DE LA RECHERCHE À L'INDUSTRIE

QUENCH DETECTION AND PROTECTION OF FUSION MAGNETS

Lectures on superconducting magnets test stands,

magnet protections and diagnostics

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OUTLINE

- INTRODUCTION TO HIGH VOLTAGES AND PROTECTION
- PROTECTION BY DUMPING THE CURENT INTO EXTERNAL RESISTORS
- VOLTAGES DURING A QUENCH
- THE HOT SPOT CRITERION
- ILLUSTRATION OF PROTECTION IN TORE SUPRA, W7-X, JT-60SA, ITER
- QUENCH DETECTION

Several projects quoted during the course

- **ITER**: A tokamak project aimed at demonstrating fusion as a possible source of energy for humanity. 700 tons of superconducting material. Superconducting magnets typically represent 30 % of the ITER cost investment construction in progress at CEA Cadarache.
- **JT-60SA**: A Japanese Tokamak (Physics machine). France + Italy provided the TF system (34 tons of NbTi strands). Construction is completed, now in the commissioning phase. First plasmas scheduled in 2024.
- **Tore Supra**: First large superconducting tokamak (only TF system), in operation in France since 1988. Stored energy 600 MJ
- **W7-X** Superconducting stellarator in operation on Germany since 2015. Stored energy 610 MJ.

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Introduction to protection

Superconducting magnets can quench and magnets have therefore to be protected against quenches. The quench does not occur just by chance but can be triggered by different sources.

The design of a magnet has to be such to avoid any quench and must therefore take into account all internal and external possible loads .

The most difficult loads are the overloads which can appear during a fault such as short circuits, non opening of current breakers, unmitigated quench etc …

From L. Bottura

Introduction to protection

Possible Origin of quench	Details
Insulation	Can occur during a Fast Safety Discharge or Plasma Initiation phase for fusion magnets. Default of insulation in connexions, terminals or bus bars for instance. Arcs. Aging of insulation
Loss of coolant	Breakdown in refrigeration Should trigger decrease of current.
Loss of insulation vacuum	Makes the coil temperature increase
Weak point in the conductor	Undetected during fabrication. Tcs is exceeded. Can appear after cycling due to strain for Nb_3Sn .
Conductor movement or local crack in epoxy	Classical in training of particle physics magnets
External causes	Beam losses in particle physics, plasma disruption or Vertical Displacement Event in fusion
mechanical	Under-designed structural components can cause quench under excessive Lorentz forces. Fatigue

Paschen tests to test insulation

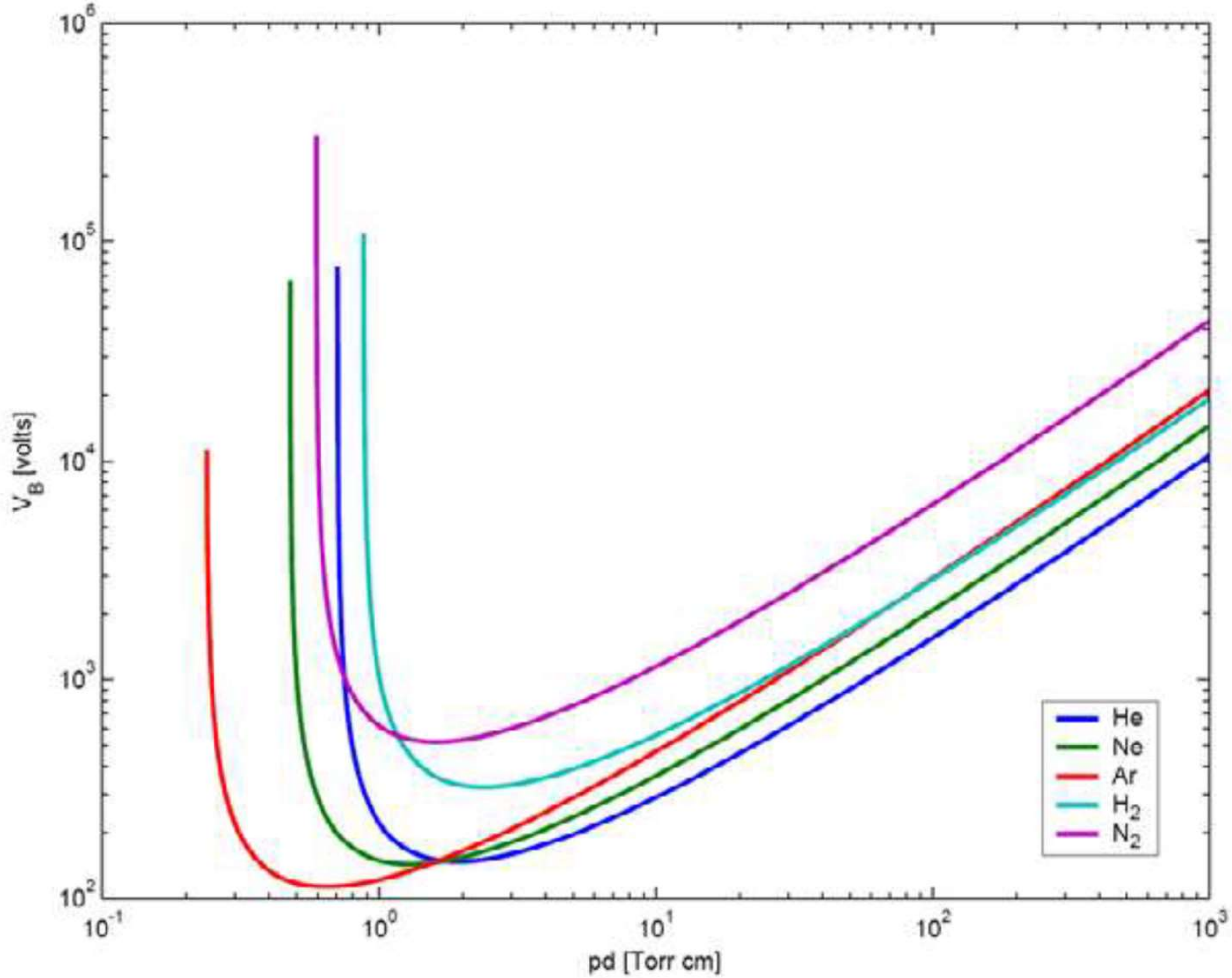
The behaviour of ITER coils under high voltages is certainly one of the main challenge of the project. Magnets are cooled down in general at 80 K in N2.

The Paschen tests are performed before and after cool down.

During Paschen tests, a DC voltage of 15 kV for one minute is applied at room temperature at different levels of N2 pressure in the cryostat from 0.01 mbar to 100 mbar .

Cryostat pressure in operation 10^{-5}–10^{-6} mbar.

1 torr=1.33 mbar



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Introduction to protection: consequences of faults

Arcing

The most serious electrical failure in magnets is arcing that can either permanently damage part of the magnets or, if the arc is moderate, can simply short circuits two neighbouring conductors

Arcing can unfortunately happen during the protection phase in a superconducting system when a quench is detected.

High voltage are induced in this phase which can trigger an arc if there is a defect in the insulation.

Overheating (meltdown)

If the magnet energy is not extracted sufficiently rapidly, the insulation can burn and the conductor can melt; Time constant of energy extraction must be carefully calculated.

Introduction to protection

The possible occurrence of a quench (irreversible loss of superconductivity) has always to be considered during the design phase of the magnet.

The protection of the magnet in case of a quench has to deal with major items such as:

- the design of the conductor itself
- the maximum voltage to the ground in case of a quench
- the quench detection which has to be very fast
- the selected dc current breaker

In case of dc coils, only during a quench a large voltage appears across the coil and to the ground due to the **magnet discharge for protection (time constant τ).**

This voltage appears during the energy extraction following a quench when the magnetic storage energy is converted into thermal energy.

In case of **fusion magnets** large voltages can appear also during plasma scenarios, especially during plasma initiation. PF coils in particular experience large voltages.

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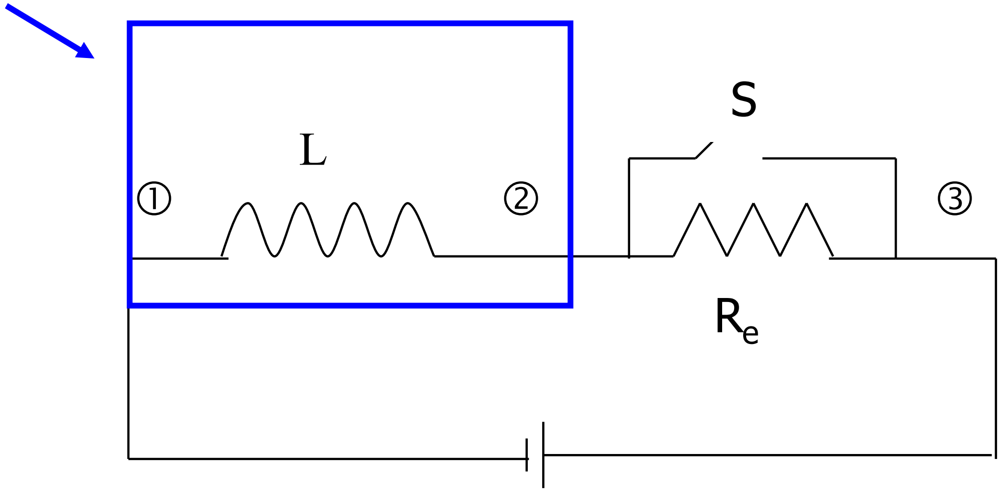
Protection by external resistor
Practical case for fusion magnets

The principle is to dissipate most of the magnetic energy outside the coil (L the coil at cryogenic temperature) into a resistor R_e at room temperature). The objective is that the hot spot will not reach a too high temperature.

- Detection of normal zone
- Opening of the current breaker

These two operations are crucial and must not fail.

In cryostat



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Protection by external resistor (fusion magnets in particular)
Voltage during a quench

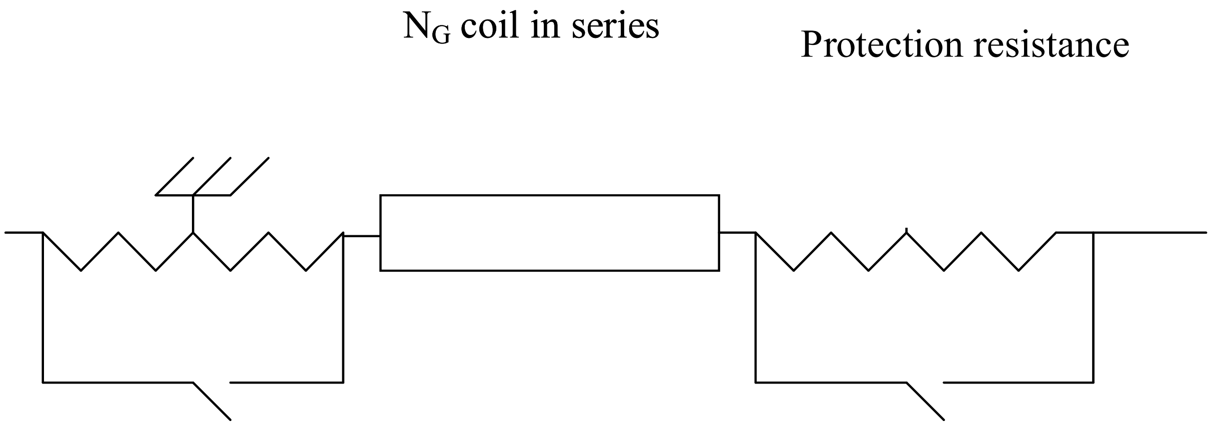
The maximum voltage $\mathbf{V_{bmax}}$ across the coil terminals of the coil is a characteristic of great importance. It is directly linked to the to the maximum voltage to the ground $\mathbf{V_{gmax}}$ **.**

It is generally possible to ground the resistor such as : $\mathbf{V_{gmax} = V_{bmax}/2}$
In a project V_{gmax} is generally in the range 1 to 4 kV.

The very simple case of protection by an external resistor is considered such as the one used in case of fusion magnets.

L inductance of the superconducting magnet, the internal resistance appearing during quench is supposed to be negligible
$\mathbf{R_e}$ external resistor connected in the circuit by opening switch S when the quench is detected
W Stored magnetic energy
PS power supply. The power supply is considered as short circuited as soon as the quench is detected.

Protection by external resistor
Voltage during a quench. The technology of subdivision



The voltage of a project is driven by its magnetic stored energy, the nominal current and the time constant of the safety discharge which is linked to the copper content and then to the current density in the cable. A way to **reduce** the voltage in the project is to subdivide if possible the coils and to interleave N discharge resistors between the coils. The Tokamak is well adapted to this method due to the presence of discrete coils.

$V_{gmax} = W/(NI_0\,\tau)$

The price to pay is the number of current leads (2N).

Ex: JT-60SA W=1. GJ τ=10 s I_0=25.6 kA N=3

$V_{gmax} = W/(3I_0\,\tau) = 1.3$ kV

Protection by external resistor
Voltage during a quench- Interest to limit V_{maxg}

$V_{gmax}=V_{bmax}/2$

Impact of V_{gmax} for the acquisition system

Part of the sensors of JT-60SA TF system, in particular the voltage sensors, must sustain a potential to the ground of V_{test}.
A discussion with specialists of acquisition systems shows that there is limit in the acceptable voltage to the ground, if standard systems are to be used. This limit is 3.5 kV.

Impact of V_{gmax} for the insulation

V_{gmax} is driving the problem of insulation especially in the terminals. The higher **V_{gmax} , the most difficult is the project.**

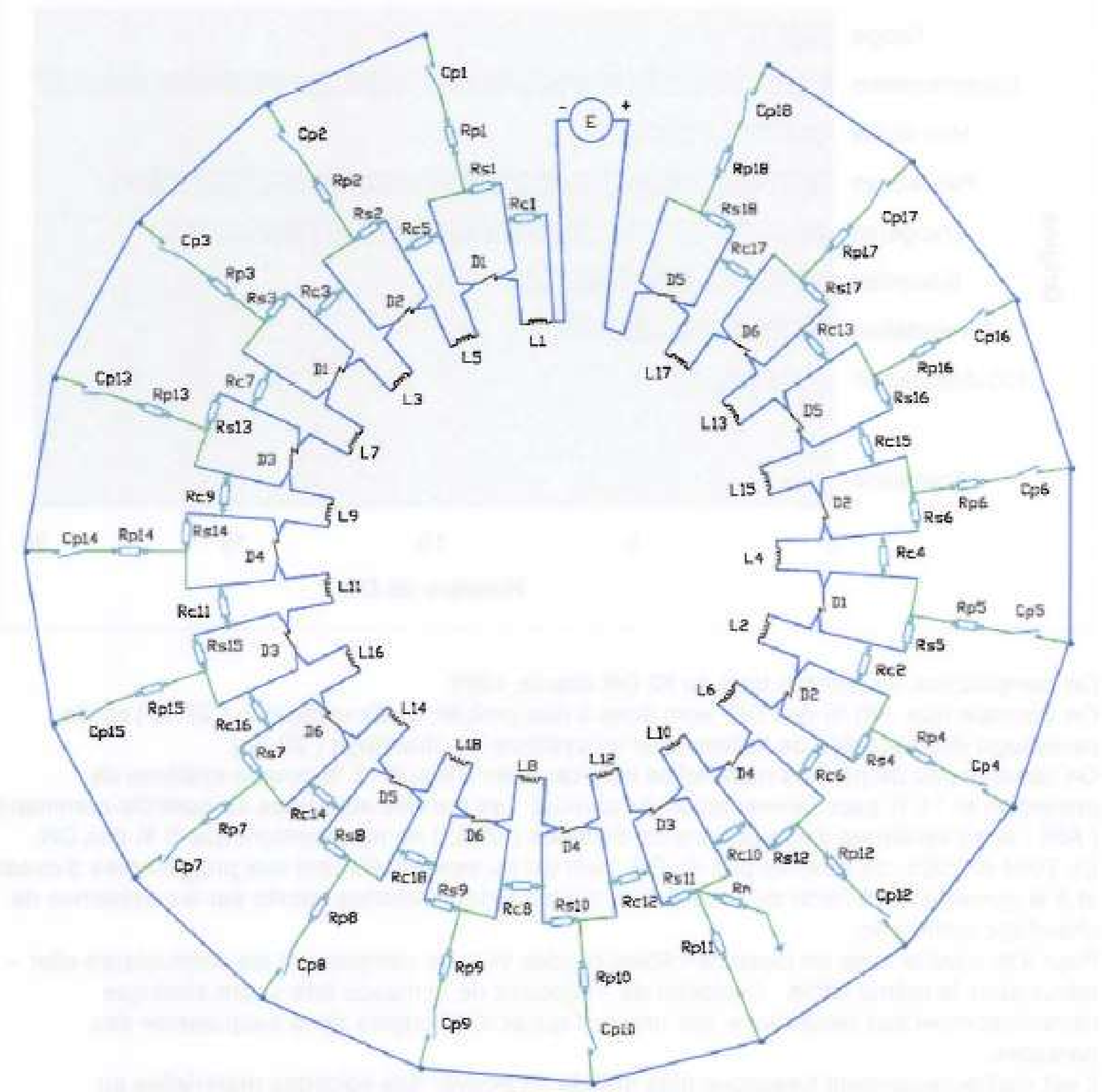
V_{gmax} ~10 kV in ITER while in most of the existing projects, it is in the range of 2 kV.

Protection by external resistor
Voltage during a quench. Subdivision. Tore Supra

In case of Tore Supra, due to the very low current, the circuit has been subdivided at maximum, 18 subcircuits to decrease V_{gmax} (N=18)

W=600 MJ I_0 =1400 A τ=120 s
V_{gmax}= W/(18I_0 τ) =200 V

In fact 400 V due to special grounding



Temperature rise: the hot spot criterion

As soon as a quench is initiated in a coil, heat dissipation exists with associated temperature increase. This temperature increase is a function of the current decay and of the current density and copper content. The calculation of the temperature increase is made on a very pessimistic assumptions that the starting point (cell) behaves adiabatically.

$$\rho(T)J^2(t)dt = \gamma C(T)dT \quad (1)$$

ρ	average resistivity of the cell	Ωm	$\rho = \rho_{cu}/\eta_{cu}$
J	average current density in the cell	A/m^2	counting **only** copper and non copper
C	average specific heat capacity	J/kg/T	
γ	average density of the cell	kg/m^3	
η_{cu}	ratio of copper in the cell		

Temperature rise: the hot spot criterion

According to the hot spot criterion, the maximum temperature increase T_{max} at the end of the current decay should not exceed 250 K in the conductor.

→ Which amount of copper in the conductor ?

→ Which time constant for the current decay ?

$$\int_0^\infty J^2\ (t)dt < \int_{T_0}^{T_{max}} \frac{\gamma C(T)}{\rho(T)} = U(T_{max}) \qquad \textbf{(1bis)}$$

The function U (T) is represented for three cases

- pure copper at 3 T with RRR=100 100% copper
- simulation of winding B=3 T, RRR=100 75 % copper (JT-60SA)
- simulation of winding B=3 T, RRR=100 50 % copper

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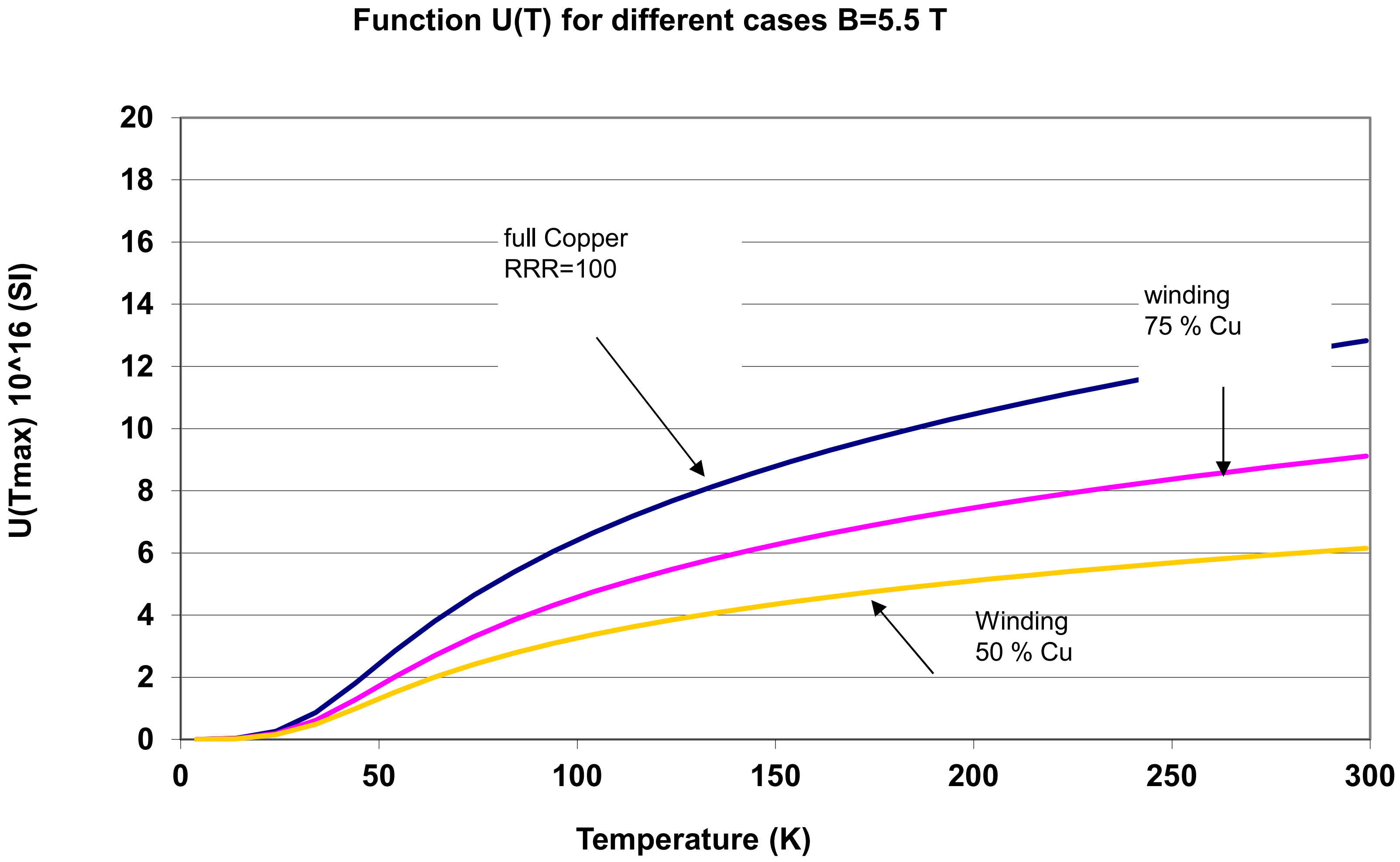
Temperature rise: the hot spot criterion
Influence of the copper content on U(Tmax)



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Temperature rise: the hot spot criterion

Application : calculation of discharge time constant τ for JT-60SA (RR=100, 75 % copper, 25 % NbTi, 5.5 T) with a detection and action time τ_{DA} of 2 s.

From (1)

$$J_0^2(\tau_{da} + \tau/2) < U(T\max) = 8.410^{16} \quad (2)$$

$$J = J_0 e^{-t/\tau}$$

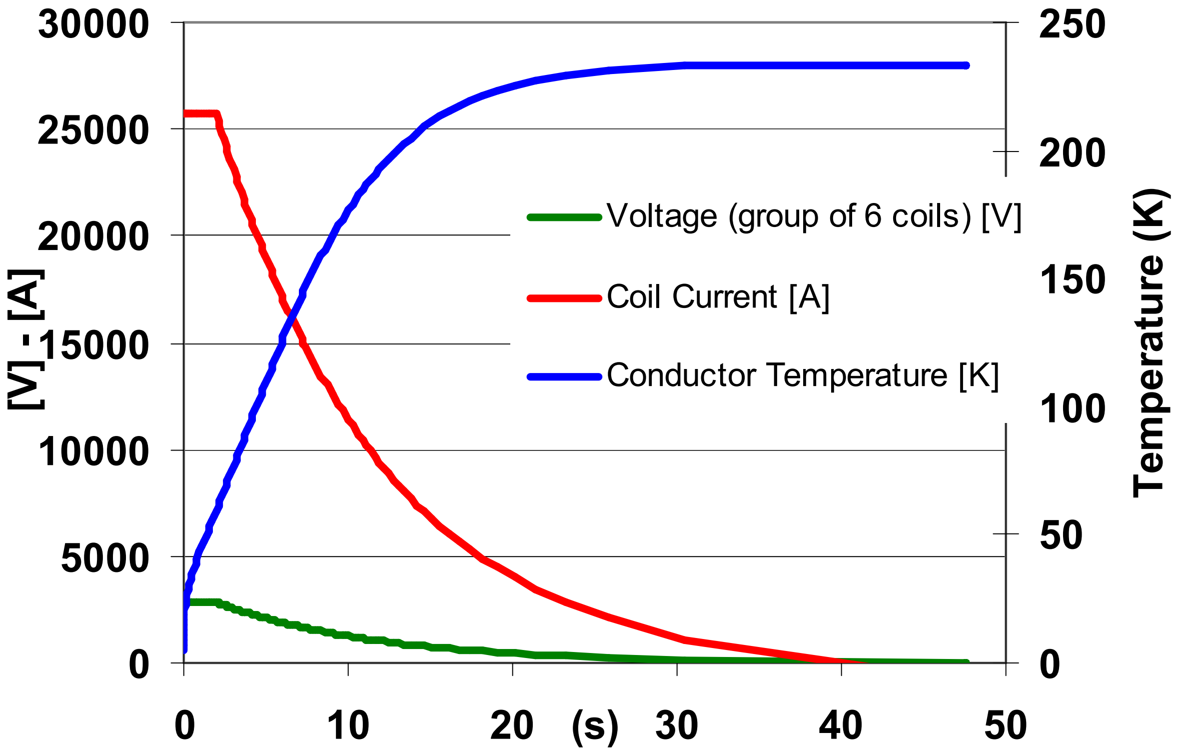
$$J_0 = \frac{I}{(Scu + Snoncu)}$$

Scu	Snoncu	**I**	J_0	τ_{da}
180 mm^2	56.8 mm^2	**25700**	109 A/mm^2	2 s

From (2) $\Rightarrow$ τ< 10.1 s

τ_{da} **=** $\tau_{propagation}$ **+** $\tau_{holding\ time}$ **+** τ_{switch}

Protection by external resistor
Voltage during a quench. Subdivision. JT-60SA



Hot spot characteristics

S_{cu} = 180 mm²

S_{NbTi} =56.8 mm²

L=3.3 H

N=3

I_0=25700 A B_{max} =5.6 T

τ=10 s

τ_{da} =2 s

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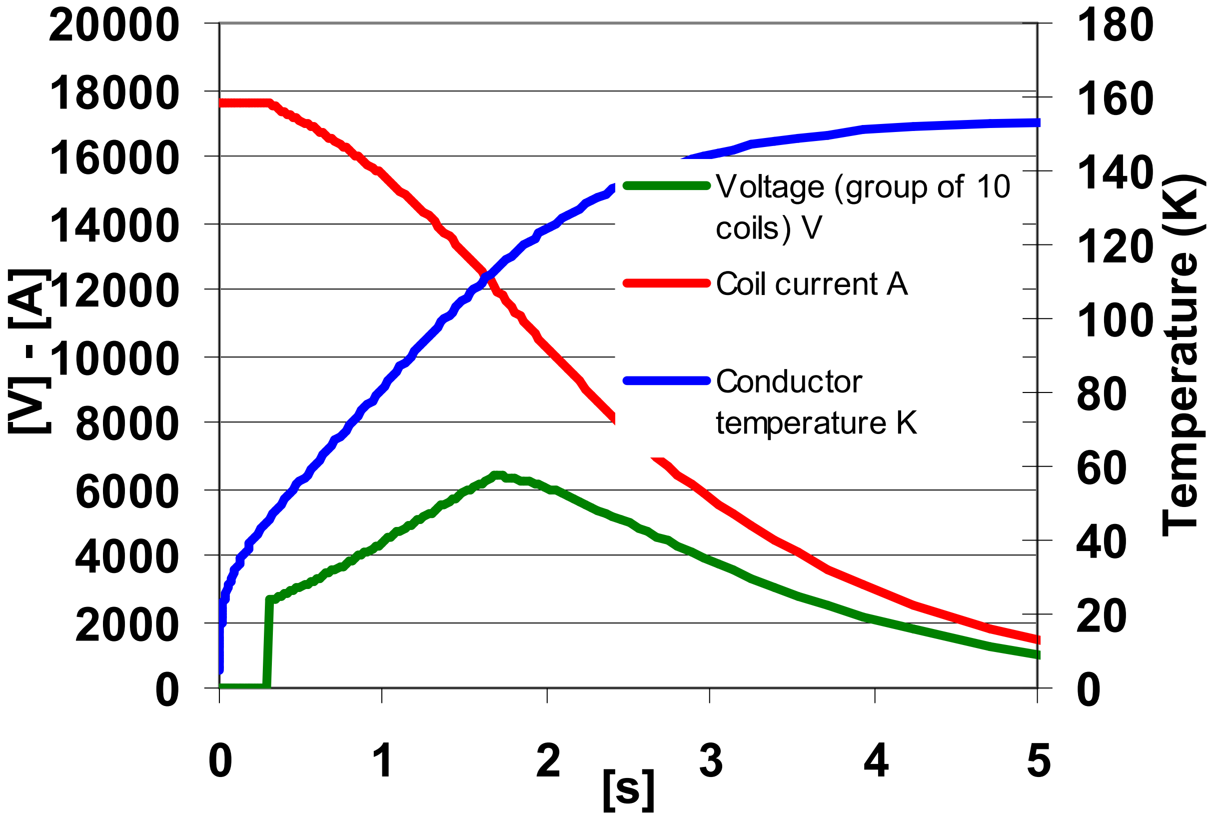
Accelerating the discharge by using a variable resistor
The case of W7-X

In case of the stellarator W7-X, subdivision was used by grouping all the coils of the same kind in a subdivision.



Hot spot characteristics

S_{cu} = 46.8 mm^2

S_{NbTi} =17.3 mm^2

L=1.1 H

N_{group}=10

I_0=17600 A B_{max} =6.4 T

τ Variable (see Figure)

(CuNi resistors)

τ_{da} =0.3 s

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Components of the quench protection circuits
Current breakers

The core of a QPU (Quench protection Unit) is generally composed of a dc Circuit Breaker (CB) which remains closed in normal operation and, when activated opens, commutating the current into a discharge resistor.

In fusion magnet systems equipped with superconducting magnets, the main solutions are based on the use of existing industrial vacuum current breakers.

This type of solution is more and more difficult to implement due to the increase of the current and of the voltage.

Components of the quench protection circuits
Tore Supra

In Tore Supra, the first large tokamak with superconducting toroidal field magnets, the protection system (1.5 kA/3.5 kV during the commissioning) is based on ac three-pole circuit breakers (6 in total) used to divert the dc current into the series resistors.
The **QPU** (Quench protection Unit) in this case is a single commutation circuit such as presented before.

Components of the quench protection circuits
W7-X

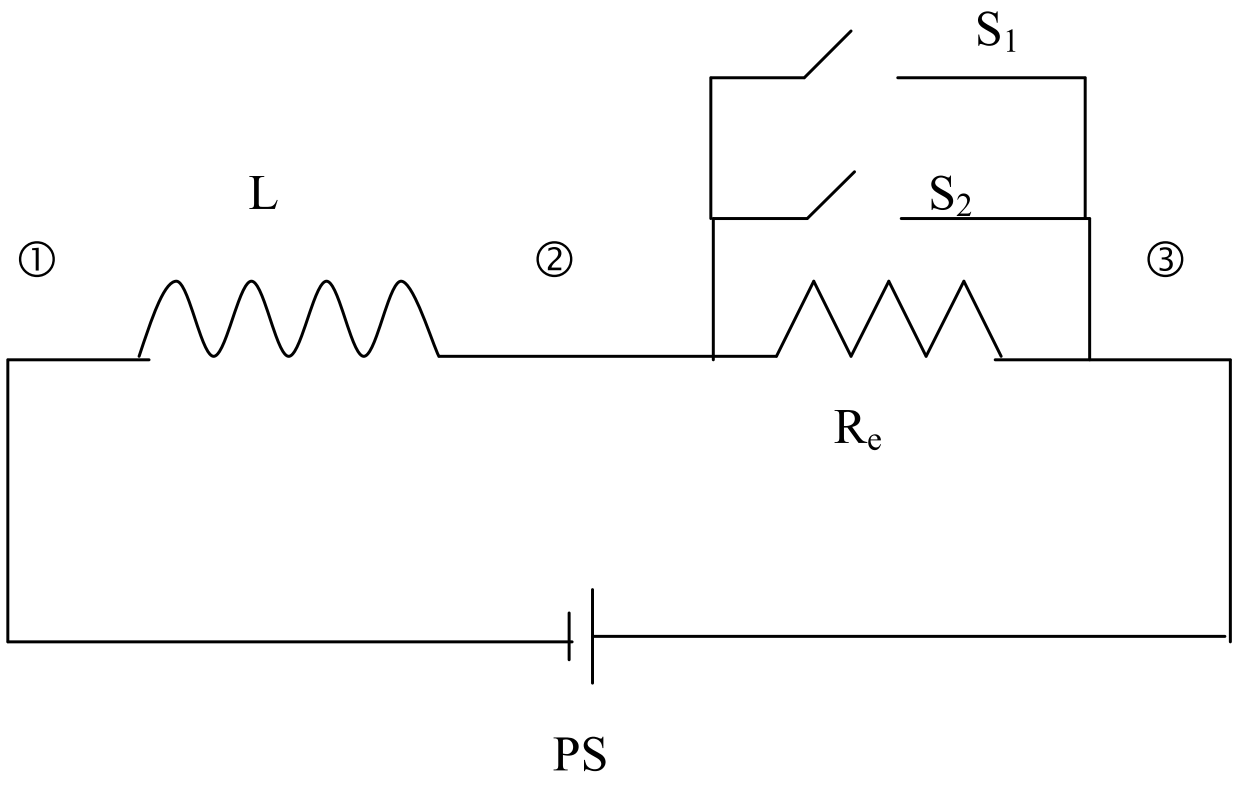
In W7-X, a solution based on a dc industrial mechanical **CB** from the railway industry, was evaluated as the best compromise in terms of availability, reliability and cost, for the design of Quench Protection Units **(QPU)** rated 20 kA/8 kV.

In this case however, the high current rating requires providing Bypass Switches (BPS) to sustain the continuous current.

The **QPC** in this case is a double commutation circuit such as presented in Figure (next slide). Before quench detection, the current is circulating in S1, which is able to sustain 20 kA continuously, but not to open the current. The current in a first phase is commutated in S2, which is not able to sustain the current continuously, but can open the current at the rated voltage.

Both switches are doubled in series for redundancy. In case of non opening an explosion fuse is activated.

Components of the quench protection circuits
W7-X



Components of the quench protection circuits
ITER

In the case of ITER, the requirement has still higher specifications than for W7-X. (70 kA /24 kV). A current Commutating Unit has been developed based on the same type as the one of W7-X presented before. The current opening is achieved in this case by means of the discharge of a counter-pulse capacitor that creates an artificial current zero in the VCB arc chamber.

Components of the quench protection circuits
JT-60SA

For JT60-SA (26.5 kA/3.5 kV), the reference solution is a quite new solution based on components made with static devices and not based on conventional current breakers.

It will use semiconductors controllable both at turn-on and turn-off such as **Gate Turn-Off (GTO) thyristors**, Insulated Gate Bipolar Transistors (IGBT) or IGCTs.

The use of these semiconductors is considered as attractive, since current interruption is very fast, arc-less, does not require counter-pulse network and static CBs are almost maintenance-free.

Components of the quench protection circuits
Discharge resistors

Discharge resistor banks for superconducting magnets can be situated far from the superconducting system. During a **FSD,** the magnetic stored energy of the magnet system is dissipated into the resistor bank which is dimensioned such as to accept the energy with an acceptable heating.

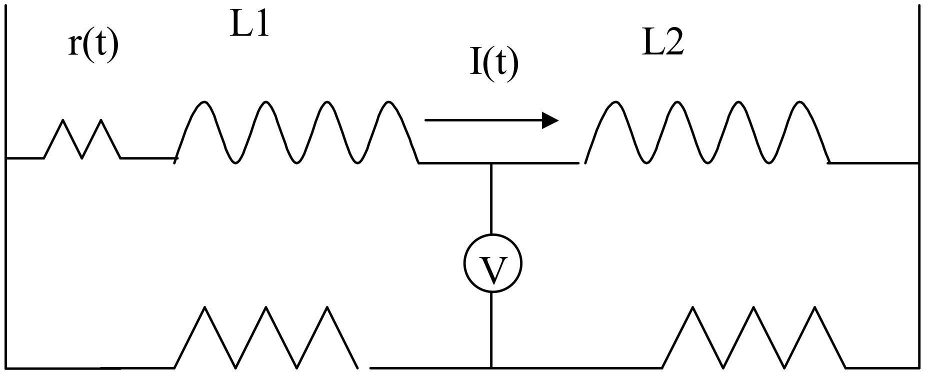
Components of the quench protection circuits
Discharge resistors Tore Supra

Stainless steel resistor bank of Tore Supra

Components of the quench protection circuits
Discharge resistors W7-X

Nickel resistor bank for W7-X magnet system

Quench detection by voltage

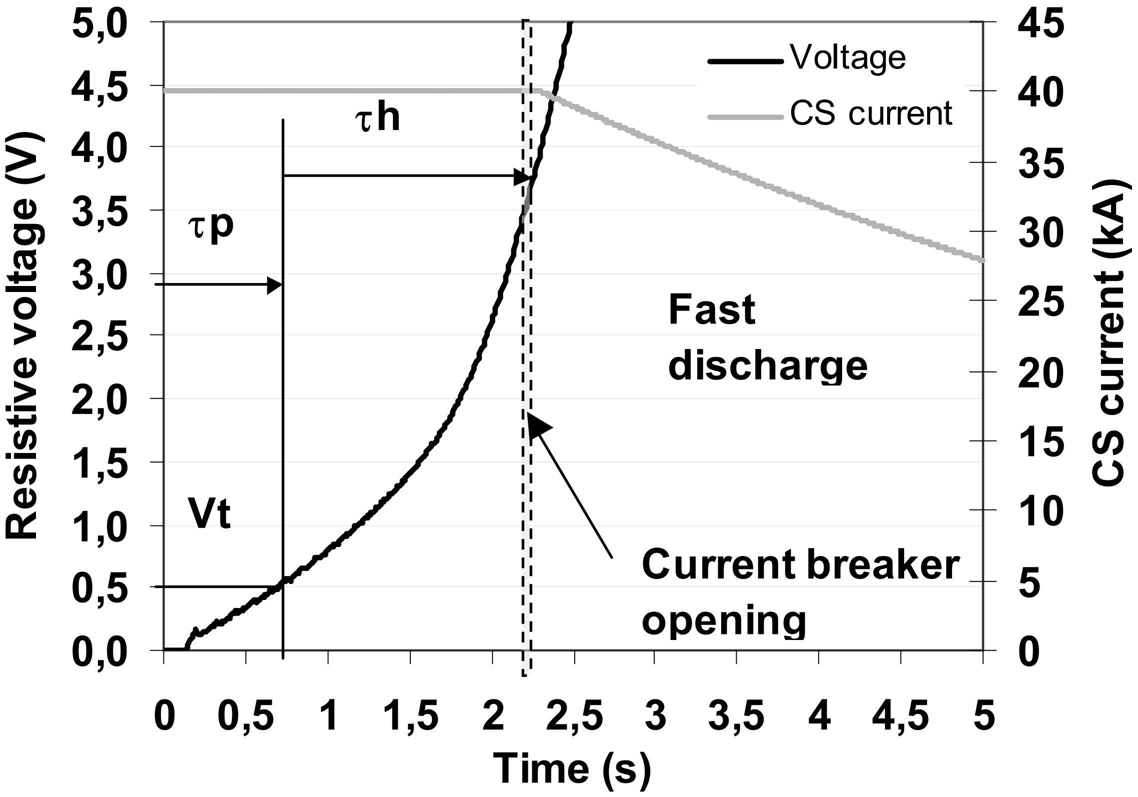


The most common quench detection is the voltage detection.
It is necessary to use a balanced circuit such as to eliminate the inductive part of the signal which is present during current ramp and keep the resistive part characteristics of a quench which can appear either in L1 or in L2.

Signal filtering is necessary to eliminate all voltage spikes.
The voltage threshold V_t cannot be typically lower than 100 mV. The delay τ_{da} (2) participates in magnet heating before switch opening is the sum of three terms:

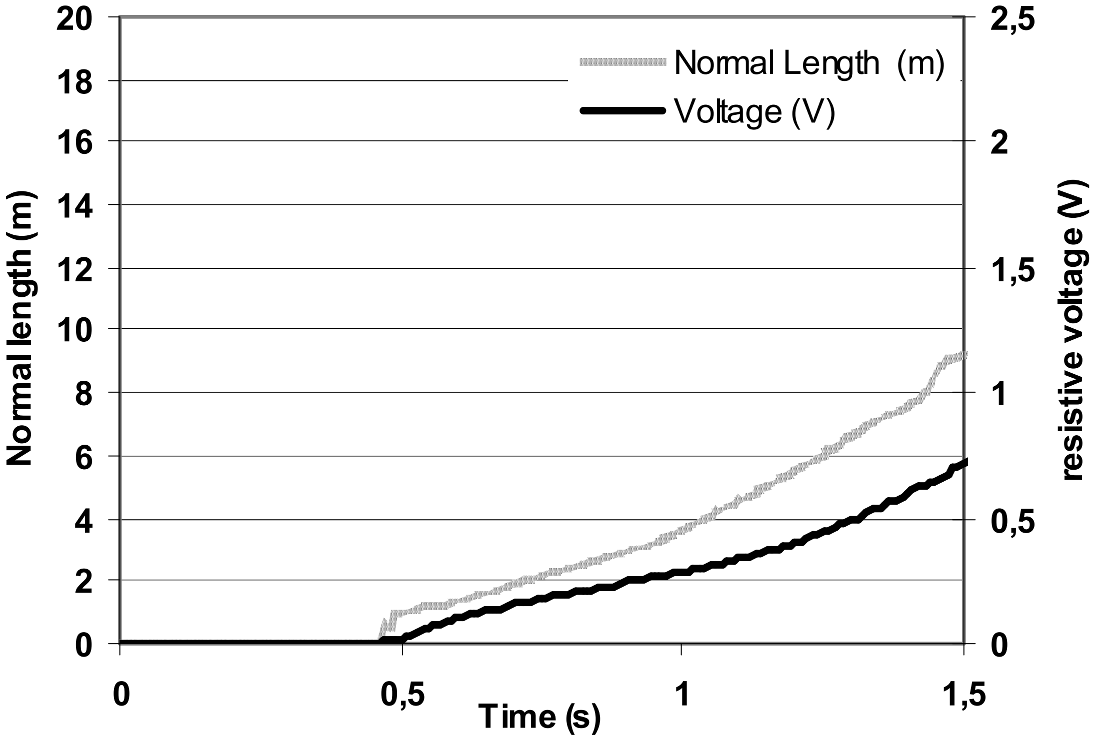
- The propagating time τ_p to reach the threshold level V_t:
- The filtering time τ_H
- The duration needed to open the current breaker τ_{CB}

Quench detection
Main parameters of quench detection indicatively in IIER CS



V_t Voltage threshold
τ_p Propagating time
τ_h Holding time
τ_{cb} current breaker opening time

Quench detection
The quench propagation: the role of the propagation velocity



An important information is the propagating time as a function of the voltage threshold. This time depends on the hypothesis related to the quench event: amount of energy deposited, length of the initial quenched length, duration of energy deposition. Taking the reference event of a quench initiated in the inner leg of the ITER TF, with 1 m initial quenched length within 0.1 s (duration of a plasma disruption), such a quench is modeled using gandalf. After 0.8 s a typical resistive voltage of 0.5 V is reached corresponding to 7 m of quenched length **(3.5 m/s one front).**

Quench detection
Mitigation of the inductive part

The voltage across the coil or a part of the coil writes:

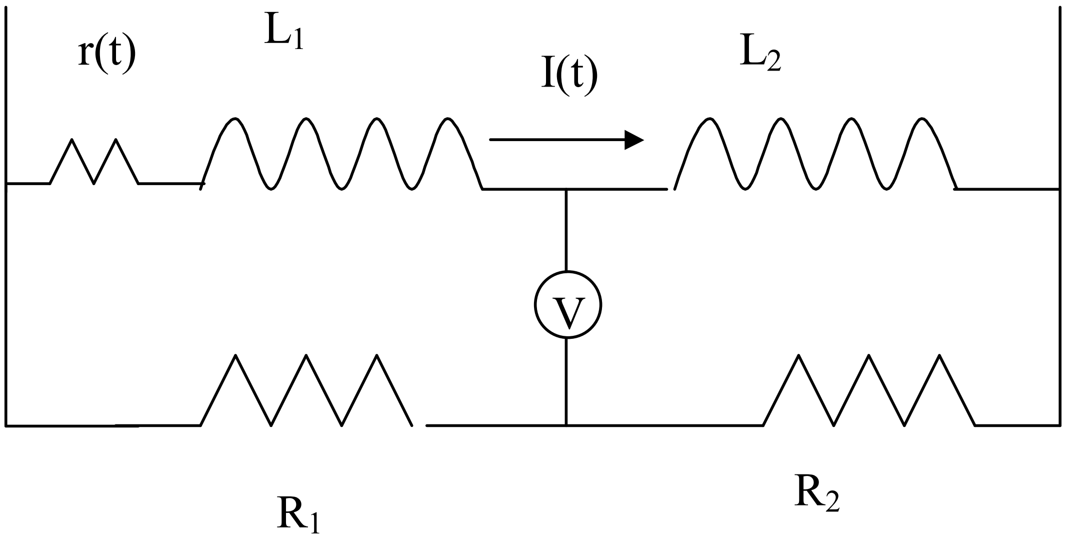
$$U_i(t) = R_{quench}(t)i_i(t) + L_i \frac{di_i(t)}{dt} + \sum_j M_{ij} \frac{di_j}{dt}$$

Where R_{quench} is the resistance of the normal zone to be detected, $i_i(t)$ is the current carried by the quenching sub-element, L_i is the self inductance of the coil, Mi_j and $i_j(t)$ refer to the mutual inductances between the quenching sub-element and the other magnetic field generating elements with their associated current.

The inductive voltage is not restricted to pulsed coils in magnet systems of fusion. Voltage are induced in the TF systems during plasma discharge and other plasma events.

To discriminate the resistive voltage from the inductive voltage the usual wayis to balance the coil voltage with another “symmetric coil”.

Quench detection
Mitigation of the inductive part: the classical bridge circuit



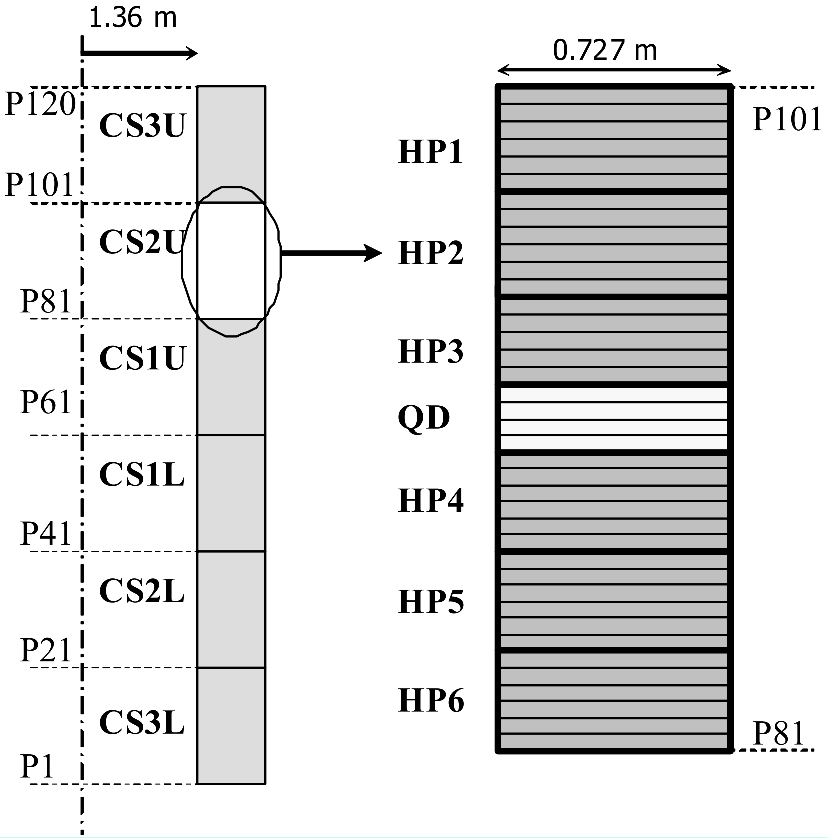
$$V(t) = \frac{R_2}{R_1 + R_2} L_1 \frac{dI(t)}{dt} - \frac{R1}{R_1 + R_2} L_2 \frac{dI(t)}{dt} + \frac{R_2}{R_1 + R_2} rI(t)$$

$$V(t) = \frac{R_2}{R_1 + R} L_1 \frac{dI(t)}{dt} - \frac{R1}{R_1 + R_2} L_2 \frac{dI(t)}{dt} = 0 \Rightarrow R_2 L_1 = R_1 L_2$$

$$V(t) = \frac{R_2}{R_1 + R_2} rI(t)$$

Quench detection

Mitigation of the inductive part: other methods (ITER CS coil)

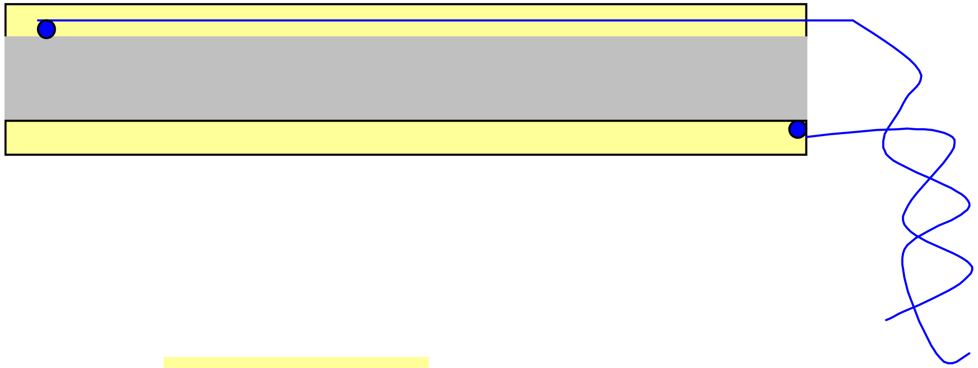


The selected model consists to oppose the voltage across each of the 60 double pancakes (DP) to the average of the two neighbouring DPs.

Balance coefficients α and β can be used to compensate for magnetic dissymmetries of sub-elements, which are not negligible among the ITER CS modules. Their role is illustrated for the central difference average voltage (CDA) ΔV associated with the monitoring of each DPi.

$\Delta V_{DPi} = V_{DPi} - (\alpha V_{DPi+1} + \beta V_{DPi-1})/2$

Quench detection
Mitigation of the inductive part: the co-wound tape



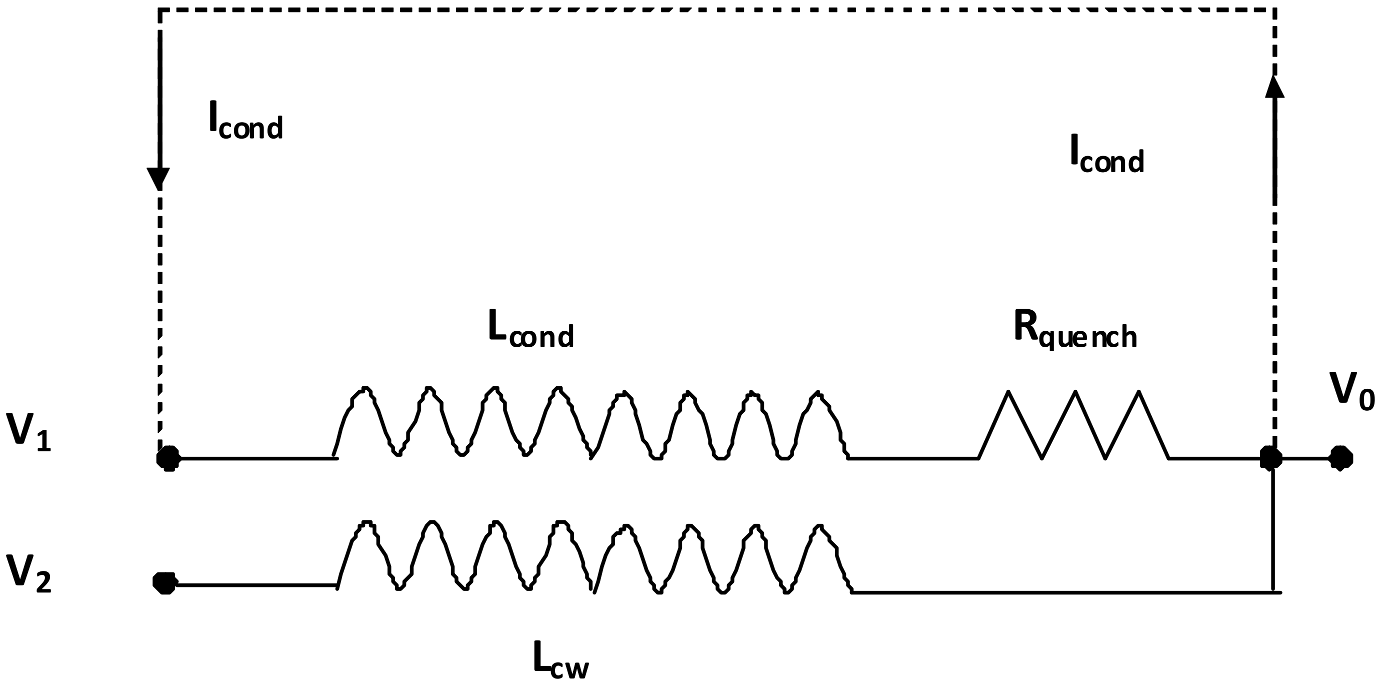
Scheme of the voltage detection in ITER TF

Conductor jacket

insulation

The voltage taps are made of stainless steel tapes that are electrically connected to the superconductor at the termination of the pancakes and routed parallel to the conductor embedded in the turn insulation.

Quench detection
Mitigation of the inductive part: the co-wound tape
Principle



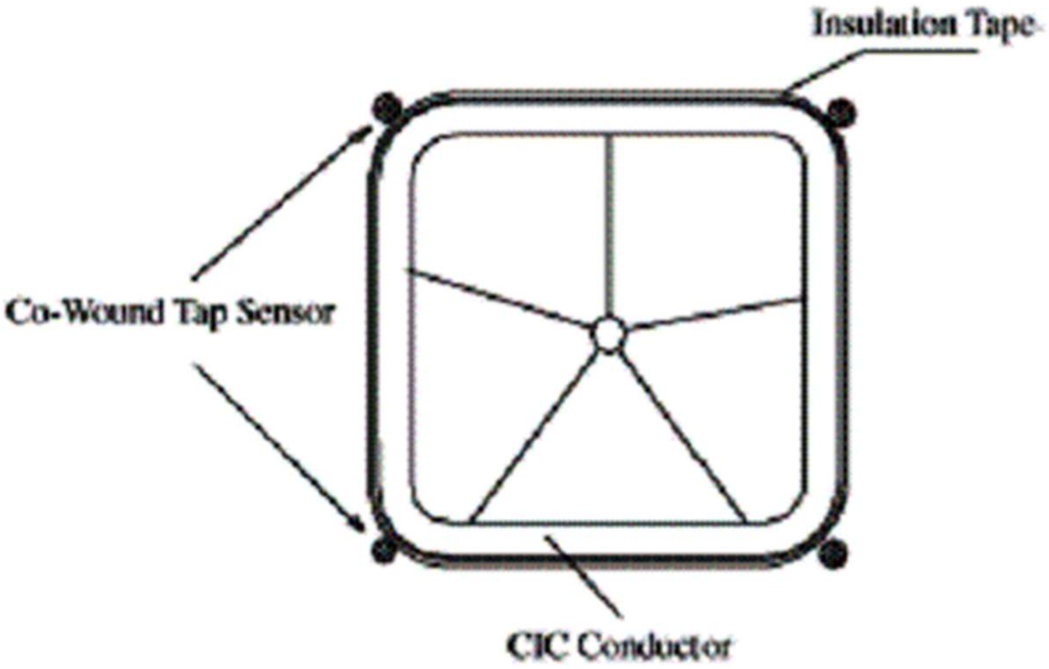
$(V_1\text{-}V_0) = V_{ps} = L\ dI_{cond}/dt$ $(V_2\text{-}V_0) = M\ dI_{cond}/dt$

Suppose that the co-wound is perfectly coupled to the TF double pancake L~M. It is certainly the case for the co-wound helix strip such as envisaged in ITER as the magnetic axis of the strip is the same as the conductor magnetic axis.

$(V_2\text{-}V_0) = L\ dI_{cond}/dt$

$\Delta V = V_1\text{-}V_2 = 0.$

Quench detection
Mitigation of the inductive part: the co-wound tape (EAST)



Quench detection
Mitigation of the inductive part: the co-wound tape (ITER)