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FIRST STUDIES ON ION EFFECTS IN THE ACCELERATOR ELSA*

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Abstract

In the ELSA stretcher ring electrons are accelerated by a fast energy ramp of 6 GeV/s to a beam energy of 3.2 GeV. The high energetic electrons ionize the residual gas molecules in the beam pipe by collisions or synchrotron radiation. The generated ions in turn accumulate inside the beam potential, causing several undesired effects such as tune shifts and beam instabilities. These effects are studied experimentally at ELSA using its full diagnostic capabilities. Both tune shifts due to beam neutralization and transversal beam-ion instabilities can be determined from the beam spectrum. Additionally the beam's transfer function can be measured using a broadband transversal kicker. In the stretcher ring at a beam energy of 1.2 GeV, a periodic beam blow-up was detected in the horizontal plane. Additional measurements of the transversal beam spectrum and ns-time resolution observations with a streak camera identified this blow-up as a coherent dipole oscillation of the beam. This horizontal instability is presumably caused by trapped ions, as there is a strong correlation with the high voltage-bias of the clearing electrodes.

INTRODUCTION

As illustrated in Figure 1, the **El**ectron **S**tretcher **A**ccelerator ELSA is a three stage electron accelerator. It consists of a linear accelerator, a booster synchrotron and the fast-ramping stretcher ring. A beam of unpolarized and polarized electrons with an energy of 1.2 GeV to up to 3.2 GeV can be provided for hadron physics experiments. Typical parameters of the stretcher ring are shown in Table 1. During high current tests at ELSA an apparent periodic beam blow-up was detected by synchrotron radiation monitors in the horizontal plane while the transversal bunch-by-bunch feedback system, which actively damps coupled bunch instabilities, was disabled. Investigations of this phenomenon substantiated further the suspicion that this effect is caused by accumulated ions, as will be discussed in this proceeding.

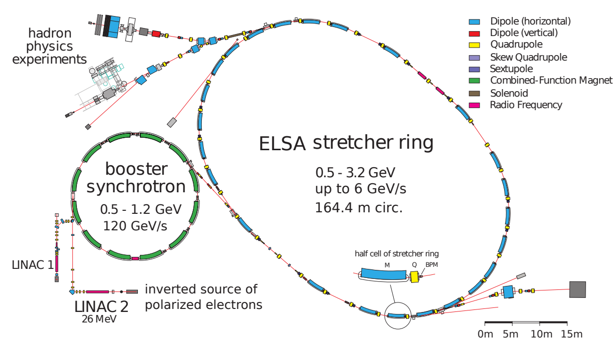

Figure 1: ELSA facility, status 2014.

Table 1: Main Operating Parameters of ELSA

Energy	1.2 to 3.2 GeV
Beam current	up to 242 mA
RF of Cavities	499.669 MHz
Revolution frequency	1.824 MHz
Horizontal tune (typ.)	4.612
Vertical tune (typ.)	4.431
Horizontal emittance	131 to 900 nm rad
Horizontal betafunction	2.4 to 17.3 m
Vertical betafunction	2.4 to 18.5 m
Coupling between planes	7.2 %
1-σ bunch length	18.5 to 80 ps
Pressure (avg.)	$5.5 \cdot 10^{-8}$ mbar

ION EFFECTS IN CIRCULAR ACCELERATORS

Production, Accumulation and Clearing of Ions

In an accelerator with finite gas pressure the passing electron beam continuously produce charged ions. Their composition mainly depend on the partial pressures of the different species in the residual gas and their corresponding ionization cross-sections. The electron beam forms an attractive potential wherein the positively charged ions can be trapped. Thus the ions accumulate inside the beam potential and neutralize the beam's charge density. Without ion clearing techniques the beam at ELSA would be completely neutralized within half a second. In order to prevent this, thus minimizing the undesired ion effects, one has to reduce the number of ions. For this purpose high voltage-biased clearing electrodes were installed at ELSA, which draw the ions away from the beam. These electrodes are placed near minima in the attractive potential which appear e.g. in every quadrupole, and are biased with typically -3 kV.

Effects of Ions on the Beam

The repulsive electrical field component of the beam's space charge field is diminished by the electrical field of the accumulated ions, while the attractive magnetic field component remains constant as the ions are moving nonrelativistic. This results in a stronger focusing of the electrons which is also dependent on their position inside the bunch. Thus an accumulation of ions causes an incoherent tune shift in the transversal planes which increases for higher ion densities.

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While ions are trapped inside the beam's potential they perform oscillations around the barycenter of the beam in the transversal plane. The oscillation frequencies, computed in the linear regime of the fields, mainly depend on the beam current and dimensions and the mass of the particular ion species. For a more realistic determination of the oscillation frequency, numerical simulations are mandatory which in addition have to take into account the effect of ion-ion space charge and (nonlinear) electric and magnetic fields [1]. This ion motion is coupled via the focusing force to the beam. In the case of an overlap between the ion oscillation frequencies and the possible transversal beam oscillation modes the ions can drive the beam to coherent oscillations. The growth rate of this so called beam-ion instability is initially proportional to the number of ions which drive the beam [2]. Because of the ion density being filamented by the shaking of the beam, the instability continue to grow non-exponential and eventually subsides when the ions are being shaken off the beam.

OBSERVATIONS AT ELSA

During the measurements presented here, ELSA was operated at a fixed beam energy of 1.2 GeV, where beam currents of up to 242 mA were stored. Because the vacuum system is not adequately suited for such high currents, we had rather bad vacuum conditions with an average pressure of up to $7.4 \cdot 10^{-8}$ mbar. During the measurements the transversal bunch-by-bunch feedback system was temporarily disabled in order to study the generation of transversal beam instabilities when operating with high beam currents.

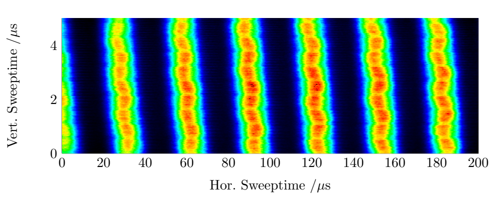

Figure 2: Streak camera scan of the horizontal coherent instability.

Periodic Beam Blow-Up

In ELSA two synchrotron radiation monitors are installed. These devices provide a direct image of the transversal beam dimensions. During the measurements a periodic blow-up of the beam dimension in the horizontal plane was detected when the feedback system was disabled. A subsequent measurement utilizing a streak camera in the slow-sweep mode allowed the monitoring of this phenomenon with nanosecond time resolution. With this method the temporal change of the horizontal beam dimension is converted to a spacial intensity distribution using a fast vertical and a slower horizontal sweep. As shown in Figure 2 a little more than nine repeating intensity patterns are visible within one vertical sweep, which undulate along the sweep axis. This corresponds to nine revolutions of the bunch train, which performs dipole oscillations with the betatron frequency. So the apparent periodic blow-up is recognized as a coherent beam instability which is periodically excited.

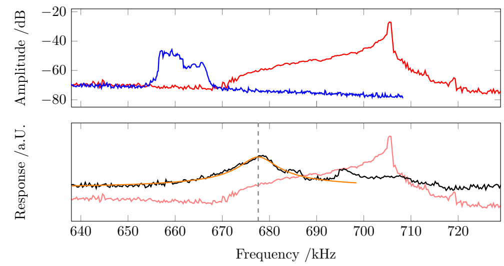

Figure 3: Beam spectrum measurement of the lower horizontal betatron sideband, measured at 100 mA.

Evidences for Horizontal Beam-Ion Instabilities

The observed coherent dipole oscillations generate sidebands in the beam spectrum, which can be measured with a spectrum analyzer connected to a standard 4-button beam position monitor. This measurement is shown in Figure 3. The red curve in the upper graph shows the time-integrated beam spectrum around the first lower betatron sideband detected at a beam current of 100 mA with the beam being horizontally instable. Coherent beam oscillations show up in a frequency range of about 40 kHz, peaking roughly at the fractional tune of 707 kHz, which is defined by the optics of the machine. As shown in Figure 4, measurements with a shorter integration time indicate that the oscillation frequency is drifting to a higher value with time. Simultaneously the amplitude of the coherent oscillations seems to rise as previous measurements with the synchrotron monitors indicate. Eventually the process which drives the oscillation stops, the oscillation is then damped by synchrotron radiation and the tune is restored to its nominal value. After some time the process starts again. These observations substantiate the suspicion that this is an effect of accumulated ions: An increasing ion density leads to an increasing positive shift of the tune. If the tune overlaps with an oscillation frequency of an ion species, a beam-ion instability can occur in which ions and the beam perform plasma oscillations. Since the ion density seems to increase during the observed instability, the ions can drive the beam to amplitudes where

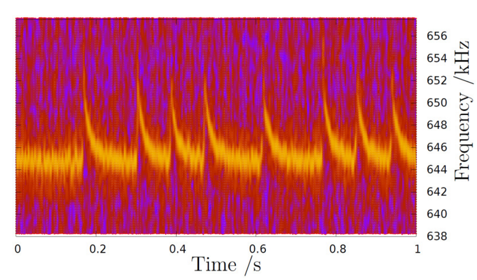

Figure 4: Dynamic behavior of the tune of the horizontal instabilities at 94 mA.

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the ions are being shaken off. When stabilizing the beam using the feedback system, thus enabling a higher ion density, one observes an instability with an even larger tune shift, as Figure 3 (blue curve) shows. The instability occurs when the tune reaches a frequency lower than 670 kHz where the feedback system cannot detect and damp this oscillations. Figure 3 (lower graph) shows a first measurement of the beam's transfer function at a beam current of 100 mA, where the response of the beam to an external excitation can be seen in the beam spectrum. One observes an increased response at around 677.6 kHz (see dashed line), which is roughly 30 kHz off the nominal tune. This can indicate the presence of a particular ion species oscillating within this frequency range [3]. Using the program MOEVE PIC Tracking, which takes into account the interactions of ions among themself as well as with the electrons, we modeled the ion beam interaction and neutralization dynamics. For this the movement of 10^6 macro-ions during interaction with 2000 bunches (10^5 macro-electrons) within ELSA's quadrupoles has been simulated allowing to determine the local oscillation frequency of an ion species (see Figure 5) and to trace the neutralization process. For heavy ions with a mass of 56 u and a beam neutralization of 25%, one obtains a peak in the oscillation frequency spectrum at 671 kHz which roughly coincide with the observed frequency. Of course other ion species with roughly equal masses are also possible candidates, which will be investigated further in additional measurements.

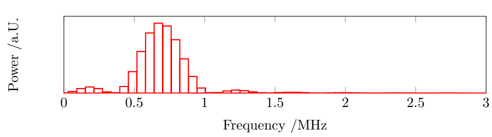

Figure 5: Horizontal frequency spectrum of ions with a mass of 56 u oscillating in the potential minimum at the quadrupole magnets, simulated with MOEVE PIC Tracking.

Influence of HV-biased Clearing Electrodes

If the observed instability is due to trapped ions, an increase of the ion density throughout the accelerator should show an effect. Therefore the high voltage (HV) of the clearing electrodes were reduced. Figure 6 shows the oscillation frequency of an instable beam, similar to Figure 4, while a reduction of the HV was carried out. This has lead to a contraction of the time difference between the start and end of the periodically occuring instability, which can be explained by the process of ion accumulation: While reducing the HV of the electrodes, the ion clearing rate is reduced, thus leading to a higher ion density. This accelerates the accumulation process, the tune shift and the growth of the instability. Since a higher ion density also reduces the oscillation frequency of the ions, the overall shift in frequency probably supports this model. The bunch-by-bunch feedback system allows to conduct grow-damp measurements, in which the initially stabilized beam amplitude can grow within 25 ms with deactivated feedback system. In this time period the amplitude of every bunch is measured every turn. Since the initial growth of the instability is exponential, one can determine a growth rate. Figure 7 shows the result of these measurements. With HV-biased clearing electrodes (red),

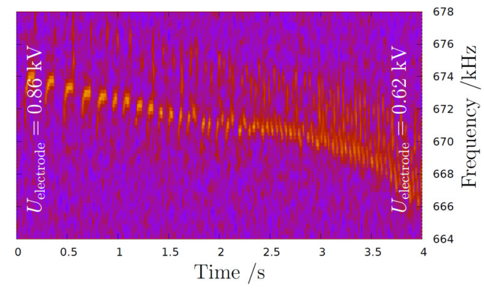

Figure 6: Influence of the clearing electrodes on the dynamic behaviour of the coherent tune of the horizontal instabilities. Measured at 1.2 GeV and 76 mA.

the growth rate exceeds the damping rate of the synchrotron radiation at around 60 mA. Above this threshold the instability's growth rate increases linearly with increasing current. Considering a stationary neutralization, the ion density increases linearly with the increasing electron density. So does the growth rate, which supports the suspicion of a beam-ion instability. When the clearing is deactivated (blue), the instability threshold is reduced and the gradient of the growth rate increment with current is a factor of about 2.5 higher, which is a clear indication for the instability being caused by trapped ions.

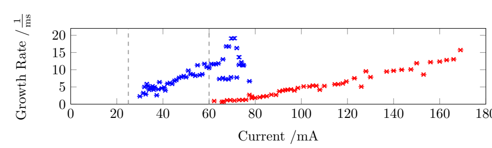

Figure 7: Measurement of the growth rates of the horizontal instabilities at various beam currents.

CONCLUSION AND OUTLOOK

First measurements at ELSA show evidences for the occurance of a horizontal beam-ion instability. The HV-bias of the clearing electrodes, respectively the ion density, has a decisive effect on the characteristics of the occurring instabilities. In near future, ion induced effects will be investigated further using ELSA's full diagnostic capabilities and detailed numerical simulations.

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