Particle acceleration by stimulated emission of radiation near a solid-state active medium

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**Abstract**

We report acceleration of electrons moving in free space near an active Nd:YAG slab. The power of a non-relativistic beam of electrons has increased by more than 30% when the medium was excited. It is demonstrated experimentally that the energy gained by the electrons is linearly proportional to the energy stored in the medium. Moreover, the energy gain traces closely the population inversion inferred by monitoring the spontaneous radiation.

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In the case of particle acceleration by stimulated emission of radiation (PASER), a virtual photon, emitted by a free electron moving in the vicinity of an excited molecule, stimulates the latter and two identical photons are emitted. Subsequently, the free electron absorbs the two identical photons implying that the kinetic energy it gains, comes at the expense of the energy initially stored in the molecule. This stimulated radiation process leads to net acceleration provided the population is inverted. In other words, there are more excited atoms than atoms where the electron is in the ground state. We performed the proof-of-principle experiment of the concept with high-energy (45 MeV) electrons at the acceleration test facility (ATF) at Brookhaven National Laboratory employing an active gas mixture similar to that used in a CO2 laser [1–3]. This latter choice was dictated by the availability of a high-power CO2 laser that modulated the electron beam. As they traverse the active medium cell, some of the electrons gained up to 200 keV corresponding to about 2,000,000 stimulated photons absorbed by each such electron. This result was made possible in spite the relative modest amount of energy stored in the gas medium. It was the modulation of the beam which made the process relatively efficient: without modulation, the spectrum generated by the moving particles is very broad in comparison to the very peaked dielectric function of the medium. Consequently, the energy exchange, determined by the overlap of the two, is practically negligible. In this proof-of-principle experiment, the electrons were bunched so that the wave-spectrum of the beam is peaked and as a result, the overlap with the medium’s dielectric function was significantly enhanced.

Recently, we demonstrated theoretically a novel concept of bunching of a non-relativistic ensemble of electrons by energy stored in the active medium. The essence of this new paradigm [4] is to combine two well-known concepts: storage of charged particles in a Penning trap and storage of energy in active medium. In the absence of the latter, electrons oscillate in the trap for a time duration determined by the cross-section of interaction, by the density of remnant (hydrogen) atoms and by the typical energy of the oscillating electrons. For our purpose this time-duration can be considered as much longer than all the other temporal parameters in the problem therefore, this process was ignored. In the absence of an interaction between the electrons and the active medium, the active medium decays back to equilibrium with characteristic time $T_{eq}$. However, if the electrons become bunched, they drain energy from the medium and escape the trap. This paradigm, is inherently an injector that generates micro-bunches whose spacing is the optical wavelength of the resonant medium. The results presented in this study rely on a set-up which is designed for the experimental demonstration of the trap-configuration but as a first stage was tested for a one-pass process rather than multiple round trips as would be required in the case of the Penning trap.

Essentially, we demonstrate that even in absence of bunching the effect of the active medium on an individual particle may become measurable, provided the energy stored in the medium is significantly elevated. Moreover, an increase of more than 30% of electrons energy is feasible for non-relativistic electrons. A pivotal role in the present set-up plays a 10 cm long and 6 mm diameter Nd:YAG slab excited ($\lambda_0 = 1.064 \mu m$) by a 45 W, 808 nm diode. Not only the energy of a single photon is by a factor of 10 higher than that stored in a CO2 molecule, but also the density of the excited atoms is significantly higher ($> 10^{22} \text{m}^{-3}$). In parallel, the interacting electrons grazing the surface of the slab, have a typical...