SIMULATION OF AN ELECTROMAGNETIC FIELD EXCITATION BY A THz-PULSE AND ACCELERATION OF AN ELECTRON BUNCH IN A DIELECTRIC-LOADED AXSIS LINAC

K. Galaydych*, R. Assmann, U. Dorda, B. Marchetti, G. Vashchenko, I. Zagorodnov
Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany

Abstract

The "Attosecond X-ray Science: Imaging and Spectroscopy" (AXSIS) experiment at DESY will use a dielectric loaded waveguide to accelerate electron bunches up to 15 MeV. Such a linac will be powered by a narrowband multicycle THz-pulse with a central frequency of 300 GHz. In this paper we focus on the reflection of the excited field at a pinhole, on the optimization of the bunch injection time and on the bunch dynamics in the acceleration process. The linac excitation by the THz-pulse and the bunch acceleration in the excited field are investigated using CST and ECHO simulations.

INTRODUCTION

The AXSIS experiment at Deutsches Elektronen Synchrotron (Hamburg) is foreseen to provide fully-coherent attosecond X-ray radiation [1]. This radiation will be used for 3D imaging and spectroscopy for structural biology problems. The fully-coherent attosecond X-ray will be provided by inverse Compton scattering of a laser beam on an electron bunch accelerated in the AXSIS linac.

The accelerating structure is a round metal waveguide, loaded by a dielectric (see Fig. 1). The round vacuum channel, in which the externally-injected electron bunch will be accelerated, is coaxial to the waveguide. The source of the accelerating field is an external radially-polarized THz-pulse which is coupled into the linac. A cylindrical dielectric-loaded waveguide was chosen as an accelerating structure it supports a travelling mode TM_{01}, which has a non-zero longitudinal electric field component, desired for the bunch acceleration, it allows the conversion of a radially-polarized electromagnetic pulse to this mode with high efficiency, and its fabrication in THz range is simple.

Electron acceleration was experimentally demonstrated using an optically-generated THz-pulse (10 μJ power and centered at 450.0 GHz) in a similar linac as the proof-of-principle in [2]. In this experiment, a maximum energy gain of 7 keV in 3 mm interaction length using nonrelativistic 60 keV electron bunch was observed.

The AXSIS linac will be a normal conducting linear electron dielectric-loaded accelerator capable of accelerating electrons to 15 MeV with an initial bunch energy of 2.1 MeV. In this paper we present the simulation results of the electromagnetic field excitation in the AXSIS linac and the relativistic electron bunch acceleration in this field.

STATEMENT OF THE PROBLEM

The radially-polarized THz-pulse is focused on the open end of the linac, propagates along the linac, and after reflection co-propagates with the externally injected electron bunch. Right after the coupler the excited field is not a TM_{01}-like mode field yet. Conversion to desired field occurs after propagation of a certain distance in the linac. The electron bunch should be injected in as pure TM_{01}-like mode field as possible. This is the reason why we inject the THz-pulse and the electron bunch from the opposite sides of the linac. Figure 1 gives a three-dimensional general schematic of the designed accelerator and the stages of the field propagation and bunch acceleration. In this paper we do not take into account the process of THz-pulse coupling into the linac and suppose that we already have a TM_{01} waveguide port as the excitation source at the open end of the linac.

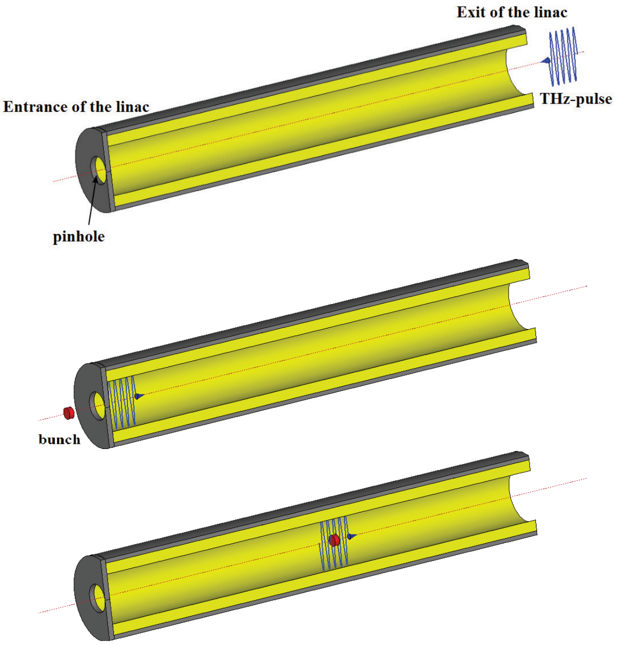

Figure 1: (Top) A dielectric-loaded metal waveguide with an electron bunch and a metal plate with a pinhole aperture at the entrance of the waveguide. (Middle) The electron bunch moves from left to right and will be injected into the linac synchronized with the reflected field by adjusting its time delay, and than accelerated by the THz-pulse (Bottom).

---

[*] kostyantyn.galaydych@desy.de

ISBN 978-3-95450-182-3

SIMULATIONS RESULTS

The main goal of the simulations were (i) the analysis of the excited field evolution, and the reflection efficiency at a pinhole, and (ii) acceleration of an electron bunch in this field with analysis of the optimal time of injection, energy gain and transverse/longitudinal rms size evolution of the electron bunch. Simulations were performed for parameters similar to the planned parameters of the AXSIS linac, electron bunch and THz-pulse. These parameters are presented in Table 1.

Table 1: Parameters of the Linac, E-bunch and THz-pulse

Parameter	Value
Vacuum radius	625.0 µm
Dielectric thickness	77.7 µm
Length of the linac	100.0 mm
Rel. permittivity of the dielectric	4.41
β_{ph}(300 GHz)	1.0
β_{gr}(300 GHz)	0.62
Injection energy	2.1 MeV
Charge of bunch	0.377 pC
RMS longitudinal size of bunch	43.0 µm
RMS radial size of bunch	10.8 µm
Temporal shape of the pulse	flat top
Frequency of the pulse	300.0 GHz
Duration of the pulse	133.3 ps
Peak E_z (on-axis)	240.0 MV/m

After being reflected, the THz–pulse co-propagates with the injected bunch. First of all we had to define the radius of the pinhole to be used. This is the critical aspect for the linac for the following reason: it is necessary to provide a low level of energy leakage of the THz-pulse, while injecting as much charge as possible. Results of the CST microwave studio [3] simulations show that it is possible to obtain $\sim$ 97% reflection for a pinhole radius less than 0.3 mm (see Fig. 2), which means that the aperture acts as a short.

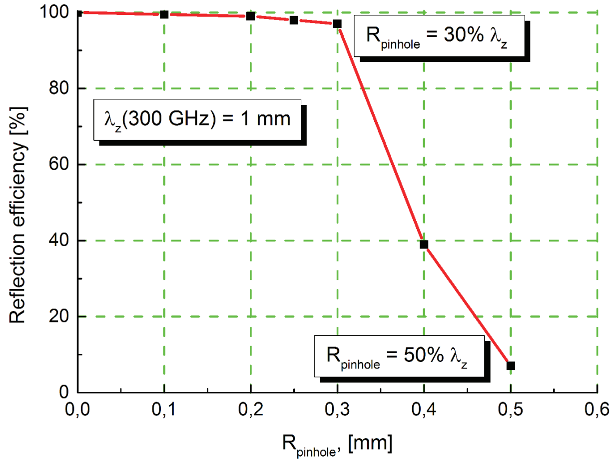

Figure 2: Dependence of the reflection efficiency on radius of the pinhole aperture. Reflection efficiency is calculated as the stored energy of the electromagnetic field after reflection of the THz-pulse, normalized to the maximum.

Analysis of the electromagnetic field evolution in the accelerator shows that after the reflection at the pinhole the THz-field is still the TM_{01}-like field desired for acceleration (as before the reflection). Further increase of the pinhole radius causes a high level of leakage and the aperture does not act as a short at THz frequencies. It should be noted that doubling the electric field amplitude at the pinhole due to reflection can lead to undesired breakdown effects. This will restrict the input power of the THz-pulse. The permissible power level should be further studied.

In order to define the characteristics of the bunch during acceleration, simulations were carried out using code ECHO [4, 5]. The Particle-in-Cell module of the code uses low-dispersive scheme for electromagnetic field calculation and leapfrog scheme for the equations of motion. The self-consistent dynamics of the charged particles is available, but in the simulations presented below we have neglected the self-fields due to the low bunch charge.

Another important point is the control of the electron bunch injection into an accelerating structure, as characteristics such as mean output energy and output energy spread are dependent on the time of injection. We are interested in the time of injection which maximizes the mean energy and minimizes the energy spread at the output of the linac. For this goal we have scanned through a range of the injection times (see Fig. 3).

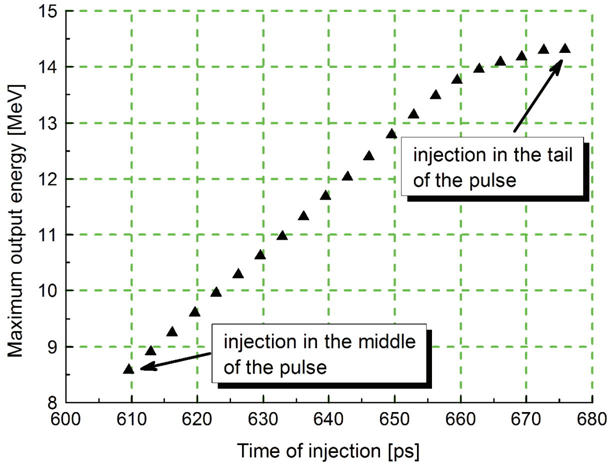

Figure 3: Maximum output energy of the bunch versus time of injection.

As the THz-pulse has a multicycle structure (as depicted in Fig. 1) the electron bunch has to pass through as many as possible cycles at the optimum phase to achieve the highest energy gain. The dependence of the maximum output bunch energy on the injection time shows that, in order to achieve the maximum output energy of the bunch, we should inject the bunch in the tail of the reflected THz-pulse as expected. More detailed analysis of the bunch injection showed that it is possible to minimize the output energy spread down to $\sim$ 3.0% (coinsides with the maximum energy gain) by more accurate tuning of the injection time. It should be noted that the accuracy of the necessary time adjustment is technically realizable using optical delay lines. Finally, after the optimization of the injection time and the radius of the pinhole aperture, the simulation of the bunch acceleration with bunch dynamics analysis including energy gain and bunch size evolution was carried out. Figure 4 shows the energy gain and the phase slippage of the bunch.

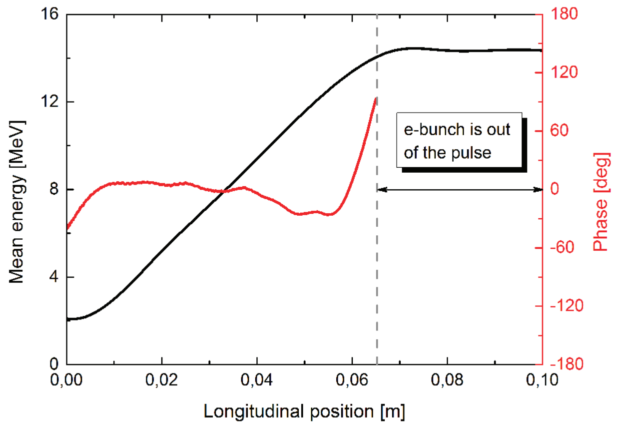

Figure 4: Mean kinetic energy gain and phase slippage.

The energy gain takes place as long as the bunch is in the accelerating phase of the reflected THz-pulse. The main reason for limiting energy gain is that the bunch overtakes the reflected ~ 30 mm long THz-pulse, which moves with the group velocity $\beta_{gr} = 0.62$, and is less than the speed of the electron bunch.

At the initial stage of acceleration, there is a significant change in the phase of the accelerating field relative to the center of the mass of the bunch. The main reason for this is that the bunch is injected at a speed which is lower than the speed of light, while the parameters of the accelerator are chosen so that, at the central frequency of the THz-pulse, the phase velocity is exactly equal to the speed of light. Further increase of the bunch velocity leads to phase stabilization until the moment of overtaking, which is described above. When the bunch reaches the leading front of the THz-pulse the phase stabilization is spoiled due to the pulse dispersion. At the final stage of acceleration a significant phase slippage occurs as well when the bunch passes the leading front of the THz-pulse with a decreasing field amplitude.

Acceleration of the bunch leads to a change of size in both longitudinal and transversal directions. Figure 5 presents the evolution of the rms sizes σ_x and σ_z. It should be noted that the injection time of the bunch was chosen in order to obtain the maximum energy gain. In this case, the accelerating field is stronger at the tail of the bunch than at the head. As a result, compression in the longitudinal direction occurs.

In the process of acceleration, transverse expansion of the bunch take place as well. It should be noted, that the simulated electron bunch has zero divergence at the linac input. The transverse rms size of the bunch increases due to the radial component of the excited electric field, which is proportional to the radial position of the particle for the operation frequency of 300 GHz. The phase velocity at this frequency is equal to the speed of light for the chosen parameters of the linac.

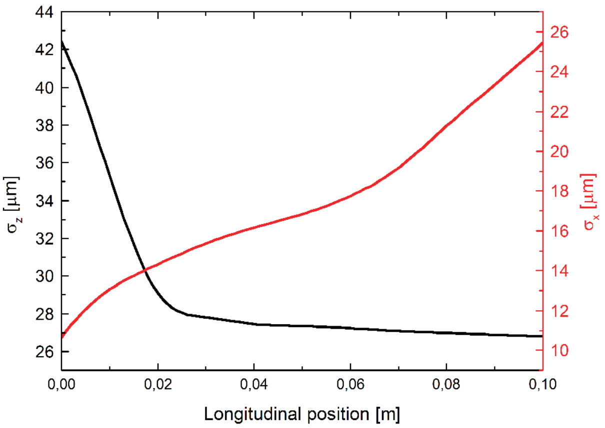

Figure 5: Evolution of the bunch size.

SUMMARY

In this paper, numerical studies of the excitation of the AXSIS linac by the THz-pulse and acceleration of an electron bunch in the excited field are presented. Using CST simulations, the reflection of the THz-pulse at the pinhole was studied. The radius of the pinhole has been optimized in order to maximize both the external injected charge and the reflection efficiency of the excited pulse. Further, more using ECHO code the dynamics of the bunch acceleration in the reflected field was investigated. The bunch injection time has been optimized. The evolution of the bunch energy and bunch size have been investigated and analyzed.

ACKNOWLEDGEMENT

We would like to thank A. Fallahi, N. Matlis and F. Lemery for many useful discussions, and D. Marx for carefully proof reading the paper. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 609920.

REFERENCES

[1] F.X. Kartner *et al.*, "AXSIS: Exploring the frontiers in attosecond X-ray science, imaging and spectroscopy", *Nucl. Instr. Meth.*, vol. 829, pp. 24–29, 2016.

[2] E.A. Nanni *et al.*, "Terahertz-driven linear electron acceleration", *Nat. Comunn.*, vol. 6, 2015, 8486.

[3] CST MWS, `http://www.cst.com`

[4] I. Zagorodnov and T. Weiland, "TE/TM field solver for particle beam simulations without numerical Cherenkov radiation", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 042001, 2005.

[5] I. Zagorodnov, "Computation of electromagnetic fields generated by relativistic beams in complicated structures", presented at the North American Particle Accelerator Conf. (NAPAC16), Chicago, USA, Oct. 2016, paper WEA1IO02.