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**QUENCH PROTECTION DIODES
FOR THE LARGE HADRON COLLIDER LHC AT CERN**

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QUENCH PROTECTION DIODES FOR THE LARGE HADRON COLLIDER LHC AT CERN

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ABSTRACT

For the quench protection of the main ring dipole and quadrupole magnets for the proposed Large Hadron Collider at CERN two lines of approach have been pursued for the realization of a suitable high current by-pass element at liquid helium temperature. Two commercially available diodes of the HERA type connected in parallel can easily meet the requirements if a sufficient good current sharing is imposed by current balancing elements. Design criteria for these current balancing elements are derived from individual diode characteristics. Single diode elements of thin base region, newly developed in industry, have been successfully tested. The results are promising and, if the diodes can be made with reproducible characteristics, they will provide the preferred solution especially in view of radiation hardness.

INTRODUCTION

The quench protection of the main ring dipole and quadrupole magnets for the proposed Large Hadron Collider at CERN is based on self-protected magnets and high current by-pass diodes. Since there is no practical way to extract a major fraction of the stored energy from the quenching magnet, which is in a series chain of magnets, self protection is achieved by stainless steel heater strips mounted on the outer layers of each magnet. As soon as a quench is detected, capacitors are discharged on the heaters and the increasing resistance of the quenching magnet causes the magnet current to commutate over to the by-pass diodes which are mounted inside the He II vessel in order to reduce the heat load on the cryogenic system caused by safety leads. During a magnet quench the diode will conduct a peak current of about 15 kA, it will be exposed to integrated current loads $\int i^2 dt$ of about $1.2 \cdot 10^{10} \text{ A}^2 \text{ s}$. The copper blocks, mounted on each side of the diode and acting as heat sinks and current connections, have to absorb an energy of about 1.5 MJ, when the whole magnet ring is de-energized with a time constant of about 100 s. Two lines of approach have been pursued for the realization of a suitable current by-pass element at liquid helium temperature:

1. Parallel connection of commercially available high current diodes of the DS-6000 type from ABB (as used in HERA at DESY).
2. Development of a single diode element in collaboration with industry to avoid the problems of parallel connection.

Furthermore the diode will be subjected to a relatively high radiation dose. The degradation of diode characteristics at low temperatures in an accelerator environment is described elsewhere¹.

TESTS ON COMMERCIALY AVAILABLE DIODES

Endurance tests

The temperature rise in the diode wafer is governed by the power generated inside the wafer and the transfer of heat to the cooler or heat sink. In the early stage of the current commutation process, a power of about 20 kW or more (depending on the forward voltage drop U_f) will be generated in the by-pass diode for the LHC magnets and must be transferred as quickly as possible to heat sinks through a sufficiently large cross-section of low contact thermal resistance. Two different types of readily available diodes have been selected for first endurance tests at 77 K starting temperature, the DS-6000 type from ABB and the JD-6000 type from PSI (USA). The DS-6000 is a heavily doped diode with a thin wafer of about 45 mm diameter only, which has already been shown to have a very low forward voltage drop U_f (on-resistance)². The JD-6000 from PSI has a thicker, less heavily doped wafer of about 75 mm diameter, and thus provides larger thermal contact cross-section area for heat transfer. The DS-6000 diode was mounted in a modified diode clamp of the HERA type² with enlarged heat sinks. For the PSI diode a special diode clamp and heat sink were constructed. In both cases the enthalpy of the copper heat sink was large enough to absorb an energy of about 1.5 MJ without exceeding an average heat sink temperature of about 400 K. During the endurance tests, the current was ramped -by applying different current rise rates up to about 30 kA/s- to flat top values between 8 kA and 12 kA of different length. Adiabatic conditions were simulated by pulling the diode out of the liquid nitrogen bath and afterwards immediately applying the current. In the tests all DS-6000 diodes survived at constant current levels from 8 to 10 kA for up to about 170 s, whereas the PSI diode burned out (punch through) at 10 kA after 25 s. Three DS-6000 diodes burned out at 12 kA after 8.5 and 30 s however and we did not test at 15 kA. It seems that the thermal resistance at the contact area from the diode to the heat sinks is too high for a sufficient transfer of the power generated in the diode wafer. Two diodes of the DS-6000 type connected in parallel will easily meet the requirements with a sufficient reserve if the current sharing ratio is not worse than about 40% to 60%. At equal current sharing only half of the power is generated in one diode and the $\int i^2 dt$ is reduced by a factor 4.

Electrical characteristics versus temperature

In order to see whether preselected diode pairs can be simply connected in parallel or whether a current balancing network must be provided to avoid the burn out of one diode, the turn on voltage V_{to} at different voltage rise rates and the dynamic current voltage characteristic $I_f = f(U_f)$ at different current rise rates has been measured on several DS-6000 diodes at 4.2 K and at 1.8 K; results are shown in Fig. 1. Due to the small heat capacity at 1.8 K the diode wafer is rapidly heated to temperatures above 40 K as indicated by the voltage drop from $V_{to} = 2.4$ V to about $U_f = 1.2$ V. Above this temperature, the forward voltage drop U_f decreases by about 1 mV/K

Fig. 1 Dynamic current voltage characteristic $I_f = f(U_f)$ of DS-6000 diodes

Fig. 2 Approximate forward voltage dependence on current and temperature for the DS-6000 diode

with increasing temperature. At slower current rise rate the temperature in the diode wafer is higher, which is indicated by the smaller forward voltage drop U_f . The diodes show almost identical behaviour with starting temperatures of 1.8 K and 4.2 K. Approximate forward voltage U_f versus temperature at different current levels is shown in Fig. 2.

The turn on voltage V_{t0} was measured during voltage ramping and monitoring the current through the diode in forward direction. Fig. 3 shows the increase of the turn on voltage V_{t0} versus voltage rise rate dU/dt measured on 6 different DS-6000 diodes at 1.8 K. The turn on voltage V_{t0} varies between 2 and 3 V in the range of dU/dt typical for quenching magnets. V_{t0} increases to about 4 V to 5 V at voltage rise rates in the order of 10^6 V/s. At voltage rise rates up to about 1000 V/s differences in turn on voltage up to a maximum of 600 mV were measured on diodes not originating from the same lot. For diodes from the same lot (SD4 and SD5) a maximum difference in V_{t0} of about 30 mV was measured, as can be seen in Fig. 4, where the turn on voltage V_{t0} versus voltage rise rate dU/dt at 1.8 K and 4.2 K is shown. These differences in turn on voltage will cause the problems for a parallel connection of diodes at liquid helium temperatures. As soon as one diode starts to conduct current -even in the 100 mA range- the small heat capacity of the silicon causes a rapid temperature increase and thus a significant decrease in forward voltage U_f . In the worst case all the current will pass through the diode which opens first and may lead to a burn out.

Parallel connection of two DS-6000

In order to observe the current sharing in a parallel connection of diodes, two diodes of the DS-6000 type with almost identical V_{t0} versus dU/dt characteristic were selected and mounted in parallel without special current balancing elements. A low resistance shunt ($\sim 10 \mu\Omega$) made of Hastelloy C22³ in series with each of these diodes allowed to measure the individual diode currents. Fig. 5 shows the total current and the individual diode currents versus time at 77 K.

Fig. 3 Turn on voltage V_{to} versus voltage rise rate for six DS-6000 diodes at 1.8 K

Fig. 4 Turn on voltage V_{to} versus voltage rise rate dU/dt for two DS-6000 diodes

starting temperature. Both diodes open at almost the same time. The initial current sharing of about 60% to 40% improved after 70 s to about 55% to 45%. This auto-balancing effect is due to the thermal link between the two diodes and the voltage drop on the Hastelloy shunts acting as balancing resistors. The same arrangement was tested afterwards at 1.8 K starting temperature. Fig. 6 shows the individual diode currents versus time with a flat top current of about 16 kA.

Thermal model calculations for the temperature of the wafer of diode SD5 derived from temperature measurements on the heat sinks have shown that SD5 opens at about 60 K. The current sharing in fact improves with time but is still unacceptable (70% to 25%). Even optimistic extrapolations for the current versus time showed that the diode SD4 would have burned out after about 25 s. The experiment was stopped after 13.5 s for cryogenic reasons and to save the selected diode pair for an experiment with current balancing elements.

Current balancing

The following methods were investigated to improve the current balancing especially already in the very early beginning of current rising process:

- resistors in series with each of the diodes;
- electromagnetically coupled reactor;
- close thermal link between the two diodes.

Since the forward voltage on the diode which opens first drops quickly to a level of about 1 V, series resistors must create an additional voltage up to several volts to open the second diode being still at liquid helium temperature. This resistance has to absorb energies in the range of MJ during the decay of 100 s time constant and additional heat sinks must be provided. The selection of suitable series resistors for the very beginning of the current rise process would lead to unacceptably high voltages and power consumption. In an electromagnetically coupled reactor the additional voltage to open the second diode is proportional to the current rise rate dI/dt in the diode which opens first. By selecting very high permeability material

Fig. 5 Current distribution in two DS-6000 in parallel at $T_0 = 77$ K without current balancing

Fig. 6 Current distribution in two DS-6000 in parallel at $T_0 = 1.8$ K without current balancing

for the reactor core, it is possible to create the required voltage difference of up to about 100 mV for V_{t0} to open the second diode at still very low current levels (up to a few amperes) inside the first diode. From quench simulations⁴ and measurements on model magnets current rise rates of about 10 A/s up to a few kA/s were estimated.

The inductance of the electromagnetically coupled reactor must be designed for the lowest current rise rate since the high permeability core will start saturating at higher current levels. For our application a coupled electromagnetic reactor of about 20 mH inductance (one turn only) saturating at a few amperes has been designed. The core material consisted of amorphous iron with a relative permeability of about 80000 at liquid helium temperatures.

To achieve a close *thermal link* between the two diodes, a minimum heat sink volume is necessary and practical limitations must be respected. The copper spacer between the two diodes acting as a heat sink has still to absorb some energy, and space must be provided for a good electrical contact to the bus bar going to the magnet. Fig. 7 shows the set-up for two diodes connected in parallel, with the electromagnetically coupled reactor -consisting of nine strip-wound cores of amorphous iron- and the series resistors for current balancing. In a special set-up, with series resistors acting as shunts to measure small currents, the efficiency of the electromagnetically coupled reactor has been verified at liquid helium temperatures. At very low current levels (< 100 mA) the current balancing was perfect, i.e. identical currents in both diodes, whereas at current levels up to 50 A the current distribution was imposed by the inequality of the resistive shunts and a current sharing ratio of about 55% to 45% was observed. For the real application at high current levels low resistive series resistors will be used in addition to the electromagnetically coupled reactor and the close thermal linking. Further tests on the parallel connection of diodes have been suspended due to the fact that meanwhile a single diode has been developed, which will eliminate the problems of parallel connection.

Fig. 7 Two diodes in parallel with coupled reactor and series resistors for current balancing

SINGLE HIGH CURRENT DIODE ELEMENTS

To avoid excessive temperatures inside the junction of the diode, a low forward voltage drop and a rapid heat transfer to the heat sink are essential. For a low forward voltage drop, the doping concentration in the silicon wafer should be very high and the silicon chip and the base width as thin as possible. These conditions give a diode with relatively low reverse breakdown voltage.

First estimations from the discharge circuit analysis show that the reverse voltage will normally not exceed 50 V. In close collaboration with CERN, two European firms developed prototypes of single diodes with a wafer diameter of 75 mm and a high doping concentration. They should be able to meet the above mentioned requirements with respect to current carrying capability and reverse breakdown voltage. These prototype diodes were submitted to current pulse tests at 2 K, 4.2 K, 77 K, and 300 K and to endurance tests at 77 K starting temperature.

High current pulse tests

The high current voltage characteristics $I_f = f(U_f)$ were obtained with a fast pulse power supply providing 16 kA, 200 μ s half sinusoidal current pulses. The details of the measuring equipment and the test procedure are described elsewhere¹.

At room temperature and peak currents of 15 kA the temperature rise in the diode junction during the 200 μ s current pulse is negligibly small, it increases by about 2 K at 77 K and by about 40 K at liquid helium starting temperature.

Fig. 8 shows the I_f - U_f characteristic at different temperatures for two different types of diode. For one of the diodes the U_f is acceptable, whereas for the other diode the increased forward voltage U_f is due to the relatively large base width. U_f increases to about 10 V at 4.2 K and 2 K.

Fig. 9 shows the reverse current I_r versus reverse blocking voltage U_r of these diodes at different temperatures. One diode shows an extremely low blocking voltage almost at all temperature ranges. On non-vented diodes reverse voltage breakdowns due to the low pressure at low temperature inside the capsule were observed above 100 V.

Fig. 8 $I_f = U_f$ characteristic versus temperature of diodes with thick and thin base region

Endurance tests

Endurance tests were first carried out at 77 K starting temperature and at constant current levels before submitting the diodes to endurance tests at liquid helium temperatures. In view of power generation in the diode junction, a constant current load of 15 kA during 100 s is about equivalent to an exponential decay from 15 kA with 100 s time constant. Concerning the maximum temperature rise, tests at constant current are even harder due to higher temperature gradients inside the diode assembly.

Constant currents of 15 kA for up to 170 s were applied and the temperature rise on the heat sink and diode capsule (anode and cathode) recorded versus time. The maximum wafer temperature was estimated from thermal modelling making use of the measured temperatures on the heat sinks. For the tests with 1600 cm³ heat sink volume, a maximum junction temperature of about 490 K was estimated and with 2500 cm³ heat sink volume T_{jmax} has not exceeded 360 K. Fig. 10 shows the measured forward voltage U_f and the diode current I_f versus time when testing in the larger heat sink.

The endurance tests at liquid nitrogen starting temperature on three different diodes mounted in different types of heat sinks have shown that the thermal contact area of about 75 mm diameter should be sufficiently large to transfer the developed power to the heat sink without overheating the wafer, if the forward voltage U_f stays reasonably small -as indicated in Fig. 10 for the thin base diode- and does not increase due to radiation, for instance. A number of diode samples will be produced and submitted to endurance tests at liquid helium temperatures in the near future.

CONCLUSIONS

Two lines of approach have been pursued successfully for the realization of a suitable current by-pass element at liquid helium temperature:

Fig. 9 Reverse bias characteristic versus temperature of two different diodes

Fig. 10 Forward voltage and current versus time during endurance test at $T_0 = 77 \text{ K}$

1. Two commercially available diodes of the HERA type connected in parallel can easily meet the requirements if a sufficient good current sharing is imposed by current balancing elements. Design criteria for these current balancing elements can be derived from individual diode characteristics at low temperature.
2. Single diode elements of thin base region developed in industry have been tested. The results are promising and if the diodes can be made with reproducible characteristics they will provide the preferred solution especially in view of radiation hardness.

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