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START-TO-END SIMULATIONS OF A THz-DRIVEN ICS SOURCE

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Abstract

We present start-to-end simulations for a fully THz-driven table-top X-ray source. A 1-pC electron bunch is generated via photo emission from a copper cathode embedded in a dielectric-loaded metallic cavity where the emitted electrons are accelerated up to 430 keV average kinetic energy. Instead of the conventionally used fundamental mode, a higher order mode (HOM) of the cavity (TM_{012} mode) at 300 GHz is used in order to keep the electrons phase matched with the oscillating THz field inside the gun.

The output beam of the gun is injected into a dielectric-loaded metallic waveguide operating as a linear accelerator. The phase velocity of the traveling wave inside the linac is adjusted in such a way that electrons see an accelerating field all the way along the tube resulting to an 18.5-MeV output beam which is then transported to an inverse Compton scattering (ICS) stage. The injection phase of the electrons into the linac can be tuned to introduce a negative longitudinal energy chirp to the electron bunch leading to a ballistic bunch compression after the linac. In addition to the longitudinal compression a set of permanent magnet quadrupoles (PMQ) is designed to focus the beam transversely at the ICS interaction point where the electron beam scatters off a 100-mJ, 1-µm laser beam and generates an X-ray beam with 2.6×10^7 photons per shot containing photon energies 2 keV < E_{ph} < 8 keV in a beam with 50 mrad half opening angle.

The required terahertz waves to power the gun and linac are 550-ps pulses at 300 GHz containing 5 mJ and 23 mJ energies respectively. These THz pulses can be generated using difference frequency generation (DFG) of two 1 J laser beams. Since all of the components in the proposed X-ray source are driven by the same 1-µm laser technology, it offers the unique possibility of inherent synchronization.

INTRODUCTION

Over the past decades demands for compact X-ray radiation sources have grown considerably due to their vast applications. Shrinking accelerator-based X-ray sources can be achieved either by making the accelerator and/or the undulator section compact. Operating at high frequencies, e.g. THz range, allows applying higher accelerating gradients which leads to high energy particles over a shorter distance [1, 2]. On the other hand, using optical undulators makes it possible to get X-ray radiation with relatively low energy electrons (few MeV range) due to their much shorter undulator period compared with permanent magnet undulators, of course at the expense of larger opening angles [3]. Here we introduce a THz driven Inverse Compton Scattering (ICS) source which layout is schematically illustrated in Fig. 1. Electrons are generated via photo emission from a metallic cathode embedded in a THz cavity operating at on of its higher order modes. The cavity delivers electrons with above 430 keV average kinetic energy. The electrons then traverse through a dielectric-loaded metallic waveguide, which operates as a linear accelerator (linac) and boosts the electron energy up to 18.5 MeV. A set of quadrupole magnets is used to focus the electron bunch and transport it to the ICS interaction section.

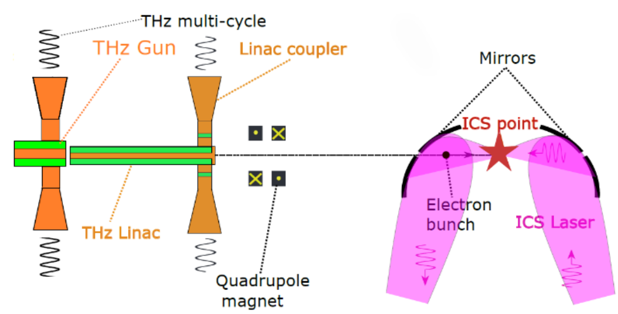

Figure 1: Schematic layout of the THz-driven compact X-ray source.

THz INJECTOR

Here, we introduce a THz gun which consists of a dielectric loaded cylindrical cavity operating at one of its higher order modes (HOM) to ensure that electrons are continuously phase matched with the oscillating electric field [4]. Figure 2 schematically illustrates the HOM gun, which consists of the main cavity and its horn coupler. The cavity itself is a cylindrical copper cavity loaded with quartz (electric permittivity of 3.85 at 300 GHz). A cross sectional view of the electric field distribution at the operating mode is also depicted in Fig. 2. The ASTRA particle tracking code [5] is used to simulate the acceleration of the 1-pC electron bunch in the gun. A 47-fs FWHM UV pulse is assumed to illuminate the cathode with a spot size of 70 µm (FWHM). Considering 5 mJ injected THz energy, the peak electric field on the axis of the gun becomes 1.4 GeV which accelerates the electrons up to 435 keV. On the other hand, the transverse field of the coupler region, focuses the beam exiting the gun to below 3 µm at a distance of 2.5 mm from the cathode. The output normalized transverse emittances are evaluated as 87 nm rad in both x and y directions, while the longitudinal emittance is 14 nm rad. The results of the ASTRA simulations are shown in Fig. 3.

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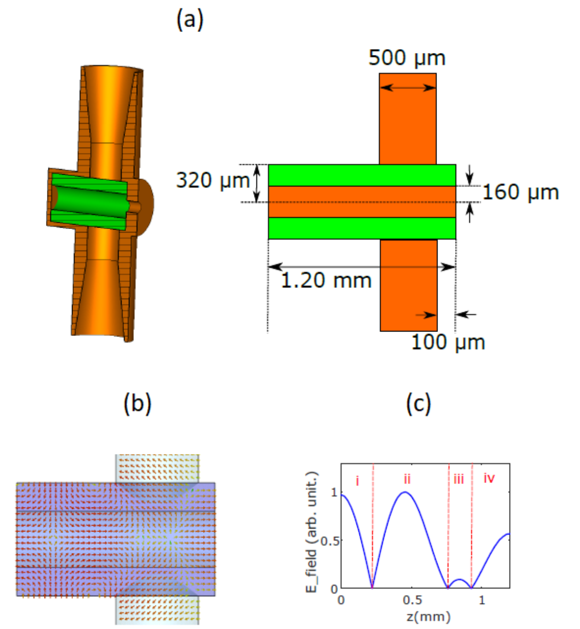

Figure 2: (a) schematic illustration of the HOM gun. (b) field distribution and (c) electric field on the axis of the gun. It consists of three accelerating regions (i, ii, iv) and one focusing stage (region iii).

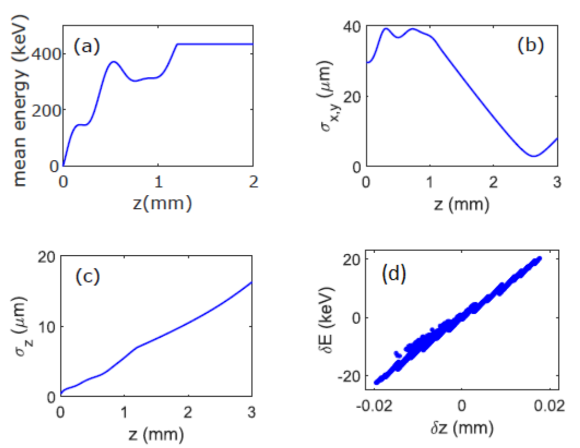

Figure 3: Simulation results of the THz injector: (a) bunch mean total energy (b) rms bunch transverese size (c) rms bunch lengths, and (d) beam distribution in longitudinal phase space.

THz LINAC

Acceleration of particles with an electromagnetic wave is possible if and only if the particle velocity is synchronized with the field variations of the wave. In order to achieve such synchronization, one has to decrease the phase velocity of the wave inside the waveguide. In THz regime it would be much simpler to adjust the phase velocity by loading the metallic waveguide with a dielectric layer as shown in Fig. 4. The electrons enter the gun with an average kinetic energy of 435 keV which is equivalent to a normalized velocity of $\beta = 0.84$. The electrons shall be accelerated to a final energy of about 18.5 MeV, corresponding to the final velocity of 99.96% of the speed of light. Therefore, it wouldn't be possible to keep the electrons synchronized with the travelling wave inside the waveguide throughout the whole linac. The solution to this problem is to set the phase velocity slightly les than the final expected velocity of the electrons and inject the electrons at a phase between $\pi/2$ and π. Table 1 shows the designed parameters of the THz linac.

Table 1: The Designed Parameters of the THz Linac

Parameter	Designed Value
Quartz inner radius	221 μm
Quartz outer radius	360 μm
Tube length	8 cm
Frequency	300 GHz
Phase velocity	0.993 c
Group velocity	0.281 c
Attenuation constant	6.2 m^{-1}
THz pulse energy	23 mJ
THz pulse duration	550 ps
On-axis field	380 MV/m

The electron bunch exiting the linac needs to be focused into the ICS interaction point, which is achieved by a quadrupole set after the linac that is also shown in Fig. 1. The quadrupole magnets should be located at 51 cm and 65 cm distance from the linac entrance with gradients of 40 T/m and 90 T/m respectively.

Beam dynamics simulations of the linac are done with ASTRA. The output bunch of the gun is injected to the linac in a proper phase to have a reasonable energy spread as well as bunch compression due to velocity bunching after the tube.

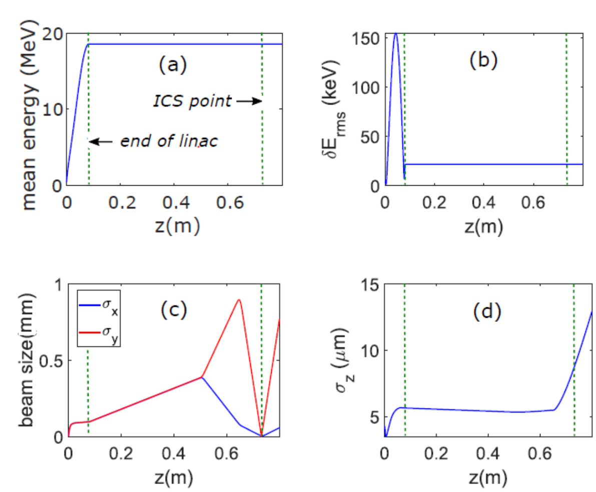

Figure 4: ASTRA simulation results for the linac: (a) average kinetic energy, (b) energy spread, (c) transverse size, and (d) bunch length.

Figure 4 shows the simulation results. The bunch exiting the linac enters the focusing lattice which reduces the transverse size down to 4.7 μm × 3.8 μm at a distance 73.2 cm away from the linac entrance.

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INVERSE COMPTON SCATTERING

The ICS simulation consists of two processes: laser-particle interaction and radiation emission. The electron motion is modelled by solving the relativistic equations of motion for charged particles. Space charge effects are neglected in the ICS simulations, although they are considered in the bunch acceleration section. This assumption originates from the very short interaction length of the electrons with the counter-propagating beam, over which space charge forces cause negligible changes in the motion of particles.

Table 2 presents the electron bunch properties as well as the assumed laser beam parameters for the X-ray source.

Table 2: Parameters of the ICS Process

Parameter	Designed Value
Electron bunch parameters	
σ_x, σ_y (rms)	4.7 µm, 3.8 µm
σ_z (rms)	9.1 µm
Mean kinetic energy	18.4 MeV
Rms energy spread	21 keV
Rms emittance (ε_x, ε_y)	(0.15, 0.58) mm mrad
ICS laser parameters	
Wavelength	1 µm
Pulse duration	1.0 ps
Spot size	20 µm
Pulse energy	100 mJ

In Fig. 5, the final output of the designed X-ray source is shown in form of the normalized energy spectrum of the emitted photons on an assumed detector located 6 mm away from the ICS interaction point. The total number of photons (N_{ph}) corresponding to each spectrum are also indicated in each figure. Here, the divergence angle is defined as the half angle of the radiation cone. As usual for an ICS spectrum, the bandwidth of the radiated X-ray increases with the captured solid angle. As a result, the total amount of photons generated depends on the solid angle considered for the X-ray beam. The number of photons generated between 2 keV and 7 keV energy range within a radiation cone with 50 mrad angle is calculated as 2.35 $\times 10^4$ photons. This amount reduces if smaller acceptance angles are considered.

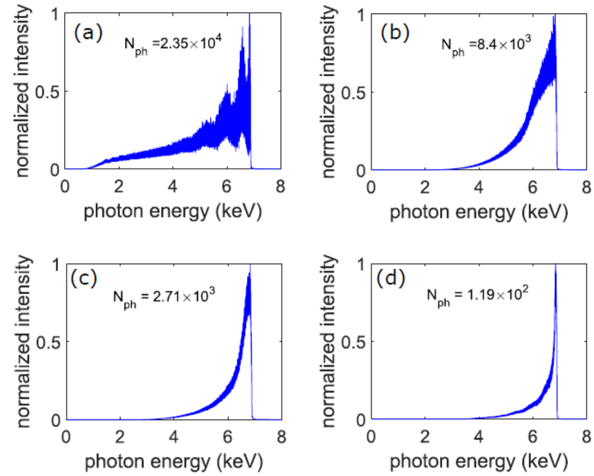

Figure 5: The normalized spectrum of the radiated X-ray beam captured within divergence angle (a) 50 mrad, (b) 10 mrad, (c) 5 mrad, and (d) 1 mrad.

CONCLUSION

In conclusion, we have presented a start-to-end simulation for a compact THz-driven x-ray source, delivering $\sim 10^5$ photons per shot cantered around $\sim$ 6.5 keV. The injector and the linear accelerator are both fed by THz pulses which are generated from a 1µm laser source which can also be used for the inverse Compton scattering process. The use of completely laser-driven schemes in the x-ray source enables synchronization of all involved elements to sub-femtosecond precision.

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