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SURFACE PLASMON ENHANCED EVANESCENT WAVE LASER LINAC

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The grating laser linac concept of Palmer will be modified to incorporate a surface plasmon excitation in the visible part of the optical spectrum. Both grating and prism coupling of light to the surface plasmon will be discussed. It will be shown that phase matching between a relativistic particle and the surface plasmon can be achieved. Finally calculations will be presented showing that accelerations up to 14 GeV/m for a grating and up to 7 GeV/m for a prism could be obtained for incident power densities less than a nominal damage threshold.

KEY WORDS: Laser-beam accelerators, Surface plasmons

1 INTRODUCTION

There is an ongoing interest in increasing the exit energy of particles from linacs. One possibility of achieving this is by Palmer[1] who showed that light incident upon a grating at skew angles could achieve very high accelerations (GeV/m). The relativistic particles travel just above the grating and are accelerated by coupling to evanescent waves.

One effect that can occur for light incident upon a metal grating is the excitation of a surface plasmon.[2] Surface plasmon excitation in the visible part of the spectrum will be explored in this paper. It will be shown that surface plasmon excitation in the visible part of the spectrum can be used to accelerate relativistic particles. Thus, the paper will be an extension of Palmer's proposal.

First, this paper presents an overview of what a surface plasmon is, and examines what can be gained by its excitation. The different methods of how a surface plasmon may be excited will be presented. Then it will be shown that a surface plasmon can accelerate a relativistic particle. Two configurations will be described for exciting surface plasmons and accelerating particles. A brief section will calculate values for acceleration for the two surface plasmon coupling mechanisms. Next comes a section that deals with some of the technological problems in using surface plasmons for accelerating particles, followed by a conclusion section.

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2 SURFACE PLASMONS

A surface plasmon (SP) is a quantized collective oscillation of the electrons (the plasma) in a metal.[3] Couplings between SPs and photons are called polaritons. The result is a wave traveling along a metal surface. There are longitudinal and transverse electric field components for this wave. Longitudinal electric fields are needed to accelerate relativistic particles. SP electric fields are evanescent and decay away from the surface exponentially. Experimentally, the propagation distance of a polariton along the surface has been found to be about 9 μm in the visible.[4]

Electron motion can be described as an elliptical orbit in a metal ion background even if the SP is not excited. The longitudinal component of the electric field determines the electron motion parallel to the surface, while the transverse component determines the electron motion perpendicular to the surface. Thus at any given point in the metal there will be times when the local charge is positive or negative. The SP excitation distinguishes itself by an increased electric field amplitude, which will be explained later.

The interface between the metal and its surroundings is important in determining if a SP is excited, because SP excitation only occurs if the metal surface is in contact with an insulator. In practice this insulator has usually been air or vacuum. The dispersion relation for the SP is Eq. (1). (The semi-infinite medium dispersion relation will be used instead of the thin-film version.[5] A possibly more exact derivation of SP behavior is Ref. 6.) In general the metal dielectric constant is complex, $\varepsilon_1 = \varepsilon_1' + i\varepsilon_1''$, with the real part negative and the imaginary part positive. For Eq. (1), a simplification will be made in that ε_1'' will be ignored. The insulator dielectric constant, ε_2, is presumed to be real and positive. Dielectric constants vary with frequency. For both materials the dielectric constant is presumed to be independent of wavevector. The asymptotic limit for the SP excitation is when $-\varepsilon_1' = \varepsilon_2$. Energy of the incident light and SP is conserved.

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} \quad . \tag{1}$$

A SP cannot be excited directly by light. The dispersion relations for light, Eq. (2), and the SP, Eq. (1), do not allow direct excitation by light because momentum is not conserved. Since the square root term is larger than unity for a metal, k_{sp} is always greater than k_0.

$$k_0 = \frac{\omega}{c} \quad . \tag{2}$$

There are two ways of increasing the momentum of the incident light. The simplest and most common method is to have the light pass through an optically dense material. This increases the momentum of the light by n_3/n_2, where n_3 is the index of refraction of the dense medium and $n_2(=\sqrt{\varepsilon_2})$ is the index of refraction of the surrounding medium. By increasing the light momentum, equality between the momentum of light and SP can be achieved. Then SP excitation by light is possible.

The surface plasmon wavevector will be along the surface and in the plane of incidence. One has to ensure that the incident light wavevector also has a component along the direction of the surface plasmon. Thus the component of the incident light wavevector along the SP direction is given by Eq. (3). It is this quantity that must equal the surface plasmon momentum, k_{sp}. P-polarized light is required for optical excitation of the SP.

$$k_{pr} = k_0 \frac{n_3}{n_2} \sin\theta \quad . \tag{3}$$

A prism is usually used as the dense optical medium. Then either scans in wavevector (angle of incidence) with fixed photon energy or in photon energy with fixed wavevector are undertaken. The amount of reflection is measured. At the appropriate angle of incidence or photon energy the measured reflection curves will show a pronounced dip. This dip occurs when energy is "lost" to the excitation of the SP.

Only angles of incidence greater than the total internal reflection (TIR) angle for the prism-surrounding medium interface can be used for coupling to the SP. Past the TIR critical angle the electric field from the prism is evanescent, and this evanescent field can couple to the evanescent field of the SP, allowing energy transfer.

The other way to couple is to use a grating or its cruder form: surface roughness. Light momentum is increased by the grating constant, $G(= 2\pi/\text{grating spacing})$, times an integer, m, representing the mode number, see Eq. (4). Again, one can make angle of incidence or photon energy scans and see a dip in the reflection when SP coupling occurs.

$$k_{gr} = k_0 \sin\theta \pm mG \quad . \tag{4}$$

For either case, care is needed to choose the proper thickness for the metal film. For prism coupling, a thickness of about 500 Å of silver is needed for maximum SP excitation in the visible. In grating coupling, the height of the grating is the important parameter.[7,8] Silver is used preferentially over gold or copper since its imaginary dielectric constant term is small.[9] This leads to SP reflection minima that are narrow and deep in angle or photon energy.

What one gains by coupling to the SP is a resonant electric field at the metal-insulator interface.[3] SP excitation causes energy absorption to occur in a very thin surface layer: a few Å, compared to the metal penetration depth of tens of Å. This causes the amplitude of the electron motion in the layer to increase, thereby increasing the electric field amplitude at the surface. Hence, the SP-induced electric field is enhanced compared to the field without the SP excitation.

The SP-induced electric field has a skin depth dependent upon photon energy, as shown in Fig. 1. The enhanced electric field amplitude is one to two orders of magnitude larger than without the SP excitation,[10] see Fig. 2. These one to two orders of magnitude allow one to increase the acceleration for constant input power density and/or decrease the input power density for constant acceleration.

The enhancement (gain) is given by Eq. (5) for a prism[3] and Eq. (6) for a grating.[3,11] The metal dielectric constant, ε_1, has both a real and an imaginary component. The prism dielectric constant is ε_3. For Eq. (6), θ can be found by inverting Eq. (4), and R is the amount of measured (or presumed) reflection.

$$\text{Gain}_{pr} = \frac{1}{\varepsilon_3} \frac{2|\varepsilon_1'|^2}{\varepsilon_1''} \frac{\sqrt{|\varepsilon_1'|(\varepsilon_3 - 1) - \varepsilon_3}}{1 + |\varepsilon_1'|} \quad . \tag{5}$$

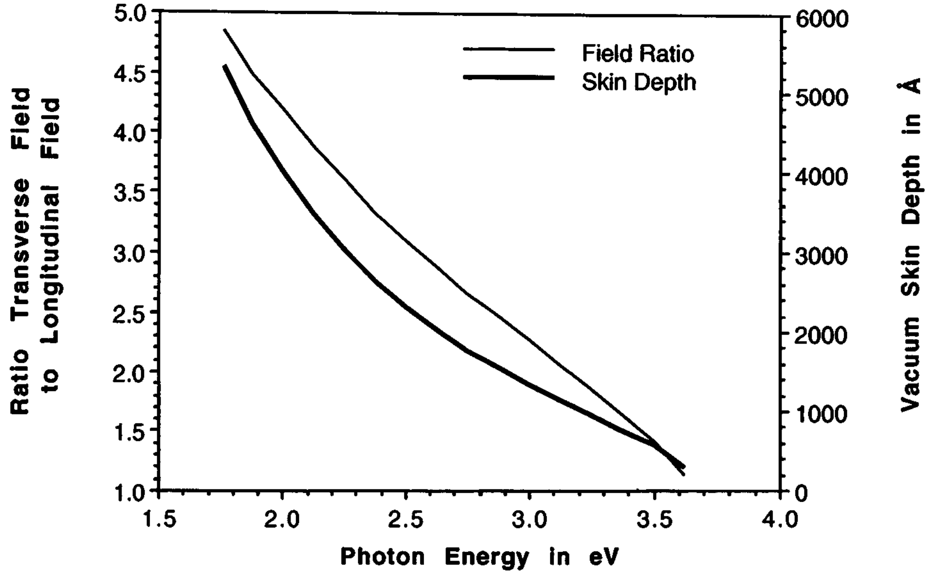

FIGURE 1: The vacuum skin depth and field ratio (transverse to longitudinal) variation with incident photon energy.

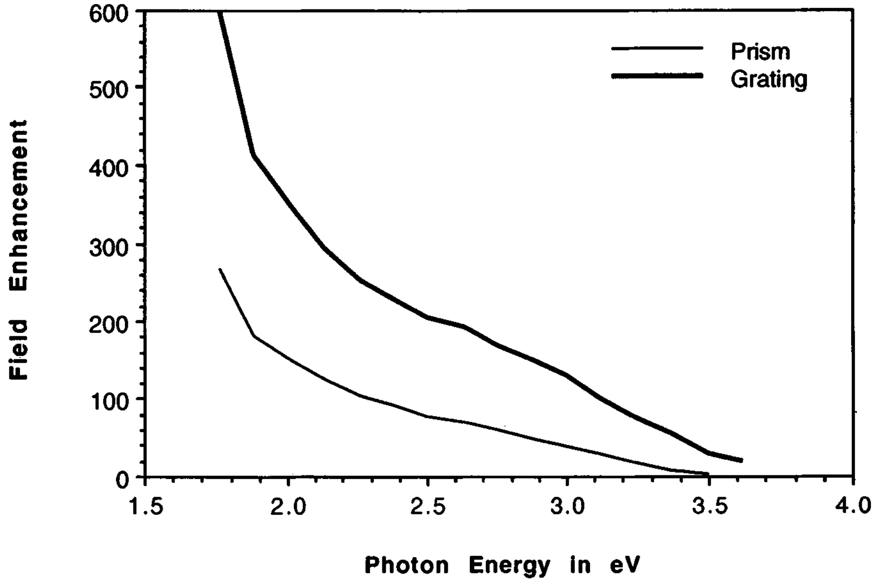

FIGURE 2: Field enhancement for both the prism and grating SP coupling schemes versus photon energy. Both enhancements are with respect to the vacuum incident electric field. For the grating, the incident angle is 25° and $R = 0.0$.

$$\text{Gain}_{\text{gr}} = \frac{2|\varepsilon_1'|^2}{\varepsilon_1''} \frac{\cos\ \theta(1-R)}{\sqrt{|\varepsilon_1'|-1}} \quad . \tag{6}$$

However, the electric field is not purely longitudinal;[3] it retains a transverse component. The ratio between the transverse and longitudinal electric field components depends upon the photon energy and is shown in Fig. 1. Though calculated for a prism it is presumed to be approximately the same for a grating.

3 SP TO RELATIVISTIC PARTICLE COUPLING

One has to match the phase velocity of the particles to the accelerating field. An equation for phase velocity matching is Eq. (7).[1] The ratio between the particle speed and the speed of light is β. The dispersion relation for the SP is k_{sp}. The vacuum wavevector of the light being used to excite the SP is k_0.

$$k_{\text{sp}}\,\beta = k_0 \quad . \tag{7}$$

The question is whether k_{sp} can be manipulated such that the equation holds. For $\beta = 0.999$ we see that k_{sp} must be $(1.001)k_0$. This implies from Eq. (1) that ε_1' must be -500, which is not possible for silver in the visible. As β approaches unity, even more negative values of ε_1' are required. Thus light incident along the particle path will not work for silver in the visible.

By having the SP direction at a skew angle to the particle path, k_{sp} is changed by a cosine term, Eq. (8). The skew angle (see Figs. 3 and 4) is the angle between the plane of incidence and the particle path. Now values of ε_1 appropriate for silver may be used and a skew angle can be found for proper matching. It turns out that the skew angles are quite realistic, depend upon photon energy, and have limiting values as β approaches unity; see Table 1. (2.13 and 2.26 eV photon energies are approximately the red and green helium-neon lines, respectively.) Equation (9) is the basic equation for coupling and is independent of how light is coupled to the SP.

$$k_{\text{sp}}\ \cos\ \phi\beta = k_0 \tag{8}$$

$$\beta = \frac{1}{\cos\ \phi}\sqrt{\frac{\varepsilon_1+\varepsilon_2}{\varepsilon_1\varepsilon_2}} \tag{9}$$

4 PRISM AND GRATING CONFIGURATIONS FOR ACCELERATION

Figure 3 shows schematically what a SP excitation in the prism system might look like. The dashed line is the particle path just outside the silver surface. The skew angle, ϕ, is between the particle path and the SP direction. The silver film on the bottom prism face is not shown. The dielectric constants for the prism and vacuum are represented by ε_3 and ε_2, respectively. The surface normal is with respect to the surface along which the

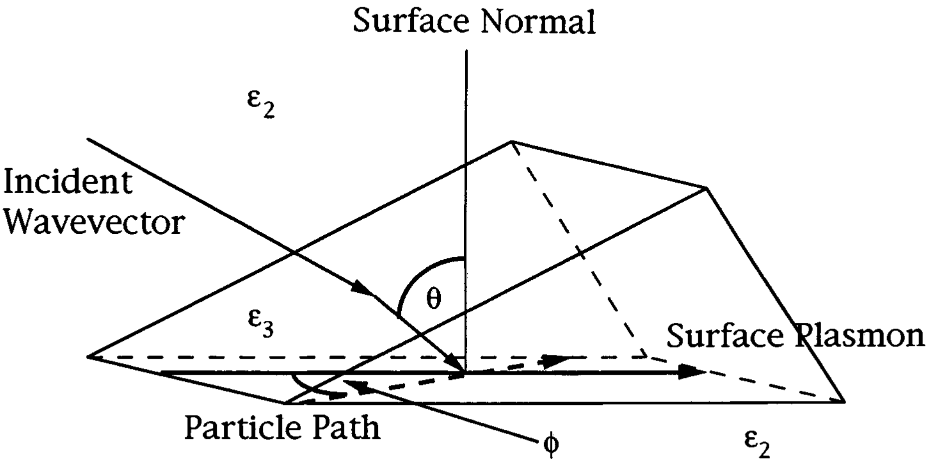

FIGURE 3: An overview of how a prism excitation of the SP would look for relativistic particle acceleration. The silver is not shown; it would be on the bottom face of the prism. For details see text.

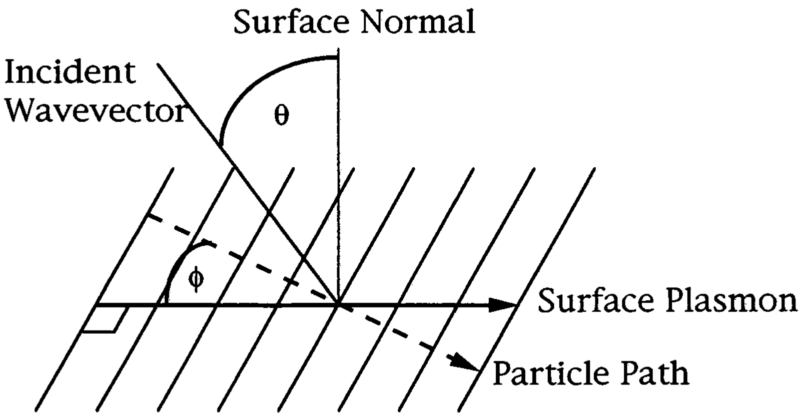

FIGURE 4: Grating coupling to the SP and relativistic particle acceleration. The grating would be of silver. Details are in the text.

TABLE 1: Skew Angle ϕ for β and Photon Energy Combinations

β	Photon Energy				
	1.76 eV	2.13 eV	2.26 eV	3.00 eV	3.5 eV
.99	8.77	12.69	14.07	24.87	44.37
.999	11.65	14.81	15.99	25.97	44.89
.9999	11.90	15.00	16.17	26.07	44.94
.99999	11.93	15.02	16.19	26.08	44.95
1.0	11.93	15.02	16.19	26.08	44.95

SP propagates. The angle of incidence, θ, is between the surface normal and the incident wavevector.

For the grating setup, the particles again travel just outside the surface, as shown in Fig. 4. The SP direction is perpendicular to the direction of the grating lines. The light is incident in a plane of incidence parallel to the SP direction. The skew angle between the particle path and the SP direction is ϕ. The angle of incidence is θ.

5 SAMPLE ACCELERATION CALCULATIONS

Acceleration, $< a >$, can be defined as by Palmer,[1] see Eq. (10). The incoming amplitude is A_0. Gain is the enhancement due to the SP excitation. Some of the field is unavailable for acceleration since not all the field is along the direction of particle propagation, cos ϕ. One also has to take into account that the field is not purely longitudinal by using a ratio (Fig. 1). Since the field is evanescent one takes into consideration the field strength away from the surface with an exponential term. K is the decay constant, while z is the distance away from the surface.

$$< a >= \frac{A_0}{2}\left[(\text{Gain})\ \cos\phi/\ (\text{Ratio}\ +1)\right]\ \exp\left(-Kz\right) \quad . \tag{10}$$

To find a value for the electric field amplitude without a SP resonance, one uses a relation between the irradiance and the electric field amplitude, Eq. (11). P is the power density in W/cm^2, ε_0 is the vacuum electric field permittivity and c is the speed of light in vacuum.

$$A_0 = \sqrt{\frac{2P}{c\varepsilon_0}} \cong 27.5\sqrt{P} \quad . \tag{11}$$

Using 10^{11} W/cm^2 as does Palmer,[1] one obtains with SP excitation, a curve for acceleration versus photon energy like that in Fig. 5 at a distance one skin depth ($Kz = 1$) from the surface. It can be seen that in the near infrared one has more than three times as much acceleration for prism coupling (7 GeV/m) and almost seven times as much acceleration for grating coupling (14 GeV/m) as in the simple grating case of Palmer (2 GeV/m). In the Palmer limit of a single-use film, the input power is 10^{13} W/cm^2. For this case, the accelerations in the near infrared are approximately 140 GeV/m for the grating and 70 GeV/m for the prism compared to 20 GeV/m. These values are spectacular and *very* speculative.

6 TECHNOLOGICAL PROBLEMS

Many problems come to mind. Survivability is foremost of these problems.[1] A metal film is destroyed when the temperature of the film is raised to the metal's boiling point by a laser pulse.[12] Silver was used for convenience in this paper since so much is known about its SP. Other metals with higher boiling temperatures could probably be used. The power limits used are adequate for a first approximation, though the boiling point of copper (2500° C) is higher than that of silver (2200° C). Another possible way around

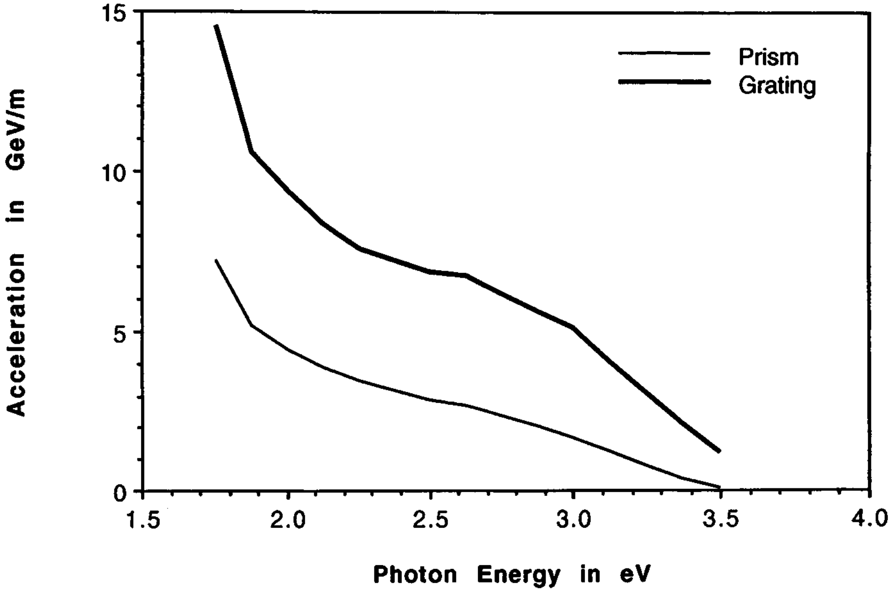

FIGURE 5: Final values for average acceleration for the prism and grating cases versus photon energy. The input irradiance is as shown in Palmer; thus these accelerations are comparable to those in Palmer. There is a factor 3.5 (prism) and factor 7 (grating) increase in acceleration for SP excitation, as compared to the case of no SP excitation.

this problem would be to use very short laser pulses (picoseconds). These pulses are too short for the lattice to respond but are still slow compared to the electron reaction times.[13]

There is the possibility of free electrons from multiphoton effects like second-harmonic photon generation,[14] leading to second-order photoemission[15] or higher-order photoemission.[16] These effects all depend upon the input power density. As the power density goes up, these problems become more severe. It might be possible to put a cap layer on the metal film to inhibit the electrons from escaping into the beam line. This cap layer would have to be several electron escape lengths thick, but still thin enough to leave an enhanced field in the beam line. Care would have to be used so that the cap layer had a lower index of refraction than the prism. Another way to minimize photoemission is to use photons whose energy is much less than the metal work function.

Another problem is the exponential decay of the electric field from the surface.[17] The amplitude quickly decays, reducing the amount of acceleration that can take place. This requires that the particles be brought very close in over the metal surface to achieve acceleration.

Film quality needs to be quite high. It is easy to produce thin polycrystalline (111) silver films on amorphous substrates like glass. With some form of molecular beam epitaxy it might be possible to grow very-large-area but thin single-crystal films. Silver, upon exposure to air, forms a sulfur layer with time, which decreases the depth of the SP.[18,19] Thus, once a silver film was made, it would need to be in a continuous vacuum or in dry nitrogen.[20]

Angle of incidence and skew angle control are important. With modern tools — piezodrivers and position-sensitive detectors — it is possible to regularly control and measure shifts of 1 Å or less.

7 CONCLUSION

The possibility of accelerating relativistic particles utilizing a surface plasmon resonance at a metal-insulator interface has been described. Phase velocity matching between the surface plasmon and the relativistic particle may be achieved by having the particle path at a skew angle to the plane of incidence for the surface plasmon excitation. The surface plasmon excitation causes a field enhancement at the surface. For the visible part of the spectrum, maximum acceleration occurs near the infrared. Possible accelerations of 7 GeV/m and 14 GeV/m for the prism and grating, respectively, were calculated for incident power densities nominally below a damage threshold.

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