STUDY OF ELECTRON CLOUD INSTABILITY IN FERMILAB MAIN INJECTOR

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Abstract

Electron cloud has been observed in Fermilab main injector. Electron signal was enhanced near the transition. The slippage factor, which suppresses instabilities, approach to zero at the transition. Instabilities must be most serious near the transition. The instability caused by the electron cloud is an important issue for high intensity operation and the future toward Project-X. Simulations of electron cloud instability are presented.

INTRODUCTION

Electron cloud has been observed at some places in Fermilab Main Injector (MI) [1]. The electrons do not affect MI operation at the presnet. The intensity of MI is being increased, and then more electrons are created. It is concerned that the electron cloud affects MI operation. We discuss how much electrons can cause the instability.

MEASURED ELECTRON CLOUDS

Electrons absorbed at the chamber wall are measured using a retarding field analyzer. The number of absorbed electrons is the same as that of produced electrons at the chamber wall due to the both of primary and secondary emissions.

The number of produced electrons by one proton per meter is given by

$$\lambda_e = 2\pi R \frac{I_e}{e} \frac{T_0}{N_p N_{bunch}} \quad (1)$$

where R is the chamber radius, I_e the electron current density at the wall, N_p the proton bunch population, N_{bunch} the number of proton bunches and T_0 the revolution time.

For a typical example in MI, N_p=1x10^{11}, I_e=1 μA/cm^2, R=5 cm, N_{bunch}=498, T_0=11 μs, the production rate is 0.0044 per meter proton. Note that the production rate is taken into account of the both of primary and secondary emissions.

The averaged volume density and line density of electrons in the chamber is estimated by a numerical simulation, or by a simple model roughly,

$$\rho_e \quad \frac{2I_e}{ev_e} \qquad n_e \quad \frac{2\pi R^2 I_e}{ev_e} \quad (2)$$

where v_e is the velocity of the electrons. The velocity is about 2x10^6 m/s (10eV) at the production and is accelerated to around 1x10^7 m/s (300eV). The density is ρ_e=1.2-6.7x10^{10} m^{-3} for I_e=1 μA/cm^2. The neutralization factor f=n_e/n_p is 0.013-0.07 for the above parameters, where $n_p = N_p N_{bunch}/cT_0$.

The density and neutralization factor are function of time: that is, they vary for the timing of the bunch passage. Numerical simulations using the production rate [2] estimate the densities more precisely.

INSTABILITY DUE TO THE CLOUDS

Beam instability arises when the electron density exceeds a threshold value. The instability is caused by collective motion of electron cloud and beam. The electron clouds give a correlation for the betatron motion with different z. The correlation can be inner-bunch, bunch-by-bunch or combined. Depending on the correlation, single-bunch, multi-bunch or their mixed instability is observed. Beam is injected at 8 GeV and passes through the transition at 20 GeV and is accelerated to 120 GeV in MI. The beam profile changes through the acceleration.

Instability at the injection

We study the electron cloud instability in two stages; one is at injection, and the other is near the transition. Longitudinal bunch profile is elliptic with the length σ_z=5.6 m in total. Bunch repetition is 5.65 m. Electron frequency and oscillation in the bunch are $\omega_e/2\pi$=87.4MHz and $\omega_e\sigma_z/c$=4.3, respectively. The electron cloud induces coupled-bunch instability for higher order head-tail mode.

A simulation is organized to study the instability as follows [3]. A bunch is expressed by 50 micro-bunches (>>$\omega_e\sigma_z/c$). 498 bunches in 588 buckets are injected and 498x50 macro-particles are tracked, interacting with electron cloud. The longitudinal slippage of the micro-bunches is removed: that is, Landau damping is taken into account later using analytic formula. Macro-particles, which represent electron cloud, are produced with the rate based on the measurement: for example 0.0044 per meter proton for I_e=1 μA/cm^2. Since the rate contains both of primary and secondary electrons, electrons hitting the chamber wall do not produced new electrons in the simulation.

Figure 1 shows growth of the maximum amplitude of micro bunches. The design emittance is plotted in the figure. The production rates, 0.1, 0.2, 0.5, 1 μA/cm^2, are investigated. The growth is saturated at several times of the design beam size.

The growth rate as a function of the production rate is shown in Figure 2. Landau damping due to synchrotron motion (slippage) is given by

$$D_L = \nu_s \omega_e \sigma_z / \sqrt{3}c = 0.02 \quad (3)$$

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where ν_s=0.008. The threshold of the electron production rate is around 0.8 μA/cm^2 in the figure. Note that it is the production rate averaged over the ring.

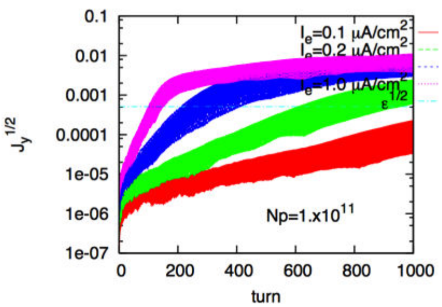

Figure 1: Growth of the maximum amplitude of micro bunches due to electron cloud instability at the injection.

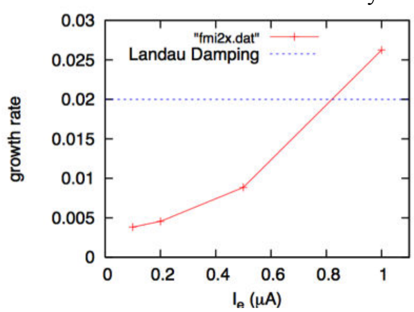

Figure 2: Growth rate as a function of the electron production rate at the injection.

Instability near the transition

The transition energy of MI is 20 GeV. Figure 3 shows the variations of ν_s, σ_p and σ_z along the acceleration. The slippage becomes slow and the bunch length is shortened near the transition. For example, the parameters are σ_z=0.27 m, ν_s=0.0012 at slight blow the transition, γ=21.3 (γ_t=21.8). Electron frequency and oscillation in the bunch are $\omega_e/2\pi$=350 MHz and $\omega_e\sigma_z/c$=2.0, respectively. Landau damping rate is $\nu_s\omega_e\sigma_z/3^{1/2}c$ =0.0015. The same simulation as the injection stage is performed for these parameters. The cases of electron production rates 0.1, 0.2, 0.5, 1.0 and 2.0 μA/cm^2 are investigated. Figures 4 and 5 show growth for electron production rate. Figure 6 shows beam profile near 200-th bunch after 800 turns. The profile expresses that dipole coupled bunch mode is enhanced. The coupled bunch mode should be suppressed by a bunch-by-bunch feedback system.

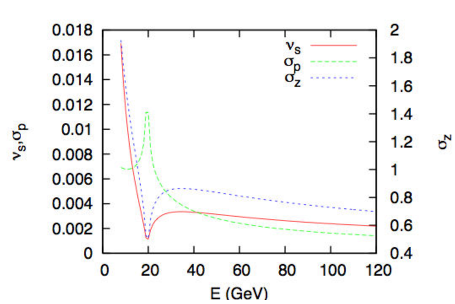

Figure 3: Variations of synchrotron tune (ν_s), momentum spread (σ_p) and bunch length (σ_z).

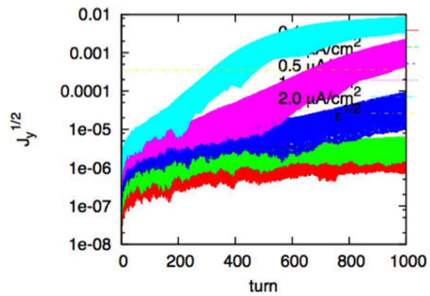

Figure 4: Growth of the maximum amplitude of micro bunches due to electron cloud instability near the transition.

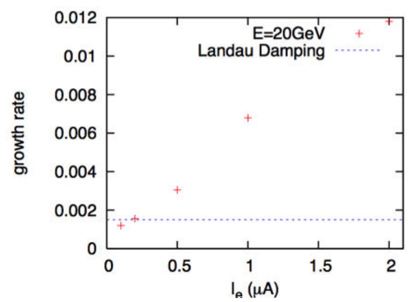

Figure 5: Growth rate as a function of the electron production rate near the transition.

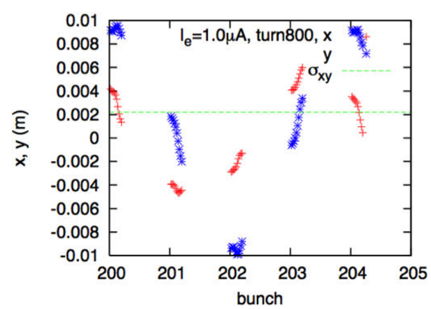

Figure 6: Beam profile near 200-th bunch after 800 turns.

We next study single bunch instability under the given electron density. Landau damping is now treated exactly. A proton bunch is represented by many (300,000) macro-particles and the interaction with macro electrons is simulated using potential solver based on the particle in cell method. Accelerating the beam energy, slippage factor and bunch length is changed as shown in Figure 7. The simulation start from E=15.938 GeV and beam is accelerated 2.29MeV/turn. The energy passes through the transition (E_T=20.4GeV) after 1972 turns.

Figure 8 shows the evolution of the transverse beam size. The electron cloud instability arises after 1000 turns at the density ρ_e=1x10^{12} m^{-3}. A small sign of the instability is seen near the transition at the density

ρ_e=0.5x10^{12} m^{-3}. We realize that the threshold electron density is ρ_e=0.5x10^{12} m^{-3}.

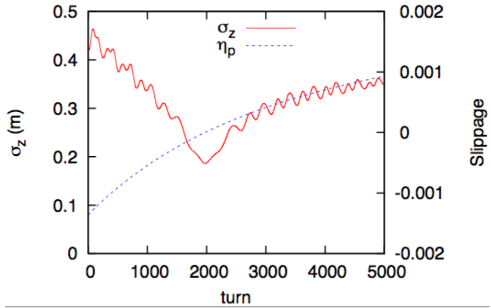

Figure 7: Bunch length and slippage factor during the acceleration. The transition crossing is at 1972-th turn.

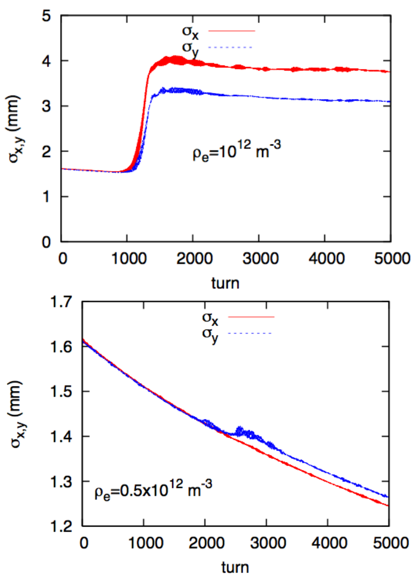

Figure 8: Evolution of the transverse beam size.

SUMMARY AND CONCLUSIONS

A coupled-bunch instability for higher order head-tail mode is caused at the electron production rate higher than I_e=0.8 μA/cm^2 at the injection. The growth rate is very fast, 0.025 (40 turns) at I_e=1 μA/cm^2.

A dipole coupled-bunch instability is caused at the electron production rate higher than I_e=0.2 μA/cm^2 near the transition. The growth rate is 0.006 (167 turns) at I_e=1 μA/cm^2 and increases linearly for the production rate. A bunch-by-bunch feedback system should suppress the dipole instability. A single bunch head-tail instability arises at the electron density ρ_e=5x10^{11} m^{-3}. The density reaches at the production rate I_e=10 μA/cm^2 in the whole ring. The coupled bunch instability is very rapid (~17 turn) at the production rate.

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