

PAPER • OPEN ACCESS

Electromagnetic and Beam Dynamics Studies for High Gradient Accelerators at Terahertz Frequencies

To cite this article: M. Marongiu *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012029

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Electromagnetic and Beam Dynamics Studies for High Gradient Accelerators at Terahertz Frequencies

M. Marongiu^{1,2}, E. Chiadroni², M. Croia², M. Ferrario², L. Ficcadenti³, S. Lupi^{1,3}, V. Martinelli², A. Mostacci^{1,3}, R. Pompili², S. Tofani³

¹ Sapienza University, Rome, Italy

² LNF-INFN, Frascati, Italy

³ INFN-Roma, Rome, Italy

E-mail: marco.marongiu@lnf.infn.it

Abstract. THz radiation is one of the most appealing portion of the electromagnetic spectrum in terms of multi-disciplinary use in basic science and technology. Beyond the numerous applications, a great interest is its potential for future, compact linear accelerators.

Conventional radio-frequency accelerating structures operating at the S and C band can reach gradients up to 30 - 50 MV/m, respectively; higher accelerating gradients, of the order of 100 MV/m, have been obtained with X-band cavities. THz-based accelerating structures enable operation at even higher gradient, potentially up to the GV/m scale, holding great potential for their application to free-electron lasers and linear colliders, for instance.

Here we present electromagnetic and beam dynamics studies about the use of a dielectric loaded waveguide to accelerate electron bunches by mean of a narrow-band multi-cycle THz pulse. The excitation of the accelerating structure by the THz pulse and the bunch acceleration in the excited field are investigated through CST Microwave Studio and GPT simulations.

1. Introduction

Nowadays, there is a growing interest for compact particle accelerators. Therefore, the main research activities in the particle accelerators field are oriented toward the design of high gradient accelerating structures. Conventional radio-frequency accelerating structures operating at the S and C band can reach gradients up to 30 - 50 MV/m [1], respectively. Higher accelerating gradients, of the order of 100 MV/m, have been obtained with X-band cavities [2]. However, the cost and the availability of RF power sources at high frequency represents a big limitation to this technology [3]. THz-based accelerating structures enable operation at even higher gradient, potentially up to the GV/m scale, using a laser to generate a THz wave instead of a RF power source. In this regard, electron acceleration has been experimentally demonstrated using an optically-generated THz pulse with 10 μ J energy and centered at 450 GHz [4]. Other examples of THz acceleration experiments known in literature can be found in [5, 6, 7].

In this paper, we present electromagnetic and beam dynamics studies about the use of a dielectric loaded waveguide powered by a narrow-band multi-cycle THz wave to accelerate electron bunches.

The geometry studied here for the accelerating structure is a round metal waveguide loaded by a dielectric, as shown in Fig. 1. The electron bunch is injected into the round vacuum



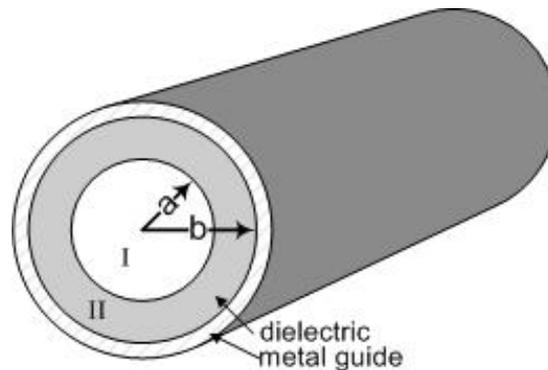


Figure 1. Cylindrical waveguide: the region “I” is a vacuum cylinder of radius a , while the region “II” is a dielectric area with an outer radius b . Picture taken from [8].

channel, coaxial to the waveguide, and accelerated by the longitudinal electric field produced by an external radially-polarized THz pulse coupled to the structure. Here, we do not take into account the process of coupling the THz pulse into the structure. The radially-polarized THz pulse starts from the open end of the waveguide, propagates along it, and after reflection co-propagates with the externally injected electron bunch. The electron bunch enters the structure through an iris whose radius is below one third of the wavelength of the THz pulse. The requirement on the iris radius is needed for the pulse to be totally reflected.

The present study, documented by both electromagnetic and beam dynamics simulations, aims to demonstrate the THz acceleration of high brightness electron beams such those needed to drive a SASE FEL. This research activity is carried out in the framework of the TERA project [9]. TERA, whose acronym stands for THz ERA, aims to build a synergic interdisciplinary collaboration among different INFN groups with the final goal to push forward a strong R&D activity on the technological development in the spectral region (0.3-20 THz), spanning from non-linear optics and laser physics, material science, detectors, and acceleration physics. Concerning advance acceleration concepts, we want to optimize THz-driven accelerating structures based on the achievable parameters of the THz source [10] and focusing on the feasibility of their implementation in the SPARC_LAB facility [11].

In this regard, two working points have been studied, one placing the THz structure at the end of the linac to demonstrate the capability of achieving high quality electron beams able to drive a FEL, the other one right after the gun to study the first stage of a THz linac. In both working points we focused on preserving the high quality of the electron beam in terms of energy spread and normalized transverse emittance, but in the high energy working point we have also paid attention to the transport of a higher, i.e. > 10 pC, charge beam which, to our knowledge, is not reported in literature. The model used for the start-to-end simulations is based on the experiments at SPARC_LAB.

2. Electromagnetic theory and simulations

In particle acceleration application, the monopole mode TM_{0n} is of main interest (particularly the TM_{01}). In a partial dielectric-loaded waveguide, such as the one in Fig. 1, the electromagnetic

fields for the TM_{0n} mode can be written as in Equations 1, 2 and 3 [8]:

$$E_z = \begin{cases} B_1 J_n(k_1 r) e^{j(\omega t - \beta z)} & 0 \leq r \leq a \\ B_2 F_n(k_2 r) e^{j(\omega t - \beta z)} & a \leq r \leq b \end{cases} \quad (1)$$

$$E_r = \begin{cases} -\frac{j\beta}{k_1} B_1 J'_n(k_1 r) e^{j(\omega t - \beta z)} & 0 \leq r \leq a \\ -\frac{j\beta}{k_2} B_2 F'_n(k_2 r) e^{j(\omega t - \beta z)} & a \leq r \leq b \end{cases} \quad (2)$$

$$H_\phi = \begin{cases} -\frac{j\omega\epsilon_0}{k_1} B_1 J'_n(k_1 r) e^{j(\omega t - \beta z)} & 0 \leq r \leq a \\ -\frac{j\omega\epsilon_0\epsilon_r}{k_2} B_2 F'_n(k_2 r) e^{j(\omega t - \beta z)} & a \leq r \leq b \end{cases} \quad (3)$$

with:

$$\begin{aligned} k_1 &= \omega \sqrt{\frac{1}{c^2} - \frac{1}{v_p^2}} \\ k_2 &= \omega \sqrt{\frac{\epsilon_r}{c^2} - \frac{1}{v_p^2}} \\ \beta^2 &= k_0^2 - k_1^2 = \epsilon_r k_0^2 - k_2^2 \\ k_0 &= \frac{\omega}{c} \\ F_n(k_2 r) &= J_n(k_2 r) - \frac{J_n(k_2 b)}{Y_n(k_2 b)} Y_n(k_2 r), \end{aligned}$$

where B_1 and B_2 are the field amplitude in the vacuum and dielectric regions, v_p is the phase velocity of the THz wave and β is the propagation constant. J_n and Y_n are the Bessel functions of order n of the first and second kind respectively, while the apex in the Bessel functions means their derivative with respect to their argument [8]. Applying the boundary condition at $r = a$ (continuity of E_z and H_ϕ), we can derive the dispersion relation and the field amplitude in the dielectric region as a function of the one in the vacuum region as in Eq. 4 and 5, respectively:

$$\frac{1}{k_1} \frac{J'_n(k_1 a)}{J_n(k_1 a)} = \frac{\epsilon_r}{k_2} \frac{F'_n(k_2 a)}{F_n(k_2 a)} \quad (4)$$

$$B_2 = B_1 \frac{J_n(k_1 a)}{F_n(k_2 a)} \quad (5)$$

In the particular case of phase velocity equal to the speed of light, k_1 is equal to 0 and the longitudinal component of the electric field in the vacuum region is radially constant as can be seen in Fig. 2.

To calculate the electromagnetic fields in the structure, the electromagnetic cad simulation software CST-Micro Wave Studio [12] has been used. This suite allows to design the structure and calculate the fields, the propagation constant and other useful parameters (i.e. scattering parameters, losses, cut-off frequency). Here, the goal is the design of a structure that can be used for the acceleration of the beam by mean of a wave with a central frequency of 300 GHz: hence, the structure parameters and the incoming THz power have been adjusted to obtain the desired accelerating field, greater than 100 MV/m. In particular, the dielectric thickness has been optimized to match the phase velocity of the TM_{01} mode to the speed of light.

Figure 3 shows a zoom near the iris of the simulated structure: it can be seen in yellow the copper walls with a thickness of 70 μm and the iris (100 μm radius); the light blue middle layer is a 78.4 μm thick dielectric layer (relative permittivity of 4.41), while the blue inner cylinder is

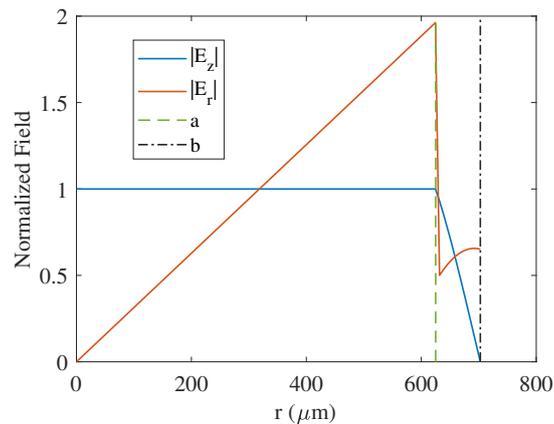


Figure 2. Normalized electric field as a function of the radius r for the TM_{01} mode in the case of phase velocity equal to the speed of light. The dielectric is placed between the 2 vertical dashed line.

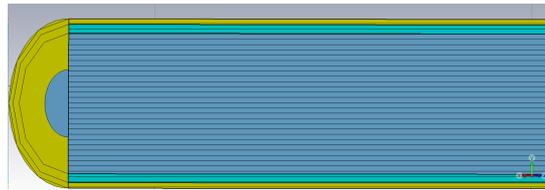


Figure 3. Details of the simulated structure. The yellow outer walls are made of copper; the light blue middle layer is a dielectric while the inner cylinder is vacuum. The structure has an overall length of 10 cm.

the vacuum pipe (624.3 μm radius). CST allows to define different type of excitation signal to simulate the incoming THz pulse: here, a flat-top 133 ps FWHM profile is used.

The simulation gives a TM_{01} mode with a peak longitudinal field of 240 MV/m assuming a THz pulse energy of about 45 mJ (see Fig. 4). The phase velocity at 300 GHz is close to the speed of light ($v_p = 0.999994c$).

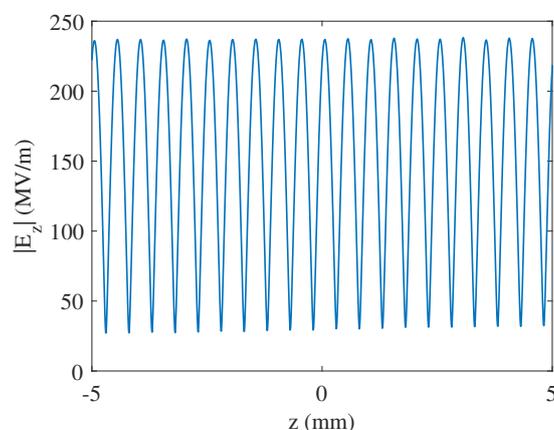


Figure 4. Profile of the module of the longitudinal component of the electric field; here, only 1 cm is shown.

Finally, the 3D field map has been imported in GPT [13] (General Particle Tracer) for beam dynamics simulations.

3. Beam dynamics simulation

Beam dynamics simulations are performed with the simulation code GPT. A first series of simulations is related to a simple configuration with a BNL/SLAC/UCLA type 1.6 cell RF gun [14, 15] with a 120 MV/m peak gradient, a solenoid magnet and the THz structure defined in the previous section placed at 605 mm from the cathode. In literature, different studies regarding electron acceleration and beam manipulation in THz-driven structures are available [16, 17, 18, 19]. A low charge beam (10 pC) in the blow out regime [20] has been considered for the low energy case. The photo-cathode laser has a flat-top profile both in the transverse and in the longitudinal plane. In particular, the transverse radius is 0.94 mm and the laser duration is 72 fs, both the values are Full Width Half Maximum (FWHM). The resulting beam parameters are summarized in Tab. 1.

Table 1. Beam parameters at the entrance and at the exit of the THz structure placed at 605 mm from the cathode.

Beam Parameter	Entrance	Exit
Charge (pC)	10	10
Mean Beam Energy (MeV)	6	21
RMS Relative Energy Spread	0.8%	0.7%
RMS Beam Spot (μm)	25	27
RMS Bunch Length (μm)	20	21
Normalized Beam Emittance ($\text{mm} * \text{mrad}$)	0.76	0.78

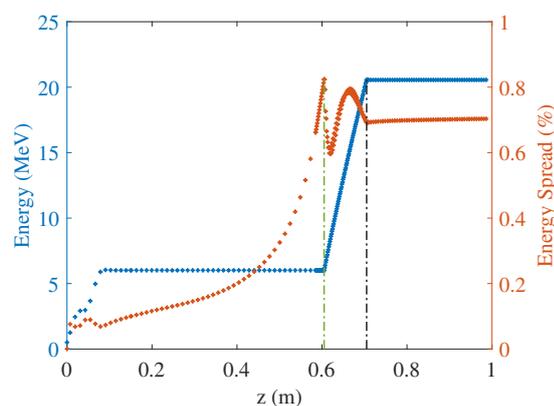


Figure 5. Mean Beam energy (blue) and RMS relative energy spread (red) from the cathode to the exit of the THz structure. The dashed lines represent the beginning (green) and the end (black) of the THz structure.

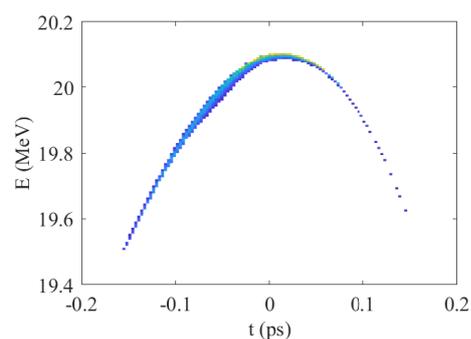


Figure 6. Longitudinal phase space at the exit of the THz structure.

Figures 5 and 6 show the simulation results. The photo-cathode laser parameters, e.g. length and transverse spot size, have been chosen to optimize the final energy spread. Indeed, the beam injected in the THz structure gains about 15 MeV, corresponding to an average gradient

of 145 MV/m, with a relative energy spread of 0.7%. Furthermore, also a change of the phase velocity allows some improvements with the relative energy spread and the longitudinal compression. Here, the phase velocity has been changed from $0.999994c$ to $1.003c$ adjusting the injection phase to maximize the final beam energy. The results of the simulations show an improvement in the relative energy spread and in the bunch length around 30%: from 0.7% to 0.4% and from 21 μm to 14 μm , respectively. However, this comes at the expense of the achievable accelerating gradient (the average gradient seen by the beam along its path) that goes from 145 MV/m to 85 MV/m. This is due to the relatively low injection energy of the beam (6 MeV) which leads to significant phase slippage respective to the accelerating field [21]. Indeed, with an injection beam energy of 100 MeV, the results in terms of energy spread and bunch length do not change for the two phase velocities.

A limitation of the proposed scheme is the amount of charge that can be accelerated since the beam at the entrance of the THz structure is not enough relativistic [4, 22]. To overcome this limitation, an already relativistic high charge beam (100 pC) coming from a high brightness electron linac in velocity bunching configuration [23] has been used as input beam. Here, the SPARC-LAB linac [11] has been used as a reference, while the structure has been placed at about 12 m from the cathode. In this working point, the laser duration is set to 6 ps while the transverse radius is 0.51 mm. Both values are FWHM and the profile is flat-top both in the transverse and longitudinal plane. In order to ease the requirements on the beam transport, an

Table 2. Beam parameters at the entrance and the exit of the THz structure placed at 11.88 m from the cathode.

Beam Parameter	Entrance	Exit
Charge (pC)	100	100
Mean Beam Energy (MeV)	116	130
RMS Relative Energy Spread	0.6%	0.5%
RMS Beam Spot x(y) (μm)	61 (41)	23 (33)
RMS Bunch Length (μm)	25	25
Normalized Beam Emittance x(y) (mm * mrad)	0.84 (0.88)	1.02 (0.82)

iris radius of 300 μm has been chosen. This does not impact significantly the peak gradient since the radius is still less than a third of the wavelength [24]: indeed, with an iris radius below this limit, the reflection coefficient envelope is almost flat and well above 0.99 [24]. Table 2 shows the initial beam parameters. The results are shown in Figures 7 and 8: the beam exits the THz structure with an energy of 130 MeV (accelerating gradient of 142 MV/m). In this case, some transverse focusing can be observed at the end of the acceleration with a transverse spot at the exit of 23 μm in the horizontal plane and of 33 μm in the vertical plane. However, due to the space charge forces, the beam explodes transversely soon after the end of the device. Hence, recapture schemes have to be studied to be able to use the beam for some experiments or a second stage of acceleration.

A relative beam energy gain around 10% may not seem appealing, especially compared to the working point showed before. However, many applications require the charge or the current as the main parameter to be maximised (i.e. FEL applications [25]). This study shows the feasibility of the acceleration and optimization of a high charge high brightness beam with this novel scheme of acceleration.

4. Conclusion

A possible scheme for terahertz-based acceleration of high brightness electron beams has been shown. The accelerating structure has been characterized both from a theoretical point of view

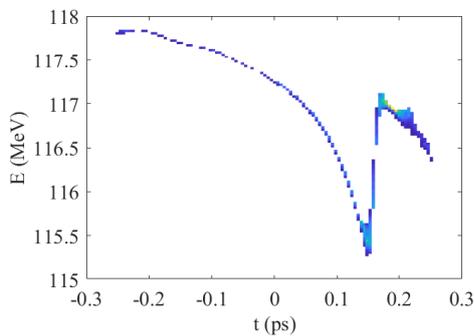


Figure 7. Longitudinal phase space at the entrance of the THz structure.

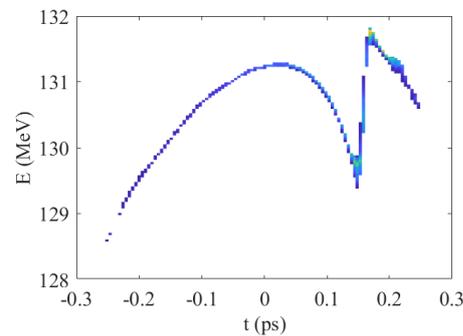


Figure 8. Longitudinal phase space at the exit of the THz structure.

and by means of electromagnetic simulations. The resulting 3D electromagnetic fields have been used to perform beam dynamics simulations with GPT.

The possibility to achieve high gradient acceleration without degrading the overall beam qualities both in the case of a low charge low energy input beam and in the case of an high charge already relativistic input beam has been shown.

More studies need to be done, especially regarding the technical feasibility and limitations of the proposed scheme.

Furthermore, the beam transport after the acceleration has to be studied in order to prepare the beam for FEL applications [25], for instance, and/or multi-stage acceleration scheme.

Acknowledgments

This work has been performed in the framework of the TERA project, funded by the 5th Scientific National Committee of INFN.

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 653782.

References

- [1] D. Alesini *et al.*, "Design of high gradient, high repetition rate damped c-band rf structures," *Physical Review Accelerators and Beams*, vol. 20, p. 032004, 2017.
- [2] A. Degiovanni *et al.*, "High-Gradient test results from a CLIC prototype accelerating structure," CERN, Tech. Rep. CERN-ACC-2014-0147. CLIC-Note-1042, Jun 2014.
- [3] R. Carter, "Rf power generation," *arXiv preprint arXiv:1112.3209*, 2011.
- [4] E. A. Nanni *et al.*, "Terahertz-driven linear electron acceleration," *Nature communications*, vol. 6, p. 8486, 2015.
- [5] E. Curry *et al.*, "Meter-scale terahertz-driven acceleration of a relativistic beam," *Physical review letters*, vol. 120, p. 094801, 2018.
- [6] M. T. Hibberd *et al.*, "Acceleration of relativistic beams using laser-generated terahertz pulses," *arXiv preprint arXiv:1908.04055*, 2019.
- [7] D. Zhang *et al.*, "Femtosecond phase control in high-field terahertz-driven ultrafast electron sources," *Optica*, vol. 6, pp. 872–877, 2019.
- [8] C. Jing *et al.*, "Dielectric wakefield accelerator to drive the future fel light source." Argonne National Lab.(ANL), Argonne, IL (United States), Tech. Rep., 2011.
- [9] "TERA project," <http://www.lnf.infn.it/rapatt/2019/TERA.pdf>.
- [10] V. Dolci *et al.*, "Characterization of optical properties of organic crystals required by high energy thz pulse generation for thz particle accelerators," in *these proceedings*, 2020.
- [11] M. Ferrario *et al.*, "SPARC-LAB present and future," *Nuclear Instruments and Methods in Physics Research Section B*, vol. 309, pp. 183–188, 2013.

- [12] “CST Micro Wave Studio,” <https://www.3ds.com/products-services/simulia/products/cst-studio-suite/>.
- [13] “General Particle Tracer,” <http://www.pulsar.nl/gpt/>.
- [14] J. Fraser *et al.*, “A new high-brightness electron injector for free electron lasers driven by rf linacs,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 250, pp. 71–76, 1986.
- [15] B. E. Carlsten, “New photoelectric injector design for the los alamos national laboratory xuv fel accelerator,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 285, pp. 313–319, 1989.
- [16] F. Lemery *et al.*, “Synchronous acceleration with tapered dielectric-lined waveguides,” *Physical Review Accelerators and Beams*, vol. 21, p. 051302, 2018.
- [17] T. Vinatier *et al.*, “Simulation of a concept for a compact ultrafast x-ray pulse source based on rf and thz technologies,” *Journal of Applied Physics*, vol. 125, p. 164901, 2019.
- [18] A. Healy *et al.*, “Electron-terahertz interaction in dielectric-lined waveguide structures for electron manipulation,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 909, pp. 199–203, 2018.
- [19] K. Galaydych *et al.*, “Beam dynamics and tolerance studies of the thz-driven electron linac for the axisis experiment,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 909, pp. 181–184, 2018.
- [20] O. Luiten *et al.*, “How to realize uniform three-dimensional ellipsoidal electron bunches,” *Physical review letters*, vol. 93, p. 094802, 2004.
- [21] T. Vinatier *et al.*, “Beam dynamics in thz dielectric-loaded waveguides for the axisis project,” in *Journal of Physics: Conference series*, vol. 874, no. 1. IOP Publishing, 2017, p. 012042.
- [22] L. J. Wong *et al.*, “Compact electron acceleration and bunch compression in thz waveguides,” *Optics express*, vol. 21, pp. 9792–9806, 2013.
- [23] L. Serafini *et al.*, “Velocity bunching in photo-injectors,” in *AIP conference proceedings*, vol. 581, no. 1. AIP, 2001, pp. 87–106.
- [24] K. Galaydych *et al.*, “Simulation of an electromagnetic field excitation by a thz-pulse and acceleration of an electron bunch in a dielectric-loaded axisis linac,” in *8th International Particle Accelerator Conference*, 2017.
- [25] L. Giannessi *et al.*, “Self-amplified spontaneous emission for a single pass free-electron laser,” *Phys. Rev. ST Accel. Beams*, vol. 14, p. 060712, Jun 2011.