KILLING THE ELECTRON CLOUD EFFECT IN THE LHC ARCS

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Summary:

The NEG-sled is a getter/electrode assembly that could suppress the regeneration mechanism of the electron cloud effect in the arc dipoles of LHC. The assembly consists of a copper foil electrode, supported through an insulating layer on a stainless steel skid, which would rest upon the flat bottom of the beam screen. The electrode is coated with NEG to provide effective pumping of all non-inert gases from the vacuum. Pumping should be enhanced by electron bombardment. By biasing the electrode \( \pm 100 \) V secondary electrons produced on the surface would be fully re-absorbed, killing the regeneration mechanism. The NEG surface can be regenerated by passing a current through the electrode to heat it to \( \sim 240 \) C. The heat transfer (radiant + conductive) to the beam screen during regeneration is estimated \( \sim 5 \) W/m, within limits to maintain the beam screen at nominal 20 K temperature during regeneration. The entire assembly has been designed so that installation does not require modification of any hardware currently being built for the LHC arcs. The electrode assembly would occupy a total space of 1 mm in the vertical aperture of the beam screen. If that loss of aperture were unacceptable, it could be installed in two of the three dipoles in each half-cell with zero reduction in aperture in the lattice. Pending rapid evaluation and decisions, construction and implementation could be accomplished on a schedule consistent with LHC installation.

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Introduction

The electron cloud effect (ECE) arises from the multipactoring of electrons within the vacuum chamber. Electrons are produced when gas molecules are ionized by beam protons and also when synchrotron light strikes the side walls. In LHC the critical energy of this light is 44 eV, for which photoemission yield is maximum for many materials.

Once an electron is liberated in the vacuum it can be accelerated to energies of \(~100 \sim 1000\) eV in the electric fields of each proton bunch, after which it will strike the side wall and may emit one or more secondary electrons. If the secondary electron yield \(\delta > 1\), the process is regenerative and the ambient electron density will grow regeneratively. For copper surfaces such as the beam screen, \(\delta\) typically has values ranging from a low of \(~1.1\) to a high of \(~1.7\). The value of this parameter, notoriously difficult to control, is thus critical to the multipacting process of the electron cloud effect.

The electron cloud has several bad effects on collider operation. First, the electron distribution responds dynamically to the proton bunch as it passes, and can excite transverse mode-coupling instability (TMCI), coupled-bunch instabilities, head-tail motion within the proton bunch, tune spread, beam loss and incoherent emittance growth. These effects have been modeled, and would likely present limits for 12.5 and 25 ns bunch spacing. Feedback correction of coupled-bunch instabilities and suppression of the TMCI-like instability by high chromaticity have been demonstrated in the SPS, but the latter requires a sizeable chromaticity and it is not clear that such chromaticity is consistent with optimum LHC operation.

Second, the electron cloud desorbs gases from the walls of the beam screen, and could push the limit for beam lifetime and pressure-bump instabilities. It has been proposed that the surfaces of the beam screen could be conditioned. Conditioning appeared to improve the
pressure in the beam screen in the COLDEX experiment [1] (Figure 1a), but the heat load attributed to electron cloud did not significantly reduce with time (Figure 1b). Furthermore cryopumping onto the cold bore relies upon there being a limited coverage of helium on the cold bore surface. If there are any cold leaks in the arcs the helium coverage reach levels that would inhibit cryopumping of the cold bore.

Lastly the energetic electrons heat the surfaces that they impact. This heat has been studied both by models and by experiment\(^2\), and is expected to be ~1-2 W/m for LHC bunch intensity, depending upon the value of secondary electron yield for the copper surfaces of the beam screen. A shield has been installed behind the slots that couple the beam screen vacuum to the cold walls in order to reduce the transport of these energetic electrons onto the cold bore. Unfortunately it also reduces cryopumping by a factor of 3. Even taking the ECE heat at 20 K, however, the refrigeration of 2 W/m corresponds to a power requirement of ~4 MW (an operating cost of ~1 MCHF/yr).
The above considerations suggest that the electron cloud effect has potential to limit the performance of LHC, constrain its operating parameters, and will surely entail significant operating cost in refrigeration. We propose a NEGSled, a getter/electrode to kill the electron cloud effect throughout the arcs of LHC, and a plan to build and install the NEGSleds in all LHC dipoles on a schedule consistent with LHC installation and commissioning.

**Dynamics of electrons in the presence of the LHC bunch structure.**

In order to appreciate how the electron cloud mechanism works, consider an electron that is near the center of the beam screen when a proton bunch passes. The design bunch intensity is $N \sim 10^{11}$ protons in a bunch length of $L \sim 10$ cm. This corresponds to a peak current of

$$I = \frac{N e c}{L} = 50A$$

The potential depression from the center to the edge of the bunch is

$$V = \frac{Ne}{4\pi\varepsilon_0 L} = 1500V.$$  

Depending upon the initial position and velocity of the electron, it can thus receive an energy gain of $\sim 100$ eV as each bunch passes. The dependence upon bunch intensity and batch length was studied in LHC bunch patterns in the SPS by Arduini et al. [3] The spectrum of electrons in the electron cloud effect was measured in the COLDEX experiment [4] in the exact geometry of an LHC dipole; the results are presented in Figure 2a. The average kinetic energy is $\sim 100$ eV. The time for a 100 eV electron to travel from the axis to the beam screen (radius $R = 2$ cm) is

$$\Delta t = \frac{R}{c} \sqrt{\frac{m}{2eV}} = 4 \text{ ns}.$$  

So secondary electrons produced by the impact of such electrons are produced and redistribute throughout the beam screen long before the next bunch arrives.

Now suppose that an electrode is placed on the bottom of the beam screen and biased $+100$ V with respect to the grounded beam screen. The clearing time $T$ to collect all secondary electrons produced within the beam screen is obtained from the kinematics of accelerating an
electron from rest: \( T = \sqrt{\frac{2m(2R)}{eE}} = 12\,\text{ns} \). Thus secondary electrons are completely cleared from the beam screen before the next bunch arrives, even for the choice of 12.5 ns bunch spacing.

Lastly the motion of electrons is strongly influenced by the magnetic field. Electrons are produced both from ionization of gas in the bore tube and by photoionization by photons striking the side wall. In either case electron motion is channeled in a tight spiral around the (vertical) field direction, with a gyroradius \( \rho = \frac{mv}{eB} \sim 10\mu m \). This effect is evident in the distribution of electrons from ECE observed in a quadrupole in the SPS experiment\(^5\), shown in Figure 2b.
Figure 2. Spectrum and angular angular distribution of electrons formed from the electron cloud effect in a quadrupole.

**Significance of electron cloud effect for beam dynamics in LHC**

There is an extensive literature on the effect of electron cloud effect on beam dynamics [6]. Zimmermann and Benedetto give a recent summary of the understanding [7]. The heat load from ECE with bunches of $10^{11}$ protons would possibly exceed installed capacity for 25 ns bunch spacing (the mode most favorable to high-luminosity physics), and might limit operation to the 75 ns bunch spacing foreseen for initial operation. Simulations using the HEAD-TAIL code indicate the possibility of long-term emittance growth that could be detrimental with storage time of hours. Also transverse mode-coupling instabilities will be excited by the electron cloud. While it has been possible to control the fast instabilities in the SPS, control has required a degree of chromaticity that could be problematic for LHC. Presently there is no cure for long-term incoherent emittance growth due to the electron cloud, if it occurs, other than reducing the electron density.
**NEGSled**

The NEGSled is a getter/electrode structure designed to integrate into the beam screen as shown in Figure 3. It contains a copper electrode, mounted on a 316LN stainless steel skid which is in turn anchored to the floor of the beam screen. The electrode is electrically and thermally isolated to operate at 100 V with respect to the beam screen.

The electrode is coated with Ti/Zr/V getter following the process developed by Benvenuti et al. [8]. The electrode is insulated from the skid by means of a thin glass plate (a standard microscope cover glass has just the right geometry). The glass is of a type that has very high but finite resistivity, so that any charge developed on it during operation will be cleared naturally. The copper electrode is attached to the glass by a tab clip; the glass is attached to the skid by two side tab clips as shown in Figure 3 and Figure 4.

It is necessary to provide sufficient thermal isolation to limit heat transfer to the liner so that NEG activation at 240 C can be performed without increasing the liner temperature. The arrangement shown does this by providing a ~ 1 cm long conduction path through the 0.2 mm thick glass from the skid clip to the copper clip.

The copper foil electrode is chosen to be 50 µm thick, sufficient to provide a low impedance for image currents of the proton beam but thin enough to provide a favorable characteristic for heating the strip during NEG regeneration. The electrode extends to the cover the edge of the skid and the glass substructure. The top surface of the side tab clips is coated with a plasma-sprayed Al₂O₃ insulating layer so that the electrode has reliable electrical isolation from ground.

The coating of a ~2 µm thick NEG layer on the electrode would be performed in the magnetron sputtering facility of Chiggiato at CERN. This facility can coat objects up to ~7 m length. We plan to fabricate each foil electrode as two 7 m objects, weld them in an overlap seam, and mount them on the stainless steel skid as shown in Figure 4.

The skid would be fabricated from six 2.5 m segments of straight 316LN material. The ends of each segment would be EDM cut to form a key-in-lock fit to the next segment. The curvature required for the 9 mm magnet sagitta of the dipole would be built into the cutting of the key-in-lock ends of the segments. The assembled skid would be rigidized by spot-welding the locking tabs between segments. The foil electrode is sufficiently flexible that it can be fabricated straight and mounted to the curved skid. During cooldown the copper electrode will shrink by a strain δL/L = 3 x 10⁻³ relative to the SS skid. This differential shrinkage will be accommodated in assembly by bowing the electrode very slightly as it is attached at the successive mounting tabs. Specifically rod spacers will be inserted between the skid and the foil electrode midway between the locations of the mounting tabs as shown in Figure 4. Once the tabs are all locked to the glass insulators the spacers will be removed.
Figure 3. NEGSled design: a) cross-section; b) detail of electrode structure; tool for installing in the beam screen.
Figure 4. Side view and edge view of the electrode assembly.
Aperture considerations

The electrode assembly occupies 1 mm of vertical aperture, as shown in Figure 3. In the three dipoles of a given half-cell of the arc lattice, the vertical betatron function $\beta_v$ has different maxima in each of the three dipoles, as shown in Figure 5. The dipole nearest the horizontally focusing quadrupole presents the most constraining vertical aperture. If one maps the effective shadow of that constraining aperture with $\beta_h$, $\beta_v$, and dispersion D, the ‘shadow’ of the D dipole at the other two dipoles are shown in Figure 3. It is thus seen that if the electrode assembly were installed in those two of the three dipoles in every half-cell there would be no reduction in beam aperture at all! If the electrode assembly were installed in the third dipole, vertical aperture would be reduced by 1 mm. The various considerations of beam optics, placement errors, etc. will determine whether this loss of aperture is acceptable in return for completely killing the electron cloud effect.

Figure 5. Periodic optics in an LHC arc cell (from Ref. 9).
Installation of NEGSled in the dipole

A significant practical challenge will come in attaching the electrode assembly to the beam screen so that it conforms locally to the flat bottom of the screen. The challenge arises because the dipoles are built with a 9 mm sagitta to accommodate the bending of the beam, and there is a $\sim \pm 1$ mm variation along the 14.5 m dipole length in the local position of the bore tube with respect to an ideal alignment from the ends. The electrode assembly thus must be locally anchored to the screen floor at intervals along the dipole so that it conforms to the local geometry and does not consume aperture.

We propose to achieve this local attachment by anchoring the skid to the slots in bottom of the beam screen. There are four rows of die-punched slots to provide for cryo-pumping to the cold bore tube. Clips are spot-welded to the undersurface of the stainless steel skid at locations that align to slots in the two outer rows of slots every ~6.4 cm along the skid.

We have devised a ‘trolley’, shown in Figure 6, which should enable local alignment of the skid to the center of the bottom of the beam screen, and compressing it downward so that the spring clips extend through the slots to the 2 mm space outside. Our strategy for installation is to position the electrode assembly in this manner in the full 14.5 m length of each dipole, then pull the skid towards the end to lock the spring clips onto the slots and anchor the electrode securely.

It has been suggested that NEG coatings may degenerate over time if stored in ambient air. This is not in fact the case. Consider three instances:

- In the LEIR machine the coated chambers were maintained in air for months without evident deterioration of the NEG performances (E. Mahner).
- XPS measurements on LSS witness samples showed only a light increase of the C concentration on the surface after 6 months air exposure. The activation process proceeded as usual (M. Taborelli).
- The ultimate vacuum of 2-m long coated chambers was tested for fresh NEG and after 8 months in air: similar results. (Pedro Costa Pinto).
Figure 6. Trolley for installation of the electrode assembly and locking to the bottom slots in the beam screen.
**Interconnection in LHC arcs**

The electrodes in the three dipoles of a half-cell would be connected in series. The leads coming from the electrode assembly could be routed out at each quadrupole package by running them through the existing pump-out lines as shown in Figure 7. The leads would be attached to a standard vacuum feedthrough (e.g. Ceramaseal) mounted on a vacuum tee at the vacuum pumping port.

![Diagram of interconnection in LHC arcs](image)

**Figure 7.** The leads from NEG/Sled would be brought out through the tubes provided for pumpout.
**Fabrication and In situ activation of the NEG layer**

The NEG layer would be fabricated in the magnetron sputtering system at CERN. This system is 8 m long and is being used to sputter-deposit NEG on all warm vacuum segments for LEIR. The 14.5 m long electrode would be made in two pieces so that it would fit in the sputtering system. It is envisaged that ~60 such pieces would be mounted on a carrier lining the side walls of the vessel of the sputtering system and coated in one batch process. Thus ~1,200 NEGSleds would require 40 batch runs (40 days of operation).

The NEG layer must be activated by heating to ~240 C for 2 hours. We have designed the NEGSled so that re-activation can be done without heating the beam screen. The thin glass insulating sheet is mounted so that conduction heat transfer must travel through the thin dimension of the glass; the estimated conduction heat transfer to the 20 K beam screen is ~1.2 W/m.

The radiant heat load from the hot electrode is estimated to be $P = \varepsilon \sigma T^4 A \equiv 150 \varepsilon$ W/m. The emissivity of the copper surfaces is $\varepsilon \sim 2\%$, so one would expect $P \sim 3$ W/m/bore. Note that it is notoriously difficult to predict such resistivities. The net heat transport is a balance between the emissivities of the electrode and the beam screen inner wall. It will be crucial to build and evaluate a prototype system in order to develop accurate estimates of the radiative heat load during reactivation.

**Measurement of vacuum in the arcs**

The current drawn by each NEGSled electrode at injection energy is proportional to the beam current and to the vacuum in the dipole. This relation is more complicated at collision energy because there is a contribution from photoionization by synchrotron light that is independent of the vacuum, but at injection energy there is no such contribution. The relation between electrode current and beam tube vacuum can be used to provide a map of the pressure in each half cell of the LHC arcs. The only information otherwise available comes from loss monitors. The pattern of losses originates from the interplay of many effects, however, and interpreting that pattern to locate vacuum leaks has proven difficult at other colliders.

As an example suppose that there were a cold leak in the vacuum system. The result would be a slow leak of helium into the vacuum at that location which would condense upon the nearby cold bore walls. If the walls were to become covered with a monolayer, cryopumping action would cease and the local pressure would begin to rise.

The key benefit of local pressure measurement is that it provides a prompt and local signal if the vacuum degenerates at any location. That information would localize to within a specific half-cell where the leak was located; indeed by interpolation from signals in neighboring cells it should be possible to isolate the origin to a particular magnet. This could prove immensely valuable in locating and repairing any leaks that may occur.
**Glow discharge cleaning of the arc vacuum**

A further collateral benefit of the NEGSled is that it would make it possible to perform glow discharge cleaning of the entire arc vacuum during cooldown of the collider. *In situ* glow discharge cleaning was first developed for accelerators at CERN, and is the ultimate way to remove contaminant gases that are adsorbed on the surfaces of the vacuum system. It was key to attaining large stored beam current in the ISR. In glow discharge cleaning a low pressure of inert gas (usually Ar) is purged through the system, and a pattern of electrodes within the vacuum is excited with a voltage of ~100 V to sustain a glow discharge that largely fills the entire vacuum. The discharge bombards the walls with energetic atoms, and this bombardment scours gas molecules that are adsorbed on the surfaces. The process works best with a magnetic field of ~50-100 G to contain electron trajectories so that they transfer energy to many inert gas atoms before striking a wall themselves.

The NEGSled electrodes could be used for this purpose in the LHC arcs to remove surface contaminant gases. The inert gas of choice for this purpose would be probably be hydrogen. Using a heavier inert buffer gas would have the likelihood of sputtering copper from the walls, which would contaminate the NEG layer. Hydrogen has a sputtering yield of ~ 0.01 onto Cu, while it makes so-called chemical sputtering with C surface contamination, transforming it into volatile CH4 with a yield of almost 1. No data readily is available on the effect onto -O adsorbed on surfaces (for example CO) but at worst it should transform it into H2O, which is already present in the system. This operation would be at a pressure of some 10^-2 mbar probably. Using a safer H2-He (or H2-Ne) mixture is probably not a valid option because the wide differential in sputtering yields between C and Cu would be reduced proportionally.

To appreciate the importance of removing adsorbed gases, consider the mass spectrum of gases in the cold vacuum of the COLDEX experiment (which is being cryopumped in the same way as the LHC arcs will be), as shown in Figure 8. Note in particular that the dominant species after scrubbing are H2, CO, CH4, and H2O. All of these species are common surface contaminants on stainless steel; all of them are readily removed from those surfaces by glow discharge cleaning.

The low-pressure H2 could be introduced in a purge flow at the quadrupoles, and the NEGSled electrode energized to drive glow discharge. If this procedure were employed during cooldown when the superconducting magnets are at ~liquid nitrogen temperature, the magnets could be safely operated in their normal-conducting state to a field of ~50-100 G to provide magnetron mode of sputtering. In this case it should be possible to clean most adsorbed gases from the LHC arcs before collider operation even begins.
Figure 8. Partial pressures of gas species in the cold vacuum of the COLDEX experiment.
Proposal for fabrication and installation of NEGSleds

I propose to develop and fabricate all NEGSleds required for the LHC arcs as a US contribution to LHC commissioning. The components would be fabricated at Texas A&M University by the Accelerator Research Laboratory and transported in batches to CERN in a special shipping carrier. The project is proposed for development in two phases.

Phase 1

CERN is requested to consider and approve that the Texas A&M group will develop and fabricate a first full-scale prototype of the NEGSled, and that the VAC and MAS groups would install it in a dipole, cool it down to operating temperature, and evaluate issues of installation procedure, thermal contraction, behavior during quench, lead connection, and NEG activation.

The Texas A&M group would commit to fabricate the prototype NEGSled and the installation trolley in a time of one month after CERN’s Phase 1 decision. It is foreseen that the above tests could be completed at the cold test facility and a report submitted by one month after delivery to CERN. CERN would then evaluate the test report and make a decision on whether to proceed with integration of NEGSled into LHC installation. Depending upon the timing of the Phase 1 decision by CERN, Phase 1 could be completed by June 15, 2005.

Phase 2

Pending the above Phase 2 decision, the Texas A&M group would manufacture 1,200 NEGSleds and deliver them to CERN in batches. A firm schedule for delivery would be developed in light of what is learned from the Phase 1 development, but it is envisaged that the following schedule could be attained.

Depending upon the timing of the Phase 2 decision, Batch 1 could be delivered to CERN by September 1, 2005, and the last batch would be delivered March 1, 2005. This schedule would miss the initial quantity of dipoles that will be installed before September, but should enable installation of NEGSleds in all subsequent dipoles.

After delivery to CERN the copper electrodes would be coated in the sputtering facility and the sleds would be assembled in a clean assembly area by Texas A&M personnel. The completed sleds would then be ready for installation in the dipoles.

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Conclusions

The electron cloud effect has been the subject of intense study, simulation, and experiment for more than a decade. Much of the leading research on the effect has been performed at CERN. As the projected importance of ECE for LHC operation has waxed and waned during that period, several ways of suppressing ECE were proposed, including coating the entire beam screen with NEG (Benvenuti), and suspending a wire electrode within the dipole aperture (Bruning and Jimenez). There were difficulties with each of those approaches. The NEG-coated beam screen required heating the beam screen for activation. The wire electrode approach would not have been efficient for collecting the secondary electrons because the spatial distribution exhibits a wing structure (Figure 2b) and the dipoles also curve with a 9 mm sagitta.

The evaluation of the importance of ECE for LHC operation has also evolved over that time. Code simulations have improved steadily. It appears from discussion among in a presentation at CERN today that there is consensus that ECE will likely impose an upper limit to bunch intensity and to bunch spacing, and that those limits will likely constrain the efforts to increase luminosity towards the design goal and also limit the options for optimizing the accelerator parameters for physics reach (e.g. making smaller bunch spacing to limit the number of interactions per bunch crossing).

There appears to be further consensus that the proposed NEGsled would kill the electron cloud effect in the LHC arcs. There is less agreement about the efficacy of adding the NEG layer to the electrode surface. Its benefits for high-capacity pumping within the beam screen must be weighed against the requirements for re-activation. It is for CERN to decide whether it wishes the NEG surface on the electrode as proposed, or whether it prefers a simpler copper electrode without NEG. The Texas A&M group commits to build the electrode assemblies either way.

This is truly a last-minute proposal. The above schedule demonstrates that from this point in April 15, 2005, every day will be precious if we are to manage to make the sequence of events in the development and construction of NEGSleds accord with the schedule for magnet installation. It is requested that CERN arrive at a decision on the Phase 1 development effort at the earliest opportunity. Should CERN decide to proceed with each succeeding phase, it will be necessary to communicate that decision to the LARP project. The Texas A&M group will undertake the Phase 1 effort from its own funds; the Phase 2 effort will require support from LARP. Initial discussions with DOE indicate that the funding can be obtained subject to CERN’s decisions, and that the schedule will not be limited by timing of funding from LARP.
Acknowledgments and Apologia

It is a pleasure to acknowledge the ideas, ingenuity and hard work of Davide Tommasini and Hans Kummer who has worked with me to evolve the design of NEGSled to one that I believe can be built and to build a short model of it.

It is a pleasure to acknowledge the leadership of the CERN vacuum and accelerator groups in teaching me about the issues at play in the electron cloud effect in the LHC arcs. Particularly I benefited from discussions with Vincent Baglin, Noël Hilleret, Miguel Jimenez, and on the extensive studies of electron cloud effect that have been made in the SPS and the simulations that have led to an understanding of its dynamics. I have benefited greatly from learning about NEG pumping technology from Chris Benvenuti Sergio Calatroni, and Paolo Chiggiato. In learning about the effects of electron cloud on the beam dynamics I have benefited from stimulating discussions with Oliver Bruning, Frank Zimmermann, Francesco Ruggiero, and Walter Scandale.

I fully realize that I am newly entering as a novice upon the complex issues surrounding this phenomenon, and that some of the assumptions and analysis that I have made in arriving at the design presented here and its potential for installation and operation in LHC may appear inadequate or naïve to the experts at CERN who will read this proposal; indeed the CERN vacuum group has for two generations been the world leader in ultra-high vacuum technology.

My reason for making so bold as to make this unreasonable proposal in the 11th hour of LHC installation is that I have developed the conviction that ECE has the potential to pose a serious limit to the performance of LHC, and that seems a pity given the immense effort, dedication, and expertise that has gone into its making. I hope that it is CERN’s pleasure to permit me to work with the above leaders to improve upon this design and try to arrive at an implementation that will best fit the needs of the project.

I wish to thank CERN and the CARE-HHH-AMT program for providing to me the framework within which I have worked during the past month at CERN, and I would like to thank Lucio Rossi and the MAS group for their hospitality. My research is supported by the U.S. Dept. of Energy, grant # DE-FG03-95ER40924.

   http://wwwslap.cern.ch/collective/electron-cloud/