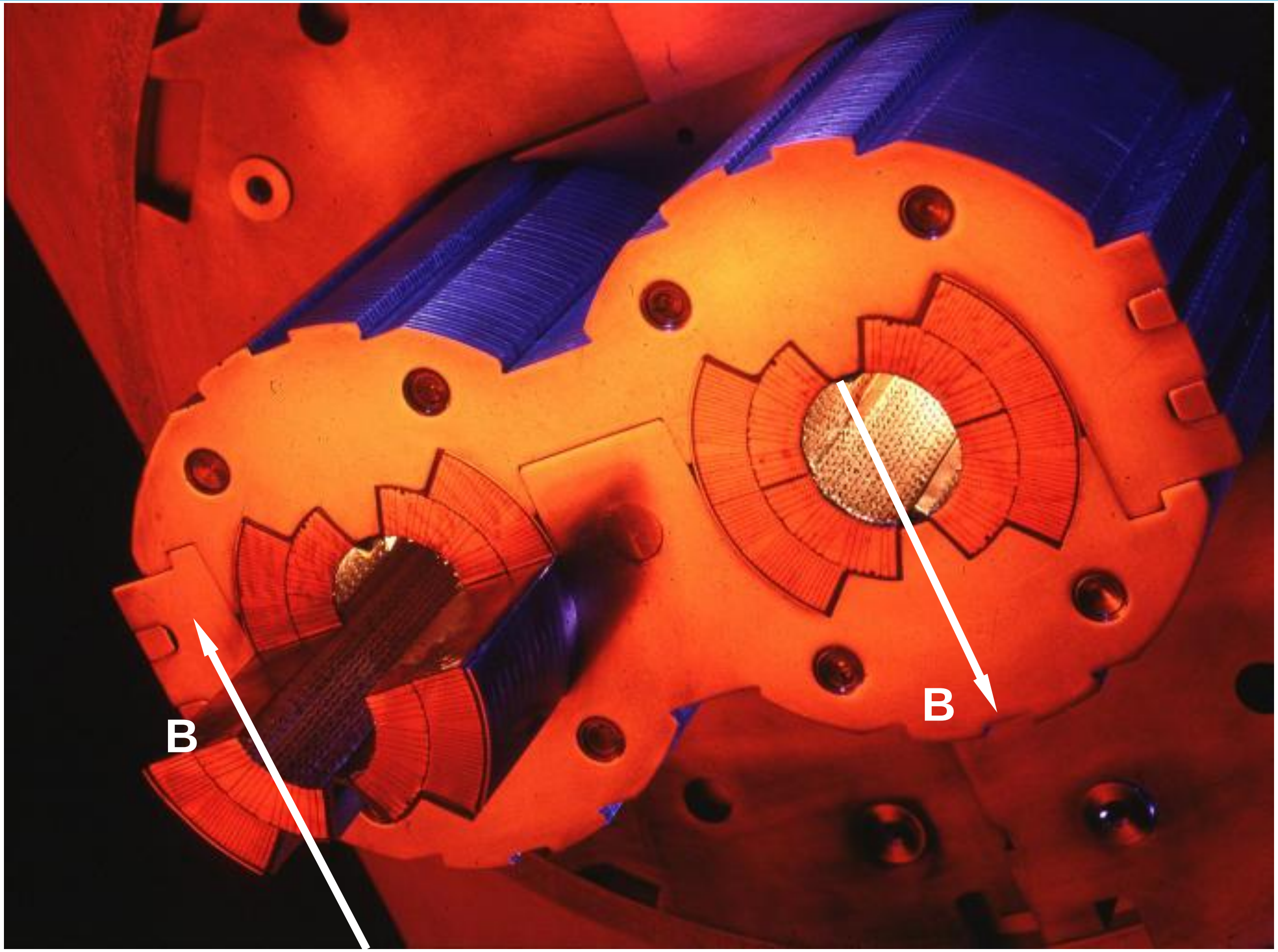
LHC dipole coils



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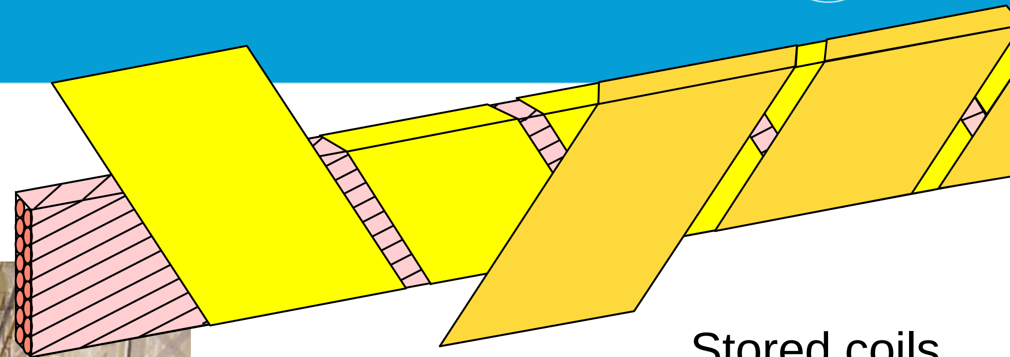
Coil winding

Cable insulation



10 μm precision !

Coil winding machine

Stored coils

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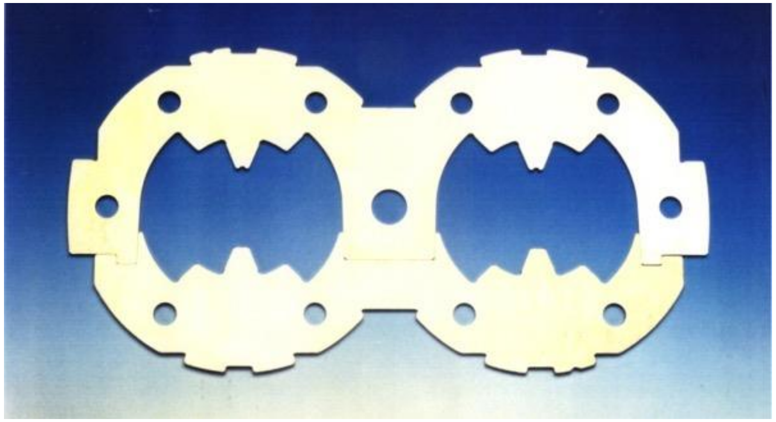
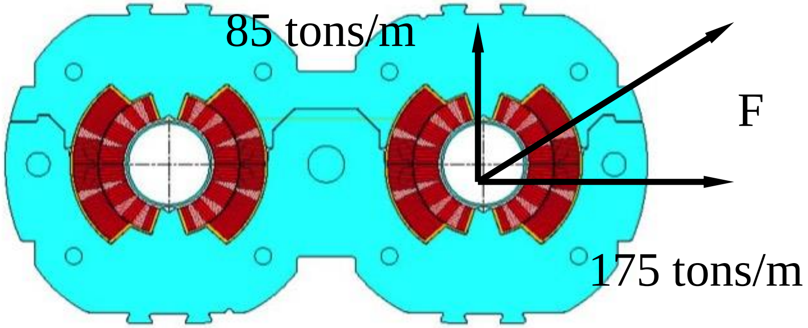
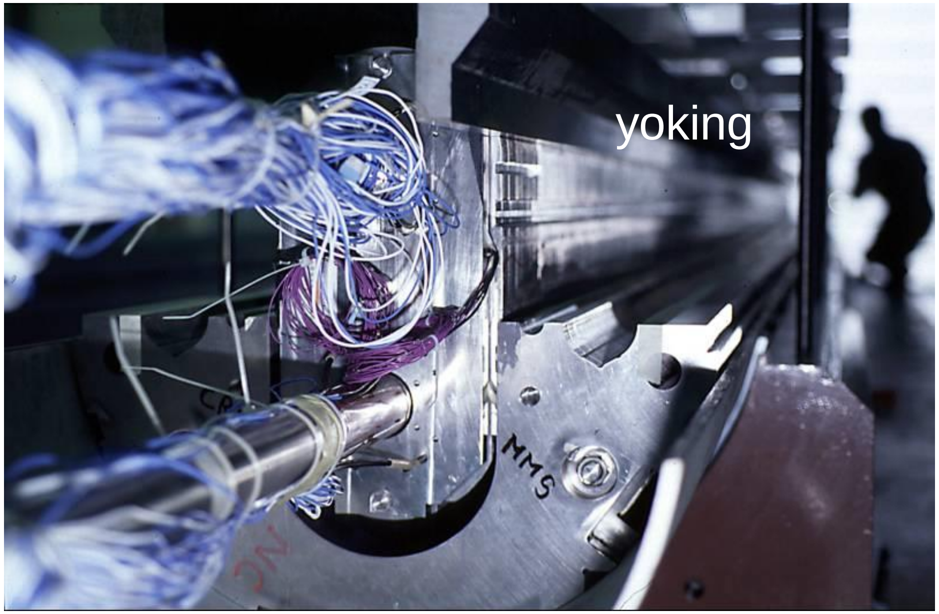
Collaring and yoking







collaring

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Cold mass

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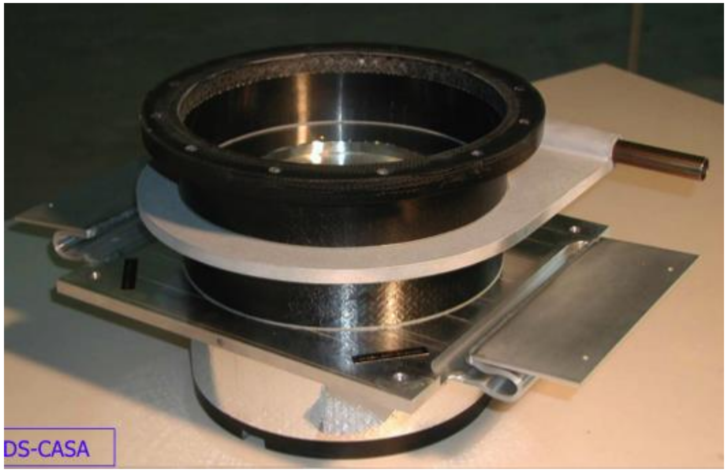
Cryostat

MLI

Thermal screens



Low conduction foot

Finally, in the tunnel !

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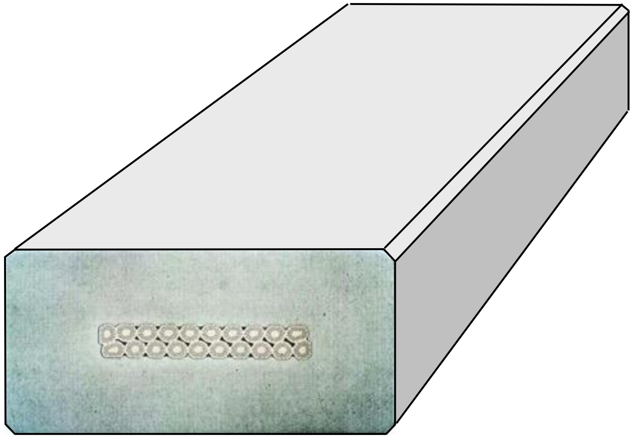
Example #2
BaBar Detector S/C Solenoid

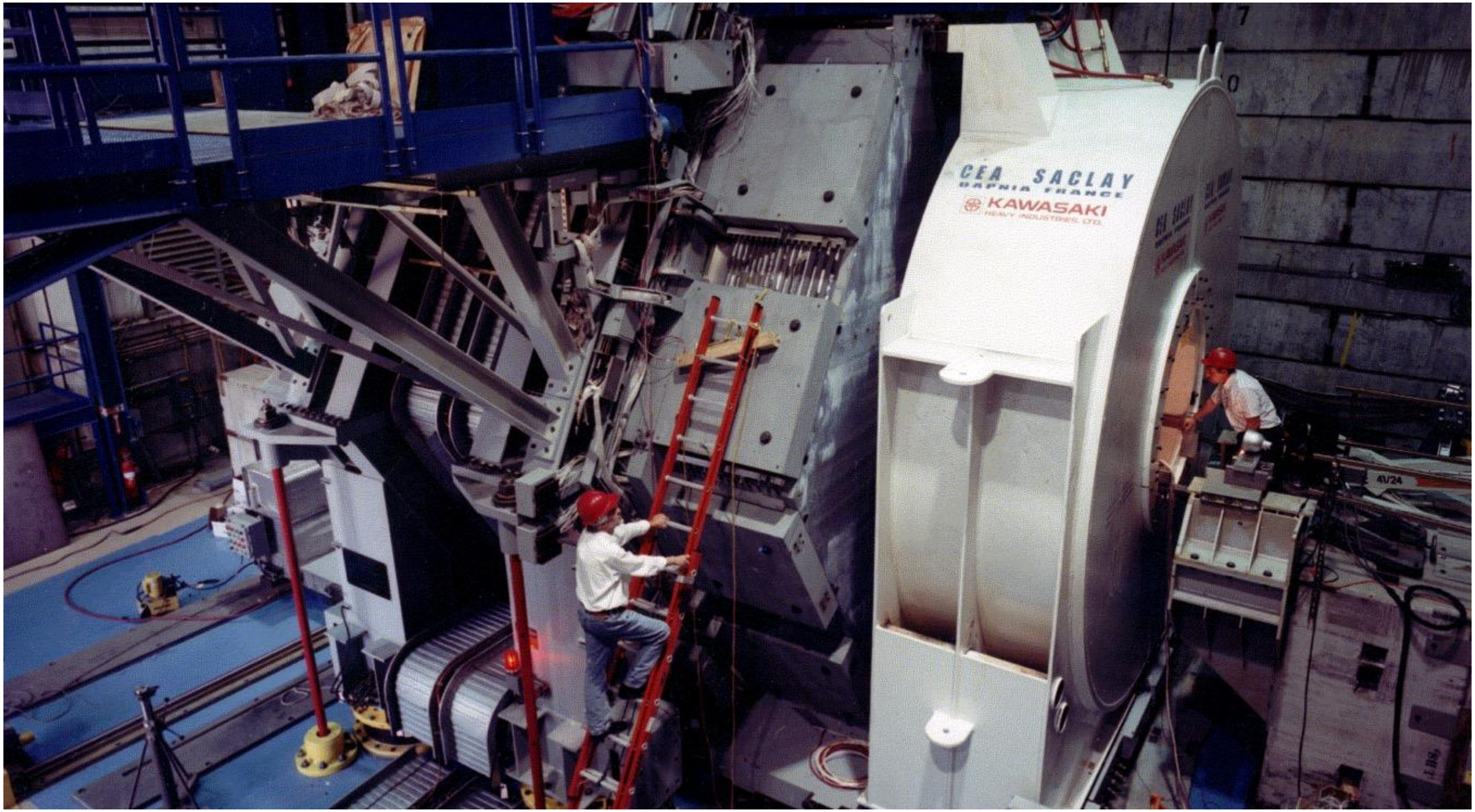
- Provided background field for particle identification for the BaBar detector at SLAC
- Physics requirements dictated a relatively thin solenoid

Properties of BaBar Solenoid

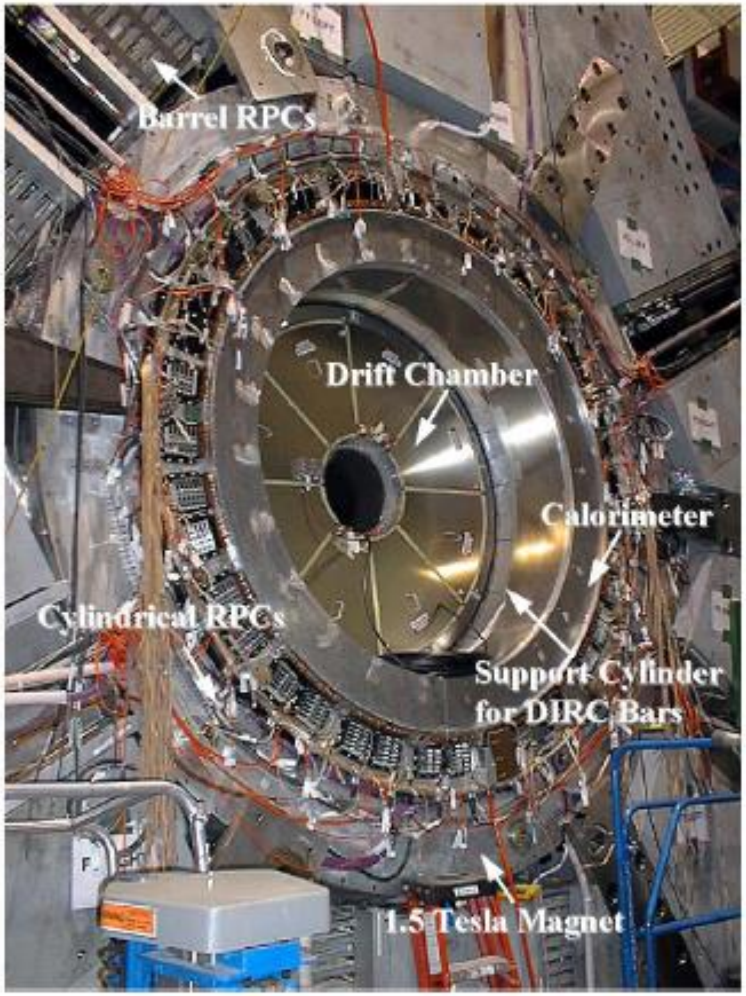


- Field: 1.5 Tesla
- Stored Energy: 27 MJ
- Operating Current: 4596A
- Tc= 8.3K
- Operating Temp: 4.5K
- Total Heat Load at 4.5K: 225liquid-liters/hr
- Cryogenics: indirectly cooled using the force flow technique where the liquid He is circulated in cooling pipes welded to the outside diameter of the support tube
- Uses NbTi highly stabilized by a pure Al conductor

BaBar Detector Under Construction



BaBar Detector



BaBar Solenoid

- Operated almost continuously for ~ 10 years
- Was very stable – only discharged due to loss of power, controls or cooling
  - Availability was > 96% from the start and better than 98% during final 3 years
    - Improvement due mainly to removing unnecessary interlocks and adding additional utility backups

Conclusions

- Superconducting magnets & SRF Cavities make possible modern accelerators : LHC, ILC, ESS, FAIR, SNS, JLAB, LCLS II
- Superconducting magnet design involves detailed engineering on a scale from the microscopic (flux pinning) to the immense (multi ton, GJ magnets)
- Superconducting magnet design involves a wide range of disciplines: materials science, electrical engineering, mechanical design, cryogenics etc.
- Superconducting magnet requirements have driven and enabled many advances in s/c materials, wire and ancillary systems
- HTS are still under development but significant niche markets are appearing

Back Up Slides

Flux Jumps

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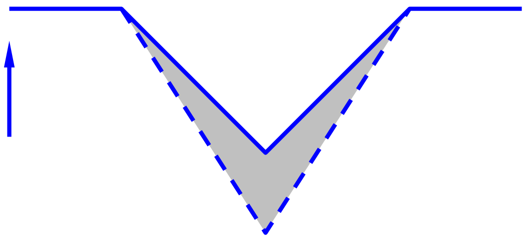
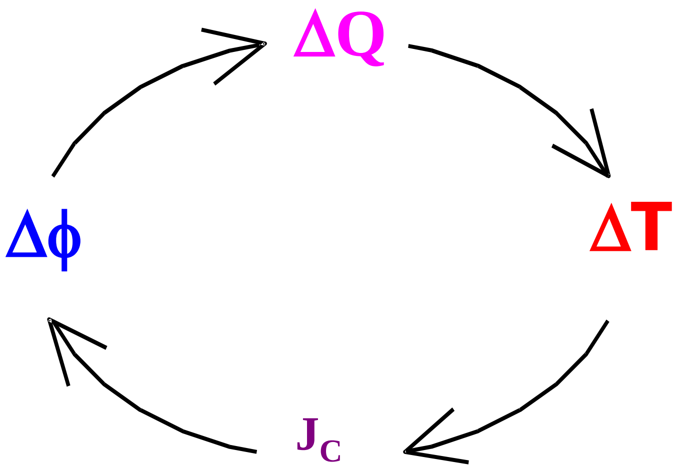
- Unstable behavior is shown by all superconductors when subjected to a magnetic field:
  - B induces screening currents, flowing at critical density J_C
  - A change in screening currents allows flux to move into the superconductor
  - The flux motion dissipates energy
  - The energy dissipation causes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

Filaments coupling

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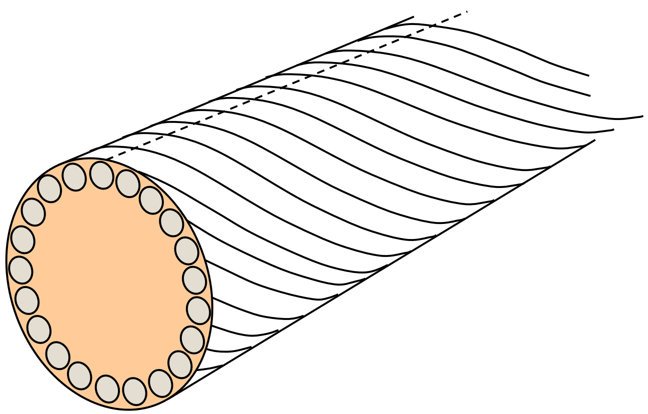

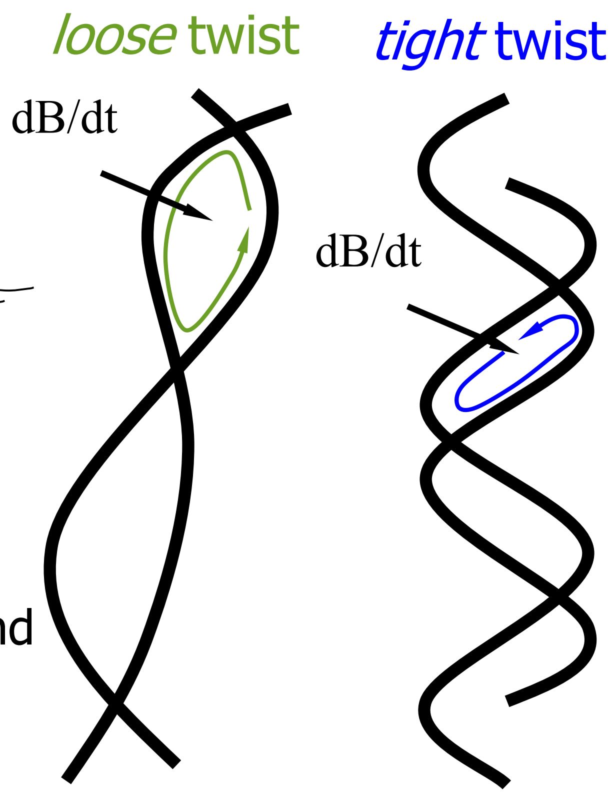

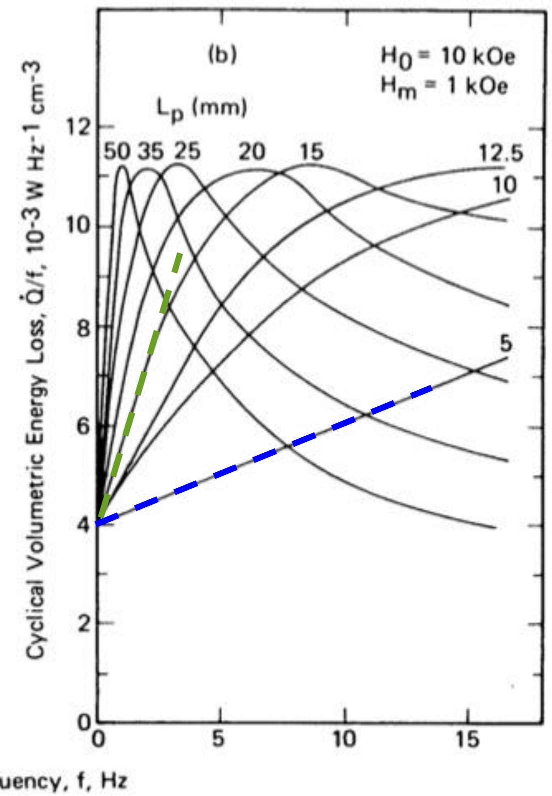

Figure 26-8. Energy loss per cycle ($\equiv \dot{Q}/f$) plotted *versus* frequency of the alternating component of an applied field $H_a(\omega) = H_0 + H_m \sin \omega t$. (a) The per-cycle *coil* loss is plotted for six values of H_m between 0.25 and 1.25 kOe at $H_0 = 10$ kOe; (b) the per-cycle *volumetric*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

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

Coupling in cables

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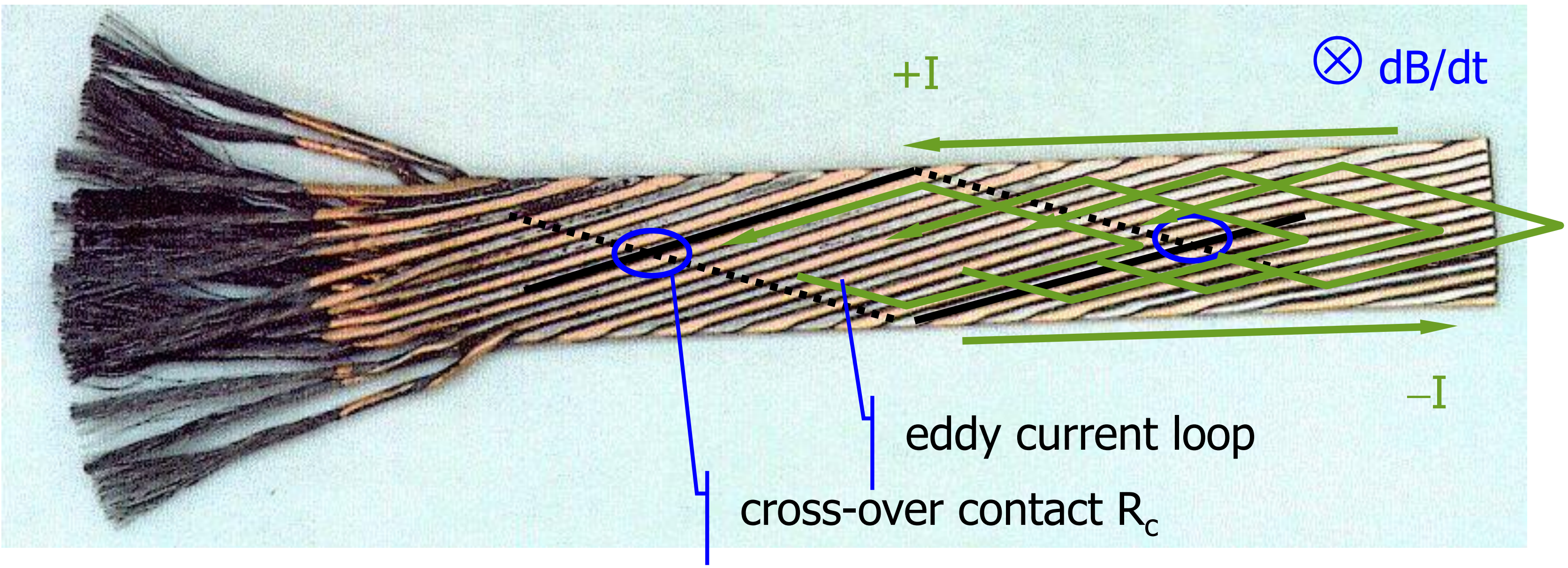

The strands in a cable are coupled (as the filaments in a strand). To decouple them we require to twist (transpose) the cable and to control the contact resistances