OPERATING THE DIAMOND LIGHT SOURCE IN LOW ALPHA MODE FOR USERS

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Abstract

Since its first introduction in April 2009, the low alpha operational mode has been continually refined in order to best meet the needs of the user community. Initially the lattice was used only to generate short x-ray pulses, for which a stable, low emittance, single bunch was requested, with the emphasis placed on increased bunch charge over shortest absolute pulse duration. More recently, the lattice has been adapted to enhance the CSR gain in the THz region of the electromagnetic spectrum. In this paper we summarise the work carried out in order to meet these two demands.

INTRODUCTION

Dedicated periods of low-alpha operation have been offered at the Diamond Light Source since April 2009, initially for the generation of short x-ray pulses [1]. This was first achieved using a lattice with a relatively large emittance of 35.2 nm.rad; however, for users of this mode it soon became clear a reduction in the emittance was desirable, prompting the development of a new lattice with 4.4 nm.rad [2].

The ideal scenario for pump-probe experiments on Diamond is to have short, high intensity photon pulses that are stable in both time and position. To meet this goal, the charge stored in the single bunch is kept reasonably high, maximising the photon flux without unduly compromising the reduction in pulse duration and beam stability. Since both closed orbit motion and instability thresholds scale with momentum compaction factor (α_c), and the reduction in bunch length is only realised at very small bunch currents, the lattice is operated with only a moderate reduction in α_c to -1×10^{-5}.

More recently there has been growing interest in making use of the gain in flux due to coherent synchrotron radiation (CSR) emission from the short bunches. This is exploited on the MIRIAM infrared beamline [3], where the scientific driver for low alpha operation is to extend the continuous spectral coverage to below 100 cm^{-1} (the long-wavelength limit in standard user mode), primarily in the sub-THz region down to 5 cm^{-1}. The broadest spectral range and maximum THz flux is observed when the bunch charge is above the bursting threshold; a mode of operation which is not compatible with the short x-ray pulse users. This has led to the development of a second, alternative low-alpha operating mode for THz users.

Table 1: Low Alpha Operating Modes

Parameter	Short Pulse	THz
α_c	-1×10^{-5}	-4.5×10^{-6}
No. Bunches	400 + 1	200
Bunch Current	50 μA	50 μA
Coupling	0.3 %	1 %
Lifetime	~20 h	~20 h
Inj. Eff.	30-40 %	15-20 %
V_{RF}	3.4 MV	3.4 MV
MBI Threshold	~35 μA	~15 μA
Bursting Threshold	~60 μA	~30 μA

OPERATIONAL MODES

For both short pulse and THz modes, the storage ring is operated with negative α_c. This benefits both sets of users, in that the bunch lengthening with current is less pronounced compared to operating with positive α_c, and the temporal bunch profile is sharper, enhancing the CSR gain at short wavelengths [4]. Two distinct instability threshold currents are observed when operating with negative α_c. The first occurs at relatively low bunch currents, above which small-scale modulations in the emitted power are observed over time. This is taken to be the micro-bunching instability (MBI) threshold. The second threshold occurs at higher bunch currents, above which strong bursts of radiation appear. These can be observed using the streak camera to cause significant bunch centroid motion. The main parameters of the two operating modes are given in Table 1.

Short Pulse Mode

In principle, the short pulse mode users require only one bunch to be stored in order to perform pump-probe experiments. However, to allow the fast orbit and RF feedbacks to be used, the ring is filled with a hybrid filling pattern, where 20 mA is stored in 400 bunches with the single bunch located in the centre of the gap. The optimal bunch current in this mode is just below the bursting threshold, as the small-scale micro-bunching does not degrade the quality of data that can be taken. The particular hybrid fill pattern used also allows data to be taken parasitically by the THz users and, to a lesser extent, by the other Diamond beamlines.

THz Mode

In order to make best use of the CSR gain, the number of electrons per bunch is kept the same in the THz mode as

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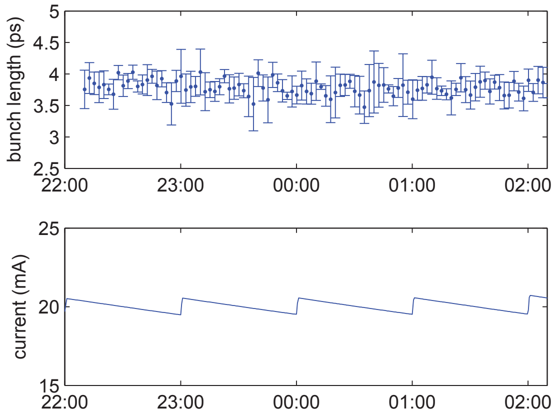

Figure 1: Bunch length data (top) and corresponding beam current (bottom) recorded for the short pulse mode (top-up) during February 2013.

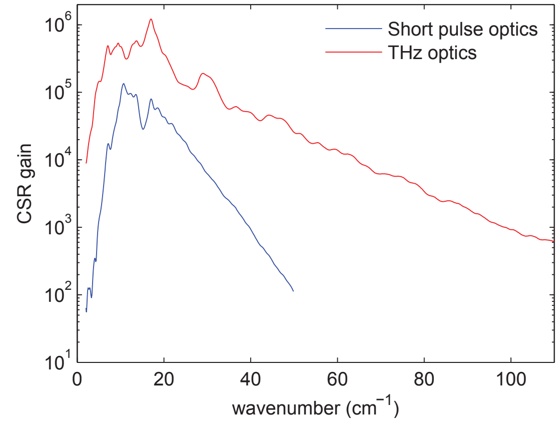

Figure 2: CSR amplification factors for the Short Pulse and THz modes (see Table 1). The CSR spectra were normalised using data recorded in standard user conditions, when 300 mA was stored in 686 bunches.

for the short pulse mode. However, the bunch is squeezed longitudinally by reducing α_c to -4.5×10^{-6}. This causes the bursting threshold to drop below the stored current value, and increases the amount of CSR emitted substantially.

At present, the total current stored in this mode is limited to 10 mA. This is a consequence of the increased transverse beam motion observed during injection, caused by non-closure of the injection bump. At this α_c, the transient beam motion is of sufficient amplitude to trip the orbit interlock.

LOW ALPHA WITH TOP-UP INJECTION

For both operating modes, a substantial improvement in performance has been achieved by switching to operate the storage ring in top-up mode. This could only be carried out following a review of the safety case [5]. At issue is the inherently lower injection efficiency in low alpha compared to standard operation. However, since the stored current is also much lower, it has been possible to define equivalent 'soft' operating limits for the top-up application for low alpha and standard user modes that limit the maximum radiation dose rates that can be received. These are listed in Table 2. Hardware limits set by the personnel safety system remain in place for all modes.

At the request of the respective Principle Beamline Scientists, the top-up interval has been set to 1 h for both operating modes. This leads to injection cycles lasting in the region of 15-20 seconds, with an average charge of 11 pC captured per shot. The standard deviation in bunch charge across the fill pattern is typically 4 pC (2.1 μA).

PERFORMANCE

Short Pulse Mode

For the short pulse mode users, the primary figures of merit when judging the switch to top-up mode are the bunch current and bunch length stability. These are shown

Table 2: Top-up Safety Limits

Parameter	Standard	Short Pulse	THz
Min Inj. Eff.	50 %	10 %	5 %
Min Lifetime	10 h	10 h	5 h
Min Current	50 mA	7 mA	7 mA
Max Current	500 mA	35 mA	15 mA

in Fig. 1, where the bunch length data was recorded using a streak camera. In this figure, each bunch length data point corresponds to the mean and standard deviation over 44 samples, and images have been deconvolved with the camera point spread function [6].

THz Mode

The spectrum of THz power measured on the MIRIAM beamline is observed to be strongly dependent on bunch charge. During a beam decay in short pulse mode from 20.2 mA to 13.4 mA, the peak power was found to fall by a factor ~2 at 10 cm^{-1} and ~4 at 20 cm^{-1}. More significantly, the spectral region where CSR gain was observed shrank from above 40 cm^{-1} to below 30 cm^{-1}.

The move to top-up operation and a dedicated THz mode has improved this situation dramatically. Measurements taken under these conditions at MIRIAM demonstrated a variation in the IR total flux of circa 9%, with the total current varying between 10.2 mA and 9.8 mA. During this time, the spectral region was measured to extend from 5 to 100 cm^{-1}.

The spectra recorded at MIRIAM in the two low alpha modes can be compared to one measured with standard operating conditions in order to calculate the CSR amplification factors, $g(\lambda)$. This was proposed in [7], where the definition

$$g(\lambda) = \frac{P_{tot}(\lambda)}{P_{inc}(\lambda)} \quad (1)$$

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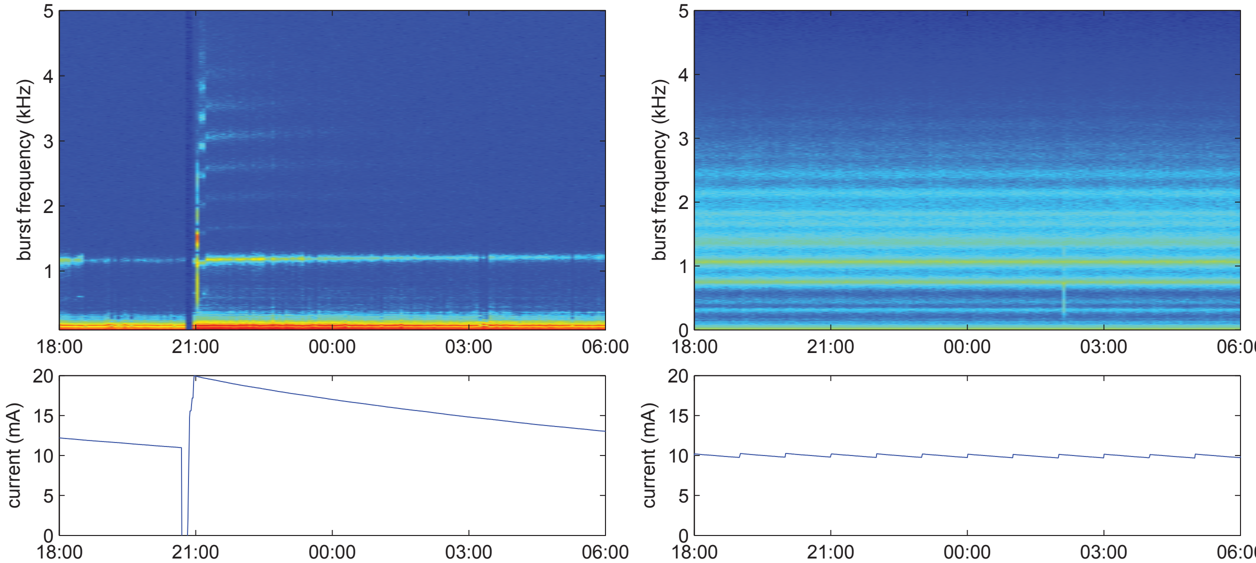

Figure 3: Spectrograms of temporal modulation in power recorded in the 60-90 GHz bandwidth using a Schottky Barrier Diode (top), along with beam current during the acquisition (bottom). The left hand images were recorded during decaying beam for the short pulse mode, and the right hand images show data recorded during top up operation in THz mode.

was used. In Eq. 1, $P_{tot}(\lambda)$ is the total power radiated at wavelength λ by the short bunches, normalised to the number of bunches stored and the number of electrons per bunch. $P_{inc}(\lambda)$ is the equivalent value measured with long bunches under standard operating conditions. The amplification factors for the two low alpha operating modes calculated using Eq. 1 are shown in Fig. 2 .

The longitudinal stability of the electron bunches is routinely monitored during user time using a 60-90 GHz Schottky Barrier Diode (SBD) installed on the mm-wave beam port [8]. A spectrogram showing data recorded in July 2012 in short pulse mode (decaying beam) is shown in Fig. 3. The period shown covers two beam decays, along with a re-injection to 20 mA. The spectrogram shows appreciable fluctuations in emitted power immediately following the injection (including a brief period where the bunches were bursting), followed by a slow variation in the frequency and amplitude of temporal modulations, eventually reaching a condition where the bunches are almost completely stable. Also shown is data recorded in October 2012 in THz mode (top-up operation). This time, the spectrogram shows a high degree of consistency over the 12 h period, despite operating with highly unstable stored bunches. Following a beam trip, the signal strength and frequency of bursting recorded by the SBD return to the same values as measured before the trip, demonstrating the reproducibility of these optics.

CONCLUSIONS

Low-alpha operation of the Diamond storage ring is approaching a state of maturity, and is now carried out routinely with top-up injection and fast orbit feedback enabled. The lattice has been demonstrated to be sufficiently flexible to allow user operations to be performed under several different configurations, and by working closely with the relevant scientists, the operation has been tailored to meet the particular requirements of each beamline.

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