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THE ELECTRON CLOUD AND ITS IMPACT ON LHC AND FUTURE COLLIDERS

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Abstract

The secondary emission of electrons and their interaction with the electromagnetic fields of charged particle beams can lead to the build-up of electron clouds in accelerator beam chambers. The interaction of the electrons with both the beam and the chamber walls leads to detrimental effects, such as transverse instabilities and emittance growth, beam loss, pressure rise and heat load. Such effects are systematically observed in the Large Hadron Collider (LHC) during operation with proton beams with the nominal bunch spacing of 25 ns. Furthermore, the severity of electron cloud effects has increased after each long shutdown period of the machine, due to a degradation of the beam screen surfaces with air-exposure. Consequently, electron cloud is already limiting the total intensity in the collider and is one of the main concerns for the performance of the HL-LHC upgrade. In this contribution, the present understanding of electron cloud in hadron accelerators is reviewed. Measurements and observations at the LHC are presented, the impact on performance is evaluated and mitigation measures are discussed along with lessons for future machines.

INTRODUCTION

Electron cloud effects have affected the operation of numerous colliders and storage rings operating with positively charged particles since the 1960s [1–3]. The first experimental observations linked to electron cloud were transverse instabilities and vacuum degradation. Over the past three decades, as electron cloud has been observed in an increasing number of both past and currently operating accelerators, many further effects, such as tune shifts, incoherent emittance growth and heat load could also be associated with electron clouds. In parallel, it has become clear that electron cloud poses a significant risk to the performance of accelerators, which is important to consider already in the design phase of conceived machines. Among currently operating machines, the LHC is one of those most significantly impacted by electron cloud effects. As such, the LHC may serve as a warning example, but also as a rich source of information for increasing our knowledge of electron clouds and their impact and mitigation.

ELECTRON CLOUD FORMATION

Electron cloud build-up occurs through an avalanche multiplication of electrons due to their interaction with the periodic electromagnetic field of a bunched particle beam. Seed electrons can be generated by a passing bunch, e.g., through residual gas ionization or photoelectron emission. When accelerated by the beam field, such electrons can reach energies of several hundred electron volts. After the bunch passage, when the accelerated electrons hit the beam chamber walls, secondary emission of low-energy electrons resulting in an increase in the electron population may occur. Such low-energy electrons are most likely simply absorbed upon impact with the walls, but any electrons that remain in the chamber until the following bunch passage will in turn be accelerated and may again produce further secondary electrons. If at each bunch passage, a significant fraction of the secondary electron population survives, this mechanism can lead to avalanche electron multiplication, or multipacting, over the passage of a bunch train and result in the build-up of an electron cloud. The build-up will eventually reach a dynamic steady state, where the space charge from the electron cloud is sufficiently strong to repel newly emitted electrons back towards the surface and electron loss and production rates become equal, resulting in a saturation of the electron density after a number of bunch passages.

Based on the description above, one can identify two main factors affecting the likelihood of electron cloud build-up: (i) the survival rate of a low-energy electron in the beam chamber between successive bunch passages and (ii) the amount of secondary electron emission. The former is influenced by several machine and beam parameters, but foremost the dimensions of the beam chamber and the bunch spacing. In addition, externally applied electromagnetic fields can influence the electron lifetime, for example in quadrupole magnets, the lifetime can be extended through magnetic trapping [4], while solenoid fields can reduce the lifetime by bending the electrons back towards the chamber surface [5].

The secondary electron emission is determined by the Secondary Electron Yield (SEY), which defines the amount of emitted secondary electrons as a function of the energy and incidence angle of an impinging electron. For a virgin material, or after air exposure, secondary emission is generally high, but can subsequently reduce to a lower level through beam-induced conditioning, or scrubbing, i.e. irradiation by the electrons of the electron cloud. For most commonly used beam chamber materials, the SEY is a non-monotonic function of the electron energy, with a limited energy range where the surface acts as a net emitter. Consequently, the secondary emission depends strongly on the bunch intensity and length, since they both affect the instantaneous beam field which determines the energy of accelerated electrons. In combination with the cyclotron motion of the electrons around magnetic field lines, this leads to a strong dependence of the transverse shape of the electron cloud on the

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applied field, with characteristic patterns for each magnetic multipole.

ELECTRON CLOUD EFFECTS

Electron cloud effects can loosely be divided into two categories: (i) direct effects on the beam dynamics due to the electromagnetic forces of the electrons and (ii) effects on the broader accelerator environment caused by the presence of the electrons or their impact onto the beam chamber [1–3]. The impact of electron cloud on beam dynamics, which includes both coherent and incoherent effects, arises through the integrated effect of the electron cloud forces from around the machine and is usually a global effect, arising when significant electron cloud is present in a large part of the accelerator. Since the electron density builds up over the first part of bunch trains, these effects mainly impact bunches towards the end of bunch trains, which encounter a higher density.

The interaction of the beam with the cloud forces can give rise to transverse instabilities, of both coupled- and single-bunch type. Coupled-bunch instabilities arise due to the offset of a bunch with respect to the electron distribution built up by the preceding bunches, which then feeds back into the motion of subsequent bunches through the electrons. Since all electrons usually impact the chamber wall between bunch passages and move very fast in the presence of a bunch, a memory of the cloud shape from preceding bunches can be retained primarily in the presence of an external magnetic field. A typical example is the horizontal coupled-bunch instability caused by a bunch offset with respect to the characteristic vertical electron stripes in dipole magnets. This type of instability can usually be successfully suppressed with standard bunch-by-bunch transverse feedback systems.

When the positively charged bunch travels through an electron cloud, the electrons are accelerated towards the bunch and oscillate transversely around the beam position over the length of the bunch. During this electron cloud pinch, the electron density increases significantly within the bunch, enhancing the impact of the cloud on the beam dynamics. This is the driver for head-tail coupling and single-bunch instabilities, associated with beam loss and strong emittance growth. Since the electron oscillations can reach a high frequency, the instabilities are characterized by a fast intra-bunch motion, which is difficult for most conventional transverse feedback systems to damp. Even when they cannot be fully suppressed, the severity of the instabilities can often be mitigated with high chromaticity and amplitude-dependent tune shift from octupole magnets, with the drawback of degradation of the transverse emittance and beam lifetime. In addition to beam instabilities, the focusing forces exerted by the pinched electron cloud can give rise to a positive shift of the coherent betatron tune, with an increasing amplitude along the bunch train, relative to the electron density.

Even when the beam remains stable, its interaction with the electrons can result in significant beam degradation through incoherent effects that slowly degrade the beam quality, which can be of particular concern in colliders, where the beam is stored for a long time. These effects arise from the strong non-linearity and position-dependence of the electron cloud forces, which lead to a large tune spread, in particular when combined with the additional detuning from the stabilization mechanisms. The tune spread can lead to resonance excitation and result in slow beam losses and transverse emittance growth.

Another impact of the electron cloud is the transfer of energy from the beam to the cloud when the electrons are accelerated by the bunch. If a significant amount of electron cloud is present around the machine, the energy loss over a single turn can be significant enough to result in a measurable shift of the synchronous phase of the bunch, which must be compensated by the RF system [6]. The energy lost by the beam to the electrons will eventually be deposited elsewhere. Most of it is transferred into the vacuum chamber walls, since the energy of emitted secondaries is much lower than that of the impacting electrons. In a superconducting machine, where maintaining the temperature of the superconducting coils is critical, while the cooling capacity is usually very limited, the additional heat load from the electron cloud can become unmanageable for the cryogenic system.

Additionally, the electron flux on the beam chamber causes vacuum degradation through electron-stimulated desorption. The pressure rise can lead to several unwanted effects, such as increased beam losses, which may cause equipment irradiation and increased background in experimental areas, as well as vacuum breakdown in high voltage devices like kickers or electrostatic septa. In practise, electron cloud-induced vacuum degradation around such devices often delays the recovery of operational conditions after air-exposure, since the pace of beam-induced conditioning is limited by the low acceptable pressures in these devices [7].

ELECTRON CLOUD EFFECTS AND THEIR IMPACT IN THE LHC

Operation in the presence of electron cloud was first experienced in the LHC during its first operational run (Run 1, 2010-2013) with the bunch spacing of 75 and later 50 ns [8]. However, severe electron cloud effects were only expected to appear when operating with the nominal bunch spacing of 25 ns, for which build-up can occur with less secondary emission, since a larger part of electrons survive the shorter bunch spacing. Indeed, most of the effects detailed above have systematically been present whenever operating with such closely spaced bunches, first during a brief pilot period in Run 1 and throughout Run 2 (2015-2018) and the ongoing Run 3 (2022-present) [9, 10].

In addition, the electron cloud effects have been observed to become stronger between each of these periods. This is understood to be due to a degradation of some of the beam screen surfaces, as a consequence of air-exposure during the long shutdown periods between the operational runs [11, 12]. It appears that exposure to humidity, together with a lower surface carbon content, can lead to a CuO layer form-

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ing on the surface, instead of the Cu_2O formed on surfaces with lower humidity and higher carbon content, when the surface is re-exposed to the flux of the electron cloud under cryogenic conditions [13]. Laboratory measurements on degraded beam screens extracted from the LHC and on lab-prepared surfaces with CuO show a different SEY and worse conditioning behaviour with electron irradiation compared to the regular beam screen surfaces.

Currently, higher bunch intensities are available for the LHC than were used in Run 2. This is in preparation for the High-Luminosity LHC (HL-LHC), which foresees a reduction in the transverse beam emittances along with a doubling of the bunch intensity from Run 2 to 2.3×10^{11} p in Run 4. During Run 3, the bunch intensity used for operation in the LHC is foreseen to be increased up to an intermediate value of 1.8×10^{11} p, with 1.6×10^{11} p reached so far. The various electron cloud effects depend in different ways on the bunch intensity, with some effects becoming less severe and others becoming stronger with increasing intensity, as discussed below.

Since the LHC is always using the transverse feedback system in operation, coupled-bunch instabilities are rarely observed, but single bunch instabilities are a common occurrence. On the injection plateau at 450 GeV, single bunch instabilities are caused by electron cloud in the arc quadrupoles, where the field lines cause the highest electron density to build up around the beam location. To control the instabilities, high chromaticity ($Q'_{x,y} \geq 15$), high octupole currents, and a high gain on the transverse feedback system are required. Even with these measures, some bunches still suffer from weak instabilities associated with a modest emittance blow-up. However, a clear reduction in the prevalence of unstable bunches has been observed with increasing bunch intensity during fills for luminosity production in Run 3, suggesting a favorable scaling of the stability with increasing bunch intensity. Such a scaling was already predicted in Run 2 based on macro-particle simulations, which show the electron density at the beam location decreasing with increasing bunch intensity, with a consequent decrease in instability growth rate [14]. The scaling has also been confirmed in dedicated measurements, where the octupole current required to ensure stability was found to be inversely proportional to the bunch intensity, as shown in Fig. 1.

Single-bunch instabilities caused by electron cloud in the arc dipoles are also systematically observed, but only at the end of fills, when the beams have been colliding for a long time. This is a consequence of how the electron density in dipole magnets is concentrated in vertical stripes. At high bunch intensity, the stripes appear far away from the center of the beam, but when the bunch intensity decreases with luminosity burn-off, the stripes approach the beam location. Eventually, the density at the beam location increases sufficiently to drive the beam unstable. Such instabilities were first observed early in Run 2 in operation with trains of 72 bunches [15]. They could be mitigated with high chromaticity ($Q'_{x,y} \geq 22$) during collisions, and eventually disappeared as the beam screen surfaces conditioned. The

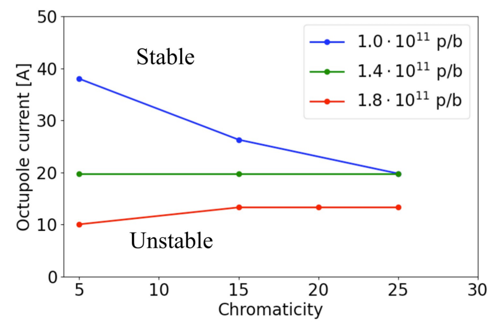

Figure 1: Measured octupole strength required for beam stability in the LHC at injection energy, as a function of chromaticity and bunch intensity.

instabilities reappeared in Run 3 and remain present during the end of fills despite high chromaticity, appearing in particular during emittance scans, when the beam-beam interactions and the tune spread they induce are reduced. The fact that these instabilities are still observed, even after conditioning, attests to the further degradation of beam screens since Run 2. Also the bunch intensity at which instabilities start appearing has increased from around 1.0×10^{11} p in Run 2 to 1.2×10^{11} p in Run 3, which is likely a consequence of the different SEY curve and higher maximum SEY associated with the degraded surfaces. Since these instabilities appear only towards the end of fills, their direct impact on the machine performance is small. However, the high chromaticity required for their mitigation also indirectly impacts the performance by degrading the beam lifetime.

In addition to coherent instabilities, several incoherent effects occur in the LHC. Together with the chromaticity and octupole currents that are needed to keep the beam stable, the electron cloud introduces a tune spread that pushes a significant amount of particles onto the third order resonance when operating with the nominal betatron tunes at injection energy. To preserve the beam lifetime, the transverse tune settings are modified whenever operating with bunch trains, in order to better accommodate the large tune footprint [9]. At injection, the LHC also suffers from slow incoherent emittance growth with a bunch-by-bunch signature that is compatible with electron cloud effects. Also this effect can be traced back to the large electron density at the beam location in the arc quadrupoles. Particle tracking simulations that take into account both the electron cloud and the non-linear magnetic fields of the lattice suggest that the electron cloud is responsible for exciting a family of synchro-betatron resonances, which drives the emittance growth, see Fig. 2 [16]. Based on these observations, the LHC optics were modified in 2023 by changing the arc-by-arc phase advance to minimize the excitation of fourth-order resonances by the lattice octupoles and of synchro-betatron resonances from the electron clouds [17]. In simulations, the optics change results in a clear reduction of the emittance growth, but a dedicated experimental verification is still pending since the 2023 LHC run was cut short due to technical issues.

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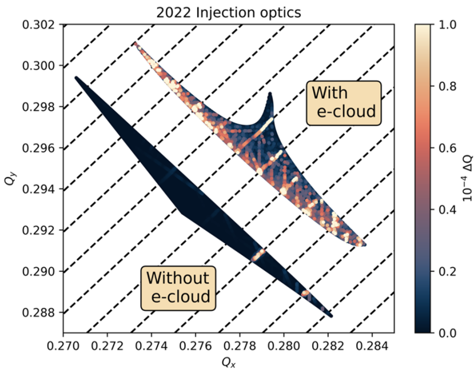

Figure 2: Frequency map analysis from simulations with and without electron cloud at LHC injection in 2022 [16].

With the beams in collision, slow losses with a magnitude that increases along the bunch trains, as expected for electron cloud effects, have been observed all along the fills in Run 2 and Run 3. The losses depend strongly on the crossing angle of the two beams, as well as on the value of the optics betatron functions at the two main interaction points. Together with further observations this has allowed to pinpoint the source of the losses to the non-linear forces of the electron cloud in the final-focusing, or inner triplet, quadrupoles around the two main experiments [11]. This is one of a rare few electron cloud effects on beam dynamics that originates from a highly localised electron cloud rather than being a global effect, which can be attributed to the enhancement given by the very large values of the betatron functions in the vicinity of the interaction points. The losses can contribute significantly to the bunch intensity decay during luminosity production, which was the case particularly in Run 2, whereas the effect has been milder in Run 3. Comprehensive simulations of the slow losses during collisions, combining the non-linear lattice model of the machine, the longitudinally resolved electron cloud in the inner triplet and beam-beam effects have recently been performed for the first time [18]. The results suggest that the larger bunch intensities used in operation contribute to the reduction in slow losses from electron cloud in the triplets.

In addition to the collective effects discussed above, the LHC is strongly impacted by the additional heat load from electron cloud. These heat loads must be efficiently extracted by the cryogenics system, without allowing the temperature of the beam screen to increase too much, in order to protect the superconducting magnets at 1.9 K and to ensure a stable vacuum. The cryogenic system consists of four pairs of cryoplants, each responsible for cooling two of the eight LHC arcs, or sectors. Depending on the cryoplants and the additional equipment requiring cooling in each sector, the maximum capacity available for the arc beam screen ranges from around 190 W to 260 W per lattice half-cell in the different sectors.

When operation with 25 ns beams started in Run 2, not only were unprecedentedly large heat loads observed, but they were also found to vary strongly between arcs, lattice half-cells, magnets and apertures. This was one of the first and the strongest indication that beam screen degradation had occurred in some parts of the machine after the end of Run 1. Initially, heat load transients at the time of injection and during the energy ramp caused large excursions of the beam screen temperatures, causing delays of injection and beam dumps. After the implementation of successful feed-forward controls based on the beam properties, no further limitations from the heat load occurred in Run 2, despite heat loads reaching on average around 160 W per half-cell in some sectors [19]. Throughout Run 3, on the other hand, the heat load has limited the total intensity in the machine. This is mainly due to significant further degradation after Run 2 in one of the eight arcs, sector 78, which is one of the sectors with the lowest available cooling capacity. The problem is further aggravated by the increase in bunch intensity, since the heat load from electron cloud, as well as from other smaller sources such as impedance heating and synchrotron radiation, increase with the bunch intensity.

On the short term, the only mitigation measure available to address this limitation is to reduce the bunch train length to lower the average heat load per bunch. The main drawback is a reduction in the maximum possible number of bunches that can fit into the machine, but as long as the number of bunches is in any case limited by the heat load, there is room for gain. The LHC design filling pattern with trains of 72 bunches allows for around 2800 bunches per beam. However, the cooling capacity is sufficient only for a predicted 2000 bunches with the current bunch intensity of 1.6×10^{11} p, as shown in Fig. 3. Instead, with the trains of 36 bunches largely used in Run 3, up to around 2500 bunches can be accommodated with the same intensity.

To enable a further increase of the bunch intensity, even stronger electron cloud suppression is required. This can be achieved with the “8b+4e” bunch pattern, which consists of trains of 56 bunches, where every 8 bunches are followed by 4 empty bunch slots. The scheme gives a strong reduction of electron cloud effects, but at the cost of roughly 30% of the number of bunches [10]. Hybrid filling schemes, combining 8b+4e beam with standard 25 ns beam with a ratio that can be adjusted to match the heat load to the cooling capacity, are a better compromise. A hybrid scheme mixing 8b+4e beam and trains of 36 bunches that was used in operation in 2023 showed a heat load reduction of around 20% per bunch, proving its potential for electron cloud suppression.

ELECTRON CLOUD MITIGATION IN FUTURE MACHINES

Based on the experience in the LHC, it is clear that suppressing electron cloud build-up is the only way to fully mitigate all electron cloud effects. Several different techniques to this aim have been developed, each of which addresses one of the two main conditions for electron cloud build-up, namely the SEY or the electron survival rate between bunch passages. Surface modifications to reduce the SEY can be achieved by coating the beam screen surface with a material

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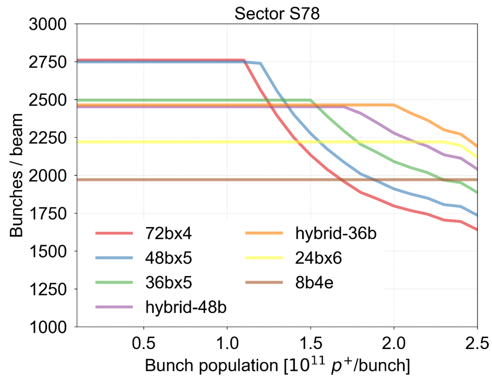

Figure 3: Predicted maximum number of bunches possible to inject in the LHC with different filling patterns, as a function of bunch intensity.

with an intrinsically low SEY, such as amorphous carbon or non-evaporable getters [20, 21]. Alternatively, a similar effect can be achieved by introducing structural changes to the surface, e.g., by increasing surface roughness with the help of laser engineering, or through the introduction of macroscopic grooves [22, 23]. To some extent, beam induced scrubbing can also reduce the SEY of surfaces exposed to electron cloud, but the achievable SEY is strongly material dependent and typically remains higher than with dedicated mitigation measures.

The electron survival rate can be reduced with external electromagnetic fields that modify the electron dynamics. This can be achieved for example with longitudinal solenoid fields, which curve emitted electrons back onto the chamber surface, or with clearing electrodes, whose electric field pulls the electrons back onto the surface [5, 24]. In addition, it may be necessary to implement measures to control the reflection and absorption of the synchrotron radiation, in order to reduce photoelectron emission depending on the photoelectron yield of the chamber material. Significant photoelectron emission can enhance the electron cloud build-up and a sufficiently large flux may cause some of the same effects as the electron cloud, even in the absence of multipacting. Many of these mitigation methods have already been used and proven their effectiveness in running machines, such as SuperKEKB, the LHC and other CERN machines and are considered in the design of future projects such as the Future Circular Collider (FCC), the Electron-Ion Collider (EIC) and the HL-LHC.

To ensure efficient mitigation in future colliders, the risk of electron cloud build-up and the required mitigation measures must be considered already in the general design phase, when the beam and machine parameters, such as bunch spacing, bunch intensity, bunch length and vacuum chamber design are defined. Since the dependence on many of these parameters is non-monotonic, the full range of parameters foreseen in operation should be taken into account to ensure mitigation for the most critical configuration, e.g., the full bunch intensity range due to luminosity burn-off in the HL-LHC or due to top-up injection in the positron ring of the FCC. The experience in the LHC also shows that it is important to evaluate the risk of electron cloud build-up and consider mitigation not only in the main lattice components, but in as much of the machine as possible, including the interaction regions, as well as areas that are unlikely to impact the beam but may cause limitations due to local electron cloud, such as high-voltage devices.

For machines that are planned to be built from the beginning, such as the FCC, effective solutions are likely to be found among the range of available mitigation measures [25, 26]. Simulation studies for the positron ring of the FCC-ee Z-mode show that already a 25 ns bunch spacing sets stringent constraints on the acceptable SEY. The most critical bunch intensities for e-cloud build-up are around 1.25×10^{11} e^+, much lower than the design peak current, but due to the top-up injection, e-cloud suppression must be ensured also at lower intensity. In the arc dipoles and quadrupoles, a maximum SEY below 1.1 is required to ensure beam stability. Although such values are challenging to achieve, they could be reached with high-performing surface treatments, such as amorphous carbon or laser engineered surfaces. In addition, effective measures to limit the synchrotron radiation scattering into the main chamber and the photoemission yield are necessary [27].

In machines that rely to a large extent on existing installations, such as the HL-LHC and EIC, the implementation of mitigation measures may be more difficult [28]. In the HL-LHC upgrade, the inner triplet magnets will be replaced, which provides the opportunity to eliminate the slow beam losses during collisions with an applied amorphous carbon coating. However, much of the machine, including the arcs, will not be exchanged. Since the LHC is already strongly limited by heat load from electron cloud, there is no doubt that the impact on the HL-LHC will be even stronger, without further mitigation. This follows from the increase in bunch intensity, as well as further surface degradation that is likely to occur with coming long shutdown periods. To avoid such strong limitations to the HL-LHC performance, a system is being developed for applying a carbon coating on selected beam screens in-situ in the next long shutdown [29]. Around a quarter of all the half-cells in the machine could be treated in the next shutdown, with further treatment possible in subsequent shutdowns, should it be needed.

SUMMARY AND OUTLOOK

The build-up of electron cloud in the beam chambers of an accelerator leads to a wide range of effects that can considerably impact the beam quality and the accelerator environment. This is particularly evident in the LHC, where increasingly strong electron cloud is significantly limiting the performance. However, with the understanding gained from LHC observations, together with a growing arsenal of tools developed for the study of even the more subtle effects, and increasing evidence of effective mitigation measures, the prospects for ensuring electron cloud mitigation in future colliders are promising.

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