INVESTIGATION ON THE ION MOTION TOWARDS CLEARING ELECTRODES IN AN ACCELERATOR

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Abstract

High brightness beams provided by linac-based accelerators require several measures to preserve their high quality and to avoid instabilities, where the mitigation of the impact of residual ions is one of these measures, in particular if high repetition rates are aimed for.

Over the last decade three ion-clearing strategies: clearing electrodes, bunch gaps and beam shaking have been applied to counteract the degrading impact of the ions on the electron beam. Currently, their merit as clearing strategies for next generation high brightness accelerators such as energy recovery linacs (ERLs) are under intensive investigations with both simulations and measurements.

In this paper, we present numerical studies for the behavior of ions generated by electron bunch passages within the field of electrodes. The objective is to investigate the ion motion towards the electrodes and to study under which circumstances and up to which ratio, equilibrium between ion generation and ion-clearing is established. Hereby several ion species and shapes of electrodes are considered with typical parameters of future high current linacs.

INTRODUCTION

The ionization of the rest gas in a vacuum chamber can be caused by different effects such as collision with the electron beam, synchrotron radiation and field emission. Once ionized, the positive ions can be trapped in the negative electrical potential of the electron beam and lead to an increase of the beam halo, to emittance blowup and to transverse and longitudinal instabilities by interacting (oscillating) resonantly with the beam. There are several measures for avoiding the ion-trapping such as utilizing clearing electrodes, beam shaking or using short or long bunch train gaps also called clearing gaps.

Clearing electrodes seem to be simple and goal-oriented as they pull out the trapped ions from the vicinity of the beam. Simulation studies of the clearing process by electrodes presented in [1] have shown that the ions cannot be fully cleared out from the electron beam. A few ions remain always trapped. As the transitory bunches ionize the residual gas continuously, the question arises under which circumstances and up to which ratio, equilibrium between ion generation and ion-clearing is established and does this equilibrium exist also in the vicinity of the electrodes.

The software tool CORMORAN developed by Compaec e. G. is applied to track the ions taking into account the continuous generation of new ions according to given ionization rates. The numerical studies are performed for four different designs of electrodes with two mixtures of residual gas. Furthermore, an electron beam consisting of bunches of 2 ps rms duration with an energy of 80 MeV, a charge of 77 pC, transverse rms beam sizes of 1.4 mm and a repetition rate of 1.3 GHz is assumed. The pressure of the gas mixtures is assumed to be 10^{-8} mbar.

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ION TRACKING WITH THE TOOL CORMORAN

The software tool CORMORAN has been developed by Compaec e. G., Rostock, in order to simulate the ionization process of residual gas and to further track the generated ions over long time ranges in interaction with passing bunches and under the influence of further external fields, such as the electrical field of clearing electrodes. The interaction between ions can be neglected because only a few ions are moving simultaneously in the pipe. Furthermore, it is assumed, that the electrical fields of the high energy bunches do not change during the passage. Consequently, the field of the bunch and the clearing electrodes can be pre-computed.

Since the shape of the beam pipe plays an important role for the shape of the potential fields of the electrodes the Python Poisson Solver (Compaec e. G. [2]) is applied for the pre-computation of the fields of the electrodes.

Model of the Ionization Process

In this paper two different mixtures of residual gas are considered (see Table 1) that were already applied for the simulations in [1]. Both gases consist of H_2^+, CH_4^+ and CO^+ ions with mass numbers 2, 16 and 28, respectively. Gas A contains mainly the light H_2^+-ions, whereas the percentage of H_2^+ in Gas B amounts roughly to 50%. The tracking process starts with one ion per cm.

According to [3], an ion of species j is generated by a bunch passage at a rate of

$$R_j = c N_e \sigma_j \frac{P}{k_B T}, \tag{1}$$

where c denotes the speed of light, N_e the number of electrons in the bunch, σ_j the ionization cross-section of ion species j (see [4]), P the vacuum pressure, k_B the Boltzmann constant and T the temperature. The resulting number of bunches that are necessary to generate a new ion per cm taking into account the percentage of the molecules in the gas mixture is given in Table 1.

Clearing Electrodes

The following four types of electrodes are investigated. *Electrode 1* consists of two round electrode-plates with a

ISBN 978-3-95450-182-3

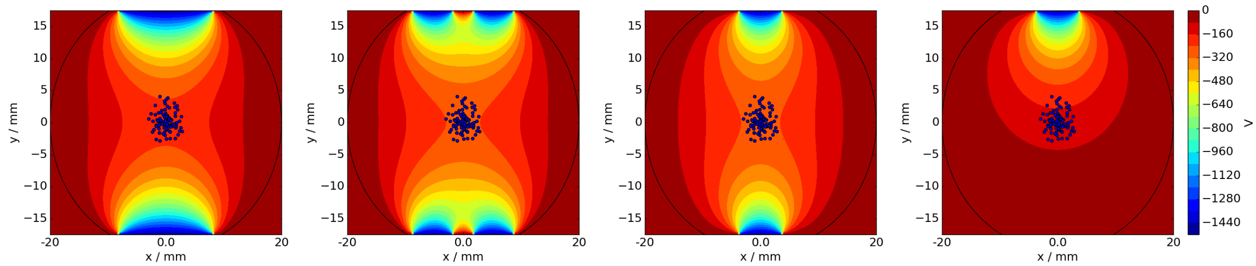

Figure 1: Potential of the electrodes 1 - 4 (from left to right), transversal cross-section shown with the first 100 generated ions.

Table 1: Mixtures of Ionized Residual Gas

ion species	**percen- tage**	**ion gener. after bunch no.**	**total no. of ions 2 cm**	**4 cm**
Gas A				
H_2^+	98 %	37	3,514	7,028
CH_4^+	1 %	565	232	664
CO^+	1 %	660	198	396
Gas B				
H_2^+	48 %	75	1,734	3,468
CH_4^+	26 %	22	5,910	11,820
CO^+	26 %	26	5,000	10,000

diameter of 16 mm positioned vertically opposite to each other at top and bottom of the beam pipe; *electrode 2* has four rectangular electrode-plates with a width of 7 mm and a length of 20 mm, placed pairwise in parallel with a distance of 4 mm whereby the pairs are again positioned vertically opposite to each other; *electrode 3* consists of two stripe electrodes each of a width of 8 mm and length of 60 mm positioned vertically opposite to each other. Hence, the potentials of these three electrodes are symmetric with respect to the y-axis. *Electrode 4* is a single stripe electrode of the same shape as the electrode 3 but only placed at top of the beam pipe. The potentials of these electrodes are shown for a voltage of −1500 V in Figure 1.

Please note that although barely visible in Figure 1, the symmetrical fields of top and bottom plates of the electrodes 1–3 cancel each other in the center of beam pipe. This diminishes the impact of the electrodes on the low energy electron bunches. The electrode 4 however has still a certain field strength in the center of the pipe which on the one hand enhances its efficiency and on the other hand could affect a low energy electron beam. The shape of the vacuum chamber is modeled as a circular pipe with flattened parts at top and bottom for the clearing electrodes as shown in Figure 1. The diameter in x-direction is 40 mm and in y-direction 35 mm.

Ion Tracking

The transverse positions of the successively generated ions correspond to a Gaussian distribution with the same transverse rms size as the bunch, whereas longitudinally the ions are uniformly distributed over a distance of 2 cm and 4 cm, respectively. The ion velocities obey the Boltzmann distribution. The bunch passage is simulated with a time step of 2 ps over 84 ps for 2 cm and over 200 ps for 4 cm interaction region, respectively. Than, the ions are tracked further with 10 time steps until the next bunch arrives. In total 65,000 bunch passages, i. e. 50 µs are simulated.

The electrons of a bunch are modeled with 1 million macro-particles generated by the *generator* procedure of ASTRA [5]. At the beginning of the tracking process with CORMORAN the potential of the bunch is pre-computed with the particle-mesh method (see [1], [2] and citations therein for more details), where Jacobi preconditioned conjugate gradients are applied as Poisson solver.

SIMULATION RESULTS

The comparison of the number of ions of the same species, that are still trapped in the beam in spite of a clearing voltage of −1500 V is shown in Figure 2 for all four electrodes simulated for a 2 cm interaction region. It can be concluded that in the volume inside the electrodes an equilibrium between ion generation and ion clearing is achieved after a short rising time of less than 1 µs. It turns out that the level of trapped ions is in all cases less than 10% of the total number of generated ions (see Table 1) and quite similar for the electrodes 1 – 3 with a small advantage towards electrode 1. As expected, electrode 4 shows the most efficient clearing. Here, the equilibrium level is only about a half of the other three electrodes.

With further simulations longitudinal boundaries of the locally restricted electrodes 1 and 2 are investigated. Here, ions were generated longitudinally over a distance of 4 cm. Consequently, the ions are not situated within the strong attracting field of the clearing electrode but get trapped by the field of the bunch. Figure 3 shows a comparison of the number of trapped ions for the electrodes 1 and 2 for both gas mixtures and two different clearing voltages: −1500 V and −2700 V. Obviously, in this case the ions accumulate even with a clearing voltage as high as −2700 V. Of course the

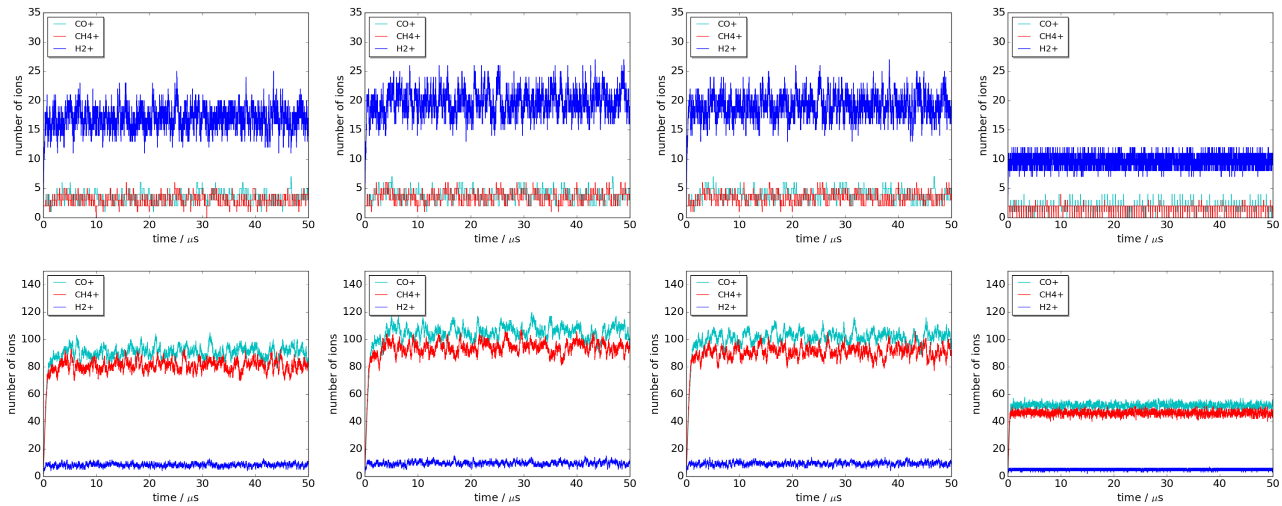

Figure 2: Comparison of electrode 1, 2, 3 and 4 (from left to right) at −1500 V. Number of ions of gas A (top) and of gas B (bottom) in the pipe generated at a length of 2 cm.

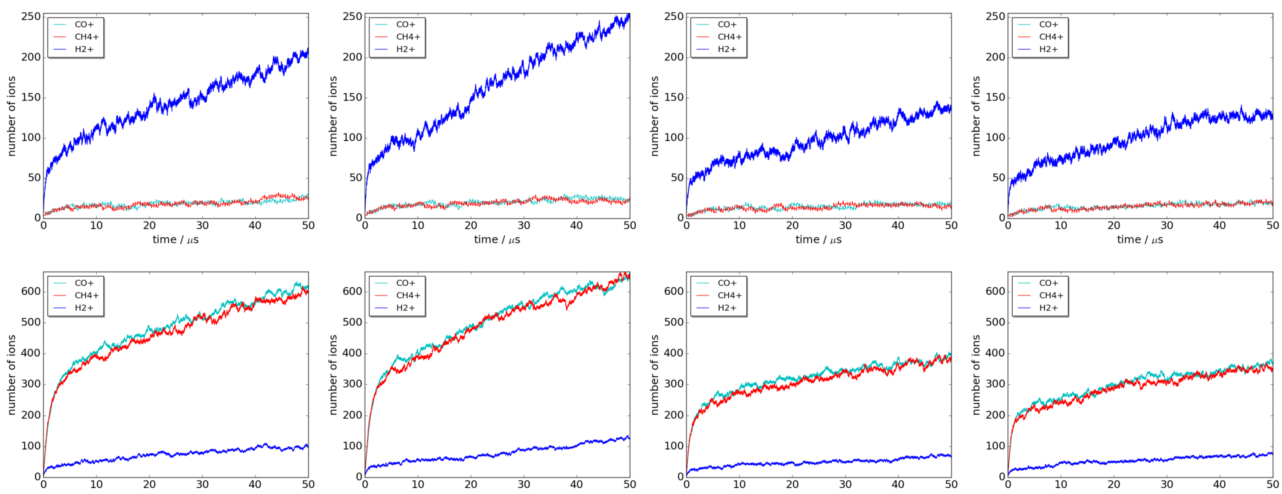

Figure 3: Comparison of electrode 1 and 2 at different voltages (from left to right): electrode 1 and 2 with voltage −1500 V, electrode 1 and 2 with voltage −2700 V. Number of ions of gas A (top) and of gas B (bottom) in the pipe generated at a length of 4 cm.

accumulation rates are higher for lower voltages. It turns out that although the clearing with electrode 1 is more efficient at the lower voltage, for a clearing voltage of −2700 V less accumulation can be observed for the heavier ions CH_4^+ and CO^+ with electrode 2. The special composition of the electrode 2 which allows for higher fields around the pipe center seems to be beneficial to clearing process of heavier ions. This is of interest because generally heavier ions tend to resist clearing attempts [6].

CONCLUSIONS

We have presented numerical studies of the clearing process of continuously generated ions by clearing electrodes, where the passing electron bunches were considered with typical parameters of future high current linacs. The ion generation and tracking was performed with the software tool CORMORAN, where the external fields of the clearing electrodes were pre-computed by the Python Poisson Solver of Compaec e. G. We investigated two gas mixtures and four different designs of electrodes partly with different voltages.

It could be proven that in the direct volume of the clearing electrodes (2 cm) all four designs have a sufficient performance. The level of trapped ions within the electrodes remains far below 10%. Outside this volume (4 cm) the ions will be accumulated. There is a hint that the special composition of the electrodes can be beneficial to the clearing process of heavier ions. Further simulation studies including the self-induced fields of the ions are necessary to explore this possibility.

ISBN 978-3-95450-182-3

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