CONSIDERATIONS ON AN UPGRADE POSSIBILITY OF THE LHC BEAM DUMP KICKER SYSTEM

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Abstract

The LHC Beam Dump System (LBDS) is designed to safely dispose the circulating beams over a wide range of energy from 450 GeV up to 7 TeV, where the maximum stored energy is 362 MJ per beam. One of the most critical components of the LBDS are the extraction kickers that must reliably switch on within the 3 μs particle-free abort gap. To ensure this functionality, even in the event of a power-cut, the power generator capacitors remain charged and hence the Gate Turn-Off (GTO) switch stack has to hold the full voltage throughout beam operation. The increase of the LHC collision energy to 13 TeV has increased the voltage levels at the GTO stacks and during re-commissioning an increased rate of high-voltage (HV) related issues at the level of the GTO stack was observed. Different solutions have been analysed and an improved GTO stack will be implemented. This paper also outlines the benefit of adding more kicker magnets to improve the voltage hold off issues and to improve the tolerance to missing kickers during extraction.

INTRODUCTION

The LBDS [1] is located as an insertion in Interaction Region (IR) 6 of the LHC and is composed of an extraction system consisting of fast-pulsing extraction kicker magnets (MKD), magnetic septa (MSD), kick enhancing quadrupoles (Q4) and magnetic dilution kickers (MKB) to safely distribute the energy stored in the beam over an absorber (TDE). A schematic of the LBDS is presented in Fig. 1 showing the two LHC beams extracted in a symmetric manner, left and right of IR6.

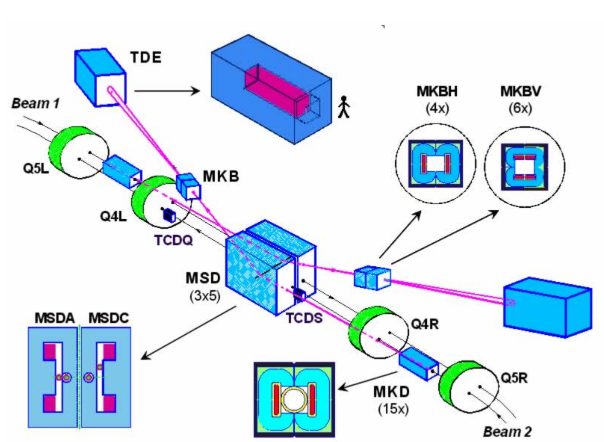

Figure 1: Schematic diagram of the LBDS at Point 6 of the LHC [2].

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Presently, there are 15 MKD magnets installed per beam with each kicker driven independently by its own power generator. The voltage on the capacitors of all the power generators is under constant surveillance by the Beam Energy Tracking System [3] to guarantee that the beam is deflected horizontally by 0.275 mrad and placed onto the correct trajectory at all energies from injection to collision, i.e. from 450 GeV to 7 TeV. The system must extract and safely dispose the beam at the end of a normal LHC physics fill but also in the event that machine failures are detected, including failures of the LBDS itself. Since the re-start of the LHC in 2015 the top energy has been increased to 6.5 TeV per beam, i.e. 13 TeV in the centre-of-mass frame, pushing the GTO switch voltage to 26.8 kV.

GTO STACK IMPROVEMENTS

A study program was launched to improve the generator reliability since the first HV-issues on the GTO stacks were observed in 2008. Analysis using numerical field simulations showed that local electrostatic fields of up to 8 MV/m in the GTO stack assembly can be present at top energies. The arcing of the GTO stack was observed during laboratory tests at the expected high-field locations as shown in Fig. 2. The arcing is seen between the GTO HV deflectors and the return conductors, which are insulated with plexiglass. Together with local parameters like geometry inhomogeneity, surface finish, dust, etc., breakdowns occur at a rather low rate. However, as the MKD generators are part of a safety critical system, even a low number of breakdowns is unacceptable. It would not only lead to the loss of beam during an LHC fill but it is a potential threat to machine protection as the resulting beam abort will, most likely, be asynchronous with the particle-free abort gap. Erratic triggering of the MKD impacts machine availability severely as each breakdown necessitates the exchange of the concerned generator followed by tests, conditioning and a reliability run and causing downtime in the order of a day.

During LHC Run 1 the maximum voltage was clamped to 21 kV, corresponding to a maximum energy of 5 TeV, in order to prevent such breakdowns. For Run 2 dielectric inserts for the high-field regions around the GTO discs have been developed, see Fig. 3 (left). Resistors were added in parallel to the gate cathode to reduce the coupling between the GTOs. All modifications were successfully tested in the laboratory.

During LS1 all GTO stacks were modified to reduce the maximum electric field below 3 MV/m in air (ionisation limit) as shown in Fig. 3 (left). The modifications worked well in the laboratory, however, in real conditions

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they showed sensitivity to pollution, e.g. dust, fibres, hairs, insects, etc. The laboratory performance could not be reproduced during reliability runs (without beam) in the machine for the post-LS1 (Long Shutdown) recommissioning. A correlation between the presence of dust particles and the breakdown rate was observed. The perforated panels on the sensitive equipment were replaced by solid, non-perforated panels to prevent dust penetration. A meticulous cleaning of the sensitive regions was carried out and the non-perforated panels will ensure dust-free operation for a longer time.

Figure 2: Long exposure photograph (30 seconds) of GTO stacks sparking in the laboratory.

Future modifications with the goal of reducing the maximum field to 1.5 MV/m will offer even more margin. The new prototype is photographed in Fig. 3 (right) and will undergo HV tests soon. The return bars are moved further from the GTO stack and the insulation of the discs and return bars has been improved. A trigger transformer upgrade was also developed that will compensate the increase in rise-time caused by the higher stack inductance resulting from the increased distance of the return bars.

Figure 3: GTO stacks: (left) installed after LS1 and (right) prototype of the new design.

ADDITIONAL MKD UPGRADE POSSIBILITIES

The motivation behind adding extra MKD kicker modules is to reduce the voltage held per generator during operation and aimed at alleviating the HV issues encountered to date. Operating at lower voltage should increase the system's availability and reduce the impact of the failure scenario in which a single MKD triggers erratically and asynchronously with the abort-gap. In addition, having more MKDs on the beam line provides more tolerance should one fail.

The 15 MKD modules installed on each beam are located between the large-aperture IR quadrupoles Q4 and Q5, named A to O outward from IR6. There is no space to integrate more MKDs between the quadrupoles and therefore different layout configurations were considered outside the Q4-Q5 region; the options are labelled A to D as shown in Fig. 4. The additional Q5 magnet (labelled *HLQ5* in Fig. 4) and the optics and layout changes that are foreseen in IR6 for the High-Luminosity LHC (HL-LHC) project [4] were considered. The Q4 is a defocusing quadrupole in the horizontal plane, which enhances the extraction kick imparted by the MKDs by 30 %, whereas the Q5 is a focusing quadrupole. Even though the polarity of the Q5 is undesirable for kickers placed upstream, it was found that the overall effect is beneficial if the additional kickers are placed as close as possible to the Q5 and the phase advance between them is small. In fact, for options A and D, the kick reduction by Q5 amounts to approximately 20 % of the kick imparted by the upstream MKDs; the kick is further enhanced by the downstream Q4 and the total voltage of the MKD system can be reduced. The downstream position of additional MKDs is limited by the protection devices installed to mask the Q4 from a sweep of the counter-rotating beam in the case of an erratic firing of the extraction system.

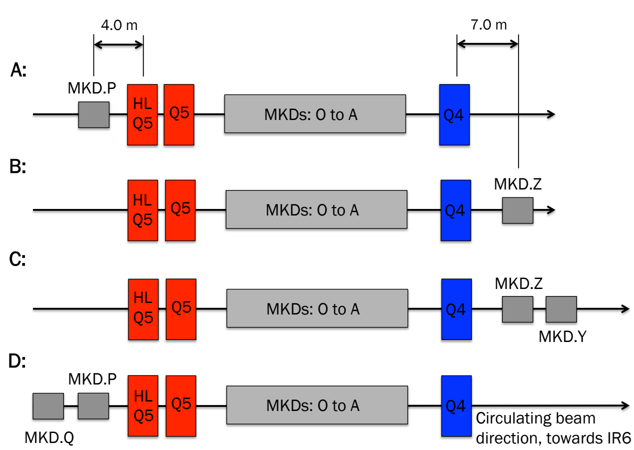

Figure 4: Options considered for installation of extra MKDs.

The results of the study are summarised in Table 1 with the kicks given for the first bunch in the LHC filling pattern located at the 100 % reference point on the MKD waveform, see [5]. The different options were compared by tuning the MKD voltage to give the same total horizontal deflection in

Table 1: MKD Voltage for Upgrade Options Considered. In all cases total kick (MKD + Q5 + Q4) kept constant at 0.359 mrad (kicks given for Bunch 1 located at the 100% point of the MKD waveform).

Option	# MKD	Kick (MKD) [mrad]	Trajectory Offset in Dump Line [mm]	MKD Generator Voltage [kV]	Change in voltage per MKD [%]	Equivalent energy of LBDS today [TeV]
Installed	15	0.275	0.0	28.9	0.0	7.00
A	16	0.272	0.3	26.8	−7.1	6.50
B	16	0.279	-0.4	27.5	−4.9	6.66
C	17	0.283	-0.8	26.4	−9.2	6.40
D	17	0.271	0.6	25.1	−13.0	6.09

the extraction channel downstream. The addition of a single MKD module could compensate the extra voltage needed to extend the operation of the LBDS from 6.5 to 7 TeV. The addition of two modules could reduce the voltage held per generator by up to 13.0 % and allow operation at 7 TeV with the same voltage required to operate at 6.1 TeV today. As the effective kick centre of the MKDs is displaced, the beam is extracted on an offset trajectory parallel to the nominal axis of the extraction beam line at an amplitude of less than 1 mm for all options considered, which represents only 2 % of the narrowest horizontal aperture restriction in the gap of the MSD.

As stated above, option A would permit the increase of LHC top energy from 6.5 to 7 TeV without any change to the present voltage of the MKDs. Options B and C are not so efficicent because the kickers placed downstream of Q4 do not profit from the extra kick that it can provide. Finally, Option D is most efficient in terms of reducing the voltage held per GTO stack and will reduce the operational voltage significantly below even the present value (at 6.5 TeV) for 7 TeV LHC operation.

The gradient of Q4 is held constant throughout operation in order to fix the extraction trajectory. Although this is also the case for HL-LHC, it is proposed to vary the gradient of the Q5 by as much as 20 % (HL-LHC optics V1.2) in IR6 to help squeeze the β^* in collision at IR1 and IR5 using the Achromatic Telescope Squeezing scheme [6]. This would have an impact on the extraction trajectory during the squeeze scenarios where MKDs are placed upstream Q5, i.e. for options A and D. In this perspective, Options B and C are more attractive because the MKDs are located downstream of the Q5 and independent to variations of the gradient of the Q5 during the squeeze. Consequently, for option A the extraction trajectory would move by approximately 0.1 mm in the MSD and by 1 mm on the TDE; for option D the effect is twice as large but still relative small compared to the aperture.

It is worth commenting that a re-configuration of the MKD system would in any case be needed if on-going studies indicate that an additional mask is needed to ensure the protection of Q5 with the higher intensities considered for HL-LHC. Additional MKD magnets will not only lower the voltage levels at top energy but also at injection. Currently, this would mean that the rise-time will be increased by $\sim$ 75 ns due to GTO switching properties at lower voltages. The proposed new trigger transformer could also compensate for this. A reconfiguration of the IR quadrupoles may also be considered to keep the MKD system grouped together and more compact.

DISCUSSION AND CONCLUSION

An improved GTO stack will be implemented in the MKD power generator and upgrade options are being considered to further alleviate HV related issues. Whilst the GTO stack improvement will boost the system's high-voltage reliability and hence its overall availability, the addition of more MKD magnets will allow to run at lower voltages further reducing the general stress on the system. It will also, most importantly, reduce the sensitivity of the semiconductor switches to radiation effects and mitigate the single event burnout risk. A dynamic voltage sharing between all kicker units will be difficult to safely realise from the controls side but would give the benefit to allow for one module to be switched off (and being exchanged only during next technical stop). The impact of the HL-LHC optics on the LBDS upgrade options will need following up along with impedance studies and detailed integration studies to assess the feasibility of the different options.

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