

# Experimental verification of the theory on the inverse Smith–Purcell effect at a submillimeter wavelength

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The inverse Smith–Purcell effect is a candidate for laser-driven linacs utilizing the interaction between laser light and an electron beam traveling just in front of a metallic grating. We have performed experiments to study electron energy spread as a function of electron beam position above the grating. A submillimeter wave laser ( $\text{CH}_3\text{F}$ ,  $496 \mu\text{m}$ ) is used as a driving source. It is found that the energy spread characteristics show exponential decay of the interaction strength (field intensity) in the direction perpendicular to the grating surface, as a classical theory on the effect predicts.

The inverse Smith–Purcell effect<sup>1</sup> was proposed in 1977 by us as a candidate for a laser-driven linear accelerator.<sup>2</sup> It uses a metallic grating as an interaction circuit. The acceleration gradient could be several GeV/m. Since our proposal, several authors discuss a possibility driver.<sup>3–5</sup> In contrast to many discussions, there has been no experimental studies and even experimental evidence of its principle until our recent studies. The reason for this may be that the experiment at these wavelengths is very difficult because the region within one wavelength of the grating must be used for the electron-light energy exchange except for relativistic electrons. In 1987 we successfully observed the effect using a submillimeter wave laser as a driving source for the first time.<sup>6</sup>

Recently a theoretical article<sup>7</sup> on the same configuration to generate x rays was published, claiming that the interaction space above the grating could be 1000 times the wavelength, with a synchronous condition (an angular distribution of the ray wavelength) different from that predicted by a classical theory of the Smith–Purcell radiation from electrons skimming over a grating. A difference between their condition and classical one is that in their scheme electrons collide with the grating surface. In this letter we report our experimental results performed to study the size of the interaction space and the synchronous condition when electrons are not colliding with the grating.

According to the classical theory, an infinite number of evanescent space harmonics are induced near the grating surface on which laser light with wavelength  $\lambda$  is illuminated at an incident angle of  $\theta$ . The  $n$ th space harmonic has a phase constant  $k_n = k_0 \cos \theta + 2n\pi/D$  in the direction of electron traveling,  $D$  is the pitch of the grating ruling, and  $k_0$  is the phase constant of the laser wave in the free space. If a longitudinal electron-velocity  $v$  is equal to the phase velocity  $v_p = \omega/k_n$ , the electron interacts synchronously with the evanescent wave with this phase velocity, being consequently accelerated or decelerated.

According to a classical theory for field distribution on the grating,<sup>8</sup> the field intensity of the evanescent wave decays exponentially along the direction perpendicular to the grating surface ( $z$  direction), and its decay constant is given by  $k_0/\beta\gamma$ , where  $\beta = v/c$  and  $\gamma = \sqrt{1-\beta^2}$ . For  $\beta = 0.5$ , the field intensity falls off by  $1/e$  times at  $z = 0.09\lambda$ .

Hence the electron beam must pass very close to the grating surface in order to obtain an effective interaction. This is the major reason why we used a submillimeter wave laser to observe the inverse Smith–Purcell effect.<sup>6</sup>

The computer simulation on energy-exchange of electrons interacted with the first order space harmonic ( $n=1$ ) shows that a laser power of 10 W with wavelength of  $496 \mu\text{m}$  will produce a maximum electron-energy spread of 300 eV at a center energy of 79 keV for the interaction length of 5 mm. The details are described in Ref. 8.

Figure 1 shows a schematic diagram of interaction with the first order space harmonic, because its amplitude is the largest among the space harmonics (Table I). Grating grooves with a rectangular cross section were cut into a Cu-alloy substrate, maintaining a tolerance of  $\pm 2 \mu\text{m}$ . The submillimeter wave  $\text{CH}_3\text{F}$  laser was pumped by a newly developed current-pulsed  $Q$ -switched  $\text{CO}_2$  laser<sup>9</sup> which produced output pulses with high repetition rate up to 9.2 kpps. The output pulse of the  $\text{CH}_3\text{F}$  laser had a single peak in the time domain for the fundamental transverse mode, which has a Gaussian profile. Two lenses concentrated the laser beam on the grating surface. The spot size at the surface was calculated to be 1.2 mm from Gaussian beam theory. The electron energy was analyzed by using a retarding-potential technique.<sup>10</sup> Our energy analyzer has a resolution of 0.8 eV (full width at half-maximum) at an electron-energy  $V_i$  of 80 keV and a current of 3 nA. This resolution includes the intrinsic thermal energy spread of the electron beam. A moveable slit with a gap of  $10 \mu\text{m}$  was placed at the end of the grating and was used to specify the position of electron beam above the grating. The position of the gap can be controlled to an accuracy of  $\pm 3 \mu\text{m}$ .

The pulsed laser output modulates the energy of the electron beam, so that the electron current through the analyzer changes during the pulse. The change in the collector current is measured by a box-car averager which is triggered by the laser pulse. Figure 2 shows the typical electron-energy spectrum (a) measured and (b) calculated with (solid line) and without (dotted line) laser illumination for  $V_i = 80$  keV and  $P_i = 12$  W (peak). The abscissa is a filter bias voltage  $V_f$  which is the retarding-potential of the energy analyzer. The ordinate is the change in electron

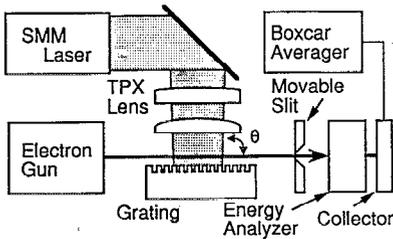


FIG. 1. Experimental setup to measure the inverse Smith-Purcell effect. A SMM laser is a submillimeter wave laser and TPX is poly 4 methylpentene-1 which is a low loss material in a submillimeter wave region.

current caused by the laser. The theoretical curve [Fig. 2(b)] was calculated by a method similar to that described in Ref. 8, except that the shape of the laser pulse has been taken into account here.

Since the energy analyzer passes all the higher-energy electrons, it is expected that, for large bias voltages the current change with laser illumination should be same as the one without laser illumination. However in Fig. 2(a) the current change with laser illumination is slightly smaller than the one without laser illumination when  $V_f > +30$  V. This shows that the laser illumination deflects the electron beam, and consequently a part of the electron beam is clipped by the aperture before the collector. We calculate that 1.3% of the electrons are lost. We have also observed that this ratio becomes larger as the laser power increases, as theoretically expected. The measured maximum energy spread, 64 eV is about a quarter of the theoretical spread. There might be two reasons for this discrepancy. First, the amplitude of the space harmonic may not be the same as the theoretical one because of fabrication errors in the groove dimensions. Second, noise in the electron-energy spectra may contribute an error.

Figure 3 shows experimental results for the synchronous condition between electron velocity and phase velocity of the evanescent wave. The ordinate is electron energy spread normalized by its maximum value. The laser power was between 8.3 and 12 W. The abscissa is the initial accelerating voltage. As the interaction length between electrons and waves is finite, the effective interaction can occur for electrons with a certain range. The largest energy spread is produced at an initial energy of 80 keV. By curve fitting, we can deduce that the effective interaction length is 3 mm. A theoretical plot for this length is also given in Fig. 3 (solid curve).

TABLE I. Experimental parameters.

Laser:	Wavelength	496 $\mu\text{m}$
	Peak power ( $P_l$ )	1-86 W
	Pulse width	30-100 ns
	Beam waist (calculated at the grating surface)	1.2 mm
Electron:	Accelerating voltage	10-100 kV
	Current	$< 1 \mu\text{A}$
Grating: (fabricated)	Pitch	$246 \pm 2 \mu\text{m}$
	Depth	$104 \pm 2$
	Width	$40 \pm 2$

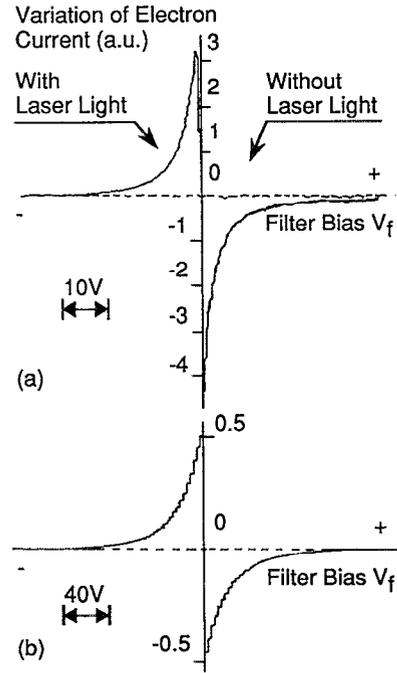


FIG. 2. (a) Measured and (b) calculated electron-energy spectrum for the electron energy of 80 keV and a peak laser power of 12 W.

As described earlier, the field intensity of the evanescent wave is theoretically proportional to  $\exp(-k_0 z / \beta \gamma)$ , where  $z$  is a distance from the grating surface. Figure 4 shows experimental results that show the field decay characteristics of the first-order and the second-order space harmonics interacting with the electron beam. We measured the energy spread of electrons as a function of the beam position ( $z$ ) above the grating. In Fig. 4 the abscissa is the electron position  $z$  which is the position of the movable slit mentioned earlier. The ordinate is the energy spread of the electron beam passing through the slit. The dotted lines show the theoretically predicted changes, i.e.,  $\exp(-0.022z)$  and  $\exp(-0.049z)$  for the first-order and the second-order waves, respectively. The experimental results are in good agreement with the theory. These results are a direct verification for the classical evanescent wave

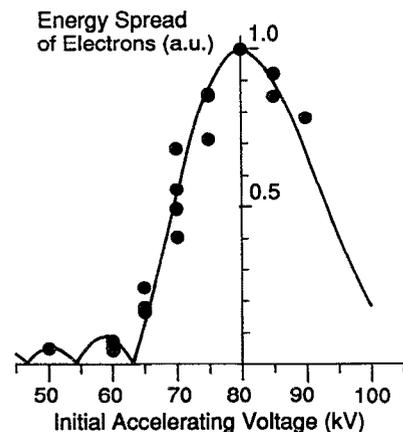


FIG. 3. The change of electron-energy spread vs the initial accelerating voltage of electrons.

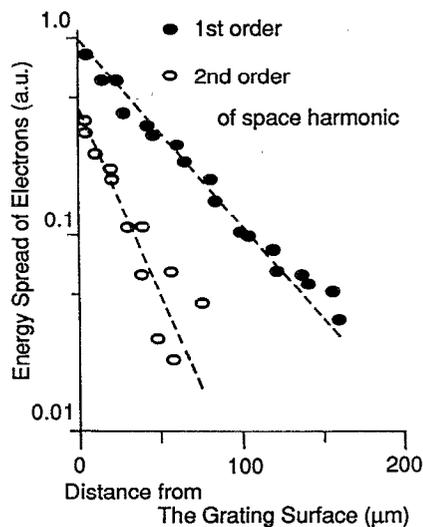


FIG. 4. The change of energy spread of the electron beam interacting with the first-order and the second-order space harmonics induced on the grating surface with the laser illumination as a function of the distance from the grating surface in  $z$  direction. The dotted lines are the theoretically predicted changes.

theory for the inverse Smith–Purcell effect.

In conclusion, we have observed electron-light interaction in the inverse Smith–Purcell effect by using a  $496\ \mu\text{m}$  submillimeter wave laser as a driving source. The experi-

mental setup was carefully adjusted so that the electrons would not collide with the grating surface. It has been found that the experimental results are in good agreement with the classical theory. In particular, the interaction strength was observed to decay exponentially away from the grating surface. This shows that the interaction space size is less than the laser wavelength. Also the theory for the synchronous condition between velocities of electron and wave on the grating was precisely confirmed.

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