EVALUATION AND MODELING OF LONGITUDINAL STORAGE RING IMPEDANCE USING CURRENT DEPENDENT BUNCH LENGTHENING AND BUNCH DEFORMING EFFECTS

K. Dunkel*, U. Berges, M. Grewe, R. Heine, T. Weis,
DELTA, University of Dortmund, D-44221 Dortmund, Germany

Abstract

DELTA is a 1.5 GeV synchrotron radiation facility. The storage ring has been designed especially for low longitudinal impedance to allow also for high electron densities in the case of few bunch operation besides the standard multibunch operation mode. Bunch length and longitudinal bunch profile depend on bunch charge as well as on the longitudinal impedance as major factor of influence. Measurement of turbulent bunch lengthening and potential well distortion effects on optical basis using a streak camera turned out to be an excellent tool to evaluate the longitudinal impedance.

The paper presents experimental data concerning bunch lengths and longitudinal profiles for various beam energies, intensities and RF-settings as well as theoretical aspects (impedance modeling of the storage ring). The analysis using the Keil-Schnell-Boussard criterion confirms the theoretical value of the impedance. The paper also presents results concerning the influence of two small gap insertion devices and a 3rd harmonic cavity.

1 INTRODUCTION

The 1.5 GeV electron storage ring DELTA is mainly operated as a local user dedicated synchrotron radiation source with a total of 3000 hours of beam time per year [1]. Besides the standard multibunch operation, DELTA also provides a single and few bunch operation mode also at lower energies (see table 1). During the design and construction of DELTA, impedance has been a major point of interest and concern to ensure FEL operation at low energies [2]. First theoretical and numerical calculations based on a broadband model for the longitudinal impedance [3] came up with a broadband impedance as low as Z/n = 0.37 Ω for the "bare" machine without insertions. To keep track with the ongoing completion of the machine (small gap devices, Landau cavities) and to evaluate the influence on few and single bunch operation parameters (mainly bunch length, electron density and corresponding Touschek lifetime) a program has been set up to constantly characterize the longitudinal impedance of the machine. First of all we used time domain numerical methodes to characterize the longitudinal impedance of the machine on a more theoretical basis as well as synchrotron radiation based optical diagnostics of single bunches, where the current dependent bunch lengths and shapes (via potential well distortion) have been analysed giving information on the resistive and inductive part of the impedance. In addition the turbulent bunch lengthening effect at high single bunch currents have been used to gain information on the more general broadband behaviour of the longitudinal impedance.

	single bunch at 540 MeV	multi bunch at 1.5 GeV
mom. compaction α	0.0053	0.0053
beam current/lifetime	25 mA/20 min.	120 mA/>10 h
bunch length (I = 0)	8.1 ps	37.8 ps
natural energy spread	0.025%	0.069%

Table 1: DELTA beam parameters

2 IMPEDANCE MODELING

2.1 Impedance Budget of Vacuum Chamber

Time domain analysis of Gaussian shaped electron bunches for each component of the DELTA vacuum chamber (MAFIA-code [4]) together with a fast Fourier transformation have been used to determine the complex longitudinal impedance Z(ω) from the calculated wake potentials. For realistic bunch lengths available at DELTA the influence of space charge impedance ($|Z/n|_{sc} \leq 1 m\Omega$) and capacitive effects on the longitudinal impedance can be neglected. Major contributions are then merely resistive and inductive and can be deduced from the complex Z(ω) giving effective values for the inductive and resistive behaviour at a given bunch length.

2.2 Resistive Wall Impedance

The complex resistive behaviour is given by Eq. (1) depending on the geometric length L, specific resistance ρ, effective radius of the tube r_{eff} and the skin depth δ_{skin}.

$$Z_{rw}(\omega) = (1 + \mathrm{sgn}(\omega) \cdot i) \frac{\rho \cdot L}{2\pi \cdot r_{eff} \cdot \delta_{skin}(\omega)} \quad \textbf{(1)}$$

The keyhole shaped vacuum chamber cross section has been replaced by an effective tube radius r_{eff} to be determined by a numerical method taking the mirror currents into account [5].

2.3 Geometrical Impedance

As mentioned above time domain analysis of Gaussian shaped electron bunches have been performed for each component of the DELTA vacuum chamber. We used 2D-calculations for cavities, small gap insertion devices,

*new affiliation: ACCEL Instruments GmbH, Bergisch Gladbach, Germany, dunkel@accel.de ceramic gaps, RF shieldings of bellows, for welding seams and valves and 3D-calculation for injection and diagnostic kicker chambers, special pumping chambers, beam position monitors (BPMs) and scrapers. The effective geometric resistance R and effective inductance L for each component is then deduced using Eq. (2, 3).

$$R = \mathrm{Re}\left(\frac{\int_{-\infty}^{\infty} V_{wake}(\omega) \cdot I^*(\omega) d\omega}{\int_{-\infty}^{\infty} I(\omega) \cdot I^*(\omega) d\omega} \right) \quad \textbf{(2)}$$

$$L = \mathrm{Im}\left(\frac{\int_{-\infty}^{\infty} V_{wake}(\omega) \cdot \omega I^*(\omega) d\omega}{\int_{-\infty}^{\infty} \omega I(\omega) \cdot \omega I^*(\omega) d\omega} \right) \quad \textbf{(3)}$$

Here V_{wake} is the wakepotential and I, I^* the spectral beam current and its conjugate complex respectively [5].

2.4 Results of Impedance Modeling

The overall effective geometric inductance L and resistance R for short range wakefield effects is the sum of all the individual contributions of the components. L and R versus bunchlength is given in figure 1.

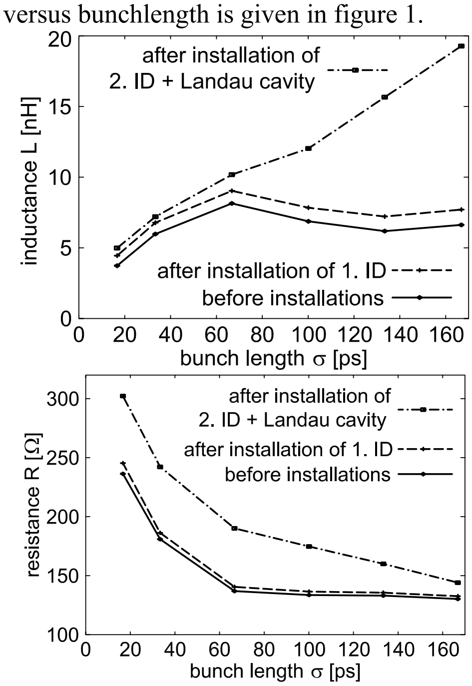

Figure 1: Overall effective L and R versus bunch length for resistive wall and geometrical impedance.

The influence of two insertion devices with vertical gaps of 10 mm (1. ID) and 14 mm (2. ID) could clearly be identified as well as the effect caused by a 1.5 GHz third harmonic cavity (Landau cavity).

3 ANALYSIS OF POTENTIAL WELL DISTORTION EFFECTS

The effective inductance and resistive impedance can also be determined from potential well distortion effects.

3.1 Theoretical Background

With increasing bunch charge the original longitudinal Gaussian shape is distorted by the inductive part L of the impedance causing a bunch lengthening and by the resistive part R causing an asymmetric shape as indicated in figure 2 (experimental data). The transformation of the longitudinal charge distribution λ(τ) is governed by an integro-differential equation (Eq. (4), for details see [5,6]) being a solution of the Vlasov equation

$$\lambda(\tau) = N_b A_\lambda \exp\left(-\frac{1}{2}\frac{\tau^2}{\sigma^2} + aL\lambda(\tau) + aR\int_0^\tau \lambda(\tau')d\tau' \right) \quad \textbf{(4)}$$

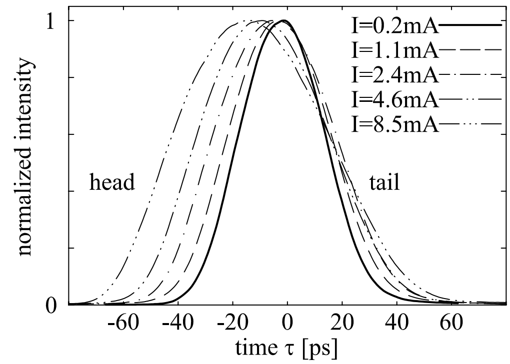

Figure 2: Example for measured longitudinal particle distributions with varying single bunch current.

3.2 SR-Diagnostics, Experimental Setup

The diagnostic beamline uses synchrotron radiation from a 3° bending magnet and parasitical parts of the FEL/UV-beamline [2]. A dual time scan streak camera (Photonetics) is situated outside the radiation shielding. It is triggered with 1/4 of the radiofrequency (500 MHz); the second, slow trigger (few Hz) is synchronised to the storage ring revolution frequency (2.6 MHz).

3.3 Image Data Post Processing

In order to get longitudinal intensity bunch profiles (time scale picoseconds) with low noise we average over many revolutions (time scale milliseconds) taking synchrotron oscillations into account.

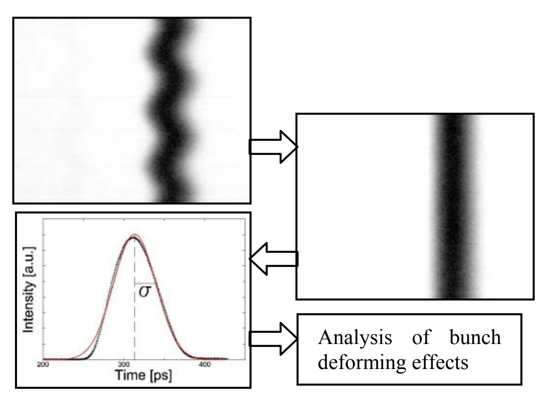

Figure 3: Post processing of streak camera data

This is achieved by image data post processing, where each pixel is normalized with respect to the numerically obtained center of the bunch. In addition to the determination of the bunch length by a Gaussian fit a further analysis of bunch deforming effects are performed (see figure 3) giving the line charge density λ of Eq. (4). For details see [5].

3.4 Results of Potential Well Distortion Analysis

Measured longitudinal bunch profiles (see e.g figure 2) have been analysed with respect to Eq. (4) using a least χ^2-fit with free parameters R and L, energy spread and center of the bunch. The effective inductance L and resistance R as a function of the bunch lengths are given in figure 4.

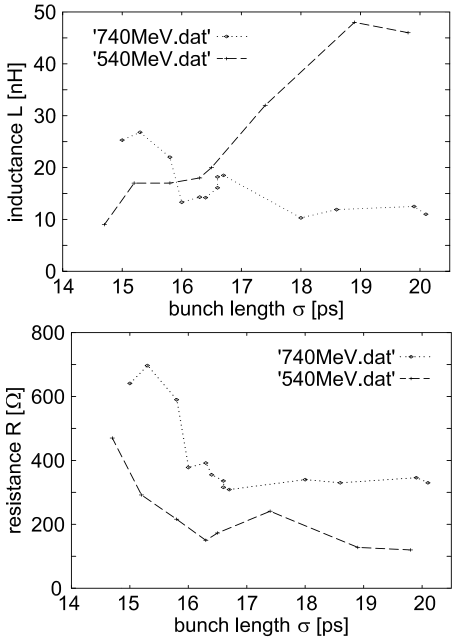

Figure 4: Effective inductance L and resistance R obtained from measurements at 540 and 740 MeV.

4 TURBULENT BUNCH LENGTHENING

In addition the bunch length has been determined as a function of the single bunch current (see figure 5) using a Gaussian fit to the image data. At high single bunch currents the turbulent bunch lengthening instability occurs. For high bunch currents I the bunch length scales with $(|Z/n|*I)^{1/3}$.

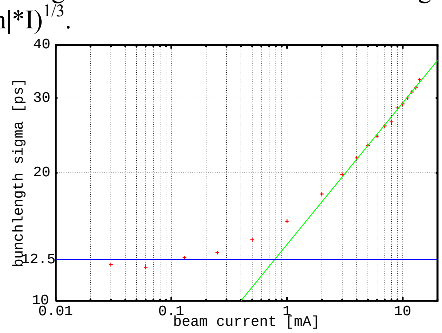

Figure 5: Bunch length versus single bunch current (typical experimental data)

Using the Keil-Schnell-Boussard criterion [7] we were able to determine the normalized broadband impedance |Z/n| over the past three years (see figure 6). They are in agreement (within a factor of 2) with data calculated for the machine without insertions [3] and show clearly the impedance increase after installation of the insertions and the Landau cavity.

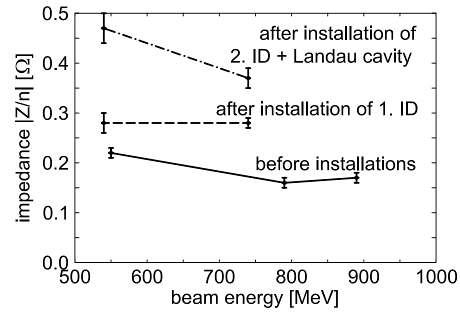

Figure 6: Influence of installed insertion devices and Landau cavity on impedance of DELTA.

5 CONCLUSION

Effective resistive and inductive impedances have been deduced from the longitudinal impedance $Z(\omega)$ evaluated from time domain numerical calculations. The effective values L and R can also be obtained from the analysis of bunch deformations caused by potential well distortions. The obtained results from theory and experiment for the resistive part R are in good agreement. The experimental result for the inductive part L fits within the same order of magnitude to the theoretical one but L seems to be also a function of the beam energy, an effect which will be subject of further studies. The broadband impedance |Z/n| evaluated via the turbulent bunch lengthening effect is in good agreement with numerical studies within a factor of 2. Both methods (effective resistive and inductive impedance and broadband impedance) turned out to be applicable to monitor the development of longitudinal machine impedance with time in a rather effective way.

6 REFERENCES

[1] G. Schmidt et al., "Status of Synchrotron Light Source, DELTA", this conference

[2] D. Nölle et al., "First Lasing of the FELICITA I FEL at DELTA", Nucl. Instr. Meth. A 445 (2000) 128

[3] M. Negrazus, "Optimierung und Messung der Longitudinalen Kopplungsimpedanz von DELTA", thesis, Dortmund University, Germany, 1994

[4] R. Klatt et al., "MAFIA – A Three-Dimensional Electromagnetic CAD System for Magnets, RF-Structures and Transient Wake-Field Calculations", LINAC 1986

[5] K. Dunkel, "Monitoring the Longitudinal Vacuum Chamber Impedance of DELTA", thesis (in German), Dortmund University 2002, to be published

[6] M. G. Billing, "Bunch Lengthening via Vlassov Theory", Cornell University Report No. CBN 80-2, USA, 1980

[7] D. Boussard, CERN Report MPS/DL-75/5, 1975