EFFICIENT PLASMA GENERATION BY POSITIVE CIRCULATING BEAM

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Abstract

Performances of high brightness circulating beams are affected by development of strong "electron-proton" (e-p) instabilities caused by the beam interaction with an electron cloud (electron cloud effect (ECE)). For suppression of the EC generation it is proposed a coating of vacuum chambers by compounds with low secondary electron emission, which is very complex and expensive for large systems like LHC or RHIC. Threshold beam intensity for EC generation can be increased during the vacuum chamber bombarding by plasma particles. These particles can be generated by beam with ECE development.

Vacuum chamber processing (scrubbing) by EC is conducted now by bunched beam with a highest possible intensity and with shortest gaps between bunches. A high stored energy of this circulating beam represents a potential danger for system.

The chamber film deposition and scrubbing by EC can be conducted with lower circulating beam parameter optimized for efficient EC generation. Highly efficient plasma generation can be produced in the coasting circulating beam of positive particles with relative low intensity and energy. With the coasting positive beam the plasma particles are generating by low energy electrons trapped by a positive beam space charge. These electrons have high cross section for gas ionization. The positive beam is serving as ideal anode of Penning discharge with electron oscillation and secondary ion electron emission. These electrons can be heated by development of e-p instability. For low modes of e-p instability amplitudes of electron oscillations are significantly larger of beam oscillation and electrons can be periodically ejected from the beam to the wall without the beam loss.

The rate of plasma generation and surface scrubbing can be increase by decrease of pumping speed and injection of selected gases. This efficient plasma generation can be tested in the Fermilab booster at injection energy.

INTRODUCTION

As was remarked in [1]: "The discovery of a beam instability induced by the electron cloud (EC) at the Photon Factory (PF) at KEK triggered intense experimental and theoretical research activity aimed at assessing a similar effect at $e+\_e-$ colliders and the Large Hadron Collider (LHC). Independently, and almost simultaneously with these instabilities studies, it was pointed out by Gro¨bner that the EC raises two other concerns in the LHC: (a) a potential pressure instability similar to the one observed at the CERN intersecting storage rings (ISR) when operated in bunched-beam mode, and (b) a potentially large power deposition on the walls of the beam screen by the electrons ''rattling around'' the vacuum chamber under the action of the beam. Since the discovery at the PF electron-cloud effects (ECEs) and their cures have been intensely researched at various laboratories around the world, and have been the subject of

various meetings and reviews. These ECEs are related to the electron-proton instabilities first observed and studied at Budker Institute for Nuclear Physics in the mid-1960's [2] , and at the LANL Proton Storage Ring (PSR) since the mid-1980's ".

Vacuum chambers coating by thin films with low secondary emission to suppress EC generation in the CERN Accelerators is discussed in [3]. Developed technology is promising : "E-cloud signal for carbon film is 4 orders of magnitude below that for stainless steel", but it is very expensive to coat very long chambers of LHC and SPS with using a discharge sputtering. For such films deposition it is possible to use a plasma generation induced by circulating proton beam with accumulated low energy electrons, similar to Penning discharge.

The possibility of "beam-induced multipacting" at the LHC had been recognized in [4]. The electron cloud, at sufficiently high density, can cause both single and coupled-bunch instabilities of the proton beam, give rise to incoherent beam losses or emittance growth, heat the vacuum chamber, or lead to a vacuum pressure increase by several orders of magnitude due to electron stimulated desorption [5].

Observation of ECE in LHC is presented in [6].

All above listed effects were observed after decrease bunches spacing to 50 ns. Fortunately, after several month of the beam scrubbing with weak EC generation the Secondary Electron Yield (SEY) of the walls was efficiently reduce to a value below the threshold for build up the strong ECE. It was provided clear evidence for surface conditioning, from an initial maximum SEY of about 1.9 down to about 1.7, with $R \approx 0.2$.

The success of the scrubbing run was proved by the subsequent smooth LHC physics operation with 50 ns spaced beams. The same procedure could be attempted for the 25 ns operation, although the required SEY reduction will be more critical.

ELECTRONS GENERATION IN A COASTING BEAM

Conditions for low SEY film deposition from a gas phase and surface processing (scrubbing) by ions and electrons can be realized with coasting positive beam. E-p instability with very low threshold linear charge density ($\sim 10^8$ p/cm) was observed during accumulation of the coasting protons beam in the small scale storage proton ring by means of charge exchange injection [7,8]. Some discussion of these experiments are presented in [9,10]. Similar instability with periodic electrons ejection was observed at the Bevatron and at the CERN ISR in 1972 as described in [5].

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Gas ionization by circulating beam and by secondary electrons and electron multiplication in RF field of bunches space charge due to the electron-electron secondary emission process on the inner side of the beam pipe are the processes discussed as main mechanisms of the electron cloud (EC) build up. For the electron cloud survival after the gap between bunches, the following explanations were proposed: beam particle leaking to the gap and high reflectivity of low energy electrons in collision with pipe wall. These mechanisms of e-cloud generation are used in computer codes developed to simulate EC generation and e-p instability [1].

In high current accelerators, a secondary ion-electron emission can be an important source of delayed electrons generated after the gap between bunches (this is needed for the explanation of bunched beam instability in Los Alamos PSR and for the EC simulation in SNS). A fast desorption of physically adsorbed molecules by ions can explain the "first pulse instability" observed in LA PSR [1].

The space charge of bunched and un-bunched beam of positively charged particles with a high current can serve as a "transparent anode" of high vacuum Penning discharge [11]. In this case new electrons are produced by secondary ion-electron emission and gas ionization by electrons. New ions are generated with a high probability in gas ionization by electrons with the energy of hundreds of eV. A secondary ion - electron emissions (SIEE) and gas desorbtion introduce a powerful positive feed back in the process of electron multiplication, leading to the explosive increase of plasma density up to space charge compensation. SIEE is also an efficient source of delayed electrons with delay time equal to the ion's time of flight necessary for explanation of electron cloud surviving after the gap between bunches. Penning discharge, used in ion pumps, can be stable in ultra high vacuum, such as 10^{-12} Torr. Cross section of gas ionization by secondary electros is several orders of magnitude higher, than ionization by ultra relativistic proton/deuteron and comparable with ionization by multiple charged ions. This mechanism of electron cloud build up can be the dominant one in systems with a coasting beam and with long bunches and not ultra high vacuum, as proton boosters and neutron sources.

Below we will consider plasma generation in the accelerator pipe with positive particle (proton, ion, positron) beam, serving as a transparent anode of Penning discharge. High vacuum discharge can be efficient in this system without magnetic field, because this system is an ideal trap for electrons. But this system is an efficient plasma generator in magnetic field of dipole magnets also. Without external magnetic field, the influence of magnetic field of intense beam can be important. With a solenoidal magnetic field, parallel to beam velocity, the beam potential can support an inverse magnetron discharge in crossed ExB fields. If the beam has intensity modulation, it can be multipactoring in DC +AC crossed ExB fields as in the RF electron multipliers or in the cold cathode magnetron. Secondary ion electron emission coefficient Y_{ie} increases with the increase of ion energy eU, where U is the potential of particle beam, determined by the linear charge of the beam λ, connected with the beam current $I_b=\lambda v_b$. For relativistic particles the potential difference between the beam centre and the edge is $\Delta U_b \sim I_b/\beta$ = 30 V per Ampere of beam current, and it is inverse proportional to the particle speed $v_b = c\beta_b$. Edition potential difference between beam edge with radius b and a cylindrical pipe wall with radius a is $\Delta U_w / \Delta U_b = 2\ln(a/b) \sim 3$,and $U \sim 4\, \Delta U_b$. The energy of electron is also determined by the beam potential. Cross sections of hydrogen atom ionization by electron and by proton are presented in Figure 1.

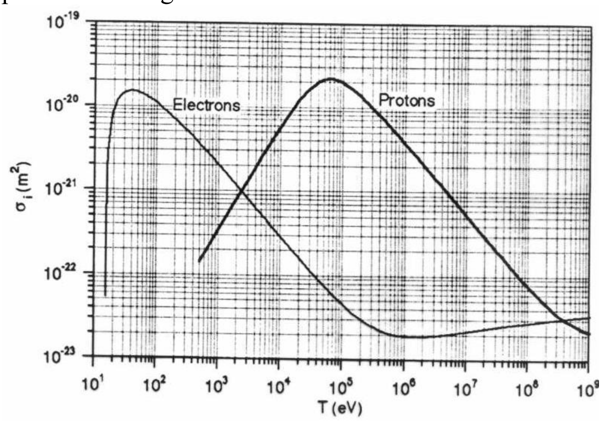

Figure 1: Cross sections of a hydrogen atom ionization by electron and proton .Cross sections of air components ionization are ~6 time larger.

Cross section of gas ionization by electros has maximum near electron energy $W_e \sim 50eV$ and maximal ionization cross section is $\sigma_e \sim 1.6\ 10^{-16}\ cm^2$ for hydrogen atom. As the fist approximation it is possible to use a linear extrapolation between $W_1 = 15\ eV$ and $W_2 = 50\ eV$ (from $\sigma_e = 0$ to $\sigma_e \sim 1.6\ 10^{-16}\ cm^2$) and inverse proportional energy for $We > 50eV$. Cross section for relativistic particles charge Z=1 is $\sigma_b \sim 2\ 10^{-19}\ cm^2$. Cross section of ionization by multiply charged ions with charge Z is Z^2 times larger. For heavier molecules cross sections increases as the number of electrons with a binding energy below electron energy. For a beam with $I_b/\beta_b \sim 1\ A$, we have $eU \sim 120eV$, and this value delivers a high rate of ionization by electrons and high secondary ion – electron emission.

$v_e\ [cm/s] = 6\ 10^7 (We\ [eV])^{1/2};\ v_i = 1.38\ 10^6 (W_i\ [eV])^{1/2}$

For Los Alamos PRS I_b is up to 50 A, for SNS I_b is 80 A. Corresponding eU are ~6 keV and ~10 keV.

For simplification we will consider at first one dimensional model of the discharge, corresponding to Penning discharge in magnetic field of dipole magnet. Residual gas with molecular mass M and density n_g is ionized by beam of circulating particles with density $n_b(x)$, energy W_b, velocity v_b, and cross section of gas molecule ionization σ_b. Produced electrons are moving in the electric field of beam with velocity v_e and ionizing residual gas with cross section σ_e. Produced ions moving in the collective electric field and bombarding the wall of vacuum pipe located in distance a from the centre of the particle beam, initiate a secondary emission of electrons with secondary emission coefficient Y_{ie}. The time of flight of ions from beam to the wall introduces a delay time between ion generation and secondary electron emission. Ion is lost in the wall (neutralized and atoms are retuned to the pipe or implanted). Position of delayed electrons can be shifted relative the beam position in this time. The geometry of this problem is presented in Figure 2, which is showing a cross section of rectangular vacuum chamber with a beam and phase space plane x, v with a beam potential distribution $U_b(x)$ for rectangular beam density distribution for coasting or bunched beam is $n_b\ (x,t)= n_o(t)$ for $/x/ < b$, and $n_b=0$ for $a > /x/ >b$. In further it is possible to use different beam profiles and time dependence (bunching).

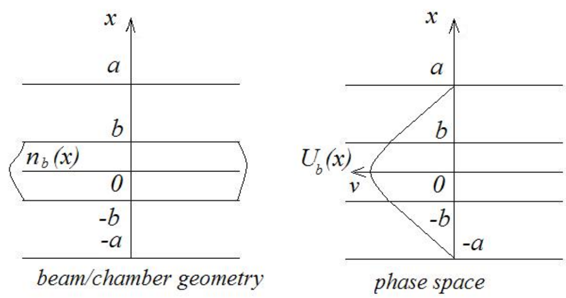

Figure 2: Geometry of one dimension problem(flat beam between two plates) and phase space plane x, v, and beam potential distribution.

We need to determine the distribution functions of electrons $f_e\ (t,x,v)$ and ions $f_i\ (t,x,v)$ by solving the Vlasov equations with sources and loss of particles, Poisson's equation for electric field and equation for gas density. Relating equations are presented in [11].

Admixture of Hydrocarbons can be used for enhanced carbon film deposition. At the CERN ISR a time of electron accumulation up to instability starting was T~1-2 s with vacuum 10^{-11} Torr [5]. At the small scale PSR with higher gas density the accumulation time was T~0.01ms [7,8].

Development of e-p instability in the coasting beam discussed in [7-12] is in good agreement with theory presented in [14,15]. Accumulation of space charge compensating particles in ion beams for ion implantation is discussed in [16].

A study of e p instability for a coasting proton beam was presented in [17], but in this report was not simulated adequately the ion and electron generation by low energy electrons an the ion electron emission.

The strong instability of coasting beam was observed in the Fermilab booster at charge exchange injection without RF voltage [18] and in the Recycler during protons accumulation without voltage on the clearing electrodes (pick ups). Deposition of carbon film to the chamber walls of Fermilab booster is visible clearly [18]. It is interesting to repeat such experiments for estimation of the wall processing and for better understanding of space charge compensation o circulating beams.

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