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ELECTRON CLOUD AND ION EFFECTS

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1 ELECTRON AND ION BUILD-UP

Electrons and ions are ubiquitous in the vacuum chambers of high intensity, high brilliance accelerators and storage rings. Electrons can be produced by ionisation of the residual gas by the beam, photoemission induced by synchrotron radiation and beam losses. Ions can be produced by residual gas ionisation. The beam-induced ionisation rate per unit length for ultra-relativistic (γ_{beam} >> 1) particles is given by:

$$\frac{d^2N_{ion}}{ds\,dt} = \lambda_{beam} c \sigma_{ion} \rho_{gas} \tag{1}$$

where λ_{beam} is the beam linear density, c the speed of light, ρ_{gas} the gas density and σ_{ion} the ionisation cross-section (1-2 Mbarn for relativistic particles on CO, it can be a factor 100 higher for electrons with energies < 100 eV) [2][3]. The mean number of photoelectrons produced by synchrotron radiation (for critical energies above the work function of the vacuum chamber material) is:

$$\frac{d^2N_{phel}}{ds\,dt} = \frac{5}{2\sqrt{3}} \alpha\, c \frac{Z_{beam}^2\, \gamma_{beam} \lambda_{beam}}{\rho} Y^* \tag{2}$$

where α is the fine-structure constant, Z_{beam} the charge state of the beam particles, ρ is the bending radius and Y^* is the photoelectron yield per adsorbed photon. Typical Y^* values are in the range 0.01-0.1. The electron production rate per unit length due to beam losses in proton machines is:

$$\frac{dN_{loss}}{ds\,dt} = \frac{r_{loss}\lambda_{beam}}{C} c Y_{ep} \tag{3}$$

where C is the machine circumference, r_{loss} is the average fractional loss per turn and Y_{ep} is the number of electrons generated per incident proton. Values quoted for PSR and SNS (γ_{beam} ~ 1) are $r_{loss} = 4\text{x}10^{-6}$ and 10^{-7}, respectively, and Y_{ep} =100 [4]. $Y_{ep} \propto \gamma_{beam}^{-0.35}$ [5]. Photoemission is the main source of primary electrons in lepton machines (e.g. ϕ- and B-factories, synchrotron light sources) and very high energy proton machines (e.g. LHC) while residual gas ionisation and beam losses dominate in proton machines at low and intermediate energy (CERN PS, PSR, SNS, CERN SPS).

1.1 Positively charged beams

The behaviour of ion species under the beam potential has been studied analytically and numerically in particular for the electron cloud build-up induced by positively charged beams [6-11]. Electrons can be trapped in the beam potential of coasting positive beams while ions with charge Ze are repelled and accelerated towards the walls of the vacuum chamber. The (round) beam potential is:

$$V(r) = \frac{Z_{beam} e \lambda_{beam}}{2\pi\varepsilon_0} \begin{cases} -\dfrac{r^2}{2a^2} + \dfrac{1}{2} + \ln\left(\dfrac{r_0}{a}\right) & r \le a \\ \ln\left(\dfrac{r_0}{r}\right) & r_0 \ge r \ge a \end{cases} \tag{4}$$

where r_0 is the vacuum chamber radius (where the potential energy is assumed to vanish), a the beam radius, ε_0 the vacuum permittivity.. The maximum energy gained by the electrons (ions) therefore corresponds to the depth of the potential well of the beam. Ions may gain energies of a few keV (as in the ISR) and they can desorb strongly bound gas molecules. Since the rate of ionisation is proportional to the gas density an avalanche process may occur resulting in a continuously increasing pressure. So far this phenomenon (ion-induced pressure instability) has been observed only in the ISR at CERN [2]. Electrons, trapped by the potential of a coasting beam, bounce with a frequency $f_{e\,x,y}$ (inside the beam of r.m.s. sizes σ_x and σ_y):

$$f_{e\,x,y} = \frac{c}{2\pi}\sqrt{\frac{r_e \lambda_{beam} Z_{beam}}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)}} \tag{5}$$

where r_e is the classical electron radius.

The ion behaviour for positive bunched beams (bunch length l_b and spacing s_b) is similar to that for a coasting beam because of the large mass and low speed.

For electrons different regimes can be distinguished, one is the ‘autonomous’ approximation, in which the time dependence of the linear charge density is neglected [7]. This can occur for low intensity beams when the electron bouncing period $1/f_e$ is much larger than the bunch spacing or for intense bunches whose length is much larger than the electron bouncing period. The actual energy gain depends on the period of oscillation and on the position of the electron at the moment of the bunch (or bunch train) passage. Electrons produced at the wall gain significant energy if produced when the bunch (bunch train) local density is decreasing and are responsible for electron multiplication if the average secondary emission yield (SEY) exceeds unity (trailing edge multipacting observed at PSR). Electrons produced at low radii or just before the bunch passage are captured in the beam potential and are responsible for the electron-cloud instabilities [4][12][13].

If the oscillation period is longer than the bunch length and smaller than the bunch spacing than the interaction between electrons at radii $r > a$ and the bunches can be represented by means of single kicks

$$\Delta p = 2N_b m_e c \frac{r_e}{r} \tag{6}$$

where N_b is the bunch population and m_e is the electron rest mass. In this case primary electrons can gain enough energy so that they can reach the wall of the vacuum chamber and generate secondaries before the next bunch arrives, in that case Beam Induced Multipacting (BIM) can occur if SEY>1.

BIM engenders an exponential growth of the electron-cloud along the batch (electrons can even contribute to residual gas ionisation [3]) until the space charge fields associated with the cloud itself cancel, on average, the beam field. This is the case for the SPS operated with LHC-type and high intensity fixed target beams, the LHC and the KEKB and PEP-II positron rings. A simple, but not strict [14], condition for BIM is [8]:

$$N_b = \frac{r_0^2}{r_e s_b} \equiv N_{th} \tag{7}$$

indeed electron cloud build-up is observed for a large range of the ratio N_b/N_{th}. Its value is an indicator of the dominance of multipacting as a mechanism for electron cloud-build-up. Far from the multipacting condition the production mechanisms of the primary electrons will also have a significant role in the electron cloud properties. Finally, the electron cloud properties are strongly dependent on the matching of the electron energy distribution with the function describing the dependence of SEY on the energy of the incident electron. The first depends on the beam characteristics (bunch intensity, beam size, bunch length - cfr. Eq. 4 - and bunch spacing) and on the geometry of the vacuum chamber, the second depends on the surface properties of the vacuum chamber. BIM is a single passage phenomenon and can also occur in transfer lines and linacs.

Due to the complexity of the phenomena involved various codes have been developed to simulate the electron cloud build-up [1] in future machines and to define the design of some of their components. In order to constrain the input parameters (not always precisely known) measurements of the electron cloud build-up (e.g. build-up length, saturation density, decay, threshold intensity) have been performed in several accelerators and compared with simulations, agreement is generally not only qualitative but also quantitative [4][12-19].

A clear dependence of the threshold for the onset of the electron cloud on bunch spacing has been observed. The thresholds measured in the SPS arcs for the LHC beam with 25 and 50 ns bunch spacing were 3 and 6 x 10^{10} p/bunch, respectively. Operation with 75 ns spacing is considered as a possible initial scenario for LHC operation. Striking is also the dependence on spacing observed at the APS [17].

BIM has been also observed for the Fixed Target beam (5 ns spacing) in the SPS during acceleration. The maximum signal does not appear at transition, when bunches have the minimum length, but later in the ramp when the beam size is shrinking [20]. This indicates that not only bunch length (as indicated by simulations) but also transverse beam size is affecting the electron-cloud build-up. The measured threshold bunch intensity for this beam is in agreement with simulations [19].

The motion of electrons and ions is strongly affected by the presence of external fields. In a vertical dipole field electrons undergo only a vertical motion during their lifetime (i.e. the time to traverse the vacuum chamber) because the cyclotron period is generally much shorter than the bunch length (this is particularly true for proton machines) and they do not receive any net horizontal kick by the bunch. Therefore, at high intensity, electrons are concentrated in two stripes, symmetrically positioned with respect to the beam, as a combined effect of the electron energy distribution and of the Secondary Emission Yield (SEY) energy dependence. At the position of each stripe the electron energy gain corresponds to the value of the energy for which SEY is maximum. A third central stripe is predicted by simulations for the LHC-type beam in the SPS at bunch intensities comparable to the nominal (N_b=1.1x10^{11}p) [19].

Measurements of the transverse distribution of the electron cloud inside a dipole field at the SPS not only have confirmed the appearance of the two stripes for $N_b >$ 0.5x10^{11} but also of the third stripe at the nominal bunch intensity [20][21]. The measured separation between the electron stripes is twice smaller than that resulting from simulations [20][19]. The experiments in the SPS have also confirmed that the threshold for the onset of the electron cloud in the arcs is 2.5 times that measured in the straight sections [21][20] in rough agreement with simulations [19]. The electron distribution (two stripes) in the arcs might be less efficient in neutralising the beam potential than in field free-regions where electrons are concentrated near the beam. In that case higher neutralisation densities could be achieved in the arcs as compared to the straight sections.

A solenoidal field can trap electrons generated at the wall of the vacuum chamber and keep them far from the beam therefore suppressing BIM and reducing the density of the electron cloud in proximity of the beam. This approach has been successfully applied in the KEKB and PEP-II positron rings [15][22]. Electrons might also be trapped in non-uniform fields such as quadrupoles, sextupoles, insertion devices[23]. Recent simulations performed for the KEKB positron ring have shown that trapping times much longer than the bunch train may occur in quadrupoles and sextupoles [19][24]. This could explain the long decay time of the electron-cloud observed after the batch passage. Most of the experiments seem to indicate that gaps of several hundred ns are necessary to completely reset the electron cloud [15][21].

Reduction of SEY is vital in machines where multipacting is the dominant source of electron production. SEY in large surfaces such as those involved in an accelerator can be reduced by [25]: a) changing the surface composition by glow discharge treatments, b) depositing TiN films (PEP-II, PSR), or Non Evaporable Getters such as TiZrV[26] (baseline solution for the LHC Experimental Areas), c) electron bombardment. The latter process has been thoroughly studied at CERN[27], it has been observed in APS[17][28], PSR[29] and recently SPS. BIM will be the tool to reduce the SEY in the LHC.

Photoemission is the main source of primary electrons in positron or very-high-energy proton machines. In the arcs the dipole field confines most of the photoelectrons at the outer wall, in a ribbon ‘illuminated’ by the synchrotron radiation, and they do not gain a significant amount of energy. Only reflected photons can originate electrons at the top and bottom of the vacuum chamber and only these electrons can approach the beam along the field lines and trigger multipacting. Reduction of the photoelectron yield and of the photon reflectivity are desirable. Y^* can be decreased by designing the vacuum chamber with an antechamber slot in the area illuminated by synchrotron radiation (PEP-II). This allows photons escaping the vacuum chamber. Experiments performed at CERN indicate that Y^* diminishes with the photon dose received by the vacuum chamber[30]. Reduction of the photon reflectivity is also a premium: the LHC beam screen will have a ribbed surface in the illuminated area in order to maximize normal incidence of the photons for which reflectivity is minimum [31].

1.2 Negatively charged beams

For a coasting beam electrons are repelled towards the wall while positive ions are trapped in the beam potential. Also in the case of negatively-charged bunched beams electron-cloud build-up, though with minor intensity, can develop [19] as observed at the APS[17][28]. In the case of a bunched beam (in the approximation $l_b \ll s_b$) ion motion is comparable to that of a charged particle in a periodic lattice consisting of a sequence of thin focussing lenses and drift lengths. The ion motion will be stable only for ions with a mass A (in proton mass units) larger than the critical value A_{crit}[23][32]:

$$A_{crit} = \frac{N_b s_b r_p}{2n\sigma_x\left(\sigma_x + \sigma_y\right)} \qquad (8)$$

where r_p is the classical proton radius, n is the number of bunches. Ions with smaller mass number are overfocussed and are lost at the wall. Trapped ions of charge Ze oscillate at a frequency:

$$f_{ion\,x,y} = \frac{c}{2\pi}\sqrt{\frac{r_p \lambda_{beam} Z_{beam} Z}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)A}} \qquad (9)$$

As the trapping proceeds ions accumulate around the beam and partly neutralise the beam potential generating a reduction of A_{crit} so that lighter and lighter ions will be trapped until neutralisation is complete. Gaps in the bunch train ($\gg 1/f_{ion}$) make the ion motion unstable (at least for several bands of ion masses) and prevent ion trapping.

2 ELECTRON CLOUD EFFECTS

Electron cloud effects (ECE) pertain primarily to positively charged beams. Historically ECE have been first observed for high intensity coasting proton beams in the ISR where electrons generated by gas ionisation were bouncing in the beam potential well and could excite beam mode numbers around f_e [33][34]. As result of that spectral lines at 40-60 MHz (corresponding to the unstable modes) could be seen and large background spikes were observed by the detectors when the electrons, oscillating with increasing amplitude, reached the vacuum chamber and were lost. Protons oscillated at much smaller amplitudes under a focussing force characterized by:

$$K_{x,y} = \frac{2 r_p \lambda_e c^2}{\gamma \sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \qquad (10)$$

and experienced a small emittance blow-up. Clearing electrodes and more powerful vacuum pumps were installed. This reduced the residual pressure by more than an order of magnitude and the above-mentioned electron effects disappeared.

The most visible ECE is a non-linear pressure increase vs. bunch current as observed at the ISR when operated with bunched beam [35], KEKB LER[36], PEP-II LER [22], SPS when operated with LHC-type beam[21], APS[28]. This effect is the result of molecular desorption induced by electron bombardment.

Any transverse movement of the bunch or of a slice of it affects the electron cloud distribution which, in turn, affects the trailing bunches or trailing slices generating bunch-to-bunch or head-tail coupling. In a field-free region the electron cloud distribution is pinched in both planes at the bunch passage. In a vertical dipole field no pinching occurs in the horizontal plane during the bunch passage and horizontal motion of the electron-cloud can occur only on time scales comparable with the electron traversal time. According to this picture single and coupled bunch instabilities may arise in both planes in field free regions while in the arcs single bunch instabilities should not appear in the horizontal plane. Fast electron cloud instabilities (ECI) are observed in several proton and positron machines (Table 1).

In the first three machines the arcs are covering a significant fraction of their circumference. In the remaining two, straight sections are dominating, in both these storage rings a significant fraction of the straight sections has been equipped with solenoids to limit BIM. In PEP II the arc vacuum chambers have been coated with

TiN. In the positron machines the evidence for single bunch instabilities is indirect and it is inferred from the emittance blow-up observed along the bunch train and on test bunches injected at different distances with respect to the bunch train [15].

Table 1: ECI in different machines. S=single-bunch, C=coupled-bunch. τ is the rise-time in number of turns $\propto N_b^{-1}$ indicates that the rise-time is decreasing with N_b^{-1}

Machine	**H-plane**	**V-plane**
PSR [37]	--	S, $\tau \sim 100$
SPS – 25 ns[38]	C, $\tau \sim 50$	S,τ~500-100$\propto N_b^{-1}$
PS – 25 ns [39]	S, $\tau \sim 1000$	--
KEKB LER[15]	C, τ~200-50 $\propto N_b^{-1}$	C,τ~300-70 $\propto N_b^{-1}$ S
PEPII LER[22]	S	--

While the observations made at PSR, SPS and KEKB fit with the qualitative description above outlined, no simple explanation can be given for the behaviour observed in the PS and at PEPII. Both the single bunch [38][40-44] and coupled bunch [38][45] instabilities induced by the electron cloud have been studied in detail. In particular the single bunch instability (higher order head-tail) can explain the blow-up observed at KEKB and SPS operated with LHC-type beams (25 ns spacing). In the SPS the synergy between electron-cloud, space charge and machine impedance is at the origin of the dipole modes and of the short rise time of the single bunch instabilities. A similar enhancement of the instability can be expected by the combination of electron cloud and beam-beam forces in colliders [46]. Recent studies evidenced that in combined function magnets (e.g. in the CERN PS) the horizontal component of the electron-cloud wake might not be suppressed as in the case of a purely dipolar field. This might explain the PS observations of an horizontal single bunch instability though it is not clear why the vertical plane appears unaffected [39][47]. Most of the computational and analytical estimations indicate the role of high positive chromaticity (above transition) as a tool to control single-bunch instabilities as observed in KEKB[15], PEP-II and SPS[48]. Transverse bunch-to-bunch feedbacks used to fight the coupled bunch instabilities could also permit to minimise the value of the chromaticity required to stabilise the beam [44].

The electron cloud will also produce coherent and incoherent tune shifts. As the density of the cloud and therefore the coupling strength are increasing along the bunch train the tune shift increases as well. Its value provides an indirect measure of the longitudinal distribution of the cloud. The decay time of the cloud can also be measured if a witness bunch is injected after the bunch train [15].

The blow-up induced by the electron-cloud reduces the bunch-by-bunch luminosity along the train and it is one of the performance limitations in B-factories. Special bunch patterns with several gaps have been conceived [49] to alleviate the effects of such blow-up. These take into account the measured decay time of the electron cloud between consecutive bunch trains and aim at a more even distribution of the luminosity among bunches.

Electron build-up can be a strong limitation to the performance of beam instrumentation in rings and transfer lines: baseline distortion in the signal provided by high-impedance electrostatic pick-ups, overwhelming noise on secondary emission and ionisation profile monitors are typical manifestations of BIM and have been observed in the PS [39] and SPS [50]. High voltage electrostatic devices might be affected as well.

Another effect is the power deposition on the vacuum chamber walls by the electrons. This additional heat load may overwhelm those due to image currents and synchrotron radiation if no care is taken in minimizing SEY and Y^* and it is a major concern for high energy superconducting machines. The position of the electron stripes in the dipoles has significant implications for the design of the pumping slots of the LHC beam-screen (operated at 4-20 K) in order to avoid unacceptable heat load on the cold bore at 1.9 K. The position of the stripes as a function of N_b has been measured in the SPS [20][21]. The implications for the design of the beam screen are being evaluated [21].

3 ION EFFECTS

Apart from the ion-induced pressure instability, ion effects pertain primarily to negatively charged beams. As for the electron cloud the beam and the ion cloud motions are coupled. For coasting beams or bunched beams with close spacings and $A>A_{crit}$ the interaction among the two-streams is identical to that discussed for the ISR beam (assuming single ionisation). Mode numbers around f_{ion} are excited and either the beam is blown up or the ions are expelled from the beam potential. The cure to ion trapping and related instabilities (used in most high brilliance electron machines) are gaps in the bunch train. For high brilliance beams the coupling coefficient $K_{x,y}$ (Eq. 10) is strongly enhanced and an ion instability may develop as a result of the linear ion build-up along the bunch train in a single turn, even in the presence of a clearing gap. Unlike the classical beam-ion instability the 'Fast Beam Ion Instability' (FBII) [51] can occur in linacs and transfer lines and it is similar to multi-bunch beam break-up. In linear approximation the bunch oscillation amplitude (in the vertical plane) is [52]:

$$y_b(s,z) \propto \exp\left(\sqrt{\frac{s}{c\tau_{FBII}}}\,\frac{z}{l_{train}}\right)$$
$$\frac{1}{\tau_{FBII}} \propto \frac{\rho_{gas}\sigma_{ion}\beta_y N_b^2 n^2 s_b^{1/2}}{\gamma_{beam}\sigma_y^{3/2}\left(\sigma_x+\sigma_y\right)^{3/2} A^{1/2}} \tag{11}$$

where s and z are the longitudinal position along the beam line and the train (of length l_{train}), respectively.

FBII has been observed at ALS [53], KEKB HER [54], ESRF [55], PLS [56] and Spring-8 [57] when operated with poor vacuum. This generally manifests itself as coupled-bunch instability and beam blow-up of the tail of the batch affecting the vertical plane only because of the beam flatness. The non-linearity of the beam-ion force, the dependence of the vertical ion frequency on the horizontal position, the presence of different ion species and the dependence of $K_{x,y}$ on the beam size introduce a spread in the ion frequencies and therefore Landau damping, which slows down the instability [58]. FBII might be of concern for future linear colliders and high brilliance synchrotron light sources where long trains of intense bunches with very small emittance will be circulating. Simulations performed for the TESLA electron damping ring and FEL Beam Transfer Line showed that FBII is avoided with vacuum pressures achievable with standard methods [59]. An adequate design of the vacuum system seems also the solution preferred for NLC [60]. Other possible cures include powerful transverse feedbacks and the creation of additional short gaps [61].

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