Magnetic Field Discontinuity as a New Brighter Source of Infrared Synchrotron Radiation

Y.-L. Mathis,* P. Roy,† B. Tremblay, A. Nucara,‡ S. Lupi,‡ P. Calvani,‡ and A. Gerschel§
Laboratoire pour Utilisation du Rayonnement Electromagnétique, 91405 Orsay Cedex, France
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Strong emission of highly collimated infrared radiation demonstrates the presence of dipole edge emission and transient undulator radiation emission. The photon flux and spatial distribution for the Super-ACO sources (both dipole edge and wiggler) including coherence effects have been evaluated using the exact expression for the emission of a charged particle. The excellent agreement between these results and measurements performed at the SIRLOIN (Spectroscopie en Infrarouge LOINtain) beam line provides a new level of understanding of infrared synchrotron radiation. [S0031-9007(97)05153-3]

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Synchrotron radiation (SR) is increasingly used in the infrared (IR) domain as an alternative for laboratory sources such as a mercury lamp or glowbar. They are especially adapted for measurements requiring more brilliance and/or more intensity in the far infrared.

Theoretical calculations have recently suggested that the discontinuity in a magnetic field [1–6] could be an alternative source of infrared synchrotron radiation (IRSR). This emission may present significant advantages in terms of brilliance and simplicity of the beam line over other IRSR sources. The object of this Letter is to demonstrate experimentally the presence of such an emission by the edge of a dipole [dipole edge emission (DEE)] and by an undulator [transient undulator radiation (TUR)]. For this purpose, we first evaluate the photon flux and spatial distribution for the Super-ACO sources (both dipole edge and wiggler), including coherence effects. These results are then compared with measurements performed at the SIRLOIN (Spectroscopie en Infrarouge LOINtain or far infrared spectroscopy) beam line [7,8], providing the first demonstration of the performances of the IRSR edge radiation.

Some recent theoretical studies report the intensity emitted by the edge of a dipole [2,3,9] or wigglers [6,9,10] when coherence effects are taken into account (in contrast with the first generation of calculations of SR in the infrared range [7,11–15]. The main result of these new calculations is the suggestion that the infrared radiation emitted by a relativistic particle entering or leaving a magnetic device presents a significantly higher brilliance (number of photons per second per unit of surface source per unit of solid angle) than the radiation emitted within the dipole (region of constant magnetic field). According to these calculations, this effect gets more pronounced as the wavelength get longer, and in the far infrared the edge radiation source is not only more brilliant but also more intense than the conventional constant field source (middle of the dipole).

We have tested these predictions at the SIRLOIN beam line, where contributions from various IRSR sources are present. The characteristics of the Super-ACO storage ring and SIRLOIN beam line [7,16] are available elsewhere. Here we only recapitulate the main parameters used for the calculations.

The Super-ACO ring is injected with positrons of 0.8 GeV energy. It is an octagon formed by a succession of eight dipole magnets (radius of curvature $\rho = 1.7$ m) and eight straight sections containing insertion devices. Positioned on one of its straight sections is the SU3 wiggler. This insertion device is 2838 mm long, has 22 periods (N), each measuring 129 mm (λ_u), and its central position is located at 3333 mm from the extraction optics. Its working K value is 5.38 and the γ parameter is 1565.

The extraction device of the beam line SIRLOIN is mounted directly on a straight section of the Super-ACO storage ring which contains the variable-gap wiggler SU3. The extracting optics is actually composed of two plane mirrors placed at 45° with respect to the ring orbit and is placed in a vacuum chamber of the ring. A gap between the two mirrors allows positrons and higher energy radiation to pass through. The separation between these can be varied between 200 mm (gap $\pm$ 100 mm) and a minimum of 10 mm (gap $\pm$ 5 mm).

The radiation collected by the extraction mirrors includes the output of the insertion device and the edge radiation from its two ends. Moreover, in addition to photons emitted by the SU3 wiggler, radiation issued from the dipole edge of the $A2$ dipole magnet (placed at 6.8 m from the collecting mirrors) will be collected. The above parameters have been used to evaluate the flux and spatial distribution for Super-ACO. These results will be further compared with measurements performed on the SIRLOIN beam line.

We recapitulate here the formalism used for the evaluation of the IRSR. We use the reference frame reported in Fig. 1 and the formalism presented in Ref. [17].

The energy emitted by a relativistic charged particle submitted to any acceleration per frequency unit per solid angle in J s rad^{-2} is given by

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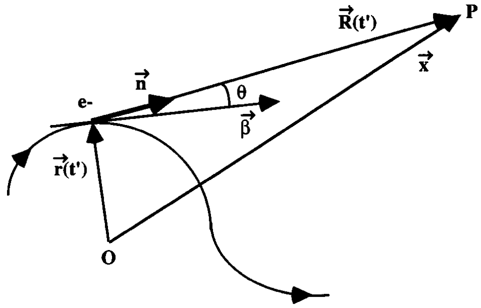

FIG. 1. Reference frame and definitions for the emission by a particle (e^-) of speed $\vec{\beta}$, at position $\vec{r}$ at time t, collected at position P.

$$\frac{d^2 I}{d\omega d\Omega} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty}\left\{\frac{\vec{\mathrm{n}}\wedge[(\vec{\mathrm{n}}-\vec{\beta})\wedge\dot{\vec{\beta}}]}{(1-\vec{\mathrm{n}}\cdot\vec{\beta})^2} + \frac{c(\vec{\mathrm{n}}-\vec{\beta})}{\gamma^2(1-\vec{\mathrm{n}}\cdot\vec{\beta})^2 R}\right\} e^{i\omega[t'+R(t')/c]}dt'\right|^2 . \quad (1)$$

This expression is valid at any collection solid angle by an observer positioned at distance R from the source. Moreover, this expression is accurate for photons in any energy range.

Equation (1) is usually rewritten once the well-known "far field" approximation is included: $|\vec{\mathrm{r}}(t')| \ll |\vec{\mathrm{x}}|$ and $R(t') \approx x - \vec{\mathrm{n}}\cdot\vec{\mathrm{r}}(t')$, where $\vec{\mathrm{x}}$ is the coordinate of the observer (cf. Fig. 1). With these approximations introduced in (1) and neglecting the term in $1/R$, one obtains the simplified expression which is used for the majority of calculations of spatial and spectral distributions for both dipole magnets and insertion devices (undulator and wiggler).

However, the far field approximation fails when a magnetic device is especially long [18] and if the observer is close to the source. In the IR range, typical distances lie at about 1 m. Therefore the simplified expression is not appropriate in this range. Consequently, the evaluation described here uses the exact formula for the "one electron" emission of Eq. (1). In the calculation, we modeled the magnetic field in the dipole as a constant value in the vertical direction ($B_y = 1.57$ T) with a sudden drop at the exit of the dipole ($B_y = 0$). The magnetic field in the wiggler varies as a sinusoidal function of the longitudinal coordinate with a maximum value $B_0 = 0.45$ T and with sudden drops to zero at the extremities of the insertion device.

The simulated intensity can be converted into a number of photons (dN/dt) per second, per 0.1% bandwidth (w_b), and for a current i in ampere by using

$$\frac{dN_k}{dt} = \left(\frac{d^2 I}{d\omega d\Omega}\right)\frac{1}{1000^2}\frac{i}{e}\frac{2\pi}{h}w_b\,, \quad (2)$$

where e is the charge of one electron and h is the Planck constant (the factor $1/1000^2$ converts into a number of photons per mrad^2).

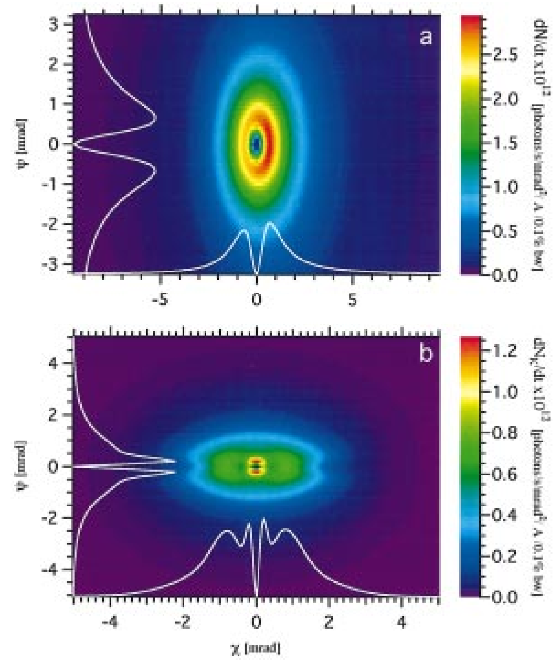

FIG. 2(color). Spatial distribution of the intensity at $\sigma = 100$ cm^{-1} calculated at the level of the extraction mirror emitted by (a) the edge of the dipole $A2$ and (b) the wiggler SU3 ($K = 5.38$). The solid lines represent the intensity at $\psi = 0$ and $\chi = 0$.

The angular distribution of the photon intensity emitted at a given wave number σ (in cm^{-1}) has been evaluated for both sources at their actual extraction distances (6.8 m for the dipole edge and 4.8 m for the entrance of the wiggler). In Figs. 2(a) and 2(b) the angular distribution of intensity (dN/dt) for the dipole edge and the wiggler sources are respectively reported for a wavelength of 100 cm^{-1}. There, for any pair χ-ψ (χ is measured in the plane of the orbit while ψ is perpendicular), the number of photons per mrad^2 for a 0.1% bandwidth (with 1 ampere injected in the machine) is represented by a tone of gray. The solid line corresponds to cuts in the middle of the spatial distribution.

Some remarks can be made concerning the angular distribution of these two sources: (i) Both sources have zero intensity on the central axis ($\chi = \psi = 0$). (ii) The dipole edge emission presents a ring-shaped intensity distribution with a maximum for angles of 1 mrad as the wiggler edge emission presents a more complex distribution (several maxima: $\psi = \pm 0.7$, $\chi = \pm 0.2$, and $\chi = \pm 1$ mrad). (iii) Both sources present narrow cones of emission. However, as the dipole source stays constant in intensity and spatial broadening as a function of the photon energy, the wiggler source becomes more intense and the emission cone gets narrower as energy increases.

To allow a complete description of the two sources (wiggler SU3 and end of the dipole magnet $A2$), the angular distributions obtained at various wavelengths have been integrated over angles corresponding to the

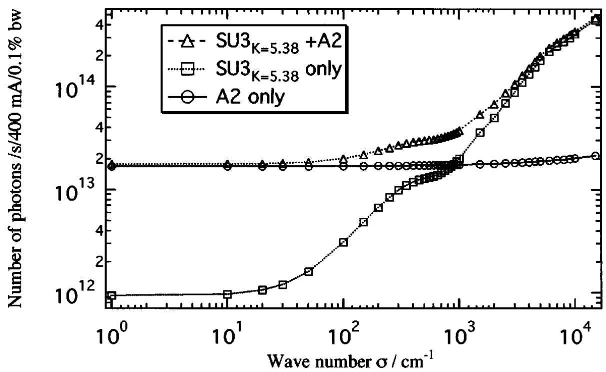

FIG. 3. Calculated infrared synchrotron radiation emitted by a SU3 wiggler (open square), end of the *A*2 dipole (open circle), and combination of both sources (open triangles), for a current of 400 mA. The integration limits correspond to the collecting optics with gap zero.

limitations caused by the vacuum chambers. The result of this integration is reported in Fig. 3 and can be summarized as follows: In the far infrared, the wiggler source presents a rapid increase in intensity between 30 and 300 cm^{-1}, in contrast with the dipole edge for which the intensity as a function of wavelength is almost constant. This lack of intensity in the far infrared for the SU3 source is caused by interferences between the various poles of emission in the insertion device [19]. In the mid infrared, the spectra of the two sources cross at about 800 cm^{-1}, and at higher energy the wiggler emission dominates.

In this calculation, no broadening due to the emittance of the positron beam is taken into account. Moreover, the calculation uses an ideal positron trajectory in both the dipole and the wiggler. Likewise, both radiation sources are modeled with a sudden change of magnetic field at their entrance and/or output in contrast with the progressive change that one may expect in real accelerators. This last effect has been discussed elsewhere, and its influence on the photon emission is predicted to appear for small wavelengths only [3]. Finally, any broadening of the sources due to diffraction in the vacuum chambers of the ring is also neglected in the calculations. In short, the spatial distribution is predicted for an ideal case, and some broadening of the observed source compared to the theoretical prediction may be expected.

The reality of the edge radiation is demonstrated by the spatial distribution of the intensity measured at the level of the two extraction mirrors. The intensity distribution in the plane of the orbit (over χ) has been obtained by varying the gap between the two extraction mirrors in the range ± 5 and ± 100 mm. These limits correspond approximately to angles of collection in the range of $\sim$0.7 to 15 mrad for the dipole and 1.5 to 30 mrad for the center of the wiggler. Measurements of the intensity in the 30–300 cm^{-1} range have been performed for various mirror separations and normalized for the current injected. To avoid contributions from reflections in the various chambers, the flux was measured through a 2.5 mm^2 iris placed at the focusing point in the sample compartment of the interferometer. From these measurements, one can extract the portion of the intensity corresponding to a given angular section. To do so, we have subtracted the intensity at a given wavelength from two consecutive measurements at two different gaps. The result of this subtraction provides the intensity collected in the portion of the extraction mirror included between the two mirror separations. When transformed into spatial distribution at the level of the collection optics, the angular distributions can be compared directly with the calculations.

The spatial distribution at four wavelengths (50, 100, 200, and 300 cm^{-1}) is represented in Fig. 4. The experimental intensities have been normalized at the theoretical value obtained at the smallest gap between the extraction mirrors. At all wavelengths, two different regimes for the spatial distribution can be distinguished: a central zone (distance from the axis smaller than 15 mm) in which the intensity rapidly decreases as the distance from the axis

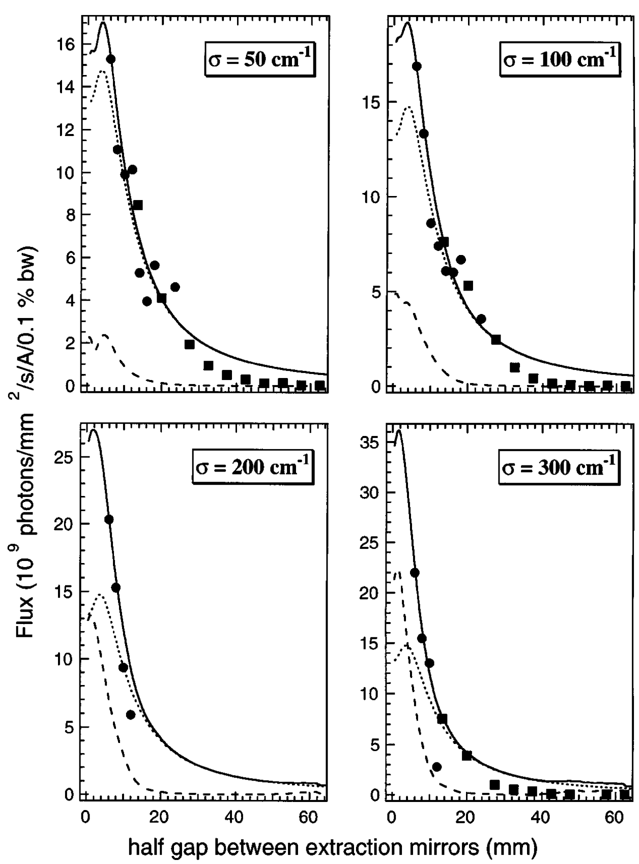

FIG. 4. Calculated spatial distribution of the intensity (number of photons per sec, per surface unit, per amp., with bandwidth 0.1%) at several wavelengths for the SU3 wiggler (- - -), the edge of the A2 dipole (···) and the combination of both sources (—), and experimental data for the emission by the two sources [(●) and (■)].

increases and an outer zone in which the decrease is much less pronounced.

The theoretical distribution of intensity was obtained from the integration of the spatial distribution through the angle Ψ for both the DEE and the wiggler contributions. The angular distribution over χ is then converted into a spatial distribution at the level of the extraction mirrors. At the lowest energies, the theoretical distribution presents a maximum around ± 4 mm. Equivalent integration for 300 cm^{-1} predicts a maximum emission of about ± 2 mm. Apart from this difference, the general behavior of the intensity distribution is similar for all photon energies: As a function of the distance from the axis, it shows a small increase of intensity followed by a large drop. At larger distances, one observes a constant or slowly decreasing photon density. These two zones correspond to the two photon production mechanism: the emission of photons from charged particles experiencing the sudden change in the magnetic field (DEE and TUR radiation) and the emission of photons from charged particles in a constant magnetic field (center of a dipole). At the level of the extraction mirrors, the dipole edge distribution is wider than the one from the wiggler, mostly because of its longer optical path. The superposition of both dipole edge and wiggler contributions results in a total spatial distribution getting narrower as energy increases, a sign that the wiggler contribution (lesser spread at the collection optics) is becoming more intense.

The experimental data are in good agreement with the theoretical behavior described above. Moreover, any broadening due to diffraction in the vacuum chambers is not observed in the present data. Indeed, this latter effect should increase the bandwidth of the spatial distribution by approximately 20% [20].

In conclusion, the excellent agreement between theory and experiment for the emission by the charged particles experiencing a sudden change in the magnetic field is a clear demonstration of the reality of this source of infrared radiation. The "edge radiation" is well evidenced here, and its advantages in terms of brilliance over other far infrared synchrotron radiation sources have been demonstrated. The evolution as a function of photon energy for the two types of sources has been studied. Compared with the emission from a constant field region (center of the dipole), the intensity distribution of the dipole edge minimizes the heating of the extraction optics caused by the higher energy part of the radiation. In the higher energy synchrotron facilities, this method of extraction will be required, as the increased heat load would restrain the extraction of infrared synchrotron radiation from the center of a dipole [21]. This method of producing a brilliant infrared source will be exploited in the near future on the 2.5 GeV source ANKA (Karlsruhe, Germany) and at the SRC (Wisconsin) [5].

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*Present address: Projekt Errichtung ANKA (PEA), Bau 687, Forschungszentrum Karlsruhe, Postfach 3640 D-76021 Karlsruhe, Germany.

†To whom correspondence should be sent.

‡Also at Dipartimento di Fisica, Universita di Roma "La Sapienza," Roma, Italy.

§Also at Chimie Physique des Matériaux Amorphes, bât. 490, Université Paris-Sud, 91405 Orsay, France.

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