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

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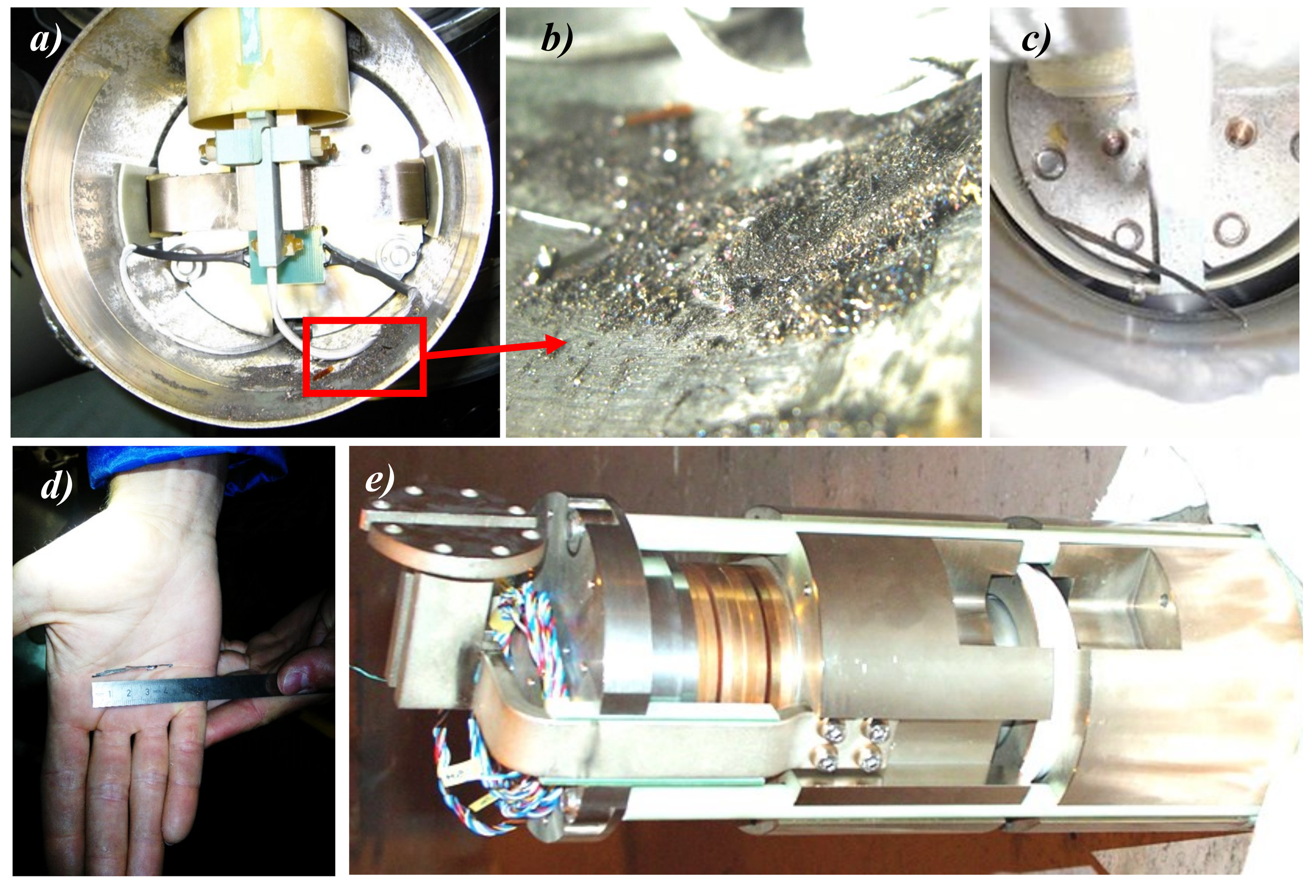
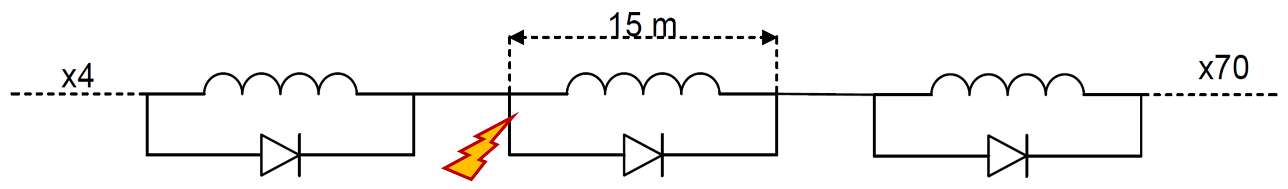
The scene

The superconducting dipole magnets of the Large Hadron Collider operate in a superfluid helium bath at 1.9K. As a part of the magnet quench protection system, each dipole magnet is equipped with a bypass diode located in the helium bath. The connection between the superconducting magnet and the cold bypass diode is made through a clamping system called "half-moon", located at the lowest point of the cold-masses. This area is prone to receiving metallic debris residual from the assembly technological processes. The metallic debris might move and create an earth fault during helium flows that occur not only during the flushing of the cryogenic installation, but also during magnet quenches at high currents. In case of appearance, the earth fault is detected by the protection system of the circuit and as a consequence the current is ramped down to zero.

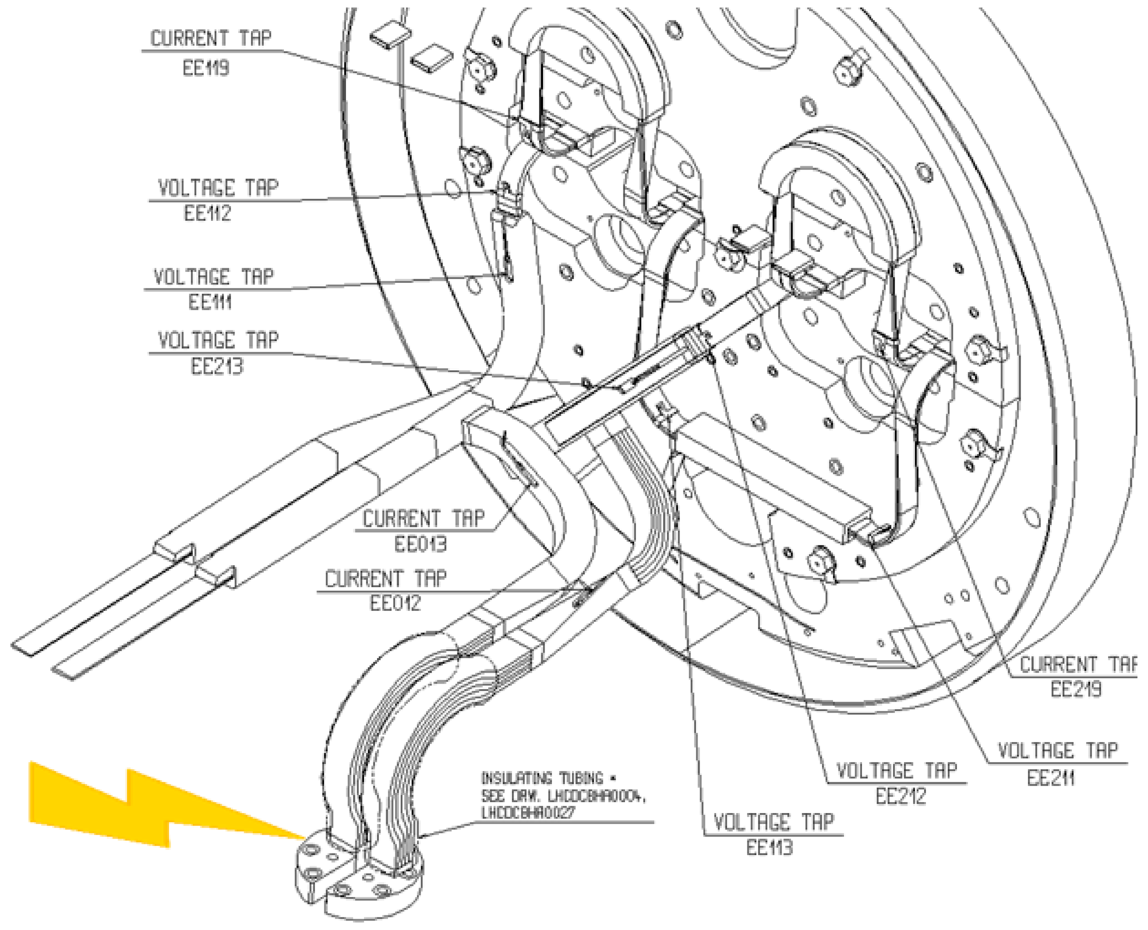


Images of the diode container and metallic debris that is at the origin of earth faults near the 'half-moon' connection: ***a)*** *Diode container with connection bus-bars,* ***b)*** *metallic debris at the bottom of the diode container,* ***c)*** *metallic chip that provokes an earth fault on the 'half-moon' connection,* ***d)*** *metallic chip (from image c) after extraction,* ***e)*** *protection bypass diode assembly including 'half-moon' connections.*

Earth faults in superconducting magnet circuits are very difficult to localize and repair. In many cases the repair work requires warming up of the affected circuit, which, in the case of the LHC, may mean the warm-up of a full 3 km long continuous cryostat of an entire powering sector. Nevertheless, the presented above types of earth faults can often be repaired without the warm-up and without opening of the fault area.



Simplified electrical diagram of main dipole magnets connected in series in one of the powering sectors of the LHC.



Mechanical layout of the connection of protection diode in the LHC main dipole magnets showing the most probable location of earth faults.

Fault localization

A number of complementary methods must be employed in order to accurately localize the fault. It is vital to differentiate between all possible fault locations: in the instrumentation wires, capillary, dilatation compensation loops, coils, bus-bars, diode connections, etc.

Due to the equipotential nature of superconducting circuits, DC methods are of a limited use and mainly AC methods have to be employed. A comparison with the powering event data serves as a final crosscheck.

Method	Precision	Comment
Global AC	120 m	Approx. location of faults in a full 3 km long sector
Local AC	40 m	Points to 2 magnets and a bus-bar
Local precision AC	3 m	Works well on superconducting bus-bars
Local precision DC	0.2 m	Resistive bus-bar sections only

Fault localization procedure: the fault needs to be localized with a precision of 20 cm in a powering segment of 3 km.

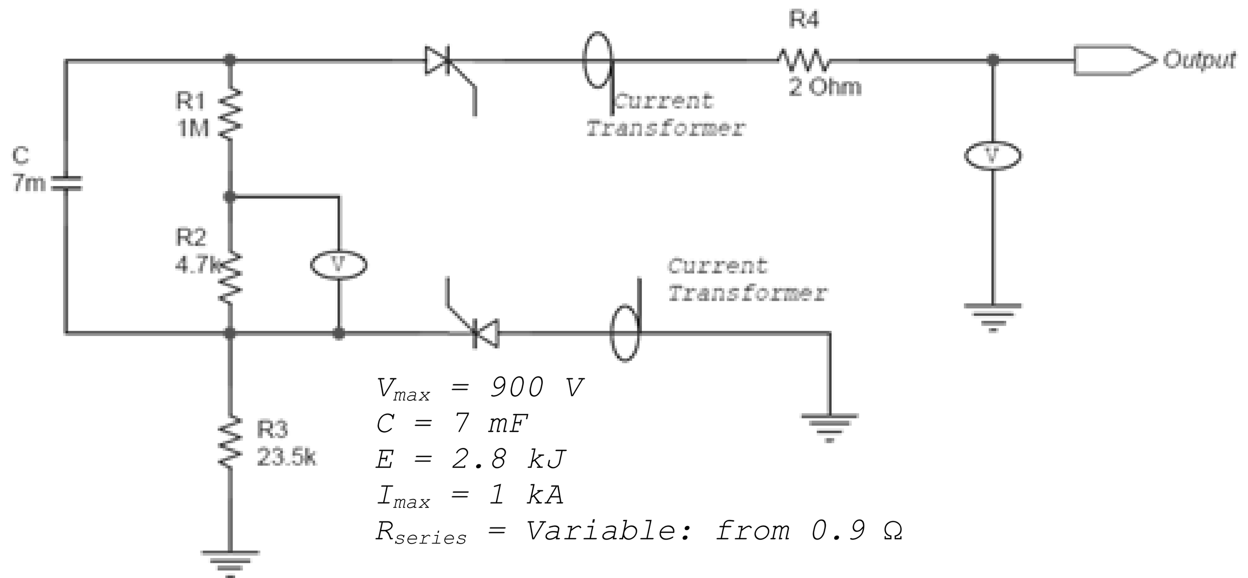
Earth fault elimination

The fault can be eliminated using a device denominated as the Earth Fault Burner (EFB). The fault elimination must follow a strict procedure as it is not fully risk-free.

A controlled high current pulse (up to 1 kA) is passed through the fault causing 3 effects:

- melting of thin pieces and making them smaller
- moving the pieces under electromagnetic forces
- causing the surrounding liquid helium to boil and move the pieces away

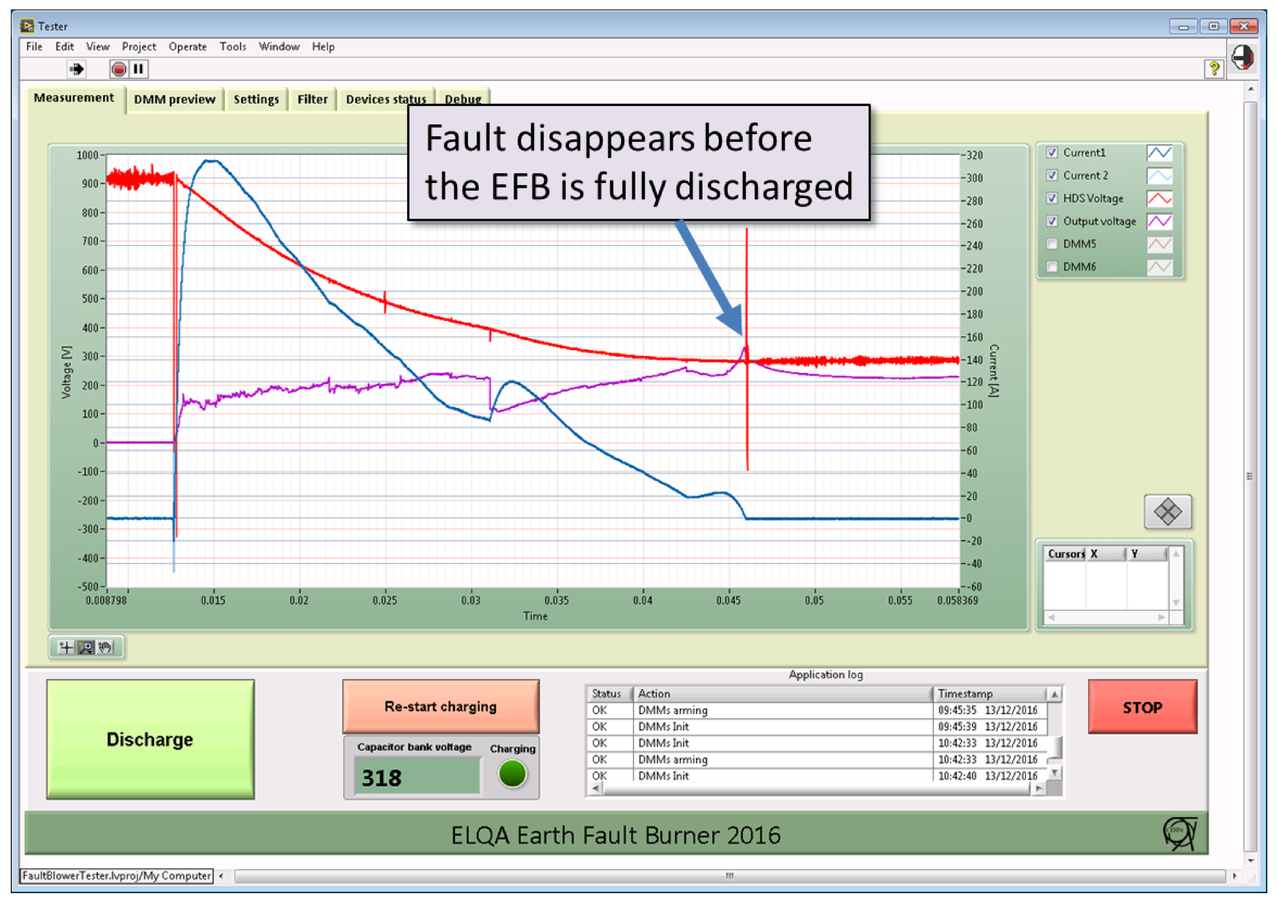
After execution of all the preparatory steps described in the EFB procedure the EFB can be applied. For safety reasons the discharge is initiated remotely from the CERN Control Centre with a dedicated application that automatically acquires and stores the measurement curves from 6 measurement channels.



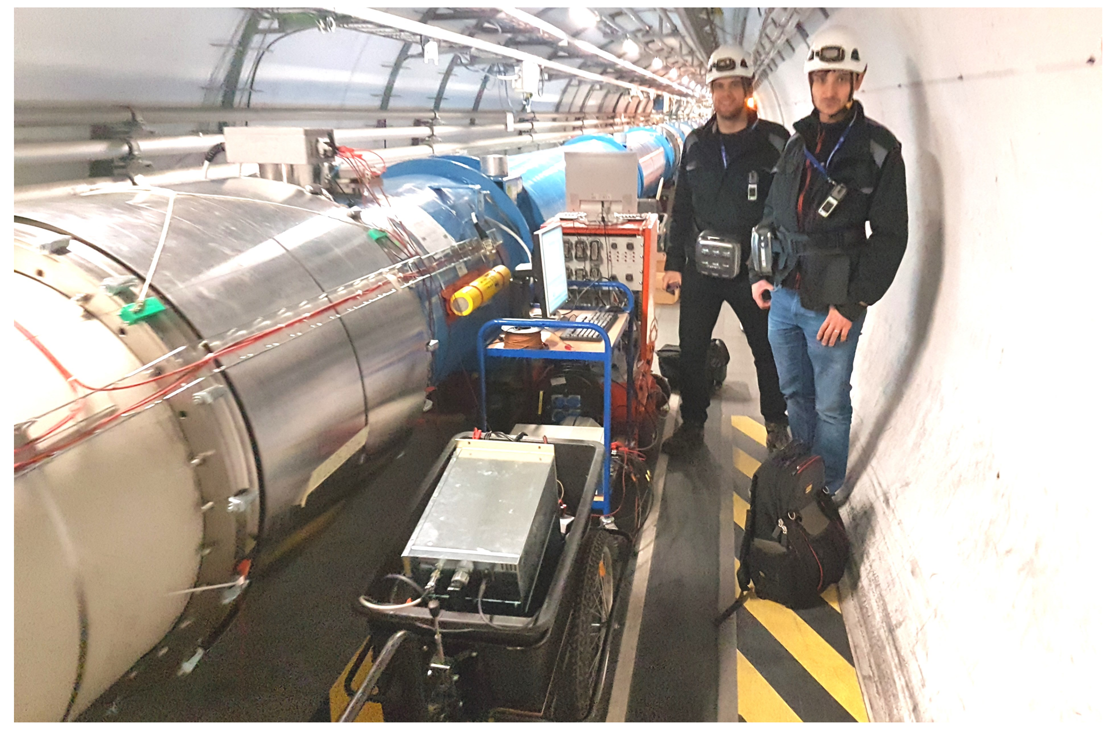
Simplified electrical diagram of the Earth Fault Burner (EFB)

Fault elimination experience

Two cases have been treated with the EFB in the LHC machine so far. Both were successful. Many more cases would be required to estimate the probability of occurrence of unrepairable faults in real operation conditions. Lab tests have demonstrated, that as long as the piece remains unfixed the application of the EFB will clear the faults if applied with maximum charge.



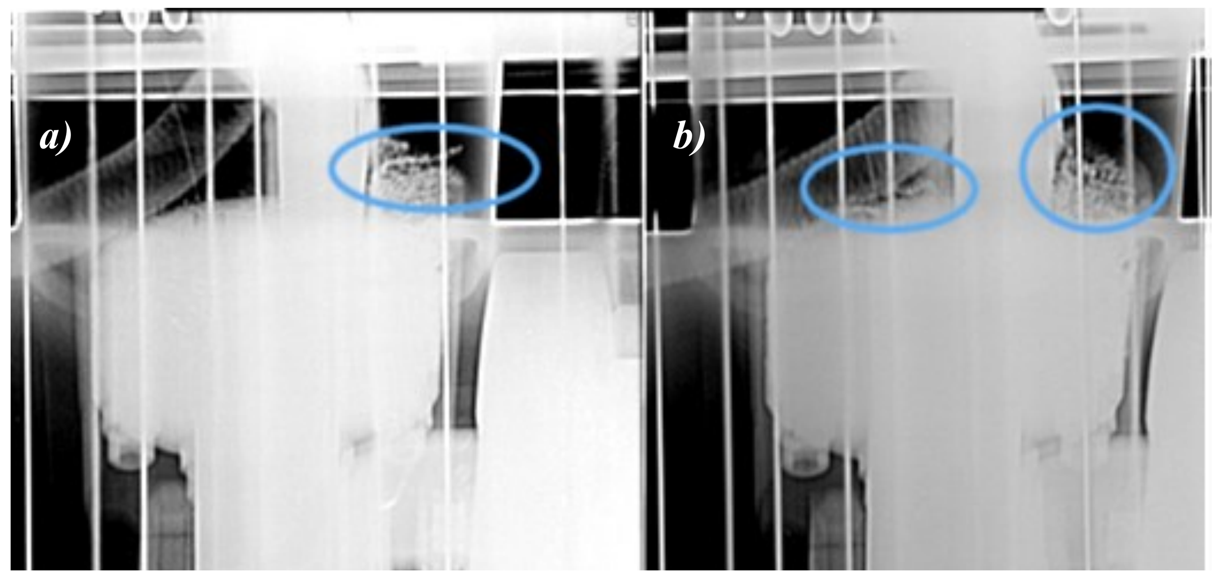
EFB application window view just after the earth fault elimination in December 2016



Installation of the Earth Fault Burner at C12L4 in the LHC tunnel

Summary

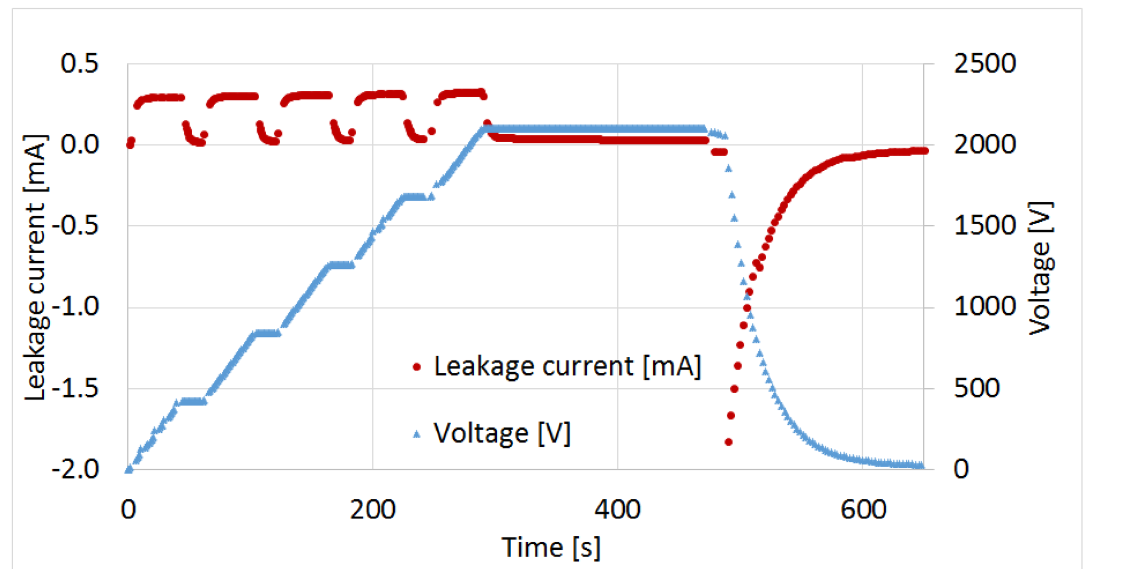
During the present Run 2 of the LHC machine, the procedure using the EFB to cure earth faults has been applied twice giving successful results and enabling the machine to be back in operation within a very short time. It is thought that most of the earth faults that may occur at the level of the main dipole bypass diodes can be safely and cleanly eliminated using the EFB. Methods for fault localization have been developed and a detailed procedures established.



X-ray images of the 'half moon' connection area: ***a)*** *before the application of the Earth Fault Burner (EFB),* ***b)*** *after the application of the EFB. The application of the EFB cleared the long and thin metallic chip. At the same time the surrounding metallic debris were redistributed.*

Final validation

After the application of the EFB the circuits need to be checked. The standard Electrical Quality Assurance (ELQA) high voltage test procedure is applied as well as dedicated high current powering tests are carried out.



Final ELQA HV test of the affected circuit: the insulation is good!