STUDIES AND CONTROL OF COUPLED-BUNCH INSTABILITIES AT DELTA

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Abstract

DELTA is a 1.5-GeV synchrotron radiation source at the TU Dortmund with 2 ns bunch spacing. At nominal operating currents, the beam exhibits significant longitudinal centroid motion due to coupled-bunch instabilities. Two techniques were successfully used at DELTA to damp such instabilities: rf phase modulation, which also improves the beam lifetime, and bunch-by-bunch feedback. Using diagnostic data from the bunch-by-bunch feedback system, modal spectra and growth rates of the longitudinal instabilities were determined. We also present a preliminary characterization of transverse coupled-bunch oscillations.

INTRODUCTION

DELTA is a synchrotron radiation source, operated by the Technische Universität Dortmund in Germany. It comprises a linear 60-MeV pre-accelerator, a booster synchrotron ramping the electron beam up to the full energy of 1.5 GeV, and a storage ring of 115.2 m in circumference with three insertion devices [1]. The rf frequency is 500 MHz, and the corresponding harmonic number is 192. Beam is routinely injected three times per day with a current of 130 mA in a pattern covering 3/4 of the circumference, and the resulting bunch current is 0.9 mA. The beam lifetime of 8-10 hours is given by a combination of residual-gas and Touschek scattering.

Above a beam current of typically 80 mA, a longitudinal coupled-bunch instability is observed, dominated by mode 54 generating strong sidebands around revolution harmonics at $(n \cdot 500 \pm 141)$ MHz (n integer) with a synchrotron frequency of $f_s = 15$ kHz. Since 2009, the rf phase is routinely modulated with a frequency of $2f_s$. This modulation not only suppresses the longitudinal instability and reduces the probability of beam loss during injection, but also improves the beam lifetime significantly.

In November 2009, a bunch-by-bunch feedback system from Dimtel, Inc. [2] was installed for a week for demonstration purposes. Besides stabilizing the beam, the longitudinal instabilities were characterized in the course of this demonstration and transverse coupled-bunch modes were identified, which were previously suspected to exist but had so far escaped detection.

In the following, the technical setup and results for both techniques to counteract coupled-bunch instabilities will be described.

RF PHASE MODULATION

The rf phase of the storage ring is modulated by applying a sinusoidal phase shift of 30 kHz (twice the synchrotron frequency) to the input of the storage ring klystron. The setup is shown schematically in Fig. 1, where an offset and additional filtering (not shown) of the input signal is applied to eliminate noise from external sources [3].

The effect of the phase modulation is evident on the spectrum analyzer (showing that synchrotron sidebands disappear), in streak camera images (see Fig. 2) and by an increase of the beam lifetime. Fig. 3 shows the relative gain in lifetime as function of the modulation amplitude expressed as degrees of the rf phase. The lifetime improves rapidly with increasing amplitude reaching an optimum around 6.7° (or 37 ps, close to the natural bunch length) and decreases slowly with larger amplitude because an increasing number of electrons exceeds the momentum acceptance, which is approximately 0.9%. The lifetime improvement is mainly due to a dilution of the electron density, resulting in a reduced Touschek scattering rate.

Numerical simulations of the electron motion in longitudinal phase space show the same reduction of the average electron density that is apparent in streak camera images. Fits to measurements of the loss rate as function of the position of a scraper suggest that the Touschek lifetime increases by more than 50% due to rf phase modulation (e.g. from 14 h to 22 h at a cavity power of 29 kW, and from 11 h to 17 h at 20 kW, for more details see [3]). Since the lifetime increase is highly appreciated by the synchrotron radiation users, rf phase modulation is routinely applied.

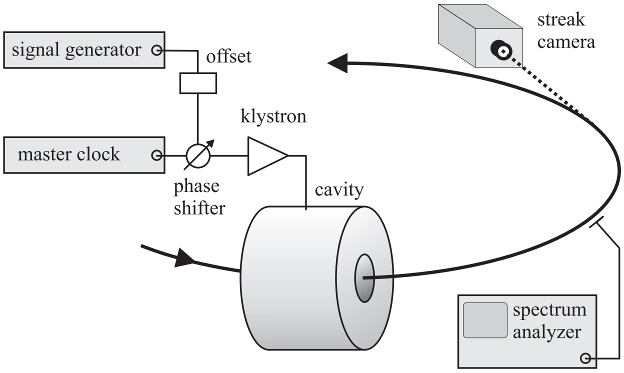

Figure 1: Schematic view of the setup for rf phase modulation and related beam diagnostics.

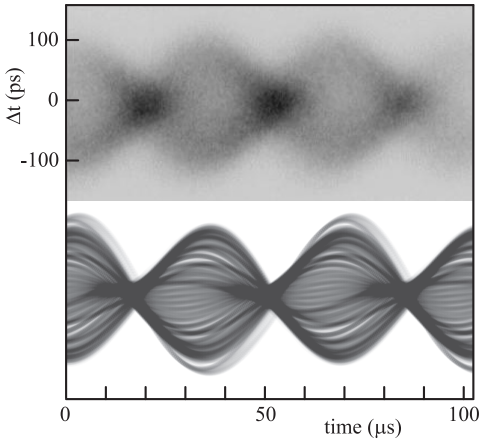

Figure 2: Streak camera image of the electron beam subjected to rf phase modulation, here shown over 260 turns, and a simulation of the electron dynamics (below). The synchrotron oscillation period is approx. 70 μs (180 turns).

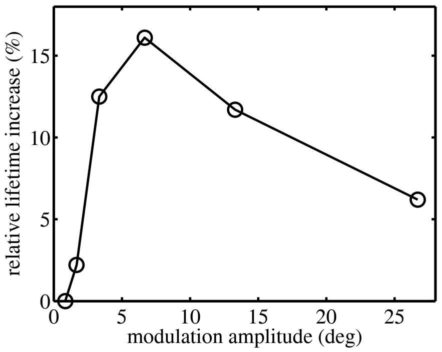

Figure 3: Relative gain in beam lifetime as function of the rf modulation amplitude. During the measurement, the beam current and absolute lifetime changed by about 10%.

BUNCH-BY-BUNCH FEEDBACK SYSTEM

In view of a future project, i.e. the generation of ultrashort radiation pulses by laser-electron interaction [4], it is mandatory to suppress longitudinal instabilities without reducing the electron density, which can be achieved by active bunch-by-bunch feedback. Transverse instabilities are also suspected to occur at DELTA, but do not exhibit a clear signature. In addition to stabilizing the beam, a feedback system with digital data acquisition is a valuable diagnostics tool, allowing, for example, to identify the unstable modes and measure their growth rates, to measure the bunch current and synchronous phase ([5] and references therein), and to trigger the data acquisition with an external event, e.g. when injecting beam into the storage ring [6].

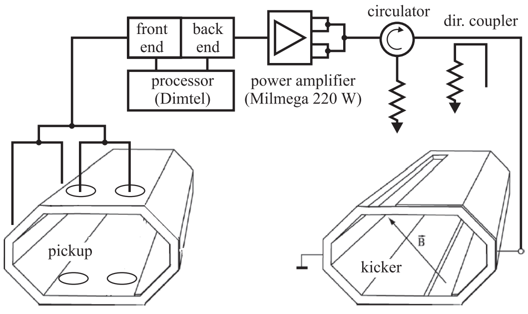

Figure 4: Schematic view of the feedback setup.

In November 2009, Dimtel, Inc. demonstrated a digital bunch-by-bunch feedback system at DELTA and also provided a thorough analysis of the data recorded by the system. As shown in Fig. 4, the sum signal from a beam position monitor (BPM) was passed to the system front/back-end module (FBE-500L) and processed at baseband by an FPGA-based bunch-by-bunch processor (iGp-192F). The back-end signal drove a power amplifier (Milmega 98635, 220 W), which was protected by a circulator against power reflected by the kicker or generated by the beam. A directional coupler was used to monitor reflected signals. The only device in DELTA that was remotely suitable to act on the beam was a slotted-pipe kicker normally used for tune measurements [7, 8], having an estimated shunt impedance below 50 Ω with a maximum around 950 MHz. The back-end unit of the feedback system was set up to modulate a $2f_{\text{rf}}$ carrier (1 GHz) with the baseband signal. The back-end timing was adjusted by exciting synchrotron oscillations in an 8-bunch train and maximizing the response. Subsequently, different experiments were performed:

- Drive-damp measurements at beam currents of 31 mA and 42 mA, exciting oscillations with positive feedback in the first part of the measurement and then switching to open-loop or negative feedback to determine the respective damping rates.
- Drive-damp and grow-damp measurements between 87 mA and 101 mA, i.e. above the instability threshold, measuring growth and damping rates as well as frequency shifts.
- Closed-loop measurements at 131 mA, stabilizing the beam longitudinally while filtering the bunch signals around the horizontal and vertical betatron frequency.

As an example of a drive-damp measurement below the instability threshold, coupled-bunch mode 8 at 42 mA exhibited an open-loop damping rate of 0.275 ms^{-1} which was shifted by the feedback to 1.01 ms^{-1}. From this and other measurements, the feedback gain and kick voltage was deduced. The maximum kick voltage was estimated to be 21 V for modes near the shunt-impedance maximum (e.g. mode 8 and 175).

A grow-damp measurement at 90 mA with mode 27 being dominant is shown in Fig. 5. From measurements at different beam currents, the growth rates and oscillation frequencies of modes 27, 54, 91 and 118 were estimated for zero current (in reasonable agreement with the radiation damping rate and synchrotron frequency) and for the nominal operation current of 130 mA. Since the back-end

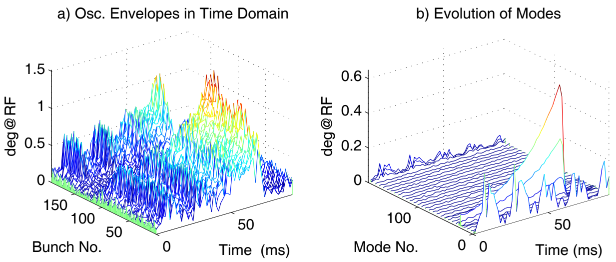

Figure 5: Grow-damp measurement at 90 mA. The temporal evolution of longitudinal oscillations is shown as function of bunch number (left) and mode index (right).

saturated due to the poor kicker impedance, there was a significant variation in the measured damping rates. From this data and a detailed simulation of the feedback loop, the required amplifier power for other values of kicker shunt impedance and beam current can be estimated, which is important in view of a permanent installation of the feedback system.

The feedback system was operated with and without rf phase modulation. When the feedback loop was opened and closed again, stability could be regained at full beam current when the rf modulation was active.

Even though the input was the sum signal from four BPM buttons, there was some residual sensitivity to transverse motion. By filtering the bunch signals around the horizontal and vertical fractional tunes at 421 kHz and 756 kHz, respectively, the transverse modal spectra shown in Fig. 6 were obtained, while the feedback system stabilized the beam longitudinally. In the vertical plane, mode 178 was detected, while horizontal oscillations were a combination of modes 146 and 188. During the temporary installation of the feedback system, the observation of transverse modes came as an unexpected bonus, and a power amplifier at baseband to perform transverse stabilization and grow-damp measurements was not available.

SUMMARY AND OUTLOOK

Rf phase modulation is an efficient and inexpensive way to damp longitudinal modes with the additional benefit of improving the beam lifetime significantly, which, however, comes at the expense of beam quality. For present-day routine operation, the dilution of the beam in longitudinal phase space appears to be of little consequence, but will be detrimental for the use of high undulator harmonics or time-resolved studies, particularly with laser-induced ultrashort pulses.

Operation of the bunch-by-bunch feedback system from Dimtel, Inc., has been successfully demonstrated at DELTA. The system not only suppressed longitudinal instabilities but allowed for a detailed characterization of coupled-bunch modes. While the longitudinal modes were known and routinely damped by rf phase modulation, the transverse oscillations were identified for the first time.

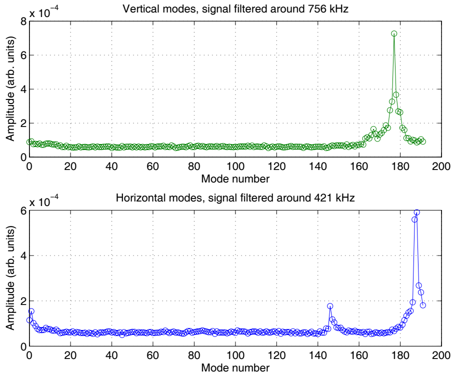

Figure 6: Vertical (top) and horizontal (bottom) modal spectra recorded at a beam current of 131 mA.

Further details on the measurements performed at DELTA can be found in [9]. To fully stabilize the beam at the nominal operation current of 130 mA, active feedback in the longitudinal as well as the transverse planes will be required, which is planned for the near future. Apart from the feedback processors and front/back-end, suitable kickers will be installed, following the design of the feedback kickers used at the BESSY storage ring in Berlin [10]. The longitudinal kicker is an overdamped cavity adapted from the original design at DAΦNE in Frascati [11] to an rf frequency of 500 MHz. The transverse kicker is a combination of a horizontal and vertical stripline pair, minimizing space requirements and HOM losses. Both kickers show excellent performance at BESSY and are easily adapted to the DELTA beampipe geometry. Their installation is envisaged towards the end of 2010.

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