PROSPECT OF AN IR OR THz BEAMLINE AT SSRL*

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Abstract

A preliminary plan for an infrared or terahertz beamline at SSRL is studied. Edge radiation may be extracted with the existing ID port to provide near to mid-infrared beam. Rebuilding a straight section with a 3-bend chicane would enable us to obtain a port with large acceptance to reach the THz regime. Under the low alpha operational mode, the terahertz beam power can be greatly enhanced by the coherent synchrotron radiation (CSR) effect. Calculations of photon beam flux and the CSR amplification effects are presented.

INTRODUCTION

Infrared (IR) and terahertz (THz) radiation offer opportunities for a wide range of appealing science through imaging, spectroscopy, etc. Synchrotron radiation (SR) is an excellent IR source for its stability, high flux and high brilliance. IR beamlines can be found in many synchrotron light source facilities. More recently it has been demonstrated that synchrotron light sources are also attractive THz sources because of their capability to produce intense coherent synchrotron radiation (CSR) when operated in the low alpha mode [1].

Currently there is no IR or THz beamline at Stanford Synchrotron Radiation Lightsource (SSRL). However, the successful test of the low alpha mode [2] at SSRL has sparked some user interest. Therefore it is necessary to evaluate the feasibility of building an IR or THz beamline and the possibility of benefiting from CSR enhancement in the THz regime.

Long wavelength synchrotron radiation has large opening angles and thus requires a port with large acceptance for its extraction. Since edge radiation (ER) at long wavelength has better collimation, it may be used as a THz source. In this study we calculate the flux for SR and ER at various wavelengths for a few potential beamline configurations. The calculation is performed primarily with the code Synchrotron Radiation Workshop (SRW) [3].

The CSR effect of short bunches for long wavelength radiation is greatly enhanced by the longitudinal bunch distortion due to CSR impedance [4]. It is necessary to solve the Hassinski equation to obtain the equilibrium bunch distribution and the CSR amplification factor. The calculation is done for the SPEAR3 case.

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POSSIBLE BEAMLINE LAYOUT AND FLUX CALCULATIONS

Collecting long wavelength synchrotron radiation poses some difficulty because of its large vertical opening angle. The rms vertical opening angle of synchrotron radiation at the long wavelength end scales as [5]

$$\sigma_\theta = 0.62 \left(\frac{\lambda}{\rho}\right)^{1/3} \quad [\mathrm{rad}], \tag{1}$$

where λ is the wavelength and ρ is bending radius. For SPEAR3 ($\rho = 8.15$ m), the vertical rms opening angle would be 26 mrad for 0.5 mm wavelength. Edge radiation is sometimes more preferable in the far IR regime because it may have smaller opening angle. Edge radiation is emitted by relativistic electrons in the transitional region when they enter and leave bending magnetic fields. In the near field (when the distance between the source and observation points satisfies $R < \gamma^2\lambda$), edge radiation forms a cone which peaks at $\theta \approx \sqrt{\lambda/R}$. It has been pointed out [6] that for a given half aperture $\theta_{\rm ap}$, edge radiation is more favorable in flux and brightness in the wavelength region $\rho\theta_{\rm ap}^3 \ll \lambda < R\theta_{\rm ap}^2$.

For SPEAR3, edge radiation may be extracted with the existing insertion device (ID) ports with minimum work. The standard ID ports have small vertical aperture which limits them from reaching the far-infrared regime. However, the ID ports are considered since the near and mid-infrared regime may also be of interest. Existing SPEAR3 dipole beamlines are not designed to collect IR radiation. The angular acceptance is greatly limited by the vacuum chamber height. It is possible to modify the dipole vacuum chamber to put a mirror shortly after a standard dipole magnet. Despite the technical difficulty, this approach is also considered. Our preferred approach is to replace a 4.7 m long straight section with a 3-bend chicane. This option allows us to re-design the vacuum chamber with a large vertical gap and insert a mirror close to the chicane magnet to effectively collect THz beam.

Flux and brightness calculations for the options are presented in the following.

IR Beamline with a Standard ID Port

The limiting aperture for a standard SPEAR3 ID beamline port is located $R = 2.25$ m from the entrance edge of the downstream dipole. The acceptance is 48 H×8 V mrad^2 (108×18 mm). When there is no insertion device in the straight section, the ID port will receive edge radiation from the exit edge of the upstream dipole and the entrance edge of the downstream edge. The two edges

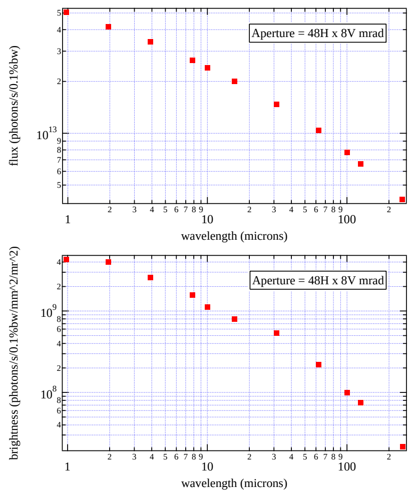

Figure 1: IR flux and brightness for the existing SPEAR3 ID port with a 8V $\times$ 48H mrad^2 aperture for a 100mA beam.

are $L = 5.29$ m apart. The long wavelength limit for which the full cone may be accepted by this port is $\lambda_{\rm ap} = h^2/4R(1 + R/L) = 25$ μm. The shielding wavelength is $\lambda_{\rm shielding} = h^2(R + L)/RL = 205$ μm [6]. Wavelengths longer than the shielding wavelength are severely suppressed due to interference with the waves reflected from the vacuum chamber wall.

Figure 1 shows the flux and peak brightness of the photon beam that can be extracted from this port. The size of the electron beam is included in the calculation. Brightness is calculated by placing a focusing lens with focal length $f = 1.125$ m at the aperture and calculating the maximum flux density at the focus spot 2.25 m downstream. The flux density is then divided by the solid angle subtended by the aperture with respect to the focus spot. Note that the shielding effect is not included in SRW calculations. In this case, flux and brightness numbers are not accurate for wavelength beyond 25 μm since the reflected wave is not considered.

THz Beamline with Modified Dipole Chamber

To extract THz synchrotron radiation from a standard SPEAR3 dipole we may modify the vacuum chamber to increase its horizontal and vertical size and put a mirror at the end of the magnet to bend the IR beam outward by 90°. It may be feasible for the angular acceptance to reach 60H$\times$52V mrad^2, considering that similar results have been achieved in other third generation light sources [7]. The flux for such a port is shown in Figure 2.

THz Beamline with a Chicane

A 3-bend chicane may be put into one of the 4.7 m straight sections in the matching cells. The three chicane magnets may be arranged symmetrically as shown in Figure 3. Parameters of the middle chicane magnet are listed

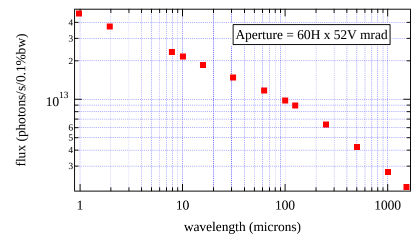

Figure 2: IR flux for a potential SPEAR3 dipole port with a 60H$\times$52V mrad^2 aperture for a 100mA beam.

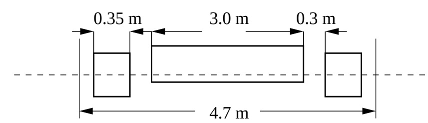

Figure 3: Layout of the chicane magnets.

in Table 1. The other two chicane magnets are each 35 cm long, with a bending angle of 33.33 mrad. Weak magnetic field is used in this magnet to reduce the vertical opening angle of SR and allow a large magnet gap. The rms vertical opening angle is 18.6 mrad for 1 mm wavelength in this magnet.

Table 1: Parameters of the Middle Chicane Magnet

parameters	value
bending angle	66.67 mrad
length	3.0 m
magnetic field	0.222 Tesla
sagita	25 mm

The vacuum chamber for this magnet will be designed to effectively collect synchrotron radiation down to 1 mm wavelength with a mirror located toward its end. This mirror is aimed to collect mainly the SR from the first half of the orbit in the chicane magnet. We assume an aperture of 52$\times$52 mrad^2 for this beamline in the flux calculations. The flux for a 100 mA beam is shown in Figure 4. The flux is 8×10^{12} photons/s/0.1% BW for 1 mm wavelength.

Modifying a dipole chamber or rebuilding a straight section with chicane are both complicated tasks. Details of the vacuum chamber design and its impact on the electron beam have not been studied. Both options seem viable to extract THz beam down to 1 mm level.

CSR AMPLIFICATION

When the length of an electron bunch is comparable to the radiation wavelength, coherent synchrotron radiation will significantly enhance the radiation power. The total radiated power density of a bunch is given by

$$\frac{dP}{d\lambda} = \frac{dp}{d\lambda} N[1 + Ng(\lambda)], \tag{2}$$

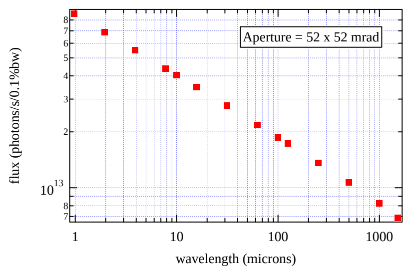

Figure 4: Flux collected by the 52×52 mrad^2 from the chicane magnet for a 100 mA beam.

where $\frac{dp}{d\lambda}$ is SR power density of a single electron, N is the number of electrons and $g(\lambda)$ is a form factor related to the longitudinal distribution of the bunch by [4]

$$g(\lambda) = |\int e^{i2\pi z/\lambda}\rho(z)dz|^2, \qquad (3)$$

where $\rho(z)$ is the normalized longitudinal bunch distribution. Normally an electron storage ring is not affected by CSR since the long wavelength synchrotron radiation is suppressed due to vacuum chamber shielding. The shielding cutoff wavelength is $\lambda_0 = 2h(h/\rho)^{1/2}$ [6], where h is the half height of the vacuum chamber and ρ is the bending radius. For a standard SPEAR3 dipole, $h = 17$ mm and $\lambda_0 = 1.55$ mm. CSR effect may become significant in the low-alpha operational mode when the bunch length is reduced to values smaller than the shielding cutoff wavelength. In this case, the CSR impedance will distort the longitudinal distribution of the bunch to make it tilt forward (when the momentum compaction factor $\alpha > 0$). Such a triangular shape will further increase the CSR effect. The equilibrium distribution can be found by solving the Hassinski equation. The CSR impedance also drives a microwave instability which can cause the bunch to radiate coherently in a bursting mode at wavelength much shorter than the bunch length. For SPEAR3, the bursting single bunch current threshold is found to be related with the zero-current bunch length empirically by $\sigma_{\min}[\mathrm{ps}] = 9.7I_b[\mathrm{mA}]^{1/3}$ [2]. When α is reduced to have a zero-current rms bunch length of 1 ps, the single bunch current threshold is about 1μA, corresponding to a total current of 0.3 mA when we fill 300 bunches.

It is preferable to operate below the bursting threshold to deliver a stable beam to the users. Solving the Hassinski equation for the current just below the threshold, we obtain the normalized longitudinal distribution, from which we derive the form factor $g(\lambda)$ according to Eq. (3). Both the free space SR impedance and the parallel plate shielding model are considered. The CSR amplification factor for two low alpha cases are shown in Figure 5. For the case with a zero-current bunch length of 1 ps, the amplification factor is 2×10^5 for a 1 mm wavelength. The flux for this wavelength would be 600 times larger than the standard 100 mA stored beam in the normal operational mode.

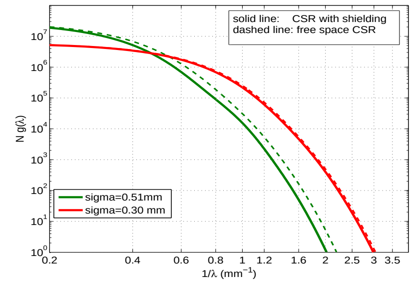

Figure 5: The CSR amplification factor $Ng(\lambda)$ for SPEAR3 in two different α-values for corresponding single bunch currents just below the bursting threshold. The rms bunch length for SPEAR3 achromatic lattice is 5.1 mm.

SUMMARY

We are in a preliminary stage of a plan to build an IR/THz beamline at SSRL. Calculations have shown that existing ID port may serve as an IR beamline using edge radiation. It is capable to reach the mid-infrared regime (to 25 μm level). To reach the THz regime, we may modify a dipole vacuum chamber to insert a mirror in the dipole or rebuild a 4.7 m long straight section with a 3-bend chicane. When the ring is operated in the low alpha mode, the THz radiation with a wavelength on the 1 mm level is greatly enhanced by the CSR effect, yielding an output 600 times stronger than the 100 mA beam. The corresponding photon beam flux would be 5×10^{15} photons/s/0.1%BW.

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