SLAC – PUB – 4161
December 1986
(A)

OPEN ACCELERATING STRUCTURES*

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1. INTRODUCTION

Oscillating fields in tree space, far from all sources (i.e., at distances r very much larger than the wavelength λ of the radiation), consist of a sum of all possible traveling electromagnetic waves. Provided the particles to be accelerated are traveling less than the velocity of light, acceleration[2] can occur. Once the velocity approaches that of light, only waves traveling in the same direction as the particles remain in phase with the particles. Unfortunately, since free radiation is transversely polarized, no continuous acceleration is possible. Despite claims,[3] no juggling with holograms, phase plates or foci can change this. In the presence of a magnetic field, the particle's direction can be perturbed in such a way as to allow continuous acceleration,[4] but this too decreases as the particle's momentum increases and significant perturbations become impractical. In[5] or near[6] a dielectric, the inverse Ĉerenkov effect will accelerate, but the field that can be used is limited, because the dielectric cannot be allowed to break down. At high fields any dielectric becomes a plasma and the situation becomes very complicated. Acceleration within such a plasma is certainly possible[7] but the practicality of such acceleration remains to be determined.

Acceleration is, of course, possible in vacuum near to an electromagnetic source or structure (where r is not large compared to λ). Electrostatic acceleration satisfies this requirement as does any conventional linac structure. And it is easy to show that a linac structure in which λ is small compared to the iris radius r has an accelerating field that falls as λ/r compared with the fields of the walls. It is also easy to show that such linac structures must be either periodic or contain a dielectric. Fields in any smooth structure (it is a waveguide) have wave velocities greater than that of light and cannot couple continuously to a relativistic particle. The periodicity or dielectric serves to slow the waves to that of the particles: they match the mode of the initial fields to the particle acceleration. Linac cavities also perform a second function: that of providing a cavity in which the fields are contained where they are required, without unwanted loss. In conventional structures this is done by using a "closed" structure. They are cavities within a continuous conducting wall. In the absence

* Work supported in part by the Department of Energy, contract DE-AC03-76SF00515 (SLAC) and by DE-AC02-76C0016 (BNL).

Invited talk presented at the 1986 Symposium on Advanced Accelerator Concepts, Madison, Wisconsin, August 21–27, 1986 of any losses they would contain accelerating modes indefinitely. Openings of some kind are needed only to make up for resistive losses.

An "Open" Accelerating Structure must first perform the mode matching function of any accelerating structure, i.e., it must couple an incoming free field to an accelerating mode (later we will see that open structures can also perform the second function of containing the accelerating fields). The simplest open periodic structure that can be considered is a grating.

Two papers have attempted[8] to employ this inverse Purcell effect[9] by illuminating a grating from directly above with plane parallel light and passing the particles over the surface of the grating at right angles to the lines (Fig. 1a). Unfortunately, it has been shown by Lawson[6] that these geometries fail to accelerate relativistic particles.

I will restate Lawson's theorem but show that it applies only to the simple two-dimensional situation.

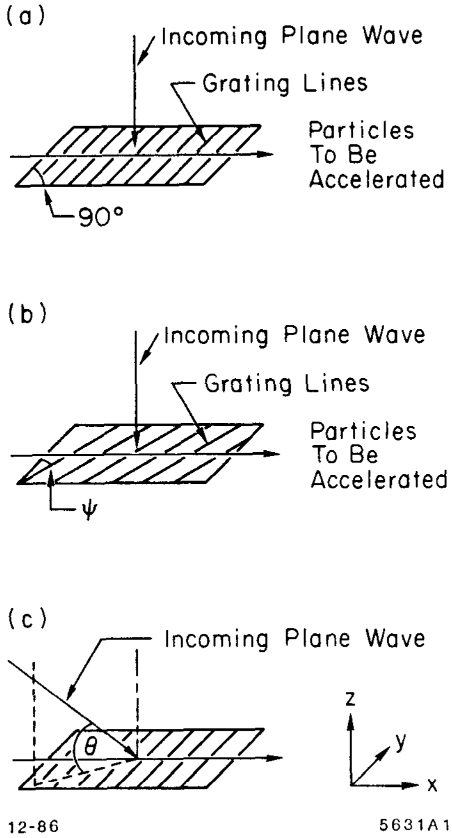

Fig. 1. Geometries of grating accelerators: a) as proposed by Takeda and Matsui; b) with skew grating to allow acceleration of relativistic particles; c) with skew initial wave as alternative to b).

2. LAWSON'S THEOREM[6]

We are considering the acceleration in fields above a linear grating when that grating is exposed to a propagating or standing free wave. In the two papers[8] referred to above, this incoming radiation consisted of plane waves falling onto the grating with the rays perpendicular to the grating lines. The acceleration was of particles traveling across the surface, also perpendicular to the grating lines. Such geometries impose the symmetry condition

$$\frac{dE}{dy} = 0 \quad , \tag{1}$$

where y is the coordinate along the grating lines and at right angles to the particles. Let z be the coordinate perpendicular to the grating and x be along the particles' direction of motion. Let S be the grating spacing.

Given condition (1), the fields above a surface in the direction of motion x of the particle can always be given[10] as a sum of fields of the type

$$E_x = A_n e^{j(p_n z + K_n x - wt)}$$

and if $E_y = 0$, then

$$E_z = \frac{A_n K_n}{p_n} e^{j(p_n z + K_n x - wt)} \quad , \tag{2}$$

where

$$p_n = \pm\sqrt{k_0^2 - K_n^2}$$
$$k_0 = 2\pi/\lambda \quad .$$

The A_n are a set of complex constants describing the amplitude and phase of the different modes n.

When $K_n < k_0$, then p_n is real and the mode is a free propagating wave either approaching (p_n negative) or leaving (p_n positive) the surface. These waves are at an angle 0 with respect to the normal given by sin $0 = K_n/k_0$. When $K_n > k_0$ and p_n is positive and complex, the mode is a surface or evanescent wave that falls off exponentially from the surface. Modes with the negative sign would rise exponentially from the surface and cannot be present.

The requirement that the field remain in phase with a particle of velocity βc is

$$K_n \beta = k_0 \quad .$$

Thus,

$$p_n = \sqrt{1 - 1/\beta^2} \quad . \tag{3}$$

As the momentum of the particles increases, β approaches 1 and from Eq. (3) we see that p_n approaches zero. From Eq. (2), we then see that E_x/E_z for that mode also approaches zero and there can be no net acceleration.

The reason for this is that the only wave consistent with the symmetry, condition (1) that stays in phase with a particle traveling at the velocity of light is a simple propagating plane wave traveling in the direction of the particle. Such a wave is always transversely polarized and thus cannot accelerate in its direction of propagation. In order to overcome this restriction, we must break the symmetry condition (1) and consider waves traveling at an angle to the beam direction. If, for instance, we simply rotate the grating by an angle ψ with respect to the beam (see Fig. 1b), then the condition for synchronism becomes

$$\begin{aligned} K_n \beta \cos\psi &= k_0 \\ p_n &= \sqrt{1 - 1/(\beta \cos\psi)^2} \quad ; \end{aligned} \tag{4}$$

now p_n and E_x no longer approach zero as β approaches unity. We thus see that Lawson's theorem, while showing that the proposed geometries do not work, does not rule out all acceleration in the fields above a grating. An alternative to a skew grating is to employ a skew initial wave (Fig. 1c). In this case, although the grating lines are perpendicular to the particle beam, the induced surface waves can still be at an angle to the beam and Eq. (4) still applies.

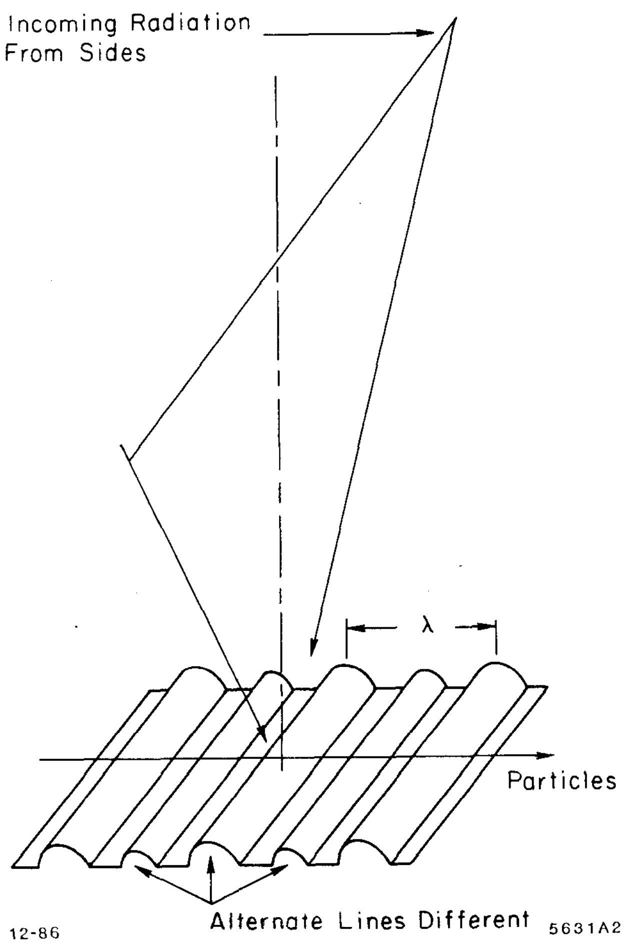

Fig. 2. Geometry of grating and incoming radiation showing perturbed grating lines to couple the radiation to the accelerating mode.

3. THE EXTENDED GRATING

It is convenient to consider the case where the incoming wave direction lies in a plane perpendicular to the beam direction, and in which a second incoming wave is introduced to symmetrize the problem about the vertical plane including the beam (see Fig. 2).

The fields are now given by

$$
\begin{aligned}
E_x &= \cos wt \cos Ky \left\{ B_0 \sin pz + \sum_{n=1}^{\infty} q/n \; B_n e^{-q_n z} \cos nk_0 X \right\} \\
E_y &= 0 \\
E_z &= - \cos wt \cos Ky \left\{ \sum_{n=1}^{\infty} B_n (nk_o) e^{-q_n z} \sin nk_0 X \right\} \quad ,
\end{aligned}
\tag{5}
$$

where

$$
\begin{aligned}
K &= \cos \theta, \theta \text{ as defined by Fig. 1} \\
k_0 &= 2\pi/\lambda \\
q_n &= \sqrt{K^2 + nk_0^2 - 1} \quad .
\end{aligned}
$$

B and B_n are now real numbers. All waves vary in the same way with both time and y position. Clearly maximum acceleration is obtained at $y = 0$ and at values of y spaced at intervervals of $2\pi/K$. The first term inside the curly bracket is that due to the incoming and outgoing waves. It is only in the x direction, varies sinusoidally with distance above the grating, and is constant along the direction of acceleration. The second term in the brackets includes all the surface waves that fall off exponentially with height above the grating and vary periodically with position in x. The average acceleration of a particle traveling in the x direction at height h above the surface is zero for all modes except 1, and since $q_1 = K$ and the average particle acceleration is

$$
\langle \mathcal{E}_a \rangle = \cos Ky \; \frac{K}{2}
$$

$$
B_1 \; e^{-Kz} \cos \theta
$$

where θ is a phase angle determined by the relative x position of the accelerated particle. As $\theta \to 90°$, $K \to 0$ and the acceleration $\mathcal{E}_a \to 0$ also, as predicted by Lawson's theorem.

This case has been studied in detail both my myself[11] and by Michael Pickup.[12] Solutions are found for various grating slopes and it is established that solutions can be found that not only couple incoming radiation to acceleration (see Fig. 3a), but also solutions that accelerate, and do not couple to any incoming or outgoing waves (see Fig. 3c). Such a solution is like a "cavity" in the sense that, in the absence of losses, it will contain the accelerating field indefinitely. It is what I define as an "open accelerating cavity." Intermediate solutions can be found (Fig. 3d) that partially couple to an incoming wave so as to allow the "cavity" to be filled and to

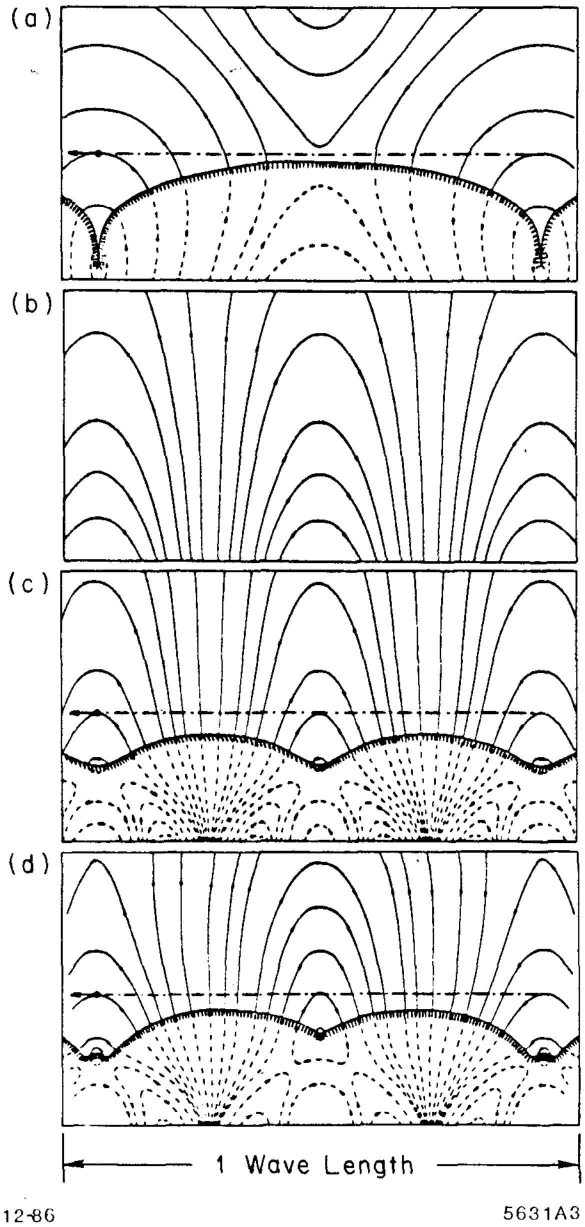

Fig. 3. The electric field patterns produced by different combinations of modes, together with the shape of the grating surfaces that will support these combinations: a) case with initial wave ($n = 0$) and the accelerating modes ($n = \pm 1$) only; b) field lines for the accelerating ($n = \pm 1$) modes alone; there is no grating surface that will support this mode alone; c) case with accelerating mode ($n = \pm 1$) and a small addition of the third mode ($n = \pm 3$); this solution does not couple to any initial wave; d) case with a small initial wave ($n = 0$), a strong accelerating mode ($n = \pm 1$) and a small addition of the third ($n = \pm 3$); this solution couples to the initial wave and provides good acceleration.

provide energy to make up for resistive losses. One notes that the simple mode converter has a λ periodicity, the cavity solution has a $1/2\ \lambda$ periodicity, and the partially coupled solution has an approximate $1/2\ \lambda$ periodicity with a λ perturbation.

4. RESTRICTED PERIODIC STRUCTURES

In the above sections we have found that accelerating fields above a grating can be made to fall off exponentially from that surface. Unfortunately, these fields will inevitably[13] spread over the full two-dimensional surface of the grating. (The hope expressed in Ref. 11 that the fields could be restricted to a narrow band along the grating by the use of cylindrical optics appears not to be possible.)

Various solutions to this problem have been discussed, and are illustrated in Fig. 4.

The iris-loaded linac (Fig. 4a) can serve as a standard for comparison. The SLAC structure, for instance, has a Q of 13,000, and this would scale as the inverse root of the wavelength (10.5 cm). The loss parameter k_1 is

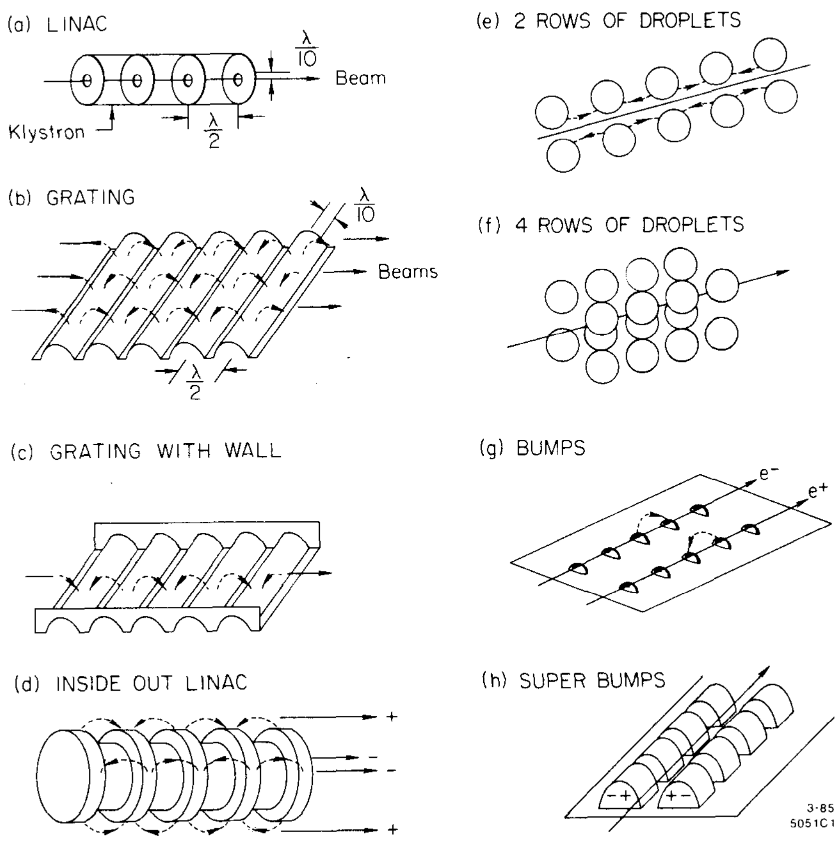

Fig. 4. New field accelerating structures.

19 volts/picocoulomb/meter, scaling as the inverse wavelength squared. The shunt impedance ($r = 4k_1 Q/\omega$) is 56 M ohms/m and this scales as the inverse root of lambda.

A. GRATING WITH SIDE WALLS (Fig. 4)

This structure has been studied by M. Pickup at Cornell.[12] The walls which, although theoretically of infinite height, need be only of the order of a wavelength high, can be placed at any multiple of half the transverse field periodicity. Pickup studied the case where they are one-half period apart. Leaving aside the question of how such walls could be constructed, Mike has shown that the Q, scaled to 10.5 cm, would be 16,000 (even higher than in the iris-loaded case); however, the loss parameter k, again scaled, is 1.7 volts/picocoulomb/meter (much lower). One must remember, however, that as the wavelength gets smaller the loss parameter rises as the square and a high initial value is not necessarily desirable.

B. INSIDE–OUT IRIS–LOADED CAVITY (Fig. 4d)

Kroll[14] has considered the fields that can be formed on the outside of a structure which is geometrically like a conventional linac. This case can also be though of as that of a grating in which the two sides have been curled under and joined together. As in the grating case, nonradiating modes exist and, also as in the grating case, these fields must be periodic transverse to the acceleration, i.e., periodic in the azimuthal angle, in this case. The number of periods around the azimuth may be described by the index m. For $m = 0$ there are no solutions, in analogy with the Lawson theorem for the grating case. He also showed that the $m = 1$ case (dipole) has a field that extends to infinity. For $m = 2$ (quadrupole) the fields do fall off but the total energy has a logarithmic divergence. Only for $m = 3$ and above are the fields truly local, with the structure behaving as a true "open cavity." Kroll also considered structures formed of more than one parallel inside-out cavity, each operating in the $m = 1$ mode. All these cases give insight into the droplet structures described below.

C. DOUBLE ROW OF DROPLETS (Fig. 4e)

An *rf* model consisting of two copper spheres places between two parallel metal plates demonstrated[7] a mode that would accelerate along the axis between two rows. The spacing between two spheres, both along the rows and between them, was $\lambda/2$, and their diameter was approximately $\lambda/3$. The measured fields were well-represented by the assumption that the sphere's act as oscillating dipole radiators with their polarization directed in towards the axis. The "measured" loss parameter k, scaled to a wavelength of 10.5 cm, was approximately 2 volts/pC/m, i.e., similar to that for the grating case. However, this case is essentially that of two $m = 1$ inside-out cavities, and the long-range fields must have the $m = 2$ character that, as was pointed out by Kroll, has a divergent energy and thus a zero k parameter. In the measurement, however, and in any practical case, a cut-off is in fact imposed either by the surroundings or by the pulse length. Thus despite the divergence this may be a useful case.

D. FOUR ROWS OF SPHERES (Fig. 4f)

With four rows of spheres the long-range fields are octupole ($m = 4$) and no divergence occurs. Such a mode was also observed with the *rf* model, but the k has not yet been measured.

E. ROWS OF BUMPS (Fig. 4g)

A second mode observed with two rows of spheres has a symmetry plane such that it would also be present over a double row of hemispheres on an infinite plane. This then represents a "grating" in which no side walls are required. Maximum acceleration in this case occurs along a line over the top of either row of bumps; in fact one row could accelerate electrons while the other accelerated positrons. The logarithmic divergence would still be present in this case, but could, if required, be removed by the use of three or more rows of bumps.

F. SUPER BUMPS (Fig. 4h)

Kroll has proposed a case derived from a double row of inside-out iris cavities. Each of the inside-out cavities is excited in a mode $m = 2$ with left-right symmetry and up-down antisymmetry. Half of this arrangement is then placed over a plane conductor to produce the structure illustrated. The long-range fields are $m = 3$ so there is no divergence, and there is even a neutral axis above the surface with quadrupole focusing fields about it.

Two versions of the super bumps have been modeled and tested. They are illustrated in Figs. 5a and 5b. The relative dimensions that established the required accelerating fields where:

Fig. 5a	$S = \lambda/2$	Fig. 5b	$S = \lambda/2$
	$h = .83\,\lambda$		$h = .23\,\lambda$
	$g = .2\,\lambda$		$g = .16\,\lambda$
	$d = .28\,\lambda$		$w = .16\,\lambda$
	$\ell = .46\,\lambda$		

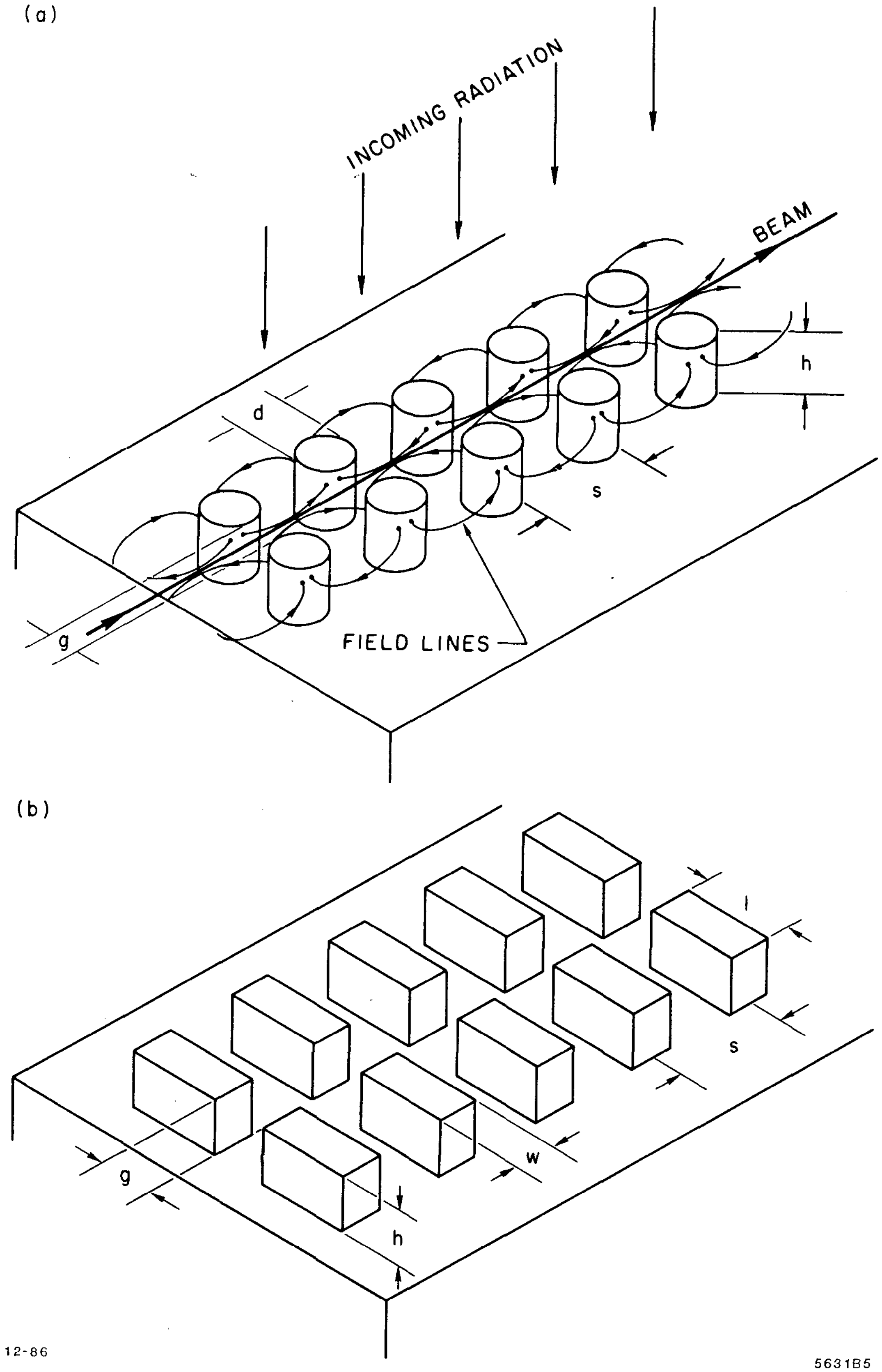

Fig. 5. Two alternative realizations of the collonade accelerating structure.

5. COUPLING TO INCOMING RADIATION

It is too early to say whether such open structures will have practical application. They have the advantage that they can be machined or etched from a solid block and can thus be made with high accuracy and small size. Fig. 6 shows such a structure etched in silicon on a scale appropriate for 10 micron wavelength radiation. A disadvantage is the intrinsic up-down asymmetry of the fields. Although no dipole fields are present on the accelerating axis, sextupole fields will always be present. Whether the quadrupole fields are an advantage (for focusing) or a disadvantage, is not clear.

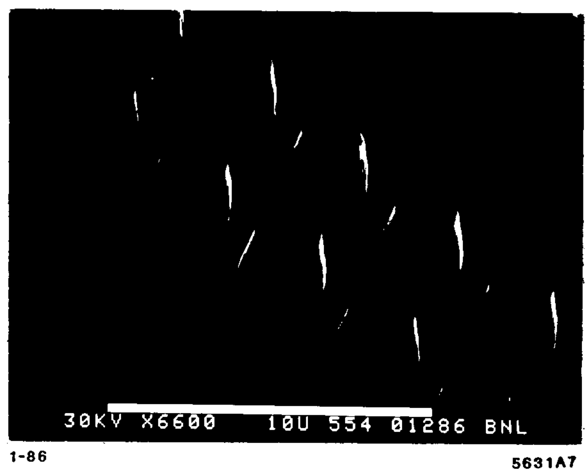

Fig. 6. Electron microscope photograph of our etched collonade structure for 10 μm radiation.

In all the above cases we have been discussing π modes in which the fields in or over successive lines or droplets are advanced by the phase π. Such modes do not radiate energy out, but also cannot be excited by any incoming radiation. In order to couple to external fields, some perturbation is needed to the symmetry. In the grating case, alternate lines can be made slightly higher. In the case of the two rows of droplets, alternate droplets can be displaced out of the plane or other perturbed. In this case the angular distribution of radiation that would be emitted, and thus the distribution of incoming radiation that would be perfectly absorbed, is shown in Fig. 7.

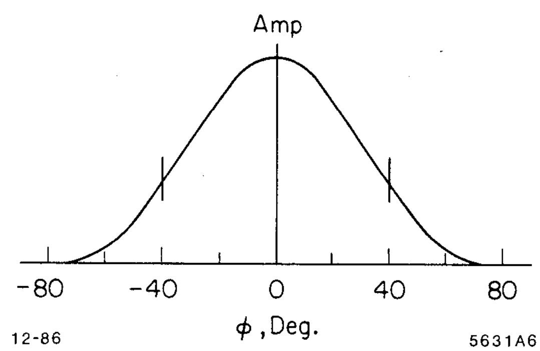

Fig. 7. Angular distribution of radiation to or from droplet structure.

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SLAC – PUB – 4161
July 1987
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This manuscript was submitted to two different Conferences:

Invited talk presented at the 1986 Symposium on Advanced Accelerator Concepts, Madison, Wisconsin, August 21–27, 1986

and also

Presented at the 1987 Workshop on New Developments in Particle Acceleration Techniques, Orsay, France, June 29 – July 4, 1987

* Work supported in part by the Department of Energy, contracts DE–AC03–76SF00515 (SLAC) and DE–AC02–76C0016 (BNL).