MEASUREMENTS OF BROAD BAND IMPEDANCE RELATED LONGITUDINAL PROPERTIES OF ELECTRON BUNCHES AT DELTA

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Abstract

DELTA is a 1.5 GeV synchrotron light source which can be operated also at 550 MeV for FEL experiments. Due to interactions with the vacuum chamber, the beam induces wake fields, which act back on the beam and result in a disturbed bunch profile because of potential well distortion and turbulent bunch lengthening. These interactions limit the obtainable bunch length and achievable peak current and therefore strongly affect the FEL-operation. Recent results obtained by streak camera measurements have shown that for short bunches with maximum bunch lengths of 40 ps the longitudinal broad band impedance has to be scaled (SPEAR-scaling) to explain the measurements. The broad band impedance fits well to impedance measurements and calculations performed throughout the last years. The energy spread related to the bunch lengthening has been measured by analysing the undulator spectrum.

INTRODUCTION

The synchrotron radiation facility DELTA is mainly operated at 1.5 GeV in multibunch mode with a beam current of 130 mA and lifetimes up to 10 h for user dedicated research at the beamlines (bl) (see figure 1).

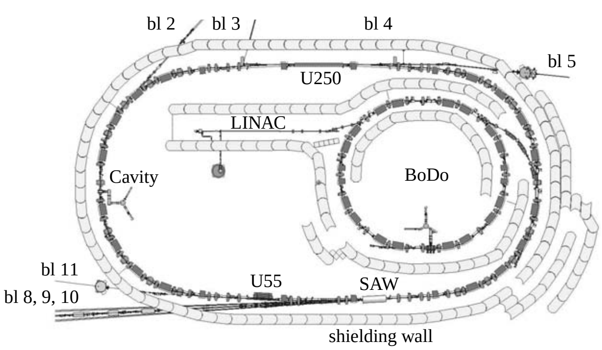

Figure 1: Schematic layout of the accelerator complex.

The storage ring can also be operated at 550 MeV for FEL operation in single bunch or few bunch mode with average single bunch currents up to 20 mA and lifetimes of appr. 15 min. The FEL consists of a planar electromagnetic undulator U250 and two mirror chambers in the northern straight section of the facility. Since the FEL gain scales linearly with the electron density it is essential to achieve high peak currents (at least about 20 A in the case of DELTA).

Because of interactions between the bunches and the vacuum chamber wakefields are induced which act back on the beam (see figure 2) resulting in a disturbed bunch profile, a modified bunch length and reduced peak current. The synchrotron light emited from the bunch is used to determine the bunch length of different bunch currents and RF-cavity loss power. The bunch length data give access to the broad band impedance $|Z_{||}/n|$ and the peak currents. The bunches are so short that due to the high frequency content the impedance has to be scaled.

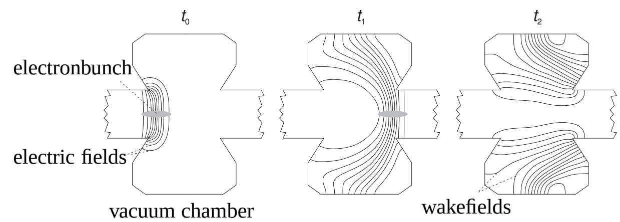

Figure 2: Temporal development of wakefields in a fictive variation of the profile of the vacuum chamber [2].

MEASUREMENT SETUP

At beamline 4 visible synchrotron light (465 nm) emitted from the electromagnetic undulator U250 (see figure 1) is used to analyse the bunch profile and spectrum of the optical klystron in single bunch mode. The spectrum is probed by a Czerny-Turner monochromator (Acton Research Corporation SpectraPro-275), the bunch profile is analysed by a dual sweep streak camera (Hamamatsu C5680) (see figure 3) that is triggered at half of the cavity RF.

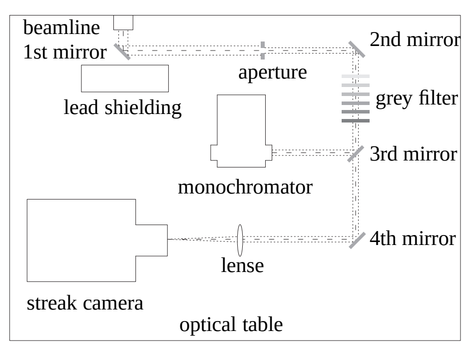

Figure 3: Schematic experimental setup at beamline 4 in downstream direction of the undulator U250.

BROAD BAND IMPEDANCE

For average single bunch currents in excess of about 3 mA and RF-cavity loss power of 20 kW the bunch length is dominated by turbulent bunch lengthening caused by an increased energy spread [5]. The instability is described by the Keil-Schnell-Boussard-criterion [3]. The relation between the scaled impedance and the bunch length is given by [1]

$$\frac{\sqrt{2\pi}I}{0,88\cdot\omega_\mathrm{u}^3 qU_\mathrm{cav}\cos(\Psi_\mathrm{s})}\left|\frac{Z_{||}}{n}\right|\left(\frac{b}{1,841\cdot c}\right)^{a-1}\leq\sigma^{2+a} \quad (1)$$

where b = radius of the beampipe, ω_U = revolution frequency, I = average beam current, q = harmonic number, U_cav = accelerating voltage, Ψ_s = synchrotron phase, c = speed of light, σ = bunch length, a = scaling parameter. In the region of interest the parameter a is smaller than unity. For very high currents and long bunches it approaches unity.

To probe the correlation between the bunch length and the energy spread the latter was determined by measuring the spectrum of the optical klystron of the undulator U250 (see figure 1). The spectral intensity distribution is given by [6]:

$$I_\mathrm{ok}(\lambda)=2I_\mathrm{u}(\lambda)\left[1+f\cdot\cos\left(2\pi(N+N_\mathrm{d})\frac{\Delta\lambda}{\lambda}\right)\right] \quad (2)$$

with the modulation depth

$$f=f_0\cdot\exp\left[-8\pi^2\left((N+N_\mathrm{d})\left(\frac{\sigma_\gamma}{\gamma}\right)\right)^2\right] \quad (3)$$

where I_u = pure undulator spectrum, N = number of undulator periods, N_d = strength of dispersive section, λ = wavelength, $\Delta\lambda=\lambda-\lambda_0$ (λ_0 = central wavelength of the undulator), σ_γ/γ = relative energy spread.

BUNCH LENGTH MEASUREMENTS

Bunch Profiles

Figure 4 shows longitudinal bunch profiles in single bunch mode at 550 MeV. These profiles are used to determine peak currents and bunch lengths. With increasing current the profiles differ from a Gaussian shape because of the distortion by turbulent bunch lengthening [7].

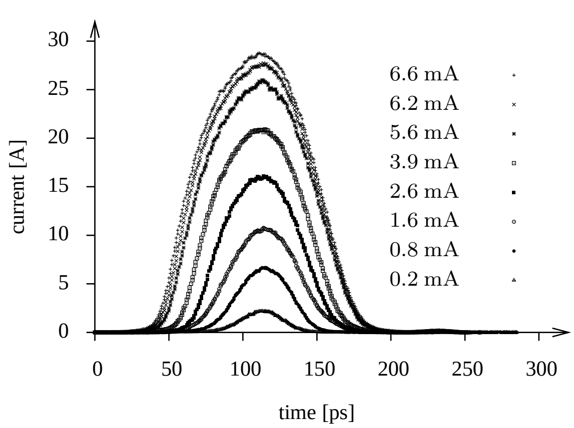

Figure 4: Series of measurements of longitudinal bunch profiles at 20 kW RF-cavity loss power.

Energy Spread and Impedance

Figure 5 shows a typical spectrum with a central wavelength of about 465 nm at 6.6 mA average beam current. The deviations are caused by magnetic field errors. Fitting equation (2) to the data of the measured spectrum of the optical klystron allows the determination of the energy spread σ_γ/γ.

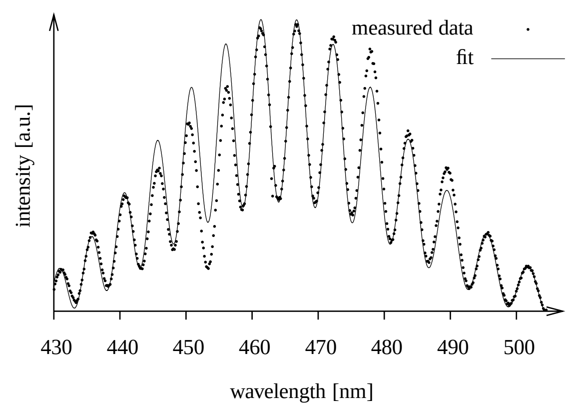

Figure 5: Spectrum of the optical klystron with a modulation depth of $f\approx 0.4$.

The bunch lengths have been analysed with respect to equation (1) (see figure 6). The results show that the parameter a is clearly smaller than one, showing that for currents of about 3 mA to 7 mA the longitudinal broad band impedance has to be scaled. The impedance for two series of measurements with different RF-cavity loss power are presented in table 1, yielding similar results for the longitudinal broad band impedance.

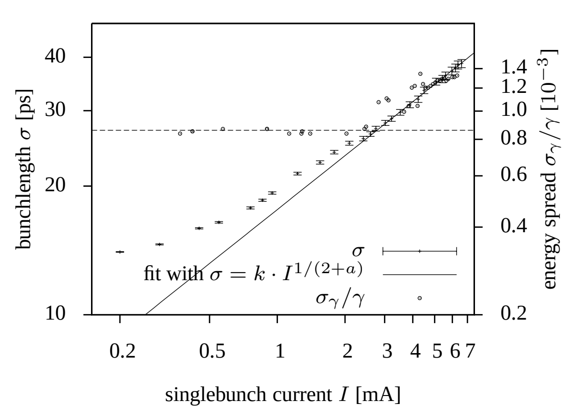

Figure 6: Bunch lengths determined from the bunch profiles (figure 4) and energy spread determined from the spectrum of the optical klystron.

$P_{\rm rf}[kW]$	$k\left[{\rm ps}\cdot{\rm mA}^{-\frac{1}{2+a}}\right]$	a	$\left\lvert\frac{Z_{\vert\vert}}{n}\right\rvert[\Omega]$
15	18.7 ± 0.4	0.40 ± 0.08	0.87 ± 0.16
20	17.6 ± 0.2	0.39 ± 0.05	0.87 ± 0.11

Table 1: Longitudinal broad band impedance for different RF-cavity loss power $P_{\rm rf}$.

For the turbulent regime the measured energy spread indeed increases with the bunch length as concluded from theory. For average single bunch currents below 2.5 mA the energy spread however is above the theoretical predictions. An explanation for that effect can be found in the resolution of the measuring apparatus. Aperture size, transverse beam dimensions and orbit excursions inside the undulator limit the possible resolution of the energy spread measurement due to the transverse Doppler effect. In our case ($\sigma_{x,y} \approx 0.2$ mm, orbit amplitude ≈ 0.1 mm, aperture radius ≈ 0.4 mm) the angular spread seen by the monochromator in an average distance of 12 m from the radiation source is about ± 60 μrad. According to the general coherence condition for the central undulator wavelength, the resulting wavelength spread can be interpreted as virtual energy spread and gives the lower limit of the resolution. Assuming only Gaussian distributions, this effect could in principle be accounted for by a simple factor to the modulation depth. However, in practise this approximation is untenable.

Peak Current

Figure 7 shows the results of the peak current determination of the bunch profiles. The threshold for FEL operation is appr. 3 mA single bunch average current yielding a peak current of about 18 A. In the turbulent regime the peak current scales with $I_p \propto I^{1-\frac{1}{2+a}}$.

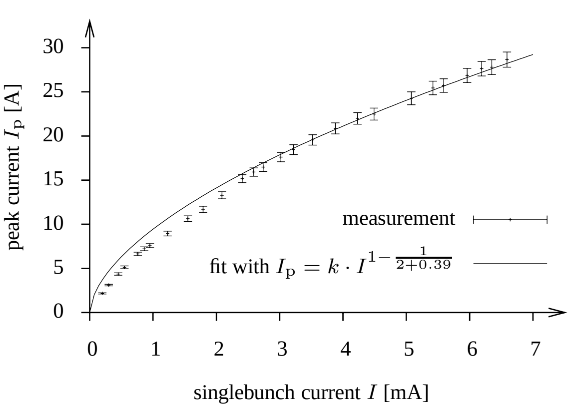

Figure 7: Peak current versus average single bunch current at 550 MeV beam energy and 20 kW RF-cavity loss power.

CONCLUSION

Bunch length measurements on an optical basis have been performed at 550 MeV and single bunch operation as a function of beam currents and RF-cavity loss power. The longitudinal broad band impedance evaluated via streak camera measurements in the region of turbulent bunch lengthening was determined to

$$\left\lvert\frac{Z_{\vert\vert}}{n}\right\rvert = (0.87 \pm 0.10)\Omega.$$

This result is in excellent agreement with calculated data [4] obtained from loss factors out of finite-element simulations in 2001 and clearly shows that mechanical alterations [7] to the machine since then had no influence on the impedance. The analysis has also shown that for single bunch currents of about 3 mA to 7 mA the longitudinal broad band impedance has to be scaled with a scaling parameter of $a = (0.40 \pm 0.05)$.

The analysis of the spectrum of the optical klystron gave the possibility to measure the energy spread. For low single bunch currents however the energy resolution turned out to be not sufficient. For high currents the energy spread increases with the bunch length as expected.

ACKNOWLEDGEMENT

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