SIMULATION OF EP INSTABILITY FOR A COASTING PROTON BEAM IN CIRCULAR ACCELERATORS

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Abstract

Instabilities for a coasting proton beam interacting with electron cloud are discussed. The electron sources are roughly classified into two categories reflecting their initial conditions: that is, the electrons produced at the chamber surface and/or at the beam position. If the beam is stable, it forms a Coulomb static potential around itself. Electrons produced near the beam position are trapped by the potential, while those produced at the chamber surface absorbed after once approaching the beam. We discuss the instability for the two cases in which electrons are produced at chamber and at beam position. The density of electrons are quite different according which initial condition. We notice that the production rate of electrons is important rather than the electron density.

INTRODUCTION

We study electron cloud instability for a coasting beam, in which the charged distribution is uniform along the longitudinal axis z. A static electric potential is formed by the coasting beam, when there is no transverse motion. We study the instability caused by electrons with two types of initial conditions: i.e., they produced at the beam position [1] and at the chamber surface.

Electrons are created by ionization of the residual gas due to the proton beam. The electrons created near the beam are trapped and accumulated, with the result that their density could arrives a threshold of the ep instability. In this scenario, a coasting proton beam is always unstable. Above the threshold density, both of the beam and electron cloud become unstable. Considering transverse momentum conservation, it is conjectured that amplitudes of electrons are much larger than that of the beam. The electrons with a large amplitudes due to the instability are smeared by the nonlinear force due to the beam-electron interaction. The size of the electron cloud is enlarged, and electrons are absorbed into the chamber wall. Electrons are diffused by the instability, while the beam still could have a small oscillation amplitudes, with the result that the beam amplitude may be kept in the small level, and may be stable in actual operations of accelerators. We now take into account the production rate of electrons. Electrons are supplied successively with causing the instabiity, therefore the strength of the instability should be affected by the production rate.

Electrons are also created at the chamber wall surface due to proton beam loss and secondary electron. The electrons are not trapped by the coasting beam, if there is no perturbation. However the electron production rate at the wall is considered to be much higher than that due to ionization depending on the condition. It my be delicate problem which electrons, ionization or wall surface, is important for the instability. Beam perturbation, which acts as diffusion source for the trapped electron in the previous case, now acts as transition from nontrapping regime to trapping regime. This is the same physics in the meaning of the transition between the trapping and diffusion. The energy of the electrons is the order of 10 eV at the wall surface, except some portion with an energy equal to incident one. Therefore the multipacting is not developed naively in the coasting beam, because of keeping the initial energies. The beam with a perturbation traps the electrons created at the chamber during a short period or accelerates them to higher energy than initial one, then electrons are accumulated at a certain level, and the multipacting may be important even in the coasting beam.

In this situation discussed above, it seems to be difficult to understand the instability with a simple threshold formula given by linear theory. Detailed studies, which is taken into account the initial condition and production of electrons, were carried out in this work.

We summarize the production rates for the two initial conditions. The electron production rate is $7.7 \times 10^{-9} e^-/(\mathrm{m}{\cdot}p)$ at 2×10^{-7} Pa for ionization of CO ($\sigma(\mathrm{CO}) = 1.3 \times 10^{-22}\ \mathrm{m}^2$).

The electron production at the chamber wall is caused by hitting of beam particles, ions created by the beam, and electrons. The production rate, which depends on the accelerator design, could be much higher than ionization depending on the condition or design of the ring. A proton with high energy and incidence of shallow angle create 100 electrons [2, 3], and an ion creates 10 electrons. For example, the proton loss and electron production rate are estimated to be $4 \times 10^{-8}\ \mathrm{m}^{-1}$ and $4 \times 10^{-6} e^-/(\mathrm{m}{\cdot}p)$, respectively, at PSR in LANL. Electrons are further amplified by secondary electron emission.

We discuss the ep instability for the coasting beam caused by electrons due to the ionization and surface loss using computer simulations. The simulation results are presented for ionization and particle loss, respectively.

INSTABILITY DUE TO IONIZATION ELECTRON

We first discuss instability caused by electrons produced at the beam position, where electrons are considered to be produced by ionization. Increase of the neutralization factor per one revolution time (T_0) is estimated to be $7.7 \times 10^{-9} e^-/(\mathrm{m}{\cdot}p) \times 1567 = 1.2 \times 10^{-5} T_0^{-1}$ for ionization at the vacuum pressure, $P = 2 \times 10^{-7}$ Pa. The build up time up to the threshold (0.21%) [1] is 170 turns (0.9 ms) for this vacuum pressure. The production rate linearly depends on the vacuum pressure, therefore build-up time becomes faster increasing the pressure.

The simulations were performed for several electron production rates, at a range between $7.7 \times 10^{-9} \sim 7.7 \times 10^{-3})e^-/(\mathrm{m}{\cdot}p)$, though the high values $> 10^{-6}$ corresponding vacuum pressure $> 10^{-5}$ Pa are impossible in an actual machine.

The simulation evaluated amplitudes of each macro-proton ($J_{x(y),i}$), electron line density (λ_e), electron rms. size (σ_e), etc. turn by turn. There was no significant result for the production rate of $7.7 \times 10^{-9} e^-/(\mathrm{m}{\cdot}p)$, correspond to $P = 2 \times 10^{-7}$ Pa.

Figure 1 shows electron line density λ_e and maximum amplitude $\sqrt{J_{x(y)}}$ for higher electron production rates of $7.7{\times}10^{-8}$, $7.7{\times}10^{-7}$, $7.7{\times}10^{-6}$ and $7.7{\times}10^{-5} e^-/(\mathrm{m}{\cdot}p)$. The rates are convereted vacuum pressure, $P = 2 \times 10^{-6}$, 2×10^{-5}, 2×10^{-4} and 2×10^{-3} Pa, respectively. Needless to say, the high vacuum pressure is nonsense for actual accelerators. Pictures (a), (c), (e) and (g) are the electron line density for the production rates. The line density increases at the early stage, is saturated, then turn to decrease, and finally settle on a certain density. The final density is around 10^{10} m^{-1} independent of the production rate, and it is 20 times of the threshold in the linear theory. Two lines, which are depicted in the pictures, are given for the line density with or without secondary electron emission. There was no remarkable difference with or without secondary emission, except for the last picture (g). Picture (g) shows a sudden increase of the electron line density with secondary emission, which is caused by strong multipactoring. Pictures (b), (d), (f) and (h) are evolutions of horizontal (red) and vertical (blue) amplitude normalized by the beam size ($\sqrt{J_{x(y),i}/\varepsilon_{x(y)}}$ for the production rates. The seconday emission is included. The amplitude is saturated at 1% and 3% of the beam size for the production rate of $7.7 \times 10^{-8} e^-/(\mathrm{m}{\cdot}p)$ and $7.7 \times 10^{-7} e^-/(\mathrm{m}{\cdot}p)$, respectively. We may not observe the instability actually due to the small amplitude (1%∼3% of the size). The amplitudes for higher rates are not saturated as long as we simulated. σ_r/10 and σ_r, respectively. If we can observe the instabilities with a resolution of 10% of σ_r, the production rate should be more than $10^{-6} e^-/(\mathrm{m}{\cdot}p)$. which corresponds to 10^{-4} Pa. This value is too high for the vacuum pressure of accelerators. Picture (g) shows sudden increase of horizontal and vertical amplitudes, which correspond to the increase seen in picture (h). These pictures show that strong multipactoring is induced by the beam oscillation with an amplitude $1/3 \sim 1/2$.

The electron line density exceeds for every cases of various production rates. The instability behavior is determined by electron production rate rather than the fact whether the density exceeds the threshold value.

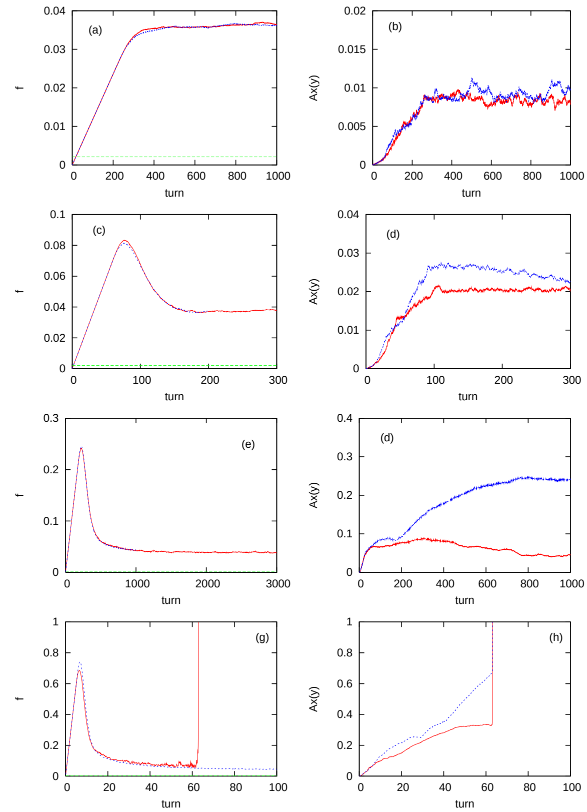

Figure 1: Evolution of neutralization factor for electron cloud and maximum normalized amplitude of beam ($\sqrt{J_{x(y)}/\varepsilon_{x(y)}}$) for various eletron production rates. Pictures (a), (c), (e) and (g) are the electron line density for the production rates given for the line density with or without secondary electron emission. The threshold density given by linear theory is drawn by Green straight line. Pictures (b), (d), (f) and (h) are evolutions of horizontal (red) and vertical (blue) amplitude. Pictures (a) and (b) are electron density and beam amplitudes for $7.7 \times 10^{-8} e^-/(\mathrm{m}{\cdot}p)$, (c) and (d) are for $7.7 \times 10^{-7} e^-/(\mathrm{m}{\cdot}p)$, (e) and (f) are for $7.7 \times 10^{-6} e^-/(\mathrm{m}{\cdot}p)$, and (g) and (h) are for $7.7 \times 10^{-5} e^-/(\mathrm{m}{\cdot}p)$.

INSTABILITY DUE TO ELECTRONS FROM CHAMBER SURFACE

We understood that the production rate is important factor for the beam instability in previous section. The ionization electron for ordinary vacuum pressure was too low production rate to cause instability. Therefore we now consider the electrons produced at the chamber wall. The electron production at the wall is considered to be much higher than that of ionization. For production rate at the chamber surface, we consider $4 \times 10^{-6} e^-/(\mathrm{m}{\cdot}p)$ as a standard value. If electrons are created with this rate and are accumulated, the density arrives at the threshold level (0.21%) for traveling of proton beam of 1/3 turn, 525 m, 1.8 μsec. The time is not very short, but is rather long, if we consider the electron oscillation frequency, $f_e = \omega_e/2\pi = 4$ nsec.

Figure 2 shows electron line density and normalized beam amplitude for various production rate, 7.7×10^{-8}, 7.7×10^{-7}, 7.7×10^{-6} and $7.7 \times 10^{-5} e^-/(\mathrm{m}\cdot p)$. The beam instability is invisible for the lowest production rate, $7.7 \times 10^{-8} e^-/(\mathrm{m}\cdot p)$. The threshold density prediceted by linear theory is drawn by green lines in the pictures. The cloud density exceed the threshold for the rate, $7.7 \times 10^{-7} e^-/(\mathrm{m}\cdot p)$, but the amplitude grows up to only 1% of the beam size. For $7.7 \times 10^{-6} e^-/(\mathrm{m}\cdot p)$, the electron density reaches 5 times of the threshold and the amplitude grows 10% of the beam size. The amplitudes may be serious level for an actual operation. A sudden increase in the line density and amplitude, which is caused by electron multipactoring, was seen for $7.7 \times 10^{-5} e^-/(\mathrm{m}\cdot p)$ in pictures (g) and (h). The beam oscillation with an amplitude $\sim 1/3$ of the size induced the multipactoring again.

The electron production rate around $10^{-6} \sim 10^{-5}$ is critical for the instability at coasting beam operation in J-PARC main ring. If one proton loss produces 100 electrons, the proton loss rate should be reduced less than $10^{-8} \sim 10^{-7}/\mathrm{m}\cdot p)$.

CONCLUSION

Electron cloud instability for a coasting proton beam has been studied. We treated electrons which are created by ionization at the beam position and by beam particle loss and secondary emission at the chamber wall surface.

The electron cloud produced by ionization at the beam position can always exceeds the threshold given by linear theory, since they are trapped by the beam. A simulation, in which the motion of beam and electrons was solved simultaneously, has been carried out to study the stability of the electron-proton system. The production rate more than $10^{-6} e^-/(\mathrm{m}\cdot p)$ was criteria to be unstable for JPARC-MR ring. The rate corresponds to 10^{-4} Pa, which is quite nonsense value for accelerators. Ionization may not be a direct candidate of the instability for the coasting beam.

Electron sources with a higher production rate, for example, proton loss and/or multipacting were paid attention. Since the electrons produced at the wall surface were not trapped by the coasting beam, they were not accumulated much, but were sufficient to cause the instability.

The simulation was applied for electrons produced at the wall. The beam amplitude grows to visible level due to the instability for the production rate, $10^{-6} e^-/(\mathrm{m}\cdot p)$. This value, which is the same as that given for ionization electrons, is now possible level for production due to proton loss in high intensity proton rings.

Production rate was important whether the instability grows to visible amplitudes. We should to change our understanding for the threshold given by linear theory. The threshold was quite inconsistent for trapped electron, which was modeled in the linear theory. If anything, the threshold is rather consistent with the case of electrons produced at the wall. It was also consistent with the case of bunched beam model [4].

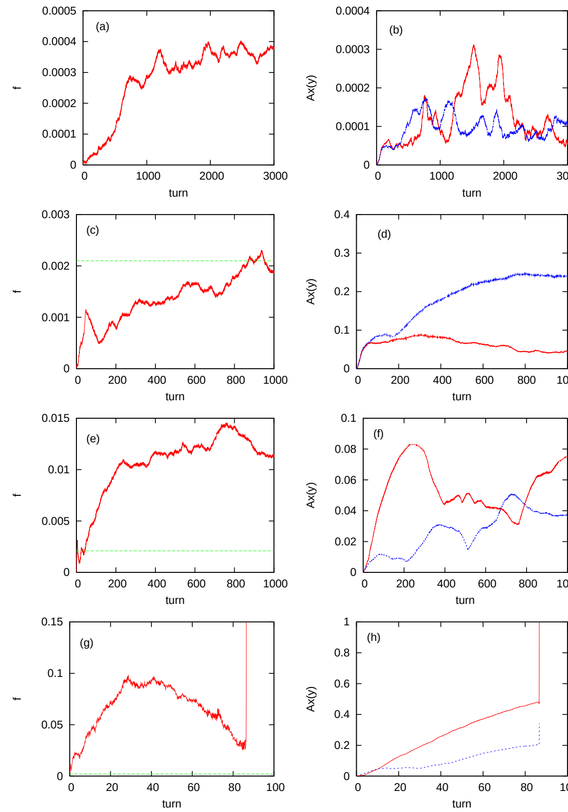

Figure 2: Evolution of neutralization factor for electron cloud and maximum normalized amplitude of beam ($\sqrt{J_{x(y)}/\varepsilon_{x(y)}}$) for various electron production rates. Pictures (a) and (b) are neutralization factor and beam amplitudes for 7.7×10^{-8}, (c) and (d) are for 7.7×10^{-7}, (e) and (f) are for 7.7×10^{-6}, and (g) and (h) are for $7.7 \times 10^{-5} e^-/(\mathrm{m}\cdot p)$. The threshold density given by linear theory is drawn by Green straight line in the pictures (a), (c), (e) and(g).

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