NUMERICAL AND EXPERIMENTAL SUBSTANTIATION OF THE ION DENSITY BEAM TRANSFER FUNCTION MEASUREMENT*

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Abstract

In the ELSA stretcher ring electrons are accelerated to a beam energy of 3.2 GeV utilizing a fast energy ramp of 6 GeV s^{-1}. Ions being generated by collision with the residual gas molecules accumulate inside the beam potential, causing incoherent tune shifts and coherent beam instabilities. Since the ion induced incoherent tune shift rises linearly with the beam neutralisation, it offers a suitable approach for evaluating the efficiency of several ion clearing measures. It was indirectly measured using a new experimental approach: By measuring the beam transfer function using a broadband transversal kicker, one was able to perceive a shift and broadening of the tune peak. Both effects could be adequately parameterized providing a quantity proportional to the incoherent tune shift and thus the average neutralisation. The impact of incoherent effects to the coherent electron beam response during the measurement has not been subject to intensive theoretical attention yet. This leaves the obtained quantity unscaled. Here new numerical simulations and experimental investigations will be presented in order to further substantiate the results of this new method.

INTRODUCTION

The **El**ectron **S**tretcher **A**ccelerator (ELSA) is a three stage electron accelerator, consisting of a linear accelerator, a booster synchrotron, and the fast-ramping stretcher ring (see Fig. 1). It is capable of providing polarized and unpolarized electrons with an energy of up to 3.2 GeV for hadron physics experiments.

When operating the stretcher ring with a continuous filling pattern, every ion species can be trapped. If the beam current exceeds certain thresholds, these trapped ions induce transverse beam instabilities. Their growth rates scale with the ion density and may lead to beam loss. Consequently the density of trapped ions has to be reduced by ion clearing measures, which can be evaluated at ELSA. In order to test their efficiency, an experimental approach was developped, allowing for an estimation of the average ion density.

It is the goal of this experimental approach to obtain information about the average ion density from the ion induced incoherent betatron tune shift applying the beam transfer function (BTF) technique. With this technique it is possible to extract information about incoherent processes from the coherent response of the beam to a known excitation. The response, a sharp peak at the betatron frequency for a low ion density, broadens and shifts to higher frequencies when the ion density increases. This broadening can be characterized by a parameter Δf, which is proportional to the incoherent betatron tune shift and thus the average neutralisation. For more information we refer to [1].

In this work, the impact of different voltages of the high voltage-biased clearing electrodes (HVCE) on the ion density was investigated using the BTF technique. The main concern of this proceeding is to focus on the numerical and experimental substantiation of this approach.

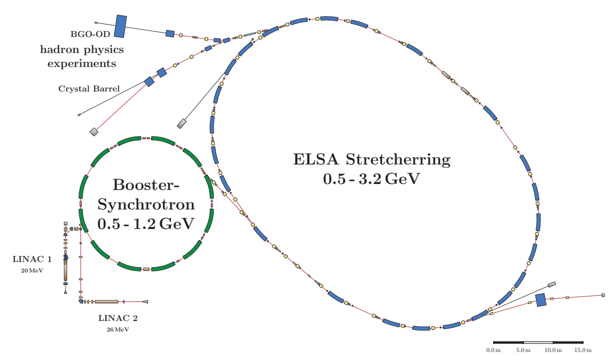

Figure 1: ELSA facility, status 2016

ION EFFECTS IN CIRCULAR ACCELERATORS

Production, Accumulation and Impact of Ions

In an electron accelerator the passing beam continuously produces charged ions. The electron beam forms an attractive potential wherein the positively charged ions can be trapped. Ion accumulation inside the beam potential consists of two adverse processes: On one hand ions are generated with a production rate R_p which mainly depends on the partial pressures of the different residual gas species and their corresonding ionization cross-sections. On the other hand every ion species has a limited life time inside the beam potential due to ion clearing measures. The inverse of the ion life time is the clearing rate R_c. Due to these adverse processes an equilibrium ion density forms which can be expressed by the local beam neutralisation $\hat{\eta}(s) = R_\mathrm{p}/R_\mathrm{c} \leq 1$. Along the accelerator with circumference C, one obtains an average neutralization with $\eta = \frac{1}{C}\int_0^C \hat{\eta}(s)\,\mathrm{d}s$.

Once the ions are trapped, the beam's repulsive electrical field caused by space charge is reduced by the superimposed space charge field of the accumulated ions, while the focussing magnetic field generated by the beam remains constant as the ions are moving nonrelativistic. This results in a decreased defocussing of the electrons whose strength is dependent on their position inside the bunch. Thus an accumulation of ions causes an incoherent betatron tune shift which increases for higher average ion densities.

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Longitudinal Drift and Ion Clearing Electrodes

The produced ions are confined in the potential and drift along the beam with termal kinetic energies. This motion is influenced by the longitudinal shape of the beam potential: Since the depth of the beam potential is inversely proportional to the beam size, it varies longitudinally along with the optical functions of the machine. The so generated longitudinal electrical field cause the ions to drift longitudinally towards the minima in the beam potential. Thus the ion density in the minima of the potential is highest.

The incoherent tune shift scales with the number of trapped ions. In order to minimize their effect, one has to reduce the number of ions. For this purpose HVCE are installed near minima and maxima of the beam potential which appear in every quadrupole. The electrodes can be biased up to −4 kV. The influence of the HVCE on the beam potential is confined to a small surrounding area and may severely change the potential in the vicinity of the electrode.

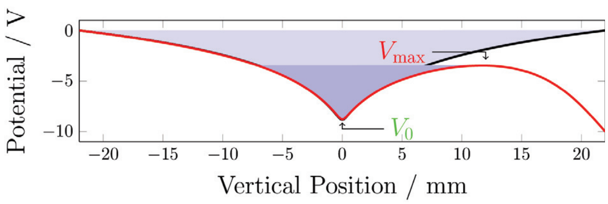

Figure 2: Vertical beam potential at 1.7 GeV and 50 mA, superimposed by the local potential of the HVCE, positioned at 22 mm, biased with −10 V (red) and 0 V (black).

TIME-INDEPENDENT η-ESTIMATION

In order to theoretically estimate the average neutralisation in an accelerator, one normally has to model the ion dynamics including production and clearing processes and space charge (SC) interactions. For an accelerator where all ion species can be trapped, it can be usefull to utilize a time-independent ansatz: Here one estimates the local ion density in its steady-state dynamic equilibrium, where the number of produced and cleared ions per time is identical. The accumulated ions shield the beam potential with initial depth $V_0(s)$ by their SC. In first order, additional ions only "see" the shielded potential $(1 - \hat{\eta}(s))V_0(s)$. Thus the accumulation will stop when the potential vanishes ($\hat{\eta}(s) = 1$). Since the ions drift with thermal kinetic energies, a steady-state with $\hat{\eta}(s) < 1$ is also possible:

If a HVCE is located in proximity to s, beam and HVCE potential superpose, thus ions can accumulate near the beam until the shielded beam potential is less attractive for new ions than the HVCE (see Fig. 2).

There can be sections, where ions can not drift longitudinally towards a HVCE, since the potential shape does not allow this. Thus ions accumulate in these so called potential wells. With increasing number of ions in the well, the local shielding increases until newly produced ions can escape and reach a HVCE.

Once knowing the beam potential in the accelerator, one can estimate the time-independent local neutralisation with

$$\hat{\eta}(s) = 1 - \frac{V_{max}}{V_0(s)} . \quad (1)$$

V_{max} denotes the local maximum of the beam potential which blocks the drift towards a HVCE. This holds true for all adjacent s where ions are produced at $V_0(s) < V_{max}$.

NUMERICAL INVESTIGATION

Since the influence of the HVCE on the longitudinal ion motion is negligibly small, ELSA's estimated local neutralisations can be separated into three contributions:

- HVCE independent, static neutralisation, $\hat{\eta}_{stat}(s)$
- HVCE dependent, static neutralisation, $\hat{\eta}_{ce}(s)$
- HVCE independent, dynamic neutralisation, $\hat{\eta}_{dyn}(s)$

In the following, these contributions will be discussed.

Dynamic Neutralisation $\hat{\eta}_{dyn}(s)$

The dynamic neutralisation $\hat{\eta}_{dyn}(s)$ is effected by the motion of ions inside the beam potential. The potential was calculated along the stretcher ring using [2]. In order to model $\hat{\eta}_{dyn}(s)$ a simple 1D ion tracking in the calculated potential was performed where transverse ion drifts were neglected. Here macro-ions, each representing 10,000 ions, of different ion species (according to estimated ion production rates at ELSA) were tracked from cradle to grave at a HVCE, using Eulers method [3]. In order to implement ion-ion SC effects, the local potential is modified to $(1 - \hat{\eta}(s))V_0(s)$. Figure 3 (bottom) shows the steady state $\hat{\eta}_{dyn}(s)$, which totals to approximately 2.4 % at 1.7 GeV and 50 mA.

Estimation of $\hat{\eta}_{stat}(s)$

The steady state neutralisation $\hat{\eta}_{stat}(s)$ is caused by the ion density, which occures due to changes in the beam pipe diameter in combination with the variation of the beam size due to changing optical functions. Here potential wells occure, in which ions can not reach a HVCE. Figure 3 (top) shows the beam potential, where localized, discrete steps result from beam pipe geometry changes. In order to identify the potential wells at position s, ions were tracked along the 1D potential until they reach a HVCE. If the tracking exceeds a certain number of iterations without the ion reaching a HVCE, a potential well exists. By consecutive ion tracking at all positions s, the well's V_{max} can be determined and the neutralisation $\hat{\eta}_{stat}(s)$ can be calculated along the well, using formula 1. The HVCE independent average neutralisation η_{stat} totals to about 1.8%.

Voltage Dependence of $\hat{\eta}_{ce}(s)$

In direct vicinity of a HVCE, the neutralisation $\hat{\eta}_{ce}(s)$ changes with the HVCE voltage. Its potential, simulated with CST EM Studio, was superposed to the beam potential in order to determine V_{max} (see Fig. 2). It varies with the HVCE voltage and is different at every HVCE since the local optical function of the machine and thus the beam potential

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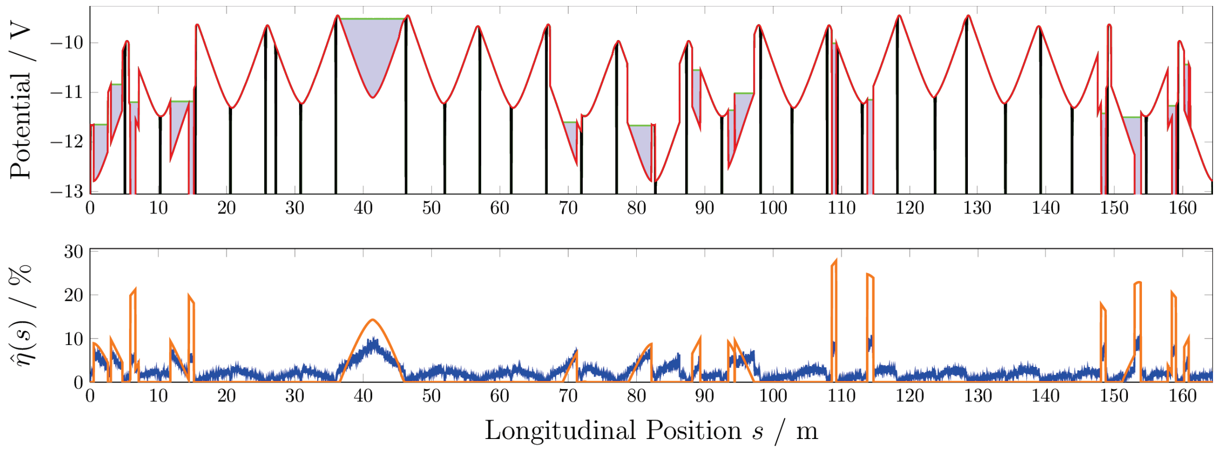

Figure 3: Top: Estimated beam potential depth at 1.7 GeV and 50 mA along the stretcher ring (red) with superimposed −3 kV-HVCE potential (black). The SC modified potential due to ion accumulation in potential wells is shown in green. Bottom: The local neutralisation $\hat{\eta}_{\rm stat}(s)$ along the stretcher ring is shown in orange and $\hat{\eta}_{\rm dyn}(s)$ in blue.

depth also changes. $V_{\rm max}$ blocks all adjacent ions, which are generated at positions where $V(s) < V_{\rm max}$, from reaching the HVCE. These ions accumulate in the potential until $(1 - \hat{\eta}_{\rm ce}(s))\, V_0(s) = V_{\rm max}$. Thus the longitudinal $\hat{\eta}_{\rm ce}(s)$-distribution, which is now a function of the HVCE voltage, can be calculated with equation 1 around every HVCE in the stretcher ring.

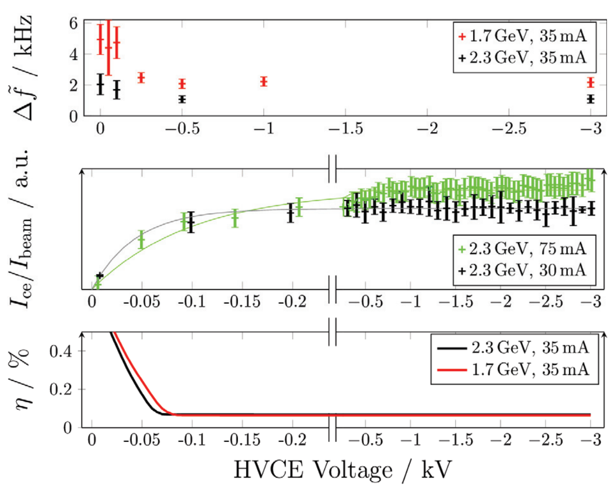

Figure 4: Top: Δf-Parameter for different HVCE voltages derived from BTF measurements. Middle: Normalized HVCE current for different beam currents with corresponding fits. Bottom: Theoretical prediction on η, summing up $\eta_{\rm stat}$, $\eta_{\rm ce}$ and $\eta_{\rm dyn}$.

COMPARISON WITH MEASUREMENTS

Applying the BTF measurement technique the Δf parameter was measured, which is proportional to the ion induced tune shift and thus the average neutralisation. Figure 4 (bottom) shows the theoretical average neutralisation, summing up all contributions $\hat{\eta}_{\rm stat}(s)$, $\hat{\eta}_{\rm ce}(s)$ and $\hat{\eta}_{\rm dyn}(s)$. It shows a plateau between −3 kV and −0.1 kV and therefore no dependence on $\eta_{\rm ce}$. For lower voltages, $\eta_{\rm ce}$ leads to a rise in η. Although the error of the BTF measurements increase for lower HVCE voltages, as can be seen in Fig. 4 (top), the behavior of Δf, and thus the average neutralisation, resembles these theoretical predictions: A plateau between −3 kV and −0.2 kV, followed by a strong increase for lower voltages. Figure 4 (middle) shows the measured HVCE current $I_{\rm ce}$ for different voltages, normalized to the beam current $I_{\rm beam}$. For low voltages ions can accumulate in the beam potential in the vicinity of the HVCE. Consequently not all accumulated ions reach the electrode. For high voltages, transverse potential wells are suppressed and all longitudinally incoming ions reach the HVCE. For higher beam currents the beam potential is deeper. Thus higher HVCE voltages are needed to saturate $I_{\rm ce}$.

The theory agrees qualitively well with all measurements, although the HVCE minimum voltage, at which η starts rising, is underestimated by the theory by roughly a factor of two. Thus the calculated beam potential depth at the HVCE seems to differ from the real one. Also $\hat{\eta}_{\rm dyn}(s)$ was assumed to be independent from the HVCE voltage, which of couse is not fully satisfied in reality. Nonetheless this method offers the possibility to roughly estimate the neutralisation level in the accelerator without time consuming numerical simulations.

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