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PROGRESS IN MASTERING ELECTRON CLOUDS AT THE LARGE HADRON COLLIDER

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Abstract

During the second operational run of the Large Hadron Collider (LHC) a bunch spacing of 25 ns was used for the first time for luminosity production. With such a spacing, electron cloud effects are much more severe than with the 50-ns spacing, which had been used in the previous run. Beam-induced conditioning of the beam chambers mitigated the e-cloud formation to an extent that allowed an effective exploitation of 25 ns beams. Nevertheless, even after years of conditioning, e-cloud effects remained very visible, affecting beam stability and beam quality, and generating strong heat loads on the beam screens of the superconducting magnets with puzzling features. In preparation for the High Luminosity LHC upgrade, remarkable progress has been made in the modeling of the e-cloud formation and of its influence on beam stability, slow losses and emittance blow up, as well as in the understanding of the underlying behavior of the beam-chamber surface. In this contribution, we describe the main experimental observations from beam operation, the outcome of laboratory analysis conducted on beam screens extracted after the run, and the main advancements in the modeling of these phenomena.

INTRODUCTION

Electron cloud effects were identified among the main performance limitations for the Large Hadron Collider (LHC) already at the time of its design and construction [1]. At that time, a significant effort was made to study the properties of the beam chambers and to develop simulation tools to model the e-cloud formation and its effects on beam stability [2, 3].

During the first operational run of the LHC (Run 1, 2010 - 2013), the 50 ns bunch spacing was used for most of the luminosity production fills [4]. It was only in the second operational run (Run 2, 2015 - 2018) that the nominal bunch spacing of 25 ns was used routinely for physics operation. As expected, with such a shorter bunch spacing, e-cloud effects were observed to be much more severe than with 50 ns [5] Furthermore, during the Long Shutdown which took place between Run 1 and Run 2 (LS1, 2013 - 2014) the surfaces of most of the beam chambers had to be exposed to air, including in particular all the beam screens in the superconducting magnets of the eight LHC arcs. This had the effect of increasing the Secondary Electron Yield (SEY) of the beam chamber surfaces, making the e-cloud observed at the beginning of Run 2 particularly violent, which resulted in beam degradation due to transverse instabilities, vacuum pressure rises, and high heat loads on the beam screens of the LHC superconducting magnets.

The e-cloud formation could be effectively reduced by beam-induced conditioning of the beam-chamber surfaces (often called "scrubbing"), which consists in the reduction of the SEY of the surfaces thanks to electron bombardment due to the e-cloud itself [6]. This was obtained at first in dedicated scrubbing runs at injection energy (450 GeV), and then parasitically during the first period of luminosity production with 25 ns beams.

This process mitigated the e-cloud formation to an extent that allowed a satisfactory exploitation of nominal 25 ns beams in physics operation. Nevertheless, the conditioning accumulated over the entire Run 2 was not sufficient to fully suppress the e-cloud formation. The impact of the e-cloud on the beams remained visible and large heat loads on the beam screens were measured, especially in some of the LHC sectors, throughout the entire Run 2.

Following these observations and in preparation for the High Luminosity LHC Upgrade, significant progress was made in the study and understanding of these effects based on: (1) the analysis of data collected during operation from the machine diagnostics; (2) the outcome of dedicated beam experiments; (3) the examination of beam screens samples extracted from the LHC after the run; (4) the developments of the methods and tools for modeling the e-cloud formation and its effects on the beams. The main observations and results from these activities will be summarized in the following sections.

EXPERIMENTAL OBSERVATIONS

Transverse Instabilities at Injection Energy

At the beginning of Run 2 only short bunch-trains with 25 ns spacing could be circulated, due to violent transverse instabilities causing losses on the trailing bunches of the trains, as shown in Fig. 1 (top). The situation could be gradually improved with two weeks of dedicated scrubbing at injection energy over which the instabilities became less and less strong. The number of bunches per train could be gradually increased and the observed beam losses reduced to acceptable levels, as shown by the different snapshots of Fig. 1.

Still, after the scrubbing run and during the entire Run 2, in order to keep the beams stable at 450 GeV, it was necessary to use high chromaticity ($Q'_{x,y} \geq 15$) and high octupole settings, together with the full performance of the LHC transverse feedback (high gain, large bandwidth settings). Even in this configuration, weak instabilities still occasionally occured, which were not causing losses but a modest emittance blow-up on some of the bunches [7].

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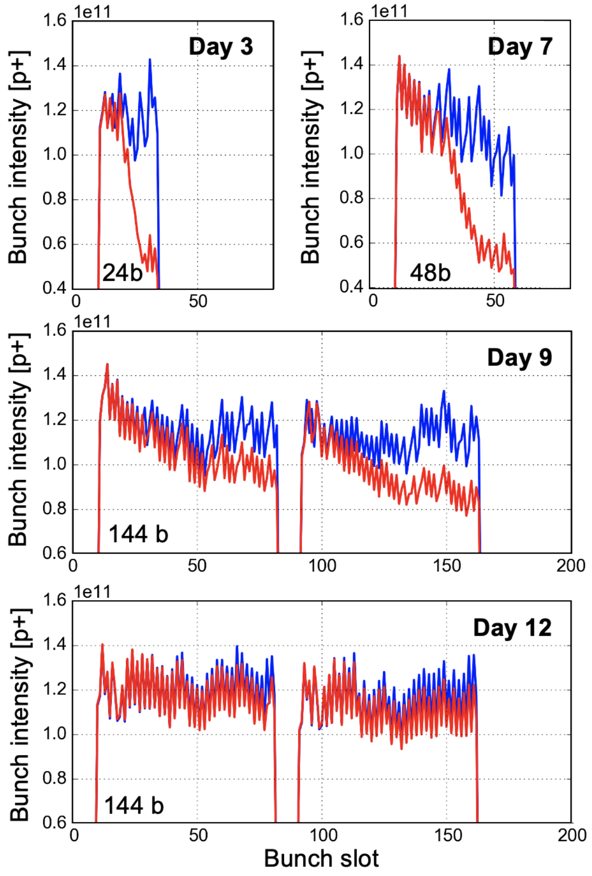

Figure 1: Intensity of bunches within an injected train measured right after the injection (in blue) and ten minutes after the injection (in red) in different moments of the 2015 scrubbing run [8].

In order to preserve the beam lifetime at 450 GeV, the transverse tune settings had to be optimized for better accommodating the large tune footprint generated by the e-cloud, the chromaticity and the octupoles, as discussed in Ref. [9].

Beam Losses at Collision Energy

Thanks to the increased beam rigidity, at 6.5 TeV the effects of the e-cloud on the beams are much weaker but still clearly visible.

A curious effect was observed at the beginning of the 2016 run, when the beams were becoming unstable in the vertical plane after a few hours in collisions. Comparison against simulations showed that the cause of this instability is the e-cloud in the dipole magnets, which becomes more dense at the beam location when the intensity decreases due to luminosity burn-off. More details on these observations and the related simulation studies can be found in Ref. [10]. These instabilities disappeared when the bunch-train length was reduced from 72 bunches to 48 bunches in order to profit from high-brightness beams available from the injectors (BCMS [11]) and no other instabilities that could be ascribed to e-cloud effects were observed at high-energy during Run 2.

Although the beams were essentially stable, slow beam degradation from the e-cloud could still be observed during the time in which the beams were kept in collision at 6.5 TeV. This is illustrated in Fig. 2, which shows the instantaneous loss rate for eight consecutive bunch trains during a nine-hour-long luminosity fill. The intensity decay due to luminosity burn off is subtracted to highlight undesired sources of losses. It is clear that bunches at the end of the trains lose significantly more particles than those at the head of the trains, for the full duration of the fill. For all bunches, the relative loss rate is practically constant during most of the duration of the fill. Stronger losses are observed at the beginning of the fill, right after collisions are established and towards the end of the fill, when the β-function at the two main experiments is reduced from 30 cm to 25 cm. These losses contribute significantly to the bunch intensity decay during the luminosity fills as can be observed in Fig. 3, where the losses from e-cloud are compared to the luminosity burn-off loss rate.

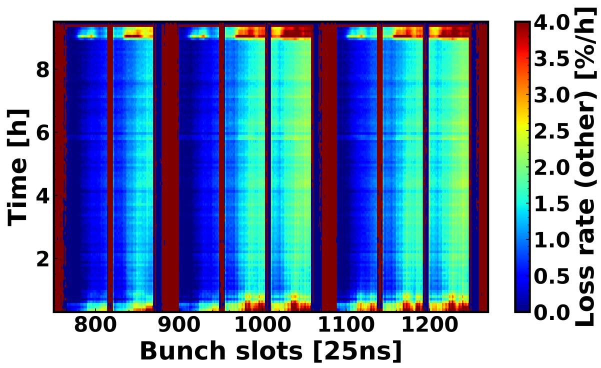

Figure 2: Bunch-by-bunch loss rate on three consecutive bunch trains during a typical LHC physics fill (loss rate from luminosity burn off is subtracted) [12].

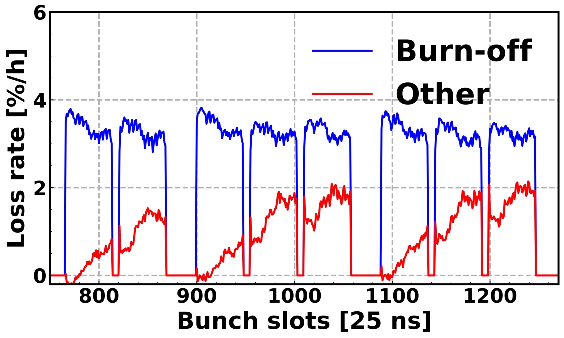

Figure 3: Comparison of the loss rates from burn-off and from other sources for the fill illustrated in Fig. 2 at the time $t = 2\,h$ [12].

The loss rate is found to be much stronger in the presence of the two colliding beams and to depend on the crossing angle between the beams. These and other experimental observations from luminosity production fills and from dedicated tests have allowed identifying as the main source of this effect the non-linear forces due to e-cloud in the finalfocusing quadrupoles (Inner Triplets), which are enhanced by the extremely large optical beta functions (~10 km) at their locations and by other non-linearities introduced by octupoles and beam-beam interactions. A detailed analysis of the observations of incoherent effects from e-cloud can be found in Refs. [12, 13].

Heat Loads on the Beam Screens of the Cryogenic Magnets

Electrons impacting on the beam screens of the arc superconducting magnets deposit a significant amount of energy. These heat loads need to be absorbed by the beam screen cooling integrated in the LHC cryogenics system [1].

Limitations to the LHC performance due to the heat loads were encountered especially in 2015. At that time, transients in heat load occurring when the beams were injected, during the energy ramp and at the beam dump, were leading to large excursions on the temperature of the beam screens, reaching the "cryo-condition" interlock levels (above which the beams are dumped and powering of the concerned superconducting circuit is aborted). This issue was solved by introducing a dedicated feed-forward logic in the cryogenics control system, which automatically applies regulations based on the measured properties of the circulating beam (number of bunches, bunch charge, bunch length, beam energy, etc.), in order to minimize the temperature transients [14].

The measured heat loads were significantly larger than expected from impedance and synchrotron radiation estimates and showed significant and unexpected differences among the eight arcs of the ring. Both these features were very pronounced during operation with the 25 ns bunch spacing but disappeared when the 50 ns bunch spacing was employed (as shown in Fig. 4). To maintain the total heat load within acceptable limits, the flexibility available in the design of the filling scheme was used to find the best compromise between the number of circulating bunches and the heat load in the arcs [8].

Surface conditioning also provided a significant mitigation of the heat loads. A strong reduction of the heat loads, driven by surface conditioning, was observed in 2015 and in the first part of 2016. After that, the heat loads remained practically constant and the observed differences among sectors remained unaffected.

Significant effort went into characterizing the heat load behavior with different beam and machine configurations and investigating the origin of the observed differences among the arcs. A comprehensive report on these studies can be found in Ref. [15]. As we will discuss in the coming section, by comparing these data against models and simulations, it was possible to identify an alteration of the SEY of the beam screens surface as the most likely cause of the observed heat load differences, which was later confirmed by surface analysis conducted on beam screens extracted from the LHC after Run 2.

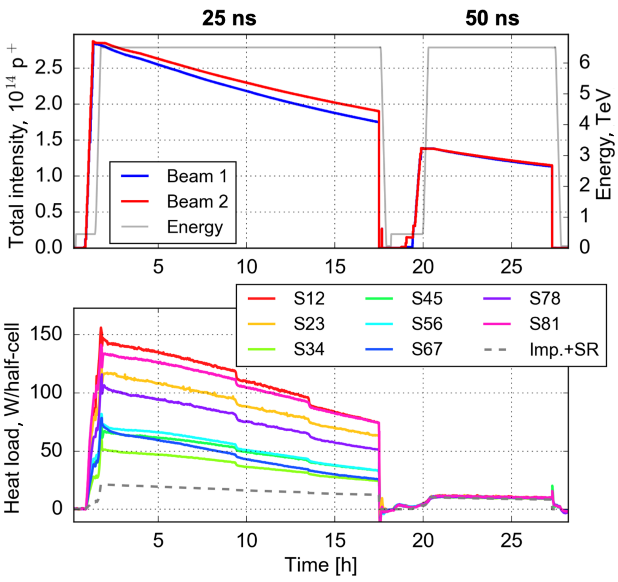

Figure 4: Heat loads (bottom) measured during a regular luminosity fill with 25 ns bunch spacing and during a subsequent test fill with 50 ns bunch spacing, both with $1.1{\times}10^{11}$ p/bunch. Heat loads are per half-FODO-cell. The total intensity of the corresponding fill is shown on the top figure.

MODELING AND UNDERSTANDING OF THE UNDERLYING MECHANISMS

Modeling of e-Cloud Formation and Heat Loads

The modeling of the e-cloud formation in CERN accelerators is largely based on macroparticle simulations performed with the PyECLOUD code [16]. The Secondary Electron Emission process is simulated using the models developed at the time of the LHC design based on laboratory measurements [17]. Additionally, an alternative and more complex surface model has been recently introduced in the simulation code allowing for benchmarks and comparisons [18].

At collision energy, synchrotron radiation generates a significant amount of electrons due to photoemission from the chamber's wall, which enhances the e-cloud formation. The modeling of this aspect has been recently reviewed and updated, as described in detail in Ref. [19].

Macroparticle simulations played a key role in the investigation on the heat loads on the beam screens of the superconducting magnets and, in particular, of the differences observed among the eight LHC arcs [20]. Notably, simulations allowed assessing whether such differences in heat load could be due to differences in the SEY of beam screen surfaces. This was done by comparing simulations against heat load measurements collected with different beam configurations (bunch intensity, filling pattern, beam energy). One set of measurements, marked by the red circle in Fig. 5, was used to estimate the SEY for each of the 46 cryogenic cells that compose the LHC arcs. Based on this model, the expected heat load could be computed from simulations for other beam configurations as shown by the lines in Fig. 5.

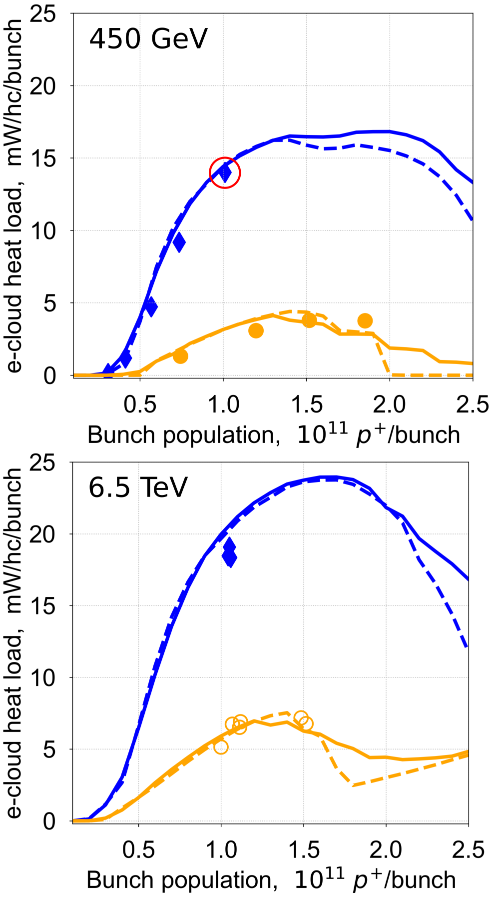

Figure 5: Simulated (lines) and measured (dots) heat loads as a function bunch intensity for long bunch trains (in blue) and for short bunch trains (in orange) in one of the LHC arcs. The dashed line represents a simplified model in which the SEY is assumed the same for the entire arc (more details about measurements and simulation model can be found in Ref. [15]).

Such results could then be compared against measurements (shown by dots in Fig. 5) finding very good agreement, therefore confirming that the observed heat loads are consistent with an alteration of the SEY of the beam screen surfaces.

A complete description of these simulation studies and of their comparison against experimental data can be found in Ref. [15].

Surface Analysis

A Long Shutdown (LS2) took place after the end of Run 2 to allow for maintenance and upgrade work over the entire CERN accelerator complex. During this period, some of the LHC cryomagnets were removed from the machine and their beam screens could be extracted and analyzed.

The surface properties of the low heat load beam screens were found to be compatible with expectations from previous laboratory studies of copper conditioning and deconditioning mechanisms. On the other hand, the surface of the high heat load beam screens showed unexpected features, namely an extremely low carbon content, the presence of cupric oxide CuO (anomalous for air-exposed copper surface) and a much slower SEY conditioning under electron bombardment at room temperature. Interestingly, the azimuthal distribution of CuO correlates very well with the distribution of electrons in the chamber obtained by PyECLOUD simulations, as illustrated in Fig. 6. This suggests that, most likely, the electron flux impinging on the chamber during beam operation played a role in the process leading to the observed surface modifications. An advanced laboratory setup is being commissioned, which should allow to reproduce and study the process in controlled conditions at cryogenic temperatures.

Further details on the study of the LHC beam screen surface properties can be found in Refs. [21, 22]

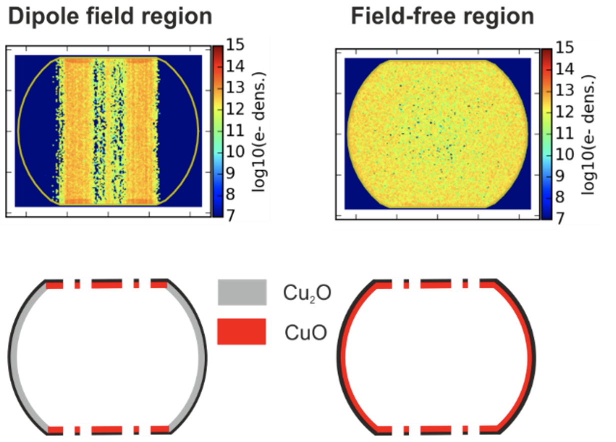

Figure 6: Top: electron distribution from PyECLOUD simulations for a dipole magnet and a field-region. Bottom: distribution of the copper oxides found in laboratory measurements [21].

Modeling of Transverse Instabilities

The study of transverse instabilities driven by e-cloud relies heavily on “Particle In Cell” codes that simulate turn after turn the coupled dynamics of the beam and of the e-cloud distributions. At CERN, this is done by interfacing the PyECLOUD code for the simulation of the e-cloud dynamics with the PyHEADTAIL code for the simulation of the beam dynamics. The PyECLOUD-PyHEADTAIL suite has been recently upgraded in order to exploit parallel computing resources. This has enabled realistic simulations of single-bunch and coupled-bunch instabilities of the LHC, which can be extremely demanding in terms of computing resources due to the very small beam size and to the relatively long instability rise times [16, 23]. This has allowed extensive simulation studies on e-cloud instabilities for the LHC, which are described in detail in Refs. [24, 25].

Recently, a different approach has been introduced to study e-cloud driven instabilities using the linearized Vlasov approach. For this purpose a simplified description of the forces exerted by the e-cloud on the bunch had to be devised, which uses a polynomial to describe the detuning forces introduced by the e-cloud along the bunch, and a set of one-dimensional response functions to describe the dipolar forces

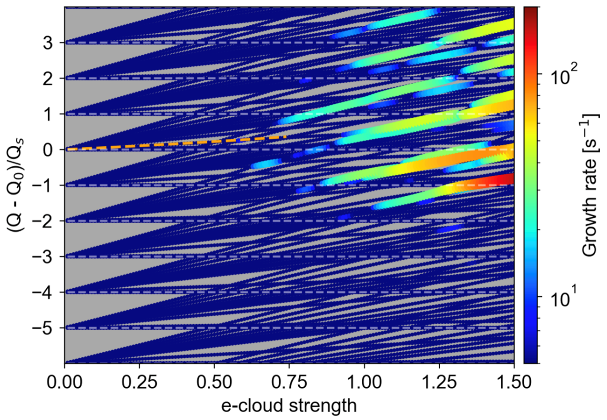

Figure 7: Bunch eigenmodes as a function of the e-cloud strength (defined as a scaling factor that is applied on all the e-cloud forces acting on the beam) as obtained obtained with the Vlasov method. For more details about the simulated scenarios see Ref. [26].

exerted by the e-cloud in response to a transverse distortion of the bunch distribution. An example of application of this approach can be found in Fig. 7, which shows the behavior of the bunch eigenmodes as a function of the e-cloud strength (defined as a scaling factor that is applied on all the e-cloud forces acting on the beam) including the effect of dipolar and quadrupolar forces from the e-cloud. A detailed description of this new method and its validation against macroparticle simulations can be found in Refs. [26, 27].

Modeling of Incoherent Effects

The modeling of incoherent effects, like the slow losses during collisions that were discussed before, is particularly challenging as it requires introducing the nonlinear forces from the e-cloud within an accurate nonlinear model of the LHC lattice and simulating extremely long timescales, corresponding to tens of millions of revolutions.

For this purpose it is possible to show that, under reasonable assumptions, the interaction of a beam particle with the e-cloud can be described by the gradient of a scalar potential and is therefore a symplectic map [28]. The potential can be extracted from PyECLOUD simulations of the cloud dynamics on a discrete rectangular grid. In order to use such a map within a long-term tracking code, a method has been developed to interpolate the discrete map in a way that preserves symplecticity. Particular care had to be taken in avoiding artefacts introduced by the interpolation scheme and by macroparticle noise from the cloud dynamics simulation [12].

The interpolator has been implemented in the SixTrackLib tracking code, which allows exploiting Graphics Processing Units to significantly boost the simulation speed [29]. Figure 8, shows one of the first simulations recently performed with this new tool, which shows its capability of simulating beam losses and emittance evolution over such very long time scales [30].

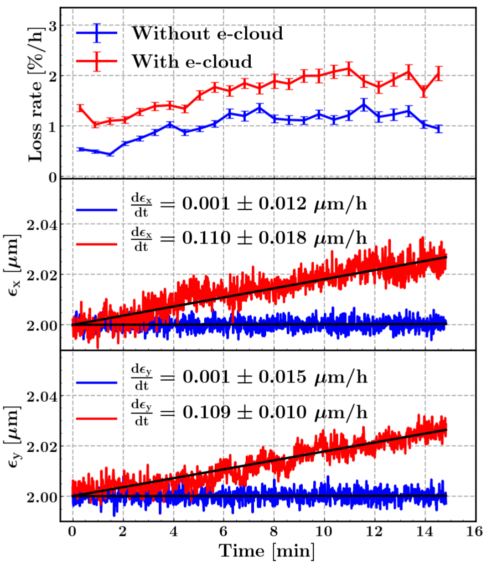

Figure 8: Simulation of loss rates and emittance blow up due to e-cloud incoherent effects.

PROSPECTS FOR INCREASING THE BUNCH INTENSITY

The High Luminosity LHC upgrade foresees an increase of the bunch intensity by almost a factor of two compared to typical Run 2 values. Extensive simulation studies based on the models and tools described in the previous sections have been performed to assess the implications of such an increase with respect to e-cloud effects.

As it can be seen in Fig. 5, simulations predict that the e-cloud heat load will increase only mildly for intensities above the Run 2 values of 1.2×10^{11} p/bunch, which should allow operation with HL-LHC intensity with the presently installed cryogenic cooling capacity [31]. This prediction was checked experimentally at the end of Run 2 using short bunch trains with bunch intensities up to 1.9×10^{11} p/bunch [15]. Similarly, a favorable dependence on the bunch intensity is expected for e-cloud driven instabilities [24].

These predictions assume no degradation of the SEY of the beam screens with respect to Run 2, while performance limitations from e-cloud would be expected if the SEY increases further. For this reason, methods are under study to treat the beam-screen surface in order to improve its SEY and its conditioning behavior, should it become necessary [21].

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