ELECTRON CLOUD STUDIES FOR SIS-18 AND FOR THE FAIR SYNCHROTRONS

F. Petrov, O. Boine-Frankenheim, Th. Weiland, TU Darmstadt, TEMF, Germany

Abstract

Electron clouds generated by residual gas ionization pose a potential threat to the stability of the circulating heavy ion beams in the existing SIS-18 synchrotron and in the projected SIS-100. The electrons can potentially accumulate in the space charge potential of the long bunches. As an extreme case we study the accumulation of electrons in a coasting beam under conditions relevant in the SIS-18. Previous studies of electron clouds in coasting beams used Particle-In-Cell (PIC) codes to describe the generation of the cloud and the interaction with the ion beam. PIC beams exhibit much larger fluctuation amplitudes than real beams. The fluctuations heat the electrons. Therefore the obtained neutralization degree is strongly reduced, relative to a real beam. In our simulation model we add a Langevin term to the electron equation of motion in order to account for the heating process. The effect of natural beam fluctuations on the neutralization degree is studied. Finally we study the effect of the two-steam instability on the neutralization degree.

INTRODUCTION

The SIS-18 and the projected SIS-100 should deliver high intensity heavy-ion beams as part of the FAIR project [1] at GSI. For the production of exotic nuclei the intense beams should be extracted over time intervals of the order of seconds. During extraction electrons generated from residual gas ionization can potentially accumulate in the space charge potential of the coasting beam. The interaction with the electron cloud can cause undesired transverse beam fluctuations and emittance growth. Also during SIS-18 injection, before the rf capture, the beam is coasting. The build up and interaction of electron clouds with coasting beams has been studied in Ref. [3] for high-energy protons and in Ref. [5] for protons and heavy-ions. In this simulation study we focus on the case of intense U^{73+} and Ar^{18+} coasting beams, using a realistic SIS-18 residual gas composition and ionization cross sections for heavy-ions. In addition we account for other effects specific to heavy-ion beams, like electron heating and the larger natural fluctuation spectrum of the beam.

IONIZATION CROSS SECTIONS

In our simulation model we use the analytical formula for ionization cross sections proposed in [6]

$$\sigma^{ion}(v) = \pi a_0^2 \frac{Z_p^2}{Z_p+1}\frac{E_0^2}{I_{nl}^2} G\left(\frac{v}{v_{nl}\sqrt{Z_p+1}}\right) \qquad (1)$$

where

$$G(x) = \frac{\exp(-1/x^2)}{x^2}[1.26 + 0.283\ln(2x^2+25)] \qquad (2)$$

Z_p is the projectile charge state, $I_{n,l}$ and $v_{n,l}$ are the ionization energy and orbit velocity, a_0 is the Bohr radius and E_0 the atomic energy unit. The cross sections show a good agreement with strict quantum mechanics calculations [7] and experimental values. The total electron yield is obtained by summation over the measured SIS-18 residual gas composition [8], with an average pressure $\approx 10^{-11}$ Torr.

ELECTRON HEATING

The circulating beam ions deposit energy in the electron cloud. The corresponding electron heating rate is given by [9]:

$$\frac{dW_e}{dt} = E_i \frac{4\pi c \rho_i r_e^2 Z_i^2}{\beta} L_C \qquad (3)$$

where E_i and Z_i are the energy in center of mass frame and charge state. ρ_i is the beam density and L_C the Coulomb logarithm. Because the heating rate scales with Z_i^2 the effect is important for heavy-ions. Macro-particle simulations exhibit fluctuations that are by several orders of magnitude larger than the natural fluctuations. Therefore one could expect an artificial electron heating in these codes. In our numerical model we track the electrons in the analytic space charge field of the beam. The Coulomb interaction between beam particles and electrons is introduced through a Langevin term in the electron equation of motion. This term causes a diffusion of the electrons.

NUMERICAL MODEL

The ion beam is divided into rigid slices along the ring circumference similar to the scheme used in [3]. Each slice can perform dipole oscillations. The EC is generated in one interaction point. The force from the electrons is applied to the beam slice center of mass. After being kicked the slice is transported through the lattice. We use only one interaction point and track the beam slices around the whole circumference. Landau damping is taken into account in a simple way

$$x_i = x_i(1-\alpha) \qquad (4)$$

where $\alpha = n\eta\sigma_E/E/\sqrt{3}$ is damping rate per one revolution and $n = \omega_e/\omega_0$. The space charge field of the electron can be added in case the neutralization degree reaches high values. Electrons that reach the wall may be reflected or may produce secondary electrons. The material of the pipe in simulations is stainless steel with corresponding parameters $\delta_{SEY,max}$ - maximal yield, $E_{SEY,max}$ - energy of maximum. Reflection probability for zero energy was set to 1. The dependence of reflection and SEY on electron energy was set according to formulae in [4]

RESULTS

Simulations were performed for parameters shown in Table 1. Gaussian and constant beam density profiles were assumed for the slices.

Table 1: SIS-18 simulation parameters.

Variable	Value
Energy, E	11.4 MeV/u, 1 GeV/u
Beam radius, A	3 cm, 1 cm
Pipe radius, R	5 cm
Beam intensity, N_{beam}	$0.5 \cdot 10^{10} - 6 \cdot 10^{10}$
Circumference, C	216 m
Momentum spread, dp/p	$0.5 \cdot 10^{-3}$, $0.15 \cdot 10^{-3}$
Transition energy, γ_t	5.4
Vertical tune, Q	3.82
$\delta_{SEY,max}$	2.7
$E_{SEY,max}$	250 eV
Vacuum pressure	10^{-11} Torr

Static beam

If the transverse motion of the ion beam is kept 'frozen' the resulting build up of EC obtained from the simulation as well as the curve following from the analytical theory presented in Ref. [9] are shown in Fig. 1. Here the electron space charge is a limmiting factor for neutralization degree and one should add it to numerical simulations as well as to analytical theory.

It is seen that the neutralization degree reaches values up to 80% for 11.4 MeV/u. At the extraction energy 1 GeV/u the heating starts to play a significant role and the maximum neutralization degree is 10%. Also the simulation confirms that the neutralization degree almost doesn't depend on the type of ion as it was obtained in analytical estimations [9]. The obtained saturation time still depends on the ion type, here it is of the order of 1 s.

Effect of Natural Fluctuations

Real beams exhibits natural dipole fluctuations (transverse Schottky noise). The expected transverse Schottky side bands as well as the spectrum of transverse electron oscillations are depicted on Fig. 2. The rms amplitude of these fluctuations [10] is given through

$$a_{rms} = \frac{\sigma_{rms}}{\sqrt{N_{beam}}} \tag{5}$$

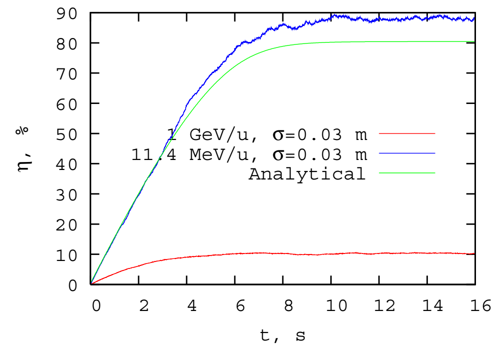

Figure 1: Evolution of neutralization degree for Ar^{18+}. Green curve is obtained from analytical theory [9]

where N_{beam} is the total number of beam particles and σ_{rms} the beam rms size.

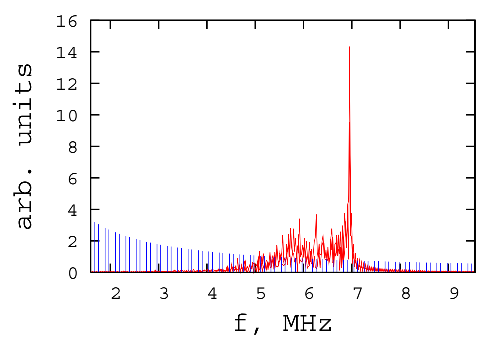

Figure 2: Electron transverse spectrum (red) and transverse Schottky spectrum (blue) for U^{73+} and $N_{beam} = 10^{10}$.

For beam $\sigma_{rms} \approx 1$ cm and $N_{beam} \approx 10^{10}$ the amplitude of fluctuations is $a_{rms} \approx 10^{-5}$cm. In our numerical model the beam centroid was perturbed with a frequency and amplitude corresponding to the expected Schottky spectra, but no visible effect on neutralization degree was observed.

Two-stream instability

The situation changes dramatically when electron-beam interaction is introduced. In this case there exists a threshold neutralization degree after which the two-stream instability develops [11]. This instability leads to dipole oscillations of the beam with amplitudes of several mm. Because of the resonant interaction electrons get lost on the pipe wall and a balance between production and loss is achieved.

Fig. 3 shows the typical behavior of the neutralization degree as a function of time. At the beginning the concentration of electrons reaches higher values than the steady-state level. Evolution of beam centroid amplitude for different beam intensities is shown on Fig. 4. The dependence of neutralization degree as a function of beam intensity for Ar^{18+} is shown on Fig. 5.

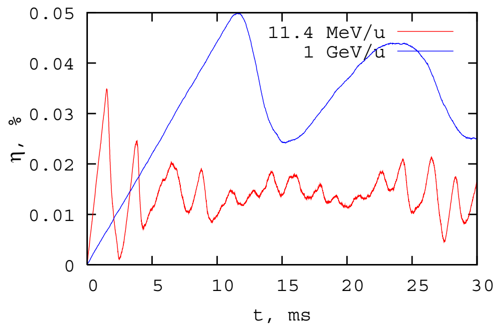

Figure 3: Evolution of the neutralization degree for Ar^{18+} for SIS-18 injection and extraction energies. $N_{beam} = 2.0 \cdot 10^{10}$

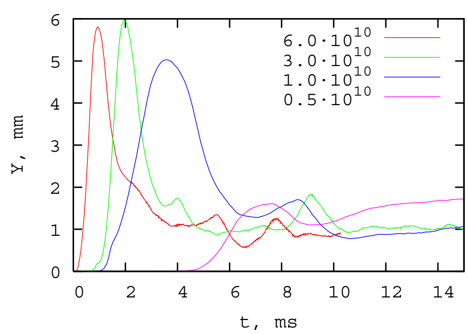

Figure 4: Evolution of the beam offset amplitude for Ar^{18+}. E = 11.4 MeV/u

DISCUSSION AND OUTLOOK

The build-up of the EC and its effect on heavy ion beams in SIS-18 was studied. In [3] it was found for high energy, coasting proton beams the oscillations are undetectable. Our results for medium energy, heavy-ion beams indicate that the electron-beam interaction may lead to observable beam dipole oscillations, even for very small neutralization degrees. The maximum of electron oscillation spectrum lies near the electron bounce frequency, which is ≈10 MHz. The average kinetic energy of electrons remains below a few tens of eV, which is not enough to trigger significant electron production due to the secondary emission. The saturated neutralization degree as a function of the beam intensity for a given energy scales according to the threshold [11] given in Eq. 6. The neutralization degree goes down with increasing intensity. We compared the results obtained from homogenous beam profiles and Gaussian beam profiles. The saturated neutralization degree is very similar. This is due to the fact that the frequency spread results from electrons that 'diffuse' to large amplitudes, outside the beam radius.

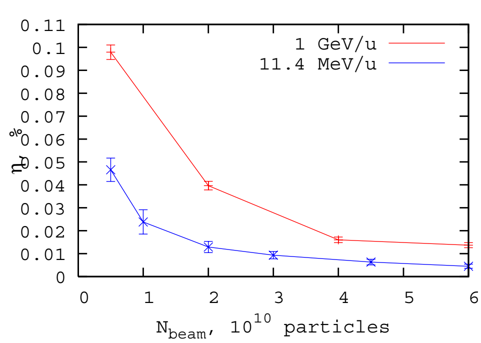

Figure 5: Steady-state neutralization degree for Ar^{18+} as a function of number of particles for injection and extraction energies.

$$\frac{\Delta Q_\beta}{Q_\beta}\frac{\Delta Q_e}{Q_e} \geq \frac{9\pi^2}{64} Q_i^2/Q_\beta^2 \qquad (6)$$

The neutralization degrees obtained from macro-particle simulations in Ref. [5] are close to the ones observed in our simulations. However, the two-stream instability did not explicitly contribute to the results presented in [5]. Instead beam emittance growth was obtained. In the following we plan to compare the results of our model with macro-particle simulations. Especially the effect of artificial diffusion will be analyzed. Our experimental efforts will focus on the measurement and interpretation of beam dipole oscillation spectra in the predicted range. We also plan to estimate the effect of electron clouds in dipole magnets. For the optimization of the slow extraction our results indicate that a small gap in the beam might strongly reduce the electron population.

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