LHC Performance Note 012

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Proposal to decrease the extraction times for dipoles and quadrupoles during the initial running of the LHC

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Summary

The proposal to decrease the energy extraction time for the main dipoles and quadrupoles during the initial running up to 5 TeV is discussed. Proposals for practical solutions are presented.

1. Introduction

Lyn Evans proposed recently to increase the di/dt, while running at reduced maximum current, to the nominal discharge rate. The issues of maximum voltage and quench-back are discussed. The proposal was presented to the LMC.

2. The dipoles

The choice of the extraction rate is dominated by the voltage limit of the dipole circuits, both with respect to the absolute limit and the quench protection noise immunity. Lowering the current from 11870 A (7 TeV) to 8500 A (5 TeV) will normally keep the τ=104 s constant. However the maximum extraction voltage will fall to 72%. We can raise the extraction voltage by increasing the dump resistors. Normally that should be by 28%. However, it is much easier to increase the extraction resistance by 33% by disconnecting one of the three parallel resistors. This will decrease the τ from 104 s to 69 s. Consequently, the maximum di/dt will go from 114 A/s to 123 A/s. This means an increase of the voltage from 889 V to 959 V. This is still within the margin of the voltage and of the (old) quench protection. The dumped energy goes from nominally 1.8 GJ per resistor to 1.4 GJ, which is good news. The eddy current losses are smaller or equal compared to the baseline configuration and quench back should not happen due to the much increased temperature margin. No measurements have been done so far.

3. The quadrupoles

The decay time is nominally 37 s. The time constant was measured to 30 s, which is accounted for by 1.8 mΩ in the warm cables. The dump resistor is 7.7 mΩ and the inductance is 286 mH. It has been measured that a di/dt =4 00 A/s can be tolerated at 11870 A. In fact, a quench was observed on the up-ramp at an even higher current [1]. To achieve this decay rate we have to decrease the decay time to τ = 8479/400= 21.2 s. This corresponds to a total resistance of $R=L/\tau$=13.5 mΩ. Taking the existing (7.7+1.8) mΩ into account a resistor of 4 mΩ is need in addition.

The maximum extraction voltage will not change: U=L*di/dt. The energy, which has to be absorbed, will partially end up in the additional resistor. Hence the energy in the existing resistor is even lowered somewhat. The additional resistor has to take

$$E=L/2 * i^2*4/13.5=2.02 \text{ MJ}$$

The (constant) heat capacity of copper is 385 J/(kg*K) and of steel 440 J/(kg*K). We will need a mass of 52.5 kg of copper or 45.9 kg of steel, assuming a temperature increase by 100 K to be tolerable.

The decrease of τ of 21.2 does not lead to a quench-back, because the same di/dt works fine at much higher current. There are however no systematic measurements done [1]. Let us assume a linear dependence of the temperature margin on the current. This gives us a margin of 0.64 K at nominal current, which seems compatible with eddy current losses ~11870*400 A^2/s. The losses will be only 8479/11870=71% at the current for 5 TeV. This argument is questioned by Louis Walckiers. He points out that in the very early time the losses are only proportional to di/dt. The temperature margin in the 5 TeV case is 2.5 K, or 3.9 times higher compared to the nominal case. Consequently a di/dt of 3.9*400 A/s would be indicated corresponding to τ = 5.4 s. However, the linear model is certainly not correct; furthermore the quench protection cannot cope with the corresponding voltage. A practical limit would be given by the noise immunity of the QPS. Probably τ = 10…15 is acceptable.

We consider now a faulty splice with a resistance, which is small compared with the extraction resistors. It takes t=-30*ln(5/11.85) s = 26 s to reach 5 kA (arbitrarily considered as safe) in the baseline case. In the presently installed case we need 16 s and with the new extraction constant 11.3 s are sufficient. Figure 1 [2] shows the difference in time to reach a certain target current between a 21 s and a 15 s case compared to the nominal (30 s) case.

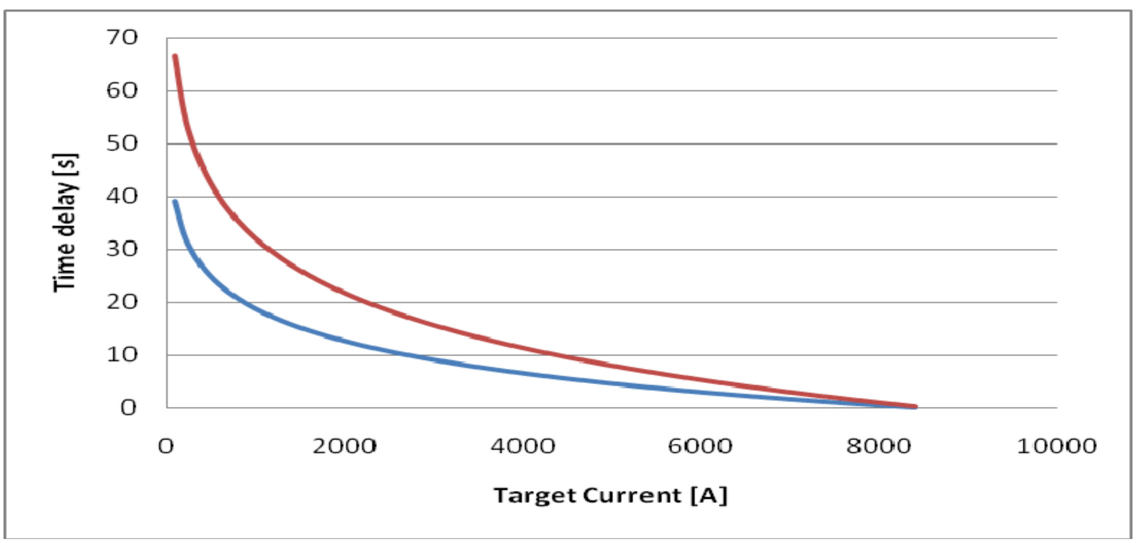

Figure 1 (courtesy Walter Venturini Delsolara) Time gained with the new solution to reach a certain current

We can state the same observation in the conventional way: In the baseline case a fault will accumulate 2106 MIITs. In the presently anticipated 5 TeV run it will be 1084 MIITs. This number can be reduced to 767 MIITs in the proposed 21 s solution. The 15 s option reduces the MIITs to 542.

4. Possible implementations

Two types of implementations come to mind. Philippe Lebrun and others made the proposal to use commercial cables. This solves the problem of insulation and makes the electrical connections easy. The drawbacks are the price and the fact that only the resistance can be a design parameter. The increase in temperature due to the energy deposition is given by the resistance (i.e. the length) and the other cable parameters. The other types of solutions would design for both a fixed temperature increase and a certain resistance.

4.1 Cable

We consider two cables with 4*95 mm^2 and 4*150 mm^2 [3]. We would connect 2 conductors in parallel or the forward and backward direction of the current. This gives one compact cable with a short at the far end. The forces are kept inside by the copper and steel bandage. The specified short circuit current limits are beyond our currents. This insures the mechanical integrity. The length of the conductors can be calculated to 44.246 m (69.862 m), which makes a length of the cable of 22.12 m (34.93 m). Assuming a constant heatcapacity of 385 J/(kg K) we reach a change in temperature of 105 K (42 K). In conclusion the smaller cable 4*95 mm^2 is sufficient, because the specification allows to operate the cable for less than 5 hours at 130°C. Moreover the heatcapacity of the copper and steel bandage and the insulation has been neglected. The natural cooling is 31.6 W/m or 1.4 kW at 130°C and 430 W at 90°C. This leads to re-cooling times of about one hour, compatible with the cryogenic recovery. Note that faster decay times are easily possible. It just scales with the length of the cable. A decay time of 15 s is achieved with 97.5 m. The temperature increase is only 52 K.

4.2 Plate

We consider a steel (304 L) plate, as they are in the store. The plate has a certain width and a certain height. We cut slots with the water jet cutter of the stores. With (n-1) vertical cuts as sketched in figure 2 we get a double meander conductor with (almost) constant width b and a length l. We now can design for a given resistance and temperature rise by varying the thickness, the number of cuts, the total width and the total height.

We choose on resistor to be 2 mΩ. Choosing a temperature increase of 100 K we arrive at a required volume of 4.43 L. Choosing a thickness of 10 mm (mainly for stability reasons) and calculating the ratio between length of the current path to electrical crossection we arrive at a required length of 2 times 3.582m. Finally, choosing 16 strips of 62 mm each we arrive at a total width of 448 mm and a total height of 989 mm (plus space for the 15 cuts of 3 mm each, making the total of 1034 mm).

Two plates can be screwed together (with appropriate standoffs) and covered by a grounded electrical protection to form 4 mΩ, when connected in series. In fact several plates can be attached to the existing resistors [4]. This fact makes the cable connection simple. A fan could be installed to improve the cooling. The bending of the strips due to the electromagnetic forces is less than 0.1 mm and negligible. It may however make some noise.

Several plates can be connected in series to achieve a shorter time constant (see figure 3). Note that the temperature increase is calculated for a 4 mΩ resistor. Adding resistors will decrease the maximum temperature. The leakage current through the resistor, caused by the small resistance of the switch is less than 15 W and negligible.

A prototype has been made.

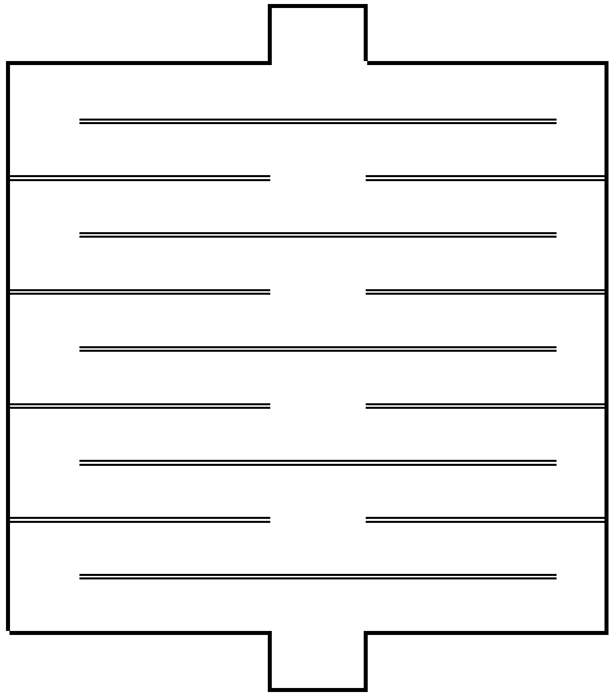

Figure 2 Possible resistor layout

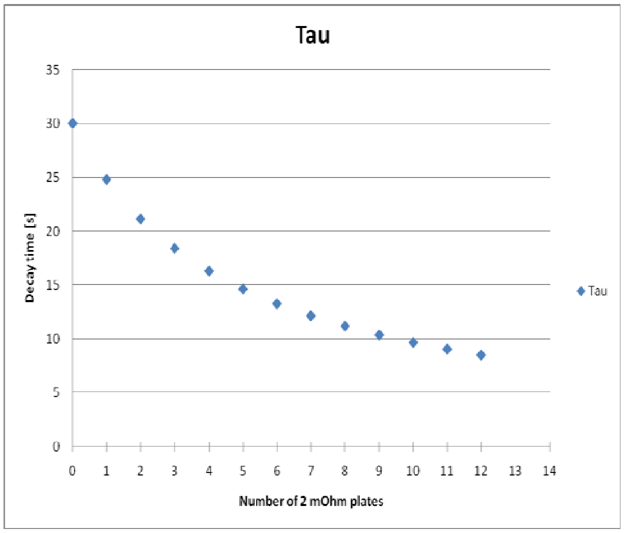

Figure 3 Extraction time [s] as a function of resistor plates connected in series

5. Acknowledgements

I would like to thank Walter Venturini Delsolaro, Louis Walckiers, Knud Dahlerup-Petersen and Noel Fournier for their help.

References

[1] Louis Walkiers, Walter Venturini Delsolaro, private communication

[2] Walter Venturini Delsolaro, private communication

[3] Cable 212658 (4*150) and 211590 (4*95), Leoni Studer AG, sales@leoni-studer.ch, availability has not been checked.

[4] Noel Fournier