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ENERGY EXTRACTION RESISTORS FOR THE MAIN DIPOLE AND QUADRUPOLE CIRCUITS OF THE LHC

K. Dahlerup-Petersen[1,] B. Kazmine[2], V. Popov[2], V. Sytchev[2], L. Vassiliev[2] and V. Zubko[2]

Abstract

When the LHC will be operating at its maximum beam energy, its superconducting dipole chains store a total magnetic energy of more than 11 GJ. At the same time, the QF and QD quadrupole circuits store a total energy of 400 MJ. Even with the sectorisation of each of the three principal power circuits into eight individually powered segments, the stored energy of a single circuit is considerable. During normal operation the energy in the dipole circuits is safely returned to the mains grid, using the thyristor-based, 'booster' unit of the power converters, operating in inversion. For the quadrupole chains, where the converter is of a mono-polar topology, the stored energy is dissipated into the resistive part of the warm d.c. power lines (busbars and cables) in a slow, controlled run-down. When a magnet quenches, however, such a slow energy transfer, taking 20 minutes from the rated LHC current, will not be possible. The 'cold' diode, taking over the magnet current in case of a quench, will not survive this slow current decay. For this reason, energy extraction facilities will be inserted into the power circuits. These systems are being designed to absorb the total circuit energy and de-excite the chains with a current decay time constant of 104 s for the dipoles and 40 s for the quadrupoles. The resulting maximum decay rates (-125 A/s and -325 A/s respectively) are comfortably below the levels where quench-back will occur.

The energy extraction systems are based on an array of special, mechanical d.c. circuit breakers and absorber resistors, which are switched into the circuit by opening of the breakers. The design and construction of these large power resistors of a unique concept are the topics of this paper.

The project is being realised as collaboration between, IHEP-Protvino, CERN and European Industry.

1 CERN, LHC Division, Geneva, Switzerland
2 IHEP, Protvino, Russia. Member of the CERN-Russia Collaboration to the LHC Project

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CERN
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1. SYSTEM CONCEPT

Energy extraction facilities can be divided into two categories: series-connected or parallel systems, depending on their place in the power circuit: It is the series system which has been chosen for all the 13 kA chains of the LHC. The 104 seconds time constant for the dipole chain requires a total dump resistance of 150 mΩ per circuit. The associated voltage, appearing across the absorbers upon opening of the breakers, will be close to 2 kV. To reduce this voltage, it is necessary to divide the extraction system into two separate facilities, one inserted at the electrical midpoint of the magnet chain and one near the negative terminal of the converter. When, in addition, the grounding of the power circuit is chosen as the midpoint of one of the two dump resistors, the voltage to ground at any point of the dipole chain during extraction is divided by four. This considerable advantage can only be achieved with a series system. The quadrupole extraction facility uses a single, series-inserted system. The very low dump resistance values (6.6 mΩ and 7.7 mΩ) would require the presence of blocking diodes in case of a parallel system. With the choice of a series system many components will be identical to those used in the dipole chains.

An LHC 13 kA energy extraction facility is composed of the following principal elements: Eight, specially designed 4 kA d.c. breakers (four units in parallel, two units in series for redundancy), equipped with snubber capacitor circuits for arc suppression, a current-equalising power distribution busway, a full-power dump resistor assembly and a powering and controls system. All these components are being developed and produced through collaborations between CERN and Institutes in Russia and India. A total of 32 extraction facilities are required, half for the dipole circuits and half for the two chains of quadrupoles.

2. DESIGN CRITERIA

The following design criteria apply to both types of energy absorbing resistors:

-The peak voltage across the resistor shall be kept at the lowest possible level, defined by the resistance at room temperature. This implies a 'zero' inductance concept of both the resistor itself and of the power cable link to the breaker array as well as the use of absorber materials with a low temperature coefficient.

-The resistors shall be dimensioned for high temperature operation but within the maximum temperatures allowed by its materials and components.

-The resistor shall be available for energy extraction without need of any infrastructure, such as mains power and cooling water, during the discharge period.

-The design shall ensure a perfect short- and long-term reliability of the complete unit.

-The heat dissipation to the surrounding air shall be close to zero, as installation is in underground areas.

-The absorber body shall be cooled by forced air.

-The resistor units shall comprise an air-to-water heat exchanger and a low-pressure water reservoir with sufficient capacity to ensure worst-case no-boiling conditions.

-The cooling period shall be maximum 2 hours.

-The layout of the dipole resistor units shall allow their installation under the beam pipes in the collider tunnel as well as vertical superposition of three units for minimising floor space occupation in the various caverns and galleries of the machine.

-Its materials and components shall withstand the integrated radiation dose absorbed when installed and operating in the machine tunnel.

-The quadrupole units shall be housed in rack-size cubicles and will always be installed outside radiation areas.

Two CERN Technical Specifications define the complete electrical, mechanical and thermal requirements [1], [2].

3. DETAILED DESIGN OF THE DIPOLE RESISTOR

3.1 General aspects

Because of the converter by-pass diodes and the 'cold' protection diode of the quenching magnet, the current in the dump resistor will follow the decay

$I(t)=(I_0+(V_{FWD}+V_{coldD})/R(T(t)))e^{-t/\tau} - (V_{FWD}+V_{coldD})/R(T(t))$

-where R(T(t)) include also the busbar and cable resistance. The energy absorption in the dump resistor is

$$E=\int_0^{t^*}\rho(1+\alpha((T(t)-T_o)+\beta(T(t)-T_o)^2)(L/A)I(t)^2\,dt$$

with $t^*=\tau \ln(1+I_0 R(T_e)/(V_{FWD}+V_{coldD}))$

The energy deposit in the dump resistors represents more than 99.7 % of the total stored energy, the rest being dissipated in the diodes, busbars and cables.

If the 75 mΩ, 700 MJ dipole resistor was built as a single unit, satisfying all the requirements listed above, it would exceed a length of 11 metres, have a weight around 8 tons and would require a sturdy self-supporting structure for its handling. Consequently, the final design features three, individual, 225 mΩ units to be electrically connected in parallel, each unit having its own water reservoir and heat exchanger, connected to a common, external de-mineralised water circuit.

3.2 The absorber body

For the resistor plates, a number of candidate materials was evaluated: normal carbon steel, corrosion protected by a chemical Ni-plating (Kanigen process), ordinary stainless steel (AISI 304) and some special resistor materials, e.g. Fecral (14 % Cr, 6 % Al) which will be used for the dump resistors of some of the LHC 600A extraction systems. The mild steel was eliminated, mainly because of the cost of the Kanigen treatment. Its high temperature coefficient, which would either cause an increase in the voltage during the extraction or, as this is undesirable, lead to a low maximum operating temperature and a larger mass of steel also made this solution less attractive, compared to the alternatives. The low temperature coefficient of the special resistor alloys was interesting, but features like weldability, machinability and cost were unfavourable. Consequently, the resistors were made from stainless steel elements. A total of 84 series-connected, 4 mm thick plates with a total mass of 1820 kg constitute the centrally placed absorber body of one 225 mΩ / 230 MJ resistor unit (fig.1). The additional resistance of the welds was determined experimentally and taken into account. The parasitic inductance is calculated to be less than 2 μH.

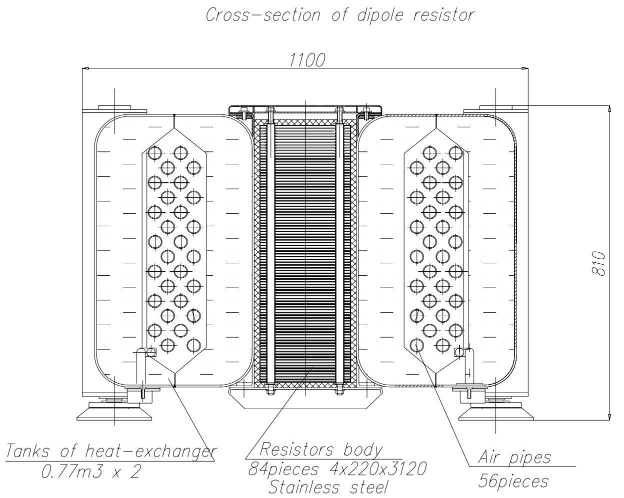

Fig. 1. Cross sections of a 225 mΩ and 3.5 m long dipole resistor

The 4 mm gaps between the horizontally mounted plates are maintained by steel spacers at the welded interconnection regions and along the plate surfaces by high-temperature insulators (Mica). The structure is clamped at one extremity but is free to expand during the extraction. The design takes into account the deformations caused by the significant temperature gradients, occurring during the heating and cooling. Four fans blow the cooled air of the closed circuit into the gaps between the hot absorber plates. The hot air is returned through the pipes of the two heat exchanger modules. Computer simulations were used to optimise the design and link together the performances of the absorber and the heat exchangers. The C++ routines calculates the heat transfers at all the surfaces between steel plates and the cooling air as well as from the hot air through the 56 steel pipes to the water of the reservoir. The results show that the steel absorber body will be cooled down to 50 °C within 1.6 hours of cooling time - see fig. 2. This will allow the re-closure of the main circuit breakers for re-powering of the chain.

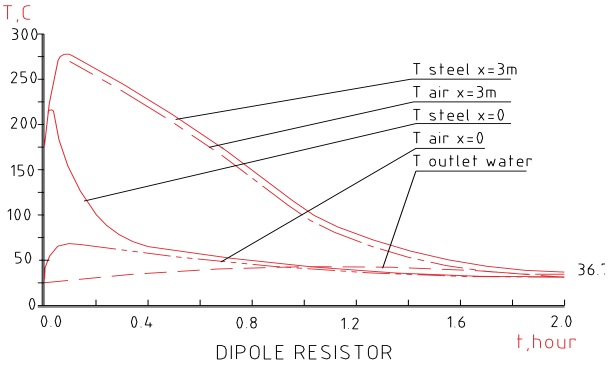

Fig.2. Calculated temperature profiles for energy extraction of 230 MJ. Assuming fan operation as from 50 °C steel temperature, water flow 30 l/min with cooling primary cooling to 25 °C.

3.3 Special components

Prototypes of certain special components were developed by European Industry. This concerned in particular the feedthroughs (bushings), the flexible high-current connectors, linking the hot resistor body to the bushings and the high-temperature sensors.

Of particular interest are the flexible power connections. Their role is to transmit the current to the absorber block without significant self-heating during the discharge period and at the same time to minimise the heat conduction from the hot body to the externally connected busbars and cables during the complete heating/cooling cycle. Following an analysis of a number of candidate conductor alloys, pure nickel was finally chosen because of its excellent electrical-to-thermal conductivity ratio. Two prototypes, each based on braids made from fine Ni filaments and the use of Cu/Be elastic lamella strips (louvers) at the cool end, were built and tested under normal and exceptional (one of three resistors broken) operating conditions.

A simplified version, using laminations of 0.5 mm Ni foils, is presently being build at Company 'Erico', Germany.

4. DETAILED DESIGN OF THE QUADRUPOLE RESISTOR

The conceptual principles and the methods used in the design of the quadrupole dump resistors are basically identical to what is described above for the dipole units. Two different resistance values, 6.6 mΩ and 7.7 mΩ, are required to obtain the same extraction time constant (40s) for the two different quadrupole circuits. The stored energy is 22-24 MJ. The absorber body is composed of three sub-assemblies, each comprising 12 series connected resistor plates. The three sub-assemblies are electrically parallel connected. The absorber body is mounted vertically at the centre of the unit, surrounded by a cylindrical tank, containing a storage of 165 litres of water and the 16 corrugated pipes needed for the heat exchange. The two fans are located at the top of the assembly and assure the forced air circulation in the closed circuit, fig. 3. The results of the associated thermal computer simulations show that the cool-down time to 50 °C is less than 1.2 hours.

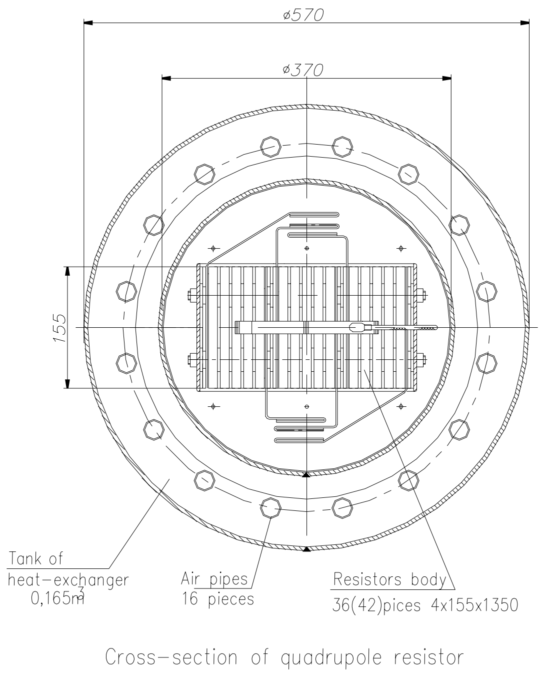

Fig.3. Horizontal cross-section of the 1.35 m long quadrupole dump resistor.

5. CONCLUSIONS

Overall performance simulations and type tests of the principal sub-components have shown, that the extraction resistor assemblies will meet the technical specification. Both types of energy absorbers are presently under construction at IHEP, Protvino. The first phase of manufacture of the required tooling was terminated in early spring 2000 and two prototypes are expected to be ready for type tests later in the summer. Four quadrupole units, in a slightly modified version, will be ready for use in the String 2 dipole circuit by late autumn 2000. The 57 dipole units and 19 quadrupole units will be supplied by IHEP through the CERN-Russian Federation Collaboration Agreement .

6. REFERENCES

[1] Magnetic Energy Extraction Resistors for the Main Dipole Power Circuits of the LHC Collider. Technical Specification. CERN January 1997.

[2] Magnetic Energy Extraction Resistors for the Main Quadrupole Circuits of the LHC Collider. Technical Specification. CERN August 1997.