Experimental validation of a radio frequency photogun as external electron

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Experimental validation of a radio frequency photogun as external electron injector for a laser wakefield accelerator

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A purpose-built RF-photogun as external electron injector for a laser wakefield accelerator has been thoroughly tested. Different properties of the RF-photogun have been measured such as energy, energy spread and transverse emittance. The focus of this study is the investigation of the smallest possible focus spot and focus stability at the entrance of the plasma channel. For an electron bunch with 10 pC charge and 3.7 MeV kinetic energy, the energy spread was 0.5% with a shot-to-shot stability of 0.05%. After focusing the bunch by a pulsed solenoid lens at 140 mm from the middle of the lens, the focal spot was 40 μm with a shot-to-shot stability of 5 μm . Higher charge leads to higher energy spread and to a larger spot size, due to space charge effects. All properties were found to be close to design values. Given the limited energy of 3.7 MeV, the properties are sufficient for this gun to serve as injector for one particular version of laser wakefield acceleration, i.e., injection ahead of the laser pulse. These measured electron bunch properties were then used as input parameters for simulations of electron bunch injection in a laser wakefield accelerator. The arrival time jitter was deduced from measurements of the energy fluctuation, in combination with earlier measurements using THz coherent transition radiation, and is around 150 fs in the present setup. The bunch length in the focus, simulated using particle tracking, depends on the accelerated charge and goes from 100 fs at 0.1 pC to 1 ps at 50 pC. When simulating the injection of the 3.7 MeV electron bunch of 10 pC in front of a 25 TW laser pulse with a waist of 30 μm in a plasma with a density of $0.7 \times 10^{24} \text{ m}^{-3}$, the maximum accelerated charge was found to be 1.2 pC with a kinetic energy of ~ 900 MeV and an energy spread of $\sim 5\%$. The experiments combined with the simulations show the feasibility of external injection and give a prediction of the output parameters that can be expected from a laser wakefield accelerator with external injection of electrons. © 2011 American Institute of Physics. [doi:10.1063/1.3610509]

I. INTRODUCTION

Accelerators based on laser-plasma interaction were first described by Tajima and Dawson in 1979.¹ In laser wakefield accelerators (LWA), a plasma is used as an accelerating medium for charged particles. When a high intensity laser pulse is focused in a plasma, the ponderomotive force of the laser pulse will repel the electrons from the region of high laser intensity. The ions, that are much heavier than the electrons, remain quasi stationary and the result is a positively charged zone behind the laser pulse. Once the laser pulse is gone, the Coulomb force pulls the electrons back which results in an oscillation of the electrons. This results in an electron density modulation in the wake of the laser pulse. The electrons oscillate around their equilibrium position and this leads to a (Langmuir) plasma wave with a phase velocity equal to the group velocity of the laser pulse. The electric fields in the plasma wave have both radial and longitudinal components so that the plasma wave can act as an accelerating and focusing structure propagating at the group velocity

of the laser pulse in the plasma. The electric fields in these plasmas waves can be of the order of TV/m,^{2,3} while the maximum accelerating field in conventional radio frequency (RF) accelerators is limited to approximately 100 MV/m.⁴ The advantage over conventional accelerators is that a plasma-based accelerator is not limited to breakdown in the RF-structure. As a consequence, plasma accelerators may become a compact alternative for conventional RF-accelerators. The laser intensity needed to drive those plasma waves is in the TW-range and became possible with the introduction of Chirped Pulse Amplification⁵ in 1985 and subsequent developments. Nowadays, TW laser systems up to 30 TW are commercially available.

In order to accelerate electrons in a plasma accelerator, the electrons need to be trapped by the plasma wave. This can be achieved by so-called wave breaking, where the plasma wave is highly nonlinear due to an over-intense laser pulse. Hot background electrons in the plasma are then trapped and accelerated. In this case, the plasma is the accelerating structure and the electron source. In this regime, successful acceleration experiments in a plasma were done by focusing a laser pulse with a power of several of terawatt into a gas jet. This led to accelerated electrons with energies up to 100 MeV over

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a distance of a couple of millimetres.^{6–10} The drawback of this method of injection of the hot background electrons in the plasma wave is that the moment of injection cannot be controlled accurately and injection continues while the laser propagates through the plasma. This leads to an energy spread of 100% with rather poor shot-to-shot reproducibility of the experiment.

Quasi mono-energetic electron bunches with an energy up to 200 MeV were produced by using a channel with a pre-formed plasma density profile in the gas jet to guide the laser pulse over a longer distance¹¹ and by adapting the plasma density to the laser pulse.^{12,13} With a carefully chosen gas density it turned out to be possible to limit the wave breaking, and therefore the injection of electrons into the accelerating phase of the plasma wave, to just a fraction of the propagation distance of the laser in the plasma. Consequently, the energy spread was reduced to order 1%.

To accelerate to higher energies a plasma density lower than $n_e \sim 10^{24} \text{ m}^{-3}$ is needed. The group velocity of the laser pulse (and with that the phase velocity of the plasma wave) is higher at lower plasma density. Electrons can then be accelerated over a longer distance and to higher energies before they outrun the plasma wave (dephasing). In this regime, the laser pulse needs to be guided over a distance much larger than the Rayleigh length, so that the electrons can be accelerated over the complete dephasing length and gain maximum energy. By combining a 40 TW laser pulse with a slow capillary discharge plasma which guided the laser pulse over a distance of 3.3 cm, quasi mono-energetic electron bunches have been produced with an energy of 1 GeV (Ref. 2). Although the energy spread in those schemes is much better than in the earliest results, there is still a large shot-to-shot energy variation of the electron bunches produced.

For LWA to have a future in applications, electron bunches with high reproducibility, consistent energy and (low) energy spread are required. This is not the case with the previously mentioned schemes that are based on wave breaking, which is a highly nonlinear process. Small changes in parameters, such as laser intensity, the laser wave front and plasma density have a considerable influence on the output properties of the accelerated electron bunches. To stabilize the electron bunch, a controlled injection of electrons in the plasma wave is necessary. One method to achieve this is by shooting a second, counter-propagating ultra short laser pulse with the same central wavelength and polarization into the plasma.¹⁴ The first laser creates the wakefield and the second laser pulse injects the electrons in the plasma wave at the point where the two pulses overlap and briefly form a standing wave. Quasi mono-energetic electron bunches up to 200 MeV with tunable energy and high reproducibility have been made using this ‘all-optical injection’ method.^{15–17} A second approach to injection is creating a density ramp in the plasma channel, which locally leads to wave breaking and thus to injection. Recent experiments have shown the feasibility of this scheme¹⁸ and the results are comparable to optical injection. A third method that has recently been demonstrated is known as ionization triggered injection, in which a helium plasma was seeded with gas containing heavier

atoms. Electrons from inner shells are ionized in the region of highest intensity of the laser pulse so that they are out of phase with the electrons forming the plasma wave and are consequently trapped in the wakefield.^{19,20}

Although these injection schemes show promising results, the drawback is that the plasma still acts as accelerating medium and electron source so that one cannot be independently varied with respect to the other. An external electron source would therefore be most desirable. Since an RF-photogun is one of the brightest pulsed electron sources with high peak current,⁴ this is the best candidate to serve as external injector. An added advantage of using an external source for the injection of electrons is that acceleration becomes possible not only in nonlinear wakefields, in which all experiments above are performed,^{21–23} but also in the linear regime with modest sub-10 TW lasers and a high repetition rate.^{21,24–26}

In the linear regime, the electron bunch is injected shortly behind the laser pulse so it can occupy the first troughs, or ‘buckets’, of the plasma wave. It was believed that the injected bunch had to be shorter than the plasma wavelength (under 50 μm) with a synchronization between electron bunch and the plasma wave driving laser pulse even shorter than the plasma wavelength (sub 10 fs) in order to obtain accelerated electron bunches with low energy spread. It has been shown that in case of an injected bunch which exceeds the plasma wavelength, the wakefield will act as a chopper and transform the injected bunch in a train of accelerated sub-bunches.^{25,27} Because only the accelerating and focusing phase is suitable for acceleration, a maximum of $\sim 10\%$ of the initially injected charge can be accelerated. The trapping conditions are determined by the combination of wakefield amplitude and the injected electron energy. A higher injected electron energy (above the trapping threshold) will result in more accelerated charge but also in a higher energy spread. Laser wakefield accelerators with a slow capillary discharge plasma in the linear regime and externally injected electron bunches from an RF-photogun is an approach in which most parameters are independently adjustable. This combined setup makes it possible to study the separate effects of source, plasma and laser on the accelerated electron bunch.

In the nonlinear regime, an electron bunch is injected in front of the laser pulse.^{22,23} If the velocity of the electron bunch is set to be lower than the group velocity of the laser pulse in the plasma, the laser will overtake the bunch inside the plasma. When the laser intensity is sufficiently strong, the electrons will be trapped, accelerated and compressed in the first trough of the plasma wave behind the laser pulse. After acceleration only one bunch is expected.

This article describes an RF-photogun and experiments to measure the properties of electron bunches to determine their suitability for injection in LWA in the non-linear regime. Only the nonlinear regime is examined as the energy of the electron bunches from the RF-photogun is only sufficient to operate in this regime. To operate in the linear regime, the RF-photogun needs further conditioning and has to be able to produce electron bunches with an energy higher than 5 MeV. The goal of this article is to remove the

suppositions that are normally made about the properties of the bunches that can be delivered into a plasma channel. Using the measured values for these properties we expect to be able to better establish the feasibility of LWA with external injection of electrons.

II. RF-PHOTOGUN

A. Design

The RF-photogun injector is a 2.6 cell cavity working in the S-band range at a frequency of 2.998 GHz. A cross section is shown in Fig. 1. The accelerator consists of three coupled pillboxes which are clamped together. The cells are made from high purity oxygen free copper (type C10100) by single-point diamond turning with 1 μm accuracy, following design with the same precision. By clamping the cells, deformation after construction by heating — which is necessary when brazing — is eliminated. Combining the clamping construction and micrometer precision manufacturing of the individual cells makes tuning plungers redundant. The length of the first cell is chosen to achieve maximum acceleration. The irises between the cells have an elliptically shaped cross section. As a consequence the maximum electric field strength is not on the irises, but on the cathode.²⁸ When breakdown occurs, it will be mostly on the cathode, which can be removed relatively easily for cleaning or polishing, because of the clamping system.

Instead of the more commonly used sideways in-coupling of the RF power in the cavity, a coaxial input-coupler was designed and built. The design was originally proposed by DESY (Deutsches Elektronen Synchrotron) for use at 1.7 GHz. It was redesigned for 3 GHz and successfully used in previous versions of this electron gun at Eindhoven University of Technology.²⁹ The coaxial input coupler transfers the RF power coming from a rectangular waveguide in the TE_{10} mode to the TM_{010} mode in the cavity. The RF power source is a klystron, producing a peak power of 10 MW (Thomson TH2157A). Inside the cavity, a standing wave is generated

with a longitudinal electric field which accelerates the electrons. A stainless steel holder suspends the cavity, thereby separating the electric and mechanical functionality of the construction. The stainless steel holder only serves to support the vacuum, preventing unwanted strain on the copper cavity structure. The normal operating pressure is $\sim 1 \times 10^{-7}$ mbar.

By using the coaxial input coupler, the construction of a completely cylindrically symmetric cavity is possible. A solenoid is placed around the cavity, whereas in most other designs, the solenoid is placed just behind the exit of the cavity. Electrons are produced at the copper cathode plate by photoemission of an incoming 50 fs, 266 nm laser pulse and are accelerated by the cavity's electric field. The magnetic solenoid lens around the cavity serves multiple functions aimed to keep the emittance of the bunch low and the length of the bunch short. It keeps the accelerating electron bunch in the cavity collimated and the radius small. Because the electric field as a function of radius inside the cavity is only constant close to the axis, the bunch radius has to remain relatively small to prevent electrons from sampling the higher order field components which would cause an increase in emittance and energy spread. In addition, path length differences between electrons on the axis and those further away are thereby limited. This keeps the bunch length at the exit of the accelerator short. Finally, the solenoid lens compensates for the exit kick from the divergence of the electric field at the end of the accelerator, which acts as a negative lens for the electrons exiting the cavity. However, at the place of electron creation, on the cathode, the magnetic solenoid creates a non-zero magnetic field. As a result, the electrons would obtain an extra net azimuthal momentum which leads to an increase of the emittance. A smaller solenoid (bucking coil) is placed outside the vacuum at the back of the cathode plate to eliminate the magnetic field at the surface of the cathode.

The temperature of the cavity is controlled by a water circuit which is connected to the cathode plate and the exit cell of the cavity. Temperatures of the first and last cell of the cavity are measured by thermocouples. A PI controller adjusts the water temperature to assure a cavity operating temperature of 30.00 °C with a stability of 0.05 °C (Ref. 30). Precise temperature control is essential in this design of the accelerator, without tuning plungers, to keep the cavity exactly resonant with the RF oscillator.

A detailed analysis of the absorption spectrum and the field balance inside the cavity is given by Van Dijk.³¹ Three different modes can be excited, the 0-, $\pi/2$ - and π -mode. The peaks in the absorption spectrum are well separated, in accordance with the SUPERFISH simulations that were used for the design of the cavity. To get optimal acceleration and use each cell for acceleration, the cavity needs to be operated in the π -mode. The (loaded) Q-factor of the cavity operating in the π -mode has a measured value of ~ 6500 and is in agreement with the SUPERFISH simulations.

B. Beam Line Setup

A beam line has been setup to measure different properties of the electron bunches produced by the RF-photogun,

FIG. 1. (Color online) Cross section of the RF-photogun, coaxial input coupler of the RF-power, magnetic solenoid lens and bucking coil.

specifically energy, energy-spread, emittance, charge and, particularly of interest to the injection in LWA, smallest focus spot and shot-to-shot stability of the focus spot. A schematic overview of the different components of the beam line can be seen in Fig. 2.

The optical part of the setup is a Titanium:Sapphire femtosecond laser system that consists of a Femtosecond oscillator and an Omega Pro multi-pass amplifier (Femtosecond Productions GmbH) that produces laser pulses of 30 fs with an energy of 0.8 mJ and a central wavelength of 800 nm. By third harmonic generation (THG- Ω 1000 by B.M. Industries) the pulse from the Ti:Sa laser is transformed to a UV-pulse with a central wavelength of 266 nm, a maximum energy of 40 μ J, and a length of $\sim$ 50 fs. This UV-pulse is reflected by a mirror in a flipper mount (FM) and a mirror (M1) to the center of the cathode of the RF-photogun. The reflection of the UV-pulse from the cathode is directed via mirror M2 and M3 through a lens L1 which makes an image of the cathode on a charged coupled device (CCD)-camera (all cameras used are Point Gray Flea 2). An interference pattern is seen on the CCD-camera, caused by the coherent UV pulses that reflect off the spiral grooves (with a depth of $\sim$ 100 nm, caused by the machining) on the cathode plate. This pattern makes the alignment of the laser on the center of the cathode straightforward [see Fig. 3(a)]. To see the real (radial) shape of the UV-pulse on the cathode, the flipper mount is moved out of the laser path and the UV-pulse is directed to a virtual cathode CCD [see Figs. 2 and 3(b)]. To get the same image on the virtual cathode CCD as on the cathode, the distance from the flipper mount to the virtual cathode CCD is set equal to the distance from the flipper mount to the real cathode. The measured FWHM of the intensity of the UV-pulse on the (virtual) cathode is 1.7 mm.

To limit bunch expansion due to space charge, the electron bunches in the RF-photogun must be accelerated as quickly as possible to relativistic speed. The acceleration due to space charge in longitudinal and in radial direction are pro-

portional to $1/\gamma^3$, with the Lorentz factor $\gamma = 1/[1-(v/c)^2]^{1/2}$, where v is the velocity of the electrons and c the speed of light.³² For this reason it is highly desirable that the electrons from the cathode surface are photo-ionized in a high accelerating field. The electron bunch can then be focused downstream to both a small spot, radially, and at the same time keeping it short in the longitudinal direction, which is a prerequisite for LWA with external injection. The phase of the RF wave at which the UV-pulse hits the cathode and electrons are created is determined experimentally by maximizing the energy of the accelerated electron bunches at a given power setting of the klystron. In the present experiments this was found to be 72° before the crest of the RF wave to assure a maximal kinetic energy of 3.71 MeV at the exit of the RF-photogun (the klystron was operated at 3.2 MW). A current-controlled spectrometer in combination with a LANEX screen, lenses and CCD camera is used to measure the energy and energy-spread of the electron bunches.

Timing jitter and stability of the output power of the klystron determine the shot-to-shot variations in energy of the electron bunches. The 3GHz oscillator driving the klystron for the RF system is synchronized to the 75-MHz laser oscillator that produces the UV pulses. The timing jitter between the two oscillators is less than 20 fs (Ref. 33). Using the specifications of the klystron and synchronization system, the energy jitter is expected to be less than 1%.

A magnetic solenoid lens is placed in the beam line at a distance of 1055 mm from the cathode plate and focuses the electron bunch on a phosphor screen 140 mm further downstream. The distance between the cathode and the magnetic solenoid lens is necessary to be able to accommodate the TW-laser beam which is needed for future LWA experiments. The phosphor screen is placed at the position of the entrance of the plasma channel in LWA experiments. The phosphor screen can be moved out of the beam line in order to measure the charge of the bunch in a Faraday cup. The magnetic lens is a pulsed solenoid, with a peak current of

FIG. 2. (Color online) Schematic overview of the beam line used to characterize the properties of the electron bunches.

FIG. 3. (Color online) Image of the UV-spot on the center of the cathode. The spiral diffraction pattern caused by the machining of the cathode indicates that the UV-pulse is aligned on the center of the cathode (a). The intensity profile of the UV-pulse on the cathode as can be seen on the virtual cathode (b). The images shown are $3 \times 3 \text{ mm}^2$.

272 A, resulting in a maximum on-axis magnetic field of 0.68 T. To eliminate induced currents in the beam pipes and ensure a magnetic field inside the beam line, the stainless steel beam pipe within the solenoid is replaced by a glass tube. By using a pulsed solenoid, no additional cooling of the solenoid is required and a relatively compact design is possible. The center of the solenoid can be placed as close as 140 mm from the phosphor screen, limited also by other geometric constraints, such as flanges and the wall of the vacuum chamber. The solenoid can operate at a repetition rate of 2 Hz at maximum current. In the present experiments, where maximum magnetic field was not required, a repetition rate of 5 Hz was achievable without overheating the solenoid or current supplies.

Finally, the path of the electron bunches can be slightly corrected by two steering coils to ensure a good alignment between the electron bunches and the spectrometer or between the electron bunches and the pulsed solenoid.

III. ELECTRON BUNCH MEASUREMENTS

All measurements presented have been done on electron bunches with a kinetic energy $E_{\text{kin}} = 3.71 \text{ MeV}$ ($\gamma = 8.25$). Sections III A – III D describe measurements of different parameters of electron bunches, all with a charge of 10 pC. Section III E deals with the effect of the charge on those measured parameters.

A. Energy and Timing Jitter

The kinetic energy of the electron bunches has been measured with a current controlled spectrometer in combination with a LANEX screen (as described in Sec. II B). A typical spectrum of one electron bunch with 10 pC of charge on the LANEX screen can be seen in Fig. 4. The green line in the figure is the profile of the measurement at highest intensity and the white line is a Gaussian fit. The (central) energy of the electron bunch is 3.71 MeV. The energy spread (standard deviation of the Gaussian fit) is $\sigma_E = 0.02 \text{ MeV}$ or 0.5%. This is in agreement with the standard deviation of the energy of the simulated particles.

Simulations show that the main contribution to the energy spread is caused by the space charge of the electron bunch. The other effects, the energy spread caused by electrons that are accelerated off-axis in a lower accelerating

FIG. 4. (Color online) Typical picture of the profile on a LANEX screen behind the spectrometer for a single electron bunch of 10 pC. The green line is the energy profile through the point of highest intensity. The white line is a Gaussian fit on the energy profile.

field due to the radial dimensions of the UV-pulse on the cathode and the energy spread caused by the different accelerating field on which the electrons are injected due to the length of the UV-pulse, are negligible compared to the energy spread caused by the space charge of the electron bunch.

The energy spread of the electron bunch results in a spread in velocity and directly leads to bunch lengthening as the electrons propagate through the beam line. This is the main reason to keep the distance between the cathode and the entrance to the plasma channel as short as possible. The propagation time of a particle with a Lorentz factor γ over a distance l is given by:

$$t = \frac{l}{c\sqrt{1 - 1/\gamma^2}} \quad (1)$$

while $t + \Delta t$ is the propagation time for a particle with Lorentz factor $\gamma + \Delta\gamma$ and

$$\Delta t = -\frac{l}{c} \frac{\Delta\gamma}{\gamma^2(\gamma^2 - 1)^3}. \quad (2)$$

Using this Eq. (2) on an electron bunch with a Gaussian energy distribution around 3.71 MeV ($\gamma = 8.25$) and a standard deviation of 0.5%, results in an extra bunch length (increase of the standard deviation) of $\sigma_{t,E} = 250 \text{ fs}$ per meter propagation distance. This extra bunch length is due to energy spread of the electron bunch and does not take path length difference of the electrons during propagation and the increasing space charge force during focusing into account. The overall (simulated) bunch length at the focus is described in Sec. III D.

The UV-pulse on the cathode and the TW laser pulse to the plasma channel are both generated from the same pulse from the laser oscillator. The timing jitter between the electron bunches at the exit of the cavity and the TW laser pulses that will be used for LWA is mainly caused by phase jitter in the synchronization between the laser pulses and the 3 GHz

RF phase. The synchronization system developed by Kiewiet³³ locks the RF oscillator to the laser oscillator, with a timing precision of 20 fs. Combined with the phase jitter added by the klystron, this results in arrival time jitter at the exit of the cavity of ~ 100 –120 fs. The shot-to-shot variation of the measured average electron energy adds to the arrival time jitter between the TW laser pulse and the electron bunch at the entrance of the plasma channel. For ten consecutive shots, the RMS spread of the average electron energy is found to be 2 keV. With the use of Eq. (2), this leads to a RMS timing jitter of $\sigma_{t,jit} = 22$ fs per meter propagation distance of the electron bunch. This is in agreement with the timing jitter measured from THz coherent transition radiation using a slightly different RF-photogun with the same synchronization system.³⁰ The total jitter in arrival time between the TW laser pulses and the electron bunches at the entrance of the plasma channel, 114 cm from cathode, is approximately 150 fs.

B. Normalized Transverse Emittance

The normalized transverse emittance of a low-charge bunch can be determined by performing a focus scan of the electron bunch. The scan is done by measuring the RMS radius of the electron spot on the phosphor screen while changing the focal length of the pulsed solenoid lens (by changing the current through the solenoid). The spatial resolution of the imaging system for this phosphor screen is $6 \mu\text{m}$. For each setting of focal strength, a Gaussian function $I = I_0 e^{-[(x-x_0)^2 + (y-y_0)^2]/2\sigma_r^2}$ is fitted over the intensity profile on the phosphor screen of a single electron bunch. Here, I_0 is the intensity at the center of the bunch at the position (x_0, y_0) and σ_r the RMS radius. The result of such a measurement for 10 pC bunches is shown as the black dots in Fig. 5. A measured RMS radius in Fig. 5 is the average of ten consecutive shots at the same focal length. The error bars indicate the standard deviation between the ten shots at each setting.

As the bunch is cylindrically symmetric, $\sigma_r = \sigma_x = \sigma_y$ and $\varepsilon_x = \varepsilon_y$, with σ_x, σ_y the RMS spread in x - and y -direction and $\varepsilon_x = \varepsilon_y$ the emittance in x - and y -direction. Using geometrical optics (neglecting space charge and possible aberrations in the pulsed-solenoid lens), the following equation can

FIG. 5. (Color online) Focus scan of 10 pC bunches to determine normalized emittance. The black dots with error bars are measurement and the red solid line is the fit using Eq. (3).

be derived for the size of the focal spot as a function of the focal strength of a (thin) lens:³⁰

$$\sigma_x = \sqrt{[l_1 l_2 - (l_1 + l_2)f]^2 \frac{\varepsilon_x^2}{\sigma_{vt}^2 f^2} + (f - l_2)^2 \frac{\sigma_{vt}^2}{f^2}} \quad (3)$$

with f the focal length of the pulsed solenoid lens, ε_x the emittance in x -direction in configuration space, and $l_2 = 0.14$ m the distance between the center of the pulsed solenoid lens and the phosphor screen. σ_{vt} can be interpreted as the RMS radius of a virtual electron bunch source at a distance l_1 before the pulsed solenoid lens. In order to determine the emittance, Eq. (3) was fitted to the measurements using ε_x, l_1 and σ_{vt} as fitting parameters. The result is shown as the solid red curve in Fig. 5. The normalized emittance, $\varepsilon_{n,x}$, is found using $\varepsilon_x = \varepsilon_{n,x}/\gamma\beta$, with $\beta = v/c$. This results in a normalized emittance $\varepsilon_{n,x} = \varepsilon_{n,y} = 1.9 \mu\text{m}$ for a ten pC electron bunch. This is slightly higher, but in fair agreement (considering the earlier assumptions) with the value of $1.2 \mu\text{m}$ found from simulations using General Particle Tracer^{34,35} (GPT).

C. Focus Spot and Focus Stability

For injection of the electron bunches into a plasma channel for LWA, one of the most important parameters is the minimum spot size that can be achieved at a certain bunch charge. In addition, the focus spot stability determines how much charge can be injected consistently.

By means of the solenoid around the RF-photogun, sub-50-pC electron bunches can be kept quasi parallel during propagation through the beam line and thus on the same order as the spot size of the UV-pulse on the cathode. The radius of the electron bunch is typically around 2 mm FWHM at the entrance of the pulsed-solenoid focusing lens. This lens focuses the electron bunch on a phosphor screen 140 mm further downstream (see Fig. 2), where the plasma channel will be placed for LWA. The current through the pulsed solenoid is adjusted to produce the smallest possible spot on the phosphor screen (the minimum of Fig. 5). A picture of the focal spot of a 10 pC electron bunch can be seen Fig. 6.

FIG. 6. (Color online) Focal spot of a 10 pC electron bunch on a phosphor screen 140 mm behind the pulsed solenoid. The intensity profile at the point of max intensity (green line) with a Gaussian fit (white line) gives an RMS radius of $40 \mu\text{m}$.

The green lines are line outs of the intensity through the center of the spot. The white lines are Gaussian fits to these line outs. The RMS radius (standard deviation) of the Gaussian fits at the focal point is $40\text{ }\mu\text{m}$ in both x - and y -direction. The plasma density of planned LWA experiments with external injection of electrons is typically around 10^{24} m^{-3} . The matched spot size for laser guiding in such a plasma is around $20\text{--}50\text{ }\mu\text{m}$ (Refs. 22–25), in the same range as the measured focal spot, so that it can be expected that a reasonable fraction of the electron bunch can be captured and accelerated in LWA (a detailed simulation using all measured parameters will be presented in Sec. IV).

An important parameter is the shot-to-shot stability of the center of the focused electron bunches, because the position of the focus needs to remain stable within a fraction of the spot size to be able to consistently inject electrons into a plasma channel for LWA. A measurement of this parameter can be seen in Fig. 7. This figure shows the number of electron bunches counted as a function of the distance between the center of each focus and the average position of the centers. This is done in x - and y -direction for 50 consecutive shots. This gives a shot-to-shot stability of the center of the focused bunch with a RMS spread in x - and y -direction of respectively $5\text{ }\mu\text{m}$ and $4\text{ }\mu\text{m}$. It is well below the measured (RMS) radius of the spot of $40\text{ }\mu\text{m}$.

D. Bunch Length at Focus

The bunch length at the focus is determined by the combination of many parameters, namely duration and radius of the UV-pulse on the cathode, RF-phase of the photogun on which the UV-pulse is injected, energy spread of the electron bunch, distance between cathode and pulsed solenoid lens, distance between phosphor screen and focusing solenoid lens, current in the focusing solenoid lens, current in the solenoid around the cavity, bucking coil current, diameter of the electron bunch in the focusing solenoid lens and charge of the bunch.

An accurate bunch length measurement of sub-picosecond relativistic electron bunches ($\beta \approx 1$) requires a separate, complicated setup, that could not be implemented in the present experiments. For bunch length, we therefore rely on particle tracking simulations using GPT. These simulations have been compared to measurements of the electric field strength of THz coherent transition radiation using electro-optical sampling in a similar setup.³⁰ The entire beam line, including the accelerator and solenoid lenses was simulated

in GPT with the same settings (RF power, charge, laser spot size and magnetic fields) as those used in the experiments. This resulted in a bunch length (standard deviation) of 405 fs at focus for a 10 pC bunch. In Sec. III A the bunch lengthening was calculated due to the measured energy spread of the bunch (caused by space charge inside the bunch). This effect accounts for 250 fs of the simulated 405 fs . The extra 155 fs compared to the result described in Sec. III A is due to the increasing space charge while the bunch is being focused.

E. Effect of Charge on Focused Electron Bunch

All the measurements above were done on 10-pC electron bunches. To investigate the effect of the bunch charge on these parameters, we have changed the energy of the UV pulse. At the cathode, the initial bunch length is approximately equal to the length of the UV pulse ($\sim 50\text{ fs}$). Changing the energy of the UV-pulse will result in a change of charge with the same initial bunch length and will therefore result in different space charge forces in the electron bunches. Space charge has an effect on almost all previously measured parameters of the electron bunch.

For higher charge, the energy spread will increase. As mentioned earlier, the (Coulomb) space charge force on the electrons in the front of a bunch will be in the forward direction, whereas the space charge force on the electrons in the rear of the bunch is in the backward direction. This leads directly to a higher energy spread at higher charge. The RF phase at which the electrons are created (72° before crest in the RF field for 3.71 MeV electron bunches) partly compensates the bunch-lengthening due to space charge, because the electrons at the front of the bunch are accelerated in a slightly lower RF field than those at the back. Another effect of space charge which relates to the energy spread is the radial expansion of the bunch. Electrons at larger distances from the axis experience a slightly different accelerating field. This effect is mostly compensated by increasing the magnetic field strength of the solenoid around the cavity when increasing the charge. The overall effect is that the energy spread of a bunch of 1 pC was measured to be 0.3% which increases to 1.5% for 35 pC bunches (see Table I).

The transverse (normalized) emittance is also affected by space charge. Higher space charge will still result in a higher (normalized) transverse emittance and consequently, in a larger spot size at the point of focus. Measurements and GPT simulations of the smallest possible focus spot can be seen in Fig. 8. The measured RMS radius of the focus spot

FIG. 7. (Color online) Shot-to-shot stability of the center of the focused electron bunch for 50 consecutive shots in x - and y -direction.

TABLE I. Properties of the electron bunches at focus for different charges. The measurements presented are the transverse RMS radius of the electron bunch, the energy spread and the transverse normalized emittance in x - and y -direction. RMS bunch lengths were simulated with GPT using the experimental settings as input parameters.

Charge [pC]	1	10	16	33
RMS radius focus spot [μm]	32	40	49	61
Simulated RMS bunch length focus [fs]	147	405	551	845
Energy spread [%]	0.3	0.5	0.8	1.5
Trans. Normal. emittance [μm]	1.0	1.9	2.3	3.7

FIG. 8. Measurements (dots) and simulation (line) of the smallest RMS radius at focus of the electron bunch on the phosphor screen as a function of the charge of the electron bunch.

becomes significantly larger at higher charge and increases from $\sim 30 \mu\text{m}$ at 1 pC to $\sim 60 \mu\text{m}$ for a 35 pC electron bunch. Simulations of the smallest possible focus spot show the same increasing trend at higher charge. The simulations have been done using the experimental settings for the current through the solenoids, bucking coil current, γ and UV spot size. The spot size in the experiments is roughly a factor of two larger than the spot size predicted by the simulations. The difference between measurements and simulations are possibly caused by the asymmetry of the field in the pulsed solenoid. During the experiments we noticed that the solenoid had to be slightly tilted ($\sim 5^\circ$) to keep the focused and unfocused bunch at the same position on the phosphor screen. This asymmetry may be due to the lead wires to the solenoid or the stray fields that possibly induced currents in the beam pipe in the vicinity of the pulsed solenoid (the beam pipe inside the solenoid is made of glass, but extends only 10 mm outside the solenoid, perhaps this needs to be increased). Such asymmetry was not taken into account in the simulations.

An overview of RMS radius and bunch length at focus, energy spread and emittance versus accelerated charge for a 3.71 MeV electron bunch can be seen in Table I.

The shot-to-shot energy stability and the shot-to-shot stability of the position of the focal spot show no dependence on charge, as expected. The (RMS) timing jitter between the electron bunch and the TW laser pulse at the entrance of the plasma channel remains 22 fs (per meter propagation distance of the electron bunch), as discussed in Sec. II A. The focus stability of the electron bunches is also charge independent and shows an RMS spread of $5 \mu\text{m}$.

Electrons in a bunch with a certain energy spread and thus a different velocity arrive at the point of focus at a different point in time. Bunches with higher charge will therefore be longer at the point of focus compared to low charge bunches. GPT simulations show that the RMS bunch length at focus in the described setup increases from 147 fs for a 1-pC bunch to 870 fs for a 35-pC bunch.

IV. SIMULATIONS OF LWA WITH EXTERNAL INJECTION OF THE MEASURED ELECTRON BUNCHES

Simulations based upon the actual measured bunch parameters from Table I have been done for LWA with externally injected electrons in front of the laser pulse. Because the length of the plasma channel is up to 10 cm, full particle-in-cell (PIC) simulations will take too long to perform and are therefore not practical. Instead, particle tracking of the injected electrons is performed using the general particle tracer (GPT) code.³⁴ The GPT package solves the relativistic equations of motion of a large number of charged particles through time-dependent electromagnetic fields. Tracking is done in 3D, and no paraxial approximations or simplifications are made. Space charge forces are calculated using the built-in multigrid PIC solver that uses anisotropic meshing adapted to the charge density to reduce CPU time.³⁵ Tracking accuracy is guaranteed by a fifth-order Runge-Kutta solver with adaptive stepsize control. The fields of the laser wakefield potential are described with a custom GPT model based on the analytical description of Andreev.³⁶ To keep the calculation time acceptable, the wakefield potential and laser pulse envelope are assumed to be time-independent in the frame of the laser pulse (quasi-stationary solution), similar to the approach of Van Dijk.^{25,26,31}

The properties of the injected electron bunches that are used as input parameters by GPT were those of the measurements described in Sec. III. During simulations the laser wakefield (potential) starts behind the electron bunch and propagates at a speed equal to the group velocity of the laser pulse in the plasma. The wakefield will overtake the electron bunch inside the plasma and part of the bunch will be focused and accelerated by the wakefield. The length of the plasma was chosen to achieve maximum average acceleration of the injected electron bunch. Maximum energy is reached when the electrons outrun the accelerating phase of the plasma wave and enter the decelerating phase, i.e., the dephasing length. When injecting the electron bunch in front of the TW laser pulse, only one accelerated bunch is expected. The measured transverse emittance of the injected electron bunch was taken into account during simulations. To determine the optimal delay between the laser pulse and the electron bunch at the entrance of the plasma channel, the charge of the electron bunch at the exit of the plasma was taken as the criterion. The optimal delay was found to be ~ 2.5 times the bunch length (standard deviation) of the electron bunch at the focus.

In the simulations, a 25 TW, 50 fs laser pulse with a central wavelength of 800 nm, focused to a waist ($1/e^2$ intensity) of $30 \mu\text{m}$ in a plasma channel with a density of $0.7 \times 10^{24} \text{ m}^{-3}$ was used (normalized laser vector potential $a_0 = 0.9$). With this combination of parameters and an optimized setting for the plasma length ($\sim 10 \text{ cm}$), the electrons are accelerated to $\sim 900 \text{ MeV}$. The plasma and laser parameters were chosen identical to the simulations by Lutikhof,^{37,38} in order to allow a straightforward comparison. Figure 9(a) shows the result of the accelerated charge at the exit of the plasma channel versus the injected charge from the RF-photogun. The red dots represent

FIG. 9. (Color online) (a) Simulations of the accelerated charge in a LWA versus injected charge coming from the RF-photogun, based on real electron bunch measurements from the RF-photogun. Red dots represent focusing of the electron bunches at the entrance of the plasma channel. The black dots are results with the focus of the electron bunches 2 cm inside the plasma channel. (b) Energy spread after acceleration when focusing 2 cm inside the plasma channel. (c) Collecting efficiency as a function of injected charge. The dashed line shows the simulations by Luttikhof (Refs. 37, 38).

simulation with electron bunches focused at the entrance of the plasma channel.

The accelerated charge initially increases with increasing injected charge. As the charge is increased further, the electron bunches become longer due to the space charge forces, as explained in Sec. III D. The charge density at the center of the bunch reaches a maximum around 7 pC. To collect maximum charge, the delay between laser and electron bunch also has to become larger for longer bunches. The larger delay together with a longer bunch results in a longer time for the laser to overtake the electron bunch. At the high-

est simulated charges, the electron bunch becomes so large that the laser will not completely overtake the electron bunch before the dephasing length is reached, where the front of the bunch already starts to be decelerated. The divergence of the electron bunch after the focus (caused by the emittance) also contributes to a decrease in the accelerated charge. For higher charged bunches (with larger initial emittance), the laser will overtake fewer and fewer electrons during propagation in the plasma channel, resulting in a lower accelerated charge. These effects together lead to a maximum accelerated charge of 0.4 pC at 6 pC initial bunch charge.

The effect of the divergence of the electron bunch after the focus can be reduced by focusing deeper inside the plasma channel. Focusing the electron bunch inside the plasma channel is effective because the average electron density of the electron bunch while being overtaken by the laser is higher compared to the case where the electron bunch is focused at the entrance of the plasma channel. The black dots in Fig. 9(a) represent simulations with the focus of the electron bunch 2 cm inside the plasma channel (which is the optimal setting). The black dots follow a trend similar to that of the red dots, but the collection efficiency is almost a factor of three higher. It should be noted that in the simulations the plasma is surrounded by a capillary with a 200 μm radius. When focusing 2 cm inside the capillary, the electrons at the outer edge of the bunch are blocked. This applies in particular to the higher charged bunches as they have a larger radius (see Fig. 8).

Higher injected charge also results in a higher energy spread, because it takes longer to overtake the (longer) electron bunch, as can be seen in Fig. 9(b). This effect becomes significant for bunches longer than ~ 400 fs, or 10 pC. At the highest charges, the energy spread stabilizes at $\sim 15\%$ because the capillary is ended at the dephasing length.

Figure 9(c) shows the collection efficiency (the ratio of accelerated charge to injected charge) as a function of injected charge. This efficiency was simulated by Luttikhof^{37,38} using WAKE³⁹ for the same plasma and laser setting and the same electron injection energy as used in this section. The collection efficiency found by Luttikhof was $\sim 55\%$. He assumed that the injected electron bunch could be focused at the entrance of the plasma channel on a spot of 27 μm RMS radius, an RMS length of 85 fs and with a normalized emittance of 1 μm in x - and y -direction. These values correspond to the bunch properties measured at 0.1 pC. The simulations of Luttikhof compare well with the simulations presented here for these settings. In the simulations of Luttikhof, the bunch length, spot size and emittance were assumed to be independent of the charge. As a consequence the accelerating efficiency was found to be independent of the injected charge. Taking the dependence on charge, as measured in Sec. III, gives the results shown in Fig. 9(c).

Both simulations (black and red dots) in Fig. 9(a) show a maximum accelerated charge around an injected charge of 10 pC. For these settings, there is no advantage in injecting electron bunches with a charge higher than 10 pC because not only does the accelerated charge decrease, but also the energy spread of the accelerated bunches increases at higher injected charges. When focusing the electron bunch at the

entrance of the plasma channel, a maximum of 0.4 pC can be accelerated. In the case of focusing 2 cm inside the plasma channel a charge of 1.2 pC can be accelerated. The accelerated bunch after LWA has a kinetic energy of ~ 900 MeV and energy spread of $\sim 5\%$. The RMS radius of the accelerated bunch was found to be $1.5\ \mu\text{m}$ and the RMS bunch length was $2.5\ \mu\text{m}$ (~ 8 fs).

V. CONCLUSION AND OUTLOOK

Measurements have been performed to characterize an RF-photogun, purpose-built as an electron injector for LWA. It was found that the RF-photogun satisfies the conditions to serve as a suitable electron injector for LWA with electron injection in front of the laser pulse. This opens the way for LWA experiments in which the effects of injected electron bunches, plasma parameters and laser parameters on LWA can be studied separately.

For LWA with electrons injected in front of the laser pulse the energy needs to be in the range 3–4 MeV. Electrons with too low energy will not get accelerated by the wakefield and electrons with too high energy will not be overtaken by the laser pulse in the plasma. In the experiments presented here, electron bunches of 10 pC were produced by the RF-photogun with a kinetic energy of 3.71 MeV and energy spread of 0.5%. These electron bunches were focused in a spot with an RMS radius of $40\ \mu\text{m}$. The shot-to-shot stability of the center of the focused bunch had a RMS spread of $5\ \mu\text{m}$. This shot-to-shot stability is well below the measured RMS radius of $40\ \mu\text{m}$. This is an important parameter to perform successful LWA experiment with externally injected electrons because a consistently large overlap between plasma channel and injected electron bunch is necessary for the production of stable accelerated bunches. This condition is fulfilled as the matched spotsize for guiding of most plasma channels considered for LWA experiments is on the order of $30\ \mu\text{m}$.

The synchronization between UV-pulse at the cathode and the phase of the RF wave, combined with the variations in RF output power of the klystron leads to a shot-to-shot energy stability of 0.05% (2 keV). This results in an extra RMS timing jitter of 22 fs per meter drift length after the exit of the RF photogun between electron bunch at the focus and the TW laser pulse. The total jitter, 1.14 m from the cathode, at the entrance of the plasma channel, is estimated to be 150 fs.

Simulations of LWA, using the measured bunch parameters as input, show that electrons can be accelerated to ~ 900 MeV with energy spread of 5% using a ~ 10 cm long plasma channel with an on-axis electron density of $0.7 \times 10^{24}\ \text{m}^{-3}$ in combination with a 25 TW laser pulse focused on a $30\ \mu\text{m}$ spot to drive the plasma wave.

The collection efficiency depends on the injected charge. Producing higher bunch charge in the RF accelerator leads to longer bunch lengths and larger focus spot size, due to space charge. To have an optimal overlap between the TW-laser and the electron bunch, the optimal delay between them was found to be ~ 2.5 times the RMS length of the electron bunch at the focus. For the electron bunch of 10 pC,

with RMS length of 405 fs, the optimal delay is 1 ps. The timing jitter of 150 fs between laser pulse and electron bunch, therefore, has little effect on the accelerated bunch.

For the parameters chosen in the simulation, there is no advantage to be gained from injecting bunches with charges above 10 pC. At higher charges, the electron bunches become too long at the focus and diverge during the time it takes for the laser pulse to overtake the electron bunch. As a result, the accelerated charge decreases and the energy spread of the accelerated bunch increases. To extend this to more general terms, the RMS bunch length of the injected electron bunch at the focus should not exceed 400 fs and its normalized transverse emittance should be lower than $2\ \mu\text{m}$.

To optimize the collection efficiency, the position of the focus of the 10-pC injected electron bunch should be placed 2 cm deep inside the plasma channel. This will result in accelerated electron bunches with a charge of 1.2 pC, accelerated to ~ 900 MeV in a bunch of ~ 8 fs.

This article shows the feasibility to inject electrons from an RF-photogun into LWA in front of the laser pulse and accelerate charges up to 1.2 pC. It will be possible to accelerate more charge if the bunch length at the entrance of the plasma channel can be shortened. This can be done by increasing the electric field on the cathode or by compressing the electron bunch at injection.^{40,41} An alternative to reach higher accelerated charge is to use more laser power in combination with a larger matched spot size for guiding, resulting in the same laser intensity at the entrance of the plasma channel. Those two approaches require a redesign of the existing setup. Operating in the linear regime and injecting the electrons behind the laser pulse is possible in the present setup with a 3 TW laser, but requires electron bunches of 6.7 MeV. For this, further conditioning of the RF-photogun is required.

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