Abstract

Novel compact accelerating structures are highly favorable compared to conventional devices for studies where high-energy bunches in small but applicable charges are required. Increasing the operation frequency and shrinking the accelerating devices is a suitable path for improving the accelerators' performance. For this purpose, energy transfer to electrons can be realized in shorter distances, which in turn means introducing higher accelerating gradients. Moreover, higher accelerating gradients enable beams with higher quality due to lower emittance growth. However, increasing the operation frequency from RF to optical regimes introduces serious challenges in synchronization, stability and acceleration of considerable charge amount. Consequently, THz acceleration will likely serve as the optimal operation regime for compact accelerators.

Despite the already-realized high power radiation sources enabling ultrahigh electric fields, increasing the acceleration gradients above the state-of-the-art values is hampered by the damage threshold of materials. Recent studies on damage mechanisms in accelerators have revealed the strong dependence of operation threshold on the time duration over which fields are influencing the device. Therefore, *fast* accelerating principles based on short excitations need to be developed for further increasing the accelerating gradient. The main goal in this habilitation thesis is conceptual developments and proof-of-principle studies for THz acceleration using short pulses. The concepts developed here pave the way towards the realisation of cheap and compact particle accelerators with control of particles over ultrashort time scales.

The concepts in this thesis comprise three groups focusing on: (1) fast electron sources, (2) THz injectors, and (3) THz linacs. First, the feasibility of ultrafast, high-yield electron emitters based on nanostructured cathodes is demonstrated. Benefitting from field enhancement effects, namely tip-enhancement and plasmonic enhancement, laser-induced field emission is realized over large, dense and highly uniform field emitter arrays. The theoretical principles of these field emitter arrays are studied and their suitability for pico-Coulomb charge production over femtosecond time-scales is confirmed. In the framework of THz injectors, two ground-breaking concepts including ultrafast single-cycle THz guns and segmented THz electron accelerator and manipulator (STEAM) devices are developed and tested. The possibility of using transient fields to realize ultrahigh acceleration gradients close to 0.5 GeV/m is confirmed. Specifically, a STEAM device capable of performing multiple high-field operations on the 6D-phase-space of ultrashort electron bunches is demonstrated. With this single device, powered by few-micro-Joule, single-cycle, 0.3 THz pulses, we demonstrated record THz-acceleration of > 30 keV, streaking with < 10 fs resolution, focusing with > 2 kT/m strength, compression to ~ 100 fs as well as real-time switching between these modes of operation. Travelling wave THz linacs based on dielectric-loaded metallic waveguides operating under few-cycle excitations are proposed. Based on this concept, keV-level energy gain through a linear accelerator using optically-generated THz pulses is demonstrated. Moreover, the possibility of electron acceleration to tens of MeV with millijoule level THz pulses is theoretically shown.

The final goal of the above studies is a fully THz-driven compact light source facility, whose start-to-end simulation is fulfilled in this thesis. The required THz pulses to excite the light source are categorized under single-cycle and multi-cycle pulses that are generated using laser-driven THz generation concepts. The single-cycle THz pulses feed an ultrafast electron gun, whose output is delivered to a THz linac fed by multi-cycle pulses. It is shown that 18 MeV beam energy can be produced using two single-cycle THz beams with 400 µJ and one 0.5 ns 300 GHz beam with 20 mJ energy. This beam is then transported to an Inverse Compton Scattering (ICS) section, where the 18 MeV electron beam scatters off a 100 mJ 1 µm laser beam and generates an X-ray beam with 4 keV central photon energy and 6×10^4 photons per shot.