FIRST EXPERIMENTAL EVIDENCE FOR PASER: PARTICLE ACCELERATION BY STIMULATED EMISSION OF RADIATION*

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Abstract

Franck and Hetrz in 1914 were the first to demonstrate that free electrons can be decelerated by mercury atoms in discerete energy quanta. In 1930 Latyscheff and Leipunksy have demonstrated the inverse effect namely, free electrons can be accelerated by energy stored in the mercury atoms (collision of the second kind). It was only in 1958 that Schawlow and Townes have used multiple collisions between photons and excited atoms to amplify radiation (MASER and LASER). In 1995 Schächter suggested to use excited atoms for coherently accelerate particles. The results of a proof-of-principle experiment (2006) demonstrating the PASER scheme are reported here. Performed at the BNL-ATF, the essence of the experiment is to inject a 45MeV density modulated electrons' beam, bunched by its interaction with a high-power CO_2 laser pulse within a wiggler, into CO_2 excited molecules cell. The electrons experienced 0.15% relative change in their kinetic energy, in less than 40cm long interaction region. The experimental results indicate that a fraction of these electrons have gained 200keV each, implying that such an electron has undergone two-million collisions of the second kind. Hence, this is the first experimnetal demonstration of coherent collisions of the second kind.

ESSENCE OF THE PASER

The Concept

For decades, the particle acceleration community has been persisting in searching for novel acceleration concepts [1]-[11] aiming to develop a new generation of *compact* particle accelerators, that could one day become a commonplace tool to be utilized in widespread applications ranging from medicine, material science, molecular biology and nanoscience to high-energy physics. Nowadays, particles are accelerated by microwave radiation stored in either a *macroscopic* cavity or series of coupled cavities, each storing a few hundreds of joules. The maximum energy stored in these cavities is mainly limited by breakdown and surface properties of metals. By operating at *optical wavelengths* the latter setback is bargained, and in many cases it is practically removed. So far, in all the different schemes, except the PASER, which use energy at optical wavelengths, the latter is stored in an active medium being ultimately converted into a laser pulse that, in turn, facilitates the acceleration according to the specific laser-electron interaction mechanism of the scheme. The PASER is the only acceleration scheme in which energy stored in *microscopic* cavities such as molecules is utilized *directly* for particles acceleration. Being able to accelerate particles without a direct need for a laser pulse within the interaction region eliminates the synchronization difficulties associated with other schemes, and therefore, making the PASER staging natural.

Historical Background

During the first three decades of the 20th century, scientists were intrigued by different phenomena associated with the interaction of atoms with photons and/or electrons. Motivated by Niels Bohr postulates of quantum mechanics leading to discrete energy states, Franck and Hertz (FH) [12] were the first to demonstrate experimentally that atoms can absorb energy from a moving free electron only in discrete quanta. They have shown that a mercury atom is raised from a lower to a higher quantum-state by using the kinetic energy of a swiftly moving electron – as illustrated schematically in frame (a) of Fig. 1. Later (1921) Klein and Rosseland [13] have coined the name of this process as "collision of the first kind". A decade later (1930), Latyscheff and Leipunsky (LL) demonstrated the inverse process [14]-[15]. Relying on the fact that stimulated absorption of radiation exhibits itself as a transition of the atom's outer electron from a low to a higher 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 and thus, raising its velocity – due to the analogy to the former, this process was called "collision of the second kind" [13],[15]; frame (b) in Fig. 1 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; hence, the electron's energy gain/loss was of the order of a few eV's. It was only in 1958, that Schawlow and Townes [16] demonstrated that the energy stored in atoms may be used for amplification of radiation by a series of *multiple* collisions of photons (the radiation) with excited atoms.

PASER-LASER Analogy

The recent PASER experiment [17]-[18] conducted at the United States Department of Energy Brookhaven National Laboratory Accelerator Test Facility (BNL-ATF), provides the first evidence for acceleration of electrons by multiple collisions with excited molecules i.e., an *accumulative* interaction takes place. In order to

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further clarify the concept, let us point out the analogy between the PASER and the well-know light amplification by stimulated emission of radiation (LASER). The latter process occurs when a photon of energy corresponding to that of an excited atom/molecule impinges upon the latter. As a result, two identical photons are obtained, and ultimately the excited atom/molecule gets back to its non-excited state – See Fig. 1 (c). Obviously, in order to reach a considerable light amplification, coherent multiple collisions of this kind must take place. By analogy, Schächter [11] has demonstrated theoretically that successive particle acceleration by stimulated emission of radiation may also take place. Frame (d) in Fig. 1 elucidates schematically the interaction from the perspective of a single atom: a *macrobunch* of electrons emits a virtual photon impinging upon an atom, and as a result, a real photon is emitted from the atom. The two resulting photons are absorbed by the bunch since their phases are identical, and consequently, the electron's kinetic energy increases; obviously, by the end of the process, the atom returns to its ground-state. According to the 200keV gain in electron's kinetic energy, as subsequently reported here, and since each CO_2 molecule stores about 0.1eV, such an electron has undergone about two-million coherent collisions of the second kind.

Based on the aforementioned LASER analogy, one should be aware of the fact that the electron-medium interaction is narrow-band and on the other hand, from the perspective of a single electron it is quite clear that in the laboratory frame of reference, its spectrum is broad-band. Hence, the effect of the medium on its kinetic energy is expected to be miniscule. In order to overcome this drawback, rather than injecting a single macrobunch of electrons, a train of *microbunches* has been launched – its periodicity being identical to the resonance of the medium. Consequently, the electromagnetic wake-field component of the train corresponding to the resonant frequency of the medium becomes dominant. The main purpose behind the current experiment, its results we report in what follows, was to demonstrate this fundamental effect.

Before proceeding to the experiment's description, it is enlightening to examine this novel concept from a slightly different perspective. In essence, any *macroscopic* process that generates radiation may be utilized to accelerate charged particles. For example, when an electron moving in a medium, exceeds the characteristic speed of light in the latter, it generates the so-called Cerenkov radiation that propagates at a specific angle, relative to the electron's trajectory, and therefore, the electron is decelerated. Illuminating the interaction region by an intense laser beam at the Cerenkov angle may lead to the electron's acceleration, assuming phase matching between the latter and the laser pulse [25]. The experimental results reported here, indicate for the first time, that the inverse of the LASER effect, i.e. PASER, may also be used to accelerate electrons.

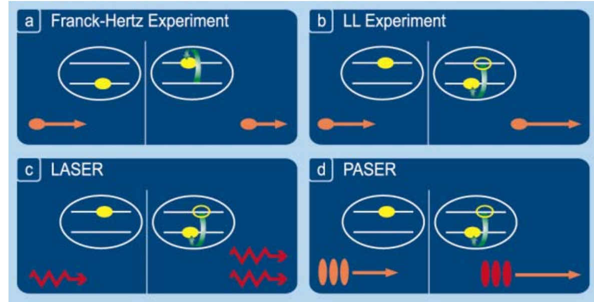

Figure 1: Illustration of light-electron-atom interaction. (a) The Franck-Hertz experiment, in which an electron is decelerated as it transfers energy to a bound electron. (b) The Latyscheff-Leipunsky experiment, in which a free electron is accelerated by energy transferred from a bound electron. (c) Light amplification by stimulated emission of radiation (LASER). (d) Particle acceleration by stimulated emission of radiation (PASER).

PROOF-OF-PRINCIPLE EXPERIMENT

Experimental Setup

The PASER experiment, its schematic layout illustrated in Fig. 2, was conducted at the BNL-ATF. A quasi-mono-energetic electrons macrobunch of an energy of ~45MeV, of 5psec duration and consisting of at least 7×10^8 electrons, was injected into a wiggler where it was bunched into about 150 microbunches by its interaction with a high-power CO_2 laser pulse (200psec,~0.5GW), operating at a wavelength of 10.2μm . A 2.5m long drift region separates the wiggler from the PASER cell. Along this drift region the velocity modulation emerging from the wiggler becomes density modulation at the entrance to the cell. The former is controlled by the intensity of the CO_2 laser pulse, and in our particular setup a ~1.5% peak-to-peak energy modulation, at the wiggler, was found to generate optimal density modulation in the PASER cell. Either stronger or weaker modulation at the wiggler, lead to less than optimal modulation, at the location of the interaction with the active medium and thus, smaller acceleration.

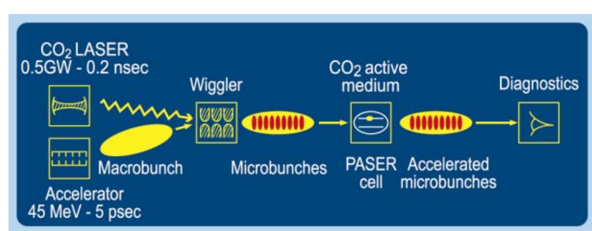

Figure 2: Schematic layout of the PASER experiment. The distance separating the wiggler from the PASER cell is about 2.5m.

Next, the train of microbunches enters the PASER cell that contains a mixture of CO_2 [CO_2:N_2:He(2:2:3)], held at a pressure of 0.25atm, activated by a 1μsec discharge driven by a 130nF low inductance capacitor, initially

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charged to 30kV. The discharge is facilitated by two 40cm×12cm aluminum electrodes which are 2.5cm apart. Two diamond windows of 1mm diameter and 2μm thickness are attached to both ends of the cell, in order to maintain the pressure in the cell and at the same time, to allow the train to propagate through the cell.

Characteristics Parameters

For the typical values mentioned above, electrical measurements (voltage and current) of the discharge, indicate that the *total* energy density stored in the mixture is, at the most, of the order of $0.1\mathrm{J/cm}^3$. Only a small fraction of this energy-density is associated with the resonance of the CO_2 molecule at 10.2μm therefore, assuming a potential efficiency (as an amplifier) of 1% we estimate the energy-density available at 10.2μm to be of the order of $1\mathrm{mJ/cm}^3$. Based on this estimate, in the volume covered by a beam of radius of 150μm, the available energy is of the order of 70μJ. However, the field associated with a relativistic bunch covers an area which effectively is γ^2 larger than the geometric beam cross section. In practice, in the vertical dimension the expansion is limited by the electrode spacing therefore, the available energy is about 200mJ. This value should be compared to 5mJ kinetic energy of the train.

Beyond the energy estimates, it is important to clarify also the time scales involved. As the gas mixture is excited, its population is inverted, and being in a meta-stable state, the population inversion decays on a time-scale of milliseconds. Furthermore, the train of microbunches has been injected with a delay of about 10μsec after the discharge was fired. Consequently, the variations in the energy stored in the medium due to jitter (~0.5μsec), are negligible. Due to various external constraints, no focusing magnetic field could be applied on the 40cm long PASER cell and, as a result, the internal repulsion forces, scattering in the input window, as well as scattering from the gas mixture, are responsible for a transmission of only 60% of the electrons i.e., about 4×10^8 electrons were measured at the spectrometer. This is consistent with a Coulomb beam divergence of 3mrad as evaluated theoretically.

Experimental Results

In Fig. 3 the raw output from the spectrometer for discharge-off and discharge-on is presented; the energy dispersion is in the horizontal plane. Evidently, the energy spectrum in frame (b) is broadened to the left in comparison to the spectrum in (a), corresponding to an energy increase of about 0.45% i.e., 200keV. Without any data processing we clearly observe the impact of the discharge on the modulated beam, and as we shall discuss subsequently, the absolute value of the energy gain is in accordance with theoretical predictions.

The energy spectra, corresponding to the raw images of the spectrometer introduced in Fig. 3, are presented in Fig. 4(a). In order to facilitate proper comparison between the two spectra, both curves were normalized to describe the density-probability of finding an electron in the range $E \to E + dE$ or in other words, the area below each one of the curves is unity. Examining the two curves we conclude that the energy spectrum with the discharge-on is wider than that with the discharge-off. Moreover, the peak of higher-energies in the case of discharge-on is shifted towards higher energies, in comparison to the corresponding peak when the discharge is off. This shift is an even clearer indication for particle acceleration due to the interaction with the excited gas. Based on these curves, we evaluated the relative change in the kinetic energy of the macrobunch (discharge on/off) estimating it to ~0.15% which corresponds to an increase of ~5μJ in the kinetic energy. In order to further emphasize the signature of the accelerated electrons, in Fig. 4(b) we plot the difference between the spectra presented in Fig. 4(a).

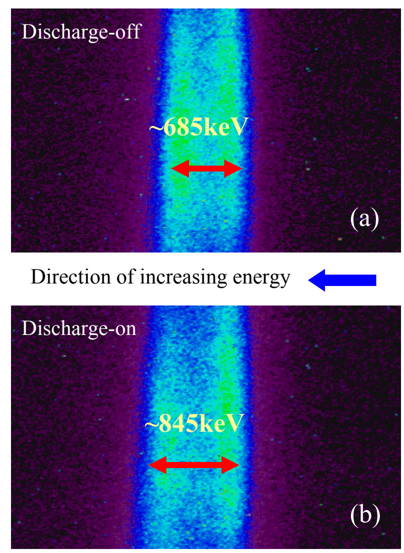

Figure 3: Single-shot electrons beam raw output from the spectrometer with and without discharge in the PASER cell. The horizontal direction corresponds to energy levels increasing from right to left. (a) Raw image without exciting the gas in the PASER cell. Peak-to-peak energy spread of ~685keV is measured. (b) Raw image with the gas excited in the PASER cell. Peak-to-peak energy spread of ~845keV is measured.

EXPERIMENT VERSUS THEORY

A deeper insight into the effect of the various parameters may be developed based on a relatively simple 2D analytic model [18], describing the interaction of a train of azimuthally symmetric microbunches traversing an active medium. In this model we have established the total energy transferred to the macrobunch as it traverses a resonant medium, which macroscopically describes an ensemble of a two-state quantum system i.e., single resonance is considered. Fig. 4(c) shows the relative energy-change in the electrons' kinetic energy versus the energy density stored in the medium at resonance for different beam radii, as well as for different interaction lengths, in all cases, the total amount of charge is kept the same. Obviously, optimal energy exchange occurs for energy densities of the order of ~1mJ/cm^3. Moreover, we observe that by keeping the charge in the train constant, the energy exchange drops when increasing the beam radius; the opposite holds if the charge density is kept constant. Furthermore, for a quantitative estimate of the relative energy gain in our experiment, three parameters need to be established: (i) the effective beam radius (R_b), as the latter changes within the cell due to scattering, as well as due to self-repulsion, (ii) the effective energy-density stored at the resonance frequency and finally (iii) the effective interaction length (d), where this effective energy-density is contained; however, edge effects may reduce this length relative to the geometric length of the electrode. We do not have an exact value for either one of these three parameters, but we have reasonable estimates that enable us to plot the region in these parameters' space, where our system operates. The ellipse in Fig. 4(c) presents the range of experimental kinetic energy gain versus the estimated range of stored energy, interaction length and beam radius. According to this estimate, and relying on our model, a maximum relative change in the kinetic-energy of ~0.05-0.17% is anticipated thus, our experimental estimate (~0.15%) is within the range predicted by the theoretical model. In what follows, we discuss the main considerations allowing us to determine these parameters.

A. Bunch Modulation: In practice, only about 50% of the total amount of charge injected is actually modulated as the bunch traverses the wiggler [20] therefore, at the most, 50% of the electrons collected at the spectrometer may have experienced acceleration -- as our model indicates no net energy exchange is achieved in the absence of modulation. Moreover, with the former observation in mind, only about 2×10^8 of the electrons should be considered.

B. Bunch Radius: The increase in kinetic energy predicted by the plot in Fig. 4(c) is consistent with an effective beam's radius of the order of $\sim 150 \div 200\mu\text{m}$, which also corresponds to the estimate of the measured transmission at the exit from the PASER cell.

C. Effective Interaction Length: The geometrical length of the electrodes that generate the discharge is 40cm. But since the spacing is of the order of 2.5cm, it would be reasonable to conclude that edge effects may dominate the first 2.5-5.0cm close to each one of the two ends. Consequently, an effective interaction length of 30-35cm would be a reasonable estimate.

D. Resonance Selection: In spite the fact that any medium has many resonances, our assumption that a single resonance plays the dominant role in the interaction, proves to be justified experimentally. Having a relatively long train (150 microbunches), provides us with the necessary selection mechanism to suppress the interaction with the nearest resonance ($9.2\mu\text{m}$) of CO_2 molecule. Based on the resonances separation, we found that, provided the number of microbunches is greater than 30, the existence of the additional resonance may be ignored.

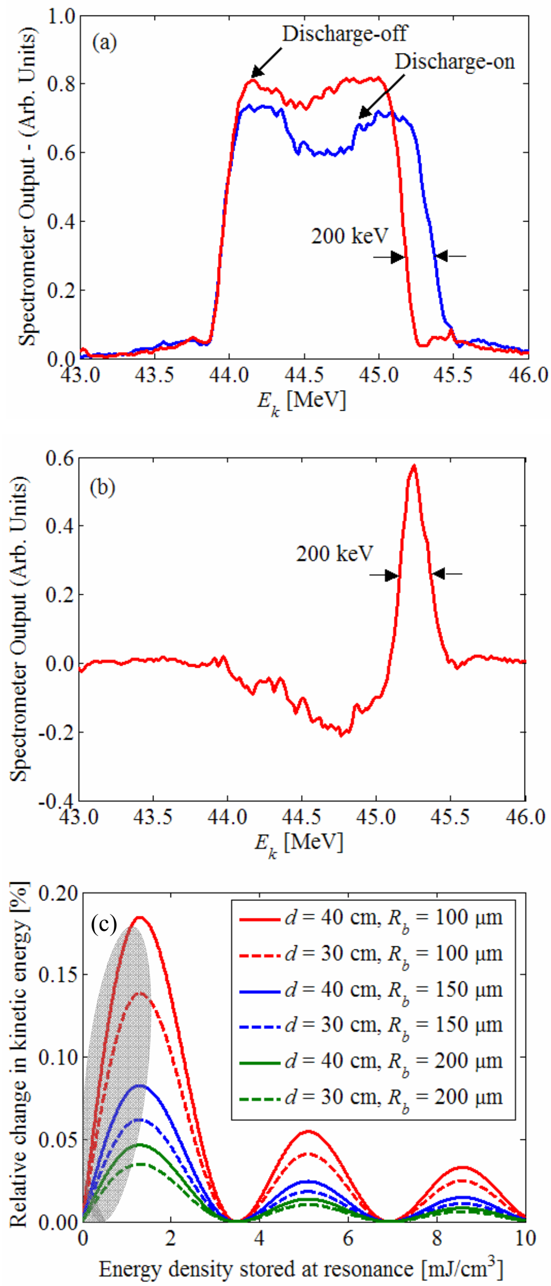

Figure 4: Single-shot energy spectra with and without discharge. The energy modulation (peak-to-peak) of the train of microbunches is ~1.5%. (a) Probability-density versus energy level [MeV] while discharge is on/off. (b) Probability-density difference (Discharge on – Discharge off). (c) The relative energy-change of the electrons as they traverse through an active medium versus the energy density stored in the medium at the resonance frequency for different radii of the macrobunch as well as for different interaction lengths. As the tail of the macrobunch is shallow we assume that the effective number of microbunches is 120.

DISCUSSION AND FUTURE DIRECTIONS

PASER is a novel technique for accelerating relativistic electrons. Two main features distinguish this technique from any other advanced acceleration scheme. First, unlike other schemes that require some type of driving source (e.g. multi-TW laser beam, sub-picosecond electron bunch), PASER only requires a train of electron microbunches with a spacing between microbunches corresponding to the transition wavelength of an active medium, such as an excited gaseous medium. The accelerated electrons extract the energy directly from the active medium via a stimulated emission process. Second, the acceleration process doesn't require any phase matching between the accelerated electrons and the active medium. This degree of freedom makes staging of PASER acceleration cells a natural process.

The proof-of-principle experiment was not designed to demonstrate high gradients nor large energy gain. By improving the current PASER system we are anticipating to increase the accelerating gradients by at least one order of magnitude. To do so, the following improvements are conceived for the near future. (I) Confinement of the *e*-beam traversing through the PASER cell by applying permanent magnets. (II) Increasing the total charge in the beam. (III) Increasing the gas pressure within the PASER cell. Hence, increasing the energy density stored in the excited gas. (IV) Achieving more efficient excitation of the active medium. Based on our theoretical model, it is possible to adjust the number of microbunches in the macrobunch and the energy density stored in the medium, by varying the different parameters of the system, in order to achieve optimum performance in which gradients of the order of 100MV/m are obtainable.

To further boost the gradient revealed by the PASER scheme one could use solid-state active medium. Harnessing solid-state active medium has two major benefits compared to the current CO_2 medium. First, more energetic photons as well as higher population inversion densities. For instance, by using Nd:YAG as an active medium the energy-density of the medium may be increased at least by two orders of magnitude. The second inherent advantage of using solid-state based PASER system is that the electrons will travel through a vacuum channel embedded within the solid-state lattice eliminating gas and window scattering. Although we are anticipating, based on theory, gradients of the order of 1GV/m in such systems, there are two main challenges to be addressed in the future. The first is to achieve density modulation of the macrobunch at short wavelengths $(\sim 1\mu\mathrm{m})$. Second, bearing in mind that the wake-field associated with the *e*-beam drops off exponentially with radius, as the electrons travel in a vacuum channel bored in the active medium, they either need to travel very close to the surface of the medium or they have to be ultra-relativistic (GeV range).

In conclusion, we have demonstrated experimentally *direct* particle acceleration by stimulated emission of radiation (PASER). In the framework of this proof-of-principle experiment, the overall gain in the kinetic energy of a 0.1nC-45MeV bunch was more than 0.1%, corresponding to about two-million coherent collisions of the accelerated electron with the excited atoms of CO_2 mixture. This paradigm paves the way to a new scheme of particles acceleration operating at the optical regime, which may be efficient and thus, utilized for the design of compact drivers for a future X-ray source.

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