MODEL OF ELECTRON CLOUD BUILD UP WITH SECONDARY ION-ELECTRON EMISSION AS A SOURCE OF DELAYED ELECTRONS

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Abstract

Beam particle leaking to the gap and anomaly high reflectivity of low energy electrons in collision with pipe wall was proposed as explanation of anomalously long electron cloud survival after the gap between bunches. Another possibility of secondary electron generation with a long delay time after bunch passing is the secondary ion-electron emission. The model of electron cloud build up with secondary ion-electron emission as the source of delayed electrons is presented and discussed. This model can be used for the explanation of bunched beam instability in Los Alamos PSR with electron survival after the gap, for the prediction of e-cloud generation in SNS, and can be important for the pressure rise in warm and cold sections of RHIC. A fast desorbtion by ion of physically adsorbed molecules can explain the "first pulse instability" observed in LA PSR.

INTRODUCTION

A strong transverse instability of circulating electron beam caused by the interaction with compensated ions (beam- ion instability) was predicted 40 years ago by B. Chirikov [1]. An analogue of this instability, electron proton (e-p) instability, was observed experimentally at the same time [2, 3]. The e-p instability of coasting beam [4-6] was in a good agreement with theory [1]. In the explanation of e-p instability of bunched beam, there was a problem with anomalously long electron life time in the gap between bunches. Now these instabilities are very important, because of the limited performances of modern accelerator systems [7].

MODEL OF ELECTRON ACCUMULATION

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 [7, 8].

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 desorbtion of physically adsorbed molecules by ions can explain the "first pulse instability" observed in LA PSR [9].

The space charge of bunched and unbunched beam of positively charged particles with a high current can serve as a "transparent anode" of high vacuum Penning discharge [10]. 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 a Penning discharge in 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

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radius b and a cylindrical pipe wall with radius a is $\Delta U_w / \Delta U_b = 2ln(a/b) \sim 3$, 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 Fig. 1.

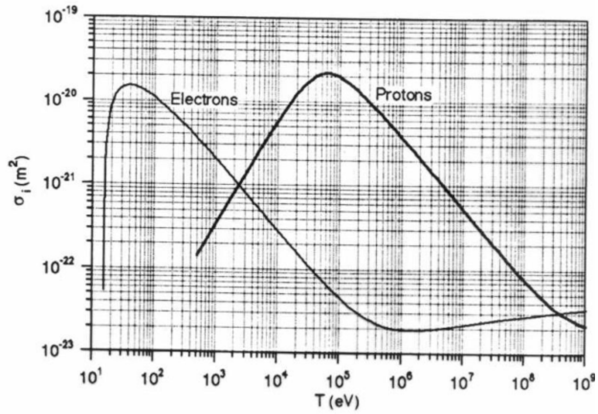

Figure 1: Cross sections of hydrogen atom ionization by electron and proton .Cross sections of air components ionization are ~ 6 times larger.

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.

For LA SPS I_b is up to 50 A, for SNS I_b=80 A. Corresponding eU are $\sim 6\ keV$ and $\sim 10\ keV$.

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 Fig. 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:

$n_b(x,t) = n_o(t)$ 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).

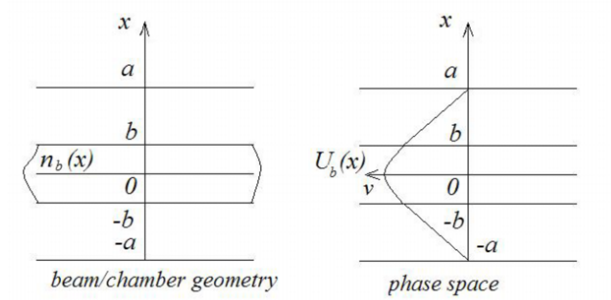

Figure 2: Geometry of one dimension problem (flat beam between two plates) and phase space plane (x, v), and beam potential distribution.

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:

$$\frac{\partial f_e}{\partial t} + v\frac{\partial f_e}{\partial x} + \frac{eE}{m}\frac{\partial f_e}{\partial v} = n_g\varphi(v_e)\sigma_b(v_b)\, v_b n_b(x,t) + n_g\varphi(v_e) \int \sigma_e(v_e) v_e f_e(t,x,v) dv_e + \varphi(v_e) \int Y_{ie}(v_i) v_i f_i(t,x,v) dv_i + \varphi(v_e) \int Y_{ee}(v_e) v_e f_e(t,x,v) dv_e - \delta(x+/-a)\, f_e(t,x,v) \quad (1)$$

$$\frac{\partial f_i}{\partial t} + v\frac{\partial f_i}{\partial x} + \frac{eE}{M}\frac{\partial f_i}{\partial v} = n_g\varphi(v_i)\sigma_b(v_b) v_b n_b\ (x,t) + n_g\ \varphi(v_i) \int \sigma_e(v_e)\ v_e f_e(t,x,v) dv - \delta(x+/-a)\ fi(t,x,v) \quad (2)$$

$$div\ E(x,t) = 4\ \pi\ e\ [n_b(t,x) + \int f_i(t,x,v)\ dv_i - \int f_e(t,x,v) dv_e\ ] \quad (3)$$

$$2a\ (dn_g/dt + n_g/\tau) = [Y_s + \int Y_{ig}(v_i)\ v_i f_i(t,x,v) dv_i + \int Y_{eg}(v_e)\ v_e f_e(t,x,v) dv_e\ ] \quad (4)$$

$$f(t=0) = 0,\ n_g = n_0\ . \quad (5)$$

Charge of ion is e, charge of electron is $-e$, ion mass is M, electron mass is m, $\varphi(v)$ is the distribution function of new born ion, and electron in velocity space. It has uniform distribution $\varphi(v) = 1/2\ v_o$, for $/v/ < v_o$ and $\varphi(v) = 0$ for $/v/ > v_o$ and v_o is velocity of ion and electron with energy 1 eV

In equation (1) the first right term is the rate of electron production by beam ionization; the second term is the rate of electron and ion production by electron ionization $\int \sigma_e(v_e)\ v_e f_e(t,x,v) dv_e = \langle\sigma_e v_e\rangle$; the third term is the rate of electron production by secondary emission with coefficient of ion-electron emission Y_{ie} shown in Fig.3 (a good approximation is $Y_{ie} = 2\ 10^{-8}\ v\ [cm/s]$; fourth term is the rate of electron – electron emission with coefficient Y_{ee} , the fifth term is rate of electron loss on the wall with

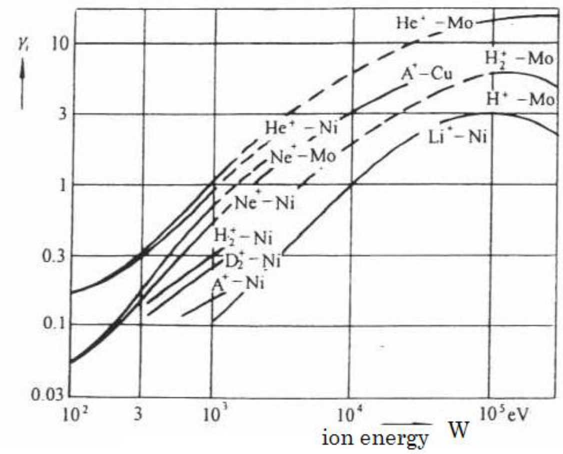

Figure 3: Secondary emission coefficient Yi, for ions of energy W, falling on the surface of various materials.

coordinate $x=+a/-a$. It is possible to introduce secondary electron- electron emission with the coefficient Y_{ee} and electron reflection R_e. Y_{ee} is used for RF multipactoring simulation [7, 8]. In equation (2) the first right term is the source of ion, rate of ion production by beam ionization; the second term is the rate of ion production by electron ionization; the third term is rate of ion loss in the wall with coordinate $x=+/- a$. In equation (3) $\int f_i(t, x, v)\, dv_i = n_i(x)$ is ion density (integration limits are +/-infinity), $\int f_e(t,x,v)dv_e = n_e(x,t)$ is electron density; $n_b(x,t)$ is the beam density.

For typical electric field of beam $E\sim 100\ V/cm$, the time of flight for ionized hydrogen atom up to the wall is $T\sim 0.25\mu s$, and it increases as the square root of molecular mass, creating a relatively long delay time for relies of secondary electrons, that can be picked up by next bunches. In equation (4) the first right term is a spontaneous gas desorbtion in a sec from a cm^2 of surface, the second term is the rate of gas desorbtion by ion with ion desorbtion coefficient Y_{ig} , the third right term is the rate of gas desorbtion by electron with electron desorbtion coefficient Y_{eg}.

For the estimation of electron accumulation in the first phase, before significant space charge compensation, it is possible to use integrated equations for the number of particles per unit of length of accelerator pipe, Ne:

$$d N_e/dt = (1+Y_{ie})n_g\, v_b\sigma_b\, N_b + (1+Y_{ie})n_g <v_e\sigma_e> N_e = A +bN_e.$$

The solution of this equation with condition $N_e(t=0)=0$ is: $Ne(t) = (A/b)\ [\exp\ (bt) - 1] = (v_b\sigma_b\, N_b / <v_e\sigma_e>)\ \{[\exp\ t\ (1+Yie)\ n_g\ (<v_e\sigma_e>)] -1\}$.

The characteristic time of electron multiplication is $T_e = (1+Y_{ie})\ n_g\ (<v_e\sigma_e>)^{-1}$. In this expression, are $n_g = 3.6\ 10^{16}\ p\ [Torr]$, where p is vacuum gauge reading in $Torr$, $<v_e\sigma_e>=1\text{-}5\ 10^9\ cm^3/s$ for different gases. For $p=10\ nTorr$, we can have $T\sim 5\text{-}30\ ms$. Y_{ie} increases with ion energy. It depends very much on the surface condition. Some adsorbate or compounds on the surface can increase secondary emission and gas desorbtion dramatically. Surface cleaning (conditioning) by backing or by ion/electron/X-ray bombardment, usually decreases the secondary emission and desorbtion. An increased secondary emission $Y_{ie}\sim 2\text{-}3$ (*for* $U_b > 1kV$) is decreased this time $(1+Y_{ie})$ times. Electron accumulation time can be the reason of delay time between the reaching of threshold intensity and the development of e-p instability, observed in many experiments. A fast increase of gas density caused by fast desorbtion by ions of physically adsorbed gas molecules is the possible explanation of the "first pulse instability" observed in the Los Alamos PSR [8]. The neutralization time with ionization by relativistic beam for this conditions is $T_b \sim (n_g\, v_b\sigma_b)^{-1} = \sim 1s$.

The system of equations represents the model of electron cloud build up with an efficient delayed electron generation after passing the gap between bunches.

REFERENCES

[1] B.V. Chirikov, Sov. At. Energy **19**, 1149 (1965).

[2] V. Dudnikov, Production of Intense Circulating Proton Beam by Charge Exchange Injection Method, Ph. D. Thesis, Novosibirsk, INP, 1966 [published in 3, 4, 5, 6].

[3] G. Budker, G. Dimov, V. Dudnikov, in *Proceedings of the International Symposium on Electron and Positron Storage Rings, Saclay, France, 1966* (Saclay, Paris, 1966), Article No. VIII-6-1. Sov. Atomic. Energy **22**, 384 (1967).

[4] G. Budker, G. Dimov, V. Dudnikov, and V. Shamovsky, in *Proceedings of the International Conference on High Energy Accelerators, Cambridge, MA, 1967* (CEA, Cambridge, MA, 1967).

[5] Yu. Belchenko, G. Budker, V. Dudnikov, et.al., in *Proceedings of the Xth International Conference on Particle Accelerators, Protvino, 1977*, v. 2, p. 287 (1977).

[6] V. Dudnikov, in *Proceedings of the Particle Accelerator Conference, Chicago, 2001* (IEEE, Piscataway, NJ, 2001).

[7] F. Zimmermann, Phys. Rev. ST, 7, 124801 (2004).

[8] L. Wang, et al., Phys. Rev. ST, 7, 034401 (2004).

[9] R. Macek, ICFA Workshop of Pressure Rise and Electron Cloud Effect, BNL, 2003.

[10] V. Dudnikov, A. Shabalin, HIPAC'92, v.2, 1025, Hamburg, 1993.

 0-7803-8859-3/05/$20.00 ©2005 IEEE