THz COHERENT SYNCHROTRON RADIATION FROM ULTRA-LOW ALPHA OPERATING MODE AT DIAMOND LIGHT SOURCE

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Abstract

The Diamond Light Source is regularly operated in low-alpha mode to provide THz coherent synchrotron radiation (CSR) and short X-ray pulses for users. In order to maintain the wide frequency range of the coherent radiation whilst improving the signal to noise ratio, an ultra-low alpha mode has been considered to shorten the bunch length even further. In order to study this mode, the analysis of single bunch dynamics resulting from a variety of wakefield sources has been investigated using a single bunch multi-particle tracking code. These results are compared with measurements recorded using a Fourier transform infrared (FTIR) interferometer on the MIRIAM beam-line at Diamond.

INTRODUCTION

A number of storage rings produce THz CSR by reducing the equilibrium bunch length operating in special dedicated modes, called low-alpha modes where alpha (or α_c) is the momentum compaction factor of the ring. In such operating modes CSR in the THz spectral range can be generated. Low alpha optics has been developed at Diamond Light Source since 2009 and is offered to users for about two weeks per year [1].

A new operating mode was tested at Diamond with the aim to push alpha to the lowest possible value that can be reached while maintaining good machine operating conditions (e.g. injection efficiency, beam lifetime, beam stability, etc.). Such machine configuration has been defined as ultra-low alpha mode and has been trialled at Diamond by shortening the bunch length to achieve higher THz frequencies with acceptable signal to noise ratios (SNR).

In this paper, we present the results of single bunch dynamics simulations with various collective effects and comparisons with measurements in the ultra-low alpha mode at Diamond storage ring.

ULTRA-LOW ALPHA OPERATING MODE

Momentum Compaction Factor and Bunch Length

The momentum compaction factor, in first-order approximation, is defined by

$$\alpha_c = \frac{1}{L}\int_0^L \frac{\eta_1(s)}{\rho}\,ds$$

where L is the storage ring circumference, η_1 is the first-order dispersion and ρ is the bending radius. This shows that the maximum reduction of alpha can be achieved by minimizing the integrated dispersion inside the dipoles which depends on the dipoles and quadrupoles strength. Therefore, the alpha can be reduced by tuning the storage ring lattice, especially the quadrupoles.

The relation between the zero-current bunch length and alpha is given by

$$\sigma_0 = \frac{c\sigma_E}{f_{rev}}\sqrt{\frac{|\alpha_c|E_0}{2\pi heV_{RF}\cos\phi_s}}$$

where e is the elementary charge, c is the speed of light, σ_E is the rms relative energy spread, f_{rev} is the revolution frequency, E_0 is the nominal beam energy, h is the harmonic number, V_{RF} is the peak voltage of the RF cavity and ϕ_s is the synchronous phase. This emphasizes that the reduction of alpha gives the shorter the zero-current bunch length.

The bunch length depends also on the stored beam current in the ring. Operation in negative alpha produces shorter bunches for moderate currents [2, 3]; therefore it was deemed to provide the best option for the ultra-low alpha mode. Diamond has already operated in the THz range up to 40 cm^{-1} and shorter bunches are expected to extend further the available THz range.

SINGLE BUNCH TRACKING SIMULATIONS

Numerical Code sbtrack

In order to study 6D phase space beam dynamics in storage rings with numerical simulations, the multi-particle tracking code *sbtrack* was developed in SOLEIL and Diamond [4]. The *sbtrack* is a single bunch tracking code with the possibility to study a variety of impedance sources. Available sources are resistive wall (RW), broad-band resonator (BBR), CSR, shielded CSR, purely inductive and resistive impedance. A distinctive feature of the version developed at Diamond is the possibility to produce spectrograms over different bandwidths as detected by Schottky barrier diodes, directly from the simulated electron beam.

ULTRA-LOW ALPHA EXPERIMENTS AT DIAMOND

In December 2015, the ultra-low alpha mode was tested in the Diamond storage ring for the first time. The optics was tuned to get lattices with alpha value of -2×10^{-6} which is 5 times smaller than the low alpha mode (with low-emittance lattice as presented in [5]). It is expected that in such mode significantly shorter electron bunches are created. The two RF cavities were set to deliver a total RF voltage of 3.4 MV. The storage ring was filled with a current up to 11.5 mA in 800 stored bunches with horizontal and vertical chromaticity set to +1 and -0.8

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respectively and horizontal and vertical betatron tune of 29.389 and 8.285.

Data were collected as a function of current with a streak camera (SC) for bunch length measurements and Schottky barrier diodes (SBD) with different bandwidths for a partial assessment of the spectral distribution of the radiation emitted. In addition, data were taken from the FTIR interferometer on the MIRIAM (Multimode InfraRed Imaging And Micro-spectroscopy) beamline B22 without any sample to measure the spectrum of the coherent radiation via a pyroelectric detector.

Bunch Length Measurements with the Streak Camera

A dual sweep SC from Optronis GmbH is used to measure the longitudinal profiles of electron bunches in picosecond scale. Images of time structure of synchrotron radiation are recorded directly with the SC. The radiation generated by the electron bunch is a replica of the longitudinal profile of the bunch. In this way the bunch profile can be reconstructed from the time profile of the radiation. The images from the SC are deconvolved with the Point Spread Function (PSF) of 1.6 ps and 2D Gaussian fit is performed to get the bunch profile in order to evaluate the rms bunch length. Figure 1 shows the rms bunch length as a function of current stored in one bunch with results from measurements and simulations which will be discussed later.

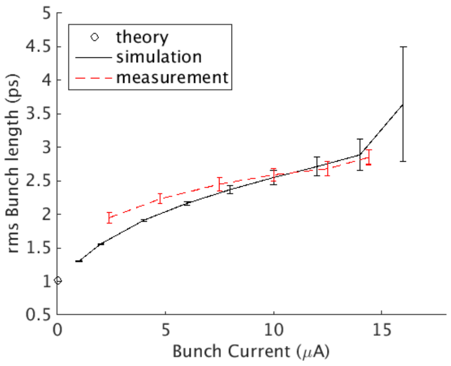

Figure 1: rms bunch length from simulations (black, solid) and measurements (red, dashed).

Spectrograms from the Schottky Barrier Diodes

In order to detect the broadest possible spectral range, an array of eight SBDs is installed at the beamline B06 of Diamond storage ring. Each of the diodes covers a specific frequency range. A total spectral range covering frequencies of 33-1000 GHz can be measured. The time signals are detected by the diodes and the time domain signals are transformed into the frequency domain by Discrete Fourier Transform.

The spectrograms at specific frequency ranges and different stored currents are shown in Figure 2. The threshold current between steady state and bursting is ~8 μA and a broad bursting structure appears at ~1.5 kHz which then shifts to ~2 kHz with increasing bunch current.

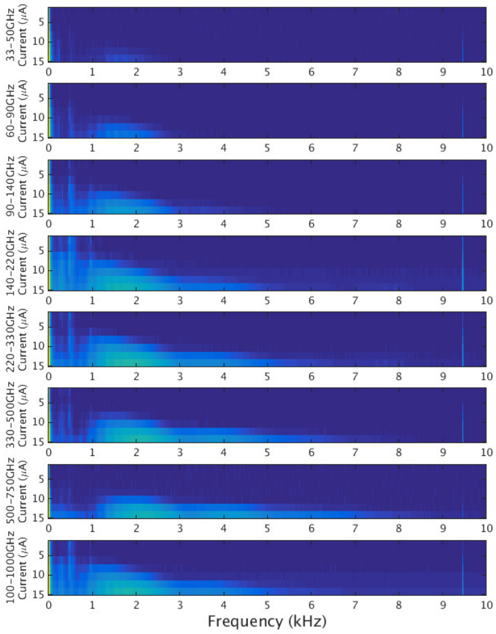

Figure 2: CSR spectrograms for α_c = -2×10^{-6} measured in 8 specific ranges of SBDs.

Spectra from the FTIR Interferometer

The FTIR interferometer is a Bruker Vertex 80 V under vacuum, used with resolution of 1 cm^{-1} and a 6-μm Mylar far-IR beam splitter with scanning velocity of 10 kHz in all experiments. FTIR interferograms were taken by a room temperature pyroelectric DLaTGS detector and processed with the software OPUS. The data are transformed from spatial domain (length of the interferometer arms) into wavenumber domain with Mertz phase correction. Results are shown in Figure 3.

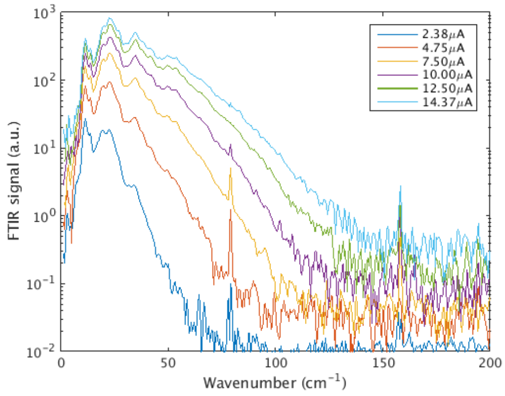

Figure 3: Raw spectra for α_c = -2×10^{-6} measured with FTIR interferometer at different bunch currents.

The threshold current is approximately 8 μA from the streak camera data. At this bunch current, 10% of the peak signal extends to cover wavenumber below 54 cm^{-1} with the SNR at this bunch current shown in Table 1. The

CSR dominated range is extended almost twice of the low-alpha mode [6].

Table 1: FTIR rms SNR at Sampling Velocity 10 kHz.

Spectral range	Ultra-low alpha	Standard user mode
10-40 cm^{-1}	141	210
40-80 cm^{-1}	5	7
10-80 cm^{-1}	6	8

COMPARISONS OF SIMULATIONS AND EXPERIMENTS

A longitudinal impedance model was developed to match the bunch lengthening curves from the streak camera. The impedance model consists of BBR, RW and CSR with shielding. The BBR impedance model is composed of two BBRs (Q = 1). The first one is a low-frequency resonator with shunt impedance R_l = 0.5 kΩ and resonance frequency f_l = 8.3 GHz used in the model of nominal optics [7]. The second is a high-frequency resonator used mainly to reproduce the measurements. The best match for the high-frequency resonator was found for R_l = 90 kΩ and f_l = 100 GHz. The RW impedance is calculated analytically using the average half-apertures of a = 40 mm (horizontally) and b = 12 mm (vertically) and the conductivity of stainless steel vacuum chamber. The bunch profile and bending radius of 7.1 m are used to calculate the CSR wakefield. The shielding effect of the dipole vessel with the half-aperture of 18 mm is included in the CSR model. The *sbtrack* code was also used to check the time structure of the THz emission as detected by the array of SBDs in the same frequency ranges available at Diamond.

Bunch Lengthening

The bunch lengthening curves as a function of bunch current from *sbtrack* simulations using the above impedance model and measurements were already shown in Figure 1. The bunch length from *sbtrack* agrees well with measurement at higher bunch current.

Spectrograms

Simulated spectrograms of CSR are illustrated in Figure 4. The bursting CSR begins at ~8 µA, which corresponds to the measured spectrograms. The bursting structure also covers broad frequency but the whole bursting structure is at 0.5 kHz lower than the measurements.

The *sbtrack* simulations are done for a single bunch model, whilst the measurements were taken with 800 bunches filling pattern. This is a plausible source of the sharper bursting peak shown in simulations. However, we can simulate the CSR behaviour in the ultra-low alpha mode with a reasonably good agreement in terms of bunch lengthening curves, bursting threshold current and broad bursting structures. The structure shift towards higher frequencies for increasing bunch current can also be reproduced.

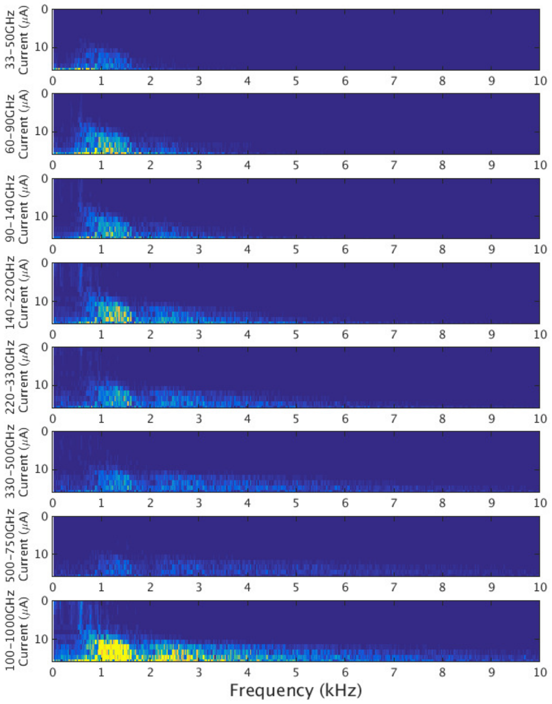

Figure 4: Simulated spectrogram for α_c = -2×10^{-6} in specific ranges as SBDs. To be compared with Figure 2.

CONCLUSION

We have studied the ultra-low alpha operating mode aiming to generate THz CSR, experimentally at Diamond and computationally with *sbtrack*. Reasonably good agreement was found in terms of bunch lengthening and CSR spectrograms. FTIR measurements also validate that the ultra-low alpha lattice extends the CSR spectra. However, the SNR is still not adequate for direct use in spectroscopy. Further study needs to be done focussing on improving the SNR in order to meet the users' requirements.

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