ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP31

ELECTRON CLOUD EFFECTS IN THE CERN ACCELERATORS IN RUN 3

L. Mether*, H. Bartosik, E. de la Fuente Garcia, L. Giacomel, G. Iadarola,
S. Johannesson, I. Mases Sole, K. Paraschou, G. Rumolo, L. Sabato, C. Zannini
CERN, Geneva, Switzerland

Abstract

Several of the machines in the CERN accelerator complex, in particular the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS), are prone to the build-up of electron clouds. Electron cloud effects are observed especially when the machines are operated with a 25 ns bunch spacing, which has routinely been used in the LHC since the start of its second operational run in 2015. After the completion of the LHC Injectors Upgrade program during the latest long shutdown period, the machines are currently operated with unprecedented bunch intensity and beam brightness. With the increase in bunch intensity, electron cloud effects have become one of the main performance limitations, as predicted by simulation studies. In this contribution we present the experimental observations of electron cloud effects since 2021 and discuss their implications for the future operation of the complex.

INTRODUCTION

Electron clouds are caused by the avalanche multiplication of electrons that can occur as a consequence of their acceleration by the beam field and the subsequent emission of further electrons upon impact on the chamber surface, as defined by its secondary emission yield (SEY). They are typically manifested as transverse instabilities, emittance growth, pressure rise, heat load in cryogenic regions, incoherent beam losses and RF stable phase shift [1]. Since electron cloud (e-cloud) build-up is most prominent with closely spaced bunches, in the CERN accelerators, e-cloud effects are observed mainly for the LHC beam with its nominal bunch spacing of 25 ns [2]. They occur to a varying degree in the LHC and its injectors, starting from the Proton Synchrotron (PS), where the 25 ns bunch structure is first produced, and continuing through the SPS to the LHC.

So far, the main strategy for e-cloud mitigation in the CERN accelerators has been to rely on beam-induced conditioning, or scrubbing, in which the SEY of the beam chamber surface is reduced due to the bombardment by the e-cloud itself [3, 4]. In practise, this is often done with dedicated scrubbing runs, during which the amount and duration of beam, as well as the beam parameters, are regularly adjusted to systematically maximize e-cloud production while keeping its effects just within the acceptable limits. However, the SEY that can be achieved through scrubbing is limited to an extent that depends on the surface material and broader machine conditions. This is evident in particular in the LHC, where e-cloud effects, after initially reducing with scrubbing, remained present and significant throughout its second operational run (Run 2), even though they did not significantly limit the performance [5, 6]. In the injectors, scrubbing has been more successful. In the SPS, the 25 ns LHC beams initially suffered from strong pressure rise, transverse instabilities and emittance growth, which could be successfully mitigated with systematic scrubbing runs over a decade, in preparation for delivery to the LHC [7].

The High-Luminosity LHC (HL-LHC), expected to start in 2029, 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 [8]. To be able to produce such beams for the LHC, the injectors underwent a major consolidation, which was finalised during the previous long shutdown period (LS2) [9]. Among the new installations was an upgrade of the SPS RF system, allowing to significantly increase the total intensity that can be accelerated to 450 GeV/c and extracted to the LHC. During the current run, the injectors are expected to fully prepare the HL-LHC beam and are already on a good path towards this goal with $2.2{\times}10^{11}$ p/b (protons per bunch) accelerated in the SPS [10]. The operational bunch intensity in the LHC is foreseen to be ramped up to an intermediate value of 1.8×10^{11} p, with 1.6×10^{11} p reached in 2023 [11]. With the significant increase in bunch intensity since Run 2, new limitations from e-cloud have been encountered, in particular in the SPS and the LHC, as will be discussed below.

INJECTORS

The RF manipulations that give the LHC beams their 25 ns structure take place in the PS at the top energy of 26 GeV/c, shortly before beam extraction [12]. During this period, transverse instabilities, baseline distortion on pickup signals and pressure rise have been observed after air exposure since 2001, but have quickly conditioned with machine operation [2, 13]. After the PS restart in 2021, pressure rise due to e-cloud was again observed in large parts of the machine and initially hindered normal operation by interlocking the pulsing of the injection kicker. The pressure rise could be conditioned by a dedicated period of scrubbing over several days, after which no further limitations from e-cloud have appeared, even with bunch intensities as high as 2.9×10^{11} p.

When the SPS resumed operation later in 2021, extensive scrubbing was needed, since much of the machine had been opened during the shutdown. Whereas transverse instabilities and emittance growth could be mitigated with chromaticity, the main limitation setting the scrubbing pace came from the vacuum pressures around the ring. One of the main bottlenecks was a vertical kicker magnet (MKDV1) for the upgraded beam dump system that was found to ex-

* lotta.mether@cern.ch

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP31

hibit poor high-voltage behaviour and therefore assigned an exceptionally low vacuum pressure interlock threshold value of 5×10^{-8} mbar. Over two weeks of scrubbing at injection with 1.4×10^{11} p/b, the pressure in the MKDV1 and other vented areas conditioned to the required level, while the number of bunches was gradually increased from 12 up to the design LHC filling pattern of four trains of 72 bunches. A newly installed stainless-steel liner in the dedicated e-cloud monitors, mimicking the conditions in the main dipoles, also required a similar amount of time to fully condition [14].

On the accelerating cycle, progress was limited by longitudinal instabilities, as the commissioning of the RF system was not well advanced, and only 10^{11} p/b in 4×72 bunches could be accelerated after another two weeks [15]. The scrubbing was also limited by erratic pressure rise and spurious vacuum spikes in the horizontal dump kickers (MKDH) [16]. In addition, the strong beam-induced heating of the last injection kicker magnet (MKP-L) forced most of the scrubbing to be interleaved with other activities to allow for intermittent cool-down. Since 2021 was largely devoted to commissioning, LHC beams were not regularly taken in the machine after the scrubbing run, which lead to a deconditioning of the vacuum chambers, requiring additional scrubbing later in the year to recover the vacuum performance of the MKDV1.

At the end of 2021, the faulty dump kicker was exchanged and another scrubbing run took place in 2022 to condition the kicker and other vented areas. The resulting pressure rise could be conditioned to acceptable levels in five days of scrubbing at injection with bunch intensity up to 2×10^{11} p, highlighting the improved scrubbing progress when only a few areas are concerned. When accelerating several trains of 72 bunches with increasing bunch intensity, the spurious pressure spikes in the MKDH began to occur more frequently, in particular at the end of acceleration, when the peak bunch current increases with the decreasing bunch length [17]. A similar behaviour was observed also on the MKP-L and together they significantly limited the scrubbing efficiency, as well as the achievable bunch intensity, which after another four weeks of scrubbing reached 1.6×10^{11} p in 4×72 bunches.

The MKP-L was finally exchanged with a new low-impedance version at the end of 2022, eliminating the need for regular cool-down during the scrubbing runs [18]. The new MKP-L, whose pressure is shown in Fig. 1, and other vented elements were successfully scrubbed within five days at injection energy for bunch intensities up to 2.2×10^{11} p. However, very strong pressure rise in the MKP-L was observed at the end of the energy ramp when first trying to accelerate the beams, with only 24 bunches and 1.4×10^{11} p/b. The pressure rise was slowly conditioned by very gradually increasing the bunch intensity and, for each intensity, slowly approaching the nominal bunch length of 1.65 ns by systematically decreasing controlled longitudinal blow-up. To optimise the scrubbing of the pressure spikes in both the MKP-L and MKDH, which occur only during a very short part of the accelerating cycle, a dedicated scrubbing cycle with an extended energy plateau of 5 s at 400 GeV/c was created. In addition, modifications were made to the logics of software interlocks to reduce unnecessary triggering, from which the recovery could take anywhere from a few minutes to hours. With these successful measures, the pressure spikes could be conditioned up to 2×10^{11} p/b in 4×72 bunches during four weeks of scrubbing, and have subsequently been scrubbed further to 2.2×10^{11} p/b.

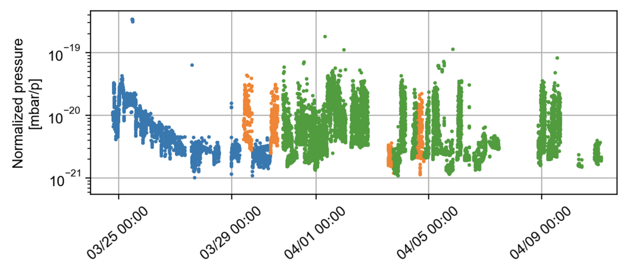

Figure 1: Normalised maximum pressure in the MKP-L during scrubbing on the injection (blue), standard acceleration (orange) and long acceleration (green) cycles.

The very strong increase in the pressure normalised with intensity at the end of acceleration, see Fig. 1, is characteristic for the MKP-L and MKDH, but is not observed in most other parts of the machine. Observations of the dynamic pressure rise, such as the large decrease when operating with an e-cloud-suppressing bunch pattern, as well as the sharp rise when going from 12 to 24 bunches, suggest that it is caused by e-cloud. However, the precise mechanism behind it is not currently understood. Simulations show an increase in electron flux with the bunch peak only for SEY curves with a maximum yield at electron energies much higher than those observed in lab measurements. A possible explanation could be the charging of the insulator surfaces, which has been shown to increase the maximum energy [19]. Another possible explanation could be that the pressure rise, instead of being caused by an increase in electron flux, is due to an increase in the electron-induced desorption yield with increasing energy of the impinging electrons.

LHC

Among the main experimental observations of e-cloud in the LHC are transverse instabilities and emittance growth occurring at injection, slow beam losses in collision, as well as additional heat load on the beam screens of the cryogenic magnets [6, 20]. Contrary to expectation and measurements during a first test with 25 ns beams in Run 1, the heat loads measured on the beam screens in Run 2 showed large variations between the eight sectors of the machine, as well as between individual half-cells, magnets and apertures. Comprehensive studies, combining measurements with beam, e-cloud simulations and surface analysis conducted on beam screens extracted from the machine, show that this is due to varying SEY caused by a degradation of some of the beam screen surfaces. The most plausible mechanism is the formation of CuO on conditioned surfaces exposed to air during the first long shutdown period [21–24].

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP31

When the LHC was brought back into operation in 2022, it quickly became evident that even further surface degradation had occurred due to LS2 [25]. From the beginning of multi-bunch operation during the scrubbing run at injection and throughout the year, the highest average heat load was systematically measured in sector 78, which showed intermediate heat loads in Run 2 [26, 27]. After the scrubbing run, the LHC beams were brought into collision for luminosity production at 6.8 TeV with a gradually increasing number of bunches of intensity around 1.2×10^{11} p. With around 2200 bunches/beam, the heat load in sector 78 reached the cooling capacity available from the cryogenic system, around 195 W/half-cell [28, 29], and limited the total beam intensity from this point on [30]. Since the e-cloud requires an estimated 20-30 bunch passages [31] to build up, the amount of e-cloud can be reduced by decreasing the length of the individual bunch trains. By changing the train length from 48 to 36 bunches, around 2450 bunches/beam could be accepted without lowering the bunch intensity. Over the remaining two months of operation in 2022, the bunch intensity could be gradually increased up to and slightly beyond the target of 1.4×10^{11} p at the start of collisions, as a result of the continued conditioning of the surfaces, as well as a modification of other beam parameters.

A comparison of the heat loads measured with similar beam parameters at different times during 2022 suggested that the beam screen conditioning tapered off, as expected with accumulated electron dose, and that significant further conditioning was unlikely to occur, leaving several sectors in a further degraded state compared to Run 2 [25]. Transverse beam stability provided an independent observation of the worsened machine state, as stronger mitigation measures in the form of chromaticity and octupole currents were required in 2022 than in Run 2, despite the expected favorable scaling of beam stability with increasing bunch intensity [32]. In addition, transverse instabilities caused by the increase in central electron density in the dipoles with decreasing intensity at the end of luminosity production, systematically occurred throughout 2022, whereas in Run 2 they were suppressed within a few months of operation [33].

During 2023, the bunch intensity in the LHC was foreseen to be increased up to 1.8×10^{11} p, which could only be achieved with further changes to the bunch train pattern. The “8b4e” bunch pattern, which consists of trains of 56 bunches, where every 8 bunches are followed by 4 empty bunch slots, provides a strong reduction of e-cloud effects at the cost of limiting the number of bunches to below 2000 per beam [34, 35]. Hybrid filling schemes, which combine 8b4e beam with standard 25 ns beam with a ratio that can be adjusted to match the heat load to the cooling capacity, are a much better compromise [3]. The expected heat load as a function of the bunch intensity for different bunch train patterns can be estimated based on a cell-by-cell SEY map of the machine. This can be obtained by comparing the measured heat loads in each half-cell to the heat loads expected from simulations with matching beam conditions. Following this procedure, the maximum number of bunches with a given bunch intensity and thus the integrated luminosity reach can be estimated, for different patterns. Based on such considerations, a hybrid scheme, with injections consisting of a single train of 8b4e beam (25 %) followed by up to five trains of 36 bunches (75 %), which allows for a similar total number of bunches as used in 2022, but is not expected to be limited in intensity below 1.8×10^{11} p, was selected for 2023 operation. Although the full potential of the filling scheme was never put to the test due to other limitations that restricted the bunch intensity to 1.6×10^{11} p, the e-cloud suppression could be observed through a clear reduction of the heat load, as shown in Fig. 2.

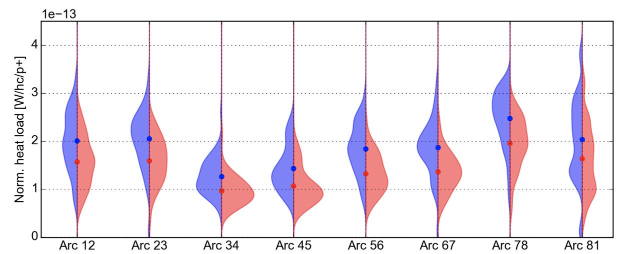

Figure 2: Comparison of the average (dots) and cell-by-cell distribution (violins) of normalised heat load in the LHC arcs with the 2022 (blue) and 2023 (red) bunch train patterns for similar bunch intensity and length.

CONCLUSION

In the injectors, the experience from Run 3 so far suggests that beam-induced scrubbing can sufficiently mitigate e-cloud effects to ensure good beam quality for the HL-LHC. However, the cost in terms of operation time needed to achieve the desired performance in the SPS is concerning for future operation. Although most of the machine conditions well, the strong pressure rise in some injection and extraction devices at high energy is particularly challenging. It remains to be seen if this behaviour can be permanently mitigated to some extent through scrubbing, as suggested by the past experience of conditioning for the LHC beams. While a complete understanding of the underlying mechanism may help to improve future designs of such devices, in the near future, additional measures to the ones already implemented in 2023, such as improved vacuum sectorisation and application of targeted surface treatment, where possible, can help to improve scrubbing efficiency.

In the LHC, on the other hand, it has become evident that beam-induced scrubbing is no longer sufficient to mitigate e-cloud, given the tendency for surface degradation with machine venting. On the short term, e-cloud-suppressing filling patterns provide partial mitigation at the cost of an approximately 10 % reduction in the total number of bunches. On the long term, as well as for future machines, it is clear that stronger mitigation strategies, such as amorphous-carbon coating or other surface treatments that provide a more robust protection against the e-cloud [23, 24, 36], are necessary in order to fully exploit the machine potential.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP31

REFERENCES

[1] G. Iadarola and G. Rumolo, "Electron Cloud Effects," in *ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators*, Benevento, Italy, Sep. 2017, pp. 49–56. doi:10.23732/CYRCP-2018-001.49

[2] G. Rumolo *et al.*, "Electron cloud effects at the CERN accelerators," in *Proc. Joint INFN-CERN-ARIES Workshop on Electron-Cloud Effects (ECLOUD'18)*, La Biodola, Elba, Italy, Jun. 2018, pp. 13–20. doi:10.23732/CYRCP-2020-007.13

[3] G. Iadarola *et al.*, "Impact and Mitigation of Electron Cloud Effects in the Operation of the Large Hadron Collider," in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2085–2088. doi:10.18429/JACoW-IPAC2017-TUPVA019

[4] R. Cimino *et al.*, "Nature of the decrease of the secondary-electron yield by electron bombardment and its energy dependence," *Phys. Rev. Lett.*, vol. 109, p. 064 801, 2012. doi:10.1103/PhysRevLett.109.064801

[5] G. Iadarola *et al.*, "Electron Cloud and Heat Loads in Run 2," in *Proc. 9th LHC Operations Evian Workshop*, Evian-les-Bains, France, Jan.-Feb. 2019, pp. 221–232. https://cds.cern.ch/record/2750297/

[6] G. Iadarola *et al.*, "Progress in Mastering Electron Clouds at the Large Hadron Collider," in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 1273–1278. doi:10.18429/JACoW-IPAC2021-TUXA03

[7] G. Rumolo *et al.*, "Electron Cloud Effects at the LHC and LHC Injectors," in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 30–36. doi:10.18429/JACoW-IPAC2017-MOZA1

[8] I. Béjar Alonso *et al.*, Eds., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN, 2020, CERN-2020-010. doi:10.23731/CYRM-2020-0010

[9] J. Coupard *et al.*, Eds., *LHC Injectors Upgrade, Technical Design Report - Vol. I: protons*. CERN, 2014, CERN-ACC-2014-0337. doi:10.17181/CERN.7NHR.6HGC

[10] G. Rumolo *et al.*, "Beam performance with the LHC Injectors Upgrade," presented at HB'23, Geneva, Switzerland, Oct. 2023, paper MOA1I1, these proceedings.

[11] N. Karastathis *et al.*, "LHC Run 3 Configuration Working Group Report," in *Proc. 9th LHC Operations Evian Workshop*, Evian-les-Bains, France, Jan.-Feb. 2019, pp. 273–284. https://cds.cern.ch/record/2750297/

[12] H. Damerau, S. Hancock, A. Lasheen, and D. Perrelet, "RF Manipulations for Special LHC-Type Beams in the CERN PS," in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1971–1974. doi:10.18429/JACoW-IPAC2018-WEPAF063

[13] R. Cappi, M. Giovannozzi, E. Metral, G. Metral, G. Rumolo, and F. Zimmermann, "Electron cloud buildup and related instability in the CERN Proton Synchrotron," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 5, p. 094 401, 2002. doi:10.1103/PhysRevSTAB.5.094401

[14] G. Arduini *et al.*, "Measurement of the Electron Cloud Properties by Means of a Multi-strip Detector in the CERN SPS," in *Proc. 8th European Particle Accelerator Conf. (EPAC'02)*, Paris, France, 2007, pp. 1437–1439. https://jacow.org/e02/papers/WEPDO002.pdf

[15] V. Kain *et al.*, "Achievements and Performance Prospects of the Upgraded LHC Injectors," in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, 2022, pp. 1610–1615. doi:10.18429/JACoW-IPAC2022-WEIYGD1

[16] M. J. Barnes *et al.*, "Measurement and analysis of SPS kicker magnet heating and outgassing with Different Bunch Spacing," CERN, Geneva, Switzerland, CERN-ATS-2009-017, 2010. https://cds.cern.ch/record/1199759

[17] F. Velotti *et al.*, "CERN SPS dilution kicker vacuum pressure behaviour under unprecedented beam brightness," presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THBP05, these proceedings.

[18] C. Zannini *et al.*, "Beam-induced heating mitigation of the SPS kickers: a crucial upgrade to move towards HL-LHC beam intensities," in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 3486–3489. doi:10.18429/JACoW-IPAC2023-WEPL157

[19] M. Belhaj, "SEY properties of dielectric materials, modeling and measurements," presented at ECLOUD'18 workshop, La Biodola, Elba, Italy, Jun. 2018. https://agenda.infn.it/event/13351/

[20] K. Paraschou *et al.*, "Emittance growth from electron clouds forming in the LHC arc quadrupoles," presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THBP16, these proceedings.

[21] G. Iadarola, G. Rumolo, P. Dijkstal, and L. Mether, "Analysis of the beam induced heat loads on the LHC arc beam screens during Run 2," CERN, Geneva, Switzerland, CERN-ACC-NOTE-2017-0066, 2017. https://cds.cern.ch/record/2298915/

[22] G. Iadarola *et al.*, "Beam-induced heat loads on the LHC arc beam screens with different beam and machine configurations: experiments and comparison against simulations," CERN, Geneva, Switzerland, CERN-ACC-2019-0057, 2019. https://cds.cern.ch/record/2705513/

[23] V. Petit *et al.*, "Beam-Induced Surface Modification of the LHC Beam Screens: The Reason for the High Heat Load in Some LHC Arcs?" In *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 3479–3482. doi:10.18429/JACoW-IPAC2021-WEPAB339

[24] V. Petit *et al.*, "Beam-induced surface modifications as a critical source of heat loads in the Large Hadron Collider," *Commun. Phys.*, vol. 4, p. 192, 2021. doi:10.1038/s42005-021-00698-x

[25] L. Mether *et al.*, "Electron cloud observations and mitigation for the lhc run 3," in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 2850–2853. doi:10.18429/JACoW-IPAC2023-WEPA091

[26] L. Mether, "Electron cloud effects at the LHC: status and prospects," presented at ECLOUD'22 workshop, La Biodola, Elba, Italy, Sep. 2022. https://agenda.infn.it/event/28336/

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP31

[27] B. Bradu, "Electron clouds and cryogenic heat loads in the LHC: updated measurements in resuming operation for Run 3," presented at ECLOUD'22 workshop, La Biodola, Elba, Italy, Sep. 2022. https://agenda.infn.it/event/28336/

[28] B. Bradu, K. Brodzinski, and G. Ferlin, "How does a cryogenic system cope with e-cloud induced heat load?" In *Proc. Joint INFN-CERN-ARIES Workshop on Electron-Cloud Effects (ECLOUD'18)*, La Biodola, Elba, Italy, Jun. 2018, pp. 73–82. doi:10.23732/CYRCP-2020-007.73

[29] G. Ferlin *et al.*, "Cryogenics Experience during Run 2 and impact of LS2 on next run," in *Proc. 9th LHC Operations Evian Workshop*, Evian-les-Bains, France, Jan.-Feb. 2019, pp. 85–90. https://cds.cern.ch/record/2750297/

[30] L. Mether, "E-cloud limitations in the LHC and mitigation strategy," presented at Joint Accelerator Performance Workshop, CERN, Switerland, Dec. 2022. https://indico.cern.ch/event/1194548/

[31] G. Iadarola, "Electron Cloud Studies for CERN Particle Accelerators and simulation Code Development," PhD thesis, Naples University, Naples, Italy, 2014. https://cds.cern.ch/record/1705520/

[32] L. Sabato, G. Iadarola, and L. Mether, "Numerical simulations studies on single-bunch instabilities driven by electron clouds at the LHC," CERN, Geneva, Switzerland, CERN-ACC-NOTE-2020-0050, 2020. https://cds.cern.ch/record/2733028/

[33] A. Romano, O. Boine-Frankenheim, X. Buffat, G. Iadarola, and G. Rumolo, "Electron cloud buildup driving spontaneous vertical instabilities of stored beams in the large hadron collider," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 21, p. 061 002, 2018. doi:10.1103/PhysRevAccelBeams.21.061002

[34] H. Bartosik and G. Rumolo, "Beams from the injectors," in *Proc. 7th Evian Workshop on LHC beam operation*, Evian-les-Bains, France, Dec. 2016, pp. 233–238. https://cds.cern.ch/record/2293524/

[35] G. Iadarola *et al.*, "Performance limitations from electron cloud in 2015," in *Proc. 6th Evian Workshop on LHC beam operation*, Evian-les-Bains, France, Dec. 2015, pp. 101–110. https://cds.cern.ch/record/2294523/

[36] C. Yin Vallgren *et al.*, "Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 14, p. 071 001, 2011. doi:10.1103/PhysRevSTAB.14.071001