A New Scheme for High-Intensity Laser-Driven Electron Acceleration in a Plasma

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September 27

~~February 2,~~ 2017

Introduction

- **Motivation**
- Small-scale accelerators (several meters in length): plasma wakefield accelerators
- In 1949 A. I. Akhiezer, Ya. B. Fainberg [1] proposed to employ the **nonrelativistic** electron bunches for **generation of Langmuir waves**
- In 1956 G. I. Budker, V. I. Veksler and Ia. B. Fainberg [2] proposed to **accelerate the charged particles in a plasma** medium using collective plasma fields
- In 1961 A. A. Rukhadze showed that the **relativistic** electron bunches can generate plasma waves with high relativistic phase velocity [3]
- Later on, other acceleration schemes were proposed: Laser-plasma wakefield acceleration, time-shifted sequence of injected into a cold plasma electron bunches
- In the work [4] of Caldwell et al., Nature Phys., 2009 there was considered a possibility of the **proton-driven plasma wakefield acceleration**.

[1] A. I. Ahiezer, Ya. B. Fainberg, Doklady Akademii Nauk SSSR, **69**, 555 (1949)

[2] G. I. Budker, V. I. Veksler, Ia. B. Fainberg *Proc. CERN Symp. on High Energy Accelerators and Pion Physics*, Vol. 1 (Geneva: CERN, 1956), p. 68, p.80, p. 84.

[3] A. A: Rukhadze, Zhurnal Tekhnicheskoj Fiziki, **31**, Nr.10, 1236 (1961).

[4] Caldwell, A., Lotov K., Pukhov, A. and Simon, F., Nature Physics, **5**, (2009).

Introduction

- Early experiments of the 60s and 70s demonstrated that

$$\eta_{beam} << \eta_{laser} \quad (1)$$

and the generated field is much lower than a breakdown (overturn) electric field representing the saturation field[5], [6] :

$$\boldsymbol{E_{p_{max}}} = \sqrt{2} m V_p \omega_p / e. \quad (2)$$

where e- electron charge, m - its mass, V_p - plasma wave phase velocity, $V_p = \omega_p / k_p$ where k_p - plasma wave vector, ω_p - plasma frequency, $\omega_p = \sqrt{4\pi e^2 n_e / m}$ with n_e being the electron density and m - its mass.

- With the appearance of the high-intensity lasers in the 80s, a new era of plasma acceleration has begun.

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[5] A.I.Akhiezer et. al. , in *Plasma Electrodynamics*, (Oxford-New York: Pergamon Press, 1975)

[6] R.I. Kovtun, A.A. Rukhadze, *ZETF*, *58*, Nr. 5, 1709 (1970)

Introduction

- **Here we present a new scheme for high-intensity laser-driven e^- acceleration in a plasma with much more durable in a time particle acceleration inside the almost constant electric field $E_{p_{max}}$.**

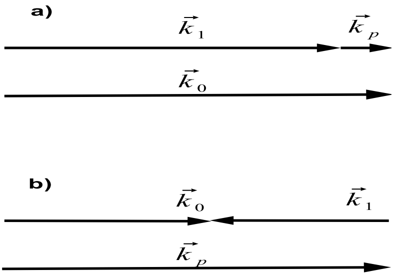


Figure: Schematic illustration of a wave vector model for interaction of the high-intensity laser pulse ($\vec{k}_0$) with plasma which generates a plasma wave ($\vec{k}_p$) and forward- ($\vec{k}_1$) (a) and backward-scattered ($\vec{k}_1$) (b) waves, where $k_0 \simeq k_1 >> k_p$ is valid for the forward-scattering case, and $|k_0| \simeq |-k_1| << |k_p|$ - for the back-scattering case.

The forward- and backward-scattering of a high-frequency transverse electromagnetic wave in a plasma

- The scattering of a **high-frequency transverse relativistic** electromagnetic wave $E_0(t) = E_0 \sin(\omega_0 t + \vec{k}_0 \vec{r})$ in a plasma which excites the longitudinal plasma wave can be described by the following dispersion relation:

The dispersion relation [7]

$$\left(\omega^2 - \frac{{\omega_p}^2}{\gamma_0}\right)\left({\omega_s}^2 - c^2 k_s^2\right) = \frac{{\omega_p}^2 k^2 {V_E}^2}{4{\gamma_0}^3}, \qquad (3)$$

where $\omega_s = \omega_0 - \omega$ - frequency of the scattered transverse wave, $\vec{k}_s = \vec{k}_0 - \vec{k}$ - wave vector of the scattered wave, here $k_s \equiv k_1$, $\omega_1 = \mathbb{R}(\omega_s)$, $\omega = \omega_p + i\delta$ with δ being the increment, ω and $\vec{k}$ are the frequency and wave vector of a generated plasma wave respectively, $\omega_p >> kv_{Te}, \omega_i$, where v_{Te} - electron thermal velocity, ω_i - ion frequency, and $V_E = eE_0/m\omega_0$ - velocity of plasma electrons oscillating in a laser field, $\gamma_0 = (1 - {V_E}^2/c^2)^{-1/2}$ $(V_E \to c)$.

[7] A.F. Alexandrov, L.S. Bogdankevich, A.A. Rukhadze, Principles of Plasma Electrodynamics (Springer, Heidelberg, 1984), pp. 167-170

The forward- and backward-scattering of a high-frequency transverse electromagnetic wave in a plasma

- The corresponding increment magnitudes are for the **forward Raman scattering**: $\delta_f \sim \omega_p ({V_E}^2 \omega_p / c^2 \omega_0 \cdot (1/{\gamma_0}^{7/2}))^{1/2}$ and for **the back scattering**: $\delta_b \sim \omega_p ({V_E}^2 \cdot \omega_0 / (2c^2 \omega_p) \cdot (1/{\gamma_0}^3))^{1/3}$ and $\delta_f / \delta_b << 1$ by $3(\omega_p/\omega_0)^{5/6} \cdot (V_E / {\gamma_0}^{9/4} c)^{1/3})$ times.
- Inspite of the fact that $\delta_b \gg \delta_f$, the phase velocity of a plasma wave $V_p = \omega_p / k_p$ generated in the **back scattering mechanism** is quite low compared to that of the laser since $k_p \simeq 2\omega_0 / c$. This leads to the dephasing b/w the laser and the plasma wave what halts the acceleration process.

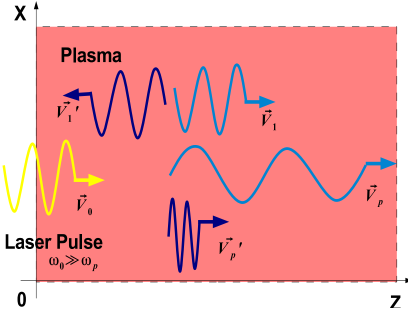
Breakdown electric field in relativistic case

$$E_{p_{max}} = \sqrt{2} m V_p \omega_p \sqrt{\gamma_0} / e, \quad (4)$$

where $V_p \simeq c$.

The parametric resonance for the stimulated forward-scatt.

- **Phase velocities**



The parametric resonance for the stimulated forward-scattering can be written as following:

$$\omega_0 = \omega_1 + \frac{\omega_p}{\sqrt{\gamma_0}} \qquad (5)$$
$$k_0 = k_1 + k_p,$$

where $\omega_0 \sqrt{\frac{\omega_p^2}{\gamma_0} + k_0^2 c^2}$, $\omega_1 = \sqrt{\frac{\omega_p^2}{\gamma_0} + k_1^2 c^2}$.

$$\left(V_0 = \frac{\omega_0}{k_0}\right) = \left(V_1 = \frac{\omega_1}{k_1}\right) = c\left(1 + \frac{\omega_p^2}{2\gamma_0\omega_0^2}\right),$$
$$\left(V_p = \frac{\omega_p}{\sqrt{\gamma_0}k_p}\right) = c\left(1 - \frac{\omega_p^2}{2\gamma_0\omega_0^2}\right) \quad (6)$$

where $V_0 = V_1 > c$, $V_p < c$ and approximately equal to each other $V_0 = V_1 \simeq V_p$ since ${\omega_p}^2/\gamma_0{\omega_0}^2 << 1$.

- **Acceleration time**

  Taking into account $\boldsymbol{E_{p_{max}}}$ we can estimate the duration of acceleration of a relativistic electron with $\varepsilon = mc^2(\gamma - 1)$, $\gamma = 1/\sqrt{1 - {u_0}^2/c^2} >> 1$.

$$\frac{u_0}{c} = 1 - \frac{1}{2\gamma^2} \quad (7)$$

$$\tau_f \simeq \frac{c\pi\sqrt{\gamma_0}/\omega_p}{|V_p - u_0|}. \quad (8)$$

Acceleration time

$$\tau_f \simeq \frac{2\pi{\gamma_0}^{3/2}\gamma^2\omega_0^2}{\omega_p|\omega_p^2\gamma^2 - \omega_0^2\gamma_0|.} \quad (9)$$

- At $\gamma = \mathbf{1}$
  The acceleration time of electron at a rest by the plasma wave generated by the forward-scattering: $\tau_f = 2\pi\sqrt{\gamma_0}/\omega_p$
- At $\gamma >> \sqrt{\gamma_0}\omega_0/\omega_p$
  The acceleration time of an injected into plasma relativistic electron: $\tau_f = 2\pi{\omega_0}^2{\gamma_0}^{3/2}/{\omega_p}^3$ [8].
  Taking into account $E_{p_{max}}$ and τ_f the following momentum and energy growth can be obtained:

$$\Delta P \approx eE_{p_{max}}\tau_f, \quad \Delta\varepsilon \approx eE_{p_{max}}\tau_f c. \tag{10}$$

[8] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

Estimated parameters and their comparison w. the simulation results obtained at the SPARC_LAB facility of INFN-LNF in Frascati, Italy[10]

- $\omega_0 = 2.35 \cdot 10^{15}$ s^{-1} ($\lambda = 800$ nm), $\omega_p = 1.8 \cdot 10^{13}$ s^{-1}, $n_e = 10^{17}$ cm^{-3}, $I = 10^{20}$ W/cm^2, $E_0 \simeq 0.3$ TeV, $\gamma_0 \simeq 7$.
- An electron with 150 MeV ($\gamma = 297$) can gain $\Delta\varepsilon_{max} \simeq 1.6$ TeV in $E_{p_{max}} \simeq 1$ GV/cm during $\tau_f = 50$ ns over $L_{max} \simeq 14$ m. Provided that a capillary could be of : $L = L_{max} \simeq 14$ m, then $\Delta\varepsilon \simeq 70$ GeV compared to the $\Delta\varepsilon \sim 0.40$ GeV obtained inside the 8 cm-length capillary for the SPARC_LAB facility. Comparing $\Delta\varepsilon$ at $L \simeq 8$ cm, we'll get $\Delta\varepsilon = 9$ GeV, which is higher than from SPARC_LAB $\Delta\varepsilon \simeq 0.4$ GeV. Reason for this: dephasing between the plasma wave and the injected electron due to the $m(\gamma_0)$ leading to the change of ω_p. In this case, the saturation field could be less than the E_{pmax} and correspondingly $\Delta\varepsilon_{max}$.
- The acceleration time $\tau_b = \pi/(2\omega_0)$, $\tau_b \simeq 10^{-15}$ s $<< \tau_f \simeq 50 \cdot 10^{-9}$ s by approx. $(\omega_0\sqrt{\gamma_0}/\omega_p)^3$ times (provided that $\gamma >> \omega_0\sqrt{\gamma_0}/\omega_p$). The plasma wave lengths $\lambda_b = \pi c/\omega_0$, $\lambda_b \simeq 0.5\mu$m and $\lambda_f = 2\pi c\sqrt{\gamma_0}/\omega_p$, $\lambda_f = 280\mu$m. We must note that account of the relativistic velocities of plasma electrons leads to the longer acceleration time by ${\gamma_0}^{3/2}$ times.

[10] A.R. Rossi et. al. in Proceedings of IPAC2012, New Orleans, Louisiana, USA.

Conclusion

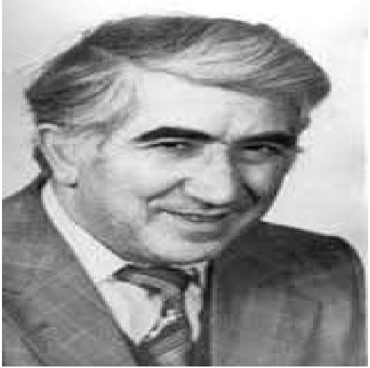
- We proposed a new scheme for high-intensity laser-driven electron acceleration in a plasma
- Our new approach employing the **stimulated forward-scattering** and injection of relativistic electrons can provide more durable particle acceleration time inside the field of a plasma wave of a much longer length compared to the backward-scattering model where electrons just slip off the wave. For such a realization the injected electrons must be **relativistic**.
- The relativity of plasma electron velocities assists at the better convergence of the phase velocities of the plasma wave and of the laser with that of the beam electrons. In Eq. for a breakdown electric field for illustration purpose we took a constant topf field because the exact electric field profile during the instability growth is not known. However, the time interval during which the breakdown field can be gained is much less than the acceleration time what justifies our choice of the field profile.
- For a better and detailed research we are planing to run simulations of the considered phenomena using the **"EPOCH"** code [11]

[11] Collaboration with Prof. Rukhadze, A.A. and EPOCH- code, University of Warwick

Acknowledgements

Thank you very much for your Attention !

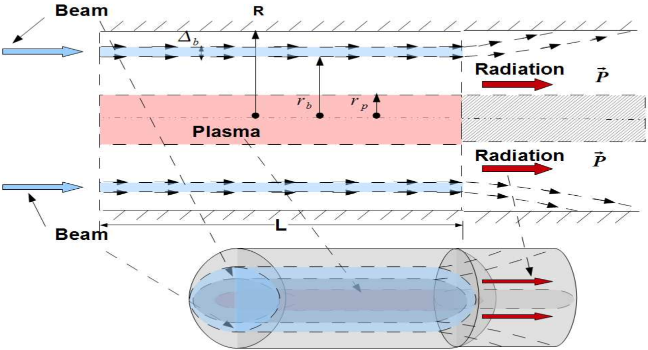
and Support and Advices of **Prof. Anri Rukhadze**



Content

Amplification of a surface electromagnetic wave by running over plasma surface ultrarelativistic electron bunch as a new scheme for generation of Terahertz radiation

- **The surface wave is a wave of E-type with the nonzero field components E_x, E_z, B_y** [3]



[3] S. P.Sadykova, A. A. Rukhadze, et al. archive: arXiv:1210.0610.

Amplification of a surface electromagnetic wave by running over plasma surface ultrarelativistic electron bunch as a new scheme for generation of Terahertz radiation

- **Estimated parameters**

- $f_0 \simeq 0.5 \cdot 10^{12}$ Hz, $\omega_0 = 3 \cdot 10^{12}$ s^{-1}
  Since $\omega_0 = \omega_p / \gamma$ then the plasma and bunch parameters can be chosen respectively.
- Electron energy of 50 MeV ($\gamma = 100$) and current density of 500 A/cm^{-2} ($n_b = 10^{11}$ cm^{-3}, net current $I = 3$ A).
- The plasma frequency should be of order $\omega_p = \gamma\omega_0 = 3 \cdot 10^{14}$ s^{-1} and $n_p \simeq 3 \cdot 10^{19}$ cm^{-3}, atmospheric pressure.
- Correspondingly, the time increment will be $\omega_0 \delta'' \simeq 2 \cdot 10^8$ s^{-1} $<< \omega_0$ at $a = 0.1$ cm and the amplification coefficient $\delta'' k_z \simeq 1/L \simeq 7.4 \cdot 10^{-3}$ cm^{-1} leading to the system length of 1.34 m where the plasma radius is $r_p = 0.1$ cm and beam radius is $r_b = 0.2$ cm; $c/\omega_p = 10^{-4} << r_p$, i.e. the plasma surface can be considered as a flat one; the condition $\gamma^2 \delta' \simeq 3 > 1$ is satisfied.
- The SEW radiation Poynting vector $|P| = c/4\pi(E_x^2) \simeq 6 \cdot 10^{11}$ W/cm^{-2} and the fields - $|E_x| \simeq |B_y| \simeq 10^7$ V/cm=10^9 V/m.

Schematic illustration of the planed experiment at the SPARC_LAB facility of INFN-LNF in Frascati, Italy