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Photocathode laser based bunch shaping for high transformer ratio plasma wakefield acceleration

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ABSTRACT

Beam driven plasma acceleration is one of the most promising candidates for future compact particle accelerator technologies. In this scheme a particle bunch drives a wake in a plasma medium. The fields inside of the wake can be used to accelerate a trailing witness bunch. To maximise the ratio between acceleration of the witness to deceleration of the drive bunch, the so called transformer ratio, several methods have been proposed. The ones yielding the most favorable results are based on shaped drive bunches that are long in terms of the plasma wavelength. We present here methods to create such drive bunches employing temporally shaped UV-laser pulses for the extraction of electron bunches from a photo-electron gun. Theoretical considerations, experimental results and possibilities for further improvements are discussed.

1. Introduction

Since the first proposal of particle acceleration in plasma wakes driven by intense, relativistic particle bunches (PWFA) [1] much theoretical and experimental work has been done to build a compact accelerator based on this scheme. Even though many aspects of beam driven plasma acceleration have already been demonstrated in experiments, like acceleration with gradients exceeding conventional ones by several orders of magnitude [2] or high efficiency acceleration [3], several other aspects are still only theoretically explored. One of these aspects of PWFA is the achievement of a high transformer ratio (TR), which is the ratio between the highest accelerating field along the witness bunch and the highest decelerating field inside of the drive bunch.

In linear wakefield theory the TR was shown to be limited to below 2 in case of symmetric drive bunches by the so-called fundamental theorem of beamloading [4]. Theoretical investigations on how to improve this ratio have already started shortly after the proposal of the PWFA [5] and different methods have been worked out, either relying on shaped drive bunches [5–7] or on multiple drive bunches of different charge densities [8,9]. For all these scenarios, as well as for other applications in wakefield based accelerators, like flattening of inhomogeneous accelerating fields by the witness bunch shape via beamloading [10], flexible beam shaping capabilities are crucial. So far the availability of such beam shaping techniques has limited the possibilities for experimental investigation of these aspects of plasma acceleration.

In the following we will present a technique on how to create shaped electron bunches with a high flexibility in the exact shape and without modifications of the accelerator beamline, by shaping the UV pulse of a photoinjector. The technique is demonstrated experimentally, possible optimisation considerations are discussed and finally the method is compared to other bunch shaping techniques.

2. Šolc fan filter cathode laser pulse shaping

Electron beams for wakefield acceleration are usually supplied by photoinjectors, as only these electron sources can provide the high electron charge densities needed to drive large amplitude wakefields. In a photoinjector the electron bunches are created by extraction of electrons from a photocathode with (UV-)laser pulses. If the charge emission is not limited by the space charge of already emitted electrons at the photocathode surface, the laser pulse shape directly translates into the electron bunch shape.

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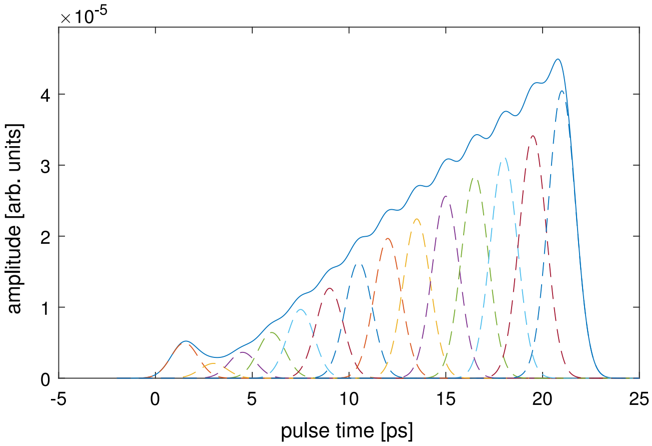

Fig. 1. Simulated output shape of an ideal birefringent fan filter with crystal angles as given in Table 1. The dashed lines show the virtual pulses that are combined to the overall shape.

To achieve flexible temporal shaping of the laser pulse a Šolc fan filter type of configuration was employed [11]. The optical setup of the original Šolc filter consists of an input polariser, N consequent birefringent crystals and an output polariser of the same polarisation direction as the input, where the n-th birefringent crystal is rotated by $\Phi = 45/N \cdot (2n - 1)$ degrees to the polarisation direction of the incoming short Gaussian laser pulse [12]. In this configuration the original Gaussian laser pulse is split into 2^N virtual Gaussian pulses, that add up to a pulse of flexible temporal shape. Fine-tuning of individual crystal angles allows to change the pulse shape to almost any shape consisting of N+1 Gaussian pulses.

In the present work a Šolc filter consisting of 13 YVO$_4$ birefringent crystals of 2.7 mm length was used at the photoinjector test facility, DESY Zeuthen site (PITZ), a 25 MeV, 1.3 GHz research accelerator. This filter was set up to improve the emittance of the electron beam by changing the temporal photocathode laser pulse shape to a long flattop [13]. Nevertheless the setup can also be used for producing various output shapes. The crystals are remotely controllable in a ±1°-range. Individual crystal temperatures are once adjusted in a 20–40°C-range to achieve optimum phase matching, found by optimisation of the output pulse shape in a single crystal setup. Fig. 1 shows a simulation of the output pulse of the PITZ pulse shaper according to the method presented in [11]. The relative intensities of the output pulses are squared twice to include the influence of the two conversion stages from infrared to green and from green to ultraviolet laser light into the calculation, as the pulse shaping is done in infrared. The simulated filter was tuned manually for a triangular output pulse shape with a small precursor (approximating a double triangular [7] or so called doorstep pulse [5]) with the crystal angles given in Table 1. Accordingly shapes like a micro pulse train, a simple triangular pulse, and others can be achieved. The input pulse is a short Gaussian of 0.7 ps RMS length. Every single crystal is measured to give the same additional delay of 2 ps to the extraordinary polarisation fraction of an incoming pulse, whereas in a multi-crystal assembly this was experimentally found to slightly depend on the number of crystals and their rotation angles, which was accounted for in the simulation of Fig. 1.

As described in [11] the linear pulse shaping inherently leads to significant losses of laser pulse energy, as the pulse is shaped by filtering the spectrum of the short Gaussian input pulse to the spectrum of a long output pulse. Losses can exceed 90% of the input laser pulse energy. Spectral losses for the pulse shape shown in Fig. 1 are calculated to be close to 80%. Additional losses are due to the polarisation filtering. A regenerative amplifier after the pulse shaper is used to compensate for this.

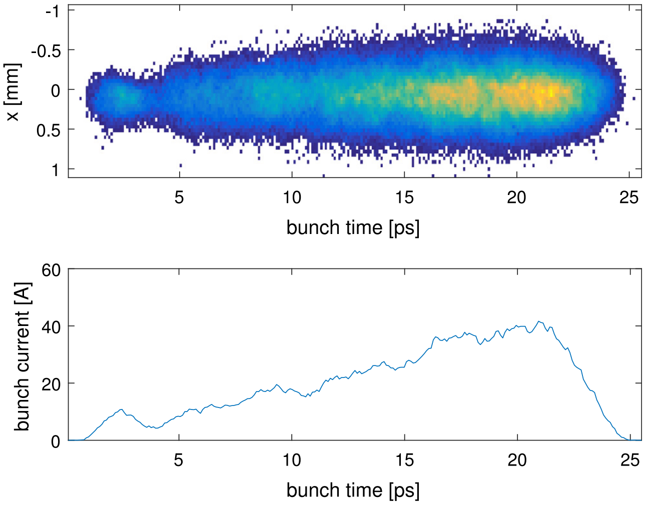

Fig. 2. Measured electron bunch shape for a short precursor in a double triangular bunch with a bunch charge of 504 ± 14 pC. The top picture shows the x–t projection of the bunch on a YAG-screen, bottom plot the corresponding current profile. Measurement resolution is 0.85 ps.

3. Experimental results

In experiment an optimisation routine based on the Nelder–Mead algorithm is employed [14] in combination with manual tuning in the 2° dynamic angular range of every crystal rotation to directly optimise the electron bunch shape measured with a transverse deflecting structure (TDS). Slow drifts in the electron bunch shape require small corrections of $\leq 0.1^\circ$ on a timescale of a few days. A measurement result for the goal shape shown in Fig. 1 can be seen in Fig. 2.

As the shape is asymmetric the length of the bunch between peak of the precursor and peak of the overall bunch is used as a figure of merit instead of RMS or FWHM length. This is also chosen considering the possibly achievable transformer ratios in a plasma wakefield, as the optimum length of the precursor is given by the plasma density and only the number of plasma wavelengths within the whole drive bunch defines the transformer ratio in linear theory [5–7]. The peak to peak length for the measurement is 18.5 ps, slightly smaller than the simulation of the laser pulse shape with 19 ps. This is accounted to a positive energy chirp and thus minor velocity bunching, as the bunch is set to the maximum mean momentum gain phase in electron gun and booster cavity.

The current setup at PITZ is being refurbished and a cross correlator for longitudinal diagnostics of the UV laser pulse is being set up. The direct access to the laser pulse shape without operation of the electron linac will give additional tuning time of the laser pulse shape, thus also enhancing the control of the created electron bunch shapes.

4. Outlook to SLM based photocathode laser pulse shaping

Besides the work on the current system, a laser system relying on another laser pulse shaping method is being set up at PITZ. This system will allow shaping of transverse and longitudinal profile simultaneously, to provide more control over the parameters of the created photoelectron bunches. The shaping method is based on transverse shaping by spatial light modulators (SLMs) in a dispersive section of the photocathode laser beamline with spectrally chirped laser pulses. The physical principle is described in [15,16] and detailed information on the design can be found in [17–19].

Shaping the laser pulse intensity both transversely and longitudinally allows to counteract space charge effects that distort the phase space of the emitted electron bunch. Figs. 3 and 4 show a comparison of the simulated phase spaces for bunches created with the birefringent

Table 1
Ideal Šolc fan filter angles and angles tuned for the pulse shape shown in Fig. 1 w.r.t. the input polarisation direction for an assembly of 13 ideal birefringent crystals.

Crystal No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Šolc angles Φ	3.46	10.38	17.31	24.23	31.15	38.08	45	51.92	58.85	65.77	72.69	79.64	86.54
$\Delta\Phi$ for Fig. 1	+1.3	+1.88	+2.22	+3.18	+4.54	+6.02	+7.36	+8.26	+8.46	+7.84	+6.24	+3.58	+0.04

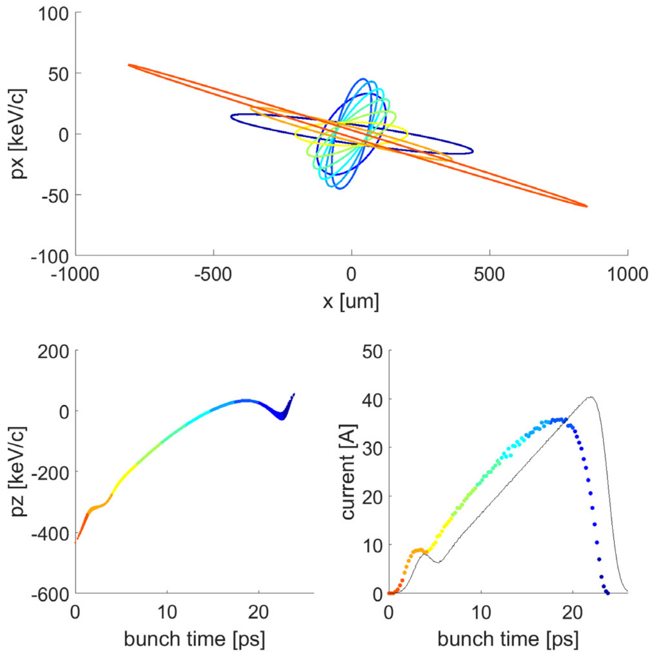

Fig. 3. Simulated transverse (top) and longitudinal (bottom left) phase spaces and bunch current (bottom right) of a 500 pC bunch for the Šolc fan filter shaping method. Colors indicating slice position. The black line in the current distribution shows the current profile emitted from the photocathode.

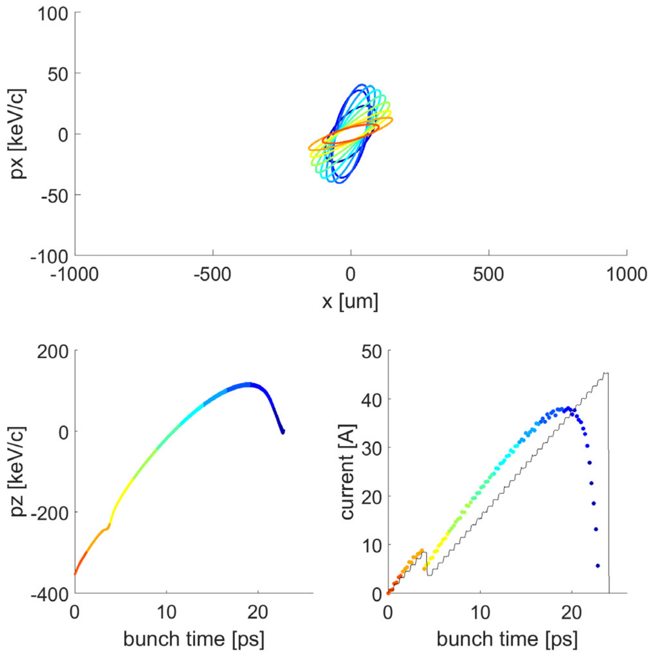

Fig. 4. Simulated transverse (top) and longitudinal (bottom left) phase spaces and bunch current (bottom right) of a 500 pC bunch for the SLM based shaping method. Colors indicating slice position. The black line in the current distribution shows the current profile emitted from the photocathode.

crystal filter and the SLM based pulse shaping methods respectively. Simulations were done using ASTRA [20] for identical beam optics.

The transverse phase space of the bunch created by a laser shaped with subsequent birefringent crystals shows significant slice mismatch, which is caused by deviation of the slice charge at constant transverse spot size. Controlling the transverse intensity distribution for every slice independently can mitigate the slice mismatch as shown in Fig. 4. It allows to improve the phase space matching especially at head (precursor) and tail of the bunch. The normalised transverse projected emittance is reduced from 1.6 mm mrad to 1.4 mm mrad. Even though the RMS energy spreads are both close to 90 keV, the slice mismatch and the average slice emittance are reduced by 20%. A minimised mismatch allows to fulfill the matching conditions in a plasma accelerator for all slices at once, thus avoiding betatron oscillations in the driver bunch. Furthermore, the control of the shape is more direct as changes in the SLM directly translate into changes of the laser pulse. This is not the case in the Šolc filter, where rotation of one crystal influences all previously created quasi-pulses. More direct control is not only a practical advantage but, as the bunch current in Fig. 4 shows, allows more accurate shaping of the bunch profile.

5. Discussion and conclusions

The presented bunch shaping method by photocathode laser pulse shaping has several advantages over other bunch shaping methods that have been proposed, like the emittance exchange method (EEX) [21], phase space manipulation with a higher frequency cavity or high frequency wakefields [22,23] or collimation in a dispersive section [24]. First its high flexibility, as e.g. no masks have to be changed inside of the vacuum beamline. Second, the loss free bunch shaping, as no charge has to be cut off the bunch. Third, there is no need for extra beamline equipment or usage of equipment that would otherwise allow to optimise beam transport (e.g. linearise the longitudinal phase space) and finally, that the method can be applied at accelerators using velocity bunching schemes, as well as the ones employing magnetic bunch compression.

One of the main limitations of the method on the other hand is the distortion of the bunch shape by space charge influences, especially at low energy, so directly at the photocathode. This can e.g. decrease the slope of the drop at the tail of a triangular bunch and could thus decrease the achievable transformer ratio [6]. Bigger laser spot sizes at the photocathode and also higher acceleration gradients, e.g. in S-band electron guns, could help to control these distortions up to a certain extent. Another practical limitation is that the shaping process with its high number of possible combinations followed by two nonlinear conversion stages to the UV is complex and requires thorough tuning. This is subject to further investigations and improvements as described in the previous section.

Nevertheless, the bunch shaping method based on temporal shaping of the photocathode laser pulse of a photoinjector by a birefringent crystal filter, that is presented here, allows for flexible shaping of electron bunches with applications in wakefield acceleration as well as in free electron lasers [25] or accelerator-based Terahertz sources [26]. Pulses of various shapes and at charges between 0.05–1 nC have been created at PITZ at MHz repetition rate, including pulses with several ramped profiles with high relevance for wakefield based acceleration schemes and microbunch trains with ps spacing. In the latter case the charge density contrast between bunches and inter-bunch spaces can reach the UV laser pulse contrast of more than 100:1, depending on microbunch charge and spacing. Fig. 5 shows an example of a measured

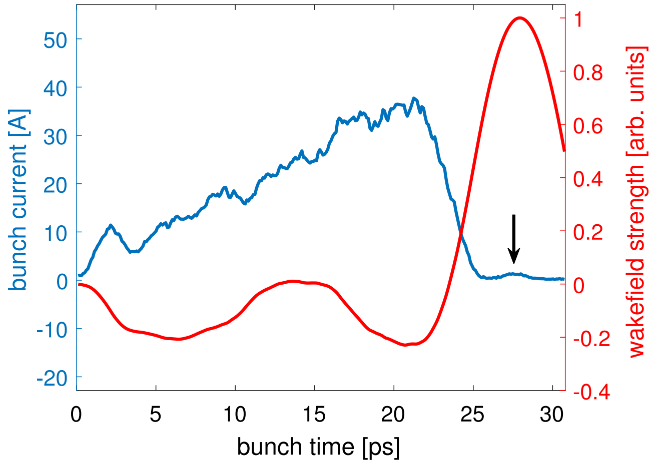

Fig. 5. Measured bunch profile (blue) with a second, Gaussian witness bunch (indicated by black arrow) at the same pulse shaper settings as in Fig. 2. The plasma wakefield in a plasma electron density of 4.5×10^{13} cm^{-3} according to linear theory is shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bunch profile, with an additional small witness bunch and the wakefield this bunch shape would excite according to linear plasma wakefield theory. The witness bunch was added via pulse splitting upstream of the laser pulse shaper. Field amplitudes show a transformer ratio of 4.4 at the witness position, significantly exceeding the limit of 2 for symmetrical bunches.

Bunches created with the presented method have also been used to achieve high transformer ratios in a plasma wakefield accelerator experimentally at PITZ [27], which demonstrates the capabilities of the presented method.

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