

# BEAM DYNAMICS IN THz DIELECTRIC-LOADED WAVEGUIDES FOR THE AXISIS PROJECT\*

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## Abstract

In this paper, we investigate with ASTRA simulations the beam dynamics in dielectric-loaded waveguides driven by THz pulses, used as linac structure for the AXISIS project [1]. We show that the bunch properties at the linac exit are very sensitive to the phase velocity of the THz pulse and are limited by the strong phase slippage of the bunch respective to it. We also show that the bunch properties are optimized when low frequencies ( $< 300$  GHz) are used inside the linac, and that the longitudinal focal point can be put several tens of cm away from the linac exit thanks to ballistic bunching. However, a strong asymmetry in the bunch transverse sizes remains for which a solution is still to be found.

## INTRODUCTION

Particle acceleration currently requires large infrastructures due to the low frequencies (a few GHz) and relatively low field amplitudes (a few tens of MV/m) used in conventional accelerating structures. One of the schemes currently studied to reduce the footprint of particle accelerators is to use structures driven by laser-generated THz fields, in which the frequencies (from 100 GHz up to 10 THz) and field amplitudes (100 MV/m to a few GV/m) are expected to be much higher than in conventional accelerating structures. This all-optical scheme would also allow avoiding the timing jitter between the photocathode laser generating the electron bunch and the accelerating field by using a unique laser as source for both. This is what the AXISIS project [1] aims for. In this project, the electron bunch will be produced by photoemission in a gun driven by single-cycle THz pulses [2, 3]. It will then be accelerated in a THz linac structure consisting in a dielectric-loaded waveguide driven by a multi-cycle THz pulse [4, 5, 6]. The goal is to obtain a 1 pC and 15 MeV electron bunch to produce attosecond X-ray pulses by inverse Compton scattering.

In this paper, we investigate with ASTRA simulations [7] the achievable bunch properties at the exit of various linac structures, using as input the bunch for which the simulated properties at the gun exit are shown in Table 1 and the longitudinal phase-space in Fig. 1. In the first part, we briefly present the ASTRA model used for simulations. In the second part, we investigate the bunch properties as a function of the phase injection into the linac and of the phase velocity of the THz pulse. In the third part, the bunch properties as a function of the frequency and amplitude of the accelerating field are investigated.

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Table 1: Input Bunch Properties used for the Simulations

Bunch property	Value at the gun exit
Charge	0.4 pC
Mean kinetic energy	1.48 MeV
Rms energy spread	82.9 keV
Rms length	43.5 $\mu\text{m}$ ( $\equiv 150.1$ fs)
Rms horizontal size	28.9 $\mu\text{m}$
Rms vertical size	18.8 $\mu\text{m}$
Rms horizontal emittance	0.102 $\pi$ .mm.mrad
Rms vertical emittance	0.083 $\pi$ .mm.mrad

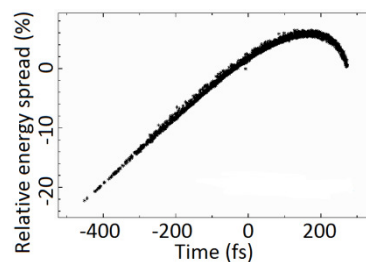


Figure 1: Bunch longitudinal phase-space at the gun exit.

## THE ASTRA MODEL

The accelerating field in the THz linac is the  $\text{TM}_{01}$  mode [8]. It consists of a pulse travelling with group velocity  $v_g$ , having a phase velocity  $v_{ph}$  and containing a finite number  $N$  of wavelengths  $\lambda$ .

To simulate this field in ASTRA, we superimpose two identical standing waves phase-shifted by  $90^\circ$ . For a given frequency, the phase velocity of the accelerating field can then simply be adjusted by changing the wavelength of the two standing waves. In our simulations, we consider a flat-top time profile for the THz pulse. However, this can be changed by changing the profile of the two standing waves given as input to ASTRA.

The finite interaction length  $L$  of the electron bunch with the accelerating field, due to  $v_g < c$  in the waveguide, is given by the following relation assuming that the bunch velocity remains close to  $c$  (speed of light in vacuum):

$$L = (N\lambda)/(1 - (v_g/c))$$

This can simply be modelled in ASTRA by the length of the accelerating structure. We choose to fix it to 6.4 cm ( $N=27$  at  $\lambda=1$  mm (300 GHz) with  $v_g=0.62c$ ) for the study as a function of frequency and amplitude of the field, and to 10 cm ( $N=42$ ) for the study as a function of injection phase and phase velocity. Finally, the limited aperture of the dielectric loaded waveguide and the particle losses it can engender are taken into account in the ASTRA model.

The main physical effect not included in the ASTRA model is the fact that the THz pulse does not consist in a single frequency, but in a spectrum with a finite bandwidth (typically a few GHz at 300 GHz central frequency). Only the central frequency of the spectrum is considered in ASTRA, and therefore the distortion of the pulse due to group velocity dispersion is not included.

### INFLUENCE OF THE INJECTION PHASE AND PHASE VELOCITY

In order to study the bunch properties at the linac exit as a function of the injection phase into the linac and phase velocity of the THz pulse, we fix the field frequency to 300 GHz and its amplitude to 150 MV/m. Figure 2 shows the obtained bunch kinetic energy and inverse rms length, as 2D colormaps, in the phase velocity range [0.985c-1c].

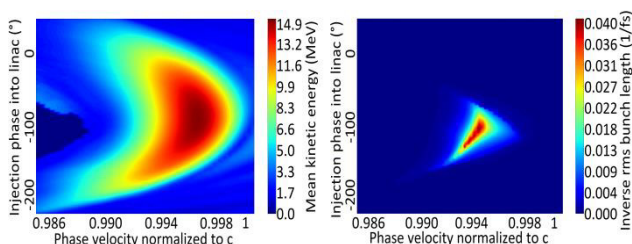


Figure 2: Bunch kinetic energy (left) and inverse rms length (right) at the linac exit as a function of the injection phase into the linac and phase velocity of the THz pulse.

Figure 2 shows that the bunch properties are highly sensitive to the phase velocity of the THz pulse, especially the bunch length, and therefore to the mechanical precision with which the dielectric-loaded waveguides can be produced. For example, a variation of the phase velocity from  $c$  to  $0.99c$  would be generated by a variation of only  $2 \mu\text{m}$  of the dielectric thickness in the linac. On the other hand, one can see that the bunch properties are less sensitive to the injection phase. Indeed one can see that, at optimal phase velocity, the energy gain remains close to the maximum ( $< 15\%$  discrepancy) in a  $90^\circ$  window and the bunch length in a  $30^\circ$  window. This allows some margins for instabilities. However, the optima for these two bunch properties are obtained in different conditions. Compromises or choices have therefore to be made.

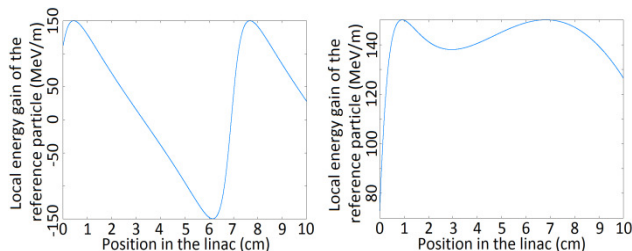


Figure 3: Local energy gain of the reference particle in the linac. Phase velocity:  $c$  (left) and  $0.9965c$  (right). Injection phase providing the maximum energy gain.

One can see in Fig. 2 that the optimal phase velocity for energy gain is not  $c$  but lower (around  $0.9965c$ ). This is

explained by the relatively low injection energy of the bunch into the linac (1.5 MeV), which leads to significant phase slippage respective to the accelerating field. This is visible in Fig. 3, which presents the evolution of the local energy gain of the bunch reference particle along its path in the linac. This phase slippage also explains why the phase velocity for optimizing the bunch length is also below  $c$  (around  $0.994c$ ).

### INFLUENCE OF THE FREQUENCY AND FIELD AMPLITUDE

In order to study the bunch properties at the linac exit as a function of the frequency and amplitude of the accelerating field, we fix the phase velocity of the THz pulse to  $c$  and the injection phase into the linac has been for each point chosen as the one optimizing the longitudinal bunch compression at the linac exit. Figure 4 shows the obtained bunch properties, as 2D colormaps, in the frequency range [90 GHz-500 GHz] and amplitude range [50 MV/m-400 MV/m].

The results in Fig. 4 show that the bunch longitudinal properties, rms length and energy spread, are optimized when low frequencies ( $< 300$  GHz) are used. The high frequencies ( $> 300$  GHz) provide worse longitudinal bunch properties, and high field amplitudes are required to obtain acceptable properties. There are two reasons explaining that. Firstly, the phase slippage, previously introduced (see Fig. 3) is a limitation for the longitudinal bunch properties, and it is intrinsically reduced when using lower frequencies. Secondly, the initial bunch length (see Table 1) is a significant fraction of the wavelength of the accelerating field, which increases for higher frequencies. This is a major source of the induced energy spread, which can grow up to several MeV above 400 GHz, and also of the longitudinal phase-space curvature which limits the longitudinal bunch compression and therefore the final bunch length. As shown in Fig. 4, the zone of high frequency and amplitude also has the drawbacks to engender particles losses due to the smaller transverse radius of the linac and the higher value of the transverse electric field which induces a transverse defocusing of the bunch.

The situation is more complicated for the transverse bunch properties, transverse sizes and emittances in the horizontal and vertical directions. Although the transverse emittances are also minimized at low frequencies, one can see that the transverse asymmetries of sizes and emittances, created in the gun (see Table 1) due to a transverse asymmetry of the field pattern, behave differently. The one for the transverse sizes is minimized for high frequencies, while the one for the transverse emittances is minimized for low frequencies. Only the combination of high frequency and field amplitude could minimize both. But as previously mentioned, this zone leads to a strong deterioration of the longitudinal bunch properties and transverse emittances, and particle losses occur.

A compromise or a choice has therefore to be made between the optimization of the longitudinal bunch

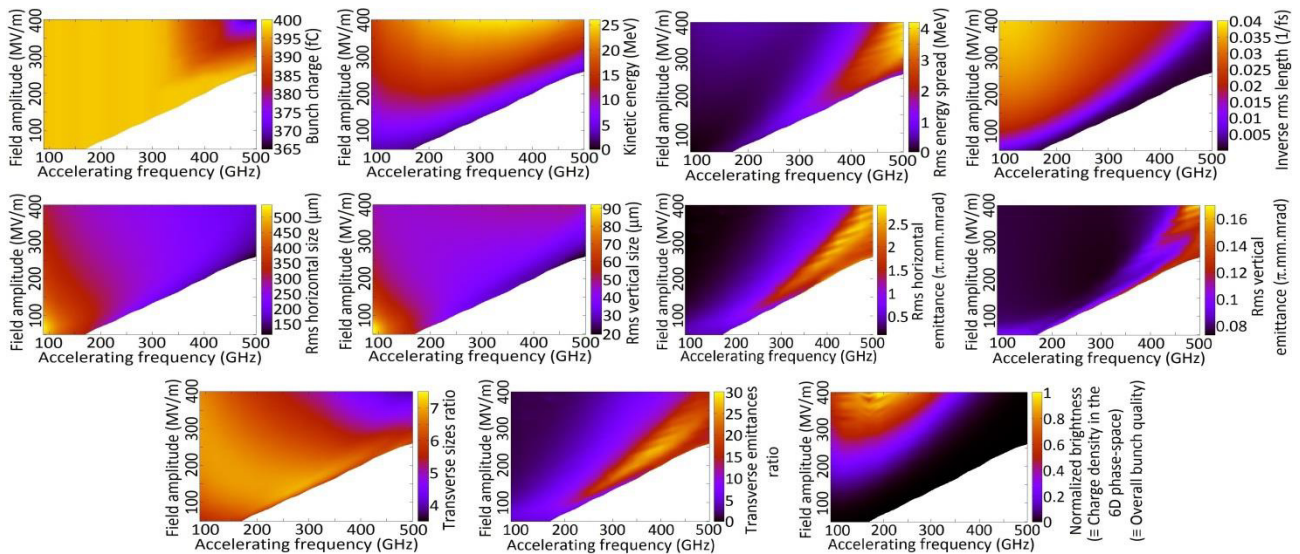


Figure 4: Bunch properties at the exit of the THz linac, simulated by ASTRA, using as input the bunch which properties are shown in Table 1. The white zone in the graphics corresponds to the case where the phase slippage of the bunch respective to the accelerating field exceeds  $360^\circ$  during its path inside the linac.

properties and the minimization of particle losses and of asymmetries of transverse sizes and emittances. One solution to overcome this difficulty would be to put the gun in a strong magnetic field (several T) parallel to the bunch propagation axis. This will confine the bunch in the gun and remove the asymmetries of its transverse properties. But the non-zero magnetic field during the bunch emission from the cathode will magnetize it and strongly deteriorate its transverse emittance, making it more difficult to transport. This solution is therefore questionable. Another solution would be to use a tapered linac structure [9], which would allow dynamically matching the phase velocity of the THz pulse to the bunch velocity. The phase slippage would then be controlled, which would allow using higher frequencies and field amplitudes without deteriorating the longitudinal bunch properties.

The results presented up to now are right at the exit of the linac structure. But the goal of the AXISIS project is to achieve a short bunch length at a certain distance (typically a few tens of cm) from the linac exit, to allow a transverse focusing of the bunch after the linac in order to use it to produce short and bright X-ray pulses. The capability of the linac structure to perform ballistic bunching, therefore to adjust the position of the bunch longitudinal focal point, has also been investigated. Figure 5 displays the evolution of the position of the longitudinal focal point and of the bunch length at this point as a function of the field amplitude for several frequencies.

Figure 5 shows that, for field amplitude  $< 400$  MV/m, the ballistic bunching process can only be performed at low frequencies ( $< 300$  GHz) and in this case longitudinal focal distances of several tens of cm can be reached. For higher frequencies, the phase slippage of the bunch respective to the accelerating field is too fast and prevents ballistic bunching to occur. This is another strong argument in favour of low operating frequencies ( $< 300$  GHz) for the THz linac intended to be used in the AXISIS project.

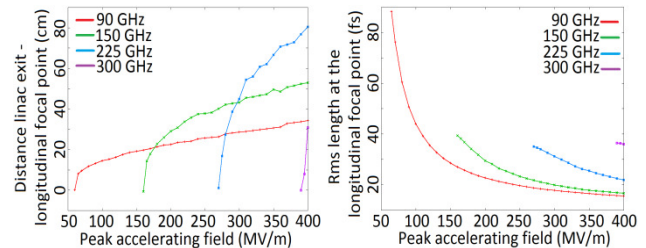


Figure 5: Longitudinal focal distance (left) and rms bunch length (right) at the longitudinal focal point as a function of the field amplitude in the linac for several frequencies.

## CONCLUSION

Our simulations demonstrate that a proper energy gain, a control of the longitudinal focal distance and margins for instabilities of the injection phase are possible with THz-driven dielectric loaded waveguides. These results will be useful for the implementation of the AXISIS project. However, improvements have still to be made to meet the final requirements of the AXISIS project. Especially, the lowest achieved bunch length in our simulations ( $\approx 15$  fs rms) is still far from the requirements ( $\leq 1$  fs rms). This is due to the already strong curvature of the bunch longitudinal phase-space at the gun exit (see Fig. 1), which limits the compression performances in the linac. This curvature is caused by the high-frequency field (300 GHz) used to accelerate the electron bunch in the gun [3]. The straightforward and most efficient way to reduce it, and therefore to improve the bunch compression in the linac, would be to use lower frequencies in the gun. For this purpose, the studies to use more classical guns, like DC-guns or S-band RF-guns, as source to then inject the bunch into a THz linac are also currently ongoing.

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