ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG47

CHARACTERIZATION OF LOW-EMITTANCE ELECTRON BEAMS GENERATED BY A NEW PHOTOCATHODE DRIVE LASER SYSTEM NEPAL AT THE EUROPEAN XFEL

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Abstract

An ultrafast laser system for driving the photocathode RF gun at the European XFEL has been recently put into operation. The new laser system, NExt generation PhotocAthode Laser (NEPAL) is capable of providing drive laser pulses of variable pulse lengths and shapes, supporting the facility to extend its capabilities to operate in multiple user-desirable FEL modes. In this paper, we present a preliminary characterization of the low-emittance electron beams produced by NEPAL in the photoinjector. Both experimental and numerical results will be presented and discussed.

INTRODUCTION

A photocathode drive laser system is prevalently utilized to drive a photocathode radio-frequency (rf) electron gun and a laser heater of modern hard X-ray Free-Electron Laser (XFEL) facilities. The reliability, stability and functionality of such a laser system is a key factor to operating XFELs for present user experiments and to developing novel FEL concepts [1, 2]. An ultrafast laser system, NExt generation PhotocAthode Laser (NEPAL), for driving the photocathode RF gun of the European XFEL has been recently put into operation. Similar systems have also been installed at different facilities at DESY. An insight to the NEPAL system can be found in [3].

The paper is organized as follows. First experimental and numerical results are presented on characterising electron bunch qualities in the NEPAL driven photoinjector of the European XFEL. Besides its main role in the user operation, NEPAL is still on a continuous development stage towards its full design capabilities. A perspective is then given on a possible improvement in the electron bunch quality benefiting from the increase of the present laser pulse length at the photocathode. Furthermore, an outlook is inspired on the potentials of unlocking the temporal pulse shaping capability of the NEPAL system and thus on a resulting combined temporal and transverse pulse shaping approach.

ELECTRON BUNCH CHARACTERIZATION

The photoinjector of the European XFEL mainly consists of a photocathode RF gun, a first accelerating module A1, a third-harmonic module AH1, a laser heater and multiple diagnostic components, as shown in Fig. 1(a). A detailed description can be found in [4]. To benchmark the initial performance of the NEPAL system, electron bunch qualities are generally optimized and measured in the photoinjector. Relevant measurement procedures are introduced in [5]. Specifically, the electron bunch length and the peak current are measured using a transverse deflecting structure (see Fig. 1(a)). Different cathode peak accelerating gradients of the gun, 55 MV/m, 57.5 MV/m and 60 MV/m are taken into account. The transverse projected emittance is measured using a multi-quadrupole scan method [6]. The emittance optimization in this case accounts for the variation of the gun solenoid strength and the RF gun phase for 250 pC bunch charge at 130 MeV. A1 and AH1 are set on-crest phasing for these measurements. An estimated laser pulse length of 5 ps FWHM is assumed in the relevant simulations included in Fig. 1. The applied temporal and transverse shape of the laser pulse is Gaussian and radial uniform, respectively. The beam spot on the cathode is 1 mm in diameter.

Figure 1 (b) shows that the measured rms bunch length is about 4.6 ps and 17.5 A at 250 pC for a nominal cathode gradient of 57.5 MV/m. Varying the cathode accelerating gradients, the simulated bunch lengths still fairly agree with the measured ones. Higher accelerating gradient results in shorter bunch length and higher peak current. Figure 1 (c) shows that the measured and simulated tendencies of the transverse emittance over the rf gun phase agree with each other. The measured smallest emittance is about 0.36 µm. The cathode accelerating gradient is set close-to a nominal value of 57.5 MV/m. This result is in good consistent with the simulated emittance of the 95% bunch core. Figure 1 (d) illustrates the transverse projected emittance of the 100%, 95%, 90% and 80% core of the simulated bunch. The simulations suggest a large halo area of the bunch which contributes a lot to the overall projected emittance (see also the inset). This is observed for the cases at 55 MV/m and 60 MV/m as well.

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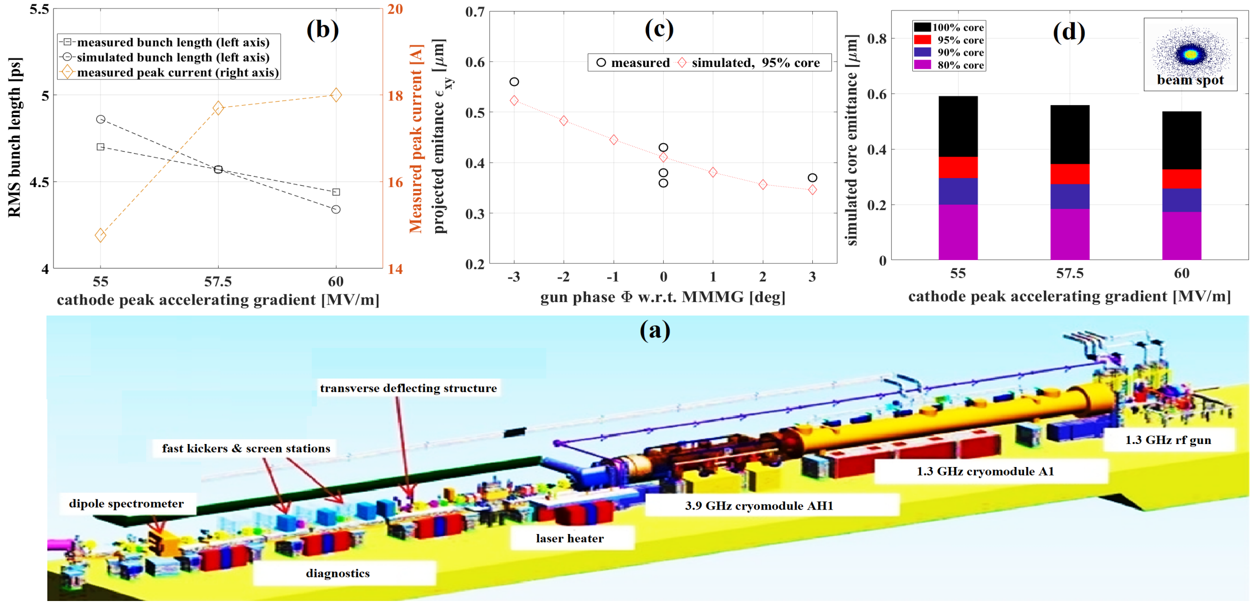

Figure 1: Electron bunch quality optimization in the EuXFEL photoinjector. (a) Layout of the injector section; (b) Measured and simulated bunch length and peak current at different cathode accelerating gradients; (c) Measured and simulated transverse projected emittance at a cathode accelerating gradient of 57.5 MV/m; (d) Simulated core emittance at different cathode peak accelerating gradients with an inset standing for a transverse beam spot.

VARIABLE PULSE LENGTH

A fully developed NEPAL system is capable of providing variable laser pulse lengths as well as adjustable temporal and transverse shapes at the photocathode. At the current stage, the application of a 5 ps cathode laser pulse of temporal Gaussian and transverse uniform distributions appears sufficient to deliver fairly good emittance of the produced electron bunch and to meet basic requirements of the FEL to lase at requested photon wavelengths below 20 keV. The lasing performance using the present version of NEPAL is compatible to the old laser system (namely Laser2), which allows an easy switch-over between the two laser systems. However, further system development of NEPAL, including a parallel installation of a second NEPAL system as an R&D laser and a backup operation laser, is still needed as a mid- or long-term interest to further improve the bunch emittance for operating the FEL in a deeper sub-angstrom regime towards 40 keV [7]. In this section, we explore a possible improvement in the bunch emittance via beam dynamics simulations by increasing the length of the cathode laser pulse to 20 ps [3], temporally still with a Gaussian shape. In this study, a transverse truncated Gaussian distribution of the laser pulse is assumed, which goes along with an expected result from a planned transverse laser pulse shaping task at the EuXFEL. Detailed simulation parameters and conditions are summarized in Table 1.

Figure 2 shows the optimization results: (a) the simulated slice emittance of the produced electron bunches at the injector exit varying the cathode laser pulse lengths from 11 ps to 20 ps using a truncated Gaussian transverse distribution (see the inset), and (b) the relative reduction in the central slice emittance as increasing the pulse length. The two dashed lines in (a) mark the levels of the cathode thermal emittance in different cases. It can be seen, that the central slice emittance gets smaller as increasing the laser pulse length. The best central slice emittance is below 0.2 µm for a laser pulse length of 20 ps. Plot (b) illustrates the effect that the benefit to get smaller emittance via prolonging the laser pulse length gets less pronounced on the way to 20 ps. A pulse length of about 15 ps could be a sweet spot where one can take the most advantages while reducing more needed technical efforts going towards even longer pulse lengths. In the following section, an outlook on cathode laser pulse shaping with NEPAL is given.

OUTLOOK ON CATHODE PULSE SHAPING WITH NEPAL

It is well recognized that cathode transverse laser pulse shaping is highly effective for reducing the space-charge contribution to the overall emittance budget of the electron bunch [8]. For the simulation results presented in Fig. 2, transverse shaped electron bunches via transverse cathode laser pulse shaping are already used for minimizing the bunch emittance. In Fig. 3, the space-charge portion of the overall emittance (same data as in Fig. 2) is explicitly re-plotted at different cathode laser pulse lengths. It can be seen that the space-charge induced emittance growth is down the stair curve as increasing the cathode laser pulse length. For a pulse length of 20 ps, the space-charge portion is about 15%. To further reduce the overall emittance without further increasing the cathode laser pulse length, the temporal laser pulse shaping, besides the transverse pulse shaping, must

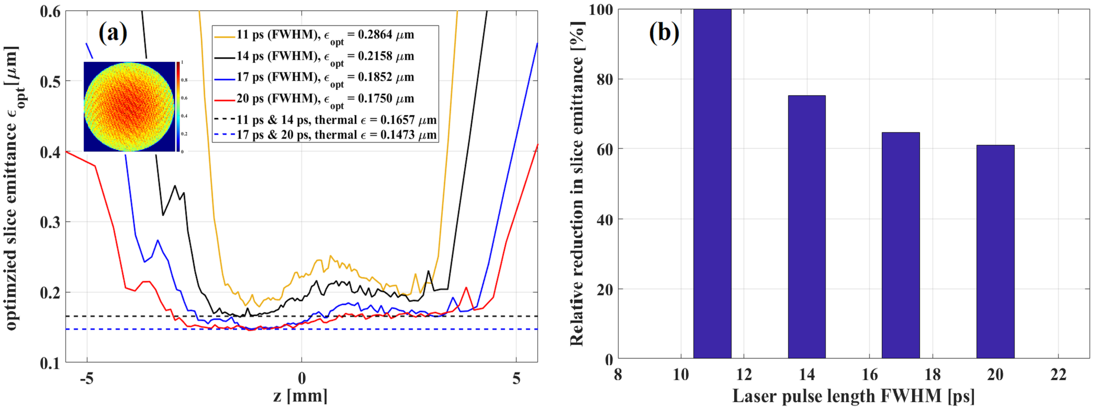

Figure 2: Simulation results for electron bunches with temporal Gaussian shapes of different lengths at the photocathode: (a) optimized slice emittance of the bunches using different pulse lengths at the cathode; (b) Relative reduction in central slice emittance as increasing the pulse lengths at the cathode.

Table 1: Simulation Parameters and Conditions

Parameter	**Value**	**Unit**
Laser pulse temporal shape	Gaussian	n/a
Laser pulse length[1]	11 - 20	ps
Laser pulse transverse shape	Truncated Gaussian	n/a
Laser pulse transverse spot size[2]	0.6 - 1.0	mm
Bunch charge	250	pC
Electron beam energy	130	MeV
RF gun gradient	58.5	MV/m
RF gun phase[3]	-4 - +4	deg

[1] in full width half maximum; [2] size of the beam shaping aperture in diameter; [3] with respect to the maximum mean momentum gain phase.

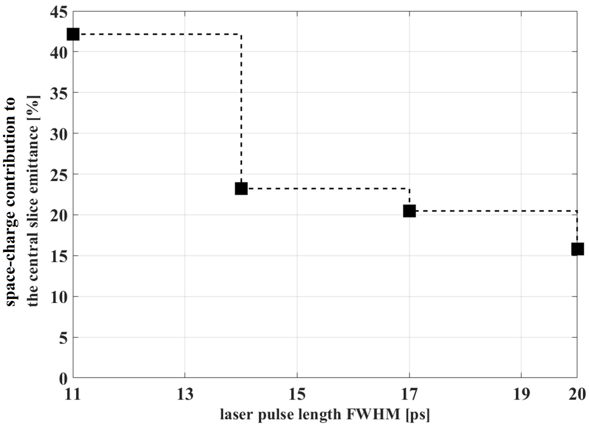

Figure 3: Simulated space-charge contribution to the central slice emittance using different laser pulse lengths.

also come into play. A combined temporal and transverse shaping approach of the cathode drive laser pulse would principally bring the overall bunch emittance further down to the cathode thermal emittance, a fundamental limit of the smallest possible emittance.

Specifically, the incorporation of a so-called waveshaper [9], a tunable optical filter allowing for full control of the amplitude and phase spectra across the wavelength range of interest, with the NEPAL system enables temporal shaping of the cathode laser pulse. In principle, arbitrary temporal shapes can be realized. In the transverse direction, the application of a laser beam shaping aperture (BSA) and the control of the laser beam size upstream the BSA via a telescope setup [10] can shape the transverse distribution of the cathode laser pulse to different shapes such as Gaussian, uniform or truncated-Gaussian.

A proof-of-principle numerical experiment is performed in [11] in the context of the future continuous-wave (CW) operation of the EuXFEL. Temporal-flattop shaped and transverse-truncated-Gaussian shaped electron bunches are used for optimizing an superconducting RF gun based CW injector. As a result, given practically valid simulation parameters, the overall transverse projected emittance of the shaped electron bunch can be reduced to the level of the cathode thermal emittance. Such a combined transverse (2D) and temporal (1D) shaping approach is now foreseen as part of the mid-term development of the EuXFEL facility.

ACKNOWLEDGEMENTS

We thank all the involved colleagues from the European XFEL and DESY, who have contributed in successfully commissioning the NEPAL-X system of the facility.

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