COHERENT mm-RADIATION EXPERIMENTS AT THE BESSY II STORAGE RING*

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Abstract

BESSY II is a low emittance, high brilliance synchrotron radiation source, started its regular user operation in January 1999 [1]. The momentum compaction factor of the machine optics during regular user shifts is rather low, $\alpha = 0.75 \cdot 10^{-3}$. By operating the ring in a dedicated low alpha mode, a further reduction of α was achieved to about $0.7 \cdot 10^{-5}$. Depending on the α-value, coherent far-infrared radiation was observed. A description of the experiment and first results of the measurements are given.

1 INTRODUCTION

Coherent synchrotron radiation (CSR) can be generated in dipole magnets by bunched electrons if two conditions are satisfied [2]. The first condition defines a kind of 'cut off' wavelength $\lambda \approx \sqrt{6h^3/(\pi\rho)}$, related to shielding effects by the vacuum chamber, where h is the full vertical aperture of the dipole chamber and ρ the bending radius of the electron orbit in the dipole magnet. Due to this condition the long wavelength part of the radiation spectrum is suppressed. For the BESSY II dipole we expect the 'cut off' value of the wavelength at around 4 mm.

The second condition is related to an interference effect of radiation emitted by individual electrons of the same bunch. If the bunch length is short compared with the length of the emitted waves, the waves will have phases differences, lower than the wavelength, independent where the source point is located within the bunch. In this case the amplitude factor of the electro-magnetic field will linearly add up, leading to a squared intensity enhancement of the radiation. The radiated power P of mode $n = 2\pi\rho/\lambda$ emitted by N particles of a bunch can be written as

$$P = NP_n + N(N-1)P_n f_n,$$

were P_n is the 'incoherent' power emitted by a single particle and f_n is a form factor, derived from the Fourier transform of the longitudinal bunch density.

For short bunches the form factor will be one and the intensity growth with N^2, yielding to a strong intensity increase. For Gaussian bunches with an rms bunch length of σ_s the form factor becomes $f_n = 1/\exp(2\pi\sigma_s/\lambda)^2$. If $(2\pi\sigma_s)/\lambda$ is approaching 1, strong constructive interference can be observed. Based on the 'cut off' condition and on a Gaussian form factor an rms bunch length of at least 0.7 mm is required for the BESSY II ring to generate CSR. Even longer, non-Gaussian bunches can show constructive interference of emitted waves within the considered range. In BESSY II a low alpha optics was applied to reduce the bunch length and to check for the emission of coherent radiation. The experimental set up is rather simple, sufficient to detect the radiation, but not sophisticated enough to analyse the emitted spectrum. Details of the experiment are given in the following paragraphs.

A detailed study of coherent dipole radiation is given in [3], based on LINAC measurements. Coherent radiation from storage rings is more difficult to achieve. The bunch length in electron storage rings is a result of a complicated dynamical process. Recently, there are two publications of storage ring based measurements, one from Brookhaven (USA) at the VUV ring [4] and the second one from Lund (Sweden) at the Max-I ring [5]. The key to both experiments is a 'low alpha' optics. In the first experiment, a specific longitudinal bunch instability is induced by the low alpha optics, yielding radiation at around 7mm. In the second experiment the low alpha optics is used to shorten the bunch, the emission shows a broad band character. In both experiments, the radiation occurs in bursts, indicating an instability process.

2 LOW ALPHA LATTICE

The momentum compaction factor is a machine parameter, which depends on the transverse beam optics, but it influences many longitudinal beam properties, such as synchrotron oscillation frequency, bunch length and bunch instabilities.

For the regular user optics we calculated for BESSY II a value of $\alpha = 0.75 \cdot 10^{-3}$, in agreement with directly measured values based on Compton-Backscattering [6], corresponding to a synchrotron frequency of 7.5 kHz.

A 16-fold symmetrical, low α optics was developed, as shown in figure 1, to reduce this value as far as possible. A key parameter to tune this optics to different α values is the excitation current of the splitted quadrupole family 'Q1' in the centre of the achromat. By tuning this quadrupole strength the dispersion around the machine changes and in turn α varies. With two more quadrupole families we keep the transverse tunes fixed. Additionally, as α approaches zero, a careful adjustment of the longitudinal chromaticity

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is required, which strongly influences the longitudinal rf-bucket size. Typically, this chromaticity requires a small negative value. It is not free of choice, but linearly related to the horizontal chromaticity. The chromaticity in all 3 planes is set to small negative values.
The values of α were measured indirectly by recording the synchrotron tune Q_s, applying the relation $\alpha \sim Q_s^2$. Optics for positive and negative α values were tested. Those with $\alpha < 0$ seems to be more stable and were used for the CSR experiments. The smallest value of $|\alpha|$ which we could routinely achieve is $-0.7 \cdot 10^{-5}$, yielding some few hours of lifetime at 50 mA average ring current, with 250 filled buckets out of 400. This value of α corresponds to about 700 Hz synchrotron oscillation frequency. Presently, we are limited to about this value, because of harmonics of 300 Hz rf-noise, coupling from the klystrons into the cavities. For further details to establish a low alpha optics see for example [7].

3 EXPERIMENTAL SET UP AND MEASUREMENTS

A regular dipole magnet beam line, not particularly optimised for infrared experiments, is used to detect CSR in the far infra red. A liquid helium cooled InSb-detector [8] is mounted at the exit of a dipole front end. This detector has a constant sensitivity in the wavelength range of 0.5 mm to 5 mm, thus it cannot resolve the recorded wavelengths. The high energy part of the dipole radiation is shielded by a 4 mm crystalline quartz window and an additional black polyethylene foil, leaving a transparent window in the detector band range. Both, the transmission efficiency of the beam line and the absolute detector efficiency are not exactly known but the lower detection limit is at about 10 μW. The size of the detector is about 0.5 cm^2 and it is placed $\approx$ 12 m away from the source point.

In contrast to incoherent radiation, CSR is emitted in proportion to the square of the stored electron current. For two different settings of α respective the synchrotron tune the radiation was measured as a function of the average ring current of a multi bunch fill. The lower curve of figure 2. is measured at 2.2 kHz ($\alpha = 0.75 \cdot 10^{-4}$) and the upper one at 0.75 kHz ($\alpha = 0.75 \cdot 10^{-5}$). The small inset of Figure 2 displays the difference of these intensities as a function of the square of the ring current, indicating a good square relation.

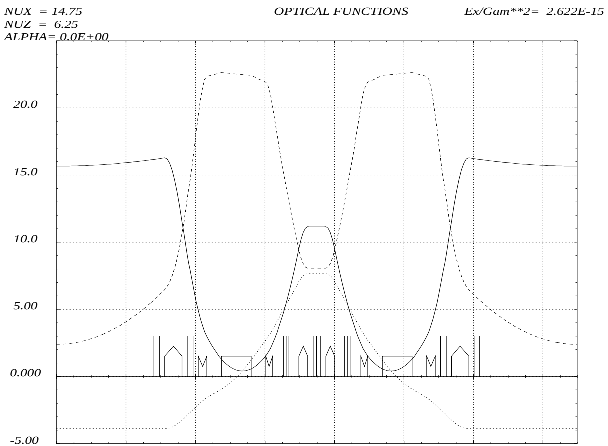

Figure 1: Optical functions of the low alpha unit cell.

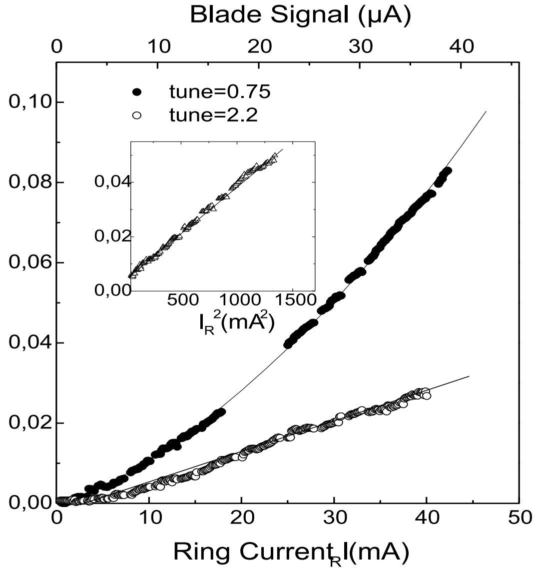

Figure 2: CSR intensity at fixed synchrotron frequency f_s as a function of the multi bunch current for $f_s = 2.24$ kHz (lower curve) and $f_s = 0.75$ kHz (upper curve). The inset shows the difference of the two signal intensities as a function of the square of the current.

Beside the regular beam current transformer, there was a second independent current proportional signal ('blade signal') monitored. This is based on a photo emission signal, installed at the same beam port as the IR-detector, but sensitive to photons of the VUV and soft x-ray range. This last one verifies that manipulations of the beam optics do not affect the incoherent intensity entering the beam line.

An alternative approach, as depicted in figure 3, is to measure the signal intensity at constant beam current as a function of the synchrotron oscillation frequency. This was performed with two scans at fixed multi bunch current. Starting from high tunes, we first see a constant signal level down to 3 kHz. Then the signal grows slowly out of this level and shows a steep increase below 1 kHz. Different symbols are related to different beam fills and some of the points were even recorded at different days demonstrating the reproducibility of the measurement. The absolute location of the CSR intensity with respect to the frequency axis might have errors of around 0.3 kHz.
During the emission of CSR the longitudinal beam signal was observed on a frequency analyser. Clear signals from dipole, quadrupole and sometimes the sextupole mode of the longitudinal synchrotron tune could be seen. The strength of these lines increased when approaching harmonics of the 300 Hz rf-noise. A systematic study of

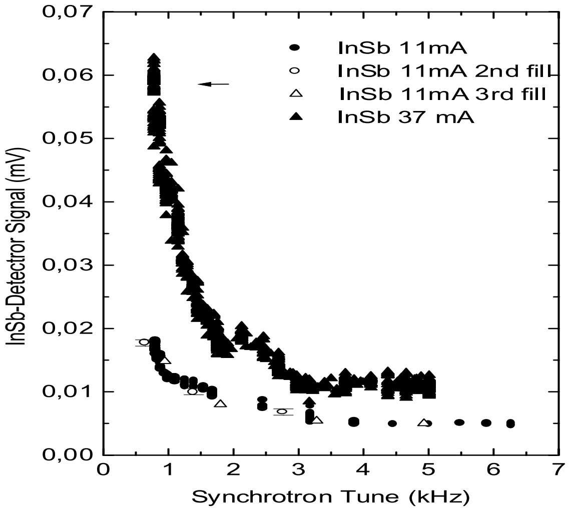

Figure 3: CSR intensity at constant multi bunch current of 11 mA (lower curve) and 37 mA (upper curve) as a function of the synchrotron tune.

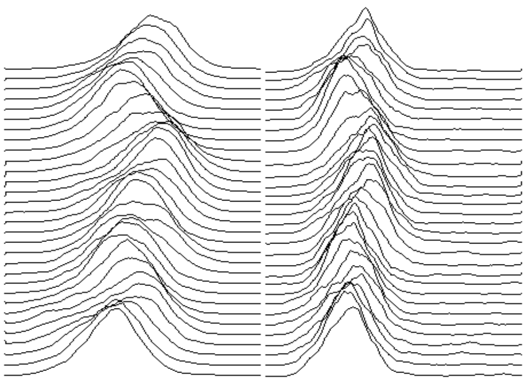

Figure 4: Streak camera records of longitudinal bunch shapes at 0.51 mA/bunch (left) and 0.077 mA/bunch (right). The vertical axis ranges over 2 ms, the horizontal axis of each part is 72 ps.

these tune lines was yet not done.

For the measurements of Fig. 2 and 3 the IR-signal was recorded with 25 ms integration time. Within this resolution no bursts could be seen. The time resolution of the detector was tested by a fast beam dump by the beam injection kicker in less than a μsecond. The response of the detector signal was within 10 to 20 μseconds back on the zero current level. A time resolved measurement for a single bunch up to the order of ms and less was yet not done. During a multi bunch filling we expect anyway a quasi constant radiation.

Bunch length measurements [9] were performed with a streak camera and single bunch filling. Some of these records are shown in figure 4. The bunch centre is oscillating with about 1.3 kHz ($\alpha = 2 \cdot 10^{-5}$). During one oscillation of the bunch centre two shape oscillation could be seen, indicating a quadrupole mode oscillation. The rms bunch lengths were 2.8 mm at 0.51 mA / bunch and 1.9 mm at 0.077 mA / bunch, respectively.

4 SUMMARY

For the first time far-IR CSR was detected on a 'third generation' light source. The experimental set up was mounted on a regular dipole beam line, using a liquid helium cooled InSb semiconductor detector. The signal was generated by the low alpha mode of the storage ring, its strength is clearly proportional to the square of the beam current over a large current range. The detector signal intensity during a multi bunch filling and 25 ms integration time was quasi stable, depending only on the beam life time of some few hours. Streak camera measurements indicate a longer bunch length then from a simple zero current length scaling is expected. Additionally to synchrotron tune observations they indicate longitudinal bunch instabilities. To clarify the underlying physical process which generates this radiation requires more refined measurements.

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