BOUND-FREE PAIR PRODUCTION IN LHC Pb-Pb OPERATION AT 6.37 Z TeV PER BEAM

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Abstract

In the 2015 Pb-Pb collision run of the LHC, the power of the secondary beams emitted from the interaction point by the bound-free pair production (BFPP) process reached new levels while the propensity of the bending magnets to quench increased with the magnetic field. This beam power is about 35 times greater than that contained in the luminosity debris and is focussed on a specific location. As long foreseen, orbit bumps were introduced in the dispersion suppressors around the highest luminosity experiments to mitigate the risk by displacing and spreading out these losses. The BFPP beams were used to induce a controlled quench of a dipole magnet, thus providing the first direct measurement of the steady state quench level and demonstrating the need for new collimators around the ALICE experiment to intercept these secondary beams.

INTRODUCTION

Ultraperipheral electromagnetic interactions of Pb nuclei at the LHC are responsible for copious lepton-pair production. Most of this is innocuous except for a tiny proportion of (single) bound-free pair production (BFPP):

\[
{}^{208}\text{Pb}{}^{82+} + {}^{208}\text{Pb}{}^{82+} \rightarrow {}^{208}\text{Pb}{}^{82+} + {}^{208}\text{Pb}{}^{81+} + e^+, \quad (1)
\]

in which the electron is bound to one nucleus. As extensively discussed previously (see, eg, [1–6] and further references therein), the modified nuclei emerge from the collision point, as a narrow secondary beam with modified magnetic rigidity, following a dispersive trajectory (Figure 1) that impacts on the beam screen in a superconducting magnet in the dispersion suppressor (DS) downstream. These secondary beams emerge in both directions from every IP where ions collide and each carries a power

\[
P_{\text{BFPP}} = L \sigma_{\text{BFPP}} E_b
\]

where \(L\) is the luminosity and \(\sigma_{\text{BFPP}} \approx 276 \text{ b}\) is the cross section at the 2015 run energy \(E_b = 6.37 \text{ Z TeV}\) [7,8]. These losses are much greater than the luminosity debris (generated by the nuclear collision cross-section of 8 b) and can quench magnets and directly limit luminosity.

ORBIT BUMP TECHNIQUE

During the 2015 Pb-Pb run [8] a peak \(L = 3-3.5 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}\) was achieved in IP1 and IP5. IP2 was levelled to the design value of \(L = 1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}\). Thus the BFPP beams emerging to the left and right of the ATLAS and CMS experiments, were carrying \(P_{\text{BFPP}} \approx 80 \text{ W}\). To reduce the risk of quenches, orbit bumps around the impact locations were implemented in order to move the losses out of the dipole and into the connection cryostat ("missing dipole" in DS). Although the cryostat does not contain a coil, it still accommodates the superconducting bus bars. However, these bus bars have a higher quench level than coils and are located above the vacuum chamber where the Pb losses are ineffectual [9]. The green trajectory in Fig. 2 shows the new path of the BFPP ions modified by an orbit bump with a maximum amplitude of \(-3 \text{ mm}\) around the quadrupole in cell 11 (Q11). These orbit bumps were used routinely and no luminosity production fill was interrupted by a quench.

BFPP QUENCH TEST

At the outset, it was thought unlikely that the available luminosity was enough to induce a magnet to quench but...
there is a large uncertainty on the knowledge of the necessary power deposition. The BFPP beams can provide a very clean loss scenario that can be reconstructed with FLUKA \cite{10,11} simulations that can then be used to improve the knowledge of the steady-state quench limit. Using the BFPP1 beam to induce a quench has the advantage that the impact point in the magnet can be controlled by modifying the orbit bumps, so that quenches at the end of the magnet, which would return less accurate estimates for the quench limits due to the specifics of the magnet design, can be avoided. Furthermore, the power in the BFPP beam is directly dependent on the luminosity, which can also be controlled with the beam separation at the IP.

Setup of the Experiment

The experiment was performed on 8 Dec 2015, with the highest available intensity and lowest transverse emittances available to that date to maximise the likelihood of a quench. The beams were prepared as for a standard physics fill up setting for the experiment. The shift of the loss peak deep into the MB (located from -403.843 m to -418.143 m) is clearly visible. In order to exactly know the luminosity value leading to the quench, the beam separation at IP5 was reduced in steps of 5 µm, waiting a few minutes at each step for conditions to stabilize.

The luminosity in CMS and evolution of the BLM signals around the BFPP impact location during the experiment are shown in Fig. 4. After performing the 4th step and arriving at the head on position, a quench occurred at an instantaneous luminosity of \( L \approx 2.3 \times 10^{27} \) cm\(^{-2}\)s\(^{-1}\) in CMS.

PRELIMINARY ANALYSIS WITH FLUKA

FLUKA shower simulations were carried out to evaluate the peak power density deposited in the magnet coils during the quench test, providing, in turn, a tentative estimate of the steady-state quench level of magnets at 6.37Z TeV. To verify the predictive power of the simulation model, simulated BLM signals were compared to measurements. The particle shower simulations were based on BFPP1 loss distributions tracked with MAD-X, assuming an orbit bump of +0.5 mm. As the actual loss location can differ by a few metres from the theoretical one (due to beam screen tolerances etc.), the loss location was adjusted in the FLUKA simulations in order to achieve the best match with the measured BLM signal pattern. This indicated that the actual loss location differed by about 1 – 1.5 m from the MAD-X prediction for the ideal machine.
Figure 5 compares the measured BLM signals and the simulated ones. In order to demonstrate the sensitivity of the BLM pattern to the impact location of the BFPP1 beam on the beam screen, the figure shows FLUKA results for two different loss locations differing by 50 cm. As can be seen in the plot, such a small shift visibly alters the ratio of BLM signals in the vicinity of the loss location. In general, a very good agreement between simulated and measured signals was achieved for an assumed loss location of 414.8 m left of IP5. Further studies are needed to investigate the potential displacement of the closed orbit and beam pipe with respect to each other, which gives rise to the observed discrepancies between theoretical and actual loss locations.

In order to derive a first estimate of the peak power deposition in the MB coils, a cylindrical mesh was placed over the model of the dipole in FLUKA recording the energy deposited in the magnet coils in volume elements $\Delta z \Delta r \Delta \phi = (10 \text{ cm}) \times (0.2 \text{ cm}) \times (2^\circ)$. Figure 6 presents the longitudinal distribution of the peak power density in the MB coils for the simulation with an loss location at 414.8 m left of IP5. Both the peak power density at the inner edge of the cable and the radially averaged density over the cable are shown. Contrary to the BLM pattern, the peak power in the coils is not affected by the position of the loss distribution, because the energy is deposited deep inside the dipole.

As the heat has enough time to spread across the cables' cross-section, one typically uses the radially averaged power density to quantify the quench level for steady-state losses. The maximum radially averaged power density is estimated to be around $15 \text{ mW/cm}^2$, which is lower than previous predictions [13]. As for the BLM pattern, these results should be considered preliminary in view of a subsequent sensitivity analysis. The peak power deposition in the coils depends strongly on the longitudinal and vertical spread of the impact distribution and hence more studies are needed to quantify the uncertainty in the peak power density.

**CONCLUSIONS**

In the 2015 Pb-Pb run of the LHC, the long-foreseen orbit bumps at loss locations were routinely used to successfully eliminate the quench risk from the BFPP secondary beams. These secondary beams were used to obtain the first accurate measurement of the steady state quench limit of the LHC dipole magnets in an experiment performed on 8 December 2015. The beam of BFPP1 ions created at a luminosity of $L \approx 2.3 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ quenched a dipole. From previous quench tests, which had never reached the appropriate regime, the steady state quench limit had been inferred to be higher [13]. The detailed analysis of the experiment continues. Nevertheless, it has been shown that the orbit bumps introduced around IP1 and IP5 were essential and will be so in the future. The need to install new dispersion suppressor collimators around IP2, to allow the ALICE experiment to operate at the luminosity foreseen in the 2020s, has also been demonstrated.

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**REFERENCES**


