Unit 12
Protection principles

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Based on the USPAS units of Helene Felice, LNBL, now at CEA, Saclay France
Thanks to T. Salmi, S. Izquierdo Bermudez for contributions
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All the units will use International System (meter, kilo, second, ampere) unless specified

PLAN OF THE LECTURES

- Part 1 – From beam dynamics to magnet specifications
  - Unit 1: The energy and specifications for cell dipole and quadrupole
  - Unit 2: The luminosity and specifications for insertion region magnets
  - Appendix A: Beam optics from stable motion to chaos

- Part 2 – Principles of electromagnets
  - Unit 3: Multipolar expansion of magnetic field
  - Unit 4: How to generate pure multipole field

- Part 3 – Basics of superconductivity
  - Unit 5: Elements of superconductivity
  - Appendix B: Maxwell and scales in atomic physics
  - Unit 6: Instability and margins

PLAN OF THE LECTURES

- Part 4 – Magnet design
  - Unit 7: Strand, cable and insulation
  - Unit 8: Short sample field/gradient of sector coils and sensitivity to parameters
  - Unit 9: Grading the current density and iron effect
  - Unit 10: Forces
  - Unit 11: Structures

  - Unit 12: Protection principles
  - Unit 13: Protection systems
  - Appendix C: A digression on costs, and two case studies, from Terminator to FCC
  - Appendix D: A parade of magnet designs

PROLOGUE

- When a local transition of the superconductor to normal state has a set of parameters (current density, conductivity, resistivity, temperature margin) that exceeds the minimum propagating zone, the transition propagates to the whole conductor in an irreversible way: quench (Unit 6)
    - k: conductibility
    - T_c: current sharing temperature
    - T_{op}: operational temeprature
    - j: current density
    - ρ: resistivity

$$l_{mpz} = \frac{1}{j}\sqrt{\frac{2k(T_c - T_{op})}{\rho}}$$

- In these conditions one has two aspects that can endanger the magnet integrity
    - Temperature induced by Joule heating (hotspot temperature)
    - Voltages induced by normal/superconducting states in the coil, and by unbalance between inductive and resistive load in the coil

PROLOGUE

- Hot spot temperature: the conductor that has crossed the critical surface (current sharing temperature) and is in normal state is heated by the Joule effect, and therefore one should get rid of the current as rapidly as possible

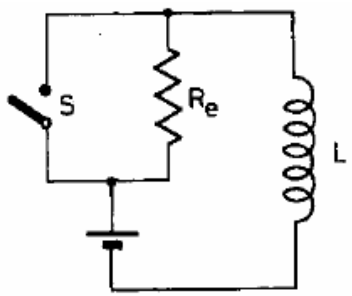
$$\rho j^2(t)dt = C_p(T)dT$$

  - where t is time, T is temperature, ρ is resistivity and C_p is volumetric specific heat

  - The circuit is a RL circuit
    - with the magnet inductance L (constant at first order, if one neglects the nonlinearities induced by non saturated iron)
    - and a highly variable resistance $R(t)$, growing with time
    - the higher the resistance, the faster the current dump, the lower hotspot

PROLOGUE

- The higher the resistance, the faster the current dump, the lower hotspot …



- Adding an external dump resistor creates a voltage at the magnet leads, proportional to the dump resistor
  - So the resistor size is limited by magnet insulation
- However, during the discharge internal voltages are also present, mainly because the part of the magnet where the transition started has a higher temperature (and resistance)
- Therefore the second critical aspect is related to voltages during quench

PROLOGUE

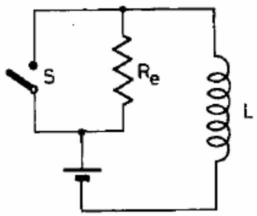
- The best way to get rid of the current is to increase the resistance, transforming the local transition in a global transition to normal conducting state
  - This corresponds to rapidly heating the whole coil above the current sharing temperature (critical surface of the superconductor)
- Both units will concern low temperature superconductors (Nb-Ti and Nb_3Sn) that have similar properties
  - HTS protection is a totally different world, not analysed here
- We split the protection units in two parts
  - Unit 12: principles of protection, i.e. related only to the magnet features – independently of the protection systems, which are the limits not to cross in magnet design to allow protection ?
  - Unit 13: protection systems, i.e. the devices used to protect the magnet – which are the protection systems, and how they work ?

CONTENTS

- Hotspot temperature in adiabatic case
- Material properties
- A digression on stored energy
- Limits of energy extraction
- Absence of energy extraction: time margin and parametric dependence

HOTSPOT TEMPERATURE

- After quench, one has Joule heating
  - Power converter is switched off
  - Magnet has growing resistance depending on quench propagation/ protection system
  - Dump maybe included in the circuit
  - We have an RL circuit
- Resistance and heat capacity strongly depend on the coil temperature, highly nonlinear problem



$$\nu\rho_{Cu}(T)\,j_{Cu}^2(t)\,dt = C_p(T)\,dT$$

$$\nu\, j_{Cu}^2(t)\,dt = \frac{C_p(T)}{\rho_{Cu}(T)}\,dT$$

- j: current density in the copper
- ρ: resistivity of copper
- C_p: volumetric specific heat of the conductor
- V: volumetric fraction of copper in the conductor

HOTSPOT TEMPERATURE

- Assuming that the heat stays locally, and just increases the temperature (adiabatic approximation) one can integrate

$$\nu j_{Cu}^2(t)dt = \frac{C_p(T)}{\rho_{Cu}(T)}dT \qquad \nu \int_0^\infty j_{Cu}^2(t)\,dt = \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)}dT$$

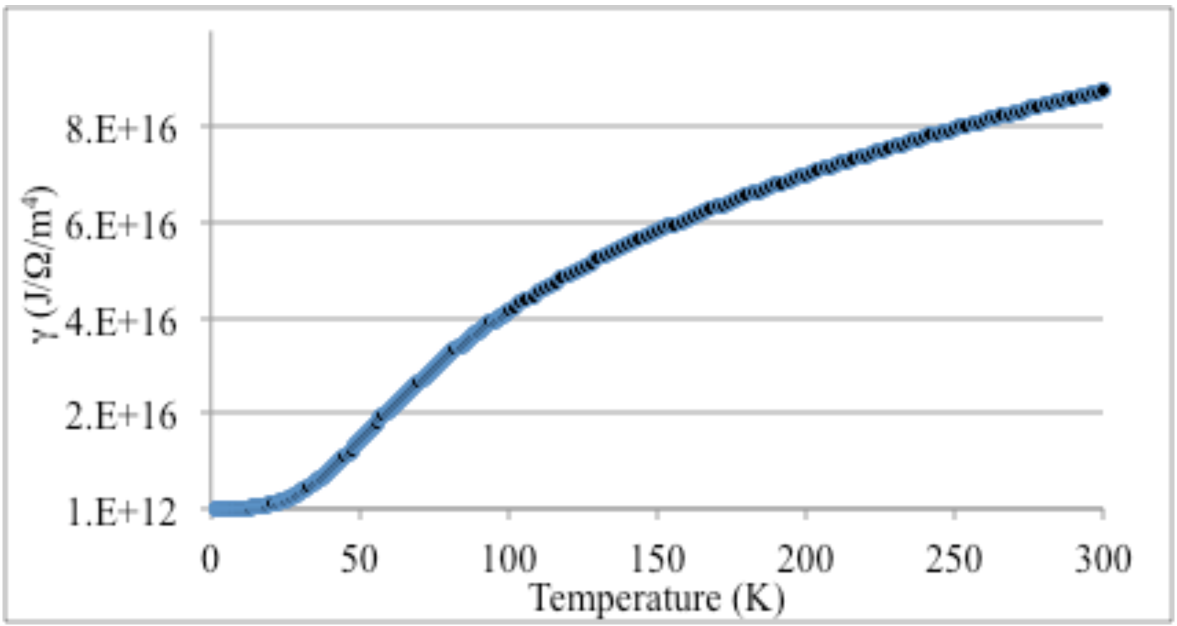
- and compute numerically $j_{Cu}(t)$
  - This is a one dimensional integration, but with non trivial features due to the wide range of ρ and C_p: and adaptive step has to be used
  - This means that you use very small time step at the beginning (much less than 1 ms), where the specific heats around the operational temperature of few K are varying a lot
  - More refined models: accounting for quench propagation, and exchange to He bath (1D-2D or 3D model meshes, plus time)
  - The adiabatic model is conservative on the hotspot, since part of the Joule heating goes away or is removed

HOTSPOT TEMPERATURE

- What is a safe T_{max} that can be reached in the coil?
    - Usually one does not want to go much beyond room temperature 30 C (300 K), at most 80 C (350 K)
  - Main reasons
    - For Nb-Ti damaging of insulation above 250 C (melts)
    - For all cases this very rapid (in fraction of second) heating induces local thermal stresses that can damage the cable
  - 350 K may be a reasonable maximum limit for high performance magnets (main magnets)
    - Some experiments prove that degradation is negligible until 400 K and beyond
    - On the other hand some margin should be kept
  - 200 K to 250 K is used for correctors, where margin is much less expensive, and therefore lower current densities can be used

HOTSPOT TEMPERATURE

- Let us consider some orders of magnitude
  - Below you see a typical plot of the right hand side integral for a typical Nb-Ti cable with half of copper in the cross-section
    - The integral is the order of 10^{17} J/Ω/m^4 for Tmax =300 K



$$\gamma(T_{max}) \equiv \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

Integral of the ratio between volumetric specific heat and Cu resistivity

HOTSPOT TEMPERATURE

- Let us consider some orders of magnitude
  - Let us compute how long can the magnet can stay at current density $j_{Cu,0}$

$$\nu \int_0^\infty j_{Cu}^2(t)\,dt \approx \nu\, j_{Cu,0}^2 t_0 = \gamma(T_{\max}) \qquad t_0 = \frac{\gamma(T_{\max})}{\nu\, j_{Cu,0}^2}$$

  - Considering $j_{Cu,0}$=1000 A/mm^2, ν=0.4, we can stay a time $10^{17}/(10^9)^2/0.4$ = 0.25 s at that current before reaching 300 K
  - Therefore the time required to dump the current is of the order of tenths of seconds

HOTSPOT TEMPERATURE

- The equation is given for intensive properties

$$\nu \int_0^\infty j_{Cu}^2(t)\,dt = \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

- We now write it in the extensive form
  - I: current in the cable
  - ρ_{cu}: copper resistivity
  - c_p^{ave}: volumetric specific heat
  - ν: fraction of copper in the insulated cable
  - A: insulated cable surface

$$I = \nu A j_{Cu}$$

$$\int_0^\infty I^2(t)\,dt = \nu A^2 \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

- And we define Γ

$$\Gamma(T_{\max}) = \nu A^2 \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho(T)} dT = \nu A^2 \gamma(T_{\max})$$

  - Γ is the capital we can spend to protect the magnet
  - This has a physical dimension of a square of current times time (A^2 s)

HOTSPOT TEMPERATURE

$$\int_0^\infty I^2(t)\,dt = \Gamma(T_{\max})$$

- The integral of the square of the current is an observable during test
  - Usually the left hand is expressed using kA, and integral of square of kA is called MIITs
- For computing this correctly we must estimate the beginning of the quench, that happens before the current decay
- Then using the curve Γ versus T we can estimate the hotspot reached
- The other relevant variable is the quench location since the field has some impact on copper resistivity and therefore on Γ
  - Also the right side (the capital of the cable, given by a combination of enthalpy and copper resistivity) can be expressed in MIITs
  - We will come back on this estimate

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- Limits of energy extraction
- Absence of energy extraction: time margin and parametric dependence

MATERIAL PROPERTIES

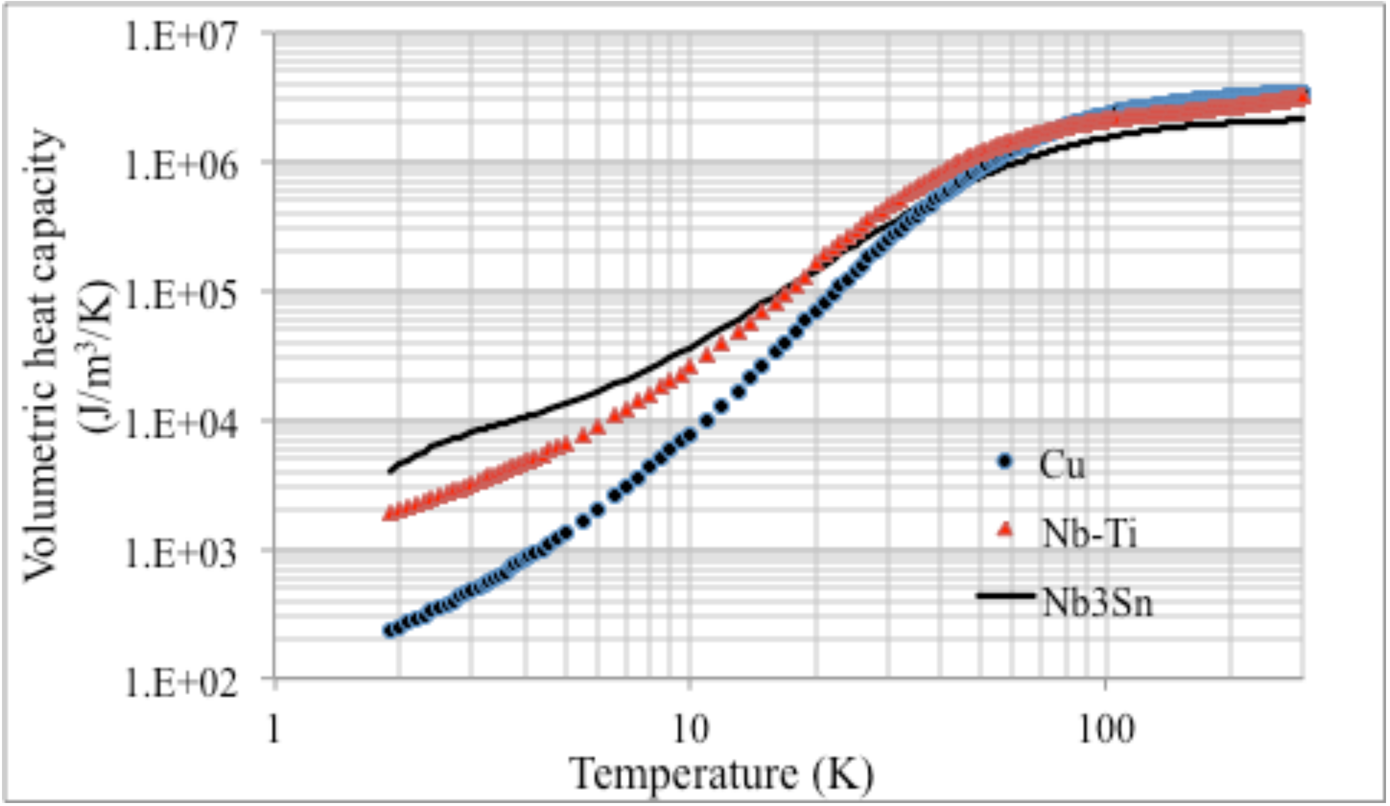
- Material properties are varying on several orders of magnitude

- Two main ingredients
  - Specific heats (for superconductor, copper, and insulation)
  - Resistivity (for copper, since the superconductor and insulation have such high resistivity that can be ignored)
    - Note the copper resistivity at low temperatures depends on RRR
    - Copper resistivity also has a dependence on magnetic field

- Due to the wide range, integration is not trivial and has to be done with an adaptive step
  - This means you use smaller steps over certain ranges, and larger over other ranges

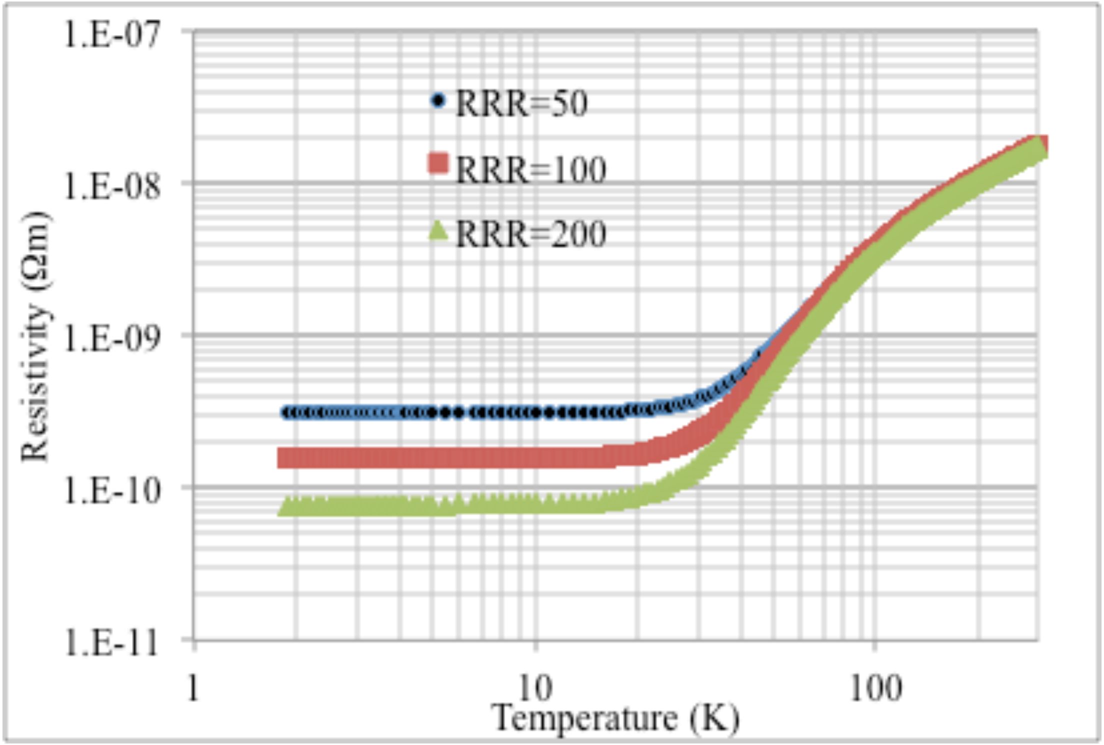
MATERIAL PROPERTIES: SPECIFIC HEATS

- Volumetric specific heats are fit with polynomials
  - They vary over 5 orders of magnitude
    - Note: Nb_3Sn and Nb-Ti data for resistive state



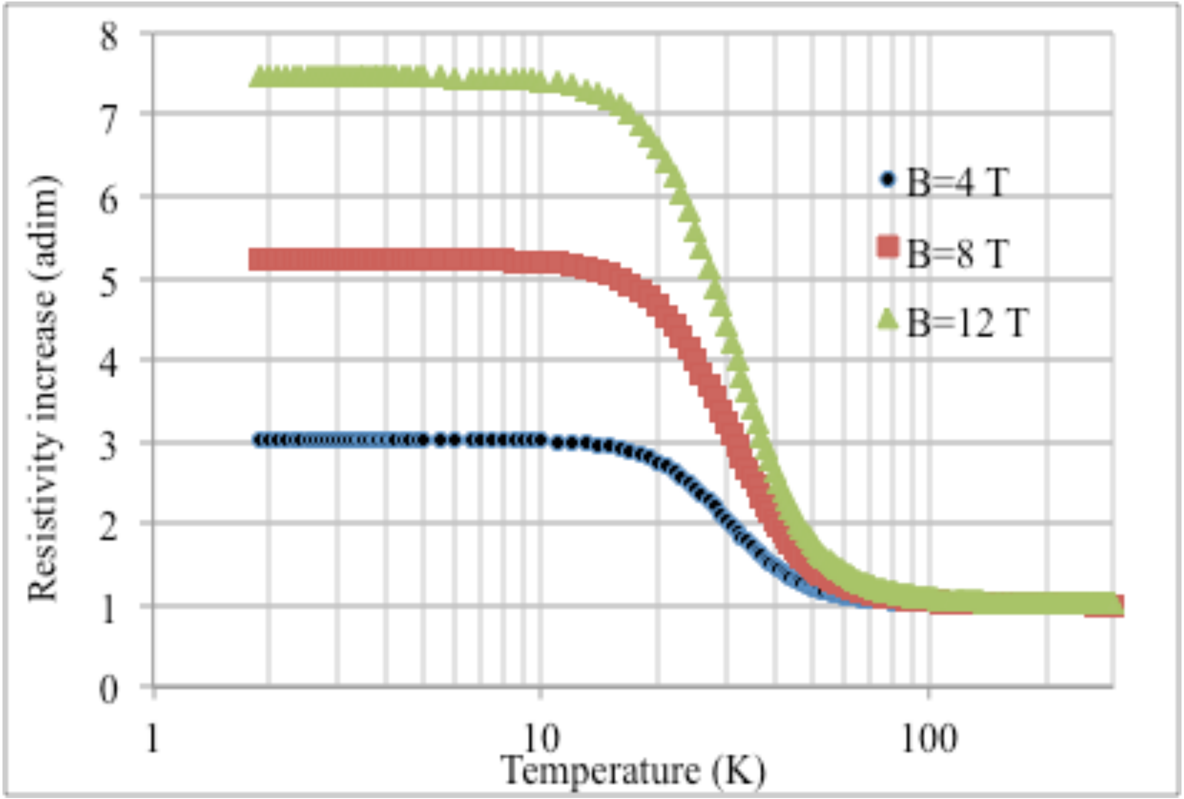
MATERIAL PROPERTIES: RESISTIVITY

- Copper resistivity is the physical quantity with the most complex dependence
  - At low temperatures, the value is dominated by the presence of impurities (measured by the so called RRR, residual resistivity ratio)



MATERIAL PROPERTIES: RESISTIVITY

- On the top of this, there is a dependence on the magnetic field
  - Larger magnetic field increases the resistivity



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A DIGRESSION ON STORED ENERGY

- The stored energy in magnetic field is given by the volumetric integration of the square of the magnetic field

$$U = \int \frac{B^2}{2\mu_0} dV$$

- How to have a back of the envelope estimate?
- Obviously a lower limit is just the square of the field on the magnet aperture

$$U_m = \frac{B^2}{2\mu_0} \pi r^2 l$$

A DIGRESSION ON STORED ENERGY

- An upper limit is given by assuming the integration volume of the bore field including the coil, which has a width *w*

$$U_M = \frac{B^2}{2\mu_0}\pi\left(r+w\right)^2 l$$

- And therefore

$$\frac{B^2}{2\mu_0}\pi r^2 l < U < \frac{B^2}{2\mu_0}\pi\left(r+w\right)^2 l$$

- We can define the fraction of the coil such that

$$U = \frac{B^2}{2\mu_0}\pi\left(r+\chi w\right)^2 l$$

A DIGRESSION ON STORED ENERGY

- We can define the fraction of the coil such that

$$U = \frac{B^2}{2\mu_0}\pi\left(r + \chi w\right)^2 l$$

  - Some examples

Magnet	Energy (MJ/m)	Aperture r (mm)	Field (T)	Coil width w (mm)	Fraction X (adim)
Tevatron dipole	0.047	38	4.3	16	0.45
LHC dipole	0.49	28	8.3	31	0.8
HL-LHC 11 T	0.89	30	11.2	31	0.8
RHIC dipole	0.037	40	3.46	10	1.0

A DIGRESSION ON STORED ENERGY

- A typical example done for giving an idea of the large size of the stored energy in the magnetic field of the LHC dipoles (7 MJ) is close to the kinetic energy of a 20 tons lorry at 100 km/h
  - $U = mv^2/2 = 20\ 000 \times 28^2 / 2 = 7.7$ MJ
  - m=20 tons
  - v=100 km/h = 28 m/s

A 7 MJ lorry (S. Spielberg, “Duel” Universal Pictures, 1971)

A DIGRESSION ON STORED ENERGY

- Or the potential energy of 700 tons of water falling by one meter
  - $U=mgh$ = 700 000 × 10 × 1 = 7 MJ

- On the other hand I can also convince you that the stored energy is small …
  - A glass of gasoline
  - Gasoline has stored energy of about 50 MJ/liter
  - That's why it is so difficult to get rid of fossil fuels …

A DIGRESSION ON STORED ENERGY

- How many dipoles can you eat?
  - BigMac has 550 cal
  - Please note that this means 550 kcal

- 1 cal = 4.18 J
  - 1 Big Mac = 2 MJ
  - 3 Big Mac + 1 French fries = 1 LHC dipole

A DIGRESSION ON STORED ENERGY

- Definition of inductance in the linear case

$$U = \frac{1}{2} L I^2 \qquad\qquad L = \frac{2U}{I^2}$$

- Definition of inductance in the nonlinear case
  - Energy is not anymore proportional to square of current
  - In these cases, inductance decreases for higher currents
  - Therefore one defines the differential inductance as

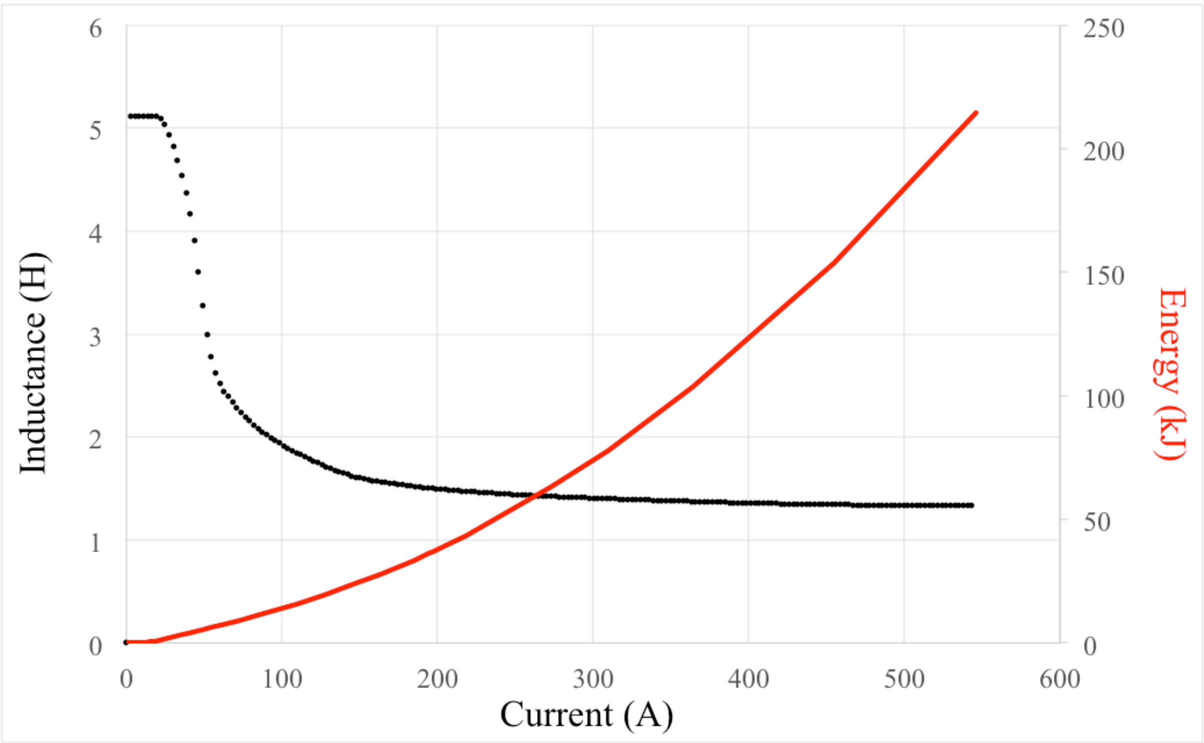
$$\frac{1}{I}\frac{dU}{dI} = L(I)$$

  - And one has

$$U(I) = \int_0^I L(i)\, i\, di$$

A DIGRESSION ON STORED ENERGY

- Example of superferric skew quadrupole for HL-LHC
  - Highly nonlinear due to iron saturation



$$U(I)=\int_0^I L(i)i\,di$$

$$\frac{1}{I}\frac{dU}{dI}=L(I)$$

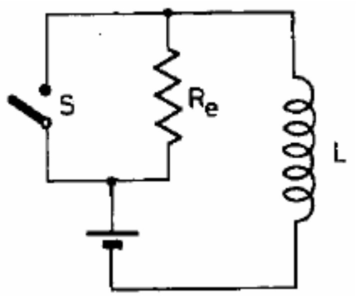
Stored energy and inductance in the skew quadrupole for HL LHC
(M. Statera et al.)

CONTENTS

LIMITS OF ENERGY EXTRACTION

- We assume that the resistance build up in the magnet is negligible

$$I(t) = I_0 \exp\left(-\frac{t}{L} R(t)\right) \approx I_0 \exp\left(-\frac{tR_d}{L}\right)$$



- So the quench integral is

$$\Gamma_q = \int_0^\infty I^2(t)dt = I_0^2 \int_0^\infty \exp\left(-\frac{2tR_d}{L}\right)dt = \frac{LI_0^2}{2R_d} = \frac{U}{R_d}$$

- The dump resistor is limited by the maximum voltage

$$R_d I_0 < V_{\max} \qquad\qquad R_d < \frac{V_{\max}}{I_0}$$

LIMITS OF ENERGY EXTRACTION

- And therefore

$$\Gamma_q = \frac{LI_0^2}{2R_d} > \frac{UI_0}{V_{\max}}$$

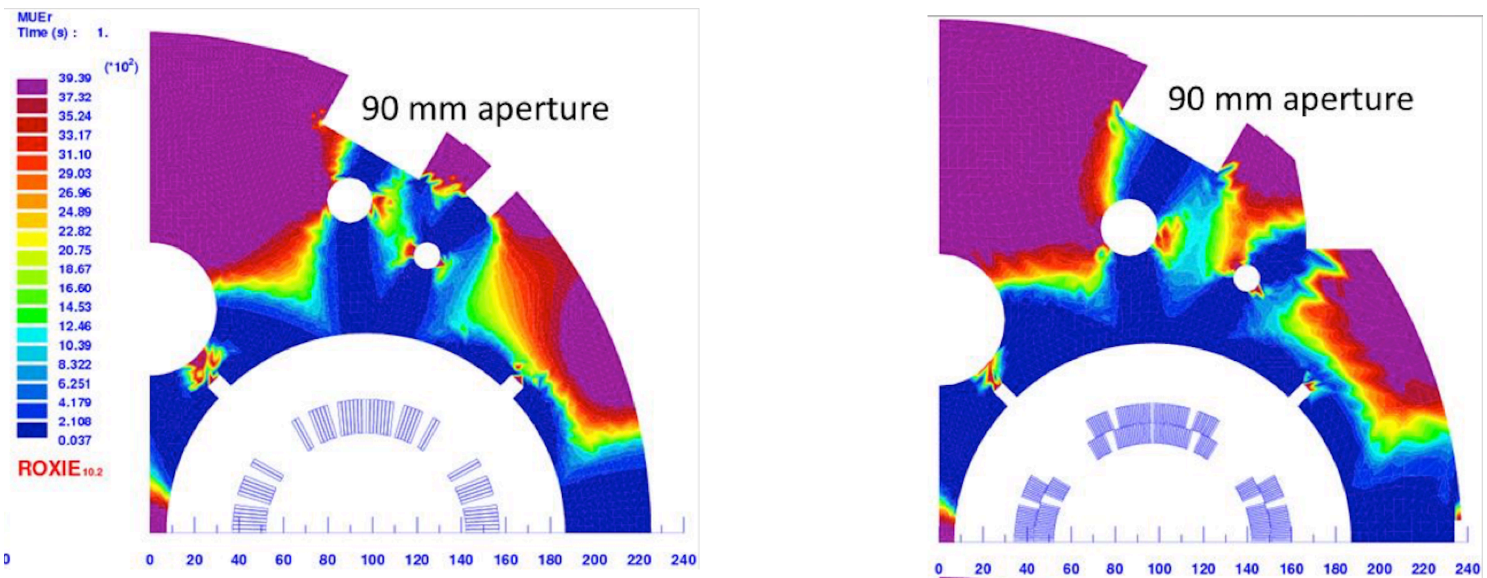
- Neglecting the time needed to detect the quench and insert the dump resistor, the condition of protection is

$$\Gamma_q < \Gamma$$

$$\frac{UI_0}{V_{\max}} < \Gamma$$

- Therefore for a given stored energy, a larger cable carrying more current can allow protection with energy extraction
  - Infact, I_0 is proportional to the cable surface, but Γ is proportional to the square of the cable surface (see slide 14)
  - Therefore increasing the cable surface one can always satisfy the above condition … unless the cable is too large to be wound

- The case of Q4 in HL-LHC
  - 90 mm aperture, 120 T/m gradient, Nb-Ti
    - First design: one layer coil, cable 15 mm width – larger current (16 kA), but can be protected via energy extraction
    - Second design: two layer coils, cable 8 mm width – smaller current (5 kA), but this cannot be protected via energy extraction



Q4 design: one layer option (left) and two layers option (right)
(J. M. Rifflet, M. Segreti, H. Felice et al)

LIMITS OF ENERGY EXTRACTION

$$\frac{UI_0}{V_{\max}} < \Gamma$$

- The LHC dipole case
  - $U = 7$ MJ
  - $I_0 = 12$ kA
  - $\Gamma \sim 3.6\times10^7$ (I will you show you why, and that this is 36 MIITs)
  - $7\times10^6\times12\times10^3/500 = 175\times10^6$
- The condition of protection is not satisfied: $175\times10^6 > 36\times10^6$
- One can have a first order estimate of Γ as follows
  - $\gamma^{300} \sim 10^{17}$ J/Ω/m^4 (see slide 12)
  - A~30 mm^2 (LHC cable surface)
  - $\nu \sim 0.40$ (fraction of copper in insulated cable)
  - $\Gamma \sim (30\times10^{-6})^2\times0.40\times10^{17} = 36\times10^6$ J/Ω/m^2

$$\Gamma = A^2\nu\int_{T_{op}}^{300}\frac{C_p}{\rho_{Cu}}dT = A^2\nu\gamma^{300}$$

DEFINITION OF MIIT

- The units of Γ are $J/\Omega/m^2$
- But they are also A^2s
  - In our case we saw $\Gamma \sim 36\times10^6$ A^2s
  - Since current is usually expressed in kA, one expresses Γ in MA^2s (also called MIIT)
  - $\Gamma \sim 36\,(kA)^2s = 36\,MA^2s = 30$ MIIT
  - Precise values are 30 and 45 MIIT for inner and outer cable respectively

$$\Gamma = A^2 \nu \int_{T_{op}}^{300} \frac{C_p}{\rho_{Cu}} dT = A^2 \nu \gamma^{300}$$

Cable		
Number of strands	28	36
Cable dimension (at room temperature)		
Mid-thickness at 50 MPa [mm]	1.900 ± 0.006	1.480 ± 0.006
Thin edge [mm]	1.736	1.362
Thick edge [mm]	2.064	1.598
Width [mm]	$15.10^{-0.02}_{+0}$	$15.10^{-0.02}_{+0}$
Keystone angle [degree]	1.25 ± 0.05	0.90 ± 0.05
Transposition pitch [mm]	115 ± 5	100 ± 5
Aspect ratio	7.95	10.20
MIITS [300 K] [MA^2 s]	45 [8T]	30 [6T]
Critical current I_c [A] 10 T, 1.9 K	> 13750	
9 T, 1.9 K		> 12960

MIITs of the LHC cable (LHC Design Report Vol 1)

LIMITS OF ENERGY EXTRACTION

- Let us try to find a limit to energy extraction in terms of stored energy and current:

$$\frac{UI_0}{V_{\max}} < A^2 \nu \gamma^{300}$$

- can be rewritten as

$$\frac{U}{A} j_0 < \nu V_{\max} \gamma^{300}$$

- Note that
  - Stored energy makes it worse
  - Current density makes it worse
  - Even if we put a lot of copper (this means ν going towards 1), we can exploit at most V_{max}
  - Any situation can be cured by using larger cable … but can become difficult or even impossible to wind
  - For long, high field magnets energy extraction is not possible

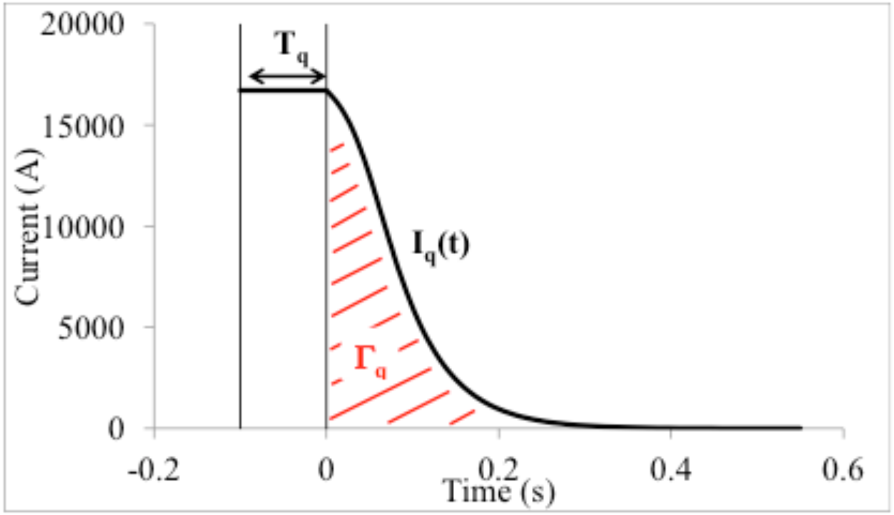
CONTENTS

TIME MARGIN

- The best protection system we can imagine is a system that in 0 s makes all the coil resistive
  - And let us assume that $I_q(t)$ is the current decay in a magnet totally resistive, and operational temperature
    - This can be estimated through numerical codes, and the quench integral can be computed

$$\Gamma_q \equiv \int_0^{\infty} I_q^2(t)\,dt$$

      - It is a property of the magnet design, independent of the protection system
  - How long we can survive at maximal current ?



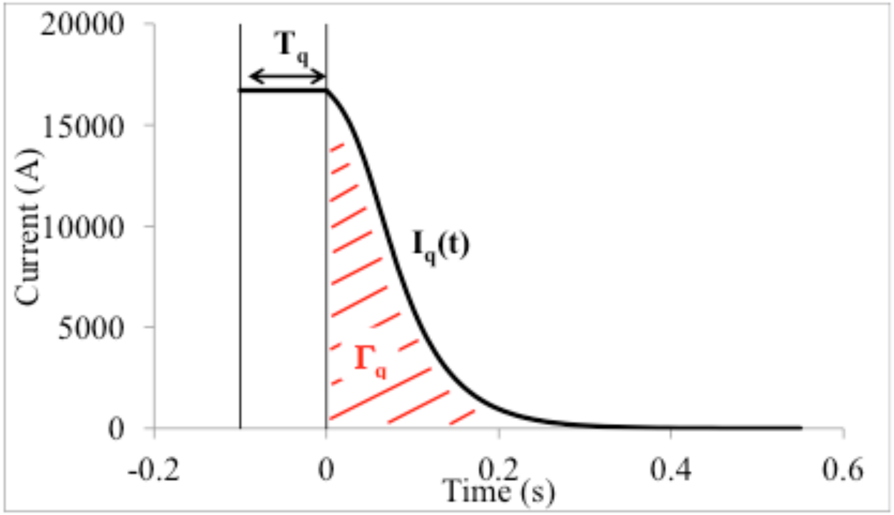
$$I_0^2 T_q + \Gamma_q = \Gamma\left(T_{max}\right)$$

$$T_q = \frac{\Gamma\left(T_{max}\right) - \Gamma_q}{I_0^2}$$

TIME MARGIN

- T_q is the time margin for protection
  - This gives the time required to react to the quench and to spread all the quench through the quench heaters before the magnet reaches T_{max}
  - Order of magnitude:
    - For Nb-Ti high field magnets the magnet design aims at having around 100 ms
    - For Nb_3Sn high field magnets we try to go towards 50 ms
      - Less becomes impossible ..
      - I will show why

$$T_q = \frac{\Gamma\left(T_{\max}\right) - \Gamma_q}{I_0^2}$$



TIME MARGIN

- One can work out an analytical estimate of the time margin

Copper fraction — insulated cable enthalpy

$$T_q = \frac{\nu}{\bar{\rho}\, j_o^2}\left(C_p^{ave} - \eta U_d\right)$$

overall current density — stored energy/ins. coil volume

- Main message is
  - Since the coil takes the heat, the energy density on the coil should smaller than the enthalpy from operational temperature to T_{max} (300 K), that is about 0.5 J/mm^3
  - As usual, there is a dependence on j^2: larger current densities reduce the margin with a square
  - Once more we see a barrier for high current densities

TIME MARGIN

- Typical order of magnitudes
  - Energy density in Nb-Ti magnets is order of 0.05 J/mm^3 , that is 1/10 of C_p^{ave} at 300 K
    - The corresponding time margin is of the order of 100 to 200 ms for high field dipoles or quadrupoles as LHC main dipole, LHC IR quadrupoles
  - For Nb_3Sn magnets, the energy density increases to 0.10-0.15 J/mm^3 (that is up to 1/4 of C_p^{ave})
    - The corresponding time margin is of the order of 50 ms
  - In the next unit we will see why we need order of 50 ms for the protection system to react

CONCLUSIONS

- Magnet protection concerns two different phenomena
  - Increase of temperature due to Joule effect
  - Increase of voltage due to a transition to resistive state only in a limited section of the conductor
- We focussed on the hotspot temperature
  - During a quench, it should not go above room temperature

$$\nu j_{Cu}^2(t)dt = \frac{C_p(T)}{\rho_{Cu}(T)}dT \qquad \int_0^\infty I^2(t)\,dt = \nu A^2 \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)}dT$$

  - Right hand side is the ability of the cable of « taking » the current (combination of enthalpy and resistivity)
  - Left hand side is the load due to the current decay, that should be made as fast as possible and is an observable

CONCLUSIONS

- Having a resistor in series with the magnet after the quench allows to rapidly get rid of the current (energy extraction)
  - This strategy is limited by the voltage, and for long magnets is not effective
- For long and high current density magnets, the only way of protection is to induce a rapid transition to resistive state in the whole magnet
  - We will show how to do this in the next lecture
  - In this case the cable enthalpy takes the magnet stored energy
  - A limit for protection is an energy density on the coil much smaller than 0.5 J/mm^3
  - The LHC dipoles had about 0.05 J/mm^3
  - The new generation Nb_3Sn magnets have 2-3 times larger energy density

CONCLUSIONS

- We defined a protection time margin, that gives the challenge of protection related to the magnet design
  - This is the time allowed to the protection system to react
  - It is order of 100 ms for Nb-Ti main magnets, and has been reduced to 40 ms for many Nb_3Sn magnets
    - This because the coil energy density is higher (higher field, and similar or higher current densities)
  - If your magnet design has less than 40 ms, increase the copper quantity in the strand or (the most effective) decrease the current density

- In the next unit we will show how to « spend » the 40 ms
  - From detection time (how to see the quench)
  - To the time needed by the systems that bring most or the whole magnet above current sharing temperature (quench heaters or CLIQ)

REFERENCES

- General principles and equations:
  - M.K. Wilson, Superconducting Magnets, Oxford, Clarendon Press, 1983.
- More on quench propagation:
  - A. Devred, General Formulas for the adiabatic propagation velocity of the normal zone, IEEE Trans on Magnetics, Vol. 25, No. 2, March 1989
- Copper resistivity:
  - F.R. Fickett, Transverse magnetoresistance of oxygen free copper, IEEE Trans. On Magn., vol 24, No 2, March 1988
- Wide literature on specific results on magnets, for instance
  - H. Felice, et al., "Instrumentation and quench protection for LARP Nb3Sn magnets" IEEE Trans. Appl. Supercond. 19 (2009) 2458-2462
  - S. Izquierdo Bermudez, et al., "Overview of the quench heater performance for MQXF, the Nb_3Sn low-beta quadrupole for the high-luminosity LHC" IEEE Trans. Appl. Supercond. 28 (2018) 4008406

REFERENCES

- An outlook for FCC high field magnets
  - T. Salmi, et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider” Phys. Rev. STAB 20 (2017)
- About the scaling, and time margin concept
  - E. Todesco, “Quench limits in the next generation of magnets” CERN Yellow Report 2013-006 10-16
- About computer codes
  - H. Felice, “Quench protection analysis in accelerator magnets, a review of tools” CERN Yellow Report 2013-006 17-20