Brilliant, Coherent Far-Infrared (THz) Synchrotron Radiation

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A new technology for generating steady state, brilliant, broadband, coherent, far-infrared (FIR) radiation in electron storage rings is presented, suitable for FIR spectroscopy. An FIR power increase of up to 100 000 compared to the normal, incoherent synchrotron radiation in the range of ~5 to ~40 cm^{-1} could be achieved. The source is up to 1000 times more brillant compared to a standard Hg arc lamp. The coherent synchrotron radiation is produced in a "low alpha" optics mode of the synchrotron light source BESSY, by bunch shortening and non-Gaussian bunch deformation.

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Electron storage rings provide synchrotron radiation from the far infrared to the x-ray region. The radiation is emitted by relativistic electrons during their transverse acceleration in magnetic fields and is normally emitted as incoherent electromagnetic waves of arbitrary phase relation. This leads to a radiation intensity proportional to the number N of electrons involved. A drastic change in the properties of emitted radiation occurs by reducing the length of the stored electron bunches to that of the long wavelength part of the radiation. Waves comparable to the bunch length now superimpose in phase and the electric fields of the waves add up coherently, leading to a radiation power whose growth scales with the square of the charges involved [1]. The coherent radiation lies in the far-infrared (FIR) wavelength region, where conventional thermal sources are of very low power. This spectral range at the boundary to the microwave region is commonly referred to as the "THz gap" covering frequencies too high to be accessible to electronics and too low for photonic devices.

Coherent FIR synchrotron radiation was first detected at LINAC-based sources [2,3]. Recently, broadband coherent enhancement of FIR synchrotron radiation was observed at the chicane of the Jefferson Laboratory free electron laser for subpicosecond electron bunches [4,5]. At several electron storage rings fluctuating bursts of coherent FIR radiation have been observed but which are not suitable for FIR spectroscopy [6–10]. For the first time, steady state, coherent FIR radiation from an electron storage ring [11,12] was achieved at BESSY (Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H., Berlin, Germany) [13].

For a given radiation wavelength, λ, the emitted power, P, can be derived from the "incoherent," single particle power, $P_{1,\text{incoh}}$ [1],

$$P = NP_{1,\text{incoh}}(1 + Nf_\lambda), \tag{1}$$

where f_λ is a form factor, derived from the Fourier transform of the longitudinal electron density in the bunch. For $Nf_\lambda \gg 1$ phase correlation is achieved and mostly coherent synchrotron radiation (CSR) is emitted. In the case of a Gaussian bunch density distribution with the rms length σ the form factor is given by $f_\lambda = \exp[-(2\pi\sigma/\lambda)^2]$. According to this relation short bunches support CSR emission at long wavelengths.

The emission of coherent FIR radiation of a few mm wavelength at the standard BESSY user optics is suppressed by shielding effects of the dipole vacuum chamber [1,14,15]. To overcome this limitation we manipulate the bunch length and shape by tuning the storage ring optics into a dedicated "low alpha" mode [16], where alpha, α, is the momentum compaction factor describing the orbit length variation with beam energy. This yields shorter bunches and at higher beam currents of non-Gaussian shape [17], shifting the CSR spectrum with respect to the shielding cutoff. Above a certain threshold current bunch instabilities are involved in the emission process, which leads to a periodic or even stochastic bursting [18,19]. These instabilities could limit the usability of the radiation for spectroscopic applications but enhance the emitted CSR power.

By changing α at a fixed voltage delivered by the rf cavities the "zero current" bunch length, σ, can be varied as [16]

$$\sigma = \sigma_0 f_s/f_{s0} \quad \text{and} \quad \alpha/\alpha_0 = f_s^2/f_{s0}^2, \tag{2}$$

where the "0" subscript refers to the operating parameters of the regular user optics. The synchrotron frequency, f_s, is detected by strip-line signals out of the beam pipe and used as a reference for the α-value applied. The values of the regular user optics are $\sigma_0 = 4.5$ mm, $\alpha_0 = 7.3 \times 10^{-4}$, 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 ($\alpha = 1.5 \times 10^{-5}$) a bunch length of

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$\sigma = 1.0$ mm was measured with a streak camera. This is nearly twice as long as the simple scaling suggests, indicating the resolution limitation of the streak camera. It should be mentioned that these short bunches are also of interest for time resolved experiments for the entire spectral range of the synchrotron radiation.

At BESSY the synchrotron radiation is emitted by short bunches of electrons circulating in the storage ring with a revolution time of 800 ns. The typical rms length of the radiation pulse is about 1 mm (equivalent to 3 ps) in the low alpha optics mode, defined by the electron bunch length. Depending on the fill pattern, there can be up to 400 bunches stored in the ring equally spaced by 2 ns (500 MHz repetition rate). In the bending dipoles, radiation with wavelength from mm to Å is emitted, most of it incoherently. Only at the long wavelength limit coherent radiation is generated within a transition region, with energies from a few wave numbers just above the shielding cutoff to about 40 cm^{-1} (1.2 THz, $\lambda = 0.25$ mm). At shorter wavelengths the coherence disappears. In the transition region the detected intensities strongly depend on the coherent superposition of waves from different parts inside the bunch, as described by the form factor, f_λ, which in turn is strongly influenced by the bunch current, the rf-voltage amplitude, the beam energy, and the α value.

The FIR measurements were performed at the IR beam line IRIS [20]. The beam line accepts infrared dipole radiation 60 mrad horizontally and 40 mrad vertically. The FIR radiation was detected with a composite-type Si bolometer operating at a temperature of 4.2 K attached to a vacuum Fourier-transform infrared (FTIR) spectrometer. The detector has a sensitivity of 1.9×10^5 V/W. Background radiation was minimized by means of a cooled filter with a cut-on wave number of 100 cm^{-1} in front of the detector element. A 6-μm Mylar beam splitter was utilized and spectra were recorded with a resolution of 1 cm^{-1}.

Figure 1(a) shows the bunch current dependence of the FIR spectrum at $f_s = 1.15$ kHz. The beam was stored as a train of 100 consecutive bunches, with a beam current per bunch from 9 up to 40 μA. For comparison, the incoherent intensity (below the detection limit level for the low alpha optics), normalized to a total current of

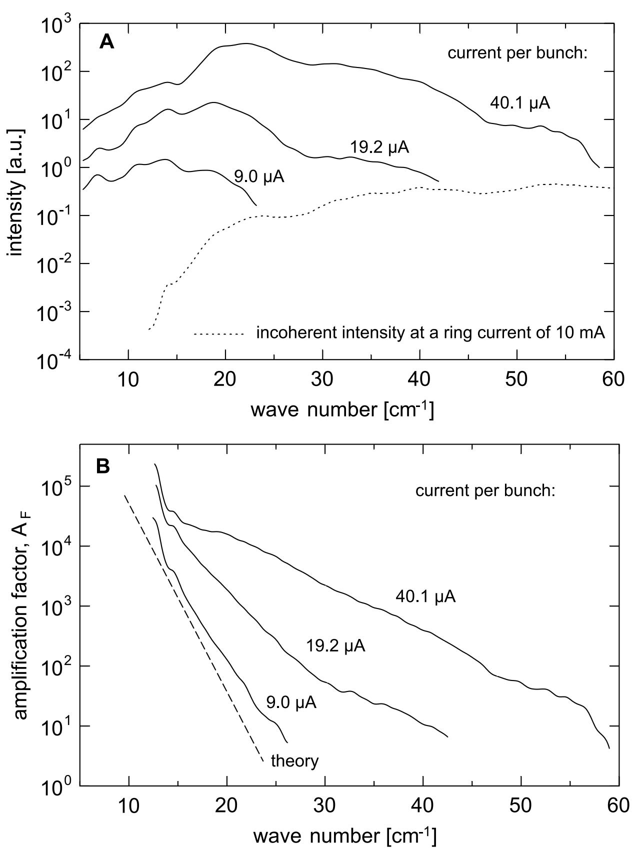

FIG. 1. Current dependence of the FIR spectra in a low alpha optics of $f_s = 1.15$ kHz at 1.7 GeV, (a) compared with the incoherent multibunch spectrum and (b) for the amplification factor, A_F. The theoretical A_F due to potential well distortion is compared to the experimental data for 9.0 μA bunch current.

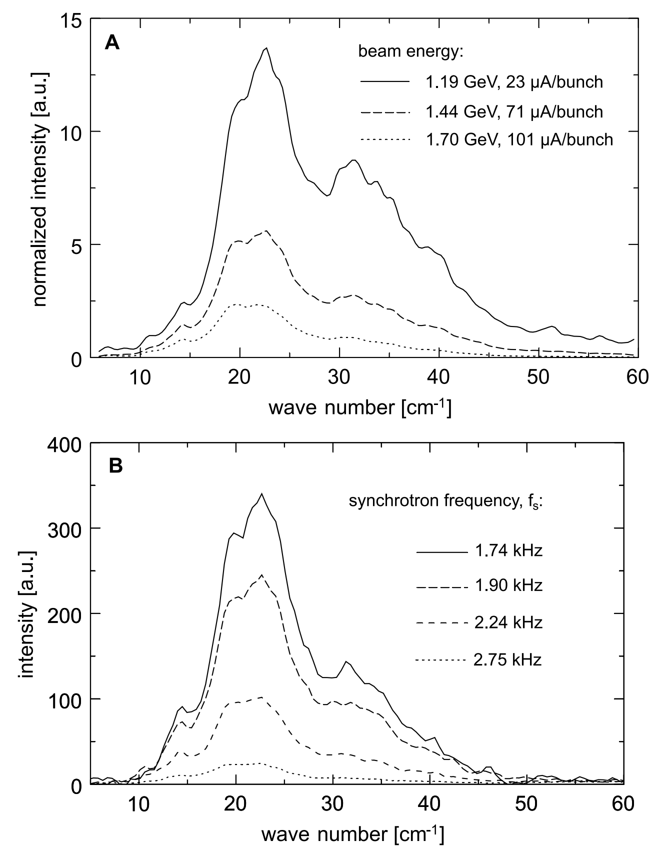

FIG. 2. FIR power spectra of the low alpha optics at (a) different beam energies and constant $\alpha = 4.5 \times 10^{-5}$; the spectra are normalized by the square of the beam current. (b) Different synchrotron frequencies and constant bunch current of 100 μA.

10 mA in the regular user optics are shown in Fig. 1(a). The coherent FIR spectrum reaches values $> 40\ \mathrm{cm}^{-1}$, extending to much higher wave numbers than expected for a strictly Gaussian bunch of 1.0-mm rms length. The tails at higher wave numbers become more pronounced with increasing current indicating static or dynamic changes of the bunch shape.

In Fig. 1(b) the current dependence of the amplification factor, $A_F = P_{\mathrm{coh}}/P_{\mathrm{incoh}} = N f_\lambda$, applying the results shown in Fig. 1(a) is plotted; the effects of cutoff, spectral transmission, and detector properties have been removed. As expected, A_F increases and should approach the number N of electrons per bunch at the long wavelength limit. Static bunch shape distortion due to the potential well distortion created by the unshielded CSR wakefield [17] just below the instability threshold [18] leads to coherently emitted radiation at higher wave numbers than expected from a purely Gaussian particle distribution. At $12\ \mathrm{cm}^{-1}$ an A_F value of more than 10^5 is achieved. The 9.0 μA curve agrees reasonably well with the theoretical calculation of A_F.

From beam energy, dipole field, and beam current the emitted power for the incoherent case can be calculated. Together with the amplification factor the power density of $0.2\ \mathrm{mW/cm}^{-1}$ emitted into the angular acceptance of the beam line can be estimated at 4 mA total current distributed in 100 bunches. Integrating over the spectral energy range from 12 to $50\ \mathrm{cm}^{-1}$ for the same current filling we obtain an average power of 1 mW and a peak pulse power of 2.4 W, respectively.

Figure 2 shows examples of the spectral FIR intensity as a function of the electron beam energy and the low alpha parameter. Note that in the case of the beam energy change [Fig. 2(a)] the synchrotron frequency and the bunch length vary as well, although the momentum compaction factor is kept constant. Here, the scaling condition given in Eq. (2) is not valid anymore.

While varying the beam energy from its nominal value of 1.7 GeV and $\alpha = 4.5 \times 10^{-5}$ to 1.19 GeV the emitted FIR intensity divided by the square of the beam current increases by a factor of 6. The spectra presented in Fig. 2(a) increase significantly at all wave numbers, where again intensities at larger wave numbers are more enhanced.

In case of the α detuning the control parameter f_s was changed from 2.75 kHz ($\alpha = 1 \times 10^{-4}$) to 1.75 kHz ($\alpha = 4 \times 10^{-5}$) at a constant beam current of 100 μA per bunch. The FIR power increased by a factor of 13; see Fig. 2(b).

To examine the brilliance of the coherent FIR synchrotron radiation source the flux was measured for different throughputs (focal area size times acceptance angle) and compared to the flux of the internal, 80 W Hg arc lamp, representing a blackbody of about 4500 K in the FTIR spectrometer measured under identical conditions. The measurements were done for both sources taking spectra through different sized circular apertures which are placed at the sample position in the sample compartment of the spectrometer, for the CSR at a synchrotron frequency of 1.8 kHz and a stored bunch current of 120 μA. The spectra of the CSR source for each aperture were divided by the spectra of the internal Hg arc lamp for the same aperture.

In Fig. 3 the ratios for aperture diameters of 15, 5, and 2 mm are shown. The ratios increase with decreasing wave number due to the drastic increase of the coherent FIR radiation from the electron storage ring. For wave numbers smaller than 20 the curves flatten out. In this region the transmittance of the IR beam line decreases due to diffraction losses resulting from the finite size of the optical elements [21] yielding a lower synchrotron radiation flux. Also in this region, the flux of the Hg arc lamp through the 2-mm aperture decreases down to the detection limit of our detector and therefore causes noisy data for the ratio. However, over the wave number region investigated and for the synchrotron parameters involved in these measurements the ratio between the coherent FIR synchrotron spectra and the spectra of the Hg arc lamp increases by a factor of about 10 when utilizing the 2-mm instead of the 15-mm aperture. At $20\ \mathrm{cm}^{-1}$ one obtains about 1000 times more flux on a sample of 2-mm diameter than from the internal source. These measurements confirm the brilliance advantage of the coherent FIR synchrotron radiation over the internal Hg arc lamp of the spectrometer. The advantage will be even more distinct for still smaller apertures down to the diffraction limit, e.g., microprobes.

The CSR source at BESSY enables FTIR spectroscopic investigations in the spectrum for the far-infrared range (THz and sub-THz) where conventional thermal broadband sources are not useful. For the stablity of the source, characterized by the signal-to-noise ratio, a value of 400 was measured in the 5 to $15\ \mathrm{cm}^{-1}$ range. These numbers

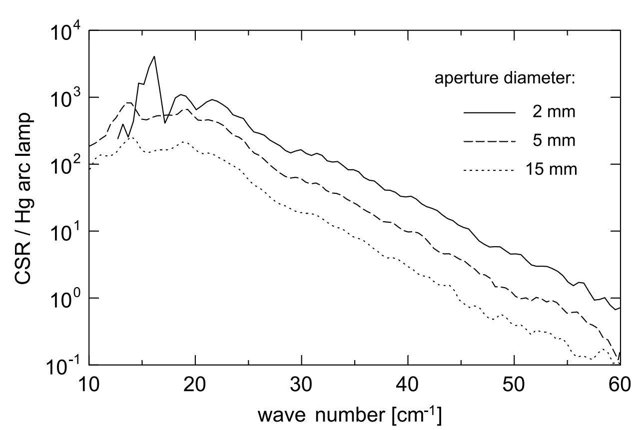

FIG. 3. Intensity ratio of the spectra of the coherent FIR synchrotron source and the spectra of the internal Hg arc lamp of the spectrometer for different apertures placed at the sample position of the spectrometer.

are dependent on the operating condition of the FTIR spectrometer and of the machine. The noise depends on typical machine and mechanical noise sources. In addition, beam current and the momentum compaction factor for the coherent emission mode have to be chosen in an appropriate way. By lowering α or by increasing the stored current per bunch the brilliance of the emitted coherent FIR radiation is drastically enhanced. However, increasing the intensity above a threshold value can act back on the beam and lead to bunch instabilities and bursting CSR [18,19]. Further investigations are necessary to explore the best mode for FIR experiments.

The brilliant, coherent far-infrared radiation produced in the storage ring using the low alpha optics makes possible experiments in a spectral region hitherto only poorly accessible to scientists. In addition the bunch shortening down to and below the mm range is of interest for accelerator physics and can have an impact on the design of future storage rings.

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