ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA071

A COMPACT X-RAY SOURCE BASED ON A LOW-ENERGY BEAM-DRIVEN WAKEFIELD ACCELERATOR*

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Abstract

Accelerator-based X-ray sources have led to many scientific discoveries. Yet, their limited availability in large national laboratory settings due to the required infrastructure is a major limitation to their disseminations to a larger user community. In this contribution we explore the use of a low-energy electron beam produced out of a photoinjector coupled to a pair of dielectric structure to produce a higher energy (10-20 MeV) beam via a beam-driven acceleration scheme. The accelerated beam can then be used to produce X-rays via inverse Compton scattering.

INTRODUCTION

Modern accelerator-based X-ray sources have led to a wave of scientific advancements in various fields. Their inception relies primarily on energetic electrons which are manipulated to radiate either via undulators or inverse Compton scattering (ICS). In both radiation mechanisms the photon energy $O(\gamma^2)$, therefore an increase in the beam energy is significant. Recently, compact X-ray sources based on X-band RF technology has been proposed [1]. Likewise an X-ray source utilizing laser-plasma wakefield accelerator have been demonstrated [2]. Finally, most recently the possible use of a THz pulse to accelerate electron bunches have been put forward [3] and tested [4]. These solutions, although appealing, are either costly (X-band technology) and/or require the use of high-power lasers currently operating at low repetition rates.

A possible alternative to increase the beam energy is to rely on collinear beam driven acceleration using high-impedance media such as dielectric lined waveguides (DLW) – for dielectric-wakefield acceleration (DWFA) – or plasmas – for wakefield acceleration (PWFA). In collinear beam-driven schemes, a "drive" bunch is used to drive the wakefield in the medium while a properly delayed "witness" bunch at the proper phase is accelerated. The longitudinal wakefield produced by the drive bunch is given by

$$E(z) = \int_{-\infty}^{z} G(z-\zeta)S(\zeta)d\zeta, \quad (1)$$

where $G(z-\zeta) = 2\kappa\cos(k\zeta)$ is the longitudinal Green's function, κ the loss factor, and $k = \frac{2\pi}{\lambda}$ with λ being the wavelength of the mode supported by the medium. Additionally, in a DLW the maximum field strength generally scales as $E_+ \propto \Lambda(z)a^{-2}$ where a is the inner radius of the DLW and $\Lambda(z)$ is the longitudinal charge density. An essential figure of merit associated to beam-driven acceleration is the transformer ratio $\mathcal{R} = |E_+^{(m)}/E_-^{(m)}|$ where the superscript "m" refers to the maximum amplitude of the accelerating (E_+) or decelerating field (E_-), which describes the efficiency of the energy transfer of the drive bunch to the wake.

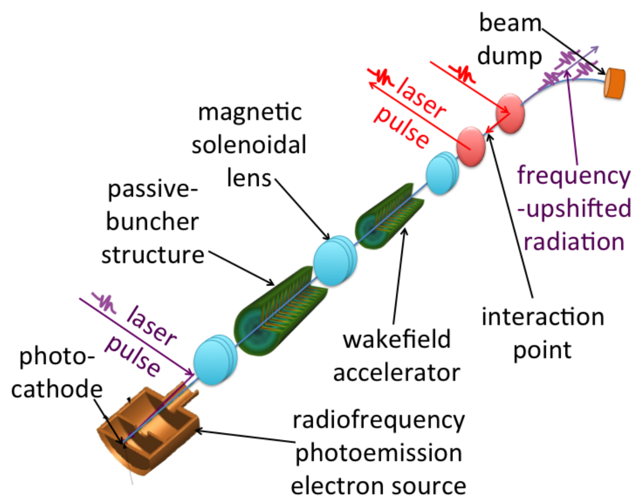

Figure 1: Overview of the compact source scheme: a photoinjected electron bunch passes through a series of DLWs for cascaded acceleration,the resulting high energy electrons are used with a laser to generate inverse Compton scattering.

Two practical challenges emerge for beam-driven acceleration at low energy. First, the geometric emittance associated to a low-energy photoinjected electron bunch sets an upper limit on the inner radius a and length L of the DLW structure. Second, the scheme relies on the production of a high-peak-current electron bunch along with the formation of a witness bunch.

To address some of these challenges, we propose an accelerator setup diagrammed in Fig. 1 based on a "cascaded acceleration" scheme. A high-quality electron bunch is produced in an RF gun and focused into a DLW structure (DLW1). The structure passively bunches the beam which

* This work is supported by US DOE contracts DE-AC02-07CH11359 to the Fermi research alliance LLC and DE-NA0001738 to Idaho Accelerator Center. F.L. is partially supported by the Dissertation-Completion Award from the Graduate School of Northern Illinois University.

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can then be used to drive a large gradient wakefield in a second DLW structure (DLW2).

CASCADED ACCELERATION

Let us now consider the use of two DLWs in series to accelerate a low energy (e.g. < 10 MeV) electron bunch. In this scheme, the first DLW is used to impart an energy modulation which leads to ballistic bunching as discussed in Ref. [5]. In this section we carry simulation of the beam dynamics considering the LCLS S-band gun operating with a peak surface field on the photocathode of 140 MV/m. Table 1 summarizes the accelerator settings employed. The large peak field helps preserve high-charge densities (especially peak current) which eventually results in higher transformer ratios. Our studies focus on the case of 2-nC bunch charge and it is important to note that this technique is very scalable to larger charges and wavelengths. The simulation was carried with ASTRA which includes a quasi-static particle-in-cell space-charge algorithm along with a non-self-consistent wakefield model based on the convolution equation Eq. 1 [6]. The Green's functions used in the wakefield calculations are computed using the six lower-frequency modes supported by the DLWs following the methodology of Ref. [7].

Table 1: Accelerator Beamline Settings and DLW Parameters Used in the ASTRA Simulations. The relative modes amplitude are normalized to the square sum of the amplitudes.

parameter	**value**	**units**
laser pulse RMS duration	2	ps
laser RMS spot size	1.3	mm
initial charge	2	nC
peak field on cathode	140	MV/m
average energy	7.01	MeV
DLW1 parameters:		
relative permittivity	5.7	–
position	0.6	m
length	10	cm
inner radius	0.8	mm
outer radius	1	mm
mode wavelengths	2.19, 0.72, 0.41	mm
relative mode amplitudes	1, 0.51, 0.23	–
DLW2 parameters:		
relative permittivity	5.7	–
position	1.7	m
length	8	cm
inner radius	0.5	mm
outer radius	0.55	mm
mode wavelengths	0.74, 0.19, 0.11	mm
relative mode amplitudes	1, 0.23, 0.07	–

Ballistic Bunching Using a DLW

A critical component to high-gradient wakefield acceleration is the requirement for a high-peak-current bunch. The needed currents are typically one order of magnitude larger than those typically produced downstream of an RF gun. Several bunching techniques could be employed but given our requirement for compactness and limited use of external power, we use a passive ballistic bunching method based on a DLW structure as investigated in Ref. [8]. The parameters of the first structure (see DLW1 in Table 1 are chosen to ensure the relative amplitude of the first three modes are significant > 0.1 and the fundamental-mode wavelength (2.19 mm) approximately corresponds to the total bunch length. Additionally, the radius of the aperture (0.8 mm) is large enough to allow for the electron beam to be fully transmitted. This wavelength choice together with the presence of significant higher-order mode confer to the longitudinal phase space a square-waveform; see Fig. 2. During a subsequent drift

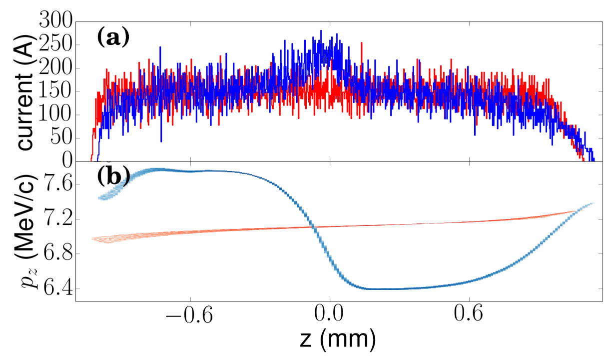

Figure 2: Longitudinal phase spaces (b) and current projection (a) before (red) and after (blue) DLW1 (with parameters listed in Table 1). The tail of the bunch corresponds to $z < 0$.

where ballistic bunching is at play, the center of the bunch will be compressed while the head and tail of the bunch will experience minor longitudinal displacements. The current profile immediately downstream of the DLW already shows sign of this "differential" compression: its center population has its peak current enhanced from ~ 150 to ~ 250 A; see current profiles in Fig. 2.

Acceleration with Compressed Bunch

Downstream of DLW1, the ballistic bunching occurs over a free-space drift of 1.1 m. The optimum locations and parameters of the following structure (DLW2) was empirically optimized to maximize the final energy of accelerated electrons in the tail. Finally, it should be noted that the evolution of the longitudinal phase space generates current profiles with complicated shaped which can be used in combination with multi-mode DLW structures to support higher transformer ratios. This ultimately increases the maximum beam energy which can be transferred from the bunch center to its tail.

Given the large parameter space constrained by these dynamical processes, we only present one optimal case devise

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via empirical optimizations. A more comprehensive study would undoubtedly lead to higher performances and will be carried with the help of a genetic optimizer. Our trial-and-error approach consisted in varying the structure parameter and its location, compute the produce wakefield and parameters that maximize the transformer ratio. An example of generated current profile (green trace) and associated wakefield (blue trace) appear in Fig. 3. The transformer ratio $\mathcal{R} \simeq 2.8$ is modest but the peak accelerating field experienced by electrons in the bunch-tail are on the order of 100 MV/m. The structure parameters are gathered in Ta-

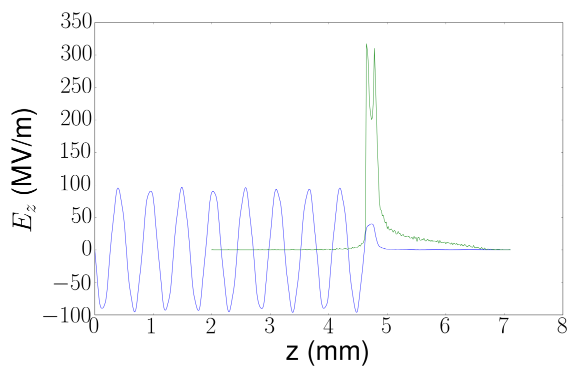

Figure 3: Longitudinal wake generated at the location of the second DLW (blue trace) from corresponding current (green trace). The tail of the bunch corresponds to $z < 0$.

ble 1. Compared to DLW1, DLW2 radius is twice as small and the dielectric-liner thickness is 50 μm resulting in a fundamental mode with wavelength ~ 3 times smaller. The small wavelength produces a modulated longitudinal phase space; see Fig. 4 (b). The modulation amplitude is comparable to the beam energy and results in highly nonlinear phase space distortions. The maximum energy reached by

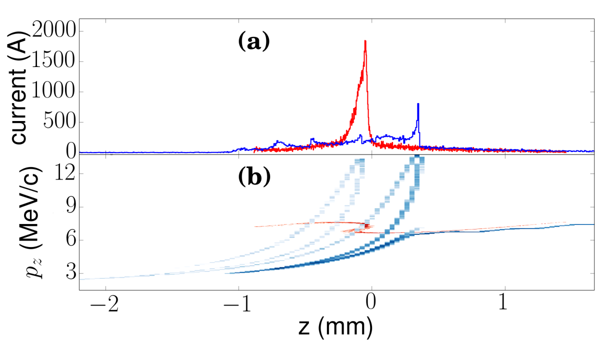

Figure 4: Longitudinal phase space (b) and current projection (a) of before (red) and after (blue) cascaded acceleration. The tail of the bunch corresponds to $z < 0$.

the electron in the tail is in excess of 12 MeV while the decelerated electrons have energies down to ~ 3 MeV. Other results showed larger final energies with correspondingly small decelerated-electron energies where dynamical wakefield effects would occur; a self-consistent particle tracking code would be necessary to investigate the properties of the bunch as it becomes non-relativistic.

Selection of Accelerated Population

Compared to a conventional drive-witness bunch, the scheme described in this paper uses part of the drive bunch to accelerate its trailing population rendering the final step of extracting the accelerated beam more intricate. Here we mentioned to possible selection processes. A first approach consists in placing a small dispersive section downstream of the DLW2 combined with a collimator. A second approach makes use of chromatic effects to differentially focus the accelerated population and defocus the rest of the beam. Both approaches are under consideration and their compatibility with high-repetition-rate operation needs to be fully assessed.

LIMITATIONS AND OUTLOOK

The "cascaded acceleration" technique proposed in this contribution seems promising. Its main advantage is the low amount of RF components. The scheme still has several challenges to overcome before its viability is fully assessed. These challenges include investigating the scaling between bunch parameters (e.g. charge, laser spot size etc) with appropriate choice of RF-gun, the investigation of transverse emittance growth, the improvement of transformer ratio (possibly using shaped photocathode laser as explored in Ref. [9]), and the investigation, via start-to-end simulation of possible options to select the accelerated population of the bunch (for further use in an inverse Compton scattering process). In addition, we have recently implemented the simulation in a particle-in-cell finite difference time-domain model based on WARP (Ref. [10]) to confirm the preliminary work carried with ASTRA. Finally, the operation of the proposed compact accelerator at high-repetition rate (limited by the RF gun) will have to be explored.

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