STORAGE RING FILL PATTERNS FOR FEMTOSLICING APPLICATIONS *

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Abstract

The generation of laser-induced ultrashort synchrotron radiation pulses (”femtoslicing”) during user operation at BESSY II may require to add several bunches with enhanced current to the routinely used multibunch fill. The paper addresses these specialized fill patterns in view of beam lifetime, stability, and the effect of beam loading on the synchronous phase angles.

INTRODUCTION

At BESSY II, a third-generation synchrotron radiation source in Berlin-Adlershof, a facility for the purpose of producing sub-100-fs x-ray pulses was commissioned in 2004 [1, 2]. This facility is based on ”femtoslicing”, a method proposed [3] and experimentally demonstrated [4] at the Advanced Light Source (ALS) in Berkeley: a femtosecond laser pulse copropagates with an electron bunch in an undulator (the ”modulator”) and causes an oscillatory energy modulation of the electrons with the periodicity of the laser wavelength. The off-energy electrons are transversely displaced by dispersive elements in order to extract their radiation emitted in a subsequent device, the ”radiator”.

It is desirable to produce femtosecond x-ray pulses during normal user operation rather than in dedicated beamtime only, but there may be conflicting requirements. At BESSY, the modulator U139 with 10 periods of 139 mm length is presently used for no other purpose, while the radiator UE56, an elliptical undulator with 30 periods of 56 mm length, and its beamlines are shared by different users. Femtoslicing requires a closed-orbit bump to produce an angle of 1 mrad between the electron orbit and the UE56 axis which serves the dual purpose of aligning off-energy electrons (and their radiation) with the radiator axis and directing the radiation fans of adjacent bend magnets away from the x-ray beamline. If imposed and removed during injection, this orbit bump does not interfere with user operation. Another concern is the required bunch fill pattern, as discussed in the following. In the standard configuration, 360 of 400 rf buckets of the BESSY II storage ring are evenly filled, leaving an ion clearing gap of 80 ns length. The injected beam current is 250 mA, i.e. 0.7 mA per bunch.

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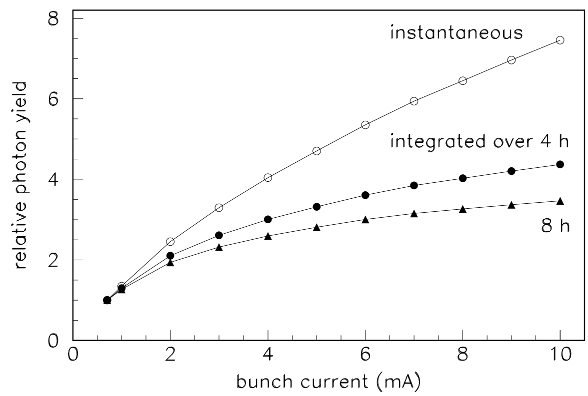

Figure 1: Photon yield after injection and integrated over 4 and 8 hours of operation as function of the injected bunch current. The results are normalized to regular multibunch operation with 0.7 mA per bunch.

REQUIREMENTS

Bunch Current

Compared to standard synchrotron radiation, the photon flux of x-ray pulses generated by femtoslicing is highly diluted by the ratio of laser pulse and bunch length ($\sim 10^{-3}$), the ratio of laser repetition frequency and bunch rate ($\sim 10^{-5}$), and an efficiency factor ($\sim 10^{-1}$), the latter being the fraction of energy-modulated electrons whose radiation can actually be extracted.

The factor that can be gained by raising the current of the interacting bunches is shown in Fig. 1 as function of the bunch current I_B. This estimate is based on a simulation, calculating the number of electrons exceeding an energy modulation of 0.7% and using bunch length data from streak camera measurements [5], where the bunch length σ_B increases $\sim I_B^{0.36}$ above a threshold of 4 mA. The injected bunch current is only relevant shortly after injection or in the case of top-up operation. Otherwise, $I_B(t)$ must be integrated over the duration of the experiment, where the current-dependent lifetime reduces the gain considerably. Figure 1 shows two examples, assuming a lifetime of 20 hours from gas scattering and $2.2 \cdot \sigma_B[\mathrm{mm}]/I_B[\mathrm{mA}]$ hours for the current-dependent Touschek lifetime. The effect of passive 3rd-harmonic cavities [6] on the lifetime depends via beam loading on the multibunch pattern and has been ignored here.

A bunch current of 4 mA, gaining a factor ≥ 2.5, appears to be a reasonable choice. Above this value, the energy spread increases $\sim I_B^{\approx 1/3}$ as measured by Compton backscattering of IR laser photons [7]. Furthermore, the onset of periodically bursting IR radiation around 4 mA [8] adds noise to the THz signal that is routinely used to monitor the energy modulation process [9].

Number of Interacting Electron Bunches

At the BESSY femtoslicing facility, a Ti:sapphire laser system [10] produces pulses with ≤ 2.8 mJ at a rate of 1 kHz. The repetition rate may be doubled at the expense of pulse energy and further increased by using more powerful pump lasers and by adding another Ti:sapphire amplifier stage. The minimum number of bunches interacting with the laser depends on the tolerable background of radiation from previously energy-modulated electrons, which have lost their time structure but are still transversely displaced. Energy modulation in a dispersive region, as in the BESSY case, excites a synchrotron oscillation as well as betatron motion with respective damping times of 8 ms and 16 ms. This kind of background was studied by two different experimental techniques [2], comparing the relative x-ray rates

- from a single bunch and five equidistant bunches interacting in turn with the laser pulses,
- from a single bunch at the time of the interaction and after 1 ms, immediately before the next laser shot.

Despite the long damping times, the detected background is only $\leq 20\%$ of the total signal, depending in detail on the modulation amplitude and the angle at which the short x-ray pulses are extracted. Obviously, the betatron phases have randomized after 10^4 periods such that the probability of an electron radiating in the direction of the beamline is greatly reduced. Without dispersion at the modulator, only longitudinal oscillations with typically 10 periods per ms would be excited and, depending on the phase of the synchrotron motion, the background would be larger.

POSSIBLE BUNCH PATTERNS

At BESSY, parasitic femtosecond x-ray production in multibunch user mode is presently performed by energy-modulating a single bunch of typically 4 mA, placed at the center of the ion clearing gap. Meanwhile, this ”hybrid” pattern has found the interest of other users and has become routine operation. As stated before, the background from previous laser-electron interactions at a rate of 1 kHz is tolerable, but tests with more than one interacting bunch were nevertheless performed in view of a possible upgrade of the laser to higher repetition rate. Simply adding more enhanced bunches to the usual multibunch fill, as shown in Fig. 2, proves to be impractical. Breaking the symmetry of the pattern creates synchronous phase differences of the order of 10 degrees (more than 50 ps) due to beam loading, and the equidistant laser pulses hitting one 4 mA bunch at the center would miss others by as much as $2.7\sigma_B$.

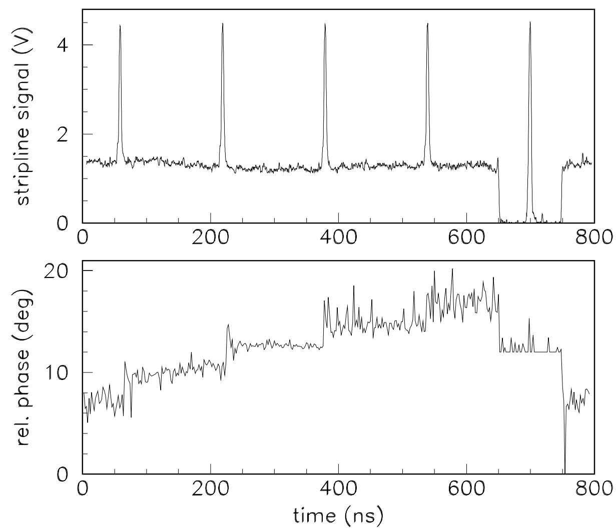

Figure 2: Oscilloscope trace of a stripline signal (top) and synchronous phase from longitudinal feedback data (bottom) as function of time. Five single bunches were added to a multibunch pattern with a 100 ns gap.

The phase variation shown in Fig. 2 (bottom) was measured using a digital bunch-by-bunch feedback system [11] that detects the longitudinal dipole moment (charge·phase). Mode-zero oscillations driven by rf noise allow to estimate the bunch charge and extract the phase information.

The requirement to maintain a symmetric fill pattern for femtoslicing with multiple bunches limits the solutions for a ring with 400 rf buckets to

- a multibunch pattern with 1, 2, 4, 5, 8,. . . equidistant gaps and as many additional bunches with enhanced current, or
- a fill pattern of 400, 200, 100, 80, 50,. . . equally spaced bunches without an ion clearing gap.

Additional conditions are a total beam current of 250 mA for user operation, a current of about 4 mA for bunches interacting with the laser, and a number of interacting bunches given roughly by the laser repetition rate in kHz. Assuming that the shape of the fill pattern is not at variance with user requirements, several other issues have to be taken into account:

– In terms of beam lifetime, a multibunch pattern with multiple gaps is clearly preferrable, since the lifetime reduction due to Touschek scattering would only affect the bunches with enhanced current.

– Multiple gaps require to make each gap shorter, and the stability of the beam against ions effects must be considered. To first order, a sequence of drift and quadrupole matrices describes the focusing effect of the electron bunches on the ions [12]. This linear theory, however, has been found to largely overestimate the ion stability [13] and experimental evidence is mandatory.

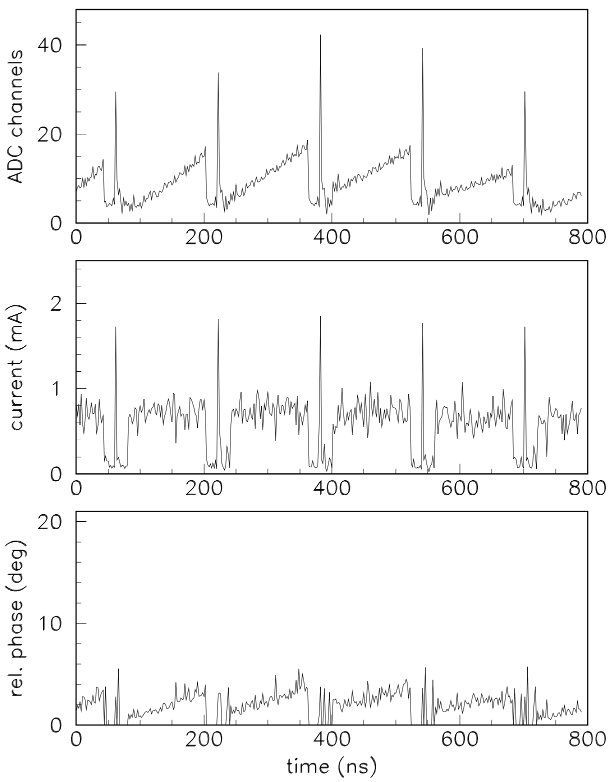

Figure 3: Raw data (top), bunch current (center) and synchronous phase (bottom) from the longitudinal feedback system as function of time. Five single bunches were added to a multibunch pattern with five gaps of 40 ns length.

– The stability of the fill pattern against longitudinal and transverse multibunch instabilities must be tested.

– The single-bunch current may be limited by instabilities such as transverse mode coupling, or by power dissipation $\sim I_B^2$ due to wake fields.

– In view of the required symmetry, the effect of typical current variations on the synchronous phase of the interacting bunches should be calculated or tested.

– Compatibility with the gun/injector system, the required injection time, and the option of top-up operation must be considered.

FIRST TESTS

While the questions raised in the previous paragraph remain unanswered for very high laser repetition rates, a realistic case for 5 kHz operation has been tested by producing a fill pattern with a total current of ≤ 250 mA, five equidistant gaps and five bunches of ≤ 4 mA each.

For multibunch operation of the BESSY II storage ring, trains of 160 bunches from a synchrotron are injected with random timing, thus evenly filling all buckets. A gap is created by exciting a betatron oscillation using a stripline such that the excited bunches are lost. The gap is defined by a function generator synchronized with the revolution trigger, which allows to produce multiple gaps simultaneously. Non-consecutive bunches can be added by single-bunch injection, where the injection rate is 10^2 times lower than in the multibunch case. Producing the fill pattern shown in Fig. 3 took about 20 minutes.

The enhanced bunches were placed at the center, at the beginning or at the end of the respective gap. With the feedback systems in operation, the beam was longitudinally and transversely stable, and no adverse effect of these fill patterns was observed. The variation of the synchronous phases, measured with the longitudinal feedback system and shown in the bottom part of Fig. 3, is sufficiently small to synchronize laser pulses to all enhanced bunches.

In conclusion, if a need for multiple enhanced bunches in femtoslicing applications arises – either by the demand of even lower background or by raising the laser repetition rate to, say, 5 kHz –, routine operation in multibunch mode at 250 mA with five gaps is possible. The effort of increasing the repetition rate to 10 kHz or more is only justified if the prospective gain is not given away by reducing the bunch current. Fill patterns with more than five enhanced bunches have yet to be tested and will probably require a different injection technique to keep the injection time within reasonable limits.

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