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Front-to-end simulations of the design of a laser wakefield accelerator with external injection

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We report the design of a laser wakefield accelerator (LWA) with external injection by a rf photogun and acceleration by a linear wakefield in a capillary discharge channel. The design process is complex due to the large number of intricately coupled free parameters. To alleviate this problem, we performed front-to-end simulations of the complete system. The tool we used was the general particle-tracking code, extended with a module representing the linear wakefield by a two-dimensional traveling wave with appropriate wavelength and amplitude. Given the limitations of existing technology for the longest discharge plasma wavelength ($\sim 50 \mu\text{m}$) and shortest electron bunch length ($\sim 100 \mu\text{m}$), we studied the regime in which the wakefield acts as slicer and buncher, while rejecting a large fraction of the injected bunch. The optimized parameters for the injected bunch are 10 pC, 300 fs at 6.7 MeV, to be injected into a 70 mm long channel at a plasma density of $7 \times 10^{23} \text{ m}^{-3}$. A linear wakefield is generated by a 2 TW laser focused to $30 \mu\text{m}$. The simulations predict an accelerated output of 0.6 pC, 10 fs bunches at 90 MeV, with energy spread below 10%. The design is currently being implemented. The design process also led to an important conclusion: output specifications directly comparable to those reported recently from “laser-into-gas jet” experiments are feasible, provided the performance of the rf photogun is considerably enhanced. The paper outlines a photogun design providing such a performance level. © 2006 American Institute of Physics.

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I. INTRODUCTION

Laser wakefield acceleration (LWA) utilizes a powerful, short-pulse laser beam guided through a plasma. The plasma modulation thus created results in a traveling wave of very high field gradients, which can be used as an accelerating structure. A major advantage as compared to conventional radio-frequency accelerators is that the electrical fields in the plasmas are not limited by the vacuum breakdown constraint. Hence, LWA promises the generation of beams of charged particle bunches with energies of GeVs in accelerators of tabletop scale.

Although the basic idea of LWA seems straightforward, the difficulty of finding working combinations of operational parameters has for a long time prevented experimental demonstration of the concept. However, publications in *Nature*, in September 2004,^{1–3} have shown the potential of LWA using the laser-into-gas jet scheme to become a realistic accelerator option. Electron beams were generated with peak current, bunch length, and brightness that are well beyond specifications reached with present rf technology. In this LWA scheme, a powerful laser, of tens of terawatts, creates highly nonlinear plasma waves. Background electrons from the plasma are injected into the wakefield through a process known as wave breaking. Thus, the plasma is both the source of the electron bunches as well as the accelerating medium.

Strongly nonlinear processes, which depend on details of the laser and gas jet profiles, determine the charge, final energy, and energy distribution of the electron bunches. As of today, the systems show poor shot-to-shot reproducibility as well as a limited parameter space.

A possible method to overcome these drawbacks is to separate the production of electron bunches and the acceleration process. In such a system using external injection, the parameter space appears to be much larger in terms of, e.g., injected charge per bunch and plasma parameters such as electron density and applied laser power. Most important, however, there seems better control over both the injection and acceleration processes.

Using external injection, plasma wakefield acceleration can be operated in linear and nonlinear regimes. In the linear regime, as will be used in the design described in this paper, a relativistic bunch is injected into the plasma wake just behind the laser pulse. In this regime, a laser power of 2 TW is sufficient, which allows possibly high repetition rates, while the system will have truly tabletop dimensions. The fraction of the current that is accelerated depends strongly on the length of the injected bunch relative to the plasma wavelength. As we will see, using present day technology, typically less than 10% of the injected bunch is captured by the accelerator. There is an alternative mode of operation in the external injection scheme: a nonrelativistic electron bunch is injected into the plasma channel ahead of a powerful laser pulse capable of driving a highly nonlinear plasma

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wakefield.^{4,5} This wakefield overtakes the electron bunch and compresses it in both longitudinal and radial directions. Even when injecting long bunches compared to the plasma wavelength, a significant fraction of the injected bunch, up to 50%, is accelerated. However, the price paid for this setup is a laser of at least 10 TW.

This paper describes the design of a LWA experiment being developed at Eindhoven University of Technology, using external injection and acceleration in the linear regime. In order to find optimized combinations of input parameters, front-to-end simulations of the entire electron beamline have been performed, which include formation of the bunches in the rf photogun as well as acceleration in the plasma channel. The plasma wave is represented by a two-dimensional (2D) periodic traveling wave with appropriate wavelength and amplitude, which is incorporated in the general particle tracking (GPT) code.⁶ Through optimization, channel parameters are found such as the plasma density and channel length, and parameters for the injected electron bunches such as the minimum energy required, bunch charge, and length. Still, even for an optimized design of the injection system, the length of the injected bunch is more than two times longer than the plasma wavelength.

For a long time the general idea was that a bunch shorter than the plasma wavelength is an essential prerequisite for controlled laser wakefield acceleration. However, as realized by Gordon *et al.*, in the case of a bunch length of the order of the plasma wavelength or even longer, a plasma wakefield not only accelerates electrons but also acts as a slicer/buncher.⁷ This is the regime that can now be tested using existing technology. For carefully chosen injection energies, regimes can be found where a fraction of the input beam is quickly sliced, bunched, and accelerated to high energies. Due to this slicing, these electrons all experience roughly the same accelerating plasma fields, leading to a low energy spread. The remainder of the bunch, i.e., the part that is outside the phase acceptance, is not accelerated properly and is ejected radially.

Based on these ideas and using front-to-end simulations, a straightforward, realistic design has been developed, see Fig. 1, making use of well-proven technology. This includes a photogun developed earlier in our group,⁸ a laser system which produces pulses of 2 TW of 50 fs pulse length and a plasma channel based on the work of Butler *et al.*⁹

II. THE SIMULATION TOOL

A. Injector and beam transport line

The beamline that we designed for the LWA experiment consists of electron optical components with different characteristics, such as the rf photogun, static-field solenoid lenses, and the plasma channel, see Fig. 1. As will be shown, typical bunch lengths are of the order of tens of micrometers, while the radius is a few millimeters, i.e., the bunches look like pancakes. Minor effects, such as pathlength differences, nonlinearities of accelerating and focusing fields, or very small energy spread, can lead to severe deformation of the pancake bunches and hence to an increase of the bunch length.

FIG. 1. Schematic overview of the controlled laser wakefield accelerator. The Ti:sapphire laser is drawn as one block, indicating that the two laser beams, to drive the plasma wakefield and to generate the electrons in the photogun, originate from the same oscillator. The figure is not on scale; the plasma channel is 70 mm long, while the total beamline measures 1.2 m.

In order to perform front-to-end simulations of acceleration and transport of such pancake-shaped bunches, thereby tracking both the radial and longitudinal dimensions and including the influence of space charge and energy spread, a multiparticle tracking code is needed. To represent the various components, the code should be capable of generating the various magnetic and electrical fields or import fields generated by separate codes. The GPT code includes all these features. This is a three-dimensional (3D) particle tracking code that solves the relativistic equations of motion of up to about a million charged sample particles in time domain. The code combines the electromagnetic fields of external beamline components, such as accelerator sections and focusing elements, with the self-fields of the charged particle bunch. However, wakefields are not included yet. In the simulations for this design, the fields of elements such as the photogun and solenoids are calculated with the SUPERFISH set of codes and fed into GPT as high-resolution 2D magnetostatic field maps.¹⁰ The fields of the plasma channel are represented by a set of analytical equations, as described in Sec. II B. The self-fields of the bunch, due to space-charge forces, are calculated in GPT in full 3D as a three-step process. Firstly, the charge density in the zero momentum frame, often denoted as rest frame, of the bunch is calculated. Subsequently, the potential is calculated by solving Poisson's equation with a tailor-made anisotropic multigrid solver. In the final step, the derivative of the potential, being the electrostatic field in the rest frame, is Lorentz transformed to the laboratory frame to yield the electric and magnetic fields to be used in the tracking procedure. The numerical challenges related to space charge calculations posed by ultrashort bunches are described in detail in Ref. 11.

B. Modeling the plasma channel for LWA

In the plasma channel, a powerful laser pulse excites a plasma density oscillation thus creating a Wakefield. In a linear model, the plasma wave generated by the laser beam can be modeled as a 2D periodic traveling wave with appropriate amplitude and wavelength and a Gaussian radial pro-

file if the following assumptions hold. Firstly, the power transferred from the laser beam to the plasma is small, such that the laser beam propagates at constant power density. The plasma wave is then periodic. Secondly, the laser power is such that the linear wakefield regime applies, i.e., the modulation of the plasma density is small and can be assumed to be sine shaped along the longitudinal coordinate. Thirdly, the wakefield accelerates the electrons, but back action can be neglected, i.e., the self-fields of the electron bunches do not significantly influence the wakefield. After the description of the fields, we will check the validity of these assumptions.

With the above assumptions, the electrical fields of the wakefield are given as.¹²

$$E_z(r, z) = k_p U_0 \sin[k_p(z - v_g t) + \theta_0] e^{-(r^2/w_l^2)}, \quad (1)$$

$$E_r(r, z) = \frac{2U_0 r}{r_l^2} \cos[k_p(z - v_g t) + \theta_0] e^{-(r^2/w_l^2)}, \quad (2)$$

with n_p the plasma density, e the elementary charge, k_p the plasma wave number, $k_p^2 = 4\pi n_p r_e$, with r_e the classical electron radius, and w_l the matched radius of the laser beam.¹³ The latter is expressed by $w_l = (0.5\pi r_e \partial^2 n_p / \partial r^2)^{-1/4}$.

The group velocity of the laser pulse, v_g , is equal to the phase velocity of the plasma wave. In approximation it is given as $v_g = c\sqrt{1 - n_p/n_{cr}}$, with n_{cr} the critical plasma density. The group velocity determines the slippage of the wakefield relative to the electron bunches. It thus sets the dephasing length of the plasma channel, i.e., the length after which the electron bunch is not accelerated further. As an approximation, in the linear regime this dephasing length can be expressed as,¹⁴

$$l_{\text{deph}} = \frac{2\lambda_p^3}{\pi\lambda_0^2}. \quad (3)$$

The phase θ_0 in Eqs. (1) and (2) gives the phase of electrons with respect to the wakefield. Generally, the phase is an important parameter because the longitudinal and radial electrical fields are $\pi/2$ out of phase, i.e., at maximum acceleration there is no radial focusing and vice versa. Consequently, only in a limited part of the phase will the electron bunches be accelerated and focused simultaneously. However, when injecting bunches much longer than the plasma wavelength, the phase has limited influence since it only determines *which part* of the bunch is finally accelerated. Hence, for long bunches the final energy and accelerated charge hardly vary with the phase.

As shown in Eqs. (1) and (2) the accelerating gradient is set by the potential amplitude U_0 of the plasma wave. Expressed in laser and plasma channel parameters U_0 is given as¹⁵

$$U_0 = \frac{e\Omega_0 P}{\sqrt{\pi m_e c^2}} \left(\frac{\lambda_0}{\lambda_p} \right) \left(\frac{\sigma_z}{2Z_R} \right) e^{-(k_p^2 \sigma_z^2/4)}, \quad (4)$$

where Ω_0 is the vacuum resistivity (377 Ω), P is the laser power, λ_0 is the laser wavelength, σ_z is the temporal half-width of the laser pulse, and Z_R is the vacuum Rayleigh length, $Z_R = \pi r_l^2 / \lambda_0$.

In order to verify that the linear regime indeed applies, the wakefield potential is expressed in the plasma density modulation. Assuming a sine-shaped plasma density modulation, the relation between the potential amplitude and the modulation depth α can also be written as $U_0 = \alpha n_p e / \epsilon_0 k_p^2$. Using this equation, U_0 can be written as

$$U_0 = \alpha e / 4\pi \epsilon_0 r_e, \quad (5)$$

so that 1% of the modulation depth gives 5 kV of wakefield amplitude. For typical operating parameters for this experiment (2 TW laser power, $n_p = 2 \times 10^{23} \text{ m}^{-3}$) the modulation depth is less than 10% and the linear wakefield regime indeed applies. Furthermore, the assumption that back action from the bunches upon the wakefield is negligible can be validated by comparing the wakefield amplitude to the internal field of the bunches. The wakefield amplitude is 8 GV/m [Eq. (4)], whereas the internal field of the injected 10 pC, 6.7 MeV bunches of 30 μm radius and 100 μm length (see Sec. III) is two orders of magnitude smaller. When the bunches are accelerated, their internal space charge forces become even smaller.

This linear model based on Eqs. (1) and (2) has been incorporated in the GPT particle tracking code, so that the entire beamline can be simulated front to end. The wakefield model has been tested against a more complete 3D particle-in-cell model developed by Reitsma.¹⁶ For small plasma modulation, i.e., a wakefield in the linear regime, the models give comparable results for final energy, energy distribution, and bunch charge. In fact, both models could have been used. However, for this design and optimization work, a large number of parameter scans was needed and we have opted for the linear 2D model, which is less CPU costly.

Using the front-to-end simulation model, regimes of parameters can be identified which provide a good trade-off between high electron energy, low energy spread, and high charge, c.q., peak current, of the accelerated bunches. Input parameters for the laser wakefield acceleration process are the plasma density and the length of the plasma channel, the power density and temporal half-width of the laser pulse, and the energy, length, radius, emittance, and charge of the injected electron bunches. Output parameters are the energy, energy distribution, temporal pulse width, charge, and emittance of the electron bunches.

III. APPLICATION TO THE TRUE DESIGN

A. General considerations and layout of the injector system

The injector system has to deliver bunches that are matched to the acceptance of the plasma channel in terms of energy, emittance, and transverse size. One of the key parameter in the design process is the plasma wavelength. Using state-of-the-art technology, in a capillary tube a plasma can be generated with a density of as low as $7 \times 10^{23} \text{ m}^{-3}$.⁹ This results in a plasma wavelength of 42 μm . Note that this is the longest wavelength possible at this time for a plasma channel. Ideally, to have all the injected current captured by the plasma wave, the bunch should be roughly shorter than a quarter of the plasma wavelength. However, this cannot yet

be realized in the present setup. Still, a length of the electron bunches as short as possible leads to higher accelerated current. The optimization process resulted in a bunch length of $100\ \mu\text{m}$ (300 fs). At these short bunch lengths, effects which are usually ignored, such as beam scalloping leading to path-length differences, play an important role.

First, we discuss two more common causes of bunch lengthening, which are space charge and energy spread. Internal space charge forces have two effects. Firstly, the repelling forces cause the bunch to grow in all directions. Secondly, the rear of the bunch is slightly decelerated while the head of the bunch is slightly accelerated, and the corresponding velocity spread will cause the bunch length to increase due to time-of-flight variation. An energy spread $\Delta\gamma$ causes a time-of-flight variation Δt after a distance Δz given as

$$\frac{\Delta t}{\Delta\gamma} \approx -\frac{\Delta z}{c\gamma^3}. \quad (6)$$

The equation shows that the bunch lengthening Δt decreases strongly with higher electron energy. For a typical electron energy, $\gamma=14.1$ (6.7 MeV), the time-of-flight variation per unit of drift space and per unit of energy spread ($\Delta\gamma=1$) is 1200 fs/m. Clearly, to minimize the effects of bunch lengthening as a result of energy spread, the beamline should be designed as short as possible and the electron energy should be high. Furthermore, to keep the energy spread as small as possible, the initial energy spread upon generation of the electron beam should be small and the space charge density should be kept low wherever possible. The initial energy spread is negligible, since the duration of the laser pulse that generates the electron bunch (50 fs) is very short compared to the rf period of 333 ps. Keeping the space charge density low while keeping the bunch as short as possible implies that the bunch radius should be large. However, this requirement conflicts with another source of bunch lengthening, beam scalloping.

Beam scalloping increases the bunch length due to the fact that on-axis electrons follow a shorter pathlength as compared to off-axis electrons. This effect is usually ignored since it only plays a role for bunch lengths of the order of tens of micrometers. In order to minimize the effect of scalloping, the beam should be transported at a radius as constant as possible. This is possible for most of the beamline, but scalloping unavoidably takes place inside the photogun and just in front of the plasma channel, where the beam is focused to a waist of micrometers dimensions. To minimize scalloping, the beam radius has to be as small as possible. However, this leads to a high space charge density and hence bunch lengthening. A trade-off between space charge effects and beam scalloping shows that an initial bunch radius of 1.7 mm gives the shortest bunch length at the entrance of the plasma channel.

Applying the above considerations results in the following design. As regards the electron energy, higher values lead to less bunch lengthening. In our photogun the maximum electron energy is 6.7 MeV, which is limited by the breakdown field strength of 100 MV/m in the injector. In Sec. IV, we will show that this energy is a good choice for the acceleration process. The focusing solenoid around the injector is

FIG. 2. Beam envelope (r_{max}) and bunch length along the beamline for a 6.7 MeV, 10 pC bunch (a) and a bunch without space charge (b). Magnetic fields at the injector and the final solenoid are set to minimize beam scalloping and to focus the beam at the entrance of the plasma channel, at 1.1 m, respectively.

operated such that the bunch is transported at near-constant radius to the final focusing solenoid in front of the plasma channel, as shown in Fig. 2(a). This figure also shows the evolution of the bunch length along the beamline, which is a result of the combined effects of scalloping, space charge blow up, and energy spread. To illustrate the influence of scalloping separately, a simulation is also given for a situation without space charge, see Fig. 2(b). The solenoids are powered such that in Figs. 2(a) and 2(b) the beam envelopes are identical as much as possible. This way, the influence of scalloping is the same in both cases and the effects of energy spread and space charge are made visible too. Comparing Figs. 2(a) and 2(b) shows that bunch lengthening inside the photoinjector is mainly the result of scalloping. Even though the beam starts at thermal energy, the space charge has only a minor effect along the short length of the injector (130 mm). In the drift space scalloping has no effect [Fig. 2(b)] as expected. Here bunch lengthening is mainly due to energy spread. Finally, beam focusing in front of the plasma channel adds significantly to the bunch length, some 20 fs due to scalloping and 10 fs due to space charge and energy spread.

The energy spread caused by the charge of the bunch is illustrated in Fig. 3, which shows its evolution along the beamline for bunches of 0 (space charge switched off), 1,

FIG. 3. Energy spread, $\Delta\gamma$, as it develops during propagation of the bunch along the beamline for a bunch without space charge and bunches of 1 and 10 pC, for beamline settings corresponding to those for the results shown in Fig. 2.

and 10 pC. The influence of tight focusing by the solenoid in front of the plasma channel on energy spread is clearly visible. However, this dramatic increase in energy spread does not translate in an equally strong increase of bunch length, because energy spread only has an effect after a long drift space.

The fact that beam scalloping and high space charge densities have to be avoided implies that no intermediate focus should be formed anywhere along the beamline. This requirement is contradictory to the design of the laser beamline. Preferably, the 45° on-axis mirror (see Fig. 1) should have a hole as small as possible for the electron beam to pass through to minimize loss of laser power. However, the effect on bunch length is quite dramatic as is shown in Fig. 4. The beam is not even extremely strongly focused, to a radius of 0.2 mm at $z=0.5$ m, but the bunch length increases to 270 μm instead of 120 μm for the optimized situation. Therefore we opt for a near-constant radius of the electron beam, a hole in the mirror of 1.5 mm radius, and accept a few percent loss of laser power and some deformation of the laser profile.

For optimum settings, see Table I and Fig. 2(a), the longitudinal bunch profile is given in Fig. 5. The total length is

FIG. 4. Same as Fig. 2 (10 pC bunch), but for magnetic fields set for an intermediate crossover at the position of the on-axis mirror, $z=0.5$ m and a waist at 1.1 m. Compare to Fig. 2 and note the dramatic increase of the bunch length due to the intermediate crossover, which causes locally high space charge forces and additional beam scalloping.

TABLE I. Input parameters for the controlled LWA experiment, optimized for maximum output energy and minimum energy spread.

Input parameter	Value
Electron energy	6.7 MeV
Bunch charge	10 pC
Normalized rms emittance	2 μm
Radius of electron bunches	30 μm
Length of electron bunches	100 μm
Plasma density in capillary channel	$7 \times 10^{23} \text{ m}^{-3}$
Radius of plasma channel	100 μm
Length of plasma channel	70 mm
Laser peak power	2 TW
Laser pulse half width	50 fs
Spot size of laser beam at channel entrance	30 μm

over 120 μm and the flat top is 40 μm , i.e., comparable to the plasma wavelength. The consequences of this bunch length for the accelerated current will be discussed in the next section.

With regard to the required synchronization between the injected bunch and the laser driving the wakefield, the consequences are the following. Due to the relatively flat top of the injected bunch, the requirement for synchronization is relaxed to a level of tens of femtoseconds. A feedback and control electronic circuit to achieve such a level has been reported by Kiewiet *et al.*¹⁷ The associated optimization of the rf cavity dimensions, necessary to obtain the same level of precision in the eventual jitter of the electron bunch at the plasma channel entrance, will be described in a separate paper.

B. Constraints and free parameters for the laser wakefield accelerator

The objective of the LWA experiment is to obtain high peak currents at high energy with low emittance and narrow energy spread. For the realization of this goal the following parameters, which are all linked, have to be matched and optimized: the plasma channel parameters, i.e., length, radius, and plasma density; the laser beam which creates the wakefield, i.e., power, pulse width, and spot size; and the

FIG. 5. Current profile in longitudinal position of a 10 pC, 6.7 MeV electron bunch at the entrance of the plasma channel.

parameters of the injected electron bunches, i.e., energy, charge, bunch length and radius, emittance, and energy spread.

The design of the plasma channel is largely determined by operational parameters set by physical properties and technological constraints. As discussed before, for the present type of discharge channels, the longest possible plasma wavelength is $\lambda_p = 42 \mu\text{m}$, which is much shorter than the injected bunch. The fraction of the bunch that is captured, however, is also determined by the wakefield amplitude. A long wavelength (low plasma density) provides a large range in phase which accepts electrons, but acceleration is relatively weak. Consequently, only a small range in accelerating gradients, and thus in phase, gives acceleration such that the electron bunches stay in phase with the wakefield. Electrons that are not sufficiently accelerated fall behind, enter a defocusing region, and are radially ejected, see Sec. II B. In contrast, for a high plasma density, a large range in accelerating gradients provides matched acceleration, but now the plasma wavelength is short.

With respect to maximum output energy and minimum energy spread, a low plasma density is favorable. This results in a low accelerating gradient, but also in a long dephasing length. Equations (3) and (4) show that the effect of the longer dephasing length is stronger than the lower gradient. Similarly, a lower gradient over a longer length results in less energy spread.⁷

The wakefield is driven by an 800 nm Ti:sapphire laser, which gives an output energy per pulse of 100 mJ. The accelerating gradient increases proportionally to the laser power, see Eq. (4). The pulses are compressed to 50 fs, which is bandwidth limited. The maximum laser power available to us is 2 TW.

The spot size of the laser is related to the electron bunch waist and the accelerating gradient. Firstly, a small laser spot gives a high accelerating gradient. Secondly, the spot size of the laser beam and the size of the electron bunch waist should be equal so as to get an optimum overlap between the wakefield and the electron bunches. Therefore, it seems advantageous to focus the electron beam in a waist as small as possible too. However, strong focusing of the electron bunch results in bunch lengthening through space charge, and therefore, since the bunch is longer than the plasma wavelength, a smaller fraction of the bunch is captured by the wakefield. Analysis of the bunch length as a function of its waist, i.e., focusing strength of the final solenoid, shows that the dependency of bunch length on bunch waist size is only weak. This is because the bunch length is also, and largely, determined by scalloping and energy spread, effects which do not depend on the focusing strength. For practical reasons, 50 mm space is needed between the solenoid and the plasma channel to mount diagnostics for the electron and laser beams. The electron bunch waist is then $30 \mu\text{m}$, and a parabolic mirror with a focal length of 762 mm (30 in.) focuses the laser beam into a $30 \mu\text{m}$ spot, thus matching the electron beam profile.

Next we look at the optimum injection energy of the electron bunches. At low injection energies the electrons immediately slip back relative to the wakefield, enter a defo-

cusing phase region, and are radially ejected. Similarly, for higher injection energies a larger fraction of the injected bunch is captured, which results in higher transmitted current. However, this will result in more energy spread. An additional requirement with respect to the injection energy is imposed by the injection system. As outlined before, for a higher injection energy, bunch lengthening due to space charge blow up and energy spread is reduced.

The charge injected into the plasma channel is chosen to be 10 pC, for several reasons. The bunch length at injection is $100 \mu\text{m}$. As will be shown in the next section, the plasma wakefield slices out three bunches, and one main microbunch containing most of the charge and two small satellites are accelerated. When injecting more charge, the injected bunch will be longer and our simplified wakefield model would predict the acceleration of a train of microbunches. In practice, however, the laser-induced wakefield consists of at most two or three buckets with appropriate acceleration and focusing properties. In order not to exceed the regime of validity of our simple wakefield model, we restricted the present study to an injected charge of up to 10 pC. Obviously, in the experiments we plan to investigate the results of injecting charges higher than 10 pC.

IV. RESULTS OF ITERATIVE OPTIMIZATION OF THE LASER WAKEFIELD ACCELERATOR

Based on the bunches produced by the injection system, optimized values for the plasma density, channel length, injection energy, and injected charge have been determined by simulations on the acceleration process. The goal was to find a trade-off for optimum final energy, energy spread, and accelerated charge. In all cases, the injected bunches are long compared to the plasma wavelength. The results are presented in Fig. 6 as functions of the injection energy and the plasma density. For each value of the plasma density the dephasing length has been estimated according to Eq. (3). In the results shown in Fig. 7 the channel length has been optimized in more detail.

Figure 6(a) shows that a low plasma density is indeed favorable with respect to final energy. The effect of the longer dephasing length is stronger than the lower wakefield amplitude. The influence of the injection energy is of minor influence in the plasma density region of interest, except that there is clearly a minimum energy, see also Fig. 6(c). Below 4–6 MeV, depending on the plasma density, electrons are not captured by the wakefield, but all electrons are radially ejected within a few plasma periods. Figure 6(b) shows that a low energy spread requires a low plasma density too, and the injection energy appears to have an optimum between 6.5 and 9 MeV.

With respect to the accelerated charge, the higher field amplitude at high plasma density leads to higher accelerated charge, even though the plasma wavelength is shorter. However, the region of high plasma density is of no interest because of the low final energy and high energy spread.

Additional simulations have been performed for fine-tuning the optimum channel length. So far the channel length has been determined using Eq. (3) to maximize the electron energy. However, a slightly longer channel can lead to a

FIG. 6. Map of the final energy in MeV (numbers 40–160) (a), standard deviation of the electron energy as percentage of the average electron energy σ_E/E (b), and accelerated charge in pC (c) as a function of the plasma density and the injection energy of the electron bunches. The injected charge is 10 pC. The length of the plasma channel is calculated for each value of n_p , according to Eq. (3). The black dot indicates the operational point of this design and of the experiment being built up. In the dark grey areas the entire bunch is lost within a few plasma periods.

more narrow energy distribution due to additional bunching. As an example, Fig. 7 shows the simulation results for energy, energy spread, and bunch charge for $n_p = 7 \times 10^{23} \text{ m}^{-3}$ as a function of the longitudinal coordinate. A channel length of 80 mm gives maximum output energy, while the minimum energy spread is indeed reached for a slightly longer channel of 90 mm. However, note that after 70 mm there is no significant improvement in final energy and energy spread.

Matching the energy of the injected beam to the plasma channel appears not to be critical. Within the range of injection energies from 6 to 10 MeV both the final energy and the energy spread of the accelerated bunches hardly varies. The accelerated current, however, would increase for higher injection energies, see Fig. 2(c). Since the formation of short

FIG. 7. Average electron energy of the bunches, E , standard deviation of the electron energy relative to the average energy, σ_E/E and charge Q , inside the plasma channel relative to the injected charge Q_0 , where Q includes all electrons that have not yet been ejected out of the channel at the given position. For input parameters, see Table I.

bunches by the injection system also requires an energy as high as possible, operating the rf photogun at maximum energy (6.7 MeV) is the best option. For optimized bunch and channel parameters, see Tables I and II, the current profile of the accelerated bunch is shown in Fig. 8. The injected charge is 10 pC, and most of the accelerated charge is contained in the central peak. The height and width of the peak show that the wakefield accelerator indeed slices parts out of the injected bunch, but that there is no strong bunching; the peak current at injection is 40 A, and is increased to 65 A at the exit of the channel. Still, the final energy is over 90 MeV, the energy width is around 10%, and the normalized transverse emittance is about $1 \mu\text{m}$. These are output parameters that are comparable to those of modern rf accelerators, realized in a device of tabletop dimensions. The bunch length, however, is an order of magnitude smaller than in rf devices.

V. OUTLOOK

According to the simulation results presented in Fig. 3, about 5% of the charge injected into the plasma channel will be accelerated and reach the exit of the channel. This is largely due to the fact that the injected bunches are $100 \mu\text{m}$ long, while the plasma wavelength is $40 \mu\text{m}$. Clearly, if substantially shorter bunches could be injected, the fraction of the bunch which is accelerated would increase.

As explained in Sec. III, the bunch length grows due to beam scalloping and internal space charge forces. A method

TABLE II. Output parameters according to GPT simulations for acceleration in a plasma channel with a plasma density of $7 \times 10^{23} \text{ m}^{-3}$ and a channel length of 70 mm. For input parameters see Table I.

Output parameter	Value
Average electron energy	90 MeV
Relative energy spread, σ_E/E	8%
Charge of accelerated bunches	1 pC
Charge of central bunch	0.6 pC
Length of central bunch FWHM	10 fs
Peak current of central peak	60 A
Normalized rms emittance	$1 \mu\text{m}$

FIG. 8. Current profile in time of accelerated electron bunches at the exit of a 70 mm long plasma channel with a plasma density of $7.0 \times 10^{23} \text{ m}^{-3}$. Other conditions are as indicated by the black dots in Fig. 6. The bunch injected into the channel is shown in Fig. 5. The injection energy is 6.7 MeV. The central bunch has an exit energy of 90 MeV. The arrows indicate the width of the central bunch, 10 fs FWHM.

has recently been described to overcome the effects of space charge by producing 3D ellipsoidal bunches, homogeneously filled with charge.¹⁸ Due to the modular setup of this experiment, sections of beamline can be replaced straightforwardly to incorporate such improvements. As an example, preliminary simulations have shown that a 100 pC bunch can be time focused to a length of 20 μm . Injecting these bunches into the laser wakefield accelerator as described results in an accelerated charge of 35 pC in a 7 fs long bunch. The final energy and relative energy spread would be 85 MeV and 2%, respectively, and the transverse rms emittance less than 1 μm .

VI. CONCLUSIONS

Based on well-proven rf photogun technology and a mode-locked Ti:sapphire laser producing a moderate output power of 2 TW, a realistic design has been made for a LWA experiment. The design is supported by simulations of the complete beamline, including the rf photogun, focusing elements, and plasma channel. The injection system (photogun and solenoid) is optimized to produce a bunch as short as possible, for an energy and beam radius that are matched to the plasma channel parameters. Effects which can usually be ignored, such as bunch lengthening due to beam scalloping (e.g., focusing), have been addressed and turn out to be of substantial influence. Even when the beam radius is kept as constant as possible along the beamline, beam scalloping inside the photoinjector and the solenoid lens adds some 50 μm to the bunch length. Another 50 μm bunch length is added through space charge effects. This increase originates from the usual space charge blow up, but also, and for a substantial part, from space-charge-induced velocity spread. After 1.1 m of beamline, the velocity spread of 0.01% adds 50 μm to the bunch length.

The bunch injected into the plasma channel has a length of 100 μm . For the optimum value of the plasma density, which is the lowest operational value of $7 \times 10^{23} \text{ m}^{-3}$, the plasma wavelength is 42 μm . However, the plasma channel acts as a slicer/buncher, and still proper acceleration of part of the injected beam occurs. By means of a simplified 2D model of the plasma wakefield, regimes have been identified in terms of injection energy, plasma density, and channel length, which lead to accelerated bunches with an energy of 90 MeV, 5% energy spread, a temporal half-width of 10 fs, and a peak current of 60 A. These are beam parameters in terms of electron energy and distribution, which are comparable to those of the laser-into-gas jet scheme, except for the bunch charge, c.q., peak current. This design is currently being implemented.

Finally, some ideas are sketched which can lead to much shorter injected bunches, thus increasing the accelerated bunch charge. Once these ideas have been realized, much higher peak currents can be realized and controlled LWA with external injection can be considered a serious option for very high performance tabletop acceleration.

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