DRIVER-WITNESS-BUNCHES FOR PLASMA-WAKEFIELD ACCELERATION AT THE MAX IV LINEAR ACCELERATOR

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Abstract

Beam-driven plasma-wakefield acceleration is an acceleration scheme promising accelerating fields of at least two to three orders of magnitude higher than in conventional radiofrequency accelerating structures. The scheme relies on using a charged particle bunch (driver) to drive a non-linear plasma wake, into which a second bunch (witness) can be injected at an appropriate distance behind the first, yielding a substantial energy gain of the witness bunch particles. This puts very special demands on the machine providing the particle beam. In this article, we use simulations to show that, if driver-witness-bunches can be generated in the photocathode electron gun, the MAX IV Linear Accelerator could be used for plasma-wakefield acceleration.

INTRODUCTION

Plasma-wakefield acceleration (PWFA) and laser-wakefield acceleration (LWFA) are two schemes for accelerating particles using the very large (10's to 100's of GV/m) electric fields sustained in plasma waves [1]. Whereas the LWFA scheme uses a powerful laser to drive the plasma wave, the PWFA scheme relies on a charged particle bunch instead. A second particle bunch, called the witness bunch, can then be injected into the wave at an appropriate distance behind the first bunch, called the driver bunch, to recieve a substantial gain in energy. While there are many benefits of this scheme, which is described further in the next section, it puts some very special demands on the machine providing the particle beam.

The MAX IV Linear Accelerator [2] is a warm S-band electron accelerator serving as full-energy injector for the 1.5 and 3 GeV storage rings [3] as well as the Short Pulse Facility (SPF) [4], where the electron bunches are compressed to 100 fs at an emittance of <1 mm mrad and a bunch charge of 100 pC to create short-pulse x-ray undulator radiation. A compact overview of the linac is shown in Fig. 1. The layout of the MAX IV facility is such that the SPF takes up one out of three available slots, located downstream of the transfer line to the 3 GeV storage ring, to which the linac can supply the electron beam. The end of the linac, from the second bunch compressor and downstream, is shown in Fig. 2, with the existing sections and possible extensions on white and orange background, respectively. Simulations indicate that it is possible to compress the bunches to well below 100 fs and still keep the emittance low [5].

The parameters of the beam from the MAX IV Linear Accelerator could then be suitable for use in a PWFA experiment, with the caveat that only single electron bunches are delivered. Our approach to solving this is to use the photocathode electron gun to generate an appropriate initial time structure for subsequent acceleration and compression of a driver-witness-bunch beam, unlike previous PWFA experiments, such as FACET [6], which have relied on splitting a single bunch into two individuals in an intermediate stage between acceleration/compression and experiment. Generating the time structure in the photo-cathode gun would require some additional work on the laser system, but minimizes the needed extension of the magnet lattice, thus minimizing the cost and complexity from the accelerator point of view. Because of the layout of the facility, see Fig. 2, this could synergetically enable experiments on two-color free-electron laser (FEL) radiation. We have used the particle tracking code `elegant` [7] to simulate the acceleration and compression of a double-bunch beam in the MAX IV Linear Accelerator.

PLASMA-WAKEFIELD ACCELERATION

The PWFA scheme relies on the electromagnetic field associated with the ultra-relativistic electrons - the same field that gives rise to radiofrequency (RF) wakefields in the linac. When injected into a plasma, the electric field repels the light, free electrons, while the heavy, positive ions remain approximately stationary on the relevant time scale. When the electron bunch has passed, the electric field from the background ions pulls the plasma electrons back towards the axis, setting up an oscillating plasma wave. If the electron bunch charge density is high enough, it can expel all plasma electrons from a region around the beam axis, creating an ion cavity. This is called the blow-out or bubble regime, and in this regime, the electric fields have excellent accelerating and focusing properties.

The plasma parameters have some restrictions which are determined mainly by two things; the driver bunch electron density, n_b must be more than a factor of ~1.8 higher than the plasma electron density, n_e, to reach blow-out [8], and the witness bunch must be injected in the rear half of the bubble, the size of which decreases with increasing n_e. However, the magnitude of the accelerating electric field increases with n_e, which makes it desirable to keep n_e as high as possible. Since there are losses in the energy transfer from driver to witness electrons, the driver charge typically needs to be higher than the witness charge if one wants to e.g. double the witness electron energies.

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Figure 1: Compact layout of the MAX IV Linac. Yellow denotes radiofrequency (RF) structures, red/green are focusing/defocusing quadrupole magnets, purple are dipole magnets, orange are sextupole magnets and blue are special magnets. PG and TG are photo-cathode and thermionic RF guns, respectively, L are the linac sections and BC1 is the first bunch compressor. This view is cut right before BC2, which is shown in Fig. 2.

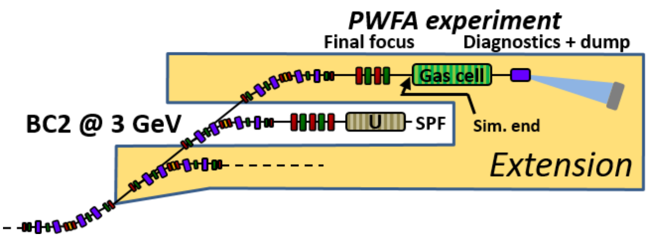


Figure 2: End of the linac (see Fig. 1) with the 3 possible beamlines, of which femtoMAX (SPF) is the only existing to date. U denotes undulator. Possible extensions are within the orange field.

BUNCH COMPRESSION

Compression and Linearization

To compress the bunches longitudinally, the MAX IV linac employs two double achromat compressors, see e.g. [5], which have a positive first-order momentum compaction, R_{56}. This means that a positive chirp, with respect to longitudinal coordinate z, is required for compression. The naturally positive second-order momentum compaction, T_{566}, has been tweaked with sextupoles in such a way that it cancels out the longitudinal phase-space curvature imposed by the RF field, rather than enhance it. This means that the phase space linearization is done using the optics alone; no higher-order harmonic cavity is employed.

One effect of this compression scheme is that the driver bunch, which arrives closer to the peak of the RF voltage, will always obtain a smaller chirp than the witness bunch. This means that the driver will be compressed less, leading to a beam where the witness bunch is shorter than the driver bunch. However, the final separation in time between the bunches is not decoupled from the final length of the individual bunches.

Wakefields and Coherent Synchrotron Radiation

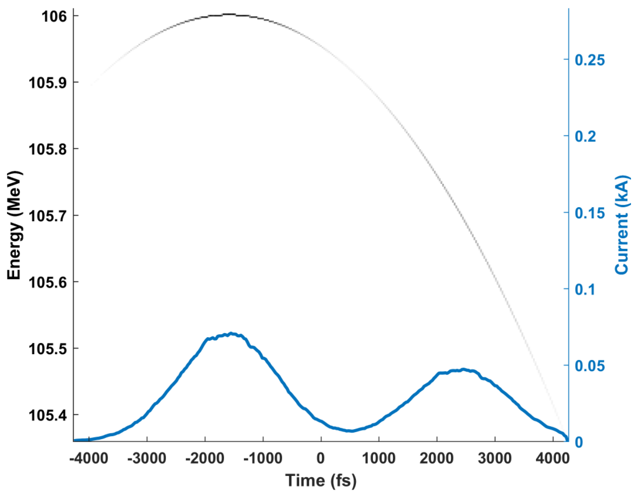
Short-range geometric longitudinal wakefields can influence the bunch chirp in the linac [9]. The effects of these wakefields increase with both bunch charge and degree of compression. Since the energy chirp is positive with respect to z, and the wakefields cause a progressive decrease in particle energy going backwards in the bunch, the total energy chirp of the bunches increases, which leads to a stronger compression. This was studied in Refs. [10, 11] for single bunches in the MAX IV linac.

Also of concern is coherent synchrotron radiation (CSR), where the bunch irradiates itself with coherent low-frequency radiation, leading to an emittance growth in the compressors. Typically, the tail of the bunch irradiates the head of the bunch, but in the case of two bunches with short length and separation, the case is rather that the witness bunch could irradiate the driver bunch.

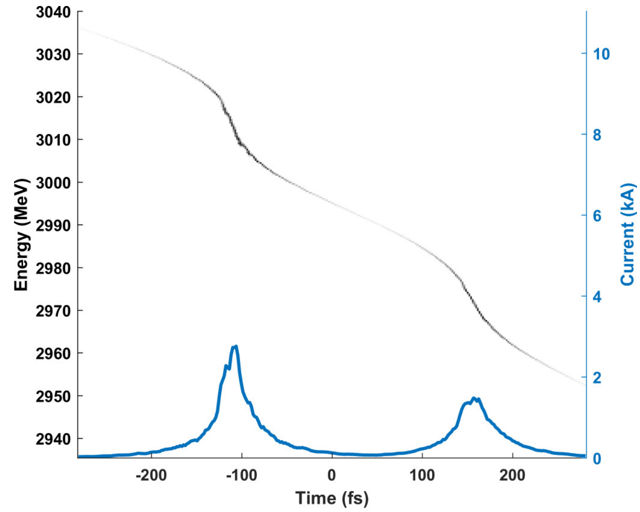
SIMULATION RESULTS

To achieve a preliminary bunch structure, a single 6 ps bunch simulated with ASTRA [12], normally used for single-bunch tracking, is duplicated. The time and longitudinal momentum coordinates are modified to provide two bunches of certain duration, temporal separation, longitudinal phase space curvature and relative charge. The results presented here are found with initial bunch lengths of 2 ps full width at half-maximum (FWHM), separation of 4 ps peak-to-peak and with the driver bunch on-crest out from the pre-injector [13], see Fig. 3a. The normalized emittance, ϵ_n, is 0.4 mm mrad in both directions and for both bunches. The witness bunch is set to contain 100 pC and the driver bunch charge, Q_d, is set to 100 or 150 pC. These "artificial" bunches are then tracked through the linac using `elegant`, with both wakefields and CSR enabled. The tracking is done from after the first linac section L_0, see Fig. 1, where the original 6 ps bunch is simulated to, to a preliminary final focus achieved with a quadrupole quadruplet, see Fig. 2. The beam profile in the focus is approximately circular with a transverse dimension of ~10 µm FWHM.

The final time structure relies heavily on the charge, especially of the driver bunch. For the lower driver charge (100 pC), the witness bunch is compressed more than the driver because of the larger chirp obtained from the RF voltage. However, the short-range wakefields affect (mainly) the driver chirp so that for the 150 pC beam, the driver is compressed more than the witness bunch. Since the driver wakefields only have little effect on the witness bunch, the bunch separation is largely unaffected by driver charge. The amount of charge in either bunch seems to be restricted by overcompression stemming from the additional, wakefield-induced chirp; the higher the charge, the more difficult it is to control both intra-bunch compression and bunch separation simultaneously, and still keep a low energy spread and emittance for the whole beam. If the relative bunch charge is not critical for the application, e.g. for two-color undulator radiation, the charge could potentially be used to tune the



(a) Simulation start



(b) Simulation end

Figure 3: 2D histograms of the longitudinal phase spaces (greyscale) and the corresponding currents (blue) at the start and end of the simulation. The histogram density ranges from white (minimum) to black (maximum). The driver bunch is to the left in the figures. Parameters of these bunches are given in the text.

bunch chirps locally. CSR effects, mainly influencing the driver bunch, are seen in all simulations, c.f. Fig. 3b.

Typical parameters achieved without detrimental emittance growth are bunch lengths τ of some 30-60 fs, with a bunch spacing Δt of 250-400 fs (correlating with τ). A more specific example is shown in Fig. 3b, which displays the longitudinal phase space of the 150 pC driver beam at the final focus. The driver (witness) horizontal normalized emittance, $\varepsilon_{n,x}$, is 0.7 (0.5) mm mrad, the bunch length, τ, is 37 (49) fs, and the bunch separation, Δt, is 267 fs. This is achieved by placing the centroid RF phases in L1 and L2-L19 (see Fig. 1) at 25 and 23 degrees off-crest, respectively, which is very far from the respective single-bunch values of ~32 and 12 degrees. The smaller off-crest phase in L1 gives a smaller compression in BC1, which in turn decreases the wakefield-induced chirp in L2-L19. The phase in L2-L19 is then increased to give a tight compression while avoiding overcompression. As a result, the final energy spread is ~0.2 % rms within the bunches and ~0.7 % between the average energy of each bunch.

For the achieved beam parameters so far, the limiting factor on the plasma electron density is not set by the electron beam density, but by the separation of the driver and witness bunches; a higher plasma density, leading to higher accelerating fields, can be used if the bunch separation can be decreased. The maximum plasma density for full blow-out is $n_e \approx 0.5 n_b \approx 4 \cdot 10^{17}$ cm^{-3}, corresponding to a linear plasma wavelength λ_p of 53 μm $\leftrightarrow$ 176 fs, which is smaller than the bunch separation achieved so far. To accommodate the witness bunch within the bubble, the plasma density would need to be lowered to $\sim 1.5 \cdot 10^{17}$ cm^{-3}, which is more than a factor of 5 smaller than the beam electron density. For these densities, the length of the driver bunch is shorter than the resonantly matched condition for driving a non-linear plasma wave [8].

CONCLUSIONS AND OUTLOOK

The main conclusion we can draw from this preliminary study is that it should be possible to conduct PWFA experiments using the MAX IV linac, provided that the photocathode electron gun can deliver an initial time structure similar to what was described above. The beam electron density is much higher than the plasma density required to accomodate the witness bunch in the bubble, which means that full blow-out should be reached. There seems to be a relatively low upper limit to the amount of charge that can be accelerated while having realistic final parameters for a PWFA experiment, but much work remains to be done.

The next step is refinement of the simulations to include the electron gun and the first linac section, where space charge effects are important, using ASTRA, as well as investigate how to tailor the laser pulses in a proper way. The Gaussian input for the simulations so far has not been entirely realistic, and a more reasonable top-hat current shape could allow the bunch separation to be decreased out of the gun, leading to a decrease in separation after BC2. An effort will also be done to increase the transportable driver bunch charge. Simulations of the beam-plasma interaction will be carried out using CALDER-Circ [14].

If an experiment is to be successfully conducted, high-resolution temporal diagnostics must be installed. Work is currently ongoing at the Lund University Department of Physics to develop temporal diagnostics using spectral measurements of coherent transition radiation (CTR) from LWFA electrons passing through thin metal foils, experiments which could have great carry-over to a PWFA experiment [15, 16].

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