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REPORT OF NEAR FIELD GROUP*

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1. ABSTRACT AND INTRODUCTION

It is a pleasure to be able to report substantial progress since the Los Alamos Workshop two years ago. A radio-frequency model of a grating accelerator has been tested at Cornell, and extensive calculations compared with observations. Alternative structures consisting of either hemispherical bumps on a plane, or conducting spheres in space, have also been rf modeled. The use of liquid droplets to form such structures has been proposed and a conceptual design studied. Calculations and experiments have examined the effects of surface plasmas, and shown that in this case the reflectivity is low. However, calculations and observa-

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tions suggest that gradients in excess of 1 GeV/meter should be obtainable without forming such plasma. An examination of wake fields shows that, with Landau damping, these are indepedent of wavelength. The use of near field structures to act as high gradient focusing elements has been studied and shows promise, independent of the acceleration mechanism. Beamstrahlung in the quantum mechanical limit ahs been shown to scale as $(DN)^{1/3}$. Finally a proposal has been made to establish a facility that would enable "proof of principle experiments" to be performed on these and other laser driven accelerator mechanisms.

2. ACCELERATING STRUCTURES

a) Iris Loaded Linac (Fig. 1a)

Although not practical as a linac for laser wavelengths, the iris loaded linac 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 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.

b) Grating (Fig. 1b)

This structure was the first proposed for laser acceleration[1], and despite earlier difficulties[2] has been shown[3] to support non-radiating (i.e. resonant) accelerating modes. These, however, are only present when the exciting radiation falls on the grating from the side, and the resulting fields are always periodic across the grating (i.e. perpendicular to the acceleration). Contrary to the hope expressed in Ref. 3, it has been shown[4] that different transverse periodicities cannot be added to restrict the transverse extent of the fields. The periodicity is fixed by the grating profile. Thus although the grating is suitable for accelerating a large number of beams, it would be very inefficient for only one.

c) Grating With Side Walls (Fig. 1c)

This structure has been studied by M. Pickup at Cornell and is discussed in a separate contribution to these Proceedings.[5] The walls, which 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.

d) Inside-Out Iris-Loaded Cavity (Fig. 1d)

Kroll[6] 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 thought of as that of a grating in which the two sides have been curled under and joined together. As in the grating case, non-radiating 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.

e) Double Row of Droplets (Fig. 1e)

An rf model consisting of two copper spheres placed between two parallel metal plates demonstrated[7] a mode that would accelerate along the axis between two rows. The spacing between the 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 spheres 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.

f) Four Rows of Spheres (Fig. 1f)

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.

g) Rows of Bumps (Fig. 1g)

A second mode observed with two rows of spheres had 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.

h) Super Bumps (Fig. 1h)

Kroll has proposed a case derived from a double row of inside-out iris cavities (see d above). 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.

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 two rows of droplets, alternate droplets can be displaced out of the plane (Fig. 2). 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. 3.

3. THE PRODUCTION OF DROPLET ARRAYS

Grating structures of almost arbitrary shape can now be made by a number of micro-machining techniques. The structures formed from spheres seem at first a lot less practical. However, liquid jets developed for ink jet printers and other more exotic purposes can place droplets with remarkable precision and at low cost. Structures formed from such droplets, besides having some nice electromagnetic properties, would have the advantage of being "disposable". Damage caused by the radiation or the beam, provided it does not spoil the structure during its few picoseconds of use, need not be considered. It is therefore interesting, as an aside, to give a conceptual design of a section of a droplet structure.

Figure 4a shows a vacuum container with entrance windows, presumably of salt, both above and below the beam. On either sideof the beam are the liquid jet assemblies mounted on micro-manipulators. Pumps are provided to remove vapor given off from the heated droplets. Figure 4b shows a jet assembly with filter and piezoelectric pump. On the right and in Fig. 4c is the jet array itself. The techniques proposed, and being developed at BNL, are extensions of those used in both some ink jet printers and masks. A silicon chip is doped on one side and then anisotropically etched to form the long channel with a thin (circa 2 micron) remaining wall. Through this wall the actual holes are ion etched.

We do not yet know how accurately droplets of the required size (3 microns) can be placed, but it is worth noting that an array used in an ink jet printer[8] was able to make 13-micron jets with an angular accuracy of 1 milliradian. If such angular accuracy could be maintained, droplets could be placed to one tenth of a micron, which would probably be sufficient.

4. LOADING AND EFFICIENCY

The maximum number of particles that can be accelerated in any structure is set by longitudinal and transverse wakes. As the structure gets smaller the wake fields get stronger, but at the same time the stored energy in the fields decreases. For longitudinal wakes it has been shown by Wilson[9] that for a given wake field effect the same fraction of the stored energy can be extracted, independent of wavelength. The situation for transverse wakes is more complicated. It was shown by Wilson[9] that A, the wake amplitude divided by the initial misalignment, is given by

$$A = \frac{N\, \beta\, z\, w\, e}{4V}$$

where N is the number of particles per bunch
β is the focusing parameter
z is the distance along the accelerator
w is the wake potential
e is the electric charge
V is the beam energy in electron volts.

Since w scales as $w = w_0/\lambda^3$, one might expect the effect to be much worse for small λ, but as we said the situation is more complicated.

Without Landau damping A grows without limit as z increases, but with a finite momentum spread between head and tail the driving frequency gets out of phase with the tail's transverse betatron oscillation and the amplitude reaches a maximum value given by substituting

$$z(\text{Landau}) = \frac{2\beta}{dp/p}$$

For N we can substitute that value that would extract a given fraction η of the stored rf energy,

$$N = \frac{\eta\, E_a}{4\, k_1\, e}$$

where E_a is the accelerating gradient
k_1 is the loss factor for the cavity $= k_0/\lambda^2$
k_0 is a dimensionless constant of the cavity geometry.

For the β we will assume RFQ focusing as discussed below in Section 7. Then

$$\beta = \beta_0\, (\lambda V/E_a)^{\frac{1}{2}}$$

where β_0 is a scale invariant constant of the cavity and focusing geometries. The focus is stronger for a shorter wavelength because the poles are closer to the axis.

Substituting, we obtain

$$A = \frac{1}{8}\,\eta\, \left(\frac{w_o}{k_o}\, \beta_o^2\right) \frac{1}{dp/p}$$

which is independent of λ and, incidentally, also of E_a and V.

Thus we find that both longitudinal and transverse wake considerations set a scale independent limit on the fraction η of rf energy that can be extracted. In practice this limit is about 5%. If only one bunch is accelerated this sets a bound on the accelerator efficiency. With many bunches removing energy in equilibrium with incoming power, however, we know that far higher efficiencies can be achieved; even as high as 80%.

The relevance of these remarks arises because a collider probably requires pulses of the order of 1 mm in length, and it is certainly simpler if they are single. If a conventional wavelength is used this pulse can only consist of a single rf bunch; in the 10 micron case, however the pulse will contain 100 micro bunches, each with only a small charge, and in these circumstances much higher efficiency (say 50% instead of 5%) may be expected. This may then offset the lower power source efficiency of a laser compared with a klystron or lasertron (5-10% vs 40-80%).

5. BEAMSTRAHLUNG SCALING

Himel and Siegrist[10] have studied the scaling of the quantum mechanical corrections to beamstrahlung. Using the approximation that the spectrum remains as in the classical calculation up to $E = E_c$ and then is cut off one obtains

$$\delta(\text{quantum mechanical}) \approx \delta(\text{classical}) \times \left(\frac{E}{E_c}\right)^{\frac{4}{3}} .$$

In fact this is always a conservative estimate. Here δ is the average fraction of beam energy lost to beamstrahlung. E is the beam energy and

$$E_c = \frac{3}{2} \hbar c \frac{\gamma^3}{\rho} = \frac{3 \hbar c \gamma^2 N r_e}{2 \quad r d}$$

where ρ = radius of curvature in field
d = bunch length (assumed uniformly filled)
N = number of particles
r_e = classical electron radius
r = radius of bunch (assumed uniformly filled).

Substituting one obtains:

$$\delta_{QM} = \frac{8}{\sqrt{3}} \left(\frac{r_e \, m \, c^2}{2 \sqrt{3} \hbar c}\right)^{\frac{4}{3}} (D \, N)^{\frac{1}{3}}$$

where $D = \dfrac{N r_e d}{\sqrt{3} \gamma r^2}$ = disruption parameter.

The simplicity of this relation is almost startling. If D = 1 is chosen to assure significant self-focusing, $\delta_{QM} \leq 0.3$ to keep the energy spread less than 10%,, and if we are in the quantum mechanical regime ($\frac{E}{E_c} < 1$), then

$$N \leq 1.2 \times 10^7$$

This is a very small number and though well suited to a laser accelerator will not match the large stored energy in cavities using larger wavelengths.

6. ACCELERATING FIELD LIMITS

At the last laser acceleration workshop limits were shown for electrical breakdown and surface heating (Fig. 5). In this case the surface heating was calculated for pulse lengths equal to the filling time of a copper cavity, and the assumption was made (correctly in this case) that for such relatively long pulses the temperature is limited by thermal conduction away from the surface. But it is not necessary to use such long pulses if adequate power sources are available. For instance a wake field accelerator uses only a single half wave. In such cases the temperature is found to be limited by the specific heat of the materials and depends only on this and the number of cycles. Kroll[6] has calculated the maximum electric fields over a plane mirror for which the temperatures do not exceed 25° below the melting point of various materials. The results are plotted on Fig. 6, and the limits for a half cycle on tungsten also indicated on Fig. 5. One sees that for tungsten this field is 28.5 GeV/m; an astonishingly high value. For currently available laser pulses of 100 cycles, the limit is 1.8 GeV/m. The shortest pulses that may be possible, using isotopic gas mixtures, were given as about 10 cycles, which would give fields of 5.6 GeV/m. Note that the accelerating field in a real structure will be less than these numbers by at least 2, nevertheless the conclusion is that very high gradients may be possible with a grating accelerator without destroying the surfaces.

A check on the above calculation is provided by an experimental observation by Corkum[11] that a gold mirror was not visibly damaged by a 3 picosecond pulse with the order of .5 terawatts per cm^2, corresponding to fields of about 4 GeV/m. This field is even higher than the tungsten calculation (1.8) and may indicate that melting for these very short times does not damage; it may be the boiling point that is relevant. It must also be pointed out that the measurement was very preliminary.

It had been hoped by this reporter that efficient acceleration would occur with these structures even when the fields were such as to form a surface plasma and subsequently destroy the surface altogether. Another observation of Corkum's is discouraing to this hope. At least at a field level of 100 terawatts/cm^2, corresponding to 60 GeV/m, he found that only 30% of the incoming light was reflected by a plane mirror. Ken Lee also presented a theoretical calculation that also predicted relatively large losses when a surface plasma is present. Such high absorption implies that the resonant structures we have been discussing would not work. There may of course be an intermediate field region above the melting point limit but below the field needed to produce a plasma, which would destroy the structure but still be suitable for a resonant structure. It should also be noted that acceleration can, in principle, still be obtained in non-resonant structures even when the losses are high. More experiments are required.

The conclusion at this point is that while the very high fields that produce plasmas will not be suitable for resonant structures, yet the fields that do not produce plasmas, and do not even visibly damage the surfaces, are very high (providing well above 1 GeV/m acceleration). For a high energy physics accelerator it may well not be necessary to go above such limits. For focusing however, higher fields may be desirable, but then an efficient resonant structure is not important.

7. FOCUSING STRUCTURES

Several people at the workshop started independently thinking of the use of these laser mechanisms as focusing elements. Already at the Frascati Conference the importance of focusing was emerging. The beam, and thus the wall plug, power needed to run a high luminosity, high energy collider can be very high, even prohibitively high. This power can be lowered if the beams can be brought to a finer focus at the collision point. In order to do this one needs higher gradient focusing elements.

We have been discussing structures that might, given short enough laser pulses or allowing plasma production, achieve average acceleration of the order of 5 GeV/m. Many of these structures would also provide quadrupole focusing average fields of the same order of magnitude at the "pole tips" only a few microns from the axes. The deflecting magnetic field corresponding to 5 GeV/m is 15 Tesla or 150 kG. This is a very high field, and when combined with the small aperture would provide quadrupole gradients equivalent to 5 million Tesla/meter. This is about 3 orders of magnitude higher than about the smallest conventional quadrupole magnet one can think of. The beta that can be produced at a focus goes as the inverse root of the gradient. The beam power goes linearly as the beta. So these high field structures offer the possibility of reducing the beam power by more than one order of magnitude.

We now review some possible focusing structures:

a) Simple grating

If the phase of the particles with respect to the fields is set for zero acceleration, then the particles see a deflection field combined with a quadrupole focusing field. In the last workshop it was proposed that the deflecting field could be corrected by a fixed magnet but at this workshop, Pickup[5] has shown that if the grating azimuthal positions with respect to the beam are rotated, then strong focusing is obtained without excessive undulation of the beam (Fig. 7a).

b) Double row of droplets (Fig. 7b)

As in the grating case the field along the axis for off phase particles is a quadrupole, only this time there is no dipole to cause deflection. In this case there is of course also acceleration for the other phase.

c) Four rows of droplets (Fig. 7c)

The accelerating mode discussed in Section 2 (Fig. 1f) contains no quadrupole fields, but another mode that can be excited in the same structure (Fig. 7c) does have such fields. This mode does not have acceleration. If a mixture of acceleration and focusing is required, one would alterate the modes between the two.

d) Super bumps (Fig. 7d)

The simple bump structures of Fig. 1g will, as in the grating case, have a combination of focusing and deflection. The super bump case (Fig. 1h) however, quadrupole focusing, no deflection, and thus a true stable orbit. It may not be quite as good as the droplets since the essential one sidedness of the structure will always introduce sextupoles or some other up-down symmetry.

At the workshop various calculations of the effect of these fields were made by M. Pickup and R. Fernow. It was shown, for instance, that with any of the above structures giving gradients of 5 million Tesla per meter, and with a phase 10° from maximum acceleration, then at 5 TeV the beta in the structure would be only .36 m. This is very small compared with that (100 m) in the SLC.

A very simple conceptual design of a final focus was worked out by J. Claus (Fig. 8). In this example the square root of the products of the initial beta and the beta at the intersection were 6.5 and 21 cm in the horizontal and vertical directions. It is reasonable to suppose that a more complicated design, symmetrical in the two directions, would have a value for this product of about 15 cm. This in turn implies that a final beta of 1 mm would involve maximum betas of the order of 22.5 m. If the invariant emittance $\leq 10^{-6}$, then the maximum beam size would be ≤ 1.5 μm. which would fit in the structure. We conclude therefore that this super high gradient RFQ focusing could give final betas of the order of 1 mm: at least 10 times smaller than by conventional means.

Pickup and Fernow checked that the synchrotron radiation with these high gradients was not a problem.

$$dE/d\ell = 1.5\ 10^{-15}\ \frac{A^2\gamma^2}{L^4}$$

$$L=2\ \pi\beta$$

$$A = (\eta\ \beta/\pi)^{\frac{1}{2}}\ .$$

With an invariant emittance of 10^{-6} the loss per meter in the accelerator (β=.36 m) at 5 TeV is only .04 MeV/m.

At the final focus just described the total loss would be only 200 MeV.

8. A POSSIBLE EXPERIMENTAL FACILITY

There was discussion within the group of the desirability and design of a facility where proof of principle experiments could be carried out. It was agreed that there was much work that could and should be done without a real test beam but that the difficulties and long time needed to design and build such a facility justified going ahead now with such a proposal.

The facility should provide a test beam with of about 10^4 particles focused to a spot of the order of one micron diameter, with a beta of at least 1 cm, a momentum spread of less than 1 MeV, and a pulse length of less than 2 mm. Such a specification demands a very high brightness beam. In principle this could be provided at any cooling electron storage ring of the order of 1 GeV, but in practice it seems likely that the SLAC source and cooling ring may well be the only such source that would be accessible for this work. A possible location of the experiment would be at the one third point where an extraction port and tunnel do now exist.

The second requirement for the experiment would be a laser capable of amplifying 3-6 picosecond pulses and delivering about 100 mJ. This specification is essentially that already demonstrated by the high pressure CO_2 laser at NRC (Ottawa, Canada).

Finally, and non-trivially, one requires a mechanism to synchronize the beam pulse with the laser. Two schemes were studied at the workshop. In the first (Fig. 9a, Pellegrini, Slater) the electron beam is used in a FEL to amplify a short section of a much longer pulse from a low power atmospheric pressure laser. This short and synchronized section is then further amplified in a high pressure amplifier and finally brought down to accelerate particles. In the second (Fig. 9b, Fernow, Himel, Corkum) the initial high intensity beam is passed through a gas Cerenkov and the light from this is focused onto a semiconductor "switch" used to cut a short section out of a larger CO_2 laser pulse. Both schemes seemed possible but require further study.

Due to the delays involved in these processes the light will be used not to accelerate the same pulse of electrons, but a second pulse will be extracted from the same cooling ring.

Some preliminary considerations were given to the design of both the collimator (Himel) and the spectrometer (Baggett). The collimator will require very small gaps and it was asked if scattering in the jaws of these gaps would give a "fuzzy" edge. An EGS calculation was quoted indicating that such "fuzziness" should be only a few microns and thus present no problem. The spectrometer, it was suggested would observe both vertical deflection and energy change. A conceptual design with a two dimensional (possibly solid state) array readout was suggested.

With such a spectrometer different phases between beam and laser would generate a combination of deflections and acceleration such as to form a hollow ellipse on the array (Fig. 10).

9. OTHER WORK TO BE DONE (Goldstone)

It is clear that the despite the great progress since the last workshop, much work remains to be done. In general qualitative understandings need developing to quantitative knowledge.

a) Polaritons (Corkum)

More study is needed on polaritons. These are surface fields that can exist over any plane dielectric or conducting surface in the presence of a complex dielectric constant. These fields can contain accelerating components and, since they are slow waves, can couple to relativistic particles when at an angle to them. They can be excited by slight surface ripples at 1 λ periodicity.

b) Structures

More study is needed of bump grating structures. We know the general concept but have not begun to identify the optimum structures. Study is needed on dielectric structures for a water droplet or solid grating accelerator.

c) Coupling

More work is needed on the coupling mechanisms including efficiency and tolerance studies.

d) Plasmas

Not only is the onset of plasmas not yet known but the mechanism and effect of the observed losses is not yet understood. Much work is needed if gradients in the 10 GeV/m are to be attempted.

e) Experiments

In connection with the proof-of-principle experiment described above, we will need many new diagnostics:

1) Beam position and shape monitors operating on the 1 micron scale: silicon strip detectors, scintillating thin layers, film, etc.

2) Structure position and shape monitors: flash TV, electron microscopy.

3) Energy flow observation: measurement of reflected and scattered light from the structures.

4) Wave front monitoring: measurements by interferometry.

5) Smith-Purcell check: measurement of light emitted by beam passing over structures.

f) Accelerator Optimization

Studies are needed on the overall optimization not only of the 10 TeV, 10^{34} machine discussed here but also of more modest stepping stone designs such as a 200 + 200 GeV, 10^{31} machine.

REFERENCES

1. Y. Takeda and I. Matsui, "Laser Linac with Grating", Nucl. Instrum. Methods 62, 306 (1968).
2. J.D. Lawson, Rutherford Lab. Rept. RL-75-043 (1975); IEEE Trans. Nucl. Sci., NS-26, 4217 (1979); P.M. Woodard, J. IEE 93, Part III A, 1554 (1947).
3. R.B. Palmer, "A Laser-Driven Grating Linac", Part. Accel. II, 81 (1980).
4. M. Tigner and J.D. Lawson, private communication (1984).
5. M. Pickup, these proceedings.
6. N. Kroll, reported at this workshop; to be published.
7. R.B. Palmer and S. Giordano, "Preliminary Results on Open Accelerating Structures", BNL 35981 and these proceedings.
8. E. Bassous, IEEE Trans. Electron Devices ED-25, 1178 (1978).
9. P. Wilson, Proc. Laser Acceleration of Particles, Ed. P.J. Channell, AIP Conf. Series No. 91 (1982).
10. T. Himel and J. Siegrist, SLAC Pub. 3572 and these proceedings.
11. P. Corkum, preliminary and private communications (1984).

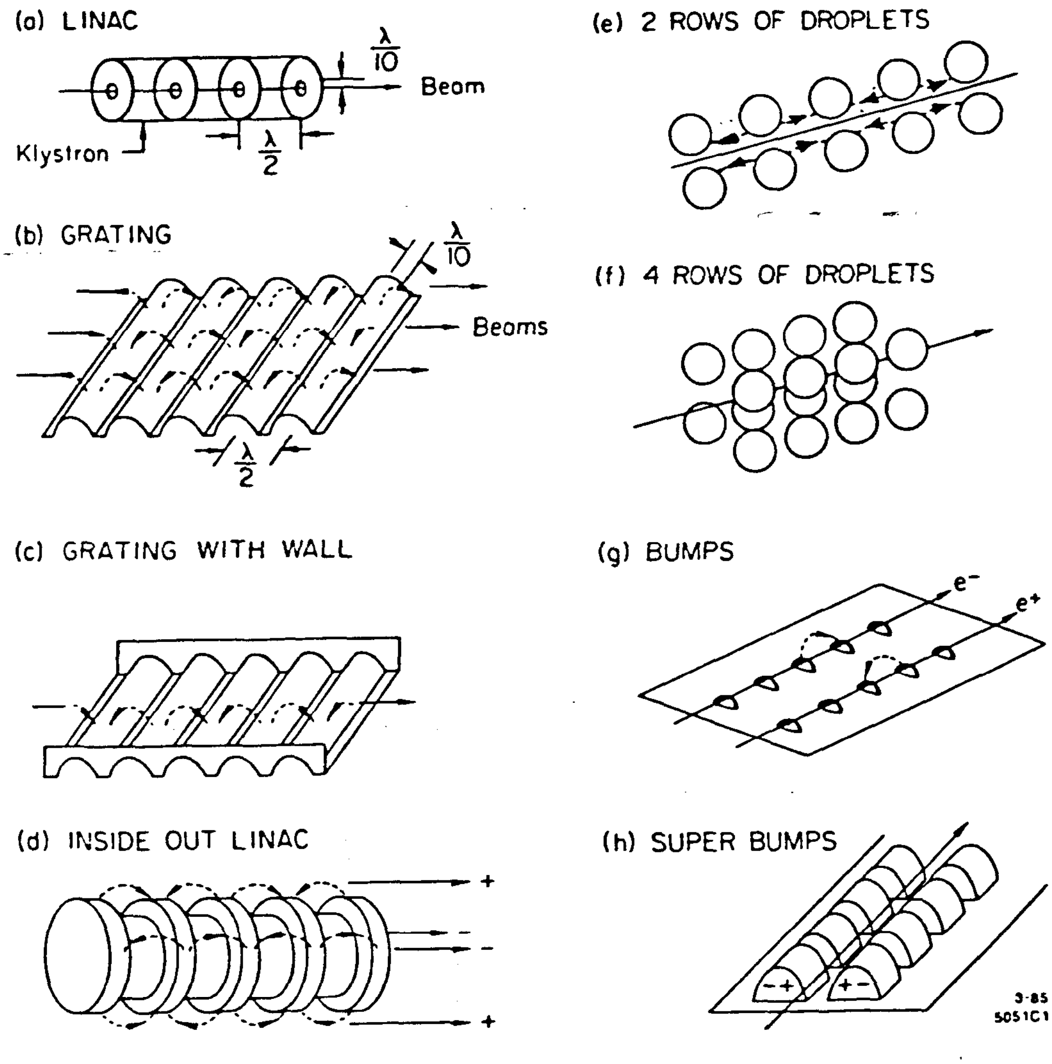

Fig. 1. Near field accelerating structures.

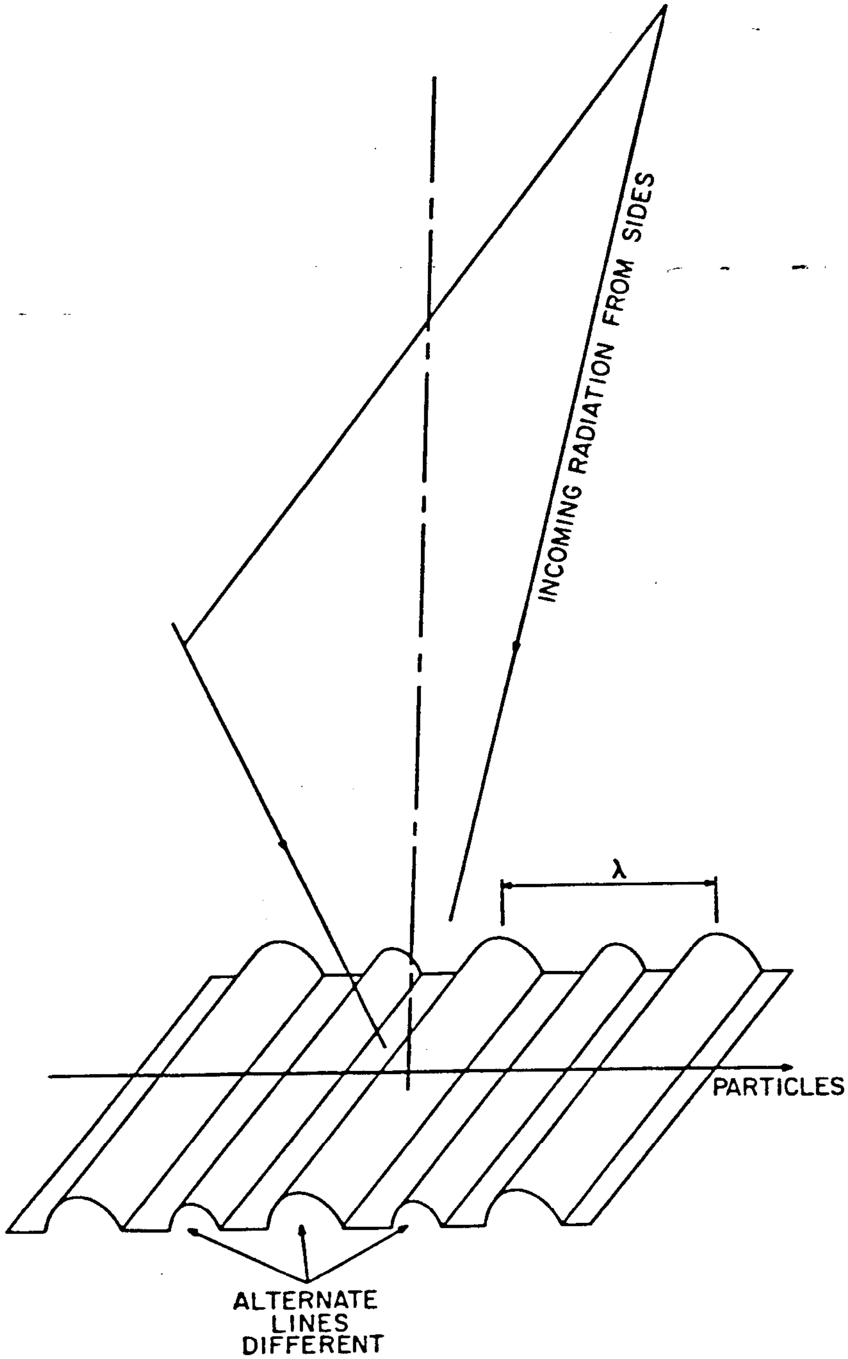

Fig. 2. Coupling to structures. (a) Grating.

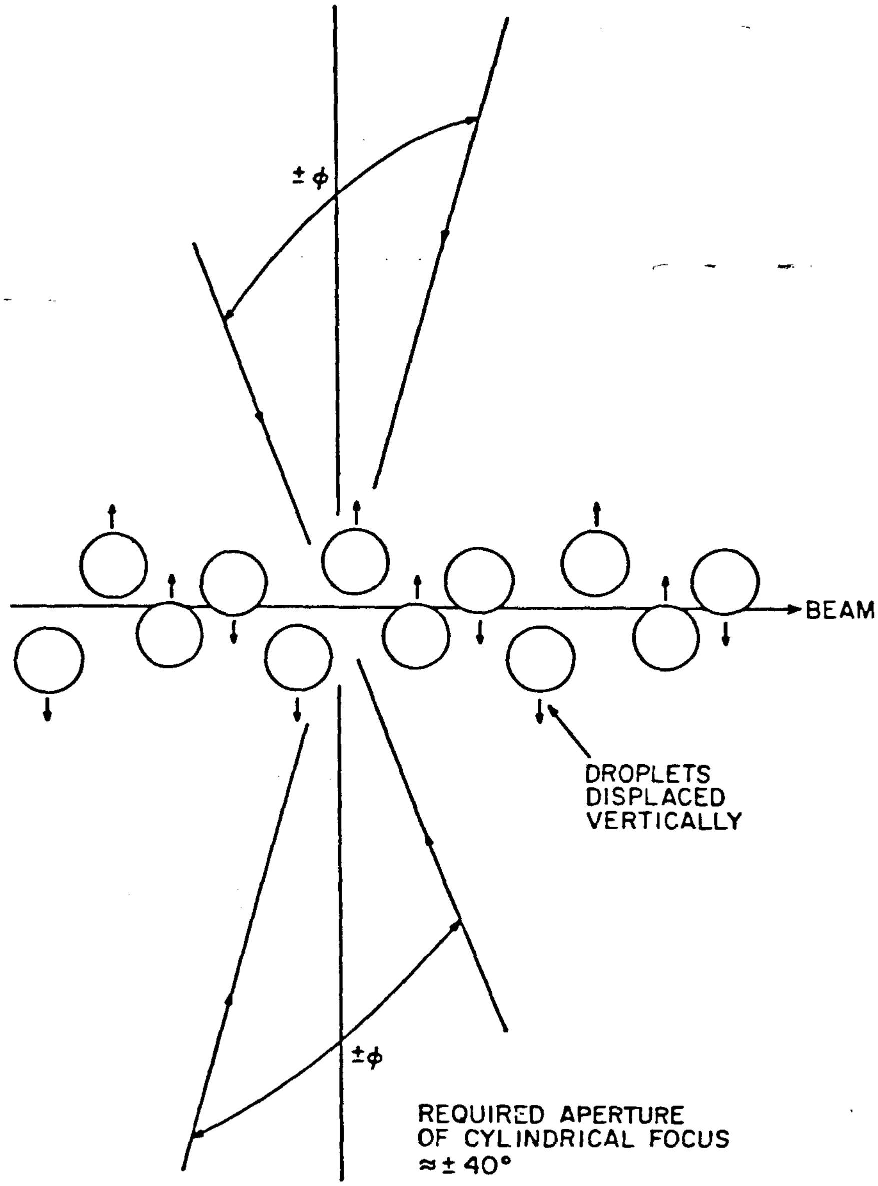

Fig. 2. Coupling to structures. (b) Double droplet rows.

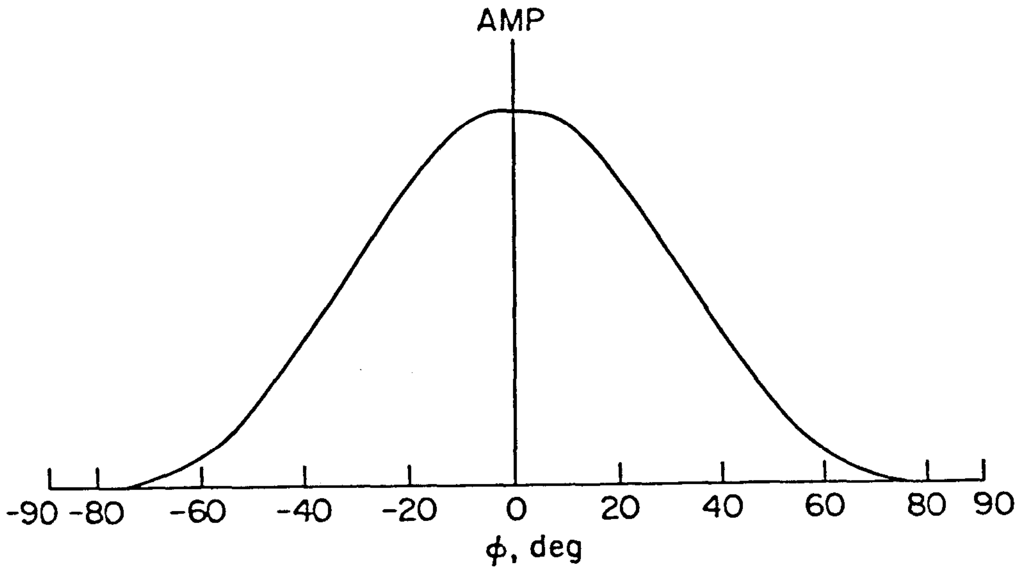

Fig. 3. Angular distribution of radiation to or from droplet structure.

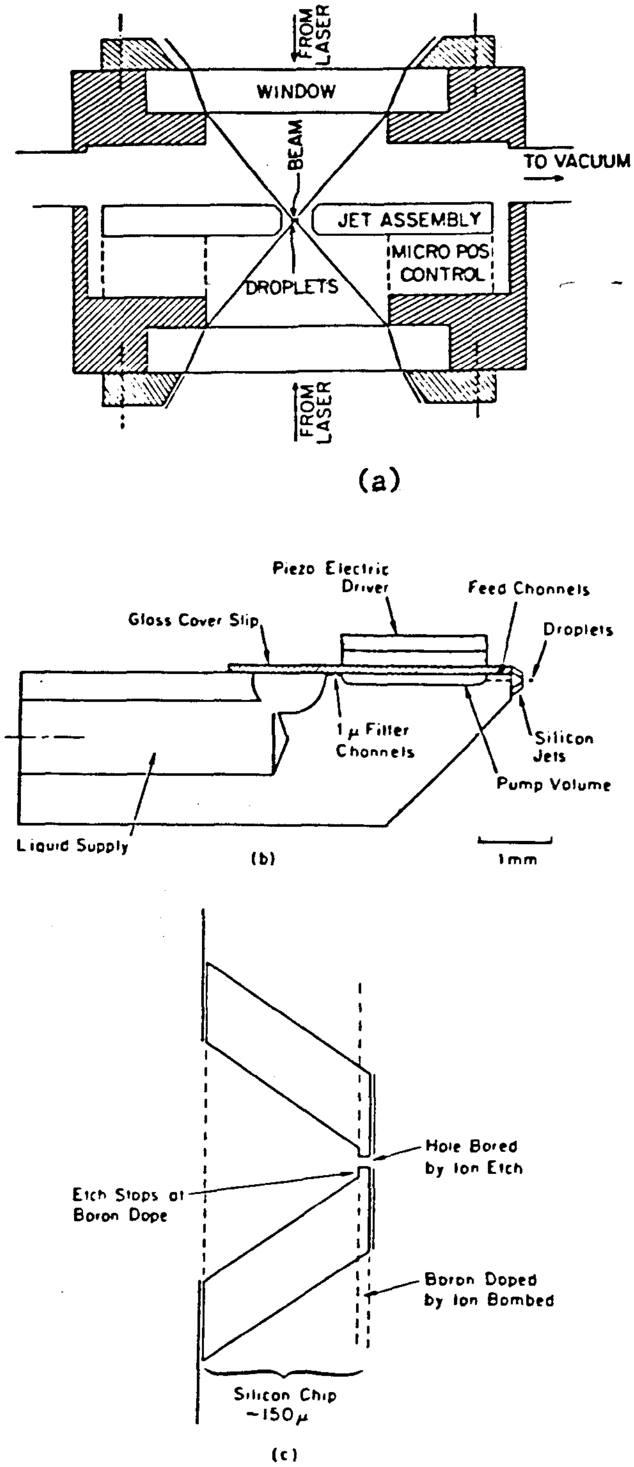

Fig. 4. Conceptual design of droplet accelerator: (a) overall section, (b) jet assembly, (c) nozzel assembly.

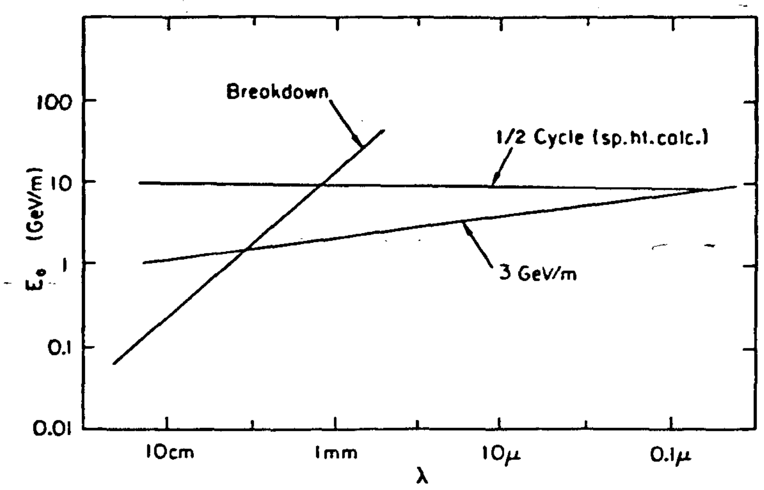

Fig. 5. Limits on acceleration gradients vs wavelength.

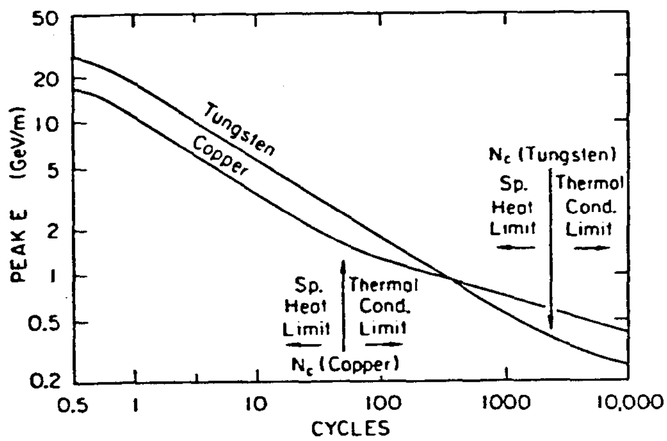

Fig. 6. Melting point limit vs number of cycles.

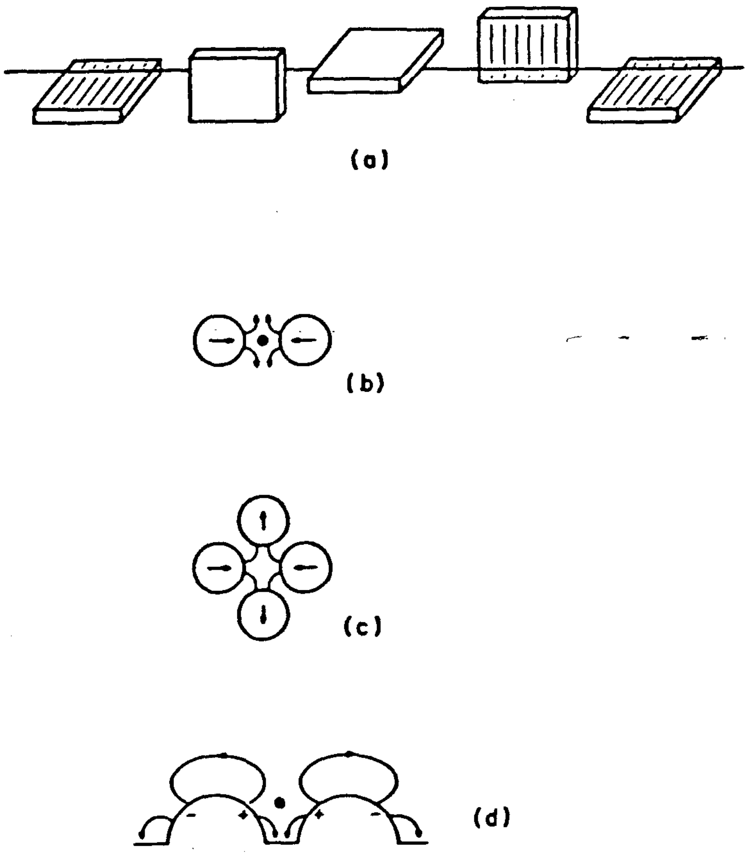

Fig. 7. Focusing structures: (a) Rotating grating arrangement, (b) fields between double rows of droplets, (c) four rows of droplets, (d) Kroll bumps.

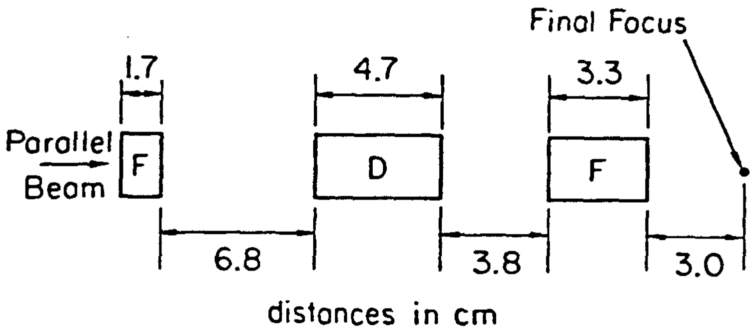

Fig. 8. Final focus.

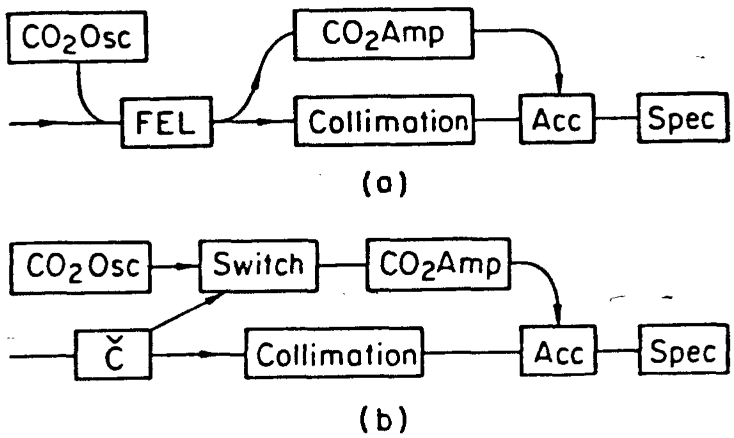

Fig. 9. Experimental facility: (a) with synchronization by FEL, (b) with synchronization by Cerenkov detector.

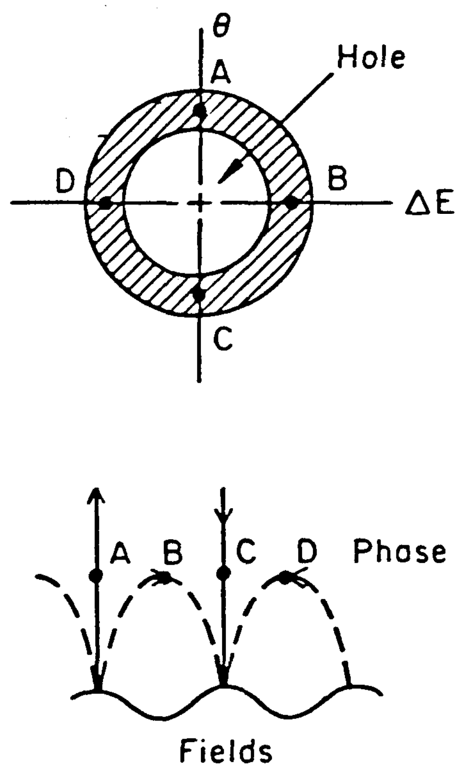

Fig. 10. Expected distribution in spectrometer.