GeV range particle accelerators using laser wakefield acceleration in plasma

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Introduction

Interaction of high intensity laser pulse with plasma is becoming popular field of research for designing and developing future particle accelerators in the high energy range. Particle accelerators based on relativistic electron beam / laser pulse injection can be used to create high electric field gradient up to the order of TeV/m which can be very useful in study of high energy physics phenomena and understanding the formation of universe [1,3]. Laser wakefield based accelerators can be substitute of kilometer long conventional accelerators facilities at CERN, BELLA or SLAC [2,4,5]. Such accelerators can be designed in a small space and are economically viable for scientific organizations.

Present study deals with nonlinear interaction of high intensity laser pulse with plasma which is responsible for generating electrostatic plasma oscillations which in turn generate wakefields in the plasma. These high gradient wakefields are further used to accelerate injected electrons or any charged particles trapped in the wake. Acceleration and speed gained by such trapped charged particles is directly proportional to the magnitude of wakefield gradient.

Mathematical Formulation

Consider a linearly polarized laser pulse represented by $\vec{E} = \hat{z}E(r,x,t)\cos(kx - \omega t)$ where pulse profile of the laser beam is $E(r,x,t) = E_0 \exp\left(-\frac{y^2+z^2}{2}\right)\sin\left(\frac{\pi L}{2}\right)$. When a laser pulse having above profile propagates through a homogenous plasma, then it creates quiver momentum among plasma ions and electrons. Due to the quiver momentum and resulting ponderomotive force, electrons which have mass much less than ions are pushed away under the effect of laser electric field but pulled back due to this electrostatic attraction between immobile ions and electrons. Due to attractive force, electrons approach towards ions but overshoots them due to their high velocity. Such phenomena happen again and again, which sets up plasma oscillations in medium. These oscillations have frequency nearly equal to frequency of laser beams hence responsible for generating high electric field gradient called wakefields. These wakefields are of the order of $10^9 – 10^{12}$ V/m and enough for generating energy gradient of order of TeV/m. Using the above discussed mathematical formulation, following results are discussed.

Figure 1 shows phase space diagram of laser pulse propagating in x - direction in a plasma having density ~ 7.7e+24 /m^3.

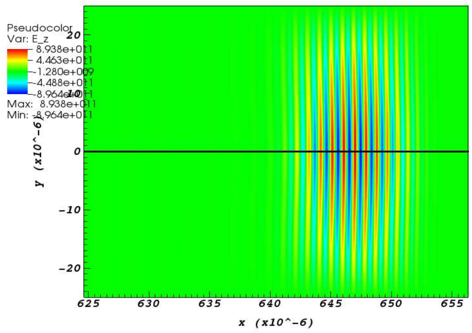

Fig.1 Femtosecond laser pulse having sine profile propagating in plasma.

Figure 2 shows 2-D diagram of sine pulse profile of the laser pulse propagating in x-direction having magnitude of electric field of the order of 10^{12} V/m

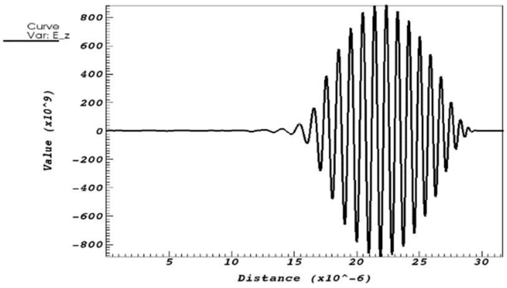

Fig.2 Sine pulse profile of laser beam.

Maximum wakefield amplitude for sine pulse profile can be obtained by using pulse length L ~ λp (i.e. 12 micron), where λp is plasma wavelength.

Figure 3 shows phase-space diagram of maximum wakefield generated in axial direction (along X-axis).

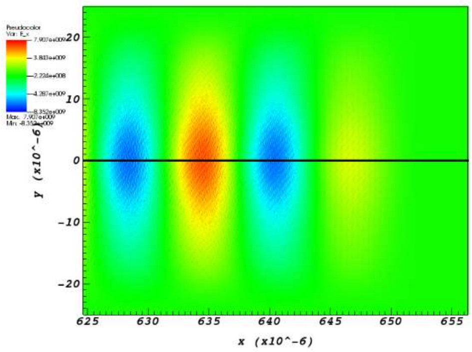

Fig.3 Axial wakefield of magnitude 7.9 x 10^9 V/m generated along x-axis.

Figure 4 shows sinusoidal variation of wakefield behind the pulse. Electrons trapped in such wakefield will gain approximate energy equals ~ qEd, where d is accelerator length, E is wakefield amplitude and q is charge of the particle.

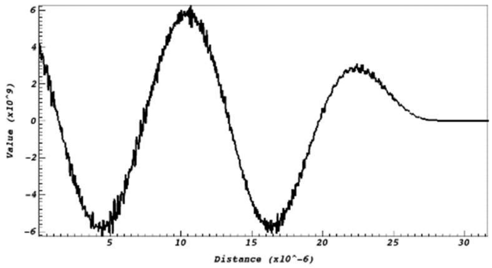

Fig.4 Sinusoidal variation of axial wakefield along x-axis

An electron trapped in wakefield of magnitude 7.9x 10^9 can gain energy of 7.9 GeV/m whereas conventional accelerators are able to achieve the same energy gradient in a kilometre-long accelerator size.

References

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