## Title
Direct longitudinal laser acceleration of electrons in free space: supplemental document



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*Abstract* – To understand direct longitudinal laser acceleration, fundamentals of laser, energy transfer, photons propagation along the longitudinal axis, medium of travel, and amplification must be understood. All these factors contribute to achieving direct laser-driven particle acceleration that is coherent and collimated.

## 1. INTRODUCTION

Lasers are widely used due to their coherent behavior and ability to produce collimated electron bunches by longitudinal laser. The laser field can manipulate particles in any medium by interacting with a focused linearly polarized optical beam to create laser-accelerated electron bunches. This method of using laser as an accelerator is pursued more than conventional accelerators because of its compactness and efficiency.

## 2. FACTORS CONTRIBUTING TO DIRECT LONGITUDINAL LASER ACCELERATION

Achieving direct longitudinal laser acceleration requires highly directional longitudinal laser acceleration of electrons [1]. This involves attaining strong longitudinal energy transfer [1], meaning the electromagnetic field that induces electric polarization in the medium must have a strong energy transfer rate to the medium. This can be expressed as the power density expended by the electromagnetic field on the polarization [2], given by the quantity

$$W_p = \boldsymbol{E} \cdot \frac{\partial \boldsymbol{P}}{\partial t} \tag{1}$$

where $\boldsymbol{E}$ is the electric field and $\boldsymbol{P}$ is the electric polarization.

Having high energy transfer in the medium is one important factor but enhancing polarized beam in the forward direction along the optical axis while interacting with generated electron bunch gives the longitudinal effect which is another important factor in driving the electrons in a collimated manner, ideal for maximizing longitudinal laser acceleration.

Breaking this down, first, laser light is formed by laser oscillation happening along a longitudinal axis with the help of an optical resonator. A laser is a device in which several atoms vibrate to produce a beam of radiation in which all the waves have a single wavelength and are in phase with each other. Creating a laser beam involves using stimulated emission to amplify light and having an optical resonator such as the Fabry-Perot resonator helps to create a narrow beam of coherent light. In addition, stimulated emission means that there would be emission of two photons from an excited atom where both the incident photon and second photon have the same frequency, direction, phase, and polarization. Applying population inversion at the active region also helps in the sense that a higher energy level will give off a photon of a certain wavelength and drop to the ground state. This photon, however, can stimulate the production of other photons of the same wavelength because of stimulated emission of radiation. Thus, many photons of the same wavelength, phase, and other similar characteristics can be generated in a short time. This high-energy radiation contributes to a strong laser field which can be accelerated.

Second, in order to have a laser accelerator, any laser oscillation must be eliminated by efficiently amplifying in the longitudinal direction. This means emission of any spontaneous photons must propagate along the longitudinal axis with merely a small divergence angle as the wiggle room, decided by the resonator. This is done strictly so that any oscillating laser field is amplified efficiently, which is crucial for resulting in laser acceleration along the longitudinal field.

Laser oscillation must be in a steady-state to maintain a constant coherent laser field which means there cannot be any additional external optical field input when there is an intracavity optical field present in the cavity. The intracavity field is along the longitudinal axis inside the optical cavity, chosen here to be at any location on the z-axis.

To create a medium of free space or vacuum which is optimal for electron acceleration, there must be a high frequency above all resonance frequencies so that there is no dispersion of electrons which limits the bandwidth of the transmission of an optical signal, as this laser field. On top of this, creating well-collimated electron bunches could be done with a collimated Gaussian model in a homogeneous medium with minimal limitation to achieve strong longitudinal energy transfer [1]. For the Gaussian beam to remain well collimated, it must be within Rayleigh range given by

$$z_R = \frac{kw_0^2}{2} = \frac{\pi n w_0^2}{\lambda} \tag{2}$$

where $k = \omega\sqrt{\mu_0 \epsilon}$ is the propagation constant of optical beam in a medium of a refractive index $n$ and Gaussian beam spot size, $w_0$ [3].

## 3. CONCLUSION

Attaining direct longitudinal acceleration of nonrelativistic electrons in free space [1], requires a strong energy transfer in the medium, along with oscillating laser beams focused along the longitudinal axis to interact with the electron bunches. The laser accelerator is capable of operating in a vacuum medium to result in highly directional laser-driven acceleration.

## 4. ACKNOWLEDGMENTS

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[3] Liu, Jia-Ming. “Optical Wave Propagation.” *Principles of Photonics*, Cambridge University Press, New York (2017).