Feasibility study for a THz acceleration experiment on the PHIL accelerator at LAL

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Abstract. We present a feasibility study for an experiment aiming to post-accelerate an electron bunch, coming from the PHIL (Photo-Injecteur au LAL) photoinjector at LAL (Laboratoire de l'Accélérateur Linéaire), in a circular partially dielectric-loaded waveguide (DLW) driven by a multicycle THz pulse generated by the infrared laser coming from the LASERIX (Installation laser XUV/IR de l'Université Paris Sud) facility. We first discuss the considerations taken into account to fix the DLW design and the THz pulse properties, especially the choice of a 160 GHz THz pulse frequency, and then provide a set of values for their main parameters. We then perform start-to-end simulations of the acceleration experiment, taking into account the current achievable range of parameters at PHIL and the THz pulse properties already achieved with LASERIX with some margins for the coupling losses. They demonstrate the possibility to obtain a 1.2 MeV energy gain for a 10 pC bunch, without charge losses, with a clear shift of the energy spectrum, which would represent a significant improvement compared to the current state-of-the-art of THz acceleration. An overview of the upcoming steps towards the realization of the experiment is finally given.

1. Introduction

Particle acceleration beyond the few-MeV level and their compression down to the single femtosecond order or below currently requires large infrastructures, due to the low frequencies (a few GHz) and relatively low field amplitudes (a few tens of MV/m in the meter-long structures) used in conventional L and S-band accelerating structures.

One of the schemes currently investigated to reduce the footprint of particle accelerators by several orders of magnitude is to use dielectric-loaded circular waveguides (DLW) driven by multicycle THz pulses [1–6], for which the operating frequency (100 GHz to a few THz) and field amplitude (up to a few GV/m) are expected to be much higher.

A demonstration experiment of this acceleration scheme is currently investigated by the authors. The basic experimental principle would be to inject the 3-4 MeV electron beam from the S-band gun of the PHIL (Photo-Injecteur au LAL) injector [7] into a DLW driven by a multicycle THz pulse coupled to the TM_{01} mode (accelerating mode). The Joule-class infrared laser from the LASERIX (Installation laser XUV/IR de l'Université Paris Sud) facility [8] has already been tested as a potential candidate for its generation.

We study in the present paper the feasibility of such an experiment. After a brief description of the PHIL/LASERIX platform at LAL (Laboratoire de l'Accélérateur Linéaire), where we intend to perform the experiment, we first present a preliminary design of the DLW intended for the experiment and explain the reasons leading to this choice. Then, we present start-to-end beam dynamics simulations of the experiment using as input all the constraints of operation at PHIL and experimental results of THz generation obtained on the LASERIX facility. Finally, the future tasks to be performed in view of setting up the experiment are presented.

2. Experimental facility

Four main methods are currently used to generate accelerating fields with a frequency in the THz range (considered to be between 0.1 and 10 THz in this paper): gyrotrons [9, 10], optical rectification of laser pulses in non-linear optical crystals [11, 12], CSR (Coherent Synchrotron Radiation)/FEL (Free Electron Laser) radiation generated in accelerators [13, 14] and beam-driven wakefields (for example in dielectric-loaded structures) [15, 16].

In this paper, we will study the feasibility of a post-acceleration experiment of the electron bunch coming from the PHIL accelerator in a DLW driven by a multicycle THz pulse generated via optical rectification of the LASERIX IR laser. The realization of this experiment will be eased by the fact that PHIL and LASERIX are currently already in synergy.

2.1. PHIL accelerator at LAL

The PHIL accelerator at LAL in Orsay (France), for which a schematic is shown in Figure 1, is an RF-gun test bench with the goal to characterize RF-guns and cathode performance, train PhD students and engineers to the accelerator physics and beam dynamics and host experiments proposed by external users with the electron beam available at PHIL. The current experimental conditions and achievable electron bunch properties at the level of the experimental area (see Figure 1) are gathered in Table 1.

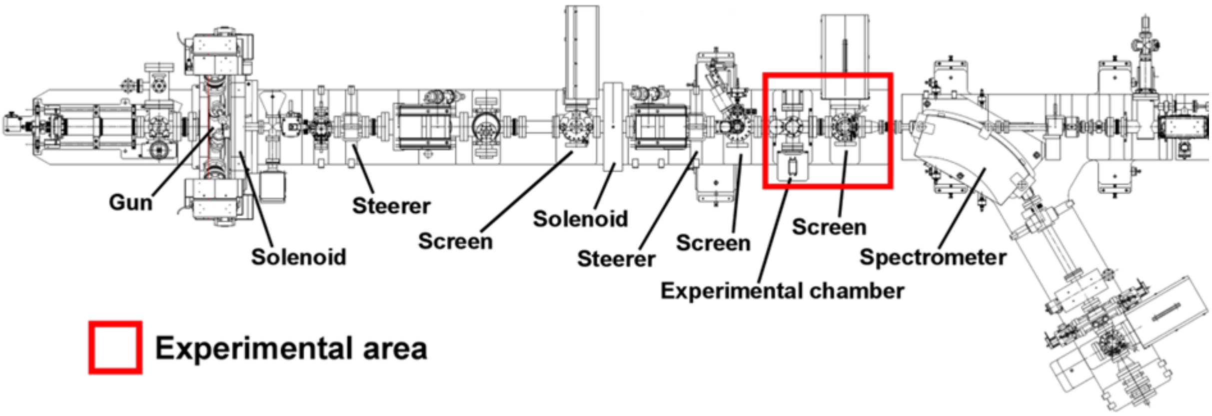

Figure 1. Schematic of the beamline of the PHIL accelerator at LAL. The diagnostics of interest for the present study are indicated as well as the potential experimental area.

Table 1. Relevant experimental conditions currently available at PHIL and achievable electron bunch properties at the experimental area (≈ 3.4 m after the cathode).

Gun peak field	Cathode laser duration $\sigma_{t,L}$	Cathode laser radius $\sigma_{r,L}$	Charge Q	Bunch length σ_t	Bunch transverse size σ_r
≤ 60 MV/m	50 fs – 1 ps FWHM (Gaussian)	0.3 – 1.5 mm rms (Gaussian)	≤ 500 pC (Cu cathode)	≥ 300 fs rms	≥ 0.1 mm rms

The objective of the THz acceleration experiment proposed in this paper is to obtain a clear shift of the bunch energy spectrum after interaction with the THz field in the DLW, and not only energy modulation. This means that the bunch energy spectra measured in the presence and absence of the

DLW should be clearly separated (see for example Figure 6 (c) for illustration) and not overlapping each other. One challenging aspect for this will be to have simultaneously a short bunch length at the experimental area (≤ 200 fs rms) while keeping a charge (≥ 5 pC) compatible with a measurement of the bunch on a screen after dispersion by the spectrometer. The challenge for this comes from the large distance between the cathode and the experimental area (≈ 3.4 m) and the absence of booster cavity after the gun to preserve the bunch length. The addition of a booster cavity right after the gun, planned in the next months, will greatly ease the experiment as will be shown in Section 4.

2.2. LASERIX IR laser at LAL

The LASERIX facility is a 10 Hz Joule-class IR laser, based on the Titanium-Sapphire technology, located at LAL next to the PHIL accelerator. This is a user facility, allowing experiments to be performed either directly with the IR laser pulse or with EUV and soft X-ray laser beams generated using high harmonic generation techniques with the IR laser. The ranges of interest, concerning the experiment we propose, for the parameters of the LASERIX laser are shown in Table 2.

Table 2. Ranges of interest, concerning the proposed experiment, for the LASERIX parameters.

Central wavelength (nm)	Pulse energy (J)	rms duration (ps)	FWHM transverse size (mm)
810	0.9 – 1.2	1.2 – 1.6	15 – 18

3. Design considerations and choices for the DLW

Figure 2 shows a schematic of the circular DLW intended for the THz acceleration experiment with the dimensions of interest for the present study defined on it.

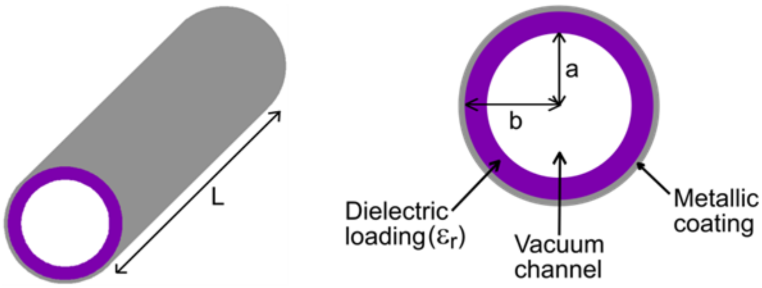

Figure 2. Schematic of a cylindrical partially dielectric-loaded waveguide.

The mode to be excited for acceleration in the DLW is the TM_{01} mode [17], for which the analytical expression of the electromagnetic field can be found for example in [18]. All the calculations in this section are performed using the analytical model developed in Section II of [5]. In this section, we will consider fused silica as dielectric material ($\varepsilon_r \approx 3.85$ in the THz range) because it has already been used in accelerator beamlines and proven to be high-vacuum compatible.

The first DLW parameter to be fixed is the vacuum channel radius a. The first limitation is that a has to be big enough such that the TM_{01} mode can propagate in the DLW. Namely, the THz pulse central frequency f has to remain above the cut-off frequency. It is also fixed by considerations on the electron bunch injection and dynamics through it (the bunch must pass through without charge losses), on the required THz power (which for a given desired accelerating peak field E_{ml} is a fast increasing function of a) and on the coupling efficiency of the THz pulse into the DLW (decreasing with a). Taking all this into account, we choose to fix a such that $2a$ is equal to the central wavelength of the THz pulse. Then, given fixed values for a, f and ε_r, the dielectric thickness $b - a$ is solely a function of the desired phase velocity v_{ph} for the THz pulse in the DLW (which we will always consider equal to c in this paper) and is determined by solving the dispersion relation for the TM_{01} mode.

The realization of a demonstration experiment for acceleration in a THz-driven DLW points towards using a relatively low frequency and a DLW with a relatively large vacuum channel for several reasons. First, a larger vacuum channel comes with more margins for the injection of the electron bunch and its transverse dynamics into the DLW. Second, a lower frequency implies more margins on the synchronization of the electron bunch with the THz pulse and on the electron bunch longitudinal dynamics in the DLW. Then, as shown in Figure 3 (left), this also implies a thicker dielectric layer in the DLW, which results in less sensitivity of v_{ph} to DLW production errors and to eventual uncertainties on the THz pulse central frequency. Finally, as shown in [19], the THz generation setup is simpler and more cost-effective. However, as shown in Figure 3 (right), the required THz power to achieve a given field amplitude in the DLW strongly increases at low frequency and becomes therefore harder to generate. As shown in [19], the LASERIX facility offers the possibility to generate at least 35 MW of THz power P_{THz} in the vicinity of 160 GHz. For the experiment under study in this paper we choose therefore to consider $f \approx 160$ GHz, implying a = 936.85 µm and $b - a$ = 182.3 µm. This represents a good trade-off between the advantages offered by a low frequency and the increasing THz power required when f decreases.

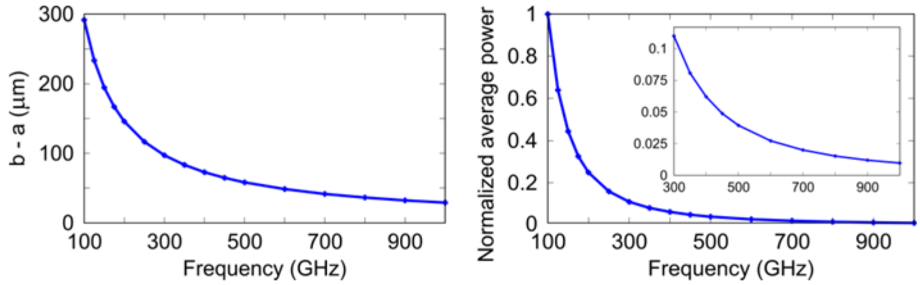

Figure 3. Evolution of the dielectric thickness (left) and of the normalized average power to reach a fixed field amplitude in the DLW (right) as a function of the central frequency of the THz pulse. $2a$ = wavelength; ε_r = 3.85; $v_{ph} = c$. The inset in the right plot is a zoom on the range between 300 GHz and 1 THz.

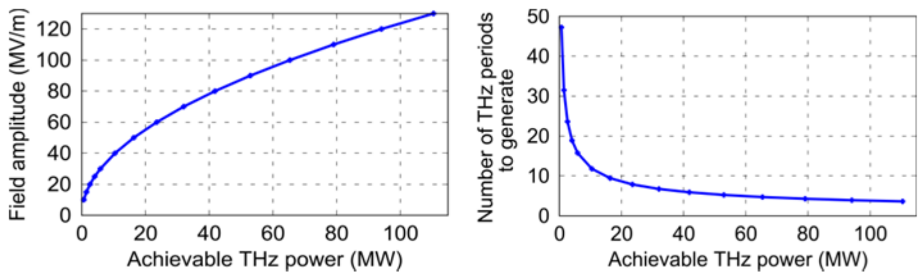

Figure 4. Evolution of the field amplitude in the DLW (left) and of the number of THz periods required to reach 1 MeV energy gain for a relativistic electron beam in a DLW (right) as a function of the THz peak power. f = 160 GHz; a = 936.85 µm; $b - a$ = 182.3 µm; ε_r = 3.85; $v_{ph} = c$.

Figure 4 shows the evolution of the accelerating field amplitude and number of THz periods required to achieve a 1 MeV energy gain as a function of the achievable THz power under the previously mentioned conditions. It shows, as expected, that maximizing the achievable power is desired since it will maximize the accelerating field amplitude and simplify the setup (the number of THz periods to generate will decrease and so will the length of the DLW). Including a margin of 30% for the expected losses during the coupling of the THz pulse results in 25 MW in the DLW, which according to Figure 4 translates into $E_{ml} \approx 62$ MV/m field amplitude (left plot) and $N_{THz} = 8$ periods in the pulse required to achieve a 1 MeV energy gain (right plot). Table 3 shows a summary of the properties we will assume in the next section for the DLW and the THz pulse driving it.

Table 3. Summary of the properties assumed in Section 4 for the DLW and the THz pulse driving it.

DLW properties				**THz pulse properties**					
ε_r	a (μm)	$b - a$ (μm)	L (cm)	f (GHz)	v_{ph}	v_g	E_{ml} (MV/m)	P_{THz} (MW)	N_{THz}
3.85	936.85	182.3	2	160	c	0.5305c	62	25	10

4. Start-to-end-simulations of the experiment on PHIL

The first quantity to be fixed for the simulations is the bunch charge. One would like to have it not too high in order to minimize the bunch length at the entrance of the DLW, and thus the induced energy spread in the DLW, so that the full energy spectrum could be recorded in one shot by the spectrometer. However, it should remain sufficiently high to have a precise imaging of the bunch after dispersion by the spectrometer. As a good trade-off between these two aspects, we fix in our simulations the bunch charge to 5 pC and 10 pC. Taking this into account as well as the current layout and set of parameters accessible at PHIL (see Figure 1 and Table 1) and the achievable THz pulse properties with LASERIX (see Table 3), we perform start-to-end ASTRA simulations [20] of the THz acceleration experiment, namely from the cathode to the entrance of the spectrometer dipole where the bunch energy spectrum will be measured, in order to evaluate the potential outcome of the experiment.

In all these simulations, the peak accelerating fields in the gun and DLW are respectively fixed to 60 MV/m and 62 MV/m. The time profile of the UV laser pulse driving the gun is assumed to be Gaussian with 100 fs rms duration. The DLW entrance is considered to be 3.4 m after the cathode, which is the position of the experimental area on PHIL, and the phase of the THz field is always set to minimize the final bunch rms energy spread σ_{Ef}. The other simulation parameters for all the cases are gathered in Table 4.

Table 4. Simulation parameters used in Section 4. Q: bunch charge; φ_g: gun RF-phase (0° = maximum energy gain); $\sigma_{r,l}$: Transverse size of the laser driving the gun (profile shape is also mentioned); $B1$: First solenoid peak field; $B2$: Second solenoid peak field; E_{mb}: Booster cavity peak accelerating field.

	Q (pC)	φ_g	$\sigma_{r,l}$	$B1$ (T)	$B2$ (T)	E_{mb} (MV/m)
Figure 5	10	-32°	1.2 mm rms (Gaussian cut at 1σ)	0.16	0.11	0
Figure 6	5	-32°	1.2 mm rms (Gaussian cut at 1σ)	0.163	0.1095	0
Figure 7	10	-32°	1.2 mm rms (Gaussian cut at 1σ)	0.14	0.1835	40
Figure 8	10	0°	0.5 mm rms (Gaussian)	0.131	0.213	55

We first consider the case without booster cavity after the gun, which is the current state of PHIL. The results of these simulations are presented in Figures 5 (10 pC bunch charge) and 6 (5 pC bunch charge). They display, in absence and presence of the THz-driven DLW, the evolution of the bunch transverse size and length from the cathode up to the spectrometer entrance, and also the bunch energy spectrum at the spectrometer entrance.

The first thing to note in Figures 5 (a) and 6 (a) is that it is possible with the solenoids available at PHIL to obtain a waist of the electron bunch at the spectrometer level (desired to perform a precise measurement of the bunch energy spectrum), while keeping a sufficiently small bunch transverse size at the entrance of the DLW at Z = 3.4 m (slightly below 0.4 mm rms) to prevent charge losses in the DLW. However, this is possible only when a relatively strong value is used for the first solenoid peak field. This leads to a relatively low electron bunch transverse size between the cathode and the second solenoid (see Figures 5 (a) and 6 (a)). As a consequence, the space charge forces remain quite strong in this area. This has the effect to significantly increase the bunch length and more as the bunch charge increases (see Figures 5 (b) and 6 (b)). This leads to a significant induced energy spread in the DLW (see Figures 5 (c) and 6(c)), due to the fact that the bunch is not very short compared to the THz wavelength (1.874 mm). Reducing the first solenoid peak field would however not be favorable, because charge losses would then occur in the DLW. In addition, the bunch transverse size would be bigger at the level of the second solenoid, resulting in an increase of the bunch length during the transverse focusing up to the DLW entrance due to simple geometrical effects.

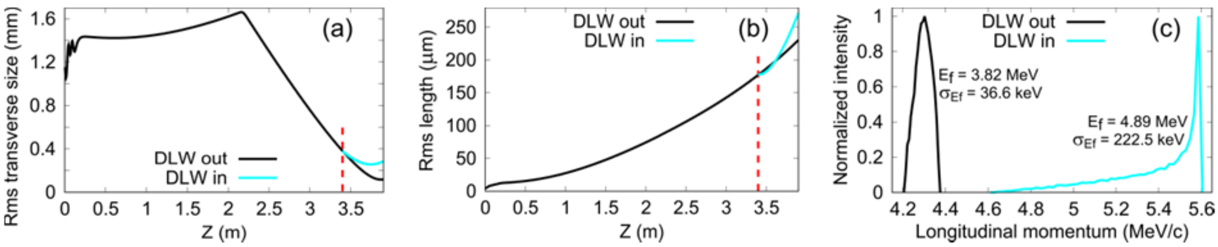

Figure 5. Evolution of the bunch rms transverse size (a) and rms length (b) between the photocathode and the entrance of the PHIL spectrometer. (c): Bunch energy spectrum at the entrance of the spectrometer. Here E_f is the final mean kinetic energy and σ_{Ef} the final rms energy spread. DLW out: DLW not included in the beamline. DLW in: DLW included in the beamline. The red dashed line marks the position of the DLW. Conditions: see Table 4 and text.

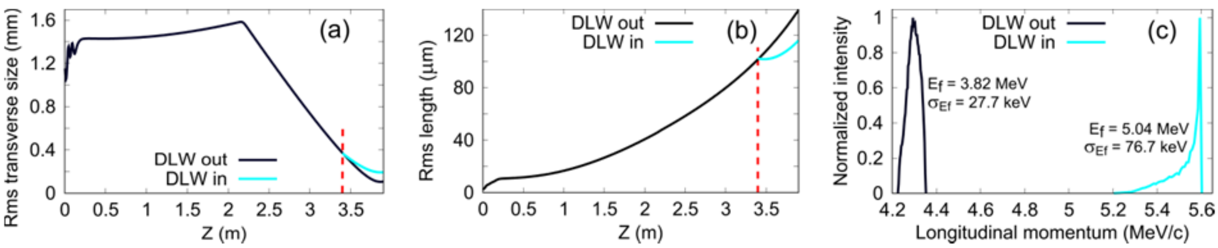

Figure 6. Evolution of the bunch rms transverse size (a) and rms length (b) between the photocathode and the entrance of the PHIL spectrometer. (c): Bunch energy spectrum at the entrance of the spectrometer. Here E_f is the final mean kinetic energy and σ_{Ef} the final rms energy spread. DLW out: DLW not included in the beamline. DLW in: DLW included in the beamline. The red dashed line marks the position of the DLW. Conditions: see Table 4 and text.

Figure 5 thus clearly points that, in absence of a booster cavity after the gun, it is very unfavorable to perform a THz acceleration experiment at 10 pC for two reasons. First, the bunch energy spectrum would be much wider than the span measurable with the PHIL spectrometer in a single shot (≈ 220 keV), thus limiting the measurement to only a fraction of the core of the spectrum. Then, the final mean kinetic energy E_f would decrease compared to the case at 5 pC, because the bunch length is covering a larger fraction of the THz wavelength (≈ 53% at 10 pC against ≈ 21% at 5 pC). On the other hand, Figure 6 shows that 5 pC would be compatible with a THz acceleration experiment thanks to a much shorter bunch length at the DLW entrance, resulting in a clearly shifted by around 1.2 MeV and narrower energy spectrum. The core of the energy spectrum would then be entirely measurable in a single shot and only a part of the low energy tail would be missing.

We then consider the case with a 3 cell 3 GHz booster cavity having is entrance located 0.35 m after the cathode, which addition is planned on PHIL in the next months. The phase of this booster cavity has always been set to maximize the energy gain. The results of these simulations are presented in Figures 7 and 8. They display, in absence and presence of the THz-driven DLW, the evolution of the bunch transverse size and length from the cathode up to the spectrometer entrance, and also the bunch energy spectrum at the spectrometer entrance. Figure 7 is, similarly to Figures 5 and 6, for a cathode laser transverse profile and a gun RF-phase φ_g (see Table 4) optimized to provide short bunches at the DLW entrance. These parameters are set differently for Figure 8 (see Table 4) and correspond to the current standard working point at PHIL.

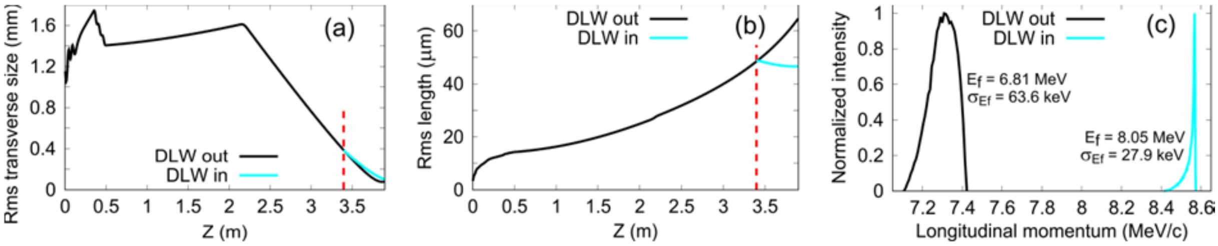

Figure 7. Evolution of the bunch rms transverse size (a) and rms length (b) between the photocathode and the entrance of the PHIL spectrometer. (c): Bunch energy spectrum at the entrance of the spectrometer. Here E_f is the final mean kinetic energy and σ_{Ef} the final rms energy spread. DLW out: DLW not included in the beamline. DLW in: DLW included in the beamline. The red dashed line marks the position of the DLW. Conditions: see Table 4 and text.

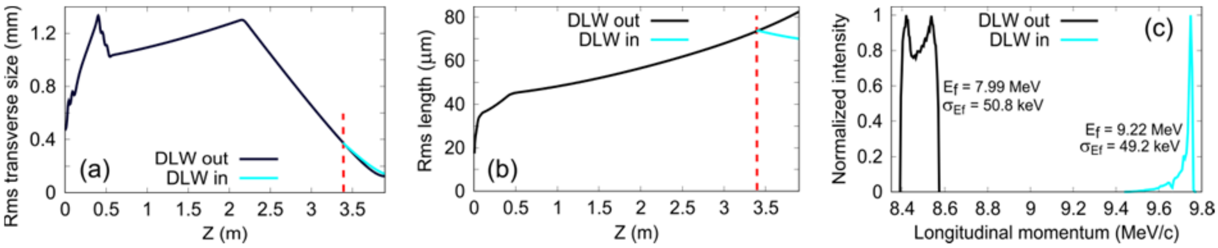

Figure 8. Evolution of the bunch rms transverse size (a) and rms length (b) between the photocathode and the entrance of the PHIL spectrometer. (c): Bunch energy spectrum at the entrance of the spectrometer. Here E_f is the final mean kinetic energy and σ_{Ef} the final rms energy spread. DLW out: DLW not included in the beamline. DLW in: DLW included in the beamline. The red dashed line marks the position of the DLW. Conditions: see Table 4 and text.

By comparison with Figures 5 and 6, Figures 7 and 8 demonstrate that the addition of the booster cavity would greatly help the THz acceleration experiment. This is due to the decrease of the space-charge forces resulting from the additional 3 to 4 MeV energy gain induced by the booster cavity. As a result, the bunch length at the DLW entrance could be twice as short at 10 pC (see Figure 7 (b)) than it would be at 5 pC without booster cavity (see Figure 6 (b)). The energy gain in the DLW would still be around 1.2 MeV, but the final energy spectrum would become much narrower than without booster cavity and entirely measurable in a single shot with the PHIL spectrometer (see Figures 7 (c) and 8 (c)). It would actually become narrower than without the DLW in the beamline (see Figure 7 (c)), due to the longitudinal compression of the bunch induced by the DLW (see Figure 7 (b)).

One has to note that the Gaussian cut at 1σ transverse profile with a 1.2 mm rms size assumed for the cathode laser in Figure 7 has not yet been used or generated on PHIL. Moreover the gun RF-phase assumed (-32°), close to the zero-crossing, is less stable for the PHIL operation than the one maximizing the energy gain (0°). However one can see in Figure 8, for which the current standard working point at PHIL is assumed (Gaussian transverse profile with 0.5 mm rms size for the cathode laser and 0° gun RF-phase), that even if the final bunch energy spectrum after the DLW is wider than for Figure 7 it remains much better than without booster cavity (see Figure 5 (c)). The experiment can therefore also be satisfactorily performed in these conditions. A higher field in the booster cavity has to be used compared to Figure 7, but this is foreseen to be within the achievable peak field range for the booster cavity to be installed on PHIL.

5. Ongoing work and future steps

Several steps are still required to be performed before the THz acceleration experiment itself could be carried out at PHIL. Work is currently ongoing to design the system to couple the THz pulse into the DLW and two options are considered for this, for which simplified schematics are depicted on Figure 9. The first one would be to come from the front, which has the advantage to have already been validated in several experiments [1, 2] but the disadvantage to introduce optical elements on the propagation axis of the electron bunch leading to the risk of charge losses. The second one, which is currently under investigation, would be to couple the THz pulse from the side of the DLW (as it is usually done for the RF pulse in conventional accelerating structures) to keep the electron propagation axis free of optical elements. An experiment to test these coupling options is intended beginning of 2020 at the LASERIX facility using a THz generation setup similar to the one already used in [19].

Following this future experiment, the size of the experimental setup will be known and its integration in the PHIL accelerator room will be defined. In the meantime, the working points for the THz acceleration experiment will be optimized via simulations, according to the presence of a booster cavity or not, and tested on PHIL without DLW in the beamline. Finally, the last preparatory experiment will be to test the injection and transmission of the electron bunch through the DLW without THz pulse injected into it.

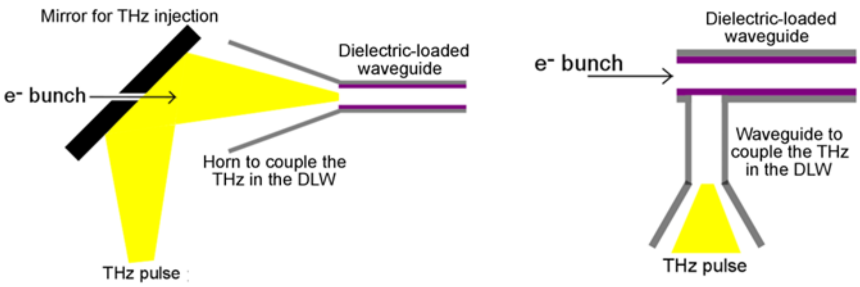

Figure 9. Schematics of the two options considered to couple the THz pulse into the DLW.

6. Conclusions

We have presented a feasibility study for an experiment aiming to post-accelerate the electron bunch coming from the PHIL photoinjector at LAL (see Figure 1 and Table 1) in a circular partially dielectric-loaded waveguide (see Figure 2) powered by a multicycle THz pulse generated by the infrared laser coming from the LASERIX facility (see Table 2).

We have introduced the considerations we took into account to define the design parameters of the DLW intended to be used in the experiment and came out with a set of values for them (see Table 3). We also came out with a set of parameters for the THz pulse driving the DLW (see Table 3) based on the experimental results already obtained at LASERIX in a first experimental campaign validating the THz generation scheme.

Start-to-end simulations have been performed, taking into account the current layout of PHIL and the achievable range of parameters, as well as DLW and THz pulse properties in accordance with the results already obtained at LASERIX (with margins for expected losses during the coupling of the THz pulse into the DLW). They demonstrate for a bunch charge of 5 to 10 pC (see Figures 5 to 8) the potential to obtain a clear shift of the bunch energy spectrum with an energy gain around 1.2 MeV, which would be significantly higher than what has already been demonstrated with schemes similarly based on DLW [1, 2, 21]. Such a result would open the way towards new compact accelerator schemes at the 10 MeV level [3–6]. This would especially be the case if higher THz frequencies are used since for the same THz power generated and a DLW vacuum channel diameter equal to two THz wavelengths, the field amplitude in the DLW (and thus the bunch energy gain) scales linearly with the THz frequency.

Work is still ongoing towards the realization of the THz acceleration experiment on the PHIL accelerator at LAL, especially on the aspect of the THz pulse coupling into the DLW for which a preparatory experiment is planned beginning of 2020 on the LASERIX facility. This should be followed by a definition of the integration of the setup in the PHIL room and finally the first experiments on PHIL.

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