The new brilliant infrared synchrotron radiation source at the DAΦNE storage ring in Frascati

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Introduction

A new powerful Synchrotron Radiation Infrared (IR-SR) source will be in operation at the DAΦNE-Light Laboratory of the INFN National Laboratory in Frascati.

SR in the infrared (IR) region[1] is a unique broadband source (from near- to mid- and far-IR), competitive to conventional broadband black-body type (BB) laboratory thermal sources (mercury lamps or glowbars), being up to 1000 times brighter, polarised and pulsed. It is also an absolute source, since the power depends on the electron beam current stored in the ring and can easily be calculated. Moreover, in the case of DAΦNE, due to the exceptionally high stability of the electron beam orbit, it is also a very stable source.

The DAΦNE-Light laboratory has been designed to utilise the intense and stable SR emitted at DAΦNE. Two beamlines, extracting SR from a wiggler and from a bending magnet of the electron storage ring, will operate in the soft X-ray range and in the IR range, respectively. The IR beamline will be the first Italian infrared beamline and one of the most brilliant IR-SR sources in the world.

The DAΦNE ring and the DAΦNE-Light Laboratory

DAΦNE is the new double-storage ring for electrons and positrons in operation at Frascati. The two rings cross in the horizontal plane in two sections where two large pieces of apparatus will enable the e^+–e^- interaction to be investigated. The electron and positron beams are injected at full-energy (0.51–0.75 GeV) coming from a LINAC and a booster. This allows the high beam current (1–5 A) and the required high level of stability of the beam orbit to be reached. The instabilities are within the dimensions of the electron and positron beams. These two characteristics, among others, make DAΦNE a unique IR-SR source, although it is not a dedicated machine.

Inside the DAΦNE-Light Laboratory two beamlines will be put into operation by the end of 1999. One will operate in the soft X-ray range. The second one, SINBAD (**S**ynchrotron **In**frared **B**eamline **A**t **D**AΦNE), will work in the infrared region.

Synchrotron radiation at DAΦNE

When electrons (or positrons) at relative velocities are forced to turn in the magnetic structures (as in a Bending Magnet) of a storage ring, they emit electromagnetic radiation in a narrow cone in the direction of motion (Figure 1): this is called Synchrotron Radiation (SR).[2,3] The horizontal emission angle depends on the arc of trajectory viewed by the extraction slit of the beamline.

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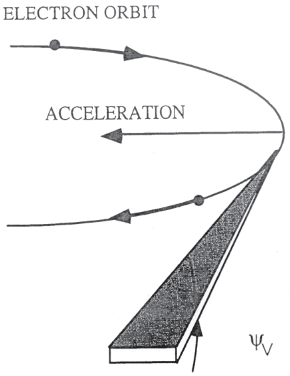

Figure 1. Synchrotron radiation is emitted in a narrow cone in the direction of motion.

Figure 2 shows the SR spectral flux (number of photons emitted in a 0.1% bandwidth integrated in the vertical angle per horizontal mrad) from a bending magnet of DAΦNE at two electron beam energies ($E = 0.51$ GeV and the planned $E = 0.75$ GeV). The spectral distribution is continuous from IR to X-rays. In the visible-IR region the flux is independent of the beam energy, depending only on the beam current and can easily be calculated. In fact, SR is an absolute source: once the horizontal angle is fixed, the photon flux can be calculated exactly at any wavelength knowing the circulating current which can be accurately measured. The beam current at DAΦNE is very high, meaning high photon flux. Here, the spectral distribution is calculated for $I = 1$ A but currents of 2–3 A up to 5 A are planned.

The vertical (perpendicular to the orbital plane) SR emission angle is of the order of mrads and increases with the cube root of the wavelength (Figure 3). This behaviour is important to understand the gain in brilliance of IR-SR with respect to a conventional broadband laboratory source. This also defines the verticcal acceptance angle at the extraction port of the ring.

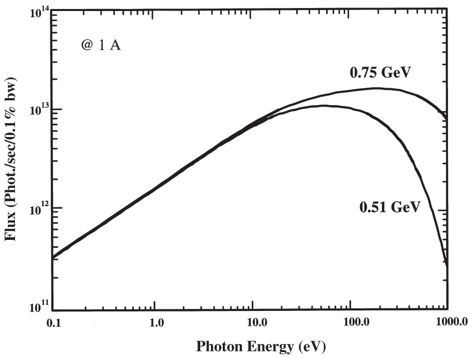

Figure 2. Synchrotron radiation spectral flux (number of photons per second emitted in a 0.1% bandwidth, integrated in the vertical angle per mrad hor.) from a bending magnet of DAΦNE at two electron beam energies: *E* = 0.51 GeV and *E* = 0.75 GeV.

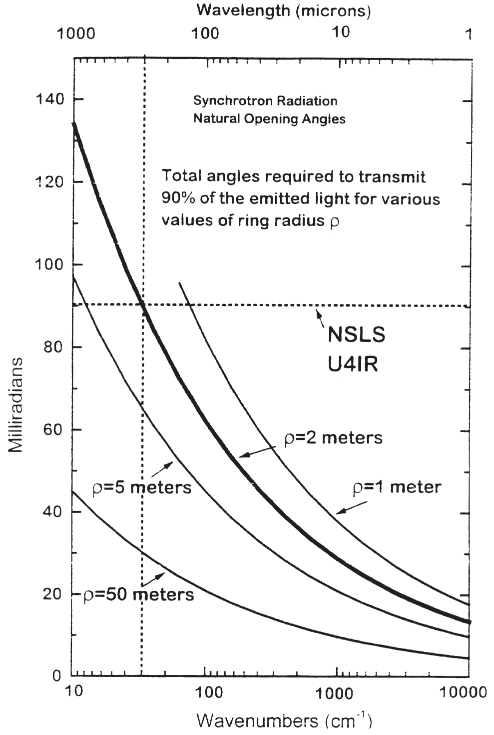

Figure 3. Wavelength dependence of the natural opening angle of synchrotron radiation for storage rings of different radii.[4] The radius of a bending magnet at DAΦNE is *R* = 1.8 m.

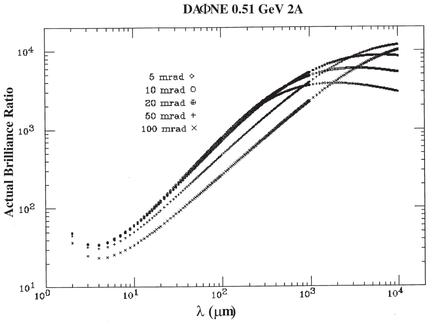

Figure 4. Brilliance ratio of the DAΦNE SR source to a black-body source (for T = 2000 K and for an emitting surface S = 0.45 cm^2).

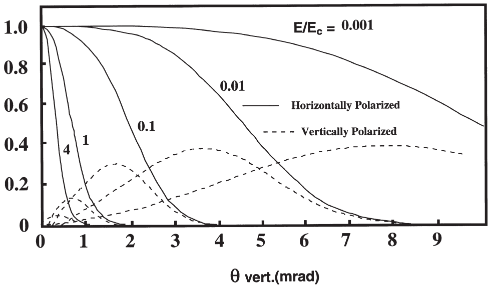

Figure 5. Polarisation characteristics of Synchrotron radiation at different photon energies (E) as a function of the vertical angle. E_c is the so called "critical energy" and is equal to 208 eV for a bending magnet of DAΦNE when the electron beam energy is 0.51 GeV. Horizontal means parallel and vertical means perpendicular to the plane of the electron beam orbit.

Remembering that a BB source emits isotropically, following Planck's law (so that the power emitted drops at long wavelengths), it is not surprising that the interplay between spectral flux and angular behaviour of SR and BB, also taking into account the optical source dimensions, gives rise to a high gain in brilliance (flux divided by the transversal dimensions of the optical source) as shown in Figure 4. These are estimated values from theoretical calculations. The minimum value of the brilliance ratio (ABR) is 25–30 and can be near to two orders of magnitude in the NIR towards up to three orders of magnitude in the far-infrared.

If we consider the low noise at DAΦNE due to the high stability of the electron beam orbit, it is clear that DAΦNE will give improved S/N ratio with respect to a conventional laboratory source in the whole IR range for brightness-limited experiments (small sample areas and microspectroscopy).

SR is also a highly polarised source (Figure 5). The radiation is linearly polarised with horizontal polarisation in the plane of the orbit, while above and below the plane a certain fraction of the emitted intensity is vertically polarised, as a function of the vertical angle and depending on the wavelength. This allows the desired degree of polarisation to be selected by placing a slit above or below the orbital plane.

Finally, SR has a naturally well-defined pulsed structure, because electrons (positrons) must travel in small bunches to be able to pick up from the radiofrequency (RF) the energy lost as radiation (total power emitted: 49 kW at I = 5A). At DAΦNE the number of bunches will range from 30 to 120, depending on the experiment being run, with a natural length of 0.81 cm. The RF is 368.25 Mhz.

SINBAD

An SR beamline includes the optical system which has to guide the SR to the experimental apparatus.

The acceptance angle of the extraction port at SINBAD is about 50 mrad. A remotely controlled 4 mm wide slit will allow radiation to be collected with the desired degree of circular polarisation above and below the orbital plane. SINBAD[5,6] is quite a long and complex beamline, due to some geometrical constraints in the DAΦNE experimental hall.

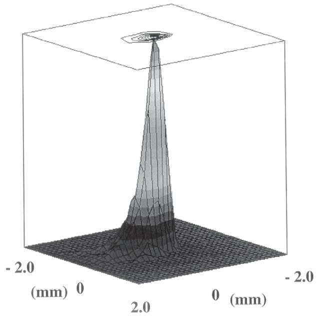

Figure 6. Intensity distribution for $\lambda = 10\ \mu$m of the last focus of SINBAD, placed at the entrance pupil of the interferometer, as obtained by ray-tracing simulations.

A diamond window separates the initial part of the beamline closest to the storage ring and working under UHV from the final part working under HV. The window, which has a 15 mm diameter and is around 800 microns thick, is wedged with an angle of 1.24° to avoid interference effects, hence minimising the reflected radiation, and it has been oriented so as to preserve the polarisation properties of the incident light. Diamond is chosen for its excellent hardness and chemical stability and for its flat transmittance in almost the whole IR domain, except for an absorption band at about 5 μm. The reflectivity limited transmittance is around 80%.

The optical system of the beamline focuses the beam on the entrance pupil of an interferometer. The estimated dimensions of the photon beam at the entrance pupil of the interferometer, as obtained by ray-tracing calculations, are about 2×2 mm^2 (Figure 6).

The interferometer is a Bruker Equinox FT-IR, coupled to an IR microscope. It has been modified to work under vacuum and it will cover the range 15000–50 cm^{-1} with a resolution of 0.5 cm^{-1}. The vacuum conditions will also allow a strong amelioration in the quality of the collected IR spectra.

Conclusions

Although the first beam diagnosis will be performed by the end of 1999, all the theoretical calculations for SINBAD indicate that it will be one of the most brilliant and stable IR-SR sources in the world and a powerful linearly and circularly polarised source. It will allow brightness-limited experiments to be performed in the whole infrared range with an improved S/N ratio with respect to conventional broadband laboratory sources. In fact, the scientific programme of the beamline includes IR spectroscopy and microspectroscopy, with special attention to biological and medical applications.[4,7,8] The polarisation properties of this IR source will allow linear and circular dichroism experiments in the IR. Moreover, the pulsed time structure of the photon beam could also allow for pump-probe experiments in the IR during the planned SR dedicated beamtime of the DAΦNE ring.

References

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