Plasma edge dynamics in ultraintense laser field

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ABSTRACT

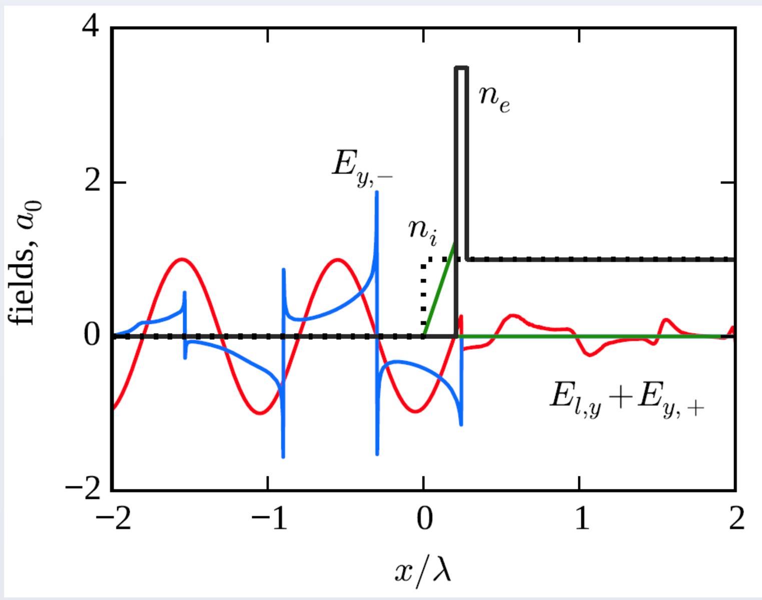
When a relativistically intense linearly polarized few-cycle laser pulse is incident on an overdense plasma, a thin electron layer that reflects the incident pulse may be formed on the plasma edge. We present a self-consistent analytical model that describes the edge dynamics in the presence of radiation reaction and apply it to the problem of synchrotron emission by ultrarelativistic plasma electrons. The analytical results agree with 3D particle-in-cell simulations for a certain range of parameters including laser pulse intensity, target density and incidence angle.

PLASMA EDGE DYNAMICS MODEL

We propose a self-consistent analytical model of plasma edge dynamics in a situation when the laser pulse is reflected from the overdense plasma and due to ponderomotive force forms a very thin and dense electron layer which has areal charge density proportional to the layer displacement: $\epsilon = n_0 x_l$, where n_0 is the unperturbed electron density (a concept known as 'relativistic electronic spring').

Main assumptions:

- electron layer areal charge density $\epsilon = n_0 x_l$
- electrons move collectively in the polarization plane (*x-y*)
- ion motion is neglected (few-cycle laser pulse)



Electron layer moves in the x- and y-directions under external fields and generates electromagnetic fields that can be found from the Maxwell equations:

$$E_{y,+} = B_{z,+} = \frac{\epsilon v_y}{2(1-v_x)},$$
$$E_{y,-} = -B_{z,-} = \frac{\epsilon v_y}{2(1+v_x)},$$
$$E_x = \frac{\epsilon x}{x_\ell} \text{ if } 0 < x < x_\ell. \qquad \epsilon = n_0 x_\ell$$

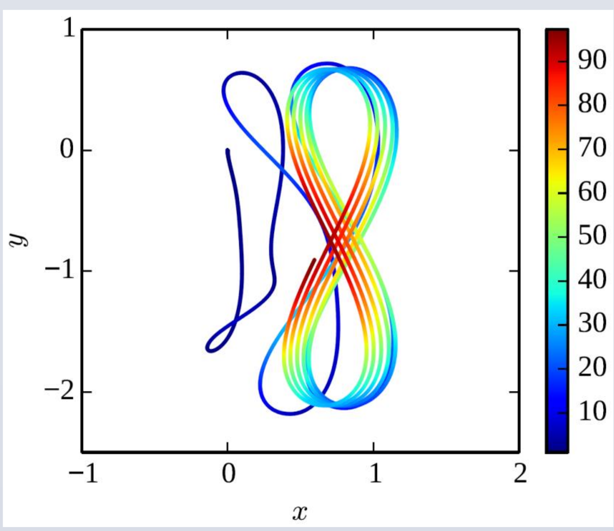
The half-sum of fields on both sides of the layer gives us the recoil force (coherent radiation reaction). Charge separation field from the ions is also taken into account.
For $a_0 \sim 100 \div 500$ we should consider the radiation reaction force from incoherent synchrotron radiation as well.

Unlike the previous models, we take into account both coherent (high harmonic) and incoherent (synchrotron) radiation reaction

Electron layer equations of motion:

$$\begin{cases} \frac{dp_x}{dt} = -\frac{S x_\ell}{2}\left(1 + \frac{v_x v_y^2}{1-v_x^2}\right) - v_y E_{0y} + F_{rx}, \\ \frac{dp_y}{dt} = -\frac{S x_\ell v_y}{2} - (1-v_x) E_{0y} + F_{ry}, \\ \frac{dx_\ell}{dt} = v_x = \frac{p_x}{\gamma}, \\ \frac{dy_\ell}{dt} = v_y = \frac{p_y}{\gamma}, \qquad \gamma = \sqrt{\frac{1}{a_0^2} + p_x^2 + p_y^2} \end{cases}$$

p is normalized by a_0



Layer trajectory (color is Lorentz factor)

$S = \frac{n_e}{a_0 n_{cr}} = \frac{n_0}{a_0}$ is the dimensionless similarity parameter

$\mathbf{F}_r$ is classical radiation reaction force in Landau-Lifshitz form:

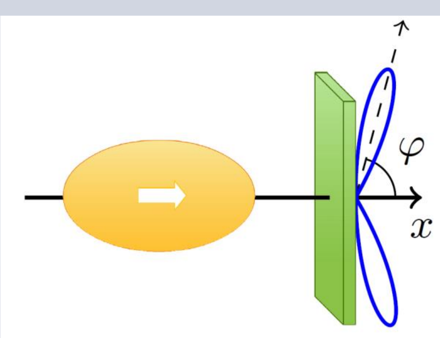
$$\mathbf{F}_r = -\frac{4\pi}{3}\frac{r_e}{\lambda}\gamma^2\left[(\gamma\mathbf{E} + \mathbf{p}\times\mathbf{B})^2 - (\mathbf{p}\cdot\mathbf{E})^2\right]\mathbf{v}$$

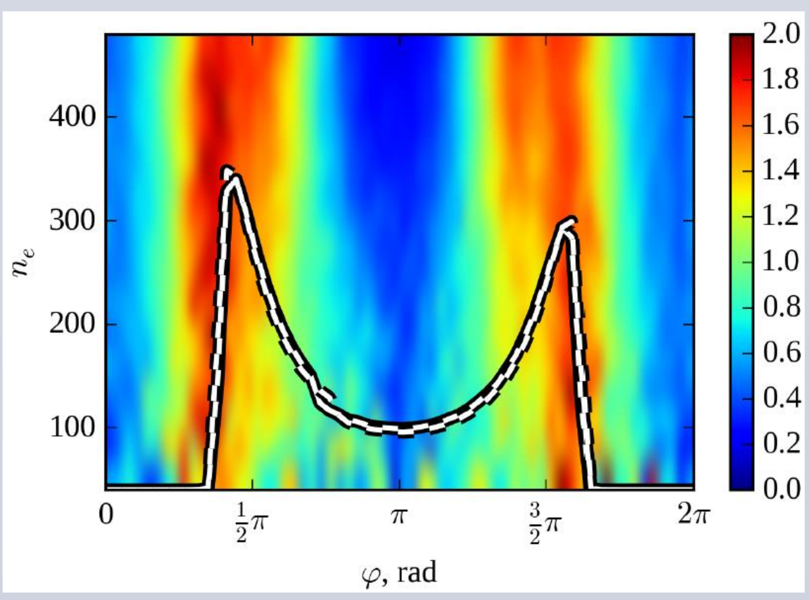
INCOHERENT SYNCHROTRON EMISSION

Radiation from the layer which moves with ultrarelativistic velocities is caused by the synchrotron radiation mechanism and its power in each direction can be calculated based on the known trajectory:

$$I_e = \frac{2e^2 c\gamma^4}{3R^2} \Longrightarrow I_{layer} = \frac{2e^2 c\gamma^4}{3R^2}\frac{n_e}{n_{cr}} x_\ell$$

We can see that radiation pattern dependence on S is vanishingly small.



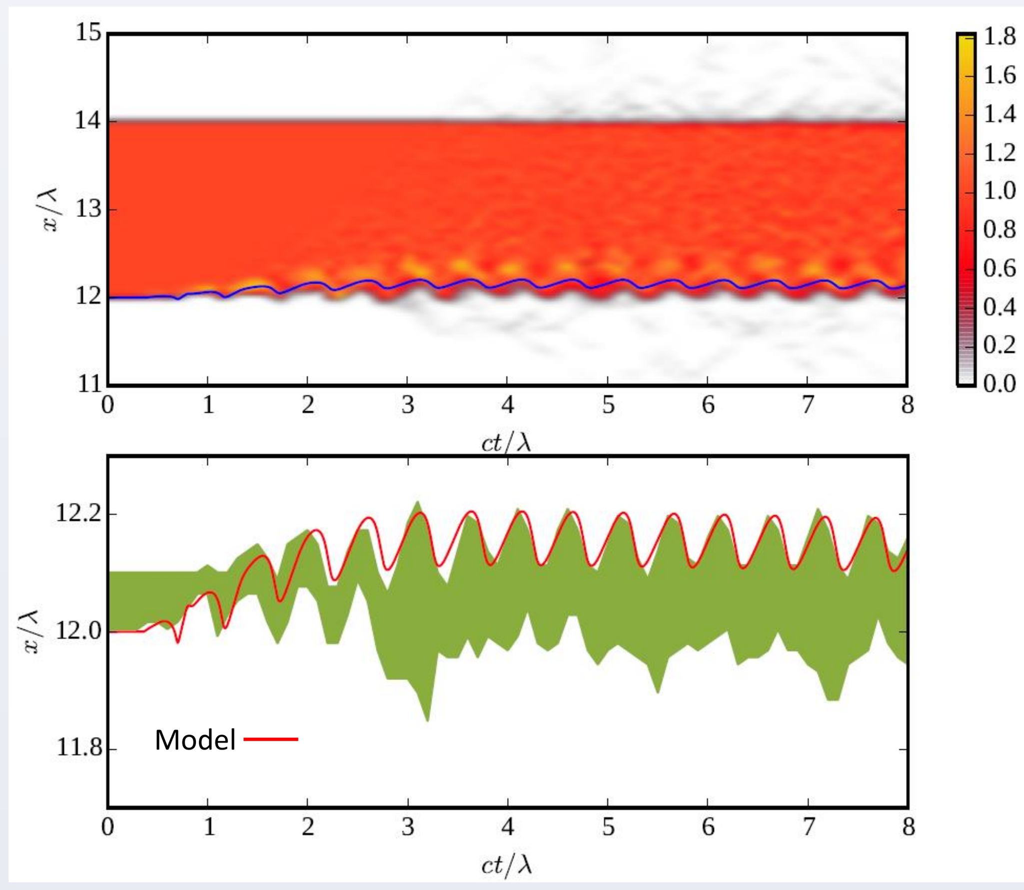


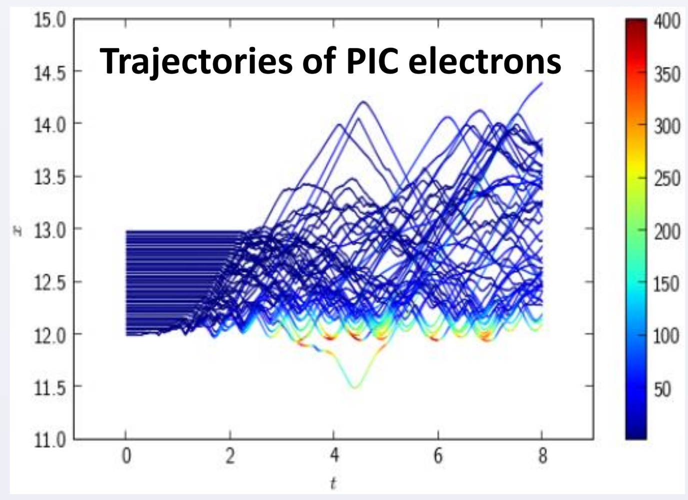
Gamma-ray radiation pattern from PIC 3D (color map) and model (lines). $S = 1$

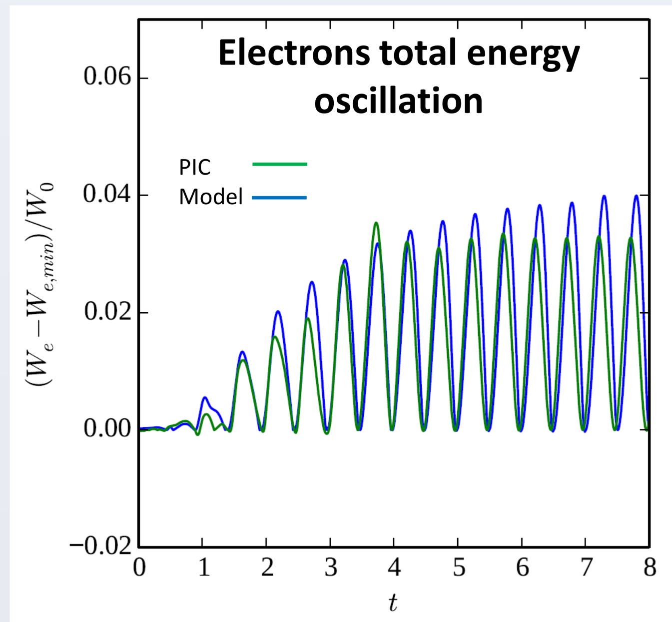
PIC 3D NUMERICAL SIMULATIONS

In PIC 3D simulations, we observe formation of a thin layer on the plasma edge if $S = \frac{n_0}{a_0} \geq 1$. Individual electrons may escape the layer, and new electrons from plasma come into their place; but on the average the layer moves as a whole.

Plasma edge *x(t)* oscillations







Model describes plasma edge dynamics and electron energy well

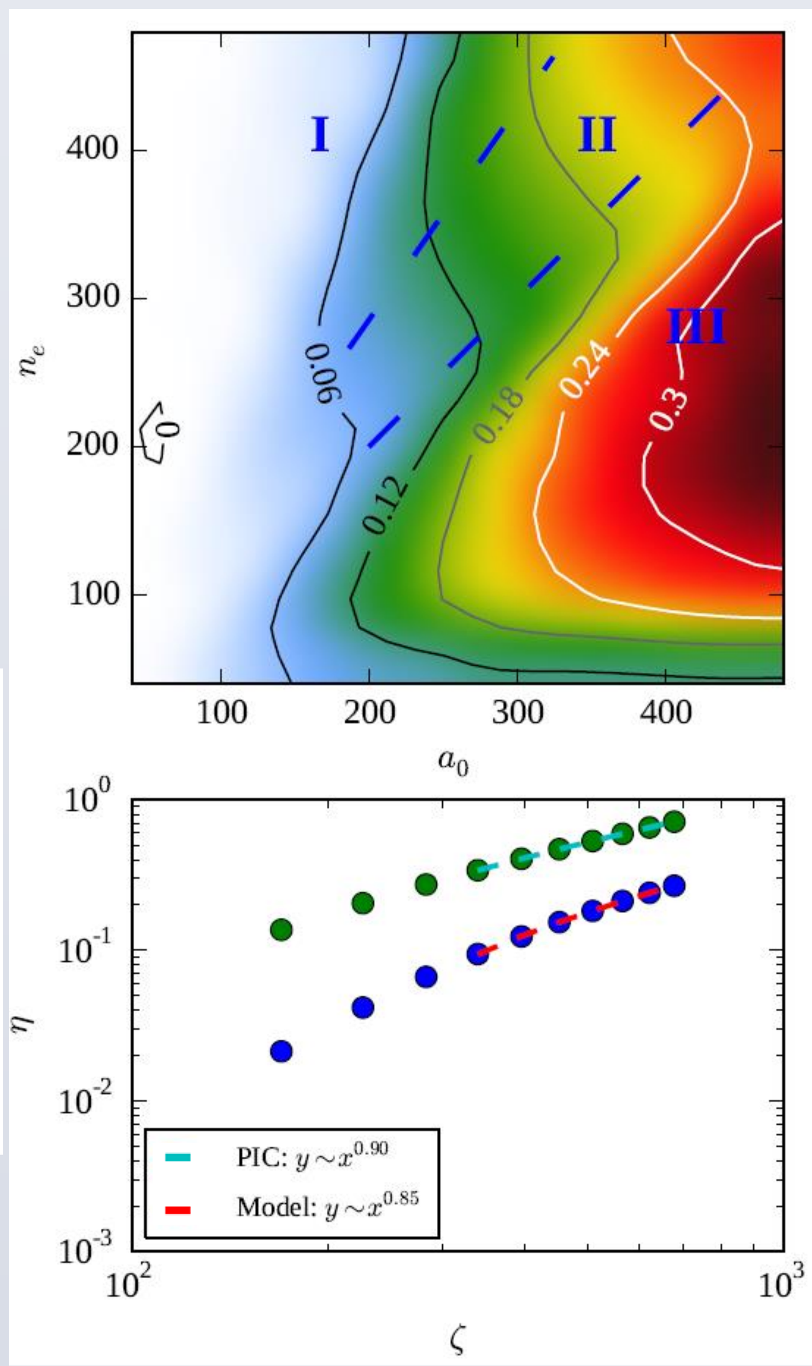
CONDITIONS OF APPLICABILITY

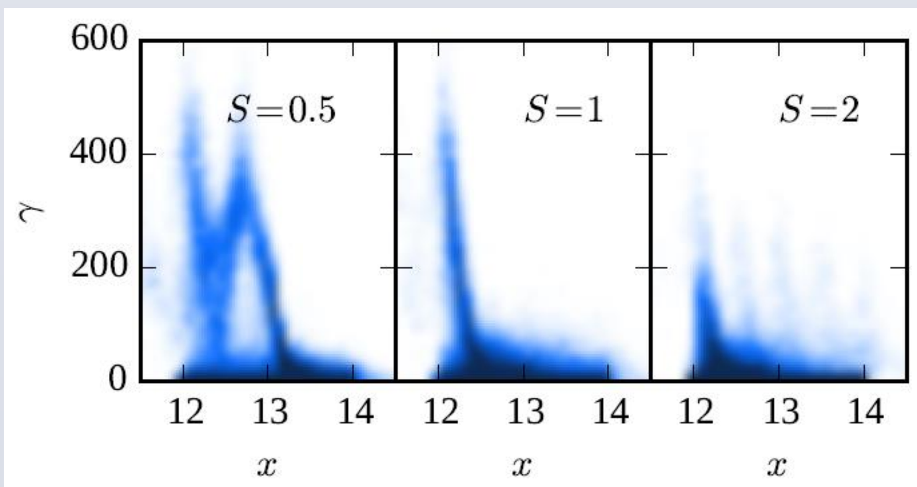
Interaction regimes are determined by the similarity parameter $S = n_0/a_0$

Regimes in PIC simulations:

I. $S \geq 2$: "weak field" region, the electrons constantly escape the moving electron layer
II. $1 \leq S < 2$: region where the model is applied
III. $S < 1$: relativistic self-induced transparency

Gamma-ray generation efficiency η





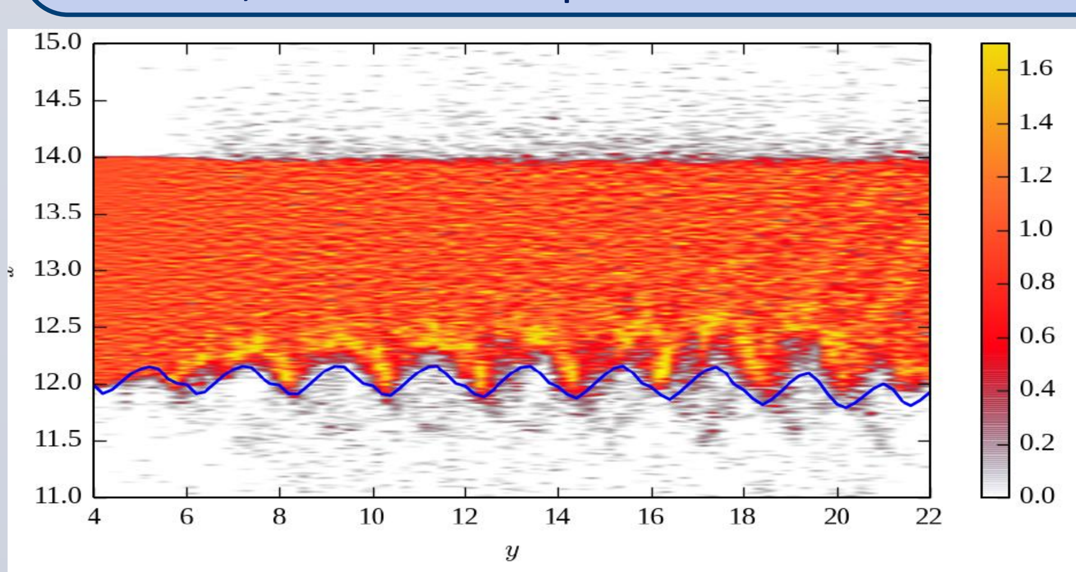
Model yields gamma-ray generation efficiency several times lower than in PIC, but the scaling is almost the same.

OBLIQUE INCIDENCE

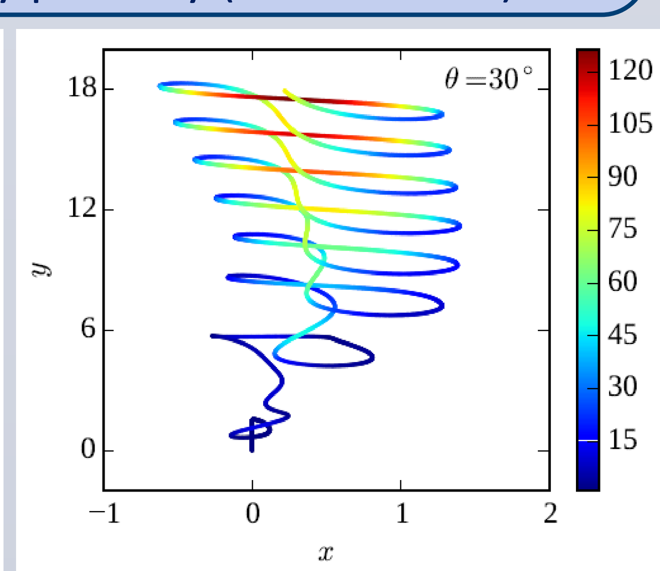
Lorentz transformation to the moving reference frame (with $v = c\sin\theta$) turns the problem with oblique-incident laser pulse to normal-incident.

We should recalculate fields and electron density into the moving frame, and add the field of ions which now move with constant speed $v = -c\sin\theta$

The model for oblique incidence describes the shape of plasma surface in PIC well.
However, the radiation pattern is described only partially (not all lobes)



Plasma surface (θ = 30°)



Layer trajectory (color is Lorentz factor)