J. Synchrotron Rad. (1998). **5**, 575–577

SINBAD, a brilliant IR source from the DAΦNE storage ring

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(*Received 4 August 1997; accepted 9 January 1998*)

SINBAD is the Italian IR synchrotron radiation beamline, designed to work at wavelengths greater than 10 μm. It is being installed on DAΦNE, a new collider that is designed to work at 0.51 GeV with a beam current up to 5 A. Due to such a high current, the IR extracted from a bending magnet will be more brilliant than that of a black body at 2000 K by two orders of magnitude at 100 μm. The beamline optical system, projected by ray-tracing simulation, consists of six mirrors that first focus the radiation on a wedged CVD diamond-film window and then transfer the collimated beam to the experimental area where a Michelson interferometer will be installed.

Keywords: IR beamlines; mirror optics; diamond windows; IR waveguides.

1. Introduction

The interest in synchrotron radiation emission in the IR (IRSR) dates back to the mid-1980s; nowadays it appears as one of the most promising applications of this source. A beamline dedicated to IRSR is presently under construction and will be connected to DAΦNE (double annular Φ-factory for nice experiments), the new electron–positron collider under construction in Frascati. This double ring is designed to produce Φ mesons by annihilating electrons and positrons with an energy E of 0.51 GeV per beam. This corresponds to a critical energy, ε_c, for the photons emitted by the bending magnets of 208 eV (see Table 1). As the IRSR intensity at fixed current does not depend on E, in spite of the low energy of the beam the DAΦNE emission is expected to be extremely intense due to the high current circulating in this collider (from 2 A at commissioning, up to 5 A).

Here we will briefly describe the optical layout and the expected performances of SINBAD, the IR beamline designed to work in the wavelength range from 5 to 5000 μm. The main parameters of DAΦNE are discussed in §2 while the characteristics and the ray-tracing calculations of the beamline are reported in §3. In the last two sections, the polarization properties of SINBAD and the estimated performance of an alternative optical scheme based on a cylindrical waveguide are discussed.

Table 1
DAΦNE single ring parameters (Bassetti *et al.*, 1991; Biagini *et al.*, 1991).

Energy	510 MeV	$\gamma = E/mc^2 = 10^3$
Dipole bending radius	1.400 m	ε_c = 208 eV
Horizontal emittance	10^{-6} m rad	
Coupling coefficient, k	0.01	
Natural bunch length, σ_z	0.81 cm	
Number of bunches	1–120	
Maximum total average current	5.3 A	
Total single beam lifetime	<3 h	

2. The DAΦNE source

The DAΦNE design (Table 1), based on conventional technology, is extensively described in several reports (Bassetti *et al.*, 1991; Biagini *et al.*, 1991). DAΦNE as a source of synchrotron radiation has been described previously (Marcelli & Calvani, 1993; Nucara *et al.*, 1995). The most relevant parameters of the DAΦNE collider are listed in Table 1.

The storage-ring lattice of the achromats is a four-period modified Chasman–Green type with a 1.8 T conventional wiggler magnet inside. This choice allows sample emittance tunability and gives strong radiation damping. Due to the low energy of the beam, the beam lifetime, τ, is expected to be of the order of 3 h and topping-off injection from an accumulator ring will take place. This is highly desirable for synchrotron radiation applications in order to keep the current at high values during the operation.

3. SINBAD optical layout

The design of SINBAD, the synchrotron IR beamline at DAΦNE, was simulated by ray tracing using the *SHADOW* program (Welnak *et al.*, 1994), which can simulate any optical system consisting of a finite number of optical elements (mirrors, crystals, slits *etc.*). In the IR region *SHADOW* takes into account geometrical broadening and beam size, but not the diffraction-limited contribution, which is not negligible in the IR domain and has been included *ad hoc* in our calculations (Nucara *et al.*, 1994; Marcelli *et al.*, 1997).

At DAΦNE the solid angle is limited by the geometrical constraint of the front-end flange placed at 1.2 m from the centre of the source. The front-end limits the clear aperture to 50 mrad, both in the horizontal and vertical plane. However, for the simulations the horizontal collection angle has been set to 20 mrad, and the optical elements have been dimensioned to accept this divergence. This allows us to optimize our IRSR emission both in the mid- and far-IR. Indeed, because of the large horizontal size of the DAΦNE source, the increase of the horizontal collection angle produces only a reduction of the brilliance (Nucara *et al.*, 1994, 1995).

Two constraints contributed to determine the SINBAD optical layout: (i) matching the divergence of the IRSR, which increases with the wavelength, to the f number of the entrance pupil of a Michelson interferometer located at ∼22.5 m from the source; (ii) using the existing tunnel in the shielding wall of DAΦNE and the available experimental area.

The optical system, showing only one intermediate point, consists of six mirrors (Table 2) (Marcelli *et al.*, 1997). The front-end on DAΦNE is about 3 m long so that the plane extraction mirror (M1) is placed at 4.5 m from the source. This mirror deflects the beam by 55° in the horizontal plane towards an ellipsoidal mirror (M2), placed 70 cm from M1. The incidence

Table 2
Mirror parameters of SINBAD.

Distances are taken from the preceding optical element. For M1 the distance is taken from the source. For M2 the reported parameters are the semi-major and semi-minor axes.

	Distance (cm)	Incidence angle	Figure	Mirror parameters Major radius (cm)	Minor radius (cm)
M1	450	27.5°	Plane		
M2	70	40°	Ellipsoidal	379	269
M3	318	45°	Toroidal	226	113
M4	50	45°	Plane		
M5	312	72.5°	Plane		
M6	1300	30°	Toroidal	116	87

angle of the ellipsoid is 40°, and its focal point is on a CVD diamond window (15 mm in diameter) that separates the UHV section of the beamline, near to the storage ring, from the second section, connected to the experimental area and working at about 10^{-6} torr. This allows one to minimize the absorption loss of the IR radiation by residual gas contained in the long pipe. The diamond window has a minimum thickness of about 750 µm and a wedge of 1.2° to reduce to <5% the signal modulation due to multiple reflections, typically observed at these wavelengths in parallel-faced windows.

The second part of the beamline was designed by comparing simulations with different optical elements. By taking into account the aberrations, the best layout turned out to consist of four parabolic off-axis mirrors (Ambrogini, 1997). In this scheme the beam is transferred as a plane wave in both planes to reduce the effect of the large IRSR divergence and possible effects due to source instabilities. However, practical and economical considerations suggested that this layout be replaced by a combination of elements that are simpler to manufacture (see Table 2). As a consequence, mirror M3 is toroidal and is placed 80 cm after the diamond window. It vertically deflects the radiation by 90°, as does the plane mirror M4, in such a way that the joint effect of the two mirrors is to shift the reflected beam upward by 50 cm, maintaining the direction parallel to that of the beam coming from the mirror M2. The mirror M5, also plane, deflects the beam in the horizontal plane into a tunnel towards the final toroidal mirror, M6, placed at the end of the beamline. The latter deflects the radiation by 60° and focuses the radiation at 0.5 m from its pole. The final spot is well focused, even if geometrical aberrations due to toroidal mirrors may be identified in the image (see Fig. 1). More complex layouts have been tested

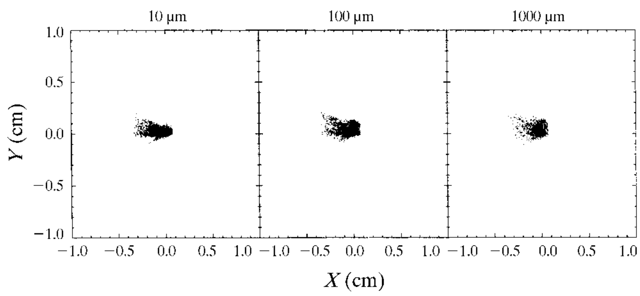

Figure 1
From left to right, respectively, plots of the image at the entrance pupil of the interferometer at a wavelength of 10 µm, 100 µm and 1000 µm. The horizontal and vertical scales are 1 cm. Diffraction effects are neglected and may considerably enlarge the spot at 1000 µm with respect to the simulation reported in this figure.

Table 3
Experimental and simulated values of the normalized transmittance (T_0/t_0) for guides of 28 mm diameter, for increasing lengths.

t_0 is the transmittance of the reference pipe with l_0 = 26 cm (Nucara *et al.*, 1998).

L/l_0	$(T_0/t_0)_{exp}$	$(T_0/t_0)_{sim}$
50/26	0.96	0.88
76/26	0.81	0.83
150/26	0.73	0.72
290/26	0.61	0.57
440/26	0.55	0.45

which produce slightly better images (Ambrogini, 1997), but these solutions imply considerable difficulties and much higher costs.

4. Polarization properties of the SINBAD IR radiation

Synchrotron radiation exhibits, in the whole range from IR to X-rays, a high degree of both linear and circular polarization. The radiation emitted in the orbit plane is almost completely linearly polarized. On the contrary, circular polarization is non-zero for the out-of-plane emission, and its sign changes when passing through the orbital plane. The lack of experimental data on the circular polarization rate in the IR domain and the increasing interest towards polarized experiments stimulated us to investigate, by ray tracing, how the SINBAD layout transfers the polarization to the interferometer. Using the parameters of the previous simulations and a small slit placed at different heights from the orbital plane, we were able to obtain at different wavelengths the degree of circular and linear polarization at the entrance of the interferometer (Fig. 2). At an angle of about 15 mrad from the orbit, the simulation returns a very high rate of circular polarization (>0.8). By selecting this off-plane emission by a suitable aperture, we find that the transmitted circularly polarized photon flux at the entrance of the interferometer is between 5 and 10%. Although we used 20000 rays for these simulations, the polarized flux is substantially reduced by the small slit, thus producing the discontinuities observed in the plots of Fig. 2.

5. An alternative optical scheme: just a cylindrical waveguide

As described in §3, SINBAD will be built with mirrors figured in the Gaussian optics framework. The use of waveguides for the IR has already been proposed. However, the performances of a simple pipe in terms of polarization, transmittance and image shape are still undetermined (Ohlmann *et al.*, 1958). Maxwell's equations for an electromagnetic field propagating in a waveguide can be solved in terms of first-rank Bessel functions, after imposing continuity conditions on both the electrical and the magnetic field (Cronin, 1995). This leads to an upper limit for the wavelength of the order of the diameter of the guide. In the IR range, for a pipe of a few cm in diameter, a description of the propagation in terms of multiple reflections will be sufficiently accurate. The behaviour of the pipe was first simulated by ray tracing and then observed by an interferometer connected to brass pipes of several diameters and lengths illuminated by a mercury lamp (Nucara *et al.*, 1998). The image spot of the source at the entrance of the pipe was 17 mm wide, while the maximum divergence was 200 × 200 mrad. A decrease in the transmitted intensity with the frequency was observed as predicted (Ohlmann

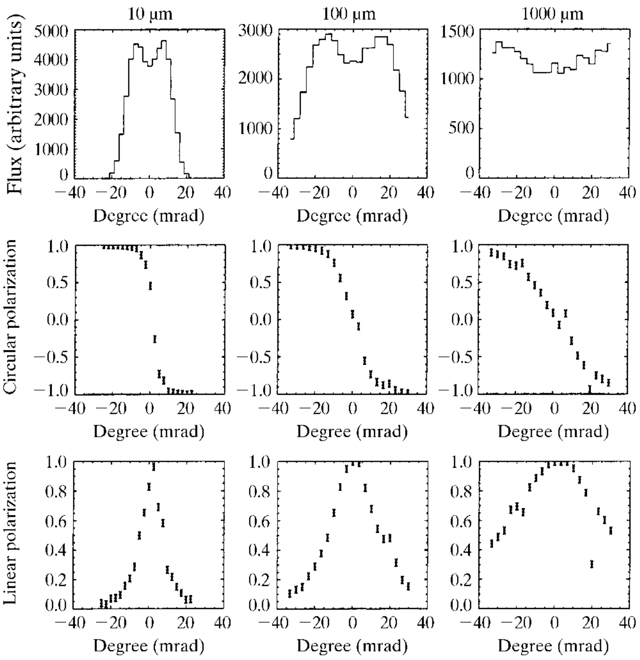

Figure 2
Transmitted flux at the entrance of the interferometer at different wavelengths as a function of the height of a slit from the orbital plane (top). Circular (centre) and linear (bottom) polarization rate of the radiation selected by a slit of 4 mm.

et al., 1958) and fitted with the same law previously used to describe X-ray capillaries (Nucara *et al.*, 1998). With the help of ray tracing, we have simulated the mercury lamp at the entrance of the guide. Then we have propagated it through the guide by means of multiple reflections on the walls. The average transmittance, T_0, of the guide is computed by

$$T_0 = T_p + T_n = (1/N)\sum_{i=1}^{n}\left(\alpha_i R_{i_p}^{n(i)} + \beta_i R_{i_n}^{n(i)}\right), \qquad (1)$$

where T_p (R_{i_p}) and T_n (R_{i_n}) are the transmittances (the reflectivities) in the plane of incidence and in the normal plane, respectively, $n(i)$ is the number of reflections for the ith ray, and the sum is extended to the N rays of the source. The coefficients α_i and β_i are proportional to the projections of the electrical field E of the ith ray on the plane of incidence and on the normal plane, respectively. For a depolarized source, for example the mercury lamp, $\alpha = \beta = 0.5$. Both the linear behaviour of the average number of reflections and the exponential decay of the transmittance are well reproduced by ray tracing. In Table 3 a comparison is shown between the transmittance of a guide, with a diameter of 28 mm, and the present simulation. Discrepancies may be due to the incertitude on the value of the refractive index.

Let us now consider a cylindrical waveguide about 12 m long for the IRSR emitted from a bending magnet of SINBAD, with the same diameter as above for the exit flange (Nucara *et al.*, 1998). In an optimized situation where all the IR radiation emitted by the source is collected by the guide, the average transmittance tends to a maximum value of ~0.7. In Fig. 3 we report both T_p and T_n *versus* the photon energy. A comparison of these values with the transmittance of the mirror layout of SINBAD allows us to conclude that a waveguide should transmit IR radiation in a comparable way. Low cost, easy maintenance and installation might make a pipe a valid alternative in future applications.

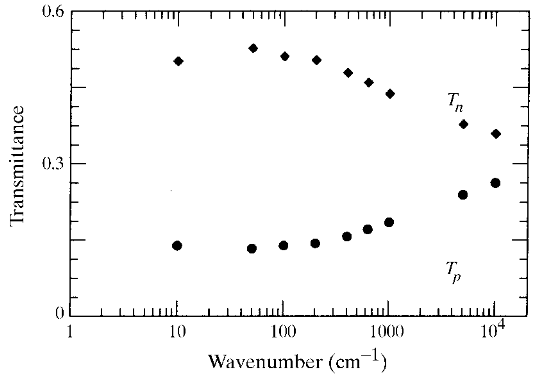

Figure 3
The measured in-plane (T_p) and normal-to-the-plane-of-incidence transmittance (T_n) for a pipe of diameter 28 mm as a function of frequency.

The authors wish to thank H. Buys, D. Cannavó, A. Grilli, A. Raco, S. Simeoni and R. S. Sussmann for useful discussions and technical suggestions. This work has been partially supported by the UE HC&M project under contract 94–0551.

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