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Electron acceleration through two successive electron beam driven wakefield acceleration stages

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ABSTRACT

Structure based wakefield acceleration may provide a viable approach for accelerating sufficiently large numbers of electrons and positrons at the high gradient needed to meet the luminosity, efficiency, and cost requirements of a future linear collider. An important step in proving its viability is the demonstration of acceleration in multiple stages. Here we show the results of the first experimental demonstration of staged two beam wakefield acceleration, conducted at the Argonne Wakefield Accelerator Facility (AWA), in which a 0.5 nC electron bunch gained equal amounts of energy in two stages (~2.4 MeV per stage, corresponding to an average acceleration gradient of ~70 MeV/m). Meanwhile 150MeV/m of acceleration in a single stage has been achieved. The demonstration experiment should be scalable to staged-acceleration at gradients of the order of 200 to 300 MeV/m. Such a development would considerably reduce both the cost and footprint of both a future high-energy physics (HEP) collider, as well as future X-ray light sources.

1. Introduction

Charged particle acceleration at substantially higher acceleration gradients than in today's conventional accelerators could open up new possibilities in fundamental particle physics research. Over the past three decades much progress has been made in the development of conventional metallic accelerators, including X-band room temperature rf accelerators capable of reaching ~100 MV/m [1–6], superconducting rf accelerators operating at ~35 MV/m [7,8], and, more recently, copper structures cooled down to cryogenic temperatures that have reached peak gradients of ~250 MV/m, albeit so far without the presence of particle beams [9]. During the same period, a large number of advanced accelerator concepts have been considered [10], but current R&D has converged to just a few promising options all based on wakefield acceleration [11–14].

Wakefields are generated by the passage of particle beams or laser beams through structures or plasmas [15–17], and they can yield short pulses of very high intensity electromagnetic radiation. These wakefields can then be used to accelerate particles at very high gradients. Two-Beam Acceleration (TBA), shown in Fig. 1, is a modified approach to structure-based wakefield acceleration. The drive beam energy is extracted into an RF pulse that is then used to accelerate the main beam (or witness beam) in a separate accelerating structure. In collinear wakefield acceleration, where the generation of wakefields and the acceleration of particles take place in the same structure or medium, it is challenging to efficiently transfer energy from the leading drive bunch to the trailing main bunch, but techniques based on bunch manipulation are under development [18–20]. In contrast, the TBA approach uses two parallel and independent structures, where a low impedance (i.e. low-gradient) decelerating structure (or power extractor) extracts energy from a high-current drive beam, and a high impedance (i.e. high-gradient) accelerating structure accelerates the main beam [21]. Thus the high efficiency energy transfer can be implemented easily through the ratio of impedances of the two structures, similarly to an electrical transformer. In addition, the energy difference between the drive and main beam rapidly increases as the drive beam loses energy and the main bunch continuously gains energy along the acceleration beamline. The beam optics in the TBA approach becomes relatively straightforward since the beams are totally decoupled.

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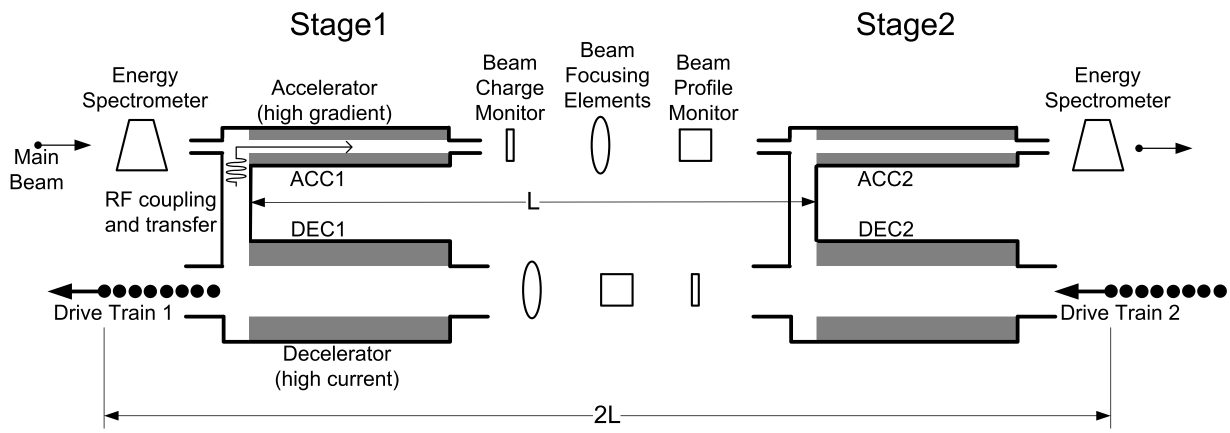

Fig. 1. Configuration of Two-Beam-Acceleration staging experiment at AWA, showing the two drive bunch trains, Drive Train 1 and Drive Train 2, and the two stages of TBA, each one composed of a decelerator–accelerator pair.

The TBA scheme provides flexibility in the selection of operating frequency, rf pulse length, and particle bunch structure. Commonly, the microwave to millimeter wave range of frequencies is chosen for the TBA scheme due to the mature technology of coupling wakefields in and out of RF structures. The CLIC group at CERN has produced a Conceptual Design Report for an electron–positron linear collider based on TBA [1]. CLIC's design utilizes two beamline rings to stack drive bunch trains, which then feed a series of PETS (Power Extraction and Transfer Structures) through numerous branched drive beamlines to generate rf pulses (240 ns, 12 GHz). These rf pulses are used to power the parallel main accelerator beamline. The CLIC R&D program has demonstrated accelerating gradients of 100 MV/m in metallic disk-loaded structures with acceptably low breakdown rate (~1e−7 pulse/meter), resulting in loaded gradients of ~80 MeV/m [1].

The Argonne Wakefield Accelerator (AWA) group at Argonne is developing a preliminary design for a linear collider based on a different TBA approach than CLIC. The AWA design has similarities with the CLIC design, since they both rely on TBA, but also considerable differences. The AWA design [22] is modular, and each module comprises several acceleration stages. The most notable difference is that the AWA approach employs shorter rf pulses, approximately 20 ns, with the goal of reaching higher accelerating gradients while minimizing the probability of arcing. The accelerating gradient is targeted at ~350 MV/m [23]. The rf breakdown is not the only factor limiting the operational gradient. Other factors include the generation of the short-duration high-charge bunch trains, high-power rf transmission, drive bunch degradation due to large energy loss, efficiency, etc. In addition, the AWA program is also developing dielectric-loaded wakefield structures, due to their potential to withstand higher accelerating gradients and lower fabrication cost [23,24] compared to metallic structures. Realization of the AWA TBA approach has multiple critical technologies that need to be demonstrated [22] and among them is the staging of sequential accelerating modules, where a beam is accelerated through two or more stages of wakefield acceleration. Demonstration of wakefield acceleration staging is the big step towards validation of the approach as a whole. It proves that wakefield acceleration is indeed possible in a modular way. Once staging is demonstrated one can achieve TeV energies by stacking these modules. This approach allows for length reduction of the accelerator, as wakefield acceleration yields a high gradient operation in a short pulse mode.

2. Experimental setup of the staged acceleration

This first demonstration of TBA staging was performed at the AWA facility [25], which houses two independent electron linacs, operating at 1.3 GHz, for generating the 70 MeV drive beam and the 8 MeV main beam. The beamline layout used for staging (Fig. 1) contains two decelerator–accelerator pairs, corresponding to Stages 1 and 2. The drive beam consists of two drive bunch trains, Drive Train 1 (DT1) and Drive Train 2 (DT2), each containing eight high-charge bunches separated by 0.769 ns (1.3 GHz rf period). The drive bunches traverse the decelerators, producing rf pulses that are sent through waveguides to their corresponding accelerators. The main beam, propagating in opposite direction, gains energy in each of the two accelerators (ACC1 and ACC2). The spacing between the two drive bunch trains, L_b, needs to be twice the geometrical spacing between the two stages, L, for synchronization to occur ($L_b = 2L$). For this simplified staging experiment, both drive trains passed through both stages but only the RF energy from one train was used to accelerate the main bunch in each stage (i.e. DT1 for Stage 1 and DT2 for Stage 2). Thus, by not directing each bunch train to a single decelerator, the experimental setup is considerably simpler, but obviously at the expense of energy efficiency. Nevertheless, this experiment demonstrated that the main beam can be accelerated by the wakes of two separate drive beams through two stages, when the synchronization condition is satisfied.

Table 1
Main parameters of the TBA structures used in the experiment.

Parameters	Decelerator	Accelerator
Frequency (GHz)	11.7	11.7
Phase advance (deg)	120	120
Beam aperture (mm)	17.6	6
Effective length (cm)	30	3.5
Group velocity (*c)	0.22	0.016
RF power (MW) by a 8×20 nC train	55	N/A
Gradient (MV/m) per 50 MW RF input	N/A	100

In the staging experiment, both the decelerators and accelerators were conventional traveling-wave, $2\pi/3$-mode, disk-loaded copper structures operating at 11.7 GHz, which is the ninth harmonic of 1.3 GHz (because of the short bunch length of the drive beam, the wakefield form factor remains at 94% for 11.7 GHz). The decelerators are 30 cm long with a 17.6 mm aperture, which is large enough for the propagation of relatively high-charge bunches without the need of complex transverse mode damping [26]. The accelerator structures are about 10 cm in length (including couplers, 3.5 cm of the effective length excluding the couplers) and have a much smaller aperture (6 mm). They are comprised of three accelerating cells plus one matching cell at each end and have a group velocity of 0.016c. The parameters of both decelerating and accelerating structures are summarized in Table 1.

The rf pulse widths from both the decelerator and accelerator were measured at the output waveguides of each structure by means of a calibrated rf pickup probe. Given the length of the decelerator (30 cm) and its group velocity (0.22c), the rf pulses from five consecutive drive bunches (there were 8 bunches in each drive train) will overlap inside