Amplification of a Wake Field Generated by a Charged Bunch in a Resonant Medium

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A bunch of electrons moving in an active medium excites a wake that is amplified by the medium. The intense radiation field generated in this process reduces the population inversion and, as a result, the field-medium interaction reaches saturation. We show that the accelerating gradient at saturation may reach the 1 GV/m level before the medium is ionized. When ionization occurs, higher gradients may develop provided that we excite resonant states of a partially stripped atom.

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The next linear collider (NLC) requires gradients in excess of 100 MV/m in order to achieve energies of 0.5 TeV (c.m.). According to the operating frequency, the various approaches, which are being pursued by groups around the world, can be divided into two categories: (i) microwave [1–8] and (ii) laser based schemes [9–12].

The need for a high gradient on one hand and power levels below the breakdown threshold on the other hand pushes the operating frequency upward. Consequently, the availability of radiation sources makes the leap from the microwave to the optical range rather natural. In all cases, the radiation is generated separately and then injected into the acceleration region. Moreover, the laser field has only a transverse component of the electric field, therefore an “intermediary” process is required in order to generate a longitudinal gradient. For example, in the case of plasma beat wave accelerator (PBWA), two lasers of relatively long pulse duration of different but close frequencies generate space-charge waves in plasma. Choosing the difference between the two frequencies to be equal to the plasma frequency enables one to utilize this resonance for the generation of an accelerating gradient. At the other extreme, the availability of top table terawatt lasers enables one to generate, for a very short duration, high electric field (TV/m) transverse to the propagation of the laser beam. Choosing the duration of the pulse to be of the order of $2\pi/\omega_p$ enables the excitation of plasma waves and, as before, these may accelerate electrons; this scheme is called laser wake field acceleration (LWFA). Both PBWA and LWFA and some variants of this concept have been reviewed by Esarey [9]. Another subgroup of laser driven accelerator schemes is one that relies on “inverse of radiation mechanisms”: these are processes that under “normal” conditions generate electron radiation. When adequate conditions are set, electrons may be accelerated by monochromatic radiation from a laser. This is the case when using the inverse Cerenkov effect [10], the inverse Smith-Purcell effect [11], or the inverse of a free electron laser (I-FEL) [12].

In the past we suggested [13] combining the concept of a wake field associated with a bunch moving in a dielectric medium with the principles that enable the operation of a laser. The essence of the idea was to inject a charged particle in an active medium, and in this way energy stored in the medium can be transferred directly to the moving particle without prior generation of radiation. Theoretically, the feasibility of this process was proven and it may be interpreted in terms of stimulated radiation as follows: An electron moving in the vicinity of an excited atom “emits” a virtual photon, and the latter stimulates the atom. The two resulting photons are absorbed by the electron since the two are phase correlated and, as a result, the electron gains energy. This scheme was called particle acceleration by stimulated emission of radiation (PASER) and it may be conceived as the inverse of the Frank-Hertz effect. For the regime of a Frank-Hertz experiment, namely, one electron-atom collision (on average), the phenomenon was demonstrated experimentally by Latyscheff and Leipunsky [14] in 1930—the accumulative process is yet to be proven experimentally.

The advantage of this process, namely, the presence of a single bunch in the system, is to some extent also its disadvantage because of two contrary requirements: On one hand, for a large accelerating gradient, it is necessary to have in the bunch as many electrons as possible. And on the other hand, in order to get reasonable energy spread at the output of the acceleration region, the spatial width of the bunch has to be as small as possible on the scale of one wavelength. In practice, it is difficult to compress a large number of electrons (say, $\sim 10^5$ to $10^6$) in a submicron bunch, and in this Letter we propose a way to separate the problem of generation of the accelerating field from the difficulties associated with compression of a large number of electrons in the driving bunch.

For this purpose we examine the wake generated by a driving bunch in a resonant medium. When the medium is active, this wake is amplified to the point that the medium reaches saturation and it is this point where the accelerated (test) bunch should be located. Since this saturation is a result of the internal mechanism (rather than external illumination), we do not anticipate significant ionization to occur [15]. Contrary to regular plasma-laser schemes where the longitudinal (accelerating) electric field depends