DAΦNE Operation with Electron-Cloud-Clearing Electrodes

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The effects of an electron cloud (e-cloud) on beam dynamics are one of the major factors limiting performances of high intensity positron, proton, and ion storage rings. In the electron-positron collider DAΦNE, namely, a horizontal beam instability due to the electron-cloud effect has been identified as one of the main limitations on the maximum stored positron beam current and as a source of beam quality deterioration. During the last machine shutdown in order to mitigate such instability, special electrodes have been inserted in all dipole and wiggler magnets of the positron ring. It has been the first installation all over the world of this type since long metallic electrodes have been installed in all arcs of the collider positron ring and are currently used during the machine operation in collision. This has allowed a number of unprecedented measurements (e-cloud instabilities growth rate, transverse beam size variation, tune shifts along the bunch train) where the e-cloud contribution is clearly evidenced by turning the electrodes on and off. In this Letter we briefly describe a novel design of the electrodes, while the main focus is on experimental measurements. Here we report all results that clearly indicate the effectiveness of the electrodes for e-cloud suppression.

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High e-cloud densities generated in the beam pipes of high energy accelerators of positively charged beams can create serious problems for the current increase and for the beam quality preservation [1–5]. e-cloud effects have been primarily observed in several proton storage rings and synchrotrons [4,6–11] and then in positron beams accumulated in the KEK Photon Factory [4,12]. The positron beam blow up due to the e-cloud effect has been first observed in the B factories KEKB [4,13,14] and PEP-II [4,15,16], while the SPS test with the LHC-type beam revealed instabilities related to the e-cloud [17–19]. They are expected to be of crucial importance for future accelerators like the Damping Rings of the International Linear Collider [20], the SuperKEKB [21], and the Super B factories [22]. The e-cloud effects are also responsible for the horizontal beam instability in the DAΦNE e^+e^- collider [23,24].

Various types of methods have been proposed, studied, and experimentally verified in order to provide a solution to the e-cloud problems. There are two basic approaches for suppressing the e-cloud effects: the first one is to modify the chamber surface properties thus reducing the secondary emission yield (SEY) by the application of surface coatings [25–33] or by an artificial surface roughness, like grooves [32,34–37]. Also the conditioning of the vacuum chamber surfaces by exposing it to synchrotron radiation or a generated e-cloud (scrubbing) can partially reduce the SEY [30,33,38,39]. The second approach consists of changing the dynamics of the electrons by the application of electric, magnetic, or electromagnetic fields such as solenoid fields [13,14,40] in straight sections to confine the electrons close to the chamber wall or a clearing electrode in the beam pipe [14,40–47] used to attract or repel electrons applying a static electric field. This second method can be used to clear the e-cloud even inside magnets, unlike the method employing a solenoid field. The first experiences with e-cloud clearing have been acquired with short button-type electrodes [40]. To cover longer sections a proposed solution with rather low impedance and good mechanical properties consists of resistive layers deposited onto a ceramic or an enamel strip inside the beam pipe. Recently, such test electrodes have been successfully installed in single wiggler magnet section of the existing machines CERN PS [48], CESR [49], and KEKB [44,45].

In the DAΦNE collider we have proposed and installed another type of electrode never adopted before [46,47]; moreover, the devices have been installed in all positron ring arcs allowing measurements never done before in other accelerators such as e-cloud instabilities' growth rate, transverse beam size variation, and tune shifts along the bunch train with the electrodes switched on and off.

DAΦNE is an electron-positron collider in operation in the National Laboratories of Frascati (Italy) of the INFN. It works at the energy of 1.02 GeV in the center-of-mass, the energy of the Φ resonance [50,51]. The maximum luminosity was achieved in collisions with the novel crab waist scheme [52]. Its best value of 4.5×10^{32} cm^{-2} s^{-1} is by 2 orders of magnitude higher than the luminosity of the Novosibirsk VEPP-2M collider [53] that was working at the same energy. This result was achieved by storing beams with high currents distributed over many colliding bunches (maximum 110 over 120). The maximum electron beam current was 2.5 A, i.e., the record value for the electron beam current ever stored in the modern colliders and synchrotron light sources. However, due to the e-cloud effects we have not been able to exceed 1.4 A in the positron ring because of a strong horizontal instability. Numerical simulations and experimental observations have shown that this kind of instability is triggered by the e-cloud pattern created in the wiggler and dipole magnets [54,55]. In addition to this beam current limitation we have been suffering from other harmful e-cloud effects affecting the collider luminosity performance such as anomalous pressure rise, vertical beam size increase, tune spread along the bunch train, etc., [23,24]. The low beam energy (510 MeV), aluminium vacuum chamber with high SEY, shortest bunch spacing (2.7 ns), and the high beam current (>1 A) make DAΦNE the most challenging machine in the world from the e-cloud effects point of view.

In order to cope with the strong e-cloud instabilities powerful bunch-by-bunch feedback systems [56] and solenoids have been used, but the problems created by the e-cloud and the horizontal instability still remained the worst trouble for the collider. For these reasons it has been decided to insert special metallic (copper) electrodes.

Differently from other installations [44,49,57,58], in DAΦNE the e-cloud clearing electrodes have been inserted in all dipole and wigglers without opening the vacuum chamber by inserting the electrodes through lateral vacuum pump ports. Such electrodes are also technologically simpler and cheaper than those previously used. The dipole electrodes have a length of 1.4 or 1.6 m depending on the considered collider arc, while the wiggler ones are 1.4 m long. They have a width of 50 mm, thickness of 1.5 mm, and their distance from the chamber is about 0.5 mm. This distance is guaranteed by special ceramic supports distributed along the electrodes. The distance of the electrode from the beam axis is 8 mm in the wigglers and 25 mm in the dipoles. The electrodes have been connected to the external dc voltage generators modifying the existing BPM flanges.

The electrodes installation in the ring was a risky operation from the beam impedance point of view. The electrode coupling impedance consists of the resistive wall impedance and the strip-line impedance. It has been estimated that for the wiggler electrode (the most critical for the impedance) the resistive wall contribution would result in the temperature rise up to 50–55 degrees [46]. In turn, the strip-line impedance depends on the external matching conditions. Even for perfectly matched electrodes the loss factor would be a factor 3 higher than that of the resistive wall. Since perfect matching is almost impossible, one could expect even higher beam losses. To keep the situation under control it has been decided to (a) mismatch the electrode intentionally to have the narrow resonances, (b) choose the electrode length to have powerful rf harmonics just between the dangerous resonances. The overall broadband impedance was reduced by decreasing the electrode-wall gap and increasing its width. The simulations have been performed using the code GdfidL [59]. Also rf measurements have been done before and after the electrode installation to verify that rf harmonics do not couple to resonances [46]. Moreover, in order to prevent this possible damage due to the excessive heating, the electrode supports are made of a thermoconducting dielectric material (SHAPAL [60]), thus providing heat transfer from the electrode to the chamber. The final estimated low frequency broadband impedance Z/n is about 0.005 Ω, and should be a small contribution to the total ring impedance. Indeed, this has been confirmed by measuring bunch lengthening in both the electron and the positron rings and comparing the results.

In order to evaluate the effectiveness of e-cloud suppression by the electrodes we have used the code ECLOUD [61,62] modified to include the effect of a vertical electric field on the e-cloud dynamics. The simulations have been performed with the following simplifying assumptions: (a) the vacuum chamber is considered to be elliptic and the magnetic field uniform and equal to the maximum value in the wiggler; (b) the electric field is vertical and uniform in the region of the chamber occupied by the electrodes and zero outside this region; (c) the SEY of aluminum has been used both for the chamber and electrode surface. The main simulation parameters are given in the figure caption.

Figure 1(a) shows the e-cloud density evolution for different values of the electrode voltage for 800 mA in 100 consecutive bunches. A nonmonotonic dependence of the saturation density on the electrode voltage is clearly observed. In particular, the maximum value is reached around $V = 150$ V. For higher voltages the density sharply decreases. We see that already at 300 V it is reduced by about 2 orders of magnitude. The same behavior is observed for different values of the beam current, as shown in Fig. 1(b).

In our opinion such a behavior can be attributed to the fact that the electrodes accelerate the electrons of the cloud and, since the SEY has its maximum at the energy of 200–300 eV, we can expect some e-cloud density

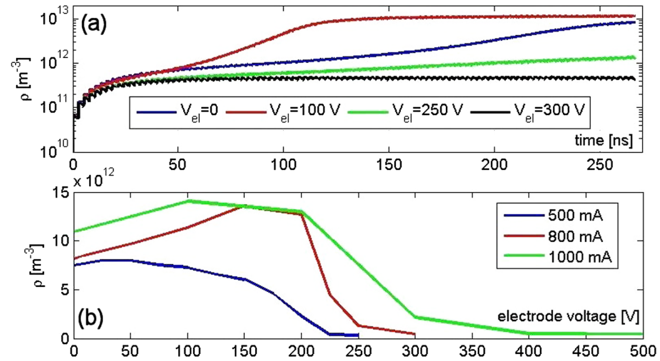

FIG. 1 (color online). (a) Evolution of the averaged cloud density for different values of the electrode voltage. (b) e-cloud density at the end of bunch train. Parameters used in the simulation are the primary electron rate 0.008, photon reflectivity 100% (uniform), maximum SEY 1.9, energy at maximum SEY 250 eV, vertical magnetic field 1.64 T, bunch length 12.3 mm, bunch hor./vert. size 1.08 mm/0.05 mm, and hor./vert. chamber sizes 12 cm/2 cm.

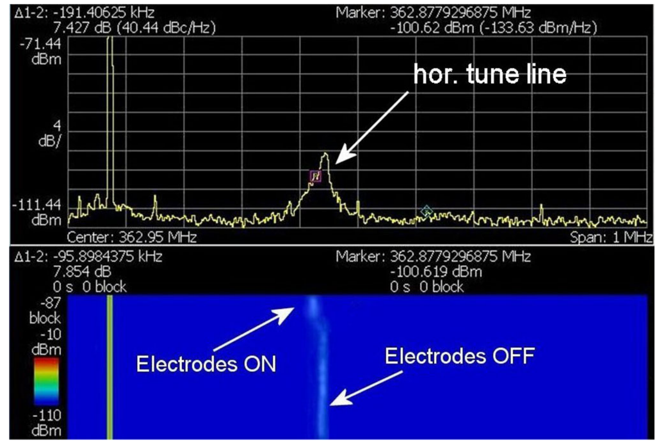

FIG. 2 (color online). Horizontal tune shift measured at 550 mA.

increase due to the secondary electrons from the electrode surface at the electrode voltages of the order of 200–300 V (assuming that the e-cloud electrons have small initial energies). Clearly the e-cloud dynamics is more complicated since one has to take into account also the beam electric potential and the e-cloud space charge effect. Namely, these studies are underway in order to characterize better the electrode effectiveness and the e-cloud evolution. On the other hand, the experimental results provide a good chance for the numeric code benchmarking.

Several experimental measurements have been performed to check the effectiveness of the electrodes to suppress the e-cloud. All measurements have been done with positive voltage polarity.

The first and most obvious measurement is the measurement of the average betatron tune shift over the bunch train. As discussed in the following there is a tune shift spread along the train. The tune measurements performed with the spectrum analyzer give its average value. The horizontal tune shift measurements with electrodes on and off are given in Fig. 2 for a 550 mA positron beam (not colliding). The frequency shift corresponds to a difference in the horizontal tune of ≈ 0.0065. The betatron tune is shifted in the positive direction while switching off the electrodes. This is a clear indication that the e-cloud density is reduced.

More sophisticated tune measurement has been performed using capabilities of the DAΦNE bunch-by-bunch feedbacks [63–65]. Off-line analysis of the signals acquired by the bunch-by-bunch transverse feedbacks allows measuring the fractional tunes of each bunch along the train. Figure 3 shows the measured tune shifts as a function of the bunch number. These measurements were performed by turning off all four wigglers electrodes and two (over eight) dipole electrodes. The bunch train was composed by 100 consecutive bunches.

We can observe the typical tune modulation along the train induced by the e-cloud density variation. The fractional tunes progressively increase and reaches a steady state regime after ≈ 20 bunches. In the horizontal plane the head-tail tune spread is about 0.006–0.008. As we also obtained in our previous estimates [66], this tune shift should correspond to the e-cloud density in the wiggler sections of 10^{14} m^{-3}. According to our simulations, despite the average density is of the order of 10^{13} m^{-3}, the density in the vacuum chamber center in the vicinity of the beam trajectory is by an order of magnitude higher. This can explain the observed tune shift. When the electrodes are switched on the tune shift reduces by a factor of 2–3, but they do not cancel completely the tune spread. We attribute this to the fact that the electrodes in the wigglers cover only 67% of their total length. In turn, as it is seen

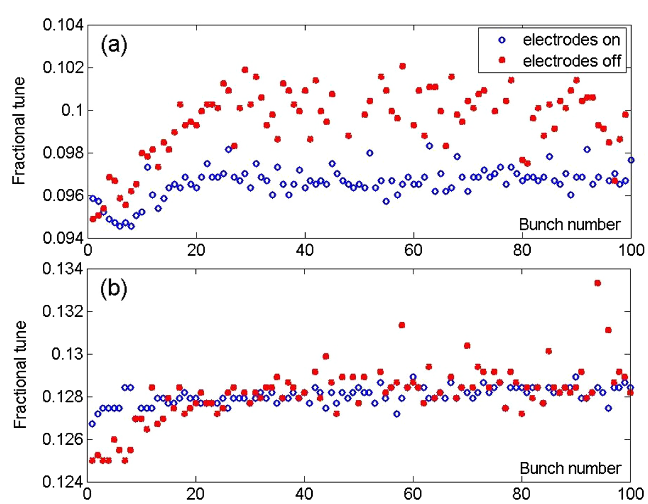

FIG. 3 (color online). Measurements of horizontal (a) and vertical (b) fractional tunes as a function of bunch number at 500 mA.

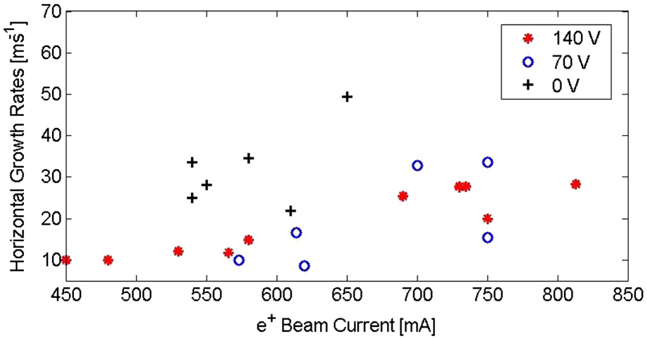

FIG. 4 (color online). Growth rates of the horizontal instability.

in Fig. 3(b), the vertical tune spread is notably smaller than the horizontal one and the electrodes almost completely cancel it. Some vertical tune variation is observed while turning on and off the electrodes. We attribute this effect to residual orbit variations during the measurements. In the presence of strong crab waist sextupoles this leads mainly to the vertical tune shift of all bunches in the train.

Another useful measurement with the feedback system is the instability growth rates [67]. The unstable mode is the mode -1. In the past it has been predicted by simulation that exactly this mode becomes unstable due to the *e*-cloud created in the dipole and wiggler magnets and having the shape of two vertical parallel stripes [54,55]. Figure 4 summarizes the results. With electrodes off the growth rate at 650 mA exceeds 50 ms^{-1} and the measurements above this current become quite difficult since the beam is strongly unstable. Such a fast instability, with a rise time of tens of revolution turns, can be explained only by the *e*-cloud effects, as shown in the past [54].

The vertical beam size enlargement has been measured at the synchrotron light monitor (SLM) by gradually turning off the electrodes as shown in Fig. 5. The vertical size increases from about 110 μm with electrodes on to more than 145 μm with the electrodes off. In our opinion, namely, the single bunch *e*-cloud instability is responsible of the vertical beam size growth. According to our

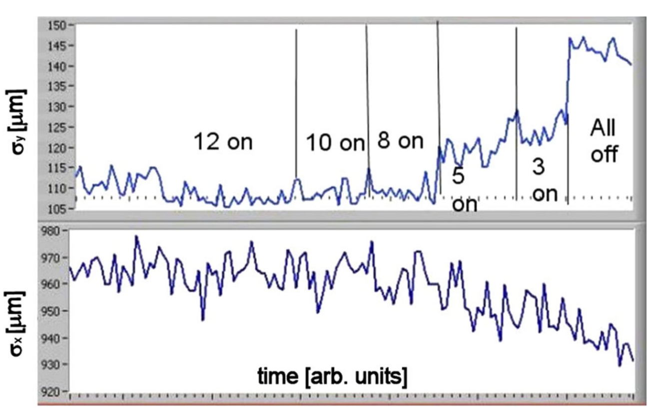

FIG. 5 (color online). Beam dimension at the SLM turning off, progressively, all electrodes ($I = 500$–600 mA, 100 bunches).

preliminary studies [68], the threshold of the single bunch instability corresponds to the *e*-cloud density ranging between 2 and 5×10^{13} m^{-3}. This is compatible with the density levels obtained both in numerical simulations and deduced from the tune shift measurements, as discussed above.

The *e*-cloud plasma can interact with rf waves transmitted in the vacuum chamber changing the phase velocity of the waves. Such measurements have been successfully done on other machines [69]. A similar approach can be used in the case of resonant waves in the vacuum chamber. Even in this case the *e*-cloud changes the electromagnetic properties of vacuum and this can result in a shift of the resonant frequencies chamber trapped modes. In principle, from these shifts it is possible to evaluate the *e*-cloud density [70,71].

Resonant TE-like modes are trapped in the DAΦNE arcs and can be excited through button pickups. A first measurement of these resonant modes has been done at DAΦNE for several beam currents with the electrodes on and off [47]. The preliminary analysis of data has given the following results: (a) all modes have a positive frequency shift with the positron beam current and it is between 100 and 400 kHz depending on the modes we are considering; (b) for almost all modes we can partially cancel the frequency shift switching on the electrodes; (c) the quality factor of the modes decreases with positron current. The observed frequency shift is reasonably consistent with the *e*-cloud density estimate given in Ref. [71]. By simply considering the case of a uniform distribution we obtain densities of the order of few 10^{12} m^{-3} that within a factor of 2–3 (lower) agrees with the average density predicted by simulations. However, a more precise evaluation can be obtained only by taking into account the HOMs electric field pattern and a more realistic *e*-cloud density distribution. The fact that for some modes the shift does not depend on the electrode voltage could depend on the fact

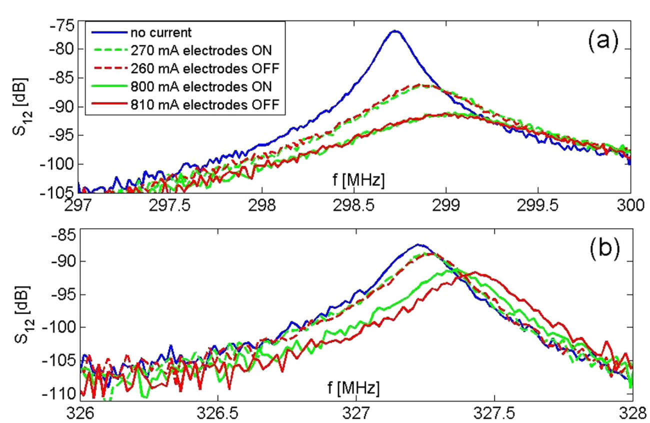

FIG. 6 (color online). Transmission coefficient between two button pickups for two different resonant modes (one pickup is located near the wiggler and the other one near the dipole magnet).

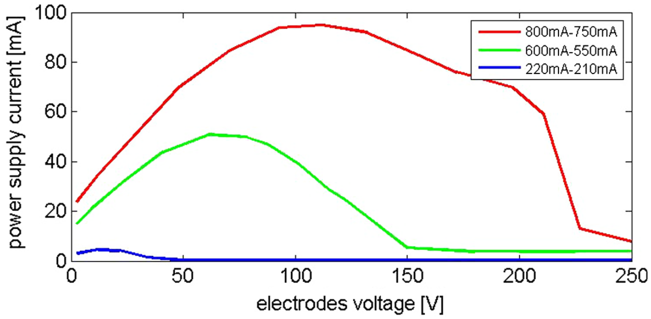

FIG. 7 (color online). Current supplied by the dc voltage generator as a function of the applied voltage and beam current.

that they are localized in different places of the arc also in regions not covered by electrodes. For instance the transmission coefficient between two button pickups in the arc chamber is given in Figs. 6(a) and 6(b) for two different modes.

The voltage generators connected to the electrodes absorb the *e*-cloud electrons. In the present layout one voltage generator is connected to three electrodes of one arc (i.e., one wiggler and two dipoles). The current delivered by the generator has been measured as a function of the generator voltage for different beam currents. The result is given in Fig. 7.

Comparing the plots of Fig. 7 with those obtained by the simulations (see Fig. 1) we can see similar qualitative behaviors.

On the basis of the numerical predictions and the measurement results we can conclude that in order to store positron beam currents higher than 1 A a voltage of the order of 250 V (presently available) is no longer adequate to completely absorb and suppress the *e*-cloud in DAΦNE. Since we and other authors [57,72] have observed that the effectiveness of the *e*-cloud suppression does not depend on the voltage polarity it is a good practice to use negative voltages in order to avoid damages to the electrodes from the electron bombardment and to the voltage generator from the reversed current. The former is particularly valid for the thin layer electrodes [44,49,57,58].

In conclusion, DAΦNE is the first collider in which long electrodes for *e*-cloud mitigation have been installed in all dipole and wigglers arcs and are used in routine operations. These electrodes not only permitted a more stable operation with the positron beam, but have allowed unique measurements such as *e*-cloud instabilities' growth rate, transverse beam size variation, and tune shifts along the bunch train with the electrodes switched on and off demonstrating the effectiveness of the *e*-cloud mitigation.

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