POWER DEPOSITION IN LHC MAGNETS DUE TO BOUND-FREE PAIR PRODUCTION IN THE EXPERIMENTAL INSERTIONS*

C. Bahamonde Castro†, B. Auchmann, M. I. Besana, K. Brodzinski, R. Bruce, F. Cerutti, J. M. Jowett, A. Lechner, T. Mertens, V. Parma, S. Redaelli, M. Schaumann, N. V. Shetty, E. Skordis, G. E. Steele, R. Van Weelderen, CERN, Geneva, Switzerland.

Abstract

The peak luminosity achieved during Pb-Pb collisions in the LHC in 2015 ($3x10^{27}$ $cm^{-2}s^{-1}$) well exceeded the design luminosity and is anticipated to increase by another factor 2 after the next Long Shutdown (2019-2020). A significant fraction of the power dissipated in ultra-peripheral Pb-Pb collisions is carried by ions from bound-free pair production, which are lost in the dispersion suppressors adjacent to the experimental insertions. At higher luminosities, these ions risk to quench superconducting magnets and might limit their operation due to the dynamic heat load that needs to be evacuated by the cryogenic system. In this paper, we estimate the power deposition in superconducting coils and the magnet cold mass and we quantify the achievable reduction by deviating losses to less sensitive locations or by installing collimators at strategic positions. The second option is considered for the dispersion suppressor next to the ALICE insertion, where a selective displacement of losses to a magnet-free region is not possible.

INTRODUCTION

Several electromagnetic processes occur in heavy ion collisions in the LHC, Bound-Free Pair Production (BFPP) being the most relevant among them with an estimated cross section of 281 barns at 7*Z* TeV [1, 2, 3, 4]:

$$^{208}Pb^{+82} + ^{208}Pb^{+82} \rightarrow ^{208}Pb^{+82} + ^{208}Pb^{+81} + e^{+1} \quad (1)$$

As can be seen from Eq. (1), the main product of these interactions is a high power secondary beam with a charge-to-mass ratio that differs from that of the primary beam, consequently following a different trajectory and impacting in superconducting magnets downstream from the Interaction Points (IPs). This phenomenon takes place in all IPs of the LHC where ions collide, although the luminosity is only high enough for BFPP to be a relevant phenomenon in IP1, IP2 and IP5. During the 2015 Pb-Pb run [4], a record luminosity was achieved in ATLAS (IP1) and CMS (IP5), $3x10^{27}$ $cm^{-2}s^{-1}$, while in ALICE (IP2) it was instead $1x10^{27}$ $cm^{-2}s^{-1}$. Several previous studies of BFPP losses in the LHC, from [2] to [3] have already estimated the energy deposition and luminosity limit. These effects are directly proportional to the luminosity, and will be of still greater concern at the higher luminosities projected for the High Luminosity LHC (HL-LHC) era. For this reason, in this paper we study the potential effects of BFPP in a HL-LHC scenario. All results presented in this paper are normalized to the anticipated HL-LHC values of energy (7*Z* TeV) and luminosity ($6x10^{27}$ $cm^{-2}s^{-1}$). We estimate the power deposition in the coils and cold mass of the affected superconducting magnets and we quantify the reduction of this power deposition using different mitigation strategies.

BFPP LOSS LOCATION AND POWER DEPOSITION IN MAGNETS

The secondary ions produced by BFPP in the aforementioned IPs form two parasitic beams that follow trajectories that differ from the main beam's and end up impacting on the magnet apertures in the Dispersion Suppressors (DS) right and left of the experimental insertions. Each DS accommodates four superconducting quadrupoles and eight superconducting dipoles arranged in four cells (8-11). In IP1 and IP5 the BFPP ions are lost in the last dipole of cell 11 (MB.B11), whereas in IP2, which has a different optics, they are lost in cell 10 (MB.B10). The small size of the parasitic beams distributes these ion losses over just a few meters longitudinally, giving rise to a localized power deposition in the magnet coils. Figure 1 shows the estimated peak power density in the dipole coils normalized to HL-LHC parameters. These results and all results in this paper were produced with FLUKA shower simulations, which used a realistic geometry model of the magnet including a beam screen, cold bore, coils, collars, and yoke. The particle distributions needed for the FLUKA simulations were all generated using MAD-X [5]. The red dots represent the spatial distribution of the BFPP secondary ions as they impact on the MB.B10 beam screen in the DS to the right of IP2. The blue dots indicate the peak power density radially averaged over cables and its longitudinal distribution along this magnet. As can be seen in Fig. 1, the peak power density profile follows closely the spatial loss distribution.

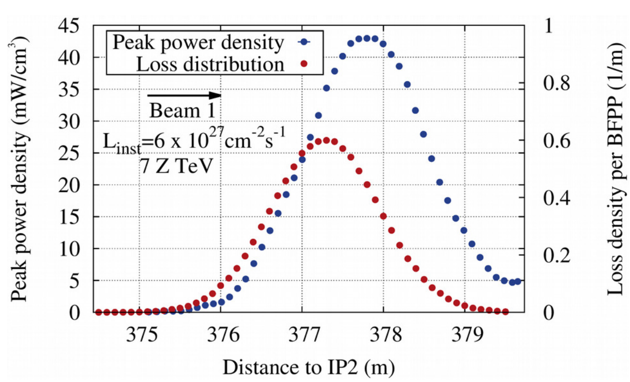

Figure 1: Peak power density and BFPP losses in the MB.B10 in the DS right of IP2.

* Work supported by EU FP7 HiLumi LHC-Grant Agreement 284404
† cristina.bahamonde@cern.ch

This loss distribution and, hence, the maximum power density exhibit some dependence on the crossing angle, the horizontal and vertical emittance, the momentum spread and therefore the longitudinal emittance. In addition, it can be affected by imperfections like small deviations from nominal magnetic field strengths or local inhomogeneities of the beam screen surface at the impact location. Taking into account these uncertainties and possible variations of beam and optics parameters, it is estimated that the peak power density can vary by some tens of percent from the maximum value of 44 mW/cm^3 from Fig. 1. Although this particular figure shows data for the DS right of IP2, results are comparable for the right and left DS of all the concerned IPs.

In 2015, a dipole quench was provoked in a controlled beam loss experiment with 6.37Z TeV BFPP beams [6]. BFPP losses were deliberately shifted inside the magnet by means of an orbit bump, and the heat deposition in the magnet was selectively increased in steps by reducing the beam separation. The magnet eventually quenched at a luminosity of 2.3x10^{27} cm^{-2}s^{-1} [6]. First results from particle shower simulations indicate that the peak power achieved during the test was around 16 mW/cm^3 [6]. Studies continue to assess in more detail the loss conditions that led to the quench. Nevertheless, the test confirmed earlier calculations [2, 3] that BFPP ions would limit the luminosity below the HL-LHC target of 6x10^{27} cm^{-2}s^{-1}. Various options have been considered to reduce the power deposited in superconducting magnets. In the following sections, we present FLUKA power deposition simulations for the various options foreseen for the DS next to IP1/5 and IP2. Besides the power deposition in magnet coils, we also study the dynamic heat load to be evacuated by the cryogenic system. For HL-LHC parameters, the secondary BFPP beam carries a power of more than 150 W, most of which is dissipated in accelerator components around the loss location. FLUKA simulations indicate that approximately 75% of this beam power is deposited in the magnet cold mass when the ions are lost deep inside the dipole although this value can be less if the losses occur close to the end of the magnet. In the DS regions, it is potentially possible to extract 150 W (120 W dynamic plus static loads) from magnet cold mass elements at 1.9 K. However, with a high dynamic load, the operational redundancy of the cooling loops becomes questionable.

MITIGATION STRATEGIES: IP1 AND IP5

During heavy ion operation in 2015 [4], horizontal orbits bumps were applied in the DS next to IP1 and IP5 in order to shift the BFPP losses from their original position inside the MB to the adjacent connection cryostat. Figure 2 shows this displacement in the DS right of IP5 as predicted by tracking simulations. A similar displacement was also applied in the DS left of IP5 and in the DS right and left of IP1 [7].

The connection cryostat, which has approximately the same length as the dipoles (~14.5 m), provides a continuity of the vacuum, electrical and cryogenic systems between the DS and the arcs.

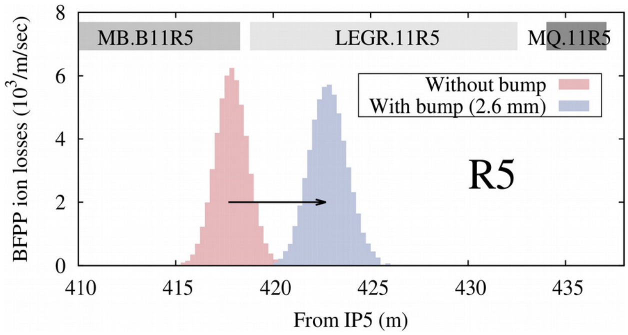

Figure 2: Shift of the BFPP losses in the right DS of IP5 using a 2.6mm orbit bump.

The electrical connection is provided by superconducting bus bars that have a much higher quench limit than the magnet coils (200 mW/cm^3 [8] at 7Z TeV instead of tens of mW/cm^3 for the magnets). FLUKA simulations suggest that the peak power density in the bus bars remains below a few mW/cm^3 even for HL-LHC parameters. In these simulations, it was assumed that the losses occur around the central shuffling module of the connection cryostat, where the bus bars are closest to the beam pipe and are therefore most susceptible to beam-induced quenches.

Shifting the BFPP losses to the connection cryostat diminishes almost completely the power deposition in the originally impacted dipole, but increases the heat load to the adjacent quadrupole (MQ.11 in Fig. 2) because the particle showers are now generated closer to the MQ. FLUKA simulations indicate that the peak power density in the quadrupole coils does not exceed 2 mW/cm3 at HL-LHC parameters if the BFPP losses remain in the upstream half of the connection cryostat. This value can be considered acceptable given that the quench limit for quadrupole magnets is estimated to be 53 mW/cm3 at 7Z TeV [9]. Together with the above findings it can be concluded that the displacement of BFPP losses to the connection cryostat is a promising solution for future ion runs at higher luminosity without risk of quenching magnets or bus bars. At the same time this solution significantly reduces the heat load to cold mass elements at 1.9 K. It is estimated that more than half of the beam power is dissipated in the connection cryostat, with a large fraction (~25%) being deposited in 1.5 cm thick lead plates that surround the cryostat vacuum chambers. The lead shielding is mainly thermalized to ~50-65 K and hence the power deposition is less critical than for components at 1.9 K. The overall effect on the cryogenic system is therefore estimated to be beneficial if losses occur in the connection cryostat as compared to the upstream dipole.

MITIGATION STRATEGIES: IP2

Because the optics around IP2 are different, an orbit bump like those as in IP1 and IP5 would not shift the BFPP losses to the connection cryostat in cell 11.

The losses can however be displaced to another dipole in cell 12 (MB.C12), with the benefit of increasing the longitudinal spread of ion impacts on the magnet aperture as compared to the original loss location in cell 10. This

ISBN 978-3-95450-147-2

in turn reduces the maximum power density in the dipole coils. Figure 3 shows the longitudinal distribution of the peak power density in the MB.C12 coils predicted by FLUKA simulations at HL-LHC luminosity.

The peak power density is found to be about 23 mW/cm^3 , which scales up to 25 mW/cm^3 at 7Z TeV. This is a reduction of almost a factor two compared to the original loss location in cell 10 (as can be seen in Fig. 1). However in view of the quench test [8] this seems insufficient. In addition, shifting the losses to the MB.C12 does not reduce the heat load to be evacuated by the cryogenic system as the losses remain inside a dipole. The results shown in Fig. 3 assumed that all BFPP losses would be shifted from cell 10 to cell 12. Operation in 2015 however showed that only a fraction of the BFPP losses could be displaced to the MB.C12 while the rest would still impact on the MB.B10, and that this distribution of the losses was not stable enough to be maintained constantly due to orbit variations. This might be beneficial as the losses would be split between two magnets but does not constitute an adequate solution for HL-LHC.

A more robust solution consists in intercepting the BFPP ions with collimators installed at strategic positions in the DS left and right of IP2. Following is the study we performed on two alternative options that have been proposed as part of the collimation upgrade program for HL-LHC. The first one assumes that a dipole is substituted by a pair of shorter higher field (11 T) magnets, what would create space for a 60 cm tungsten collimator in between the new magnets. The new magnets and the collimator would be installed upstream of the MB.B10 in order to intercept the ions before they touch the aperture. The second solution, which is the preferred solution and would not require new magnets, assumes that a 60 cm tungsten collimator is installed further downstream in the connection cryostat (at its longitudinal center). This solution still would rely on orbit bumps so that the ions remain within the machine aperture until they reach the collimator location. In both cases, the collimator jaws are estimated to absorb more than half of the power carried by BFPP ions (about 70 W in the impacted jaw and about 10 W in the opposite jaw).Figure 4 shows the longitudinal distribution of the peak power density in the coils of the 11T magnet just downstream from the collimator.

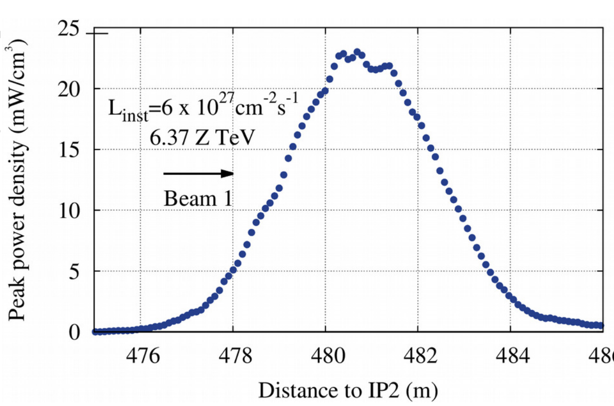

Figure 3: Peak power density in the coils of the MB.C12 located in the DS right of IP2.

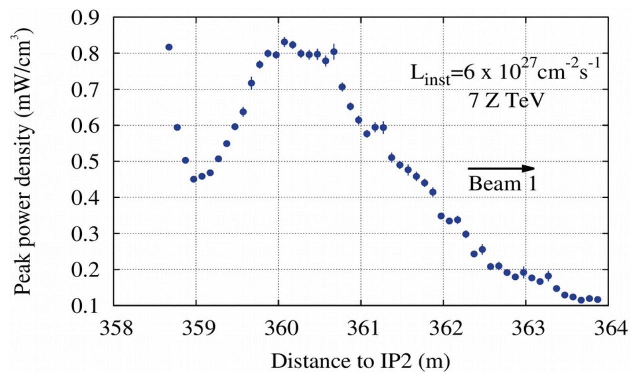

Figure 4: Peak power density in inner coils of the MB11T.B10 located in the DS right of IP2.

All values are found to be below 1 mW/cm^3, therefore remaining safely below the estimated quench levels for this magnet [10, 11]. The peak power density in the MQ.11 case is even lower, remaining below 0.15 mW/cm^3 everywhere in the magnet. The absorbing properties of the tungsten jaws also reduce the heat load to be removed by the cryogenic system. The total power deposited in the 11 T magnet is estimated to be less than 20 W and the situation is even better for the second option as most of the power (26 W) escaping from the collimators is dissipated in the connection cryostat.

CONCLUSION

During heavy ion operation in the LHC, BFPP losses dissipate a significant power in the DS regions around the IPs. Without any mitigation measures, they would quench various superconducting magnets at present and future energy and luminosity [2, 3, 4]. We have reported the quench assessment of the magnets concerned as well as a heat load estimate for all adjacent components as suitable mitigation measures are applied.

In IP1/5, the risk of quench was found to be avoided by applying an orbit bump that would displace the BFPP losses to a connection cryostat adjacent to the affected dipole. In IP2, the most robust solution was found to be the installation of a collimator that would partially intercept the BFPP losses before they impact in the beam screen of the dipole. In all three IPs, the solution was also proven to have an even distribution of the heat load among the various components, facilitating its evacuation by the cryogenic system.

REFERENCES

[1] H. Meier et al., “Bound-Free Electron-Positron Pair Production in Relativistic Heavy Ion Collisions”, Phys. Rev. A, 63:032713, 2001.

[2] J. M. Jowett, J. B. Jeanneret and K. Schindl, “Heavy Ions Beams in the LHC”, Proc. 2003 Particle Accelerator Conf., Portland, 2003 TPPB029 pp 1682-4.

[3] R. Bruce, D. Bocian, S. Gilardoni and J. M. Jowett, “Beam losses from ultraperipheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation”, Phys. Rev. ST Accel. Beams, 18, 071002 (2009) and references therein.

[4] J. M. Jowett et al., "The 2015 Heavy-Ion Run of the LHC", TUPMW027.

[5] M. Schaumann, A. Stahl and J. M. Jowett, “Heavy-ion performance of the LHC and future colliders”, Master’s Thesis, RWTH Aachen U., Aachen, Germany, 2015.

[6] J M. Jowett et al., "Bound-Free Pair Production in LHC Pb-Pb Operation at 6.37Z TeV per Beam", TUPMW028.

[7] A. Bertarelli et al., “Design Report and Functional Specification: Deliverable: D5.7”, CERN (2015).

[8] A. Verweij, private communication.

[9] A. Verweij and B. Auchmann, “Quench limits: extrapolation of quench tests to 7 TeV”, LHC Coll. Review 2013, CERN (2013).

[10] B. Auchmann et al., Phys. Rev. ST Accel. Beams, 18, 061002 (2015).

[11] P.P. and R. Van Weelderen, IEEE Trans. Appl. Supercond., Vol 24 (2014).

ISBN 978-3-95450-147-2