# Summary of CERN-GSI Workshop on Electron Cloud

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## *Abstract*

The bilateral CERN-GSI Electron Cloud Workshop was organized with the main goal to review the status of CERN and GSI electron cloud studies in order to find synergies between the two laboratories and to define a common strategy for future developments in terms of simulation tools, diagnostics and mitigation techniques. The workshop took place on 7–8 March 2011 at CERN (BE Auditorium) and welcomed 30 registered participants coming from CERN, GSI, INFN-LNF, KEK, CELLS, CINVESTAV, TUD, and several other institutes. It was supported by CERN and GSI, and sponsored by the European Commission under the FP7 "Research Infrastructures" project EuCARD (grant agreement no.227579), work package "Accelerator Science Networks" (AccNet).

## INTRODUCTION

The workshop program featured 6 sessions:

1. general introductory talks,
2. vacuum and surface properties,
3. CERN simulation tools and results,
4. GSI simulation tools and results,
5. electron-cloud detection and diagnostics, and
6. coherent and incoherent effects of the electron cloud.

The workshop was opened by F. Zimmermann (CERN), who recalled history, motivation and goals of this workshop. Since the workshop was meant to focus on CERN and GSI specific problems, the scene was further set by G. Arduini (CERN), who described electron cloud indicators observed in the LHC during last year's run, by O. Boine-Frankenheim (GSI), who presented an overview on the collective effects expected to play a role in the FAIR project and emphasized at which stages the electron cloud could also appear in the frame of FAIR, and by K. Ohmi (KEK), who reviewed electron-cloud observations and simulations for KEKB and predictions for LHC, including a new study on the effect of random cloud fluctuations.

Subsequently, vacuum and surface properties, experimental observations as well as simulation models, methods and results were reviewed in great detail.

The following sections concisely describe the six sessions. Some important points that, in the opinion of the workshop organizers, should be retained for further discussion and follow up have been specially highlighted.

## E-CLOUD AT FAIR, LHC AND KEKB

G. Arduini reported that the plan for 2011 is to scrub the LHC with 50-ns beams for one week in order to gain a factor larger than 10 improvement in pressure rise and to ensure stable operation with long trains of 75-ns beams. For an efficient scrubbing, the electron activity should be ideally always kept at a constant level by topping up with more beam when the pressure activity is seen to decrease. Scrubbing at injection energy should be effective also at top energy (3.5 TeV). It is not yet clear if scrubbing at injection will be sufficient, since a non-negligible contribution from photo-electrons will be present after acceleration. Given the critical photon energy of about 5.5eV for the synchrotron radiation (SR) of protons at 3.5 TeV, the photoemission yield (PEY) is expected to be about 1% or less, or up to one order of magnitude lower than at 7 TeV, assuming that this yield scales linearly with the critical photon energy [1]. In addition, at 3.5 TeV the absolute number of photons emitted per proton and radian is also reduced by a factor of 2. Both these effects will obviously contribute to a much slower SR conditioning than that expected at 7 TeV (anticipated reduction of the PEY to half of its original value after 1 day of nominal LHC operation). While SR conditioning significantly reduces photo-emission yields, for reducing the secondary emission yield it has been found to be less efficient than scrubbing with electrons. Therefore, LHC will focus on electron conditioning to decrease secondary emission. Thanks to the saw-tooth machined beam pipe, the specular reflection of photons is strongly reduced, at the expense of some increase in the (lower) diffuse reflection. The reduced reflection lowers the number of photoelectrons produced away from the initial SR emission cone. Such electrons could propagate to the middle of the beam chamber around the circulating beam.

O. Boine-Frankenheim explained that GSI accelerators presently do not exhibit any evidence of electron cloud formation. Extrapolating SIS18 parameters to those required in its high intensity operation for the FAIR project and looking at the parameters of the future SIS100 synchrotron, there is, however, a concern about possible electron cloud build up with bunched beams in both SIS18 and SIS100, and also two-stream instability with coasting beams in the SIS100 during the slow extraction process. Tools are being developed to study these effects and also an experimental set up in the SIS18 is being put in place to be able to measure electron accumulation in a specially wide beam chamber and by using a train of purposely created short bunches.

K. Ohmi discussed that in positron machines, electron cloud is a wide-spread issue, causing both single and coupled bunch instabilities. The main reason is that, because of photo-emission due to synchrotron radiation, even in absence of multipacting the electrons can accumulate to such high densities as to endanger the beam stability. Several codes have been developed to study these effects and they have been applied both to existing and future machines. Measured and simulated single bunch instabilities exhibit an upper sideband spaced by about 1.5 times the synchrotron tune from the main tune line. K. Ohmi explained this by a coupling of higher order modes, e. g. the $m = 1$ and 2 modes, although the relation between electron cloud instability and mode coupling may require further studies. **A feedback system seems to be unable to suppress this side-band, while it can damp the coherent motion associated to the main tune line if it has high enough gain**. In recent Cesr-TA measurements, also a lower side-band sometimes appeared and it seems that the dominant side-band is determined by the number of oscillations performed by the electrons during the bunch passage. In particular, the lower side-band is associated mainly to a high number of oscillations inside the bunch, while the upper one is associated to low numbers of oscillations. Simulations of the single-bunch instability at LHC injection using K. Ohmi's code PEHTS show electron cloud density thresholds at $3 \times 10^{10}\text{m}^{-3}$ in field free regions and $6 \times 10^{10}\text{m}^{-3}$ in dipoles, in perfect agreement with previous HEADTAIL simulations. Thresholds are found to be about a factor 5 higher at top energy, again in agreement with HEADTAIL simulations. **Possible electron cloud density fluctuations in space and time have been shown to possibly increase the threshold for the onset of the electron cloud instability, but also to worsen the incoherent emittance growth below the instability threshold by a significant factor**. K. Ohmi drew attention to the fact that randomness and/or characteristic frequencies of these fluctuations may strongly influence their effect on the beam. Effects of electron-cloud fluctuations and randomness had first been looked at by G. Stupakov in 1997 [2].

## ELECTRON CLOUDS VERSUS VACUUM & SURFACE PROPERTIES

Talks in this session covered electron-cloud vacuum obsevations and forecast for the LHC by G. Bregliozzi (CERN), surface properties of the electron-cloud vacuum chambers by V. Baglin (CERN), and surface studies for SEY reduction through scrubbing and ultra-thin graphitization by R. Cimino (INFN-LNF).

LHC suffered from electron cloud in 2010, when beams with 50 and 75 ns bunch spacing were injected. Pressure rise, however, had been observed already earlier in the common pipes during operation with beams of 150-ns bunch spacing. This pressure increase could be suppressed locally by powering weak solenoid coils that had been wrapped close to the vacuum gauges at the "A4L1" and "A4R1" transitions, in the region of the D1 separation dipole, during one of the technical stops. Clear electron cloud indicators with 50 and 75-ns spaced beams were pressure rise measured at the gauges located at cold-warm (unbaked) or warm-warm (baked) transitions, instability and emittance growth of the last bunches in a series of trains. An additional heat load was also measured on the beam screen in the cold regions with 50-ns beams. **Similar pressure rise evolutions were observed at all the gauges located at cold-warm transitions and warm-warm transitions with and without an additional ion pump**.

The pressure rise measured with 75-ns beams was about 15 times lower than the one measured with 50-ns beams. The pressure measured in the gauges between warm sections (baked sections between NEG coated pipes) was more than a factor 10 lower than the one measured at the cold-warm transitions, which are unbaked. However, as presented by G. Bregliozzi, **taking into account the shape and magnitude of the pressure rise at all gauges, the local pumping speed, and realistic local molecular desorption yields, the local electron flux appears to be comparable at all the locations**. Differences in the absolute pressure values can be fully explained by different desorption yields and different pumping speeds, determined by the local and neighboring configurations. The situation improved after operating the machine for about 20 h with 50-ns beams mainly at injection energy (scrubbing run). The pressure rise measured at the gauges for the same beam conditions decreased by a factor 6 over this time span.

**Scrubbing, or conditioning, is usually ascribed to a graphitization of the surface under photon or electron bombardment, and has been demonstrated to work efficiently both in warm and cold sections**. Scrubbing with low energy electrons (below 50 eV) is highly uneffective, however, as also proven experimentally, partly due to the large probability of elastic reflection of low-energy electrons. A few suggestions were put forward in order to facilitate efficient machine scrubbing:

- **Beams with the largest fraction of high energy electrons ($>$ 50 eV) accelerated to the walls could in principle be the most effective to optimize the scrubbing time**. However, it is the product of the absolute flux of electrons to the wall and of the scrubbing efficiency (given by the incidence energy) which determines the scrubbing speed. This means that, even if 75-ns beams with an electron cloud produce 20% high-energy electrons hitting the walls, while 25-ns beams only 10%, 25-ns beams still remain the most efficient because they produce a much larger flux of electrons to the wall for the same $\delta_{\max}$.
- Since scrubbing results from surface graphitization, it could be aided by **growing on a surface some monolayers of graphitic C (so called graphene)**, instead of depositing several tens of $\mu$m of amorphous C, as is currently under study for the SPS upgrade. R. Cimino reported that a pertinent R&D programme is underway at INFN Frascati. This idea raised some concerns about the stability of such a thin layer in the acceler-

> ator environment (i.e., with regard to beam loss, ion bombardment, mechanical stress), but the evidence of the efficacy of scrubbing in accelerators should in principle be a proof that this solution would indeed be stable.

Past and recent measurements show either a monotonic decrease [3, 4] or increase [5] of $E_{\max}$ with decreasing $\delta_{\max}$ as an effect of surface conditioning by electron bombardment, synchrotron radiation, baking or (NEG) activation. If scrubbing refers to the process of surface cleaning followed by graphitization it is sensible to assume that $E_{\max}$ approaches the bare metal value during the cleaning phase and eventually tends towards the value of graphite [6].

## SIMULATION TOOLS AT CERN AND GSI

Talks in this session included a review of CERN electron-cloud simulation tools by G. Rumolo (CERN), a presentation of build-up simulations for the LHC arcs by H. Maury Cuna (CINVESTAV), parameter studies of the electron-cloud build up by O. Dominguez (CERN), LHC simulations with 75-ns beams and scrubbing scenarios by U. Iriso (CELLS/ALBA), electron-cloud simulations and measurements in SIS18 by F. Petrov (TUD), and a 3D EM PIC code to study electron-cloud effects for short bunches (<50 ns) by F. Yaman (TUD).

G. Rumolo reviewed the two electron-cloud simulation work horses at CERN: the code ECLOUD, modeling the build up, and the code HEADTAIL, modeling the effect on the beam. Example ECLOUD results for the LHC demonstrate that the simulated **electron cloud density exhibits a non-monotonic dependence on the beam current** and for high bunch intensities decreases with a further increase in current. Also, **a smaller transverse emittance makes the beam more unstable** in HEADTAIL simulations. This prediction has been confirmed in SPS beam measurements. Overall there is a non-trivial dependence on many of the physical parameters. Reasons and estimates were presented why a fully 3D self-consistent electron-cloud model would be extremely challenging vis-a-vis the computing resources and time required.

H. Maury Cuna has simulated the electron-cloud build up in the LHC arcs at 450 GeV amd 3.5 (4) TeV, considering trains of bunches spaced by 50 ns with a train separation of 225 ns. These parameters correspond to LHC beam conditions from the fall of 2010. The **threshold value of $\delta_{\max}$** above which multipacting occurs is found to be **lowest in the quadrupoles magnets**, followed by the dipoles, while the field-free regions are considerable more stable. For higher values of $\delta_{\max}$ the simulation **results are sensitive to the step size between bunches** used in the simulation. Interestingly, a finer step size tends to lead to higher electron density.

O. Dominguez applied a method pioneered by D. Schulte for the SPS [7] to **determine the LHC secondary emission yield and elastic electron reflection by benchmarking simulations against vacuum observations for different bunch-train spacings**. The result depends on the number of grid points employed. Another important parameter, the **base pressure** value to be used in each simulation was in doubt. It was pointed out that the vacuum gauges do not provide accurate absolute pressure values, and suggested to repeat the excercise for a **different location** with only one dominant gas species and a different type of (higher-precision) gauge. In parallel the simulated electron energy spectra for different bunch-train spacings could be compared.

U. Iriso used the ECLOUD code for perfoming build-up simulations with 75-ns bunch spacings and benchmarked these against LHC observations. The multipacting threshold for two different apertures and fields were found. The sensitivity to aperture was explored. A **chamber radius of 35 mm gives rise to much stronger electron-cloud build up than an aperture radius of 20 mm**. The electron energy sprectrum shows a "hump" related to the occurrence of stripes. Multipacting thresholds are roughly the same at 3.5 TeV and at 450 GeV. Even for a pressure as high as 960 ntorr, at 3.5 TeV the number of photo-electrons is 3 orders of magnitude larger than the number of ionization electrons, assuming a photomission yield of 0.02. If photoelectrons from synchrotron radiation are taken as the primary source of electrons at top energy, the resulting electron distribution inside the vacuum chamber looks different from the case of gas ionization at injection. This indicates a possibility that **scrubbing at injection and at top energy might affect different regions inside the vacum chamber**. The transverse energy contained in the cyclotron motion with respect to the up-down motion should be examined. A possible inaccuracy in the ECLOUD code concerning the backtracking of lost electrons to the chamber wall should be examined and, if necessary, improved.

F. Petrov (TUD) presented studies of electron accumulation in a coasting beam performed for benchmarking purposes. It was pointed out that analytical estimates and simulations considered different beam radii. The dependence on aperture, bunch length, bunch shape and harmonic number was investigated. The final electron energy was computed as a function of transverse and longitudinal position along the bunch. A two stream instability is predicted. **A first electron-cloud experiment at GSI is scheduled for the period 1–7 April 2011 using a button pickup as diagnostics**. This button pickup is installed near the extraction septum, a location which offers the possibility to bias the nearby scraper and use it as a cleaner, as well as a residual gas analyzer in the vicinity (H. Kollmus). Introducing a gap may cure the electron build up. The near-term plan is to develop a full-blown PIC code. Electron-cloud is not expected to appear for bunched beams in SIS18 except for the location of the button pick up. Electron cloud may be a severe problem for coasting beams in SIS100. A reference with analytical formulae for ionization cross sections was provided [8].

F. Yaman (TUD) presented the **development of a 3-D**

**PIC code to model build-up, instability, and cures**. The code imports the beam-pipe geometry from CST Particle Studio. Algorithms and equations were described. The pinch is already modelled and a wake potential can be calculated. A transient effect occurring when the beam hits the electron cloud is removed from the final wake field. Origin of this transient and adequacy of its removal may require further studies. From the modified wake field a point impedance was extracted. **A strong dependence of the resulting point impedance on the initial bunch length** was presented. In the future, the simulation results will be compared with wake potential computed by analytical approaches [9]. The question was raised whether the **impedance concept** can be used for the electron cloud. A generalized 2-D impedance for the electron cloud had been proposed by E. Perevedentsev in 2002 [10].

## ELECTRON CLOUD DETECTION AND DIAGNOSTICS

This session comprised talks on electron-cloud suppression and clearing in the CERN PS by E. Mahner (CERN), on microwave diagnostics in the PS by S. Federmann (TU Vienna), on SPS measurements and mitigation techniques by M. Taborelli (CERN), and on measurements of the energy loss through the synchrotron phase shift by E. Shaposhnikova (CERN).

E. Mahner summarized the observations at the different **PS electron cloud measurement setups** from 2007 until 2010. The setups consisted of vacuum and electron diagnostics, different clearing electrodes a dipole magnet and different chamber coatings. It was shown that the electron cloud can be suppressed by application of a sufficiently large voltage of either polarity onto the clearing electrode. However, in the case of a dipole magnetic field it was demonstrated that the **clearing-electrode polarity plays an important role**. **Enamel clearing electrodes** where successfully tested in 2008. In 2010 priority was given to low SEY coatings and the suppression of the electron cloud in a carbon-coated chamber was demonstrated.

S. Federmann presented a comparison of the **microwave transmission in carbon-coated and in uncoated SPS sections** (see also [11]). The method measures the integrated electron cloud density in the section. The results show the **mitigation of the electron cloud density in the coated section**. The method takes advantage of the phase modulation of the signal by the electron cloud. Future optimizations are expected from an improved coupling by removing the pumping port shielding.

**Measurements of electron cloud currents in the SPS** using liners with holes were presented by M. Taborelli. The currents were measured for different coatings and magnetic field strength. Already weak magnetic fields were sufficient to generate large electron cloud currents. **Carbon coating of a central strip was found to be sufficient to suppress the cloud.** However, the measured **pressure rise was the same for both coated and uncoated liners.**

E. Shaposhnikova presented observations of an **intensity dependent rf phase shift in the LHC**. The phase shift increases for smaller bunch spacing. To distinguish the energy loss caused by resistive impedances or synchrotron radiation from a possible energy loss caused by electron clouds one has to measure the phase shift of individual bunches. **Measurements of the rf phase shift are also planned in the SPS for different bunch spacings.** The measurement should be accompanied by theoretical efforts to quantify the energy loss in electron clouds.

## COHERENT AND IONCOHERENT EFFECTS OF THE ELECTRON CLOUD

In this session E. Benedetto (CERN) reviewed the single-bunch electron-cloud instability and incoherent emittance growth, K. Li (CERN) electron-cloud instability thresholds and tune footprints, and G. Franchetti (GSI) incoherent effects and long-term behavior below the electron-cloud instability threshold.

In her presentation E. Benedetto showed HEADTAIL simulation results for the evolution of a preexisting cloud interacting with a single bunch. The **pinching of the cloud together with a roughly linear increase of the electron density along the bunch** is observed. The emittance growth as a result of the head-tail instability is obtained. If instead of the electron cloud PIC model an **analytic wake field model** as proposed in [12] is used in HEADTAIL only the instability onset can be reproduced correctly. The emittance growth below the instability threshold is attributed to periodic resonance crossing due to the incoherent tune shift induced by the cloud. **A comparison of the slow emittance growth below the threshold between the codes HEADTAIL and MICROMAP** gave a very good agreement.

K. Li showed **tune footprints for a LHC bunch in a self-consistently pinched electron cloud**. The tune footprints were obtained post-processing the results of HEADTAIL simulations. A newly developed software tool allows the analysis of the beam evolution under the effect of an electron cloud in tune space. Tune spreads at LHC injection as large as 0.01–0.02, in the horizontal plane, were found for an integrated electron cloud of about $2 \times 10^{11}$ $\mathrm{m}^{-3}$. A possible question to address is the interpretation of the incoherent tune footprint in an unstable, evolving bunch distribution. The thresholds for coherent instability were also calculated for different values of longitudinal and transverse emittances (corresponding to realistic LHC operation parameters), and the values calculated for the same input parameters were found to be in perfect agreement with previous evaluations by E. Benedetto, as well as K. Ohmi's calculations presented in Session I.

G. Franchetti presented **MICROMAP simulations of the incoherent effect of electron clouds in LHC**. The nonlinear tune shift resulting from the pinched cloud is obtained from a separate numerical model (see also [13]). The model is solved for drift, dipole and quadrupole sections. In a dipole magnet the electron motion is tied to the magnetic field lines. **In quadrupole magnets the approximation of a strong magnetic field fails near the axis.** Therefore the electron equation of motion including the quadrupole magnetic field and the bunch electric field should be solved. Alternatively, one could analyze the different drift terms (for finite Larmor radius) for the guiding center motion. For LHC the MICROMAP simulation predicts a slow emittance growth of up to 6 percent per hour. However, the results strongly depend on the detailed structure of the pinch and on other simulation parameters.

## MAIN FOLLOW UP

Various items for further joint studies were identified:

- simulating **long-term behavior of the beam under the action of an electron cloud**; the model here should include "elements" with a detailed pinch, a realistic distribution of the electron cloud around the ring, and, possibly, elements of randomness; this item will be followed up by G. Franchetti (GSI), K. Li and F. Zimmermann (CERN), K. Ohmi (KEK), and others;
- **3D self-consistent calculation of single-bunch electron-cloud wake fields**, in particular quantifying the energy loss, and studying the influence of the electron magnetic field on the transverse wake; these challenges will be taken on by F. Yaman (TUD), O. Boine-Frankenheim (GSI), G. Rumolo (CERN), E. Shaposhnikova (CERN), and others; different **contributions to the electron-induced energy loss** as well as any **transient effect** will need to be understood; predictions will be compared with measurements at the LHC and the SPS;
- **electron-cloud build-up simulations** with ECLOUD code; in particular for the LHC warm-warm transitions with the present pressure-rise data (CERN), and benchmarking with F. Petrov's code for SIS18 bunches (GSI); persons involved include F. Petrov (TUD), G. Bregliozzi, V. Baglin, O. Dominguez (CERN), and H. Maury (CINVESTAV).

Other follow up and miscellaneous questions comprise the effect of a **wide-band transverse feedback**, a possible rewrite of the ECLOUD code, an exploration of **coupled-bunch higher-order head-tail wakes and the resulting instability rise times**, specific studies on **electron-cloud fluctuations**, the question of primary (ionization) **electrons generated outside the beam** and the emergence of electron stripes at high magnetic field, scrubbing optimization or artificial **graphitization** (change of $E_{\rm max}$, beams leading to high electron energies), **benchmarking of the measured synchronous phase shift with cryogenic heat load and simulations**, some **open questions pertaining to a-C coating of the SPS** (little effect on vacuum pressure rise, and aging). and the role and parametrization of **re-diffused secondary electrons**.

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