Trapping and Beamloading in hybrid Plasma Wakefield Accelerator schemes

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CONTENTS

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.

1.6 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 ?

1.7 Electron Trapping in plasma accelerators

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.

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

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.

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

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 potential" i.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:

1.7.1 luminal wakefield, electron injected 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 ($v_\mathrm{i} \approx 0$). Here Equation 1.15 simplifies to

$$\Delta\bar{\Psi} = -1 \tag{1.16}$$

Examples of this case are the underdense photocathode, or Trojan Horse injection [?], or wakefield induced ionization injection [?].

1.7.2 subluminal wakefield, electron injected at rest

$$\Delta\bar{\Psi} = \gamma_\phi(1 - \frac{v_\phi^2}{c^2}) - 1 = \gamma_\phi^{-1} - 1 \tag{1.17}$$

This formula can for example be applied to ionization injection in LWFA [?] or beam-driven ionization injection schemes in which the wake's phase velocity is retarded such as the Downramp-assisted Trojan Horse (DTH) [?], which this work has as special focus on. In latter case mathematically strictly speaking $\frac{dH}{dt} \neq 0$, but for small changes $\frac{dH}{dt} \approx 0$ during the injection process of the electrons, equation 1.17 can still be applied.

1.7.3 subluminal wakefield, electrons at rest

1.7.4 superluminal wakefield

There are physical situations imaginable in which the wake or at least part of the wake move with a phase velocity faster than the speed of light. This is the case for example when a beam driven wake traverses an electron density upramp. From the previous deductions it seems obvious, that trapping electrons in such a superluminal wakefield is not possible, as γ_ϕ^{-1} becomes complex for $v\phi > c$.

However, if the superluminosity is only transient as with a short density upramp, the phase velocity will return to c right after the transition. In this case trpping can be possible, but the mathematic tool presented in this section is insufficient to describe the trapping and the phase velocity after the transition is setting the demand on the potential.

1.7.5 From the Trapping Potential to the Current Profile - velocity bunching at it's max.

1.8 laser ionisation description

(see diss by Ihar Shchatsinin FU Berlin)

1.8.1 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

$$\gamma = \sqrt{\frac{E_{bind}}{2U_p}} \tag{1.18}$$

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

1.8.2 ADK theory

Tunnel ionization is great

1.9 Influence of the ionization behaviour

Here it is to be described how for TH the co-moving frame is advantagous. dependence of ionization front to create witness beams. Image of Ionization front.

1.9.1 Rake injection

It could be discussed here how a witness generation might be different for the wake electric fields. For example, there is no movement of the release position in xi. But the release won't happen in the potential minimum.

1.10 Downramp assisted Trojan Horse

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

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

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

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

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

3.1 The FACET experimental setup

3.1.1 Laser energy calibration

The FACET laser system ... The energy that can be used on target of the OAP is controlled at two points in the laser-beamline. At each point a cube-polarizer is surrounded by two $\lambda/2$-waveplates, where the upstream one is motorized. The main energy waveplate is located in the laser-room and the probe-energy waveplate is located in the tunnel area shortly after the split between main laser path and probe laser path at the main sampler, which means that the probe laser energy is determined by both waveplate settings while the main laser energy is set by the main laser energy waveplate only. From the power-meter in the laser-room, that measures shot-by-shot laser pulse energy, all the way down to the tunnel a variety of optical components are used until the laser is finally focused onto the The typical shot-to-shot laser energy jitter is $\approx 5\%$ FWHM.

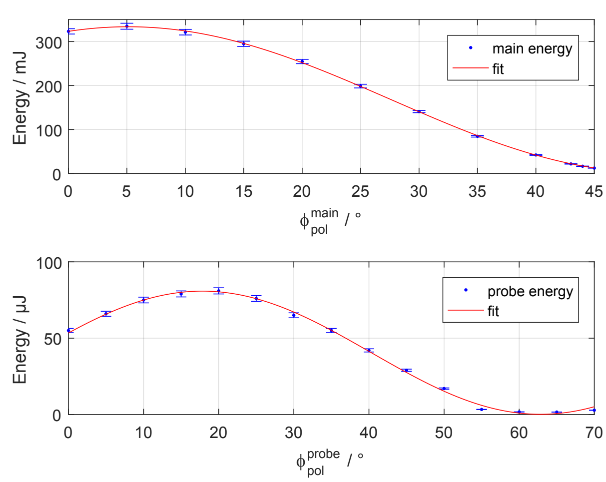

Fig. 3.1: Laser energy calibration for main energy waveplate (upper plot) and probe energy waveplate (lower plot)

All measured losses in optical components combined with the fitted functions for the waveplate energies (see figure 3.1) combined give the on target energy applicable by axilens and OAP respecively.

$$\begin{aligned} W_{\text{Laser}}^{\text{OAP}} &= W_{\text{Laser}}^{\text{Laserroom}} \times 1.25 \times 10^{-2} \\ &\times \big(0.994 \cos^2(\frac{2\pi}{180}(\phi_{pol}^{main} + 66.9)) + 1.16 \times 10^{-3}\big) \\ &\times \big(0.998 \cos^2(\frac{2\pi}{180}(\phi_{\text{pol}}^{\text{probe}} - 17.8)) + 1.62 \times 10^{-3}\big) \end{aligned}$$

$$W_{\text{Laser}}^{\text{Axilens}} = W_{\text{Laser}}^{\text{Laserroom}} \times 0.253 \tag{3.1}$$

$$\times \big(0.994 \cos^2(\frac{2\pi}{180}(\phi_{\text{pol}}^{\text{main}} + 66.9)) + 1.16 \times 10^{-3}\big) \tag{3.2}$$

$$\tag{3.3}$$

This means that for a typical laser energy output of 500 mJ a maximum energy of 6.2 mJ on OAP target and 125.9 mJ on axilens could be used.

3.2 Electro Optical Sampling (EOS)

3.3 Torch kick

3.4 Ionization test

3.5 Plasma glow diagnostic

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

The plasma glow diagnostic as 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 the recombination light. It was observed that this

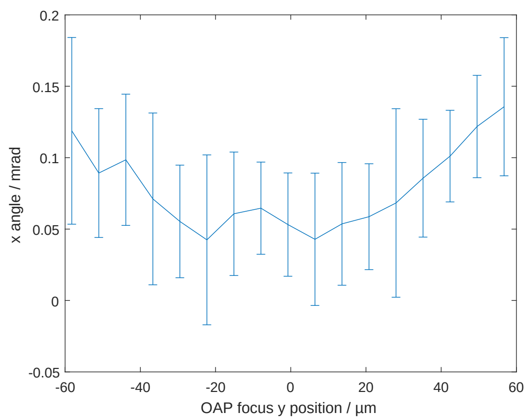
0.2
0.15
0.1
0.05
0
-0.05
x angle / mrad
-60
-40
-20
0
20
40
60
OAP focus y position / µm

Fig. 3.2: 'test'

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