PROGRESS ON DEVELOPMENT OF AXSIS: A FEMTOSECOND THz-DRIVEN MeV ACCELERATOR AND keV X-RAY SOURCE

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Abstract

We report on the design and progress on construction of a first prototype demonstrating the concept of a THz-driven relativistic electron accelerator and an associated X-ray source. The nascent technology of THz-driven acceleration offers several key advantages over conventional accelerators, including order-of-magnitude increases in driving field, to the GV/m range; short, mm-scale wavelengths enabling ultra-high-gradient manipulations of electrons, as well as a compact foot print. Combined, these features enable electron sources with unique capabilities, including sub-10 fs bunch durations and intrinsic synchronization to laser source resulting in the capability to create electron and diffraction instruments of exceptional temporal resolution beyond the state of the art. Our machine is designed to reach 20 MeV electrons, using several-mJ pulses of THz radiation generated via nonlinear down conversion of customized lasers, and X-rays in the few keV range will be created by counter-propagating them with an "optical undulator" laser.

INTRODUCTION

The development of an electron acceleration technology driven by terahertz radiation (THz) [1,2,3,4] brings unique advantages for creation of electron and light sources with properties that are well adapted for studying material structure and dynamics on atomic scales at the limits of temporal and spatial resolution. In particular, the short wavelength of THz waves enables the possibility of sustaining electric and magnetic fields as well as field gradientsorders of magnitude higher than those in conventional accelerators yielding strong acceleration and manipulation electron beams. Over the last decade, THz-driven accelerator technology has emerged from a novelty to a fast-growing research field aimed at exploring the benefits not only for fully THz-driven accelerators and associated light sources, but also for performing high-field manipulations of electrons in conventional accelerator systems. Recent

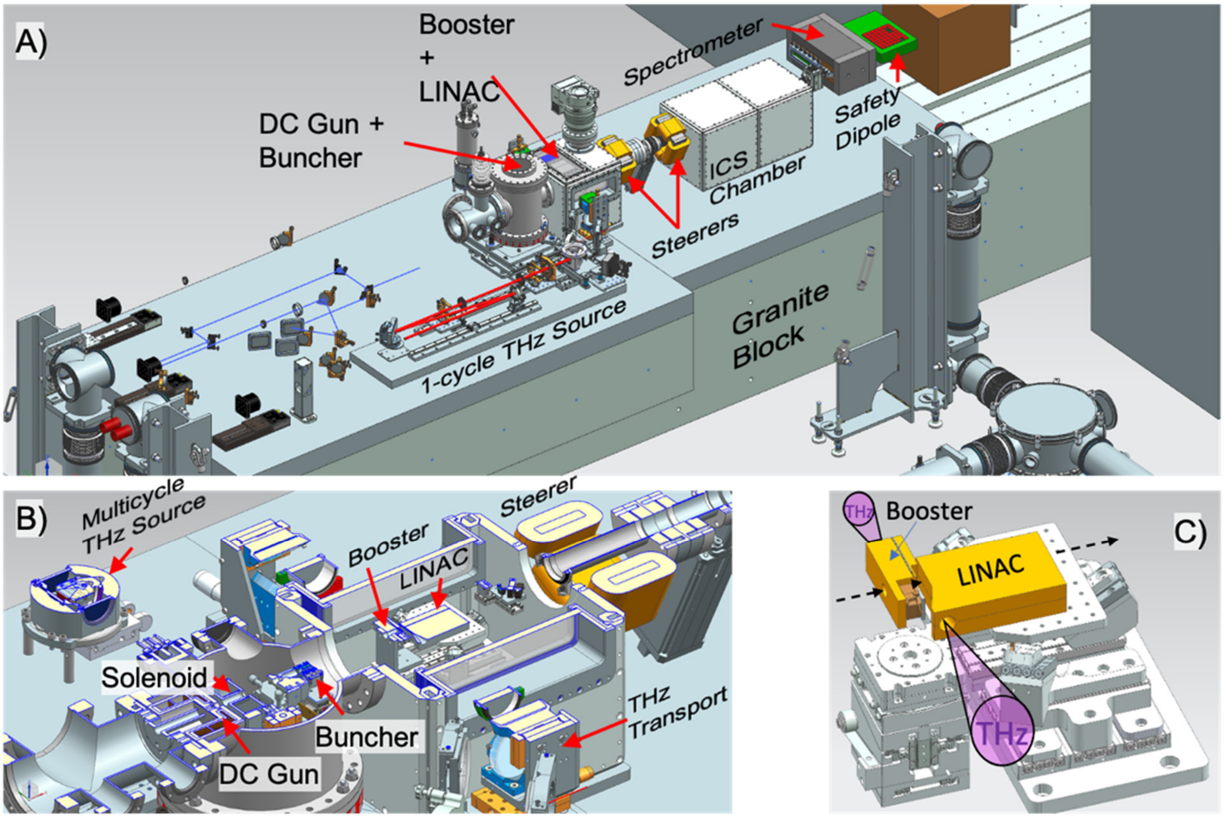

Figure 1: (A) 3D CAD Layout of the AXSIS THz-Driven X-ray Light Source Prototype. (B) Detail of the THz-Accelerator. (C) THz-driven Booster and LINAC.

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successes include demonstration of THz-driven photogun sources producing keV electrons [3,5]; versatile THz acceleration and manipulation modules capable of multiple beam manipulations, including acceleration, streaking, compression and focusing with ultra-high fields [6]; staging of multiple linear accelerator modules [7], post acceleration of multi-MeV electrons from an RF source, and enhancement of bunch duration and overall temporal resolution in ultrafast electron diffraction instruments [8]. This growing body of work is serving to demonstrate not only that THz-driven accelerator technology is viable, but also that it can provide unique capabilities in strong-field control of electrons at a fraction of the cost of conventional analogues, with a diverse range of applications. These early successes are therefore setting the stage for more ambitious achievements based on this technology. The Attosecond X-ray Science – Imaging and Spectroscopy (AXSIS) project [1], aims to develop a fully THz-powered electron accelerator to serve as a source of ultrashort electrons for direct application to ultrafast electron diffractometry, as well as for generation of ultrashort pulses of X-rays pushing the limits of temporal resolution to the attosecond regime.

Fig. 1 shows the design of a first prototype of the AXSIS light source. Electrons sourced from a 55 keV DC gun are first compressed by a THz-powered buncher, then accelerated in a THz-powered “booster” to 400 keV and finally accelerated to 20 MeV in a THz-powered LINAC. The electrons are then transported and focused to overlap with a counter-propagating laser to produce X-rays by inverse-Compton scattering (ICS). AXSIS requires development on multiple technological fronts, including THz-driven accelerator technology as well as extension of laser-driven THz sources to orders of magnitude higher pulse energies, necessitating significant improvements of conversion efficiency as well as development of novel high-power lasers highly tailored for THz generation.

This hierarchy of developments brings an additional challenge in that designs must accommodate large uncertainties in the performance of each component. The first AXSIS prototype addresses this challenge. First, since a fully THz-powered electron gun, envisioned for the final machine, is not yet ready to serve as the front end of the accelerator, a DC gun has been substituted. Although electron beams from DC guns suffer from low acceleration voltages and associated emittance growth, this choice enables parallel development of both the gun and LINAC technologies, albeit at lower performance levels. Second, subsequent acceleration modules and diagnostics have been designed to handle large variations in the THz pulse- and the resultant accelerated-electron energies.

As the maximum electron energy produced by the DC gun is ~ 55 keV, post acceleration using a LINAC (in which the electrons and a monochromatic THz wave co-propagate) is not practical due to the large change in electron velocity that occurs during acceleration and the resultant dephasing. Therefore, a booster device based on the STEAM concept [6] is implemented which uses a segmented interaction pumped transversely by single-cycle pulses in order to maintain phasing (Fig. 2). Based on previous work [9] and on the performance of our laser powering the Booster THz source (1 µm wavelength, 200 mJ pulse energy, 400 fs pulse duration), a single-cycle THz pulse with centre frequency of 300 GHz and pulse energy of up to 400 µJ is expected to be possible. Guided by simulation, a booster prototype was developed (Fig. 2A) employing three layers and a one-sided pumping scheme that uses reflection of the incident THz pulse to generate a short-lived standing wave at the interaction [10,11]. Optimized performance was simulated to produce electrons with a peak energy of 430 keV but a long tail of lower energy resulting in an RMS energy spread of 99 keV (Figs. 2 B, C & D). This result was then used as the starting point for simulations of the THz-driven LINAC.

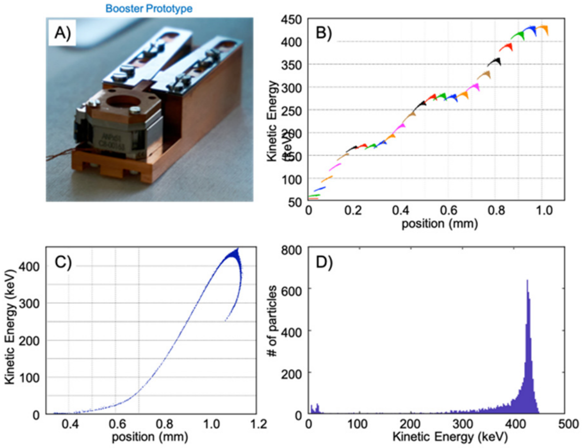

Figure 2: THz-driven booster. (A) Photo of the booster prototype. (B) Evolution of the longitudinal phase-space distribution throughout the interaction. (C) Final longitudinal phase-space distribution of the accelerated beam. (D) Resultant electron energy spectrum.

The range of targeted electron energies for the LINAC analysis was determined by consideration of the potential for producing X-rays of interesting photon energies. The photon energy can be estimated as $E_{X-ray} \approx 4\gamma^2 E_{laser}$, where $\gamma$is the electron relativistic factor and $E_{laser} \approx 1\ eV$ is the photon energy of the optical undulator laser. For electrons of target energy 20 MeV, $\gamma \approx 40$, and thus $E_{X-ray} \approx 6.4\ keV$, which is an interesting range for many biological systems. Due to the quadratic dependence, a factor of two reduction in electron energy to 10 MeV results in a 4-times drop in X-ray photon energy to $E_{X-ray} \approx 1.6\ keV$, which is still relevant for material science. A further factor of two drop to electron energies of 5 MeV produces only $E_{X-ray} \approx 0.4\ keV$ photons, which is already in the range of what can be achieved by high-harmonic laser sources. However, considering that the technology exists to up-convert the optical photons to the $E_{laser} \approx 4\ eV$ range by 4th harmonic generation, electrons at 5 MeV can still be used to generate interesting X-ray photons, although with significantly lower counts. This argument sets the energy range of interest to $E_{electron} \approx 5 - 20\ MeV$. Due to the energy-dependence in both the acceleration and transportation of electrons, the required design must be flexible.

Fig. 3 shows the results of simulations of the interaction of electrons from the Booster co-propagating with monochromatic (< 1% bandwidth) multicycle THz pulses in a 7 cm long dielectric-lined waveguide LINAC structure [4]. A range of THz pulse energies was assumed in order to determine the flexibility of the THz acceleration scheme. The results show that by appropriate tuning of the injection phase and THz phase velocity in the waveguide, varying the THz pulse energies from 9 – 19 mJ results in final electron energies in the range of 8 – 19 MeV (Fig 3A). Besides the electron energy, the LINAC performance, as measured by the bunch duration and the bunch energy spread, is also improved at higher THz pulse energies (Figs. 3 B – D).

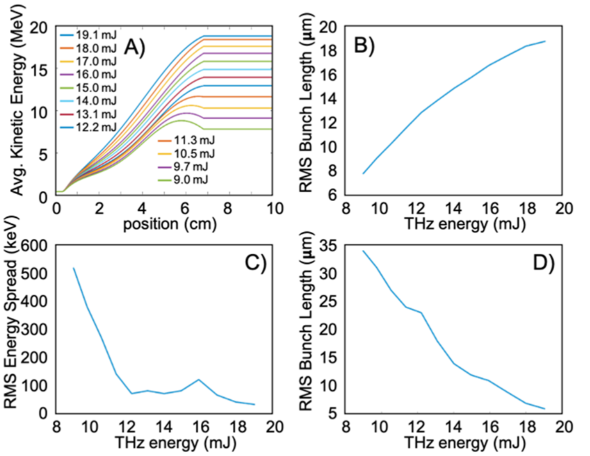

Figure 3: Simulated LINAC performance. (A) Evolution of the electron energy with distance inside a 7 cm DLW. (B, C & D) Summary of final energy, energy spread and bunch length, respectively, vs THz pulse energy.

These results demonstrate a high degree of flexibility in the acceleration of the electrons. However, to make the light source work, the electrons must also be transported to the ICS interaction point, and to achieve the optimum X-ray brightness, the electrons must be both spatially and temporally focused. The temporal focusing of the electrons is achieved by operating the LINAC in a mode producing a correlated energy spread at the output resulting in temporal compression through velocity bunching.

To achieve spatial focusing of the electrons, a system based on permanent-magnet quadrupoles (PMQs) was designed. A quiver of twelve PMQs of different strengths were used to span an energy range of 5.6 – 18.4 MeV (Fig. 4). Nine distinct focusing solutions involving unique pairs of PMQs were then found for subsets of the energy range, with the idea that once the maximum energy of the electron beam is determined, the appropriate set of PMQs would be implemented. Each pair allows a small range of energy tuning, enabling the full range to be covered without break.

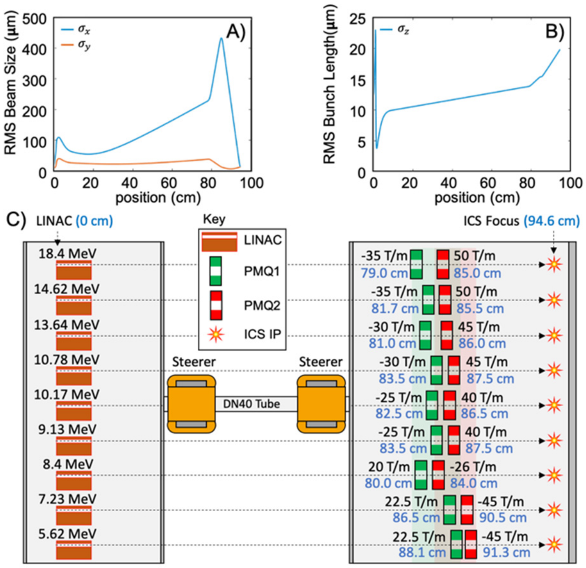

Figure 4: Solution for spatially focusing electrons over 5 – 20 MeV range. (A & B) Transverse and longitudinal beam dynamics from the LINAC to the interaction point for the highest-energy case. (C) Configuration of PMQs for focusing each electron-energy case.

SUMMARY

A flexible design for the first prototype of a THz-driven electron accelerator and X-ray light source is presented. The design addresses the challenges of proving that THz-driven acceleration is a viable solution for implementation of such a source.

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