LASER PLASMA LINAC*

R.B. Palmer, N. Baggett, J. Claus, R. Fernow, A. Ghosh, S. Giordano, V. Radeka, I. Stumer, P. Takacs, J. Warren

Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

The grating accelerator concept is reviewed. The use of a double row of conducting droplets instead of a conventional grating constrains the fields to a narrow band. The use of droplets also allows fields that will destroy the structure. RF modelling results are presented together with a simple theory of the fields. Coupling to incoming radiation is described. A possible laser specification is also given.

1. Introduction

The concept we describe is essentially that of a conventional linear accelerator (LINAC), but with a laser instead of a klystron as the RF power source. The most suitable laser would use CO_2 because of its high energy efficiency (10%) and relatively long wavelength (10 microns). Even 10 microns is very small compared to the wavelength used in conventional linacs (10 cm) and as a result the structure used to couple the radiation to the particles must be small, and of necessity much simpler, than that of a linac. If the available power of CO_2 lasers is employed it should be possible to attain accelerating gradients as high as 10 GeV/m (as high as in a plasma beat wave accelerator). In this case the structure surfaces will become layers of plasma. This will still be an accelerating structure since the plasma layer will be conducting, but it does mean that the entire structure will be destroyed after each pulse. A "disposable" grating is required.

Before describing this "disposable" grating, we will introduce the subject by a brief digression on the history of "grating" accelerators, since they were the historical source of the idea.

2. The Grating Accelerator

Any linac structure must convert incoming radiation into slow modes, since only a slow mode contains longitudinal electric fields and can couple energy to a relativistic particle. In order to do this the structure must, if not containing a dielectric, be periodic. The simplest such periodic structure is a grating. It had been demonstrated in 1953 that when particles travel over the surface of a grating, light is emitted (Smith Purcell, Ref. 1). It seemed reasonable, therefore, that in 1968 Takeda and Matsui should propose what they believed to be the inverse of this effect as an accelerator (Ref. 2). Unfortunately, however, Lawson in 1975 proved that the proposed geometry would not work for relativistic particles (Ref. 3). It was not until 1980 that Palmer (Ref. 4) showed that it was only for the particular geometry of Takeda and Matsui that Lawson's theorem applied and that for skew or otherwise more three dimensional geometries acceleration could indeed be obtained. It was shown further that the grating, if given one half lambda periodicity, could act as a true "cavity". That is, it had accelerating modes that were restricted to the surface and did not radiate energy away from that surface (Fig. 1a). These surface fields are composed of four slow "evanescent" waves crossing the grating surface diagonally (Fig. 1b). The resulting interference pattern provides fields periodic not only along the beam direction but also across it. Acceleration thus occurs within a sequence of channels across the grating. M. Tigner and M. Pickup have experimentally studied this structure using 3 cm radiofrequency fields (Ref. 5). In order to excite these surface fields with incoming radiation some modification to the half lambda periodicity is introduced (Fig. 2). The incoming radiation is then brought onto the grating as two interfering plane waves coming down from either side of the vertical.

Two difficulties remain with this grating accelerator. Firstly, as was pointed out by Tigner and Lawson (Ref. 6), the field must inevitably extend over the entire grating surface. Walls or some other agency are needed if the accelerating fields are to be confined to a narrow strip. The second problem is to invent a way of generating a

---

*Work performed under the auspices of the U.S. Department of Energy.

disposable grating. Both of these challenges seem to have been solved in the following proposal.

3. The Droplet Structure

The idea is to form a narrow "grating" out of two rows of conducting droplets that have been ejected from appropriate rows of ink-jet-printer like jets (Fig. 3). The droplets could be intrinsically conducting if formed of mercury or another liquid metal, but at high fields any surface will become coated with a conducting plasma and thus any liquid could be employed. The structure would obviously be disposable. Does it have the required properties?

We have made models of such a structure using two 10 cm spheres between square conducting planes that, acting as mirrors, reproduce the fields of an infinite double row of such spheres. With radiofrequency at a wavelength of about 30 cm we were able to study the fields in detail. A cavity-like accelerating solution was found in which the individual spheres act approximately as dipole oscillators, each with its direction of polarization facing in towards the axis. The fields from the two rows add along the axis to provide the required acceleration (Fig. 4a). Particles with Phase $\pi/2$ ahead or behind that needed for acceleration will experience an RF quadrupole field (Fig. 4b). Figure 5 shows the measured accelerating fields along the axis compared with their calculated values assuming that the spheres act as simple dipoles. Clearly this is a good assumption.

Coupling to incoming radiation, as in the grating case, requires some perturbation of the structure. In this case the most effective arrangement seems to be to displace alternate droplets above or below the plane containing their initial centers (Fig. 6). Assuming again that the spheres act as point dipoles we can calculate the azimuthal distribution of incoming radiation that would perfectly couple into the required mode. This (Fig. 7) turns out to be peaked towards the directions perpendicular to the plane, with a half width at half height of about 35 degrees.

With the above information we can now sketch a conceptual design of an accelerating section (Fig. 8). Windows above and below allow the entry of the laser light. Jet assemblies are on both sides to place the droplets in the required positions; micro position controllers are provided to align the droplets with the exact beam axis. Assuming that a volatile liquid, such as water, is used, large vacuum pumps would be provided to remove the vapour between pulses.

4. Jet Construction

Jets, for ink jet printer use, have been discussed in the literature for some time. Already in 1977 Bassous et al. (Ref. 7) had described the production of precision jets whose size was 13 microns and whose precision was such that the resulting droplets were ejected with an angular accuracy of 1 milliradian. Such an accuracy is adequate for our use. For 10μ radiation 3 micron diameter droplets are needed and the holes must then be about 1.5 microns instead of 13μ. Although we know of no liquid jets this size, holes for other purposes have been made as small as .4 microns (Ref. 8).

To pump the liquid out to form the single droplets, either piezo electric pumps or tiny heaters can be used. Either a single pump could be used for a line of jets, or, if needed, a separate pump provided for each jet allowing control of individual droplet positions.

5. Laser Requirements

In order to demonstrate high gradient acceleration with a droplet structure, one needs a single 10-100 millijoule pulse of diffraction limited 10 micron radiation with pulse length of a few picoseconds. The very short pulse is needed both to generate a surface plasma and accelerate particles before the plasma can grow to distort the original droplet geometry. A laser with such characteristics has been run at NRC in Canada (Ref. 9). It employs semiconductor switches to cut a few-picosecond micro-pulse from a conventional CO_2 laser output. The switch is operated by a dye laser amplified mode locked 600 μm laser pulse. The 10 μm micro pulse is amplified regeneratively in a 10 atmosphere CO_2 gain module to approximately 15 millijoules, sufficient for an experiment.

For an accelerator of interest to high energy physics, however, one would require similarly short pulses but at a high repetition rate (a few kilohertz) and with total power of a few kilojoules per pulse. Table I gives an example of parameters for a 5 TeV accelerator suitable for use as a collider (two such accelerators would be required, one facing the other). In this example it is rather arbitrarily assumed that 150 10 joule lasers would be used in preference to one 1500 joule unit.

TABLE I. "Typical" Laser Requirements

Final beam energy	5 TeV	
Accelerator length	500 meters	(× 2 for collider)
Accelerated particles per pulse	$4\ 10^8$	
Repetition rate	3 kilohertz	
Luminosity (when used as collider)	10^{33} cm^{-2} sec^{-1}	
Average beam power	1 M watt	(× 2 for collider)
Average laser power	5 M watts	(× 2 for collider)
Average wall plug power	50 M watts	(× 2 for collider)
Number of lasers	150	
Individual laser specifications		
Wavelength	~10 μm	
Power	10 joules	
Pulse length	5 pico seconds	
Watts	2 TW	
Repetition rate	3 kHz	
Efficiency	10%	

The conceptual design of lasers capable of meeting such a specification is the subject of an ongoing study by Math Sciences Northwest.

References

1. S.J. Smith and E.M. Purcell, "Visible Light from Localized Surface Charges Moving Across a Grating," Phys. Rev. 92, 1069 (1953).
2. Y. Takeda and I. Matsui, "Laser Linac with Grating," Nucl. Instrum. Methods 62, 306 (1968).
3. J.D. Lawson, Rutherford Lab. report RL-75-043 (1975); IEEE Transactions on Nuclear Science, NS-26, 4217 (1979); P.M. Woodard, Journal IEE 93, Part III A, 1554 (1947).
4. R.B. Palmer, "A Laser-Driven Grating Linac," Particle Accelerators II, 81 (1980).
5. M. Tigner and M. Pickup, private communication (1983).
6. M. Tigner and J.D. Lawson, private communication (1984).
7. E. Bassous, IEEE Trans. Electron Devices ED-25, 1178 (1978).
8. H. Bohler, U. Behringer, J. Keyser, P. Nehmiz, W. Zapka, W. Kulcke, "High Throughput Submicron Lithography with Electron Beam Proximity Printing," Solid State Technology Vol. 27, 210 (1984).
9. P.B. Corkum, "High Powered, Subpicosecond 10 μm Pulse Generation," Optics Letters 8, 514 (1983).

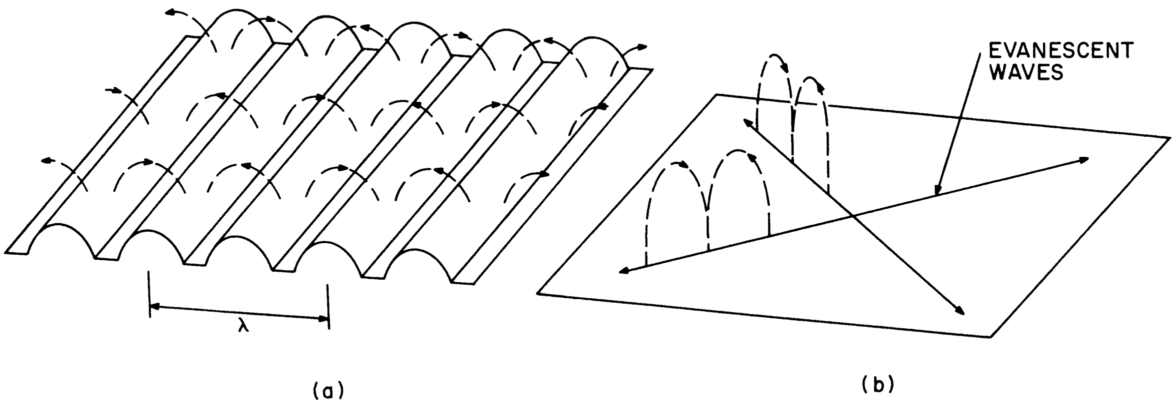

Fig. 1 (a) Fields over a resonant grating. (b) Components of these fields.

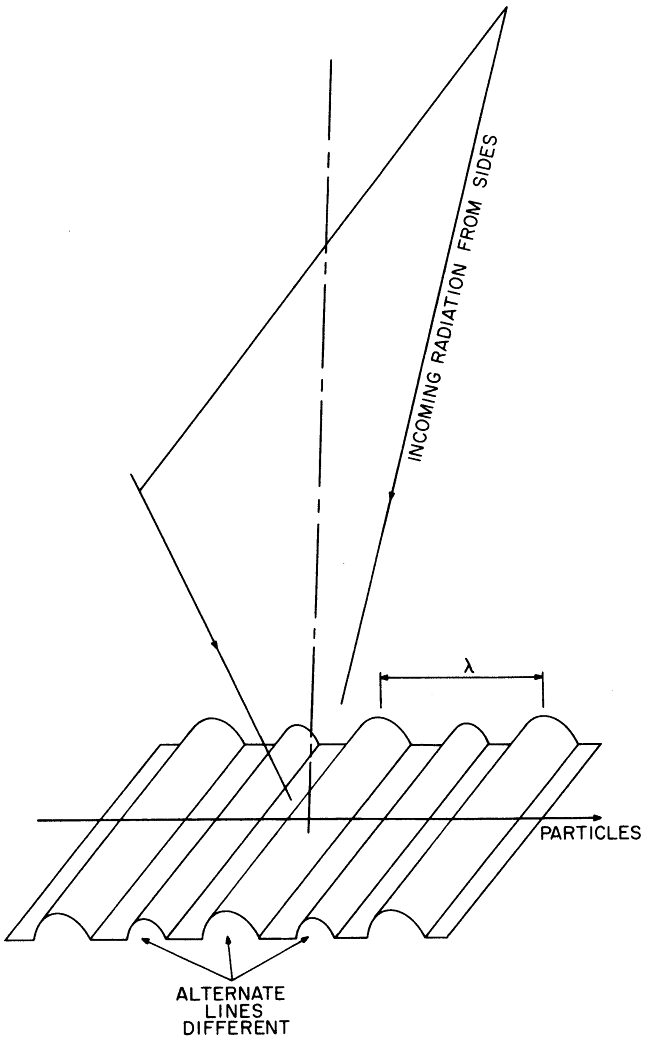

Fig. 2. Modified grating coupling to incoming radiation.

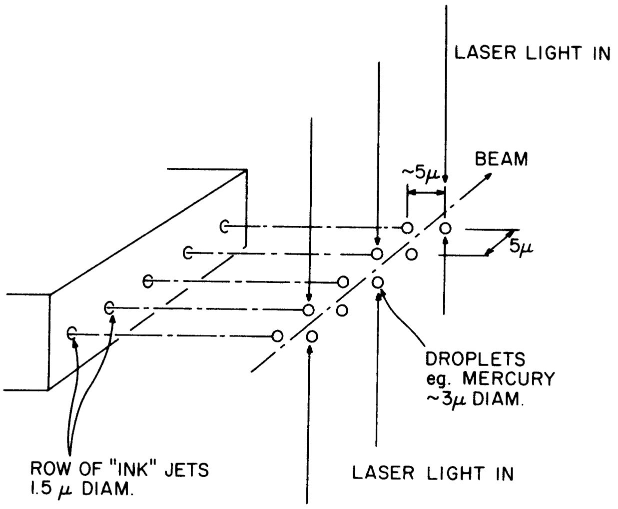

Fig. 3. The droplet accelerator concept.

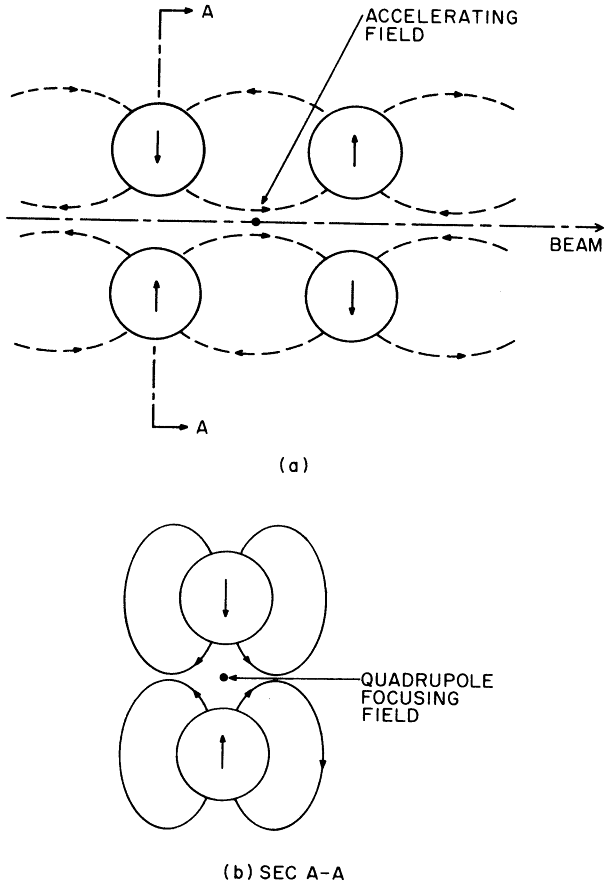

Fig. 4. Fields in resonant droplet structure; (a) viewed from above, (b) section across the beam.

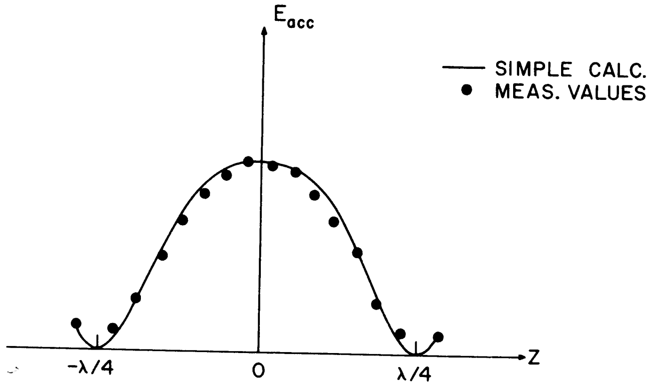

Fig. 5. Measured and calculated accelerating fields along the axis of a droplet structure.

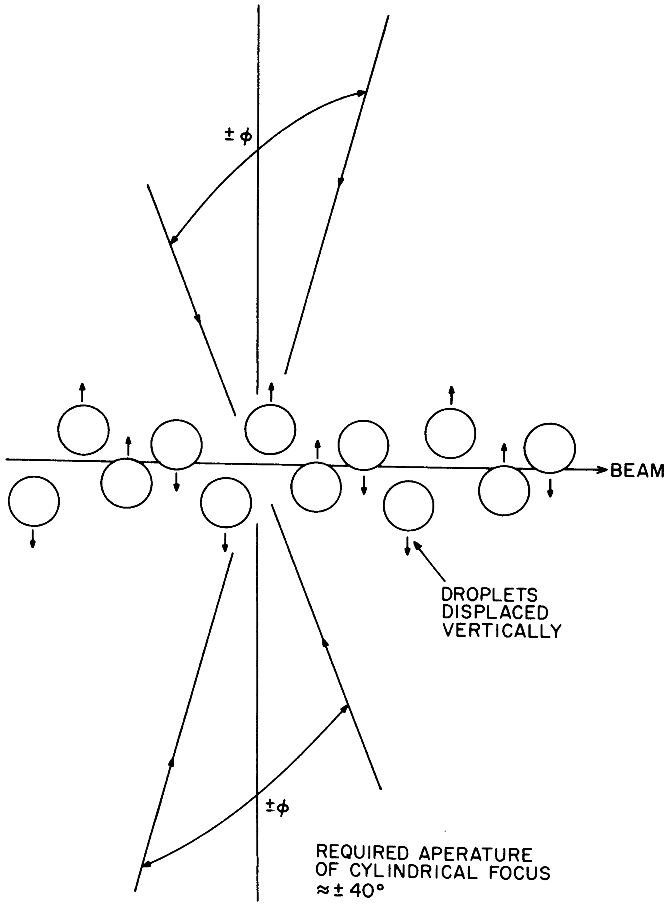

Fig. 6. Modified droplet structure to couple to incoming radiation.

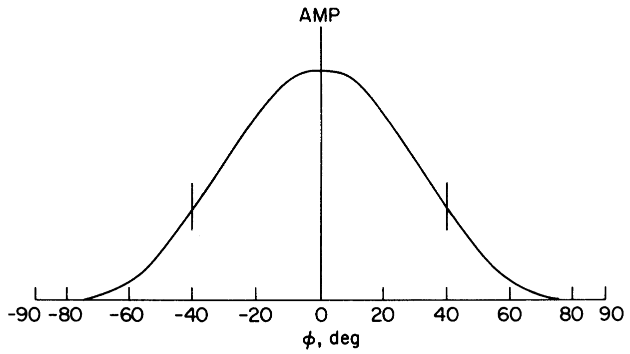

Fig. 7. Azimuthal distribution of incoming light that will 100% couple to the droplet structure.

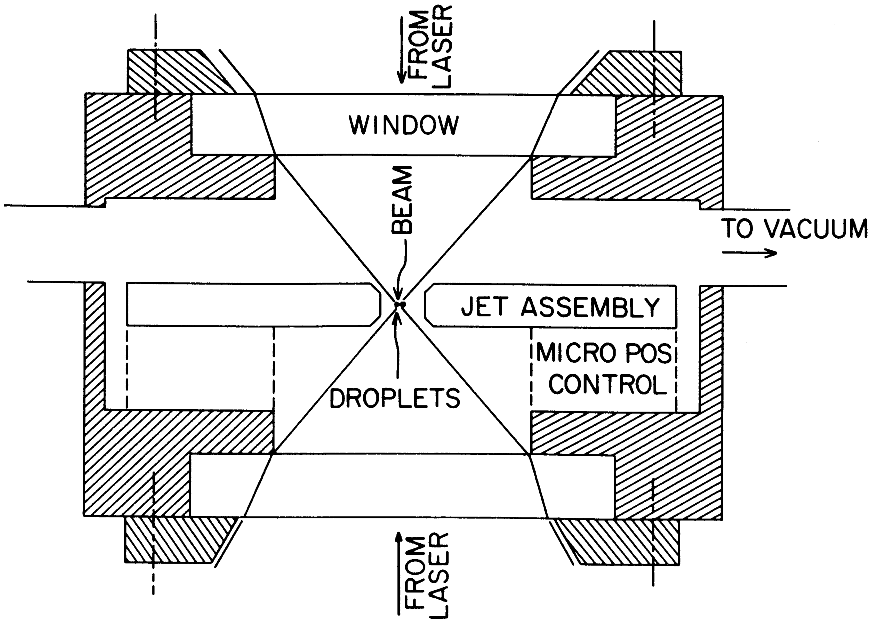

Fig. 8. Conceptual design of accelerator section.

Discussion

J.D. Lawson, RAL

I should like to comment that it is interesting to regard this as a receiving antenna. Matching to the beam impedance will be essential if power from the laser is not to be reflected.

B. Zotter, CERN

Breaking up a long bunch into a series of microbunches does not help to reduce the wakefield unless the memory of the structue is extremely short.

Answer

By keeping the Q smaller than 10, the wakefield should be small after 10 wavelengths. I might add that, according to Perry Wilson at Los Alamos, the transverse wakefield depends on the fraction of stored energy you try to take out and is independent of size. Perhaps he would like to comment.

P. Wilson, SLAC

In answer to your statement that dipole wakefield effects also scale if the fraction of the stored energy removed by the bunch is kept constant, that is correct if the focusing strength is also increased (betatron wavelength reduced in proportion to λ).

K. Witte, Garching

How precise is the estimation of the laser energy? Did you take into account engineering factors like incomplete coupling of the laser radiation to the droplet structure or losses in the laser structure?

Answer

No. We have made only very rough estimates to get an idea of the orders of magnitude involved.

J. Mulvey, Oxford

Would one of the plasma experts like to comment on the lifetime of one of your droplets?

J. Dawson, UCLA

The droplet lifetime depends on temperature. No experiments exist in this range. One can estimate the plasma temperature in the 10's of KeV and expansion sound speed in the neighbourhood of 10^8 cm/sec. The total laser energy is modest so the whole drop cannot be heated to very high values. The drop will disassemble at the sound speed ~ 10^8 cm/sec so that in 1 psec it will move 1 μ.