ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI046

DYNAMICS OF ION DISTRIBUTIONS IN BEAM GUIDING MAGNETS*

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Abstract

Ions generated by synchrotron radiation and collisions of the beam with the rest gas in the vacuum chamber could be a limiting factor for the operation of electron storage rings and Energy Recovery Linacs (ERL). In order to develop beam instability mitigation strategies, a deeper understanding of the ion-cloud behaviour is needed. Numerical simulations of the interaction between electron beams and parasitic ions verified with dedicated measurements can help to acquire that knowledge. This paper presents results of detailed simulations of the interaction in quadrupole magnets and drift sections of the Electron Stretcher Accelerator ELSA in Bonn. The focus is on the evaluation of the dynamics of different ion species and their characteristic distribution in quadrupole magnets.

INTRODUCTION

The ions generated by collision in electron storage rings or energy recovery linacs can be trapped in the beam potential if the ion mass number A_{ion} satisfies following condition:

$$A_{\text{ion}} \geq \frac{N_e r_p}{2(\sigma_x + \sigma_y)\sigma_y} \triangle L_g. \qquad (1)$$

where N_e is the number of electrons and $\sigma_{x/y}$ the transverse rms. size of the bunch, r_p is the proton radius and $\triangle L_g$ is the bunch spacing. For a storage ring operation of ELSA (see Table 1) where each single bucket contains a bunch, the condition (1) yields $A_{\text{ion}} \geq 1.7 \cdot 10^{-3}$ which means that any produced ion by collision will be trapped by the beam. Depending on the operational mode and the pressure in the vacuum chamber, the density of the trapped ions can even reach the beam neutralization density i.e. equals the beam line density. The time needed for the beam neutralization τ_{col} can be computed by

$$\tau_{\text{col}} = (c\sigma_{\text{col}}\rho_{\text{gas}})^{-1}. \qquad (2)$$

The density of the rest gas ρ_{gas} is computed from the pressure p_{gas} divided by the Boltzmann constant and the temperature $\rho_{\text{gas}} = p_{\text{gas}}/(k_B T)$. The collisional cross-section σ_{col} for different ion species depends on the beam energy [1]. The collisional cross-section for H_2 ions at the beam energy of 1.2 GeV was taken to be σ_{col}=1 Mbarn=10^{-22}m^2. The neutralization time τ_{col} at 1.2 GeV computed for different rest gas pressure is given in Table 2. Obviously in the storage ring mode (Table 1), when the ion clearing electrodes are switched off, the beam is neutralized after a very short time.

* Work supported by by the German Federal Ministry of Education and Research (BMBF) under contract number 05K13HRC.

Table 1: ELSA Parameter Used in the Simulations

Parameter	Symbol	ELSA
Circumference	L	164.4 m
Beam energy	E_b	1.2 GeV
Length (rms)	σ_z	5.55 mm/18.5 ps
Emittance	ϵ_x	131 nm rad
	ϵ_y	9.4 nm rad
Betatron tune	$\nu_{x(y)}$	4.612/4.431
Momentum compaction factor	α	6.072‰
RF Frequency	RF	499.669 MHz
Beam Current	I	200 mA
Bunches	n_b	274
Bunch Charge	Q_b	0.4 nC
Electrons per Bunch	N_e	$2.5 \cdot 10^9$
β function	$\beta_{x/y}$	2.285/19.202 m
Transverse beam size (rms)	σ_x	0.570 mm
	σ_y	0.425 mm

The effects of the beam neutralization are experimentally studied at ELSA within our BMBF founded collaboration MILOS. The observed horizontal tune shift and a beam blow-up have been identified as a coherent dipole oscillation of the beam due to a beam neutralization as there is a strong correlation with the bias voltage of the clearing electrodes.

Table 2: Neutralization Times for Different Pressures

p_{gas} [mbar]	5e-8	1e-8	5e-9	1e-9	5e-10
τ_{col} [ms]	13.4	67.4	134	674	1340

INTERACTION IN A QUADRUPOLE MAGNET

In order to investigate the behavior of the ions in the horizontal plane simulations of the interaction between the passing beam and the parasitic ions are performed with MOEVE PIC Tracking [3]. Since the horizontal motion of the ions is hampered by the guiding fields of a dipole and since the clearing electrodes, whose bias voltage can be manipulated during measurements, are installed in every quadrupole, the simulations of the interaction are performed in the ELSA quadrupole QD31 (B_x = 2.526[T/m]y, B_y = 2.526[T/m]x). Typically the simulation covers several thousands of bunch passages through the ion cloud.

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Remarks about the Simulation

- The beam bunches and ions are macro-particle distributions. In case of neutralization the line charge density of the beam and ions is equal: $\lambda_{\text{ions}} = \lambda_e = \frac{N_e}{\Delta L_g}$.
- The intensity distribution of a bunch is parameterized by a Gaussian distribution of particles in each direction between -3σ and $+3\sigma$.
- Due to the focusing of the beam the average rms size of the ion cloud is smaller by a factor of $\sqrt{2}$ [1].
- The force on the bunch particles $\mathbf{F_b}$ consists of the ions space charge field $\mathbf{E_i}$ and the quadrupole magnetic field $\mathbf{B_{ext}}$:

$$\mathbf{F_b} = q(\cancel{\mathbf{E_b}} + \mathbf{E_i} + \mathbf{v_b} \times (\cancel{\frac{\mathbf{v_b} \times \mathbf{E_b}}{c^2}} + \mathbf{B_{ext}})).$$

- The force on the ions $\mathbf{F_i}$ consists of their own $\mathbf{E_i}$ and space charge field of the bunch $\mathbf{E_b}$ as well as the magnetic field of the beam and the quadrupole:

$$\mathbf{F_i} = q(\mathbf{E_b} + \mathbf{E_i} + \mathbf{v_i} \times (\frac{\mathbf{v_b} \times \mathbf{E_b}}{c^2} + \mathbf{B_{ext}})).$$

  However the longitudinal component of their own space charge field $E_{i,z}$ is switched off to prevent artificial blow-up of the ions in longitudinal direction.
- After the interaction of a single bunch with the ions (typical dt=1,2 or 4 ps), the bunch leaves the computational domain and only the ions are tracked (dt=185 ps) further during the gap until the next bunch arrives.

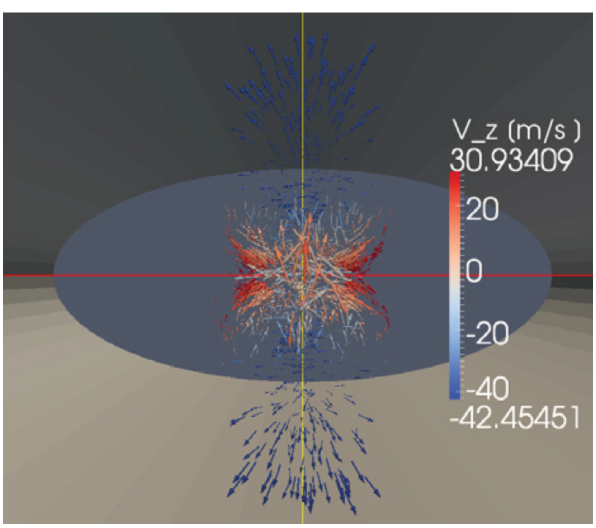

Figure 1: Ions oscillating in the quadrupole field receive a longitudinal component of the velocity.

The beam pipe has an elliptical shape (a = 51.5mm, b = 22mm) and limits the computational domain in the transversal plane with a Perfect Electric Conductor (PEC) boundary condition (b.c.). Generally the simulation shows that the ions in spite of the round beam ($\sigma_x \approx \sigma_y$, see Tab. 1) have different dynamics in $x-$ and $y-$direction (Figure 2). This can be explained by the space charge field distribution of both species which has to satisfy the PEC b.c. on the elliptical vacuum chamber and thus is different in $x-$ and y-direction. Figure 1 shows typical ion distribution during oscillation in the quadrupole field. Although the ions receive a longitudinal velocity component in the magnetic field due to the oscillation around the beam axis the net longitudinal movement can be neglected.

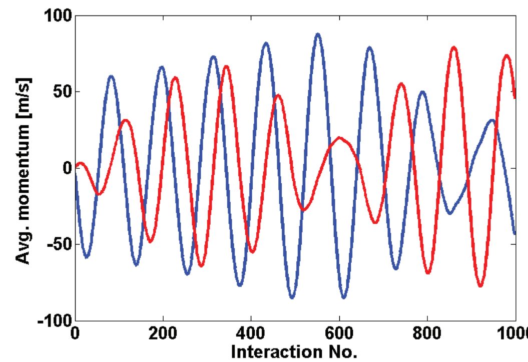

Figure 2: Average vertical (blue) and horizontal (red) velocity of the H_2 ions during interaction with 1000 bunches in a quadrupole. The ion charge density is a quarter of the beam neutralization charge density.

ION OSCILLATION FREQUENCIES

The ions perform oscillatory motion within the beam potential. The oscillations are considered to be coherent and the frequency depends on the beam parameters and the ion mass:

$$\omega_{y,i} = c(\frac{4\lambda_e r_p}{3\sigma_y(\sigma_x + \sigma_y)A})^{1/2}. \qquad (3)$$

Expression (3) is used to compute the wake fields due to the beam ion interaction which are further used to evaluate the coupled bunch instability (e.g. in [2]).

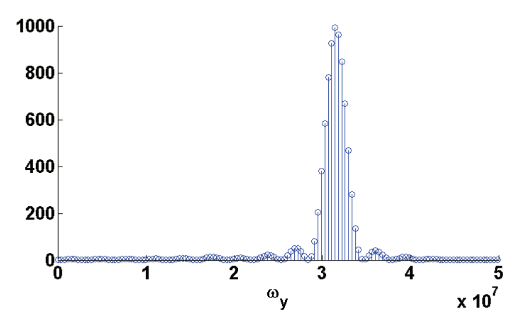

Figure 3: Oscillation frequency spectrum of the H_2 ions in a quadrupole. The ion charge density is a quarter of the beam neutralization charge density.

However the main approximation in expression (3) is the negligence of the own space charge forces of the ions which

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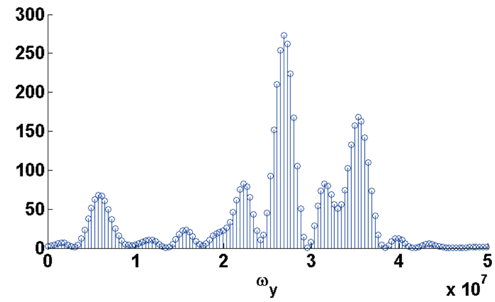

Figure 4: Oscillation frequency spectrum of H_2 ions in a quadrupole. The ion charge density neutralizes the beam charge density.

with the growing ion density increasingly destroys the coherence of their motion. The evidence of which can be seen in Figure 3 and 4, both showing the oscillation frequency of H_2 ions in a quadrupole. Figure 3 shows a coherent oscillation of the ions at a quarter of the beam neutralization density whereas Figure 4 shows incoherent oscillations with several sideband as a results of the beam neutralization of the ions. A further proof of the effect of the own space charge fields of the ions can be seen in the results of the simulations in a drift section. Figure 5 shows the frequency spectrum when the ions neutralize the beam whereas Figure 6 shows the frequency of the ions when their own space charge fields are artificially switched off. Simulations with different ion species and densities show a shift of the ion oscillation frequency towards lower frequencies with increasing ion density, which can be explained with the repulsion of the ions due to their own space charge forces.

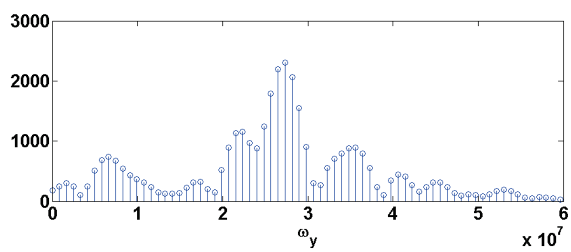

Figure 5: Oscillation frequency spectrum of the H_2 ions in a drift. The ion charge density neutralizes the beam charge density.

Observations at ELSA

The observations are results of studies on ion effects at ELSA (see [4]). Figure 7 shows the beam transfer function in horizontal direction at 100 mA, measured when the ion clearing electrodes were switched off and the ion density gradually increased. Thereby the beam is over focused and the betatron frequency increases. If the betatron frequency happens to coincide with the oscillation frequency of certain ion species a beam-ion instability may occur. The increased response at 677.6 kHz indicated such a resonant behavior and the subsequent interaction simulations of the beam with

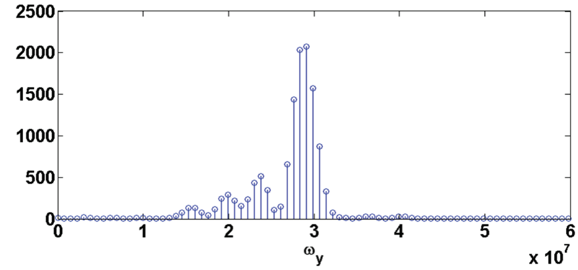

Figure 6: Oscillation frequency spectrum of the H_2 ions in a drift. The ion charge density neutralizes the beam charge density. The own space charge fields of the ions are artificially switched off.

ions of $A = 56$ (e.g. Fe^+) show an ion oscillation frequency of 671kHz as shown in Figure 8.

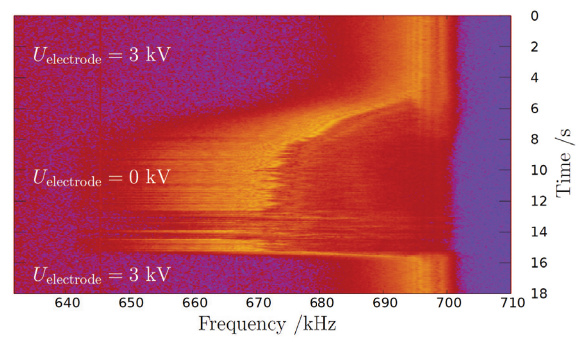

Figure 7: Beam transfer function.

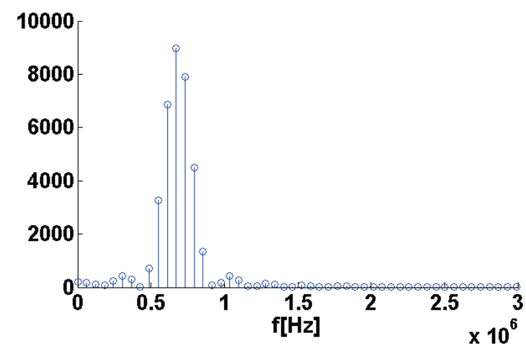

Figure 8: Oscillation frequency of iron ions interacting with 100 mA beam.

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