BEAM COUPLING IMPEDANCE MEASUREMENTS AT THE ANKA ELECTRON STORAGE RING

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Abstract

We present results of a series of measurements aimed at characterizing the beam coupling impedances in the ANKA electron storage ring. The measurements include transverse coherent tune shifts, bunch lengthening and synchronous phase shift as a function of single bunch current. These were performed under a variety of conditions in the ANKA ring, including injection energy (500 MeV), nominal operating energy (2.5 GeV) as well as at 1.3 GeV and in the low alpha mode and are part of a longer term effort to understand the ANKA impedance over a wide frequency range.

INTRODUCTION

Collective effects play a fundamental role in determining the ultimate performance limits of both existing and planned electron storage rings. In particular, at the ANKA 2.5 GeV electron storage ring operated by the Karlsruhe Institute of Technology in southern Germany, collective effects have been investigated since some time [1]. These studies are important to determine current limitations at the relatively low injection energy (500 MeV) adopted at ANKA as well as to shed light on the origin of the beam induced heat load in superconducting insertion device which has been in operation since 2005 [2].

The results presented in this paper constitute one step further in the on-going efforts to understand the ANKA longitudinal and transverse beam coupling impedance. Whereas previous similar experiments carried out at the ANKA machine have been performed in multi-bunch mode, the experiments reported here all make use of the recently available single-bunch mode, which was made possible by the installation of a new electron gun and timing system [3].

LONGITUDINAL MEASUREMENTS

Longitudinal impedance studies were carried out by analysis of single bunch longitudinal charge density profiles and single bunch synchronous phase shifts as a function of beam current. While the synchronous phase shifts give us information on the longitudinal loss factor, i.e., the convolution of the real part of the beam coupling impedance with the beam spectrum, the analysis of changes to the bunch profile (bunch lengthening) can give us information on the reactive part of the impedance, for currents that are low enough that the main bunch lengthening effect is potential well distortion. For higher beam currents, turbulent bunch lengthening sets in and information on the absolute value of the longitudinal coupling impedance (and possibly also on its behaviour, or characteristic roll-off at higher frequencies) can be obtained.

The single bunch longitudinal profiles and synchronous phase shifts were obtained by using a Hammamatsu C5680 [4] dual axis streak camera, which was installed at the ANKA IR1 and IR2 infra-red beamlines. In both setups, an optical system composed of mirrors, filters and attenuators was used to guide and focus visible radiation collected at dipole sources in ANKA into the input slit of the camera. A 500 MHz clock signal derived from the storage ring RF system was used to trigger the camera´s synchroscan unit (responsible for the fast vertical scan in the pictures shown below), whereas the revolution clock (or rather a submultiple of the revolution clock, given the camera repetition rate limitations) was used to trigger the slow horizontal axis.

The two types of measurements reported here (bunch length and synchronous phase shift) impose different experimental needs and challenges. In the case of synchronous phase shifts, our main interest is to accurately locate the position of the centroid of the bunch, the precise bunch length being of no relevance. This allows us to use extensive averaging of the images, without the need to compensate for the effect of inevitable synchrotron oscillations. In bunch length measurements, however, it is imperative (particularly for the shorter bunch lengths) to take the synchrotron oscillations into account by actually resolving such oscillations in each image and subtracting the resulting centre of mass motion from the overall profiles, which would otherwise result longer (for a more detailed description of this algorithm, see [5]).

Synchronous Phase Shift vs Current

Even though averaging can effectively deal with the effects of the relatively fast synchrotron motion, other (slower) effects imposed important limitations to the synchronous phase shift measurements. These include timing fluctuations in the synchroscan trigger signal delivered to the camera with respect to the RF voltage in the cavities, as well as intrinsic long term (tens of minutes) thermal drifts of the camera itself.

In order to minimize the relevance of such effects in determining the actual synchronous phase shifts, we have used not one, but two-bunch fills. In those custom-made fills, one of the bunches contains most of stored current, whereas the other very weak bunch serves as a timing

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reference for the first one. The two bunches must be spaced by an odd number of buckets, since our streak camera operates at a synchroscan frequency of 250 MHz (i.e., half the RF frequency) and therefore even and odd bunches show up as two distinct horizontal regions on the streak-camera image when dual axis operation is used. Finally, since one of the bunches is observed along the upward synchroscan sweep, whereas the other is observed along the downward sweep, it is the average (sum) position of the two observed peaks that carries the information on the relative time position of the two bunches. In fact, this average position is then largely insensitive to phase variations of the synchroscan 500 MHz trigger signal with respect to the RF voltage in the storage ring cavities.

Figure 1 shows an example of averaged dual axis image with two bunches stored in the machine and the corresponding averaged fitted profiles. The average of the positions of the two peaks contains the information on the synchronous phase (or the difference in synchronous phase for the two bunches) and its variation with beam current (or rather with the difference in current between the two bunches) is related to the longitudinal loss factor.

Figure 2 shows a short term (1 min) stability estimate of the synchronous phase measurement obtained using the method described above. We note that, even though the effects related to external timing fluctuations can be effectively eliminated by the use of the reference bunch, longer term drifts (possibly associated with thermal drifts in the camera itself) still persist and are, at present, the limiting factor in determining small synchronous phase shifts. These longer drifts show rates of several tens of fs per minute in the first few minutes and an exponential-like decay.

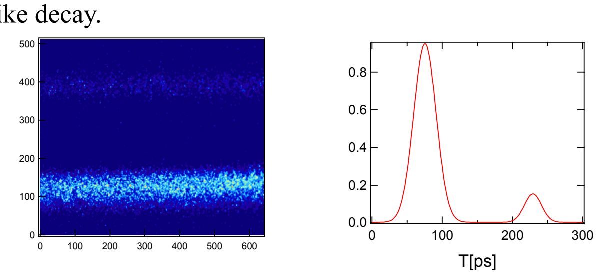

Figure 1: Typical dual-axis streak camera image (left) in two bunch fill and corresponding fit profile (right). Fast axis (vertical): 300 ps. Slow axis (hor): 2 ms.

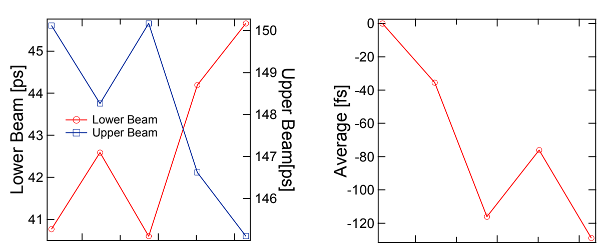

Figure 2: Short term stability test of synchronous phase measurements. Individual peaks move by up to 5 ps, whereas the average moves by up to 120 fs.

Figure 3 shows an example measurement of synchronous phase shift as a function of beam current obtained at 1.3 GeV in the low alpha (*squeezed*) mode.

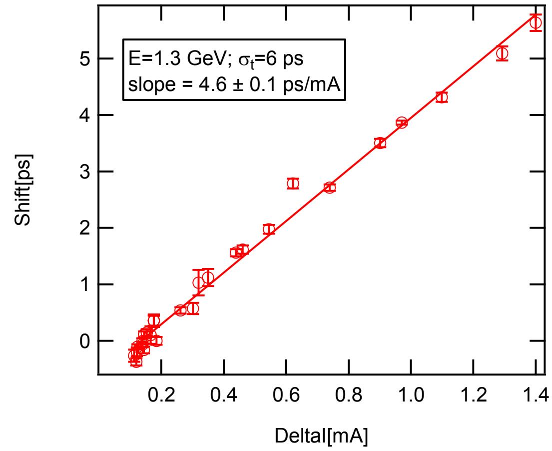

Figure 3: Synchronous phase shift measurement at 1.3 GeV.

Experiments were performed at 1.3 GeV with two different optics, with varying momentum compaction factor, corresponding to natural bunch lengths from 3 to 8 ps. The longitudinal loss factor was determined from the fitted slopes of synchronous phase as a function of current using the relation:

$$k_{loss} = \frac{V_0}{T_0}\cos(\phi_s)\frac{d\phi_s}{dI},$$

where V_0 is the peak RF voltage, T_0 is the revolution period, ϕ_s is the synchronous phase and I is the average beam current. Table 2 summarizes the results, indicating the expected increase in loss factor for shorter bunches.

Table 2: Summary of Synchronous Phase Shift Measurements.

Energy [GeV]	**Natural bunch length [ps]**	**Loss factor [V/pC]**
1.3	14.2	10.3
1.3	6	23.5

Bunch Lengthening

Bunch lengthening was measured as a function of single bunch current at three different energies for the standard (*non-squeezed*) optics, allowing us to cover both the potential well distortion as well as the turbulent regimes. The measured RMS bunch lengths as a function of current were fitted according to the expressions below[6]:

Potential Well Distortion:

$$\left(\frac{\sigma}{\sigma_0}\right)^3-\left(\frac{\sigma}{\sigma_0}\right)=\frac{1}{\sqrt{2\pi}}\frac{\alpha I}{Q_s^2\,\frac{E}{e_0}}\frac{1}{(\omega_0\sigma_0)^3}\left(\frac{Z}{n}\right)_0$$

Turbulent bunch lengthening:

$$\left(\frac{\sigma}{T_0}\right)^3=\frac{1}{(2\pi)^3\sqrt{2\pi}}\frac{\alpha I}{Q_s^2\,\frac{E}{e_0}}\left|\frac{Z}{n}\right|_0$$

and the corresponding values for the low frequency reactive longitudinal coupling impedance (potential well distortion regime) and the absolute value of the longitudinal impedance are summarized in Table 3.

Figure 4 (right) shows an example of such a fit for the 1.3 GeV case. For that energy, and for the range of currents used in the experiment, we expect to be below the threshold for turbulent bunch lengthening. The same procedure was used for the analysis of the 2.5 GeV data sets. On the other hand, for 500 MeV (**Figure 4** left), we expect to be above the threshold and use correspondingly the expression for that regime.

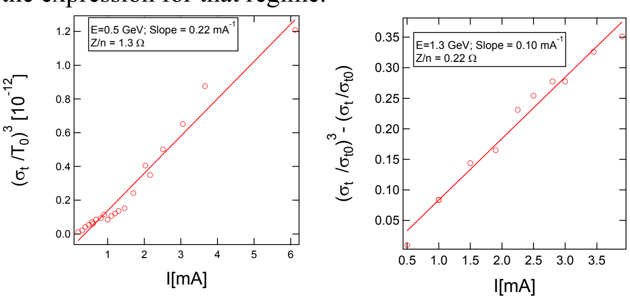

Figure 4: Bunch lengthening as a function of single bunch current at 500 MeV and 1.3 GeV.

Table 3: Summary of Bunch Lengthening Measurements

Energy [GeV]	Regime	Z/n [Ω]
2.5	PW Distortion	0.8
1.3	PW Distortion	0.22
0.5	Turbulent	1.3

TRANSVERSE MEASUREMENTS

The betatron tune shifts were measured with a TEKTRONIX RSA 3303A real time spectrum analyser connected to a button pickup. Excitation of betatron motion is accomplished by a set of stripline kickers fed from a white noise source. Although experiments were performed both at injection and intermediate energies, significant shifts as a function of single bunch current could only be observed at injection, **Figure 5** shows the measured vertical betatron tune as a function of average single bunch beam current.

Taking an average of 10 mm for the measured bunch length at injection energy (which is largely determined by turbulent bunch lengthening and is much longer than the natural bunch length), we obtain an estimate for the reactive transverse (vertical) coupling impedance of Z = 72 kΩ/m, somewhat smaller than the value obtained previously with a multi-bunch beam [1].

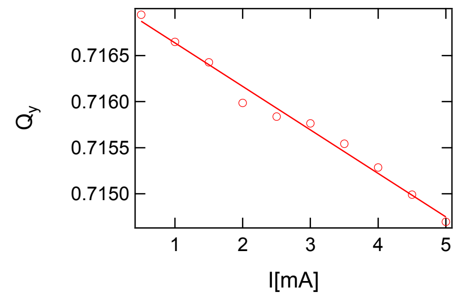

Figure 5: Vertical tune shift as a function of single bunch current.

The corresponding horizontal tune shift is much smaller and presents a positive slope [1].

SUMMARY

We have presented results of longitudinal and transverse impedance measurements in the ANKA storage ring. Measurements performed with a single bunch under a variety of conditions indicate a longitudinal loss factor ranging from 10 to 23 V/pC, a reactive longitudinal impedance ranging from 0.2 to 0.8 Ω and an absolute value for the longitudinal impedance of 1.3 Ω. The vertical impedance was measured to be 72 kΩ/m. These results are smaller than but still consistent with previous measurements performed in multi-bunch mode given the experimental uncertainties. Further experiments are necessary before a complete understanding of the ANKA impedance and its frequency dependence can be obtained.

ACKNOWLDGEMENTS

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