Performance of the Large Hadron Collider's Cryogenic Bypass Diodes over the First Two Physics Runs, Future Projects and Perspectives

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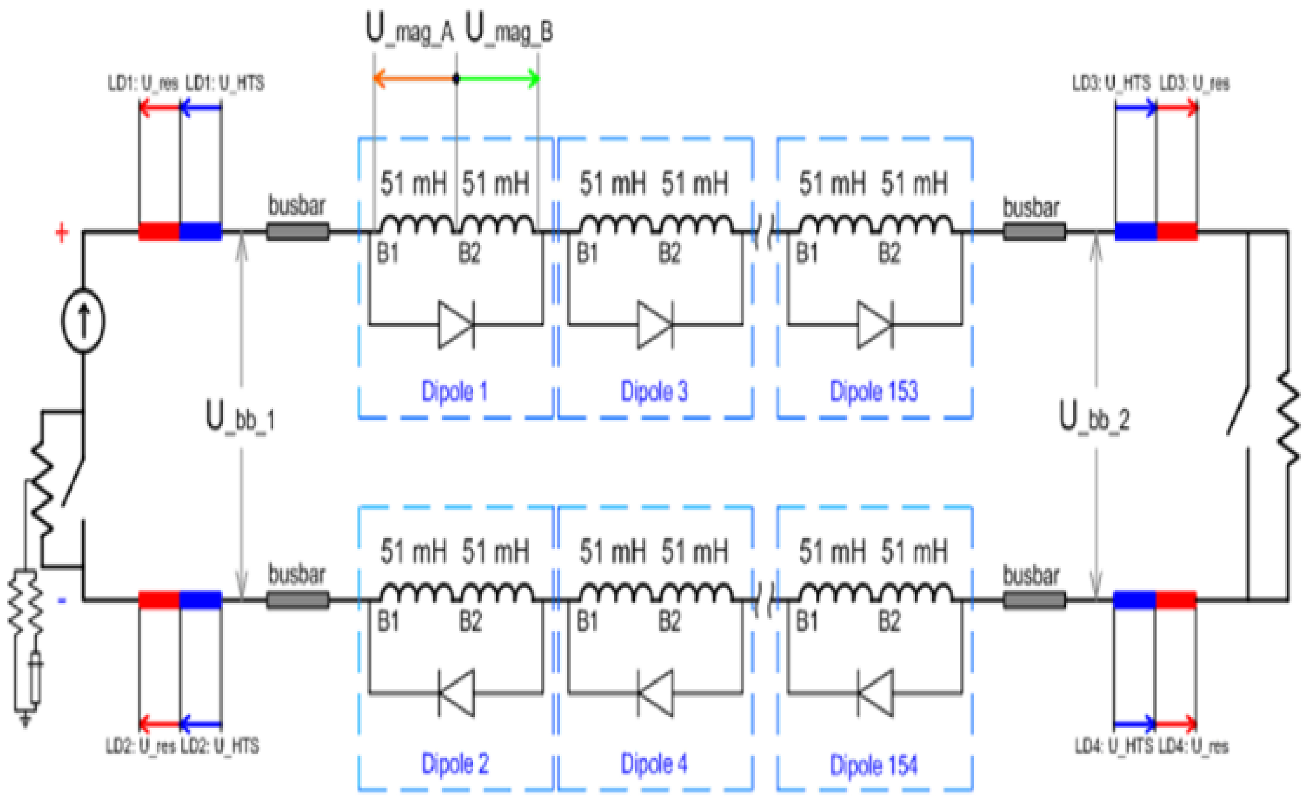
Introduction:

The cryogenic bypass diodes are fundamental components for the protection of the main superconducting circuits of the LHC, operating at 1.9 K in superfluid helium, up to a nominal current of 11.85 kA. One hundred and fifty four superconducting dipoles connected in series forming one circuit, and fifty one superconducting quadrupoles connected in series per family (focusing, de-focusing) are composing the main superconducting circuits. Each superconducting magnet is protected in case of quench by the combined effect of quench heaters, the cryogenic bypass diode connected in parallel and energy extraction systems inserted at the extremity of the circuits. In the case of the bending dipole circuits, two energy extraction systems are connected, one at each end of the sectors.

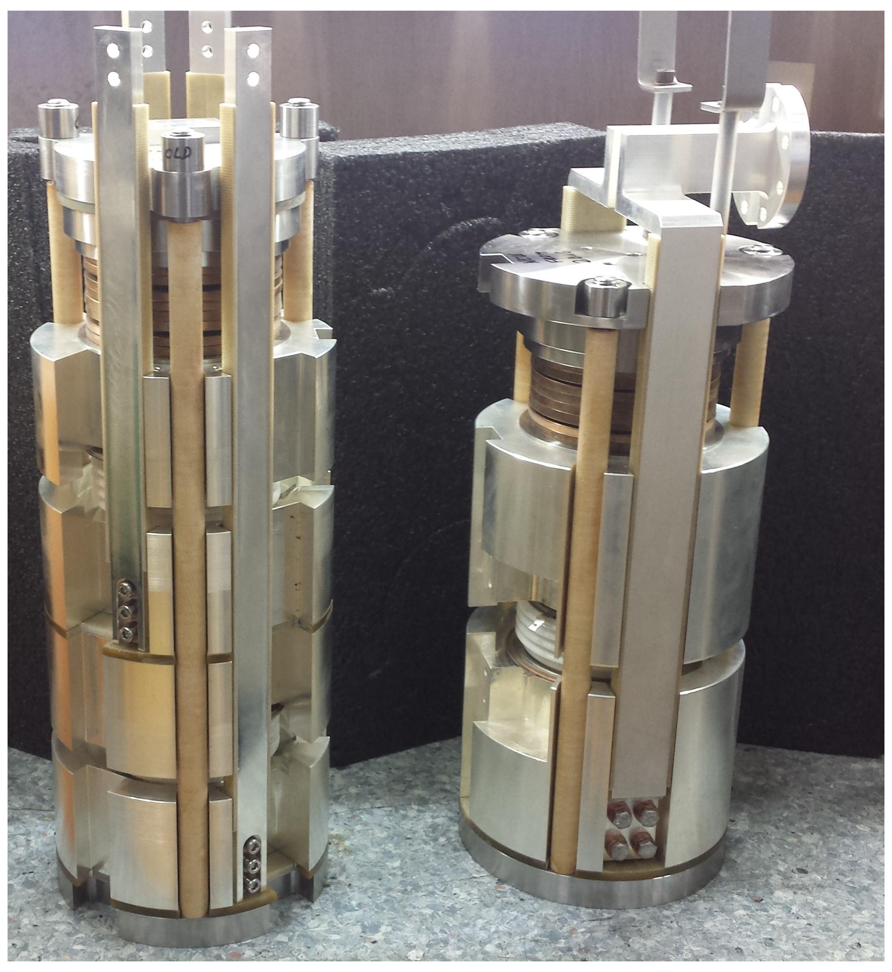
In case of a magnet quench, the diode will bypass the magnet while the current of the entire circuit is discharged following an exponential decay due to the effect of the energy extraction systems that insert resistances in the circuit by opening their electromechanical switches. The decay times are respectively 100 s for dipole circuits and 30 s for the quadrupole circuits.



Diode stack:

The dipole diode stack is a mechanical assembly made of two current leads allowing the connection to the magnet using bolted connections, heat sinks to absorb the energy dissipated and one power bypass diode.

The quadrupole diode stack is based on the same principle. One quadrupole diode stack protects two different coils of a superconducting quadrupole magnet. Therefore two diodes are required.



Quadrupole diode stack Dipole diode stack

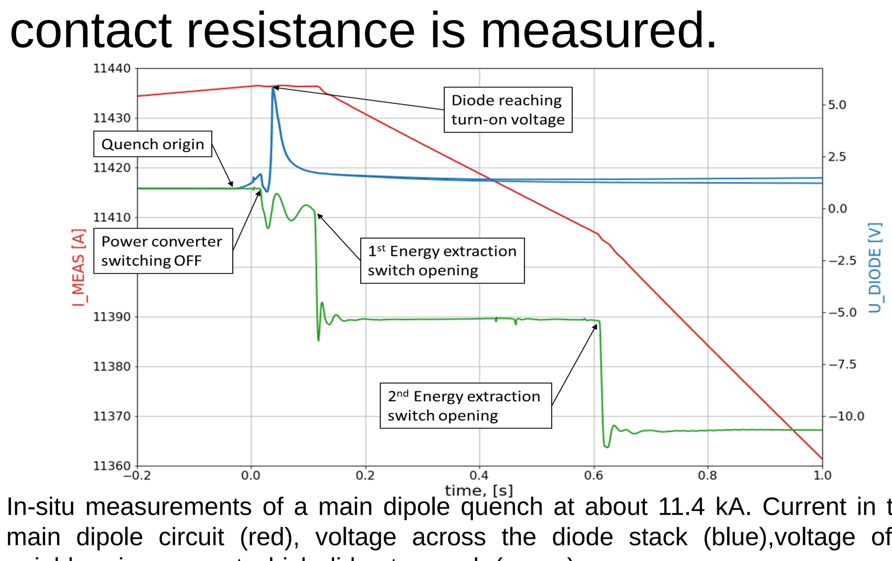
Diode stack into the LHC machine:

All quadrupole connections were consolidated during LS1

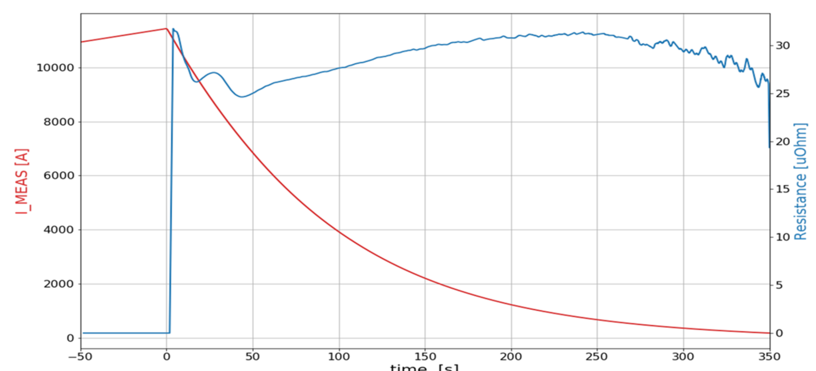
All dipole connections were measured during LS1 and then validated by CSCM, before RUN2.

Continuous monitoring during machine RUNs is taking place when a quench occurs.

All half-moon connections insulation are being consolidated during LS2 to avoid fault to ground. During this process the contact resistance is measured.

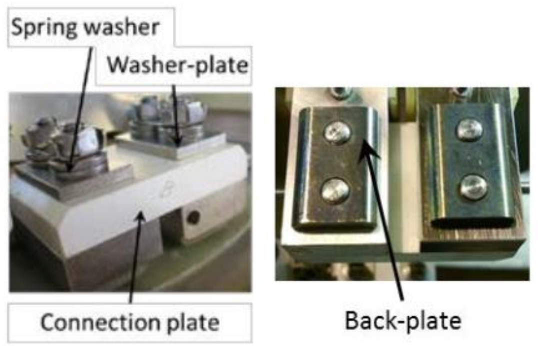


In-situ measurements of a main dipole quench at about 11.4 kA. Current in the main dipole circuit (red), voltage across the diode stack (blue),voltage of a neighbouring magnet which did not quench (green).



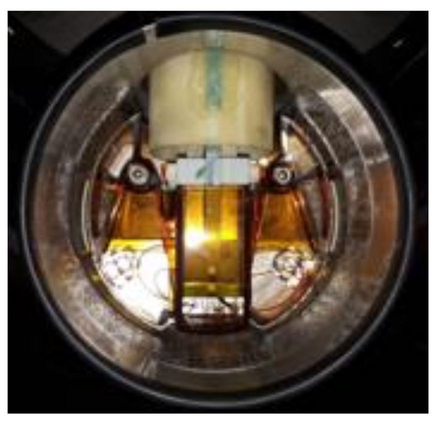
Evolution in the case of a magnet quench of the circuit current (red) and the resistance of the two diode leads (blue) deduced from the voltage drop measurement.

Quadrupole diode stack with bolted connection before consolidation

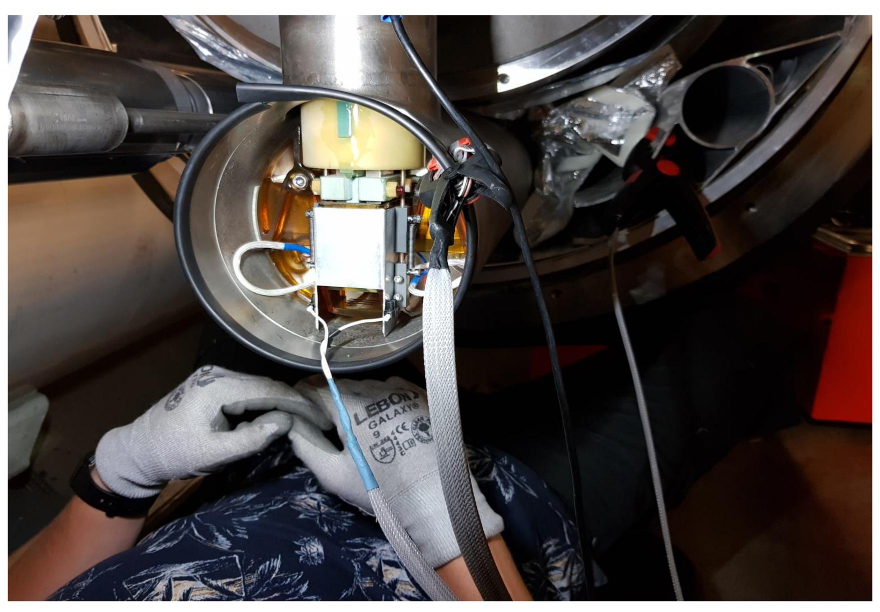


Consolidated quadrupole diode connections during LS1

Consolidated dipole diode stack half-moon connection.



Consolidated insulation of the dipole diode stack in the diode container.



Measurement of dipole diode stack contact resistances during the consolidation of the insulation to ground.

Stack qualification:

Main parameters are tested at 300K, 77K and 4.2K :

Contact resistances:
- Bus bar to heat sink: <2 µΩ
- Heat sink to diode: <5 µΩ

Forward characteristics of the diode

Reverse blocking voltage of the diode

Insulation to ground

Stack improvements:

Assembly procedure: avoiding Ni oxidation.

Additional voltage tap lug: quality and reliability of contact resistance measurement.

Surface treatment changed from Ni to Ag coating: decreasing contact resistances.

Manufacturing of the dipole stack lead: improving the quality of the assembly avoiding misalignment leading to weak insulation.

Insulator pieces extended and molded.

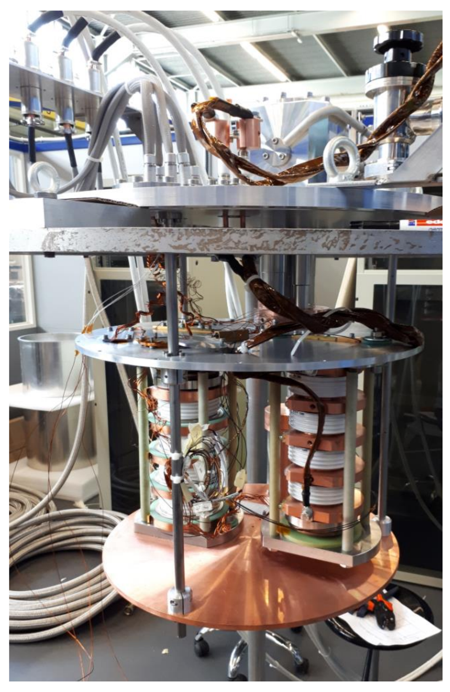
Exploring HL-LHC era:

Qualification under radiation in CHARM test facility

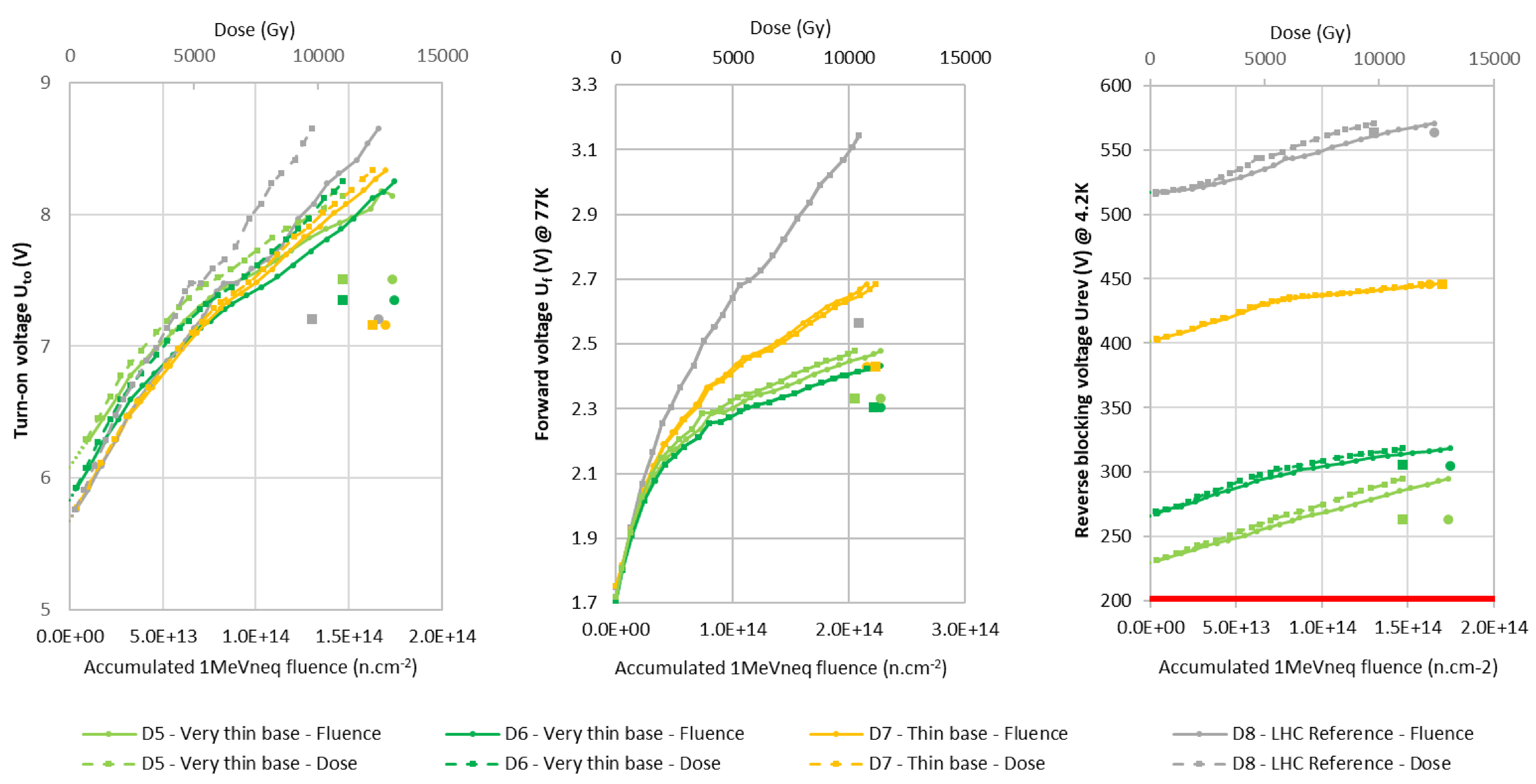
Measurement of diode characteristics as function of radiation.

Annealing studies at the end of the test campaign.

Cryostat containing diodes installed in the target area of CHARM



Insert holding the 8 diodes to be irradiated and tested



Electrical characteristics of the diodes measured as a function of the integrated dose and neutron fluence: turn-on voltage, forward bias voltage and reverse blocking voltage, measured on new diodes of three different types: LHC reference, Thin base and Very thin base

Conclusion

Since their first installation in the LHC and machine operation from 2009, more than 250 quenches occurred at high current in the main dipole circuits. During all these events the bypass diodes behaved as expected, properly fulfilling the protection function.

The electrical performance of the diode stacks has been looked with an attentive eye and improvements have been implemented. Regular monitoring of the diodes, as well as consolidation actions, have been fundamental steps towards a very successful experience over the many years of operation of the diodes within the LHC collider.

This experience together with the recent irradiations tests and validations at higher dose/fluence set a solid ground for the future use of the present cold diodes in the main magnets circuits and a modified version of those (with very thin base) in the inner triplets of LHC during the High Luminosity era