ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPTY006

STUDY OF ELECTRON CLOUD INSTABILITIES IN FCC-hh

K. Ohmi, KEK, Tsukuba, Japan
L. Mether, D. Schulte, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

Electron cloud effects are serious issue for LHC and future hadron colliders, FCC-hh. Electron cloud causes coherent instabilities due to collective motion between beam and electrons. Electron cloud also causes incoherent emittance growth due to nonlinear force of beam-cloud electron force. We discuss the fast head-tail instability and the emittance growth in FCC-hh.

INTRODUCTION

The future circular hadron collider FCC-hh has been designed as 50 TeV×50TeV proton collider with 100 km circumference. The relativistic gamma factor (γ=53,000) is higher than those of many electron storage- ring light sources. The wave lengths of the emitted photons are in the X-ray region, which is comparable with those as light sources. Electrons are produced by the photons which hit the surface of the beam screen inside the cryostat.

Electrons are attracted and accelerated by the beam force. Electrons accumulated in the beam chamber may contribute an additional heat load to the cryostat, and cause beam instabilities and emittance growth. In this paper we focus on the beam instabilities and emittance growth caused by the electron cloud.

THRESHOLD ELECTRON DENSITY OF FAST HEAD-TAIL INSTABILITY

Electrons oscillate in the field of the proton beam. The oscillation frequency near the beam centre is given by

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}} \tag{1}$$

where λ_p and $\sigma_{x(y)}$ are the line density of the proton bunch and its transverse beam size, respectively. r_e is the classical electron radius.

Electron cloud induces a short range wake force with the frequency of Eq. (1). Threshold of electron density is determined by a balance of the strength of the wake field and Landau damping due to the slippage (synchrotron motion). The threshold density is given by [1,2]

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} \tag{2}$$

K characterizes how many electrons contribute to the instability and *Q* is the quality factor of the wake field. We use $K=\omega_e\sigma_z/c$ and the empirical formula $Q=\min(\omega_e\sigma_z/c,7)$. Table 1 shows parameters for FCC-hh and the corresponding electron threshold density. The tune shift induced by an electron cloud at the threshold density is also included in the table.

#ohmi@post.kek.jp

Table 1: Parameter List for FCC-hh.

		inj	top
Energy	E(TeV)	3.3	50
Bunch population	N_p (10^{10})	10	10
Emittance	ε (nm)	0.625	0.0413
Averaged beta	β (m)	200	200
Bunch length	σ_z (m)	0.08	0.08
Synchrotron tune	ν_s	0.0019	0.0019
Electron freq.	$\omega_e/2\pi$	3.56GHz	14 GHz
Electron osc.	$\omega_e\sigma_z/c$	5.97	23
Threshold density	$\rho_{e,th}$	4.4x10^{10}	5.7x10^{11}
Tune shift at thr.	$\Delta\nu_{th}$	0.00039	0.00033

SYNCHROTRON RADIATION AND PHOTO-ELECTRON EMISSION

Charge particles passing through a bending magnet emit photons in the form of synchrotron radiation. The number of photons emitted by a particle per metre is expressed as

$$N_\gamma = \frac{5\alpha}{2\sqrt{3}}\frac{\gamma}{\rho_{Bend}} \tag{3}$$

For FCC-hh, with ρ_{bend}=11.3 km, the number is 0.035/p.m (per proton metre) at 50 TeV and 0.0023/p.m at injection energy of 3.3 TeV. The critical energy

$$E_c = \frac{3\hbar c}{2}\frac{\gamma^3}{\rho_{Bend}} \tag{4}$$

is 3.96 keV at 50 TeV (1.1 eV at 3.3 TeV). The quantum efficiency of photoelectron emission is 0.2-0.3 for shallow angle of photon incidence. Most of the photons hit the outside wall of the screen. Some part of the reflected photons hit a wide area of wall. The number of electrons produced by a bunch passage per metre is 10^9 (50 TeV) - 10^8 (3.3 TeV). Considering the chamber cross section 10 cm^2, the density resulting from the photoelectrons of a single bunch, $\rho_e=10^{12}$ - 10^{11} m^{-3}, already is higher than the instability threshold. Electron production can be suppressed by several kinds of surface

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPTY006

treatments, and/or if most of electrons are prevented from approaching the beam by a strong magnetic field. While electrons produced by reflected photons can approach to beam. It is essential to study how high an electron density is generated at the beam position. Detailed study for the electron cloud build up in FCC-hh is presented in [3].

SIMULATIONS FOR ELECTRON CLOUD INSTABILITIES

The fast head-tail instability has been studied by computer simulations. Interactions between a bunch and electron cloud is calculated by the same algorithm as used to model the strong-strong beam-beam simulation. To study the head-tail motion, a bunch is sliced into many pieces more than $\omega_e\sigma_z/c$, while the electron cloud is located at several places of ring. To evaluate the head-tail instability, the interaction between a bunch and the cloud should occur multiple times during one synchrotron period. Several interactions per turn are sufficient to study the fast head-tail instability for FCC-hh.

We now consider the instability at top energy. The electron clouds are located at 4-16 places in the ring (100 km long). A proton bunch, which is represented by 1,000,000 macro-particles is sliced into 100 pieces. Electron cloud at each location is represented by 100,000 macro-particles.

We first present simulations for a drift space, in which the electrons move only under the influence of the beam electric field. Figure 1 shows the simulated evolution of the vertical beam size. The top plot shows the beam size behaviour near the threshold electron density, ρ_e=3-6x10^{11} m^{-3}. The beam size increases above the threshold density, $\rho_{e,th}=5.7\times10^{11}$ m^{-3} given by Eq. (2). However the increase is rather weak, less than 1% after 4000 revolutions. The instability does not grow if the density is increased another several time. . The bottom plot shows the beam size evolution at much higher electron densities, ρ_e=2x10^{12} - 5x10^{13} m^{-3}. A strong beam enlargement is seen above the density $\rho_e=2\times10^{13}$ m^{-3}. Figure 2 shows the beam and electron averaged oscillation amplitudes along with the beam size during the interaction along z. A coherent signal is not evident at the low cloud density $\rho_e=6\times10^{11}$ m^{-3}, while such a signal is clear for the high density, $\rho_e\times5x10^{13}$ m^{-3}. The electron frequency $\omega_e/2\pi=c/2\sigma_z$=1.9 GHz in y_e is slower than the value in Table 1, since the beam size increases by a factor 5-10. Similar behaviours are seen in the horizontal plane.

Figure 3 presents the results of a simulation for a strong bending magnet, B_y=20 T. There is no beam enlargement at all, for the density near ρ_e=3-6×10^{11} m^{-3}. Again a clear signal is seen for much higher density, ρ_e=2-5x10^{13} m^{-3}. For a strong bending magnet, pinching of the electron cloud is limited to the vertical direction, thus K may be lower than $\omega_e\sigma_z/c$.

We consider that the threshold is $\rho_e=6\times10^{11}$ m^{-3}: that is even if there is only a weak beam enlargement or beam size fluctuation, the luminosity performance will degrade on the longer term. The difference between the analytically estimated and the simulated threshold density, of two orders of magnitude, is not negligible. More detailed studies are necessary.

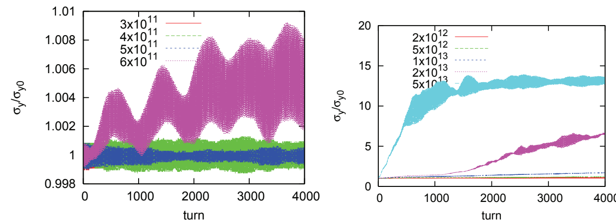

Figure 1: Evolution of the proton beam size with electrons in a drift space.

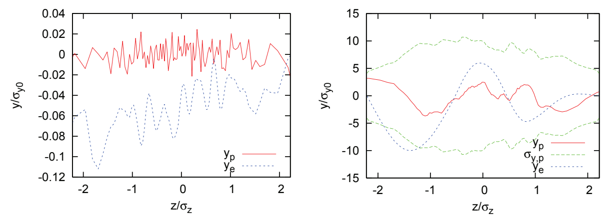

Figure 2: Electron averaged oscillation amplitudes and transverse size of beam and electrons during their interaction along z. The top plot is obtained for $\rho_e=6\times10^{11}$ m^{-3} after 1500 turns, and the bottom corresponds to $\rho_e=5\times10^{13}$ m^{-3} after 500 turns.

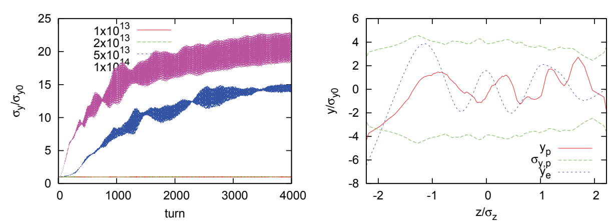

Figure 3: Evolution of the beam size and beam/electron profile during the beam-electron interaction in a strong bending magnet, B_y=20 T. The bottom plot refers to $\rho_e=5\times10^{13}$ m^{-3} after 500 turns.

INCOHERENT EMITTANCE GROWTH

Tune shift/spread due to the electron cloud can generate incoherent emittance growth. When the tune footprint overlaps with a resonance line of sufficient strength, the emittance growth arises. The tune shift depends on the transverse electron distribution. The tune-shift values in Table 1 assume a uniform electrons distribution near the beam. However, the distribution changes during the interaction with a bunch. Figure 4 shows the evolution of the transverse electron distribution in a drift space. Figure 5 presents the number of electrons in the area of $|x|<\sigma_x$ and the rms value of the cloud size, where initial velocity of electrons was taken to be 10^6 m/s. During the bunch passage the number of electrons within 1σ increases 5 times, and correspondingly the density 25 times. The size, which starts from a wide uniform distribution, shrinks to 1 σ_x quickly. The peak density of $\rho_e=25\times5.7\times10^{11}$ m^{-3} yields a maximum tune shift of 0.0083. This value is too small to lead to an overlap with low order resonances, such as 1/3 or 1/4.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPTY006

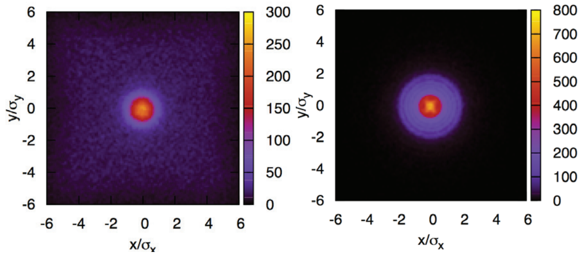

Figure 4: Electron distribution in the transverse plane during the interaction with a proton bunch in a drift space. The interaction times are z=-ct=2.4 σ_z (left) and 0.4 σ_z (right), where z=0 for the bunch centre.

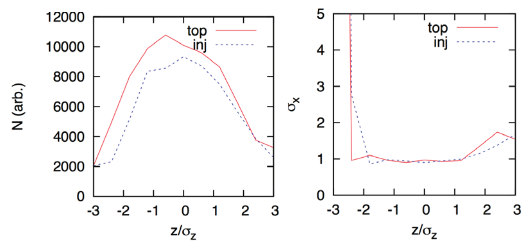

Figure 5: Evolution of electron cloud profile during the interaction with a proton bunch in a drift space.

Figure 6 and 7 present the analogous electron distributions for a bending magnet. The numbers seen in Fig. 7 right refer to $|y|<\sigma_y$. The electrons are pinched only along the vertical direction in a bending magnet, so that the density here increases 5 times. At the peak density of $\rho_e=5\times5.7\times10^{11}$ m^{-3} the tune shift is 0.0016..

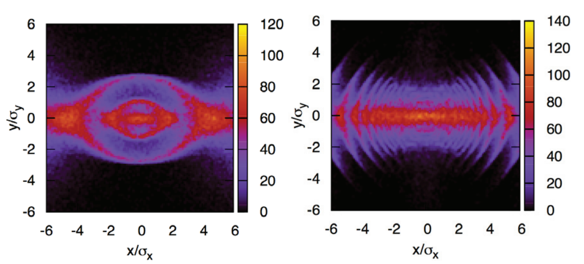

Figure 6: Electron distribution in the transverse plane during the interaction with a proton bunch in a bending magnet. The interaction times are z=-ct=1.8 σ_z (left) and -0.6 σ_z (right).

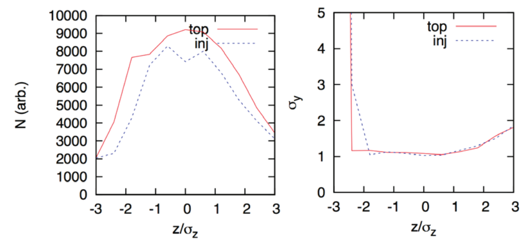

Figure 7: Evolution of electron cloud profile during the interaction with a proton bunch in a bending magnet.

CONCLUSION

The threshold of the fast head-tail instability caused by electron cloud has been estimated for FCC-hh. The threshold density is $\rho_{e,th}=5.7\times10^{11}$ m^{-3} using Eq. (2). Simulations results are consistent with this threshold estimate, but the instability growth is not strong close to the threshold density. Strong instability growth is seen at 100 times higher densities, $\rho_e=5\times10^{13}$ m^{-3}. We continue to study the threshold in more detail.

The tune shift at the threshold density is small, with regard to a possible overlap in tune space with some low order resonances. The resonance strength for higher order resonances >5th order due to the electron cloud force will be evaluated in the future.

ACKNOWLEDGMENT

This work is supported by the Large Scale Simulation Program No. 14/15-25 (FY2014) of High Energy Accelerator Research Organization (KEK), and by the European Commission under the FP7 Capacities project EuCARD-2, grant agreement 312453.

REFERENCES

[1] K. Ohmi, F. Zimmermann, E. Perevedentsev, Phys. Rev. E65, 016502 (2001).
[2] K. Ohmi, Proceedings of ECLOUD'04.
[3] G. Rumolo, L. Mether et al., IPAC'15, these proceedings.