SIMULATION OF THE DISTRIBUTION OF PARASITIC IONS IN THE POTENTIAL OF AN ELECTRON BEAM*

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Abstract

In an electron machine, positively charged ions are generated by direct collision between the beam and the residual gas molecules or by synchrotron radiation. If no countermeasure is employed, they can be trapped in the beam potential and accumulate over time until the full beam neutralization is reached [1]. Ion clouds can cause incoherent tune shifts and coherent beam instabilities, therefore they are a performance limiting factor for high current electron storage rings as well as Energy Recovery Linacs (ERLs). In order to give a detailed estimation of their effects on the beam dynamics and to further optimize the existing ion clearing techniques, accurate knowledge on the ion density distribution is required. In the following we present numerical studies on the distribution of ionized gas while interacting with electron bunch trains. The simulations have been performed with the software MOEVE PIC Tracking developed at the University of Rostock.

INTRODUCTION

An analytical model describing the equilibrium distribution of ions trapped in the beam potential is already available [2]. In addition, the distribution of the ions has been computed numerically in [3], where also the self-space charge of the cloud was taken into account.

Nevertheless, since the residual gas which populates the vacuum chamber of an accelerator is composed by many chemical species, further insight on the transverse behavior of each component is required. Knowledge about the regions occupied by different ionized chemical species is important because of its implication on the clearing techniques. Regardless of which particular technology is employed, these techniques have to be optimized considering that each species has its own dynamics, depending on the mass-to-charge ratio.

Furthermore, measurements of the so-called "Beam Transfer Function" (BTF) have been performed at the Electron Stretcher Accelerator (ELSA) in Bonn, in order to estimate the incoherent tune shift and therefore to obtain preliminary information about the average density of trapped ions [4]. The simulations presented here are also intended to enforce the development of the new applications of the BTF method by computing the evolution of the ion density around the beam on a time scale which is too short to allow experimental investigations.

Therefore, the simulated system has been chosen very similar to the one of the related measurements and a realistic ionized gas mixture has been employed.

SIMULATED PHYSICAL SYSTEM

The simulations focused on the behavior of parasitic ions in a drift session of the ELSA stretcher ring and were carried out with the 3D Particle-In-Cell code MOEVE PIC Tracking developed at the University of Rostock [5]. The operating parameters of the machine which are relevant for the numerical studies are shown in Table 1. As it can be seen, four different fill patterns have been chosen. When present, the clearing gaps were added all together after the bunches: for instance, in the scheme with a gap of 220, 54 bunches were followed by 220 empty buckets.

Table 1: Parameters of the ELSA Storage Ring

Parameters	Values
Beam energy	1.7 GeV
Bunch charge	27.4 pC
Bunch horiz. rms size	2.258 mm
Bunch vert. rms size	0.2253 mm
Bunch rms length	9.57 mm
Harmonic number	274
RF period	2 ns
Clearing gaps	220, 150, 70, 0 buckets
Ion cloud temperature (initial)	300 K
Neutralization level (initial)	50 %
Vacuum chamber, hor. diameter	103 mm
Vacuum chamber, vert. diameter	44 mm

The bunches were modeled with $2 \cdot 10^4$ macro-particles each, distributed according to a 3D Gaussian distribution. The ion cloud was also composed by $2 \cdot 10^4$ macro-particles, which were loaded all at once at the beginning of the simulation. Their initial distribution was chosen to be Gaussian in the transverse plane, with the same horizontal and vertical standard deviations as the bunches. In the longitudinal direction they were uniformly distributed. This initial distribution is the one that is considered to best resemble the ion generation map due to direct collisions of the beam electrons with the residual gas molecules. The composition of the cloud was chosen in accordance with the spectrometric measurements and is presented in Table 2.

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Table 2: Ion Cloud Composition

Species	Mass number	Mole-fraction
H_2^+	2	0.5
CH_4^+	16	0.08
OH^+	17	0.03
H_2O^+	18	0.1
CO^+	28	0.1
CO_2^+	44	0.16
Others	-	0.03

RESULTS

For each fill pattern, the interaction of the beam with the positively charged cloud was simulated for more than ten thousands radio-frequency periods. The settings with 0 and 70 gaps were simulated for 24 µs, whereas for the cases with 150 and 220 gaps the tracking time was 55 µs. The required computational time was in the order of two weeks per computation, on a machine with a 3.40GHz processor and 256GB of RAM.

Transverse macro-ion distributions around the beam at the end of the tracking have been computed and are shown in Fig. 1 and 2.

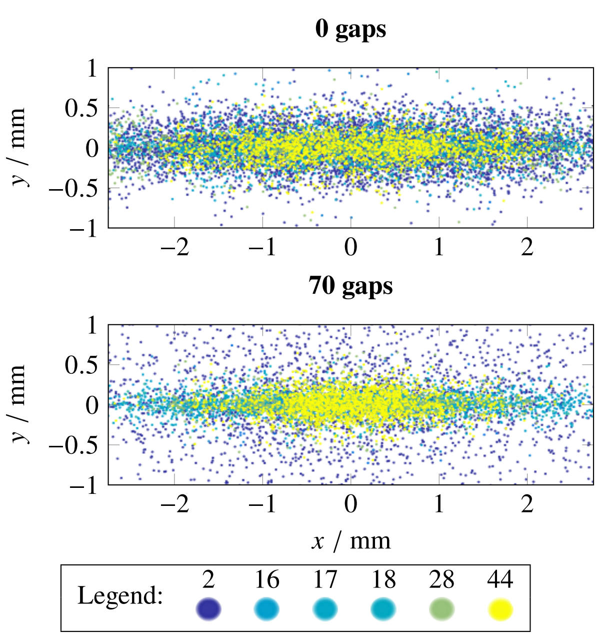

Figure 1: Transverse distribution of the macro-ions zoomed at the center of the beam pipe, after 24 µs, for the machine configuration with 0 and 70 gaps. The legend shows the correspondence between the dot colors and the ion masses in atomic mass units.

It is clear from these plots that the heavier components of the cloud seem to concentrate closer to the beam axis than the lighter ones. This is especially true for the yellow macro-

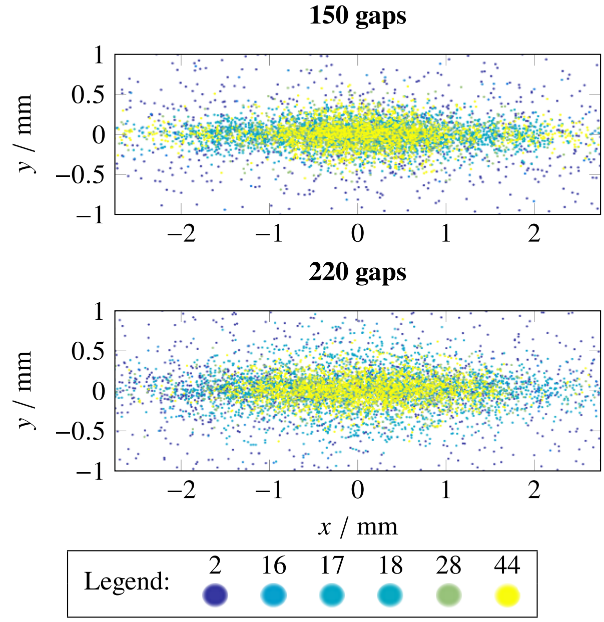

Figure 2: Transverse distributions of the macro-ions zoomed at the center of the beam pipe, after 55 µs, for the machine configuration with 150 and 220 gaps. The legend shows the correspondence between the dot colors and the ion masses in atomic mass units.

particles, corresponding to the ions of carbon dioxide, which are mostly located at the center of the plots, whereas the dark blue macro-particles, corresponding to the hydrogen ions, are much more spread out.

Furthermore, as a meaningful parameter for the ion density in the vicinity of the beam, it has been chosen the number of macro-ions which are transversally located inside an elliptic cylinder defined by the following equation:

$$\mathrm{C}_n = \left\{ (x, y, z) : \frac{x^2}{(n\sigma_x)^2} + \frac{y^2}{(n\sigma_y)^2} \leq 1 \right\}, \tag{1}$$

where σ_x and σ_y are the transverse root mean square sizes of the beam and $n = 1, 2, 3$. This quantity is then normalized to the total number of macro-ions present at the beginning of the simulation. Figure 3 and 4 show the values of the mentioned density parameter during the evolution of the cloud interacting with the beam, for $n = 1$ (blue line), $n = 2$ (red line) and $n = 3$ (yellow line).

CONCLUSION AND OUTLOOK

The transverse distribution of parasitic ions in a drift section of the ELSA stretcher ring has been computed. According to these studies, the component of the ionized gas mixture with the higher molecular mass tends to stay closer to the beam axis with respect to the region occupied by the lighter one. This result triggers speculations on the accumulation of heavy ions in the vicinity of the beam and its implications on the clearing efficiency.

Moreover, the dynamics of the charge density of the ion cloud has been presented. These simulations represent a step

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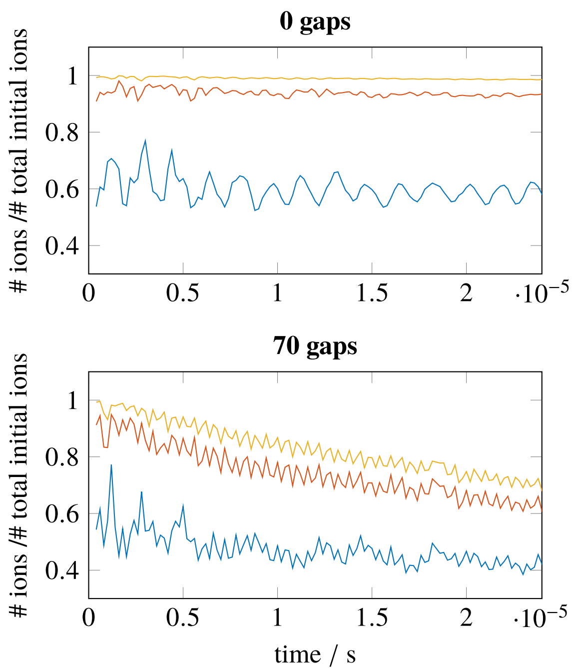

Figure 3: Time evolution of the number of ions inside the elliptic cylinder C_1 (blue), C_2 (red), C_3 (yellow), for the fill patterns with 0 and 70 gaps.

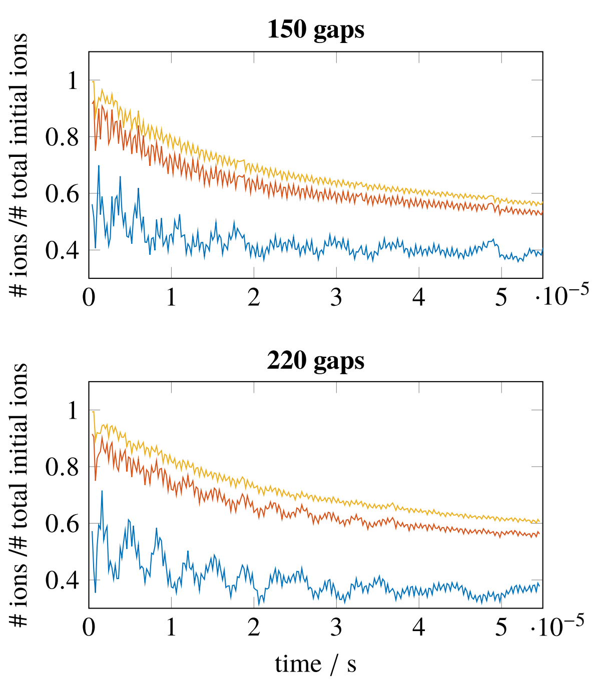

Figure 4: Time evolution of the number of ions inside the elliptic cylinder C_1 (blue), C_2 (red), C_3 (yellow), for the fill patterns with 150 and 220 gaps.

forward towards a deeper understanding of the incoherent tune shift due to parasitic ions and its characterization via BTF measurements.

Further numerical and experimental studies will follow, to map the ion density under different beam currents and in other locations of the ELSA. This will eventually allow for an accurate assessment of the ion cloud contribution to the machine tune and for a study of the distribution of the different ionized gas components also in the beam optics.

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