COMPACT ELECTRON INJECTORS USING LASER DRIVEN THz CAVITIES

M. Fakhari[*], A. Yahaghi, D. Zhang, C. Zhou, G. Vashchenko, T. Viantier, K. Galaydych, U. Dorda,
B. Marchetti, R. Aßmann, A. Fallahi, N. Mathlis, F. Kärtner[1,2]

Deutsches Elektronen-Synchrotron, Hamburg, Germany

[1]also at The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg

[2]also at Department of Physics, University of Hamburg, Jungiusstrasse 9, 20355 Hamburg

Abstract

We present ultra-small electron injectors based on cascaded cavities excited by short multi-cycle THz signals. The designed structure is a 3.5 cell normal conducting cavity operating at 300 GHz. This cavity is able to generate pC electron bunches and accelerate them up to 250 keV using less than 1 mJ THz energy. Unlike conventional RF guns, the designed cavity operates in a transient state which, in combination with the high frequency of the driving field, makes it possible to apply accelerating gradients as high as 500 MV/m. Such high accelerating gradients are promising for the generation of high brightness electron beams with transverse emittances in the nm-rad range. The designed cavity can be used as the injector for a compact accelerator of low charge bunches.

INTRODUCTION

Particle acceleration is fulfilled using radio-frequency (RF) cavities in the most conventional accelerators It is well-known that RF acceleration schemes suffer from large energy consumption for applications requiring only low charge bunches. The last decades have witnessed extensive efforts to increase the efficiency of RF cavities which have led to enormous progress in this technology. Engaging higher accelerating gradients for instance, makes it possible to produce beams with higher quality in conjunction with less power consumption and manufacturing expenses. Further improvements however, are mainly limited by the damage thresholds of metallic surfaces. There exist several mechanisms through which the structure of an accelerator is damaged, including thermal melting, mechanical stress, electron field emission, and magnetic pulsed heating. The last two effects seem to be the main obstacles for the implementation of high-frequency compact accelerators.

It has been empirically demonstrated that the breakdown threshold due to field emission scales as $f^{1/2} \cdot \tau^{-1/4}$, where f is the operation frequency and τ is the pulse duration [1]. Employing frequencies beyond V-band has therefore the potential to open new horizons in accelerator technology. Considering that ultrafast near infrared (NIR) lasers offer multi-GV/m accelerating gradients based on chirped pulse amplification, optical acceleration seems to be a very promising choice for acquiring compact accelerator devices. The THz frequency range offers an appropriate compromise between the low accelerating gradient of the RF regime and short wavelengths of the optical signals [2]. It is experimentally demonstrated that in frequencies around 100 GHz the breakdown limits can be pushed to a few GV/m for nanosecond pulse durations. Moreover, the tight limitations on charge per bunch are strongly relaxed; for instance 1° phase precision in 300 GHz, corresponds to 10 fs bunch length which allows the acceleration of hundreds of fC to a few of pC electron bunches. Applying high accelerating gradients at the GV/m level in THz injectors prevents emittance growth of the electron bunches immediately after their generation. In a THz gun electrons become relativistic after traveling a smaller distance compared with their RF counterparts. Therefore, space charge forces have less time to influence the bunch emittance and deteriorate the beam quality. There exists another remarkable advantage in using laser-driven THz generation for electron acceleration. Recent progress in laser driven THz generation provides the possibility to use one single optical seed to generate the input THz signal as well as the UV pulse for the photo emission process. Hence, tight synchronization between the electron bunch and the accelerating electric field can be fulfilled well below one femtosecond. In addition, problems caused by laser drifts, which are common sources disturbing the synchronization, are largely suppressed. Here, we present how the concept of cascaded cavities can be tailored to inject and accelerate electron bunches using multi-cycle laser-driven THz pulses. A four cell photo cathode electron gun operating at 300 GHz has been designed as the electron injector. The design precess and considerations are explained in Section II. Section III is devoted to the electromagnetic as well as the beam dynamics simulations of the designed cavity.

CAVITY DESIGN

In this section, we present the design of a four cell cavity to be used as a THz gun. Figure 1 shows a cross sectional view of the designed cavity. The operating mode is the TM_{010} π-mode with operation frequency at 300 GHz. The on-axis electric field is 500 MV/m and the ratio of peak electric field to the accelerating field (E_{peak}/E_{acc}) is 3 that means a maximum electric field of 1.5 GV/m which is below the damage threshold of copper in this frequency and pulse length. In order to synchronize the electrons with the electric field, the lengths of the cells should be equal to the distance that electrons fly in each cycle. In the first cycles, electrons velocity is very sub-relativistic and therefore the traveling
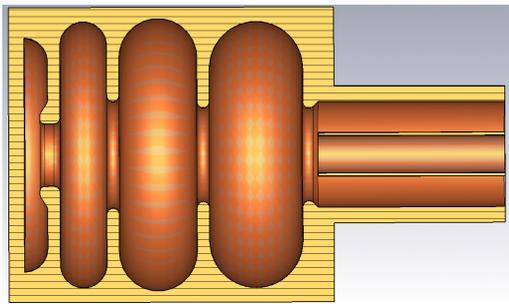
---

* moein.fakhari@desy.de

Figure 1: Cross sectional view of the designed three and half cell gun.

Figure 2: Door knob waveguide-coaxial adapter.

Figure 3: Schematic view of the designed gun with its coupler and UV laser.

distances in the first cycles are shorter than the next cycles. Considering a sinusoidal spatial and temporal distribution of the electric field along the axis of the cavity, it is possible to calculate the distances that electrons traverse in each cycle to find the optimum length of the cells. In the designed cavities, these lengths are found to be $75\,\mu m$, $150\,\mu m$, $250\,\mu m$ and $300\,\mu m$ from the first to the last cell. Due to the extremely small dimension of the first cell, high Lorentz forces are exerted on the walls of the cavity around the first cell. In order to overcome this problem a nose cone iris is designed to decrease the surface currents and to increase the distance between the cavity walls. However, the nose cone iris for the first cell reduces the field strength in this cell. Therefore, in order to keep the electric field of the first cell equal to the other cells its radius is decreased, which can also be seen in Fig. 1. The radius of the iris between the first two cells is also less than other iris radii.

Coupling the input power to the cavity is a big challenge in our design. Since the amount of THz energy that we can use is seroiusly limited, we would like to operate the cavity at the end of threb transient state and nopt in the seady state. Therefore we have to design the coupler in such a way to minimize the energy that is needed to load the cavity. According to [3] the optimum coupling constant between the cavity and its input coupler depends on the unloaded quality factor of the cavity which for the designed cavity should be around 1.7. There are several methods to couple the generator power to the cavity, including side-coupling and on-axis injection of the power. However, side-coupling removes the cylindrical symmetry of the cavity and increases the beam emittance, making the axial coupling the superior choice for the gun. For axial injection of the power to the cavity, one can use a coaxial cable whit a beam pipe inside the inner conductor of the cable (Fig. 1). Next step is to design a waveguide-coaxial adapter to convert the waveguide mode to the TEM mode of a coaxial cable. In this respect, we have designed a so called door-knob adapter which is shown in Fig. 2. It is possible to adjust the transmission efficiency by changing the distance between the door knob shaped conductor and the closed end of the waveguide. In order to change the coupling between the coupler and the cavity, changing the longitudinal position of the inner tube in the coaxial line or changing the opening iris of the outer
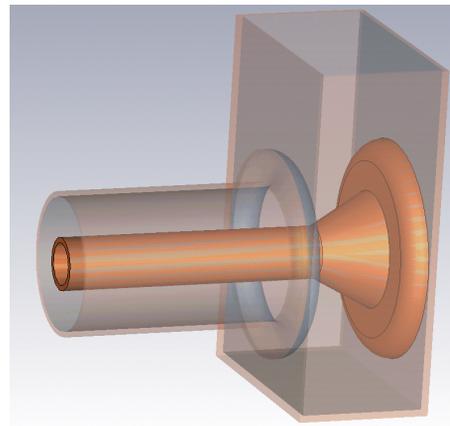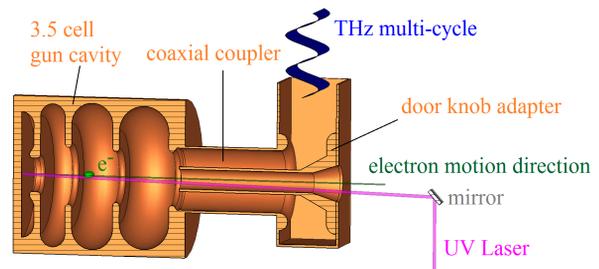
tube can be followed. Using such couplers also reduces the magnetic field in the coupler region which leads to a considerable reduction in pulsed heating. Figure 3 shows a schematic view of the cavity together with its coupler, waveguide to coaxial adapter and the UV laser for the photo emission process.

SIMULATION RESULTS

According to the simulation results obtained with CST Microwave Studio [4], the unloaded and external quality factor of the designed cavity are 900 and 500 respectively, which means a coupling constant of 1.8, being close to the optimum coupling constant. In order to find the number of the THz cycles needed to fill this cavity and consequently the amount of required energy, transient simulation has been performed for the designed cavity with its coupler. The transient evolution of the longitudinal field at the center of the fourth cell on the axis of the cavity for a 1 MW input power is shown in Fig. 4. According to the transient results after about 1 ns the cavity reaches the steady state level, meaning that a THz energy of 1 mJ within 300 cycles is required for the desired operation.

Electron bunch acceleration is also simulated using AS-TRA [5]. We study the longitudinal and transverse dynamics of the electron bunches to gain an intuition about the beam quality at the end of the gun as well as after the accelerating components. The photo emission process for generating the electrons is simulated using the ASTRA model. 10'000
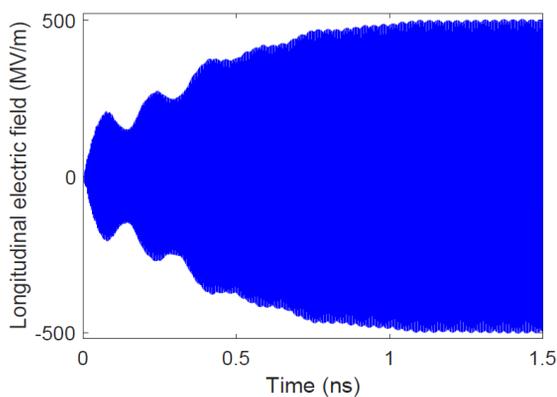
Figure 4: Time domain simulation for on-axis longitudinal electric field at the center of the fourth cell for the input power equal to 1 MW.
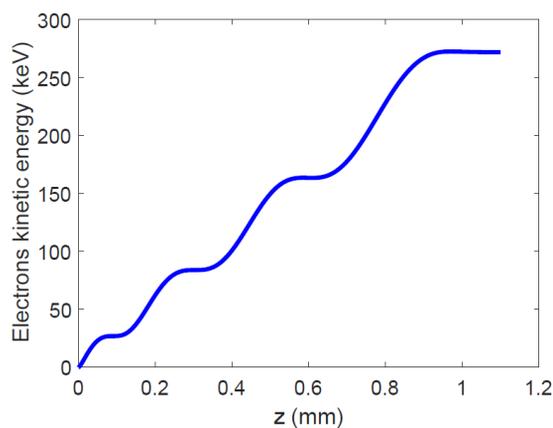

Figure 6: Transvere emittance (red) and RMS bunch length (blue) of the bunch at the gun exit for different spot sizes.

Figure 5: Particle acceleration in the designed gun.

with the output of laser-driven THz generation schemes. A four cell gun is designed to increase the electron energy up to 250 keV. Coaxial couplers with the so-called door-knob adapters are used to inject the THz power into the cavities. The coupling constant between the cavities and their couplers are adjusted to minimize the required THz energy for cavity loading. The gun require 1 mJ within 300 cycles. With this gun it is possible to achieve bunches as short as 10 um with transverse emittance of 30 nm rad.

ACKNOWLEDGMENT

macro-particles with a total charge of 100 fC are injected from the cathode located at the end plate of the gun and accelerated along the axis. Figure 5 shows the simulation results for the average kinetic energy of the particles inside the gun, in which the four steps of acceleration corresponding to the four cells are clearly observed. The final energy of the particles is about 250 keV with an RMS energy spread of 1 keV. According to the simulation, the transverse beam emittance is 0.3π mm mrad and the RMS bunch length is $2 \mu m$ which corresponds to a 10 fs bunch.

By decreasing the spot size, it is possible to decrease the transverse emittance down to few nm rad at the expense of an increase in bunch length. Figure 6 shows the trade-off between the transverse emittance and bunch length at the gun exit as a function of spot size. Form these curves a spot size around $25 \mu m$ seems to be the best choice.

CONCLUSION

In this paper we introduced the design procedure for an electron gun using THz pulses with 300 cycles, which match
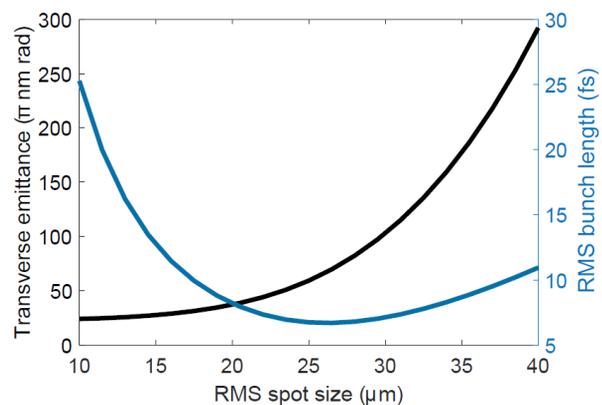
REFERENCES

[1] J.W. Wang and G.A. Loew, "Rf breakdown studies in copper electron linac structures," in *Proc. IEEE 1989 Particle Accelerator Conference (PAC'89)*, Chicago, IL, USA, Mar. 1989, pp. 1137–1139.

[2] A. Fallahi, M. Fakhari, A. Yahaghi, M. Arrieta, and F. X. Kärtner, "Short electron bunch generation using single-cycle ultrafast electron guns," *Physical Review Accelerators and Beams*, vol. 19, p. 081302, 2016.

[3] M. Fakhari, A. Fallahi, and F. X. Kärtner. "THz cavities and injectors for compact electron acceleration using laser-driven THz sources," *Physical Review Accelerators and Beams* 20.4 (2017): 041302.

[4] CST - Computer Simulation Technology, 2016, `https://www.cst.com/`

[5] Klaus Floettmann. "ASTRA: A Space Charge Tracking Algorithm," Manual, Version 3, 2011.