

EFFECTS OF ULTRAPERIPHERAL NUCLEAR COLLISIONS IN THE LHC AND THEIR ALLEVIATION

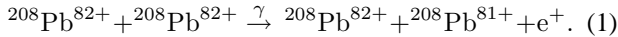
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Abstract

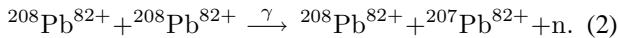
Electromagnetic interactions between colliding heavy ions at the LHC are the sources of specific beam loss mechanisms that may quench superconducting magnets. We propose a simple yet efficient strategy to alleviate the effect of localized losses from bound-free pair production by spreading them out in several magnets by means of orbit bumps. We also consider the consequences of neutron emission by electromagnetic dissociation and show through simulations that ions modified by this process will be intercepted by the collimation system, without further modifications.

INTRODUCTION

Collisions of beams of $^{208}\text{Pb}^{82+}$ nuclei in the LHC [1] will present new challenges, not present in proton runs. Some of these arise from strong electromagnetic interactions between the colliding beams. In bound free pair production (BFPP), an e^+e^- pair is created with the electron caught in a bound state of one ion, thus changing its charge:



Another process is electromagnetic dissociation (EMD), where an ion loses one or two neutrons. The one-neutron reaction can schematically be written as



Both these processes create ions with an altered magnetic rigidity $(B\rho)(1 + \delta)$, where $(B\rho)$ is the rigidity of the original beam and δ is given by

$$\delta = \frac{Z_0 A}{A_0 Z} (1 + \delta_{\text{kin}}) - 1. \quad (3)$$

Here (A_0, Z_0) are the atomic mass and charge number of the original beam, (A, Z) of the altered beam, and δ_{kin} is the fractional momentum deviation. These ions might be lost where the locally generated dispersion function from the IP has grown sufficiently. If that occurs in a superconducting magnet, the induced heating may result in quenches [2, 3].

Measurements at RHIC [4] confirmed that losses caused by BFPP exist and that the simulation procedure used to quantify their effect in LHC operation, described in Refs. [1, 3, 5, 6, 7] is accurate within a factor two. This means that quenches caused by lost BFPP particles are possible in the LHC and that methods to avoid them have to be found. In the following sections, we describe such a method, as well as simulations to further quantify the effect of losses caused by EMD.

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ALLEVIATION BY ORBIT BUMPS

The horizontal orbit of the BFPP particles coming out of IP2 in a perfect lattice, as calculated by MAD-X [8], is shown in the top part of Fig. 1 together with the nominal beam. The BFPP orbit oscillates with the *locally generated* dispersion function, d_x , and the affected particles are lost very close to its first maximum. Thus, if a local horizontal orbit bump displaces the beam towards the centre of the beam pipe, a fraction of the losses escapes downstream to the next maximum. Similarly, other bumps can be introduced at consecutive local maxima of d_x in order to make a certain fraction of the BFPP particles continue. To displace the orbit, we propose to use the existing orbit correctors, which are found close to the quadrupoles in the LHC lattice. By tuning the orbit bumps we distribute the losses caused by BFPP over n dispersion maxima by $n - 1$ orbit bumps using $n + 1$ correctors in such a way that a fraction $1/n$ is lost at each impact point. This decreases the maximum heating power in a single element by $1/n$ and could bring it below the quench limit if n is made large enough.

To determine the required bump amplitudes Δ_m at each impact location s_m we consider the initial phase space at the IP. The particles lost at a location with horizontal aperture $A_x(s_m)$ satisfy (for $m \in [1, n - 1]$)

$$C_m x_0 + S_m p_{x0} + x_B(s_m) + \Delta_m > A_x(s_m), \quad (4)$$

where x_B is the central off-momentum trajectory, (x_0, p_{x0}) the starting conditions at the IP and C_m, S_m the elements of the transfer matrix from the IP to position s_m . These inequalities define regions R_m in the initial phase space, which vary with Δ_m . The fraction f_m of particles lost at s_m is the integral of the assumed Gaussian distribution function $P_\beta(x_0, p_{x0})$ over the phase space area outside the aperture limitation (4) and not outside any previous aperture limitation:

$$f_m = \iint_{R_m \cap (R_1^c \cup R_2^c \dots \cup R_{m-1}^c)} P_\beta(x_0, p_{x0}) dx_0 dp_{x0} \quad (5)$$

where R^c denotes the complement of region R .

The Δ_m can then be determined by demanding

$$f = 1/n, \forall m \quad (6)$$

and solving Eqs. (5) recursively, starting at $m = 1$, which can be solved analytically to yield

$$\Delta_1 = \sqrt{2}\sigma_1 \text{erf}^{-1}\left(\frac{n-2}{n}\right) + x_B(s_1) - A_x(s_1). \quad (7)$$

Here $\sigma_1 = \sqrt{\beta(s_1)\epsilon_x}$ is the RMS beam size and ϵ_x the beam emittance. Numerical integration and solution has to be used for higher values of m .

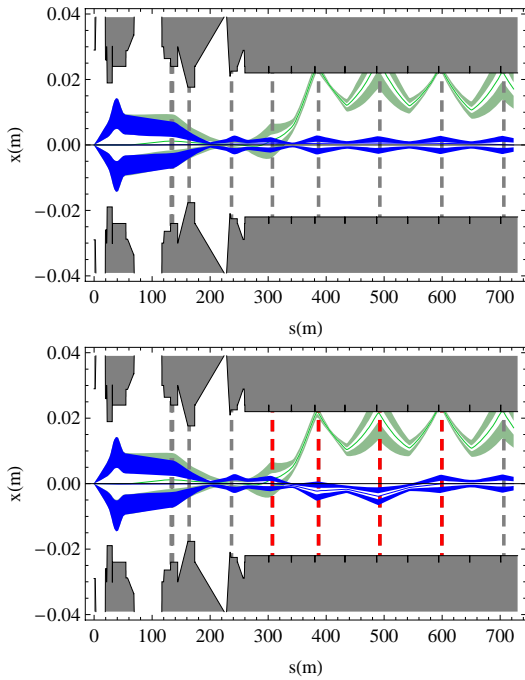


Figure 1: The horizontal 6σ envelopes of the nominal (top) and with 2 orbit bumps (bottom) $^{208}\text{Pb}^{82+}$ beam (blue) and the $^{208}\text{Pb}^{81+}$ BFPP beam (green) coming out of IP2, shown together with the aperture. The white space in the centre of the envelopes represents the uncertainty in the closed orbit. The vertical dashed lines show the locations of horizontal corrector magnets and the ones indicated in red are active.

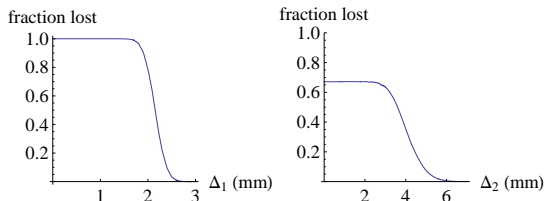


Figure 2: Left: The fraction f_1 , given by Eq. (5), as a function of the bump amplitude Δ_1 . Right: The fraction f_2 lost at the second max, when Δ_1 is chosen so that $f_1 = 1/3$.

BUMPS AFTER IP2

We illustrate the method with the example of 2 orbit bumps with 4 correctors ($n = 3$) after IP2 (ALICE experiment). The parameters Δ_m , presented in Tab. 1, should be chosen such that $1/3$ of the BFPP beam is lost at each impact location, with Δ_1 given directly by Eq (7) and Δ_2 determined numerically. Fig. 2 shows f_1 and f_2 as a function of Δ_1 and Δ_2 . The cuts in initial phase space introduced by the first two aperture limitations, according to Eq. 4, are shown in Fig. 3.

We then use the calculated values of Δ_m together with the condition that the nominal orbit should be flat after the bump to calculate the required angles of the four corrector magnets. The location of available corrector magnets

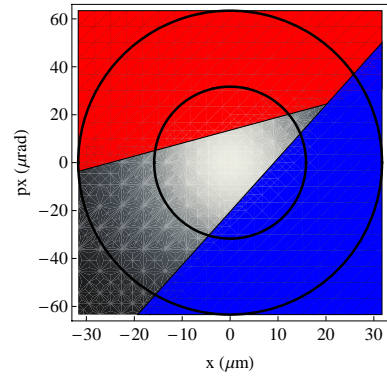


Figure 3: The initial phase space at IP2, with the areas in blue and red covering the losses at the first and second impact locations. The remaining part is lost at the third location where no orbit bump is present. The bumps are tuned so that $1/3$ is lost at each location. The black circles represent 1σ and 2σ of the distribution.

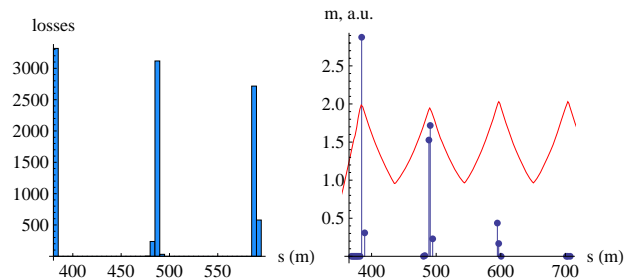


Figure 4: The loss map (left), binned in 5 m intervals, and the estimated BLM signals (right), obtained by single particle tracking downstream of IP2 using 2 orbit bumps. Each loss location receives $1/3$ of the total losses. The red line shows the locally generated dispersion from IP2.

are shown in Fig. 1 and the ones used in the example are marked in red. The obtained values are presented in Tab. 1 together with the required strengths.

The resulting orbits of the BFPP beam and the nominal beam are shown in Fig. 1. The maximum deviation of the nominal orbit is 3.8 mm in this configuration and it is clear from the figure that the 6σ envelope is still far from the aperture. A histogram of the resulting loss map using single particle tracking is shown in Fig. 4. As required, $1/3$ of the initial particles is lost at each impact location.

Table 1: The distance s between IP2 and each corrector magnet, the bump amplitudes Δ , angle θ , field strength B and the percentage r of maximum strength needed in the case of $n = 3$.

s (m)	Δ (mm)	θ (μrad)	B (T)	r (%)
307.394	2.23	-17.5	0.45	14.6
386.922	4.06	-28.5	0.74	23.8
492.547		-14.4	0.52	17.7
599.444		-22.2	0.80	27.3

OPERATIONAL ASPECTS

Operationally the orbit bumps have to be introduced at low luminosity, in order to avoid potential quenches. This can be achieved by a vertical van der Meer scan, in which the luminosity is varied by scanning the beam orbits transversely across each other at the IP.

The orbit correctors have to be fine-tuned around the theoretically predicted values of the kicks due to imperfections in the real machine. Simulations show that steps on the order of 0.1% of the total strength of the magnets is the necessary resolution. In order to ensure a correct distribution of the losses, the beam position monitors (BPMs) and the beam loss monitors (BLMs) have to be used. The BPM signals for a certain configuration can be obtained by calculating the offset of the nominal orbit. However, this might be inaccurate since BPMs are placed very close to the BFPP impact positions and therefore might be perturbed by the losses. Furthermore, there is a 1 mm uncertainty on the LHC aperture, meaning that the bump amplitudes have to be changed correspondingly to have the same loss distribution. This means that the BPM readings change by the same value and can therefore not be used alone to tune the orbit bumps.

To estimate the ratio between different BLM signals in a certain configuration we consider the energy deposition $\varepsilon(s)$ in a hypothetical infinite BLM outside the cryostat caused by a single particle impacting at $s = 0$ in an LHC magnet, as simulated in Ref. [7]. An approximation of the total energy deposition from all ions lost at positions s_i , obtained by single particle tracking, is the sum $\varepsilon_{\text{tot}}(s) = \sum_i \varepsilon(s - s_i)$. Since the BLM signal is proportional to energy deposition, the ratio between the signals on two BLMs located at s_1 and s_2 is estimated by $\varepsilon_{\text{tot}}(s_1)/\varepsilon_{\text{tot}}(s_2)$. This method gives the approximate loss pattern shown in Fig. 4, which one should try to obtain operationally. However, a more accurate estimate of the BLM signals is desirable, since the difference in angles between the impacting particles and variations along s in the physical design of the magnetic elements are neglected. Thus it is wished to perform FLUKA simulations of the BLM signals in the full magnet geometry at each impact position.

With the given uncertainties on the expected BPM and BLM signals, we can not expect to achieve exactly 1/3 of the losses at each location. Depending on where the actual quench limit is, more bumps might have to be introduced to compensate for the uncertainties.

It should also be noted that the locations of the impact point along s can change by a few metres because to the orbit bumps. With two bumps, the centre of the first loss spot moves from a dipole magnet to an MQML quadrupole.

The β -beating is at most 1.7% using two bumps, which is well within the limits of what can be corrected [9].

ELECTROMAGNETIC DISSOCIATION

The ions affected by 1-neutron EMD stay within the acceptance of the ring [7] due to the lower $\delta \approx -0.0048$ but

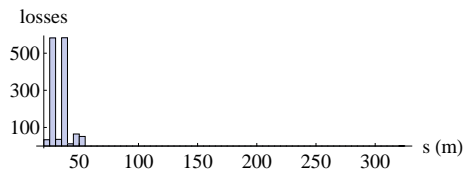


Figure 5: The loss map of ions affected by EMD downstream of IP2. A total of 10^5 particles were tracked.

should be intercepted by the collimation system. The collimation of ions is however predicted to be less efficient than requirements due to fragmentation processes [10]. Therefore tracking from IP1, IP2 and IP5 of ions affected by EMD was performed with ICOSIM [10], which includes the particle-matter interaction in the collimator. It was found that around 99% of all ions stopped in the collimators and that 1% was lost in the ring. A loss map downstream of IP2 is shown in Fig. 5.

A rough estimate of the heat load from the EMD beam is obtained by scaling the predicted heating from the BFPP beam (7.2 mW/cm^3 [6]) by the ratio of the cross sections ($\sigma_{\text{in}}^{\text{EMD}} \approx 215 \text{ barn}$ [11], $\sigma^{\text{BFPP}} \approx 281 \text{ barn}$ [12]). Taking 1% of that gives a heat load of 0.055 mW/cm^3 , which is much lower than the quench limit (estimates for different magnet types range from a few up to several tens of mW/cm^3). The 2-neutron process does create particles outside the acceptance lost in localized loss spots but has a lower cross section ($\sigma_{2n}^{\text{EMD}} \approx 0.2\sigma^{\text{BFPP}}$ [11]). Thus we conclude that the heating induced by losses caused by EMD should pose no danger.

CONCLUSIONS

Beam losses due to BFPP during $^{208}\text{Pb}^{82+}$ operation might quench magnets in the LHC but can be alleviated by distributing the losses over several locations through orbit bumps, thus lowering the heat load in single elements. Losses caused by EMD are cleaned by the collimation system and are not expected to cause quenches.

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