Simulation study of the electron cloud effect in EicC proton ring

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Abstract

The EicC (Electron-Ion Collider in China) project aims to achieve a high luminosity goal in the medium energy region, provided both beams have high bunch intensity and short bunch spacing. It is well known that the electron cloud effect will impose severe limitations on the safe operation and luminosity performance of hadron machines. In order to investigate the design feasibility and parameter rationality of the pRing (proton ring) of EicC project, the electron cloud buildup and beam stability are studied via numerical simulations. The electron cloud induced heat load is simulated for multiple parameters under several magnetic field configurations. The results indicate that the additional heat load from the electron cloud at nominal beam parameters is not a serious problem, as pRing is a normal-conducting machine in the current design stage. Some non-monotonic dependences of the heat load on the beam parameters are observed and explained. In modeling beam-cloud interactions, the linearized method is adopted, in which the impact of electron cloud on beam particles is characterized by a generalized 2D wakefield and a transverse detuning force varying along the longitudinal direction. The simulation results show that the beam motions are very different in the two transverse planes due to the significant differences in linear forces, especially the detuning forces, and the margins are large enough to ensure the beams free from destructive instability at nominal design parameters. Furthermore, a simple case study using PIC simulations is carried out to check the results obtained by the linearized model.

Full Text

Preamble

Simulation study of the electron cloud effect in EicC proton ring∗ Lei Wang1, † and Jian Cheng Yang1, ‡ 1Insititue of Morden Physics, Chinese Academy of Sciences, Lanzhou 730000, China The EicC (Electron-Ion Collider in China) project aims to achieve a high luminosity goal in the medium en- ergy region,

provided both beams have high bunch intensity and short bunch spacing. It is well known that the electron cloud effect will impose severe limitations on the safe operation and luminosity performance of hadron machines. In order to investigate the design feasibility and parameter rationality of the pRing (proton ring) of EicC project, the electron cloud buildup and beam stability are studied via numerical simulations. The elec- tron cloud induced heat load is simulated for multiple parameters under several magnetic field configurations.

The results indicate that the additional heat load from the electron cloud at nominal beam parameters is not a serious problem, as pRing is a normal-conducting machine in the current design stage. Some non-monotonic dependences of the heat load on the beam parameters are observed and explained. In modeling beam-cloud interactions, the linearized method is adopted, in which the impact of electron cloud on beam particles is char- acterized by a generalized 2D wakefield and a transverse detuning force varying along the longitudinal direction.

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Keywords: Electron cloud buildup, Beam cloud instability, Linearized model, Generalized wakefield

INTRODUCTION

The EicC [1] (Electron-Ion Collider in China) accelerator facility, which enables the collisions between highly polar- ized electrons and protons with the center of mass energy of

16.7 GeV and the luminosity of 2$×$1033 cm—2s—1, is pro-

posed as a future nuclear physics project. It will be con- structed based on the upgrade of the HIAF [2] (High Inten- sity Heavy Ion Accelerator Facility) project, which is under construction. The layout of the EicC complex is shown in Fig. 1 [Figure 1: see original paper], and the main parameters are shown in Tab. 1. In the current design, pRing (proton ring), one of the major accelerators of the EicC project, serves as the booster ring (from

9.3 GeV to 19.08 GeV) and the collider ring of proton beams.

For a hadron machine in the medium energy region, the beam density will be severely limited by space charge effects [3, 4], hence increasing the collision frequency becomes the most effective way for a higher luminosity [5]. There are

448 pro- ton bunches circulating in the pRing with a bunch spacing of 10 ns. The electrons created by beam loss or residual gas ion- ization are likely to be captured and accelerated by the bunch trains with high bunch intensities and short bunch spacings.

As the bunch passes through, these energetic electrons will hit the chamber wall and produce secondary electrons. the secondary electron yield (SEY) of the chamber surface is large enough, then the secondary electron multiplication process will cause the electron density in the vacuum cham- ber to increase dramatically [6, 7]. The dynamic equilibrium is reached until the space charge self-field of electrons is on average balanced by the attractive beam force. The forma- tion of the electron clouds can cause heating of the vacuum ∗ The work is supported by the National Natural Science Foundation of China (No. 12425501 and No. 12505168). † Corresponding author, wangl@impcas.ac.cn ‡ Corresponding author, yangjch@impcas.ac.cn component [8], as well as degradation of the vacuum [9] and diagnostic [10]. Most importantly, the beam instability and emittance growth can be triggered by the highly concentrated electrons at the beam position [7, 11, 12]. Electron cloud has indeed become a significant limitation that seriously hin- ders the safe operation and luminosity performance of the ma- chine. Therefore, an exhaustive study of the electron cloud ef- fect in the conceptual design stage of pRing is a prerequisite to ensure the design feasibility and a cornerstone for propos- ing mitigation measures and optimizing beam parameters.

The electron cloud buildup process is interdependent with machine parameters (such as the SEY of the vacuum cham- ber’ s surface, chamber shape and size, and vacuum degree) and beam parameters (such as bunch intensity, bunch spacing, and bunch length). The beam-cloud interaction is also closely related to multiple parameters. As a consequence, the numerical approach becomes the irreplaceable tool for any at- tempt to model the electron cloud effect realistically [6, 13].

In this paper, the electron cloud effect in pRing is studied us- ing GOAT [14], a beam dynamics simulation code developed for multiple high-intensity effects.

In GOAT, the electron cloud buildup and the beam tracking are modeled separately, which is applicable to pRing-type bunch trains with short bunch spacings [15]. In modeling electron cloud buildup, the interaction between the electrons (represented by macroparti- Fig. 1. The layout of EicC complex.

TABLE 1 . The main parameters of EicC. Parameter Circumference [m] Kinetic energy [GeV] Collision frequency [MHz] Bunch spacing [ns] Intensity [1011 ppb] Emittance (H/V) [nmrad] Bunch length [cm] y [m] x /βave Transverse tune νx/νy Longitudinal tune νs Beam-beam parameter Crossing angle [mrad] Luminosity [cm−2s−1] Proton Electron 300/180 0.04/0.02 10.04/9.58 0.31/0.32 0.004/0.004 60/60 0.20/0.06 8.67/7.60 0.08/0.06 0.088/0.048 2\$×\$1033 cles) and a pre-generated static bunch profile is depicted. Al- though the computational speed of the buildup simulation is limited by the number of macroparticles, the

accuracy in the field solvers, and the time step for integrating the equations of motion, it is always inconsequential since the equilibrium electron cloud distribution can be reached in one or a few bunch revolutions. On the other hand, for beam tracking, in spite of the fact that the PIC method is the most reliable way for beam-cloud interaction studies, the computational time and resource requirements are quite demanding because the instability growth time can be rather large [12].

Over the years, many attempts have been made to char- acterize the electron cloud instability as correctly and fast as possible [16–20]. Recently, a linearized method has been pro- posed in Ref. [21, 22] by splitting the force from an electron cloud into dipolar and quadrupolar components. The dipolar force is described by a small set of response functions re- sulting from a distortion of the bunch distribution, and the quadrupolar force is described by a polynomial representing the betatron detuning along the bunch. The instability simulation results obtained by such a linearized method are compa- rable to those obtained by the PIC method in terms of mode- frequency shifts and instability growth rates [21], while the computational cost is reduced by about an order of magnitude In the conceptual design stage of the pRing, there or two. are a large number of parameters to be investigated. Based on this effective method, it is possible to learn the demands and limitations imposed by the electron cloud on the machine and beam parameters with minimal efforts. Therefore, the linearized method will be adopted in this paper for electron cloud instability studies as well. However, another quantity, called the generalized 2D wakefield [23, 24], a mathemati- cally equivalent expression regarding the dipolar component of an electron cloud, will be used here to describe the electron cloud induced driving forces. The electron pinch effect [21] can easily be taken into account by using this quantity. Be- sides, the longitudinal-dependent quadrupolar detuning force is obtained by simulating the beam tune spread through the PIC method.

The 2D wakefield is a lower triangular matrix, which can substantially improve the computational speed for instabil- ity simulations. This is because, firstly, the requirement for the number of proton slices can be reduced and is sufficient as long as the oscillation period of electrons can be fully captured with a fixed initial transverse offset. Secondly, the wakefield matrix can be applied directly to calculate the mo- mentum kick for corresponding particles without any other manipulations. However, a very severe numerical problem will be encountered in obtaining the wakefield matrix due to the finite number of macroparticles. To cope with this issue, an effetive approach is employed to noticeably suppress the numerical noise in wakefield simulations by introducing a set of control groups. With the powerful linearized model, to- gether with the noise suppression technique, the beam stabil- ity studies in this paper require only a few tens of hours. The computation efficiency is greatly improved in comparison to the PIC simulation, and the results are almost comparable at design parameters.

The remainder of this paper is organized as follows. The simulation methodologies for electron cloud buildup, lin- earization of the electron cloud force, and beam tracking are given in Sec. II. The heat load, energy spectrum, and electron distribution in different types of field regions for a set of parameters are discussed in Sec. III. Sec. IV presents the sim- ulation results for linearized electron cloud forces and beam instabilities. The summary in Sec. V ends the paper.

II. METHODOLOGY A. Electron cloud buildup In modeling the electron cloud buildup process, the fol- lowing three steps are included: (i) primary electron genera- tion, (ii) electron motion in the electromagnetic field, (iii) sec- ondary electron emission. Two types of primary electron gen- eration mechanisms are implemented in GOAT, i.e., the resid- ual gas ionization and the beam loss on chamber walls. In practical simulations, the cold electron distributions with very low densities (typically in the order of 106 e−/m 107e−/m) are used as seed electrons instead of accumulating the pri- mary electrons through the above two mechanisms. Such an approximation does not have any effect on the equilibrium state of the electron cloud (such as the quantities of most in- terest, including the electron density and cloud distribution), as this would only have an impact on the most initial transient stage of the electron cloud buildup (e.g., the buildup rate).

In subsequent simulation steps, the primary electron genera- tion mechanisms will be taken into account at each time step, even though this contributes little to the exponentially grow- ing electron densities.

The electromagnetic fields interacting with the electrons include the beam field, the space charge field of electrons, and the external magnetic field. Since the electron cloud buildup is very rapid and has a negligible effect on beam distributions, it is not necessary to use macroparticles to represent the beam. The static proton bunches with 3D Gaussian pro- files are used for the simulation. The filling pattern of the bunch train can be arbitrary. For the elliptical chamber, the Bassetti-Erskine formula [25] is used to calculate the beam field. The boundary conditions including image charges can also be taken into account [10]. For other chamber shapes (including the elliptical ones), the beam field is calculated by the finite difference (FD) Poisson solver [26] and saved at the initialization stage of the simulation. The kicks are applied to the electrons at each time step according to the longitudinal beam line density. As for the space charge field of electrons, the FD solver is employed at each simulation step with mesh grids considering the chamber geometry. So far, the dipole and quadrupole magnetic fields can be taken into account in the simulation. The direct integration of the Lorentz equation is utilized to describe the time evolution of electron motions.

There are various methods to achieve this purpose, such as the Boris pusher, Vay pusher, and Higuera-Cary pusher [27].

The choice of the method depends on specific requirements.

In general, the Boris pusher is preferred because it is second- order accurate, time-reversible, and fast.

When electrons hit the chamber surface with some ener- gies, they will be elastically scattered or produce true sec- ondary electrons with SEYs [6], δelastic(E) = R0 (cid:32) √ E + E0 E + E0 (cid:33)2 δtrue(E) = δmax (cid:16) E (cid:17)2 , where E denotes the energy of incident electrons, R0 is the electron reflectivity with zero energies, E0 is the fitting pa- rameter of experimental data for elastically scattered elec- trons, s is the fitting parameter for secondary electrons, Emax is the energy of the electrons at which the SEY is maximum, and δmax is the maximum SEY at normal incidence. The δelastic and δtrue denote the SEY of elastically scattered elec- trons and true secondary electrons, respectively. The proba- bility of an electron being elastically scattered depends on the ratio between δelastic and δtotal, where δtotal = δelastic + δtrue. The larger the value, the greater the opportunity for the electrons to be elastically scattered. If there is an angle be- tween the incident electrons and the chamber wall, the SEY formula should be updated to be angle-dependent [6]. In ad- dition, the newly generated true secondary electrons obey the "log-normal" energy distribution [6] and the "3D cosine" an- gular distribution[6, 8, 10].

B. Linearized electron cloud forces In the wakefield simulation, the aim is to calculate the deflection force of the electromagnetic field excited by the source charge on the test charge located behind it. The evolu- tion of the wakefield depends only on the relative distance be- tween the test charge and the source charge. However, since the electron pinch leads to a significant variation in electron densities and cloud oscillation frequencies at the beam loca- tion, the wakefield generated by the electron cloud does not satisfy the translation invariance. In addition to the coherent property, the contribution of the incoherent effect from the electron cloud at different longitudinal positions varies with the electron density as well. Therefore, sufficient caution is needed when describing the beam-cloud interaction using a linearized approach.

To obtain the wakefield generated by the electron cloud, the proton bunch is first sliced in the longitudinal direction with uniform bins and the bunch slices are numbered sequentially from bunch head to bunch tail. The electron pinch effect can be taken into account if one considers constantly changing the longitudinal position of the source slice while allowing the electron cloud to interact continuously with the centered slices' train before encountering this source slice. This means that a series of simulations is needed by displacing the source slices according to pre-defined indexes. In other words, the wakefield depends not only on the position of the test slice but also on the position of the source slice, i.e., the gener- alized 2D wakefield. Different from the buildup simulation, the electrons and beam are characterized by macroparticles here. The cloud distribution can be uniform, Gaussian, or re- alistic electron coordinates extracted from dedicated buildup simulations. The beam distribution is generally 3D Gaussian.

The offset attached to the source slice is 0.1σx,y, which is a reasonable value to exclude the electron cloud nonlineari- ties. In addition, the generalized wakefield can be computed by choosing the same numerical parameters that will be used for instability simulations, i.e., the same number of slices and macroparticles, as well as the distribution truncation condi- tions, to get a further speedup in the computation efficiency.

In generalized wakefield simulations, the results would not even be reproducible when an excessively small number of macroparticles is used. Partial mitigation can be realized when the number of macroparticles is raised to about 108 or more. To address the numerical issues, a set of control groups is introduced in the simulation, which shares the same beam distribution as the experimental groups but without attached transverse offsets. That is to say, the control group is used as the base of the numerical noise, and the dipolar compo- nent of the electron cloud force is derived from the difference between the experimental group and control group. Besides, the electron distribution used here is created by merging ten realistic distributions from buildup simulations to further reduce the fluctuations. With these techniques, the simulation results can be made almost independent of numerical noise using only 106 macroparticles.

The incoherent effect caused by the local electron density variation is obtained by simulating the beam-cloud interaction in a self-consistent way through PIC simulations [28, 29]. In general, multiple interaction points along the ring are required to avoid artificial effects. The synchrotron motion of the beam is frozen to obtain the instantaneous tune spread. The change of the particle' s betatron oscillation frequency is calculated from the difference in the coordinates with respect to the lin- ear transfer matrix. The results should be averaged over many turns to minimize numerical errors. Then, the longitudinal- dependent quadrupolar detuning force can be calculated by averaging the tune spread of beam particles according to their longitudinal positions.

In addition, it should be noted that both the dipolar and quadrupolar forces obtained here are averaged over the parti- cle distribution of each slice. This is understandable since the electron cloud is excited by a bunch slice with definite distri- butions instead of a point charge. The electron cloud forces at the bunch center are orders of magnitude larger than the averaged ones.

C. Beam-cloud interaction Based on the linearized electron cloud model including the dipolar generalized 2D wakefield and the quadrupolar detun- ing force, it is possible to model the electron cloud instabil- ity through the well-established method used for the beam- impedance interactions [30, 31]. The two-dimensional in- terpolation method should be applied because of the two-dimensional form of the wake force. In simulations, the lon- gitudinal centroids of individual slices can be viewed as mo- tionless in transverse instability simulations when the number of macroparticles is large enough. At this moment, the gener- alized 2D wakefield can be represented as a lower triangular matrix and the transverse detuning force can be described by a one-dimensional array. The simulation of the beam-cloud interaction is therefore accomplished by two multiplication operations, where the first multiplication takes between the wakefield matrix and the array of slice centroids and the sec- ond is the product of the detuning force and the transverse particle coordinates. Afterwards, the kick is applied to up- date the momentum coordinates of each particle.

In beam particle tracking, the bunch is sliced in the longi- tudinal direction with uniform bins. All the numerical param- eters are the same as the ones used to obtain the linearized electron cloud forces. The electron cloud is concentrated at N interaction points, which are evenly distributed along the ring. In each interaction ponit, the strength of the linearized electron cloud forces is scaled to 1 N . Between two interaction points, the beam particles perform betatron and synchrotron oscillations. In the transverse plane, the smooth approxima- tion is adopted for the ring lattice and the particles are tracked via linear transfer matrix with a phase advance of νx,y N . In the longitudinal plane, the particles execute drift motion in be- tween segments and the energy kick from the RF cavity is lumped at a single location. The nonlinear components of the electron cloud is naturally ignored in the linearized model.

This will be captured and simulated by using PIC simula- tions in a simple case study at design parameters. In addition, the lattice nonlinearities, chromatic effects, and other high- intensity effects are not covered in this paper.

III. BUILDUP SIMULATION RESULTS When the energetic electrons hit the chamber, some or all of the energy is transferred to the wall, causing an additional contribution to the heat load. In the following subsections, the heat load induced by the electron cloud in different types of magnetic field regions is calculated for multiple machine and beam parameters. The heat load is the average result after the electron cloud reaches equilibrium. In some cases, electron cloud density and energy spectrum of impacting electrons are shown in order to interpret and understand some phenomena observed in simulations. Table 2 presents the parameters used in the simulation.

A. SEY parameter The SEY of the chamber surface material is of most concern in electron cloud buildup as it determines the average number of secondary electrons that each impacting electron can produce. To obtain the allowable limits of this parame- ter, the maximum SEY, δmax, of the stainless steel vacuum chamber surface is scanned with and without considering ex- ternal magnetic fields. Figure 2 [Figure 2: see original paper] shows the electron line den- sities inside the chamber for drift, dipole, and quadrupole re- gions, where each curve corresponds to a different bunch in- tensity.

It can be seen that the electron cloud multipacting threshold decreases first and then increases as the bunch in- tensity becomes higher in different configurations. Once the multipacting threshold is exceeded, the electron line density shows a linear growth with increasing δmax, except for the lowest bunch intensity. For nominal beam parameters, the multipacting threshold is 1.0 in all regions. The coating treat- ment seems to be necessary to reduce the SEY of the cham- ber surface, but this strongly depends on the degree to which the electron cloud affects the accelerator components and the beam stabilities. Moreover, for a fixed bunch intensity, the threshold is higher in the field-free region than in dipole and quadrupole magnets when the threshold is larger than one.

The electron distribution is far from homogeneous in the saturated clouds due to the space charge self-field. Fig- ure 3 shows the snapshots of the electron distribution in drift, dipole, and quadrupole regions. In the field-free region, the central electron density is only about 4% of the average den- TABLE 2. Parameters used for the electron cloud buildup simula- tions.

Parameter Beam size, σx,y [mm] Maximum SEY, δmax Bunch intensity, Nb Bunch spacing [ns] Bunch length [cm] Horizontal chamber aperture, a [mm] Vertical chamber aperture, b [mm] Energy of δmax, Emax [eV] s for true secondaries Electron reflectivity, R0 E0 for elastic scatters [eV] Dipole field [T] Quadrupole gradient [T/m] Value 1.7355/1.3132 0.25 × 1011-2 × 1011 Fig. 2. Total number of electrons in the vacuum chamber as a function of δmax for (a) Drift, (b) Dipole, and (c) Quadrupole regions after reaching the dynamic equilibrium. Simulations are conducted for different bunch intensities. The electron line densities are taken as average values when the dynamic equilibrium is reached. The bunch spacing is 10 ns and the bunch length is 4 cm.

Fig. 3 [Figure 3: see original paper]. Snapshots of electron cloud distributions 4×σz before the bunch peak for drift, dipole, and quadrupole at bunch intensity of 1.25$×$1011 and δmax=1.5. The yellow ellipse represents the vacuum chamber. The bunch spacing is 10 ns and the bunch length is 4 cm. sity. At this moment, the cloud distribution is severely limited by the space charge self-field, resulting in almost all elec- trons being gathered in a sheath of a few millimeters at the surface. The local electron density in the vicinity of the hor- izontal chamber surface can be up to 7$×$1013 e−/m3, which is about 7 times larger than the value in the vertical plane. It is also noticed that the central electron density is significantly enlarged in the presence of a magnetic field, and the higher the order of the field, the larger the value. The lower the elec- tron density at the beam location, the less it affects the beam.

It suggests that the electron cloud formed in the quadrupole magnet might have a considerable effect on beam stabilities at design parameters, which is in agreement with the experience of the LHC [7, 12, 21]. Although the total length occupied by the quadrupole magnets in the pRing is very modest, and their contribution to the beam stability is not as tremendous as that of the LHC, one cannot take it lightly. Figure 4 [Figure 4: see original paper] shows the relative density (defined as the ratio between the electron density at the beam position and the average electron density in the chamber) dependence on δmax for the bunch intensity of 1.25$×$1011. In different magnetic field configurations, the saturation of the relative density occurs when δmax exceeds

1.5. It means that the electron density at the beam position

also increases linearly with δmax. As the electron cloud gets saturated, the spatial morphologies of the electron distribu- tions are very similar for different δmax.

Besides, for all considered bunch intensities, the relative density saturates in different types of field regions as the δmax exceeds a certain threshold. Table 3 summaries the de- pendence of the δmax threshold on the bunch intensity. For those SEYs that the electron clouds are saturated, as shown in Fig. 5 [Figure 5: see original paper], the central electron density becomes larger and larger as the bunch intensity decreases (except for the field-free re- gion at the bunch intensity of 0.25$×$1011). The δmax = 2.0 is taken since the relative density saturates for all bunch inten- sities at the moment. The dependence of the central and aver- age electron densities in drifts and dipoles on the bunch inten- sities obtained here is very similar to the results presented in TABLE 3. The dependence of the δmax threshold on bunch intensi- ties and magnetic configurations when the relative density saturation occurs.

Intensity (ppb) 0.25$×10110.50×10110.75×10111.00×10111.25×10111.50×10111.75×10112.00×$1011 Quadrupole Dipole Drift central density becomes higher and higher with de- creasing bunch intensity and the relative density can be as high as sev- eral times. This can be understood directly by observing the electron distributions. In Fig. 6 [Figure 6: see original paper], the snapshots of electron dis- tribution in dipoles and quadrupoles are plotted for different bunch intensities. For dipole magnets, the electrons are local- ized within a single thin strip in the central region of the hor- izontal chamber at a low bunch intensity. With higher bunch intensities, the strip splits into two or more parts, and these strips are moving away from the center, causing a reduction in central electron density. In the presence of the quadrupole magnetic field, the relative density changes more drastically.

As the bunch intensity increases, the electrons at the beam location gradually dilute, and more and more electrons are captured by the gradient of the magnetic field and distributed along the magnetic field lines. Based on these observations, it can be concluded that the dependence of the central density on the bunch intensity is complicated. It depends on the en- ergy spectra of electrons impacting the chamber, the electron distribution (i.e., the distribution of the space charge force), and the presence of magnetic fields.

In addition, it can be inferred that the electron cloud instability will likely become a hidden issue as the bunch intensity becomes progressively smaller in luminosity productions [7, 12].

B. Bunch intensity The bunch intensity, which determines the energy gain of electrons, is the most crucial beam parameter for electron cloud buildup, since the SEY curve is essentially energy- dependent. Figure 7 [Figure 7: see original paper] shows the heat load as a function of the bunch intensity for drift, dipole, and quadrupole, respectively, where each curve corresponds to a different δmax. It can be observed that for most configurations, the heat load is high- est in the field-free regions, followed by the quadrupole mag- nets, and smallest in the presence of dipole magnetic fields.

However, some anomalous phenomena can still be identified.

For large δmax, the heat load increases almost linearly with the bunch intensity. While for small δmax, such as 1.1 to 1.4, the heat load increases first and degrades later. This non-monotonic dependence of the heat load on the bunch in- tensity behaves independently of the types of external mag- netic fields. Similar results are also observed and reported in Ref. [32].

The heat load is jointly determined by the electron flux and the electron energy deposited on the chamber. The secondary electron emission also strongly depends on the electron en- ergy. In order to understand the observed phenomena, a qual- itative explanation is first attempted based on these quanti- ties. Figure 8 [Figure 8: see original paper] shows the energy spectra of electrons impacting the chamber for different bunch intensities and the SEY curves for different δmax. As expected, the energy gain of the electrons gets larger with increasing bunch intensity, caus- ing a shift of the energy spectrum towards higher energies.

The secondary electron multiplication effect reaches the max- imum when the electron energy spectrum effectively overlaps with the fraction of the SEY curve higher than 1 (e.g., for Fig. 4. The relative density as a function of δmax for drift, dipole, and quadrupole regions. The electron density is sampled at 4×σz before the bunch peak. The bunch intensity is 1.25$×$1011, the bunch spacing is 10 ns, and the bunch length is 4 cm.

Fig. 5. Electron densities as a function of bunch intensity for drift, dipole, and quadrupole. The electron density is sampled at 4×σz be- fore the bunch peak. The central density denotes the electron density at the beam location, and the average density corresponds to the elec- tron density averaged over the vacuum chamber. The δmax = 2.0, the bunch spacing is 10 ns, and the bunch length is 4 cm.

Ref. [15]. In the field-free region, the average density reaches it maximum around the bunch intensity of 1$×1011*anddropsafterwards.Thisisbecausethegenerationofsecondaryelec−*
tronsstronglydependsontheenergyofprimaryelectronsandtheSEYreachesitsmaximumandthendropsasthea
imumshifttowardslowerbunchintensity.However, thebe−haviorofthecentraldensityisstillnotwellunderstoo
before the bunch peak in the presence of (a) dipole magnetic field and (b) quadrupole magnetic field for 0.25$×1011, 0.50×1011, 0.75×1011, 1.00×1011, 1.25×1011, 1.50×1011, 1.75×1011,
bunch populations (from top left to bottom right). The yellow ellipse represents the vacuum chamber. The δmax=2.0, the bunch spacing is 10 ns, and the bunch length is 4 cm. The color bar is in units of e−/m3. δmax=1.2, the electron energy ranges from 58 eV to 343 eV).

At this point, the large electron flux on the chamber dom- inates the heat load. With larger bunch intensities, the elec- tron energies become higher, but the secondary electron emis- sion is weakened. This translates into a reduction in electron density and a lower heat load. The final heat load is deter- mined by the relative contribution of the two factors. Using the statistics extracted from simulations, the qualitative expla- nation can be quantified by the average energy of electrons, the electron line density, and the product of the two, as shown in Fig. 9 [Figure 9: see original paper]. The field-free region is taken as an example and three values of δmax exhibiting different tendencies are chosen. The average energy of electrons increases monotonically with increasing bunch intensity while the electron line density first increases and then decreases, which matches well with the above qualitative analysis. These two quantities do not show differences between different δmax. However, it should be recognized that the smaller the δmax, e.g., δmax=1.2, the average energy of electrons can be rather high, whereas the energy window for effective secondary electron multiplica- tion is instead smaller and narrower. This leads to a sharp drop in the electron line density. The combined contribution of these two quantities is given by their product, as shown in the bottom figure, which is in perfect agreement with the sim- ulated heat load. This explanation also holds for the presence of a magnetic field.

At nominal beam parameters, the maximum temperature rise of the vacuum chamber resulting from the electron cloud is about 6 ∘C, which is an acceptable level for a normal- conducting machine and would not be a tricky problem. In addition, it turns out from the simulation results that for some intermediate values of δmax, the electron cloud induced heat load can be significantly suppressed as the bunch intensity in- creases. However, for other simulation conditions, such as Fig. 7. Electron cloud induced heat load as a function of bunch intensity for (a) Drift, (b) Dipole, and (c) Quadrupole regions. Simulations are conducted for different δmax. The heat load is calculated by averaging over 20 successive bunch passages after reaching the dynamic equilibrium. The bunch spacing is 10 ns and the bunch length is 4 cm.

Fig. 8. (Top) SEY curves with different δmax. (Bottom) Normalized energy spectrum of the electrons impacting the chamber surface in the field-free region for different bunch intensities and δmax=1.2.

Other parameters used in the simulations are the same as in Fig. 7. different bunch spacing, chamber shape, and chamber aper- ture, the suppression of the head load may happen for other values of δmax. The degree of suppression may also change and new simulations should be performed. Anyway, it is not a bad choice to consider operating the machine at higher inten- sities as the SEY gets lower after certain treatments (e.g., sur- face coating or dedicated scrubbing run), provided that other high-intensity effects or hardware are acceptable.

C. Bunch spacing The equilibrium electron density depends on the compe- tition between electron generation and extinction rates. The balance is strongly related to the bunch spacing. Two sce- narios are considered here, denoted as case A and case B, to Fig. 9. The (top) average energy of electrons impacting the chamber wall, (middle) the electron line density in the chamber, (bottom) and the product of the two values for different bunch intensities. The results are extracted from buildup simulations for different SEYs.

Other parameters used in the simulations are the same as in Fig. 7. investigate the role of the bunch spacing on the heat load. In case A, the nominal bunch intensity is fixed, and the bunch spacing is changed by adjusting the ring circumference while keeping the number of bunches constant; in Case B, the aver- age beam current is fixed, and the bunch spacing and bunch intensity are varied simultaneously while keeping the ring cir- cumference constant. Figure 10 Figure 10: see original paper shows the heat load as a function of the bunch spacing for case A with three selected δmax. Here, the heat load is calculated as a weighted aver- age result of independent simulations for drift, dipole, and quadrupole according to the fraction covered by each type of in these two elements contributes much to the weighted result at the smallest bunch spacing for $\delta\text{max} = 1.3$.

The observed phenomena can be summarized as follows: the multipacting threshold is raised in case of small and large bunch spacing limits, and the impact of magnetic fields on multipacting thresholds is considerable at very short bunch spacing. This can be explained by the fact that for a very large bunch spacing, the low energy electrons cannot effec- tively gain energy from the bunch train for a long time, and the chamber behaves like an absorber. The electron extinc- tion rate progressively prevails as the bunch spacing contin- ues to increase. This leads to an increase in the multipacting threshold, a lower electron density, and hence a smaller heat load. For a very small bunch spacing, even if the electrons could gain suitable energy from the previous bunch, they will be captured again by the next bunch before hitting the cham- ber. Only a very limited number of electrons can break the bondage of the beam attractive field to reach the chamber sur- face, and thus the multipacting threshold is increased and the heat load is reduced. In addition, at a very small bunch spac- ing, there exists a confinement effect from the magnetic fields on electron motions, causing the electron density to decay with the order of the magnetic field, which induces a corre- sponding change in the heat load.

For case B, the weighted heat load is shown in Fig. 11 [Figure 11: see original paper].

The values are noticeably suppressed for small bunch spac- ings compared to the results for case A. The heat load de- pendence on bunch spacing is basically the same for different δmax, which shows a non-monotonic pattern and is independent of external magnetic fields. The multipacting threshold also becomes higher in the large bunch spacing limit for the same reason as in case A. Concerning the short bunch spacing limit, the heat load is reduced but is not evident compared to case A since the bunch intensity does play a very significant role.

At nominal beam parameters, the simulation results sug- Fig. 10. (a) The weighted heat load as a function of bunch spacing (case A) for different SEYs. (b) The heat load as a function of bunch spacing (case A) in drift, dipole, and quadrupole for δmax=1.3. The bunch intensity is 1.25$×$1011, the bunch length is 4 cm. field. For simplicity, the ring is assumed to be constituted of FODO cells, and the elements in the interaction region are not included. The fractions covered by drift, dipole, and quadrupole are 46%, 32%, and 13% of the ring circum- ference, respectively. It can be seen that for larger δmax, i.e., 1.5 and 1.7, the heat load decreases monotonically with bunch spacing. The contribution from each magnetic configuration has the same trend as the weighted results. For δmax=1.3, as the bunch spacing constantly shrinks, the weighted heat load increases gradually to the maximum and then decreases rapidly. This non-monotonic phenomenon can be explained by Fig. 10(b), where the heat load dependence on the bunch spacing is now correlated to the external magnetic fields for the bunch spacing of 2.5 ns. Since the drift and dipole cover almost 80% of the ring, the sharp reduction of the heat loads Fig. 11. The weighted heat load as a function of bunch spacing (case B) for three different SEYs. Other simulation parameters are the same as in Fig.10. gest that the electron cloud effect would not be a significant problem. However, if one considers to increase the luminosity by reducing the bunch spacing, i.e., more bunches and higher collision frequency, both SEY parameter and bunch spacing have to be small enough and below some certain thresholds.

D. Bunch length The change in the bunch length would cause a variation in energy kick obtained by the electrons at each time step, though the integral result is constant. The dependence of weighted heat load on bunch length is shown in Fig. 12 Figure 12: see original paper.

It can be seen that the impact of the bunch length on the weighted heat load is negligible and there is no difference Fig. 12. (a) The weighted heat load as a function of bunch length for three different SEYs. (b) The heat load as a function of bunch length in drift, dipole, and quadrupole regions for δmax=1.3. The bunch intensity is 1.25$×$1011, the bunch spacing is 10 ns. in trend between different δmax. The results for each type of field are shown in Fig. 12(b), where δmax=1.3 is taken as an example. The heat load positively varies with the bunch length in the field-free region and the trend turns to be neg- ative when external magnetic fields are present. From the perspective of electron cloud induced heat laod, the nominal beam parameters are reasonable.

It is shown that the electron cloud buildup and the conse- quential heat load are not sensitive to the bunch length, how- ever, the longer the bunch length, the lower the cavity volt- age, i.e., the smaller synchrotron tune, in case the longitudinal emittance is kept constant. If the single-bunch instability is triggered by mode coupling, the synchrotron tune will play an important role since it is closely related to the transverse mode coupling instability threshold. At this moment, the im- pact of the bunch length on beam stability is much more severe than its effect on heat load.

E. Chamber aperture The chamber aperture affects the time of flight for electrons to reach the chamber wall after being accelerated by the beam field and determines the boundary conditions used for solving the Poisson equation, thus having a considerable influence on the buildup process. Ignoring the magnet aperture limitation, the effect of chamber aperture on heat load is investigated. As a preliminary estimate, all vacuum chambers are assumed to be elliptical. Figure 13 [Figure 13: see original paper] shows the heat load as a function of the chamber aperture in drift, dipole, and quadrupole, respec- tively. The horizontal axis represents the horizontal chamber aperture, and each curve corresponds to a different vertical aperture.

The electron cloud buildup varies drastically with the chamber aperture in different magnetic configurations. The results for the field-free region are presented in Fig. 13(a).

For the smallest vertical aperture b=15 mm, the increase in the horizontal aperture leads to a saturation of the heat load after a rapid growth. For other vertical apertures, the heat load oscillates between 60 W/m to 120 W/m without an obvious pattern to follow. According to the results, the small round vacuum chamber is more favorable for electron cloud sup- pression in the field-free region with nominal beam parame- ters. In the presence of the dipole magnetic field, the heat load dependence on the horizontal aperture is heavily influenced by the vertical chamber aperture, as shown in Fig. 13(b). The heat load decays monotonically towards a larger horizontal chamber aperture when the vertical aperture is small or large.

For those intermediate values, the heat load climbs up slowly with the horizontal chamber aperture and then degrades at a faster rate. Moreover, with current design parameters, it can be found that a larger horizontal aperture helps to suppress the electron cloud regardless of the vertical ones. Figure 13(c) shows the scenario in quadrupole magnets. The heat load is nearly stable at the level of 45 W/m if the vertical aper- ture is relatively small. However, for larger vertical apertures, the evolution of the heat load exhibits a mountain shape and peaks in proximity to a round chamber. In order to prevent Fig. 13. The electron cloud induced heat load as a function of horizontal chamber aperture for (a) drift, (b) dipole, and (c) quadrupole regions.

Simulations are conducted for different vertical chamber apertures and δmax=1.5. The bunch intensity is 1.25$×$1011, the bunch spacing is 10 ns, and the bunch length is 4 cm. electron clouds in quadrupole magnets at nominal beam pa- rameters, long elliptical or flat elliptical shaped chambers are advisable.

INSTABILITY SIMULATION RESULTS A. Generalized 2D wakefield Figure 14 [Figure 14: see original paper] shows the generalized 2D wakefield obtained by averaging over the whole ring according to the lengths occu- pied by different types of field regions. The results for hor- izontal and vertical planes are shown in (a) and (b), respec- tively. Horizontal and vertical axes in each figure denote the longitudinal positions of the source slice and the test slice, and z > 0 indicates the bunch head. The nominal beam pa- rameters are used and the beam distribution is truncated at $±4 $z in the longitudinal direction. The realistic clouds ex- tracted from buildup simulations for δmax=1.5 (a value for the well-scrubbed stainless steel vacuum chamber [33, 34]), i.e., Fig. 3, are used since the spatial distribution (even veloc- ity distribution) has a significant impact on the wakefield it produced. In addition, ten instantaneous cloud distributions sampled at -4σz before the bunch peak are merged to mini- mize the numerical noise, as stated above. It is worth spec- ifying that the lower right part of the pink dashed line has zero values due to the causality, as the source slice is located behind the test slice.

Apparently, the translational invariance is broken due to the strong electron pinch effect. There are remarkable differ- ences in the horizontal and vertical planes in the areas where the source slice is located at the bunch head and the test slice at the bunch tail, i.e., zi $>$ 0 and zj $<$ 0. As the electron cloud is perturbed by the source slice in this area, the result- ing wakefield increases from the bunch head then declines near the bunch center and grows again towards the bunch tail.

The oscillation pattern is essentially the same in both direc- tions. However, in the horizontal plane, the amplitude is al- ways positive. While in the vertical plane, the oscillation of the wakefield extends to the negative half-axis. The maxi- mum amplitude in the vertical plane is slightly larger than the one in the horizontal plane. In addition, the electron density at the beam position increases sharply due to the electron pinch, resulting in the wakefield at the bunch head being about one order of magnitude lower than the value at the bunch tail.

B. Quadrupolar detuning force Figure 15 [Figure 15: see original paper] shows the betatron tune shift variation along the bunch length, i.e., the quadrupolar detuning force. The sim- ulation conditions are the same as those used for the dipolar force, and the weighted average results are presented. The horizontal and vertical planes exhibit similar shape. The tune shift rises rapidly from the bunch head to a flat top at the bunch center and then increases towards the bunch tail at a relatively uniform and slow rate.

In the vertical plane, the tune shift between bunch head and bunch tail differs by about one order of magnitude, while for the horizontal plane, the difference is more pronounced. Meanwhile, the vertical tune shift is much larger than the horizontal one. This difference can be up to two orders of magnitude at the bunch head and stabilizes at about 2.5 times in the range from bunch center to bunch tail. There are two reasons responsible for this phe- nomenon: (i) In the presence of a dipole magnetic field, the electron motion in the horizontal plane is almost frozen, and its effect on the beam is severely weakened. In Fig. 15, the horizontal detuning force contributed by the dipole magnets is a very small positive value at the bunch head and becomes negative at the bunch tail. (ii) As discussed in Sec. III A, the space charge limitation in the field-free region is much more critical in the horizontal plane for nominal beam pa- rameters. This makes the bunch head experience a defocusing force in the horizontal plane as it enters the unperturbed elec- tron cloud. The horizontal detuning force becomes positive until the bunch center passes through the cloud. The appear- ance of the negative betatron tune shifts of beam particles in drift and dipole can be viewed as a direct consequence of the Fig. 14. The generalized 2D wakefield in the (a) horizontal and (b) vertical planes. The horizontal axis zi and vertical axis zj denote the longitudinal position of the source slice and test slice, respectively.

In the calculations, the bunch intensity is 1.25$×$1011, the bunch length is 4 cm, and the semiaxis of the elliptical chamber are 26 mm and 19.7 mm. The bunch spacing of 10 ns and δmax=1.5 are used in the electron cloud buildup simulation. electron distribution. The electric field seen by the beam is a superposition of the fields from central electrons and from the electrons near the chamber wall. Since the distribution of the saturated electron cloud is highly nonuniform, the central electron density is very low in these two magnetic configu- rations, as can be seen in Fig. 3 and Fig. 4, causing the hor- izontal electric potential near the chamber wall to be much higher than the center, which results in a defocusing effect.

One can expect that in modeling beam-cloud interactions in- cluding the quadrupolar detuning forces described here, the horizontal and vertical planes will definitely yield very differ- ent results, as it is an important guarantee for the correctness Fig. 15. The quadrupolar detuning term of the linear electron cloud force as a function of longitudinal position. The simulation parame- ters are the same as in Fig. 14. of the linearized method.

C. Beam-cloud instability In constructing the linear expressions for electron cloud forces, the realistic cloud extracted from dedicated buildup simulation should be adopted since both the spatial and veloc- ity distributions of electrons play important roles. However, in the case of similar cloud morphology (e.g., for fixed beam parameters and varied δmax, as shown in Fig. 2 and Fig. 4), the assumption can be made that the 2D wakefield matrix could be obtained directly through a scaling law according to the electron density at the beam position. The baseline should be given by the simulation, i.e., Fig. 14 and Fig. 15. It should be noted that the rule only applies when δmax is greater than some specific thresholds, as summarized in Tab. 3. That is to say, the scaling law is exactly applicable to large enough SEYs and can be used to determine the upper limit of δmax where the beam is stable. In fact, the difference between the results obtained from the scaling law and the realistic simula- tion at different δmax (up to 2.0) is acceptable. Such a scaling law also holds for the quadrupolar force.

The results shown in Fig. 14 and Fig. 15 are taken as the baseline, i.e., the electron cloud strength equals the unit. The beam spectra obtained by scanning the electron cloud strength are shown in Fig. 16 [Figure 16: see original paper] and Fig. 17 [Figure 17: see original paper] for the horizontal and ver- tical planes, respectively, where (a) only considers the gen- eralized 2D wakefield and (b) the linearized electron cloud model includes the dipolar and quadrupolar forces. The spec- trum is obtained by the FFT of the beam centroid sampled at each turn. In tracking simulations, 11 interaction points are chosen based on the convergence studies and a longitudinal Fig. 16. The real part of the normalized mode-frequency shifts as a function of the electron cloud strength in the horizontal direction considering (a) the dipolar force and (b) the dipolar and quadrupolar forces.

Fig. 17. The real part of the normalized mode-frequency shifts as a function of

the electron cloud strength in the vertical direction considering (a) the dipolar force and (b) the dipolar and quadrupolar forces. linear focusing force is applied to produce a synchrotron tune of 0.0125. Although the RF nonlinearity can slightly reduce the average synchrotron tune and may have a small impact on the instability threshold, it also leads to a broader synchrotron tune spectrum and makes the transverse spectrum blurred. To highlight the effect of the quadrupolar detuning force on beam stabilities, the linear RF bucket is created to realize a single distinct value for the synchrotron tune.

In the horizontal plane, the instability is caused by the mode coupling between the 0 mode and -1 mode, indepen- dent of whether the detuning force is taken into account or not, but the spectra for these two cases show different behav- In the case of considering the dipolar force only, the iors. shift of the 0 mode towards the negative frequency direction triggers the mode coupling as the electron cloud strength in- creases. By taking into account the detuning effect, the can- cellation between the dipolar force and the quadrupolar force causes the coherent frequency remains nearly constant, and the shift of the -1 mode towards the positive frequency di- rection is responsible for the mode coupling. The instabil- ity threshold is slightly elevated due to the presence of the quadrupolar force. However, in contrast to the definite in- stability threshold observed in Fig. 16(a), there are instabili- ties that can be distinguished from Fig. 16(b) even though the mode frequencies are still separated. This is consistent with the instability growth rate, as shown in Fig. 18 Figure 18: see original paper, which is Fig. 18. The electron cloud instability growth rates in the (a) horizontal and (b) vertical directions, which corresponds to Fig. 16 and Fig. 17, respectively. obtained by an exponential fitting of the horizontal centroid.

In fact, the slow instabilities already exist at very low elec- tron cloud strengths due to the longitudinal-dependent beta- tron tune modulation. Such instabilities appearing below the mode coupling threshold have also been reported in previous studies [18, 19]. Moreover, the quadrupolar force has a damp- ing effect above the instability threshold, though the effect is limited.

In the vertical plane, the instability is also caused by the mode coupling when ignoring the quadrupolar force, as shown in Fig. 17(a). Two transverse planes have almost the same mode coupling instability thresholds. However, the slow instabilities below the threshold are visible when the 0 mode and -1 mode are not yet fully merged together. The blue dots in Fig. 18(b) confirm this observation. This phe- nomenon can be attributed to the more aggressive oscillations of the generalized 2D wakefield in the vertical plane, where the interaction between different synchrotron sidebands pro- duced by the dipolar force itself already exists. The intro- duction of the quadrupolar force, on the other hand, completely changes the beam stability characteristics, as shown in Fig. 17(b). There is no mode coupling that appears up to 10 times the baseline cloud strength. The coherent tune in the vertical plane becomes positive and shifts to higher values with electron cloud strength as the effect yielded by the quadrupolar force is much larger than the dipolar force.

A large number of radial modes attached to each azimuthal mode appear. At this moment, the beam motion is still domi- nated by the interaction between the 0 mode and the -1 mode and the instabilities with extremely small growth rates can be captured as shown by the orange pentagram in the zoomed plot in Fig. 18(b). However, the destructive mode coupling instability is completely suppressed.

The simulation results show that under certain conditions, the effect of the electron cloud on beam stabilities can be quite different in the horizontal and vertical directions. This differ- ence is mainly attributed to the quadrupolar component of the electron cloud forces. This demonstrates once again the importance of using a complete linearized electron cloud model to characterize the electron cloud effect.

For the electron cloud built in the well-scrubbed stain- less steel vacuum chamber, i.e., the nominal electron cloud strength, the beam is stable in both horizontal and vertical planes, and the margin is large enough. From the point of view of beam stabilities, the requirement for δmax can be re- laxed to at least 2.0 or more at nominal beam parameters.

It can be concluded from above results that a relatively large quadrupolar detuning force is beneficial for the electron cloud instability. Furthermore, the instability threshold will likely be further raised if the space charge limitation of the electron cloud in the horizontal plane can be alleviated in the field-free region.

D. Case study: Comparison with PIC simulations In the previous subsection, the beam stabilities are stud- ied using the linearized model. This method provides a large improvement in computational efficiency, but fails to include the electron cloud nonlinearities. In this subsection, the PIC method will be used to simulate the beam-cloud interactions.

However, considering the fact that the PIC simulation is very time-consuming, it takes more than several months to obtain the results as shown in Fig. 16 and Fig. 17. Therefore, a case study is carried out here, and the electron distribution ex- tracted from buildup simulations for δmax = 1.50 and nominal beam parameters is used as an example. In addition, the results obtained by PIC simulations can serve as a verification of the linearized model.

The simulation results indicate that the beam is stable in Fig. 19 [Figure 19: see original paper]. Comparison of the (a) horizontal spectrum and (b) vertical spectrum obtained by the linearized model and PIC simulations. The electron distributions used for the PIC simulations are taken from the buildup simulation with a bunch spacing of 10 ns and δmax = 1.50.

The bunch intensity is 1.25 × 1011. Fig. 20 [Figure 20: see original paper]. Comparison of the (a) horizontal emittance and (b) vertical emittance as a function of the number of turns. both horizontal and vertical directions. Figure 19 shows the beam spectra obtained from the FFT analysis of bunch cen- troid motions. It can be seen that the longitudinal sidebands of bunch oscillations are shifted upward under the influence of the electron cloud, and the results predicted by the lin- earized model and the PIC simulation are basically the same.

However, the broadening of mode-frequencies, especially for the 0 mode, is not well captured by the linearized model.

A possible explanation is that the linearized model uses the quadrupolar detuning force averaged over the bunch distri- bution, and therefore underestimates the focusing effect in- troduced by the electron cloud. This is only a conjecture and is difficult to verify since the dipolar and quadrupolar forces cannot be considered separatedly in PIC simulations.

Nevertheless, the simulation results demonstrate the power and accuracy of the linearized model. Figure 20 shows the time evolution of the beam emiitance obtained by these two methods. It can be found that both methods predict a signif- icant increase in beam emittance, with a better agreement in the horizontal direction, whereas the PIC simulation yields a somewhat faster emittance growth in the vertical direction.

Meanwhile, even though the linearized model ignores the electron cloud nonlinearities, it still leads to the emittance growth. This may be caused by the excessive modulation of the betatron oscillation frequencies of beam particles inside the bunch, as illustrated in Fig. 15. The emittance growth seems to be unacceptably large and requires more attentions and studies in the future.

Several PIC simulations are also run for the slow instabil- ity regime, i.e., with electron cloud strength ranging from 4 to 6 in Fig. 18, but no beam instabilities are observed in both horizontal and vertical directions. The mode-frequency shifts yielded by PIC simulations, particularly for the -1 mode, are much smaller than the ones in Fig. 16(b) and Fig. 17(b). There are two possible reasons responsible for this phenomenon. First, the electron could nonlinearities, which are completely neglected in the linearized model, could be sufficient to damp this slow instability. Second, the spatial distribution of the electrons may change very significantly with a large increase in the electron cloud strength, and therefore the scaling law that uses the central electron density as a reference becomes invalidated. As a matter of fact, the lin- earized method should be used in conjunction with the PIC simulation, with the former providing a rough understanding of the electron cloud instability in an efficient manner and the latter allowing for more detailed investigations upon this foundation. In this way, the computation cost can be greatly reduced.

V. SUMMARY In this paper, a comprehensive and systematic study of the electron cloud effect is carried out for the pRing of EicC project. The simulation techniques are first introduced. modeling the electron cloud buildup, the widely-used "weak- strong" model is utilized to describe the interaction be- tween macro-electrons and static bunch trains. The linearized method is adopted for beam tracking by characterizing the [1] D. P. Anderle, V. Bertone, X. Cao et al., Electron-ion col- lider in China. Frontiers of Physics 16 (6) 64701 (2021). https://doi.org/10.1007/s11467-021-1062-0 [2] J. Yang, J. Xia, G. Xiao et al., High Intensity heavy ion Accelerator Facility (HIAF) strum. Methods Phys. Res., Sect. B 317 263-265 (2013). https://doi.org/10.1016/j.nimb.2013.08.046 in China. Nucl. [3] G. Franchetti, Space charge in circular machines. CERN-2017- 006-SP, p. 353. https://doi.org/10.23730/CYRSP-2017-003 [4] A. Oeftiger, Space Charge Effects and Advanced Modelling for CERN Low Energy Machines. CERN-THESIS-2016-170. https://doi.org/10.5075/epfl-thesis-7337 [5] S. Abeyratne, A. Accardi, S. Ahmed et al., Science Re- quirements and Conceptual Design for a Polarized Medium Jefferson Lab (2012).

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The heat loads induced by the electron cloud are simu- lated for a large set of parameters. It is shown that the sur- face treatment should be considered since the multipacting thresholds are 1.0 in all accelerator elements. The maximum temperature rise caused by the electron cloud is 6 $^\circ$C for nominal beam parameters and practical machine parame- ters. This is acceptable as pRing is a normal-conducting ma- chine. The simulation results also suggest that partial mitiga- tion of the heat load and further increment of the luminosity can be achieved by adjusting the beam parameters, such as increasing the bunch intensity or decreasing the bunch spac- ing when the SEY is reduced, and applying special-shaped vacuum chambers.

The beam stability is studied using the linearized method and is simply checked by the PIC simulation. These results suggest that the stability difference between the two trans- verse directions can be essentially attributed to the quadrupo- lar forces and the margin of the mode coupling instability is large enough for nominal beam parameters. Some slow insta- bilities with growth time on the order of seconds are predicted by the linearized moethd below the mode coupling threshold, but they are not observed in PIC simulations. The electron cloud nonlinearity and the failure of the scaling law may be the source of this difference. Nevertheless, it can be argued that the impact of the electron cloud on coherent beam dy- namics is not a significant concern with the help of some other damping mechanisms (e.g., the machine nonlinearity), but the slow emittance growth should be further studied to ensure a good beam lifetime. 2018-299. https://repository.cern/records/vbmy7-5jk76 [8] H. Maury Cuna, J. G. Contreras, F. Zimmermann, Sim- ulations of electron-

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Note: Figure translations are in progress. See original paper for figures.

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