Paper submitted to the IEEE Conference on Infra-Red and Submillimeter Waves, Miami, Florida, December 12-14, 1984.

BNL--34491

DE84 010542

INTENSE, BROADBAND, PULSED I-R SOURCE AT THE NATIONAL SYNCHROTRON LIGHT SOURCE*

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Abstract

We describe a broadband (1 μm - 1 mm) synchrotron radiation infrared source, pulsed each 20-180 nseconds and delivering about 10^{15} photons/sec/1% bandpass into f10 optics. The source size is diffraction limited. This source is thus 100-1000 times brighter than a 2000°K black body, very stable and capable of being used for calibration.

Introduction

This paper is intended to provide an introduction to the use of synchrotron radiation from electron storage rings as an infrared source. In particular, details and properties of a specific source, the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, will be described. The present treatment will summarize the results of calculations which describe the NSLS. We have recently (1) published details of how such calculations can be applied in general to synchrotron radiation sources. In this paper we presented simple and useful approximations, valid at infrared wavelengths, to the equations governing the emission.

*Work supported by the U.S. Department of Energy.

The Electron Storage Ring

Before describing the source itself in detail we show in Figure 1 a floor plan of the NSLS. This shows that there are two electron storage rings, one of circumference 170 m at electron energy 2.5 GeV and a smaller one of circumference 50 m and energy 0.75 GeV. The inset illustrates an important aspect of these sources which is that the emitting electrons are relativistic. When the Lorentzian correction is applied their (dipole) radiation emission pattern appears from a laboratory frame to be highly collimated in the forward tangential direction. The normal diffraction law appears to be violated. Thus, the beam lines shown in Figure 1 are all tangential to the orbit.

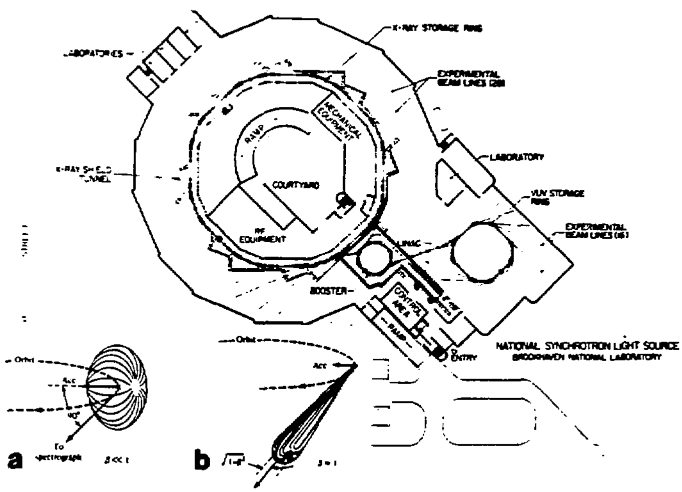

Fig. 1. Plan view of the National Synchrotron Light Source. Inset: emission of light by (a) non-relativistic and (b) relativistic electrons.

The majority of the existing beam lines are intended for hard x-ray or soft x-ray use depending respectively on whether they are on the high or low energy ring. Beam lines are placed downstream of the dipole magnets which bend (and hence accelerate, causing radiation emission) the electron trajectories around the ring. In between the dipoles are straight sections which incorporate focussing magnets and are long enough to allow for the future installation of wigglers or undulators which are higher brightness sources (2).

It is on the smaller circumference ring that the infrared beam line is proposed. This ring is shown in the photograph in Figure 2 which was taken before the shielding and existing beam lines were installed. In this ring up to 1 ampere of circulating beam is planned (0.3 amperes has been achieved so far). The circulating electrons are arranged in "bunches" of length approximately 25 cm. Once per revolution each electron bunch passes through a 50 MHz radio-frequency cavity which restores the energy lost by synchrotron radiation. Up to nine bunches can be circulating in the ring, the orbit frequency being 180 nseconds.

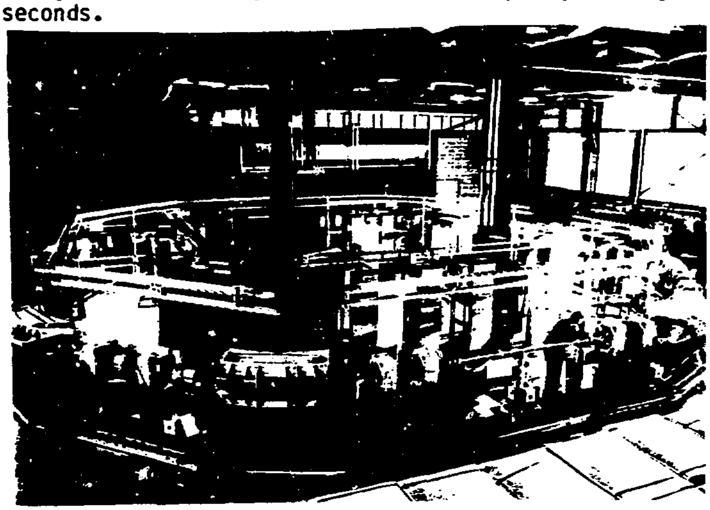

Fig. 2. Photograph of smaller storage ring at the National Synchrotron Light Source before installation of shielding and beam lines.

The Infrared Source

A. Time Structure

Having described the electron storage ring we now turn to the ring as a light source. In order to use it as such, we cut a hole in the ultra-high vacuum electron beam containment vessel, tangential to the orbit in a dipole. We now see light while an electron bunch passes. The light is "on" for 1 nsecond and "off" until the next bunch arrives. This off time varies from 20 nseconds if there are 9 bunches in the machine to 180 nseconds if there is just one. Other methods such as moving the beam vertically in the machine, may be used to extend the "off" time if necessary although no such facility exists at present.

B. Source Size

The source size is the size of the spatial spread of the 10^{12} electrons or so which constitute the bunch. It is of the order of 200 µm vertically by 500 µm horizontally. As we shall see when we discuss the radiation opening angle, the normal diffraction limit is not satisfied in the laboratory frame. As soon as the beam sees the first laboratory frame component, however, the usual diffraction conditions apply and this has the effect of increasing the apparent source size.

C. Radiation Opening Angle

The inset of Figure 1 shows how the emitted radiation if forward collimated. The half-angle of the cone shown in Figure 1b is plotted in Figure 3 as a function of wavelength (λ). It is around 60 mradians (3°) at λ = 1 mm.

As the electrons circulate the cone sweeps around the horizontal so that the emission angles in the horizontal and vertical may be different. For the NSLS infrared line we collect from a 5° (100 mradian) arc horizontally and allow for a vertical half-angle of 2.5° (50 mradians) to pass through the aperture in the machine. Due to the narrow separation of the dipole coils and the location of the beam, this turns out to be quite a challenging piece of engineering.

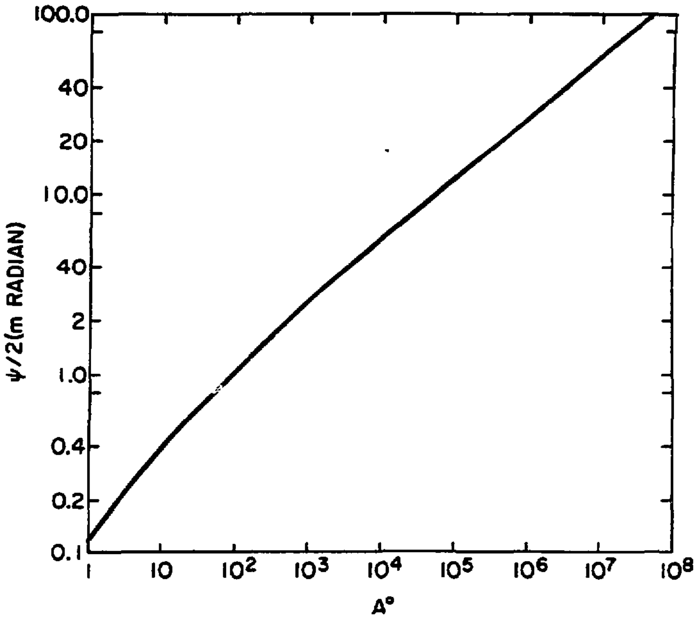

Fig. 3. Natural half-opening angle for synchrotron light emission from the small storage ring at the National Synchrotron Light Source (1 μm = 10^4Å, 1 mm = 10^7Å).

D. Photon Flux

Synchrotron radiation is a broadband source which falls off at long wavelength as $\lambda^{-5/2}$ rather than λ^{-4} as is the case for a black body. The output flux from the NSLS infrared facility can be readily derived from Figure 4 in photons per second per unit bandpass ($\Delta\lambda/\lambda$). From these units it can readily be converted to power. This power is confined to a narrow cone as discussed in the previous section so that synchrotron radiation is a very bright source.

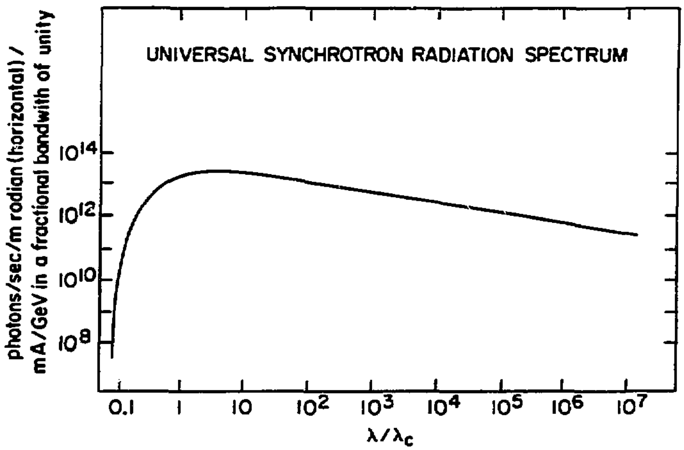

Fig. 4. Universal synchrotron radiation spectrum. For the National Synchrotron Light Source $\lambda_c \approx$ 25 Å. In general $\lambda_c = 5.59\ \rho/E^2$ where ρ is the bending radius in meters, E the electron beam energy in GeV and λ_c is in Angstroms.

E. The NSLS Infrared Beam Line

Details of the proposed beam extraction for the NSLS infrared beam line are shown in Figures 5 and 6. A plane mirror M1 close to the elecron orbit and downstream of a dipole intercepts approximately 100 mradians x 100 mradians of infrared radiation and directs it upwards. A second plane mirror M2 will reflect the infrared radiation back along the electron orbit to an off axis ellipsoid M3 which will image the source to a primary focus with a magnification of unity (f10 optics) outside the ring. Various vacuum protection devices are installed near the primary focus.

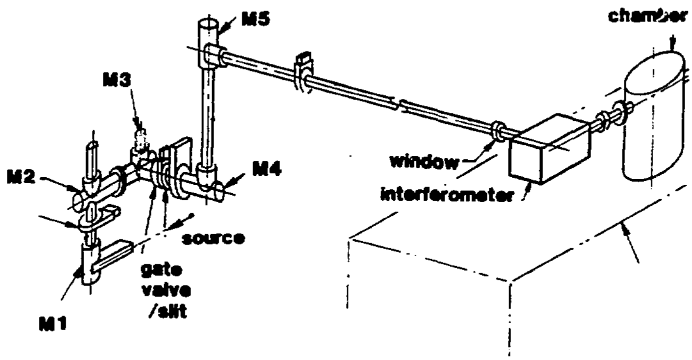

Fig. 5. Schematic of the National Synchrotron Light Source infra-red beam line to be installed around September 1985.

The entire system is at ultra-high vacuum and therefore bakeable. For stability M1, M2, and M3 are supported on a floor-mounted frame, separated from the ring vibrations by a bellows. In addition, M1 and M2 can be translated through an all-metal 6" gate valve for inspection or replacement.

Mirror M1 has to be water-cooled due to the severe thermal load. Inspection of Figures 3 and 4 reveal that some 150 watts of power are emitted by the source at around 30 Å wavelength into half angle of just less than a mradian. The power density on the mirror is thus 600 watts/cm^2. Thus M1 will probably be fabricated from SiC, coated with a highly conducting reflecting surface such as gold, silver, aluminum or molybdenum. It is critical for the surface layer to have good thermal contact with the SiC substrate at these power loadings.

The beam line will continue after M3 upwards and outwards so that a secondary f10 focus will be provided at the edge of a concrete platform on which various experiments can be mounted.

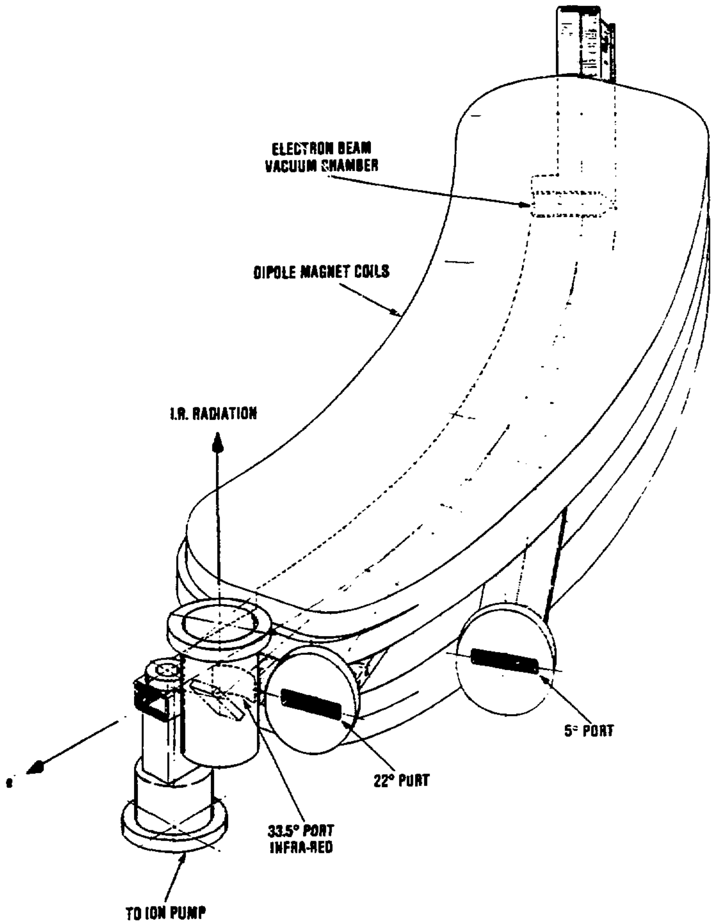

Fig. 6. Artists impression of the infra-red beam extraction at the National Synchrotron Light Source. The infra-red beam emerges vertically. the two horizontal ports are for soft x-ray extraction.

λ(μm)	(A) Radiation Opening Angle (mrads) V x H	(B) Source Size V cm x H cm	(C) NSLS Emittance[2] cm^2 sr(AB)
1	9 x 100	0.03 x 0.3	8 x 10^{-6}
10	20 x 100	0.05* x 0.3	3 x 10^{-5}
100	75 x 100	0.13* x 0.3	3 x 10^{-4}
1000	100 x 100	1* x 1* *Diff. Limited	1 x 10^{-2}

λ(μm)	(D) NSLS Flux Photons/sec 0.1% Δλ/ λ	(E) Black Body Flux Units as A	(F) Black Body Emittance[2] cm^2sr
1	5.8 x 10^{14}	1.4 x 10^{16}	0.63
10	2.9 x 10^{14}	1.8 x 10^{16}	0.63
100	1.2 x 10^{14}	2.5 x 10^{14}	0.63
1000	5.6 x 10^{13}	3.5 x 10^{12}	0.63

λ(μm)	(G) NSLS Brightness D/AB	(H) Black Body Brightness E/F	Brightness NSLS/BB
1	7.3 x 10^{19}	2.2 x 10^{16}	3318
10	9.7 x 10^{18}	2.9 x 10^{16}	334
100	4.0 x 10^{17}	4.0 x 10^{14}	1000
1000	5.6 x 10^{15}	5.6 x 10^{12}	1000

Table 1. Comparison of the National Synchrotron Light Source and a black body source in the infra-red.

Summary

To facilitate an understanding of the properties of this unique infrared source, we have tabulated the flux, opening angle, source area and brightness at 1 µm, 10 µm, 100 µm and 1000 µm. For comparison we also show the figures for a black body source of dimension 10 mm x 1 mm and at 2000° K with an emissivity of unity. It can be seen that the NSLS infrared source is 2 to 3 orders of magnitude brighter. Also we expect it to be more stable. Further, since the photon flux output is proportional to electron beam current, it should be useful as a reference source, once calibrated.

Acknowledgements

I deeply appreciate the interactions I have had with M. Howells, P.Z. Takacs, P. Richards, Y. Chabal, R. Klaffky and M. Shleifer, regarding this paper.

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