ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK060

TRANSVERSE-TO-LONGITUDINAL PHOTOCATHODE DISTRIBUTION IMAGING

A. Halavanau[1,2], G. Qiang[3,4], G. Ha[5], E. Wisniewski[3], P. Piot[1,2], J. G. Power[3], W. Gai[3],
[1] Department of Physics and Northern Illinois Center for Accelerator & Detector Development, Northern Illinois University, DeKalb, IL 60115, USA
[2] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3] Argonne Wakefield Accelerator, Argonne National Laboratory, Lemont, IL, 60439, USA
[4] Accelerator laboratory, Department of Engineering Physics, Tsinghua University, Beijing, China
[5] POSTECH, Pohang, Kyoungbuk, 37673, Korea

Abstract

In this paper, we present a tunable picosecond-scale bunch train generation technique combining a microlens array (MLA) transverse laser shaper and a transverse-to-longitudinal emittance exchange (EEX) beamline. The modulated beamlet array is formed at the photocathode with the MLA setup. The resulting patterned electron beam is accelerated to 50 MeV and transported to the entrance of the EEX setup. A quadrupole channel is used to adjust the transverse spacing of the beamlet array upstream of the EEX, thereby enabling the generation of a bunch train with tunable separation downstream of the EEX beamline. Additionally, the MLA is mounted on a rotation stage which provides additional flexibility to produce high-frequency beam density modulation downstream of the EEX. Experimental results obtained at the Argonne Wakefield Accelerator (AWA) facility are presented and compared with numerical simulations.

INTRODUCTION

A controllable electron bunch train is often required in light sources, dielectric wakefield and electron cooling setups [1–7]. Previously, it was demonstrated that transverse-to-longitudinal emittance exchange beamline can be utilized for such beam tailoring [8–10].

We have recently investigated the use of microlens arrays in transverse laser shaping and developed a method of generating a multi-beam array [11]. In this paper we extend these studies to the case of EEX setup located downstream of the 50 MeV photoinjector. First, a multi-beam array is formed and transported to the EEX entrance. Then due to the exchange of phase spaces $(\mathbf{X}, \mathbf{X}') \leftrightarrow (\mathbf{Z}, \delta')$ initial transverse modulation is converted into longitudinal modulation. By varying the transverse spacing of the beamlets and its projection onto x-axis upstream of the EEX, the bunch train separation can be tuned accordingly.

A typical EEX setup consists of two dipoles (first "dogleg") that followed by a time deflecting cavity (TDC1), which is in turn followed by two more dipoles (second "dogleg"). In order to register the resulting time domain profile, a second time deflecting cavity (TDC2) followed by a viewer was used downstream of the EEX setup; see Fig. 1.

Under thin-elements approximation the mapping between $(\mathbf{X}, \mathbf{X}') \leftrightarrow (\mathbf{Z}, \delta')$ occurs while $(\mathbf{Y}, \mathbf{Y}')$ phase space being unaffected by the exchange. EEX phase space transformation can be explicitly written as:

$$z = -\frac{\xi}{\eta}x_0 - \frac{L\xi - \eta^2}{\eta}x_0', \quad \delta = -\frac{1}{\eta}x_0 - \frac{L}{\eta}x_0', \qquad (1)$$

where (η, ξ) are horizontal (vertical) dispersions, (x_0, x_0') is the particle's initial position in transverse phase space, (z, δ) is the corresponding position in the longitudinal phase space. Thus, a modulation in x-projection of the particle distribution will result in bunch train formation. In this paper we utilize EEX setup at the Argonne Wakefield Accelerator (AWA) facility and optical laser transverse shaping for tunable bunch train formation.

MULTI-BEAM FORMATION

Multi-beam array is formed by the MLA setup and optical transport deployed at AWA facility and described in detail in [11]. In brief, the setup consists of two MLA plates placed with s=3 mm sepration, a convex lens that forms the resulting shaped laser spot, and a 4-lens optical transport that projects the MLA-formed laser spot onto Cs:Te the photocathode. Note, that nominally two MLA plates are configured to produce transversely homogeneous laser beam that improves electron beam quality at AWA. Previously, it was demonstrated that inital multi-beam separation of $d \approx 2$ mm at the photocathode is fully contained at the energy of up to 50 MeV at charges below Q =250 pC [11]. A further increase of charge cause pattern distortion due to collective space-charge effects and eventually mitigates the transverse modulation. In order to rotate the multi-beam distribution, the MLA setup was placed on a rotatable mount. Note, that rotation via solenoidal lens alters the spacing between beamlets along with rotation due to its imaging properties, therefore laser pattern rotation is needed.

EXPERIMENTAL SETUP

Transverse EEX experimental setup was built and commissioned at AWA facility as a part of AWA drive beamline (AWA-DB) [8, 12]. Prior to the experiment, a few electron beam studies were performed. Homogenized round beam emittance was measured with a scanning slit method and reported in [11]. Bunch length measurements for round and

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK060

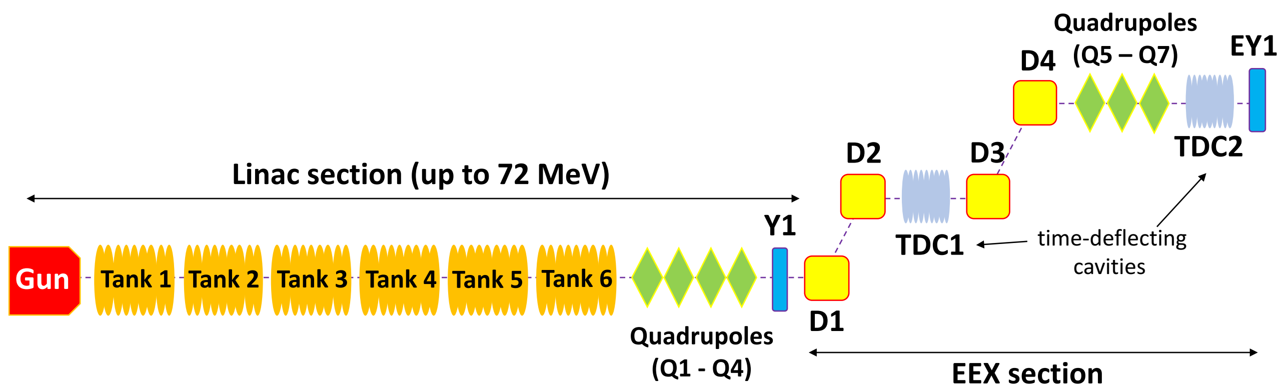

Figure 1: The AWA-DB beamline layout with the EEX setup. D1-D4 represent the double dogleg emittance exchange setup, and Y1/EY1 are the viewers up-/downstream of the EEX setup.

Table 1: Electron Beam and Machine Parameters of the AWA-DB Beamline

Parameter	Symbol	Value	Units
Energy	E	46.7 ± 1	MeV
Energy spread	σ_E	0.07 ± 0.03	%
Bunch duration (round beam, Q=250 pC)	σ_t	1.4 ± 0.1	ps
Bunch duration (multi-beam, Q=250 pC)	σ_t	1.2 ± 0.1	ps
Norm. vertical emit. (1 nC)	ε_x	11.6 ± 4.3	µm
EEX horizontal dispersion	η	0.9	m
EEX vertical dispersion	ξ	0.33	m
Time-deflecting cavity voltage	V_{TDC}	4.1	MV
Time-deflecting cavity resolution	τ	0.5	ps

multi-beam were performed with a Michelson autocorrelator [13] and the signal was detected with Helium-cooled bolometer. Bunch energy and energy spread were measured with a dipole D1 depicted in Fig. 1. The resulting electron beam properties are reported in Table 1.

Figure 2 depicts the initial laser distribution with the separation $d = 2.5$ mm that was imaged onto the photocathode. In the experiment, a $Q = 250$ pC multi-beam was formed and accelerated by L-band RF-gun and 4 L-band cavities up to the energy of 46.7 MeV. Accelerating cavities 4 and 6 were turned off during the experiment; see Fig. 1. Initial Larmor rotation in the RF-gun was compensated with a rotatable stage to ensure the multi-beam orientation is upright at the entrance of the EEX setup. The beam was then propagated through a quadrupole channel and further through the EEX setup; see Fig. 1.

QUADRUPOLE IMAGING

In order to tune the multi-beam array spacing upstream of the EEX, a quadrupole channel is used; see Q1-Q4 in Fig. 1. To demonstrate the quadrupole matching downstream of the EEX, for simplicity, a middle row of the laser distribution is masked; see frame in Fig. 2. We refer the reader to Ref. [10] where this process was explored in a great detail. Quadrupoles 1 and 4 are used to match the beam at the EEX entrance. Quadrupole 1 current is varied in range of 700 to 1350 mA, while Quadrupole 4 current is set to −700 mA. These settings allow a beam waist at the EEX entrance and large beamlet separation at the upper(lower) current limit. As it can be inferred from Fig. 3, an initial beamlet separation at the photocathode of $d = 2.5$ mm can be translated into the range of bunch train separation from sub-ps scale to 6 ps. Thus, the quadrupole imaging method can be considered for 1:1 imaging of the transverse photocathode laser distribution into time domain. Alternatively, it can be seen as a method of sub-ps scale bunch train generation. One can notice the linearity of the separation scaling and the following EEX time conversion indicating wide range of bunch train separation achievable in such a setup. Additionally, the ratio between the two curves in Fig. 3 gives the compression ratio which was found to be $\eta = 0.33$. This value matches the theoretical compression ratio of the AWA EEX setup.

HIGH-FREQUENCY HARMONICS GENERATION

In this section we will describe a technique to achieve tunable separation of the bunch train through multi-beam rotation. The MLA setup was configured for multi-beam generation and placed on a rotatable mount. A rotation of the MLA yields in rotation of the laser pattern on the photo-

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK060

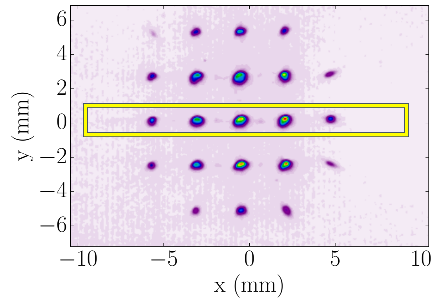

Figure 2: Laser spot shaped in square multi-beam configuration with the MLA setup. The beamlet separation is set to be $d = 2.5$ mm. The yellow frame corresponds to the row of beamlets selected for quadrupole imaging experiment.

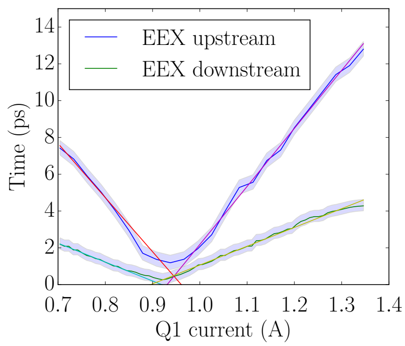

Figure 3: Calculation of the EEX setup compression ratio. The transverse modulation converted in time upstream of the EEX is compared against the time domain modulation downstream of the EEX as a function of quadrupole current.

cathode surface. For the case of a square arrangement, given the symmetries of the initial laser distribution, a rotation within 0-45 degrees is needed to explore the entire possible frequency range.

We start with an upright multi-beam orientation which results in 5 nominal peaks displayed in Fig. 2. In this case, the bunch train separation generated by the EEX setup is equal to $\tau = 5$ ps. As it can be inferred from Fig. 4, the corresponding bunch train time separation at $\theta = 45$ degress is $\tau = 3.5$ ps. Thus, via electron beamlet pattern rotation,

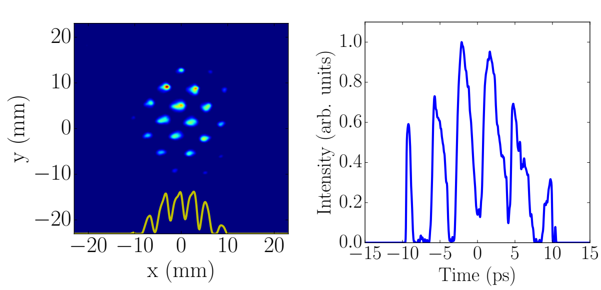

Figure 4: Rotated multi-beam pattern and its x-projection (left). Measured bunch-train time profile (right).

one can tune the bunch length separation downstream of the EEX.

SUMMARY

We demonstrated two simple and robust techniques for tunable bunch train generation in transverse-to-longitudinal emittance exchange setups using a multi-beam formed by a microlens array. In particular, we showed that quadrupole imaging can generate bunch train in sub-ps to several ps range, with possible 1:1 imaging of the photocathode laser distribution in time domain. Additionally, we verified that multi-beam rotation yields to sub-ps scale bunch train generation. We conclude that this simple and inexpensive optical setup along with EEX beamline has a wide range of applications requiring tunable bunch train generation.

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy under contract No. DE-SC0011831 with Northern Illinois University. The work by the AWA group is funded through the U.S. Department of Energy, Office of Science, under contract No. DE-AC02-06CH11357. The work of A.H. and partially P.P. is supported by the US Department of Energy under contract No. DE-AC02-07CH11359 with Fermi Research Alliance, LLC.

REFERENCES

[1] V. N. Litvinenko and Y. Derbenev, *Phys. Rev. Lett.*, **102**, p. 114801, (2009).

[2] L.-H. Yu, *et al.*, *Science*, **289** (5481), pp. 932–934, (2000).

[3] C. Jing, *et al.*, *Phys. Rev. Lett.*, **98**, p. 144801, (2007).

[4] P. Piot, *et al.*, *Phys. Rev. Lett.*, **108**, p. 034801, (2012).

[5] J. G. Power, Wei Gai, and P. Schoessow, *Phys. Rev. E*, **60**, pp. 6061–6067, (1999).

[6] M. Tzoufras, *et al.*, *Phys. Rev. Lett.*, **101**, p. 145002, (2008).

[7] S. Antipov, *et al.*, *Phys. Rev. Lett.*, **112**, p. 114801, (2014).

[8] P. Piot, Y.-E Sun, J. G. Power, and M. Rihaoui, *Phys. Rev. ST Accel. Beams*, **14**, p. 022801, (2011).

[9] Y.-E. Sun, *Angular-momentum-dominated electron beams and flat-beam generation*. PhD thesis, Chicago U., (2005).

[10] T. J. Maxwell, *Measurement of Sub-Picosecond Electron Bunches via Electro-Optic Sampling of Coherent Transition Radiation*, Ph.D. thesis, Northern Illinois U., 2012.

[11] A. Halavanau, *et al.*, Spatial control of photoemitted electron beams using a microlens-array transverse-shaping technique. *Phys. Rev. Accel. Beams*, 20:103404, Oct 2017.

[12] P. Emma, Z. Huang, K.-J. Kim, and P. Piot, *Phys. Rev. ST Accel. Beams*, **9**, p. 100702, (2006).

[13] D. Mihalcea, C. L. Bohn, U. Happek, and P. Piot, *Phys. Rev. ST Accel. Beams*, **9**, p. 082801, (2006).