Trapping and Beamloading in hybrid Plasma Wakefield Accelerator schemes

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INHALTSVERZEICHNIS

1. THEORY

1.1 The history of wakefield acceleration

Tajima Dawson great Idee, MTV bubble regime, same time PWFA von Rosenzweig... first linear measurements for PWFA

1.2 Plasma physics

An introduction into plasma physics is given by starting with chens definition. Topics are

1.2.1 debye shielding

1.2.2 time scales

scattering can be talked about

1.2.3 plasma definition

There are different types of plasmas, but we are only handling with thin, cold weakly coupled plasmas

1.2.4 electromagnetic waves in plasmas

dispersion relation needs to be talked about. Especially the dispersion relation of lasers during ionization should get some insight here. One has to look into ionization defocussing.

1.2.5 fluid model of plasmas

1.2.6 waves in plasmas

So far everything still flows nicely with working along Chen and Mulser. However now the turn needs to be taken. The reason is wavebreaking

1.2.7 wavebreaking

Wavebreaking gives us the the ideal way to go from plasma description to blowout description.

1.3 PWFA theory

1.3.1 history of PWFA

A short historic overview is given. Maybe mention landau damping? Then of course, Tajima,Dawson. Also MTV and Rosenzweig should be mentioned.

1.4 The blowout regime

1.5 Descriptions for the blowout regime

Lotov, Suk, breakdown of fluid theory Q-tilde and resonant wake excitation.

1.5.1 Trapping conditions

Basic calculations for the trapping potential are shown. The particle movement must be solved in 3D and in 1D. Make a picture of the comparisons.

1.6 Accelerator physics

Acc. physics should clearly be introduced. Emittance, brightness, twiss parameter need to be defined. Floettmann. A good book should be used here. Don't know which one,yet. TBD.

1.6.1 Panowsky-Wenzel Theorem

$$W_r = \partial_r W_z \tag{1.1}$$

This theorem is so important, it clearly needs a subsection. But where ?

1.6.2 Trapping in PWFA

In order to derive an expression for the trapping condition of a single electron in PWFA, one has to start with the equation of motion for such a single electron.

$$F = \frac{d\vec{p}}{dt} = q(\vec{E} \times \vec{B}) \tag{1.2}$$

with the electron charge q electric field $\vec{E}$ and magnetic field $\vec{B}$

This leads to the single particle electron hamiltonian $H = \gamma mc^2 + \Phi$ with the temporal derivative.

$$\frac{dH}{dt} = \frac{d}{dt}(\gamma m_e c^2) + \frac{d}{dt}(q\Phi) \tag{1.3}$$
$$= \vec{v}\frac{d\vec{p}}{dt} + \frac{d}{dt}(q\Phi) \tag{1.4}$$
$$= q\vec{v}(-\nabla\Phi - \frac{\partial \vec{A}}{\partial t}) + \frac{\vec{v}\times\vec{B}}{c} + \frac{d}{dt}(q\Phi) \tag{1.5}$$
$$= q(\frac{d}{dt}\Phi - \vec{v}\vec{\nabla}\Phi - \vec{v}\frac{\partial \vec{A}}{\partial t}) \tag{1.6}$$
$$= q(\frac{\partial \Phi}{\partial t} - \vec{v}\frac{\partial \vec{A}}{\partial t}) \tag{1.7}$$

If one assumes now, that the wake fields are constant during the trapping process, then

$$(\frac{\partial}{\partial t} + v_\phi \frac{\partial}{\partial z})f = f(z - v_\phi t) \tag{1.8}$$
$$(\frac{\partial}{\partial t} + v_\phi \frac{\partial}{\partial z})f = 0 \; \forall \; f(\vec{r}, z - v_\phi t) \tag{1.9}$$

which is especially true for the hamiltonian.

$$\frac{d}{dt}H = q(\frac{\partial \Phi}{\partial t} - \vec{v}\frac{\partial \vec{A}}{\partial t})$$
$$= -qv_\phi(\frac{\partial \Phi}{\partial z} - \vec{v}\frac{\partial \vec{A}}{\partial z})$$

Since $H - v_\phi P_z = \text{const.}$

$$H - v_\phi P_z = \text{const.} \tag{1.10}$$
$$\gamma mc^2 + \Psi - v_\phi p_z - v_\phi q A_z = \text{const.} \tag{1.11}$$
$$\gamma + \frac{q\Phi}{mc^2} - v_\phi \frac{p_z}{mc^2} = \text{const.} \tag{1.12}$$
$$\gamma - v_\phi \frac{p_z}{mc^2} - \underbrace{\frac{q}{mc^2}(\Phi - v_\phi A_z)}_{\bar{\Psi}} = \text{const.} \tag{1.13}$$

$\bar{\Psi}$ is the trapping potential, that determines the potential difference for an electron in a potential that moves with a phase velocity v_ϕ with respect to the laboratory frame. It is valid for small as for relativistic velocities. With the trapping potential one can calculate if an electron inside the plasma wake will be accelerated or not i.e. if electrons will be able to catch up with the wake's velocity during the propagation of the wake or if it will slip out of the potential. From the prior calculations a general formula can be determined, that compares

$$\Delta\bar{\Psi} = \bar{\Psi}_{\mathrm{i}} - \bar{\Psi}_{\mathrm{f}} = \gamma_{\mathrm{f}} - \gamma_{\mathrm{i}} - \gamma_f \frac{v_\phi v_{\mathrm{f}}}{c^2} + \gamma_{\mathrm{i}} \frac{v_\phi v_{\mathrm{i}}}{c^2} \tag{1.14}$$

In order to honor the name trapping potentialï.e. to apply this derivation to make predictions of the electron trapping behavior in the plasma wake, it is necessary to define a trapping condition. An obvious and conventional choice is that an electron should catch up with the wake's velocity so that $v_{\mathrm{f}} = v_\phi$. Equation 1.14 consequently simplifies to

$$\Delta\bar{\Psi} = \gamma_\phi - \gamma_{\mathrm{i}} - \gamma_\phi \frac{v_\phi^2}{c^2} + \gamma_{\mathrm{i}} \frac{v_\phi v_{\mathrm{i}}}{c^2} \tag{1.15}$$

Equation 1.15 can be further separated into different physical cases:

luminal wakefield, electron release at rest

In this case the plasma wake travels with a phase velocity near the speed of light, which is the case for beam-driven scenarios with high γ driver beams ($v_\phi \approx c$), and electrons starting inside the wake initially at rest ($v_{\mathrm{i}} \approx 0$)

1.7 laser ionisation description

(see diss by Ihar Shchatsinin FU Berlin)

1.7.1 Keldysh Parameter

With E_{bind} being the binding energy and $U_p = \frac{q^2 I}{2 m_e \epsilon_0 c \omega^2}$ being the ponderomotive energy

$$\gamma = \sqrt{\frac{E_{bind}}{2U_p}} \tag{1.16}$$

$\gamma > 1$ -> Multiphoton Ionisation
$\gamma < 1$ tunnel ionisation or BSI

1.7.2 ADK theory

Tunnel ionization is great

2. SIMULATIONS

2.1 Start-to-End simulations for a Trojan Horse at FlashForward experiment

2.2 The trapping potential

2.3 plasma density profile optimisation

2.3.1 Density Downramp facilitated Trojan Horse Acceleration

In wird beschrieben, wie sich ein negativer Dichtegradient auf die in einer Plasmawelle getrappten Elektronen auswirkt. Ausgangspunkt ist dabei die LWFA mit der Annahme, dass bei konstater Elektronendichte der Laserpuls, sowie die Bubble sich mit c bewegen.
Die Welle bewege sich in z-Richtung.
Die Länge der bubble ist Abhängig von der Plasmadichte n. Da sich diese über eine downramp von n_i auf n_f verringert, vergrößert sich auch die bubble über diese Strecke. Sei

$$\xi = z - ct$$

die Position relativ zum Laserpuls. $\xi < 0$ beschreibt die Position eines Elektrons in der Bubble hinter dem Laserpuls. Das Elektron bleibt am gleichen Ort relativ zur Bubblestruktur, aber die Bubble verändert sich. Die Phase der Bubble verändert sich von

$$\Psi_i = \frac{\omega_{pi}}{c}\xi$$

nach

$$\Psi_f = \frac{\omega_{pf}}{c}\xi$$

mit der Phasendifferenz:

$$\Delta\Psi = \Psi_f - \Psi_i = \Psi_i[1 - (\frac{n_f}{n_i})^{1/2}]$$

Die entsprechende Phasengeschwindigkeit errechnet sich aus

$$v_p = -\frac{\frac{\partial\Psi}{\partial(ct)}}{\frac{\partial\Psi}{\partial z}} = \frac{c}{1 + \frac{1}{2\omega_p(z)n(z)}\frac{\partial n(z)}{\partial z}\xi}$$

$$\Delta\lambda_{\mathrm{p}} \propto \left(e^{\frac{1}{2}C_{\mathrm{ramp}}z_1} - e^{\frac{1}{2}C_{\mathrm{ramp}}z_2}\right)$$

$$\approx \frac{1}{2} C_{\mathrm{ramp}}(z_1 - z_2)$$

2.3.2 density transition injection suppression

See paper by Suk

2.4 Laser Beam shaping for optimisation

2.4.1 my beamloading description

2.4.2 beamloading in theory

2.4.3 beamshaping in reality

-pulse-shaping by spatial light modulator(SLM) (Meshulach adaptive real-time fs pulse shaping)

2.5 Magnetic Field facilitated Trojan Horse Acceleration

3. EXPERIMENT

3.1 FACET

3.1.1 The FACET experimental setup

3.1.2 Plasma glow diagnostic

One huge advantage of the hydrogen FACET setup compared to the oven setup is that now several viewports allow for observing the interaction or **??**.

The plasma glow diagnostic is a very simple tool, that turned out to be extremely helpful in controlling the alignment and synchronization of the experimental setup. The main idea is to have a camera integrate over all the light from the plasma during its recombination time. $I = I_{x,y} W_{\mathrm{Laser}} / (2 * \sqrt(\pi) * \sigma_t * (\mathrm{res} * 10^-6)^2)$

3.2 FlashForwad

3.3 Clara