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TITLE: COHERENT SMITH-PURCELL RADIATION AS A DIAGNOSTIC FOR SUB-PICOSECOND ELECTRON BUNCH LENGTH

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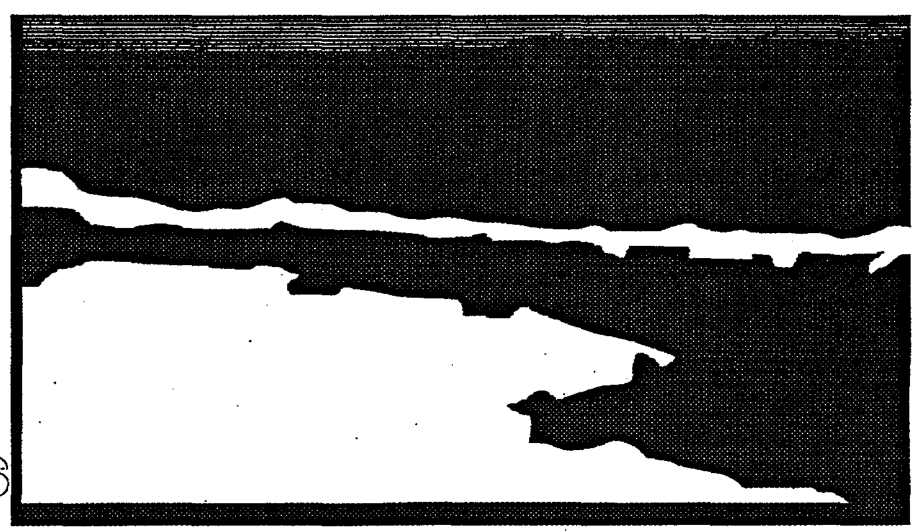

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Coherent Smith-Purcell Radiation as a Diagnostic for Sub-picosecond Electron Bunch Length*

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Abstract

We suggest a novel technique of measuring sub-picosecond electron bunch length based on coherent Smith-Purcell radiation emitted when electrons pass close to the surface of a metallic grating. With electron bunch lengths comparable to the grating period, we predict that coherent Smith-Purcell radiation will be emitted at large angles with respect to the direction of beam propagation. As the bunch length shortens, the coherent Smith-Purcell radiation will be enhanced over the incoherent component that is normally observed at small angles. Furthermore, the angular distribution of the coherent Smith-Purcell radiation will be shifted toward smaller angles as the bunch length becomes much smaller than the grating period. By measuring the angular distribution of the coherent Smith-Purcell radiation, one can determine the bunch length of sub-picosecond electron pulses. This new technique is easy to implement and appears to be capable of measuring femtosecond electron bunch lengths.

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Introduction

Recent experiments on electron pulse compression have produced subpicosecond electron bunches [1, 2] with high peak currents and brightness. These high-brightness electron bunches are the enabling technology for the next-generation synchrotron light sources, x-ray free-electron lasers, and plasma wakefield accelerators. In these applications, a direct, real-time, and non-intercepting diagnostic of the electron longitudinal bunch length is highly desirable. Yet, as the electron pulse length falls below a picosecond, it becomes very difficult to measure the bunch length directly. Although streak cameras with subpicosecond resolution exist, the streak camera measurement of a single electron bunch using optical transition radiation (OTR) is often plagued with inadequate OTR intensity. Consequently, these measurements often have to be performed repetitively over many electron pulses in the synchroscan mode which, due to rf phase jitter, limits the measurement temporal resolution to a few picoseconds.

Several indirect methods of measuring subpicosecond electron bunches have been studied [3-6]. These generally fall into two categories: the frequency-domain methods and the autocorrelation method. In the first category, the electron bunch length is deduced from the spectra of the coherent radiation generated by the electron in a short undulator (coherent undulator radiation) [3] or around a bending magnet (coherent synchrotron radiation) [4]. The second method involves optical autocorrelation of the long-wavelength coherent transition radiation generated when electron beams hit a screen [5], or measuring the energy spread of a bunch on a screen with a spectrometer and then tomographically reproducing the initial bunch longitudinal phase space [6]. In this paper, a new approach of measuring subpicosecond electron bunches based on coherent Smith-Purcell radiation (SPR) is studied. Compared to the other indirect methods, this new technique is easy and inexpensive to implement. With high-quality electron beams, the temporal resolution can be scaled to femtosecond pulses. The capabilities of this new technique is studied for characterizing longitudinal property of femtosecond electron bunches after compression in a magnetic buncher.

Coherent Smith-Purcell Radiation

When an electron beam passes close to the surface of a metallic diffraction grating, it emits incoherent Smith-Purcell radiation (SPR). This radiation is emitted over a large range of angles, with the shortest wavelength directed in the forward direction (0°), and the longest wavelength directed in the backward direction (-180°), according to the following expression,

$$\lambda = \frac{d}{n}(\frac{1}{\beta} - \cos\theta) \tag{1}$$

where d is the grating period, n is the diffraction order (assumed to be 1 throughout this paper), β is the usual beam velocity normalized to the speed of light, $\beta = \frac{v}{c}$, and θ is the angle of the emitted SPR with respect to the direction of beam propagation. If the electron bunch length is long compared to the SPR wavelength, the radiation emitted by a relativistic electron beam occurs mostly in the forward direction, as has been observed by Doucas et al. [7]. For relativistic beam (E > 5 MeV) and small height, the plot of SPR intensity versus θ reaches a maximum at an angle given approximately by

$$\theta_{\max} = \cos^{-1}\left(-\frac{1}{\beta} + \frac{\sqrt{1+3\beta^2}}{\beta} - \frac{2\pi\beta h}{\gamma d} \right) \tag{2}$$

where h is the beam height above the grating, and γ is the beam relativistic factor. Note that the first two terms in parentheses asymptotically approaches $1 - 1/2\gamma^2$ in the limit of $\beta \sim 1$. Thus, it is possible for incoherent SPR to be emitted at large angles if the beam height is comparable to d.

Recent experiments on SPR using short, but not subpicosecond, electron pulses [8, 9] hinted that the coherent SPR should be orders of magnitude stronger than the incoherent one, due to the large number of electrons in the bunch. As the electron bunch length becomes comparable to the SPR wavelength, the plot of intensity versus angle will exhibit additional high-intensity lobes. Since long wavelengths occur at large angles, the degree of coherent enhancement should increase with angle. Thus, we expect coherent Smith-Purcell to be detected first at large angles, almost in the backward direction.

The intensity of SPR per unit solid angle per unit grating length as a function of emitted angle is given by the following equation,

$$\frac{dP_n}{d\Omega} = \frac{eIn^2\beta^3}{2\varepsilon_0 d^2}|R_n|^2(1+Nf(\sigma_z,\lambda))\left(\frac{\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^3}\right)e^{-\frac{4\pi h}{\gamma\lambda}} \tag{3}$$

where e is the electron charge, I is the beam current, n is the grating order, ε_0 is permitivity of free space, $|R_n|^2$ is the square of the grating reflectivity, N is the number of electrons in the bunch, θ and ϕ are the angles of observation with respect to the beam direction, and $f(\sigma_z,\lambda)$ is the factor between 0 and 1 as given by the square of the Fourier transform of the longitudinal density function, $S(z)$

$$f(\sigma_z,\lambda) = \left| \int S(z) e^{\frac{i2\pi\sigma_z}{\lambda}} dz \right|^2 \tag{4}$$

The form factor $f(\sigma_z,\lambda)$ approaches 1 when the bunch length σ_z is comparable to or less than the grating period. Equation (4) is only correct for one-dimensional beams, i.e. beams with zero transverse profile. For electron beams with finite transverse dimensions, one must apply additional corrections to take into account three-dimensional effect.

Because N is a very large number, on the order of 10^8, the coherent signal is much larger than the incoherent radiation as the form factor becomes 1. With a judicious choice of the grating period, for a given electron bunch length, we can find a range of angles whereby the coherent SPR will appear as a strong lobe or lobes at large angles above an almost-zero background of incoherent SPR at small angle. By measuring the angular position of these coherent SPR peak or by ratioing its intensity to the incoherent SPR peak, we can deduce the electron bunch length.

A possible experimental setup for the Smith-Purcell bunch length measurement is shown in Figure 1. To obtain adequate light intensity, the grating must be sufficiently long but not too long so as to deviate significantly from a point source model. Two detectors, one for the incoherent infrared SPR and one for coherent far-infrared SPR, mounted on platforms whose angles with respect to the beam propagation direction can be adjusted. In the cases where the bunch length is comparable to the grating period, the ratio of the intensity of the coherent SPR to that of incoherent SPR is measured. From the intensity ratio, the bunch length can be estimated. In the cases where the electron bunch length is much less than the grating period, the detector platforms will be rotated to map out the angular distribution of the coherent SPR. One can then determine the bunch length from the angular distribution of the coherent SPR.

Calculations

For the purpose of studying the capabilities of the new subpicosecond bunch length measurement technique, we performed calculations for a representative case where a 20-MeV electron beam is compressed in a magnetic chicane. The electron bunch length is 6 mm (approximately 20 ps) before compression and varies between 0.015 mm (50 fs) and 0.16 mm (533 fs) after compression. The grating period is 0.16 mm (density = 6 lines/mm) and the beam is a one-dimensional line traveling at a height of 0.1 mm above the grating. The number of particles in a bunch is assumed to be 10^8 (charge ~ 16 pC).

In Fig. 2, the calculated wavelength is plotted versus angle, showing the typical progression toward longer wavelength at large angles. For relativistic beams (β ~ 1), the plot in Fig. 2 is almost independent of beam energy. Note that the long wavelengths dominate at large angles. For a given bunch length, one expects the degree of coherence to be enhanced at long wavelengths, and thus, large angles.

The calculated intensity-angle distribution of an uncompressed gaussian bunch is shown in Fig. 3a. Due to a relatively large ratio of height over period, the plot of the calculated intensity versus angle shows a peak corresponding to incoherent SPR at an angle of 0.5 radian. After weakly compressed to 0.16 mm, the bunch begins to emit coherent SPR at $\theta = 2.7$ radians with intensity comparable to the incoherent peak (Fig. 3b). As the bunch gets shorter, the ratio of the coherent to incoherent SPR increases rapidly from approximately 6:1 for the bunch length of 0.15 mm (Fig. 4a) to about 22:1 for 0.14 mm (Fig. 4b).

In the regime where the bunch length is much shorter than the grating period, the angular distribution of the coherent SPR peaks at different angles. For example, the coherent SPR from a gaussian bunch with rms length equal to 0.03 mm peaks at $\theta = 1.6$ radians (Fig. 5a), whereas the same bunch with half the length peaks at $\theta = 1.2$ radians (Fig. 5b).

We can also use the spectral distributions of the SPR signals collected over all angles to determine the bunch length. Unlike coherent undulator and coherent synchrotron radiation, coherent SPR from a gaussian-shaped pulse exhibits a peak at a characteristic wavelength dependent upon the rms bunch length (Fig. 6a and 6b). This is due to the competing effects of coherent enhancement at long wavelengths and the natural tendency of SPR to peak at short wavelengths.

The electron bunch shape also has a significant effect on the intensity-angle distribution of the coherent SPR light, as illustrated by Fig. 7b, where the calculation was done with a rectangular pulse with rms bunch length of 0.03 mm, compared to the calculation with the same pulse with a gaussian shape in Fig. 7a. Due to the large harmonic contents in a rectangular pulse, the intensity-angle distribution exhibits a number of structures at smaller angles in addition to the main lobe. Note that the position of the main lobe is also shifted, a complication that requires us to scan over a large range of angles in order to determine the bunch shape prior to measuring the bunch length.

Conclusions

We present a new technique of measuring sub-picosecond electron bunch length via coherent Smith-Purcell radiation. This technique requires scanning the detector over a range of angles of observation to determine the intensity-angle distribution of the coherent SPR light. The new technique offers a number of advantages: it is simple and inexpensive to set up; it appears to be scaleable to the femtosecond regime; and it does not intercept the electron beam. With a array of detectors, one can measure the intensity-angle distribution of a single electron bunch. In addition, if the grating can be rotated about an axis perpendicular to the grating surface and the beam propagation direction, the grating period can be varied in real time. Thus, one can "dial" in the correct grating period for a particular bunch length measurement.

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Figure Captions

Fig. 1 Experimental setup to measure subpicosecond electron bunch length via coherent Smith-Purcell radiation.

Fig. 2 Smith-Purcell Radiation angular dispersion for the nominal case: grating period = 0.16 mm; beam height above grating = 0.1 mm; and beam energy = 20 MeV.

Fig. 3 Calculated Smith-Purcell Radiation intensity-angle distribution for the nominal case with gaussian pulse shape and $N = 10^8$; a) rms bunch length = 6 mm (20 ps); and b) rms bunch length = 0.16 mm (533 fs).

Fig. 4 Calculated Smith-Purcell Radiation intensity-angle distribution for the nominal case with gaussian pulse shape and $N = 10^8$; a) rms bunch length = 0.15 mm (500 fs); and b) rms bunch length = 0.14 mm (467 fs).

Fig. 5 Calculated Smith-Purcell Radiation intensity-angle distribution for the nominal case with gaussian pulse shape and $N = 10^8$; a) rms bunch length = 0.03 mm (100 fs); and b) rms bunch length = 0.015 mm (50 fs).

Fig. 6 Calculated Smith-Purcell Radiation spectral distribution for the nominal case with gaussian pulse shape and $N = 10^8$; a) rms bunch length = 0.14 mm (467 fs); and b) rms bunch length = 0.03 mm (100 fs).

Fig. 7 Calculated Smith-Purcell Radiation intensity-angle distribution for the nominal case with rms bunch length of 0.03 mm (100 fs); a) gaussian bunch shape; and b) rectangular bunch shape.

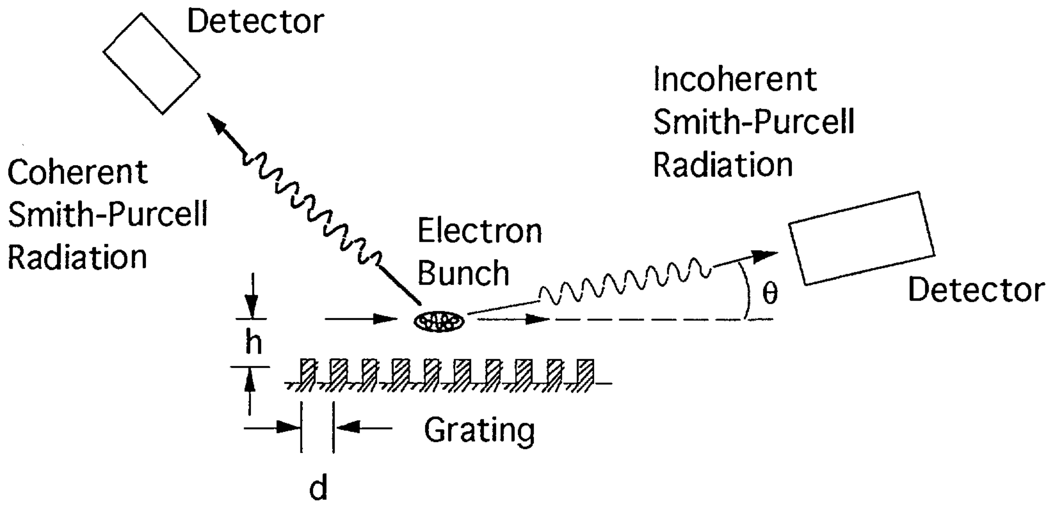
Detector
Incoherent
Smith-Purcell
Radiation
Coherent
Smith-Purcell
Radiation
Electron
Bunch
θ
Detector
h
Grating
d

Figure 1

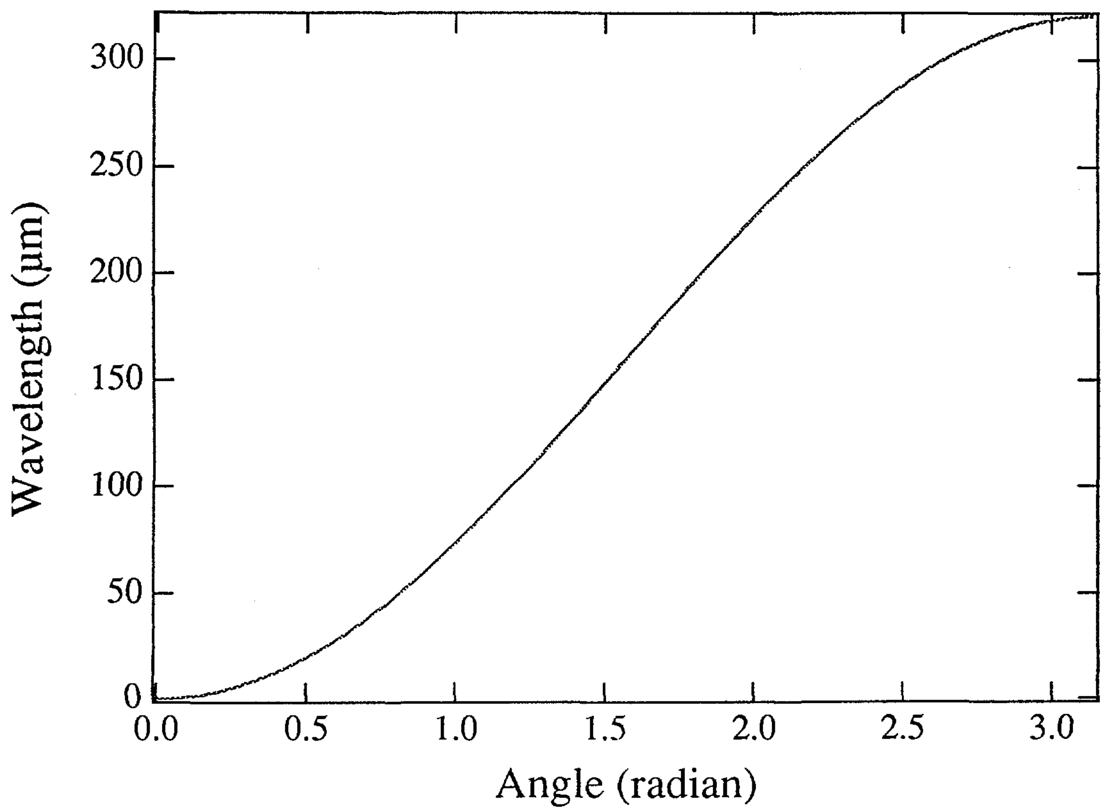
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength (μm)
Angle (radian)

Figure 2

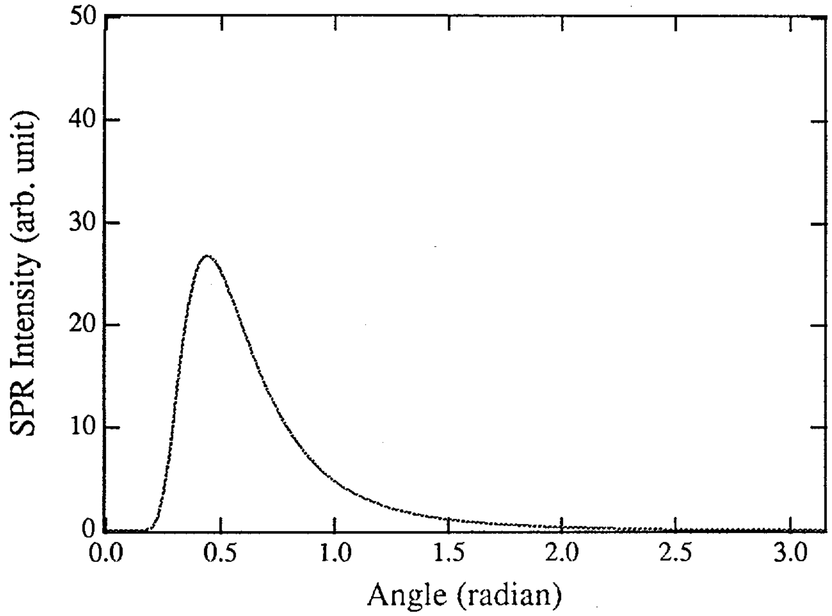

Figure 3a

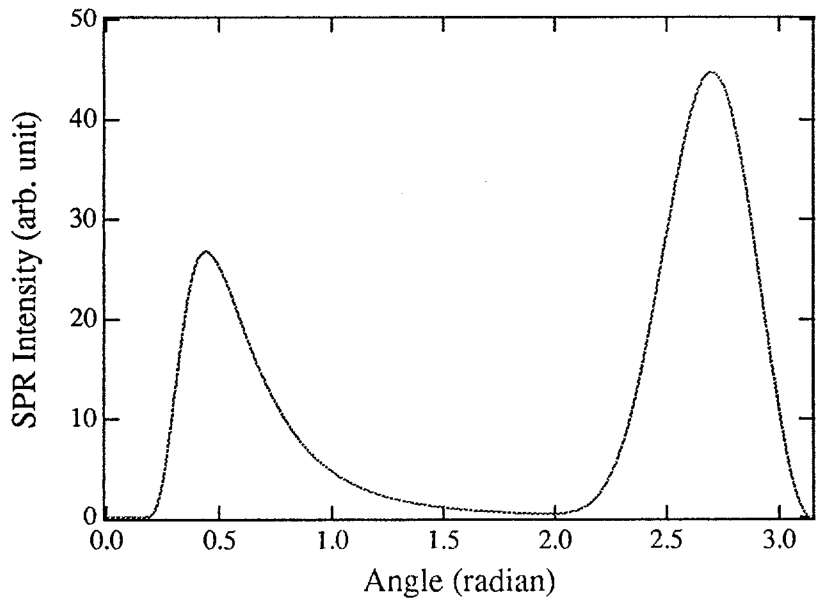

Figure 3b

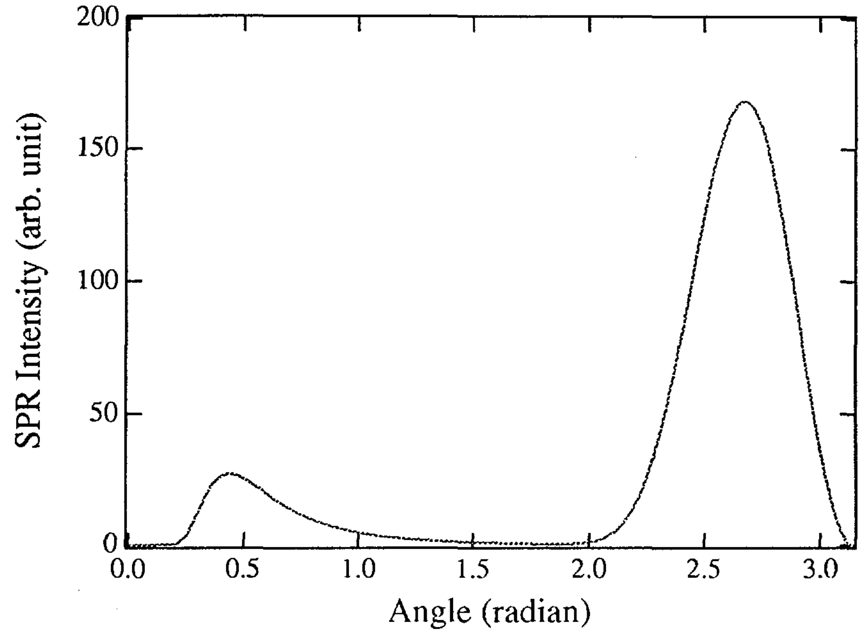

Figure 4a

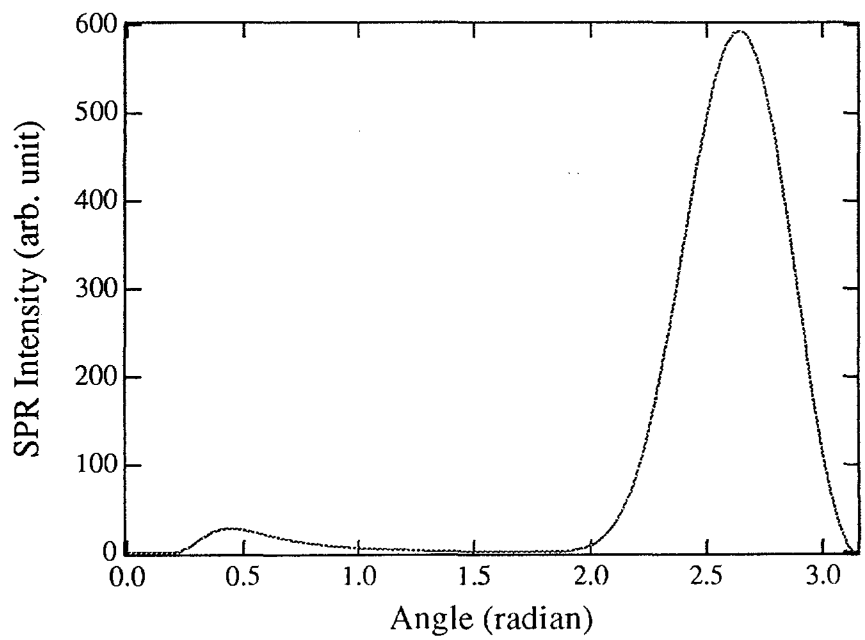

Figure 4b

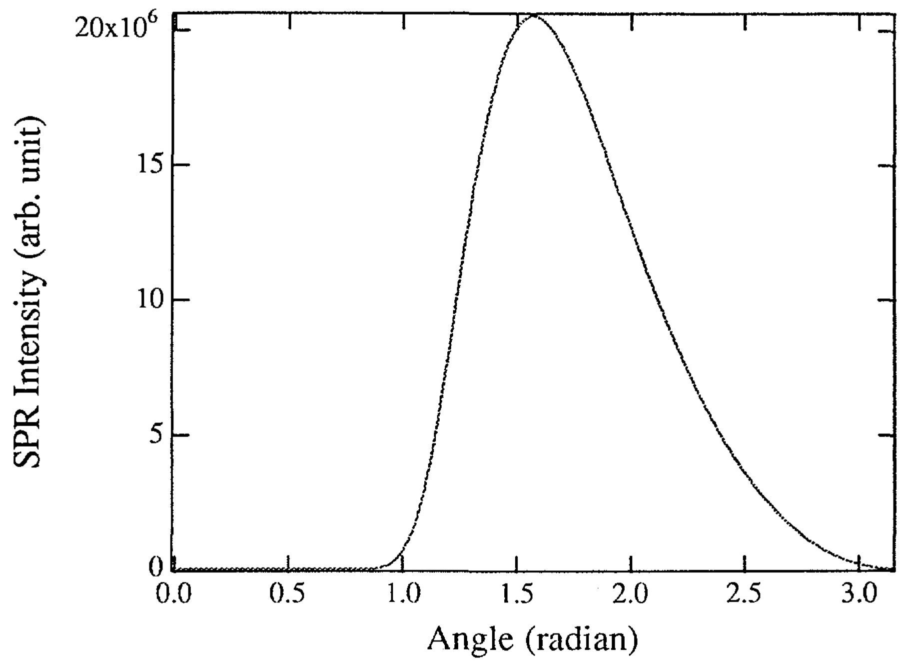

Figure 5a

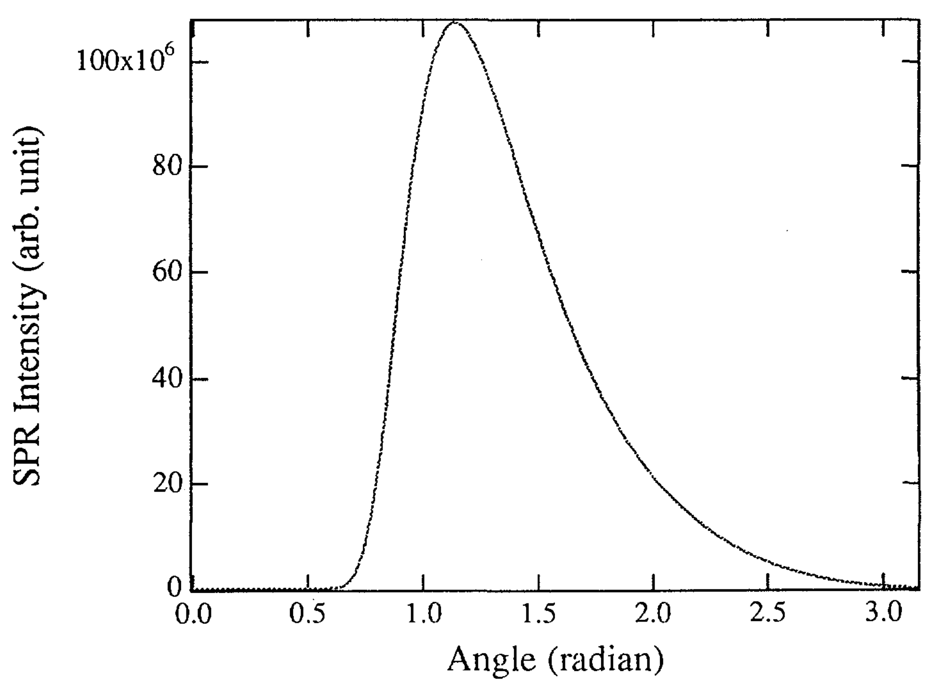

Figure 5b

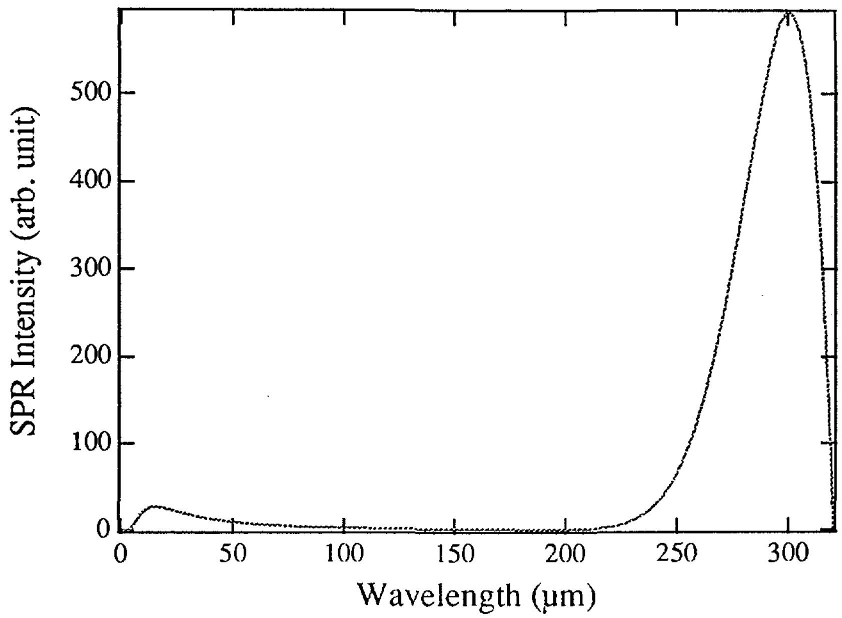

Figure 6a

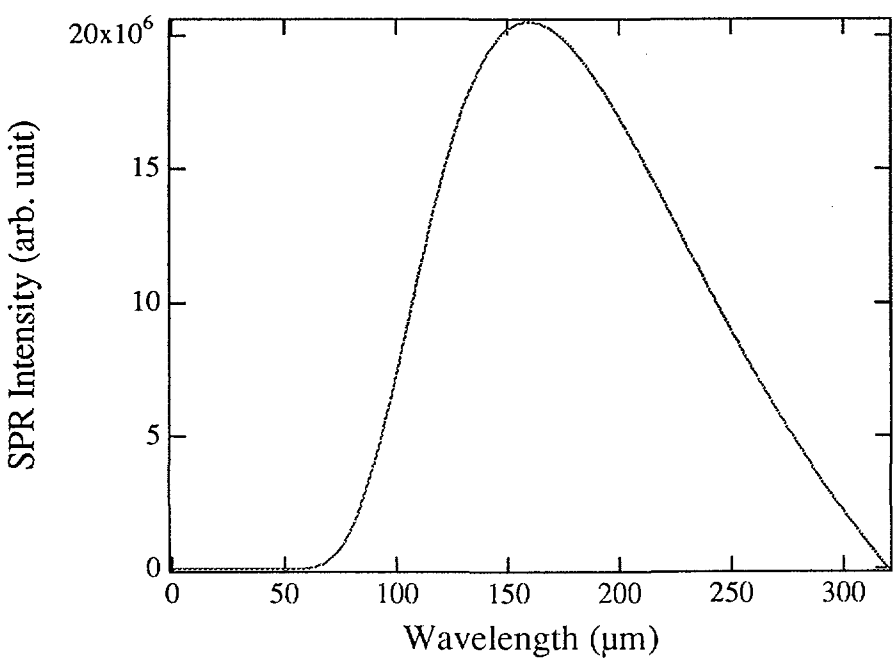

Figure 6b

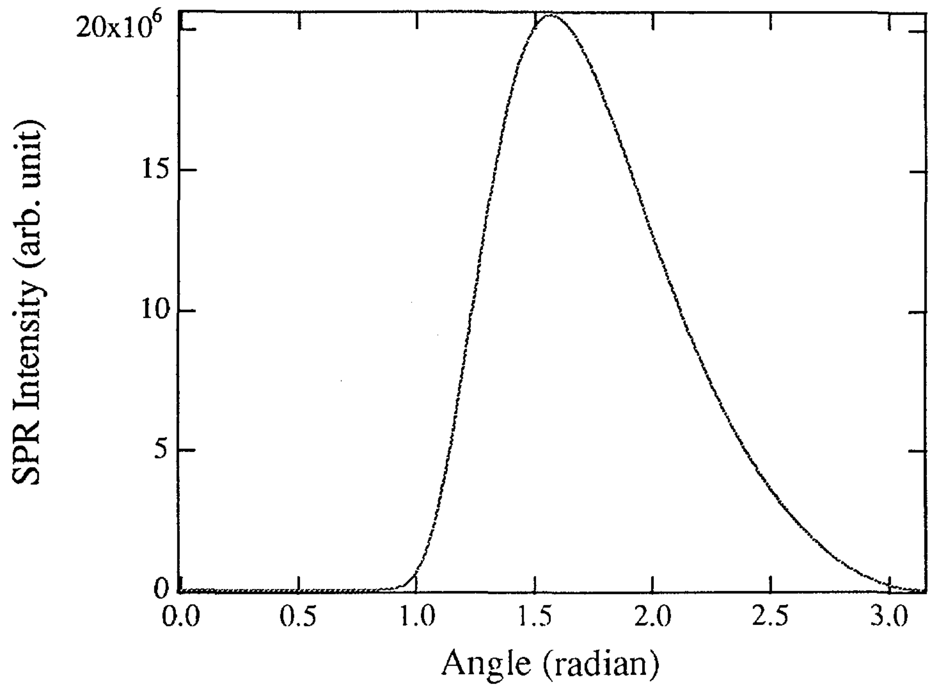

Figure 7a

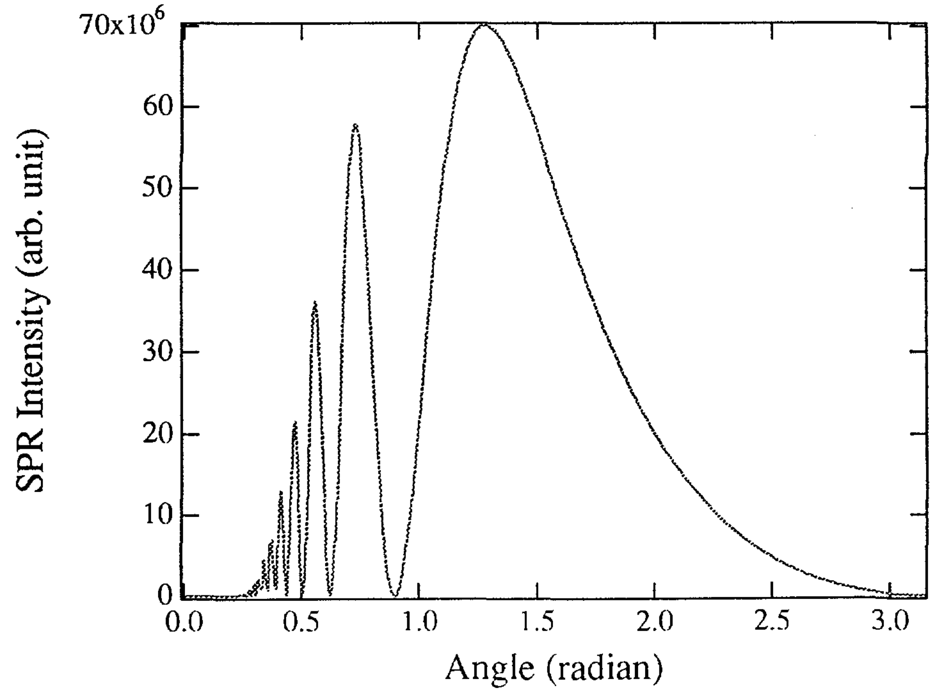

Figure 7b