DIELECTRIC AND THz ACCELERATION (DATA) PROGRAMME AT THE COCKCROFT INSTITUTE

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Abstract

Normal conducting RF systems are currently able to provide gradients of around 100 MV/m, limited by breakdown on the metallic structures. The breakdown rate is known to scale with pulse length and, in conventional RF systems, this is limited by the filling time of the RF structure. Progressing to higher frequencies, from RF to THz and optical, can utilise higher gradient structures due to the fast filling times. Further increases in gradient may be possible by replacing metallic structures with dielectric structures. The DATA programme at the Cockcroft Institute is investigating concepts for particle acceleration with laser driven THz sources and dielectric structures, beam driven dielectric and metallic structures, and optical and infrared laser acceleration using grating and photonic structures. A cornerstone of the programme is the VELA and CLARA electron accelerator test facility at Daresbury Laboratory which will be used for proof-of-principle experiments demonstrating particle acceleration.

INTRODUCTION

In particle physics, future linear colliders such as CLIC or ILC require ultra-short, sub-picosecond, bunches to obtain the luminosity necessary for the particle physics science exploration. In accelerator based x-ray sources, sub-10 fs bunches open new capabilities in femtosecond time-resolved material science. With existing linear accelerators delivering beams on the femtosecond scale already on the km scale, and tens of km scale machines proposed, higher gradient structures are sought for the potential to shrink the size and cost of linear accelerators. Current metallic microwave structures are limited by electric breakdown to around 100 MV/m, and superconducting structures are restricted to even lower gradients. Particle acceleration driven by laser and (laser generated) THz radiation has the potential for GV/m acceleration gradients; The sub-ps to few–fs oscillation periods of THz and laser electromagnetic fields are also well suited for acceleration and control of femtosecond duration electron bunches. While only a very limited number of demonstrations of laser and THz acceleration have been achieved, such approaches remain promising for high gradient acceleration of high energy beams in the long term. In the short-term future, laser and THz acceleration has high potential for applications in generation of femtosecond few-MeV beams for electron diffraction, and for compact soft and hard x-ray sources with intrinsic femtosecond synchronization with lasers.

The Cockcroft Institute has initiated a multi-themed programme, Dielectric and THz Acceleration (DATA), to investigate particle beam acceleration using sub-picosecond electromagnetic fields. The programme is divided into three themes of (i) Laser generated THz acceleration and deflection; (ii) Beam driven (wakefield) THz acceleration in dielectric and metallic structures; and (iii) Dielectric Laser Acceleration. THz electromagnetic fields, with electric field oscillations in the range of 100 fs-1000 fs, will be examined for their potential for efficient and phase-controlled capture and acceleration of electron beams. For the laser generated THz acceleration, both free space and and dielectric waveguide mechanisms are being investigated for acceleration or deflection for beam diagnostics. For beam driven THz sources, the programme is investigating corrugated metallic structures and dielectric waveguides for Wakefield acceleration. Laser-dielectric structures are being examined for their potential in very-high gradient acceleration of high-energy femtosecond beams. In this latter theme we are investigating inverse grating and photonic band-gap structures excited by visible and near-IR lasers. The programme will undertake a range of proof-of-concept demonstrations of laser and THz radiation driven electron acceleration with the VELA and CLARA electron accelerator test facility at Daresbury Laboratory. These test facilities include a 5MeV RF photo-injector gun, a beamline with a suite of diagnostics including a transverse deflecting cavity, and 2 metre long experimental chamber followed by an electron spectrometer. The facilities are currently being upgraded with a second injector and dog-leg transfer line; this new injector will provide beams up to 50MeV. The VELA and CLARA test facilities are described further in reference [1] of this conference.

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LASER GENERATED THZ ACCELERATION

The programme has been active in the development of high field strength THz sources tailored to several concepts of acceleration and beam manipulation. For direct acceleration in free space with co-propagating THz and particle beams, sources with a strong longitudinal component have been demonstrated and characterized. We have developed a radially biased large-area photoconductive antenna (PCA) that provided the largest longitudinally polarized terahertz electric field component ever measured from a PCA. Using a 76 mm-diameter GaAs photoconductive antenna, a longitudinal component with a peak amplitude of 2.22 kV/cm has be obtained [2].

To enable even higher longitudinally polarized terahertz electric field strengths to be obtained, together with the ability to temporally tune the terahertz radiation, we have explored the potential of non-linear optical crystals for terahertz generation. Magnesium-oxide-doped stoichiometric lithium niobate (MgO:SLN) has become a popular non-linear material for generation of linearly polarized terahertz radiation with a high peak electric field strengths in excess of 1 MV/cm. In order to apply these sources to accelerator applications requires conversion to a mode with a strong longitudinally polarized component, and we have developed a novel scheme employing a matched pair of polarity-inverted MgO:SLN crystals. The interferometric recombination of the two polarity-inverted terahertz pulses effectively formed a Hermite-Gaussian 01 (HG01) spatial mode and enabled the generation of longitudinally polarised single-cycle terahertz radiation with an electric field amplitude of 11.7 kV/cm. Using commonly employed techniques this generation method could in principle be scaled to produce longitudinally polarized terahertz electric fields with field amplitudes in excess of 1 MV/cm [3]. The higher fields strength sources now available with the Hermite-Guassian source are being adapted for coupling to dielectric lined waveguide for acceleration and manipulation of electron beams. For acceleration within waveguides we are investigating the use of rectangular waveguides loaded with dielectric. While the shunt impedance is reduced with respect to circular waveguides, it can be made to be tuneable and the coupling can be made more efficient. Our rectangular waveguide is made of two L-shaped blocks with one side coated with CVD diamond, such that the spacing can be altered. This allows the structure to be tuned after manufacture. In addition each layer of the dielectric coating can be expanded in thickness at the ends of the structure to create a coupling taper into the dielectric-lined waveguide. Such an arrangement also allows each side to be fed independently, and for either acceleration or deflection modes to be excited. Further details are given in Ref [4].

One of the central challenges of laser generated THz acceleration is obtaining velocity matching of the particles and the extremely broad bandwidth pulses. Dielectric lined waveguide obtain this velocity matching but suffer from dispersion of the injected high field single-cycle pulses. We have developed an alternative approach where the source of the single-cycle pulse is itself propagating in synchronism with the particle beam [5]. Our scheme uses optical rectification to generate single-cycle THz pulses with longitudinal electric fields co-propagating with an electron beam. To maintain a sub-luminal THz velocity matching the electron beam, and to eliminate the dispersion of the single-cycle pulse, we produce an effective sub-luminal group velocity on the laser which generates single-cycle THz pulses nearby to the electron beam. We have demonstrated the generation of sub-luminal THz pulses with velocities from 0.77c to 1.75c, with several different THz generation media [5], and are currently preparing for experiments in acceleration and deflection of the VELA electron beam with such a source.

DIELECTRIC WAKEFIELD ACCELARTION

As well as generating THz via a laser, the electron beam can also excite a THz frequency wakefield in the structure. Experiments will demonstrate and examine in detail the process of acceleration of a witness bunch from a leading drive bunch or bunch train. Schemes for energy de-chirping will also be investigated. The DATA project will consider two structure types, a dielectric loaded slab and a corrugated metallic waveguide.

The dielectric structures are highly synergetic with the dielectric loaded waveguide work for laser-generated THz, except that while the laser-generated structure will be a waveguide with four walls the beam driven dielectric will be a slab with only two walls. While this gives a lower impedance it allows much better flexibility for studying the complex wakefield interaction with the beam. Initial experiments aim to produce a highly tuneable THz wakefield, with one of the key applications bunch de-chirping. They will be focused on single bunch interaction with a tuneable structure. The wakefields that will be produced will be analysed using a Martin-Puplet interferometer once coupled out of the structure. Bunch self-wake interaction will also be assessed, including the influence of initial transverse and longitudinal profiles and removal of the chirp required for compression. Potential applications of this bunch manipulation include complementing novel and existing accelerator technology. Long term goals include two bunch acceleration and implementing more complex structure design. Analytical methods [6], CST and VSim simulations have been carried out to optimise the structure design. Current activity is based on designing the structure output coupler and developing the MP-I diagnostic.

The application of corrugated metallic structures with 1D and 2D periodic surface lattices (PSLs) are being investigated, and structures constructed and characterized. The 2D PSLs offer advantages in mode se-lection and control. While these structures are more complicated to manufacture [7] they provide a higher interaction impedance, and hence a higher accelerating gradient.

ISBN 978-3-95450-169-4

DIELECTRIC LASER ACCELERATION (DLA)

As frequency-selective synthetic media, photonic band-gap (PBG) structures are very attractive to confine a speed-of-light mode in a vacuum channel for dielectric laser accelerators (DLAs). In particular, the use of all dielectric two-dimensional and three-dimensional PBG structures for DLAs has been investigated for operation in the visible/near IR wavelength range. Previous work has also demonstrated in theory that one-dimensional PBG structures (such as the Bragg waveguide) can provide a suitable optical acceleration structure, with high characteristic interaction impedances. The confinement in this hollow core all-dielectric waveguide is achieved by alternating a series of dielectric layers to form the waveguide cladding where reflected waves from the different layers interfere constructively (Bragg reflection). To allow for single mode operation, the beam channel must be in the range 0.5 λ – 1.1 λ.

We propose the tuning planar and cylindrical 1D PBG waveguides to the mid-IR range to relax some of the practical issues of the shorter wavelength structures from the literature, allowing for larger beam apertures. For operation in the 5-10 μm range, the vacuum channel can be in the range 2.5 - 11 μm, depending on the operation wavelength. *Appropriate* choice of refraction indices of the Bragg dielectric layers can provide high values of acceleration gradients. The mid-IR range structure developed in this project could serve as a second stage acceleration following a THz-driven buncher.

Dielectric laser-driven accelerators (DLAs) are promising candidates to shrink the size of particle accelerators. They provide access to accelerating gradients of up to several GV/m due to the higher damage threshold in dielectrics as compared to metals. So far two experiments have successfully demonstrated accelerating gradients of up to 300 MV/m [8] and 690 MV/m [9] for relativistic electrons in fused silica dual-grating structures while accelerating gradients of 25 MV/m [10], 220 MV/m [11] and 370 MV/m [12] were observed in fused silica and silicon structures for the case of non-relativistic electrons.
Optimization studies into dual-grating structures have already been performed at the Cockcroft Institute with the aim to increase the maximum accelerating gradient and optimize the distribution of the electric field inside the structure [13-16]. However, only few studies have been done into the particle beam quality that can be obtained in a DLA, although this is one of the most essential parameters of any accelerator. Investigations into the beam quality of a small electron bunch travelling through a 100-period dual-grating structure have been carried out in 2016 focusing on the final beam emittance, beam energy spread and maximum accelerating gradient [17]. Work is now underway to manufacture these structures in collaboration with Paul Scherrer Institute for measurements with beam. The medium term goal is to optimize low and high beta structures in experiment and simulation.

ACKNOWLEDGEMENT

This work was supported by the United Kingdom Science and Technology Facilities Council [Grant No. ST/G008248/1] and the Accelerator Science and Technology Centre through Contract No. PR110140.

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