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RESULTS FROM THE LHC BEAM DUMP RELIABILITY RUN

J. Uythoven, A. Antoine, E. Carlier, F. Castronuovo, L. Ducimetière, E. Gallet, B. Goddard,
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The LHC Beam Dumping System is one of the vital elements of the LHC Machine Protection System and has to operate reliably every time a beam dump request is made. Detailed dependability calculations have been made, resulting in expected rates for the different system failure modes. A 'reliability run' of the whole system, installed in its final configuration in the LHC, has been made to discover infant mortality problems and to compare the occurrence of the measured failure modes with their calculations.

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The LHC Beam Dumping System is one of the vital elements of the LHC Machine Protection System and has to operate reliably every time a beam dump request is made. Detailed dependability calculations have been made, resulting in expected rates for the different system failure modes. A 'reliability run' of the whole system, installed in its final configuration in the LHC, has been made to discover infant mortality problems and to compare the occurrence of the measured failure modes with their calculations.

INTRODUCTION

The LHC Beam Dumping System [1] must be able to safely abort the high intensity LHC beams at any given moment. The nominal system consists per LHC beam of 15 horizontally deflecting kickers (MKD), 15 vertically deflecting septum magnets (MSD) and 10 dilution kicker magnets (MKB). Beam abort must take place upon request within a delay of less than 3 turns (about 300 μs) and be adjusted to the beam energy which varies between 450 GeV at injection and 7 TeV at top energy.

The energy stored in one nominal LHC beam is 360 MJ, about 200 times larger than at HERA or the Tevatron. The energy stored in the superconducting magnets is 10 GJ. These amounts of energy, with their large damage potential, result in stringent requirements for the performance of the Machine Protection System [2, 3].

The LHC Beam Dumping System (LBDS) is at the heart of the Machine Protection System. The design of the system was underlying stringent safety requirements and an in-depth dependability analysis of the system has been made [4, 5]. According to these studies the resulting unsafety of one beam dumping system is $2 \cdot 10^{-7}$ per year, which corresponds largely to SIL4 (Safety and Integrity Level), and four safe 'false dumps' per year are expected per beam dumping system.

RELIAIBILITY RUN

Reason for Testing

The aim of the reliability run of the LBDS is to:

- Validate the reliability figures presented in [4, 5];
- Troubleshoot 'infant mortality problems';
- Check for unexpected failure modes;
- Obtain operational experience with the beam dumping system and the systems it interfaces to.

The first item can be quantified for the solid state power switches of the MKD generators. In the reliability analysis of the LBDS a failure rate of the switches of $\lambda = 2.4 \cdot 10^{-6}$ per hour is used, according to the estimate of the manufacturer. The test hypothesis for the reliability run is more pessimistic with a switch failure rate of $\lambda \leq 10^{-4}$/h, allowing for a realistic test period. This corresponds to a safety level of SIL3 for a complete beam dumping system, which is still acceptable considering the complete LHC Machine Protection System. With this assumed failure rate, a running period of 3 months of both Beam Dumping Systems, with 75 % effective running time and pulsing on average one time every hour, would result in 6 switch failures, with a 95 % one-sided confidence level, see Fig. 1. It should be noted that a single switch failure, as looked for in the reliability run, is acceptable due to the large redundancy in the system.

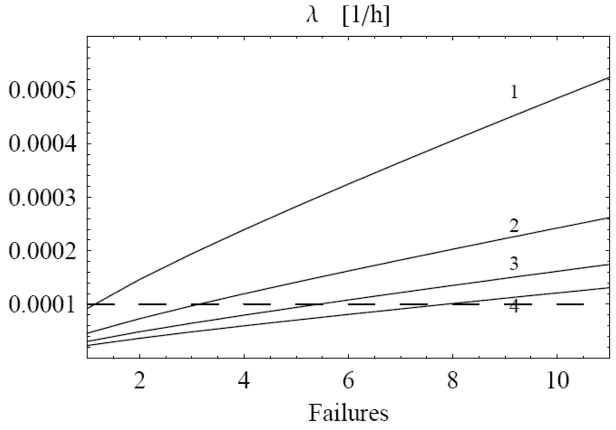

Figure 1: Lines corresponding to the testing period in months relating the different MKD switch failure rates λ to the expected number of failures [5].

Execution of the Tests

The pulsed power systems MKD and MKB have been carefully tested and calibrated in the laboratory [6]. After installation in the LHC tunnel the systems have been commissioned in their final configuration. For the first year of LHC operation, only 4 MKB magnets are installed per beam, and the reliability run was performed with this reduced configuration. In November 2007 the Beam 1 dumping system was operational in local mode and the first automated tests started. Gradually the system was connected up to the external systems: the Beam Interlock System (BIS), a Beam Energy Simulator, the Timing System and the RF-system. The Beam 2 System became operational in December 2007 and most of the data for this system have been collected in local mode.

During the reliability run the diagnostics to automatically detect any system errors was operational:

- Hardware systems to check the redundancy of the signal paths and that the measured voltages and currents are within the predefined tolerances.

- An Internal Operational Check (IPOC) which analysis the required MKD and MKB waveforms, calculates typical points and compares these with the references. The IPOC is executed by the kicker system hardware.
- An External Operation Check (XPOC) of the MKD and MKB waveforms, which executes a similar check as the IPOC, but executed on a central server, which also includes other LBDS analysis related to Beam Instrumentation measurements [7].
- Logging of all important parameters, for a large fraction provided by the IPOC and XPOC analysis.

Statistics of the Executed Tests

Data from the logging system has been collected, summarising the effective operational time of the two beam dumping systems and the different energies the system has been operated at. The reliability run is still ongoing at the moment of writing; only data up to the end of May 2008 are presented here.

Data collection for the Beam 1 system started on 8 November 2007. Until end of May 2008, the system has been pulsing 19648 times with an effective running time, defined as the time between pulses being less than 13 hours, of 1593 hours. It is assumed that the system will have been operational for about 75 % of these 1593 hours, according to the reliability run requirements. The different energies at which the system has been pulsing are shown as a function of time in Fig. 2. The distribution for the different energies is shown in Fig. 3. Although the number of pulses at 7 TeV is limited (6 %), most of the 'waiting time' under high voltage took place with 7 TeV settings (31 %). Table 1 summarises the operational data for the Beam 1 and the Beam 2 system.

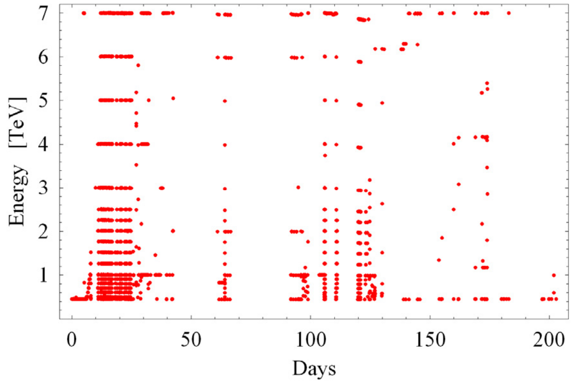

Figure 2: The different energies at which the Beam 1 system has been pulsing as a function of the running time.

Table 1: Summary of the running time for both beams.

	Beam 1	**Beam 2**
Number of pulses	19648	1332
Period considered	6.8 months	5.6 months
Effective running time	2.2 months	1.3 months
Pulses at 7 TeV	6 %	5 %
Time at 7 TeV	31 %	14 %

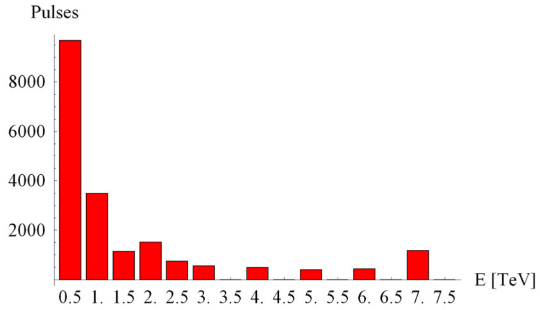

Figure 3: The number of pulses as a function of energy for the Beam 1 system.

RESULTS OF THE TESTS

Overall Results

The most important overall result is that for the MKD extraction kicker system no critical failures occurred which would have resulted in a non-acceptable beam dump. No 'asynchronous' beam dumps were recorded. However, an unexpected common mode failure on the dilution kickers MKB was identified.

MKD Switch Failures

During the reliability run up to the end of May the equivalent running time for the two beams was 1.8 months. According to Fig. 1 for this period 3 switch faults are expected, for the assumed failure rate of the reliability run of $\lambda = 10^{-4}$/h. During the testing period four switches needed to be replaced due to a short circuit of one of the GTO discs; three on the Beam 1 system and one on the Beam 2 system. All failures were safe with the surveillance system triggering the beam dump after an error was detected.

Other Failures

The system has been constantly monitored with the IPOC and XPOC systems and the typical points have been recorded [6]. A falling trend in the pulse length, identified for two MKD systems, was traced back to a decreasing value of the capacitor used in the compensation circuit. These capacitors of the self-healing type are expected to reduce in value during their 'burn-in period', but should then stabilise, which was not the case for these two systems. These capacitors have been replaced.

A fuse in the trigger circuit of the MKD systems broke down on five occasions. This was explained by an 'under design' of a part of the circuit, which will be adapted before operation with beam. During the testing period two power converter failures occurred, one for the main circuit and one for the compensation circuit. This is an average failure rate of $2 \cdot 10^{-5}$/h, which is worse than the assumed $1 \cdot 10^{-6}$/h. It is shown in [5, p.138] that this only affects the number of expected false dumps per year, not the safety.

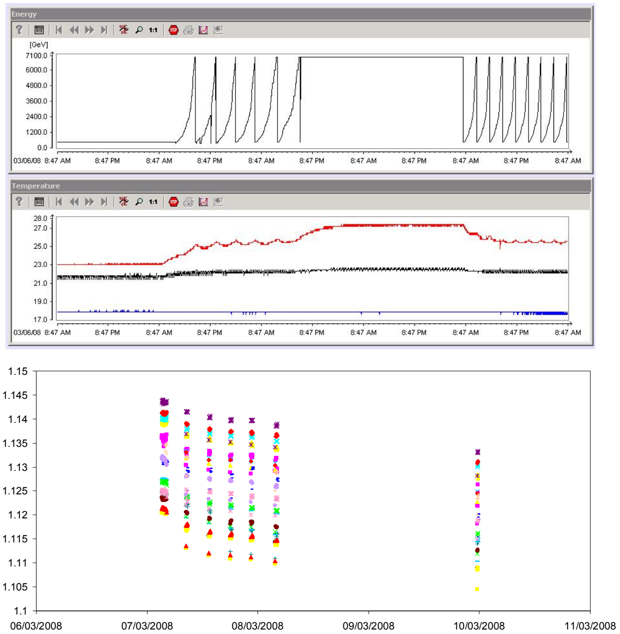

Figure 4: Demonstration of the dependency of the MKD kick current [kA] at injection energy (bottom figure for 15 generators) on the generator temperature (middle) which depends again on the generator energy setting (top).

Temperature Effect of MKD Switches

It was found that the kick amplitude of the MKD system was reduced by up to 1.4 % at low energies, after it had been operating for longer periods at higher energies. This was traced down to an unexpected temperature sensitivity of the solid state switch, either due running at higher energies or due to environmental temperature changes, see Fig. 4. A temperature regulation of the generator switch compartment is presently under development and will be installed for operation in 2009. This is also expected to be beneficial for the GTO lifetime.

MKB Magnet Break Down

The diluter magnets MKB are housed in vacuum tanks and operate under vacuum. After a longer period of operation both systems have shown simultaneous magnet break-downs, as illustrated in Fig. 5 for one magnet. The failure for the Beam 2 system was explained by a non-operational vacuum interlock, which allowed the system to pulse during several days under bad vacuum conditions, leading to damage due to glow discharge. However, 3 out of 4 magnets of the Beam 1 dilution system also showed a simultaneous break down, after many months of stable operation. This is worrying because it indicates the possibility of common mode failures which had not been anticipated [5].

CONCLUSIONS

The two LHC Beam Dumping Systems have been operational in the LHC tunnel for an average effective running period of almost two months. During this period four MKD extraction kicker switch failures occurred, which is close to the expected three failures. This confirms the assumed failure rate $\lambda = 10^{-4}$ /h and is compatible with a SIL3 level of the system. However, this failure rate is not as low as stated by the switch manufacturer ($\lambda = 2.4\cdot10^{-6}$ /h). All failures which occurred during the reliability run were "safe" failures

The reliability run allowed detecting some flaws on the system electronics, which will be upgraded accordingly. A temperature regulating system will be installed for the MKD generator switch compartment to guarantee sufficient pulse stability.

A common mode failure of simultaneous break-downs of three out of the four installed MKB dilution system magnet occurred. This effect is not yet completely understood and is under further investigation.

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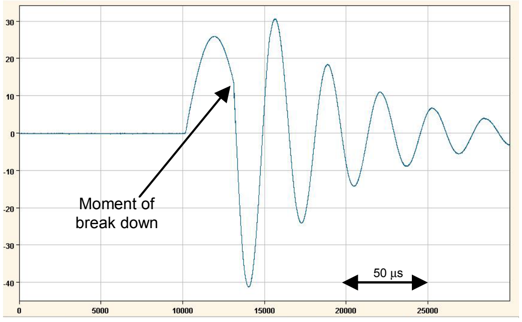

Figure 5: Measured MKB current [kA] versus time during a break down.

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