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TRANSVERSE ELECTRON RESONANCE ACCELERATOR*

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ABSTRACT

Transverse (to the velocity, $\bar{v}$, of the particles to be accelerated) electron oscillations are generated in high (e.g. solid) density plasmas by either an electromagnetic wave or by the field of charged particles traveling parallel to $\bar{v}$. The generating field oscillates with frequency $\omega \approx \omega_p$, where ω_p is the plasma frequency. The plasma is confined to a sequence of microstructures with typical dimensions of $d \approx 2\pi c/\omega_p$, allowing the generating fields to penetrate. Since ω_p is now high, the time scales, T, are *correspondingly reduced. The microstructures are allowed to explode* after $t \approx T$, until then they are confined by ion inertia. As a result of resonance, the electric field, E, inside the microstructures can exceed the generating field E_L. The generating force is proportional to E_L (as opposed to E_L^2). Phase matching of particles is possible by appropriate spacing of the microstructures or by a gas medium. The generating beam travels outside the plasma, filamentation is not a problem. The mechanism is relatively insensitive to the exact shape and position of the microstructures. This device contains features of various earlier proposed acceleration mechanisms and may be considered as the limiting case of several of those for small d, T and high E.

DISCUSSION

The underlying principles of a transverse electron resonance accelerator was originally described during the first workshop on the Laser Acceleration of Particles (1). It makes use of the large internal electric fields which can be generated in a dense plasma by resonantly oscillating electrons.

The accelerator contains a sequence of relatively high density objects, whose density may reach solid state densities. (2) The typical dimension of these objects is small, as explained below, therefore we will refer to them as "microstructures". The microstructures are to be located at appropriately chosen positions along, and close to, the trajectory of the particles to be accelerated (See Fig. 1).

Denote the free electron density inside the microstructures by ρ_e, and the plasma frequency by ω_p. Electron oscillations are generated in each microstructure by an oscillating generating electric field of amplitude E_g, and circular frequency ω. Choose

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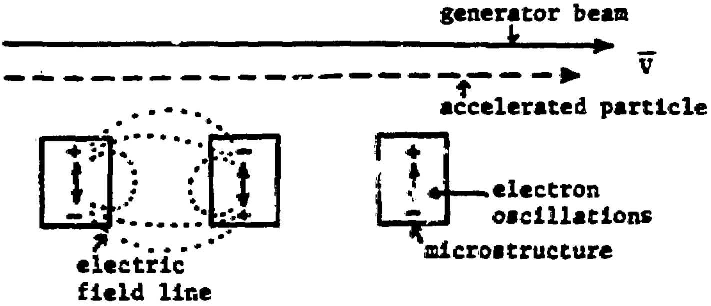

Fig. 1

$$\omega = \omega_p \ , \tag{1}$$

so that the generating field is in resonance with the plasma frequency. The oscillating electrons move along lines transverse to the velocity, $\bar{v}$, of the particle to be accelerated. As a result, a charge separation will be generated inside the microstructures, and those, in turn, create field lines which have a component parallel to $\bar{v}$ at the particle trajectory. This component will accelerate the particle. (Fig. 1 shows field lines corresponding to dipole type charge separation.) The oscillations are set up either by an electromagnetic wave or by bunches of charged particles which may move parallel to $\bar{v}$.

The typical diemsnion, d, of the microstructures is chosen to be of the order or less than λ_p, as defined below

$$d \lesssim 2\pi c/\omega_p = \lambda_r \ . \tag{2}$$

This condition insures that although ρ_e is high ($\lesssim 5\cdot 10^{24}$ cm^{-3} $= \rho_{em}$), therefore so is ω_p ($\lesssim 1.3\cdot 10^{17}$ sec^{-1} $= \omega_{pm}$ for non-relativistic electrons) and although $\omega > \omega_p$, nevertheless the genereting field can easily penetrate the microstructures from at least one, and perhaps several, directions.

As a result of resonant electron oscillations, large charge separations and high internal electric fields can be set up inside the microstructures. If the electrons can stay in resonance for N oscillations, where $N > 1$, the internal fields, E, can exceed the generating electric field amplitude E_g. For example, when $\rho_e = \rho_{em}$, one could reach $E = 3.3\cdot 10^3$ GeV/cm $= E_m$ in about $N = 30$ to 10^3 oscillations, depending on the exact initial conditions. The nominally high value of E_m seems to justify further study of this mechanism.

We note that the electron oscillations being transverse, they are driven by a force proportional to E_g, which allows faster oscillation buildup than would be possible if the force were proportional to E_g^2.

The high internal fields will cause the microstructures to explode after a time T. For $t < T$ most electrons will be confined by the electrostatic force exerted by the ions, while those will be inertially confined. Since ω_p can now be high, even $N = 10^3$ oscillations will take place within a very short time interval (For $\rho_e = \rho_{em}$, this time is only $= 5 \cdot 10^{-14}$ sec), and confinement need to persist only during that interval.

The accelerating fields can be kept in phase with the accelerated particles in several ways:

a) Interrupt the sequence of microstructures in regions where dephasing would otherwise occur. Allow the particles to simply drift through these regions until the correct phasing is reestablished, and there resume acceleration.

b) If the generating field is due to an electromagnetic wave, that wave can be allowed to travel in a gas to insure phase matching. This is similar to "inverse Cherenkov acceleration", except that in contradistinction to that mechanism, in the present case the full transverse electric field in the wave <u>can</u> be utilized.

Thus we note with relief that to avoid dephasing of the oscillations, one does not have to resort to sophisticated devices, such as the proposed surfatron, or wave guiding structures. On the other hand, the present mechanism is flexible enough to allow "surfing", if one wishes to use that. In other words, the generating beam does not have to travel parallel to the sequence of microstructures, the generating fields need not penetrate the microstructures from the front, but may penetrate them obliquely, or from any other direction. If laser light is shone obliquely on the microstructures, then dephasing would tend to occur more often, but one can take care of that as described above. Since the generating laser light beam travels mostly outside the microstructures, no plasma related instabilities (e.g. filamentation) will develop in that beam.

Figure 2 a. illustrates a situation where tansverse resonant quadrupole electron oscillations are set up inside the microstructures. In this case the generating beam consists of a sequence of charged particle mcirobunches located at a distance λ_p from each other, and moving parallel to $\vec{v}$. (Microbunches can be generated in Transverse Optical Klystrons or in Free Electron Lasers. Values of λ in the visible range are feasible, and one expects eventually reach at least soft X-ray wavelengths[3]). The figure is drawn looking down on the microstructures, assuming they are located below that beam. The accelerated particles may move either above or below the microstructures. Quadrupole oscillations have the advantage of reducing collective radiation losses.

Figures 2b, 2c and 2d show schematic side views (unlike Fig. 2a) of certain alternative configurations.

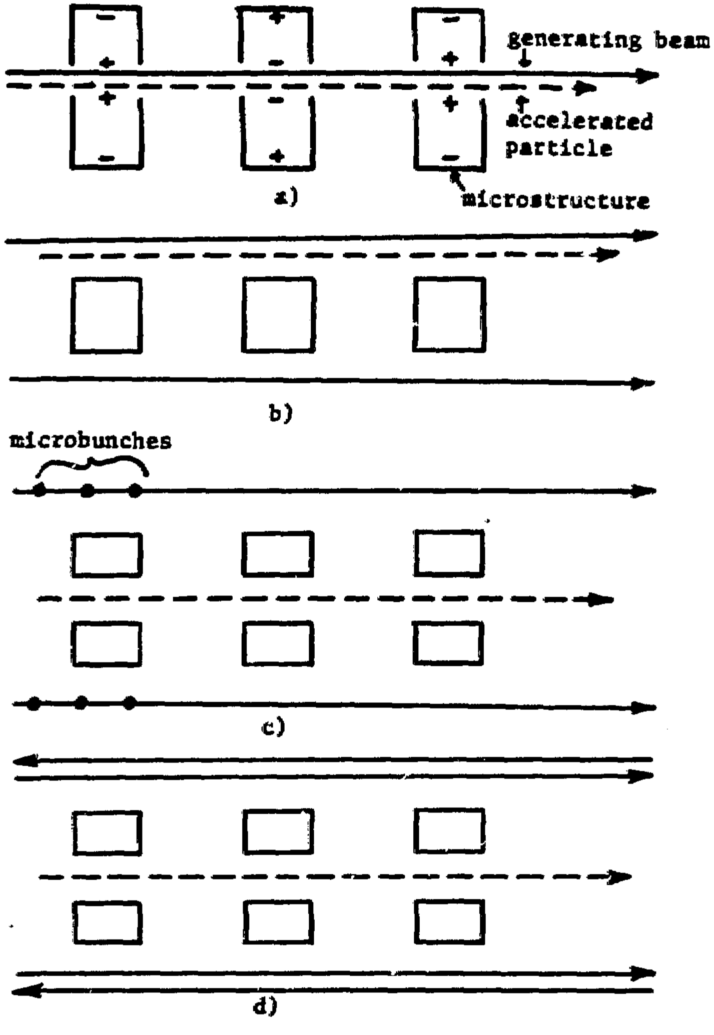
generating beam
accelerated particle
microstructure
a)
b)
microbunches
c)
d)

Fig. 2

In all configurations shown, particle acceleration will be most effective if the accelerated beam passes the microstructures at a distance $\lesssim \lambda_p$. That underlines the importance of producing small crossection beams, including microbunched ones. For high energy colliders small beam crossections are required also by luminosity and power considerations.

If the oscillating electrons become relativistic, detuning of ω_p can be compensated in principle by changing λ_p for the generating beam. In microbunched beams that means changing the distance between microbunches (i.e. the corresponding particle density Fourier wavelength).

It is advantageous to induce electron oscillations with stronger electric fields, because the electron thermalization time increases with energy, so that a large initial amplitude will decrease randomization and increase N.

To illustrate, consider two cases. Parameters for the second case are more ambitious and are given in parentheses. Choose $\rho_e = 1.11\cdot10^{19}$ cm^{-3}, $\omega_p = 1.88\cdot10^{14}$ sec^{-1}. Let the generating field be due to a microbunched electron beam in which the particle density is 100% modulated with a Fourier wavelength 10 μm (1 μm). The beam passes the microstructures at a distance of 10 μm (1 μm), and the number of electrons per microbunch is 10^9 (10^8). Choose N = 1, a most pessimestic assumption. Then the internal field set up as a result of electron oscillations in the microstructures will be $E \approx 10$ GeV/m (10^2 GeV/m). Of course, in reality one expects larger N, and therefore larger E. On should feel encouraged by these estimates.

The transverse electron resonance accelerator contains features from several distinct accelerating mechanisms proposed earlier. It is, of course, related to plasma accelerators, since plasma oscillations are induced. It is closely related to the acceleration by internal fields induced in a plasma focus, although there the charge separation is longitudinal. If a gas is used for phase matching, then in that respect it resembles an inverse Cherenkov accelerator. Since the generating beam travels mostly in vacuum, in that it is similar to far field accelerators. The presence of microstructures recalls the trend towards miniaturization in near field accelerators, such as when droplets are used as a wave guide, or in the two beam acceleration mechanism. One may argue with some conviction that in a certain sense the acceleration mechanism presented here is the limiting case for these various mechanisms, when the accelerating field is increased, breakdown of the materials is allowed, and sizes as well as times are reduced to what appears to be their minimum useful dimension. What one hopes to gain from this assortment of features, is a high accelerating field. Whereas that may not represent the supreme value in accelerator design, it is certainly a tempting goal.

Before the accelerator here described can hope to be of practical value, one will have to establish how large can N be for various realizable cases, how short microbunches can be created, and how close the microbunched beam can be allowed to pass near the microstructures.

Agenda for the near future: 1) Theoretically study electron oscillations, including numerical analysis. 2) Experimentally observe induced dipole amplitudes, and quadrupole amplitudes. 3) Study higher harmonic generation in TOKs and FELs.

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REFERENCE

1. Paul L. Csonka, in "Laser Acceleration of Particles", ed. Paul J. Channell. AIP, Conference Proceedings, Number 91, (1982), p. 216.
2. In principle, the density may exceed solid state density, but that case will not be considered here.
3. Paul L. Csonka in "SSRP Wiggler Workshop, (1977), and Particle Accelerators 7, 21 (1978), and 11, 45 (1980).