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PRELIMINARY RESULTS ON OPEN ACCELERATING STRUCTURES*

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I. INTRODUCTION

Conventional accelerating structures consist of cavities or enclosed transmission lines with the particles to be accelerated passing along the axis of the enclosure. Electromagnetic modes can be excited within such structures with electric components in the direction of the particle motion. Their wave velocity is inevitably less than that of light unless the cavity is loaded with a dielectric or periodic structure. Conventionally some periodic structure is used.

In a plasma linac the conducting surfaces of the structure are replaced by plasma surfaces. The dimensions of the structure are drastically smaller (with wavelengths less than 100 microns) and the electric fields can be much higher (of the order of 10 GeV per meter or more). For this application, a closed cavity is probably not suitable. A grating surface has been suggested¹ in which the surface of the grating is turned into a thin layer of plasma. Such a structure may be described as a semi-open structure. The accelerating fields are restricted to within a few wavelengths of the grating surface, but inevitably spread in the two dimensions over that surface. (The hope expressed in Ref. 1 that the fields could be restricted to a narrow band along the grating by the use of cylindrical optics now appears to have been in vain.²)

In this paper we consider periodic structures consisting of rows of spherical conductors. In a plasma linac, these spherical conductors would be formed from liquid droplets on whose surfaces a plasma would be formed. For this paper, the field configurations have been investigated using copper spheres approximately 11 cm diameter and microwave radiation of approximately 30 cm wavelength. No suitable accelerating mode was found for relativistic particles using a single row of spheres, but with two parallel rows of spheres both accelerating and focusing modes were found.

In Section II we re-examine the accelerating modes over a grating surface, including a grating formed of parallel conducting rods. In Section III we discuss the coupling of these structures to incoming radiation.

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II. GRATING STRUCTURES

In Ref. 1 it was shown that a grating surface existed over which a standing wave pattern could be established, with the fields restricted to a limited region above the grating. The fields were periodic both with respect to the grating periodicity and along the direction of the grating lines. Such an electromagnetic field was shown to include an accelerating mode, accelerating particles perpendicular to the grating lines just above the surface, providing the particle trajectory was not at one of the nodes in the periodic field. In fact if a trajectory were chosen in the next periodic maximum and the phase is left the same, deceleration would occur. Perpendicular to the surface the fields fall off exponentially, these fields being evanescent waves. If a rectangular section of grating is surrounded by vertical conducting walls, see Fig. 1a, then this structure behaves as an accelerating cavity with standing waves within the walls and losses only due to resistive wall effects. Since no lid is required on this cavity, it is open in one dimension.

A natural extension of the grating cavity of Fig. 1a is shown in Fig. 1b. Here the grating is replaced by a series of cylindrical bars and the resulting cavity is open in both the upward and downward directions. When the electric field lines are examined, it is seen that the charge and current distributions in the rods approximate a series of dipole antennas with vertical polarization and phase alternating both along the rods and from one rod to the next. It is a natural further extension from Fig. 1b to speculate whether an array of spherical conductors with each one behaving as a dipole oscillator would also provide an accelerating non-radiating solution (see Fig. 1c).

An experiment to test this idea was set up using one copper sphere and four aluminum conducting surfaces (see Fig. 2a). A resonant (i.e. non-radiating) solution was found. The observed Q is relatively low because of an inadequate wall height H . It is clear that if this height were extended to infinity, the Q would be limited only by resistive losses.

Such an array of droplets could easily be produced by an array of liquid jets, but still suffers from the objection that the radiation will leak out transversely unless constrained by a conducting wall on either side of the particle trajectory. We therefore examined a structure consisting of a single row of droplets.

III. ROWS OF CONDUCTING SPHERES

We first examined a single row of spheres and searched for a non-radiating π mode. In such a mode, all the field directions reverse from one sphere to the next and thus all field lines must be perpendicular to a plane half way between any two spheres. We can thus investigate such modes by using the experimental arrangement shown in Fig. 2b, which has one sphere placed between two conducting surfaces. One can think of these surfaces as behaving like mirrors and thus producing an infinite number of multiple

images of the single sphere. First a search was made for axially symmetric modes by placing an exciting probe at A' and a pickup probe at A. No such symmetric modes were seen. An exciting probe was then placed off center at B' and pickup at B. Now non-radiating modes were observed for various spacings d , as shown in Fig. 3. The sphere diameter is plotted in units of the observed resonant wavelength and the spacing between the plates (d) is given in units of half the wavelength. This latter fraction corresponds to the velocity β of a particle passing along the row of spheres that would be in phase with the oscillating electric fields. The observed excited modes are illustrated in Fig. 4a. To first approximation the spheres act as transverse dipole oscillators and the fields provide good acceleration above and below these resonators. Unfortunately, as is seen from Fig. 3 the Q of the observed resonance states falls as the velocity of the in-phase particles approaches one. The mode is only suitable for accelerating particles when they are less than relativistic. The low Q was found to correspond not to resistive losses but to a large forward radiation from the structure. Indeed it can be seen that the radiation from all spheres is coherent in the forward and backward directions when $\beta = 1$. This situation is analogous to that obtained with a grating exposed to radiation from directly above. In that case we know from Lawson's theorem² that there is no acceleration and that the electrical excitation of each line of the grating is in phase to radiate in the forward and backward directions. We remember that the solution¹ to this problem was to bring the light not from directly above, but from either side. In this way a transverse periodicity is introduced on the grating surface such that along one line one may have acceleration, then along a nearby parallel line one has deceleration. Correspondingly the forward radiation from one of these lines is exactly out of phase with the neighboring one, and no net forward radiation occurs. The corresponding situation with spheres is of course to have a complete grid as discussed in Section II where we did find satisfactory resonant conditions at $\beta = 1$ without forward radiation. A possible simpler solution, however, would be to employ two rows of spheres with one row out of phase with respect to the other so that again the forward radiation is suppressed.

A double row of spheres was therefore investigated using the experimental arrangements of Fig. 2c and d. In both cases resonant excitation was observed for $\beta = 1$ for various different sphere spacings (S) (see Fig. 5). The modes excited in the two cases are illustrated in Figs. 4b and c.

In the first case (Fig. 4b and also Fig. 6a) we see that the spheres are acting to first approximation as dipoles oscillating in the plane of the double row, 180° out of phase, and we see that a very favorable condition occurs for acceleration along the axis between the rows.

In the second case, the spheres are acting as dipoles oscillating transverse to the plane, also 180° out of phase. In this case there are no accelerating fields along the axis but there are such fields above and below the poles of the individual rows of droplets

(Fig. 4c). An interesting feature of this mode is that the fields are all perpendicular to a plane passing through the centers of all spheres. The mode would thus exist over a conducting surface with two rows of hemispherical bumps on it as indicated in Fig. 6b. Such a surface could be generated by ion etching or other techniques and provides a solution to the grating problem of radiation leaking out sideways.

One final arrangement of spheres was also tried consisting of four rows of spheres arranged in a square about the axis. Again, a resonant non-radiating solution was found. This mode involved the four spheres acting as transverse dipole oscillators with all the dipoles facing in towards the axis.

III. COUPLING TO INCOMING RADIATION

The arrangements of spheres that we have described above have resonant non-radiating modes which would provide acceleration if excited. They are, however, like closed cavities in that we have provided no mechanism for introducing radiation into them. What is required is a perturbation on the structures such as to couple the near field modes, that are restricted to small distances from the structure, to outgoing or incoming waves. The addition of these perturbations may be regarded as equivalent to providing slots in a conventional cavity in order to couple a waveguide to it.

Almost any perturbation on the position or size of any of the structures described will cause it to radiate. If for instance, all the spheres in one row were slightly larger than the spheres in the parallel row, then the cancellation of the forward radiation would not be exact and the structure would couple to forward radiation.

Another interesting case is that in which alternate spheres are either slightly lifted or slightly depressed from the plane in which they initially lay. Such perturbations couple the modes to radiation propagating either upward or downward perpendicular to the plane containing the spheres. Calculations of azimuthal angular distributions of radiation from such structures are in progress.

REFERENCES

1. R.B. Palmer, "A Laser-Driven Grating Linac", Particle Accelerators, Vol. II, pp. 81-90 (1980).
2. J.D. Lawson, Rutherford Lab. report RL-75-043 (1975); IEEE Transactions on Nuclear Science, NS-26, 4217 (1979).

Fig. 1. Grating solutions: (a) original one-sided grating, (b) a two-sided rod grating, and (c) array of spheres grating.

Fig. 2. Experimental arrangements: (a) for array of droplets grating, (b) for single row of droplets, (c) for double row of droplets with acceleration on axis, and (d) for double row of droplets with antisymmetry.

Fig. 3. Results of single row experiment: the Q and droplet diameter D as a function of the synchronous velocity β .

Fig. 4. Fields of resonant solutions: (a) single row, (b) double row with acceleration on axis and (c) double row with acceleration on the side.

Fig. 5. Resonant conditions for double row. The sphere diameters are given as function of distance between the two rows for a) acceleration on axis, b) acceleration on side.

Fig. 6. Double row solutions: (a) case with acceleration on axis-opposed mode and (b) case with acceleration above rows-parallel mode. In this case a conducting plane is inserted without changing the solution.

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