ESTIMATION OF THE ION DENSITY IN ACCELERATORS USING THE BEAM TRANSFER FUNCTION TECHNIQUE*

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Abstract

The ELSA stretcher ring of Bonn University serves external hadron physics experiments with a quasi continuous electron beam of up to 3.2 GeV energy. Ions, being generated by collisions of the circulating electrons with the residual gas molecules, accumulate inside the beam potential, causing *incoherent* tune shifts and *coherent* beam instabilities. Detailed measurements were carried out in which ion dynamics is studied in dependence of beam energy and current, filling patterns and bias voltages of the ion clearing electrodes. By measuring the beam transfer function using a broadband transversal kicker, we were able to derive an estimate of the average ion density from the shift and broadening of the tune peak. In this contribution first results of these measurements are presented.

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 Figure 1). It is capable of providing polarized and unpolarized electrons with an energy of up to 3.2 GeV for hadron physics experiments.

An energy dependent equilibrium beam emittance in the stretcher ring is caused by damping due to synchrotron radiation. Thus the resulting transversal beam dimensions are scaling with the beam energy as well, which is shown in Table 1 in which also important operating parameters of the stretcher ring are presented. This energy dependency has an observable impact on the occurrence of transversal beam instabilities when storing high beam currents. Investigations have shown that these instabilities are mainly caused by trapped ions [1]. Since the dynamics of ion generation and motion in circular accelerators is i.a. influenced by the size of the beam, these instabilities arise in the horizontal and in the vertical plane at different beam energies. The growth rates of these instabilities scale with the ion density and may lead to beam losses during operation. In order to reduce the density of trapped ions, several ion clearing measures are applied at ELSA. To evaluate their efficiency, it is essential to develop a technique to estimate the average ion density. For this purpose an approach using beam transfer functions (BTF) was developed and will be discussed in this contribution.

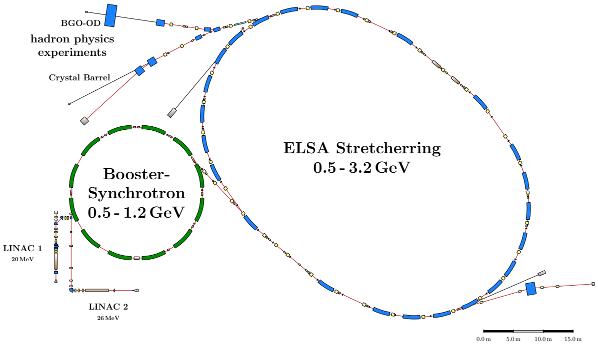

Figure 1: ELSA facility, status 2015

Table 1: Main Operating Parameters of ELSA

Energy	1.2 to 3.2 GeV
Beam current	up to 200 mA
Harmonic number	274
Revolution frequency	1.824 MHz
Horizontal tune (typ.)	4.612
Vertical tune (typ.)	4.431
Horizontal emittance	131 to 752 nm rad
Horizontal betafunction	betw. 2.4 and 17.3 m
Vertical betafunction	betw. 2.4 and 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 Impact of Ions

In an accelerator the passing electron beam continuously produces charged ions. Their composition mainly depend on the partial pressures of the different residual gas species and their corresponding ionization cross-sections. The electron beam forms an attractive potential wherein the positively charged ions can be trapped.

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* tune shift in the transversal planes which increases for higher ion densities.

Additionally trapped ions perform transversal oscillations inside the beam's potential around the barycenter of the

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beam. The oscillation frequencies, computed in the linear regime of the fields, mainly depend on the beam current and size and the mass of the particular ion species. The ions interact with the beam via their space charges. The impact on the beam can be described in the picture of a broadband impedance. In the case of an overlapping of the coupling impedance caused by the ions and the possible transversal beam oscillation modes *coherent* oscillations can be excited.

Ion Clearing Measures

The *incoherent* tune shift and the growth rate of the instabilities scale with the number of trapped ions. In order to minimize these effects, one has to reduce the number of ions. For this purpose high voltage-biased clearing electrodes (HVCE) are installed at ELSA, which draw the ions away from the beam. These electrodes are placed near extrema in the attractive potential which appear in every quadrupole, and are biased with typically −3 kV.

As an optional measure, gaps of arbitrary length in the filling pattern of the stretcher ring can be produced utilizing the bunch-by-bunch feedback system (FBS). A filling gap is generated by selective excitation of unwanted bunches during injection time, leaving their buckets unpopulated during the following operation. In this gap the attractive potential, which binds the ions to the beam, vanishes. The resulting perturbation of the motion of the ions is strongly dependent on the mass of the particular ion species and can lead to instable ion trajectories. In this case the trapped ions will escape from the attractive potential.

BEAM TRANSFER FUNCTION TECHNIQUE

The technique of BTF measurements normally is used to relate the *coherent* beam response to a known external excitation in order to extract information about the machine impedances [2]. Recent advances in theory, supported by simulations and measurements, show that it is also possible to obtain informations about *incoherent* processes [3]. These *incoherent* processes manifest in the *coherent* response of the beam to an external excitation. They emerge as additional contributions to the nominal beam response. Since the *incoherent* tune shift is proportional to the average density of trapped ions, it is reasonable to adapt this technique in order to investigate the efficiency of the ion clearing measures at ELSA.

The BTF measurements are conducted utilizing the FBS in the vertical plane: During a period of 20 ms the damping by the FBS is disabled and the beams' response to a simultaneous excitation, applied by a broadband transversal kicker, is measured. This weak excitation consists of a single frequency sweep with a broad span around the vertical betatron tune of the beam. The *coherent* beam response to this excitation is detected by a standard 4-button beam position monitor which is read out by the FBS for every bunch passage. This time domain response is converted to frequency domain by a fast fourier transformation. The *coherent* beam response to the excitation emerges as a lower betatron satellite[1] displaced from the revolution harmonics by the frequency of the excitation in the beam spectrum.

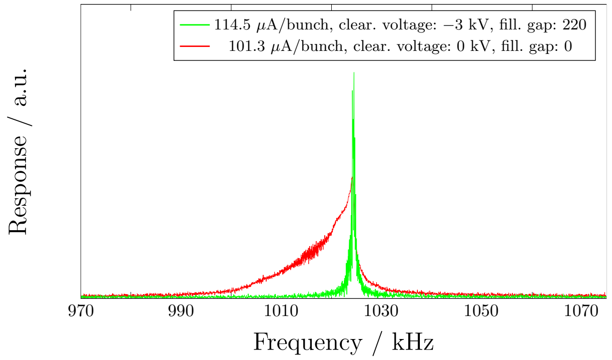

Figure 2: Exemplary BTF measurements of the lower betatron satellite for high (red) and low (green) average densities of trapped ions at a beam energy of 1.7 GeV.

ION CLEARING EFFICIENCY

Influence of Ions on the Beam Response

In order to visualize the influence of ions on the BTF measurements, Figure 2 shows two measurements with similar bunch currents but different ion densities. In one measurement (red) no clearing measures were applied, whereas in the other measurement (green) the ion density was reduced significantly by a large filling gap of 220 bunches in addition to HVCE with full-scale high voltage. For low ion densities, the beam response shows a narrow, symmetric betatron tune peak whose width is mainly determined by the chromaticity and energy width of the beam. For high ion densities, the *coherent* response extents to lower frequencies. Since the lower betatron satellite is excited, this indicates an extension to higher betatron tunes while the response peaks at the same frequency.

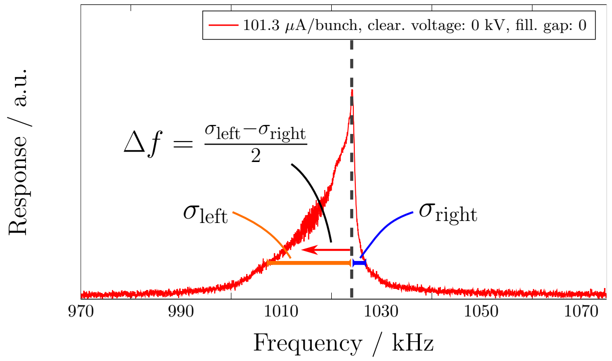

Figure 3: Visualization of the empirical analysis of the BTF measurement.

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[1] The lower satellite denotes the low-frequency betatron sideband around the revolution harmonic in the beam spectrum. It emerges in case of a *coherent* transversal beam oscillation and has a distance of the non-integer part of the betatron tune to the revolution harmonic.

Empirical Evaluation

Since we found that BTF measurements show clear indications of an influence of trapped ions on the induced *incoherent* tune shift, it seems reasonable to extract an empirical quantity representing this shift.

Figure 3 shows the concept of the analysis of the BTF measurements. In order to approximate the resonance-like beam response, two Lorentz distributions are fitted, one to the left and one to the right flank of the peak in order to extract a corresponding $\frac{1}{2e}$-half width (σ_{left}, σ_{right}) of the response. Half of the difference of these widths gives the parameter Δf, which characterizes the asymmetry of the response. This quantity is equal to zero for a symmetric tune peak and greater than zero for an asymmetric one. Therefore Δf depends on the *incoherent* tune shift and thus represents a measure of the average density of trapped ions. Normalizing the tune peaks' width and respectively Δf with the corresponding energy width of the beam, the obtained value $\Delta\tilde{f}$ can be utilized for qualitative investigations of the efficiency of the ion clearing measures.

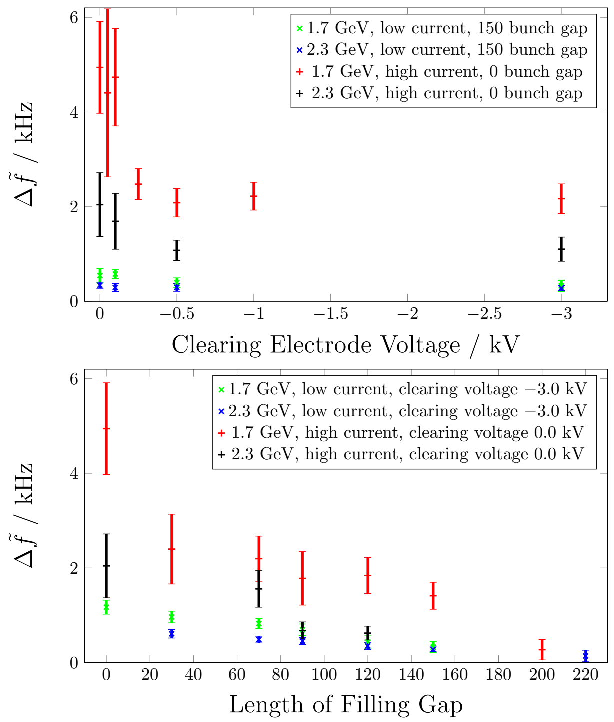

Figure 4: $\Delta\tilde{f}$-Parameter for different HVCE voltages (up) and length of filling gaps (down) for two parameter settings at 1.7 GeV and 2.3 GeV with complementary ion clearing measures being applied (red, black) and not applied (green, blue).

Implications on the Ion Clearing Efficiency

With the $\Delta\tilde{f}$-Parameter at hand, estimating the average density of trapped ions, first investigations have been conducted. The aim was to study the efficiency of the ion clearing measures which can be applied at ELSA. Therefore BTF measurements were carried out for an extensive parameter space: Beam energies of 1.7 GeV and 2.3 GeV, four different bunch current settings reaching from 40 μA/bunch to 135 μA/bunch, different settings of HVCE voltage, and different filling patterns.

The result of these measurements are shown in Figure 4. For convenience only scenarios with high (red, black) and low (green, blue) ion densities are shown.

It turned out that $\Delta\tilde{f}$ for the red and black scenario is constant between −3 kV and −500 V, thus implying a nearly constant ion density. For lower voltages the ion density rises nonlinear. Especially for high beam currents this can lead to beam ion instabilities during a BTF measurement. These *coherent* instabilities superimpose additional contributions to the BTF response, which results in larger measurement errors.

Increasing the length of the filling gap leads to decreasing $\Delta\tilde{f}$-values. Eventually for a short bunch train consisting of only 74 bunches and a corresponding filling gap length of 200 bunches respectively, $\Delta\tilde{f}$ reaches values compatible with zero. Here the ion density in both scenarios show the same asymptotic behaviour for large filling gaps.

By comparing the measurements taken at high ion densities (black, red), which differ only by their beam energy, one notices that for 2.3 GeV the decrease of the $\Delta\tilde{f}$-value is slightly steeper. This implies that for this beam energy filling gaps of approximately 90 bunches are already sufficient to reduce the ion density to that of the corresponding low-ion-density scenario (blue). This behaviour seems reasonable since the size of the beam at 2.3 GeV is, as stated earlier, larger than at 1.7 GeV, resulting in a beam potential which is less deep. Therefore the ions are more loosely bound to the beam. Thus shorter filling gaps are sufficient to clean them out.

CONCLUSION AND OUTLOOK

The dependency of the $\Delta\tilde{f}$-Parameter to the applied ion clearing measures is in agreement with our expectations. In near future these results will be compared to congruent numerical simulations with MOEVE PIC Tracking [4]. Further investigations will follow, studying the influence of the machine's impedance on the measurements. This will hopefully enable us to derive a more quantitative information on the average ion density derived from the $\Delta\tilde{f}$-value.

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