



ENERGY EXTRACTION IN THE CERN LARGE HADRON COLLIDER A PROJECT OVERVIEW

K. Dahlerup-Petersen¹,
A. Medvedko² and A. Erokhin²,
B. Kazmin³, V. Sytchev³ and L. Vassiliev³

Abstract

In case of a resistive transition (quench), fast and reliable extraction of the magnetic energy, stored in the superconducting coils of the electromagnets of a particle collider, represents an important part of its magnet protection system. In general, the quench detectors, the quench heaters and the cold by-pass diodes across each magnet, together with the energy extraction facilities provide the required protection of the quenching superconductors against damage due to local energy dissipation. In CERN's LHC machine the energy stored in each of its eight superconducting dipole chains exceeds 1300 MJ. Following an opening of the extraction switches this energy will be absorbed in large extraction resistors located in the underground collider tunnel or adjacent galleries, during the exponential current decay. Also the sixteen, 13 kA quadrupole chains (QF, QD) and more than one hundred and fifty, 600 A circuits of the corrector magnets will be equipped with extraction systems. The extraction switch-gear is based on specially designed, mechanical high-speed DC breakers, in certain cases combined with capacitive snubber circuits for arc suppression. This paper is an overview of the complete project with emphasis on the arguments and motivation for the choice of equipment and methods. It presents the basic properties of the principal components, the operational aspects and the present state of advancement. Finally, it highlights the implications of the extraction process on other systems of the LHC collider.

1 CERN, CH-1211 Geneva 23, Switzerland

2* BINP, Lavrentyev 11, RU - 630090 Novosibirsk, Russia.

3* IHEP, RU- 142284 Protvino, Russia

* Members of the CERN-Russia Collaboration to the LHC Project.

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In case of a resistive transition (quench), fast and reliable extraction of the magnetic energy, stored in the superconducting coils of the electromagnets of a particle collider, represents an important part of its magnet protection system. In general, the quench detectors, the quench heaters and the cold by-pass diodes across each magnet, together with the energy extraction facilities provide the required protection of the quenching superconductors against damage due to local energy dissipation. In CERN's LHC machine the energy stored in each of its eight superconducting dipole chains exceeds 1300 MJ. Following an opening of the extraction switches this energy will be absorbed in large extraction resistors located in the underground collider tunnel or adjacent galleries, during the exponential current decay. Also the sixteen, 13 kA quadrupole chains (QF, QD) and more than one hundred and fifty, 600 A circuits of the corrector magnets will be equipped with extraction systems. The extraction switch-gear is based on specially designed, mechanical high-speed DC breakers, in certain cases combined with capacitive snubber circuits for arc suppression. This paper is an overview of the complete project with emphasis on the arguments and motivation for the choice of equipment and methods. It presents the basic properties of the principal components, the operational aspects and the present state of advancement. Finally, it highlights the implications of the extraction process on other systems of the LHC collider.

I. INTRODUCTION

The concept of the systems, proposed for the LHC machine, is based on experience from design, manufacture and operation of several prototype facilities, built and used for magnet protection in various magnet test benches at CERN during the last ten years. Semiconductor switches, electromechanical switch-gear and combinations of these, together with their control electronics, have been thoroughly tested in such pilot installations.

The major part of the almost 300 tons of extraction equipment for the LHC machine will be obtained through collaboration agreements with CERN non-member States. Components, representing as much as 89 % of the total cost and 95 % of the total supplies, are in this way procured through Research Institutes in Russia and India. Whereas most of the control electronics was designed by CERN, the detailed layouts of the electrical power components were elaborated within the framework of the collaborations,

sometimes with the partner Institute itself and sometimes with Industry in the two countries, appointed by the local Institutes. Because of the special nature and particular requirements for most extraction components, it was rare to find standard equipment in current production, even sub-components, having the required characteristics. Almost everything is tailor-made to the application. This is the reason why special attention is being paid to careful type testing, certification testing and reliability and lifetime test programs. Furthermore, with the now available, almost definitive pre-series systems, real operating experience is being obtained through their installation in the LHC String experiment.

II. THE BASIC SYSTEM CONCEPT

A. 13 kA Circuits

1) Circuit Topology

Whereas the choice between the two possible circuit topologies, the parallel- and the series-insertion of the extraction system, is relatively unimportant for the quadrupole and the corrector circuits of LHC, for which both methods can easily be adopted, only the series system will satisfy the requirements of the dipole chains. The choice is closely related to the maximum admissible voltage to ground occurring in the dipole chain during the energy extraction and which is basically determined by the value of the dump resistance. This parameter results from a compromise between the maximum current decay rate, which does not cause quench-back in the magnets and the admissible heat dissipation in the cold by-pass diode and its heat sinks and busbars. In this way, the time constant of 104 s was determined, giving a total, initial decay rate of 125 A/s, a dump resistance of 150 m Ω and a resultant total system voltage of 1950 V at 13 kA. Although earthing the power circuit at the dump resistor mid-point will halve the voltage to ground, this value is still too high to be safely applied repetitively to the chain during the extraction. With a breakdown into smaller sub-systems, however, it is possible to further divide this maximum voltage to ground. Only a series topology provides this possibility. It should be noted that these considerations were also important for the choice of the sectorisation of the three principal electrical power circuits of the LHC machine into eight individually powered segments. With two, identical, series-inserted sub-systems, one with the circuit earthing at its mid-point (through 1 Ohm), the maximum voltage to ground is limited to 488 V. This topology has the further advantage to allow a sharing between the sub-systems of the total dissipated energy of the sector. It will equally limit the arc voltage of the

extraction switches and halve the voltage rise of the converter terminals with respect to ground, compared to a parallel topology. The series system requires the presence of by-pass thyristors across the converter terminals to ensure circuit continuity after switch-off of the power source. However, the free-wheel thyristors, required for the correct operation of the converter, will perform this function.

For the LHC quadrupole and corrector circuits, where only a single extraction system per magnet chain is required, it was, for reasons of standardisation, decided to apply the same principle of series insertion.

2) Switch-gear Selection

The basic criteria for the choice of extraction switch for the various circuits are reliability, lifetime, voltage drop (losses) and radiation hardness (only the dipole units). The following arguments can be highlighted as being decisive for the selection of electromechanical gear instead of thyristors, GTOs or other semiconductor switches:

-A semiconductor device relies entirely on a single, active system to turn off, i.e. forced commutation by reverse cathode voltage application or gate current injection. Mechanical switch-gear, however, can be equipped with both an active and a passive release.

-The voltage drop of a high-current GTO or a power thyristor is typically 1.4 V compared to 60 mV at 4 kA of a mechanical breaker, giving 10 times lower losses.

-The breaker can be cooled by natural air convection, whereas the semiconductor switch relies on water-cooling.

-The semiconductor device has much higher radiation sensitivity than mechanical devices.

-Even in the case of 600 A circuits, where opening time is a major issue, the electromechanical breaker is fast enough to eliminate the risk of overheating of the quenching superconducting coils and busbars.

-A mechanical switch has the capability to interrupt very large short-circuit currents, often more than ten times the rated current. This is important in a system with several parallel-connected switches, where it is the 'slowest' device, which will break the full system current.

3) The Choice of a Mechanical Extraction Switch

A technical survey revealed that no single, existing DC breaker satisfied all the CERN requirements. Most of the requested features could, however, be found on various, commercially available devices. A common CERN/Russia development work was undertaken to create a breaker with the following features:

-two independent release systems, one completely passive, based on under-voltage release, the other active, based on a discharge pulse trigger.

-magnetic displacement of the arc into the arc-shute, driven by the main current itself, providing fast and reproducible arc extinction, even at low currents

-no mechanical catch and latch, the 'on' state being maintained entirely by the excitation of the holding coil

-arc-free separation of the main contacts, i.e. opening prior to separation of easily replaceable arc contacts

-high overload and high current breaking capability combined with low 'on'-state losses

Two versions were elaborated: a 1500 V type for the dipoles and a 200 V type for the quadrupoles. The only difference is the construction of the arc-shute and the electrostatic, de-ionising muffler. The rated current is 4.0 kA with a continuous overload at 4.5 kA. The breaker, named VAB49 and manufactured by the company UETM in Ekaterinburg, is based on a unique, four-limb magnetic circuit, on which both the closing/holding coil and the pulsed coil are mounted. The two systems will, combined or independently, open the device. The total opening time represents 5 ms +- 1 ms for the fast (pulsed) release and 20 ms +- 1 ms for the slow (under-voltage) release. Triggering of the two systems will always happen simultaneously.

Parallel to the development of these main switches, the associated powering and control electronics was developed at CERN. For this design work, coils, magnetic circuits and mechanical components (such as springs) of the future breaker were modelled into one, large electrical circuit. The synthesised model was used to simulate the overall performance of the strongly non-linear device, -a joint collaboration with the BINP Institute, Novosibirsk [1]. It led to the determination of the required operational sequences as well as the permissible range and safety margin of every single parameter in the powering circuit.

The verifications of the prototype and pre-series breakers, the control electronics and the over-current relays comprised:

- Electrical and thermal type testing of both types at the premises of the manufacturer
- Certification testing according to IEC 947, carried out at an independent high-power Institute
- A program of reliability and lifetime tests at 13 kA with 2000 opening and closing cycles, performed at the IHEP, Russia
- A program of mechanical reliability and life expectancy with 5000 cycles, performed at CERN
- Evaluation and testing by a specialised company of certain vital mechanical parts of the breaker
- A Failure Mode Analysis of breaker and electronics
- Installation and operation in the CERN's String 2 experiment of a complete 13 kA system

In total 280 units, one half of each type, are required for the 32 MB, QF and QD facilities. Series production will be supervised by inspectors from IHEP and from a specialised, independent organisation.

4) The Breaker Array

Each extraction facility is composed of eight VAB49 breakers, in four parallel branches, each with two series-connected units to recover some of the redundancy lost by the parallel connection. All four branches must be closed in order to generate the 'power permit' for the circuit. A minimum of three branches is required for safe operation of the breakers; consequently one branch may open by failure during

operation without incident. In case of accidental opening of a second branch, a 'power abort' is generated, opening all the switches for extraction in the circuit. The breakers are arranged around a quasi-coaxial power busway (Fig.1), which role is to distribute the currents to the four branches in a balanced way, with low losses and a minimum of stray field. The bus is directly water-cooled but is able to operate 30 minutes without water flow. 32 such busways are under construction at the BINP Institute in Novosibirsk. A long version with all 8 breakers at one side only is required for the installation in the LHC collider tunnel (left and right of Point 3 only), where the system co-exists with the beam pipes. For all other installations, in underground caverns and galleries, the short version (Fig. 1) is used. The current balance depends on both the breaker impedance and the symmetry of the busway; it will change slightly with temperature and the deformation of the breaker main contacts. The extrapolation of measurements suggests variations within $\pm 5\%$ maximum. The two 13 kA connections to the busway are provided through a combined electrical and hydraulic connector, developed for the purpose. Capacitor banks, typically 200 mF, have successfully been applied for arc suppression as snubber circuit across the complete assembly. It significantly reduces the amplitude of the audible shock wave during breaker opening at high currents.

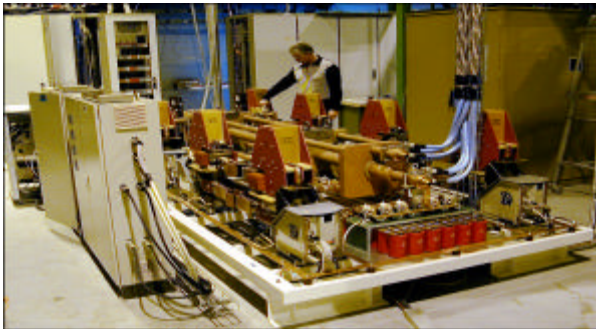


Figure 1: A prototype 13 kA Breaker Assembly with its two electronic control cabinets and the acquisition and monitoring rack (extreme left).

5) The Breaker Electronics

The power part of the control cabinet has four individual modules for driving four breakers. Each module shall provide the current necessary for closing ($22 A_{DC}$) and for maintaining the device closed ($0.6 A_{DC}$). It shall enable slow opening by de-excitation of the holding coil and generate the pulses ($4 \times 800 A_{peak}$) for the fast release by capacitor discharge through thyristor firing. The electronic control part shall provide the local control of the power part by application of the incoming commands. It shall treat the interlock signals and transmit them to the Interface Module and, finally, it shall provide the logic control of the status of the breakers.

Particular features of these modules are:

- The cabinets will be powered from both mains and UPS grids. Mains are needed only for providing the high closing currents

- The selected components are radiation resistant. Special attention is paid to radiation hard low-voltage power supplies, which will be used for the tunnel installations. The complete cabinet will be radiation tested.

- Both power and controls parts will be manufactured to the highest possible standards.

- The printed circuit boards of the final series will use surface mounted components and be subjected to a burn-in at $70^\circ C$

- The cabinets have been certified against electromagnetic interference.

The hard-wired signal for the vital interlock 'switch open failure', signalling that one or more branches of breakers did not open in spite of the command, is also generated in the cabinet.

The series of 70 units, required for the project, will be manufactured through a collaboration agreement with India.

6) The Dump Resistors

In spite of the large energy difference, the dipole and quadrupole extraction resistors have many common design features. The basic principles for both types are:

- In order to limit the peak voltage to the lowest possible level, as defined by the dump resistance at room temperature, a 'zero' inductance concept is applied and an absorber material with low temperature coefficient is chosen.

- For an optimum use of the materials the operating temperature shall attain $250-350^\circ C$ at the end of the energy deposit.

- The equipment shall always be available for extraction during powering of the magnet chain. It shall not rely on any external infrastructure, such as mains power or cooling water, for accepting the energy deposit.

- The resistor body shall be cooled by forced air. Direct water cooling by immersion is prohibited because of the risk of shorts through the liquid.

- Due to the underground installation, the heat dissipation to the surrounding air shall be close to zero. Consequently, the units shall contain an air-to-water heat exchanger and a water reservoir with sufficient capacity to ensure worst-case no-boiling conditions.

- The cooling period shall be maximum two hours. Re-powering of the magnet chain will be possible only after cooling of the resistor body.

- The material selection for the dipole resistors shall take into account their installation in the LHC tunnel in areas with high radiation levels (collimator regions).

With an energy deposit of more than 650 MJ, a single $75 m\Omega$ dipole unit would be 11 meter long and have a mass of 8 tons. For reasons of handling and space allocations an alternative solution with three individual, parallel-connected sub-units of $225 m\Omega$, 220 MJ was adopted.

The resistor body, consisting of 84 series-connected stainless steel plates, the forced-air cooling circuit and the pipe heat exchangers were dimensioned through computer calculations of temperature profiles related to the closed air and water cooling circuits. Particular attention was paid to the need for free expansion-contraction and for a uniform cooling across the resistor body to avoid buckling, twisting and other deformation during the fast energy deposit and the slow cooling. The 6.6 m Ω (and 7.7 m Ω), 22 – 24 MJ quadrupole extraction resistor is small enough to be housed in a rack-size cubicle.

The calculation and design work for both types was made within the framework of a collaboration agreement with IHEP, Protvino. The prototypes include sub-components made by European Industry in collaboration with CERN. The 54 dipole units and the 22 quadrupole units will be produced in the IHEP workshops [2]. A photo of the successfully type tested dipole resistor is shown in Fig. 2.



Figure 2: The first 225 m Ω prototype dipole resistor

B. 600 A Extraction Equipment

The LHC corrector circuit families to be equipped with such systems are: MCS, MCD, MO, MQS, MQT, MQTL and MS, with stored energy ranging from 2 to 108 kJ. The extraction equipment is here based on two series-connected, high-speed electromechanical, 3-phase AC breakers with common and simultaneous operation of the three poles. The switches are equipped for the purpose with the same two release systems as the VAB49. In addition, the breakers are fitted with special DC arc shutes. The total opening time is 17 ms (pulsed release) and 25 ms (zero-voltage release). For the corrector magnets and their busbars the extraction time is a critical parameter because of the limited amount of stabilising copper in the superconductors. Capacitive snubbers (typically 320 μ F, bi-polar) are here systematically used for arc suppression, herewith reducing the contact erosion, the total opening time (by 20 %) and the acoustic noise (with 15-20 dB). The extraction resistors, 0.7 Ω or 0.2 Ω , are made from a low temperature coefficient material, such as FeCrAl. The control part comprises the electronic circuits for driving the switches, the remote-control cards and an acquisition and supervision electronics. Two such facilities occupy one standard Euro-rack. BINP and IHEP supplied each three prototype systems, one unit for installation in the String 2 experiment and two units for reliability tests at CERN and in the local Institute.

The two systems are using different components and technologies.

III. IMPLICATIONS ON OTHER SYSTEMS

The energy extraction facilities will have an impact on the other systems in the power circuit. When opening, the voltage waves, sweeping through the magnet chains, will have amplitudes, which are many times higher than the ramping voltage and will stress the dielectrics of the magnets. Voltage oscillations in the magnet chains can be predicted by simulation [3] and must be attenuated. In the LHC MB and QF/QD chains such oscillations occur in particular for magnets no. 5 to about 15, counted from each extremity of the half-chains. Attenuation is achieved by individual damping of each magnet, for the MB strings with typically 70 Ω connected across the dipole terminals. With use of a RC circuit the DC current deviated during ramping can be avoided and dangerous, fast voltage transients across the diode can be attenuated. However, a too low value of the series capacitor will reduce the effect of damping at the low propagation velocity of the waves. Optimisation of these parameters are an important part of the design work. The two extraction systems of the LHC dipole chains cause further complication as unavoidable delays between the opening of the two breaker systems will result in additional voltage oscillations, which are very difficult to attenuate. This subject is presently being carefully analysed.

IV. CONCLUSIONS

Following successful type testing of all equipment and sub-components, the project has now entered the phase of reliability tests, risk analysis and complete system performance evaluation. Although preparations for series production of the equipment have already started, results of these final investigations are mandatory for approving the beginning of the manufacture of the series. Installation of the first equipment in the LHC tunnel is scheduled for end of 2003, with the first sector tests planned for mid 2004.

V. REFERENCES

- [1] A. Erokhin and A. Medvedko, BINP, K. Dahlerup-Petersen, CERN, A. Kussul and V. Anuchat, UETM: 'Modelling and Computer Simulation of the Pulsed Powering of Mechanical DC Circuit Breakers for the CERN/LHC Superconducting Magnet Energy Extraction System'. Invited Paper for ICAP2000.
- [2] K. Dahlerup-Petersen, CERN, B. Kazmine, V. Popov, V. Sytchev, L. Vassiliev and V. Zubko, IHEP: 'Energy Extraction Resistors for the Main Dipole and Quadrupole Circuits of the LHC, EPAC2000.
- [3] F. Bourgeois and K. Dahlerup-Petersen, CERN: 'Modeling and Transmission-line Calculations of the Most Recent Superconducting Dipole Chains of CERN's LHC Collider: Methods and Results', Paper for PPS2001.