Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

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(Received 4 June 2006; published 28 September 2006)

We report the first experimental evidence for direct particle acceleration by stimulated emission of radiation. In the framework of this proof-of-principle experiment, a 45 MeV electron macrobunch was modulated by a high-power CO2 laser and then injected into an excited CO2 gas mixture. The emerging microbunches experienced a 0.15% relative change in the kinetic energy, in a less than 40 cm long interaction region. According to our experimental results, a fraction of these electrons have gained more than 200 keV each, implying that such an electron has undergone an order of magnitude of $2 \times 10^6$ collisions of the second kind.

DOI: 10.1103/PhysRevLett.97.134801 PACS numbers: 41.75.Jv, 41.60.Cr

A growing demand for compact accelerators in medicine, nanoscience, and high-energy physics has triggered an intensive effort in search of novel acceleration concepts [1–15]. Presently, particles are accelerated by microwave radiation stored in a macroscopic cavity or in a series of coupled cavities, either one storing a few hundreds of joules. The maximum stored energy is limited primarily by the breakdown characteristics of the metallic surfaces. Operation at optical wavelengths [1–14] not only reduces but in many cases virtually eliminates this problem, and it obviously benefits from significantly more energetic photons. In all the various paradigms which use energy at optical wavelengths, the energy is stored in an active medium, eventually being converted into a laser pulse, facilitating acceleration according to the specific interaction mechanism. In this Letter, we report the first experimental evidence for direct particle acceleration by stimulated emission of radiation (PASER) [15–20], namely, energy stored in microscopic cavities (e.g., molecules) may be directly utilized for electron acceleration.

Motivated by the possibility of accelerating charged particles by radiation at optical wavelengths, we now take a closer look into the amplification (absorption) of radiation and acceleration (deceleration) of particles at the microscopic level. This brings us to the early days of quantum mechanics when Franck and Hertz [21] were the first to demonstrate (1914) that an electron moving in the vicinity of a mercury atom transfers part of its kinetic energy to a bounded electron in discrete amounts, causing it to jump from a lower to a higher energy state—as illustrated schematically in Fig. 1(a). Eventually, the bounded electron returns to its original level by spontaneously emitting a photon. Later, in 1930, Latyscheff and Leipunsky demonstrated the feasibility of the inverse process [22,23]. Relying on the fact that stimulated absorption of radiation reveals itself as a transition of the atom’s outer electron from a low to an upper energy state, they illuminated vapors of mercury with light from a mercury lamp. When a free electron was injected into the vapors, it was found that it may gain energy in quanta corresponding to that stored in the mercury atoms. In this process, the outer electron in the excited atom has dropped to the lower energy state, delivering the energy to the free electron—the process being known as “collision of the second kind” [22]; Fig. 1(b) illustrates schematically this process. Both the Franck-Hertz as well as the Latyscheff-Leipunsky experiments were designed for a single encounter of a free electron with a mercury atom, and, naturally, the electron’s energy gain (or loss) was of the order of a few electron volts.

It was only in 1958 that Schawlow and Townes [24] demonstrated the use of the energy stored in atoms for the amplification of radiation by a series of multiple collisions of the radiation with excited atoms. Nowadays, after another 50 years, it is the present Letter that provides the first experimental evidence of acceleration of electrons by multiple collisions with excited molecules. In order to clarify the concept, let us point out that what is well known as light amplification by stimulated emission of radiation (LASER) occurs when a photon of energy, corresponding to that of the excited atom, impinges upon the latter. The outcome is two identical photons and a nonexcited atom—see Fig. 1(c). Evidently, in order to attain a significant amplification, multiple collisions of this kind must occur. By analogy, Schächter [15–20] has demonstrated theoretically that successive particle acceleration by stimulated energy transfers.