EXPERIMENTAL DEMONSTRATION OF BALLISTIC BUNCHING WITH DIELECTRIC-LINED WAVEGUIDES AT PITZ

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Abstract

We report on the experimental demonstration of ballistic bunching of photoinjected, nC-scale electron bunches at the PITZ facility. In the experiment, electron bunches emanating from the photocathode were directly focused into a mm-scale dielectric-lined waveguide. The wakefield excited by the bunch acts back onto itself, leading to an energy modulation, which at a relatively low energy of 6 MeV, is converted into a density modulation before entering the linac ~1 m downstream. We discuss the basic theory, experimental layout and results.

INTRODUCTION

High-impedance mediums such as dielectric-lined waveguides (DLWs), corrugated structures, and plasmas have attracted attention in the past decades for their versatile applications to charged particle beams. Techniques have demonstrated particle acceleration [1, 2] manipulation [3, 4] and diagnostic [5] capabilities. The foundation of these schemes relies on electromagnetic wakefields which are generated when a charged particle passes through the medium. In a DLW, the resulting longitudinal wake is given by the convolution of the current profile of the electron bunch $I(z)$ with the Green's function of the medium, $G_m(z) = \kappa_m \cos(k_m z)$,

$$W(z) = \sum_{m=1}^{N} \int_{-\infty}^{z} I(z - z') G_m(z') dz'. \quad (1)$$

Here κ_m is the loss factor of the m'th mode, $k_m = \frac{2\pi}{\lambda_m}$, where λ_m is the wavelength and N is the number of modes taken into account. The parameters κ_m and k_m depend on the transverse structure dimensions (a, b, ϵ_r) where a is the inner (vacuum) radius of the structure, b is the outer radius where the region bound by $a < r < b$ is filled with dielectric material with relative permittivity ϵ_r, finally the outer radius b is coated with a conductor, see Fig. 1 for schematic, and [6] for theoretical details.

Recently [7, 8], experimental demonstration of energy modulations in DLWs was observed at the ATF facility. In these experiments, a 130 pC, 57 MeV bunch was passed through a DLW; the resulting energy modulation was converted into a density modulation by using the appropriate longitudinal dispersion (R_{56}) of a downstream magnetic chicane.

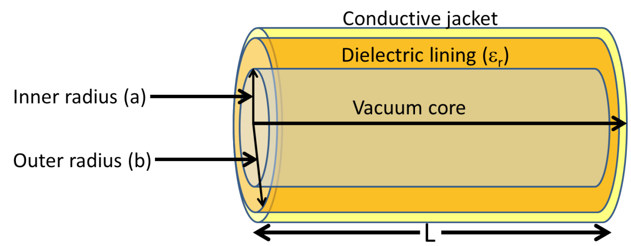

Figure 1: A cylindrical dielectric-lined waveguide (DLW) with dimensions (a, b, ϵ_r, L) is illustrated. The region $r < a$ is vacuum, $a < r < b$ is filled with dielectric material with relative permittivity ϵ_r and the outer radius is coated with a conductor. The length of the structure is L.

We report on a similar experiment at low-energies with higher charge. At low-energies e.g. sub-10 MeV, the non-ultrarelativistic nature of the beam results in significant velocity differences between the energy modulated electrons in the bunch; over a subsequent drift, these energy modulations can be converted into density modulations i.e. $R_{56}=\frac{z_d}{\gamma^2}$ where z_d is the drift length, and γ the Lorentz factor. Such an approach was investigated theoretically in Ref. [9].

The experiment, performed at the Photoinjector Test Facility at the DESY location in Zeuthen (PITZ) [11], focusses a ~6 MeV, 1.1 nC, 13 ps (FWHM) bunch directly from the electron gun into a DLW with dimensions (a, b, ϵ_r, L)=(450 μm, 550 μm, 4.41, 5 cm) . The imparted energy modulation was converted into a density modulation over a ~1 m drift before being relativistically frozen in a linac which increased the electron bunch energy to ~21 MeV. The pulse-stacking capability of the PITZ facility enabled the use of flat-top, super-Gaussian electron bunches [10]. In this paper we give a brief overview of the experiment and present some experimental results.

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Table 1: Accelerator Parameter Settings Relevant to the Experiment. Phases are listed with respect to the maximum-mean-momentum-gain (MMMG) phase.

Parameter	Symbol	Nominal	Unit
laser launch phase	ϕ_l	0	deg
laser diameter	d	2	mm
RF gun peak field	E_0	60	MV/m
max p_z at DLW	p_z^d	~6.5	MeV/c
linac phase	ϕ	0	deg
linac power	P	2.8	MW
linac peak field	E_1	18	MV/m
bunch charge	Q	1.1	nC
final beam momentum	p_z	20-24	MeV/c

EXPERIMENT AT PITZ

The PITZ facility is illustrated in Fig. 2 [11]. The 1.3 GHz RF-gun is operated at ~60 MV/m, yielding 6.54 MeV/c electrons from a high-quantum-efficiency Cesium Telluride photocathode illuminated by an ultraviolet laser pulse opti-

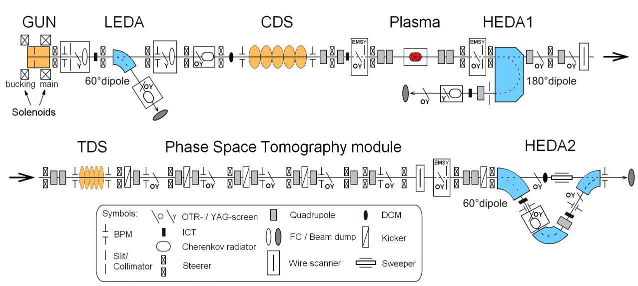

Figure 2: Experimental layout of the PITZ photoinjector. The acronyms "LEDA", "CDS", "HEDA" and "TDS" respectively refer to the "low energy dispersive area", "cut-disk structure", "high-energy dispersive area", and "transverse-deflecting structure".

mized to follow a plateau-like distribution with full-width half maximum (FWHM) duration $L_t \simeq 13$ ps.

The DLW is located at a distance of 1.5-m from the solenoidal lens surrounding the gun (i.e. 1.78 m from the photocathode) and is tuned to focus the beam at the center of the DLW structure for a charge per bunch $Q = 0.6 - 1.6$ nC, the rms beam size at the center of the structure is measured to be $\sigma_\perp^* = 130$ μm. The energy modulated bunches are further transported in a drift space and bunch ballistically before being accelerated in a L-band cut-disk structure (CDS) linear accelerator (linac) to a final energy of ~21 MeV. Downstream of the linac, a suite of beam diagnostics can be used to measure the beam phase-space distribution and associated parameters. The relevant parameters associated to the experimental setup are summarized in Tab. 1.

The main diagnostic employed in our experiment is an S-band (2.99 GHz) transverse deflecting structure (TDS) [12, 13]. The TDS vertically streaks the beam so that the vertical beam distribution measured on a YAG:Ce screen located ~ 1.5 m from the TDS centre is representative of the temporal bunch distribution given that the vertical coordinate of an electron is related to its axial position via $y \simeq \mathcal{S}\zeta$ where the shearing parameter $\mathcal{S}$ [14] is inferred from a beam-based calibration procedure. It should be noted that in the present experiment the temporal resolution of the streaking was ~ 1 ps.

A DLW mount and holder was designed and fabricated, see Fig. 3. The assembly was directly installed in a standard YAG-screen holder at a location 1.78-m downstream of the cathode. The fundamental wavelength of the DLW employed in our experiment was computed to be $\lambda_0 = 1.03$ mm.

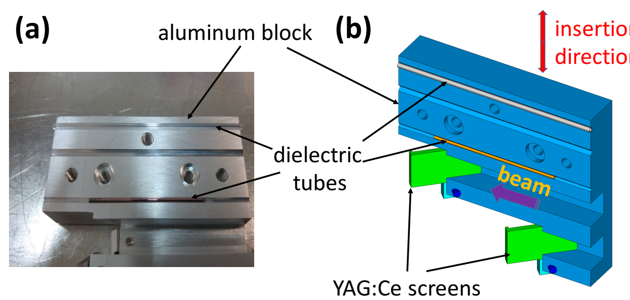

Figure 3: Picture (a) and schematic (b) of the DLW holder designed and built for PITZ. Here several tubes were mountable and YAG:Ce screens were used for beam-alignment. The mount was placed in an actuator for vertical alignment; horizontal and angular alignments were done upstream with beam steerers.

EXPERIMENTAL MEASUREMENTS

The TDS was essential to measure the time-resolved microbunching of the electron bunch. In our run we tried a variety of photocathode laser pulse lengths and distributions e.g. Gaussian and flat-top. The largest density modulations were observed for flat-top pulses; this is due to several reasons, (1) the spectral content of a flat-top pulse is larger which excites a stronger wake, (2) the reduced transverse emittance of the beam allows for more efficient transmission through the DLW and (3) longer bunches also produce more microbunches for the same wavelength.

In Fig. 4, we show the resulting calibrated current profile with and without the DLW. The contribution of the current profile is evident on the microbunching, where a strong asymmetric (head-to-tail – left-to-right) bunching is observed. This is due to the accumulated contribution of spectral content in the time-domain of the asymmetric bunch which leads to larger wake amplitudes across the bunch. Additionally, the strong dipole-modes which were excited from small misalignments contributed to fluctuations between the two zero-crossings of the TDS. This helped us correct the alignment into the DLW and mitigate the dipole mode by minimizing the difference in measurement resolution between the two zero-crossings. For the calibrated measurement we observed a maximum peak current of ∼150 A.

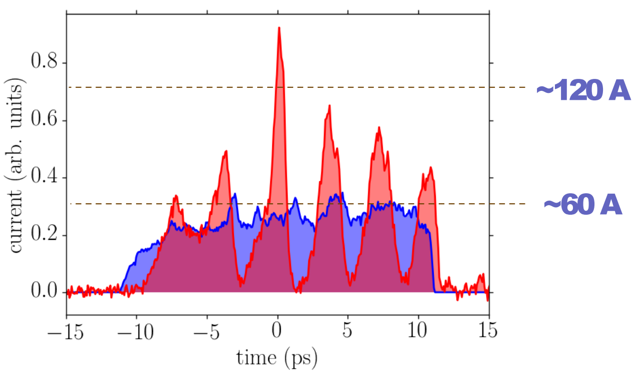

Figure 4: Current profile with (red trace) and without (blue trace) the λ=1.03 mm DLW; head of the bunch is on the left side i.e. negative time. The peaks are consistent with the wavelength of the structure ∼3.3 ps. The asymmetric bunching is due in part by the non-rectangular current profile and also from any curvature within the bunch bunch.

We transported the beam to HEDA2 to perform the longitudinal phase space (LPS) measurements; this was particularly useful to explore the impact of the linac phase on the electron bunch. In Fig. 5 we show the measured LPS with and without the DLW structure. Here the linac was operated 18° off crest to provide a quasi-linear head-tail correlation. The effect of the micro-bunching is apparent with the structure. In addition, the ability to impart a time-energy correlation with the linac points to potential applications in time-resolved imaging and multi-color FELs (where each microbunch has defined energy).

Finally, we note that we passed a bunch train with MHz repetition rate through the structure; no dynamical effects of the energy modulations or degradation of the DLW were observed.

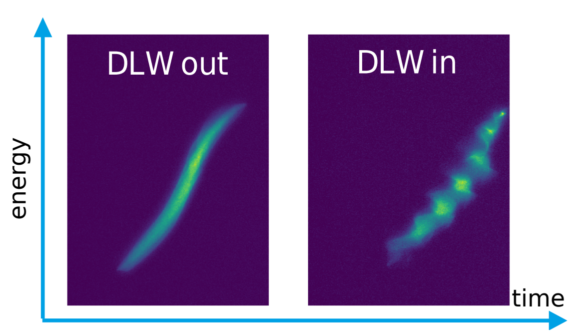

Figure 5: Uncalibrated longitudinal phase spaces without (left) and with (right) the DLW structure inserted in the beam path.

CONCLUSION

We have described a recent experiment on ballistic bunching using dielectric-lined waveguides at the PITZ facility. In the experiment, 1.1 nC, 6.54 MeV/c bunches from the rf gun were directly focussed and transmitted through a DLW with fundamental (TM) wavelength λ=∼1 mm. The transmitted, energy modulated bunches transform into density modulations over a ∼1 m drift before being relatvistically frozen in a LINAC. We were able to measure the longitudinal current profile and phase space of the bunch with a transverse deflection structure; we measured peak currents up to ∼150 A, nearly tripling the initial peak current of the plateau distribution. Such microbunched beams could have a wide-range of applications such as THz-generation and electron-diffraction imaging.

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