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<td>Name: R. A. Bosch</td>
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ABSTRACT

The large opening angles of far-infrared synchrotron radiation, near-field effects and vacuum chamber shielding may reduce the flux and brightness of focused infrared radiation from an electron storage ring. For edge and ordinary synchrotron radiation, expressions are presented for the long-wavelength limitations from these effects.
1. Introduction

Focused spots of infrared (IR) radiation extracted from an electron storage ring are increasingly utilized for microspectroscopy [1,2]. At long wavelengths, large opening angles, near-field effects, and shielding by the storage ring vacuum chamber may reduce the flux and brightness of a focused spot. The wavelength limitations from these effects are considered for edge radiation and ordinary IR synchrotron radiation. The long-wavelength cutoffs are then estimated for two existing IR beamlines.

2. Edge radiation

In an electron storage ring, an aperture downstream of a straight section may be utilized to collect bright infrared (IR) radiation produced at the edges of bending magnets [2]. For sufficiently sudden deflections of the electrons in the bending magnet fringe field, the "edge" radiation is equivalent to transition radiation from a conducting foil. In this case, the far-field radiation peaks at an angle $1/\gamma$ from the straight section axis, where $\gamma$ is the relativistic factor. Provided that the half-angle $\theta_{\text{sp,half}}$ of an approximately square aperture exceeds $\sim 10/\gamma$, a large flux of far-field edge radiation from the downstream bending magnet may be focused to a bright spot [3].

Consider an aperture at a distance $R$ from the radiation source at the downstream bending magnet edge. Near-field radiation is expected to be important when the far-field radiation cone width ($\sim R\theta_{\text{opening half}}$) is smaller than the diffraction limit ($\sim \lambda/\theta_{\text{opening half}}$), where $\lambda$ is the radiation wavelength and $\theta_{\text{opening half}} \sim 1/\gamma$ is the half-opening angle of the far-field radiation. This occurs when $\lambda > R\theta_{\text{opening half}}^2 \sim R/\gamma^2$ [4]. Constructive interference with near-field radiation and radiation from the upstream end of the straight section greatly reduces the flux and brightness of focused radiation for $\lambda > R_{\text{eff}}\theta_{\text{sp,half}}^2 = [RL/(R+L)]\theta_{\text{sp,half}}^2$, where $L$ is the straight section length and $R_{\text{eff}} = RL/(R+L)$ [3].

The long-wavelength limitations imposed by a conducting vacuum chamber may be estimated by considering an ideal case in which image charges represent the vacuum chamber shielding. Consider a typical rectangular vacuum chamber whose height $h_{\text{chamber}}$ is much smaller than its width. Image charges lie at a vertical distance $h_{\text{chamber}}$ from the electron beam. A unity-magnification lens at the entrance aperture will image the far-field edge radiation from an electron to a hollow spot with diameter (a.k.a. the effective source diameter) $d_{\text{spot}} \approx 2\lambda/(2\theta_{\text{sp,half}}) = \lambda/\theta_{\text{sp,half}}$. Because the radial polarization of edge radiation from a sudden deflection results in a hollow spot, the effective spot diameter is about twice that which would result from a uniform radiation field [3,5]. The radiation from image charges is focused at a transverse distance $h_{\text{chamber}}$ from that of the real charge. The focused spots are resolved when the effective source diameter is smaller than the vacuum chamber height: $d_{\text{spot}} \approx \lambda/\theta_{\text{sp,half}} < h_{\text{chamber}}$, i.e., $\lambda < h_{\text{chamber}}\theta_{\text{sp,half}}$. For $\lambda < h_{\text{chamber}}\theta_{\text{sp,half}}$, the flux and brightness of the focused edge radiation are nearly unaffected by the vacuum chamber. At longer wavelengths, destructive interference between the focused spots of real and image charges may degrade the flux and brightness.
For $\theta_{ap\;half} = 1/\gamma$, $h_{chamber}\theta_{ap\;half}$ equals the long-wavelength cutoff $h_{chamber}/\gamma$ that has been previously obtained for the central cone of transition radiation from a target of transverse dimension $h_{chamber}$ [6]. For $\theta_{ap\;half} \gg 1/\gamma$, $h_{chamber}\theta_{ap\;half}$ greatly exceeds $h_{chamber}/\gamma$, indicating that the long-wavelength cutoff from shielding is increased with a larger aperture. When the vacuum chamber height exceeds the aperture half-height $R\theta_{ap\;half}$, $h_{chamber}\theta_{ap\;half}$ exceeds $[(RL)(R+L)]\theta_{ap\;half}$, indicating that near-field effects, rather than shielding, are expected to limit the long-wavelength flux and brightness.

In summary, an approximately-square entrance aperture with $\theta_{ap\;half} \geq 10/\gamma$ may effectively collect edge or transition radiation for $\lambda < \min((RL)(R+L))\theta_{ap\;half}^2, h_{chamber}\theta_{ap\;half}^2$.

3. Ordinary synchrotron radiation

At wavelengths exceeding the critical wavelength, ordinary far-field synchrotron radiation is collected optimally when the entrance aperture angle equals the natural opening angle of far-field radiation: $\theta_{ap\;half} = \theta_{opening\;half} = (\lambda/\rho)^{1/3}$, where $\rho$ is the radius of curvature of the electron orbit in the bending magnet. The flux and brightness are decreased by more than ~50% when the aperture angle is less than half of optimal [3]. Thus, a substantial flux and brightness reduction occurs for $\lambda > 8\rho\theta_{ap\;half}^3$, where $R\theta_{ap\;half}^2$ is the wavelength optimally collected with aperture half-angle $\theta_{ap\;half}$.

At a distance $R$ from the radiation source, significant near-field radiation is expected when the far-field radiation cone width ($\sim R\theta_{opening\;half}$) is smaller than the diffraction limit ($\sim \lambda/\theta_{opening\;half}$). This occurs when $\lambda$ exceeds $\sim R\theta_{opening\;half}$). Accordingly, a significant loss in flux and brightness is predicted for $\lambda > 0.64 R\theta_{opening\;half}$ [7]; this criterion may also be written as $\lambda > R^3/(3.8\rho^2)$.

For long wavelengths where the radiation opening angle exceeds the entrance aperture angle, a unity-magnification lens at the entrance aperture will image the far-field synchrotron radiation from an electron to a spot diameter $d_{spot} \approx \lambda/(2\theta_{ap\;half})$ [3,5]. The radiation from image charges representing the vacuum chamber shielding is focused at a transverse distance $h_{chamber}$ from that of the real charge. The focused spots are resolved for $d_{spot} \approx \lambda/(2\theta_{ap\;half}) < h_{chamber}$, i.e., $\lambda < 2h_{chamber}\theta_{ap\;half}$. For $\lambda < 2h_{chamber}\theta_{ap\;half}$, the flux and brightness of the focused synchrotron radiation are nearly unaffected by the vacuum chamber shielding. At longer wavelengths, destructive interference between the focused spots of real and image charges may degrade the flux and brightness. The cutoff wavelength from vacuum chamber shielding exceeds that from large far-IR opening angles provided that $h_{chamber} > 4\rho\theta_{ap\;half}$.

Therefore, an approximately-square entrance aperture may effectively collect ordinary synchrotron radiation for $\lambda < \min(8\rho\theta_{ap\;half}^3, R^3/(3.8\rho^2), 2h_{chamber}\theta_{ap\;half})$.

4. Examples

Consider the IR edge radiation beamline at the Synchrotron Radiation Center with $R = 1.5$ m, $L = 3$ m, $\theta_{ap\;half} \approx 10$ mrad, and $h_{chamber} = 50$ mm [2]. For these parameters, effective radiation collection may be limited to $\lambda < \min((RL)(R+L))\theta_{ap\;half}^2, h_{chamber}\theta_{ap\;half}^2$.
min (100 μm, 500 μm) = 100 μm. Near-field effects, rather than the vacuum pipe, are expected to limit the long-wavelength flux and brightness.

As an example of ordinary synchrotron radiation, consider a far-IR beamline at the National Synchrotron Light Source with \( R = 0.44 \text{ m}, \theta_{\text{ap, half}} = 45 \text{ mrad}, \rho = 2 \text{ m} \) and \( h_{\text{chamber}} \approx 50 \text{ mm} \) [1]. In this case, effective radiation collection may be limited to \( \lambda < \min \left( \frac{8 \rho \theta_{\text{ap, half}}^3}{R^3/(3.8 \rho^3)}, 2 h_{\text{chamber}} \theta_{\text{ap, half}} \right) = \min (1.5 \text{ mm}, 5.6 \text{ mm}, 4.5 \text{ mm}) = 1.5 \text{ mm}. \) At wavelengths exceeding 1.5 mm, the large opening angle of the far-IR radiation is expected to degrade the flux and brightness.

5. Summary

The long-wavelength cutoffs from the large opening angles of far-IR synchrotron radiation, near-field effects, and vacuum chamber shielding have been considered. An approximately-square entrance aperture with \( \theta_{\text{ap, half}} \geq 10/\gamma \) may effectively collect edge or transition radiation for \( \lambda < \min \left( \frac{RL(R+L)}{\gamma^2}, h_{\text{chamber}} \theta_{\text{ap, half}} \right). \) An approximately-square entrance aperture may effectively collect ordinary synchrotron radiation for \( \lambda < \min \left( \frac{8 \rho \theta_{\text{ap, half}}^3}{R^3/(3.8 \rho^3)}, 2 h_{\text{chamber}} \theta_{\text{ap, half}} \right). \)

For edge radiation, the long-wavelength cutoff from shielding exceeds that from near-field effects provided that \( h_{\text{chamber}} > R \theta_{\text{ap, half}}, \) where \( h_{\text{chamber}} \) is the vacuum chamber height and \( R \theta_{\text{ap, half}} \) is the entrance aperture half-height. For ordinary synchrotron radiation, the long-wavelength cutoff from shielding exceeds that from large far-IR opening angles provided that \( h_{\text{chamber}} > 4 \rho \theta_{\text{ap, half}}^2, \) where \( \rho \) is the radius of curvature of the electron orbit and \( \theta_{\text{ap, half}} \) is the half-angle of the entrance aperture. In these cases, the focused spot diameter for unity magnification (a.k.a. the effective source diameter) is smaller than the vacuum chamber height for those wavelengths where the brightness is high. The flux and brightness may then be determined by a computer code that neglects shielding by the vacuum chamber (e.g., the Synchrotron Radiation Workshop [8,9]).
References


9 R. A. Bosch, “Flux and brightness of the SRC infrared beamline computed by the Synchrotron Radiation Workshop (SRW)”, SRC Technical Note SRC-190, Synchrotron Radiation Center (1999).