# SHORT-PULSE OPERATION OF STORAGE RING LIGHT SOURCES*

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*Abstract*

Short-pulse operation of synchrotron light source storage rings can be useful for both the production of IR and THz-band radiation and high repetition rate pump-probe science in the X-ray regime. Different approaches to short-pulse generation include low-alpha optics configurations, two-frequency RF potential manipulation, laser-induced femtoslicing, longitudinal crab-cavity deflection and pseudo-bunch operation with a fast kicker to isolate a single bunch. This talk should review each of these techniques and discuss implications for machine operation in terms of pulse length, beam intensity, beam stability, pulse repetition rate, output radiation beam quality and potential applications.

## INTRODUCTION

Short electron bunches emit short photon pulses from the X-ray to the Terahertz (THz) frequency range. There are many examples for ultrafast science, profiting from the time resolution provided by short pulses of radiation. One example is time domain spectroscopy, another are the pump-probe studies, where intermediate states of chemical reactions can be studied or the time resolved X-rays can be used to watch nuclear motion in phonon excitation or chemical reactions. Typical thermal electron-phonon equilibrations times, for example, are of the order of 1 to 10 ps.

Short radiation pulses of these lengths can be generated in storage ring light sources from short electron bunches. There are many ways to achieve short bunches or short structures on a longer bunch the radiation of whom is then considered. In this paper, an overview over the existing methods is given. However, the field is too wide to be covered exhaustively. Therefore the key issues are discussed by means of selected examples.

## GENERATION OF SHORT PULSES

In the following, a brief introduction to different ways to produce short pulses from storage ring light sources is given in a dedicated section. A topical overview over accelerator-based sources of coherent infrared/THz radiation can be found in [1].

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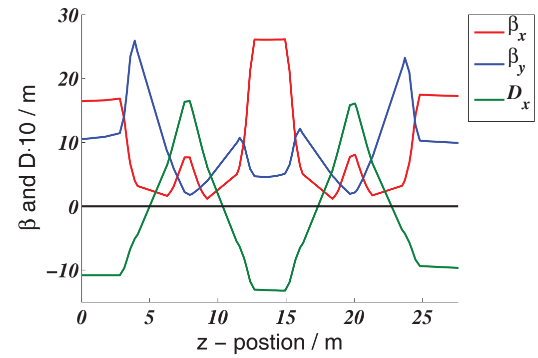


Figure 1: Example of betatron functions and horizontal dispersion of the low alpha optics or one of four sectors of the ANKA storage ring with an $\alpha_c$ of $4.6 \cdot 10^{-4}$.

### *Low-$\alpha$ Optics*

A well established and widespread method to reduce the length of the bunches in a storage ring is the usage of an optics with reduced 'momentum compacting factor' $\alpha_c$. An overview of low-$\alpha$ operation of electron storage rings can be found in [2]. The relative path length change $\Delta L/L_0 = (L - L_0)/L_0$ for particles with a momentum deviation with respect to the reference particle depends on the momentum deviation and the amplitude of the betatron oscillation. It defines $\alpha_c$ like [2, 3]

$$\frac{\Delta L}{L_0} = \alpha_c \frac{\Delta p}{p_0} - \pi \left(\xi_x \epsilon_x + \xi_y \epsilon_y\right) \tag{1}$$

with the transverse emittances $\epsilon_x$ and $\epsilon_y$. $\xi_x$ and $\xi_y$ are the horizontal and vertical chromaticity, respectively. An expansion of the momentum compaction factor in terms of the momentum deviation yields:

$$\alpha_c = \alpha_0 + \alpha_1 \frac{\Delta p}{p_0} + \alpha_2 \left(\frac{\Delta p}{p_0}\right)^2 + \ldots \tag{2}$$

where the leading term is

$$\alpha_0 = \frac{1}{L_0} \oint ds \, \frac{D(s)}{\rho(s)}, \tag{3}$$

with dispersion function $D$ and local bending radius $\rho(s)$. By rendering the dispersion partially negative, for example, a reduction of the momentum compaction factor is achieved. Figure 1 shows the optics functions of the low-$\alpha_c$ optics for one of the four sectors of the ANKA storage ring.

The natural bunch length for an RMS energy spread $\sigma_\epsilon$ can be expressed as

$$\sigma_s = \frac{\alpha_c c \sigma_\epsilon}{2\pi f_s} \quad \text{with} \quad f_s = \sqrt{\frac{e\alpha_c}{2\pi \langle\rho\rangle m_0 \gamma} \frac{dV_{\mathrm{RF}}}{ds}} \tag{4}$$

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where $m_0$ is the electron rest mass. The bunch length $f_s$ therefore scales linearly with the synchrotron frequency ($\sigma_s \propto f_s$). A strong RF gradient be used to reduce the bunch length.

When the leading term of $\alpha_c$ approaches zero, the control of higher order terms becomes more important. The first machine build with a dedicated scheme for the control of higher order terms of the momentum compaction factor is the Metrology Light Source (MLS) [4]. An entire facility dedicated to coherent infrared radiation (CIRCE) is proposed at Lawrence Berkeley National Laboratory in the USA [5]. Typical bunch lengths that are achieved in this type of operational mode are of the order of 1 ps.

### *Simultaneous Long and Short Bunches*

The longitudinal phase space in low-$\alpha_c$ operation can be dominated by nonlinearities caused by the higher order $\alpha_c$ terms [6,7]. An example exhibiting alpha-buckets is shown in Fig. 2. Due to the phase space topology, the particles trapped inside the different alpha buckets have slightly different energies. This can be exploited to separate the buckets of different bunch lengths spatially in a dispersive region. Thus a simultaneous operation with long and shorter pulses is feasible as has been demonstrated, e.g. in [7].

Another way to achieve simultaneous operation with long and short pulses has been proposed as an upgrade for BESSY II in [8]. Here strong RF voltage gradients from superconducting cavities with different resonance frequencies generate a beating pattern of the voltage. At the different stable fixed points locations of this pattern, long and short bunches with 15 and 1.5 ps respectively are produced in an alternating way.

### *Laser-Based Methods*

Ultra short photon pulse durations in storage rings can be obtained with the method of "femto slicing". A short laser pulse, co-propagating with an electron bunch in an undulator (modulator) causes a periodic energy modulation in a short section of the longitudinal charge distribution ("slice"). After passage through a dispersive section, the off-momentum electrons show a transverse displacement. The radiation emitted by these off-momentum particles in a second undulator (radiator) is also transversally displaced and can be extracted with the help of an aperture. However, this procedure also limits the photon intensity. The achieved radiation pulse lengths are of the order of 100 fs [9–11]. The charge distribution after slicing resembles a hole with two side lobes of higher electron density. The dispersion in the ring leads to a rapid decay of the generated structure and the side lobes disappear within a few revolutions. The hole survives for a slightly longer time. The emitted THz signal clearly shows that the hole radiates intense coherent THz radiation of short duration (see Fig. 3).

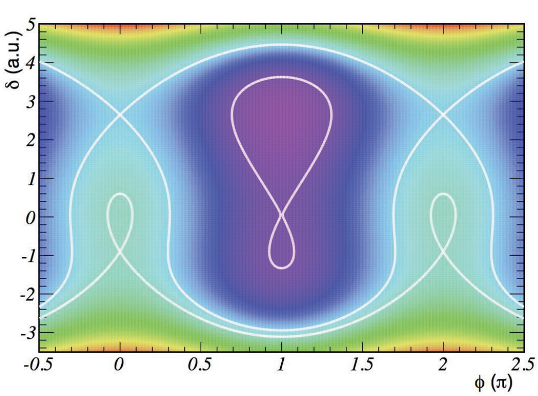


Figure 2: Nonlinear longitudinal phase space with alpha buckets (see [7] for a detailed description).

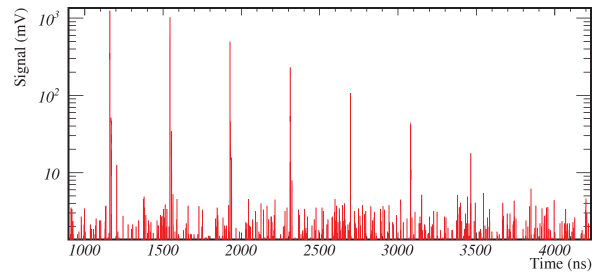


Figure 3: Laser-induced THz radiation recorded with a HEB detector system over about 10 revolutions at the DELTA a 1.5 GeV synchrotron light source at TU Dortmund [12].

The photon rate limitation of this method can be overcome by employing Coherent Harmonic Generation (CHG) of VUV photons. Here the laser-modulated electron beam passes through a chicane the effectively folds the longitudinal phase space so that distinct structures are generated on the longitudinal charge density. These structures the radiate coherently while passing the radiator. Most recently, this method has successfully been established at the DELTA storage ring [13]. An extension of this idea is the Echo Enabled Harmonic Generation (EEHG) [14] scheme which allows for even shorter photon wavelengths.

### *Transverse-Longitudinal Coupling*

A local reduction of the bunch length can be achieved by first inciting a transverse-longitudinal bunch rotation with a deflecting cavity and the cancelling the effect with a second cavity [15]. This method has already been successfully employed for High Energy Physics accelerators, e.g. at KEKB [16] and is presently under development for the Short Pulse X-ray project at the APS [17].

### *Other Ideas*

Another scheme to be mentioned in this context is the operation with so-called pseudo-single bunches which allow to separate the radiation of an isolated single bunch within a multi-bunch fill (often referred to as camshaft

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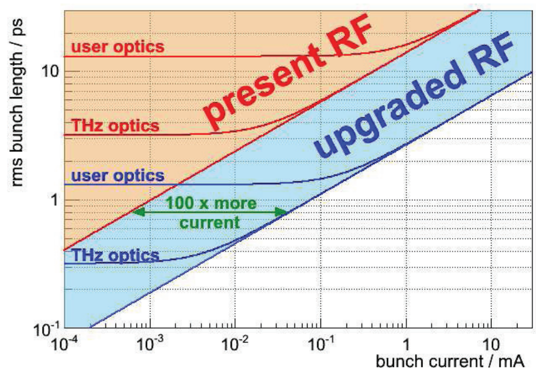


Figure 4: Bunch length as a function of bunch current at BESSY II for the present situation and with a 100 time stronger RF gradient [8].

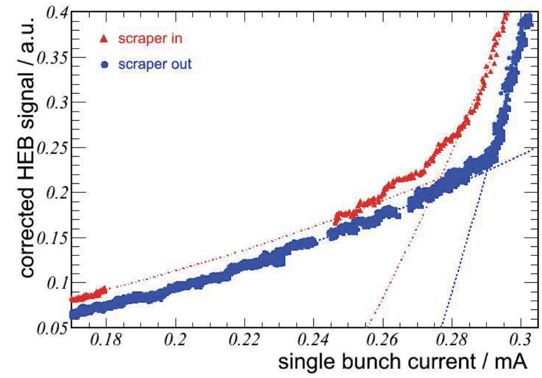


Figure 6: Time averaged amplitude of the THz signal measured with a NbN detector system as a function of the single bunch current with and without a scraper positioned close to the beam at ANKA. The dashed lines represent fits to the steady state and bursting regimes, respectively. The crossing points can serve as an estimate for the bursting threshold [27].

bunch) from the radiation of the other bunches by special orbit kicks. The pseudo single bunch can then be tailored to the user needs. This method is successfully in use for example at the ALS [18] or at SOLEIL [19].

A vertically tilted bunch and thus a transient short bunch length can also be generated by a vertical kick due to non-zero chromaticity (synchrobetatron coupling) [20].

Alternatively, an injection of a short bunch, for example from a linac, into a storage ring with isochronous lattice can be used to provide short photon pulses, albeit with repetition rates coupled to the linac injector [21].

## PHYSICS AND PHENOMENOLOGY OF SHORT BUNCHES

There are many common issues shared by all types of short bunches in electron storage rings. For sufficiently short bunches the radiation is emitted as coherent synchrotron radiation (CSR) for wavelengths longer than the bunch length. The spectrum of CSR, extends to higher frequencies for shorter bunches, resulting in a higher total power of the emitted synchrotron radiation with strong electro-magnetic fields. This gives way to instabilities, the most prominent in this context being the micro-bunching instability that occurs above a threshold [22, 23].

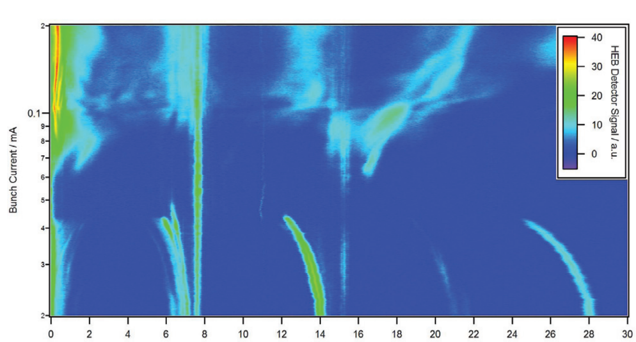


Figure 5: Spectrogram of the turn-by-turn THz signal measured with the HEB detector system at ANKA as a function of the single bunch current [24].

### *Instabilities and Bursting CSR*

The so-called 'bursting threshold' marks the point where (dynamic) sub-structures occur on the charge distribution [25]. Above the threshold current, the radiation, which is in the THz frequency the range due to the typical size of the emitting structures, shows strong intensity fluctuations with time due to dynamic nature of the generating sub-structures (e.g. [26]). At the same time, an increase in bunch length caused by the instability is observed (see also Fig. 4). Very short bunch lengths can therefore only be achieved for very low bunch currents. A way to overcome this problem has been proposed in the context of the simultaneous operation with long and short bunches in BESSY II [8]. According to Eq.(4) the bunch length decreases for strong RF gradients. Figure 4 shows the bunch

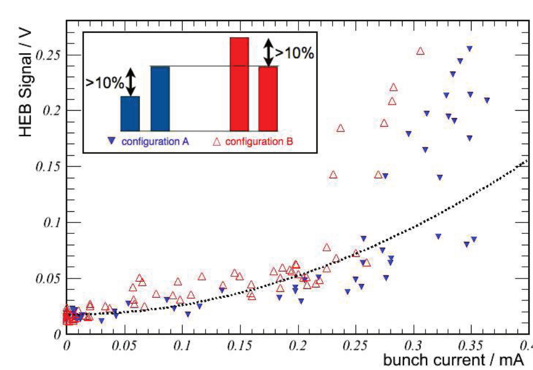


Figure 7: THz signal from a NbN detector for the individual bunches of a multi-bunch filling pattern at ANKA. The colour coding represents the current ratio of the leading bunch to its successor. The dashed curve is a global fit to all data points below the bursting threshold. The earlier onset of the bursting and the higher steady state power are clearly visible [27].

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length as a function of single bunch current for different optics (different $\alpha_c$). It can be seen how the bunch lengthens while approaching the bursting threshold. The proposed increase in RF gradients allows to shift the bursting threshold so that about a factor 100 more current can be stored for the same bunch length. With this scheme, bunch lengths down to about 300 fs will be possible.

The threshold value for the observation of bursting CSR depends various parameters, such as the RF voltage (see Fig. 4), vacuum chamber geometry, bending radius, but also on the filling pattern. A Fast Fourier Transform (FFT) of the THz signal measured as a function of bunch current reveals thresholds for different modes of the instability. Figure 5 shows an example measured at the ANKA storage ring (see [24] for details).

Figure 6 shows how the chamber impedance, in this experiment varied by moving a scraper inside the vacuum chamber, can both increase the emitted radiation power in steady state emission and shift the bursting threshold. Another influence on the bursting threshold is given by the presence of other bunches in a multi-bunch filling pattern [28].

### *Experimental Methods for Short Bunch Studies*

The experimental investigation of the complex dynamics in short bunch longitudinal phase space requires ultra-fast detectors with high resolution (ps) and high dynamic range that are able to operate at high repetition rates (500 MHz) for long observation times (s to hrs). Both indirect (detection of coherent and incoherent radiation from microwaves to the visible) and direct (detection of bunch Coulomb fields) methods can be employed.

For the study of correlations of the bursting emission between different bunches in an multi-bunch filling pattern, an ultra-fast combination of DAQ and THz detector has become available recently (see Fig. 8 and [24]). This system also allows an instantaneous determination of the bursting threshold by measuring the THz intensity for each individual bunch in an inhomogeneous fill and online-tuning of bursting thresholds is easily achieved.

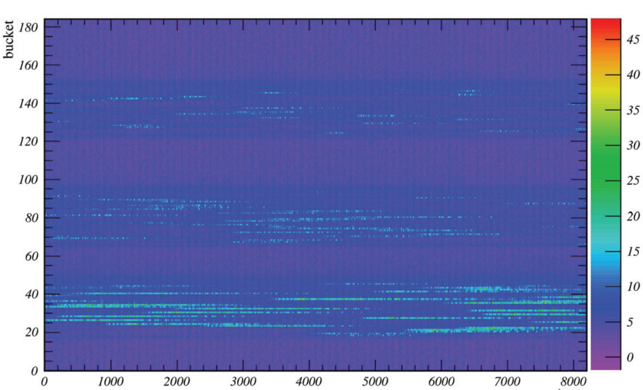


Figure 8: Quasi-simultaneous measurement of THz signals from all bunches in the ANKA storage ring measured with an ultra-fast YBCO detector and dedicated DAQ system [24, 29, 30]. The bursting signature is clearly visible in all three trains.

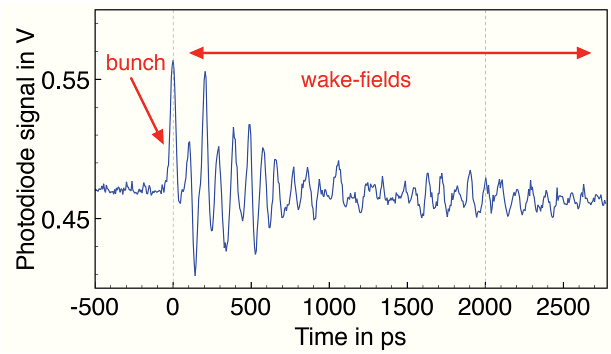


Figure 9: Electro-optical sampling measurement of the electric field induced birefringence inside a GaP crystal from a passing electron bunch inside the ANKA vacuum chamber [31].

Electro-optic (EO) methods allow the direct detection of bunch electric fields inside the vacuum chamber. EO sampling (EOS), for example, measures the wake field after a trailing bunch, whereas single shot methods, such as EO spectral decoding (EOSD) can detect the bunch profile. EO techniques are well established for linear accelerators. Now, for the first time, EO measurements have also been performed in the ANKA storage ring [31, 32], allowing to directly observe the wake field of a short bunch (Fig. 9) and to study the dynamic change of bunch profiles above the bursting threshold. Previous methods, such as streak camera profile measurements, average out the dynamical change and the structural dynamics could only be seen indirectly by the temporal evolution of THz bursts. Figure 10 compares streak camera measurements with averages single shot profiles from EOSD for a single bunch above the bursting threshold. In Fig. 11 single shot bunch profiles are

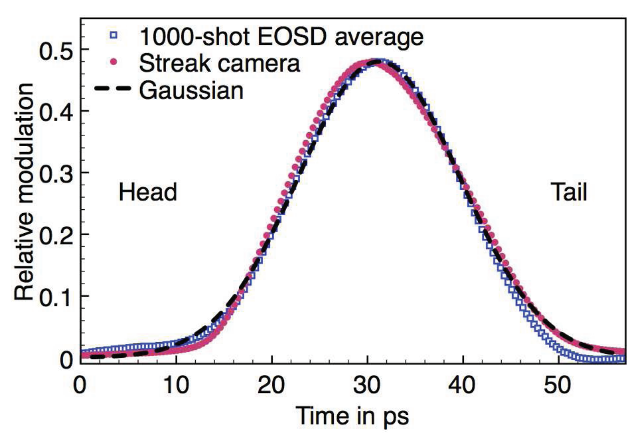


Figure 10: Averages of bunch profiles obtained from streak camera measurements and from single shot profile acquisitions with the electro-optical spectral decoding method. The smooth average shapes of both methods are similar [31].

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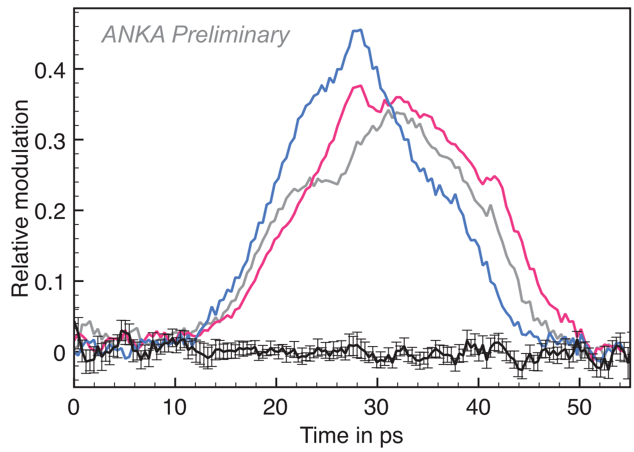


Figure 11: Single shot measurements recorded with the electro-optical spectral decoding method (coloured curves) within a few seconds. The black line correspond to the average of 100 background acquisitions. The error bars reflect the standard deviation of these data sets. The single shot measurements exhibit significantly different bunch shapes and structures (Courtesy N. Hiller, see also [31] for more details).

displayed for a current above the bursting threshold. The calculated RMS bunch length at zero current (without the current depending bunch lengthening) for this case is 2 ps. The method clearly reveals the phase space dynamics and shows a strong similarity to simulation results presented in [25].

## SUMMARY

There is a strong science case for short pulses of radiation from the THz range to hard X-rays. Many different ways exist to generate short photon pulses, such as the procurement of short electron bunches, e.g. in the low-$\alpha_c$ operation mode, the transverse-longitudinal correlation to rotate bunches with deflecting cavities, as well as laser-based methods (e.g. femto slicing, CHG, EEHG). New, promising, developments, such as the proposed operation of a storage ring with string alternating RF focusing, could offer long and short pulses simultaneously. The study and optimisation of short bunch operation requires ultra-fast detectors with high resolution and high dynamic range that are able to operate at high repetition rates for long observation times. New and recent developments in the direction of turn-by-turn and single shot detection will help to unravel the complex dynamics of short electron bunches, thus improving the short bunch operation of storage ring light sources.

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