SHORT BUNCHES IN ELECTRON STORAGE RINGS AND COHERENT SYNCHROTRON RADIATION*

G. Wüstefeld[1], BESSY, Berlin (Germany)

Abstract

There is an increasing interest for the production of pico- and subpico-second long electron bunches in storage rings [1, 2]. One interest is motivated by time resolved measurements with short x-ray pulses, the other relates to the production of intense, coherent THz radiation [3, 4, 5, 6]. Dedicated 'low alpha' optics at some few storage rings, originally not built for such a purpose, can presently supply reliable and stable $\approx$ 3 ps rms long electron bunches. The tuning of the 'low alpha' optics, its limits and upgrade options are discussed and properties of emitted coherent radiation are presented.

INTRODUCTION

Electron linacs are probably the preferred machines to produce short and intense electron bunches, as part of free electron lasers [7] or energy recovery linacs [8]. The production of short electron bunches in storage rings attracts increasing interest in the last years. These rings are in general not designed for this task, but possibilities to produce these bunches are explored at several places. By applying a low alpha optics, bunches of 3 ps rms length can be produced at some storage rings, under reliable and stable operating conditions. There are competing methods to achieve shorter bunches in storage rings, like laser slicing [9], injection of short bunches into storage rings [10], and others [11, 12, 13]. These methods produce short bunches for a short time or at limited places in storage rings. In this note we focus on storage ring based sources which apply a low alpha optics, to produce short bunches in a kind of (quasi) equilibrium state. This operation mode is nearly done without any dedicated hardware installation, simply by tuning the ring in an appropriate way. There are two rings, BESSY II and ANKA, which presently schedule 12 days per year for user shifts in this mode, to generate coherent synchrotron radiation (CSR) in the THz range or for short x-ray pulses [14, 15].

The following note is a short overview of this field, not intended as an introduction, many papers are quoted for further information. The first part of the paper discusses the tuning of the optics into the low alpha mode. The second part summarizes properties of the coherent radiation, emitted by short bunches.

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[1] Author: wuestefeld@bessy.de

LOW ALPHA OPTICS FOR SHORT BUNCHES

The relative path length change $\Delta L/L_0 = (L - L_0)/L_0$ of a particle orbit around a storage ring as a function of momentum deviation $\delta = (p-p_0)/p_0$ and betatron oscillation amplitude defines the 'momentum compaction factor' α as [16, 17]

$$\Delta L/L_0 \quad = \quad \alpha\delta + \xi \qquad (1)$$

where ξ includes amplitude dependent terms and is given as $\xi = -\pi(\xi_x\epsilon_x + \xi_y\epsilon_y)$, [18]. This term depends on the Courant-Snyder invariants ϵ_x, ϵ_y and vanishes with the transverse chromaticity ξ_x, ξ_y. The momentum compaction factor can be expanded with respect to δ

$$\alpha \quad = \quad \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 ... \qquad (2)$$

where different definitions exist. The leading term of α is derived from the linear dispersion function D and the dipole bending radius ρ, $\alpha_0 = \oint(D/\rho)ds/L_0$. The function D depends on the quadrupole settings and controls α_0, however, the tuning range of D is limited.

The value of α enters the longitudinal equations of motion. They are used to derive expressions for fixed points, bucket size and so on [16, 19]. For example, the natural bunch length (rms) σ and the synchrotron oscillation frequency f_s are given as

$$\sigma = \frac{\alpha c \sigma_e}{2\pi f_s} \text{ , and } f_s^2 = \frac{e\alpha}{2\pi R m_e \gamma}\frac{dV_{rf}}{ds}, \qquad (3)$$

with the speed of light c, rms energy spread σ_e, the electron charge e, the average ring radius R, the electron mass m_e, the Lorenz factor γ, respectively. Applying equations (3) we get $\sigma \propto f_s$, and $\alpha \propto f_s^2$. Reducing the bunch length by a factor 10 due to a 100 times smaller α value seems presently the limit low alpha rings. A reduction of the storage ring energy E compresses the bunches further with $\sigma \propto E^{3/2}$. This relation indicates, that short bunches are easier obtained in low energy rings, with smaller energy spread σ_e. A different option, increasing equivalently the rf-gradient dV_{rf}/ds by a factor 100, requires a large hardware installation.

While tuning the low alpha optics of a machine, one can monitor f_s at different α values by means of a spectrum analyzer. From f_s of equations (3) a scaling can be derived, to get the associated values of α and σ. If α is dependent on δ these results, specially at small values of $|\alpha_0|$, could be modified by higher order terms of α. At this parameter range, fixed points can disturb the phase oscillation at places where $\alpha = 0$. To avoid these complications,

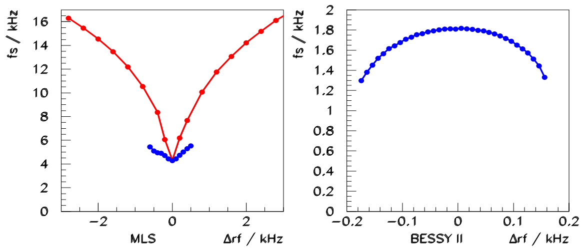

Figure 1: Synchrotron frequency fs (dipole mode) as a function of the rf- detuning Δf_{rf} for the low alpha optics. Left: MLS with octupoles correction on (red) and off (blue), at $\alpha_0 = 1{\cdot}10^{-4}$. Right: BESSY II, at $\alpha_0 = 4{\cdot}10^{-5}$.

higher order terms of α have to be shaped in such a way, that f_s increases with deviating rf-frequency respectively off momentum orbits. For the first time, such a scheme was suggested and applied for the recently commissioned MLS [20] ring. Figure 1 shows measurements of f_s as a function of Δf_{rf}. These two variables are more convenient for the practical machine tuning, they can be transformed to α and δ [21]. The tuning of α is achieved by adjusting the slope of f_s with respect to Δf_{rf}, the longitudinal chromaticity, to zero or to a small value to suppress longitudinal beam instabilities. To correct the longitudinal chromaticity independent of the two transverse chromaticities, three well placed sextupole families are required. Further more, the curvature of f_s with respect to Δf_{rf} is controlled by a suitable placed octupoles.

In general, machines are not optimized for low alpha operation and this tuning could become difficult. There are measurements from some machines of f_s for a low alpha optics as a function of the rf-frequency detuning. At BESSY II (Fig. 1), UVSOR [22], ALS [23] and ANKA [24] f_s is decreasing with Δf_{rf}, at NewSUBARU [25] it is increasing, see also [1, 14, 26].

To go to even shorter bunches one should be aware of physical limits, beside increased demands on low noise power supplies [27]. For example, the coupling between the transverse and longitudinal plane leads to a locally modulated length dependent on H [28], where H is the chromatic invariant. At the MLS ring the THz beam port is placed at a location of small H, to have the potential to observe 0.3 ps long bunches [29], based on 6-dimensional tracking simulations. A further limit is due to the quantum character of the synchrotron emission process [30], producing a final longitudinal emittance, like the transverse one. Ion trapping and intra beam scattering, as typical for smaller rings, increase not only the transverse beam dimension, but also enlarge bunch length and energy spread. Further, at low beam energies, where damping is missing, the bunch dimension in phase space could be additionally widened by CSR [31]. Very likely, a mixture of these last effects might lead to reduced CSR detection at the low energy range of the MLS ring [32].

For DAΦNE [33] a scheme of strong longitudinal focusing was studied, employing a high rf-gradient, superconducting cavity, leading to a position dependent bunch length along the circumference. This could relax beam dynamic problems compared to the case, where bunches are short all around the ring.

COHERENT SYNCHROTRON RADIATION (CSR)

Generation of CSR

A radiating electron bunch can be considered as a point charge, if waves longer than the bunch are emitted. In case of CSR emission they all have the same phase relation with respect to the bunch, the photons are superimposed coherently. Waves shorter than the bunch have random phase relations, they are added up incoherently. The calculated emitted power P_n per bunch for coherent and incoherent emission requires to take into account the correct phase relation between the emitted waves [34, 35]. This is summarized in the expression

$$P_n = p_n(N_e + N_e(N_e - 1)g_n), \qquad (4)$$

where p_n is the power of the nth radiation harmonic emitted by a single electron, N_e is the number of electrons per bunch and g_n is a form factor. For forward directed radiation the form factor g_n is the modulus squared of the Fourier transform of the longitudinal charge density $n(z)$ of the bunch

$$g_n = \left|\int_{-\infty}^{\infty} n(z)\mathrm{e}^{2\pi iz/\lambda}dz\right|^2, \qquad (5)$$

where the phase information is lost. As typical for Fourier transforms, g_n is very sensitive to the bunch shape. It describes the degree of coherence, full coherence $g_n = 1$ for a point-like bunch and $g_n = 0$ for the incoherent case of a long bunch.

An amplification factor can be derived by normalizing the total power P_n by the incoherent one p_nN_e, $P_n/(p_nN_e) = 1 + N_eg_n$. In the full coherent case this amplification approaches the value N_e. Typically there are about 10^8 to 10^9 electrons per bunch, leading to huge amplification factors.

Very long waves are in general not detected, their propagation is suppressed by shielding effects of the vacuum chamber. This effect is characterized by the ”cut off” wave length of the chamber, λ_{cutoff}, which limits the detectable wavelength to waves shorter than λ_{cutoff}. The chamber cut off, derived from impedance calculation of a simplified, parallel plate model, is given as [36, 37] $\lambda_{cutoff} = 2h\sqrt{h/\rho}$, where h is the full height of the vacuum chamber in the dipole and ρ the dipole bending radius. This favours dipoles with small bending radii, as applied in low energy rings. For Gaussian beam optics, this cut off can be interpreted as the minimum transverse chamber height h required for the propagation of a diffraction limited source of wave length λ_{cutoff} [38, 39]. For example, at BESSY II

$\lambda_{cutoff} = 6$ mm and the rms bunch length is tuned to σ= 1 mm (=3 ps) for producing stable coherent radiation [14].

Current dependent CSR Effects

The CSR radiation is emitted in the dipoles and transported by a large acceptance beam line to the experimental place [40]. At ANKA the radiation is taken from the dipole edge [24]. A variety of diagnostics methods can be applied [41] to analyze the radiation. Several types of sub-THz and THz detectors are used [42, 43]. They differ in spectral sensitivity and time resolution. Besides room temperature detectors, sensitive, liquid Helium cooled detectors such as Si-bolometers of about 1 kHz band width or InSb detectors of 1 MHz band width are common. At BESSY II, an InSb detector is able to resolve the 1.25 MHz THz signal modulation by the revolution of the bunches around the ring, enabling a sensitive lock-in technique. In case of a single bunch filling, even at low currents, this detector can follow the turn-by-turn development of THz signals.

The time dependencies of the detected radiation can be measured and analyzed in time and frequency domain. If the bunches are stable and of constant shape, the emitted radiation is also stable [44]. At low currents these bunches are of Gaussian shape in momentum and position space. Nonlinear effects of the magnetic guide field can lead to deviations from the Gaussian shape.

With increasing bunch charge, there is a range of static, current dependent shape variations. As soon as the bunch is deformed by its own CSR field [45, 46, 47] it deviates from the Gaussian shape, enhancing higher harmonics in the power spectrum. The CSR fields modify the bunch energy distribution and in turn the particle distribution. The resulting deformation can be estimated by the Haissinski equation [45], where the influence of the CSR is described by a wake potential. As shown for the unshielded CSR in [47], the steepest static deformation of the bunch of natural bunch length σ leads to a form factor value of $g_n = 1.7 \cdot 10^{-3}$ at $\lambda = \sigma$, several orders of magnitude larger than the corresponding value of a Gaussian bunch.

If the static bunch shape deformation becomes too large, the CSR drives the bunch into the 'bursting instability' [48]. The bursting is a self amplified, dynamical process driven by its own CSR field. The CSR produces energy fluctuations inside the bunch. These are transformed to density fluctuation smaller than the bunch ('micro bunches') which emits even more CSR bursts. The bursts extend to shorter wave lengths, related to the induced density fluctuations and can be detected also in case of originally long bunches. The bursting stops, when the bunch is widened in phase space and starts again after the synchrotron radiation damping.

Bursts are detected at several places, triggered by CSR or any other ring impedance, [49, 50, 51, 52, 53]. Time and frequency domain measurements at BESSY II are shown in [44], where stable and bursting CSR can be clearly distinguished.

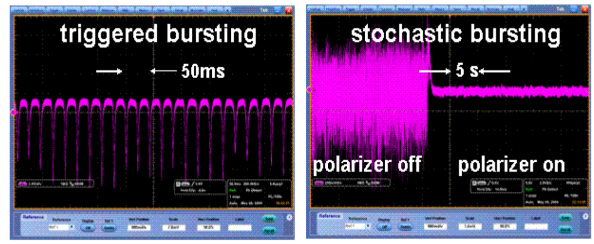

Figure 2: Oscilloscope records of time domain THz bursting at MLS, measured with a liquid He cooled Si-bolometer. Left: 30 Hz bursting triggered by a spontaneous, horizontal beam instability. Right: Stochastic bursting, the signal is partly blocked by a polarizer grid in front of the detector.

Just above the threshold of this instability, the bursting appears as a periodic time pattern. At higher currents it turns into an irregular, stochastic emission, e.g. [54]. The periods of the bursting are extremely sensitive to bunch current and machine parameters. The onset of the bursting is easy to detect and the threshold current can be measured. At BESSY, there is a current dependent bunch lengthening of 50% before the bursting threshold is reached [55]. The bursting as a function of bunch length [56] and beam energy [57] agrees well with theoretical predictions. The bursting threshold is calculated by applying a standard instability analysis ('Keil-Schnell-formula') with the CSR impedance. At BESSY II it was found, that the bunch length grows beyond the threshold with the current I as $\sigma \propto I^{0.384}$ [54], independent on α. The bursting can also be triggered by other effects, such as transverse beam instabilities, Fig. 2 and [68], kicker, scraper and so on. The stochastic bursting is shown in the right panel of Fig. 2. For a clear identification all photons are blocked by filters, only transparent to THz radiation. For further checks, the THz transmission is temporally blocked by a polarizer grid. By a careful tuning of the optics, stable CSR is generated in the MLS.

Several numerical methods are developed to simulate the interaction of the CSR with the bunch [31, 39, 58, 59]. Simple analytical models to describe for example the periodic bursting are still missing.

Power Spectra

For more detailed information, the emitted CSR can be characterized by the frequency power spectrum, for example, derived by autocorrelation measurements with a Fourier transform spectrometer [60, 61]. The spectra include a frequency dependent factor, which could originate from the folding with the transmission efficiency. At storage rings the bunch length can be easily manipulated and the power spectrum for the incoherent and the coherent case can be measured with the same experimental set up. Normalizing the coherent by the incoherent spectra yields

$N_e g_n$, the form factor times the particle number. Frequency dependent transmission efficiencies are the same for both cases and cancels out. The form factor of the bunch shape can be determined with good accuracy; in case of bursting, its averaged shape. A back transformation of the form factor to the bunch shape is not directly possible, because the autocorrelation spectrum contains no phase information. A procedure applying a Kramers-Kronig relation can be used to reconstruct the phase information and in turn the bunch shape [35, 62].

At BESSY, the measured form factor is declining at wave numbers around 10 cm^{-1}, different to the theoretical expectation where it should approach the value of 1 [60, 64]. Missing power in this part of the spectrum makes it difficult to reconstruct the bunch shape. Examples of sub-ps bunches analyzed with a Fourier spectrometer are shown in [64], where measured power spectra and simulated power spectra from bunch shape calculations are compared. The spectrum of coherent radiation measured at several storage rings ranges from some few to about 50 cm^{-1} [65, 66, 67, 68, 69].

The emitted average THz power is in the few 100 μW range measured at a not fully adapted far infra red beam line, where the transmission below 10 cm^{-1} declines by orders of magnitude [5, 70].

Future Upgrade Possibilities

The good agreement between experiment and prediction of the bursting threshold provides confidence into the underlying physical picture. This model can be applied for designing or upgrading storage rings to produce short bunches and CSR. Already for few MeV electrons, the characteristic wavelength of the dipole spectrum is much shorter than THz waves. In this case the emitted THz power is independent on the particle energy and a dedicated THz source can be designed as a low energy electron storage ring. The first results achieved at MLS favor an energy of several 100 MeV, to get reliable short bunches, not affected by bunch lengthening [32].

Based on recent low alpha and CSR experiences, proposals coming up for dedicated or upgrading existing rings. The MLS ring [63] is the first example, which just started user operation. It is not an exclusive THz machine, but it includes a dedicated low alpha optics scheme and already produces intense THz radiation in one of several operation modes. The coherent THz source CIRCE [71] was proposed by the ALS and studied in detail. For the small, 600 MeV ring a sub-THz photon flux of 10^{22} Photons/(s/0.1$\%$BW) is expected. Recently, the dedicated THz source IKNO, a more compact version of CIRCE, is proposed for Italy [72]. The achieved THz power depends strongly on the number of particles per bunch and the bunch repetition rate. To compare the performance between different schemes, the power spectrum, the number of particles per bunch, as well as stable and bursting CSR have to be considered.

A low alpha optics with stable bunches below the bursting threshold is limited to low currents. The low alpha optics of BESSY II achieves an amplification factor of $N_e = 2 \cdot 10^8$ for stable CSR, corresponding to 15 mA multi bunch current. To overcome this current limit, an upgraded of the rf-system is suggested [55]. A factor of 100 larger rf-gradient seems possible using a higher harmonics, super conducting cavity. For a fixed bunch length up to 100 times more increased bunch charge could be achieved. This generates up to 10000 times more THz power. If shorter bunches are preferred, then the presently used, well established low alpha optics can be used in combination with the suggested rf-upgrade, leading to further compressed bunches, from 3 ps to 0.3 ps at 5 mA average current and 500 MHz repetition rate.

SUMMARY

The present results of low alpha operation of storage rings are encouraging, to serve user groups interested in coherent THz radiation and short x-ray pulses. The THz radiation enables a lot of detailed diagnostics of beam dynamics. For the future, machine tests are required to explore the 0.3 ps bunch length range for current limits and beam stability. The full potential of such an operation mode requires an upgrade of the rf-power.

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