An Empirical Model for the Interaction of Ultra-Intense Laser Pulses with Fully Ionized Plasmas Including Electrostatic Effects

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Summary

Self-consistent electrostatic fields make a significant difference to the electron orbits in ultra-intense laser fields

- A new model has been developed whereby a radial electrostatic field is calculated self-consistently with the particle motions
- For realistic laser pulse durations of ~1 ps and greater, the electrons emerge with low energies in the absence of an electrostatic field because they are not confined sufficiently long to experience the peak laser fields
- The radial electrostatic field grows to an amplitude that exceeds the ponderomotive force and, therefore, serves to confine the remaining electrons in the interaction region for much longer times
- The majority of the electrons eventually escape the interaction region, but predominantly in the laser direction
- The angular distribution of the escaped electrons is found to be peaked in the longitudinal direction but not sufficiently collimated for fast ignition

Abstract

This work investigates the capability of ultrafast lasers with irradiance $I \geq 10^{18}$ W cm^{-2} to produce highly energetic electron beams in a Gaussian focus in a low-density plasma. A simple particle simulation code including a physical model of collective electrostatic effects in relativistic plasmas has been developed. Without electrostatic fields, free electrons escape very quickly from the Gaussian focal region of a 10-ps petawatt laser pulse, well before the laser field reaches its maximum amplitude. In this case very small net energy transfer occurs, indicating that free electrons cannot extract enough energy for ignition. However, it has been demonstrated that the electrostatic field generated by the electron flow is able to strongly modify the range and direction of the laser-generated MeV electrons by allowing trapped electrons to experience much higher laser intensity peaks along their trajectories and, therefore, be accelerated to higher velocities, drifting along the laser direction. This modeling predicts some collimation, but not enough to meet the requirements of fast ignition.

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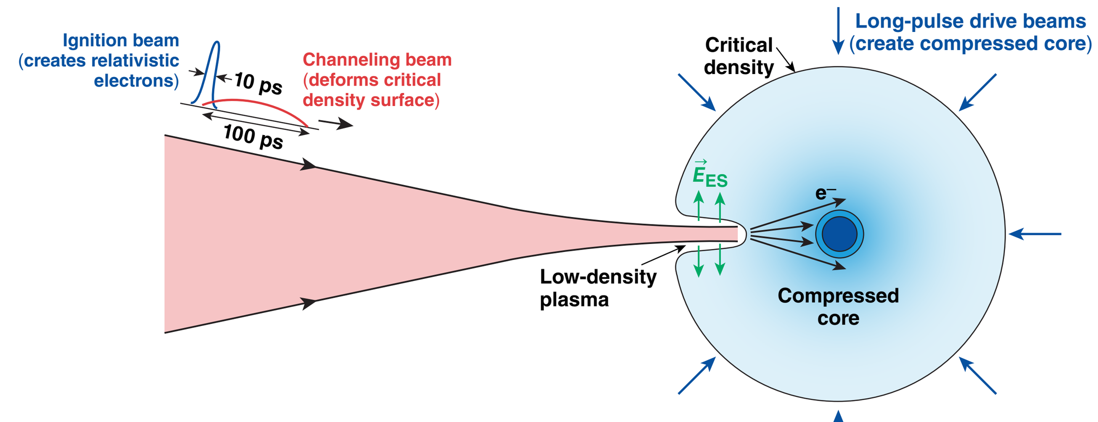
This work addresses the collimation of relativistic electrons required for fast ignition*



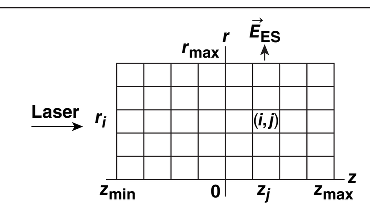
- Fast ignition depends on the creation of a collimated and energetic electron beam
- The electrostatic field (E_{ES}) produced by charge separation helps confine and collimate the electrons

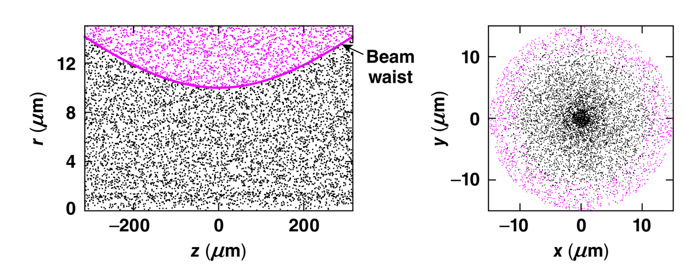
*M. Tabak *et al*., Phys. Plasmas 1, 1626 (1994).

The electrons move in the given electromagnetic wave and the self-generated electrostatic field

$$\frac{d\vec{p}}{dt} = \underbrace{-e\left(\vec{E}_{EM} + \frac{\vec{v}}{c} \times \vec{B}_{EM}\right)}_{\text{Analytic Gaussian beam}} \underbrace{-e\,\vec{E}_{ES}}_{\text{Electrostatic field due to electrons that have escaped}}$$

The charge density is accumulated in the (r,z) plane to enable the electrostatic field to be calculated





- The particles are initially uniform (but random) in the (r,z) plane

This particle code is similar to a PIC code but has some differences

	Particle-in-cell (PIC) code	This particle code
Particle model	Superparticles	Superparticles
Electromagnetic field	Evolved on grid	Analytic Gaussian beam + Self-consistent radial electrostatic field
Algorithm	Leapfrog method (second-order accuracy)	Runge–Kutta–Fehlberg method (fifth-order accuracy)
Time step	$\omega_p \Delta t \sim 0.1$	$\omega_p \Delta t \sim 0.003$
Spatial grid	$\frac{c}{\omega_p} \sim 1.2\ \mu$m	$\Delta r = 1.5\ \mu$m

The particles are chosen to be uniform in the (r,z) plane at $t = t_0$

- $n_{e0}V_0$ = number of real electrons
- N_0 = number of electrons in simulation distributed uniformly in the (r,z) plane
- Average charge of each particle is $-\left(\frac{n_{e0}V_0}{N_0}\right)e$
- For the particles to represent a uniform plasma, the charge of the particle must be taken to be proportional to the initial particle radius r_0

Particle charges are interpolated onto the grid in a way that ensures a zero net charge at $t = t_0$

- For a cell (i, j) $$\sum_{p=1}^{N_{cell,(i,j)}} q_p = -\left(\frac{n_{e0}V_0 e}{N_0}\right)\alpha_{(i,j)} \sum_{p=1}^{N_{cell,(i,j)}} r_p \qquad (1)$$

  where $N_{cell,(i,j)}$ is the number of particles in the cell (i, j);
  $\alpha_{(i,j)}$ is a coefficient to be determined
- Interpolation: volume weighting*

$$\rho_{(i,j)} = -\frac{1}{\Delta V_{(i,j)}}\left(\frac{n_{e0}V_0 e}{N_0}\right)\sum_{i',j'}\left[\alpha_{(i',j')}\sum_{p=1}^{N_{cell,(i',j')}}\beta^{(i,j)}_{p,(i',j')} r_p\right] + n_{e0}e$$

  where $\rho_{(i,j)}$ is the charge density and $\Delta V_{(i,j)}$ is the cell volume at (i, j)
  $\beta^{(i,j)}_{p,(i',j')}$ is a bilinear interpolation coefficient
  n_{e0} is the background ion number density
- Requiring $\rho_{(i,j)} = 0$ at $t = t_0$, Eq. (2) is a matrix equation that is solved to give $\alpha_{(i,j)}$. At later times, Eq. (2) gives $\rho_{(i,j)}$.

*C. K. Birdsall and A. B. Langdon, in *Plasma Physics via Computer Simulation* (Adam Hilger, Bristol, England, 1991), p. 331.

The radial electrostatic field is solved using Poisson's equation in 1-D

$$\frac{1}{r}\frac{d}{dr}(rE_{ES}) = 4\pi\rho \qquad (3)$$

with $E_{ES}\ (r = 0) = 0$.

- The particles move in a combination of
  - the full expression for the laser field in a vacuum given by Quesnel and Mora,** including the first-order components E_z and B_z
  - the electrostatic field E_{ES}

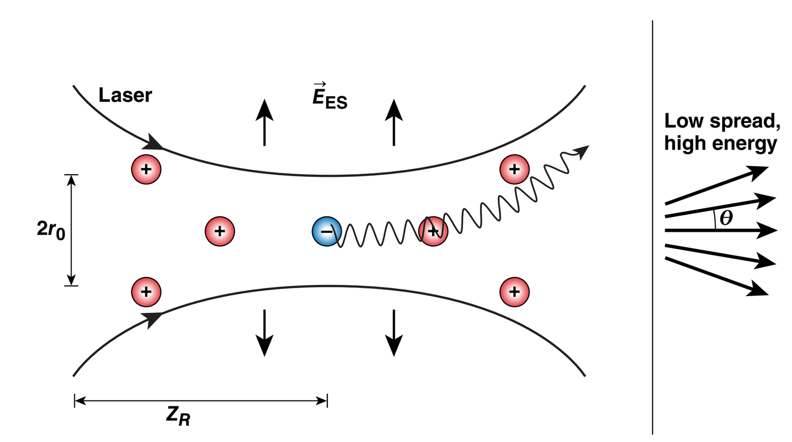
**B. Quesnel and P. Mora, Phys. Rev. E. 58, 3719 (1998).

The simulations used a high-intensity, short-pulse Gaussian beam

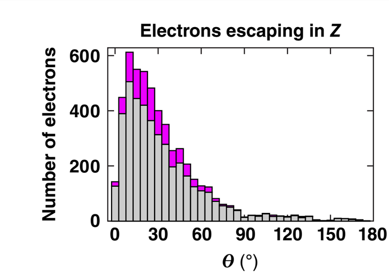
- Laser intensity: $I = 10^{21}$ W cm^{-2}
- Pulse width: $\Delta\tau = 10$ ps
- Beam radius (1/e) at best focus: $r_0 = 10\ \mu$m
- Rayleigh length: $Z_R = 314\ \mu$m
- Background ion-number density: $n_{e0} = 2 \times 10^{19}$ cm^{-3}

With Electrostatic Field

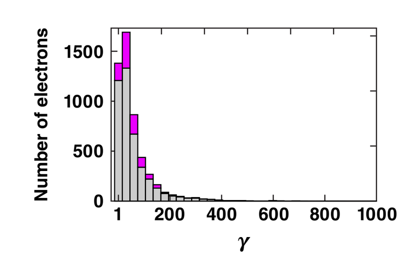
With the electrostatic field, the electrons emerge with low spread and high energy



The electrons escape in the forward direction with modest collimation

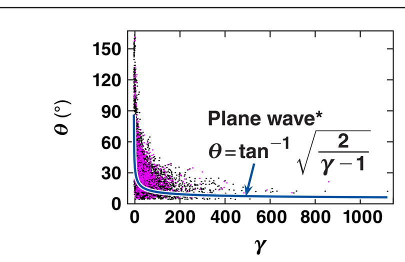


The electrons are strongly relativistic



The electrons are trapped long enough to experience the peak laser field.

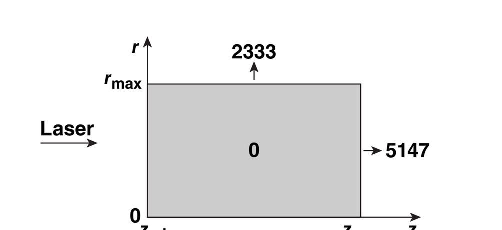
The escaping electrons show a lot of spread in angle



The plane wave prediction is not followed.

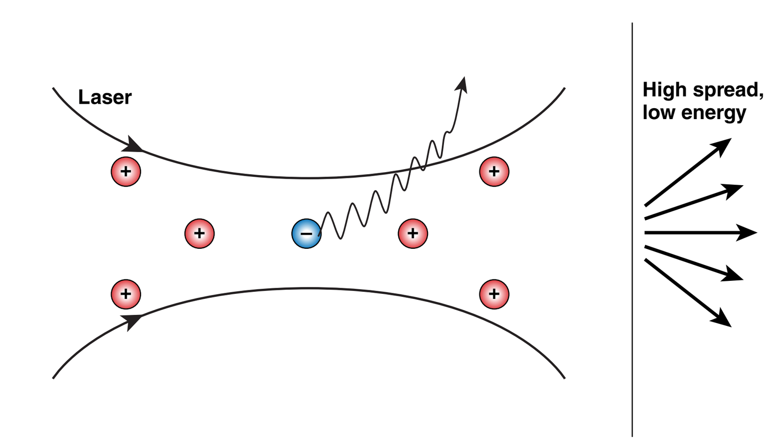
*P. B. Corkum, N. H. Burnett, and F. Brunel in *Atoms in Intense Laser Fields*, edited by M. Gavrila (Academic Press, New York, 1992), p. 109.

The electrons escape predominantly in the longitudinal direction (across $z = z_{max}$)

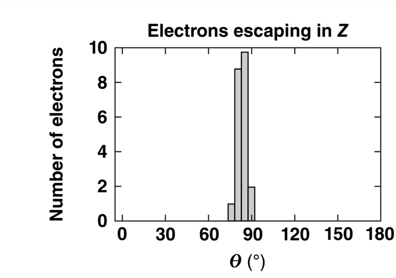


Without Electrostatic Field

Without the electrostatic field, the electrons emerge with high spread and low energy

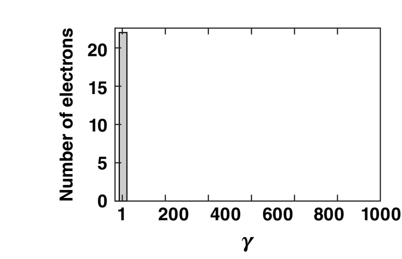


The electrons escape perpendicular to the laser beam

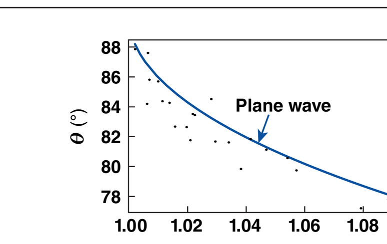


Most of the electrons escape in radius, also close to $\theta = 90°$

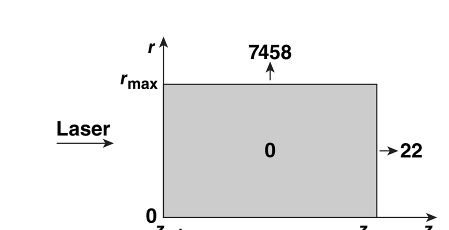
The electrons rapidly escape from the laser field so never gain significant energy



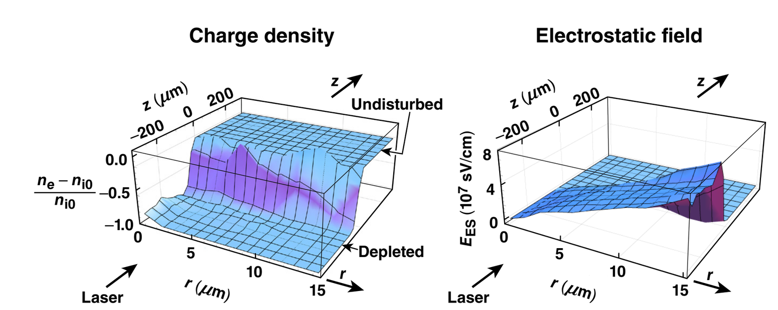
The escape angle is close to the plane-wave prediction



The electrons escape predominantly in the radial direction



For 0.2-ps pulses, electrons are rapidly depleted from the laser region leading to a large electrostatic field



$I = 10^{21}$ W cm^{-2}, $\Delta\tau = 0.2$ ps

Simulations have been carried out for a variety of conditions, with and without a radial electrostatic field

	$\Delta\tau = 0.2$ ps						$\Delta\tau = 10$ ps			
	10^{12} W cm^{-2}		10^{18} W cm^{-2}		10^{21} W cm^{-2}		10^{18} W cm^{-2}		10^{21} W cm^{-2}	
	With	Without	With	Without	With	Without	With	Without	With	Without
Number of confined electrons	7480	7480	5311	33	366	0	1439	0	0	0
	(100%)	(100%)	(71%)	(0.5%)	(4.9%)	(0%)	(19.3%)	(0%)	(0%)	(0%)
Number of radially escaped electrons	0	0	2133	7415	5946	7262	1094	7472	2333	7458
	(0%)	(0%)	(28.5%)	(99.1%)	(79.5%)	(97.1%)	(14.6%)	(99.9%)	(31.2%)	(99.7%)
Number of longitudinally escaped electrons	0	0	36	32	1168	218	4947	8	5147	22
	(0%)	(0%)	(0.5%)	(0.4%)	(15.6%)	(2.9%)	(66.1%)	(0.1%)	(68.8%)	(0.3%)

Summary/Conclusions

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