SHORT RADIATION PULSES IN STORAGE RINGS

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Abstract

The time resolution of experiments with synchrotron radiation, presently limited by a typical bunch length of 30-100 ps in electron storage rings, can be improved by making the bunches shorter or by establishing a longitudinal-transverse correlation. Several methods, their respective merits, shortcomings and present status are discussed.

INTRODUCTION

Despite the progess in linac-based free-electron lasers (FELs) [1], synchrotron light sources based on electron storage rings are still planned or under construction, e.g. SOLEIL [2], DIAMOND [3], PETRA III [4] and others. It is therefore worthwhile to consider possible extentions of their capabilities, particularly in terms of time resolution, which is limited by the bunch length to typically 30-100 ps (full width at half maximum, fwhm), which is 3 orders of magnitude longer than femtosecond laser pulses in the visible regime.

One way to improve the time resolution is to reduce the bunch length, another is to introduce a correlation between the longitudinal (temporal) coordinate and a quantity which is more easily accessible, usually the transverse coordinate or angle.

BUNCH LENGTH REDUCTION

The natural length of an electron bunch in a storage ring is given by the energy spread, which is in turn governed by the equilibrium between random excitation due to synchrotron radiation emission and radiation damping. For the present purpose, the energy spread, the beam energy $E_\circ$ and the circumference $L_\circ$ of a storage ring are considered to be constant. The motion of an electron in longitudinal phase space can be described by

$$\Delta z = \alpha \frac{L_\circ}{E_\circ} \cdot \Delta E \qquad \text{and} \qquad \Delta E = ec\frac{dV_{\rm rf}}{dt} \cdot \Delta z. \quad (1)$$

For a short bunch length, the motion Δz along the longitudinal axis should be slow, which implies a small momentum-compaction factor α, whereas the motion along the energy axis should be fast, driven by a large gradient $dV_{\rm rf}/dt$ of the rf voltage.

Low Momentum-Compaction Factor

The momentum-compaction factor α is approximately given by

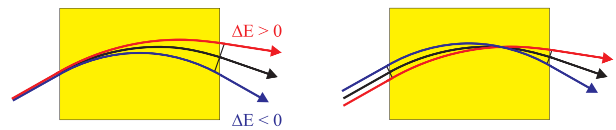

Figure 1: Off-energy electrons in a bend magnet. Left: Dispersion increasing from zero, which is the case in conventional achromatic lattices. Right: Dispersion changing sign, leading to smaller path length variations.

$$\alpha \equiv \frac{\Delta L/L}{\Delta E/E} = \frac{1}{L_\circ} \oint \frac{D(s)}{R(s)} ds, \quad (2)$$

i.e. by dispersion $D(s)$ in dipole magnets with bending radii $R(s)$. In conventional achromatic lattices, the dispersion starts from zero and increases along a dipole magnet. If, however, $D(s)$ is allowed to change its sign at the expense of increasing the horizontal emittance, α can be reduced to very small values (see Fig. 1). As an example, a reduction of more than two orders of magnitude was demonstrated at BESSY/Berlin [5], reducing the natural bunch length from 12 ps to 0.7 ps (rms), while the horizontal emittance increased from 5 nm rad to 30 nm rad. Meanwhile, user operation of the BESSY II storage ring in a 3.5-ps low-α mode is offered on a regular basis [6]. When lowering the first-order momentum-compaction factor, quadrupoles and sextupoles must be carefully tuned as to control the working point, the transverse chromaticity and the longitudinal chromaticity (higher-order α).

The natural bunch length is the low-current limit of the actual length. When raising the bunch current $I_{\rm b}$ from zero, the bunch length σ increases moderately due to potential-well distortion. At a certain threshold current, indicated by the onset of coherent synchrotron radiation (CSR) bursts, the bunch length increases more rapidly. For various values of α, a universal limit of $\sigma \sim I_{\rm b}^{0.38}$ was found for BESSY [5]. The power law depends in detail on the impedance of the respective storage ring, but generally implies that a reduction of the bunch length by a factor of 10 requires to reduce the bunch current by three orders of magnitude.

Strong RF Focussing

Reducing the bunch length by increasing the gradient

$$\frac{dV_{\rm rf}}{dt} = \hat{V}_{\rm rf}\omega_{\rm rf}\cos\phi_{\rm s} \quad (3)$$

of a sinusoidal rf voltage implies increasing its amplitude $\hat{V}_{\rm rf}$ or frequency $\omega_{\rm rf}$. For given synchrotron radiation losses W, a large rf voltage (i.e., a large overvoltage factor) also optimizes the synchronous phase $\phi_{\rm s}$ =

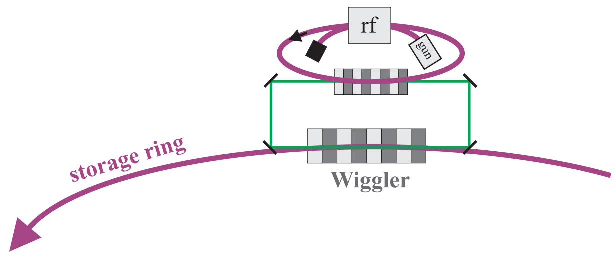

Figure 2: Schematic view of a mm-wave generated by a free-electron laser and interacting with electron bunches in a wiggler, as proposed in [10].

$\cos^{-1}\left(W/e\hat{V}_{\rm rf}\right)$. Alternatively or in addition, one may deviate from a purely sinusoidal shape by adding a higher harmonic voltage. Passive normal-conducting third-harmonic cavities are often used to lengthen the bunches in order to reduce Touschek scattering, e.g. [7]. The same cavities can be tuned as to shorten the bunches by a factor of ~ 2, depending on the beam current that drives these cavities. A larger factor can be gained by filling a whole straight section of a synchrotron light source with a third-harmonic superconducting rf structure, driven by a moderate external power source, as proposed for BESSY [8]. Here, the rf gradient can be increased by two orders of magnitude, reducing the bunch length by a factor of 10.

A novel strong rf-focussing scheme was studied for the case of the Φ-factory DAΦNE [9] in order to diminish the hour-glass effect at the interaction point. Here, a large rf voltage and variations of the R_{56} parameter (describing the path length as function of energy) would produce a modulation of the bunch length along the ring.

A variation of the strong-focussing idea is the use of a mm-wavelength FEL, driven by a short energy-recovery linac, as proposed for the Duke storage ring [10] and sketched in Fig. 2. The interaction of the mm-wave with the electron beam in a wiggler would act like a mm-modulation of the rf potential, creating micro-buckets for extremely short bunches.

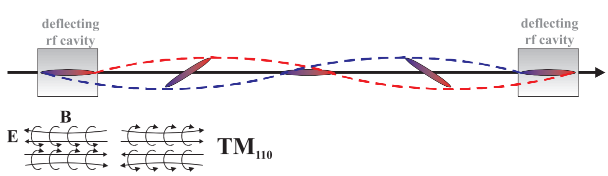

Figure 3: Transverse deflection of electron bunches by a TM110-mode rf cavity and cancelled by a second cavity. Head (red) and tail (blue) of the bunches perform betatron oscillations with opposite phase.

LONGITUDINAL-TRANSVERSE CORRELATION

A correlation between the longitudinal electron position and its transverse position or angle can be used to select synchrotron radiation from a bunch slice or to compress radiation pulses.

RF Orbit Deflection

If a bunch passes a dipole-mode (TM110) rf cavity ("crab" cavity) at a position with beta function $\beta_{\rm rf}$ while the fields change sign, head and tail of the bunch will receive opposite transverse kicks and will perform betatron oscillations with opposite phase [11], as shown in Fig. 3. For a single electron, the correlation of longitudinal position z and maximum transverse displacement y or angle y' is

$$\begin{aligned} y(z) &= \frac{e\hat{V}_{\rm rf}}{E_\circ}\sqrt{\beta_{\rm rf}\beta}\,\sin(\omega_{\rm rf}z/c) \\ \text{and}\;\; y'(z) &= \frac{e\hat{V}_{\rm rf}}{E_\circ}\sqrt{\beta_{\rm rf}/\beta}\,\sin(\omega_{\rm rf}z/c), \end{aligned} \tag{4}$$

respectively, with the same symbols as above and β being the beta function at the position of maximum displacement or angle. This correlation is diluted by the non-zero beam emittance and the angular radiation characteristics. Selecting synchrotron radiation from such a bunch by an aperture imposes a temporal restriction, corresponding to a bunch slice. The intensity losses are essentially given by the ratio between the restricted and the total pulse length. Alternatively, the longitudinal-transverse correlation of the whole radiation pulse can be used, either by employing a position-sensitive detector to obtain different time slicies simultaneously or by compressing the pulse using optical methods [11].

The kicks received in one cavity must be cancelled by corresponding kicks in a second cavity – otherwise, the transverse emittance would blow up, spoiling the longitudinal-transverse correlation and the beam quality in general. Electrons may arrive at the second cavity with the wrong betatron phase (due to uncompensated chromaticity and other nonlinearities) and/or at the wrong time (due to path length differences) and may not receive the correct kick to stop their betatron motion. This problem has been studied extensively in view of applying an rf-deflection scheme at the APS/Argonne [12]. It was found that a carefully tuned set of sextupole magnets can limit these variations as to achieve a time resolution of 1 ps using a cavity voltage of 6 MV at 2.6 GHz (i.e., the 8th rf harmonic).

Femtosecond Laser Slicing

A femtosecond laser pulse can be used to transversely displace electrons within a thin slice of an electron bunch. As proposed by [13], electrons undergo a periodic energy

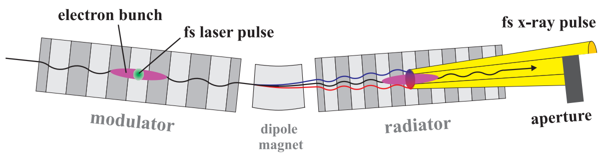

Figure 4: Principle of femtosecond slicing: energy modulation of electrons co-propagating in an undulator with a fs laser pulse (left), transverse separation by a magnet (center) and transversely separated radiation of bunch core and off-energy electrons (right).

modulation while co-propagating with the laser pulse in an undulator (the “modulator”). These off-energy electrons are then displaced in transverse position (spatial separation) or angle (angular separation, see Fig. 4) by dispersive elements and their synchrotron radiation from a subsequent dipole or insertion device (the “radiator”) has essentially the duration of the laser pulse, stretched by path length variations between modulator and radiator. The footprints of several implementations of this scheme are shown in Fig. 5. The principle has been demonstrated at the ALS/Berkeley with a bend magnet as radiator [14, 15]. In 2006, three undulator-based sources with be operational: at BESSY (installed in 2004 [16]), at the ALS and at the SLS/Villigen (both currently being commissioned [17, 18]). As shown in Table 1, the three installations are complementary in several respects. With a laser system of 20 kHz repetition rate, the ALS will lead in photon flux, while the SLS and BESSY promise better time resolution (due to the proximity of modulator and radiator) and a larger signal-to-background ratio (inherent to the angular separation scheme). The SLS and ALS sources are both designed for a wide range of photon energies, while the BESSY installation is the only one offering circular polarization for magnetic studies.

Compared to conventional synchrotron radiation, the photon flux of laser slicing is strongly limited by the small fraction of electrons in the bunch slice and by the laser repetition rate. On the other hand, the flux is orders of magnitude larger than that of laser-based sources like higher-harmonic generation at photon energies above 0.5 keV and

Table 1: Parameters of fs slicing facilities as of 2006

	ALS	BESSY	SLS
beam energy (GeV)	1.9	1.7	2.4
photon energy (keV)	0.2-10	0.4-1.4	3-8
polarization	linear	lin.+circ.	linear
separation scheme	spatial	angular	angular
pulse length (fs, fwhm)	200	100	100
phot./pulse (0.1% bw)	$2 \cdot 10^3$	10^3	10^3
rep. rate (kHz)	20	1	1

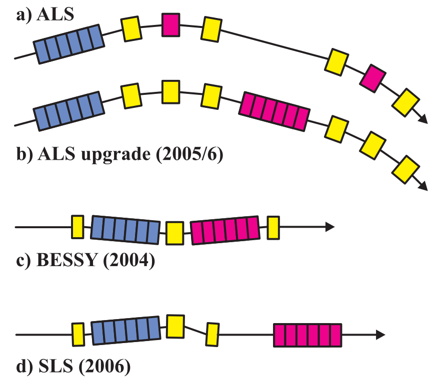

Figure 5: Footprints of femtosecond slicing facilities (not to scale) indicating the respective modulator (blue) and radiator (magenta).

plasma sources in the multi-keV regime [17].

The prime method to detect and optimze the laser-electron interaction is THz radiation, as proposed in [15]. Path length differences of energy-modulated electrons cause a short dip in the longitudinal bunch profile which gives rise to coherent radiation at wavelengths of 100 μm and above. In addition to being an ideal diagnostics tool (non-invasive, online available and with a large dynamic range), this radiation can be a useful source for laser-synchronized sub-ps THz radiation for time-resolved experiments [19].

While the theoretically expected pulse duration at the BESSY slicing source is 100 fs (dominated by the R_{51} value between modulator and radiator), recent pump-probe data (to be published) suggest a time resolution of 150 fs. These experiments with data collected over 8 hours give a premonition of the challenges at future short-pulse radiation sources. A thermal variation of $\Delta L/L = 10^{-6}$ of a laser path with $L = 45$ m corresponds to 150 fs. For a spot size of 1 mm, an angle of 1° between pump and probe pulse accounts for 60 fs uncertainty. Pulse lengthening in the monochromator (wavelength times the number of illuminated grid lines) also becomes a critical issue.

SUMMARY

Table 2 is an attempt to compare different strategies for obtaining shorter synchrotron radiation pulses in storage rings. Femtosecond slicing promises and has already proven to reach a time resolution of the order of 100 fs and is inherently synchronized with a laser for pump-probe applications, whereas all other schemes aim at the 1 ps regime and would suffer from temporal bunch jitter.

On the other hand, slicing offers by far the lowest photon flux. However, the benefits of photons/pulse and repetition rate depend strongly on the respective application as shown in Fig. 6 for experiments at the full bunch rate and for pump-probe applications with a 1-kHz pump source.

Bunch-reduction schemes can be beneficial for all users, while longitudinal-transverse correlations are resticted to

Table 2: Comparison of schemes to generate short radiation pulses in storage rings

scheme	time resolution	inherent sync.	photon flux	users	effort
low momentum compaction	$\sim$ 1 ps	no	low	all	–
strong rf focussing	$\sim$ 1 ps	no	good	all	$\sim E$
rf orbit deflection	$\sim$ 1 ps	no	good	single/few	$\sim E$
fs laser slicing	100 fs	yes	very low	singel/few	$\sim E^2$

one or a few positions along the storage ring circumference. For rf-based schemes, the effort increases linearly with beam energy, while fs slicing requires a laser pulse energy $\sim E^2$ which makes it unattractive for 6-8 GeV rings.

Finally, combinations of these schemes, e.g. strong rf focussing with low-α or with fs slicing, can be envisioned. In any case, improving the time resolution of synchrotron radiation can extend the capabilites of a ring-based source to new scientific frontiers. In addition, experience can be gained in view of short-pulse detection, synchronization, FEL seeding and other issues relevant to linac-based future light sources.

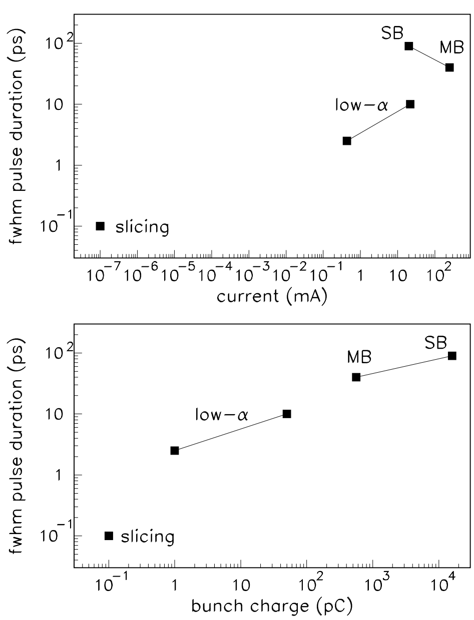

Figure 6: Comparison of femtosecond slicing, low-α operation and normal operation of the BESSY II storage ring with a single bunch (SB) and multiple bunches (MB). Left: pulse duration versus contributing current, which is proportional to the photon flux at the full bunch rate. Right: pulse duration versus contributing change, relevant in the case of pump-probe experiments with a pump pulse rate of 1 kHz.

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