A COLLECTIVE ACCELERATOR FOR ELECTRON COLLIDERS*

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Abstract

A recent concept for collective acceleration and focusing of a high energy electron bunch is discussed,[1] in the context of its possible applicability to large linear colliders in the TEV range. The scheme can be considered to be a member of the general class of two-beam accelerators, where a high current, low voltage beam produces the acceleration fields for a trailing high energy bunch.

1. Introduction

This concept for a collective electron accelerator[1] uses a low-energy, high-current "charging beam" propagating in relatively low density gas in the so-called "ion focused regime"[2-4] to generate a very thin unneutralized ion column. This ion column provides a medium for focusing and accelerating a second pulse of high energy electrons. The acceleration fields are generated by rapid neutralization of the ion space charge from a laser-induced ionization "wave" moving a short distance behind the charging beam at the speed of light.

The achievable parameters of the high energy electron beam pulse appear suitable for application to the linear collider concept. The desirable features of the present collective accelerator concept are:

(a) The possibility of high acceleration gradient, hopefully an appreciable fraction of the radial space-charge field of the charging electron beam (60 I/a, of order 5-10 MeV per centimeter with Advanced Test Accelerator (ATA) technology).[5]

(b) Strong radial focusing of the high energy beam without any magnets.[5]

(c) No requirement for accelerator structures with precise tolerances, or RF power sources.

(d) Elimination of emittance growth from transverse interactions with accelerator structures.

Application of this approach to a linear collider with useful luminosity will likely require rep rates of several hundred hertz or more, and the advent of magnetically-driven induction accelerators makes this practical.[6] Taken together, these features imply a very low projected capital cost for such an accelerator -- if it actually works as indicated by the preliminary analysis. The efficiency of the accelerator is, of course, a crucial issue in determining the practicability of collider accelerators with regard to the electrical power consumption. The analysis is still too primitive at this stage for anything beyond preliminary conjectures on the key issue of efficiency.

2. Acceleration Concept

A schematic representation of the essential elements are shown in Fig. 1. A modest energy UV laser pulse with sufficient peak power to weakly ionize the background gas in the tube (of order 10^{-3} Torr for representative design parameters) can be used, if desired, to make a plasma column that provides initial focusing for the low energy charging beam propagating down the tube.[7] Typical parameters of the low energy charging beam pulse would be similar to the ATA beam: 10-15 kA, 50 MeV, 50 ns pulse length, and a normalized r.m.s. emittance of 0.3π rad-cm.[5] The charging beam

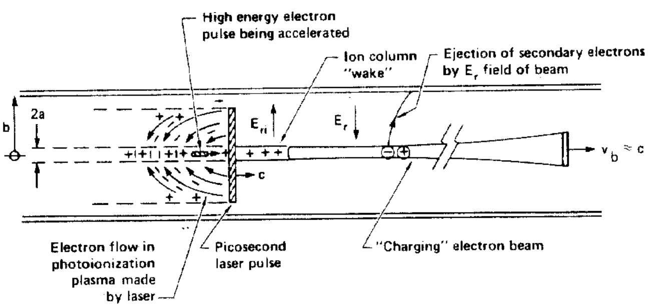

Fig. 1 Schematic of accelerator concept showing essential elements.

generates further ionization by collisions, and the secondary electrons are expelled to the wall by the strong radial space charge field. As the ion density builds up through the pulse, the beam radius collapses (and ion oscillations can contribute to further ionization). The appropriate choice of gas pressure for a given pulse length is governed by the fractional neutralization at the beam tail,

$$f_e = \lambda_i/\lambda_B \qquad (1)$$

with λ_i and λ_B the line densities of the ion column and electron beam, respectively. We want f_e as close to one as possible, but there is a limit to f_e set by our desire to have all the secondary electrons escape to the wall even at the end of the pulse. Limits of 0.4-0.5 are indicated by this requirement.

The charging beam radius at the pulse tail is of order 1 mm or less for the ATA parameters given above, so the ion column reaches a density of several times 10^{13}/c.c. The charging beam must be "preconditioned" to have a very fast (less than one nanosecond) fall time in current to "uncover" this ion column abruptly before ions can disperse radially. When this condition is satisfied, a positive radial field of order f_e times the beam's space charge field will be generated by the ion column. The energy stored in the ion space charge potential comes from the charging beam, of course, and the analysis given in Ref. 1 shows that the deceleration of the primary beam electrons is uniformly partitioned over the pulse length (when beam ionization is dominant). The electrostatic field energy per unit length left behind the charging beam is approximately $f_e/2$ times the energy loss rate (J/m) of the charging beam, with the difference $(1-f_e/2)$ accounted for by the kinetic energy of the plasma electrons striking the wall.

The high energy electron pulse follows the charging beam within a nanosecond or so; it is focused very strongly by the radial electric field of this ion cloud. An axial acceleration pulse keeping in step

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with the high energy electrons is achieved by creating a "plasma creation wave" moving at the speed of light. This ionization wave is set up by a very short pulse laser (duration of order several picoseconds) that photoionizes the gas surrounding the ion column.

Determination of the optimum radial configuration for the photoionization plasma, including the beam loading effects, has not yet been accomplished. A numerical simulation has been formulated by Teague and Yu to address this problem, and preliminary results are reported elsewhere in the conference proceedings.[8] An analytic treatment of the fields resulting from the instantaneous creation of a uniform high density plasma[1] shows that peak axial accelerating fields of order 0.8 times the peak radial field of the unneutralized ion column are created at a time $\pi/2\omega_p$, for $\omega_p a/c \sim 1$, where ω_p is the electron plasma frequency of the photoionization plasma.

The general features of the acceleration fields produced by prompt laser photoionization of the gas surrounding the ion column can be estimated from the following equation, a direct consequence of Maxwell's equations with a dependence on $\tau = t - Z/c$ and r;

$$\frac{\partial E_z}{\partial r} = \eta J_r \tag{2}$$

with $\eta = (\mu_o/\varepsilon_o)$ 1/2. As a simple example, consider a thin annulus of plasma with line density λ_s created at a radius $r_e > a$. The inward acceleration of the plasma electrons creates an outward radial current, hence an axial electric field on axis of

$$E_z = -\eta \int_o^b J_r dr \tag{3}$$

$$\simeq \frac{\eta \lambda_s e}{2\pi r_e(\tau)} \frac{dr_e}{dt} .$$

With ion column parameters like those cited above, the plasma electrons would be quickly accelerated to radial velocities of order c, hence as the electron ring approaches $r_e \sim a$, an axial electric field approaching

$$(E_z)_{peak} \sim \frac{-\eta e \lambda_s c}{2\pi a} \sim \frac{\lambda_s}{\lambda_i} E_{ri} \tag{4}$$

would be created, where E_{ri} is the (peak) radial electric field of the ion column and $\lambda_i = f_e I_b/ec$ is the ion column line density. The assumption that the inward acceleration of the electron ring can be treated as a rigid ring limits λ_s to a fraction of λ_i, but E_z fields of order E_{ri} are achievable levels, based on this simple model.

The duration of the axial accelerating electric field is of order a/c (it moves in z, of course, as a "wave-like" pulse at a velocity c, in synchronism with the picosecond laser creating the annular plasma column). The current profile of the high energy beam could, in principle, be "tailored" in τ to produce a time-dependent radial electric field strong enough to give a net deceleration of the plasma electrons (after their initial acceleration by the ion column) in a manner that keeps $E_z \simeq$ const. during the high energy pulse ($r_e(\tau) \sim \exp(-\alpha\tau)$ would accomplish this in the the simple ring model). This strategy of optimum "beam loading" implies a line density of the high energy energy beam exceeding λ_i (10^{12}/cm), over a pulse length of 1-2 mm, so bunches exceeding 10^{11} particles can be accelerated. If the plasma electrons are decelerated back to low velocities as they approach the ion column, we would have extracted a large fraction of the available electrostatic field energy of the ion column when $\lambda_s \sim \lambda_i$. This conclusion follows from the observation that the final state immediately following the passage of the high energy beam would then consist of a neutralized electron-ion column on axis, and an unneutralized ion ring located at a radius $r_e(o) \simeq b$; the electrostatic field energy in this state is much less than the initial state, and little kinetic energy is left in the plasma electrons. This "ideal" would be very difficult to achieve, of course, but one could still hope for a reasonable efficiency of energy conversion for this phase of the process.

A serious limitation with the thin annular ring is the diffraction of the laser beam; it would have to be refocused and/or reinjected frequently down the acceleration tube. As already noted, we have no conclusions at this point on the most practical and/or desirable profile for the plasma.

3. Conceptual System

In spite of the primitive state of analysis and experimental verification of the basic acceleration mechanism, it is worthwhile to try to visualize the architecture of an overall system to see if it is compatible with a high energy collider. In Fig. 2, we illustrate such an architecture. The induction accelerator beam has its "tail" sharpened by a laser ionization "kicker" before injection into the conducting accelerator tube (~ 1-2 centimeters in diameter). The high energy bunch would be desired from a damping ring, as in the SLC. The diffraction length of the laser pulse, and the "smearing" of the sharp tail on the charging electron beam, both limit a single stage of the accelerator to a few hundred meters (~ several 10's of a GeV at general MeV per centimeter gradient). The high energy beam would travel straight through the stage connections, while the low energy beam would deviate to a tail resharpener and possibly reacceleration. The laser would be refocused or reinjected with gain from a parallel path beam propagating alongside the accelerator tube (to keep the timing precision).

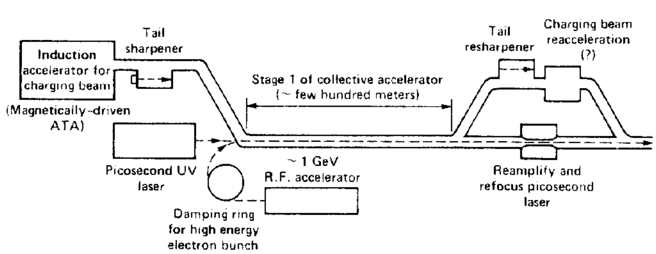

Fig. 2 Conceptual System

The charging beam will tend to center itself in the conducting tube through image forces, so the main alignment requirement is on the picosecond laser with the tube (order of one microradian jitter in one stage). The timing of the picosecond laser with the high energy electron bunch must be done to within a picosecond or so, less than the plasma electron "implosion" time. Some axial tuning of plasma frequencies, etc., might be possible by controlling the gas pressure profile.

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