Electrical integrity tests and electrical failure diagnostics in superconducting circuits

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With many contributions from
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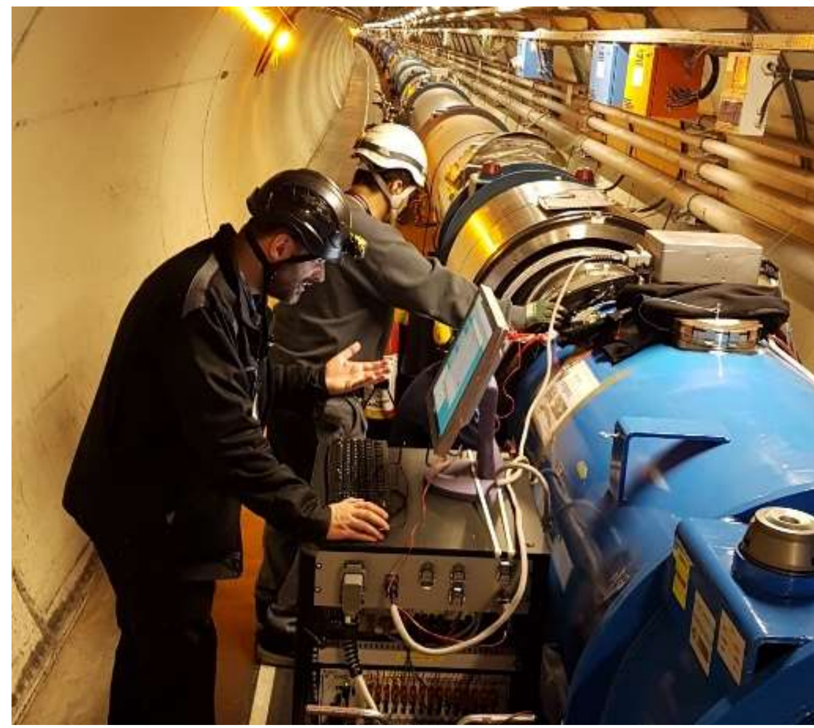
and other team members



Outline

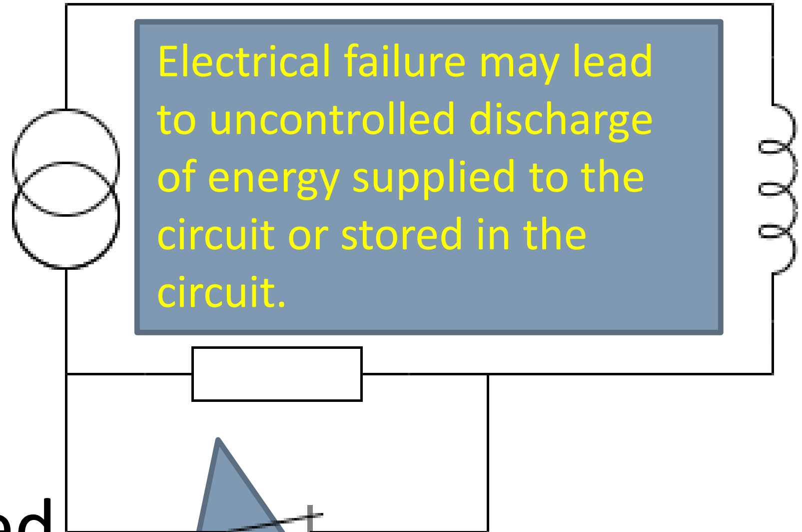
- Risks related to electrical failures and mitigation measures
- Types of tests
- Key aspects related to testing and fault localization
- Common trouble shooting techniques
- Data management
- Planning of tests and diagnostics, including safety aspects

Risks related to electrical failures

Circuit is usually powered by mains-connected power converter. Typically capable of delivering high current.

Inductive circuits store energy in the magnetic field.

$$E = 0.5\,LI^2$$



Electrical failure may lead to uncontrolled discharge of energy supplied to the circuit or stored in the circuit.

We are trying to avoid a situation when uncontrolled electric current flows through sensitive components or human body.

In a normal situation, stored energy is discharged in a controlled way. Often a circuit is equipped with Energy Extraction System. A significant voltage can be developed across the resistor and circuit during the discharge process.

https://xkcd.com/643/

Measures

Very simplified approach, only some examples

- Preventing failures
  - Use of proper insulation
  - Mechanical structure able to contain Lorentz forces
  - Careful assembly
- Detecting failures
  - Electrical Integrity Tests – before powering
    (What this lecture is supposed to be about)
  - Powering tests
    (What this lecture is not about)
- Managing failure modes
  - Floating circuit ➞ single earth fault will not create uncontrolled current path
  - Online earth fault detection system integrated with power converter
  - Redundant protection systems and redundant circuits

What do we actually test?

- Magnets and their assemblies
- Bus-bars
- Current leads
- Instrumentation
    - Voltage taps
    - Electronics connected to the voltage taps
- Quench heaters
- Cabling
- Entire circuits

When do we test?

- ✓ During the magnet manufacturing
- ✓ At the reception from industry
- ✓ Before the installation in the tunnel
- ✓ During the assembly of the machine
- ✓ Before and after thermal cycle
- ✓ In case when a fault appears during operation
- ✓ After large interventions on the magnet chain or the instrumentation

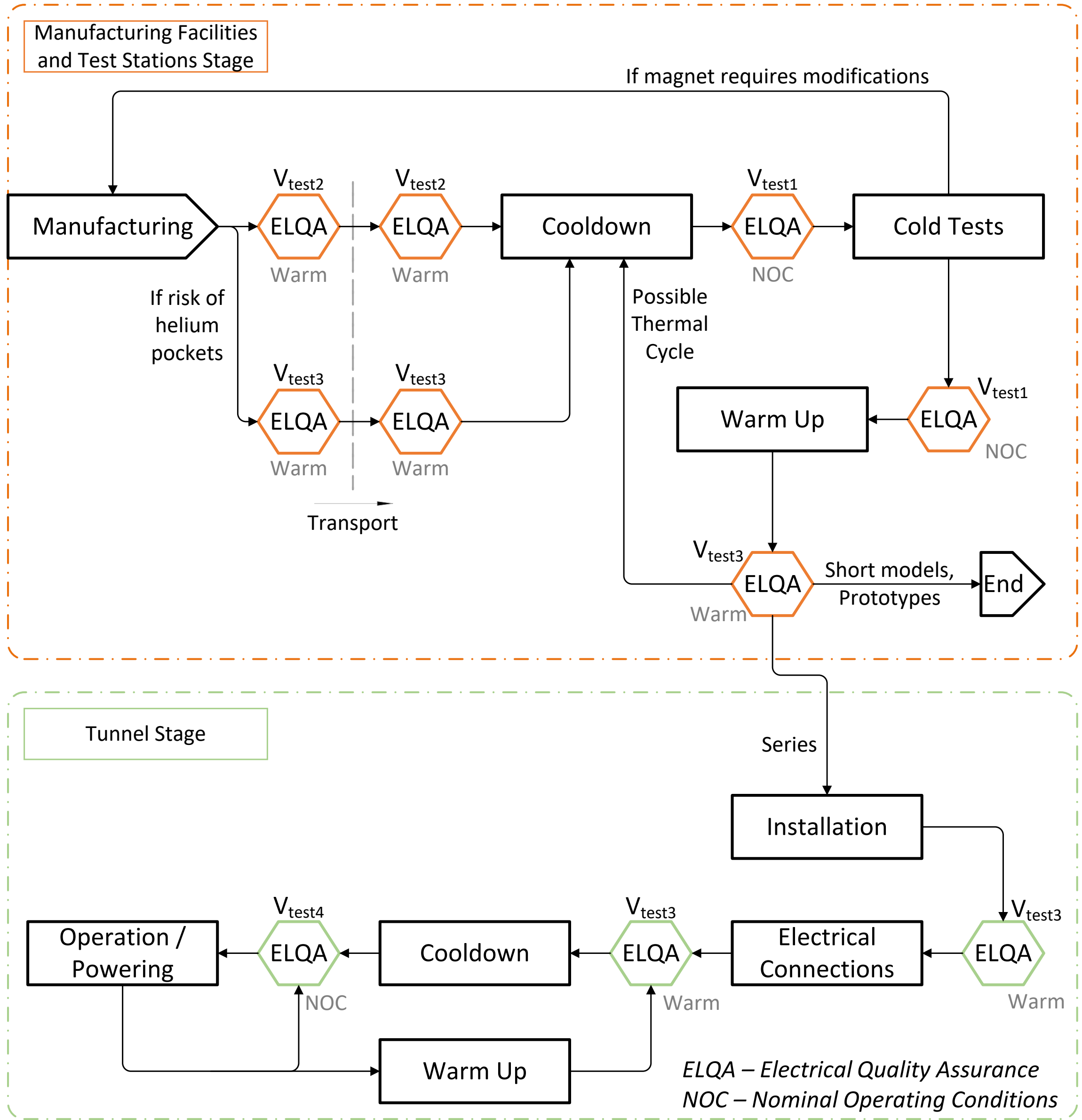


Image from Electrical Design Criteria for the HL-LHC Inner Triplet Magnets document by T. D. C. R. da Rosa, M. Bednarek, F. Rodríguez Mateos

Types of tests

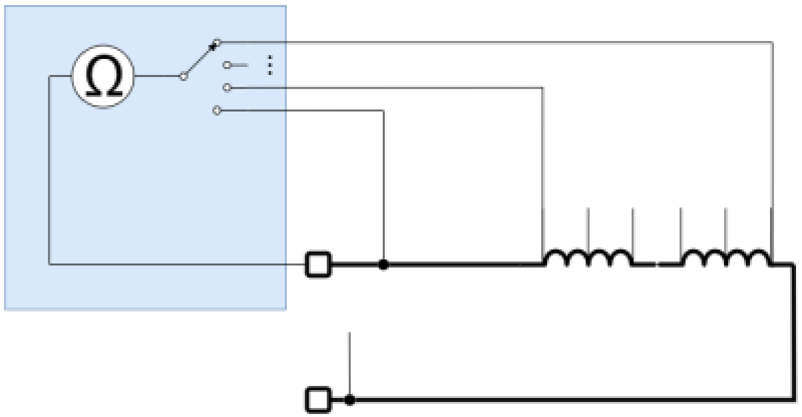
- Resistance measurements
  - Continuity tests
  - Sequence checks
- HV insulation tests
- Measurement of other electrical parameters
  - Complex impedance measurements,
  - Capacitor discharge tests (internal insulation + impedance)
- Time domain reflectometry (TDR)

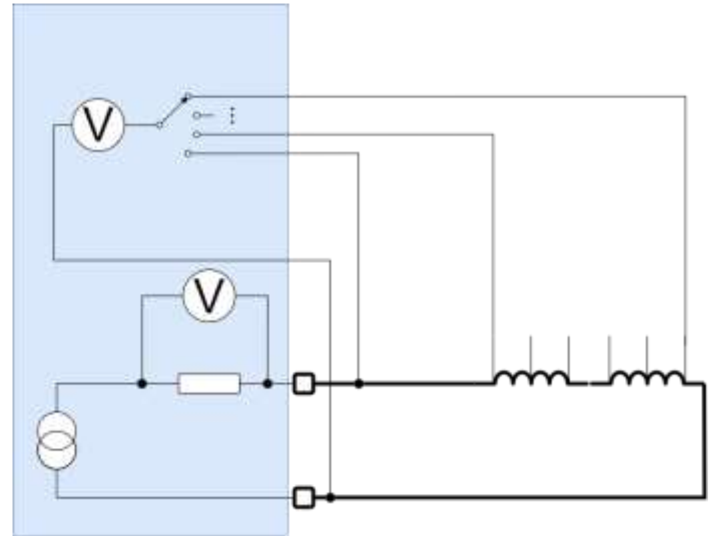
Some tests should be performed in a specific order, i.e.

- *Make sure that circuit is continuous before you do anything else*
- *The insulation test should be done at the very end, in order to minimise the risk of not detecting the insulation fault caused by the manipulations needed for the previous tests*

Testing is important step to ensure safe operation of the superconducting circuits.

Resistance measurements

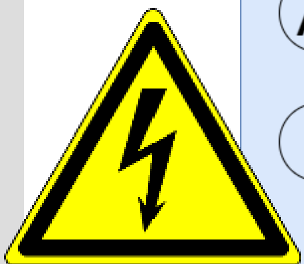


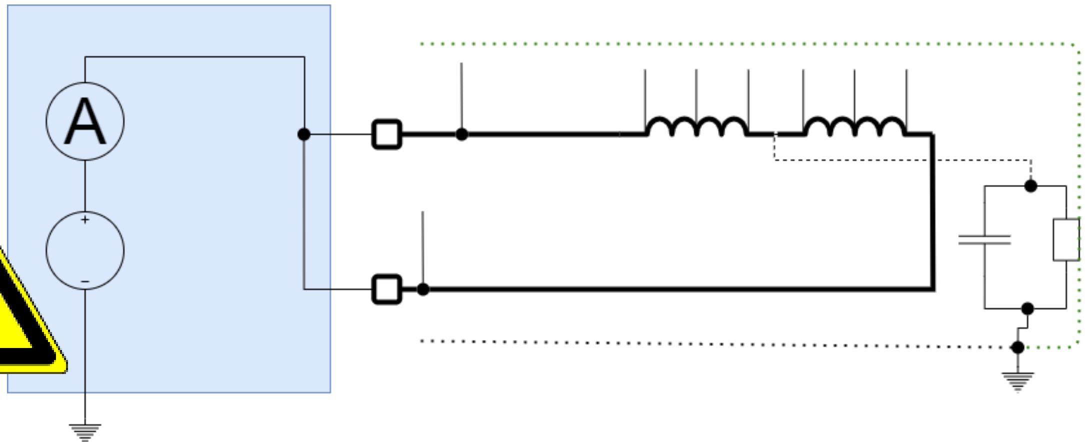


- Checking if the circuit is closed
- Making sure that resistive parts have expected resistance
- Checking the routing or sequence of wiring

For precise measurements **four wire method** is used.
Can be done by hand, but it's better to use automated systems.
When applying current through sensitive components, particular care must be taken.
A fault can be considered a sensitive component.

HV Insulation Tests





Safety measures must be in place.

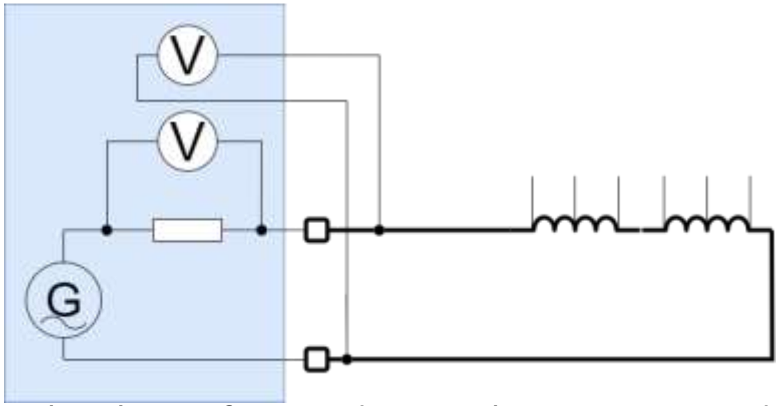
The current measured by the device has two components:

- Leakage current related to the resistance of the insulation
- Charging current related to the capacitance between circuit and grounded surrounding

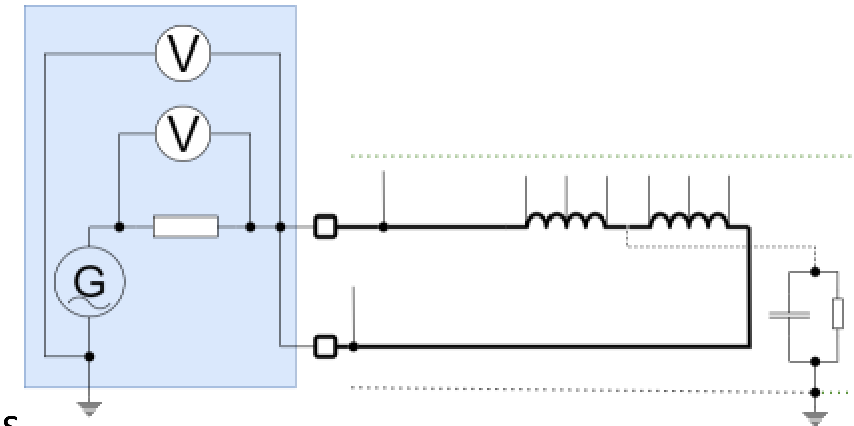
In case of insulation breakdown, a significant energy can be dissipated in the fault location, damaging the tested component further.

Test parameters depend on the circuit properties and test conditions. Test voltage is typically decided based on “worst case scenario” quench + margin. Tests in gaseous helium are conducted at lower voltages than the ones in liquid.

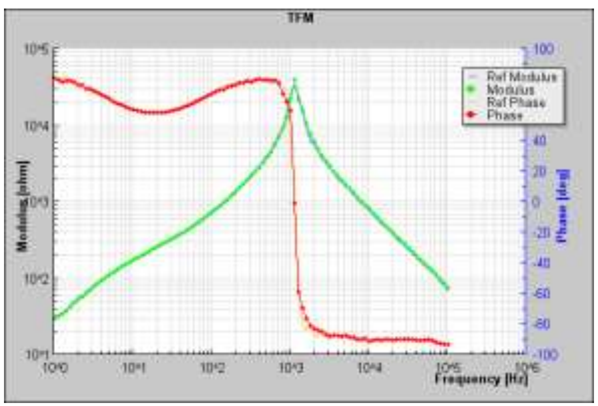
Complex Impedance Measurements



- Checking if impedances have expected values
- Detecting internal short circuits

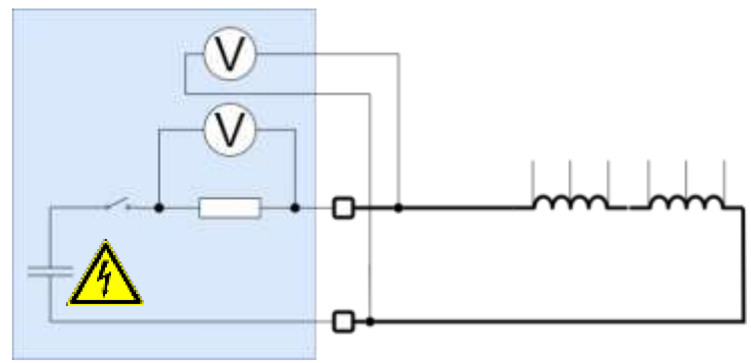


Impedance of insulation can also be measured.



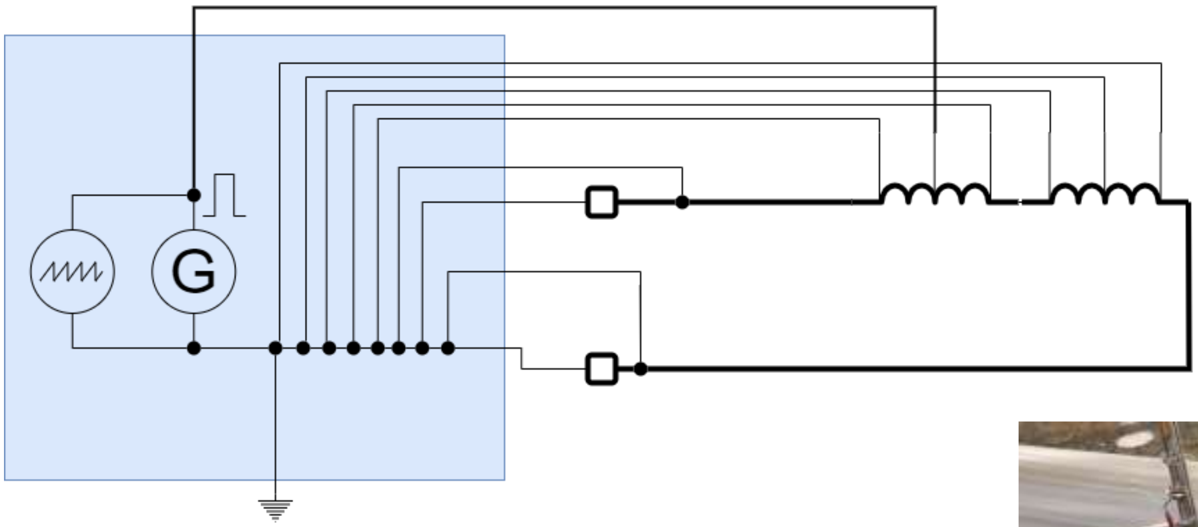
Circuit is powered with an AC source, typically not more than 10 V/1 A. Value and phase of current and voltage across the circuit are measured to calculate the complex impedance.

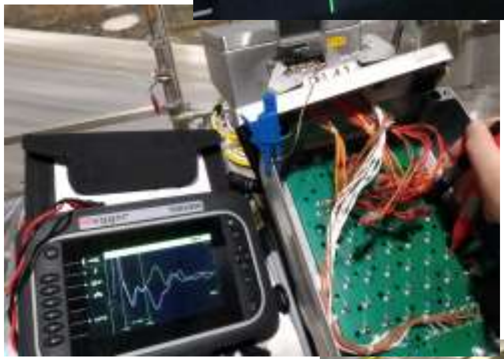
The AC source is swept across range of frequencies.



Very similar setup is used in case of capacitor discharge test. AC source is replaced with a capacitor charged to a high voltage.

Time Domain Reflectometry





- Locating detached conductors
- Locating short-circuits

Usually applied when one of previous tests reveals a fault. With complicated circuits it's good to have a reference measurement done before the fault appeared.
Tested wire is part of a waveguide. The remaining part of such waveguide (current return path) must be taken into consideration.

How do we do it for the LHC

All types of measurements
Except for TDR (soon to be added) and capacitor discharge.

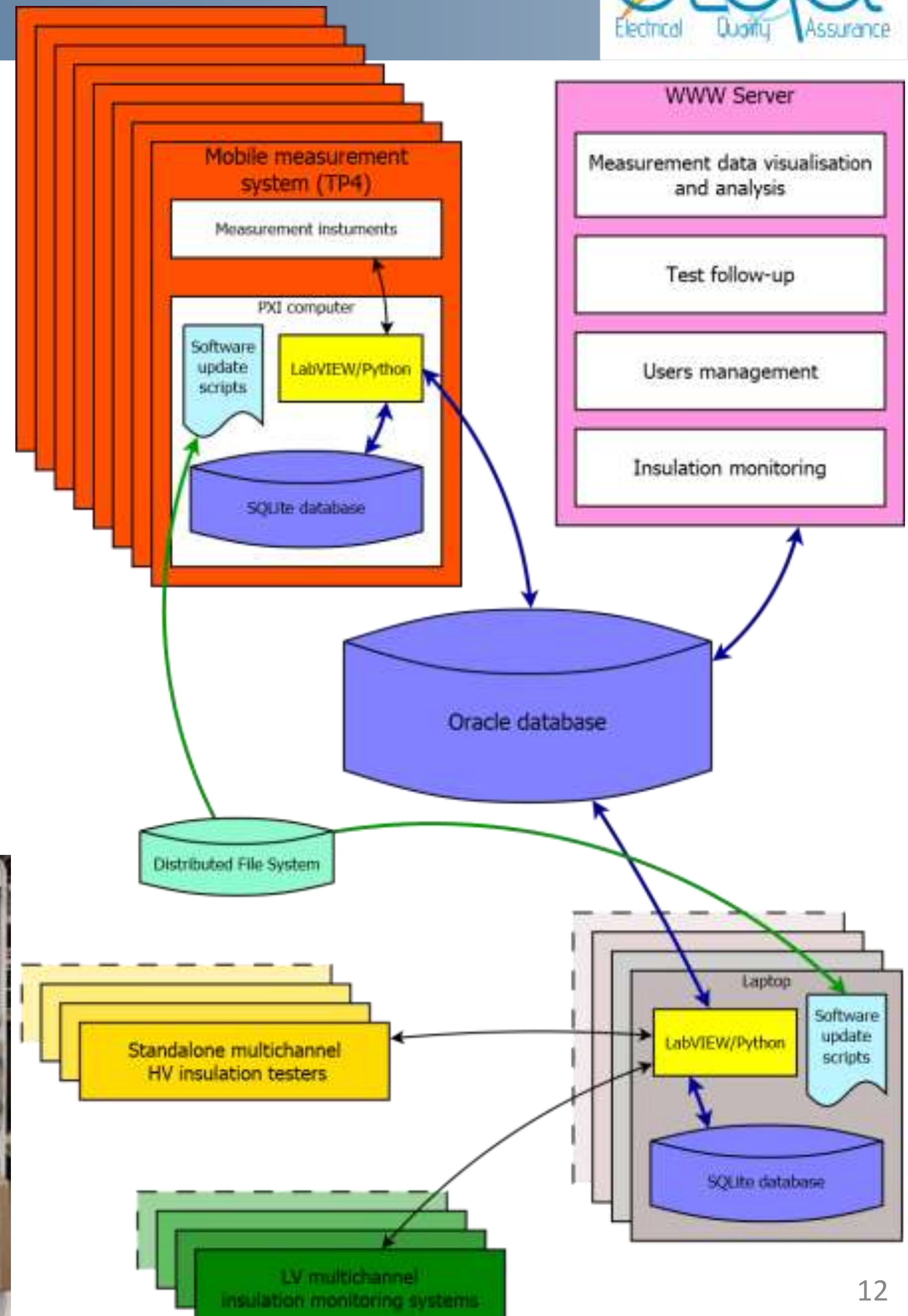
8 x

40 and 80 channel insulation testers up to 3 kV
and off-the-shelf testers for higher voltages.

10 x

Continuous insulation monitoring at 48 V during thermal transition.

4 x



Failure scenarios

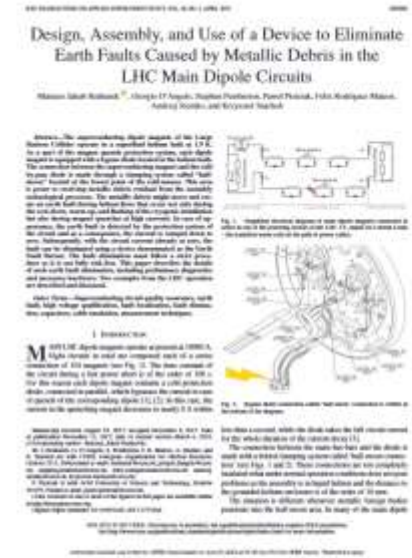
Many fault scenarios are possible (the following list is not exhaustive):

- Insulation failure
  - To ground (earth fault)
    - Solid low impedance short
    - Solid high impedance short
    - Multiple shorts
    - Short that appears above a certain voltage (breakdown)
  - Between circuits
  - Within one circuit
    - Inter turn short
    - Between bus-bars
    - Between V-taps
- Resistive circuit (special case: open circuit)
- Polarity or routing error

- Faults can appear when in room temperature, during thermal transitions or in cryogenic conditions
- Faults sometimes occur only when powering one or more circuits
- Faults can be intermittent
- Faults can be introduced by manipulation of circuit components (e.g. disconnecting and connecting a connector)

Important remarks

- A fault in electric circuit **can disappear**. It is important to conduct the investigation and localisation in the way which **does not alter** the state of the circuit.


Design, Assembly, and Use of a Device to Eliminate Earth Faults Caused by Metallic Debris in the LHC Main Dipole Circuits

https://ieeexplore.ieee.org/document/8106785

- You must **know your tools**. Before you start any measurements, please **read the users manual** of the measurement device.

Diagnostic procedures

- The fault appears due to existing weakness in the circuit
- The fault may disappear, but the weakness remains and may manifest itself during the operation
- Selection of the right diagnostic method is important
  - We will have a look at only few scenarios

Typical approach:

1. When possible, isolate components of the circuit, e.g. by disconnecting instrumentation
2. Global diagnostics – needed at the circuit level
3. Local diagnostics – narrow down the fault location to identify the faulty component

Insulation failure localization techniques:

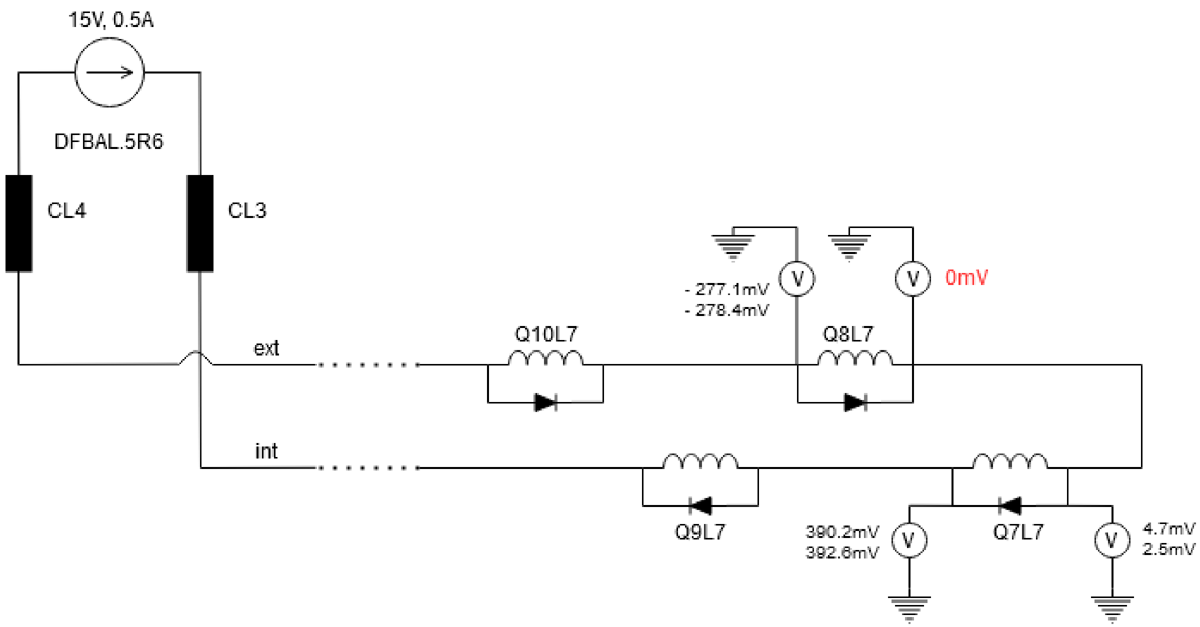
- Normal conducting state – DC methods based on resistive voltage drop measurements *(Example 1)*
- Superconducting state – AC methods based on inductive voltage drop measurements (complex impedance measurements)
- Reflectometry techniques *(Example 2)*
- Propagation delay techniques *(Example 3)*

✓ *It may be useful to warm-up slightly the circuit to transition from superconducting state to normal conducting state (for NbTi, 20 K gives good results)*

✓ *Modifying liquid helium level, gas pressure, or gas composition could help when dealing with breakdowns*

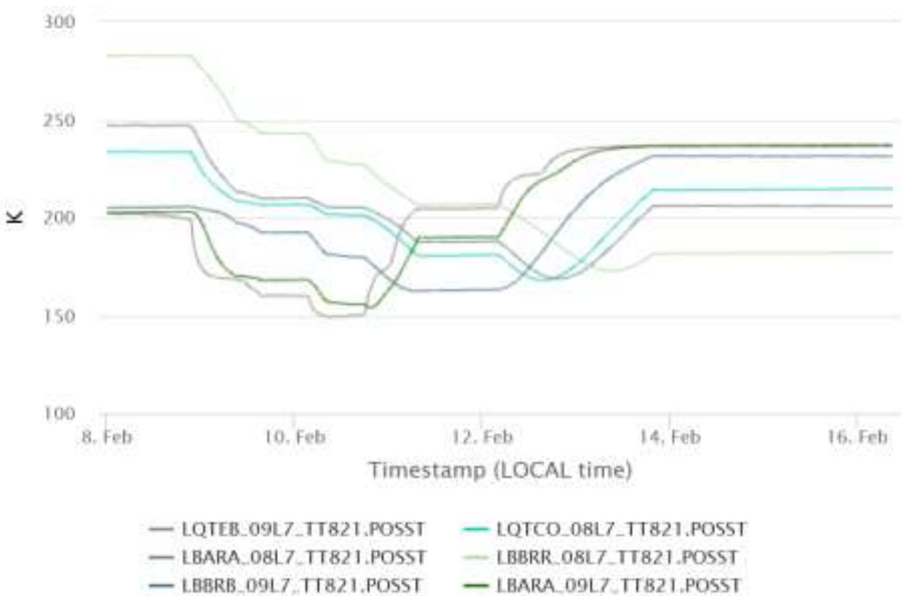
Example 1 - rough location estimation

- During the cool-down of LHC sector our automatic insulation monitoring system detects earth fault on one of the main quadrupole circuits (51 magnets in series).
- The cool-down is stopped, but the temperature is still changing by itself due to thermal gradient.
- Quick diagnostics with floating current source and voltage measurements to ground point us to a specific location along the magnet chain.
- We disconnect warm instrumentation and confirm that it's not the source of the problem
- As the temperature keeps changing, the fault disappears

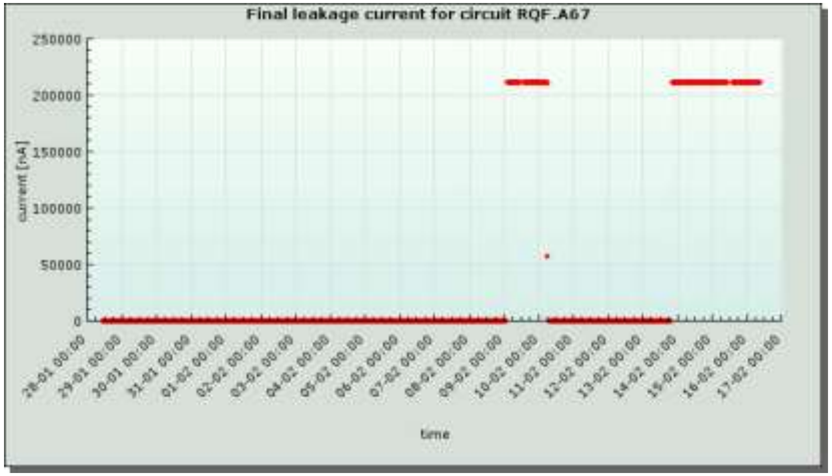


Example 1 - the scarry moment

- The decision is made to partially warm up the sector.
- As the temperature raises, the fault re-appears.



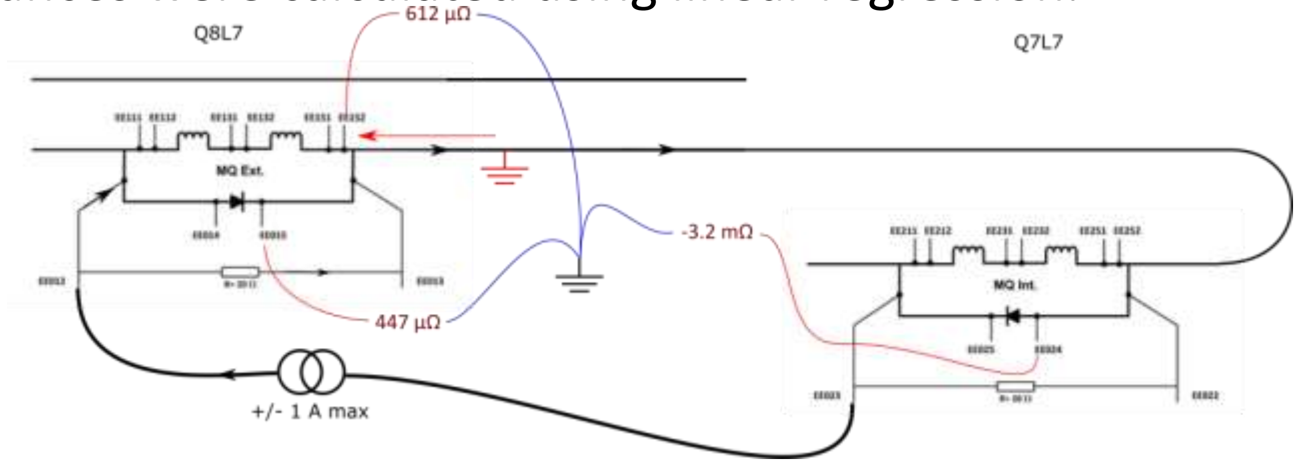
Temperature changes in the fault region



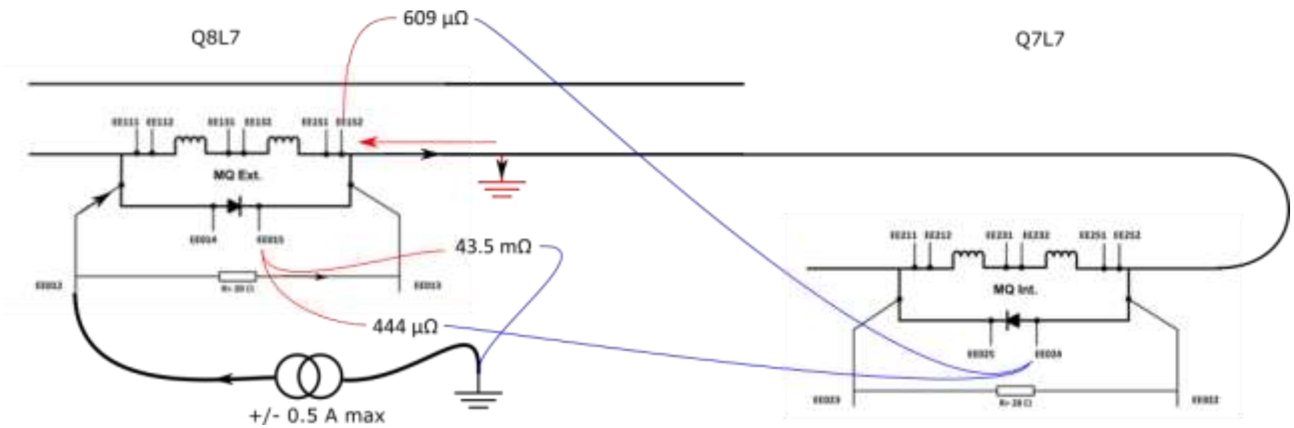
Leakage current readouts from the ELQA insulation monitoring system

Example 1 - precise measurements

- Using the available voltage taps we applied current in steps (Mayan pyramid) and measured voltages in selected locations. The resistances were calculated using linear regression.

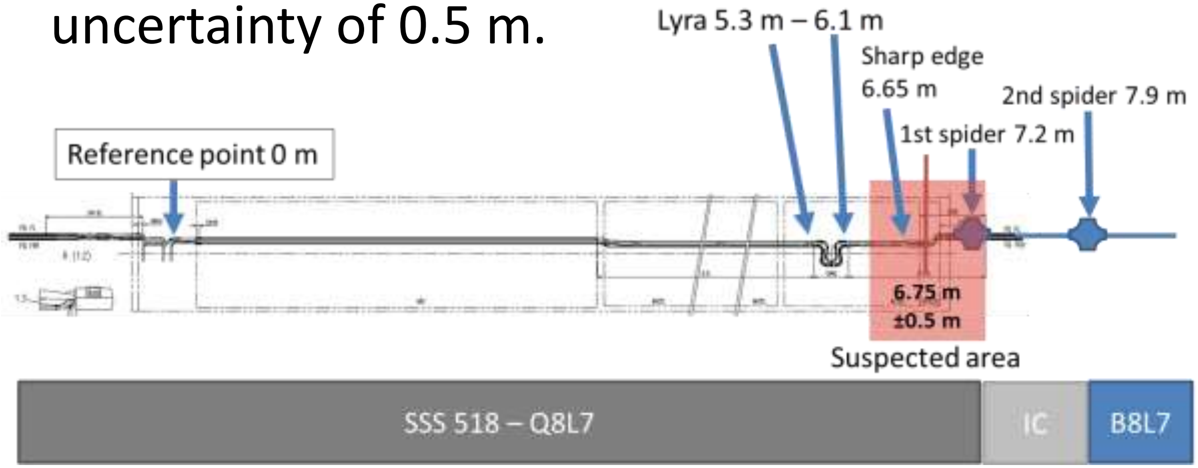


- When applying the current through the fault, we were monitoring the stability of its resistance.

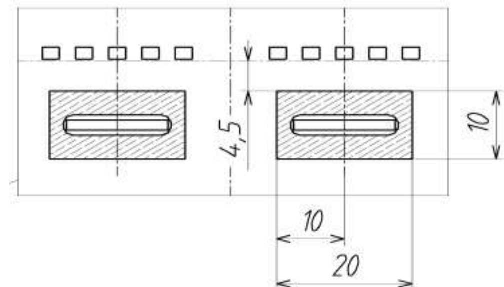


Example 1 - happy end

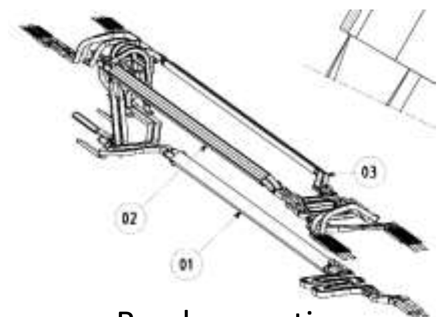
- We calculated the linear resistance of 13 kA quadrupole bus-bar in room temperature based on previous measurements.
- Using the temperature sensor data, the linear resistance was adjusted for current conditions (212 K)
- We calculated the length of the bus-bar from the known location of the V-tap, with estimated uncertainty of 0.5 m.



- The fault was found and repaired using endoscopic methods by CERN's Special Intervention Team



Bus-bar cross-section

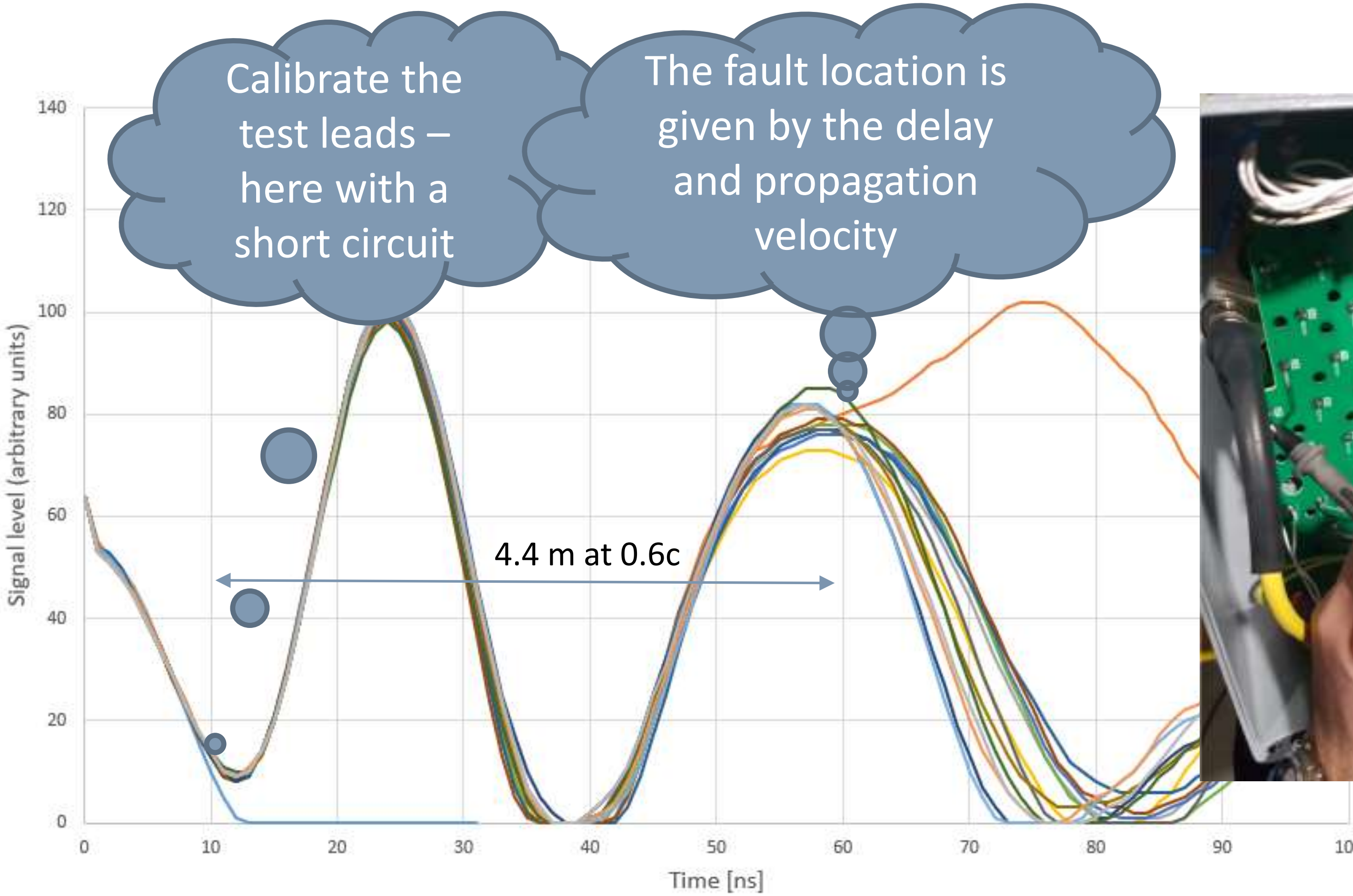


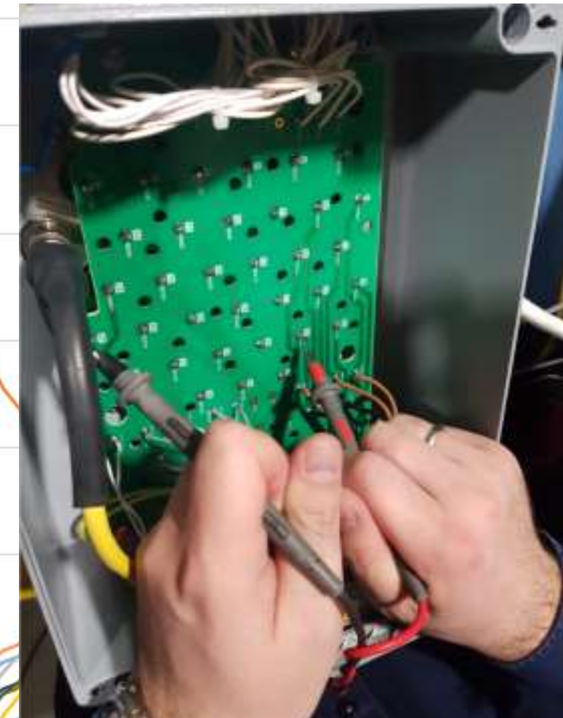
Bus-bar routing


Finding the insulation fault with a grounded copper braid.
Image credit Sandrine Le Naour

Example 2

- Time domain reflectometry of faulty quench heater connection

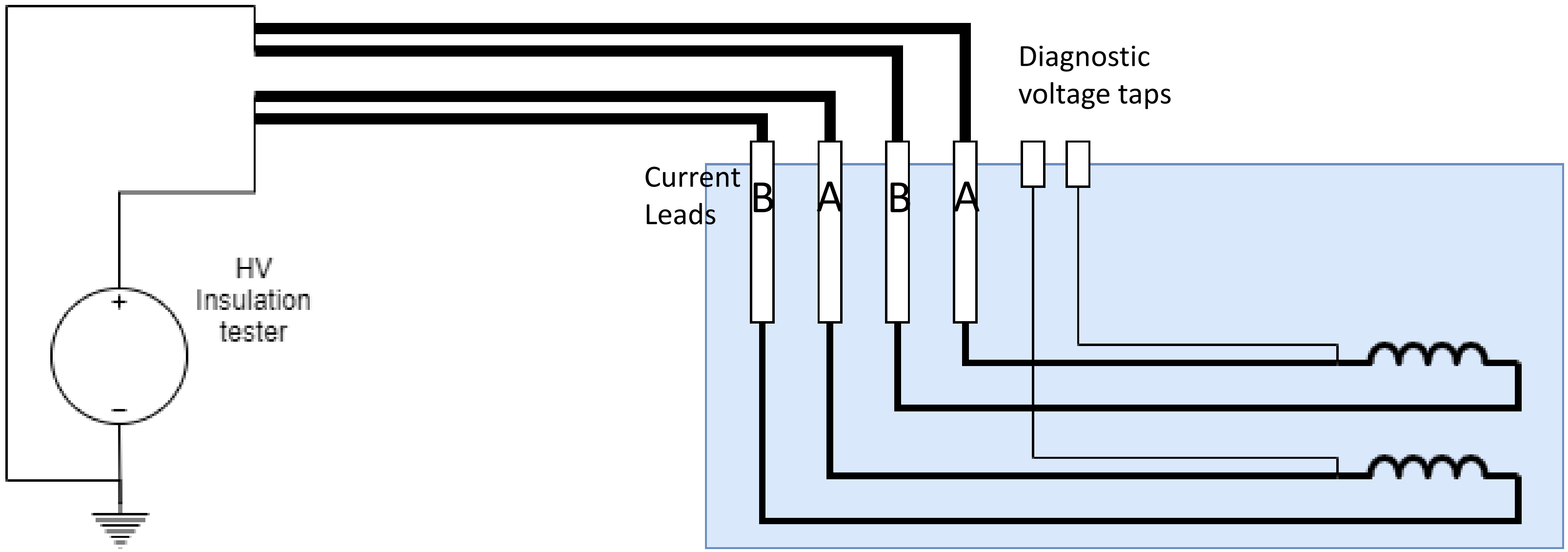




- The best way to know the propagation velocity for the specific type of conductor is to measure it using a known sample
- In this case the fault was located at the quench heater to wire interface

Example 3

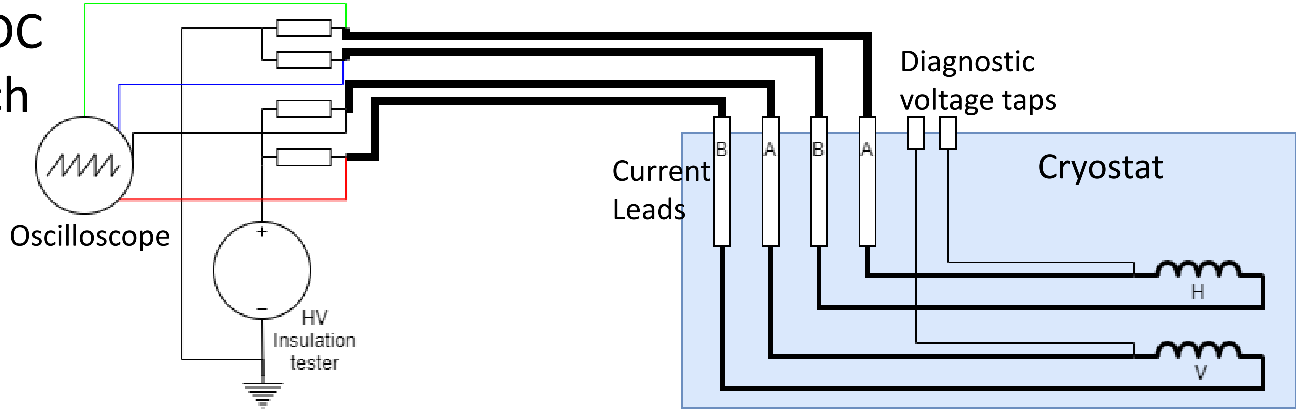
- During standard tests campaign two circuits experienced an insulation breakdown at a similar voltage

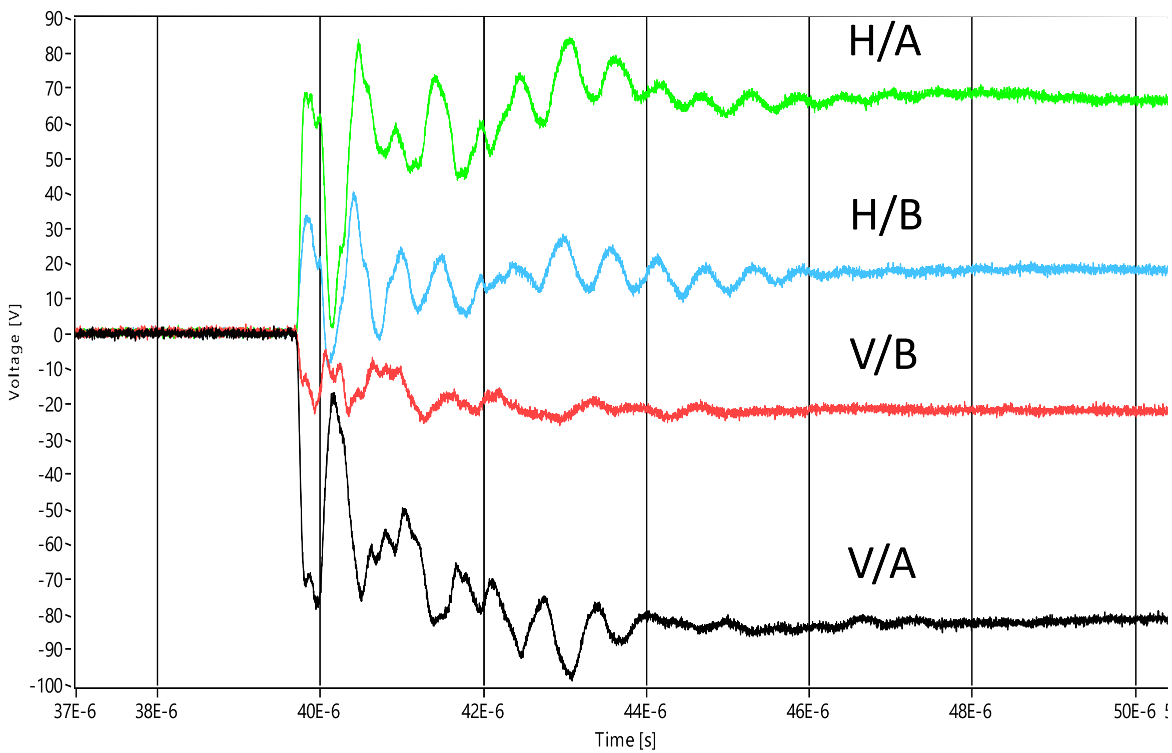


- In the first stage of the investigation we checked that the fault is located between the circuits

Adding oscilloscope with DC blocking capacitors on each lead, near the HV tester.

The H circuit is grounded via two 10 kΩ resistors.

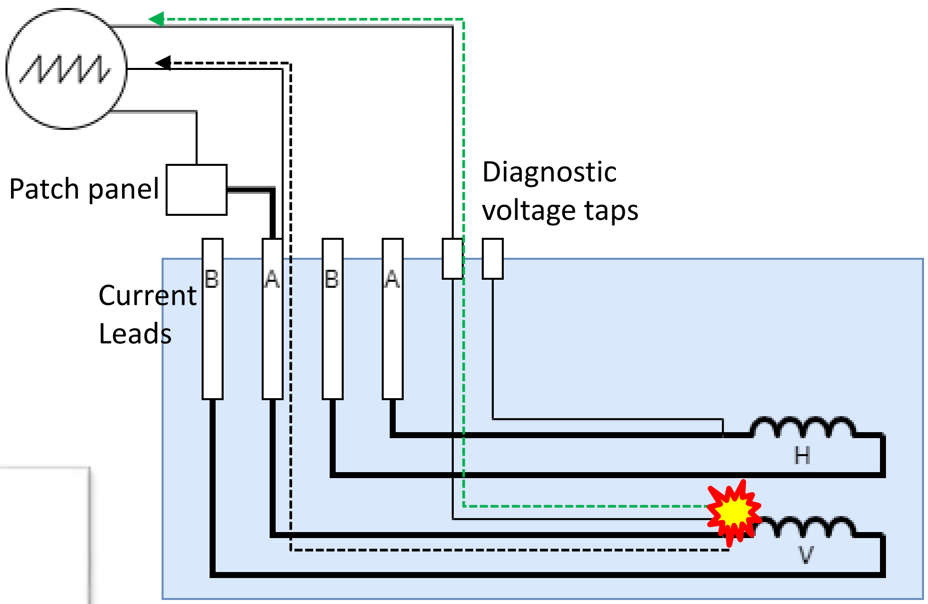




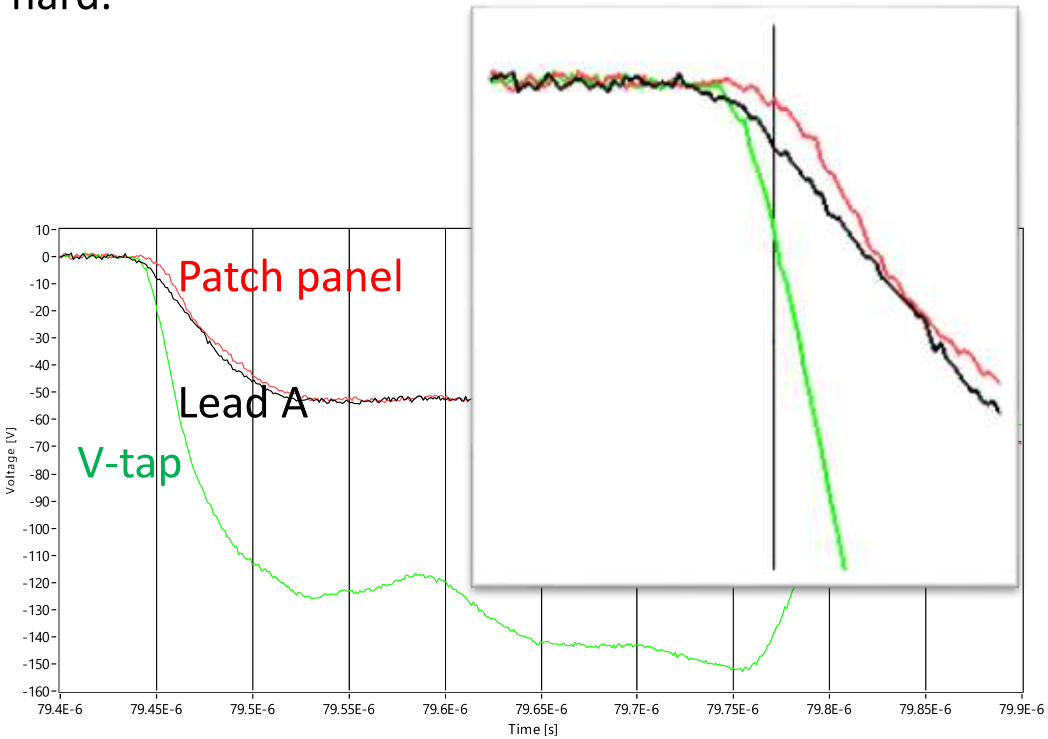
The electric charge is transferred from Lead A of tested circuit (V) to lead A of grounded circuit (H). From the fall/rise time of the signal and several provoked discharges at 50 V in various locations, we conclude that the fault must be close to or inside the cryostat.

Example 3

- Move close to the cryostat
- Disconnect the DC cables at the local patch panel
- Continue testing from there

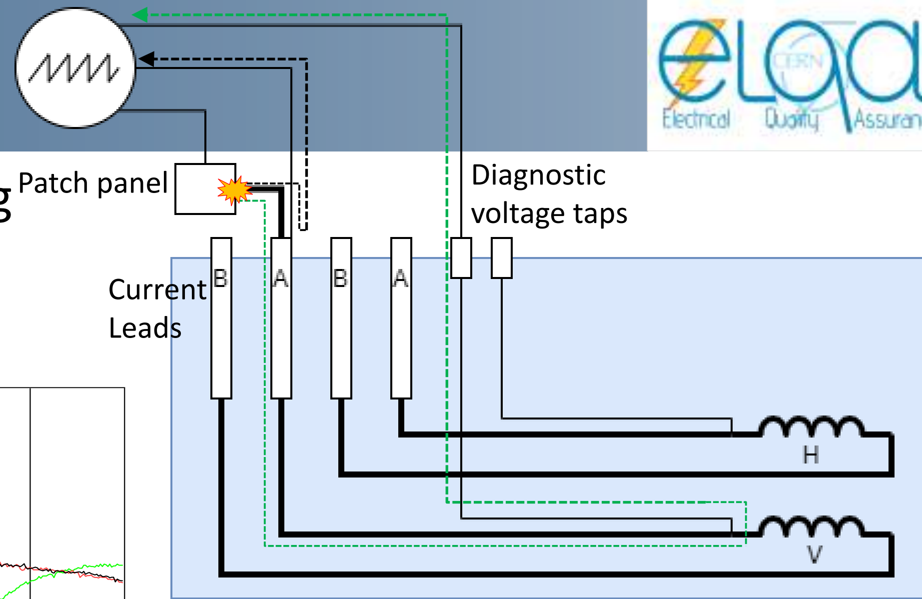


Next to the current leads there is a connector with diagnostic voltage taps. The access to this connector and to current leads is extremely hard.

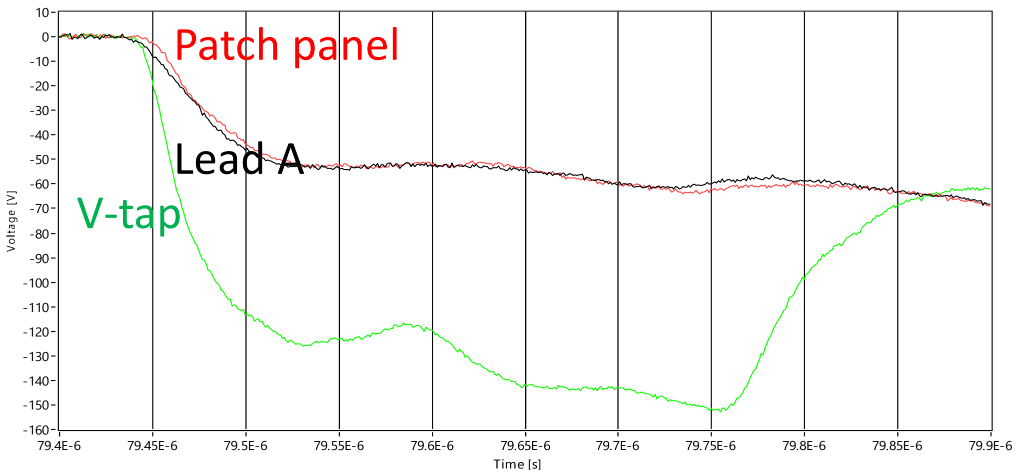


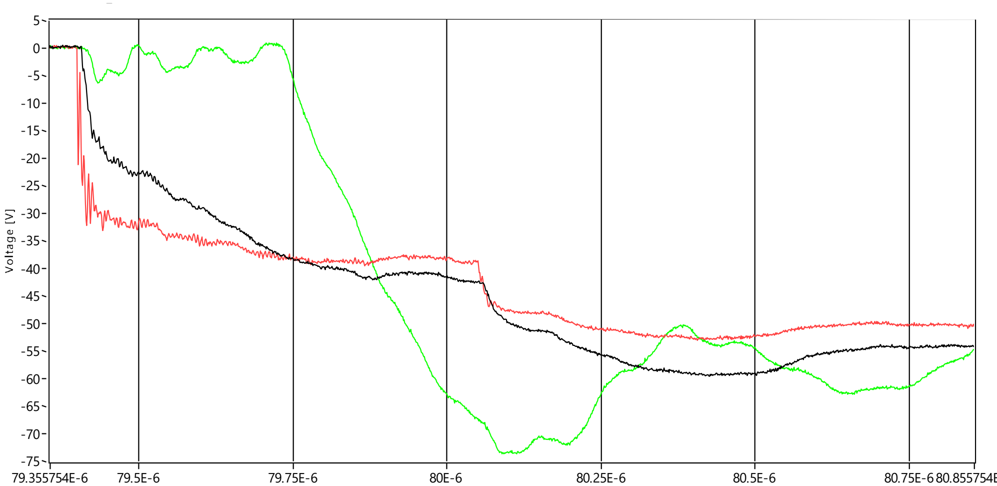
The breakdown signal takes a very similar time to propagate via bus-bars and through the diagnostic V-tap wiring. If we assume similar signal propagation velocity for the bus bar and instrumentation wire, then this image suggests that the **fault is close to the connection point of the V-tap to the superconducting bus bar**.

Example 3



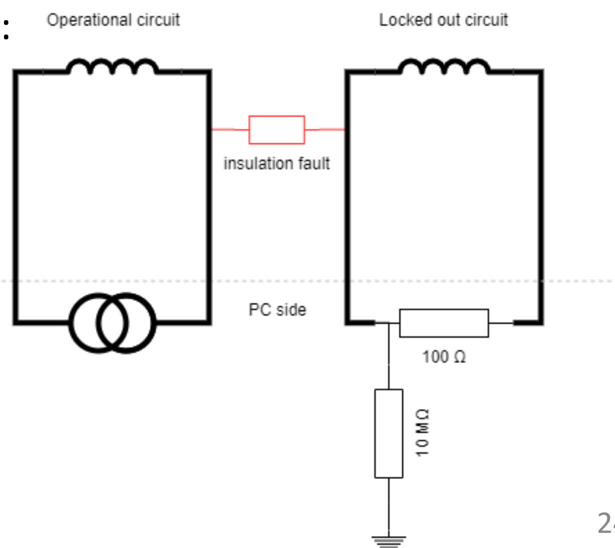
We confirm the hypothesis, by comparing the real fault signal with provoked discharges at different locations.





Provoked discharge at the patch panel

We know that the fault is deep inside the cryostat, between the two circuits. Repair is impossible. A decision is made to lock out one of the circuits and keep using the other one. Special lockout scheme is applied:



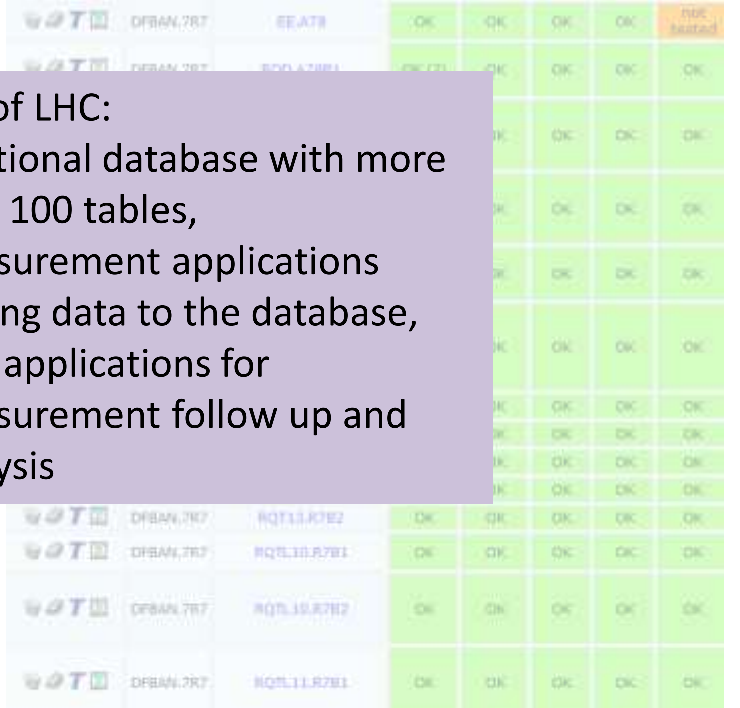
More examples

For other examples please check slides from Mateusz Bednarek's talk during 2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

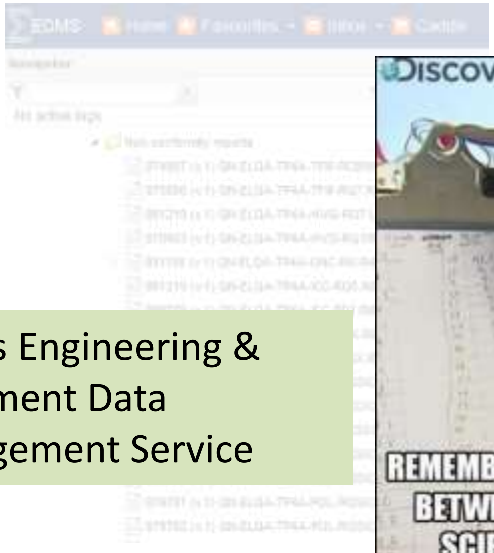
https://agenda.infn.it/event/32061/contributions/193775/

Data management

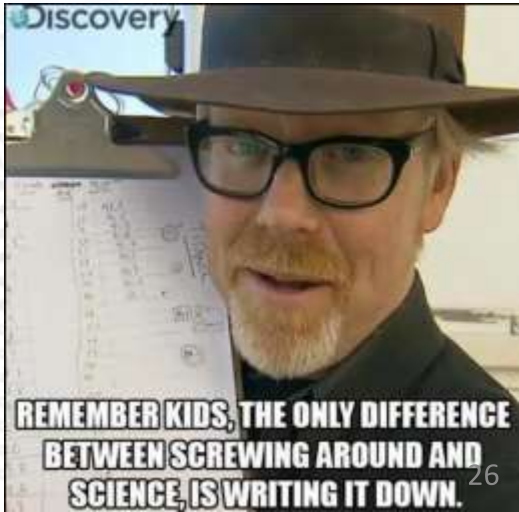
- Storage of test data
  - Test parameters
  - The information which tests were already executed
  - Test results - Pass/Fail information is not enough. The raw measurement data is needed
- Repository of the investigation reports



In case of LHC:
- Relational database with more than 100 tables,
- measurement applications writing data to the database,
- web applications for measurement follow up and analysis



CERN's Engineering & Equipment Data Management Service



Planning and Procedures

- Everything must be documented
- Start with electrical design criteria to define test parameters
- The tests executed during the qualification of the circuit must be well defined in the test procedure
- When conducting a nonstandard fault investigation, prepare a procedure which describes what you are going to do and have it accepted

Safety

The safety aspects should be taken into account already when preparing the test procedure or investigation procedure.

Some of the things we should think about when writing the procedure:

- What kind of training do we need to perform the test?
- What kind of authorisation is needed?
- What protective equipment do we need?
- How do we ensure safety for other people?
- How do we make sure that circuit to be tested is disconnected from the energy sources?
- How do we ensure that no one is manipulating the circuit during our test?
- How do we proceed in case of an emergency?

Summary

- Our role is to make sure that electric current flows where it is expected to flow and that it can't flow where it shouldn't.
- The tests must be designed to address specific failure modes.
- Electric integrity tests are straight forward in case of simple circuits. Things get more complex as the scale and number of circuits increases.
- Faults in electrical superconducting circuits need to be detected and localised as early as possible with the use of appropriate methods.
- Safety should always be the first concern.

Thank you

THE UNITED STATES OF AMERICA
IN GOD WE TRUST
THE REST WE TEST
ONE
ONE DOLLAR

Further reading

1. D. Bozzini et al. “Fault detection and identification methods used for the LHC cryomagnets and related cabling” - https://cds.cern.ch/record/977784/files/lhc-project-report-963.pdf
2. D. Bozzini et al. “Detection and location of electrical insulation faults on the LHC superconducting circuits during hardware commissioning” - https://cds.cern.ch/record/1151304/files/LHC-PROJECT-REPORT-1144.pdf
3. D. Bozzini et al. “Electrical Quality Assurance of the Superconducting Circuits during LHC Machine Assembly” - http://cds.cern.ch/record/1124072/files/LHC-PROJECT-REPORT-1141.pdf
4. D. Bozzini et al. “Automatic System for the D.C. High Voltage Qualification of the Superconducting Electrical Circuits of the LHC Machine” - http://cds.cern.ch/record/1124082/files/LHC-PROJECT-REPORT-1145.pdf
5. M. Bednarek, J. Ludwin “Software Tools for Electrical Quality Assurance in the LHC” - https://accelconf.web.cern.ch/icalepcs2011/papers/wepms008.pdf
6. J. Ludwin, P. Jurkiewicz “Upgrade of the Automatic Measurement System for the Electrical Verification of the LHC Superconducting Circuits” - https://ieeexplore.ieee.org/document/7389366
7. M. Bednarski et al. “Upgrade of the Arc Interconnection Verification System for the Large Hadron Collider” - https://ieeexplore.ieee.org/document/8787158
8. M. Bednarek et al. “Design, Assembly and Use of a Device to Eliminate Earth Faults Caused by Metallic Debris in the LHC Main Dipole Circuits” - https://ieeexplore.ieee.org/document/8106785
9. J. Ludwin et al. “Preparation and Execution of the Electrical Quality Assurance Program On the LHC Superconducting Circuits During the Second Long Shutdown” - https://ieeexplore.ieee.org/document/9380391
10. M. Bednarek “Methods and instrumentation for insulation defects measurements and electrical issues with superconducting magnets and circuits” - https://agenda.infn.it/event/32061/contributions/193775/