NUMERICAL STUDIES ON THE IMPACT OF IONIZED RESIDUAL GAS ON AN ELECTRON BEAM IN AN ERL *

G. Pöplau†, U. van Rienen, University of Rostock, Rostock, Germany
A. Meseck, HZB, Berlin, Germany

Abstract

Energy Recovery Linacs (ERLs) are the most promising candidates for next-generation light sources now under active development. An optimal performance of these machines requires the preservation of the high beam brightness generated in the injector. For this, the impact of the ionized residual gas on the beam has to be avoided as it causes instabilities and emittance growth. Typical measures to reduce the effect of ion clouds are clearing electrodes and clearing gaps in the bunch train.

In this paper, we present numerical studies of the impact of ion clouds on the electron bunch train. The simulations are performed with the software package MOEVE PIC Tracking developed at the University of Rostock. The model for the bunch and the ion cloud takes into account a distribution of macro particles and particles, respectively. The interaction of the bunch with the ion cloud is computed with a 3D space charge model. Hence, particle tracking allows for detailed studies of bunch characteristics such as the emittance. Especially, we consider several mixtures of ions in the residual gas. The presented numerical investigations take into account the parameters of the ERL B*ERL*inPro with the objective to deduce appropriate measures for the design and operation of B*ERL*inPro.

INTRODUCTION

Energy Recovery Linacs put very high demands on preservation of beam brightness and reduction of beam losses. Ions in vicinity of the electrons have a ruinous impact on the brightness and stability of the beam. It is therefore important to reduce the density of ions in the vicinity of the beam to a tolerable amount. In storage rings typically ion-clearing gaps, e. g. short gaps in the filling pattern, are used. A clearing gap leads to a leak of the ion-focusing forces caused by the electron beam every time this gap travels around the ring. The length of the bunch train and of the gap are chosen to overfocus ions and let them oscillate to large amplitudes out of the beam center. In pulsed linacs, the gaps are often long enough to allow ions to drift out of the beam region. In an ERL, however, one cannot easily turn off the beam via a bunch gap, as it could interrupt the ERL process. Also many short gaps in the beam are rather undesired because they can disrupt the high current operation envisaged for most ERLs. In this context ion clearing electrodes seem to be a far desirable countermeasure.

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† gisela.poeplau@uni-rostock.de

Recently, we have presented simulations for the clearing of ionized residual gas with electrodes performed with an upgraded version of the software package MOEVE PIC Tracking [4, 5]. In this paper, we especially consider the influence of different compositions of the residual gas on the ion clearing dynamics and investigate the properties of the electron beam such as emittance. For this, several mixtures of ions in the residual gas are modelled. The data of these residual gas compositions were taken due to investigations in [4] and additionally due to recent simulations for B*ERL*inPro [1](see Table 3). The presented numerical investigations take into account the parameters of the ERL B*ERL*inPro due to [3], summarized in Table 1, with the objective to deduce appropriate measures for the design and operation of B*ERL*inPro. Further for the presented simulation studies two different beam pipe shapes are considered: a pipe with circular and with elliptical cross-section, respectively.

Table 1: Main parameters of B*ERL*inPro [3].

maximum beam energy	50 MeV
average beam current I	100 mA
nominal bunch charge Q	77 pC
maximum repetition rate	1.3 GHz
normalized emittance	1 mm mrad
bunch duration σ_t	2 ps

SIMULATION TOOL MOEVE PIC TRACKING

In the past few years MOEVE PIC Tracking has been developed at the University of Rostock for the simulation of the interaction of an electron bunch with an ion cloud including the full 3D space charge forces both of the bunch and the ions. Hereby the distribution of the electrons in the bunch are modelled as macro particles and the ions as single particles.

During the interaction time the space charge fields $\mathbf{E}_\mathrm{b}$ and $\mathbf{E}_\mathrm{i}$ are computed for bunch and ions separately at each time step in the tracking process by the particle mesh method (see [6] and citations therein). This fields are applied to the forces as follows. The force on the bunch $\mathbf{F}_\mathrm{b}$ is approximated by $\mathbf{F}_\mathrm{b} = q\mathbf{E}_\mathrm{i}$. This simplification is satisfied for low bunch charges and high beam energies. The force on the ions $\mathbf{F}_\mathrm{i}$ is computed by $\mathbf{F}_\mathrm{i} = q(\mathbf{E}_\mathrm{b} + \mathbf{E}_\mathrm{i})$. It has to be mentioned that in our implementation the field $\mathbf{E}_\mathrm{i}$ for the ions consists of two parts: the field between the ions

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Table 2: Pressures of residual gas and resulting number of ions per cm.

	pressure [mbar]	♯ ions [Mio]	♯ simulated ions [Mio]
mixture 1-3	$1.000 \cdot 10^{-10}$	30.36	1.0
mixture 4	$4.000 \cdot 10^{-10}$	212.5	2.125
mixture 5	$0.280 \cdot 10^{-10}$	14.88	1.488
mixture 6	$0.035 \cdot 10^{-10}$	1.86	1.86

and the field of the electrodes.

For an ion cloud with the extension of 1 cm an interaction time of 44 ps – corresponding to the flight time of a bunch through the cloud – was simulated in time steps of 1 ps. The further evaluation of the ions in the cloud between two bunch passages (1.3 GHz = 769 ps) was simulated with a time step of 76.9 ps.

MODELS OF ION CLOUDS

The total vacuum pressures and the composition of the residual gas were taken on one hand from studies in [4] on the other hand from recent simulations of the possible profiles of the vacuum pressure in B*ERL*inPro under three different conditions [1]. The six compositions we have chosen for the numerical studies are given in Table 3.

With the first three compositions of residual gas we have taken two mixtures from literature: mixture 2 due to studies for the Cornell ERL [2] and mixture 3 from SPEAR3 in [7]; mixture 1 is pure H_2^+ for comparison reasons (see [4]).

In case of the simulated profiles [1] the vacuum pressures vary from $4.000 \cdot 10^{-10}$ to $0.035 \cdot 10^{-10}$ mbar due to different conditions. In comparison to our earlier studies [4] the percentage of heavy CO^+ ions is with 93.7 %, 71.6 % and 26.0 % much higher.

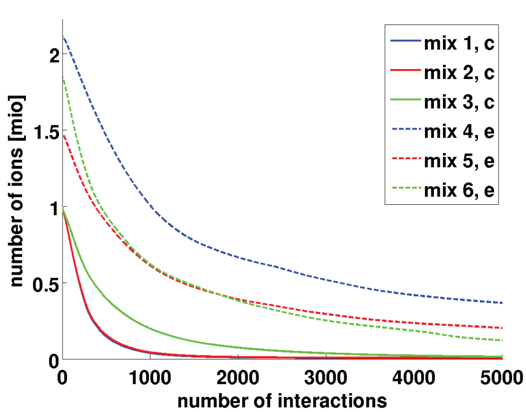

Figure 1: Clearing times of ion clouds with different compositions in a circular (solid lines) and elliptical (dashed lines) shaped beam pipe.

Table 3: Mixtures of ionized residual gas used for the simulations, mixture 2 [2], mixture 3 [7], mixture 4-6 [1].

	ion species	percentage	mass number
mixture 1	H_2^+	100 %	2
mixture 2	H_2^+	98 %	2
	CH_4^+	1 %	16
	CO^+	1 %	28
mixture 3	H_2^+	48 %	2
	CH_4^+	5 %	16
	H_2O^+	16 %	18
	CO^+	14 %	28
	CO_2^+	17 %	44
mixture 4	H_2^+	5.0 %	2
	CH_4^+	1.3 %	16
	CO^+	93.7 %	28
mixture 5	H_2^+	28.0 %	2
	CH_4^+	0.4 %	16
	CO^+	71.6 %	28
mixture 6	H_2^+	48.0 %	2
	CH_4^+	26.0 %	16
	CO^+	26.0 %	28

NUMERICAL RESULTS

The impact of ion clearing with clearing electrodes on the characteristics of the bunch were studied on a beam pipe with circular and elliptical cross-section, respectively. Hereby, the circular beam pipe has a radius of 20 mm and the elliptical cross-section has half axis of 35 mm and 20 mm, respectively. The electrodes are modelled as in [4], i. e. button-like electrodes with a diameter of 10 mm in the circular beam pipe and with a diameter of 16 mm in the elliptical beam pipe. The electrodes are located on opposite sides of the beam pipe and the voltage of each is set to the same value of 2700 V due to the observations in [5].

Ions are attracted by the field of the electrodes as well as by the field of the bunch. In the beginning mainly the ions in the neighborhood of the electrodes are cleared. Figure 1 shows the steepest descent for mixture 1 and 2, where the percentage of the light H_2^+ ions is very high. Later in the clearing process more and more ions in the vicinity of the beam are attracted to the electrodes. The field of the electrodes snatches away the remaining ions from the beam. The change in the slope of the curves in Figure 1 marks the onset of this process. It coincides with the oscillations of the horizontal emittance ε_x shown in Figure 2. After some time, the extend of which depends on the specific ion mixture, the majority of the remaining ions are located inside the bunch area. Figure 3 shows an example of the horizontal and vertical phase space of the remaining ions. The electron beam axis is at (0,0). The ions obtain strong vertical momenta aimed towards the electrodes while their horizontal momenta aim in different directions. The overall motion

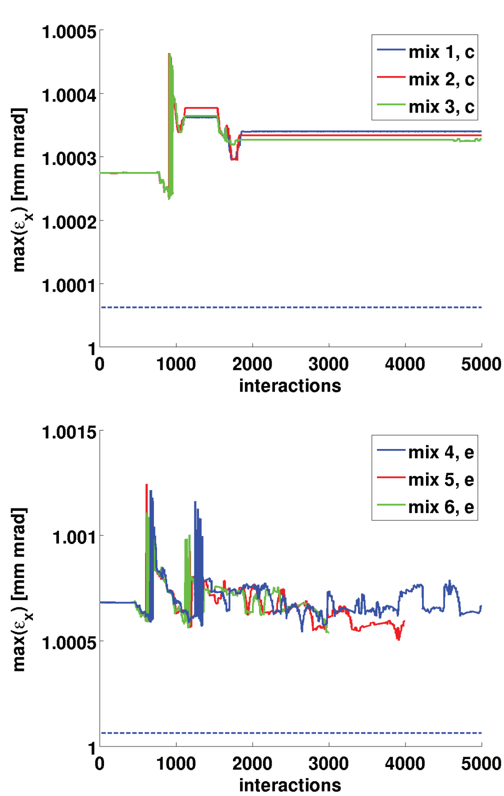

Figure 2: Maximal emittance of a bunch after interaction with different ion clouds: mixture 1 - 3 in a circular beam pipe (top), and mixture 4 - 6 in an elliptical beam pipe (bottom). The dotted line indicates the designed emittance.

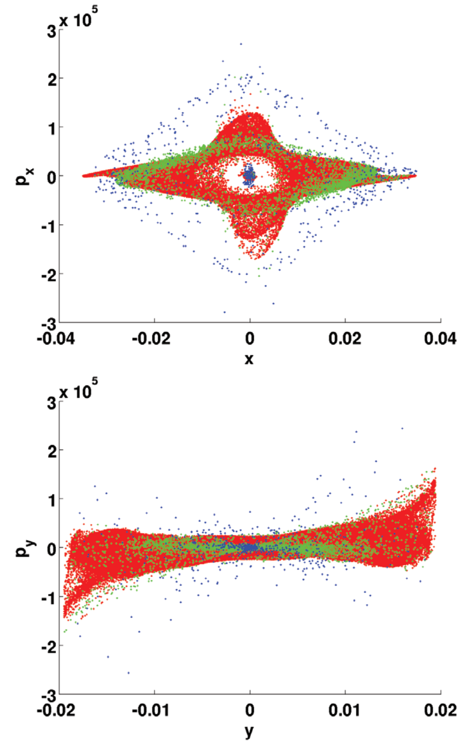

Figure 3: Distribution of the ions in mixture 4 in phase space (x, p_x) (top) and (y, p_y) (bottom) after 5000 interactions with the electron bunch, CO^+ - red, CH_4^+ - green, H_2^+ - blue.

of the ions is a spiraled motion towards the electrodes.

The oscillations in the values of the emittance vanish at some level in the case of the circular beam pipe or get much smaller within the elliptical shaped beam pipe. Please notice, that due to the different diameters, the clearing forces of the electrodes in the elliptical shaped beam pipe is larger than in the circular one. Consequently, the momentum of the ions is much larger and thus the impact on the horizontal emittance. Furthermore, in case of the elliptical shaped beam pipe we stopped the computations after 4000 interactions with the electron bunch for mixture 5 and after 3000 interactions for mixture 6, because the dynamics of the few remaining light H_2^+ ions adulterate the results such that the model is no longer applicable. The impact on the vertical emittance is quite small for all mixtures.

CONCLUSIONS

We have presented numerical studies of the impact of ion clouds on the B*ERL*inPro type electron beams utilizing the software package MOEVE PIC Tracking. We investigated several ion mixtures and two types of beam pipes, both including clearing electrodes. The circular beam pipe with a lower effective clearing field leads to an equilibrium emittance some what higher than the initial value, while the elliptical pipe with a higher effective field leads to oscillations of the emittance even after 5000 bunches. It seems however to tend to the initial emittance values on average.

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