First dielectric wakefield experiments at Daresbury Laboratory

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Abstract. The first dielectric wakefield acceleration (DWA) experiments have been conducted at the CLARA/VELA test facility at Daresbury Laboratory, UK. The DWA structures were of planar geometry with variable gap and dielectric thicknesses ranging from 0.025 to 0.2 mm. The facility, in its current state, provided electron bunches with up to 100 pC bunch charge, and variable 0.2-2.0 ps bunch lengths at the beam energy of 35 MeV. All major wakefield effects have been observed including energy modulation in longer bunches, energy dechirping, and transverse streaking and focussing. With a modest bunch charge of $\sim 50$ pC, a decelerating field of $\approx 8$ MV/m was measured. Using this variable gap planar structure, we have also demonstrated generation of continuously tunable narrowband THz. A summary of experimental results and near future developments are presented.

1. Introduction

Dielectric wakefield acceleration (DWA) is one of the novel acceleration concepts aimed to develop future compact and cost effective light sources and particle colliders \[1, 2\]. The study of DWA has been actively pursued, especially in the last decade, because of simplicity of accelerating structures and their ability to withstand high gradient electric fields, without breakdown, of up to GV/m levels \[3\]. Accelerating gradients exceeding 300 MV/m have been recently demonstrated \[4\].

DWA belongs to the larger family of structure wakefield accelerators (SWFA) which also includes metallic corrugated structures that share similar underlying physics with DWAs. The attractiveness of SWFA concept is further complimented by the proven applications to modern conventional accelerators and free electron lasers (FEL). These include energy dechirpers for FELs \[5, 6\], fresh slice two colour FEL generation \[7\], energy modulation of longer electron bunches with subsequent conversion to density modulation (microbunching) \[8, 9\], passive streaking as a longitudinal bunch length diagnostic \[10\], and longitudinal bunch profile manipulation \[11\]. These wakefield structures have also been demonstrated to be powerful sources of THz radiation \[12\].

Construction of the CLARA accelerator facility is ongoing at Daresbury Laboratory. Completion and commissioning of the CLARA Front End linked to the already existing VELA beamline via a short dog-leg section \[13\] enabled DWA experimental studies on this machine as part of an overall exploitation programme. First experiments were conducted at the end of 2018 using planar DWAs with variable gap and aimed to demonstrate a continuously tunable...
THz generation and, more generally, to act as a stepping stone for a further experimental DWA programme at Daresbury Laboratory.

2. Experimental setup

An electron beam with 10 Hz bunch repetition frequency is generated in a RF photoinjector gun of the CLARA Front End followed by an RF linac providing the electron energy of up to 50 MeV. The beam is then injected into VELA beamline via a short dog-leg section where longitudinal bunch compression takes place. The bunch compression is controlled by the linac off-crest phase. The VELA beamline transports the beam to a dedicated experimental area, Beam Area 1 (BA1), with a large - 2.3 m long - and easily accessible vacuum chamber. The BA1 beamline is equipped with a standard set of diagnostics (energy spectrometer, YAG screens, beam position monitors) and is shown schematically in Fig.1.

The vacuum chamber contains additional YAG screens on motorised translation stages and a multi-axis in-vacuum motorised support for DWA structures at an interaction point (IP) to ensure alignment of structures to the electron beam. The IP assembly is complimented by a coherent transition radiation (CTR) target for bunch length measurements. An off-axis parabolic mirror is used to extract and transport either the CTR or coherent Cherenkov radiation (CCR) from the DWA structures to the outside of the vacuum chamber through a z-cut quartz window. The CTR and CCR spectra are collected by a Martin-Puplett interferometer positioned next to the quartz window.

All experiments were conducted at fixed electron beam energy of 35 MeV and bunch charges of up to 100 pC. The upstream quadrupole triplet (see Fig.1) focuses the beam to approximately 100 µm RMS beam size at IP. The downstream triplet matches the beam optics to the energy spectrometer and ensures good energy resolution, which was estimated to be 50 keV. The bunch length near maximum longitudinal compression measured with the CTR technique was 0.2-0.3 ps RMS. In these experiments, however, longer electron bunches of up to 2 ps RMS we also used.

The design of the DWA assembly is shown in Fig.2. The structure gap was remotely controlled by two picomotors. Three structures were employed with different dielectric (quartz) thicknesses of 25, 100 and 200 µm and were interchangeable within the same assembly (Fig.2). The overall structure length was 60 mm, with the dielectric layers being 40 mm long; leaving first 10 mm as the beam collimator and the last 10 mm were machined as an output coupling antenna with 12° half angle opening. The 25 µm structure was 2 mm wide and the other two thicker dielectric structures were 10 mm wide. More detailed description of these structures can be found in [14].
3. Continuously tunable THz generation

Stepwise tunability of THz generation from dielectric lined waveguides (DLWs) was earlier demonstrated by interchanging cylindrical DLWs with different frequency spectra [12]. Several other methods to change the frequency of radiation were proposed and tested but none of them could offer a continuous tunability in a wide range. Continuous tunability can be however attained with planar DLWs of variable gap and correct choice of dielectric lining with thickness of a few tens of micrometres as follows from the wakefield theory [15].

Continuous tunability within 0.55-0.95 THz range was demonstrated using a planar structure with 25 μm thick quartz plates while varying the gap from 0.14 to 1.1 mm as shown in Fig. 3. The radiation was measured to be predominately in a single fundamental mode with bandwidth below 50 GHz (the lower limit of the bandwidth was determined by a finite length of the interferometer translation stage travel), see Fig. 4a. For comparison, frequency measurements of DLWs with thicker dielectric layers of 100 and 200 μm were also conducted. With these structures, the tunability is greatly reduced (Fig. 3) and multi-mode operation is evident (Fig. 4b) as expected. It is worth noting a good agreement between measured frequencies and those calculated from analytical theory [15] (lines in Fig. 3) in a wide range of structure gaps and dielectric thicknesses.

The THz pulse energy varied significantly across the tunability range. At lower frequencies, the pulse energy reduction was mainly due to increased structure gap. At higher frequencies, the main factor was reduction of coupling efficiency between the beam and the wakefield due to finite bunch length. No sizeable THz power was detected outside 0.55-0.95 THz frequency range as a result. Maximal pulse energy was registered at 0.65 THz frequency and estimated to be $\approx 0.6 \mu J$/pulse with modest 70 pC bunch charge. A detailed description of this experiment and its results are presented in [14].

4. Dielectric wakefield effects

When the electron bunch is slightly overcompressed in the dog-leg section such that the bunch is still short, $\approx 0.3$ ps RMS, but develops a negative chirp (with the head of the bunch having lower energy than the tail), the space charge effects during long $\approx 15$ m transport to BA1 resulted in very low energy spread in the BA1 energy spectrometer. This allowed a sufficiently
accurate evaluation of the decelerating wakefield strength by measuring the beam energy loss (Fig. 5b). The measured dependence of the energy loss on the structure gap is presented in Fig. 5b, with maximum value of 0.3 MeV at the gap of 0.23 mm (green crosses), which translates to decelerating field of 7.5 MV/m. These measurements were made with a bunch charge of 70pC and transverse beam size at the interaction point of 120 μm. The relatively large beam size resulted in 40% beam loss at the entrance to DLW due to collimation. Without beam collimation, the maximal energy loss would be expected to reach 0.6 MeV as follows from the Green’s function calculations (Fig. 5b, red dots) with a corresponding decelerating field of ≈ 15 MV/m [16]. These calculations, adjusted for the beam loss, follow closely the experimentally measured values (Fig. 5b, black squares).

With the DLW having 25 μm dielectric thickness, a strong energy modulation was observed similar to that reported in [8]. At smaller structure gaps below 0.4 mm, the modulation peaks split (Fig. 6a) while at a larger gap of 0.7 mm they remain singular (Fig. 6b) and can be detected in the energy spectra of bunches with up to ∼2 ps RMS length even at a relatively small bunch charge of 70 pC.

With the known fundamental frequency at a given DLW gap (see Fig. 3), the energy
modulation can be applied to evaluate the bunch length by calculating the number of energy modulation periods. This method is especially useful for longer bunches when conventional techniques, like CTR spectral measurements, cannot be used due to insufficient signal strength. On the other hand, this method cannot be applied to very short bunches with the length smaller than the wavelength of the wakefield. The bunch length at 10% of the peak level as a function of the linac off-crest phase measured by the energy modulation method is presented in Fig. 7 by red dots. This data is complemented by CTR measurements of bunch lengths near maximum compression (green crosses). The experimental data is also well matched with simulations performed in the beam dynamics code elegant, shown in Fig. 7 by black squares. In the latter case however, the simulation data had to be shifted towards the linac crest by 2°. The cause of this discrepancy is currently under investigation and can be possibly ascribed to differences in how the linac crest phase is determined in practice and in simulations.

Other wakefield effects have been observed but not studied in detail due to sub-optimal electron beam characteristics at the time of these first experiments (predominately the low bunch charge) and short length of the DLW structure employed. These include bunch energy dechirping, with a factor of two FWHM energy spread reduction measured, and transverse wakefield effects. Both beam focussing in horizontal plane caused by quadrupole-like mode of the planar structure and transverse “streaking” with the tail of the bunch kicked transversely

Figure 5: Typical beam energy loss as a result of decelerating wakefield in DLW with gap 400 µm (a) and dependence of the energy loss on the structure gap (b).

Figure 6: Beam energy modulation at two DLW gaps of 0.3 mm (a) and 0.7 mm (b) and bunch charge of 70 pC.
Figure 7: Variation of bunch length at 10% of peak level with the linac off-crest phase as measured by the energy modulation (red dots) and CTR (green crosses) techniques. Elegant simulations results are shown by black squares.

when the beam propagates off-axis through the structure were observed. The latter has potential to be an effective passive method for longitudinal bunch length and profile measurement.

5. Conclusions and future plans

The first experiments at CLARA/VELA accelerator facility at Daresbury Laboratory demonstrated a capability of this machine to conduct various SWFA studies. Even with the current limitations on the available electron beam, we were able to observe all major wakefield effects and demonstrate continuous tunability of a DLW based THz radiation source. The facility is undergoing a phased design, with construction, commissioning, and further improvements planned. In 2020, upgrades to the RF photoinjector gun and the photoinjector laser are expected to enable electron beams with higher bunch charges and lower transverse emittance, and variable longitudinal laser pulse profiles for bunch shaping; including an option to generate pairs of laser pulses to form drive/witness pairs of electron bunches. Additional hardware for beam manipulation, including movable set of collimators and scanning slits, will be added to an experimental setup. These new features will allow more detailed investigation of wakefields with the emphasis on a transverse beam dynamics with the use of both planar and circular DLWs.

The next phase of the CLARA construction will see the electron beam energy increased to a design value of 250 MeV. For this CLARA extension, an energy dechirper has been designed, manufactured and is currently being commissioned, see Fig. 8a. It is similar in design to the LCLS/RadiaBeam dechirper [17] having two planar structures with variables gaps and orthogonally oriented with respect to each other. Due to lower beam energy, each structure is only 200 mm long and the major difference is that the dielectric lining plates of 200 µm thickness are employed rather than metal corrugations as in [17]. The mechanical design of the CLARA dechirper is presented in detail in [18]. Preliminary simulations [19] [20] show significant reduction of the energy spread of the CLARA beam (Fig. 8b), by a factor of ~ 70 [20].
Figure 8: (a) Mechanical design of the CLARA dechirper shown in cross section (b) energy spectra of CLARA beam at the entrance to and exit from the dechirper.

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