POWERFUL, STEADY STATE, COHERENT SYNCHROTRON RADIATION AT BESSY II*

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Abstract

A new technology for generating high quality and powerful far infrared radiation (FIR) in electron storage rings is presented. Controlled, steady state, coherent synchrotron radiation (CSR) [1] is produced by a 'low alpha' optics mode of the synchrotron light source BESSY II [2]. We report on recent results of CSR experiments, demonstrating a FIR power increase of more than 10 000 compared to the incoherent case in the range of 10 cm^{-1} to 25 cm^{-1} (λ = 1 mm to 0.4 mm). The influence of various machine parameters on the emitted FIR radiation is investigated.

1 INTRODUCTION

Coherent synchrotron radiation can be generated if electro-magnetic waves, emitted by the relativistic electrons, superimpose at equal phase. For a given radiation wavelength, λ, the emitted power, P, can be derived from the 'incoherent', single particle power, P_{incoh},

$$P = NP_{incoh}(1 + N \cdot f_\lambda),$$

where N is the number of electrons in the considered bunch volume and f_λ is a form factor, derived from the Fourier transform of the longitudinal electron bunch density. For $N \cdot f_\lambda \gg 1$ mostly CSR is emitted. In case of a Gaussian bunch density distribution with the rms length σ the form factor is simply given by $f_\lambda = \exp(-(2\pi\sigma/\lambda)^2)$. This relation states, that short bunches and long wavelengths support CSR emission.

Since the emission of long wavelengths is suppressed by shielding effects of the vacuum chamber, we manipulate the bunch length and shape by tuning the storage ring optics into a dedicated 'low alpha mode', see figure 1. By changing the momentum compaction factor α at a fixed rf-voltage the 'zero current' bunch length σ can be varied as $\sigma = \sigma_0 f_s/f_{s0}$ and $\alpha/\alpha_0 = f_s^2/f_{s0}^2$ [3], where the synchrotron tune f_s is detected by stripline signals out of the beam pipe. The values of the regular user optics are $\sigma_0 = 5$ mm, $\alpha_0 = 7.3 \cdot 10^{-4}$ and f_{s0} =7.5 kHz at 1.3 MV rf voltage and 1.7 GeV beam energy. With the low alpha optics f_s could be reduced by more than a factor of 10, corresponding to a 100 times smaller α. For example, at 10 μA per bunch and f_s = 1.1 kHz ($\alpha = 1.5 \cdot 10^{-5}$) a bunch length of σ = 1.1 mm was measured with a streak camera [4]. This is 50% longer than the simple scaling suggests, indicating a current induced bunch lengthening.

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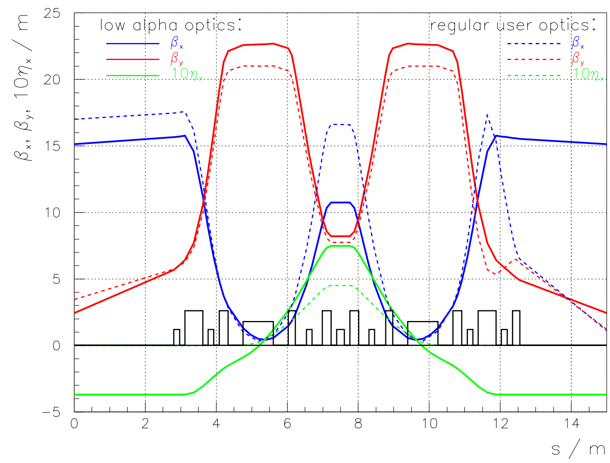

Figure 1: Optical functions: 8-fold symmetric regular user optics and 16-fold symmetric low alpha optics.

In a different beam optics set up CSR experiments have been performed with the regular user optics, were a similar FIR spectrum as in the low alpha optics was measured.

2 EXPERIMENTAL SETUP

The FIR measurements were performed at the IR beamline IRIS [5]. The beamline accepts infrared dipole radiation 60 mrad horizontally and 40 mrad vertically. The radiation above and below the storage ring midplane is collected by a horizontally split, plane mirror and is then refocused by an anamorphotic optic near a wedge CVD diamond window, which separates the ultra-high vacuum system of the front end from the fore-vacuum environment of the next section of the optical path. Then, a set of focusing and plane mirrors reflects the radiation to an entrance port of the vacuum FT-IR spectrometer Bruker 66/v. The far infrared radiation was detected with a Si bolometer of composite type, operating at a temperature of 4.2 K. The detector has a sensitivity of $1.9 \cdot 10^5$ V/W. A 6 micron thick Mylar beamsplitter was utilized and spectra were taken with a resolution of 1 cm^{-1}. For comparison of the FIR synchrotron radiation with a commonly used spectroscopic FIR source the internal 87 W Hg arc lamp of the Bruker 66/v was used.

3 MEASUREMENTS WITH LOW ALPHA OPTICS

Figure 2 shows the current dependency of the FIR spectrum at f_s = 1.15 kHz. The beam was stored as a multi-

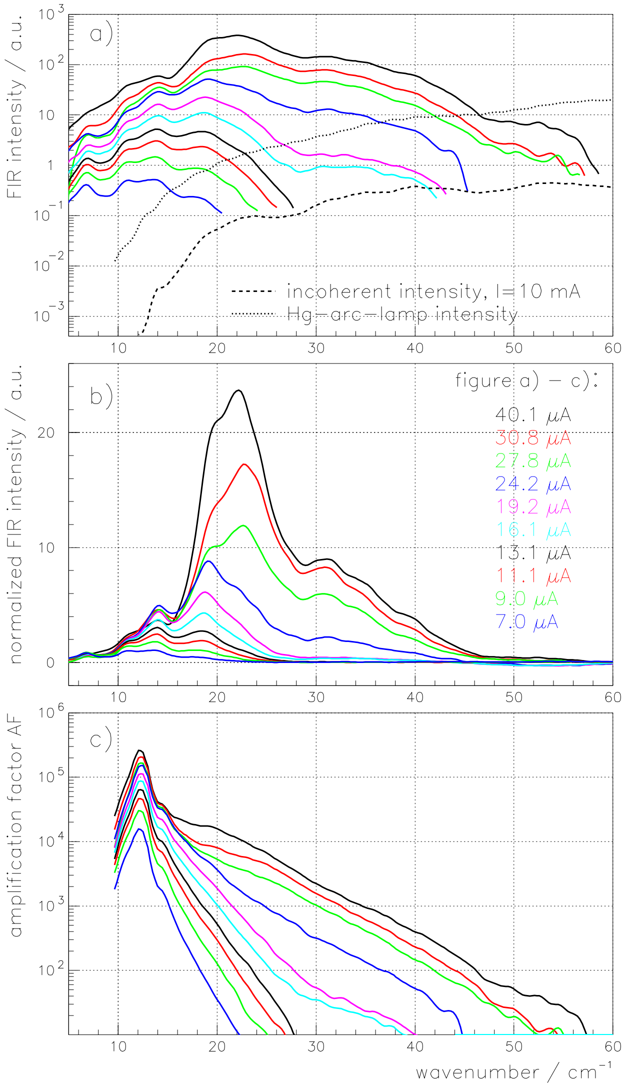

Figure 2: Current dependency of the FIR power spectrum in a low alpha optics of f_s = 1.15 kHz, a) compared with incoherent spectrum of 10 mA multibunch current and a Hg-lamp spectrum, b) normalized by I^2, c) amplification factor P_{CSR}/P_{incoh}.

bunch filling in 100 consecutive bunches, with a beam current per bunch from 7 μA up to 40 μA - at higher currents the detector becomes saturated. For comparison, also the incoherent intensity (below detection limit level in the low alpha optics), measured at 250 mA beam current (0.65 mA / bunch) distributed in nearly 400 buckets and linearly normalized to 10 mA beam current (100 μA / bunch) in the regular user optics, as well as the spectrum of a Hg-arc-lamp are drawn (Fig. 2a).

The FIR spectrum ranges nearly to values < 50 cm^{-1}, extending to much larger wavenumbers than expected for a strictly Gaussian bunch of 1.2 mm rms length. The tails at larger wavenumbers become more pronounced with increasing current.

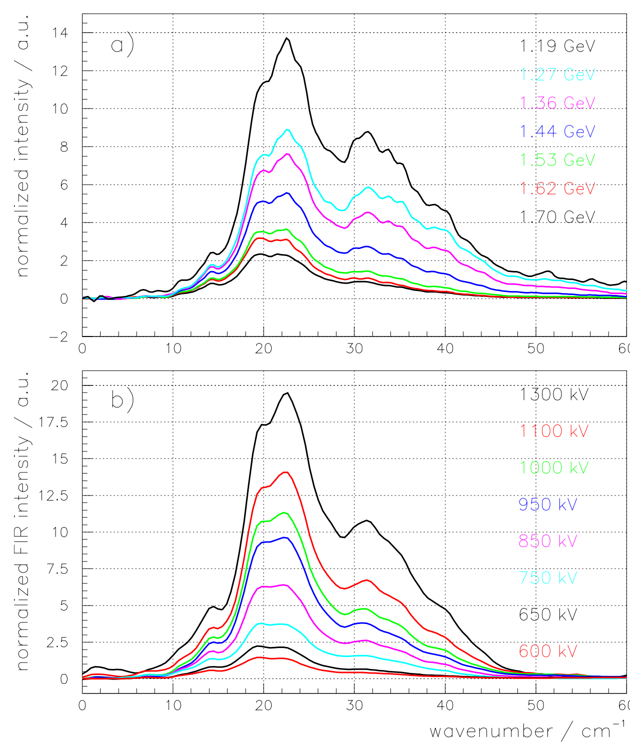

Figure 3: FIR power spectra normalized by I^2 of the low alpha optics at a) different beam energies, $\alpha = 4.5 \cdot 10^{-5}$ and I=100 μA to 23 μA, b) different rf voltages, α=1.5$\cdot$10^{-5} and I=50 μA to 46 μA.

A different display of the current dependency is shown in figure 2b, where the intensities are normalized to the square of the average beam current. For increasing beam current we see a strong gain of the emitted radiation power. In case of a constant form factor f_λ these normalized CSR intensities should be current independent, different to the presented results. A simple, form invariant current dependent bunch lengthening would lead to even less emitted power. We expect an additional bunch deforming leading to a growth of the form factor and thus enhances CSR emission in this spectral range.

In figure 2c the current dependency of the amplification factor $A_F = P_{coh}/P_{incoh} = N \cdot f_\lambda$ is plotted, to become independent of cutoff, spectral transmission and detector properties. The A_F should be a mainly decreasing function, starting with the number N of electrons per bunch at 0 cm^{-1}. Different to this expectation, A_F is strongly growing in the range from 10 cm^{-1} to 12 cm^{-1}, which probably arises from too weak and incorrectly measured, incoherent intensities. At 12 cm^{-1} a peak A_F of more than 10^5 is achieved. From beam energy, dipole field and beam current the emitted power for the incoherent case can be estimated. Together with the maximum amplification factor this leads to a peak power density of 0.2 mW/cm^{-1} at 40 μA per bunch and an integrated value of 1mW in the range from 0 cm^{-1} to 50 cm^{-1}. This is not the maximum achievable

peak power density, because we limited the beam current to avoid saturation of the detector.
Figure 3 shows records of the FIR spectrum as a function of the electron beam energy and rf-voltage amplitude. Note that in both measurements synchrotron tune and bunch length changed, although the momentum compaction factor was kept constant.
While varying the beam energy from its nominal value of 1.70 GeV and α = 4.5$\cdot 10^{-5}$ to 1.19 GeV the emitted FIR intensity is growing by a factor of 6. The spectra presented in figure 3a grow significantly at all wavenumbers, where again intensities at larger wavenumbers are more enhanced. The power gain at around 60 cm^{-1} has to be verified more carefully. The detuning of the energy was done be scaling the excitation current of the magnets at fixed transverse tunes, whereas the transverse and longitudinal chromaticities were not controlled. Therefore, the magnet optics might not have scaled exactly, which could lead to an additional influence on the appearance of the spectra. In an earlier measurement (not shown) it was found that emitted FIR intensity depends on the chromaticity, for example, a current change of the longitudinal chromatic sextupoles by about 1 % could change the emitted power by 30 %. This dependency has to be studied in more detail.
In case of the rf voltage detuning the amplitude was changed from the regular value 1.3 MV and α=1.5$\cdot 10^{-5}$ to 600 kV which results in the FIR power change of a factor 14, see figure 3b.

4 MEASUREMENTS WITH THE REGULAR USER OPTICS

According to previous single bunch experiments with the regular user optics [1], also multi bunch FIR measurements have been performed. The most important result is that in spite of longer bunches (compared to the low alpha case) CSR was detected. In Figure 4 spectra recorded at average ring currents up to 2.5 mA per bunch are displayed, where the detector saturated at higher current values. For wavenumbers from 25 cm^{-1} to 100 cm^{-1} the incoherent FIR (proportional to the ring current) dominates the spectrum. At wavenumbers < 40 cm^{-1} there is an increasing coherent contribution to the spectrum. With growing current not only the intensity increases extremely, but also the wavenumber range of coherent radiation shifts to higher values. For comparison, a low alpha spectrum (f_s =1.15 kHz, I = 19 μA) is included in figure 4. Although in general quite similar, the FIR emission is less intense compared to the low alpha optics, but still powerful.
A bunch current of $I \approx 2$ mA indicates a threshold for CSR emission - below this value only the incoherent radiation remained. Compared to the low alpha measurements, where we found no indication for a current threshold of CSR emission, we suppose to observe another kind of emission process, possibly caused by an electron beam instability [6]. This instability mechanism could vary the bunch shape and the form factor respectively, leading to the coherent emission.
Although the quality of the spectra generated by the user optics indicates a stable source, a final statement on the stability of the detected CSR is presently not possible.

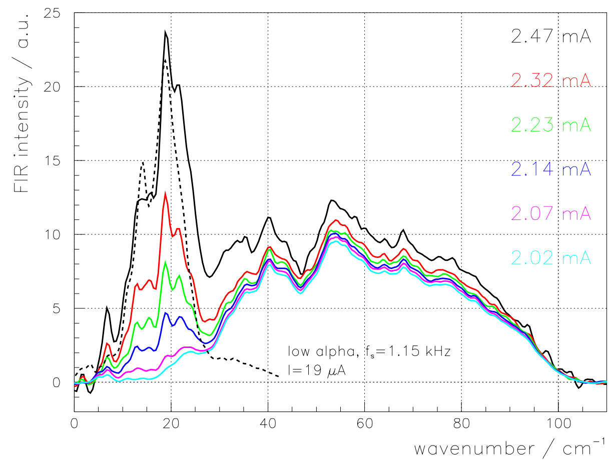

Figure 4: Current dependency of the FIR spectrum in the regular user optics.

5 SUMMARY & ACKNOWLEDGEMENT

The presented measurements demonstrate the possibility to produce high quality and powerful FIR. These results could be useful for desinging storage rings for coherent radiation [7]. Beam current effects which probably lead to bunch deformations increase the achieved power. The upper limit of the extracted power is not yet explored, we expect a limit given by the bursting threshold [6].
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6 REFERENCES

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