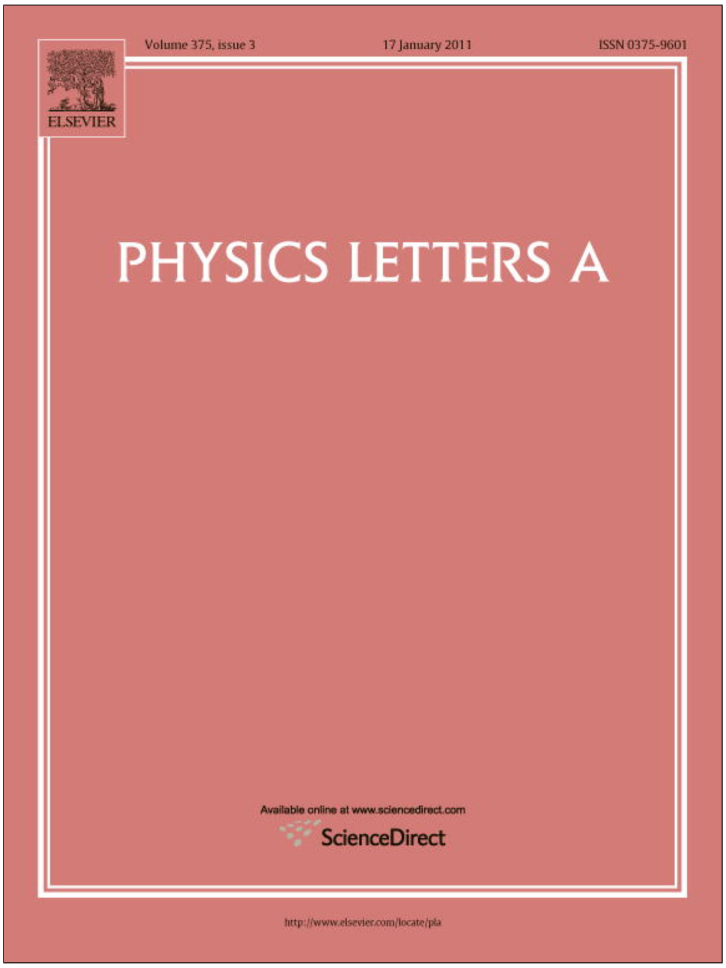
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Particle acceleration by stimulated emission of radiation near a solid-state active medium

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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.

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 accelerator test facility (ATF) at Brookhaven National Laboratory employing an active gas mixture similar to that used in a CO_2 laser [1–3]. This latter choice was dictated by the availability of a high-power CO_2 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 ($\lambda_0 = 1.064$ μm) 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 CO_2 molecule, but also the density of the excited atoms is significantly higher ($> 10^{22}$ m^{-3}). In parallel, the interacting electrons grazing the surface of the slab, have a typical

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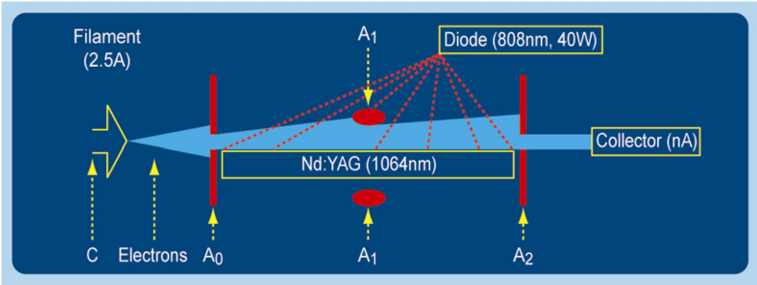

Fig. 1. Schematic of the set-up used to demonstrate particle acceleration by stimulated emission of radiation (PASER) with solid active medium; the dc current which heats up the filament is 2.5 A. In principle, the maximum power the diode can deliver at atmospheric pressure is 45 W but in vacuum we have never activated it with a current that corresponds to more than 40 W in vacuum. In fact, all the experimental data presented, was taken with a maximum 30 W at the output.

energy of a few hundreds eV's instead of 45 MeV in the experiment we performed at ATF.

A vacuum chamber maintains a base pressure of typically less than 3 μTorr and Fig. 1 illustrates the schematics of the system employed for the experimental demonstration. A filament of an electron-microscope is used for the generation of free electrons and its voltage relative to the vacuum chamber is kept negative (−90 V); about 4.6 mA of current are emitted by this cathode. Located 4 mm from the tip of the filament and having a positive bias of +30 V, the first anode (A_0) collects most of this current (3.63 mA). The remainder current enters the interaction region through a 1 mm diameter aperture whose lower edge is at the same height as the outer surface of the Nd:YAG slab allowing the electrons to graze its surface. In order to minimize the damage of impinging electrons to the rod, anode A_1 has a loop shape its diameter being 12 mm and it is held at about +560 V thus absorbing most of the remnant current (0.9 mA); A_1 is located in the middle of the rod 5 cm from both A_0 and A_2. The latter is held at a slightly lower voltage (+540 V) and it drains about 50 μA of the total current that enters the interaction region. A small fraction of the current leaves the interaction region through an aperture identical to the input one (in A_0). At 1 mm from A_2, in front of the aperture, a collector is located. It is held at about +100 V and if the slab is not excited, it measures 116 nA.

The vacuum chamber contains also the 45 W diode-laser (Coherent Ltd., Model FAP400-HT-45W-805.0, 808 nm, 1.93 nm FWHM) which pumps the Nd:YAG slab. For efficient heat dissipation, we attach the diode to the stainless-steel chamber wall and a high-power 400 μm diameter, 1 m long optical fiber guides the radiation. An aluminum parabolic reflector spreads the radiation uniformly along the slab on the side that faces the electrons.

With the set-up specified above, we performed two main sets of experiments. In the first case, the illumination was virtually *continuous* and each round typically lasted 2–3 min for ensuring that the system reaches equilibrium. In each round, the collector current was stabilized to the same value (116 nA) with zero pump, we then turned on the pump and the current-increase was measured. We changed the power of the pump and for each value the measurement was repeated three times – as summarized in Fig. 2. The latter clearly shows that the change in the collector current is proportional to the pump's power. In fact, since the voltage on the collector is kept constant, we may conclude that the power transferred to the electrons is proportional to pump power. Moreover, we observe that at 30 W we obtain an increase of 30% in the exchanged power. This is the first important result presented in this study.

Before we proceed to the second set of experiments an important comment is in place: Two factors determine the actual number of accelerated electrons: the geometry and the location of the anodes on the one hand, and the effective number of electrons that are actually affected by the active medium on the other hand. While we made no attempt to optimize the former, the latter needs to be clarified. A virtual-photon emitted by the free electron, decays exponentially in the direction perpendicular to electron's motion. As a result, only those electrons that traverse at a distance of the order of $\Delta_{\rm int} \sim \lambda_0 u/c$ from the surface of the active medium, are expected to interact. Consequently, only a small fraction of the electrons is expected to be accelerated; u represents the characteristic velocity of the electron. For example, if the beam width is denoted by $\Delta_\perp$ and its height by $\Delta_{\rm h}$ then the effective area of the interacting beam is $\Delta_\perp \Delta_{\rm int}$ or nominally, only $\Delta_{\rm int}/\Delta_{\rm h}$ of the electrons interact with the active medium.

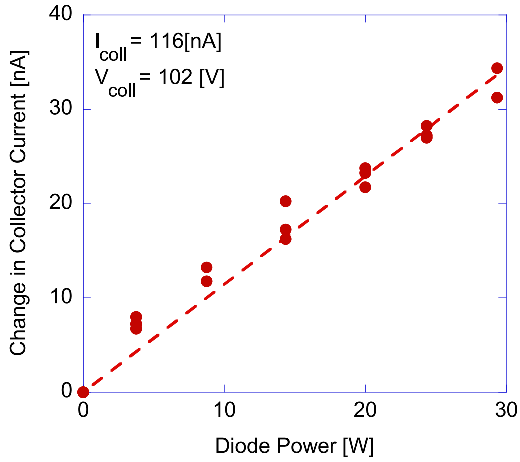

Fig. 2. The change in the collector current as a function of the pump power. Since the charge density is not expected to vary, the change in the current is due to the increase in the velocity of the electrons.

Our next step is to examine the "inertia" associated with the process. Rather than cw operation we operate the diode in *pulse* mode; specifically, we can generate 1 ms long pulses with a repetition rate of up to 1 kHz. Two quantities associated with the diode can be directly measured outside the vacuum-chamber: the driving current of the diode is illustrated in the upper (yellow) of Fig. 3 – this was measured with a Pearson (Pearson Electronics Inc., Model 4100) current monitor. Its peak value is directly related to the pump power however, we focused our attention on the start time of each pulse as reference to the spontaneous emission pulse and the change in the electrons current, due to activation of the diode, as measured on the collector.

The second quantity we monitored, is the spontaneous radiation from the Nd:YAG as illustrated by the middle curve (blue). A 1064 nm filter (Edmund Optics R43-101) is placed in front of an optical detector (Thorlabs PDA55 with a response-time of 20 ns). In principle, this curve has a characteristic rise/decay time that, at low pump levels (25 W), is of the order 200 μs whereas at high power levels (40 W pump), this characteristic time is more than

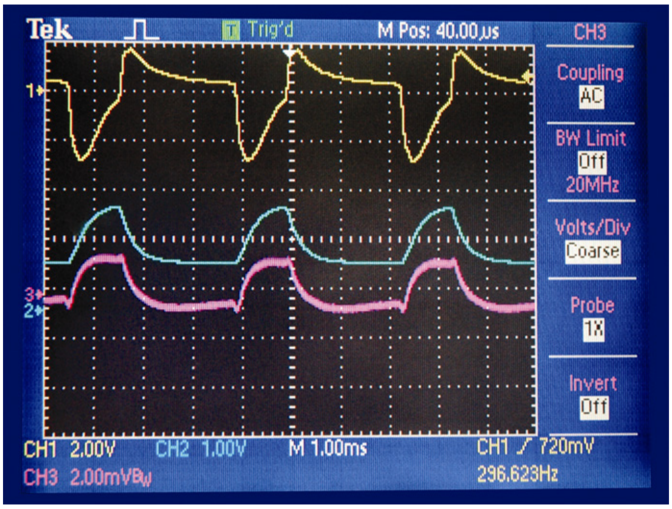

Fig. 3. The dependence of the diode current (upper curve, yellow), intensity of 1064 nm radiation intensity emitted by Nd:YAG (middle curve, blue) and the collector current as a function of time. For the experimental result presented here, the diode output was 28 W and the pulse duration was 1 ms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

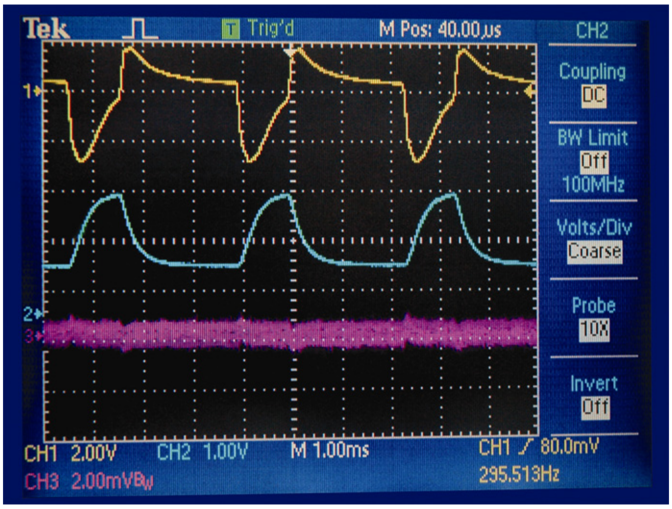

Fig. 4. The collector current in conditions similar to that of Fig. 3, except that the filament current is zero. No indication of photo-electrons or inductive coupling. For the experimental result presented here, the diode output was 28 W and the pulse duration was 1 ms.

twice this value. Superimposed in the same frame, we present the change in the collector current (bottom/pink curve) due to the activation of the Nd:YAG medium. This is the second important result of this study: in spite the fluctuations associated with the space-charge present in the vicinity of the anodes, we observe that the excess of current follows the spontaneous radiation which in turn is proportional to the population inversion.

In order to rule out the possibility of photo-electrons playing a role in this configuration we repeated the experiment with zero current from the filament and maximum sensitivity (110 V) on the collector. The result is illustrated in Fig. 4. It is evident that the collector current is zero and there is no indication of either photo-electrons or inductive coupling; this test was performed also for the continuous illumination case with similar conclusion regarding the photo-electrons.

Two results warrant a brief theoretical consideration: the measured current and the energy gained. For a rough quantitative explanation of these results, let us consider an electron moving with a velocity u at a height h from the Nd:YAG slab. This height, is assumed to be much smaller than the resonant wavelength $h \ll \lambda_0 u/4\pi c$. The glass is doped with 1.1% atoms of Nd corresponding to a maximum theoretical density of $n_{\mathrm{Nd}} = 1.5 \times 10^{26}\ \mathrm{m}^{-3}$. In our configuration it is difficult to assess exactly the population inversion density (Δn) however, the n_{Nd} is evidently an upper value for the former. For a more precise estimate, consider the upper value of the actual pumped energy (30 W). The length of the slab (L) is 10 cm and its diameter 6 mm (thus its volume is $V \sim 3 \times 10^{-6}\ \mathrm{m}^3$). Bearing in mind that the spontaneous life-time is of the order of 230 µs then assuming the efficiency of the pump is 100%, the population inversion density is $\Delta n = P_{\mathrm{pump}} T_{\mathrm{sp}}/\hbar\omega_0 V \sim 1.2 \times 10^{24}\ \mathrm{m}^{-3}$. The stimulated emission cross-section for Nd:YAG is $\sigma_{\mathrm{st}} \simeq 1.8 \times 20^{-22}\ \mathrm{m}^2$ consequently, the number of collisions an electron encounters is $\Delta n \sigma_{\mathrm{st}} L \sim 22$ therefore it gains about 25 eV on top of the $\sim$100 eV associated with the collector voltage. This is comparable with the 30% increase in the power linked to current increase as reflected in Fig. 2.

A second estimate is that of the characteristic current affected by the active medium. In our experiment, the typical current emitted by the filament is of the order of a few mA's ($I_{\mathrm{F}} \simeq 4$–5 mA); for simplicity sake, we ignore the effect of the exact geometry and location of the anodes. For the present purpose, we need to bear in mind that the spectral component of the longitudinal electric field associated with an electron moving in free-space at a constant non-relativistic velocity u is $E_z(r,\omega_0) \propto K_0(\omega_0 r/u) \propto \exp(-\omega_0 r/u)$ where $\omega_0 = 2\pi c/\lambda_0$ is the resonant frequency of the medium. If the electron is at a height h from the surface of the active medium, whatever impact the medium has on the particle, it is proportional to $\exp(-2\omega_0 h/u)$. Due to this exponential decay, the effective impact of the medium on the electron is suppressed by a factor $\exp[-2(2\pi c/\lambda_0 u)h]$ therefore, the typical current that is actually affected by the medium is

$$I_{\mathrm{eff}} = J\Delta_\perp \int_0^{\Delta_h} dh\, \exp\left[-2\left(\frac{2\pi}{\lambda_0 u/c}\right)h\right] = I_{\mathrm{F}} \frac{1}{4\pi}\frac{\lambda_0}{\Delta_h}\frac{u}{c}. \tag{1}$$

For a typical anode/collector voltage of a few hundreds volts ($u/c \sim 10^{-2}$) and a beam of about 1 mm thickness, this current is less than 10 nA in accordance with the currents we measured on the collector (0–30 nA).

In conclusion, electrons may be accelerated when moving in near a solid-state active medium. The force exerted on a single electron is proportional to the population inversion. Up to 30% increase in the beam power was observed when the grazing electrons were moving parallel to an active Nd:YAG slab. Although, in this non-relativistic regime the number of accelerated electrons is miniscule, in a relativistic regime, where the exponential decay, $\exp(-4\pi h/\lambda_0 c\beta\gamma)$, is negligible the number of interacting electrons and the number of stimulated Nd atoms may increase exponentially by many orders of magnitude. In order to grasp the potential of this non-relativistic, top-table result let us assume that a similar percentage of energy transfer occurs at relativistic energies [5]. In the Nd:YAG slab it is possible to store order of 100 Joules. Consider now a 30 GeV–1 nC beam similar to the one planned to be operational next year at SLAC/FACET. Such a beam carries 30 Joules of energy. Subject to our previous assumption and ignoring fluence constraints, a similar experiment as that reported here, may lead to energy doubling along the 10 cm long slab.

Acknowledgements

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